Combining Batteries with Super-capacitors to Store Energy in Fuel Cell Vehicles: a review with suggestions

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***Abstract*— A fuel cell vehicle is primarily an electric vehicle. The motorization is provided by one or more electrical machines and the power is supplied by the fuel cell system. Since the production of electrical energy is carried out without greenhouse gas emissions, a fuel cell vehicle is considered non-polluting (locally). In the context of automobile use, the fuel cell is therefore generally assisted by a secondary source of electrical energy. This type of vehicle is then called a "fuel cell hybrid vehicle".**

Hybridization distributes the power demand between the fuel cell system and the secondary energy source. The operating points of the fuel cell system can thus be shifted to higher yield areas by using appropriate control strategies, thereby reducing hydrogen consumption. The secondary source can be recharged by kinetic energy recovery or by the fuel cell system. In a fuel cell vehicle, two technologies are generally retained to form the secondary source of energy: batteries and super-capacitors. The fuel cell and hydrogen have the highest specific capacity, followed by batteries and super-capacitors. Conversely, super capacitors have the largest specific power, followed by batteries and fuel cells. Both technologies have very different characteristics. Some authors favor the use of super-capacitors because of their energy efficiency and specific power, but their low capacity can be a handicap. Conversely, batteries are able to store a large amount of energy but are penalized by their specific power. One solution is to couple batteries and super-capacitors to combine their advantages (power and energy).

***Keywords*— Fuel Cell Vehicles; Fuel Cell; Secondary source of energy; Battery; Super-capacitors; Specific Power; Specific Energy.**

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I. INTRODUCTION

A fuel cell vehicle is primarily an electric vehicle. The motorization is provided by one or more electrical machines and the power is supplied by the fuel cell system. Since the production of electrical energy is carried out without greenhouse gas emissions, a fuel cell vehicle is considered non-polluting (locally).

A fuel cell is capable of supplying electrical power as long as it is fed with reagents (oxygen and hydrogen). This implies that a fuel cell cannot operate alone and needs a set of peripheral components to function. This battery needs a set of conditions to produce electrical energy [1]: it must be supplied with hydrogen and air, the membrane must be permanently humidified, and the heat produced must be evacuated. The auxiliary components have the role of ensuring the proper functioning of the fuel cell. The fuel cell and ancillary components assembly is called a fuel cell system. In the context of automobile use, the fuel cell is therefore generally assisted by a secondary source of electrical energy. This type of vehicle is then called a "fuel cell hybrid vehicle". The secondary source can be recharged by kinetic energy recovery or by the fuel cell system. In a fuel cell vehicle, two technologies are generally retained to form the secondary source of energy: batteries and super-capacitors.

The fuel cell and hydrogen have the highest specific capacity, followed by batteries and super-capacitors. Conversely, super capacitors have the largest specific power, followed by batteries and fuel cells [2]. Both technologies have very different characteristics. Some authors favor the use of super-capacitors [3] [4] because of their energy efficiency and specific power, but their low capacity can be a handicap. Conversely, batteries are able to store a large amount of energy but are penalized by their specific power. One solution is to couple batteries and super-capacitors to combine their advantages (power and energy) [5] [3] [4].

Fuel cell vehicles without other secondary sources of electrical energy such as General Motors' Hydrogen 3 prototype vehicle [6], we find Honda FCX [7] powered by fuel cells, with super-capacitors as a secondary source of energy, Toyota Highlander FCHV [8] powered by fuel cells and battery type Ni-MH battery as a secondary power source. As it is for a vehicle Nissan X-Trail FCHV [9] depends on battery type Li-ion as a secondary source of energy.

II. FUEL CELL VEHICLES

The fuel cell vehicle Fueled directly with hydrogen, it generates no local air pollution. Fuel cell vehicles combine on the one hand a fuel cell for on-board electricity production and on the other hand an element for storing electrical energy (super-capacitors, batteries, etc.) (See the figure 1). These vehicles have the benefits of electric cars including zero emissions and total independence from oil on the one hand and on the other hand, the advantage of a conventional vehicle namely better autonomy and a possibility of rapid refueling with the use of hydrogen stored in pressure tanks or produced on board. A fuel cell vehicle therefore uses a secondary source of electrical energy that is reversible in power (charging and discharging operation).

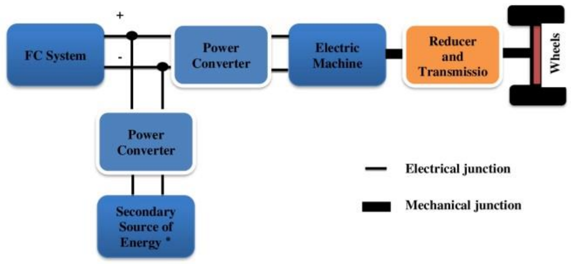


Fig. 1 Fuel cell vehicle architecture.

III. FUEL CELL

Fuel cells are still sources of high current and low voltage. Their rational use in vehicle power trains often involves raising the voltage level by means of suitable static converters. In order to optimize these chains globally, it is also necessary to ask the question of the hybridization of the battery by a buffer device allowing intermediate storage of the power. Indeed, the on-board power source must both provide sufficient energy to ensure the autonomy of the vehicle and deliver significant power during transient phases, corresponding to acceleration or a slope crossing. The source must therefore meet these two different needs, while respecting acceptable mass and volume criteria. One solution is to decoupling energy source / power source. Components with appropriate characteristics are then associated with these two sources: fuel cell generator and buffers such as super-capacitors. Among the different types of fuel cells, the PEM ("Proton Exchange Membrane" type cell, also called PEFC ("Polymer Electrolyte Fuel Cell") (figure 2), is the technology generally used for automobile use.

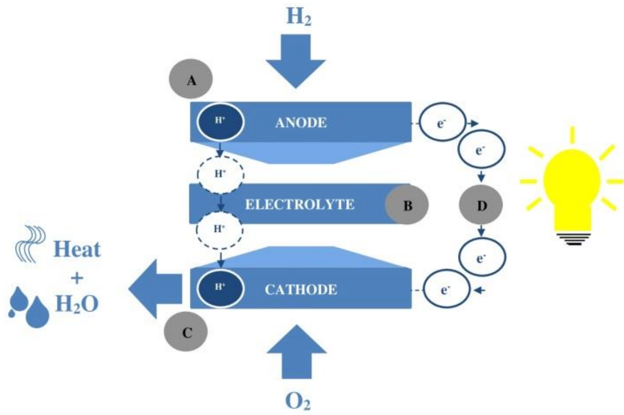


Fig. 2 Principle of operation of a PEM fuel cell.

A single fuel cell is composed of an anode (a negative electrode that generates electrons), an electrolyte in the center, and a cathode (a positive electrode that accepts electrons).

- Anode

As hydrogen flows into the fuel cell anode, a catalyst layer on the anode helps to separate the hydrogen atoms into protons (hydrogen ions) and electrons.

- Electrolyte

The electrolyte in the center allows only the protons to pass through to the cathode side of the fuel cell.

- External Circuit

The electrons cannot pass through the electrolyte and are forced to flow through an external circuit. This electron flow is electricity that can power an electric load.

- Cathode

As oxygen flows into the fuel cell cathode, another catalyst layer helps the oxygen, protons, and electrons combine to produce pure water and heat.

Several reasons explain this choice [10] [11] [12]:

- Density of power:

The propulsion of a vehicle requires a power of a few kilowatts to a hundred kilowatts. In addition, the power train must have an acceptable mass and size. The PEM type is best meets these constraints with a power density of between 1 kg / kW and 3 kg / kW.

- Operating temperature:

The PEM fuel cell has an operating temperature of between 50 ° C and 80 ° C, which is suitable for automotive use.

- Solid structure:

The PEM fuel cell is composed of solid elements (especially the polymer membrane). This solid structure guarantees a certain mechanical resistance with respect to the constraints related to the automotive environment.

IV. SECONDARY SOURCE OF ENERGY

In a fuel cell vehicle, two technologies are generally retained to form the secondary source of energy: batteries and super-capacitors. The main characteristic of the secondary source of energy is that it is reversible in power. The secondary source can be recharged by kinetic energy recovery or by the fuel cell system (Table 1). Within the power train of a fuel cell vehicle (Figure 1), several modes of operation can be identified. These modes of operation (traction, braking and stopping) induce different energy flows; they were illustrating in the following figures: figure 3, figure 4 and figure 5.

- Traction mode

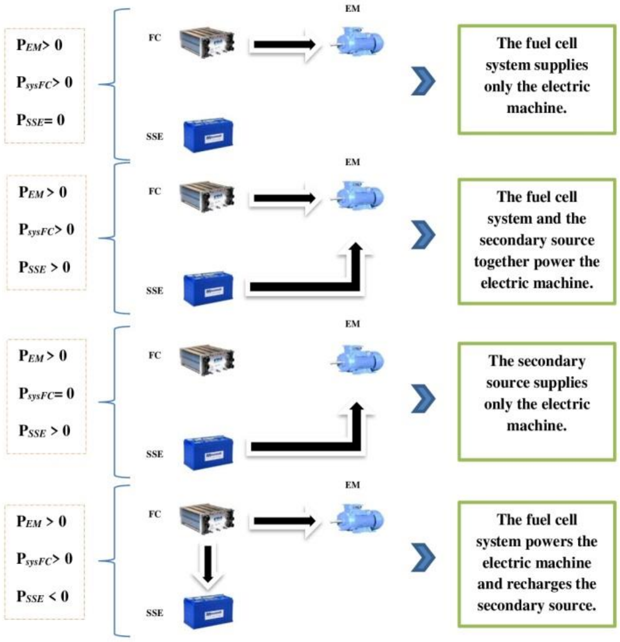


Fig.3 Power flow in the powertrain – Traction mode

- Braking mode

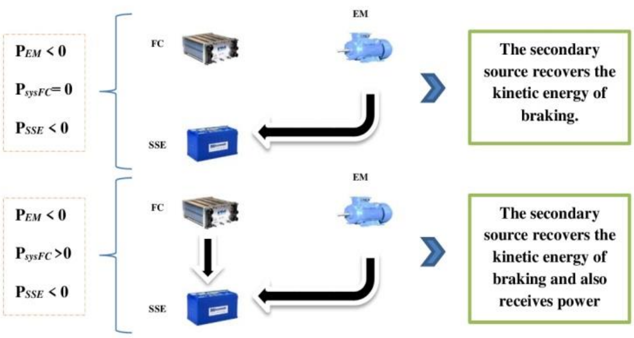
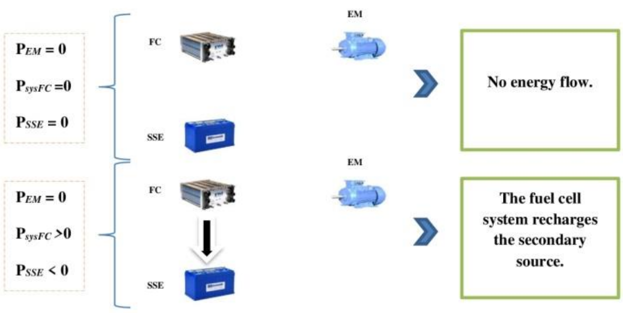


Fig.4 Power flow in the powertrain – Braking mode

- Stop mode



SYSFC: system FC
SSE: Secondary Source of Energy
EM: Electric Machine

Fig.5 Power flow in the powertrain – Stop mode

Where:
P_{EM} : Electric machine power
P_{SYSFC} : Power of the FC system
P_{SSE} : Power of secondary energy source

The roles of secondary source of energy are [13]:

• Power assisting the fuel cell:
The secondary source provides additional power when the fuel cell reaches its maximum power (for example during vehicle acceleration).

• Recover kinetic energy during braking:
The recovery of kinetic energy during braking phases saves hydrogen and increases the vehicle range.

• Introduce a degree of freedom in the distribution of powers:
Hybridization distributes the power demand between the fuel cell system and the secondary energy source. The operating points of the fuel cell system can thus be moved to areas of better efficiency by using appropriate control strategies, which reduces the hydrogen consumption.

A. Super-capacitors

A super-capacitor (or double-layer capacitor) stores the energy electro-statically by polarizing an electrolytic solution. There is no chemical reaction involved, resulting in high lifetimes (a super-capacitor can be charged and discharged hundreds of thousands of times). Super-capacitors have an extremely low specific capacity but have a significant specific power. In addition, their efficiency in charge and discharge is high. In a hybrid application, super-capacitors are intended to satisfy the strong power peaks [14].

B. Batteries

A battery is an electrochemical energy converter that stores energy in a chemical way. In the case of hybrid vehicles, the main technologies used are lead-acid batteries, Nickel Metal Hydride (Ni- MH) batteries and Lithium-ion (Li-ion) batteries [15]. Ni-MH technology is the most popular because it offers good performance in terms of capacity, life and cost. Li-ion technology has a higher specific power (W / kg) and a better specific capacity (Wh / kg), but improvements are still necessary concerning the cost, the safety of operation, the service life and performance at low temperatures. Lead technology suffers from a low specific capacity due to the high weight of the batteries; however, it is a robust technology available at low cost and still benefiting from developments [16].

V. Comparison between batteries and super-capacitor

A fuel cell, a battery and a super-capacitor have extremely different electrical characteristics. The Ragone plan (Figure 6) illustrates the differences in terms of specific powers and specific capacities of different power sources [17]. The fuel cell and hydrogen have the highest specific capacity, followed by batteries and then super-capacitors. In contrast, super-capacitors have the highest specific power, followed by batteries and fuel cells.

One of the challenges in the design of a fuel cell hybrid vehicle is to determine an ideal combination of the fuel cell system and the secondary energy source to satisfy the dynamic performance of the vehicle while ensuring sufficient autonomy.

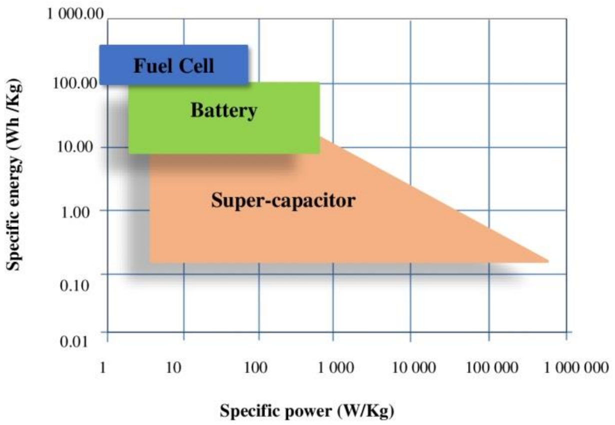


Fig.6 Plan of Ragone [17].

Regarding the fuel cell is an energy converter and not a storage element. The TABLE I summarize the performance of the two storage elements presented above.

TABLE I
COMPARISON BETWEEN BATTERIES AND SUPER-CAPACITOR.

Performances	Storage elements	
	Super-capacitor	Battery
Charging time t	1s < t < 30 s	1 hour < t < 5 hours
Discharge time	1s <t< 30s	0.3 hour < t < 3 hours
Yield (charge / discharge)	Between 85% and 98%	Between 70% and 85%
Power density (W / Kg)	10^4	10^3
Energy density (Wh / Kg)	Between 1 and 10	Between 10 and 100
Lifetime - Number of cycles	10^6	10^3

According to the data of the table above, it is clear that the super-capacitor is potential element combined energy storage as a source of high power demand for a few seconds. Its use in the automotive sector reduces pollution linked to exhaust gases. Studies in this area have shown that the use of super-capacitors in the vehicle can reduce consumption by about **15%**, and up to **20%** that of buses for public transport.

VI. DIMENSIONING OF THE HYBRID POWER SOURCE

The sizing of the power source (fuel cell system and secondary energy source) has an essential impact on both the dynamic performance of the vehicle (driving pleasure) and the hydrogen consumption (vehicle range).It is obviously a function of a specification related to the application. The solutions obtained for this specification can be many and varied (choice of secondary source for example).In this case, to make a choice, one must be sure to have a control strategy that makes the best use of energy exchanges. The choice of components and the control strategy are therefore intimately linked for sizing. Sizing must take into account several aspects:

A. Driving situations and dimensioning:

It is not possible to take into account all possible driving situations. The specifications therefore impose minimum performance for "characteristic" driving conditions. For the special cases of constant speed and constant acceleration of the vehicle (Figure 7), minimum limits can easily be calculated for the energy and power of the secondary energy source:

- Case of the constant speed of the vehicle:

The vehicle must be able to drive at a constant speed V_{const} for an extended period of time (typically on the highway for several tens of minutes), which equates to a constant power demand P_{speed_const} of the engine. Since the secondary power source has a limited amount of power, it cannot provide extended power assistance to the fuel cell system. The fuel cell system must therefore have a maximum power sufficient $P_{sysFCmax}$ to maintain the speed of the vehicle [18] [19] [20] [21].

- Case of acceleration of the vehicle:

The acceleration of the vehicle is characterized by power peaks P_{accel} of limited duration of the engine (a few seconds).The fuel cell system is not always able to ensure the acceleration of the vehicle alone either because its dynamics is limited or because its maximum power $P_{sysFCmax}$ is limited. The missing power P_{accel}- $P_{sysFCmax}$is then supplied by the secondary energy source [21] [19].The hybrid configuration is also particularly interesting to overcome the limit dynamics of the fuel cell system [22] [23].

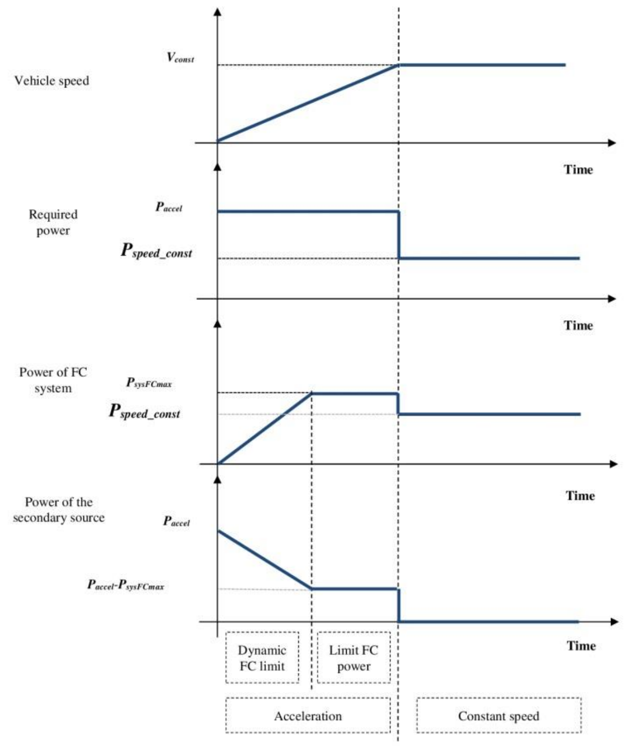


Fig. 7 Example of the powers involved in accelerating and maintaining the speed of the vehicle.

B. *Energy criteria and sizing*

An important part of hydrogen saving is obtained by kinetic energy recovery [24] [19] [25]. The sizing of the secondary source must therefore make it possible to recover as much as possible the braking energy [26] [18] [27]. However, the kinetic energy recoverable and the power demand of the motorization depend on the envisaged use of the vehicle (urban, periurban or highway, mixed...).As a result, the sizing of the power source is specific to a particular application [28] [29] [19].

VII. ENERGY VS. POWER: BATTERY OR SUPER-CAPACITOR?

It is difficult to advocate the use of battery or super-capacitor, the two technologies having very different characteristics. Some authors favor the use of super-capacitors [18] [29] because of their energy efficiency and specific power, but their low capacity can be a handicap. Conversely, batteries are able to store a large amount of energy but are penalized by their specific power. One solution is to couple batteries and super-capacitors to combine their advantages (power and energy) [30] [18] [29], but this inevitably increases the complexity and cost of the secondary energy source. Figure 8 shows the proposed model that combines its advantages (power and energy).

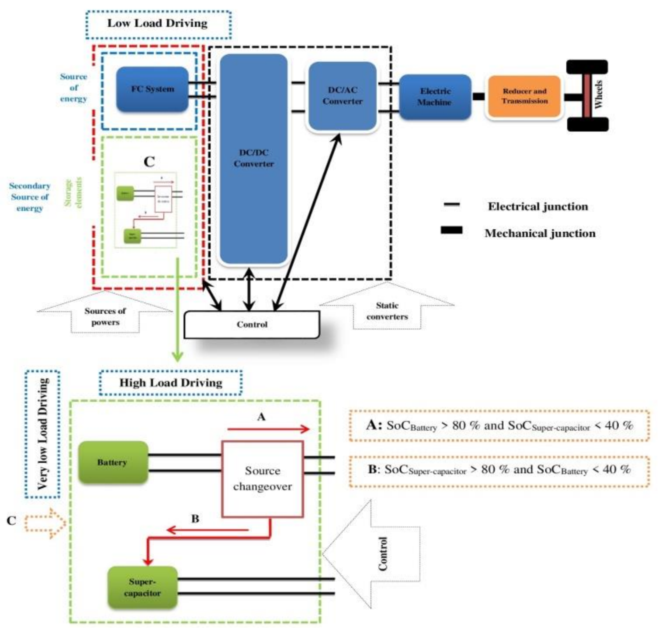


Fig. 8 Fuel cell vehicle architecture proposed (It includes two secondary sources of energy).

In this proposed model, we are working to increase the efficiency of the vehicle was done by using appropriate control strategies where the energy demand is distributed between the fuel cell, battery and super-capacitor, and it is through the following cases:

- Very low load Driving: When starting, the secondary source supplies only the electric machine.
- Low Load Driving: The fuel cell system powers the electric machine and recharges the secondary source.
- High load Driving: The fuel cell system and the secondary source together power the electric machine. In addition, the secondary source of energy consists of a mixture between the battery and the super-capacitor in order to increase the efficiency of the car. The demand for energy is distributing alternately between these two sources according to their ***state of charge*** (SOC).

If the battery charge is more than **80%** and the charge of super-capacitor has less than **40%**, then the fuel cell system and the battery work together to power the electric machine.

If the super-capacitor charge is more than 80% and the charge of battery has less than 40%, then the fuel cell system and the super-capacitor work together to power the electric machine.

VIII. RESULTS AND DISCUSSIONS

The power demand is distributing between the fuel cell system and the secondary power source. The operating points of the fuel cell system can thus be shifted to higher yield areas by using appropriate control strategies, thereby reducing hydrogen consumption. In this study, were combined their power efficiency and the ability to store a large amount of energy. The first is the super capacitors and the second is in the battery. In summary, in the context of automotive use, if there is consensus on the interest of a fuel cell system, the choice of secondary source technology remains open. Lifetime constraints [30] or cost criteria [31] are also involved in the sizing process.

IX. Conclusion

When designing a fuel cell vehicle, the dynamic performance of the vehicle is specified by the specifications. These dynamic constraints make it possible to calculate the limit sizing of the hybrid power source, meaning the minimum powers to the fuel cell system and the minimum capacities of the secondary energy source. The objective, on the one hand, is to determine the permissible sizing from the specifications and, on the other hand, to assess the influence of the sizing on the energy consumption of the vehicle. In a fuel cell vehicle, it is difficult to advocate the use of battery or super-capacitor, the two technologies having very different characteristics. Some authors favor the use of super-capacitors because of their energy efficiency and specific power, but their low capacity can be a handicap. Conversely, batteries are able to store a large amount of energy but are penalized by their specific power. One solution is to couple batteries and super-capacitors to combine their advantages (power and energy), but this inevitably increases the complexity and cost of the secondary energy source.

Finally, the hydrogen consumption is not based only on the control strategy implemented but on the relevance of the sizing of the electrical energy source (heat pump system + secondary energy source).

X. Limitations and Future Studies (Vehicle mass problem)

Hydrogen consumption is influenced by the mass of the vehicle. The mass of the power source (fuel cell system + secondary energy source) is therefore an important factor in the design process [28] [32] [25]. At the limit, the overweight introduced can go as far as canceling the benefits obtained thanks to the secondary source. In addition weight introduced by the secondary source of energy (Super-capacitor + Battery) as well as the increase in the complexity of the powertrain, can be considered the use of a single fuel cell, which naturally has a high efficiency over a wide range of use [33].

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