ENERGY MANAGEMENT OF FUEL CELL SYSTEM AND SUPERCAPS ELEMENTS

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Abstract—The use of Fuel Cell and Supercaps as energy elements in transport application is now a reality. Having two power sources on board allows a certain energy management strategy. Defining this strategy some iteration must be made with an accurate model to extract the optimal solution. In order to reduce computation time consumption, a simplified physical fuel cell model is proposed. This model is used in algorithms to compute the two power references of the two sources allowing the minimum hydrogen consumption and maximum braking energy absorption for a tramway following an actual power demand. *Copyright © 2005 IFAC*

Keywords—Circuit Model – Power management - Optimisation

1. INTRODUCTION

Due to environmental constraints, classical thermal engines fed with mineral oil start to be replaced by other engines or other energy source. Using fuel cell in transport application in the heart of cities has 2 main interests: air pollution reduction (fuel cell only produces water, no CO_2) and allows catenaries suppression (all energy sources and converters are on board). Our study takes place in rail transport application domain and particularly tramways. The COPPACE project supporting this study concerns a 900kW tramway application and the vehicle is made with a fuel fell and storage elements. The technology chosen is Proton Exchange Membrane Fuel Cell (PEMFC) designed for a 400kW max power and works at low pressure (about 2bars or less) and mid-temperature (about 80°C). Supercaps compose the Energy Storage System, added to help the fuel cell supplying the high power demand and to absorb energy providing by the load because the PEMFC is not reversible (see Solero(2001) and Corgier(1997)).

Numerous studies analyze the fuel cell behavior and model is requested to see the behavior of such system (Jemeï(2002), Friede(2002)). The electro-chemical model has been built but is heavy and time consuming. So, based on the physics of the fuel cell this paper propose in the first part, not only a simple model of the controlled fuel cell system but also losses estimation of each component to know energy used and lost in the FCS, ESS and Converters. In the second part an energy management is detailed to compute the two source references in order to maintain the two elements in their own limits and to reduce the ESS size and the hydrogen consumption. In the last part results on an actual power profile measured on an actual tramway is shown.

2. FUEL CELL MODEL

2.1 Based-Cell Model

Anode, cathode, membrane and electrode elements constitute the based-cell. With serial and parallel connections a more powerful fuel cell is build to have the fuel cell needed in transport application (tramway in this study described in Lachaize2003). The chemical to electrical behavior starts to be well known for PEMFC and complex model can be found in: Amphlett(1995) and Alstom-CEA-LEEI(2002). The FC voltage *Ufc*, depends on the current in the fuel cell *I*, the partial pressures (of hydrogen P_{H2} and oxygen P_{O2}), the temperature of the reaction T_{fc}, and the hydration of the membrane l_{H2O}.

$$Ufc = f(I, PO_2, PH_2, T_{fc}, l_{H_20}) \qquad (1)$$

Assumptions: - Non significant Anode activation voltage - Uniform current density and temperature.

The voltage variations of the fuel cell are computed with a quasi-static model, because the dynamics of the chemical reactions is faster than the system dynamics. The output voltage expression is:

$$Ufc = E_{rev} + h_{act} - R_m \cdot j \qquad (2)$$

Where, the reversible voltage E_{rev} is:

$$E_{rev} = a_1 + a_2 \cdot (T_{fc} - 298.15) + a_3 \cdot T_{fc} \cdot \left(\frac{1}{2} \cdot \ln P_{O_2} + \ln P_{H_2} \right)$$

The cathode activation over voltage h_{act} is:

$$h_{act} = b_1 + b_2 \cdot T_{fc} + b_3 \cdot T_{fc} \cdot \ln(j\, 5.10^{-3}) + b_4 \cdot T \cdot \ln c_{O_2}$$

Where c_{O2} the concentration of dissolved oxygen, can be defined by henry's law (mol/m^3) according to:

$$c_{O_2} = \frac{P_{O_2}}{5.08 \cdot 10^6 \cdot \exp\left(-\frac{498}{T_{fc}} \right)}$$

With parameters extracted from literature: α_1=1.229 α_2 = -8.5 10^{-4} α_3 = 4.3085 10^{-5} β_1=-0.9514 β_2=3.12 10^{-3} $\beta3$ = -1.87 10^{-4} β_4 = 7.4 10^{-5} and R_m= f(T_{fc}, l_{H2O}) ohmic resistance (0.097mΩ.m²) and for the fuel cell made with *N* based-cell, $R_{fc}=R_m*N*S$=0.11Ω; *j* = current density.

2.2 Fuel Cell System

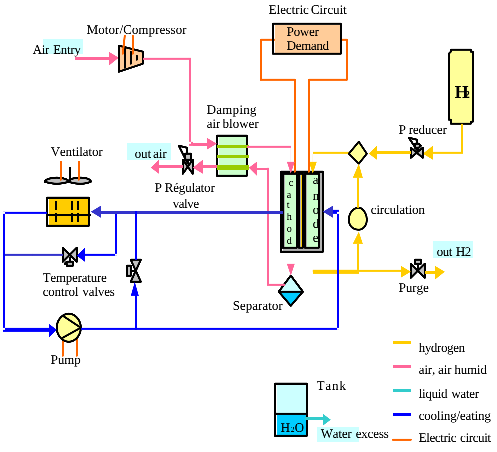

Fig 1. Complete Fuel Cell System

Fuel cell needs also some auxiliaries to control the different gas loops and different important values as: pressure, flow and temperature. So adding compressor, pump, radiator and valves with their own control a fuel cell system given in Fig 1 is obtained. In the hydrogen loop there is no special control because an ideal source of hydrogen is considered represented by only an infinite tank and a passive reducer to fixe the 2bar absolute pressure in this compartment whatever the flow is. In the cooling water loop a pump assures a constant flow and a cooling radiator and 2 valves assure the temperature regulation with a suitable decoupling and compensating control structure. The temperature is regulated around the optimal temperature defined (80°C). So the most difficult compartment to model is the cathode (oxygen) compartment where a compressor and a valve must provide the desired flow under the 1.5bar absolute pressure fixed. All controls have been studied in Lachaize(2004) and considered to be effectives. So, a simplified model must be extracted considering the controllers acting and keeping the fuel cell in their own settings.

2.3 Simplified Fuel Cell Model

The main phenomena represented in the model provide the fuel cell voltage behavior taking into account the most significant dynamics in the loops. So the controlled compressor has its importance in voltage source (U_{o2}) as well as equivalent resistance present in the circuit. In the working zone (nominal point fixed) 3 voltage sources can be generated.

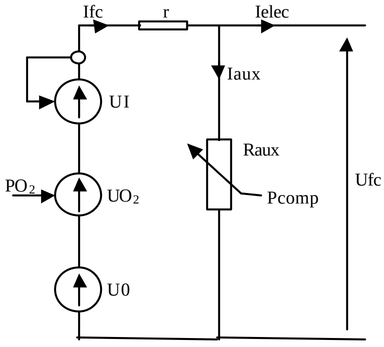

Fig 2. Simplified Fuel Cell Model

1 - If temperature T_{fc} and hydrogen pressure P_{H2} are constant (inside pressure is constant because input pressure is fixed and T_{fc} fixes the saturated pressure in the cell), a constant source U_0 representing the constant voltage of the fuel cell is computed by:

$$U_0 = a_1 + a_2 \cdot (T_{fc} - 298.15) + a_3 \cdot T_{fc} \cdot \ln P_{H_2} + b_1 + b_2 \cdot T_{fc} \qquad (3)$$

2 - The fuel cell voltage depends on the current delivered I_{fc}, so a varying voltage source U_1 can be detailed by writing:

$$U_I = b_2 \cdot T_{fc} . \ln\left(\frac{I_{fc}}{S} 5.10^{-3} \right) \qquad (4)$$

3 - The last voltage source corresponds to the voltage due to the fuel cell parameters and the oxygen pressure P_{O2} and the temperature of the fuel cell T_{fc},

so , U_{o2} is written as:

$$U_{02} = a_3 .Tfc. \frac{\ln P_{o2}}{2} + b_4 \cdot T_{fc} .\ln\left(\frac{P_{O2}}{5.08.10^{-6} \exp(-498/T_{fc})} \right) \quad (5)$$

a_i and b_i coefficients are the same defined above.

The current needed for auxiliaries (compressor, pump…) is consumed before providing the usable current to its exit to feed the converter (*Ielec=Ifc-Iaux*). This consumption is represented by a varying resistance *Raux*. Resistance of the Fuel Cell is represented by *r*. *r*, *Raux* and PO_2 must be computed to have an accurate representation of the controlled fuel cell system behavior.

- $r=N^*(r.e/S)$

With N=586 the number of based-cell used, e=50µm width of the membrane, S=0,1956m² the equivalent surface and r depends on air humidity injected and temperature (if both are regulated r = 72.4mΩ.m)

- $Raux=U_{fc}^2/Pcomp$. *Pcomp* is computed with the compressor characteristics depending on its velocity (flow *Fcomp*) and the PO_2 pressure. The air pressure is fixed to 1.5bar so the compressor map can be read to obtain the equivalent *Pcomp* to deliver the current I_{fc}. In real time U_{fc} is the previous computed voltage value. The electrical model is shown on Fig2.

- PO_2 also varies and depends on the fuel cell behavior, so identification is made with the complete physical fuel cell model provided by our partner (CEA).

The oxygen partial pressure is computed by the number of mole presents inside the compartment, so the calculus is made in 3 steps:

* The flow in the controlled loop can be seen as a second order transfer function:

$$F_{o_2}(s) = \left(\frac{1}{(1+t_{fbf}\, s)^2} - 1 \right) X_{02air} .F_{ref}(s) \quad (6)$$

with : s=Laplace operator, t_{fbf} the flow time constant fixed in the closed loop controller (0.02s), X_{o2air}=21% the oxygen ration in ambient air at the beginning and F_{ref} computed by faraday's law $F_{ref} = \frac{NI_{fc}}{4F}$ and I_{fc} is known using the power reference : $I_{fc}=P_{ref}/U_{fc}$

* So number of mole is known by integration:

$n_{02}(s) = \frac{1}{p} F_{o2}(s)$ with initial condition *IC*, adjusted after a first simulation using the complete model to track the fuel cell behavior. Initial Condition depends on the fuel cell characteristics, here $IC=P_{cath}V_{cath}/R.T_{fc}).\, Xo2_{init}$

With: $Xo2_{init}$=8.21% oxygen ratio in the cathode; P_{cath}=2bar; V_{cath}=0.11m^3; R=8.1J/K/mol; T_{fc}=298°K

* Inside pressure behavior can be described by transfer function (7) after parameters identification:

$$P_{02}(s) = (n_{02}(s). \frac{R.T_{fc}}{P_{cath} .V_{cath}}) \left(P_{cath} - K_{ins} F_{comp}(s) \right) \quad (7)$$

With K_{ins} a coefficient describing the fuel cell behavior which must be identified by measures made with our simulator to compute the ratio from entry and interne pressure on the compressor flow:

$K_{ins}=(P_{incath}-P_{internal})/(Fcomp)$ -> $K_{int}=Ka.Fcomp+Kb$

And after simulation: Kb=996.2 and Ka= -0.28

This simple model is compared to the complete model which takes into account all electro-mechanico-chimical phenomena (fluid behavior, chemical reaction, gas propagation, direct and reverse flow see Bird1960). This simplified model generates little relative error but is 100 times faster.

2.4 Losses Estimation

Adding to the model, losses estimation is of paramount importance to have an accurate and significant energy management. The fuel cell system efficiency is known and is fast computed with our simplified model with different power references. These compose a losses map for the fuel cell system to be used in energy management. Only Joule's losses in the equivalent resistance (Plosses=rsc.Isc²) are considered in Supercaps Element.

Information present in Fig 3, will be used latter to adjust our energy management taking into account the different losses in each elements. Losses estimation due to conduction losses and switching losses is added in the control of each converter. All losses are function of the fixed switch frequency *fc*, current and tension on the converter: *Plosses*=f(*fs*,*I*,*Udc*). Based on constructor data sheets we can evaluate all losses in diodes and IGBT, knowing the fuel cell behavior and the ohm losses due to the equivalent resistance in the supercaps.

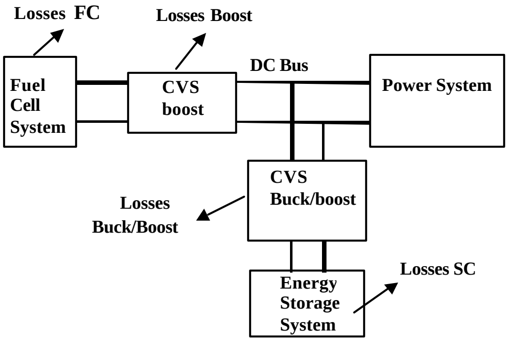

Fig 3. Losses Estimation

3. OPTIMISATION

To provide a power demand with the 2 sources (FCS and ESS) an algorithm must manage the 2 references given to the 2 converters not only to follow the desired global power reference but also to satisfy some other criterions. In this study to obtain a good exploitation capabilities and the same behavior as an actual tramway the energy management strategy is :

- recover all braking energy

- provide the constant auxiliaries power (43kW) with the fuel cell system (to not stop the fuel cell and to not have a too big storage element)
- have a 400kW maximal power on the fuel cell and a storage element as little as possible.
- limit the power variation on the fuel cell to 300kW/s (control and design limitation)
- start - stop with storage element fully charged.

An optimal power repartition, without the 2 sources dimension knowledge is given in a 2 steps solution. The power demand and the velocity on the actual tramway are the input data of our algorithms.

3.1 *Step 1*

All null velocities (during about 20s) correspond to a stop in stations so, the total power profile is decomposed in series of *n* segments called interstations. On each interstation all negative power references must be absorbed by the ESS because the fuel cell is not reversible, thus from the beginning to the end of the profile (from *i*=1 to *n*) we must adjust the power references to absorb this braking energy (different on each interstations). The energy storage system power (*Pess*) is forced to follow the braking absorption, so in a given interstation *i* the energy to be absorbed is linked to the power demand itself and the power already delivered by a defined fuel cell system power *Pfcs* (constant line on Fig 4 and Fig 5).

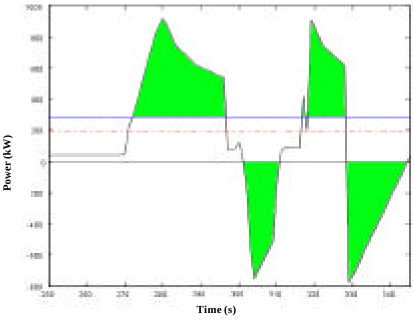

Fig 4. Power absorption and repartition 1.

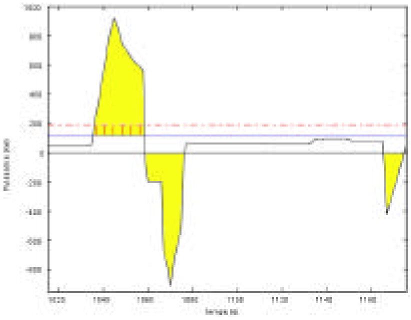

Fig 5. Power absorption and repartition 2.

A first iterative algorithm (Fig 6) is used to find the *Pfcsup* limit providing the balance through the areas above the limit and under 43kW.

It consists only on fixing an initial condition on *Pfcsup* equal to 0kW. Increasing step by step (1kW by step is sufficient) computing the areas and stop when equality is reached. Find this limit *Pfcsup* means a power repartition as shown on Fig7. If we do the same on the *n* interstations the average power on the energy storage element is null on each interstation and no more optimisation can be made. The main constraint on the State Of Charge consists in a 100% charge at the beginning and at the end of the profile, that means different SOC can be reached at the end of *i*=1 to *n*-1. To do that, it is sufficient to vary the FCS contribution and forced the *Pfcsup* found before to be higher than a value *Pmin* ([43kW..400kW]).

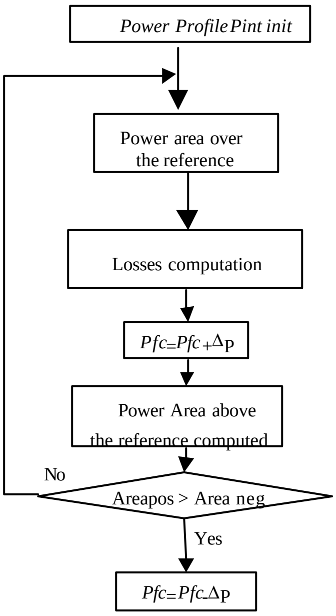

Fig 6. *Pfc* superior limit on a given interstation

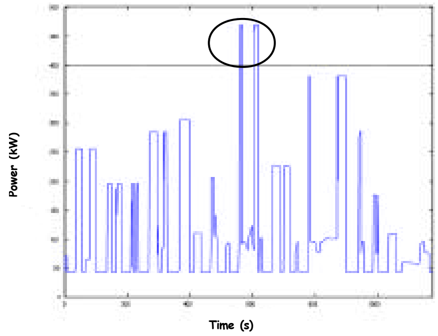

Fig 7. FC power limitation management

It is important to note that the FC efficiency is better when the power is high. As high is the *Pmin* value as high is the hydrogen consumption but on the global profile, efficiency will be better (so less H_2 global consumption) and as little the storage element will be too. In fact, if the fuel cell provides more energy the ESS must be discharged in another way in order to absorb the energy *DE* (dashed area on Fig 5). Discharging ESS during an interstation before the braking instant, forces to use the ESS to deliver an equivalent energy (only equality of surface areas over and above the fuel cell limit on the global profile not only on an interstation).

Two cases can be found and detailed in the algorithm

(Fig 8) with a fixed *Pmin* and shown on fig 4 and 5:

- *Pfcsup* is found higher than *Pmin*. No more problems (Fig 4).
- *Pfcsup* is lower than *Pmin*. In this case an energy ΔE (dashed area on Fig 5) must be rejected to compute in a new reference.

The interstation chosen to absorb this energy is the interstation with *Pfcsup* higher than the maximum 400kW (as in Fig 7). If no solution can be found, *Pmin* can not be applied. There is a compromise to use the fuel cell to deliver maximal power using optimally the energy storage element and reducing the hydrogen consumption, sometimes a solution is found sometimes the solution can not be adjusted providing a non optimal solution or a non acceptable one. The *Pfcsup* violating *Pmin* is recorded and the critical interstation number is registered (*k*=*i*) to start the next research from *k* to avoid unnecessary computation from the beginning.

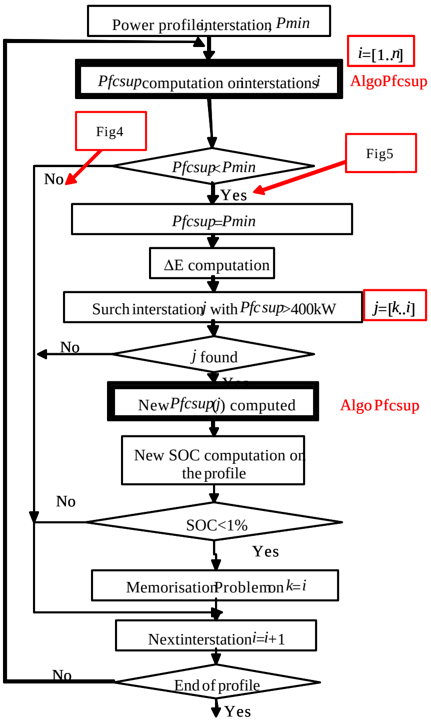

Fig 8. First Step Algorithm : Power repartition

If *Pfcsup* is found higher than 400kW (Fig 7), the energy area is computed and reported and the ESS reference to limit the Fuel Cell reference and the SSE SOC is computed to the next interstation.

3.2 Step 2

Computing in the second algorithm (Fig 9) all possibilities with *Pmin* from 43 to 400kW with 1kW step allows to analyze the different criterions obtained and to extract the best *Pmin*. To initiate algorithm, a sufficient (non optimal) size of ESS is determined. Maximal braking energy is computed and this maximum is computed on each interstation with the sum of negative power. The most critical interstation gives the ESS first size.

At the end if a non null report is seen that can be avoided by non fully charged ESS (sometimes a 92% SOC tolerance is sufficient for difficult profiles) or a bigger SSE size must be chosen. *Pmin* references violating criterions can be canceled and in the possible solutions it is easy to choose the reference providing the minimum H_2 consumption because the fuel cell efficiency (and losses) are also computed and indicates the H_2 volume consumed on a given profile. Moreover, this *Pmin* value also fixes the energy necessary to be stored so the optimal size of the ESS element and *Pmin*<*Pfcsup*<400kW.

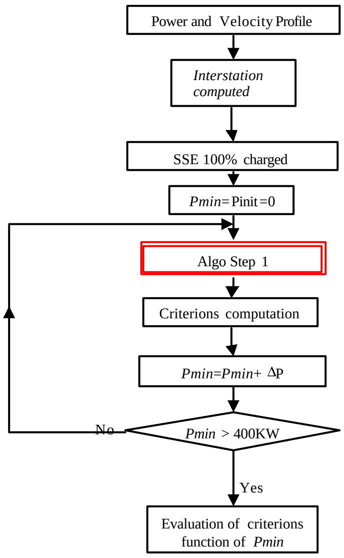

Fig 9. Second Step Algorithm : *Pmin* variation

4. RESULTS

For each *Pmin* 7 criterions are computed, some of them are shown. On Figure 10 and 11 intervals can be found respecting the fuel cell characteristics and energy constraints on SOC. Discontinuities are directly linked to the power profile we use and when a power level pass over a power peak the power repartition can change drastically.

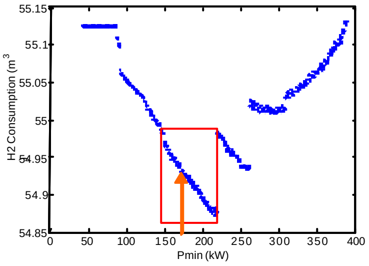

Fig 10. Hydrogen consumption

At the end, the minimum hydrogen consumption can be reached with the Pmin value computed providing the power reference of the FC (limited to 400kW) and the necessary energy on the ESS allows to build it with its optimal size. On the actual power profile example (red arrows) Pmin=164kW, H2=54.95m3 to pass the profile and Ess=3,3kW.h is necessary provided by 290 series and 9 parallel supercaps elements.

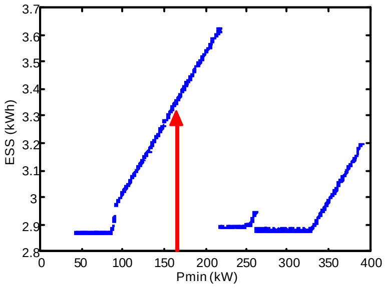

Fig 11. Energy in supercaps

We can note in the selected interval, the hydrogen consumption is quite the same but repeating the profile it can be important to minimize this consumption. Without another criterion to choose one solution from ESS size and FC consumption we choose the ESS optimal size on this profile. Computing all references from 43kW to 400kW for *Pmin* with the quick accurate model allows iterations in few hours with a step *DP*=1kW. With one solution *Pmin* found, Fig12 presents the power repartition with *n* interstation values *Pfcsup*.

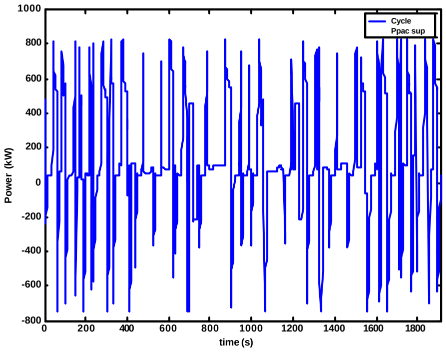

Fig 12. Final SSE power reference

The FC references are shown on figure 13:

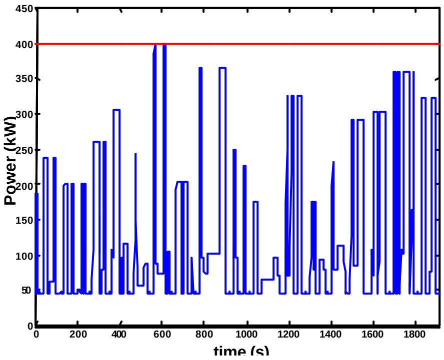

Fig 13. Final FCS power reference

Providing these 2 references to the converters allow to provide the power demand and to use the Fuel Cell and the Supercaps in there limits, to absorb all braking energy and to reduce hydrogen consumption.

5. CONCLUSIONS

A simplified Fuel Cell model is established to have an accurate voltage behavior without prohibitive simulation time. The model is based on physical main phenomena in the different controlled loops which compose the Fuel Cell System. Using fuel cell and supercaps as energy sources an algorithm computes the two references to manage the energy on board to follow an actual power demand. The algorithm used consists in defining in a first step the superior reference of the fuel cell to have an effective braking energy recovery. Adjustment of the fuel cell power minimum reference is computed to have not only the respect on the limits established but also to choose the reference providing the less hydrogen consumption. This algorithm computes all possible references (during 5hours) and with losses and efficiency estimation of all components an effective solution is found on a given profile. The most critical constraint seems to be the state of charge of the energy storage element. The constraints are to absorb all energy and to let it 100% loaded at the beginning and at the end of a profile. Using the proposed method on different profiles provides different sizes of Supercaps depending on the profile. The model is close to a real fuel cell, some experiments must be made with a 400kW to verify the accuracy on a real experimental setup build by our partner (Alstom).

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