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Multi-stack fuel cells powering a vehicle

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Abstract

Current issues concerning global warming and fossil fuel energy shortages impose to find alternatives in order to meet the growing planet's energy demand. The automotive sector is particularly concerned with these issues. The fuel cell seems to be a very promising technology. This article addresses a technological aspect of the integration of fuel cell on a vehicle. The chosen configuration is a multi-pack system favoring the use of several reduced power fuel cells. The energy management method is described along with the sizing and some simulation results.

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Keywords: Fuel cell; electrical vehicle; multi-stack; modelling.

1. Introduction

The global population growth and the increase in industrial activity are real issues with regard to global warming and power reserves. Fossil fuels tend to disappear and the use of new natural resources is more and more encouraged. Governments have the responsibility to initiate the energy transition. Measures have been taken and concerted effort concerning wind, solar, geothermal energy and biofuels are in progress all over the world. But, another resource seems very promising: hydrogen. Indeed, hydrogen has an energy density of 140 MJ/kg, which is 3 times higher than oil and 200 times higher than a lithium battery. The automotive sector, in particular, is one of the major contributors to the greenhouse effect. Indeed, there were already 1.015 billion cars in 2010 owing to Wardsauto [1]. However, new motor technologies emerge and reduce gas emissions.

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Hybrid technologies combining heat engine and electric engine are currently in use:

- In 1997, the Toyota Prius was the first mass-marketed hybrid vehicle.
- In 1999, the Honda insight was born.
- Then, in 2002 the Honda civic hybrid was marketed.

But, to make further progress, it is also possible to feed an electric motor only thanks to a fuel cell (FC). Gaseous hydrogen is used as fuel and air (oxygen) as combustive. The only byproduct are water and heat. This is a zero emissions technology. This FC can be reinforced with batteries and ultra-capacitors. Consequently, it is actually the source which is hybridized and not the engine.

Various types of FCs exist. The PEMFCs (Proton Exchange Membrane Fuel Cells) seem to be the most promising for transportation. This FC is composed of an electrolyte membrane allowing the passage of ions and preventing the passage of electrons. Around it are two porous electrodes containing hydrogen and oxygen: the anode and cathode. Electrons migrate from the anode through the electrical load to the cathode. Therefore, the electric current is created.

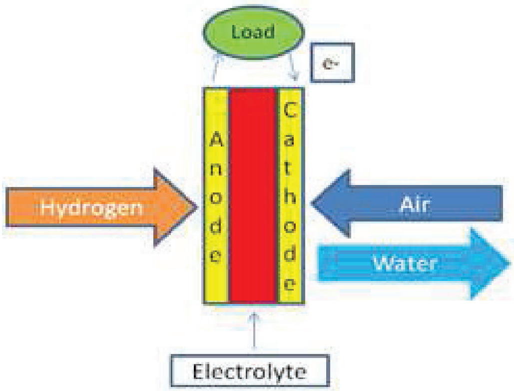


Figure 1 - Principle diagram of a cell

Two bipolar plates are present to feed the system in gaseous hydrogen and air, displace the water produced by the cathode, allow a cooling fluid to circulate, make the electrical connection between elementary cells of the FC and ensure the mechanical resistance of the entire system [2].

So, it's a basic oxide-reduction reaction which takes place within the FC. It is represented by the following chemical equation [3], [4], [5]:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + electricity + heat \quad (1)$$

The faster the rate of the reaction at the level of the electrodes is, the more the FC is effective. This is why, platinum is used as a catalyst material to form the surface of the electrodes. Three criteria can affect the efficiency of the reaction in a PEMFC (one can also add the air or oxygen pressure):

- The first is temperature, which must be between 60°C and 80°C.
- The second is the hydrogen intake pressure directly controlled by the current flowing the FC.
- The third is the suitable humidification of the polymeric membrane.

Actually, several auxiliaries take part in the operation of the FC. The package including the FC and the auxiliaries is called FC system [2], [6].

2. Description of the fuel cell model

The described modelling is of a multi-pack FC. It is an innovative concept in terms of architecture: FCs are connected in parallel. In this way, in a vehicle, if one of the FCs suddenly goes down, it may be replaced without changing the entire system. It improves the reliability by acting on failures. Their combination provides energy to auxiliary systems and allows the vehicle to progress at a constant rate. This solution can be in complementary with other researches on FC fault diagnosis [7], [8], [9], [10] as well as research on optimization or maximization of the FC system functioning [10], [11] or the modelling [12], [13], [14], [15], [16], [17] and identification of the FC system [18]. Recent researches are also related to multi-stack FC systems as it can be seen in [19], [20], [21] and [22].

The power and energy demand of the electric engine are supplied by an assisting battery and the FCs respectively. FCs supply the energy required to drive the vehicle forward, it does not include transient phases (high acceleration and deceleration). The battery plays the role of a power source [4], [5], it absorbs and supplies transient phases: it allows high acceleration by adding up its power to the FCs one and recovery during breaking phases.

FCs are connected to the electric engine through the power bus. But, the voltage of this bus may be imposed by other elements such as the battery. This is why, it is necessary to insert a static converter between the FCs and the bus. This way, the low output voltage of the FCs is improved.

Each FC is composed of several elementary cells. An elementary cell is electrochemically modeled [2]. It's an electrochemical model in the sense that it is characterized by its enthalpy or, a fortiori, its Gibbs free energy. The model has three inputs:

The hydrogen intake pressure	The temperature	The current flowing the FC

This provides three outputs:

The power	The cell voltage	The consumed hydrogen flow

Several parameters are also involved:

The air intake pressure	The various losses (activation, Joule and concentration)

On the basis of the chemical equation (1) that the electricity is produced by the FC. To achieve this, our system is characterized by its own quantity: the enthalpy H. The variation ΔH of this value represents the variation of total chemical energy taking place in a reaction, and consequently potentially, the electrical energy that could be recovered from chemical energy.

However, the second law of thermodynamics imposes:

$$\Delta G = \Delta H - T\Delta S \tag{2}$$

Here, ΔH represents the variation of total chemical energy, and TΔS represents the energy quantity that cannot be recovered by the system because it is converted to heat (ΔS represents the variation of entropy and T the temperature). Therefore, the recoverable energy is the variation of Gibbs free energy ΔG.

The variation of Gibbs free energy ΔG is based on equation (1):

$$\Delta G = \Delta G^0 + RTln\frac{1}{P_{H_2} * \sqrt{P_{O_2}}} \tag{3}$$

Here, R represents the perfect gas constant ($R = 8{,}3144621\, J \cdot mol^{-1} \cdot K^{-1}$) and T the temperature.

The term ΔG^0 allows us to define a standard potential at a given thermodynamic state. So, the maximum potential theoretically accessible in standard pressure and temperature conditions is:

$$E^0 = -\frac{\Delta G^0}{nF} \tag{4}$$

Here, n is the number of electrons involved in a reaction, which is 2. F is the Faraday constant which is 96 485 Coulomb/mol. This difference of standard potential is specific to O_2 / H_2 couple. At 25°C and 1 bar, E_0 = 1.23 V in the case where the water produced by the cathode is liquid (that is the case here). The electrochemical potential of the cell is given by the following expression:

$$E = E^0 - \frac{RT}{nF} ln\frac{1}{P_{H_2} * \sqrt{P_{O_2}}} \tag{5}$$

The current is generated by the flow rate of hydrogen, however, it is imposed by the entire system. Consequently, the current is an input of the cell. The current flowing the cell is given by the following law:

$$i = n * F * J_{H_2} \tag{6}$$

J_{H_2} is the molar flow rate of hydrogen.

Figure 2 shows the polarization curve of a PEM elementary cell: the red continuous curve shows the ideal voltage of the cell and the blue dotted curve shows the real voltage of the cell.

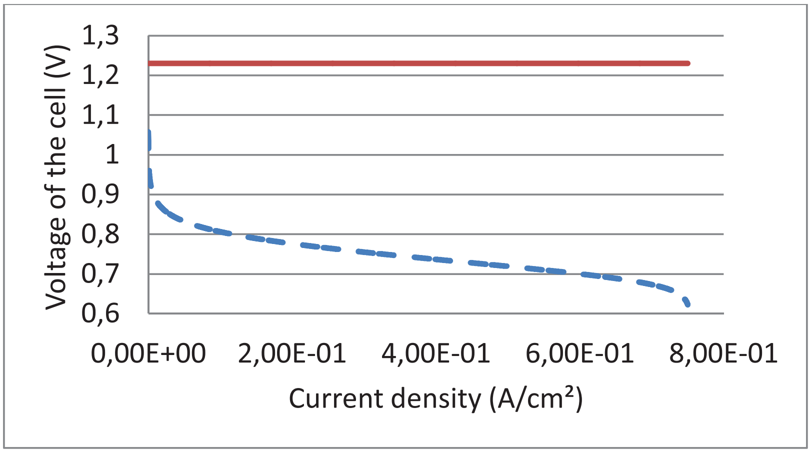


Figure 2 - Polarization curve of a PEM elementary cell

Three types of losses have been taken into account in order to obtain this curve:

- Activation losses occur at low current density. A certain amount of energy is necessary to initiate the reaction. The expression of this losses is given by the Tafel law:

$$V_{act} = \frac{RT}{\alpha 2F} \ln \frac{i}{i_0} \tag{7}$$

Here, i_0 is the current density of exchange which represents the nominal value supplied by the cell (i>i0) and α is the charge transfers coefficient, between 0 and 1.

- Joule losses occur at medium current density. These losses are due to the electrical resistance present in the cell components, as the electrolyte or the electrodes. These losses are given by the following expression:

$$V_{\Omega} = R_e * i \tag{8}$$

Here, *Re* is the equivalent resistance of the package (cathode + anode + electrolyte).

- Concentration losses occur at high current density. When the current density is too high, the gas diffusion is not enough fast to maintain the reaction [2]. These losses are given by the following expression:

$$V_{conc} = \frac{RT}{nF} \ln\left(\frac{i_L}{i_L - i}\right) \tag{9}$$

Here, i_L is the limit current that can be delivered by the cell.

Modelling allows us obtaining the figure 3(a) which shows the power supplied by the FC. The blue continuous curve shows the power of the cell before the converter and the red dotted one shows the power after the converter. Modelling also provides the efficiency curve of a FC on figure 3 (b). The blue continuous curve shows the efficiency of the single FC and the red dotted curve shows the efficiency of the package FC + converter.

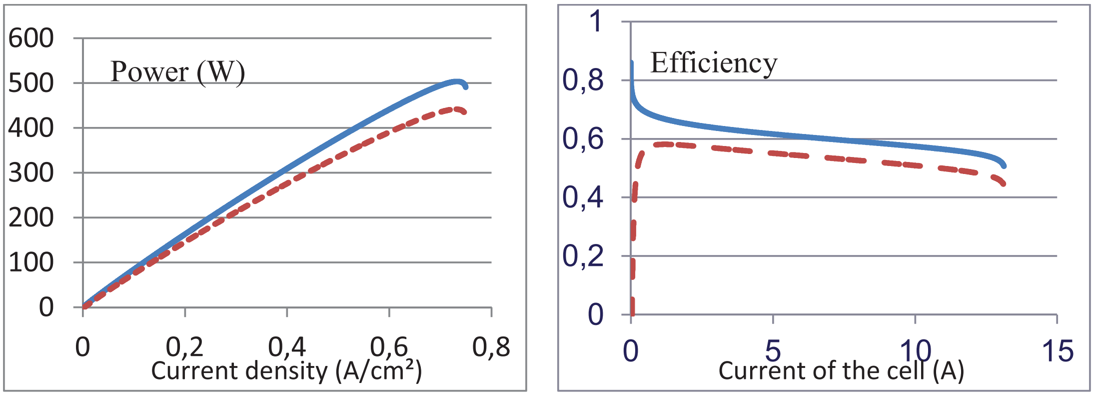


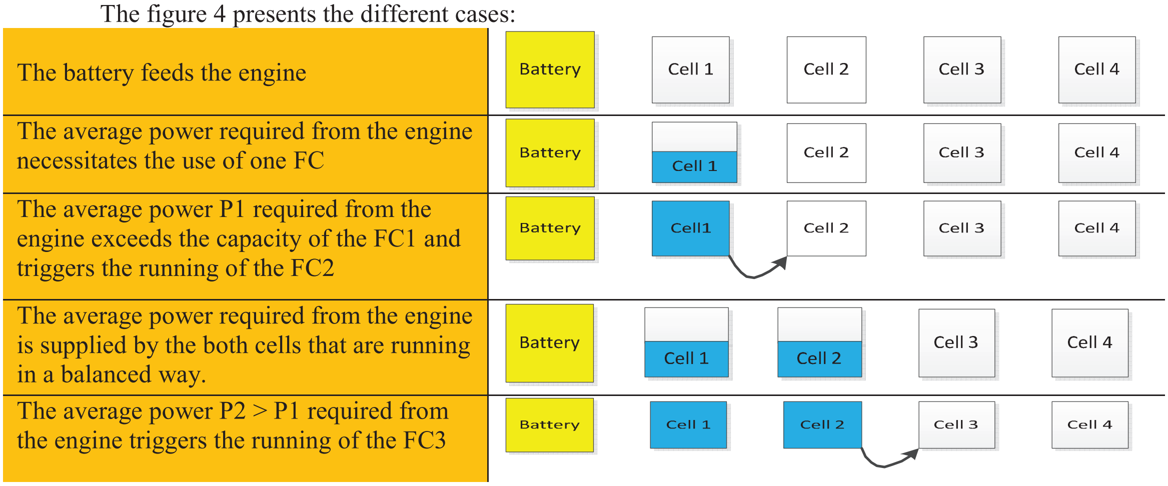
Figure 3 – (a) Power supplied by the FC, (b) - Efficiency of the FC

3. Multi-stack technology interest

The use of a multi-pack system has several advantages:

- First, from a maintainability point of view, FCs may be separately replaced because it is installed in parallel.
- The main advantage to use a multi-pack system could be the operating mode of the cells. Indeed, according to the type of road journey, the average power demand differs. FCs are activated according to the average power demand. In fact, it is acceptable to trigger FCs one by one when an average power threshold is exceeded. Therefore, the first average power threshold will require the use of the first cell, the second average power threshold will require the use of the first two cells. And so on. In every case, the battery is the first device to be triggered. Let's not forget that it is essential to seek to minimize as far as possible the number of cycle start/stop of each cell. Indeed, it is directly tied to the lifespan of the cell. The lifespan of a cell is approximately 500 cycles. This is why, in our configuration, in a phase of deceleration where the average power necessary to the vehicle progress is less significant, the FCs energy contribution is reduced instead of stopped. This way, all cells are balanced together in energy according to the communicating vessels principle.

The figure 4 presents the different cases:



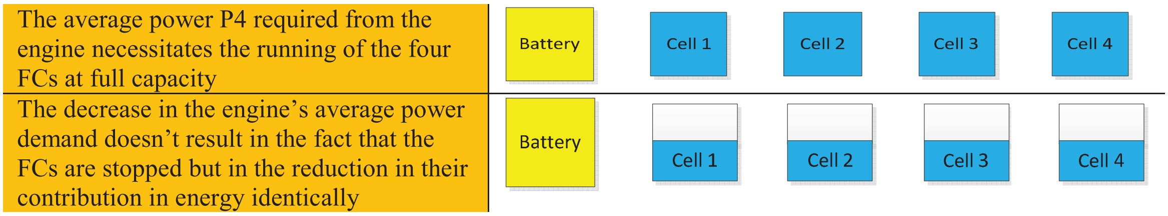


Figure 4 - Operating mode of the package battery + FCs

Previous developments are described with a system including 4 FCs but, analogously, it is possible to generalize to a system of N FCs.

4. Pre-sizing of the fuel cells

The number of FCs that are running is determined by the average power required to allow the vehicle to progress at a constant rate. By this way, and according to the speed of the vehicle, the required average power is obtained, and consequently, the number of cells to run is determined. The multi-stack configuration is introduced to use several power reduced FCs rather than using a single high power FC. This is why; the pre-sizing has been carried out with 3 types of FC of relatively low power: 500W, 1000W and 2000W. These values for power are well below what can be found in the automotive market. As an example, the FC chosen by the German carmaker Volkswagen is around 100 kW. This configuration brings an alternative to existing technologies.

The following pre-sizing results are part of the skills of Segula Technologies. These results were obtained using MTCSIM (Mathematical Temporal Calculation Simulation).

The Tables 1, 2 and 3 describe the number of cells used in the different cases:

	Power (W)	**Number of requested FCs**		
		500 W	**1000 W**	**2000 W**
Average power required at 50km/h (stabilized, slope 0%)	1390,9	15	8	4
Plus auxiliaries	**6390,9**			
Average power required at 90km/h (stabilized, slope 0%)	7683,3	29	15	8
Plus auxiliaries	**12683,3**			
Average power required at 130km/h (stabilized, slope 0%)	22956,3	64	32	16
Plus auxiliaries	**27956,3**			

Table 1 - Estimation of the stacks number that are running for the average power need for a Compact vehicle

	Power (W)	**Number of requested FCs**		
		500 W	**1000 W**	**2000 W**
Average power required at 50km/h (stabilized, slope 0%)	1506	15	8	4
Plus auxiliaries	**6506**			
Average power required at 90km/h (stabilized, slope 0%)	8005	30	15	8
Plus auxiliaries	**13005**			
Average power required at 130km/h (stabilized, slope 0%)	23779	66	33	17
Plus auxiliaries	**28779**			

Table 2 - Estimation of the stacks number that are running according to the average power need for a City vehicle

	Power (W)	Number of requested FCs		
		500 W	**1000 W**	**2000 W**
Average power required at 50km/h (stabilized, slope 0%)	1848.8	16	8	4
Plus auxiliaries	**6848.8**			
Average power required at 90km/h (stabilized, slope 0%)	9894.8	34	17	9
Plus auxiliaries	**14894.8**			
Average power required at 130km/h (stabilized, slope 0%)	29424.3	79	40	20
Plus auxiliaries	**34424.3**			

Table 3 - Estimation of the stacks number to run according to the average power need for a Crossover vehicle.

5. Control strategy:

The control law has 4 inputs:

The battery state of charge	The number of activated fuel stacks
The instant power received or supplied by the engine	The number of operational fuel stacks

It has also 2 outputs:

The number of extra stacks that must be activated	The power that must be supplied by the FCs

The engine average power demand and the number of activated FCs allow us to determine the number of extra FCs that must be activated. The number of operational FCs, the engine average power demand and the battery SoC allow us to determine the power that must be supplied by the FCs.

According to the battery SoC, there are 4 operating modes:

- When the battery SoC is below 25 % (extreme situation) the FCs are controlled to operate at full power in order to recharge the battery.
- When the battery SoC is between 25 % and 70 %, the FCs supply a power above the one demanded by the engine in order to recharge the battery gradually.
- When the battery SoC is between 70 % and 90 %, only the FCs supply the engine energy. The battery recharges only thanks to the brake energy recovery. It should be noted that on a braking phase, the engine power demanded becomes negative. Yet, the FCs should not be stopped; this is why it supplies in this case a minimal energy that is 10 % of their full power. This energy is recovered by the battery.
- When the battery SoC exceeds 90 %, here again only the FCs supply the energy for the engine. In the case of a braking or a parking, the FCs are controlled to supply 0.5 % of their full power. Because, by leaving the FCs operate at 10 % of their power, the battery will quickly be recharged at 100 %. And, once this threshold is reached, there is a risk of wasting the energy of the FCs.

The figure 5 describes the functioning of the system with the control strategy.

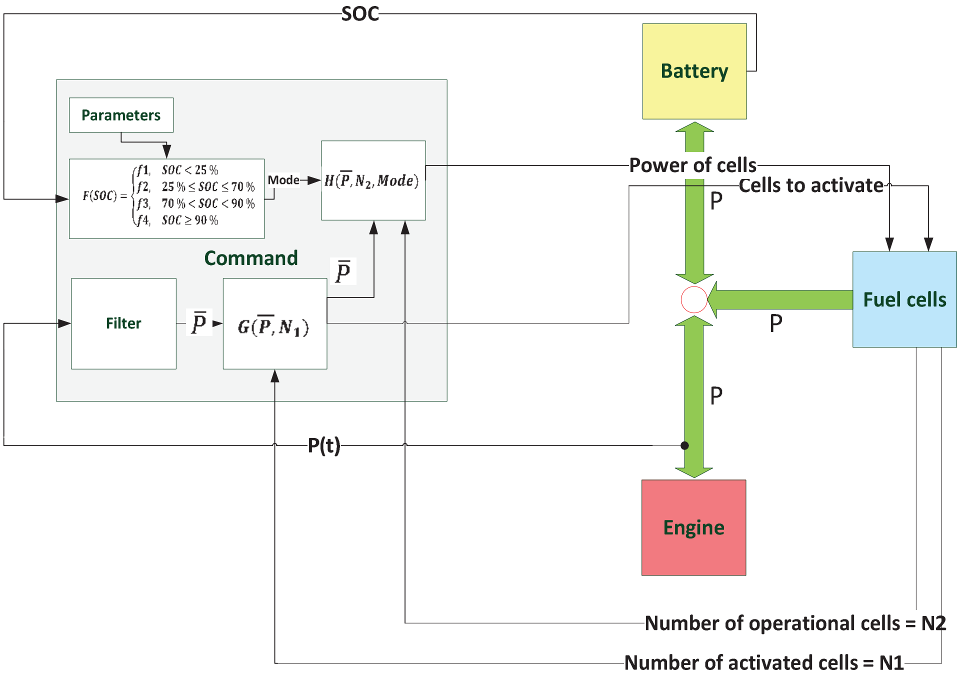


Figure 5 – Functioning of the system with the control strategy

6. Time response and fuel cell sizing results.

The pre-sizing results are now introduced in our model with a simple PI controller. At first, simulations are carried out with a special speed cycle that is called cycle A (Fig. 6(a)).

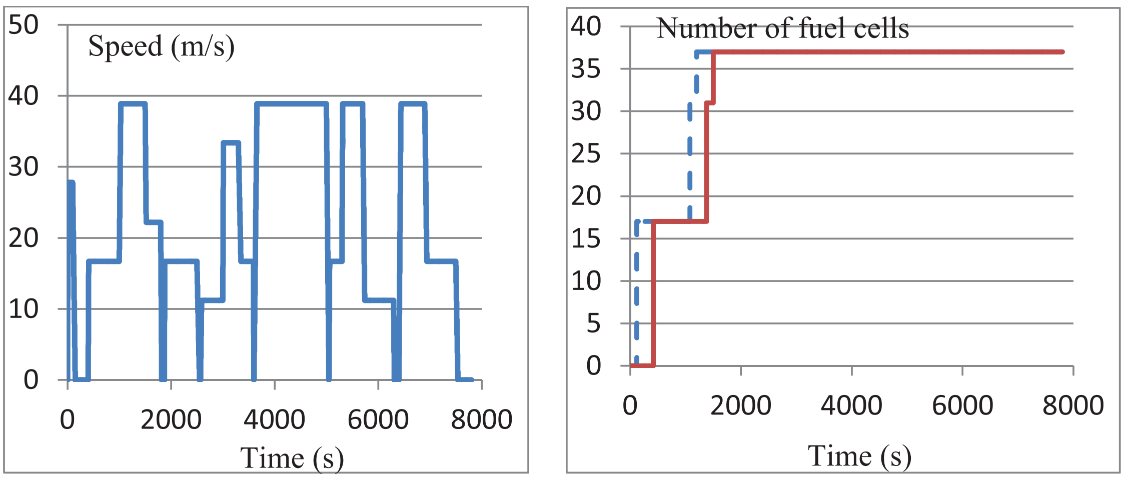
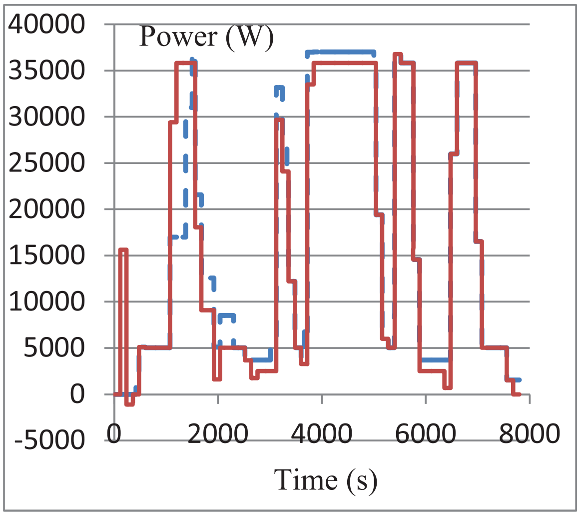


Figure 6 – (a) Speed cycle A used in simulations, (b) Evolution of the number of activated cells (in dotted blue) and operational cells (in continuous red) on the cycle A for a city vehicle

The FCs are triggered according to the average power calculated on a previous time interval. This value is periodically estimated. This is why a time lag is seen between the number of activated cells and operational cells.

This time lag reflects the startup time of the FCs. It is described on the figure 6(b). The activated FC is the “woke ep” and is waited to be heated in order to be operational (i.e. to deliver energy)

At the beginning of the simulation the number of operating FCs is inadequate to deal with the average power demand, this is why the average power curve and power supplied by cells curve are not combined on the figure 7 (a). When the number of operating stacks is adequate, the power given by stacks curve follows the average power curve. After the stacks startup phase, it is observed that the power given by stacks curve exceeds the average power demand. Indeed, the battery has been discharged during the startup time of the stacks and its SoC decreases below 70 %, this is why afterwards the FCs are controlled to supply the energy necessary to recharge the battery in addition to the engine energy. When the average power diminishes significantly, it is also observed that the power supplied by FCs reaches a minimum threshold. Moreover, when the battery SoC reaches again 70 %, the battery recharges only thanks to the braking energy, the FCs only supply the energy for the engine, this is why after a time, curves are superposed. The variation of battery SoC is described on the figure 7(b)



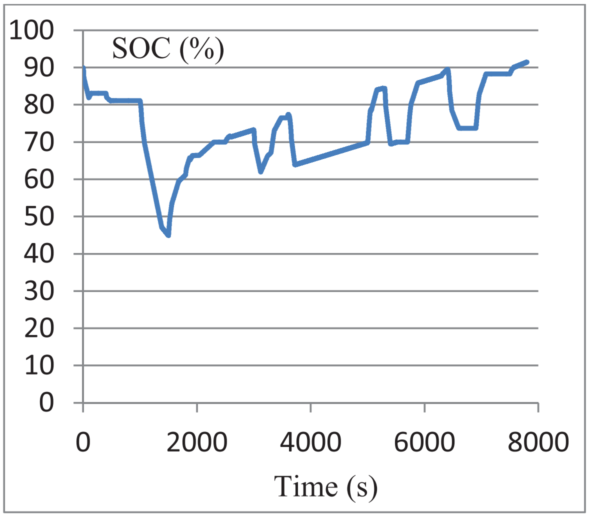


Figure 7 – (a) Average power (red continuous line) and power supplied by FCs (blue dot line) on the cycle A for a city vehicle, (b) Battery SoC with the cycle A for a city vehicle

One can see that at the beginning of the cycle, the battery SoC diminishes significantly. This is due to the FCs startup time. The battery must supply the energy needed by the engine. Once the FCs are operational, they are controlled to recharge the battery because its SoC is below 70 %. Then, the battery continues to be recharged thanks to braking energy recovery. It is seen in figure 7(b) that the SoC reaches 90 % gradually.

Second, simulations are carried out with the pre-urban cycle EUDC-Low:

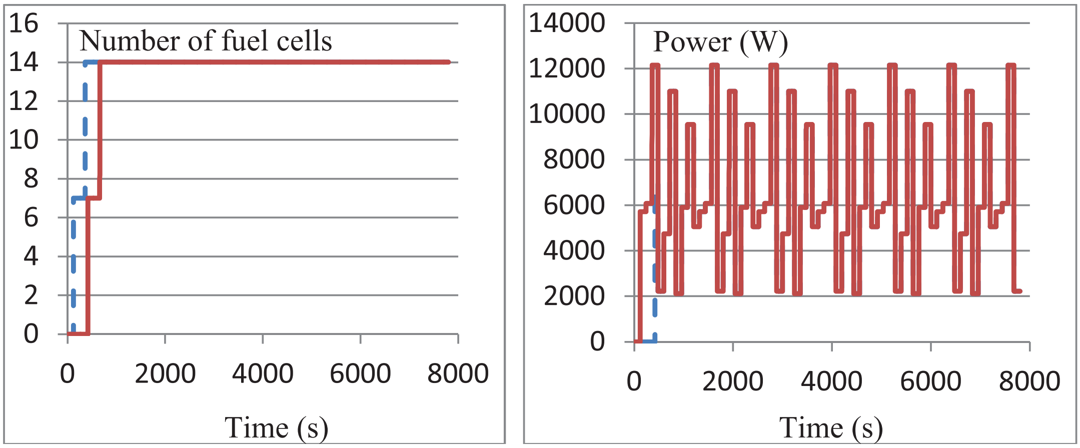


Figure 8 – (a) Number of activated cells (blue dot line) and operational cells (red continuous line) on the pre-urban cycle for a city vehicle, (b) Average power (red continuous line) and power supplied by FCs (blue dot line) on the pre-urban cycle EUDC_Low for a city vehicle

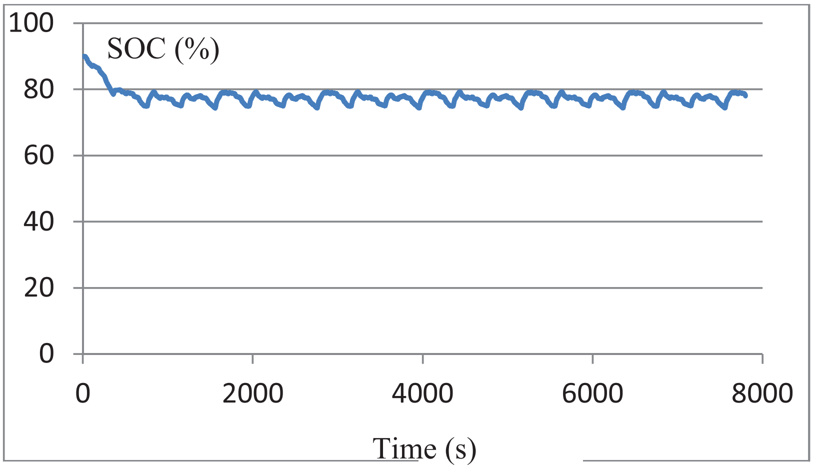


Figure 9 - Battery SoC on the pre-urban cycle EUDC_Low for a city vehicle

The simulations give us the average power required to allow the vehicle progress according to the road circuit. Consequently, it gives the number of FCs operating and the state of charge of the battery before and after the simulation.

The results are described in the tables 4, 5 and 6:

Road trip type	Speed standard cycle	Average power (W)	Number of FCs (1000W)	Initial battery SoC	Final battery SoC
Urban	NYCC	1200	2	90 %	89 %
Pre-urban	EUDC_Low	10000	11	90 %	81 %
Highway	REP05	18000	19	90 %	71 %

Table 4 - Simulations results for a compact vehicle

Road trip type	Speed standard cycle	Average power (W)	Number of FCs (1000W)	Initial battery SoC	Final battery SoC
Urban	NYCC	1800	2	90 %	88 %
Pre-urban	EUDC_Low	13000	14	90 %	78 %
Highway	REP05	23000	24	90 %	72 %

Table 5 - Simulations results for a city vehicle

Road trip type	Speed standard cycle	Average power (W)	Number of FCs (1000W)	Initial battery SoC	Final battery SoC
Urban	NYCC	2100	3	90 %	88 %
Pre-urban	EUDC_Low	14000	16	90 %	76 %
Highway	REP05	27000	29	90 %	72 %

Table 6 - Simulations results for a cross-over vehicle

According to the simulations, the number of operating FCs is small on urban road trip. The multi-pack configuration improves the system lifespan because it only triggers the necessary FCs to drive the vehicle forward. For pre-urban or highway road trip the average power increases. Consequently, the number of operating FCs is increased. The battery SoC, after simulation, remains above 70 %. For urban and pre-urban trip, the SoC doesn't decrease below 70 %. On a highway trip, the SoC decreases below 70% but the FCs are controlled to recharge the battery. This is why whatever the type of vehicle is, the battery SoC, after a highway trip, is above 70 %.

7. Conclusion

A simple model of FC system was described. It is based on the equations that describe electrochemical phenomena that take place within an elementary cell. These phenomena are known and well described by the literature. The gas and fluids lines have been described. It includes a hydrogen circuit, an air circuit, a humidification circuit and a coolant/heating liquid circuit. The interest of a multi-stack system was presented. The multi-stack technology consists in several low powered FCs instead of a single high powered FC. This way, only the stacks necessary to supply the energy needed by the engine are triggered. Moreover, the FCs may be replaced separately as a result of their installation in parallel. The addition of a cycle counter on each FC also allows distributing the cycles on all FCs. The global durability of the entire system is increased. The complementary roles of the battery and the FCs as power and energy sources are highlighted in the description of the energy management. The battery is a key element into the system operation. The cold start and warming-up time issues have been taken into account in the sizing of the battery. At first, a pre-sizing of the FC system was carried out. This pre-sizing has been carried out for different rates of the vehicle. Then, simulation results of the introduced model with a control law, allowing the energy management with the cycling of the cells, are presented. This command law ensures the recharge of the battery. This model has been tested on standardized speed cycles and on a cycle built by Segula Technologies. Finally, a size and weight study is also presented.

Variable	Description	Units
G	Gibbs free energy	$J.mol^{-1}$
H	Enthalpy	$J.mol^{-1}$
T	Temperature	K
S	Entropy	$J.K^{-1}.mol^{-1}$
R	Perfect gas constant	$J.K^{-1}.mol^{-1}$
n	Number of electron involved in the reaction	-
F	Faraday constant	$C.mol^{-1}$
P_{H_2}	Hydrogen pressure at anode inlet	bar
P_{O_2}	Oxygen pressure at cathode inlet	bar
J_{H_2}	Hydrogen molar flow rate	$mol.s^{-1}$

V_{act}	Activation losses	V
V_{Ω}	Joule losses	V
V_{conc}	Concentration losses	V
i	Current density	A/cm^2
i_0	Nominal value of current density	A/cm^2
α	Charge transfers coefficient	-
R_e	Equivalent resistance of the package (cathode + anode + electrolyte)	Ω
i_L	Limit current density that can be delivered by the cell	A/cm^2
$\overline{P}$	Average power	W
N_1	Number of activated cells	-
N_2	Number of operational cells	-

List of the variables

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