A fuel cell hybrid power source for a small electric vehicle

Denis Candusso, Elisabeth Rullière, Ianko Valero

Laboratoire d'Electrotechnique de Grenoble- UMR 5529 INPG/UJF-CNRS
elisabeth.rulliere@leg.ensieg.inpg.fr

Abstract - **Proton Exchange Membrane Fuel Cells (PEMFC) can be used in a variety of power-train configurations ranging from an exclusively fuel cell engine to hybrids that utilise some ratio of fuel cell and other sources such as batteries, flywheels, supercapacitors… which provide the peaks of power. We show the interest of a hybrid PEMFC source by comparing two power-train configurations for a small Electric Vehicle providing an average power of 2 kW and a maximum power of 9 kW. The first configuration includes a 9 kW PEMFC as an electric source and the second one associates a 4,5 kW Fuel Cell and supercapacitors able to provide 5 kW for a few seconds. The comparison is performed by simulating the two configurations thanks to ADVISOR software (ADvanced VehIcule SimulatOR). We have also been able to test different power control strategies. The simulation is performed on a traditional urban cycle as well as on another one corresponding to long distance running.**

1. Introduction

It is generally accepted that pure electric cars cannot demonstrate a satisfactory drive range. Nevertheless, fuel cells seem to be a promising technology to power vehicles and the Proton Exchange Membrane Fuel Cell (PEMFC) is certainly the most interesting one as it is quite compact and operates at low temperatures. However, fuel cells are not likely to be ready for volume production for a few years as there are some drawbacks such as price, infrastructure for hydrogen delivery which are not solved yet.

This is why one can think of hybridizing the energy source in order to reduce the cost of a fuel cell based power system. The fuel cell will run at the average power while the buffer power source, such as ultracapacitors, will provide high power pulses. In this paper, we compare two power train configurations for a small electric vehicle providing an average power of 2 kW and a maximum power of 9 kW. The first configuration includes a 9 kW PEMFC as an electric source and the second associates a 4.5 kW FC and supercapacitors able to provide 5 kW for a few seconds.

At first, the vehicle as well as the drive train are described. Then we give some information about the software we used to implement our models of the source as well as about the models of the electromechanical components of the drive train. We also present the models of the source elements (fuel cell, ultracapacitors). In the next part, we explain the basis of the energy control strategy that it is implemented in order to minimize the fuel consumption on a drive cycle. Then we give the simulation results for the two configurations.

2. Vehicle characteristics

The vehicle we simulate may require up to 9kW from the power source during acceleration. The average power on a urban drive cycle is about 2kW. The total weight of the vehicle is about 250kg.

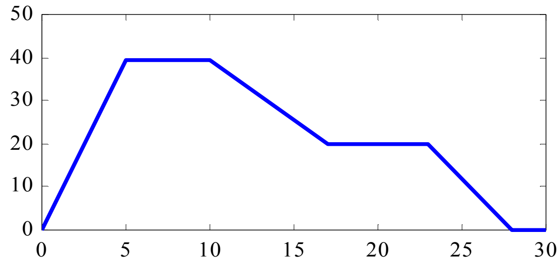


Fig. 1 : Urban driving schedule (vehicle speed [km/h] as a function of time [s])

The hybrid structure of the drive train is a series structure. The drive train integrates two axial permanent flux Brushless Direct Current Motors (BDCM) ; each one is fed by an inverter controlled thanks to a pulse width modulation scheme. This one is optimized in both cases : motoring and regeneration modes [1]. In order to realize the voltage adaptation and the energy management between the fuel cell system and the ultracapacitors bank, an electronic converter is used.

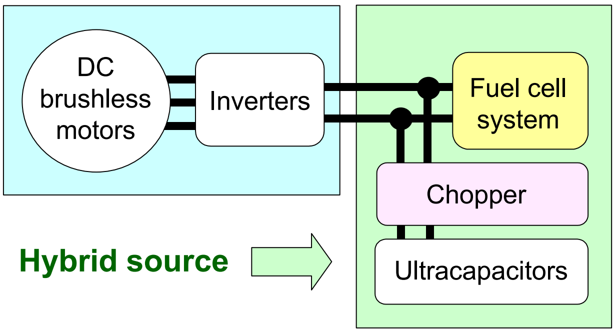


Fig. 2 : Structure of the vehicle drive train

3. Advisor Software

ADVISOR (ADvanced VehIcle SimulatOR) is dedicated to analysis and simulation of conventional electric or hybrid vehicles [2]. It has been developed by the NREL (National Renewable Energy Laboratory) and is available on the Internet. This software uses the Matlab/Simulink environment. The models which are provided are quasi-static ones. They have been elaborated thanks to static data and low transients can be introduced, such as motor inertia, by changing the operating point at each calculation step ; but it is not possible to take fast transients into account – fast meaning that they last less than a second. The model input and output are the respective input and output powers, ADVISOR dealing in power.

4. Fuel cell system

The fuel cell system is the device that converts the fuel (hydrogen) into electrical energy for the drive train.

The most common way to characterise the fuel cell performances is the polarisation curve. The main parameters which affect the fuel cell performances are the membrane and electrode characteristics, the cell design, the operating pressure, temperature and purity of the gases. Figure 3 shows such a polarisation curve (voltage of the cell versus current density). The shape is due to four major irreversibilities : activation losses, fuel crossover and internal currents, ohmic losses in the electrodes and in the membrane, mass transport or concentration losses.

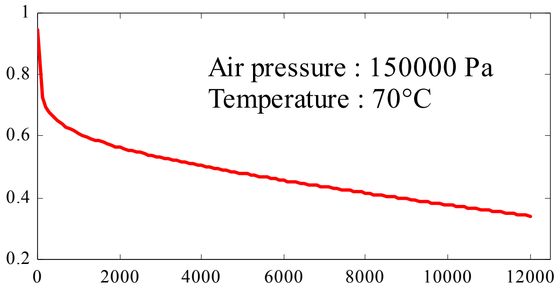


Fig. 3 : Graph showing the voltage [V] of a cell as a function of current density [A/m^2] (polarisation curve)

The voltage of a single cell is quite small. This means that to produce enough voltage several cells have to be connected in series to create a stack.

From the basic operation of the fuel cell, we know that the hydrogen usage [g/s] is :

$$H_2 \text{ usage} = (2 \times I \times N_{cell}) / (2 \times F)$$

Where :

- I is the current in the cell [A],
- N_{cell} the number of cells in series,
- F = 96485 [F] the charge of one mole of electrons.

Air and fuel will need to be circulated through the stack using pumps, fans and a compressor. These devices are known as auxiliaries or parasitics.

4.1 Model of the fuel cell

To model the stack, a static approach is chosen, that is to say that pressures, temperatures in the fuel cell system are kept constant. A quite limited dynamical aspect is given to the simulation of the whole fuel cell system as far as the fuel cell output power will increase and decrease no faster than a prescribed rate.

4.2 Fuel cell stack design

The fuel cell stack can be specified by its maximum gross power, polarisation curve, current density and number of cells. The first choice to be made is the desired maximum gross power of the fuel cell stack : about 5kW in our case. Then the current density under conditions of maximum power is chosen : $12000 A/m^2$ for a cell voltage of 0,34V ; this means a power density of $408 mW/cm^2$. The total active area of the stack is :

$$\text{Total active area} = \frac{5}{408} = 1{,}225 \text{ m}^2$$

Then we determine the number of cells to connect in series in order to fit the standard voltage of 48V under maximum power conditions. The current in the inverter is limited to 100A which gives the maximum power conditions.

$$N_{cell} = \frac{48}{0{,}34} = 140$$

$$\text{Cell active area} = \frac{1{,}225}{140} = 90 \text{ cm}^2$$

For such a stack, the power needed to drive the compressor and the other auxiliaries is between 40 and 540W.

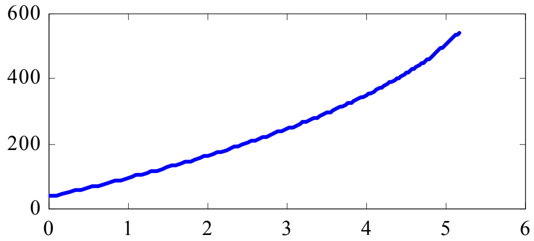


Fig. 4 : Power consumption of the auxiliaries [W] as a function of the FC brut power [kW]

4.3 Fuel cell system efficiency

The system efficiency is based on the following calculation :

$$\eta_{FC\ sys} = \eta_{rev} \times \eta_u \times \eta_f \times \eta_m \times \eta_s$$

- η_{rev} is the maximum energetic efficiency (#83 %).
- η_u is the voltage efficiency (#57%).
- η_f is the faradic efficiency (#100%).

Considering that hydrogen is generally supplied above the stoechiometric rate, $\eta_m \approx 95\%$, η_s is the system efficiency. It takes into account the power provided by the fuel cell to the auxiliaries.

5. Ultracapacitor bank

Ultracapacitors or electrochemical double layer capacitors take advantage of the charge stored in their electrochemical double layer and provide high capacities. Thanks to their compacity, ultracapacitors can store a higher amount of energy than conventional capacitors. Moreover, ultracapacitors are currently available on the market with capacitance ranges up to 2700F for a voltage of 2 to 3V ; they can release energy at high or low rate.

Ultracapacitors can provide up to 20 times the power a battery can deliver. This means that ultracapacitors have a typical specific power [W/kg] which is about 10 times higher than for lead acid batteries ; the charge time is much lower too. As for the energy density, it is 10 to 100 times the one of conventional capacitors.

Considering energy and power density, ultracapacitors are situated between batteries and electrolytic capacitors. Moreover, because of their ability to be cycled more than 500000 times, they are virtually maintenance-free over the life of any product in which they are used.

Ultracapacitors are ideally suited for applications requiring repeated bursts of power during fractions of seconds to several minutes. In hybrid electric vehicles, ultracapacitors are often used in tandem with other energy sources. They have to provide bursts of power during short duration events, such as accelerations, and to buffer the energy generated by braking. They can also improve vehicle performances considering fuel economy, reduction of emissions levels…

The model we used in our simulation is a simple first order model (RC circuit). It was convenient enough for what we aimed at.

Design of the ultracapacitors stack

The ultracapacitors stack is dimensioned according to the power it must provide (6kW) during a few seconds.

- Number of ultracapacitors : 48 / 2,3 = 20
- Total capacity : 2700 / 20 = 135 F
- Total internal resistance : 0,02 Ω

6. Control strategy

The control strategy we describe is similar to the one that is currently used by ADVISOR [2] for series hybrid electric vehicle. It attempts to minimise fuel use with the fuel cell system working with a good efficiency, while maintaining ultracapacitors state of charge (SOC) higher than a certain rate in order to be able to provide enough power in the case of a sudden large acceleration. This means that the fuel cell system should work between two powers *cs_min_pwr* and *cs_max_pwr* in order to allow the best efficiency.

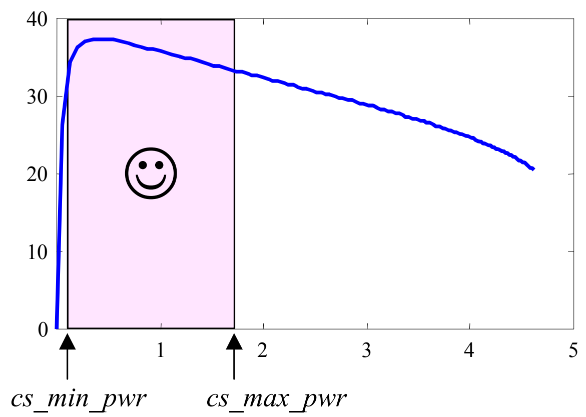


Fig. 5 : FC system efficiency [%] as a function of the net power [kW] and good efficiency area

The control strategy works in the same way as a thermostat where the FC system turns on when the ultracapacitors SOC reaches the low set point (lowest state of charge allowed defined by the parameter *cs_lo_soc*) and turns off when the SOC reaches the high set point (highest state of charge allowed *cs_hi_soc*). For ultracapacitors, typical values for *cs_hi_soc* and *cs_lo_soc* are respectively 95% and 50%.

The FC system output power is computed so that the ultracapacitors state of charge tends to be in the middle of the range [*cs_hi_soc* , *cs_lo_soc*]. It is equal to the sum of :

- the power required for propulsion and accessory loads,
- the power (negative or positive and function of the variable *cs_charge_pwr*) needed to get the right SOC.

For example, if the ultracapacitors SOC is 75%, the FC system provides energy to the drive train only.

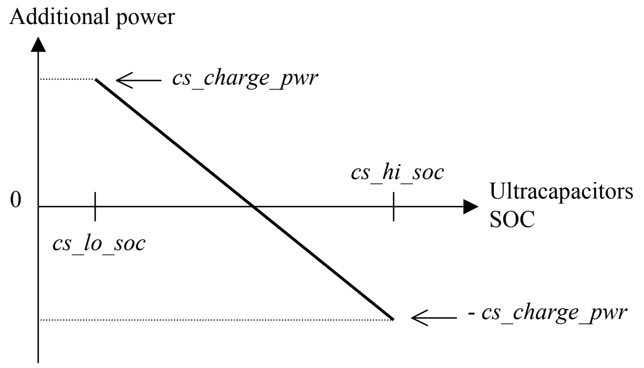


Fig. 6 : Computation of additional power for ultracapacitors SOC correction

7. Control strategy optimisation

The value of the parameter *cs_min_pwr* can be easily chosen to avoid the FC system to work at very low loads, in a range of power where the FC system efficiency is bad. The choice of the parameters *cs_max_pwr* and *cs_charge_pwr* is not so evident. The three following results of simulations made on an urban driving schedule show that these are linked variables.

Table 1: H2 consumption for three parameters sets

Parameters configuration	**1**	**2**	**3**
cs_min_pwr [W]	300	300	300
cs_max_pwr [W]	1400	1400	1000
cs_charge_pwr [W]	4500	1500	4900
H_2 consumption [g]	0,75	0,88	0,88

A control strategy optimisation routine is available in ADVISOR. Its purpose is to determine the set of control strategy parameters that meet the user-specified objectives and constraints. This is ensured by adjusting the control strategy parameters and reevaluating the performance criteria until all the specifications or constraints are met. There are two ways of doing this thanks to ADVISOR. The first one is Matlab-based and uses one- and two-dimensional multi-level parametric sweeps and some built-in logic to determine the appropriate settings. The second uses VisualDOC optimisation software to determine the appropriate settings. The control strategy optimisation routine that was used here is the Matlab-based one. It does not consider the interactions between all design variables and no global optimum is computed. However, good solutions of the problem can be found relatively quickly. The routine was here simply modified to take into account that, in our example, *cs_max_pwr* and *cs_charge_pwr* are linked variables and that they consequently have to be dependently evaluated.

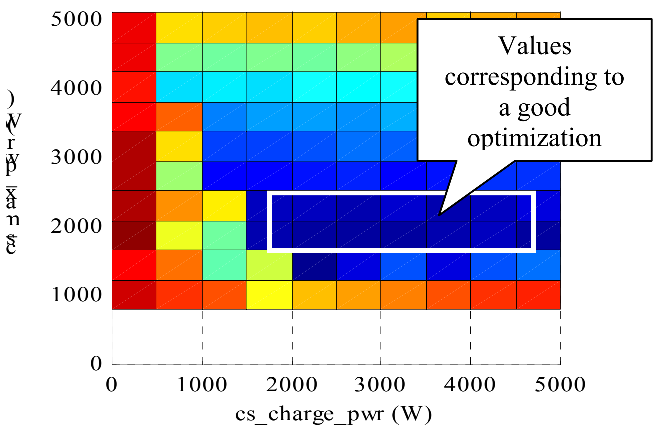


Fig. 7 : Computation of the parameters *cs_max_pwr* and *cs_charge_pwr* for the urban driving schedule

A good optimisation on one drive cycle may not necessarily provide good results on other drive cycles. Let us study the good location of *cs_max_pwr* and *cs_charge_pwr* in the case of a 20 km/h constant speed drive cycle :

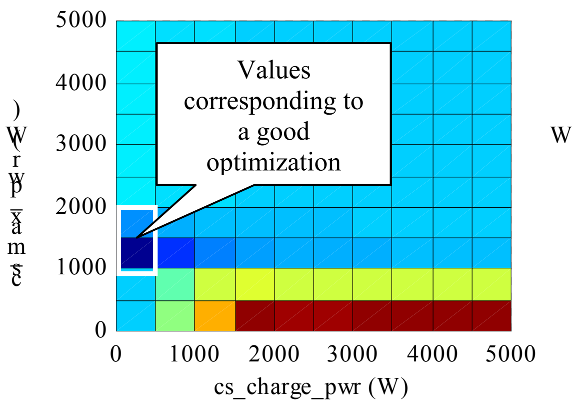


Fig. 8 : Computation of the parameters *cs_max_pwr* and *cs_charge_pwr* for the constant speed driving schedule

On line adaptation of the parameters can be achieved.

In many cases power requirements are also unpredictable but can be estimated considering recent past vehicle behaviour.

8. Rate of hybridisation

Two power sources are now compared with the goal of determining which one provides the highest fuel economy. In the first one, the FC system 1 is hybridised by 20 ultracapacitors of 2700F. In the second one, the FC system 2 supplies all the power.

Table 2 : Characteristics of the two FC systems

FC system	**1**	**2**
Gross power [kW]	5	10
Active area per cell [cm^2]	90	180
Number of cells	140	140
Auxiliaries power consumption except compressor [W]	40	80

It is assumed that the weights of the two power sources are equal. The comparisons over the two driving schedules (urban and constant speed) are made with parameters computed thanks to the control strategy optimisation routine. The change in SOC between the beginning and end of the cycles was less than ±0,5%, so that simulations can be considered charge-neutral.

Power source 1

- On the urban driving schedule :
  - Hydrogen consumption = 0,75g
  - cs_min_pwr = 300W
  - cs_max_pwr = 1400W
  - cs_charge_pwr = 4500W

- On the constant speed driving schedule :
  - Hydrogen consumption = 1,45g
  - cs_min_pwr = 300W
  - cs_max_pwr = 1000W
  - cs_charge_pwr = 200W

Power source 2

- On the urban driving schedule :
  - Hydrogen consumption = 0,91g

- On the constant speed driving schedule :
  - Hydrogen consumption = 1,36g

On the urban drive cycle, hybridisation reduces hydrogen consumption by 15% but increases it on the constant speed driving schedule. Figure 10 sums up all these results.

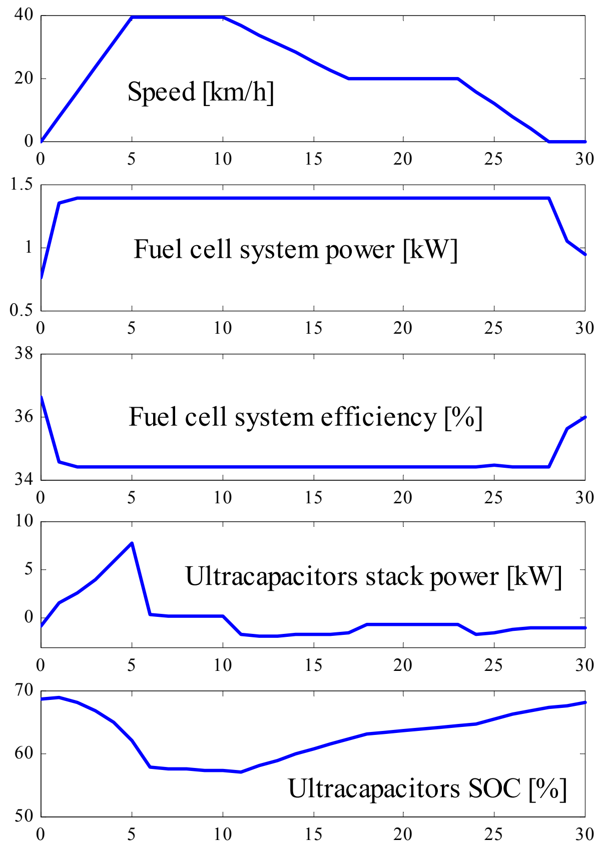
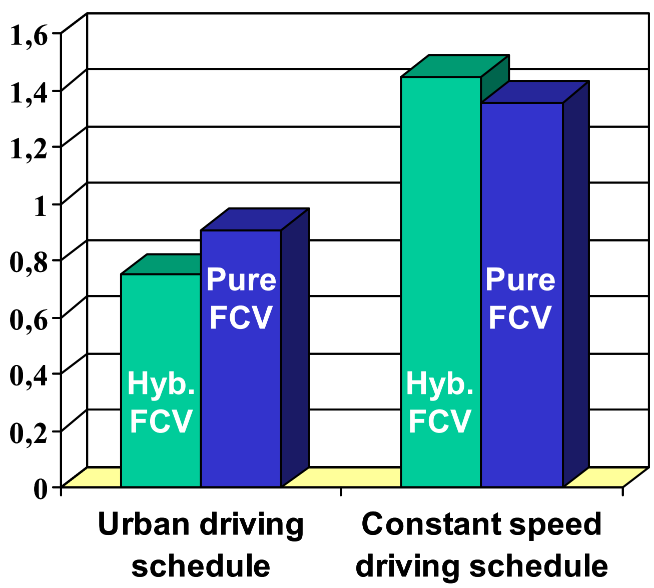


Fig. 9 : Simulation of the vehicle with the power source 1 on the urban driving schedule



■ Hybrid FCV 5kW gross power FC & Supercapacitor 135F
■ Pure FCV 10kW gross power FC

Figure 10: hydrogen consumption (in g) for two vehicles of the same weight depending on the driving cycle.

9. Conclusion

Fuel economy benefits are highly dependent on the driving conditions.

A hybrid structure will be preferred when the power requirements are quite variable (urban drive cycle) [3]. Indeed, when the power requirements are quite constant, there is no need for a power buffer. The hybrid source is very interesting because of its ability to recover energy while braking. Costs and volumes must be carefully considered. Anyway, fuel cells are still very expensive, that is why power buffers such as ultracapacitors are of great interest.

An experimental bench [4] has been built in order to validate these results and improve the model of the power train. At present, the power source we intend to hybridise is a 250W PEMFC and it drives a small robot moved by two 60 W DC brushless motors.

10. References

[1] D. CANDUSSO, E. RULLIERE, P. BAURENS: Simulation d'un véhicule électrique à source hybride pile à combustible – éléments intermédiaires de stockage de la puissance, *Colloque Piles à combustible et interfaces pour les transports* – Belfort Nov 2000, pp. 145-152.

[2] ADVISOR – Advanced Vehicle SimulatOR. National Renewable Energy Laboratory, DOE USA http://www.ctts.nrel.gov/analysis/

[3] D.J. FRIEDMAN: Maximizing Direct-Hydrogen PEM Fuel Cell Vehicle Efficiency: Is Hybridization Necessary ? Presented at the SAE International Congress and Exposition, 1-4 March 1999, Published in : Fuel Cell Power for Transportation (SP-1425), SAE# 1999-01-0530, Society of Automotive Engineers, Warrendale, PA, 1999.

[4] D.CANDUSSO: Hybridation du groupe électrogène à pile à combustible pour l'alimentation d'un véhicule électrique, Thèse de l'INP Grenoble- 29 Novembre 2002