Design and Simulation of a Fuel Cell Hybrid Electricity Generating Unit

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Abstract **– The authors are interested in the realisation of the function "electricity generator" starting from a PEM fuel cell. As they show it, reflections and methodologies proposed in this paper are applicable to numerous applications different from the considered system. Their aim is to develop a low power electricity generating unit structured around a 200W PEM fuel cell (energy source) and ultracapacitors (power source) delivering a standardised single-phase voltage. Firstly, the authors describe the properties of a PEM fuel cell : its operation principle, its technology and its implementation, its dimensioning and its electrical use. Secondly, they present the design, the energy management and the simulation of the studied electricity generating unit. An original control of the fuel cell voltage is proposed.**

1. Introduction

The new energy situation results from environmental, economical, political and technological factors. In addition to the quasi inexorable long-term rarefaction (about a hundred years) of fossil energies, humanity must manage in the medium term the impact of those on the climatic evolution of our planet. Many solutions are considered to exploit other unfailing resources: wind power, sun radiation, water power, biomass, water (hydrogen synthesis by electrolysis), oxygen (of the air)… For a rational use of these resources, two energy vectors are possible: electricity and hydrogen.

The fuel cell will play probably an important part in this context. Its principle consists in making react hydrogen and oxygen to produce water, electricity and heat. Its theoretical energy efficiency is very high (particularly in the case of co-generation) and it generates no polluting emissions (water production, quiet operation). Nevertheless, its development requires important efforts, especially for the hydrogen storage.

In this paper, the authors are interested in electricity generation starting from fuel cells for mobile and autonomous systems (portable applications, transportable applications, transports…). The heat released by the fuel cell is not exploited in the proposed application.

The most generic architecture of an electricity generator is the hybridisation of an electric energy source and an electric power source (Fig. 1). *An electric energy source* can deliver, by definition, an electric power over one duration comparable with that of the typical system missions. *An electric power source* can deliver, by definition, an electric power over one short duration compared with that of the typical system missions. These two concepts are closely bound and have a significance only presented simultaneously and comparatively.

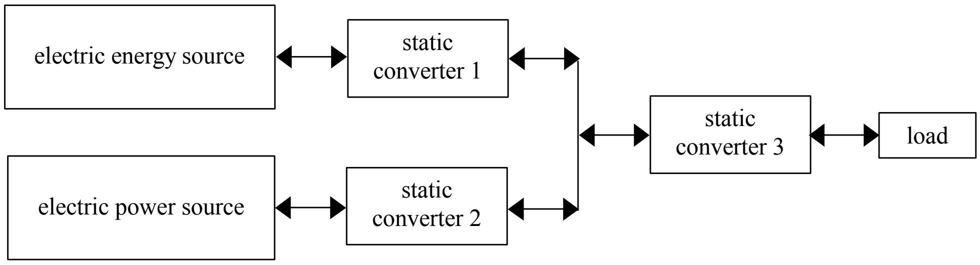


Fig. 1 Generic architecture of an electricity generating unit

The electric energy source can be seen like the main electricity generator. It is typically dimensioned to deliver a power of value equal to that of the mean power necessary to achieve the typical system missions. Among the energy sources, we can quote: the fuel cell associated with its fuel (hydrogen) and its combustive (oxygen), the solar generator associated with solar energy, the wind generator associated with wind energy, the accumulator (acid-lead, Li-ions…)…

The electric power source can be seen like the secondary electricity generator. The direct corollary of its definition is its necessarily rechargeable character in order to be usable punctually throughout a mission. It is consequently a storage device like an accumulator, an ultracapacitor, an inertia wheel...

The hybridisation rate is delicate to define because it will be very strongly related to the typical system missions. It will be a function of impacts of the events (occasional, repetitive…) occurring during these missions in terms of amplitude (required powers) and of duration. Nevertheless, general objectives of hybridisation can be listed:

- to smooth the power delivered by the electric energy source.

For example, the absorption of the random positive or negative power peaks required by the load (acceleration or braking phases of electric vehicles…). In other words, the system has to be able to punctually deliver powers higher than the mean power of the electricity generator or to recover energy to recharge the electric power source.

- to replace the electric energy source for one limited duration because of its partial or total unavailability.

For example, starting of a fuel cell, sun masked by clouds in the case of a photovoltaic generator…

One of the useful tools to dimension this hybridisation is the Ragone plane which makes it possible to compare the energy and power mass densities of various electric sources (Fig. 2).

Hybridisation objectives make necessary the definition of *energy management strategies* which will be implemented thanks to static converters (Fig. 1). The configuration with three static converters is the most general. This configuration is not systematically necessary, but offers the greatest flexibility and richness to control the power delivered by each source and to supply the load in a transparent way for the user.

The function "electricity generator" presents a general character illustrated in this introduction. Methodologies suggested in this paper are thus applicable to numerous applications different from the considered system by the authors. Their aim is to develop a low power electricity generating unit structured around a 200W PEM fuel cell (energy source) and ultracapacitors (power source) delivering a standardised single-phase voltage.

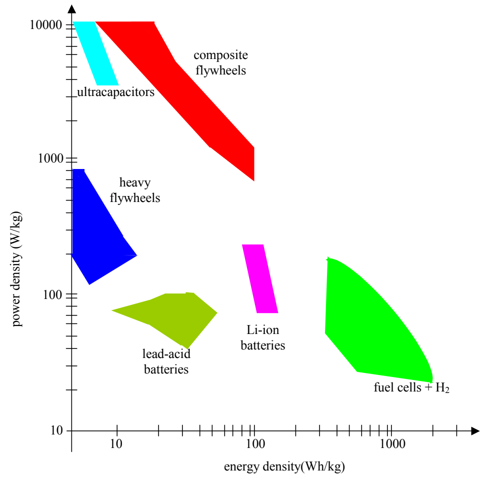


Fig. 2 Ragone plane with some electricity sources

Firstly, the authors describe the properties of a PEM fuel cell : its operation principle, its technology and its implementation, its dimensioning and its electrical use. Secondly, they present the design, the energy management and the simulation of the studied electricity generating unit. An original control of the fuel cell voltage is proposed.

2. PEM fuel cell properties

2.1 Operation principle

The operation principle of a PEM (Proton Exchange Membrane) consists in making react hydrogen and oxygen to produce water, electricity and heat. It is an oxidation-reduction reaction in the presence of platinum, opposite of the water electrolysis reaction:

$$2H_2 \rightarrow 4H^+ + 4e^- \text{ (anode)} \quad (1)$$

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \text{ (cathode)} \quad (2)$$

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + electricity + heat \text{ (total reaction)} \quad (3)$$

2.2 Elements of technology : constitution and implementation

A PEM fuel cell consists of a stacking in series of elementary cells (Fig. 3). Each cell comprises two electrodes (anode and cathode) separated by an electrolyte which is electronic insulator and ionic conductor [2].

Bipolar plates

Except for the terminal cells, the cells within a stack are interconnected using bipolar plates (typical thickness of one centimetre) allowing an important compactness. The bipolar plate functions are in fact multiple: 1) electric connection between two juxtaposed cells (the electric connection with the external circuit is ensured by the terminal plates) - 2) boundary between two juxtaposed cells (mechanical resistance, separation of the reagents) - 3) gas channels on two faces: O_2 for the cathode of a cell, H_2 for the anode of the juxtaposed cell (it justifies the name "bipolar plate") - 4) excess gas and produced water emptying - 5) bond with the heat exchangers (temperature control, co-generation).

The requirements are high for the constitutive material of these bipolar plates: 1) to be good electronic conductor - 2) to be chemically inert - 3) to be impermeable for hydrogen and oxygen - 4) to be good thermal conductor to evacuate the reaction heat - 5) to be enough friable to allow the creation of complex gas channels - 6) to be mechanically rigid.

To date, only graphite answers all these criteria with an economically viable realisation. But the cost remains rather high.

Electrodes

The electrodes have a typical thickness of a few hundreds of micrometers (400µm). To make possible the water synthesis, the protons (in solution in water), oxygen (gas in solution in water) and platinum (solid catalyst) must simultaneously be present on the reaction site: it is called the "triple contact point" (gas, electrolyte, catalyst). To be in favour of the creation of the triple contact point, the electrodes must have the following characteristics: 1) to be porous to allow the gas diffusion to the reaction sites. They are generally in carbon felt or carbon paper - 2) to be impregnated of catalyst (paste with platinised carbon) and of membrane particles. The creation of this triple contact point is a major difficulty for the PEM fuel cell design if one wants to minimise the platinum quantity and thus the stack price (let us recall that platinum is a noble metal!).

Moreover, the electrodes must have other characteristics: 3) to present a hydrophobic character to facilitate the water emptying. The PTFE (Teflon) material is generally added. - 4) to be good electronic conductor (electron collection and conduction towards the bipolar plates) - 5) to be flexible to increase the contact surface with the electrolyte.

Electrolyte

The electrolyte is a solid membrane with a typical thickness of a hundred micrometers (100µm). This membrane must have the following properties: 1) to be good ionic conductor - 2) to be good electronic insulator - 3) to be impermeable for hydrogen and oxygen - 4) to have a good mechanical resistance for thermal and hydration stresses.

Let us recall that if this membrane were permeable or had suddenly broken, hydrogen and oxygen would be directly put in contact; they could then react always to form water, but this time, with an explosive character!

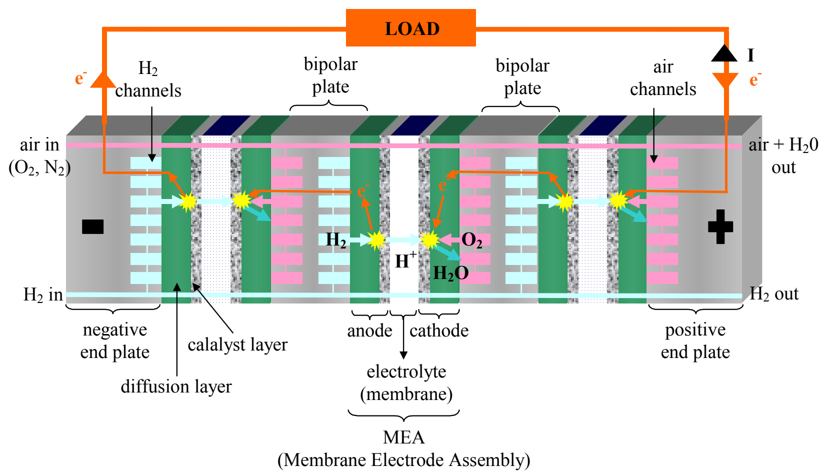


Fig. 3 PEM fuel cell fed by hydrogen and air (stack of 3 cells in series electrically ; parallel gas supplies)

The membrane conductivity depends primarily on its temperature and its hydration rate. This last point makes particularly difficult the PEM fuel cell implementation. The membrane materials are Nafion, Dow, Aciplex, Gore... To date, Nafion is the most used but it imposes a fine hydration management. The PEM Nafion fuel cell operation towards 80°C is justified by a good ionic conductivity of Nafion at this temperature. Let us notice that this aspect is in fact in contradiction with the thermodynamics which would impose a low temperature operation to obtain a better thermodynamic efficiency [2]. It is thus there about a compromise.

Management of a PEM fuel cell

The PEM fuel cell control remains delicate and complex (Fig. 4). It is necessary to control its operation point and to guarantee the stack integrity. The gas pressure and temperature control makes it possible to optimise the efficiency and the delivered power, but also to avoid membrane ruptures and the thermal runaway of the stack. It is imperative not to exceed a certain pressure difference between the anode and cathode in order not to destroy mechanically the membrane (ΔP typically lower than 1 bar). Moreover, the use of oxygen from the ambient air imposes generally the use of a compressor which consumes a significant part (higher than 10%!) of energy provided by the fuel cell.

To guarantee good performances, it is necessary moreover to control the membrane hydration and the produced water emptying (risk of flooding). The water management is a particularly delicate point in the PEM fuel cell. This difficulty is increased because water is mainly produced in liquid form. It is necessary to make purging sequences to avoid the formation of clogs in the gas channels. Moreover the membrane hydration have to be controlled in order not to dry it (risk of rupture) and to have a good ionic conductivity. The two main strategies consist in either humidifying gases at the gas channel inputs (simplicity but difficulty to hydrate all the membranes), or to use a specific water circulation circuit to supply each membrane (can be used to control the stack temperature, but delicate to implement).

The produced heat extraction is not easy because of the weak temperature difference between the ambient air and the stack (ΔT typically of 50°C). Several solutions are possible: natural evacuation (insufficient), cooling by a specific water circulation circuit (circuit which can be also used to hydrate the membranes and/or to preheat the fuel cell), fan cooling or cooling by an internal air circulation circuit. After its extraction, this heat can be exploited (electricity production, warm water production…).

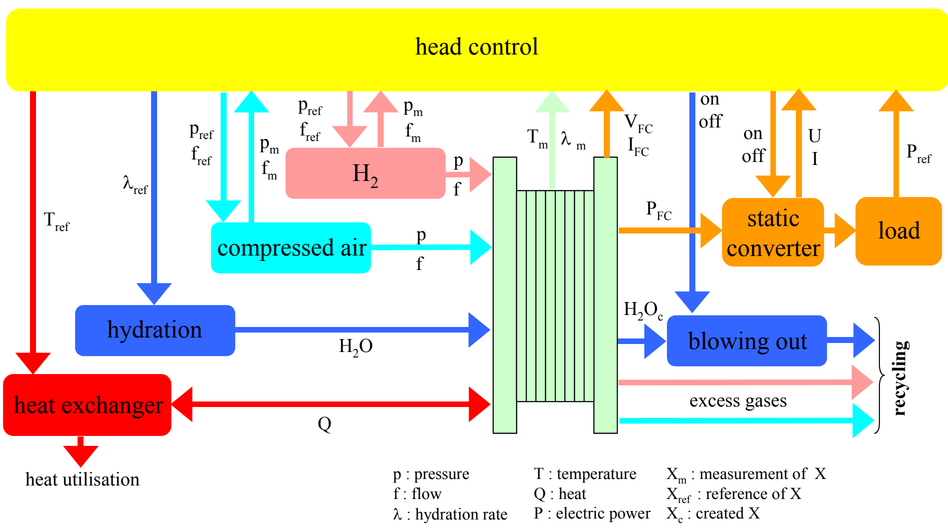


Fig. 4 PEM fuel cell management

In order to optimise the energy consumption, it can be interesting to recycle excess gases (particularly hydrogen) and produced water (membrane hydration, fuel cell cooling).

All the presented solutions are currently tested by the industrialists and it is difficult to foresee which technology will be essential.

2.3 Elements of dimensioning

To dimension the PEM fuel cell hart corresponding to the specifications of a given project, the electrical engineer has two degrees of freedom: the number N of elementary cells put in series which fixes the stack voltage and the surface S of each elementary cell which fixes the stack current. The technological limits are currently: $N \leq 100$; current density $\leq 1A/cm^2$ (typically $0{,}6A/cm^2$) ; $S \leq 750cm^2$. The typical nominal characteristics of a cell are: nominal cell voltage of 0,7V and (practical) open circuit cell voltage of 1V.

2.4 Main physicochemical phenomena to model

E_{th} is the theoretical thermodynamic potential which represents the chemical energy conversion into electric energy; it is a function of the temperature and the pressure:

$$E_{th} = E^0 + \frac{RT}{nF} ln\left[\left(P_{O_2}\right)^{\frac{1}{2}} P_{H_2}\right] \quad (4)$$

$$E^0 = -\frac{G^0}{nF} \quad (5)$$

$$\Delta G^0 = \Delta H^0 - T\Delta S^0 \quad (6)$$

In practice, this theoretical potential (1.23V) is never reached because of losses. Indeed, there are voltage drops (that the electrochimists often call "overvoltages") due to the activation and concentration (or diffusion) phenomena and the ohmic losses:

$$E = E_{th} - \eta_{act,a} - \eta_{act,c} - \eta_{conc,a} - \eta_{conc,c} - \eta_{membrane} \quad \text{(a = anode ; c = cathode)} \quad (7)$$

The activation "overvoltages" translate in a simplified way the chemical reaction kinetics laws. The concentration "overvoltages" are the consequence of the dissolved gas transport from the water surface to the reaction site in the electrode. The ohmic losses are mainly localised in the membranes (the other ohmic losses from the electrodes and from the bipolar plates are generally included in these losses).

Another important phenomenon which will influence the fuel cell dynamics is the double layer capacitor C_{dl}. It is physically present at the interface electrode/electrolyte (Fig. 6). No charge carrier transfer exists in theory at this interface. The distance between the species being very weak, this capacitor has a great value (several hundreds of mF).

On Fig. 5 is shown the static characteristic V-I of the LEEI's PEM fuel cell (Fig. 10). The various loss phenomena in a PEM fuel cell are presented by preponderance zones. The typical use zone of a fuel cell is the "ohmic losses" zone. The "concentration losses" zone will be systematically avoided. On Fig. 5 is also traced the fuel cell power evolution according to the current. This power presents a maximum value which it is not recommended to seek to reach because this point is at the limit of the strong instability zone.

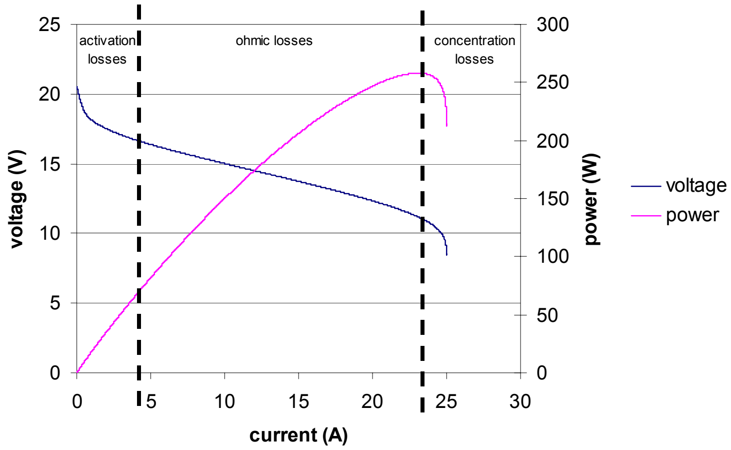


Fig. 5 Steady state V-I and P-I characteristics (simulation with P=2bars ; T=60°C ; hydration factor = 10)

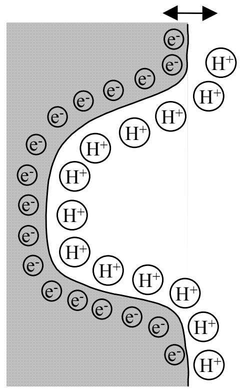


Fig. 6 Double layer capacitor

In conclusion, the fuel cell is concerned by many fields of physics: chemical, hydraulic, thermal and electric phenomena. Its modelling is thus not easy. The authors proposed a fuel cell modelling in [5][6] using the Bond Graphs [8] allowing an unified representation of the laws of the various fields of physics. Only the hydraulic part was not modelled. The model parameters were identified on the LEEI's PEM fuel cell [4][7] presented in the paragraph 3.1. It is this Bond Graph modelling which was used for all simulations in this paper.

2.5 Steady state operation modes of a fuel cell: voltage source, current source, other

By analysing the fuel cell static characteristic, it is difficult to conclude on its nature: voltage source? Current source? Other? The reflections at the LEEI lead the authors to affirm that the fuel cell can be used in three operation modes which they will describe.

Operation with the load power

The fuel cell naturally operates with the required load power when one does not impose its voltage or its current to it. The load power fixes its operation point (Fig. 7). We will notice that two operation points are a priori possible, but only a point will be stable: that with weak current. For example, a fuel cell operates in this mode if it is followed by a boost converter.

Current source operation

The "current source operation" can be imposed by connecting a voltage source at the fuel cell terminals. This voltage source can be implemented, for example, by the association of a storage device, a DC/DC static converter and a capacitor directly connected at the fuel cell terminals. It is then possible to directly control the fuel cell operation point by controlling the the DC bus voltage.

Voltage source operation

The "voltage source operation" can be imposed by connecting a current source with the fuel cell (Fig. 9). For example, by associating a storage device, a DC/DC static converter and an inductance, it is possible to control the DC bus current making it possible to force the fuel cell operation point.

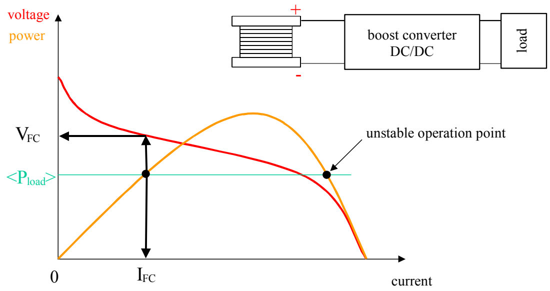


Fig. 7 Example of "operation with the load power" of a fuel cell

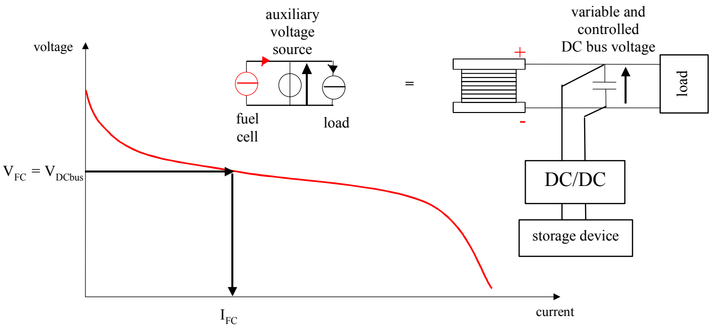


Fig. 8 Example of "current source operation" of a fuel cell

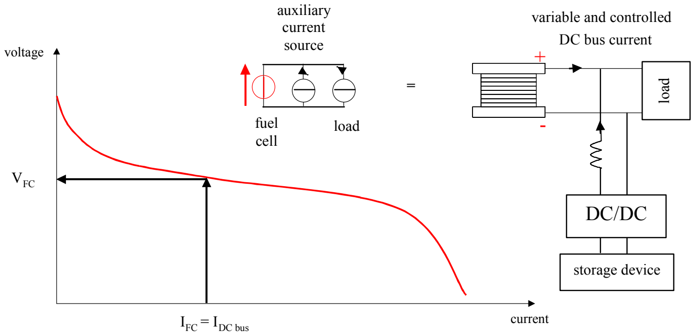


Fig. 9 Example of "voltage source operation" of a fuel cell

3. Design and simulation of an electricity generating unit based on a 200W PEM fuel cell

3.1. Objectives

The LEEI has got a 200W PEM fuel cell (Fig. 10). It consists of 20 cells (50cm²; 0,3A/cm²) in series. The bipolar plates are in graphite and the membranes in Nafion.

Fig. 10 200W PEM fuel cell

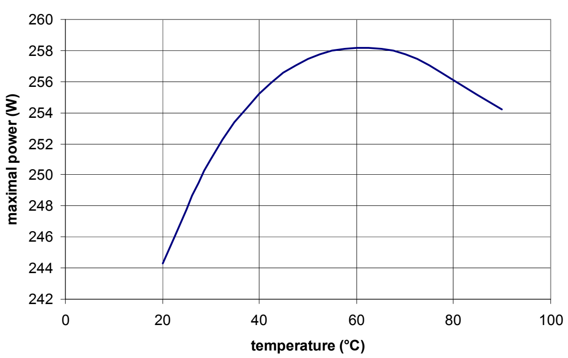
Currently, this PEM fuel cell is supplied by hydrogen and oxygen. The membrane hydration is ensured by an input gas hydration. The fuel cell cooling is carried out by two fans under it (plexiglass box). The produced water emptying is made by gravity (slope of 30°) and by gas circulation. There are no recycling of excess gases and produced water and no exploitation of the produced heat. This implementation is not realistic within an industrial framework, but it is not the current objective. For the moment, the objective is to well control the fuel cell and to couple it with a storage device as in this paper.

In order to exploit their fuel cell within a realistic framework, the authors imagined to carry out a low power Electricity Generating Unit (EGU) delivering a standardised single-phase voltage. Their specifications are thus:

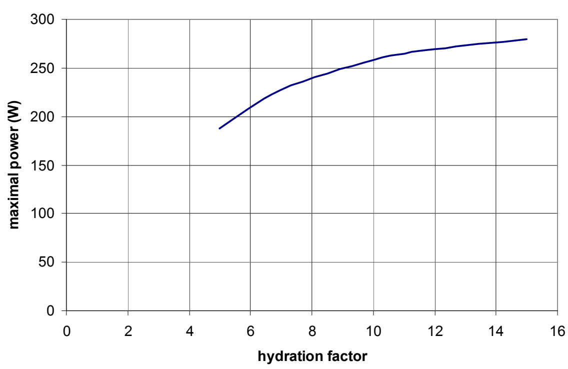
- nominal EGU power: 200W
- nominal load voltage: single-phase voltage 127Veff / 50Hz
- open circuit fuel cell voltage: 19V
- nominal fuel cell voltage: 13V
- nominal fuel cell current: 15A
- maximal load voltage ripple : 5%
- maximal inductor current ripple : 10%
- switching frequency : 20kHz.

The difficulty is to fix a maximum transient power in order to dimension the storage device which the authors want to associate with their fuel cell. If one considers the example of low power electricity generating units commercialised to supply loads like freezers or pumps, it is necessary to deliver during the start-up a transient power equal to about 3 to 4 times the nominal power. The electricity generating units with diesel motors, dominant technology (98%) in this power range and applications, are oversized to allow such start-up. It is the order of magnitude which is retained for the specifications: 800W transitorily, that means a transient current equal to 4 times the nominal current.

In addition to this transient need for load power, it is necessary to specify that during the start-up of the PEM fuel cell, the full power is not available by the combination of two phenomena: the PEM fuel cell must go up in temperature (to reach 60-70°C) and it must be hydrated (to reach a hydration factor between 10 and 14). The evolution of the maximum power (operation point not recommended to reach in practice) delivered by the fuel cell according to these two phenomena was simulated using our Bond Graph modelling and is illustrated on the Fig. 11. For these reasons, a storage device is also to dimension if one wishes to have the nominal power from the electricity generating unit start-up.



maximal power versus temperature
[P=2bars ; hydration factor (=10) independent of temperature]



maximal power versus hydration factor
[P=2bars ; T=60°C ; hydration factor independent of temperature]

Fig. 11 Maximal power evolution of a 200W PEM fuel cell during a start-up

3.2 Electrical architecture of the PEM fuel cell hybrid system

Among the numerous solutions and those which the authors studied, the solution proposed on Fig. 12 was chosen for this paper because of its very original character:

- the fuel cell operates in the current source mode (paragraph 2.5); its voltage is controlled by a DC bus whose voltage is controlled.
- the inverter stage DC/AC is not traditional ; this is a boost inverter whose operation is described in the following paragraph.
- the storage device are ultracapacitors [12] in series, constraining a specific energy management because their voltage varies with their state of charge. Their energy is formatted by means of a traditional DC/DC reversible current boost converter.

In this paper, the authors model the ultracapacitors in series like a single equivalent capacitor with a resistor in series. The necessary voltage balance system [13] is not taken into account.

3.3 The boost inverter

The boost inverter [9][11][12] makes it possible to transform in a single step a DC voltage into an amplified alternating voltage. This is in fact an original use of the DC/DC current reversible boost converter. The single-phase boost inverter exploits the properties of the differential connection. Each of the two inverter legs delivers a voltage with a DC component (at least equal to the DC bus voltage) plus a sinusoidal component:

$$V_{C1}(t) = V_{DC} + V_{max} \sin \omega t \tag{8}$$

$$V_{C2}(t) = V_{DC} - V_{max} \sin \omega t \tag{9}$$

The two sinusoidal components being in phase opposition, one obtains by differentiation:

$$V_{load}(t) = V_{C1}(t) - V_{C2}(t) = 2V_{max} \sin \omega t \tag{10}$$

Concerning the control strategy, this topology has a double requirement which consists in controlling the inductor currents and the capacitor voltages.

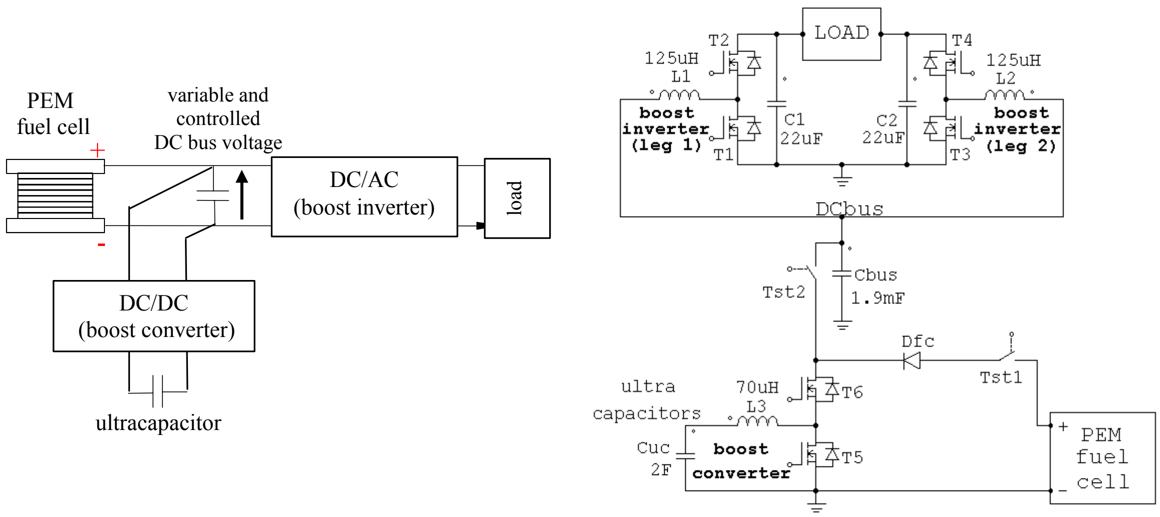
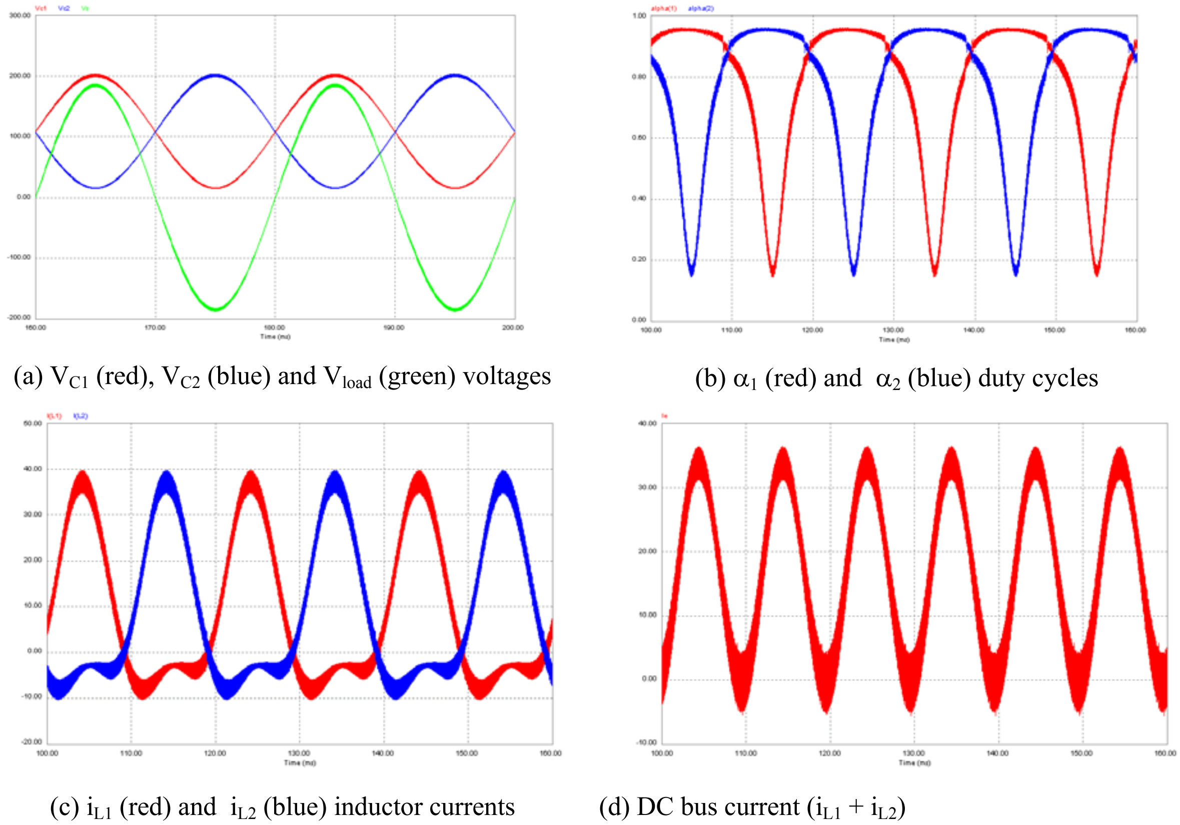


Fig. 12 Electrical architecture of the electricity generating unit



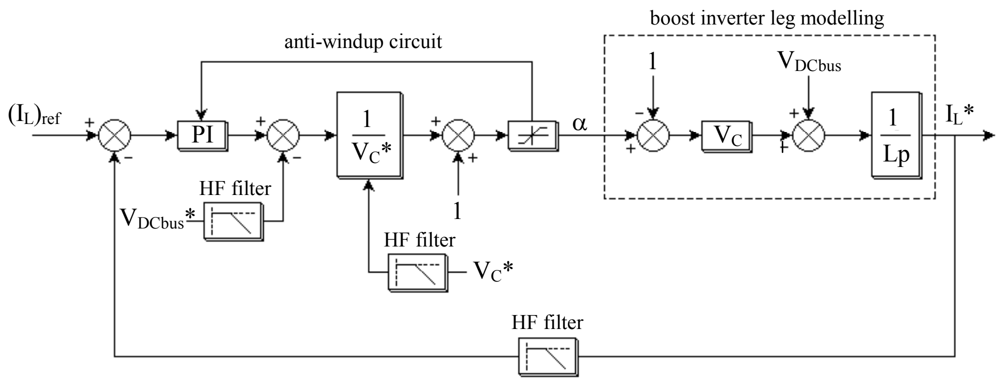
(a) V_{C1} (red), V_{C2} (blue) and V_{load} (green) voltages

(b) α_1 (red) and α_2 (blue) duty cycles

(c) i_{L1} (red) and i_{L2} (blue) inductor currents

(d) DC bus current ($i_{L1} + i_{L2}$)

Fig. 13 Nominal waveforms of the inverter boost (resistive load)



* = measured ; PI = proportionel-integral controller ; α = duty cycle ; HF = high frequency ; p = Laplace's variable = jω

Fig. 14 Inner inductor current control loop for one boost inverter leg

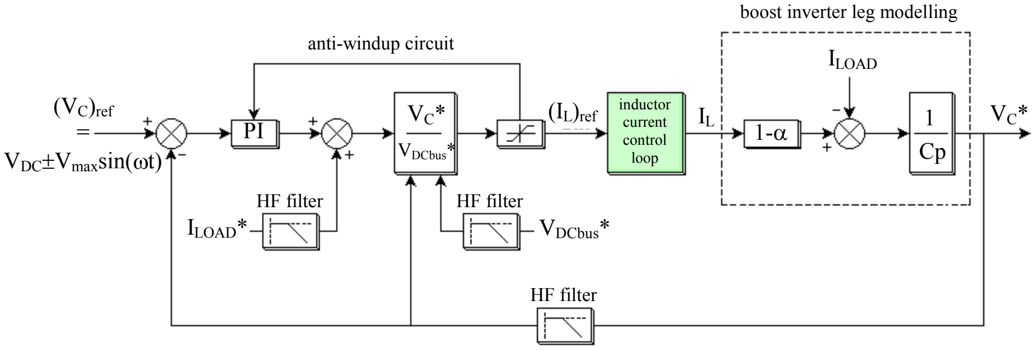


Fig. 15 Outer capacitor voltage control loop for one boost inverter leg

The authors chose [10] a control strategy with two imbricated loops and with total compensation of non-linearities (Fig. 14 et Fig. 15). A fast mode corresponding to the inductor current (inner loop) and a slow mode corresponding to the capacitor voltage (outer loop) can be defined for each inverter leg. A PWM strategy is used in order to have a fixed switching frequency.

3.4 Energy management

The authors propose an original fuel cell piloting strategy by imposing its operation voltage by means of a DC bus whose voltage is controlled (Fig. 12). The DC bus is in fact the output capacitor of a DC-DC boost converter having for input source the ultracapacitors in series. This converter is current reversible to allow the ultracapacitor recharge.

If one considers the definitions presented in the introduction, the fuel cell associated with its oxygen and hydrogen tanks constitutes the energy source of the EGU and the ultracapacitors the power source. The role of this power source is double:

- to smooth (start-up, load steps…) the power of the fuel cell which will have to deliver the required mean load power. Because of a single-phase operation, it is necessary to supply the fluctuating power in steady state. The authors propose that the power source supplies it more especially as the fuel cell is non current reversible.
- to compensate for a temporary unavailability of the full fuel cell power during its start-up (Fig. 11) or during a temporary sequence of flooding of one or several cells.

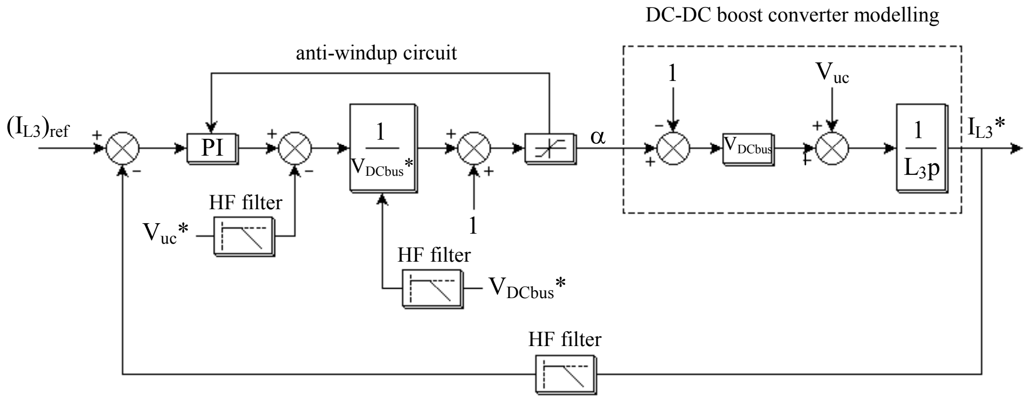


Fig. 16 Inner inductor current control loop for the DC-DC boost converter

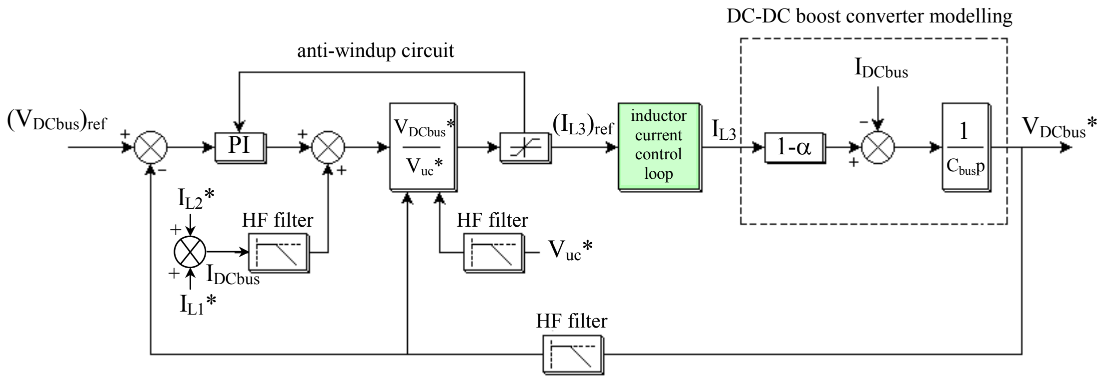


Fig. 17 Outer DC bus voltage control loop for the DC-DC boost converter

All the EGU energy management will be thus ensured by the piloting of the DC-DC boost converter. This piloting is naturally close to that used for the boost inverter. The authors still chose a control strategy with two imbricated loops and with total compensation of non-linearities (Fig. 16 et Fig. 17).

The problem is finally to define the reference $(V_{DCbus})_{ref}$ for the DC bus voltage control loop of the DC-DC boost converter. The fuel cell must provide the required mean load power in the proposed strategy ($\langle P_{FC} \rangle = \langle P_{LOAD} \rangle$). This mean load power is calculated over several load voltage periods. A mean power control is thus implemented and will define the reference $(V_{DCbus})_{ref}$ (Fig. 18).

It is necessary to associate with this mean power control an ultracapacitor energy control (Fig. 18) for two reasons:

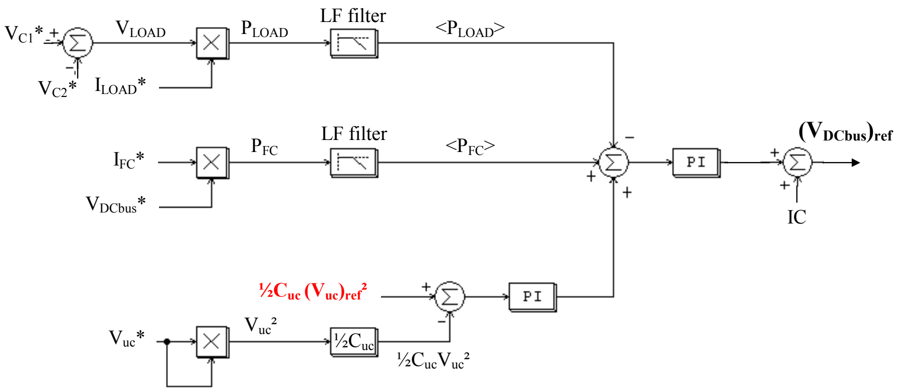
- to force the fuel cell to supply the system losses
- to allow the ultracapacitor recharge following a power transient.

In the case of a constant load power operation (constant load), the mean power control would be sufficient if there were no loss in the system. Indeed, with this only mean power control, the system losses are compensated only by the storage device and cause its discharge as that is illustrated on Fig. 19 (a). Before t =3.2s, the simulated system is ideal (without losses) and the mean power control operates very well. After t =3.2s, the system is not ideal any more (losses) and the storage device quickly discharges.

Thanks to the ultracapacitor energy control, their voltage will remain constant as the simulation presented on Fig. 19 (b) shows it. The simulation starts without the ultracapacitor energy control. It starts only after one second. The mean losses are well supplied by the fuel cell (<P_{FC}> higher than <P_{LOAD}>).

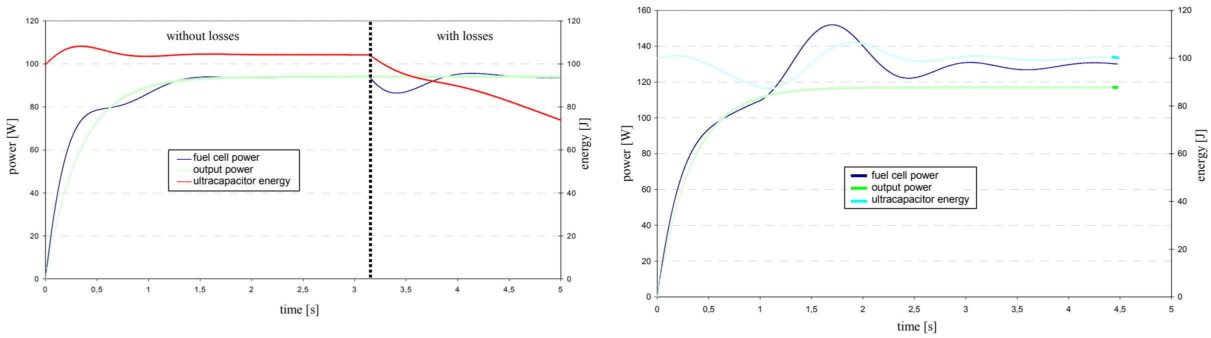
The most delicate problem to solve remains the choice of the time-constants of the various control loops concerned in the energy management (Fig. 18). Indeed, the controlled quantities are not linear. The oscillations (Fig. 19 (b)) are due to the choice of regulators to have faster simulations.

The storage device must smooth the electric fuel cell power on the one hand, by supplying the fluctuating power (single-phase operation), on the other hand, by absorbing the required load power transients. Simulations on Fig. 21 et Fig. 20 make it possible to check these two points simultaneously. It should be noted that they were not carried out for the nominal load voltage.



* = measured ; PI = proportional-integral controller ; <> = mean value ; FC = fuel cell ; LF = low frequency ; IC = initial condition

Fig. 18 Energy management



(a) without loss compensation (b) with loss compensation

Fig. 19 Simulation of the mean power control strategy

Before t = 2,5s (Fig. 20) is illustrated the effectiveness of the active filtering of the fluctuating power. The fuel cell delivers a current equal to the mean value of the DC bus current and whose ripple is weak (<10%). The ultracapacitors supply the 2ω fluctuating current.

At t = 2,5s a load step is caused during 50ms. The required transient load power is 235W whereas the mean power that it consumes before and after the step is 95W. The Fig. 20 illustrates the very good operation of the mean power control: the transient current is supplied by the storage device, the 2ω fluctuating current too. The fuel cell, as for it, changes very little its operation point. On Fig. 21, even if the load power peak does not clearly appear (filtered quantities), there is well a transient load power of 235W as that is confirmed on the Fig. 20 by making the product of the load voltage by the load current.

After t = 2,55s, the ultracapacitor energy, supplied to the load during the short transient, is recovered thanks to the ultracapacitor energy control (Fig. 21). The fuel cell supplies this energy necessary to their recharge.

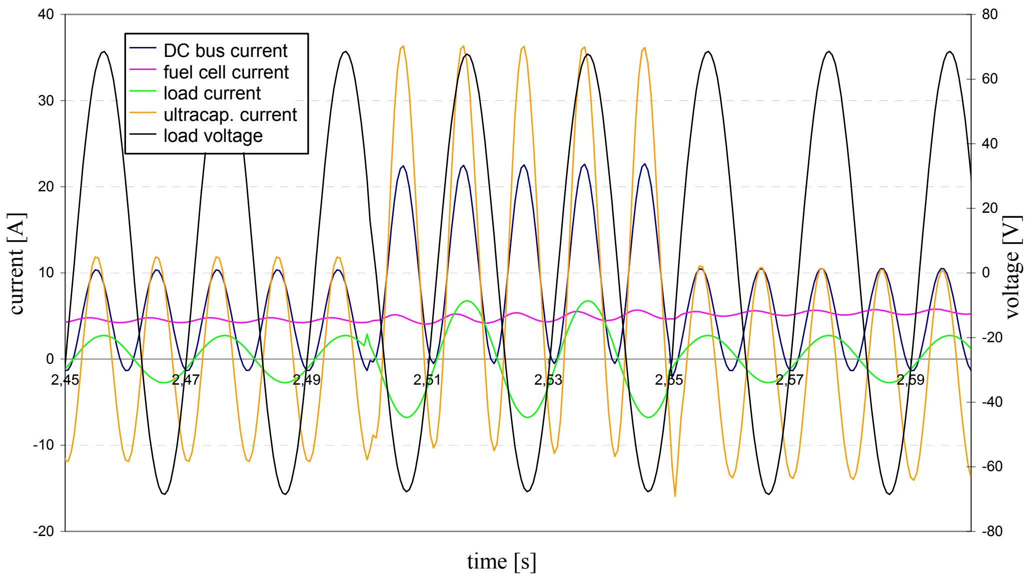


Fig. 20 Simulation of a load step from 95W to 235W during 50ms – Currents and voltage

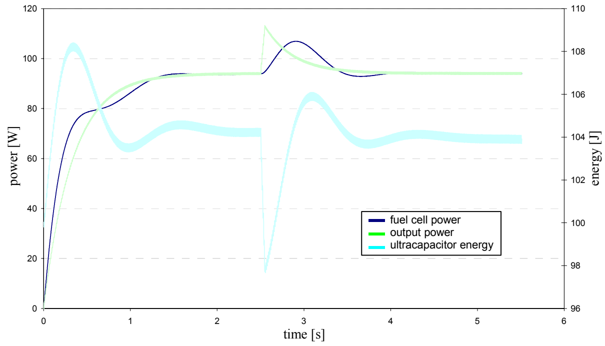


Fig. 21 Simulation of a load step from 95W to 235W during 50ms – Filtered powers and energy

3.5 System start-up and stop

The system start-up is allowed thanks to the presence of the diode D_{FC} and the contactors T_{st1} and T_{st2} (Fig. 12). The load being null, the start-up procedure is the following one: 1) to open T_{st2} - 2) to close T_{st1} - 3) to start the fuel cell - 4) to pre-charge the ultracapacitors until their reference energy using the fuel cell (at constant current) - 5) to open T_{st1} - 6) to close T_{st2} - 7) to pre-charge the DC bus up to a voltage value slightly higher than the fuel cell open circuit voltage so that the diode D_{FC} is off - 8) to close T_{st1}.

The fuel cell supplies no power because the diode D_{FC} is off, but the system is ready to operate. The presence of this diode makes it possible moreover to protect the fuel cell against the negative currents.

The system stop procedure is the following one: 1) to charge the DC bus up to a voltage value slightly higher than the fuel cell open circuit voltage so that the diode D_{FC} is off. The fuel cell cannot deliver power any more - 2) to open T_{st1} - 3) to stop the fuel cell - 4) to open T_{st2} - 5) the DC bus capacitor and the ultracapacitors are discharged thanks to great value resistors.

4. Conclusion

The most important point for the authors of this paper is incontestably the very original voltage piloting of the fuel cell. This piloting principle is currently experimentally validated confirming its viability.

The proposed architecture for the studied electricity generating unit is original. It imposes the use of nine sensors: 4 not isolated voltage sensors and 5 current sensors. It remains to validate experimentally its operation and particularly the energy management strategy.

Lastly, the authors want to precise that the whole electricity generating unit was modelled and simulated with Bond Graphs (Fig. 22) even if that does not appear clearly in this paper.

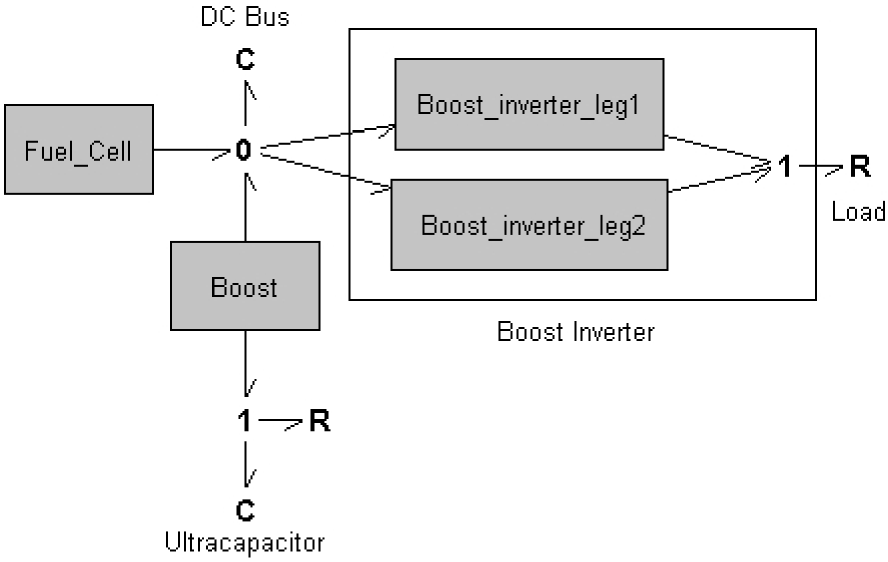


Fig. 22 Bond graph modelling of the electricity generating unit

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