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Modelling of a Fuel Cell Hybrid Power Source for a small Electric Vehicle

Denis Candusso, Elisabeth Rullière, Seddik Bacha

Abstract

This paper deals with the hybridisation of a small PEM (Proton Exchange Membrane) fuel cell system by an ultracapacitors bank. This kind of hybrid source could be used for instance to supply the DC brushless machines of a small electric vehicle. Modelling and simulation are derived from ADVISOR software. Two energy flow control strategies are described; globally, the fuel cell should operate in a power range, which ensures a good efficiency for the whole fuel cell system and, at the same time, an ultracapacitor state of charge about 75%.

Keywords: fuel cell, ultra capacitors, hybrid electric vehicle, hybrid strategy, simulation

1 Introduction

Since fuel cells (FC) are still expensive, hybridisation may be considered as an interesting way to minimise the FC size. The cost of the pure FC system and the cost of the hybridised system have to be compared. Weights and volumes have to be taken into account. The hybridisation degree depends on performances targets (grade and/or acceleration sustaining).

If the bus power requirements are quite variable, hybridisation can lead to an improvement in fuel consumption, especially due to the possibility of energy recovering through regenerative braking. Thanks to a hybrid system, some FC technologies with low dynamical capabilities could be more competitive. It would eliminate the disadvantage of slow start up or transients.

This work of modelling and simulation applies to a small vehicle but the technologies and the principles, which are described in this paper, are transposable to vehicles with different kinds and sizes. Energy management is a key factor to minimise fuel consumption and to take entire benefits of the hybridisation.

At first, the driving train is presented as well as its specifications. Then, the FC and the ultracapacitors models are explained. In a third part, the general architecture of the system is given, showing how the control management of the various elements as well as the energy flow management are implemented. The fourth part concerns the development of an example of energy control strategy. Some simulation results on an urban driving schedule with such a management are presented. At the end, some ideas about the voltage/current control of the various elements are given.

2 Vehicle characteristics

The considered vehicle may require up to 10kW from the power source during an acceleration phase. The average power on an urban drive cycle is about 2kW. The total weight of the vehicle is about 250kg. 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 optimised in both cases: motoring and regeneration modes [1]. In order to realise the voltage adaptation between the fuel cell system and the ultracapacitors bank, a DC-DC boost converter is used. It is also needed to manage the energy flow between the two devices. The FC system is directly connected to the DC bus or connected through a boost converter in order to control the DC bus voltage. The following figure deals with the two possibilities, which are described above. Notice that only the first configuration is considered in this paper (figure 1.a).

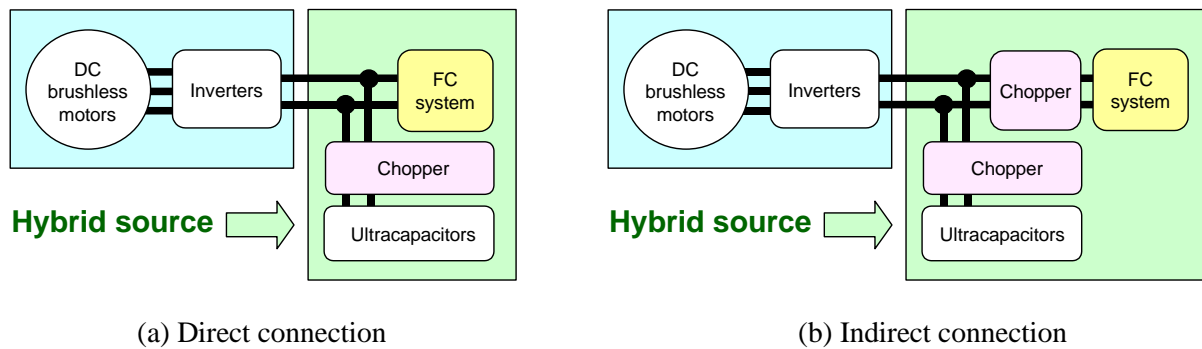


Figure 1: Two structures of the vehicle drive train

3 Fuel cell and ultracapacitors modelling

3.1 The fuel cell system

The FC system converts the fuel (hydrogen) into electrical energy for the drive train. The most common way to characterise its performances is the polarisation curve. The main parameters which affect the FC performances are the membrane and electrode characteristics, the cell design, the operating pressure, temperature and purity of the gases. Figure 2 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.

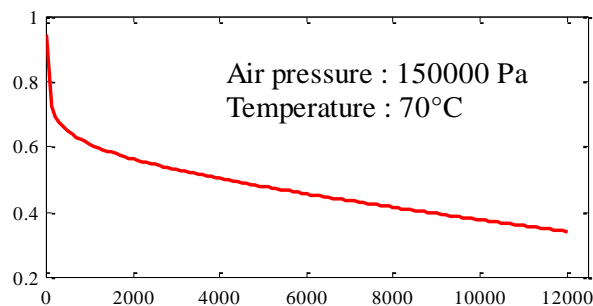


Figure 2: Graph showing the voltage [V] of a cell as a function of current density [A/m²] (polarisation curve)

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.

Furthermore the FC stack cannot operate alone: 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.

A static model for the stack is chosen, that is to say that pressures and temperatures are supposed to be constant. A quite limited dynamical aspect is given to the simulation of the FC system as far as the FC output power will increase and decrease no faster than prescribed rates.

In order to get the FC system operating curve, the system efficiency $\eta_{FC\ sys}$ is calculated thanks to the following formula:

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

Where:

- η_{rev} is the maximum energetic efficiency.
- η_u , the voltage efficiency.
- η_f , the faradic efficiency.
- η_m takes into account that hydrogen is generally supplied above the stoichiometric rate.

- η_s takes into account the power provided by the FC to the auxiliaries.
If P_{net} is the power which is provided to the DC/AC converter and P_{raw} is the power supplied by the FC, P_{aux} being the power consumed by the auxiliaries, then:

$$\eta_s = \frac{P_{net}}{P_{raw}} = \frac{P_{raw} - P_{aux}}{P_{raw}}$$

Design of the FC system

The FC stack can be specified by its maximum gross power, polarisation curve, current density and number of cells.

Table 1: Characteristics of the FC system

Gross power of the FC stack	5kW
Current density under conditions of maximum power	12000A/m ²
Cell voltage under conditions of maximum power	0.34V
Number of cells connected in series	48 / 0.34 = 140
Cell active area	1.225 / 140 = 90cm ²

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

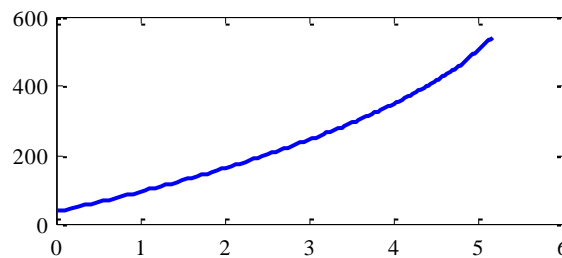


Figure 3: Power consumption of the auxiliaries [W] as a function of the FC brut power [kW]

3.2 The ultracapacitors 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 500 000 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 used model is a simple first order one (RC circuit). It is enough convenient for what we aimed at.

Design of the ultracapacitors stack

The ultracapacitors stack is sized according to the power it has to provide during a given number of seconds. The number of elements in series has to fit a voltage lower than 48V. The modelling is based on the properties of the 56V Ultracaps module from Epcos [2] (28 elements of 2700F in series).

Table 2: Characteristics of the ultracapacitors stack

Number of ultracapacitors	22
Total capacity	$2700 / 22 = 123F$
Total internal resistance	0.015 mΩ
Operating voltage range of a single element	1.1 – 2.1V

4 General architecture of the simulated system

The motor requires a given power. Thanks to the energy flow strategy, this power will be split into one power required from the FC system and one from the ultracapacitors system (ultracapacitors bank and chopper). The simulations are performed using ADVISOR (ADvanced VehIcule SimulatOR) [3]. This software has been developed by the National Renewable Energy Laboratory in USA. This modular Matlab simulation program mostly uses empirical, quasi-static models and deals in power in electrical components communication with each other. Consequently it is well suited to evaluate control laws rapidly.

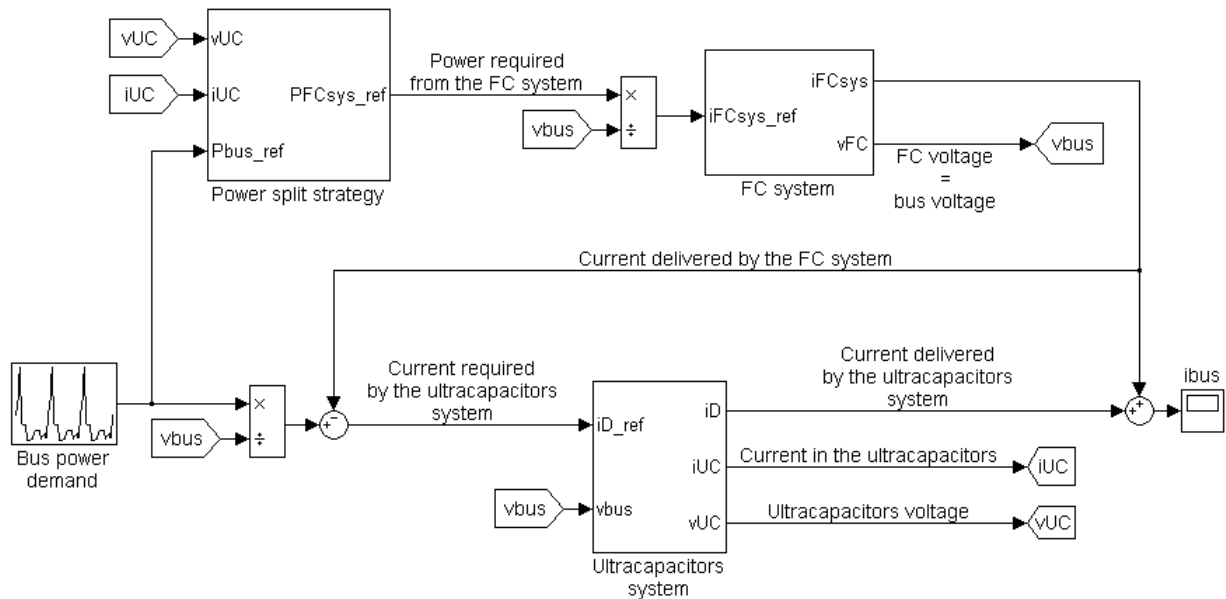


Figure 4: Global scheme of the drive train model, similar to the one which is proposed in ADVISOR

In the FC system, there is a controller as well as rate limitations. The ultracapacitors system includes the ultracapacitors bank, a chopper, controllers and various rate limitations.

5 Energy flow management

As the fuel converter is a PEMFC, there is no need to minimise the gas emissions. The main aim of the control strategy is the minimisation of the vehicle fuel consumption while matching the driver demand. For our series HEV, the inverter input power appears as the sum of the FC system and the ultracapacitors bank contributions. Consequently, the control strategy has to compute the instantaneous power split between the two sources.

Two control strategies have been implemented: static and real time control strategies.

5.1 Static control strategy

This first strategy attempts to minimise fuel consumption and balance the ultracapacitors state of charge (SOC). A set of static parameters, which are optimised according to the driving cycle, is used [4]. The strategy operates as a kind of thermostat turning on the FC system when the ultracapacitors SOC reaches the lowest SOC allowed value (about 50%) and turning it off when the highest allowed value is reached (about 100%). The FC system also turns on in the following cases:

- the power required by the DC bus gets high enough and the FC system was off since a time specified by the user,
- the power required by the DC bus is greater than the power that the ultracapacitors stack alone would be able to provide.

The FC system should stay in a range allowing the best efficiency as often as possible as it is shown in the following figure.

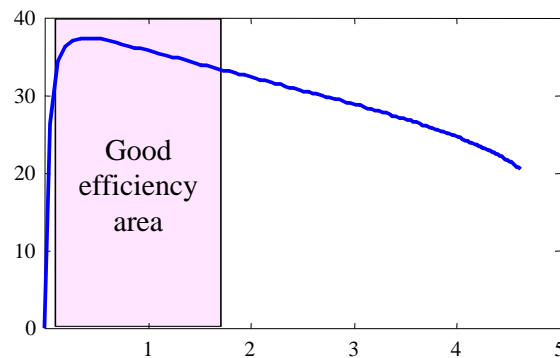


Figure 5: FC system efficiency [%] as a function of the net power [kW] and good efficiency area

The FC system output power is computed so that the ultracapacitors SOC tends to be near 75%. This power is equal to the sum of:

- the power required for propulsion and the accessory loads,
- the power (negative or positive) needed to fill up the ultracapacitors and get a correct SOC.

The optimal set of control parameters is computed taking into account the user specified objectives as well as the constraints (e.g. grade and acceleration sustaining). Unfortunately this optimisation depends also a lot on the drive cycle. That is why we developed another strategy.

5.2 Real time control strategy

Like the previous one, the aim of this control strategy is the minimisation of fuel consumption. It is derived of strategies developed for parallel HEV [5, 6].

5.2.1 Problem

Let be a drive cycle which duration is n seconds.

The power distribution between the FC system and the ultracapacitors can be made second by second. Each second $i \in \{1 \dots n\}$, a power P_{bus_i} must be provided at the DC bus.

$$P_{bus_i} = P_{FC_{system_i}} + P_{ultracapa_i}$$

Example

If the bus power demand is 3kW, the distribution between the two sources can be :

- 1kW from the FC system and 2kW from the ultracapacitors (if their SOC is not too low) or
- 2kW from the FC system and 1kW from the ultracapacitors or
- 4kW from the FC system and -1kW from the ultracapacitors
- etc

In the third case, the fuel cell system provides the power required for propulsion and charges the ultracapacitors.

The strategy considers a range of possible FC system – ultracapacitors power pairs. At any time i , the operating point of the hybrid source is defined by $P_{FCsystem_i}$ and D_i is the fuel flow rate [g/s] given by the chosen power split. The aim would be to find the vector $\{P_{FCsystem_1} \dots P_{FCsystem_n}\}$ that leads on the cycle to the minimal and optimal fuel consumption. This one is given by:

$$D_{min_opt} = \text{Min} (D_1 + \dots + D_n)$$

In fact, the driving schedule is not known a priori and the global criterion has to be replaced by a local or instantaneous one, that can be used for real time control. The minimal, but non optimal, consumption will then be equal to:

$$D_{min} = \text{Min} (D_1) + \dots + \text{Min} (D_n)$$

However, minimising instantaneous consumption only of the FC system is not a good solution. For instance, if the ultracapacitors provide as much power as possible, their SOC will get soon to the lowest value, so that they will have to be refilled and the overall hybrid source efficiency won't be very good.

5.2.2 Notion of total equivalent fuel flow

If one wants to compute the consumption of a hybrid electric vehicle, the fuel consumption as well as electrical energy consumption must be considered, including the notion of energetic equivalence. To compare the results of various control strategies on a driving schedule, there should be no variation of the buffer power SOC between the beginning and the end of the cycle. It means that the whole energy used to propel the vehicle comes from the fuel only (assuming that globally there is no variation of the vehicle potential energy). This means that in our case the electrical energy removed during an ultracapacitors discharge phase has to be refilled later using the hydrogen from the tank, either directly from the FC system to the ultracapacitors stack or indirectly through regenerative braking.

The hydrogen fuel flow rate D is computed from the current delivered by the FC stack. Since the relation between the current and the net power of the FC system is known, a fuel flow D is defined for each power required from the FC system.

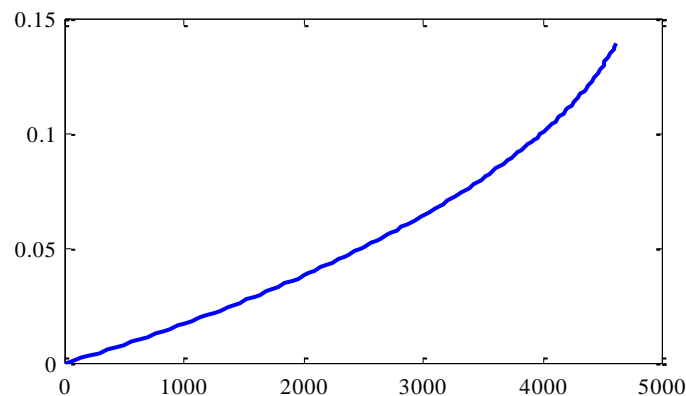


Figure 6: fuel flow D [g/s] as a function of the net power [W] delivered by the FC system

The ultracapacitors bank acts as an energy buffer. It can be seen as an auxiliary reversible fuel tank. Two cases can be considered:

- The ultracapacitors are discharged. The electrical energy being consumed must be later refilled, it will lead to an additional future FC system consumption.
- The ultracapacitors are charged. The electrical energy being stored will be later used in order to alleviate the FC system, saving fuel consequently.

In both cases, an equivalent fuel flow $Dequi_i$ can be associated with the power delivered by the ultracapacitors at the instant i . This equivalent fuel flow $Dequi_i$ is computed using a mean operating point for the FC system. This one is characterised by the power PFC_{sys_mean} that should be the mean power delivered by the FC system on a given driving schedule. An average efficiency equal to 90% is also associated to the chopper.

We have: $Dequi_i = D(PFC_{sys_mean}) \square Pultracapa_i / PFC_{sys_mean} / 0.9$

A total equivalent fuel flow $Dequi_tot_i$ can now be defined. It is the sum of:

- the real instantaneous fuel flow of the FC system D_i ,
- the equivalent fuel flow $Dequi_i$.

We have: $Dequi_tot_i = D_i + Dequi_i$

5.2.3 Process

The first step considers the whole range of potential operating points for both the FC system and the ultracapacitors stack allowing the proper range for the ultracapacitors SOC. In the simulations, ten different power distributions were considered at each second. During the second step, the total equivalent fuel flow $Dequi_tot_i$ for each power combination is computed. It is the one that leads to the lowest fuel cost which is then selected. The consumption on the drive cycle will be equal to:

$$Dequi_tot_{min} = \text{Min} (Dequi_tot_1) + \dots + \text{Min} (Dequi_tot_n)$$

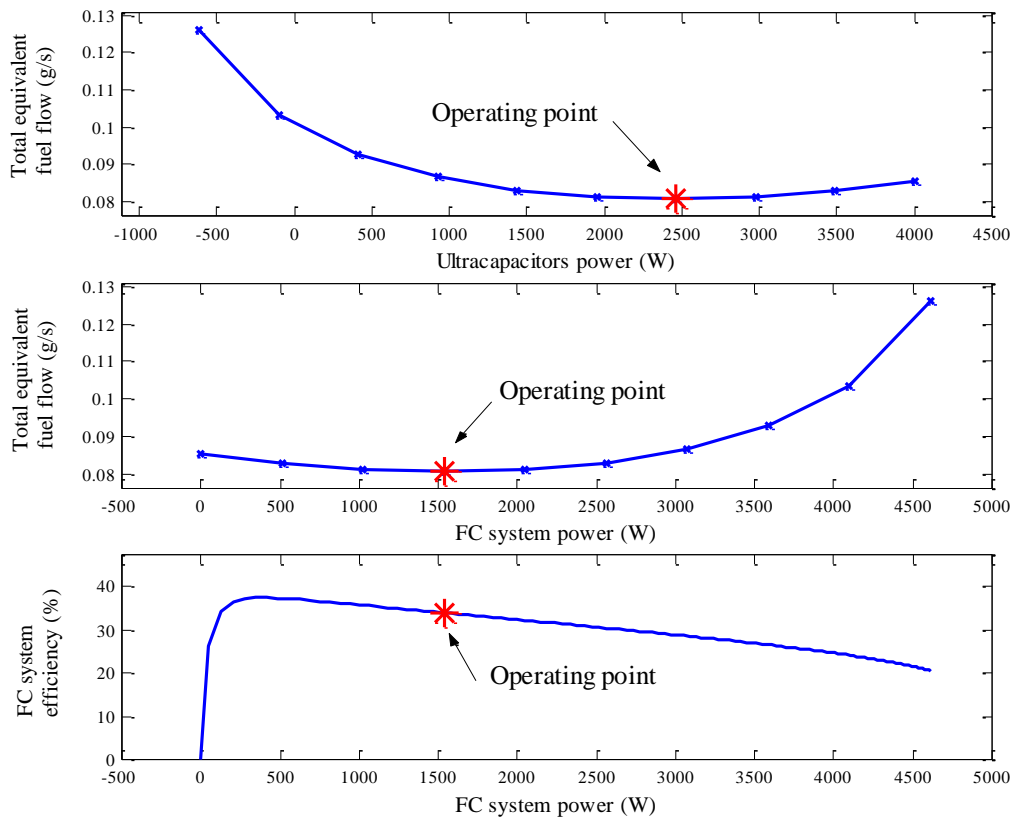


Figure 7: Example of a power distribution with $P_{bus_i} = 4kW$ and a high initial ultracapacitors SOC

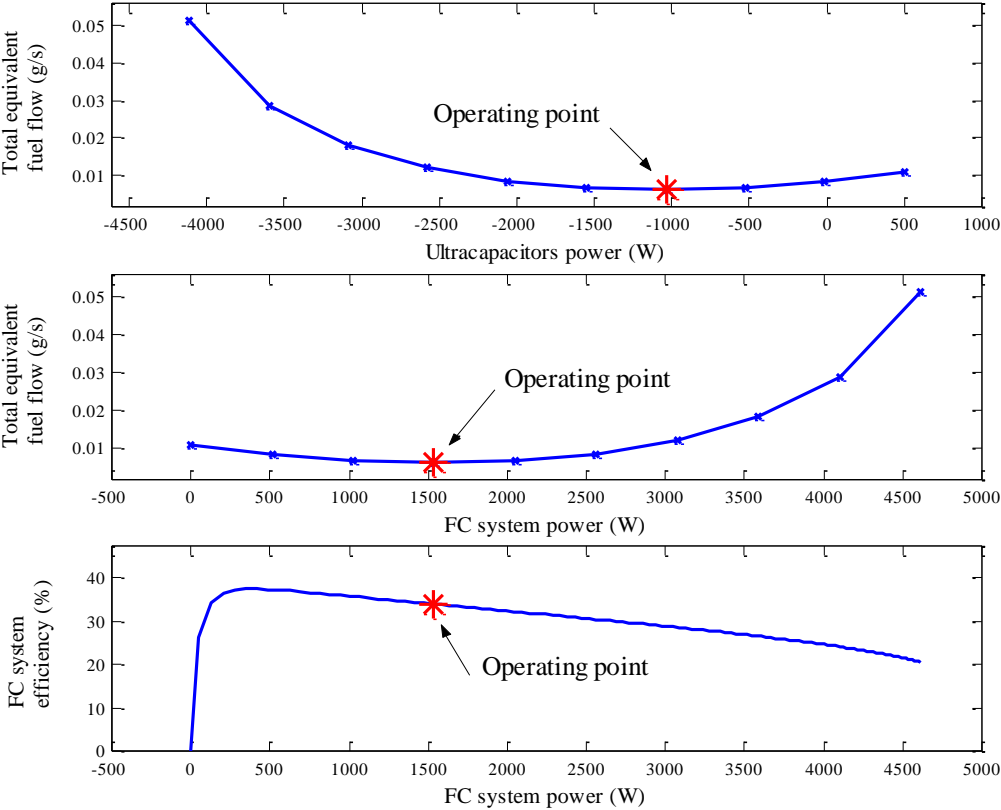


Figure 8: Example of a power distribution with $P_{bus_i} = 0.5kW$ and a low initial ultracapacitors SOC

The strategy was implemented and simulations are done over two consecutive urban driving schedules. The parameter $P_{FC_{sys_mean}}$ was equal to 1.5kW.

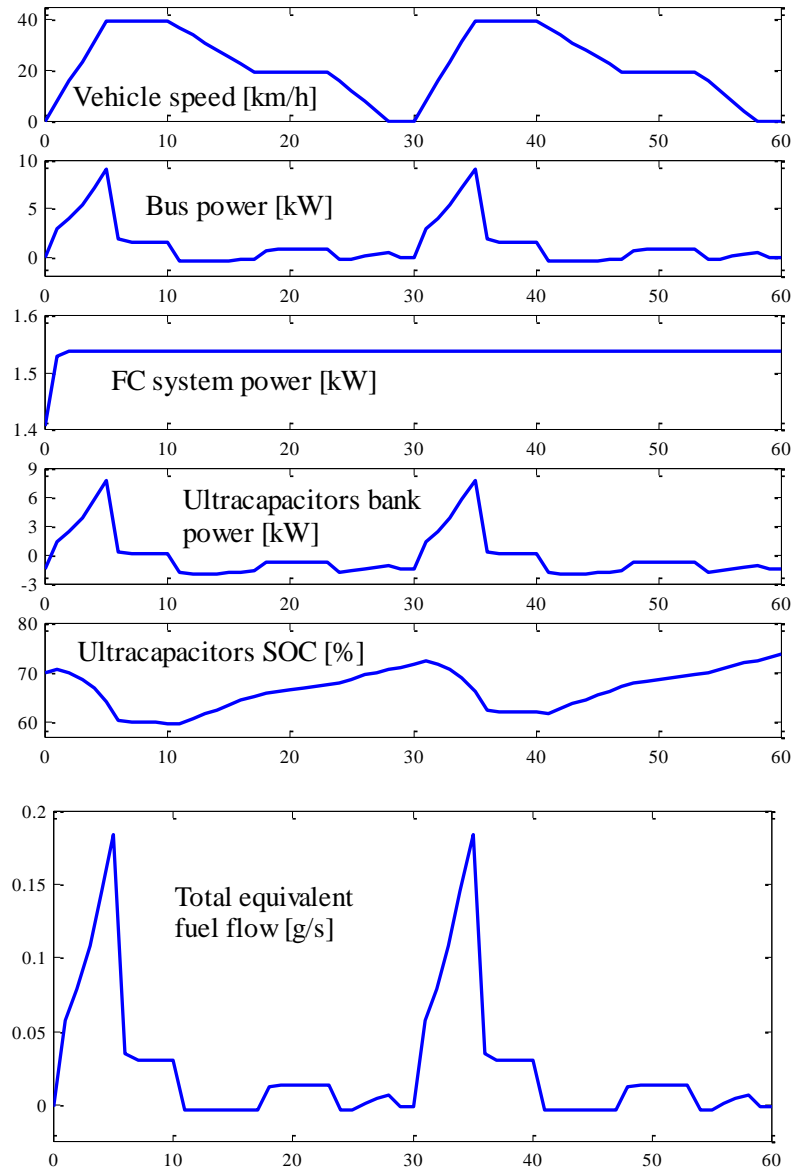


Figure 9: Real time control strategy on two consecutive urban driving schedules

5.2.4 SOC correction

For some particular drive cycles, the value of the parameter PFC_{sys_mean} may not be adapted. Operating the hybrid source according to the optimal power distribution is not always sufficient in order to regulate the ultracapacitors SOC with accuracy. To avoid a SOC drift, several methods can be used. The retained method is described below.

The optimal power distribution is first defined. Next, it is shifted up or down according to the actual SOC. A linear correction factor similar to the one of the static control strategy can be used. A non linear penalty function like the one depicted in the following figure can be employed too. This function is quite flat around 75%, allowing the optimal distribution to be nearly kept when the actual SOC is close to the target value. The additional power (positive or negative) that the FC system has to provide becomes larger when the SOC approaches the preset low and high limits. Consequently the further the actual SOC is from 75%, the more the optimal distribution is shifted.

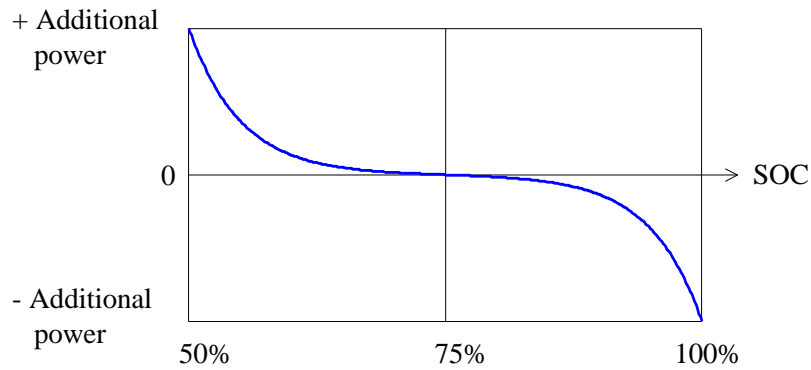


Figure 10: Additional power needed to correct ultracapacitors SOC

5.2.5 Optimisation according to several criteria

In the strategy we have described, the unique criterion to be optimised is the fuel consumption. In addition to this criterion, we can also have other objectives. For instance, the FC system components reliability (related to the temperature TFC of the FC stack, the membrane humidity...) could be considered. They could be taken into account using a cost function representing the effects of the FC system operation on fuel consumption and also on components reliability.

For each candidate power distribution, the strategy would select the operating point which leads to the minimum value of the cost function, the relative importance of the different criteria depending on their respective weightings (α, β, \dots).

Example of cost function:
$$\text{cost_function} = \frac{\alpha \text{Dequi_tot}_i + \beta |TFC_ref - TFC_i|}{\alpha + \beta}$$

6 Control management of the system

Specific accurate dynamic models are developed for the various components of the power train.. These models are declined in several levels: averaged models and topological ones. Thanks to this modelling, the current and voltage controllers are implemented foreseeing what could be done on an experimental bench intended to validate the simulation work and the two energy management strategies. The current and voltage regulations work very fast compared to the global energy management (current split strategy) which occurs every second or so. Simulations are done on short duration, that is to say a few ten seconds or a few seconds maximum, if respectively average models or topologic models are used for the converters.

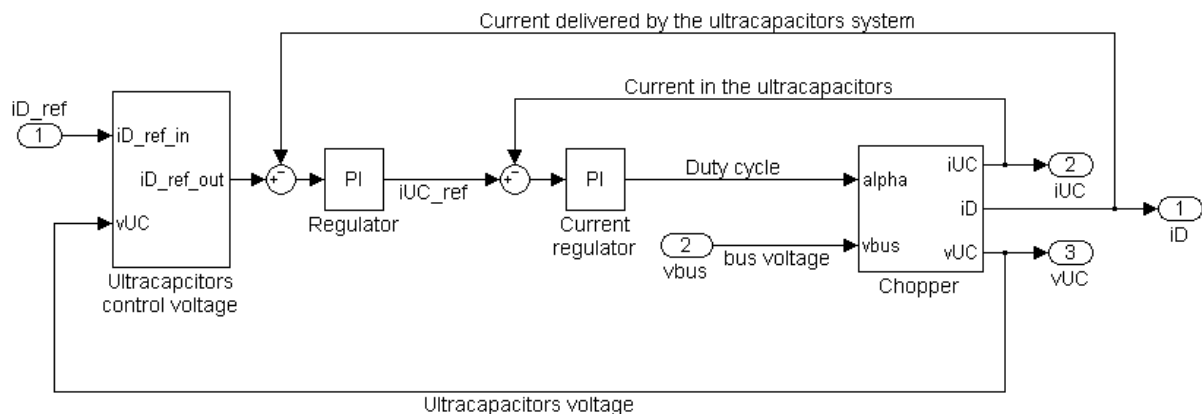


Figure 12: A possible scheme of the ultracapacitors system model

7 Conclusion

Is it interesting to hybridise or not a FC system? That is the question we would like to answer! Thanks to our modelling and simulation work, we would like to evaluate the potential strengths and weaknesses of each option. We also would like to help to define the hybrid source of a vehicle, in order to match the power and energy requirements as well as the size and cost requirements.

This paper mainly deals with the energy management. In the control strategy we developed, the energy management is performed in real time (every second) on board of the vehicle thanks to an equivalent fuel consumption for the buffer energy storage.

Whatever the strategy is, if one wants to have an adaptive control management, then some parameters values have to be adapted following the driving conditions, the main difficulty being to predict a driving load pattern. This can be done considering the vehicle recent past behaviour, averaging for instance the power required by the DC bus. But more sophisticated methods should be used to identify the cycle.

However, the real time strategy seems to be more flexible than the static one as far as the on line adaptation of its parameters can be done in a simpler way. Besides, a multi parameters optimisation can be achieved.

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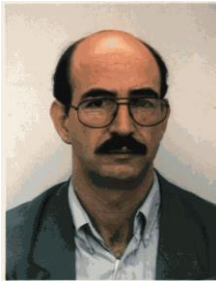
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