

Design, Modeling and Energy Management of a PEM Fuel Cell / Supercapacitor Hybrid Vehicle

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Abstract—This work concerns the study and the modeling of hybrid Proton Exchange Membrane (PEM) Fuel Cell electric vehicle. In fact, the paper deals with the model description of the powertrain which includes two energy sources: a PEM Fuel Cell as a primary source and a supercapacitor as a secondary source. The architecture is two degrees of freedom permitting a stability of the DC bus voltage. The hybridization of primary source with an energy storage system can improve vehicle dynamic response during transients and hydrogen consumption. The proposed energy management algorithm allows us to have a minimum hydrogen consumption. This algorithm is based on supercapacitor state of charge (SOC) control and acceleration/deceleration phases making possible braking energy recovery. The proposed model is simulated and tested using Matlab/Simulink software allowing rapid transitions between sources. The obtained results with the New European Driving Cycle (NEDC) cycle demonstrate a 22% gain in hydrogen consumption.

Keywords—PEM Fuel Cell; Powertrain; Electric vehicle; Supercapacitor; Energy management; Power system; hydrogen gain

I. INTRODUCTION

Fuel cell hybrid electric vehicles are currently considered as solution to reduce the pollution in the sector of urban transportation. The fuel cells represent one of the most promising renewable energy clean sources because of its zero emissions gas [1]. Proton Exchange Membrane (PEM) Fuel Cell is the primary preference in transportation sector due to the high power density, lower operating temperatures, good stability when submitted to mechanical vibration [2] and a low power on time compared to other types [3].

Integration of a bidirectional secondary source with PEM Fuel Cell like supercapacitors or battery allows reduction of

fuel cell nominal power, minimizes hydrogen consumption and braking energy recovery [4]. Many works are presented in literature where different topologies and strategies are discussed. In the work of Erdinc.O et al. [5], the supercapacitor SOC and vehicle speed are used to perform power management between the two sources. N. Mebarki et al. [6] proposed battery as a secondary source because of its higher specific energy. In this case, battery low power density may present some limitations in acceleration /deceleration phases. H.Aouzellag et al. [7] proposed to combine ultracapacitor with battery to overcome power delivery limitations of the PEM Fuel Cell. Different power management algorithms are presented in literature with the main objective to reduce hydrogen consumption and autonomy improving [8] among these algorithms we find dynamic programming, optimal control and intelligent techniques. This paper deals with the use of a supercapacitor as secondary source because of its high specific power and unlimited number of charge/discharge cycles compared to the battery [9]. The power train is modeled as presented in fig.1. It's composed mainly of a PEM Fuel Cell, supercapacitor, boost, buck-boost converter and permanent magnet synchronous motor (PMSM) connected to the inverter. The whole model of the power train is validated with Matlab Simulink software.

In this paper we present a simple energy management algorithm compared with other methods. This strategy allows simple implementation and good results especially with urban cycles. This paper is structured as follows: an introduction is presented in Section I. In section II, we presented the power sources modeling. In Sections III-IV, we presented the power train and motor description models. The proposed energy management strategy is presented in Section V. Simulation results and conclusion are presented and discussed in sections VI-VII.

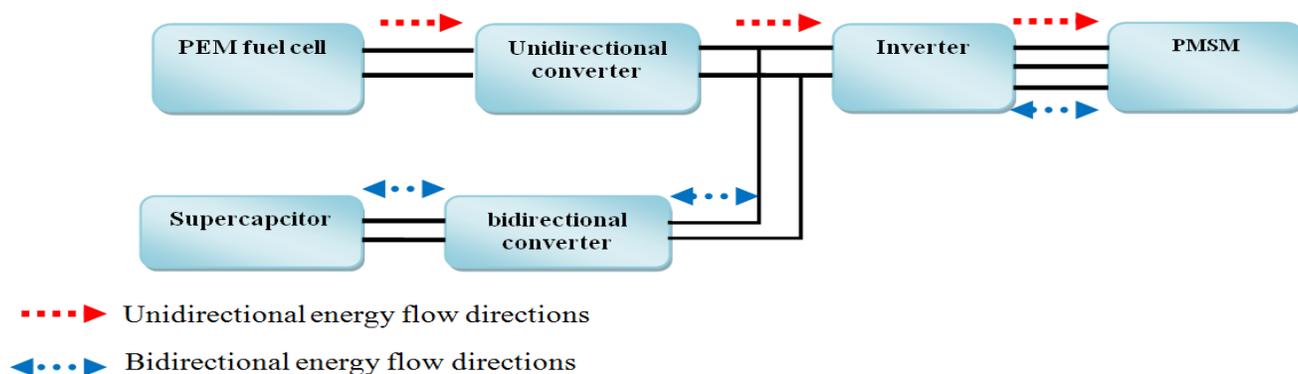


Fig. 1. Power system of fuel cell/SC hybrid vehicle

II. ENERGY SOURCES

A. PEM Fuel Cell modeling

One of the objectives in this paper is to study the mathematical model of the PEM Fuel Cell. Several works [10,11] proposed a dynamic models that describe the polarization curve of the PEM Fuel Cell. When a current flows in the external circuit, the potential of the cell is lower than the theoretical potential. This is due to different voltage drops: the activation, the ohmic and the concentration losses.

The Fuel Cell chosen in this work is the Mark 902 PEM Fuel Cell from Ballard [12] with 85 kW nominal power at 280V. The parameters of the fuel cell are given in table 2. A boost converter is used to interface the PEM Fuel Cell to the DC bus voltage [13].

The PEMFC output voltage can be written as follows:

$$V = E_{\text{nerst}} - V_{\text{act}} - V_{\text{ohm}} - V_{\text{conc}} \quad (1)$$

Where:

$$E_{\text{nerst}} = E^0 - RT \ln \frac{P_{\text{H}_2} \sqrt{P_{\text{O}_2}}}{P_{\text{H}_2\text{O}}} \quad (2)$$

Where V , E_{nerst} , V_{act} , V_{ohm} , V_{conc} , P_{H_2} , P_{O_2} , $P_{\text{H}_2\text{O}}$ are respectively: the fuel cell voltage (V), the activation Voltage losses, the ohmic Voltage losses (V), the concentration Voltage losses (V), the voltage Nernst (V) and the partial pressure of hydrogen ,oxygen and water (atm).

The activation losses can be expressed by the Tafel equation:

$$V_{\text{act}} = \frac{RT}{2\alpha F} \ln \left(\frac{I_{\text{FC}}}{I_0} \right) \quad (3)$$

The ohmic losses are given by the following equation:

$$V_{\text{ohmic}} = I_{\text{FC}} R \quad (4)$$

The concentration losses can be expressed as:

$$V_{\text{conc}} = -\frac{RT}{2F} \ln \left(1 - \frac{j}{j_{\text{max}}} \right) \quad (5)$$

Where I_{FC} , α , I_0 and j_{max} are respectively: the current of PEMFC(A), the tafel slope for the activation(mA/cm²) and the maximal current density for the concentration(A/cm²).

The quantity of hydrogen consumed is expressed as follows:

$$H_{2\text{conso}} = \frac{N_{\text{cell}} I_{\text{FC}}}{2F} \quad (6)$$

Where $H_{2\text{conso}}$, N_{cell} are respectively: the H_2 consumption amount(mol/s) and the number Cell of PEM Fuel Cell.

TABLE I. PARAMETRS OF THE PEM FUEL CELL

Parameters	Symbol	Values	Units
The constant of faraday	F	96439	C/mol
Universal gas constant	R	8.314	J/mol
Resistance of the electrolyte	R_M	0.00003	Ohm
Temperature	T	80 °C	Celsius
Nominal Current	I_{nominal}	300	A
Voltage	V_{fuel}	280	V
Power	P_{fuel}	85	KW

The simulation current-voltage characteristic of a **MK 902 PEM Fuel Cell** model is shown in Fig. 2

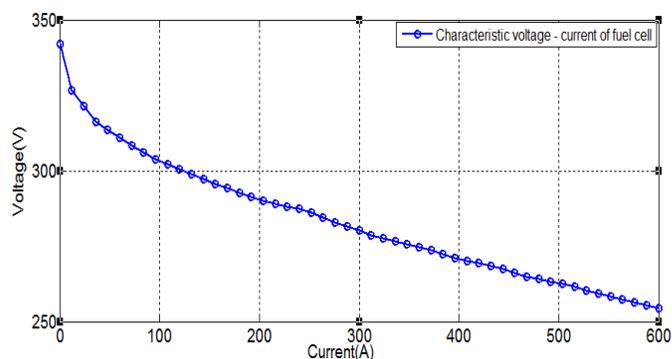


Fig. 2. PEM fuel cell voltage-current characteristic

B. Supercapacitor

This second energy source is chosen to respond to power requirements of hybrid vehicle. A 63F Maxwell BMOD0063-P125B08 module [14] is used in this work. The parameters of the supercapacitor model are given in table 2. A buck/boost converter is used to interface the supercapacitor to DC voltage bus [15].

This converter allows the power flow between the energy storage system and the PMS motor. In the Buck mode operation, the secondary source receives the energy during braking phases (charge phase of the supercapacitor). In the boost mode operation, the supercapacitor generates the power and assists the fuel cell (discharge phase of the supercapacitor).

The open circuit voltage of a supercapacitor is given by the following expression:

$$E_{sc} = E_{sc0} - \frac{1}{C_{sc}} \int_0^t i_{sc} dt \quad (7)$$

Where C_{sc} and I_{sc} are respectively: the capacity of the supercapacitor (F) and the supercapacitor current (A).

The energy of a supercapacitor is:

$$X_{sc} = \frac{C_{sc} E_{sc}^2}{2} \quad (8)$$

$$X_{sc-max} = \frac{C_{sc} E_{sc0}^2}{2} \quad (9)$$

The state of charge (SOC) can be written as:

$$SOC = \frac{X_{sc}}{X_{sc-max}} \quad (10)$$

The output voltage of a supercapacitor is:

$$V_{sc} = E_{sc} - R_{sc} i_{sc} \quad (11)$$

Where X_{sc} , X_{sc-max} , and R_{sc} are respectively :the internal resistance of a supercapacitor(Ω),the energy contained in a supercapacitor (J) and the maximum energy contained in a supercapacitor(J).

TABLE II. PARAMETERS OF THE SUPERCAPACITOR

Parameters	Values	Units
Rated Capacitance	63	F
Maximum ESR	18	m Ω
Rated Voltage	125	V
Absolute maximum current	1900	A
Leakage current at 25°C	10	mA
Capacitance of individual cells	3000	F
Mass, typical	61	Kg
Usable specific power	1700	W/kg
Specific energy	23	Wh/kg

III. POWERTRAIN DESCRIPTION MODEL

The powertrain model is composed of four sub-models: the electrical machine, the reducer / transmission, wheels and the vehicle [16].

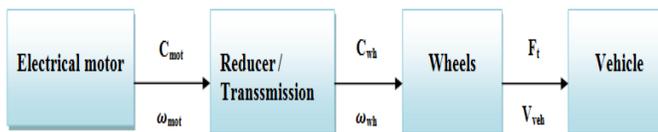


Fig. 3. Scheme of the powertrain

The traction force is given by the following equation:

$$F_{traction} = F_{mot} - F_{roll} \quad (12)$$

Where the acceleration force and the friction force to the

advancement are respectively given as follows:

$$F_{mot} = \frac{C_{wheel}}{R_{wheel}} \quad (13)$$

$$F_{roll} = M_{veh} g C_r \cos(\alpha) \quad (14)$$

The coefficient of friction C_r is given as follow:

$$C_r(V_{veh}) = C_r^0 + K_c V_{veh}^2 \quad (15)$$

The aerodynamic force F_{aero} is given by :

$$F_{aero} = \frac{1}{2} \rho_{air} A_f C_x V_{veh}^2 \quad (16)$$

The resistance of mounted side F_{slope} is :

$$F_{slope} = M_{veh} g \sin(\alpha) \quad (17)$$

The fundamental principle of the vehicle dynamics is given by the following equation:

$$\frac{dv(t)}{dt} = F_{traction} - F_{aero} - F_{slope} \quad (18)$$

The torque and speed motor are given by equations (19) (20):

$$C_{mot} = \frac{C_{wheels}}{r_{red}} \quad (19)$$

$$\omega_{mot} = \omega_{wheels} \quad (20)$$

The final expression of load torque is given by the following expression:

$$C_r = \frac{R_{wheel}}{r_{red}} (F_{roll} + F_{aero} + F_{slope}) \quad (21)$$

The different extracted parameters are defined as:

- α :Road slope angle (rd)
- R_{wheel} : Wheel radius (m)
- ρ_{air} : Air density (kg/m³)
- C_x : Aerodynamic drag coefficient
- F_{tire} :Rolling resistance force (N)
- F_{roll} : Friction force to the advancement (N)
- M_{veh} : Vehicle weight (kg)
- V_{veh} : Vehicle speed (m /s)
- F_{aero} : Effort of aerodynamic resistance (N)
- A_f : Front area of the vehicle (m²)
- F_{slope} : Resistance of mounted side (N)
- g : Gravitational acceleration (m /s)²
- $F_{traction}$:Traction force (N)

The parameters of the Hybrid fuel cell Vehicle model are given in Table.III

TABLE III. PARAMETERS OF HEV VEHICLE MODEL

Parameters	Symbol	Values	Units
Vehicle total mass	Mv	1300	kg
Rolling resistance force constant	F r	0.01	s ² /m ²
Air density	ρ	1.20	kg.m ³
Aerodynamic drag coefficient	C_x	0.30	-
Acceleration due to gravity	G	9.8	m.s ⁻²

The Simulink model of the vehicle power train given in fig.4 is used to validate our control method.

IV. PMSM MODEL

The model the PMSM in d-q frame can be expressed by the following equations [17]

$$\begin{cases} V_q = R_s I_q + L_q p i_q + \omega_r L_d i_d + \omega_r \Phi_f \\ V_d = R_s I_d + L_d p i_d - \omega_r L_d i_q \\ \Phi_d = L_d i_d + \Phi_f \\ \Phi_q = L_q i_q \\ T_{em} = \frac{3}{2} p (\Phi_f i_q + (L_d - L_q) i_q i_d) \end{cases} \quad (22)$$

where the rotor speed is derived from the following equation:

$$T_{em} = T_L + B\omega_m + J \frac{d\Omega}{dt} \quad (23)$$

A Space Vector Pulse Width Modulation (SVPWM) technique is applied to inverter in order to minimize converter losses. This technique is a better control method of output voltage under DC voltage variation than classical PWM [18].

The different extracted parameters are defined as:

- V_d, V_q : d, q voltage (V)
- i_d, i_q : Stator currents (A)
- L_d , and L_q : Inductances (H)
- Φ_d and Φ_q : Stator flux linkages (Weber)
- R_s : Stator winding resistance (Ω)
- ω_r : Rotor speed (rd/s)
- T_L : Load torque (Nm)
- Ω : Mechanical pulse of the rotor (rd/s)
- J : Total inertia brought back to the rotor ($kg.m^2$)

V. ENERGY MANAGEMENT

The energy management in hybrid fuel cell vehicle is the most important factor that can improve fuel cell lifetime, cost and hydrogen consumption [19]. The energy management must power flow between the storage system (UC) and the power train with the goal to minimize FC current and to capture the braking energy during the various driving phases especially in urban cycles. There are three principal methods of energy optimization in literature:

- Dynamic programming methods with different initial and final conditions. These methods are used with predefined cycles and are not optimal for other trajectories [20].
- Optimal control methods based on a minimization of analytical expression of energy under constraints [21]. This is a hard task and requires a long time of calculus when implemented. The accuracy of optimal point strongly depends of the used model [22].
- Intelligent techniques like fuzzy logic [23] or neural network are proposed to overcome the problems of previous two methods [24]. These methods are heavy to implement and need a powerful DSP and may present some oscillations [25].

In this paper, we present a simplified algorithm based on

the state of charge of the supercapacitor and the driving phase.

The energy management algorithm proposed chosen is to minimize the fuel cell power, which corresponds to the minimization of the hydrogen consumption. The Supercapacitor provides the difference between the power delivered from the fuel cell and the demanded power from the PMS Motor. The relationship of power between the fuel cell, the supercapacitor and the load is given as follows:

$$P_{Load} = P_{fuel} + P_{Sc} \quad (24)$$

This energy management algorithm is given in fig.4 and includes 3 operating modes:

Mode 1: This mode is characterized by the activation of Storage system. The supercapacitor recovers the energy braking (deceleration phase).

Mode 2: This mode is characterized by the activation of fuel cell. At this moment, the PEM fuel cell supplies the PMS motor (steady speed)

Mode 3: The load composed of the PMS motor receives the power from the storage system (Acceleration phase).

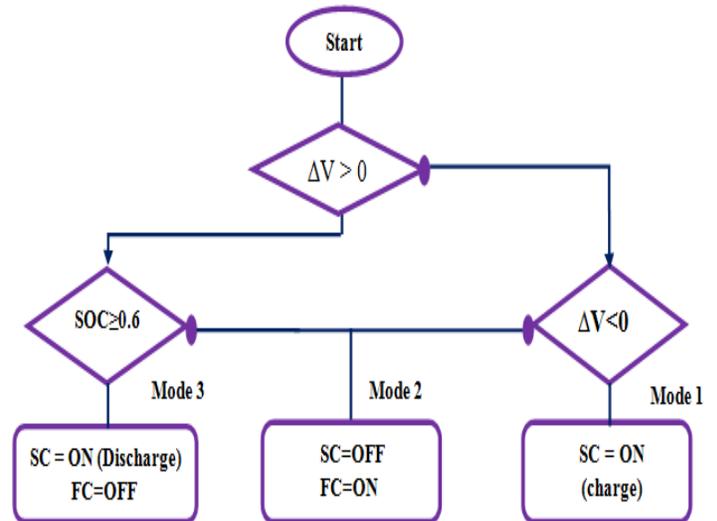


Fig. 4. Energy management algorithm

VI. SIMULATION RESULTS AND DISCUSSION

The Fuel cell hybrid electric vehicle model was tested in Matlab/Simulink software with urban NEDC (New European Driving Cycle) driving cycle using the parameters given in tables 1, 2 and 3.

The NEDC cycle is given in fig.5. It's applied to the vehicle during 1200s and is characterized by a maximum speed of 120km/h, maximum acceleration of 1.042m/s² and average speed of 33.35km/h.

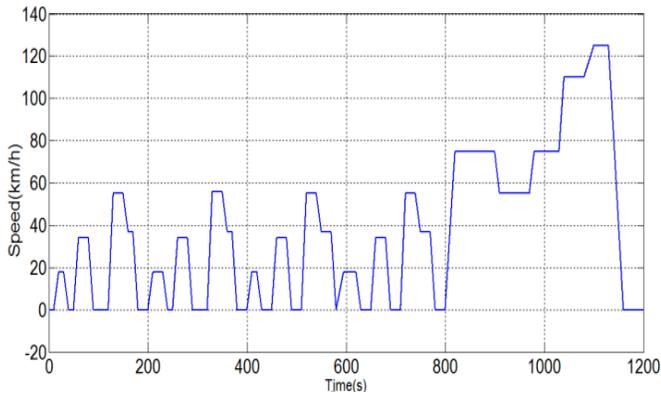


Fig. 5. The NEDC profile

The hydrogen consumed by the fuel cell alone without energy management algorithm is 250 g during this driving cycle is given in fig 6. The hydrogen consumed when the proposed energy management algorithm is implemented is 180 g during this driving cycle is given in fig 7. The efficiency of the proposed energy management algorithm in urban cycles is validated by fig.8. By using the proposed energy management the consumption of hydrogen is improved by seventy grams.

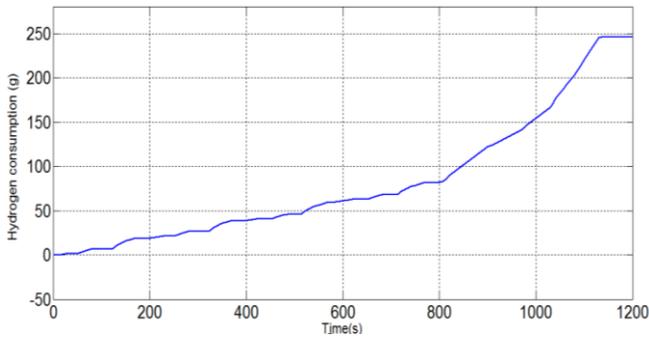


Fig. 6. Hydrogen consumption without supercapacitor

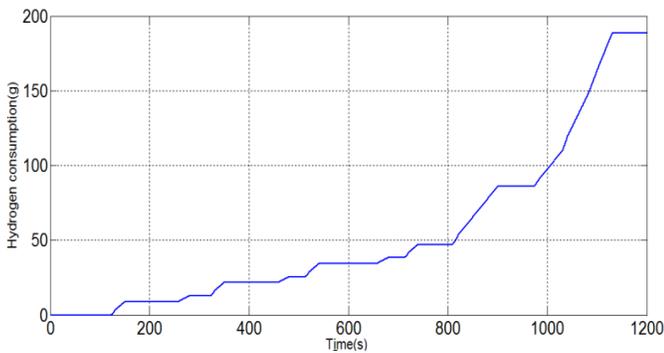


Fig. 7. Hydrogen consumption with our energy management algorithm

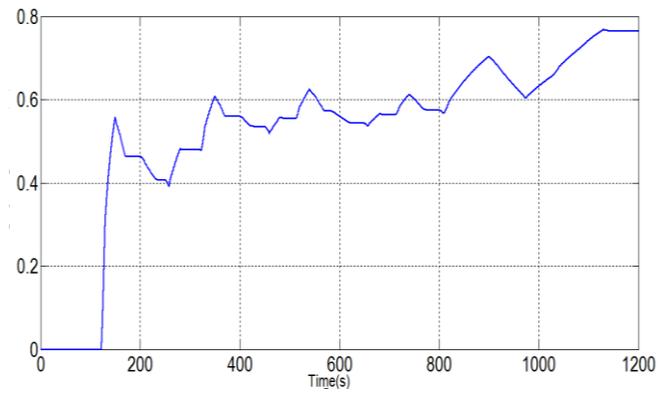


Fig. 8. Gain in hydrogen consumption in pu

Table IV shows the gain consumption of hydrogen of each algorithm for "optimal control, fuzzy logic, proposed energy management algorithm ". We can show that the proposed method attains the biggest values gain in consumption hydrogen compared to other mentioned methods.

TABLE IV. COMPARISON OF DIFFERENT METHOD FOR THE DIFFERENT POWER MANAGEMENT ALGORITHM

Method	Gain hydrogen consumption
Optimal control [22]	18%
Fuzzy logic [26]	18.7%
Proposed algorithm	22%

The proposed energy management algorithm was tested with a minimal SOC value of 0.6. The simulation results given in fig.9 show a good control of the state of charge of the supercapacitor while optimizing hydrogen consumption of the fuel cell hybrid electric vehicle. The hole braking energy is recovered without exceeding allowed SOC values which means a good choice of supercapacitor value.

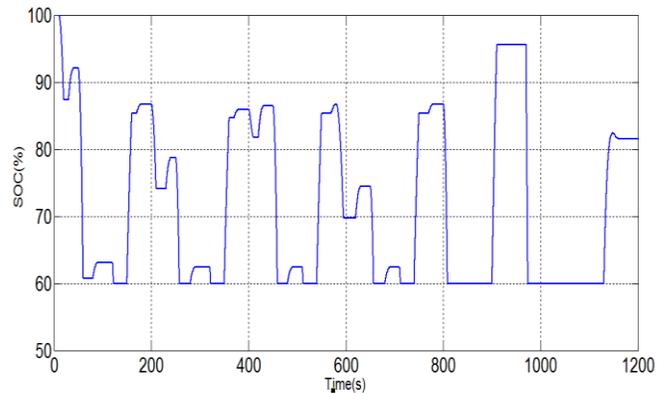


Fig. 9. The state of charge of the supercapacitor

VII. CONCLUSION

In this paper, we proposed a fuel cell hybrid electric vehicle model which includes a PEM fuel cell, a supercapacitor and PMS motor. The power system includes a buck boost static converter with the secondary source allowing bidirectional energy flow.

We developed a simplified energy management algorithm based on SOC of the supercapacitor and the sign of the acceleration. NEDC urban cycle simulation results obtained by implementation of the whole system in MATLAB-Simulink software shows a 22% gain of hydrogen consumption. SOC simulation during this cycle proves recovery of the whole braking energy. A perspective of this work is the implementation of this optimization algorithm on an embedded electronic board in order to validate the simulation obtained results using Matlab / Simulink.

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