Control Strategy of Fuel Cell/Supercapacitor Hybrid Propulsion System for an Electric Vehicle

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Abstract-This work aims to develop an energy management approach (EMA) for a fuel cell vehicle whose main role is to reduce the fuel consumption of the main element source. To achieve this goal, the proposed technique and whose main role is to guarantee the configuration of the most optimized system in order to manage the flow of energy between the different sources. Thus, the integration of storage device as solution guarantees continuity of energy production and in order to benefit as much as possible to minimize the hydrogen consumption. The results obtained by simulation show the effectiveness of the EMA and also proves an almost 51 % gain in hydrogen consumption.

KeywordsPEM Fuel Cell, storage device, Powertrain, supervisory technique.

1. Introduction

FCEV are a very efficient solution especially in vehicular applications that no pollutants are emitted [1, 2, 3].This type of vehicles exploits the advantages of PEMFCwhich is the preferred choice. This latter presents different advantages such as: high efficiency, low-temperature operation and are clean functioning [4, 5].

Thanks to the different advantages of fuel cell systems, especially a Proton Exchange Membrane (PEM) which presents the best candidate and a very efficient solution especially forvehicularapplications [6, 7, and 8]. However, a PEMFC have a slow dynamic response which keeps it from responding quickly.

Besides, the integration of auxiliary energy source guarantees to overcome these problems and provide high efficiency [9, 10, and 11].For this reason, many researchers were oriented towards using at least one additional storage energy working with fuel cell in order to guarantee power production for power train during transient phases and in order to minimize of hydrogen consumption[12, 13].Thispower sourcepresent very effective solution in solving the dependence of fuel cell power generation on different driving cycle and allow the main energy source to have more flexible and reliable working performance [14, 15].

Therefore,an Energy Management Approach (EMA) is always needed for electric vehicle powered with different energysource in order to manage the energy flow from different sources to supply the motor [16,17].

The importance of using an efficient EMA resides in providing enough to cover the power load demand during the different driving phases. This latter must be always developed in a way that ensures that the fuel consumption of the main energy source as low as possible.

The work presented in this paper, focused on the synthesis of an Energy Management approach (EMA) for an electrical vehicle system powered by a fuel cell energy source with storage element device. Itwill spree over three sections organized as follows:

In the second section, we will devote to present the studied energy system. In this context, the different mathematical models of FC generator and supercapacitor will presented.

Then, the Section.3 will devote for the control strategy description. For this, two controls loop will develop for each of these parts:

- The first one control loop is used to ensure the speed control of the PMSM based on the direct flow oriented control (FOC).

- The second one is based on two controllers at the level of the fuel cell and supercapacitor devoted to ensure its generated power to the DC interface level.

Finally, we will devote in section.4 to present the proposed EMA and describe their principle operation.

2. PEM fuel cell/SC electric vehicle configuration

The studied system in our work is composed of a hybrid energy source feeding a power train system as shown in Fig.1.

In this respect, the present work consists in integrating a second energy storage device into a power train in terms to guarantee a power production andminimizing the fuel consumption. This auxiliary source chosen is a supercapacitor.

Then, in order to guarantee an optimized operation of the system, a proposed control strategy is implemented to manage the flow of energy between the different sources and in order to limit the use of the fuel and benefit as much as possible the storage element.

Thus, the developed approach isused in order to control the different sources and the power train system through the different static converters. The detailed controls structure and the proposed energy management algorithm will be treatedand demonstrated in our work.

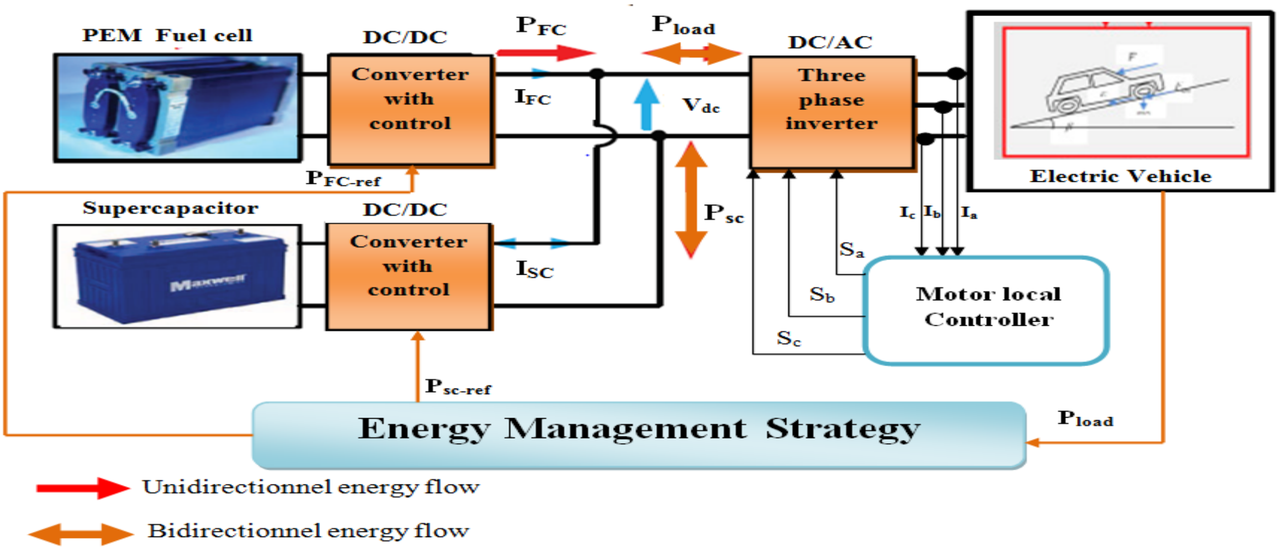

Fig.1. The studied system configuration

2.1. Power source modeling

2.1.1. PEM Fuel cell modeling

Based on the given electrical circuit in fig.2, the fuel cell generated voltage can be calculated as in (1) [18]

$$V_{Cell} = E - V_{con} - V_{act} - V_{ohm} \quad (1)$$

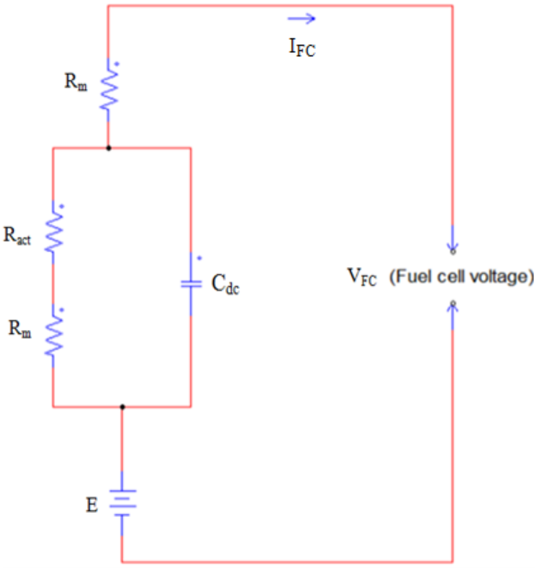

Fig. 2.PEMFC electrical circuit model.

With:

$$E = E^0 + \frac{RT}{F}\ln\left(\frac{PH_2PO_2^{0.5}}{PH_2O}\right) \quad (2)$$

- V_{con}: Gazes Concentration losses given by (7).
- V_{act} : Activation losses given by (3).
- V_{ohm} :Ohmic losses given by (5)

$$V_{act} = [\xi_1 + \xi_2.T + \xi_3.T.\ln(CO_2) + \xi_4.T.\ln(I)] \quad (3)$$

ξ_iRepresent parametric coefficients for each cell model

The concentration of oxygen is calculated according to[18]:

$$CO_2 = \frac{PO_2}{5.08\times10^6 e^{-498/T}} \quad (4)$$

The ohmic voltage is expressed by: [19]

$$V_{omh} = R_m I \quad (5)$$

$$R_m = \frac{\rho M.l}{A} \quad (6)$$

The concentration voltage is defined as : [19]

$$V_{con} = -B\left(1 - \frac{J}{J_{max}}\right) \quad (7)$$

Where:

- R_{conc}: Concentration resistor.
- R_{act}: Activation resistor.
- R_{ohmic}: Ohmic resistor.
- V_{FC}: Fuel Cell Output Voltage.
- E: Theoretical potential of the Cell.
- R: perfect gas constant = 8.14 J/K/mol
- T: Operating temperature of the cell.
- F: Faraday constant = 96485 C/mol.

-J, J_{max}: Current density and Current maximal density (A/cm^2)

The mathematical model of fuel cell is presented in fig.3.

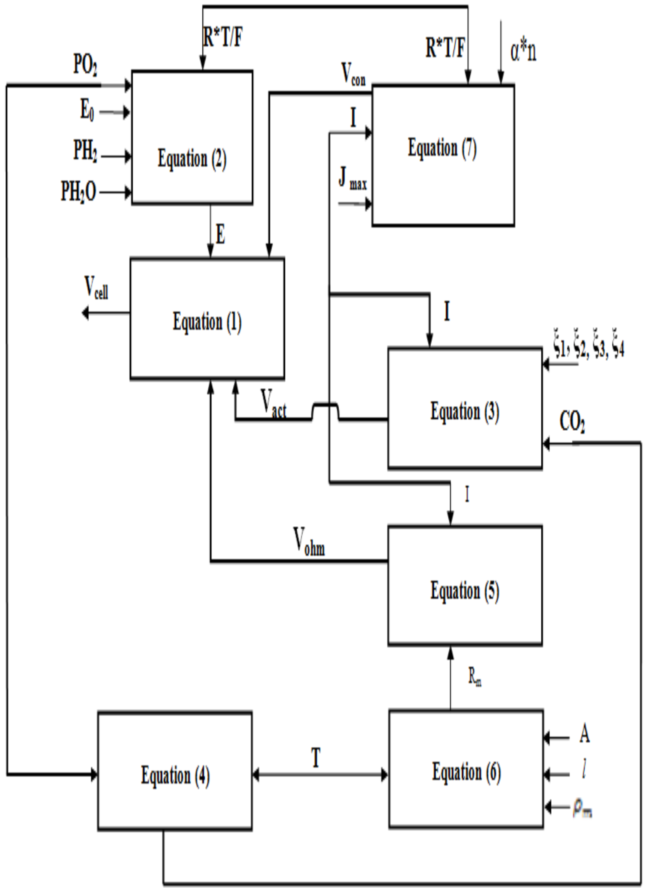

Fig.3.mathematical model of PEM fuel cell

Different parameters of the PEMFC model used in this work are given in Table.1.

Table 1. Characteristics of the studied Fuel cell [8]

PEMFC parameters	
Nominal power	85KW
Number of cell	400cell
Temperature	60°C
Air pressure	2bar
Hydrogen pressure	2bar

2.1.2. Supercapacitor modeling

Figure.4 presents the electrical supercapacitor (SC) circuit [19,20]. It is the simplest equivalent circuit model which is a simply made of an of a capacitance C_{sc}, a series resistance R_{sc}.

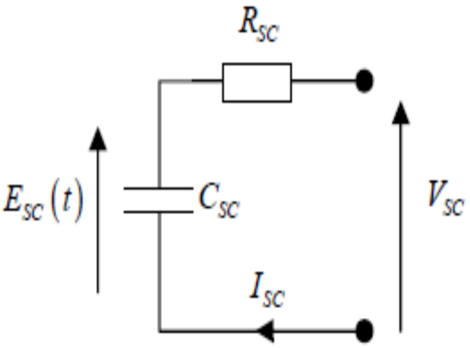

Fig.4. Simplified model of the SC

The output voltage of the SC is expressed in (8): [20]

$$V_{sc} = E_{sc} - R_{sc} I_{sc} \tag{8}$$

The open circuit voltage is determined as in (9): [20]

$$E_{sc} = E_{sc}(0) - \frac{1}{C_{sc}} \int_0^t i_{sc}\, dt \tag{9}$$

The instantaneous power delivered at the SC output is expressed by (10): [20]

$$P_{sc} = V_{sc} I_{sc} \tag{10}$$

The single cell's current can be calculated by (11):

$$i_{sc} = \frac{V_{sc}}{2R_{sc}} - \frac{1}{2R_{sc}} \sqrt{V_{sc}^2 - 4R_s.P_{sc}} \tag{11}$$

Moreover, the state of charge (SOC)is expressed by (12):

$$SOC_{sc} = \frac{X_{sc}}{X_{sc-max}} = \frac{\frac{C_{sc}\, E_{sc}^2}{2}}{\frac{C_{sc}\, E_{sc-max}^2}{2}} = \frac{E_{sc}^2}{E_{sc-max}^2} \tag{12}$$

Where:

R_{SC}:Internal resistance of SC (ohm)

C_{sc}: The supercapacitor of SC (F)

The supercapacitor mathematical synoptic scheme is presented in fig.5.

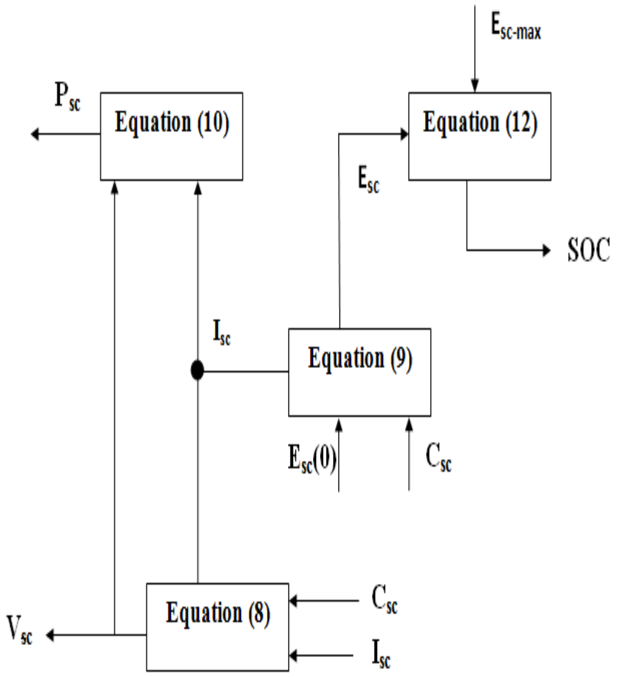

Fig.5.Supercapacitor mathematical model

2.1.3. Power train modeling

The traction force is given by (13): [21, 22]

$$F_{traction} = F_{mot} - F_{res} \qquad (13)$$

Where $F_{mot}$is the acceleration force given by (14):

$$F_{mot}(t) = \frac{C_{roue}}{R_{roue}} \qquad (14)$$

The resisting forces (F_{res}) given by (15) depending on of the aerodynamic force (F_a) and rolling resistances of mounted side (Fs) the friction force to the advancement (Fr).

$$F_{res}= F_p+F_a+F_r \qquad (15)$$

Where: the following forcesF_r, $F_a$and $F_p$are given by 16, 17 and 18 [22]

$$\begin{cases} F_r(t) = M_{Veh}gC_r\cos(\alpha(t)) & (16) \\ F_a(t) = \frac{1}{2}\rho_{air}A_fC_xV_{Veh}^2(t) & (17) \\ F_p = M_{Veh}g\sin(\alpha(t)) & (18) \end{cases}$$

The fundamental principle expression given by (19):

$$\frac{dv}{dt} = \frac{F_{mot}-F_{res}}{M_{veh}} \qquad (19)$$

The vehicle demand power is given as:

$$P_m = \frac{F_{mot}V_{veh}}{\eta_{red}} = \frac{(F_r+F_a+F_p+M_{Veh}\frac{dV_{veh}}{dt})V_{veh}}{\eta_{red}} \qquad (20)$$

With:fr is the resistance of the tire rolling, $A_f$is the frontal surface area of the vehicle, C_x is the aerodynamic parameter, M is the total mass and α is the road slope angle.

Table.2 presents the parameters of the FCEV vehicle used for this study [8].

Table 2. Differentmodelparameters

Parameters	Symbol	Value
Rolling resistance force constant		$0.01s^2/m^2$
Air density	ρ_{air}	$1.2kg/m^3$
Frontal surface area of the vehicle	C_x	$0.3m^2$
Aerodynamic drag coefficient	A_f	2.6
Acceleration due to gravity	g	$9.8m/s^2$

3. Control Strategy Description

3.1 Power sources converters control

The developed control system shown in Fig. 7 is composed of a two DC-DC converters controlled by a PWM signal generator which generates for these latter a control signals. Thus, the control structure developed given in Fig.7 is composed of:

- Power sources: a PEM fuel cell generator and a supercapacitor storage system used to adapt the generated power to the DC interface level.

- A supervisory system: which is based on developed EMA used in a way to achieve these main objectives:

- Optimized working performance during different driving cycle of the vehicle.
- Generated two output variables: a references power ($P_{sc\text{-}ref}$ and $P_{FC\text{-}ref}$) which are divided respectively from the voltages of fuel cell (V_{FC}) and a supercapicitor(V_{sc}) in order to give the two references current ($I_{SC\text{-}ref}$ and $I_{FC\text{-}ref}$).

- PI action controls: which is used to minimize the error between the generated current (I_{SC} and I_{FC}) and the reference currents ($I_{SC\text{-}ref}$ and $I_{FC\text{-}ref}$) in order to determine the duty cycle value needed to generate the PWM For each DC/DC converter.

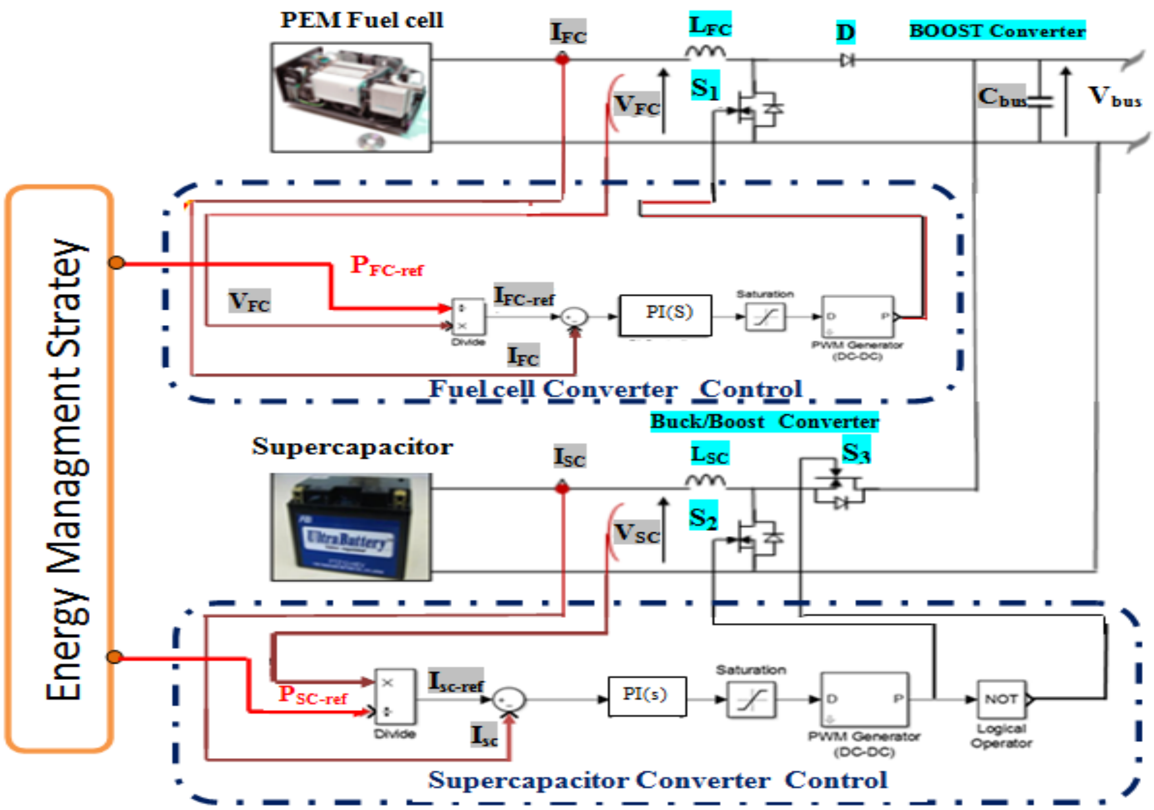

Fig.7. Control principle of the power sources

3.2. Motor controller

The direct Field Oriented Control (FOC) technique is chosen in this study to control the speed control system for a 3 phased permanent magnet synchronous motor (PMSM). [23, 24, 25].

The chosen method is given in Fig.8 that mainly composed by:

-Bloc 1: Two transformations (PARK and PARK inverse).

-Bloc 2: Speed and current controls loop

-Bloc 3: PWM signal control for inverter.

-Bloc4: Decoupling

The working principle of the developed controller is shown in Fig.8. Initially, the initial three current I_a, I_b, I_c are transformed on the two current I_{sd} and I_{sq} using Park transformation system

Then the measured values of quadrature current (I_{sq}) and direct current (I_{sd}) are compared with the references values (I^*_{sd} and I^*_{sq}).

After that, the output of the proportional-integral (PI) applied to decoupling block in order to generate a two references voltage V^*_{sd} and V^*_{sq}. Then, Park inverse transformation is used to obtain the three -phase model of the PMSM machine on the (a, b, c) frame related to the rotating field from the initial (d, q)frame. Finally, the output of thislatter generates the pulses signals for the different switches of inverter based on pulse width modulation technique (PWM).

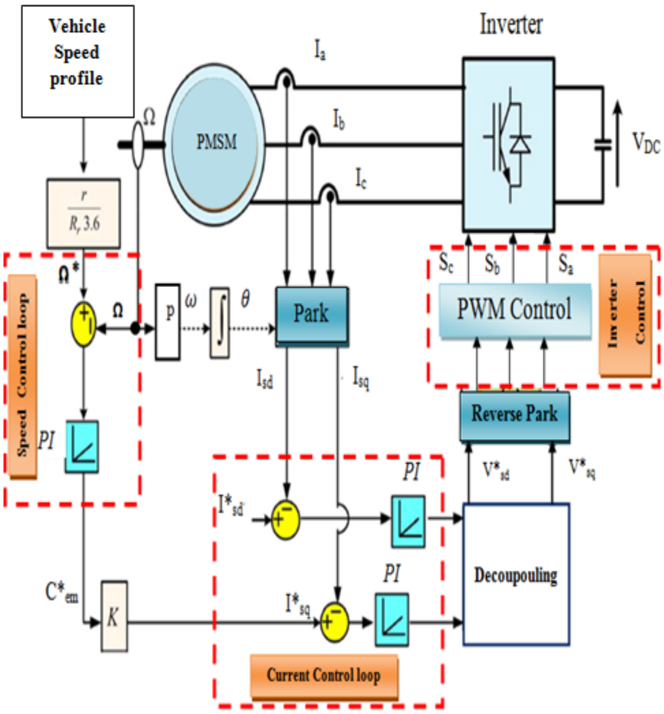

Fig.8. Adopted FOC control scheme

4. Proposed energy management approach (EMA)

The developed EMA mainly ensures the minimization of energy production of fuel cell, as well as the guarantee of energy continuous availability to satisfy load demands at any time.

Figure 9 shows the general of the developed EMA. Its main role resides in treating and to generate the sequence of control signals (switches activating for DC/DC converters) according to the operating process of vehicle (acceleration, deceleration, stopping phase).

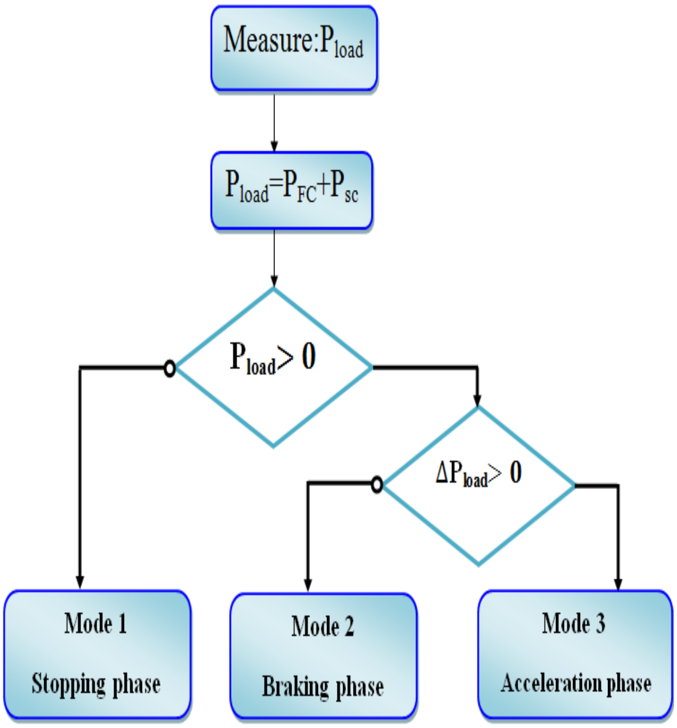

Fig.9. EMA working principle

Where: P_{load} is the load power.

These EMA must be developed in a way to achieve these main objectives that must be taken in consideration:

- The highest priority is for the supercapacitor during the acceleration phase if always be higher than 60% in order to make economic benefits in hydrogen consumption.

- The use of the PEMFC must be kept as minimum as possible in order to reduce hydrogen consumption.

- Storage device can be charged through the power required by the load in deceleration phase.

The different scenarios of each operation mode, described by Fig. 10, Fig. 11 and Fig. 12 are to ensure a continuous energy flow optimization according to the availability of the different power sources listed in Table 3.

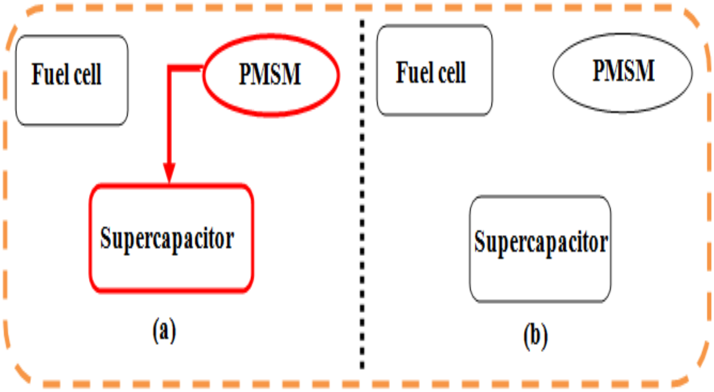

Fig.10. Energy flow in deceleration mode

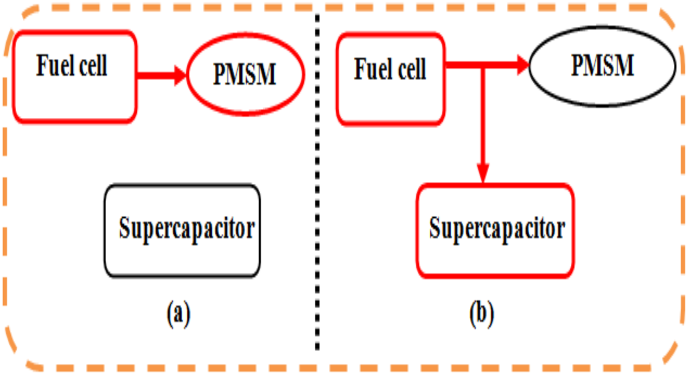

Fig.11. Energy flow in steady speed mode

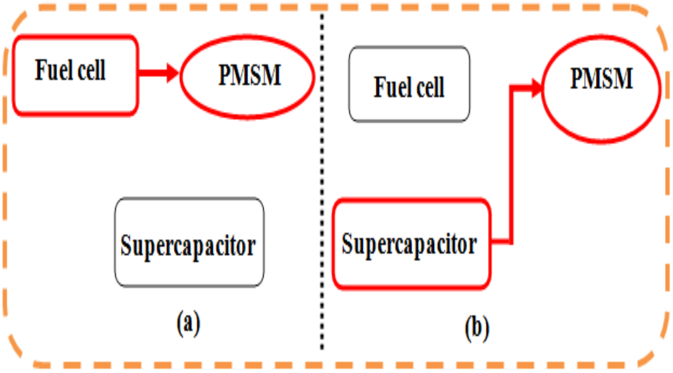

Fig.12. Energy flow inacceleration mode

Table3. Different modes of electric vehicle

Powers			**Supercapacitor State of charge**	**Vehicle state**
P_{FC}	**P_{SC}**	**P_{load}**		
>0	**=0**	**>0**	SOC<45%	Traction (fig12.a)
=0	**>0**	**>0**	SOC≥60%	Traction (fig.12.b)
>0	>0	>0	SOC≥60%	Steady state speed (fig.11.a)
>0	>0	>0	SOC<45%	Steady state speed (fig.11.b)
=0	<0	<0	SOC≥80%	Deceleration (fig.10.b)
=0	<0	<0	SOC<80%	Deceleration (fig.10.a)

5. Simulation results and discussion

This section is devoted to test and evaluate the efficiency of the developed energy management algorithm for the FC/SC vehicular system which is developed by matlab/simulink. In this case, a driving cycle presented in Fig. 13 is chosen to apply for the powertrain system.

Based on the different obtained results given in Fig.13, Fig.15 and Fig.16, we notice three operating modes are set and explained as next :(Tab.5).

The buck/boost operating mode and the cycle of charging and discharging of the storage device depending on the different driving mode applied of the system extracted from the obtained results which are given in Fig. 13, Fig.17 and Fig.18are explained as next: (Tab.4)

Table.4. Failover periods of Buck / Boost converter

Supercapacitor State	**Vehicle state**	**SC**	**Buck /Boost operation mode**
[0s-9s] and [10,15s]	Acceleration	Discharge	Boost
[20s-25s] [30-35s]	Deceleration	Charge	Buck

The hydrogen consumed by enabling the PEMFC only and with total absence of SC (without EMA) is shown in fig.19. There is consumption equal to 35g /s. Then, the simulation given in Fig. 20 is used to evaluate the hydrogen availability at the level of the PEMFC when the EMA is implemented. It is minimized by 19g.The comparison of the last two simulations proves the efficiency of the developed EMA because they show that a remarkable reduction in the hydrogen consumption.

Figures 20 and 21 shows the simulation results proving the efficiency of the developed EMA that has ensures perfectly its economic objective by enabling the PEMFC only in critical cases. In this context, obtained result shown in Fig. 21 proves that the developed approach is guaranteed a 51% gain at the level in fuel consumption.

Table.5. Different operations mode of the FCEV

Time range	**Supercapacitor State**	**Vehicle state**	**PEMFC**	**SC**	**The working mode**
[5,10s],[15,20s] [25,30s]	SOC<45%	Traction	Deactivated	Activated	SC supplies the motor (discharged storage device)
[0,5s] [10,15s]	SOC≥60%	Steady state speed	Activated	Deactivated	PEMFC supplies the PMS motor
[20,25s] [30,35s]	SOC<80%	Deceleration	Deactivated	Activated	SC receives power from the PMS motor(charged storage devices)

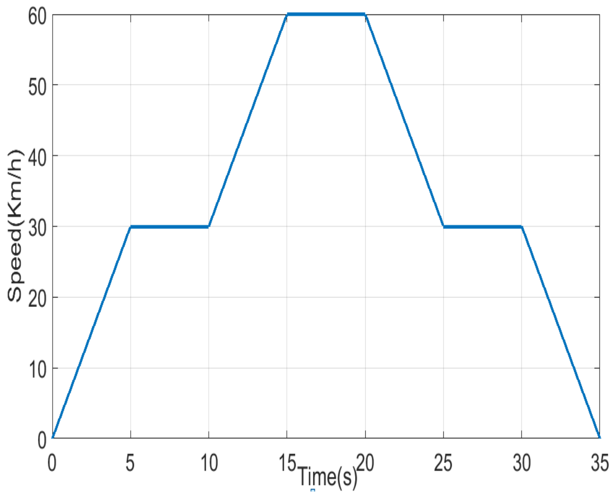

Fig.13. Driving cycle

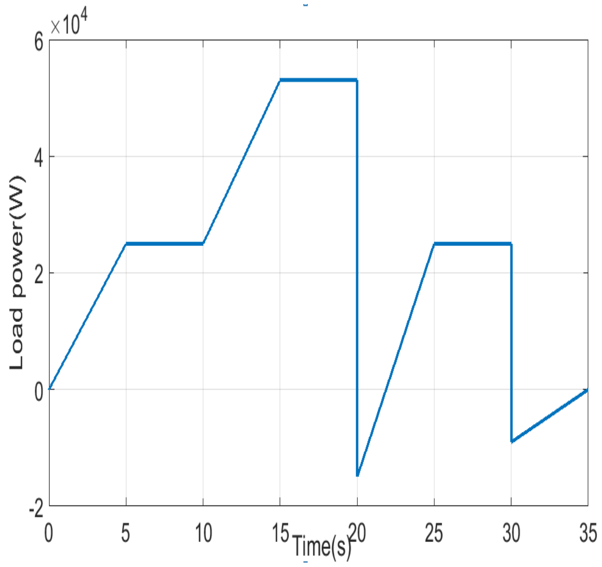

Fig.14. Load power

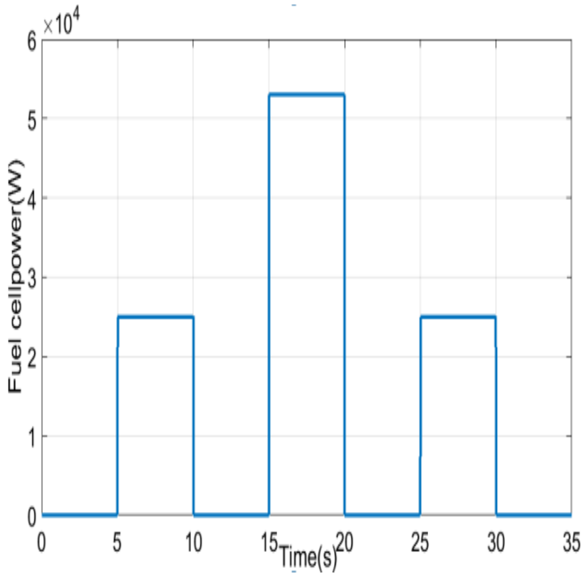

Fig.15. Fuel cell power

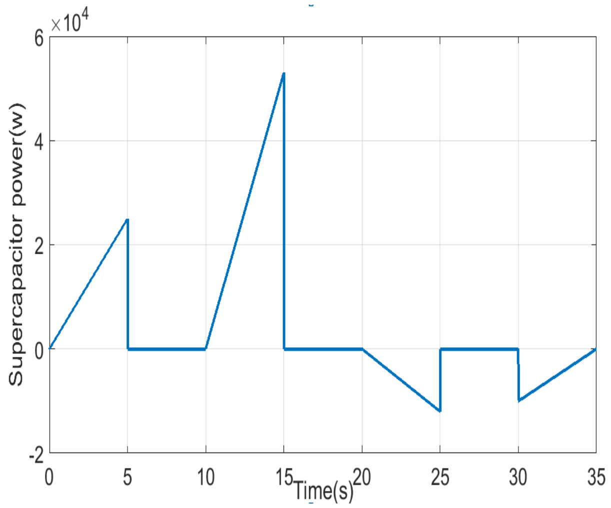

Fig.16. Supercapacitor power

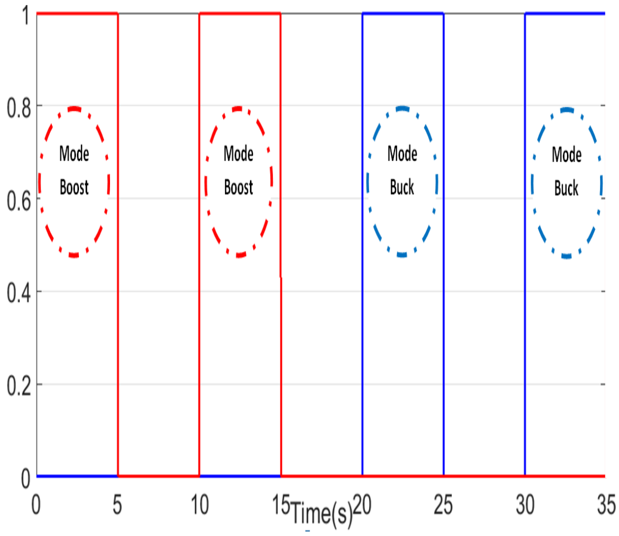

Fig.17. Conduction interval of buck/boost converter

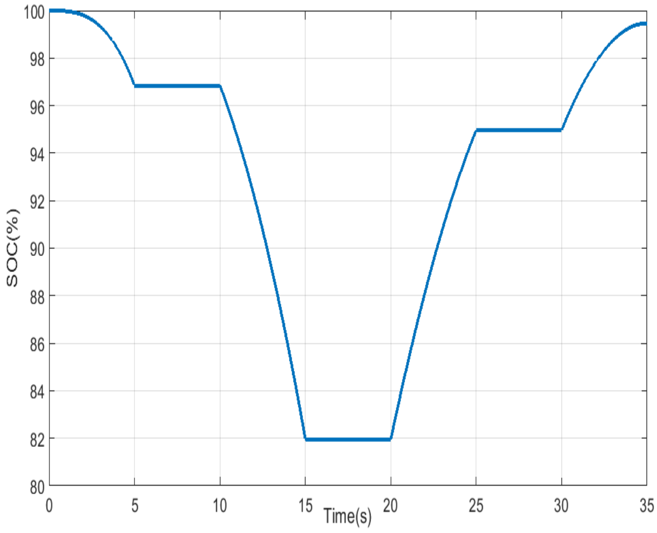

Fig.18. Supercapacitor state of charge

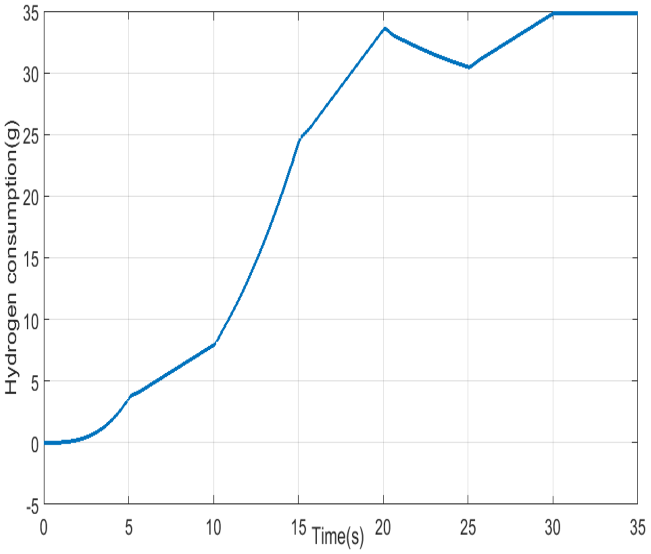

Fig.19. Hydrogen consumption without supercapacitor

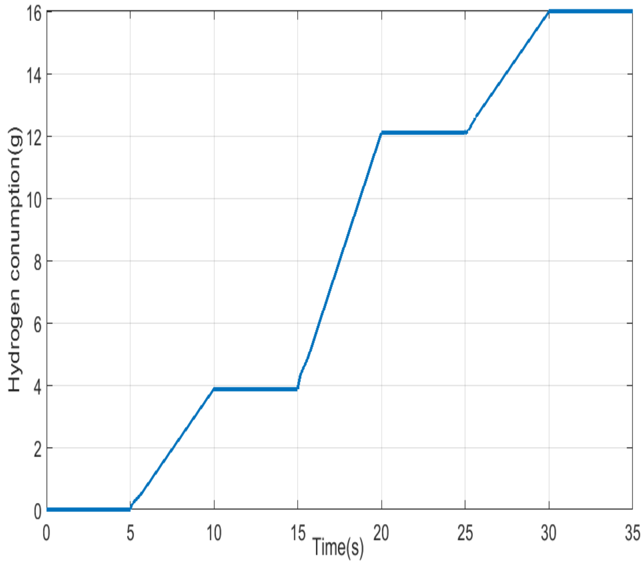

Fig.20. Hydrogen consumption with EMA

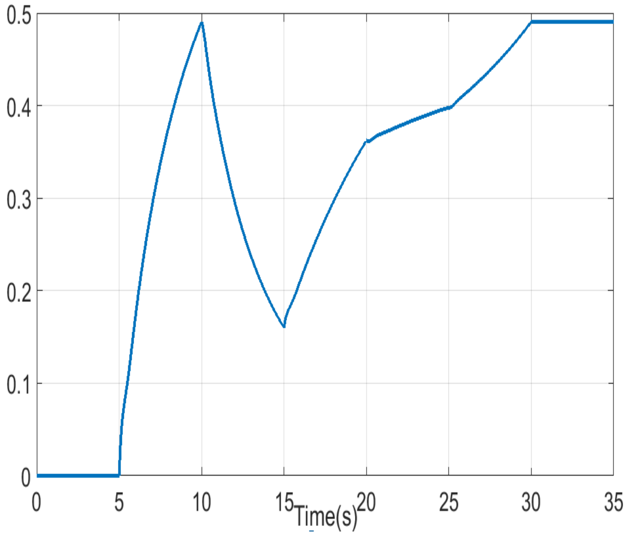

Fig. 21. Gain in hydrogen consumption

Conclusion

A developed approach used to ensure an optimized energy management of the studied system was presented and synthetized in this paper. This EMA was tested by simulation under the Matlab-Simulink environment in order to verify the good working performance. The obtained results under various operating process of vehicle proved its efficiency in guaranteeing an economic benefit at the level in hydrogen consumption.

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