Study of the Energy Performance of a PEM Fuel Cell Vehicle

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Abstract- If the need of the individual transport is growing; the methods proposed are strongly questioned by the society. Emissions from combustion engines are accused of contributing to global warming and air pollution. In addition, the oil resources are finite while demand increases inevitably based on economic growth (31% of global energy consumption for transportation sector). So, an alternative to the combustion engine becomes essential. The hybrid fuel cell vehicle represents one of the alternatives solutions. The present work is a numerical simulation of the energy performance of a PEMFC fuel cell vehicle rolling on a driving reference cycle (FTP cycle). The simulations are conducted and performed with the ADVISOR simulation tool using the MATLAB environment. The results concerning the battery power, fuel cell power and the thermal state of the battery show a very candidate of this vehicle to replace the conventional engine.

Keywords Transport, fuel cell, PEMFC, batteries, fuel cell hybrid vehicle, simulation, ADVISOR.

1. Introduction

With the development of the industry for several decades, we consume more and more energy resources in order to meet the growing energy needs of the population. Almost 80% of global energy production comes from coal, oil, natural gas and the rest of the nuclear, etc. [1]. The depletion of these resources may be an issue that concerns all of us, energy issues at present cover two areas. One is related to the risk of depletion of fossil and fissile resources, including that of oil, which at the current rate of consumption, is scheduled for a century or less. The other is the problem of environmental pollution, including CO_2 emissions (greenhouse gas) and gaseous pollutants (SO_2, NOx, CO, CH_4, solid particles, etc.) [2].

Since its origins, the transport sector remains totally dependent on oil production. This results in an increased demand for that source of energy [3-4]. In 2012 and according to the EIA statistics (Energy Information Administration), the transport sector is highly responsible for the increase of the global power consumption (27% of total world consumption) and emissions of pollutants and greenhouse gases (33.7% of global emissions) [5-6]. Among the various means of transport, road transport alone represents 76% of the energy consumption. However, for its operation, an amount about 96% was from oil [7].

It is now important to stop this progression and reduce that consumption. Two solutions are proposed.

- The optimization of combustion engines involves: improving engine efficiency (injection, engine, equipment, etc.) and hybridization (electric and thermal).

- The use of new energy sources such as: biofuels, CNG (Compressed Natural Gas Vehicle), LPG (Liquefies Petroleum Gaz) and hydrogen.

The main alternative for the means of transport in city centres', in order to limit carbon dioxide emissions, is electromobility [8]. In recent years, car manufacturers have developed and produced a new generation of electric vehicles, which are divided in general into: batteries electric vehicles and fuel cell electric vehicle.

For the transport sector, the fuel cell vehicle is one of the solutions recommended by vehicle manufacturers and research organizations to remedy the energetic autonomy problems of the battery electric vehicles. Electricity is produced on board the vehicle, in the fuel cell. It results from the inverse principle of water electrolyte (dissociates water on his constituents) it is an electrochemical reaction between the hydrogen, stored in a tank under a high pressure which is designed for this purpose, and oxygen. The only products released are water and heat. It is a good way to use this energy vector that can be obtained from different raw materials such as natural gas, methanol, water and biomass products using well from renewable sources. Fuel is made up of two electrodes (an anode and a cathode), separated by an electrolyte (a material which blocks the passage of electrons; it may be liquid, but is usually solid, it is then referred to as a membrane). Among all the existing families of fuel cells, we will only focus on low-temperature batteries, in particular the PEM polymeric membrane-exchange membrane batteries. This technology has today a high power density, extended life, low corrosion sensitivity and a relatively low operating temperature (50-100 °C), which The fastest starts which makes it the most mature and closest commercial stage. PEM systems reach efficiencies of about 50% and more [9]

The concept of a fuel cell electric vehicle is based on the use of a traction system generally composed of a power train (electric machines powered by static converters regulated by appropriate electronic circuits) and a power source PEM main power assisted by another auxiliary source (in our case a Li-ion battery).

There are a number of useful references in the literature focusing on fuel cell performance. In their work, R. Govindarasu et al show that the pressure drop variation between first and last cells increases with the number of cells and stoichiometric ratio of reactants [10]. MayankShekhar JHA et al develop an efficient solution towards the prognostics of industrial Proton Exchange Membrane Fuel Cell [11].

Another group of studies of the scientific community are focused on the modeling of batteries, most of these studies concern lithium technologies. Many efforts are cited on [12,13]. It seems that Lithium-battery technology however has a much reduced voltage range between charge and discharge and therefore a much improved efficiency for these raisons it would be the major candidates for electric vehicles.

In this context, the work presented focuses on an analysis and simulation of a PEM fuel cell electric vehicle. The simulations are performed with the simulation tool ADVISOR (Advanced Vehicle Simulator) using MATLAB environment. Our goal is to show the performance of the fuel cell vehicle on a reference driving cycle during which all modes of operation are covered, ie start-up, normal driving, the case of strong acceleration, braking, recharging the battery.

2. Modelling

2.1. *Presentation of the fuel cell vehicle studied*

The electric vehicle studied is considered as a complex system consisting of a wide range of different kinds components (mechanical, electrical and electrochemical) in interaction. Figure 1 shows the block diagram of the vehicle concerned. The engine is fully electric, using a primary source (PEM fuel cell) and a secondary power source (Li-ion battery) reversible power (charge / discharge). The roules of the secondary source of energy are:

- Power assisting the fuel cell: The secondary source provides additional power when the battery reaches its maximum power (for example, during vehicle acceleration).
- Recover kinetic energy during braking: Recovery of kinetic energy during braking phases saves hydrogen and increase the vehicle's range.
- Introduce a degree of freedom in the distribution of powers:

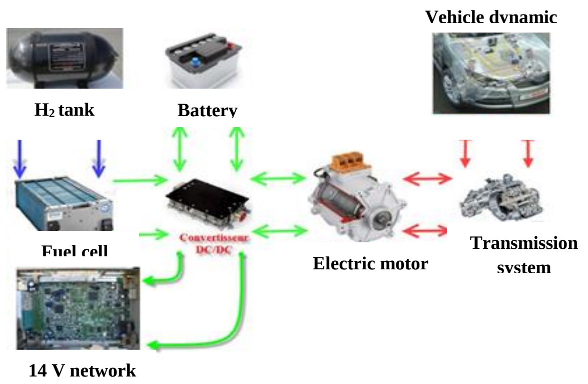

Fig. 1 Diagram of the vehicle configuration studied

The simulation is carried out by the software advisor under the Matlab environment, the model of the simulation is presented in the figure 2.

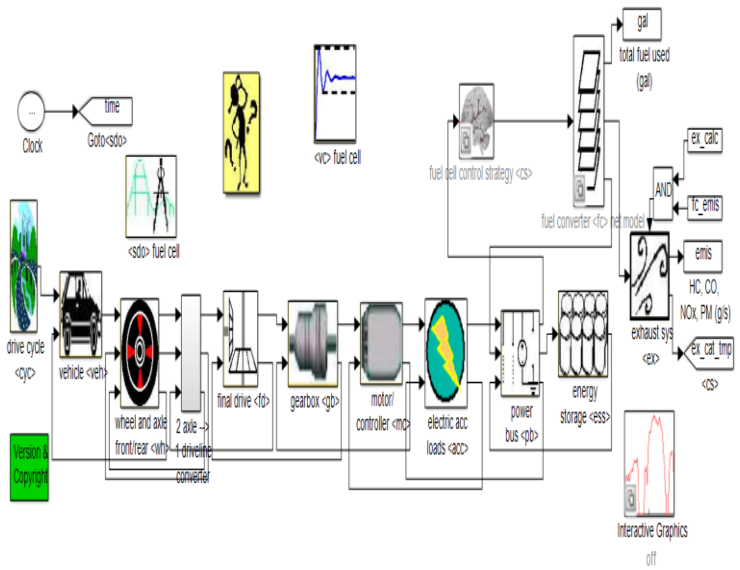

Fig. 2 Simulink diagram of the vehicle studied.

2.2. *Vehicle Dynamics*

The vehicle movement along its direction of movement is completely determined by all the forces acting on it in that direction. As shown in figure 3, the durability opposing movement includes the aerodynamic force F_a (1), the resistance force F_r rolling (2) and the force due to F_s slopes (3) [14-15-16-17]. The rolling resistance is resulting from the deformation between the wheels and the road. The resistance of the air from the front air buoyancy. The resistance due to the slope (or gradient force) characterized climbing a slope of the vehicle [17-18].

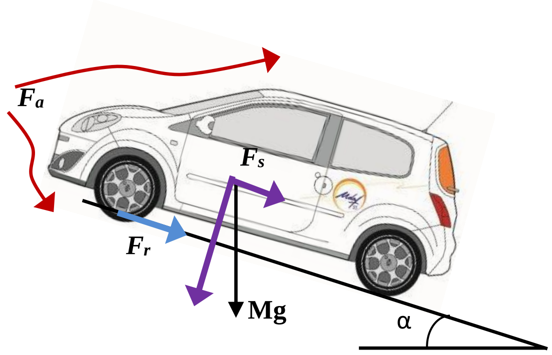

Fig. 3 Balance of forces acting on the vehicle.

$$F_a = \frac{1}{2}\rho.A_f.C_w.V^2 \tag{1}$$

$$F_r = m.g.C_r.cos\alpha \tag{2}$$

$$F_s = m.g.sin\alpha \tag{3}$$

Where, V is Relative speed of the vehicle (m/s), ρ is Air density (kg/m^3), A_f is frontal area of the vehicle (m²), C_w is the aerodynamic drag coefficient, m is mass of vehicle (kg), C_r is coefficient of rolling resistance of the wheels, g is gravitational acceleration (m/s²), *and* α is titl angle (degree).

Indeed the resistive torque applied to the electric motor is the product of the total force and the radius of the wheel R_r [19-20]

$$C_{roue} = (\frac{1}{2}\rho.A_f.C_w.V^2 + m.g.C_r.\cos\alpha + m.g.C_r.\sin\alpha).R_r \tag{4}$$

Thus, engine power output is given as follows:

$$P = V.(\frac{1}{2}\rho.A_f.C_w.V^2 + m.g.C_r.\cos\alpha + m.g.C_r.\sin\alpha + m.\frac{dV}{dt}) \tag{5}$$

2.3. *Electric Vehicle Modeling*

2.3.1 The fuel cell system:

The embedded fuel cell electric vehicle is composed of stacks. Thereafter, instead of modeling each stack, we simply model a single cell. The voltage of a fuel cell to cell PEM drop depending on the current output due to losses. These losses are due to irreversibility, they manifest into three elements: activation losses, ohmic losses and concentration losses [21].

The electrical characteristic of a cell is given by its polarization curve linking cell voltage V_{cell} at its current density i_{PAC}:

$$V_{cell}\, i_{PAC} = E_{cell} - V_{act}\, i_{PAC} - V_{ohm}\, i_{PAC} - V_{conc}\, i_{PAC} \tag{6}$$

The open circuit voltage of a cell and the voltage drops (of activation, ohmic and of concentration) are calculated for the given operating conditions and dependent on reactive gas pressure, the temperature of the fuel cell, the relative humidity of the gas and the moisture content of the membrane.

- Activations losses

The Tafel equation was derived from the experimental results regarding the voltage drop caused on the surface of the electrodes with different electrochemical reactions. It allows for the voltage drop in the following form [22]:

$$\Delta V_{act} = A \cdot ln\left(\frac{I}{i_0}\right) \tag{7}$$

Where, i_0 is the exchange current density in the cathode as the cathode overvoltage is greater than that of the anode, i_0 is of the order of (0.04 mA/cm^2) ;

I is represents the internal current density equivalent to the migration of some hydrogen molecules, and A is Tafel coefficient.

- Ohmic losses

The ohmic losses are induced by the internal resistances of the electrodes and the membrane resistance during the passage of protons; the consequent voltage drop linearly dependent on the current and can be expressed by the following expression:

$$\Delta V_{ohm} = (R_{élé} + R_{mem})I = R \cdot I \tag{8}$$

Where, R_{ele} isThe specific resistance of the electrodes, R_{mem} is the specific resistance of the proton membrane, it strongly depends on the amount of water present in the membrane, and R represent the total specific resistance.

- Concentration losses

The voltage drop due to loss of concentration is higher for large current densities. A decrease in the concentration causes crumb decrease in the partial pressure with respect to the reference pressure causing a voltage drop. This voltage drop is expressed by the empirical formula [22]:

$$\Delta V_{conc} = -m \cdot exp(nI) \tag{9}$$

Where m and n are two constants used in the expression for the voltage drop due to the loss of concentration. The value of « m » if of the order of 3×10^{-5}, and « n » is of the order of 8×10^{-3} cm^2.mA^{-1}.

By grouping all losses causing voltage drops in a PEM fuel cell, the voltage of a cell can be expressed in terms of the current by the following equation [23-24]:

$$V_{cell} = E - R \cdot I - A \cdot ln\left(\frac{I}{i_0}\right) + m \cdot exp(n\,I) \tag{10}$$

Where « E » is the reversible circuit voltage of the cell, it is of the order of 1.2V.

Normally the load transfer phenomenon occurs only when exceeding a certain value of the current. Therefore, this phenomenon is not taken into account. Thus, the voltage of the cell will be expressed by the equation:

$$V_{cell} = E - R_{cell} \cdot I_{cell} - A \cdot ln(a \cdot I_{cell} + b) \tag{11}$$

Where, I_{cell} is teh current delivered by a cell, and R_{cell} the membrane resistance of a cell that represents the ohmic losses, a and b are real constants. R_{cell} was simply calculated by the following expression:

$$R_{cell} = \frac{\Delta V_{cell}}{\Delta I_{cell}} \tag{12}$$

ΔI_{cell} is calculated for a current of (40A≤ I_{cell} ≤ 60A), a and b were calculated by solving a system of two equations derived from two different values of I_{cell}.

To get higher operating voltage, FCs are connected in series and in case of having a FC stack consisting of N cells the voltage of the stack is given [21]:

$$U_{pac} = N_{cell} \cdot V_{cell} = N_{cell}\left(E - R_{cell} \cdot \frac{1}{2} I_{pac} - A \cdot \ln(21.273 \cdot I_{cell} + 96.297)\right) \tag{13}$$

Where N_{cell} is the total number of cells in the stack.

2.3.2 The traction battery:

A key parameter in the electric vehicle is the state of charge (SOC) of the battery. The state of charge (SOC) of the battery, defined as:

$$SOC = \frac{Remaining\ charge\ in\ Ampere\ hours\,(Ah)}{Capacity\ of\ the\ battery\ in\ Ampere\ hours\,(Ah)} \tag{14}$$

Provides vital information about the status of the battery. Numerous approaches can be found in the literature for tracking the SOC of the battery. The knowledge of SOC and battery capacity is used to estimate the time to shut down or time to fully charge the battery. It is understood that the battery capacity varies with temperature and that it fades over time depending on usage patterns and age. Accurate tracking of battery capacity is a critical element of battery fuel gauging; however, it has received relatively little attention in the literature [25].

To define mathematically, it is considered a fully discharged battery. The battery is charged with Ibatt charge current. So from time t_0 to t, the battery will hold an electric charge:

$$\int_{t_0}^{t} I_{batt}(t).dt \tag{15}$$

The total charge that the battery can hold is given by:

$$Q_0 = \int_{t_0}^{t_2} I_{batt}(t).dt \tag{16}$$

Where t_2 is the breaking time when the battery no longer takes any supplement. Next, the state of charge can be expressed as [26]:

$$SOC = \frac{\int_{t_0}^{t} I_{batt}(t).dt}{Q_0}.100\% \tag{17}$$

In practice, the SOC of the battery is maintained between 20 and 95% [27].

The depth of discharge (DOD) is the percentage of the battery capacity when the battery is low. The depth of discharge is given by:

$$DOD = \frac{Q_0 - \int_{t_0}^{t} I_{batt}(t).dt}{Q_0}.100\% \tag{18}$$

3. Simulations Results and Interpretations.

In this part of our study, we simulated the vehicle in a standard driving cycle which expresses the evolution of the speed of the vehicle as a function of time. The driving cycles were used in the design phase, development and testing of vehicles. Indeed, these driving cycles define the use of the vehicle from which it is possible to size the battery capacity and optimize the energy management strategy hybrid. In our case, we chose to cycle UDDS (Urban Dynamometer Driving Schedule) (Figure 4). Also called FTP-72 (Federal Test Procedure). In the US, it is used for the certification of emissions from light vehicles.

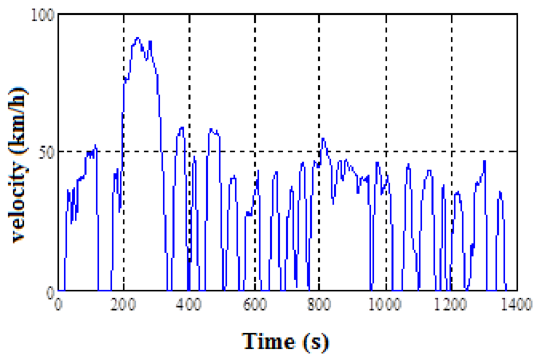

Fig. 4 driving cycle FTP-72 or UDDS

Results of the fuel cell vehicle model studied

3.1. *Emissions and fuel consumption (H_2) :*

The figure 5 illustrates the emission of gases namely HC, CO, NO_x, PM during the working cycle studied, knowing that the vehicle consumes 0,111 m^3/100km equivalent to 7.5 l/100 km fuel for 11.3 km, emissions of pollutants gases (HC, CO, NO_x, PM) are zero. This allows us to see that the two power sources for propulsion shall constitute no polluting gases.

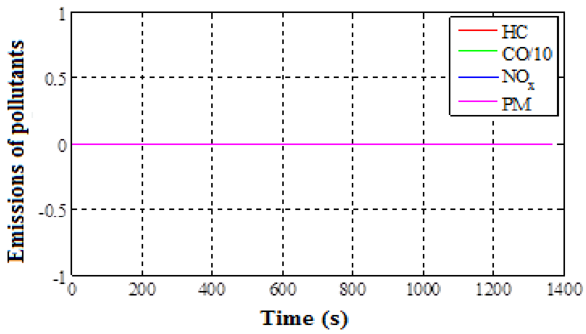

Fig. 5 Gas emissions (g/s)

3.2. *The fuel cell:*

- Electric power:

The figure 6 illustrates the evolution of the electrical power the fuel cell obtained during operation. Note that the fuel cell delivers the same power required by the drive motor shown in Figure 8. This means that the fuel cell is the main energy source

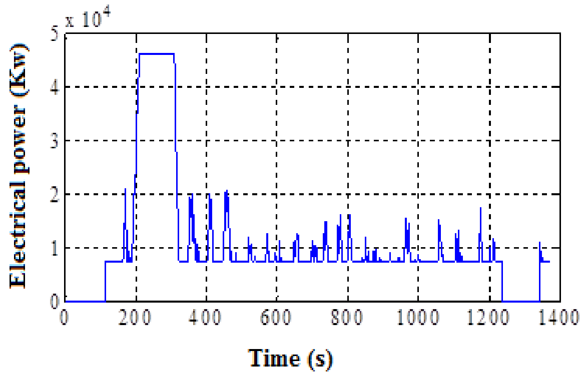

Fig. 6 Electrical power supplied by the fuel cell

- Average efficiency of the fuel cell:

The figure 7 shows the effectiveness of the PEM hang cycle work. It is found that the battery is most effective (60%) when the power demand exceeds 10 kW. At the end of the considered cycle is characterized by a drop in speed results in a braking vehicle, we found low efficiency (minimum) leaving parte to the battery to be charged by recuperating of the vehicle kinetic energy.

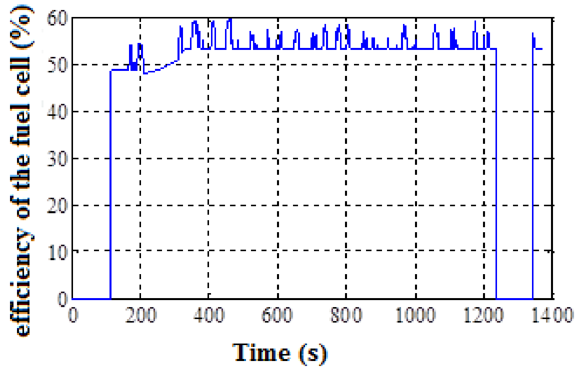

Fig. 7 Average efficiency of the fuel cell

- Fuel usage (hydrogen) :

The figure 8 shows the use of hydrogen that is to say the flow rate consumed by the fuel cell. We note that consumption follows the driving cycle. There is a maximum consumption (0.8 g/s) when the maximum speed of the cycle is reached (92 km/h). This situation is observed during the period [200-370s]. Excluding this simulation period, the hydrogen consumption is between 0.1 and 0.3 g/s.

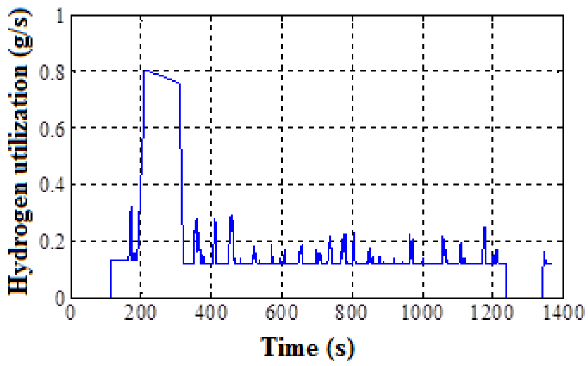

Fig. 8 Fuel utilization

3.3. *The electric motor*

- Electric motor power

The figure 9 illustrates the evolution of the power of the electric motor during the simulation period. There is considerable appeal to power approximately 45.5 KW during the same period characterized by the maximum vehicle speed [200: 370 s].

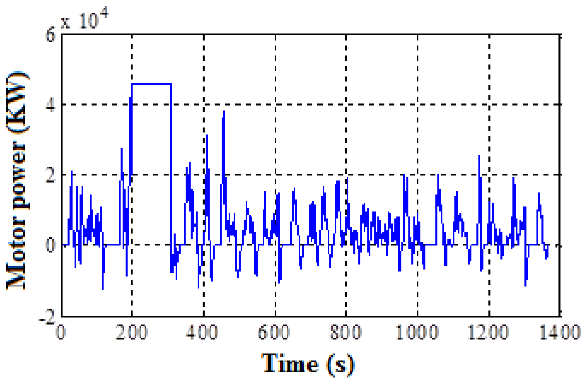

Fig. 9 Power demand of the electric motor

- Motor Torque

On figure 10 we present the engine torque evolution . It is observed that in order to propel the vehicle, the electric motor must develop a higher torque than or equal to 50 Nm.

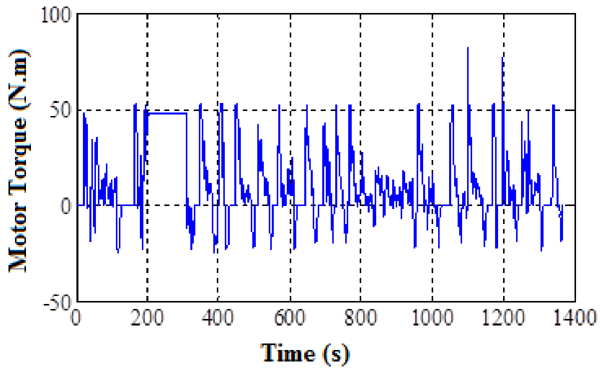

Fig. 10 Motor torque

- Electric motor temperature

Among the problems associated with electrical devices and particularly the electric motor is the heating of the latter. For this reason we therefore want to ensure that the engine operates within acceptable temperatures to ensure proper operation and long life of the coil. Figure 11 shows changes in the maximum temperature of the surface of the engine continuously without interruption over time. Note that the temperature rises steadily until reaching its maximum value (46°C, acceptable) corresponding to the maximum speed of the cycle in the range [200:400 s].

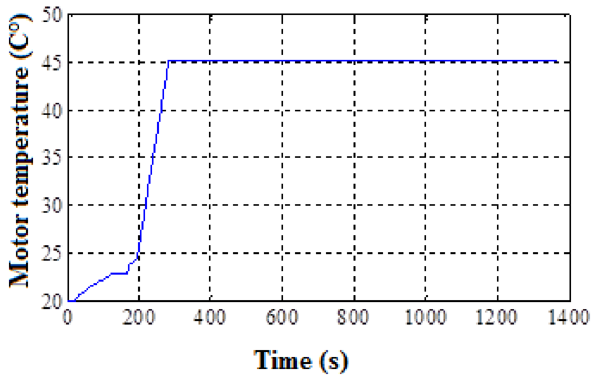

Fig. 11 Average temperature engine

3.4. ***Battery:***

- Power of the battery :

The power required by the electric motor increases in order to meet the vehicle's velocity profile. The oscillations at the beginning of the interval are due to the fact that the battery provides power suddenly, causing the transitional arrangements. The discharge mode is indicated by positive values and charging mode is indicated by negative values relating to the braking corresponding to the speed drop in the FTP 72 cycle considered.

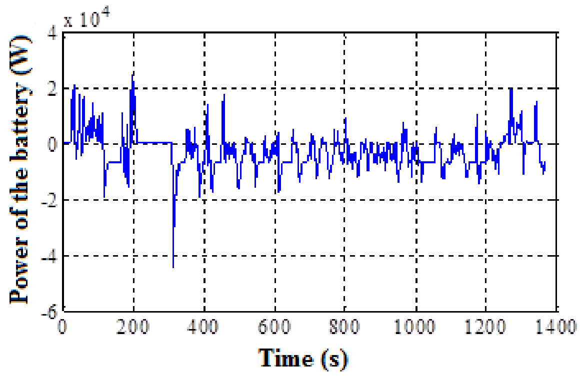

Fig. 12 Power of the battery

- State of charge of the battery (SOC):

The second mode of operation encountered during simulation is the battery charging mode (figure 12). The generator provides full power required to recharge the battery. This mode corresponds to the period of operation of the braking vehicle. In this case, 1 the kinetic energy of the vehicle is returned to the battery via the electric motor in generator operation and the battery is charged to 10% (ie. D: 70% to 80%) in about 1000 s (28 min). The charge mode of the battery is indicated by negative values of power in the graph of figure 13.

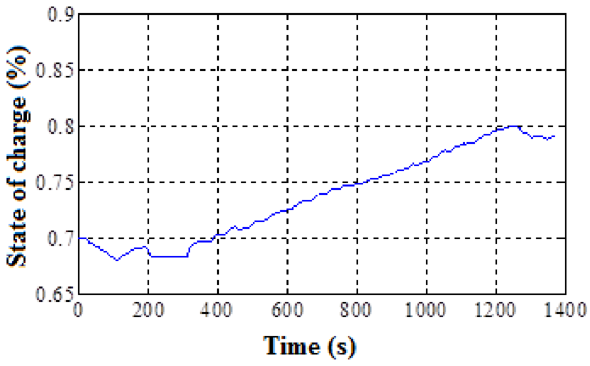

Fig. 13 State of charge of the battery

- Average temperature of the battery:

Temperature has a significant impact on the life of the batteries. When the temperature increases by 10 ° C, the speed of dual electrochemical reactions: the average life of the batteries decreases by a factor of 2 each 10 °C because the corrosion is accelerated when the temperature drops, the life batteries increases, but their ability decreases. One for that you need to control the battery temperature during operation. Figure 14 shows the average temperature of the battery which indicates that the maximum temperature (around 23°C) is reached at the end of the cycle corresponding to the charge of the battery. This temperature is low and does not affect the battery performances.

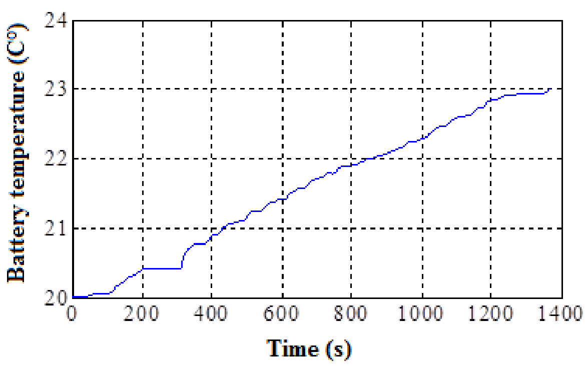

Fig. 14 Evolution of the average temperature of the battery

4. Conclusion

The work presented in this paper aims simulation analysis of the performance of a hybrid electric vehicle fuel cell. Before the simulations, we conducted a preliminary stage of the system modeling. This is essential to understanding the phenomena involved in the organs and the interactions between these subsystems. In order to achieve the simulation, we used the ADVISOR software (Advanced Vehicle Simulator).

The observation results of the simulations show that the performance of the vehicle fuel cell studied, namely: the vehicle speed, power of the electric motors, the efficiency of the fuel cell, the use of hydrogen, torque motor and battery power were coherent and consistent with theory by showing very stable throughout the period of time for the cycle.

To conclude, we can say that the hybrid fuel cell vehicle has one of the alternatives being considered to replace the conventional vehicle including a performance about two times higher than a petrol engine urban cycle. However it is an alternative that will take time, technological advances and investments in order to achieve consistent levels of costs with distribution on mass markets. Manufacturers expect a maturity of at least 20 to 30 years for those vehicles reach a significant market share. Until then, and probably beyond, the engine will remain the dominant drive mode while the hybrid and electric vehicles have begun to take a significant market share.

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