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A Fuel Cell Hybrid Power Source for a Small Electric Vehicle

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Abstract – *This paper deals with the simulation of a small fuel cell hybrid vehicle. The models of the PEM fuel cell system and of the buffer peak power source (ultracapacitors) are described as well as the control strategy to manage the power flow between the different elements of the drive train. The parameters of the strategy are chosen in order to minimize the hydrogen consumption on a given drive cycle. A comparison of the hybrid with a pure fuel cell vehicle is performed*

Résumé – *Cet article présente la simulation d'une petite cellule d'un carburant d'une véhicule hybride. Les modèles de la cellule du carburant du système PEM et buffer de la source de puissance maximal (ultra condensateurs) sont décrit aussi bien que la stratégie de control pour la gestion du flux de la puissance entre les différents éléments du train de commande. Les paramètres de la stratégie sont choisit affin de minimiser la consommation de l'hydrogène sur un cycle de commande donne. Une comparaison entre le véhicule hybride et une cellule réelle de carburant d'un véhicule est effectuée.*

Keywords: Simulation – Fuel cell – Hybrid vehicle – Power source – Hydrogen consumption.

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 present the simulation of a small vehicle with a hybrid PEMFC source. This vehicle provides an average power of 2 kW and a maximum power of 9 kW. At first, the vehicle as well as the drive train are described. Then we give some informations 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 results of two simulations : one for a hybrid ultracapacitors / PEMFC source system and the other for a system supplied by a fuel cell alone.

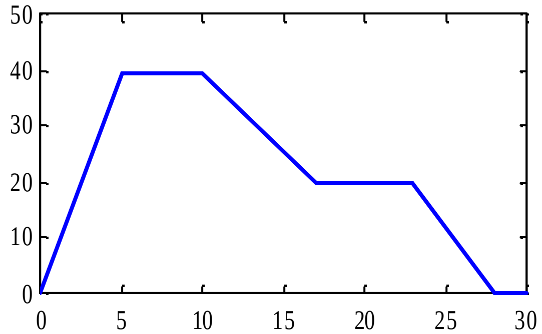

Fig. 1: Urban driving schedule (vehicle speed [km/h] as a function of time [s])

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.
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 between the fuel cell system and the ultracapacitors bank, an electronic converter is used. It is also needed to manage the energy flow between the two devices.

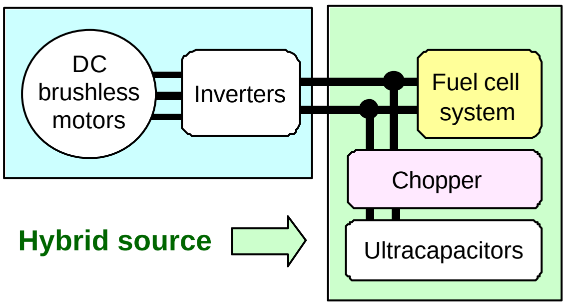

Fig. 2 : Structure of the vehicle drive train

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 meanig 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.
Basic principle of a cell In order to model the fuel cell, one must remember its principle. At the anodic side, a catalyst allows to dissociate hydrogen molecules into protons (H^+) and electrons (e^-) according to the reaction :

$$2H_2 \rightarrow 4H^+ + 4e^-$$

Then, the proton migrates through the electrolyte (solid polymer membrane) while the electrons flow through the external load. The overall electrochemical reaction with oxygen of the air is :

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$$

The most common way to characterize the fuel cell performances is the polarization 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 polarization 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.
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.

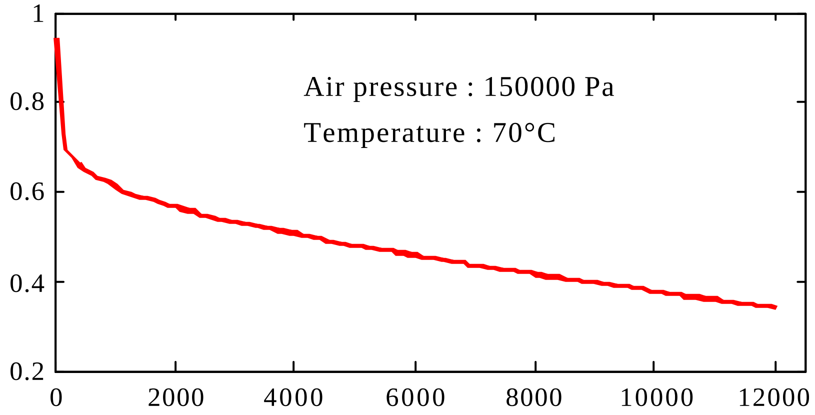

Fig. 3 : Graph showing the voltage [V] of a cell as a function of current density [A/m²] (polarization curve)

Model of the fuel cell system: 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.

Fuel cell stack design: The fuel cell stack can be specified by its maximum gross power, polarization 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 : 12000A/m² for a cell voltage of 0,34V ; this means a power density of 408mW/cm². The total active area of the stack is :

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

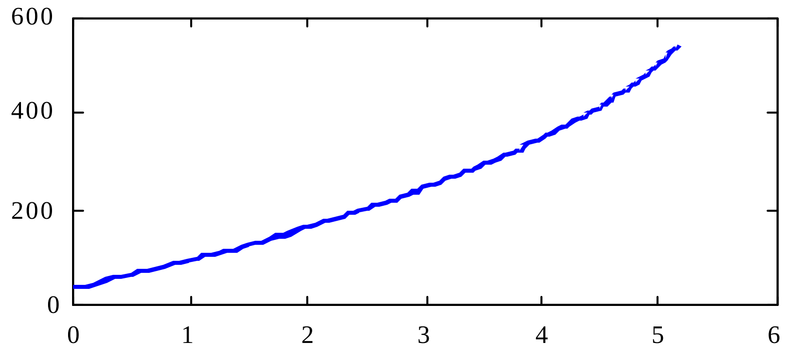

Fig. 4 : Power consumption of the auxiliaries [W] as a function of the FC brut power [kW]

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.

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. It is equal to the ratio between the theoretical maximum work provided by the fuel cell when working in a reversible way W_{max} and ΔH, the enthalpy variation during the reaction.

$$\eta_{rev} = \frac{W_{max}}{\Delta H} = \frac{\Delta G}{\Delta H} = \frac{237}{285} = 83\%$$

at 25°C and if the water is condensed back to liquid.

▪ η_u is the voltage efficiency. Because of the irreversibility of the reactions, the operating fuel cell voltage is less than E_{max} = 1,23V so that, for example :

$$\eta_u = \frac{0,7}{1,23} = 57\%$$

▪ η_f is the faradic efficiency. It allows to take into account the effective number of electrons got for one mole of hydrogen which is not always equal to the theoretical calculations.

$$\eta_f \approx 100\%$$

▪ 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.

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

5. 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 an 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 dimensionned 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 minimize 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.

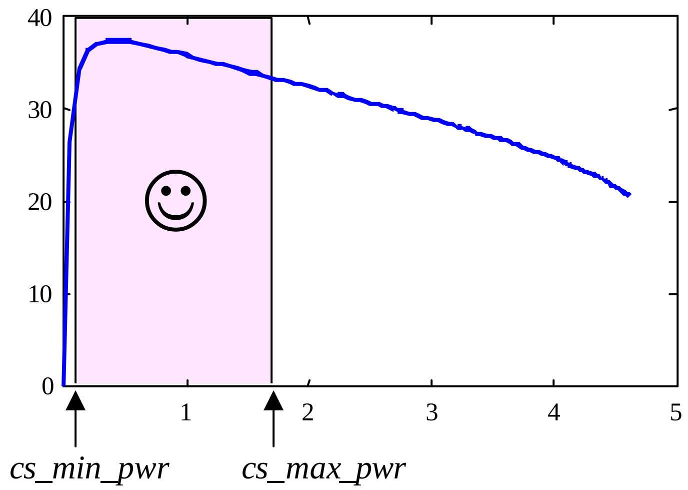

Fig. 5 : FC system efficiency [%] as a function of the net power [kW] and good efficiency area

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.

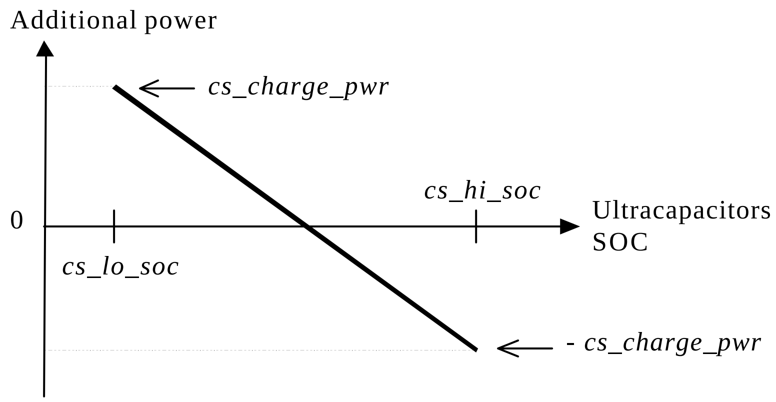

Fig. 6 : Computation of additional power for ultracapacitors SOC correction

Control strategy optimization: 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 : H_2 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 optimization 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 optimization software to determine the appropriate settings. The control strategy optimization 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.

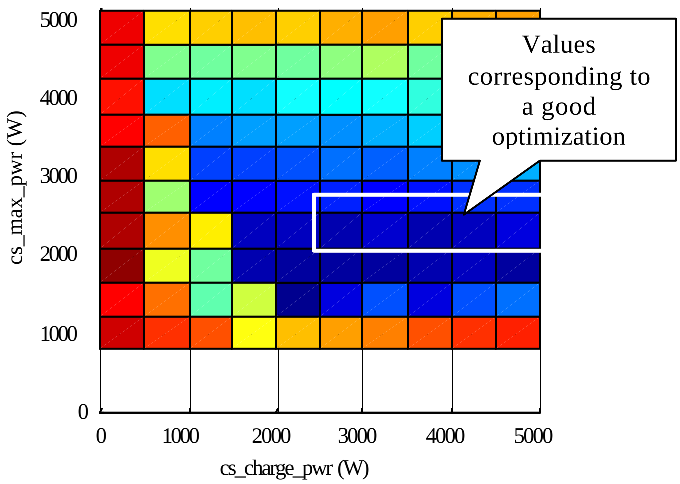

Fig. 7: Computation of the parameters *cs_max_pwr* and *cs_charge_pwr* for the urban driving schedule

A good optimization 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 :

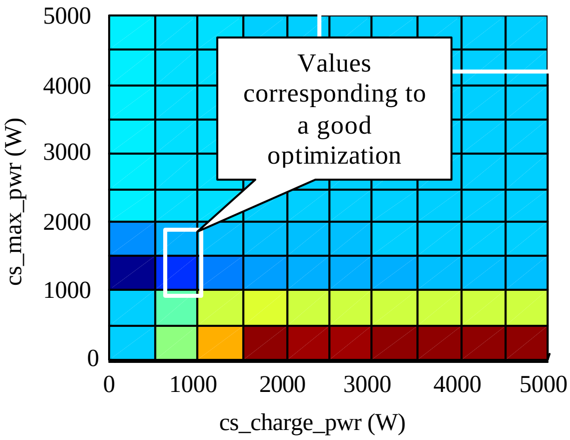

Fig. 8 : Computation of the parameters *cs_max_pwr* and *cs_charge_pwr* for the constant speed driving schedule

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.

7. 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 hybridized 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 optimization 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, hybridization reduces hydrogen consumption by 15% but increases it on the constant speed driving schedule

8. 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.

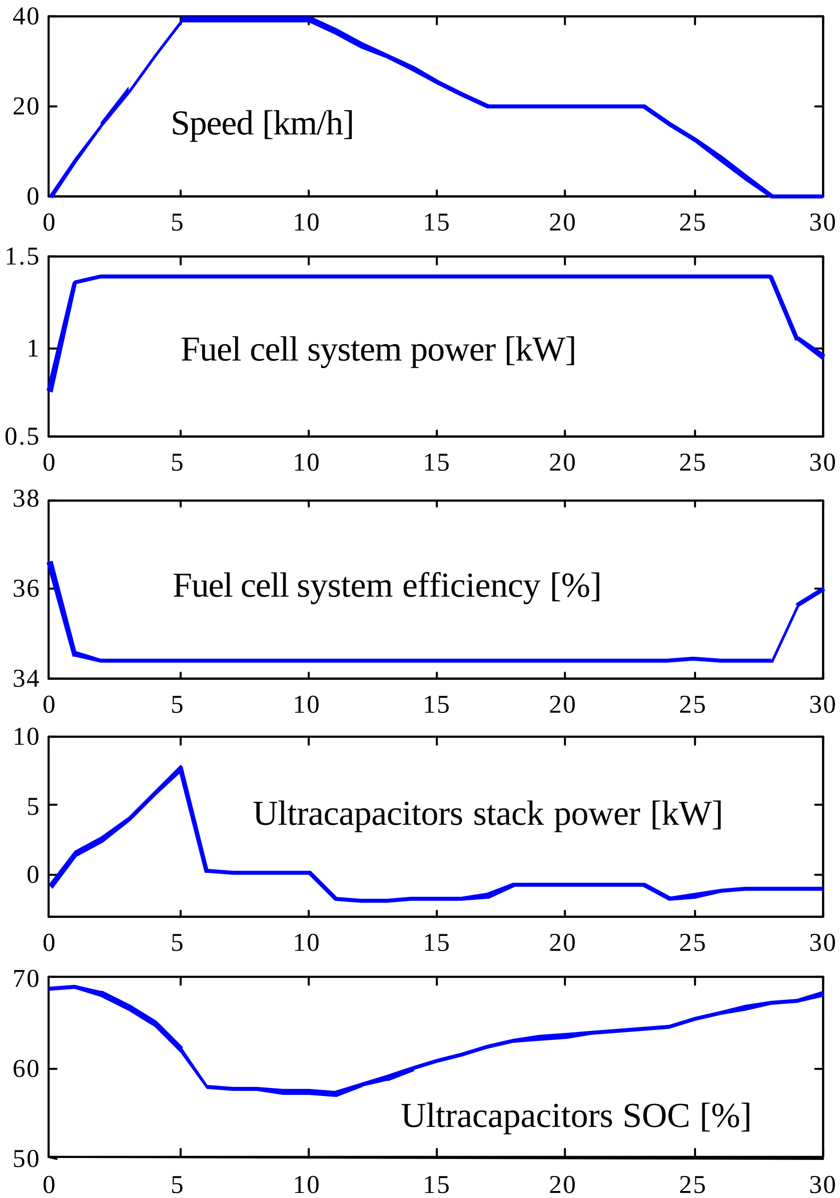

Fig. 9 : Simulation of the vehicle with the power source 1 on the urban driving schedule

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