INTERNATIONAL JOURNAL OF RENEWABLE ENERGY RESEARCH
Islem LACHHAB and Lotfi Krichen ,Vol. 5, No. 1, 2015

Impact of Ultra-Capacitor Sizing Optimization on Fuel Cell Hybrid Vehicle

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Received: 08.11.2014 Accepted: 18.12.2014

Abstract- Fuel Cell/Ultra-Capacitor vehicle is a hybrid system, where the two energy sources produce electricity to supply the traction motors. An accurate sizing is a key factor to achieve the driving performances and the economical viability. The Fuel Cell (FC) is the main energy source; it ought to be able to supply power during steady speed. The hydrogen tank is sized depending on the required autonomy. The Ultra-capacitor (UC), as a second energy source, assists the FC during fast power demand periods and recovers the braking energy. Two different methods for UC sizing are presented in this paper: (1) a full sizing where the UC is capable to deliver the total energy needed during the maximum acceleration and (2) an optimized sizing where the FC participates with the UC to realize the maximum acceleration. The FC/UC vehicle system is modelled and simulated using a random drive cycle. Simulation results obtained with the two sizing methods demonstrate a compromise between the UC size and the FC durability.

Keywords—FC vehicle, Ultra-Capacitor, Sizing, Optimization, Hydrogen consumption.

1. Introduction

Several solutions are presented today to benefit from an individual or collective transport while reducing the environmental impact and fuel costs of locomotion. Among these solutions, FC vehicles have received much attention as an alternative to conventional ones [1, 2]. In the literature, there is a consensus on the proton exchange membrane (PEM) as the best technology for automotive applications [3-5]. This technology has a high power density with low temperature operation, high efficiency and its start-up is faster than others technologies. Despite these advantages, the FC low dynamic remains the weakest point [6]. Indeed, the period of cold start can last 5 to 6 minutes [7] and the power dynamic is limited. To supply sudden and quick power variations in the vehicle system, the FC should be oversized which can extremely increases its cost, its dimensions and the hydrogen consumption [8]. Frequently, the FC is insufficient to provide energy to the traction system especially in acceleration periods wherein it can suffer from oxygen starvation problem in its membrane and consequently its durability can be affected [5, 9]. The FC lifetime can be extended if it operates in steady state conditions [10, 11]. Hybridization of FC vehicle by a secondary energy source has the advantages not only of improving the dynamic response and the system efficiency [12-15] but also of reducing the power system cost by downsizing the FC which is the most expansive component. So, the secondary source permits to assist the FC by providing the lack of power during acceleration and recover the braking energy. Ultra-capacitors, as a secondary energy source, exhibit a power density greater than of batteries, and much higher energy density than of conventional capacitors. Concerning urban cycles, vehicle power variations are frequently observed in daily operations. This power can easily and effectively provided by the UC due to its high power density [16, 17]. Furthermore, its lifetime, with millions of cycles, may be beyond the vehicle one [18].

In the literature, many sizing methods are used to determine energy sources dimensions in vehicle systems. For example, a statistical description of a random driving cycle is applied on FC truck in [19]. The authors in [20] use a sizing methodology where the load power profile, known or approximated a priory, is distributed between the energy sources, and the FC supplies the constant average power. An optimal sizing technique is used in [21] to minimise the operating costs in plug-in fuel cell electric vehicles by considering performance requirements. Authors in [22] apply a parallel chaos optimization algorithm and in [23] authors use the convexifying methodology to determine the components sizing in a plug-in hybrid electric.

In this paper, the two energy sources are sized according to vehicle parameters and drive performances. FC sizing is detailed firstly, depending on the steady drive conditions. Then, two different methods are used to determine the UC dimensions. In the first technique, the secondary energy source is sized so that it is able to deliver the totality of the maximum acceleration energy. The UC dimensions are optimized in the second technique. In fact, the two sources supply together the needed energy during acceleration, whilst respecting the FC power dynamic. The two sizing methods are discussed and compared by applying a random drive cycle.

2. System Sizing Methodology

2.1. System Description

In the studied vehicle system, FC and UC exchange energy with a DC link through two adapting stages as shown in Fig. 1. Each stage contains a DC/DC converter and an inductance. A unidirectional boost converter is used for the FC; however, the UC needs a bidirectional converter in order to supply power during acceleration and to recover the breaking energy. The two inductances are employed to respect sources alternation. The DC link supplies two motor-wheels using a three phase inverter for each motor. An energy management strategy is developed to control the power flow. This strategy depends on the UC state of charge and the vehicle speed level. The detailed modelling and the energy management strategy have been demonstrated in previous work [24].

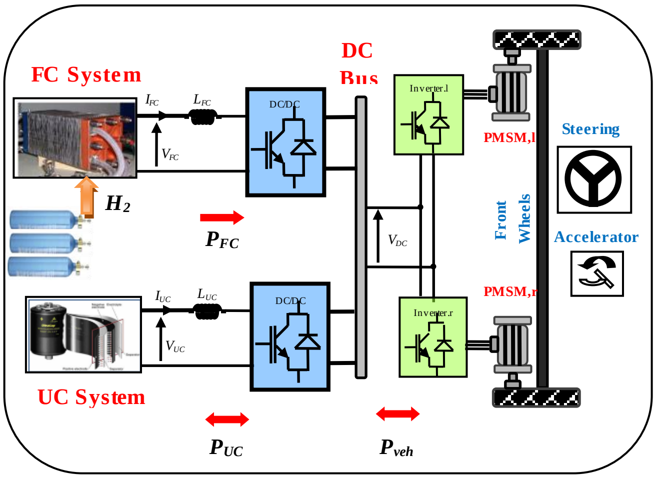

Fig. 1 FC Vehicle structure

2.2. Vehicle Power

The vehicle power depends on traction forces needed during acceleration, resistance forces and the required speed. The power demand during acceleration $P_{veh,acc}$ is given by the following equation [25]:

$$P_{veh,acc} = (M_{veh}.g.f_r.\cos(\alpha) + \frac{1}{2}\rho_a.A_f.V_{veh}^2 + M_{veh}.g.\sin(\alpha) + M_{veh}.\frac{dV_{veh}}{dt}).V_{veh} \quad (1)$$

Where M_{veh} is the vehicle weight, g standard gravity, f_r is the resistance coefficient of the tire rolling, ρ_a is the air density, A_f is the front area of the vehicle and V_{veh} is the vehicle speed and α is the road slope.

The required power for a vehicle rolling at constant speed is calculated by Eq. 2.

$$P_{veh,acc} = (M_{veh}.g.f_r.\cos(\alpha) + \frac{1}{2}\rho_a.A_f.V_{veh}^2 + M_{veh}.g.\sin(\alpha)).V_{veh} \quad (2)$$

In this study, the parameters of the considered vehicle are depicted in Table 1. According to these parameters, the energies of the maximum acceleration and of the braking are calculated.

Table 1. Vehicle parameters

$M_{veh} = 850\ \text{kg}$	$\rho_a = 1.225\ \text{kg/m}^3$
$g = 9.8\ m/s^2$	$A_f = 1.225\ \text{kg/m}^3$
$f_r = 0.0136$	$T_{acc,\max} = 12\ s$

A simple drive cycle is applied to the vehicle model on flat road, as presented in Fig. 2. The obtained vehicle power is shown in Fig. 3.

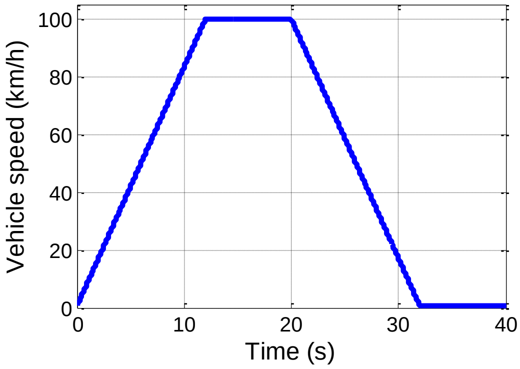

Fig. 3. Speed profile

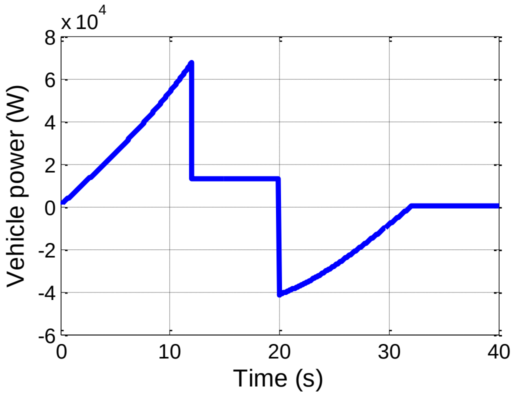

Fig. 4. Vehicle Power

During the maximum acceleration phase, the energy $E_{acc,\max}$ can be calculated with the following expression:

$$E_{acc,\max} = \frac{1}{T_{acc,\max}} \int_0^{T_{acc,\max}} P_{veh}(t) = 116.67\, W.h \qquad (3)$$

Where $T_{acc,\max}$ is the maximum acceleration time.

The second energy source should be able to recover the most of the regenerative energy, which is lower than the acceleration energy. As a result, just the acceleration energy is taken into account for the UC sizing.

2.3. Sizing Methodology

The energy sources are dimensioned according to the power demands needed to meet the desired dynamic performance of the vehicle (speed and acceleration). The calculation of the filter inductances and the DC bus capacity ensures the smooth operation of choppers and inverters. Operating point's converters must guarantee the security of sources and motors, and minimizing losses by choosing the best duty cycles. The hydrogen tank is sized according to the desired autonomy. Indeed, the sizing depends also on the type of vehicle use (urban, suburban, highway). For this, two different driving situations are considered. First, driving at a constant speed: the vehicle must be capable of running at a constant speed for a long time, and then a constant power is required. Since the secondary source has a limited energy density, the FC must provide sufficient power to ensure the speed maintenance. Second, acceleration: This phase lasts few seconds with a significant required power. The secondary source attends the FC and provides the necessary power.

- DC bus and filters sizing

The DC voltage may be selected freely as long as the operating points of converters are in the possible range of use. For the purpose of obtaining lower currents and thus minimizing losses for the same power, the DC bus voltage is fixed as $V_{DC} = 700V$. Both inverters are powered from the DC bus. The DC voltage is required to be stable during the system operation with low ripple factor. The DC bus capacity, depending on the maximum current transferred to inverters $I_{\max}$, the maximum voltage ripple $\Delta V_{\max}$ and the inverters control frequency F , is given by the following expression:

$$C_{DC} = \frac{I_{\max}}{4\Delta V_{\max} F} \qquad (4)$$

Where:

$$I_{\max} = \frac{P_{veh,\max}}{V_{DC}} \qquad (5)$$

Likewise, filter inductances are calculated by considering the chopping period T and the current ripple $\Delta I_{\max}$ as described in the following equation:

$$L = \frac{T V_{DC}}{4\Delta I_{\max}} \qquad (6)$$

- FC sizing

As the FC is the primary energy source, it provides the basis power demand $P_{nom} = 30KW$. A great number of element cells are combined to achieve the satisfactory power. Electrical connections are made in series or in parallel for adjusting voltage and current according to the needs. The FC sizing consists of determining the number and the surface of the cells. The FC size does not depend only on the basic power of the traction motors but also on the auxiliary consumption and its own performances. The auxiliary consumption (mainly air compressor) varies from 10% to 15% of the nominal power. The FC performances depend on the used hydrogen. If the H_2 is reformed or produced directly on-board the vehicle, the fuel cell system efficiency cannot exceed 35%. Whereas, the hydrogen storage with high pressure improves the efficiency to 50%. Today, FC is developed with an efficiency of 60% [26-28]. The FC total power $P_{FC,tot}$ is given by the following equation [29]:

$$P_{FC,tot} = \frac{P_{nom} + P_{aux}}{\eta_{FC}} = 58.5KW \qquad (7)$$

Where: the FC efficiency is $\eta_{FC} = 60\%$, and the auxiliary consumption is $P_{aux} = 15\% P_{nom}$

The FC exchanges power with the DC bus through a boost chopper. To obtain efficiency greater than 90 %, the adequate duty ratio is equals to 2. So, the FC nominal voltage $V_{FC,nom}$ is calculated using the following equation:

$$\frac{V_{DC}}{V_{FC,nom}} = 2 \;\Rightarrow\; V_{FC,nom} = \frac{700}{2} = 350V \qquad (8)$$

The nominal current supplied by the FC $I_{FC,nom}$ is evaluated as:

$$I_{FC,nom} = \frac{P_{FC,tot}}{V_{FC,nom}} = 167A \tag{9}$$

By considering the cell voltage $V_{cell,FC} = 0.64V$ and the current density $j_{FC} = 0.65A/cm^2$, the cells number n_{FC} and the surface S_{FC} are calculated by the following equations:

$$n_{FC} = \frac{V_{FC}}{V_{cell,FC}} = 547 cells \tag{10}$$

$$S_{fc} = \frac{I_{FC}}{j_{FC}} = 257 cm^2 \tag{11}$$

- Hydrogen tank sizing

According to the French Association for Hydrogen and Fuel Cells (AFHYPAC), the FC vehicle consumes between 0.8 and 1.2 kg of H_2 for 100 km and the quantity of H_2 to be stored in the reservoir varies from 2 to 6 kg depending on the vehicle type and the intended use. The hydrogen tanks usually have a pressure between 350 and 700 bars [20]. The studied FC vehicle has a medium speed equal to 80 km/h and autonomy about 400 km with full tank. The total needed power of the FC to drive the vehicle in a medium speed range is determined using Eq. 2 and Eq. 7. The instantaneous fuel consumption of hydrogen is expressed by the following relationship [19]:

$$\dot{m}_{H_2} = \frac{M_{H_2}\, n_{FC}\, I_{FC}}{2F} \tag{12}$$

Where M_{H_2} is the hydrogen molar mass and F is the Faraday constant.

The hydrogen volume can be deduced from the needed mass to achieve the vehicle autonomy at medium speed. To calculate the tank volume, the different densities of hydrogen in different storage states are defined in Table 2.

Table 2. Stored hydrogen characteristics

Hydrogen states	***Density kg/m³***	***Volume (m³)***
Liquid hydrogen	70.8	0.04
350 bar	19.5	0.15
700 bar	39	0.075

3. UC Sizing Optimization

Ultra-capacitor can be charged either by the braking energy or by the FC according to the energy management strategy. This strategy sets the SOC in order that the storage device is able to deliver or absorb the remaining power. These features reduce the size and the cost of the FC and increase the system performances [3]. This storage device comprises of a combination of unit cells in series and in parallel. The sizing of the UC is ensuring by the determination of cells number that can guarantee the vehicle acceleration. In this work, this goal is achieved by two methods.

2.4. A full Sizing

For the full sizing, the UC is considered to supply all the needed energy during maximum acceleration. In fact, the FC isn't supposed to deliver any power during this phase. The power diagram of this sizing method is presented Fig. 4.

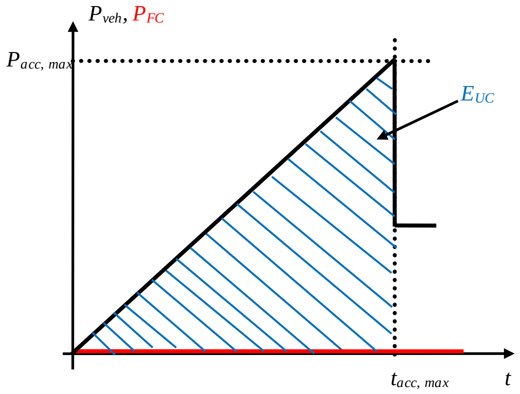

Fig. 5 Power diagram of full sizing

The UC energy is calculated taking into account the state of charge SOC constraints, as given in the following equation [9]:

$$E_{UC,\max} = \frac{E_{acc,\max}}{SOC} = \frac{116.67}{0.8} = 146W.h \tag{13}$$

The UC unit parameters are summarized in Table 3 [5]:

Table 3. UC parameters

Maxwell BOOSTCAP PC2500	
Capacity $C_{UC,unit}$	*2700F*
Rated voltage	*2.5V*
Maximal voltage	*2.7V*
Stored energy $E_{UC,unit}$	*8400J*
Weight	*725g*
Volume	*0.6l*

The UC units' number is calculated using the following equation:

$$N_{UC} = \frac{E_{UC}}{E_{UC,unit}} = 63 units \tag{14}$$

To increase the voltage level, the UC units are connected in series. The total capacity is equal to:

$$C_{UC} = \frac{C_{UC,unit}}{N_{UC}} \approx 42.8F \tag{15}$$

2.5. Optimal Sizing

During acceleration, the two energy sources can supply together the required energy. Certainty, the FC can deliver a quantity of this energy while respecting its power dynamic. Consequently, the requested energy from the UC is decreased and its size will be reduced. This result can be shown by comparing the blue hatched areas in Fig. 4 and Fig. 5.

To calculate the reduced size, the UC optimal energy $E_{UC,opt}$ should be determined firstly. This energy is equal to the maximum acceleration energy by subtracting the main source provided energy. Or, the FC generated energy depends on its power slope, its maximum power $P_{FC,\max}$ and the required time to reach this power t_{FC} .

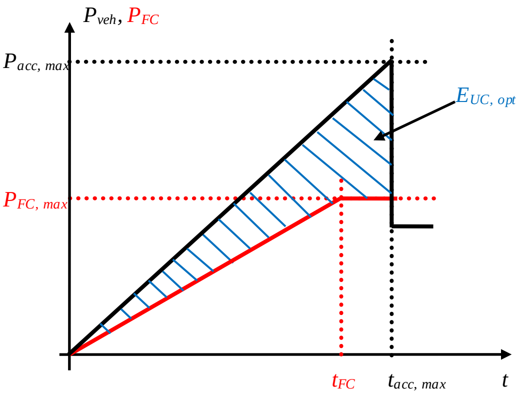

Fig. 6. Power diagram of optimized sizing

The power slope PS, depending on the FC surface and the rated voltage is calculated by the following expression:

$$PS = 0.04 S_{FC} V_{FC} \tag{16}$$

By calculating the blue area in Fig. 5 and using Eq. 14, Eq. 15 et Eq. 16, the optimal UC parameters are: $E_{UC,opt} = 95.5 W.h$, $N_{UC,opt} = 41 units$ and $C_{UC,opt} \approx 66 F$.

4. Simulation Results and Discussion

The vehicle model is developed by MATLAB-Simulink. Fig. 6 represents an aleatory drive cycle which is applied on the system model during 410 s and as 110 km/h maximum speed. The vehicle power is presented in Fig. 7. The simulation results are obtained by considering the two UC sizing methods.

Considering the full UC sizing, the FC and the UC powers, the UC SOC and the hydrogen consumption are presented in Fig. 8, Fig. 9, Fig. 10, and Fig. 11, respectively.

For the optimal sizing, the FC and the UC power, the UC SOC and the hydrogen consumption are presented in Fig. 12, Fig. 13, Fig. 14 and Fig. 15, respectively.

Based on the drive cycle profile, the vehicle takes 6.8 minutes to achieve 7.7 km. Comparing the FC power in the two sizing cases, it is clear that the power profile in the optimal sizing has more variations than in the full sizing especially in 91s and 326 s. As a result, the hydrogen consumption increases from 28 g to 28.8 g by considering these two points. Regarding to the UC system, it is completely charged and the SOC is equal to 1 in 226 s, [235 252s], 395s and [406 410s]. Therefore, the UC cannot recover any extra barking energy.

To conclude, the optimal sizing decreases the UC dimensions although the system efficiency is affected: the hydrogen consumption is increased and the barking energy may not be recovered totally. In addition, the FC receives more variation in the power demand which will minimize its durability.

5. Cost Evaluation

A comparison of UC and hydrogen costs allows evaluating the sizing methods profitability. The UC cost is assumed to €6/Wh [30]. Whereas, the hydrogen cost depends on the production methods. The production by fossil fuel reforming (especially methane) costs today about €1.5/kg of H_2. The hydrogen price generated by industrial electrolysers can fluctuate between 5 and €30/kg depending on electricity prices. However, this price can be reduced effectively if the electricity is produced by renewable energy sources (Wind/Photovoltaic) [26].

The price discount of the UC system PD is:

$$PD = (E_{UC} - E_{UC,opt}).€6 = €300 \tag{17}$$

The hydrogen increment H_2I is about:

$$H_2 I = \frac{28.8 - 28\,(g)}{7.7\,(km)} = 0.1\,(g\,/\,km) \tag{18}$$

By considering the reforming price, the vehicle will roll over two million km to achieve the UC price discount of the optimized sizing. However, the extra stress caused by this sizing method on the FC should be taken into account.

6. Conclusion

In this work, a FC vehicle is presented where an UC is considered as a secondary energy source. The sizing methodology consists of finding out the sources dimensions as well as filters and hydrogen tank by considering driving performances. A full and an optimized sizing of the UC are presented. Although the UC dimensions are bigger in the first sizing methods than in the second one, but the hydrogen consumption and the power variations are increased in the case of the full sizing. As a result, a compromise exists between the reduction of the UC size and the FC durability.

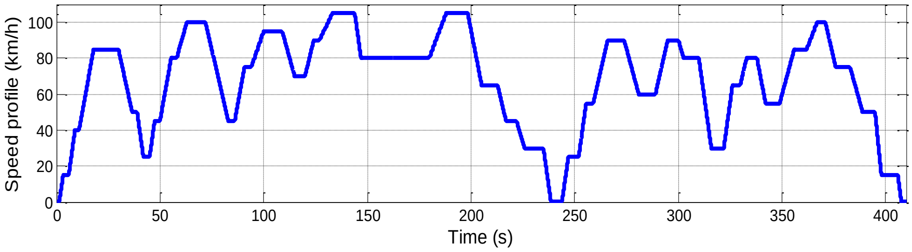

Fig. 7. Speed profile

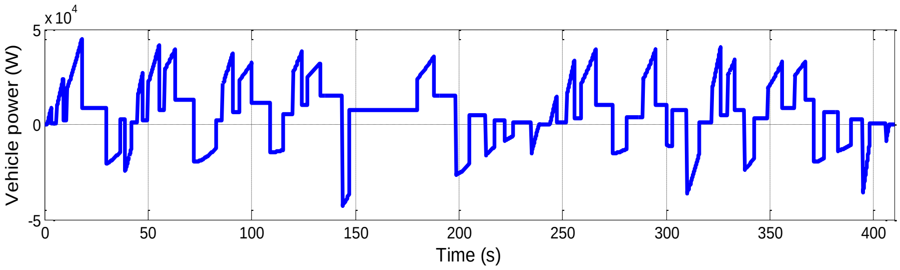

Fig. 8. Vehicle power

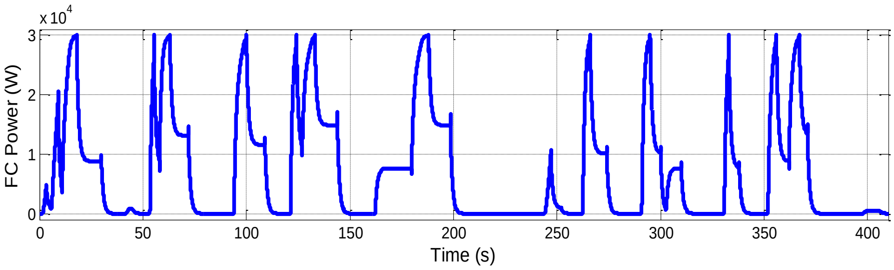

Fig. 9. FC power

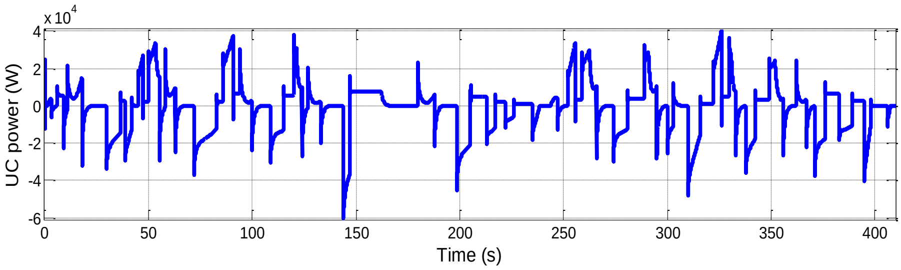

Fig. 10. UC power

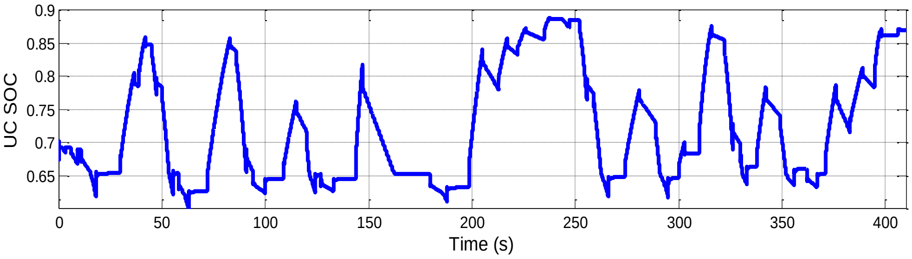

Fig. 11. UC State Of Charge

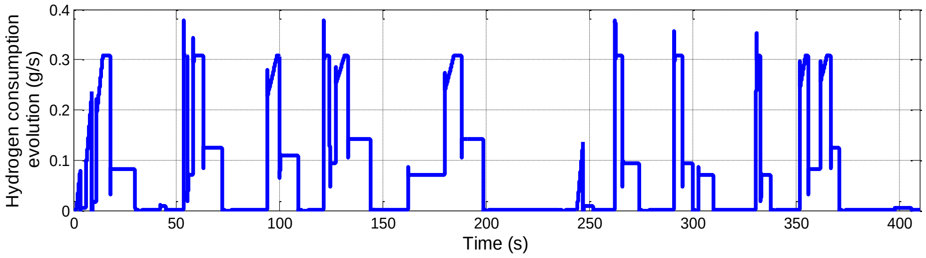

Fig. 12. Hydrogen consumption evolution

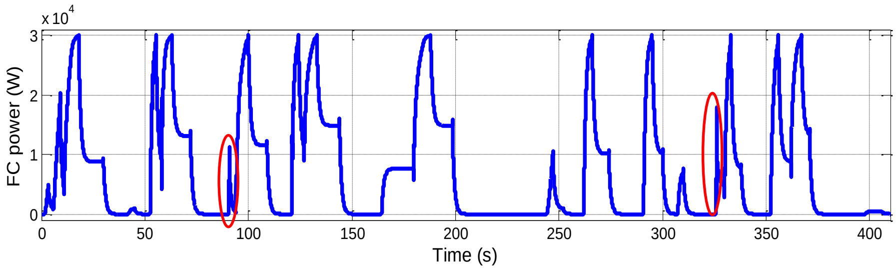

Fig. 13. FC power

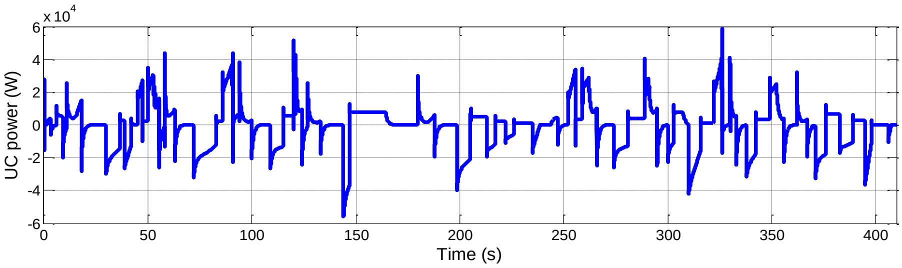

Fig. 14. UC power

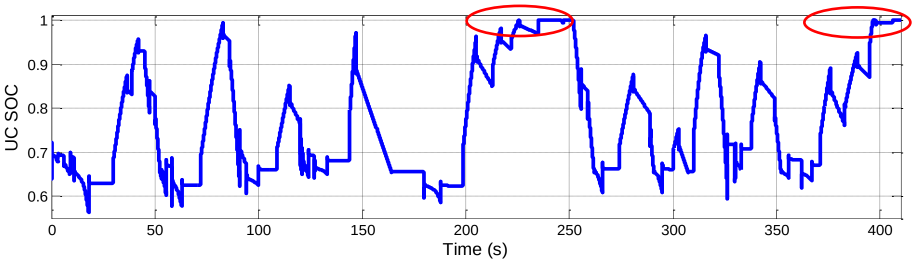

Fig. 15. UC State Of Charge

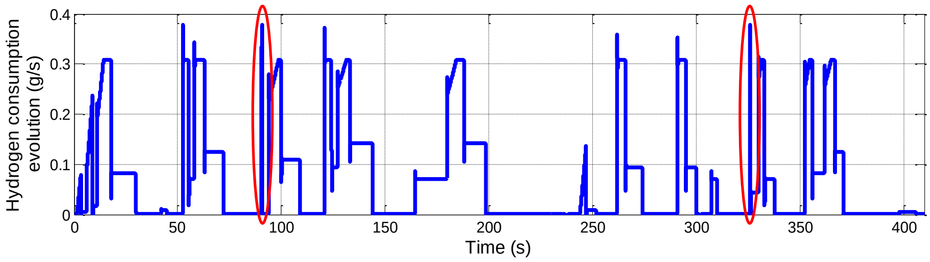

Fig. 16. Hydrogen consumption evolution

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