Fuel cell based hybrid systems

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***Abstract*-This paper presents different works which are currently developed in the field of fuel cell hybrid systems in different public laboratories in France. These works are presented in three sections corresponding to: 1. Hybrid fuel cell/battery or supercapacitor power sources; 2. Fuel cell multi-stack power sources; 3. Fuel cell in hybrid power systems for distributed generation. The presented works combine simulation and experimental results.**

I. Introduction

A hybrid power system associates different power sources to obtain better characteristics than the ones of each single source. For fuel cell systems the better characteristics concern:

- The balancing of the power flow and the sizing of the fuel cell for the average power instead of the peak power [1, 2, 3];
- The energy demand in transient state which will allow fast variations. Such variations are limited with a single fuel cell by the fuel delivery system and may cause damage to the stack [4, 5];
- The possibility to operate after fault of components [6];
- The capacity to deal with intermittent availability of renewable energy sources [7, 8].

Hybrid power sources are currently developed for many applications such as mobile electronics [9], electric vehicle [6, 10] or distributed generations [7, 8], in a range of power from a few dozen watts to hundred kilowatts.

Systems actually developed in different public laboratories in France concern these applications and can be presented into three sections: 1. Hybrid fuel cell/battery or super-capacitor power sources; 2. Fuel cell multi-stack power sources; 3. Fuel cell in hybrid power systems for distributed generation.

Hybrid power sources with batteries or super-capacitors bring a response to the need for high-energy and high power densities of applications. Full cell multi-stack power sources associate elementary fuel cell stacks with power electronic interfaces. Certain redundancy is achieved and systems can operate under fault conditions. In distributed generation, fuel cells are used as alternative generation system to compensate intermittent operating of renewable energy sources and can be associated with short terms (supercapacitor, battery) and long terms (flywheel, electrolyser and storage vessel) energy storage tanks. Most of the presented works are under development for years and combine simulation studies with experimental results to validate the proposed power electronics interfaces and control.

II. Power sources with battery or supercondensator

Many hybrid fuel cell system configurations have been studied and documented. One can classify them in three main categories [11]: series architecture, parallel architecture and cascade architecture. It has been proven that parallel structure is the most advantageous one [11, 12]: less components constraints, easy energy management, good reliability…

The parallel structure presented in Fig. 1 consists in associating a static converter with its control device to every source. It is the simplest structure to implement because by the mean of current control, one can monitor very precisely each power source. This strategy, using a great number of degrees of freedom, has been validated in various works [3, 5-7, 13, 14].

Fig. 2 gives an example of parallel structure designed from a given household profile to suit the dynamic variations of the load. The fuel cell works quite close to its maximum power at anytime.

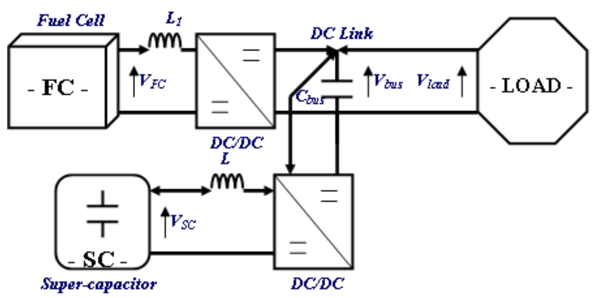

Fig. 1. Parallel structure for hybrid power system associating FC and SC.

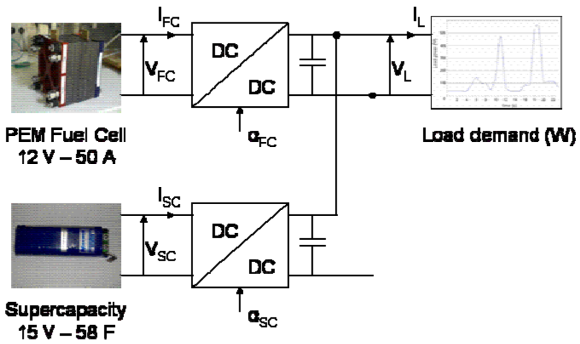

Fig. 2. Example of hybrid power system [14].

Some experimental results are shown in Fig. 3. For a power level of 75%, the system performs as expected: at load step, the output voltage of 24 V has a variation lower then 1 V. As the fuel cell current response is too slow, the supercapacitor provides the required power. When the fuel cell is no more limited, it supplies the load without the participation of the supercapacitor.

However the drawback of parallel structure lies in the inevitable losses associated with every static converter which reduces the power delivered by the fuel cell. Therefore, another possibility is to suppress one converter and to connect directly the fuel cell to the DC bus or the load, the power fluxes being adjusted by a single converter (Fig. 4), [15, 16].

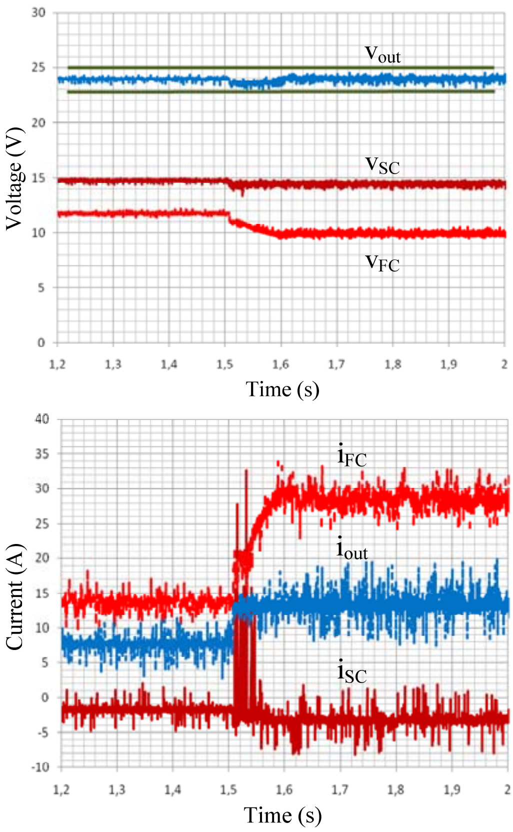

Fig. 3. Example of response to a load step [14].

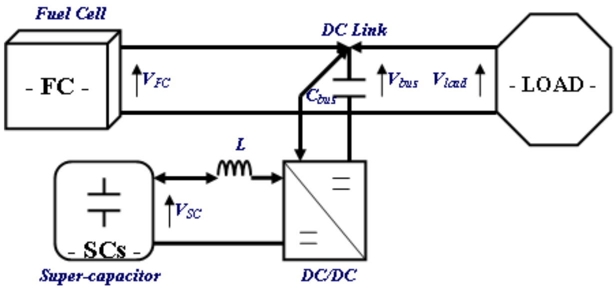

Fig 4. Direct Parallel Structure for hybrid power system associating FC and SC.

This converter is used only in an intermittent way because it adapts electrical values (voltage/current) between super-capacitor and electric load. The sizing of this converter is thus identical to that of the parallel classic structure. It is a buck-boost topology because the nominal super-capacitor voltage is quite low compared to the voltage of most fuel cells. Because of the direct connection of the fuel cell to the load, this electrical architecture is called "Direct Parallel Structure". Its main advantages are to be simple and to reduce both losses and costs of the power management interfaces.

For any structure, the two key points are first the sizing of fuel cell and storage device, and second the energy management of different sources.

A. *Sizing procedure*

The methodology presented here is called “frequential power sharing method” [17-18] and summarized in Fig. 5.

Three steps can be distinguished:

Step 1 - Fourier analysis of the temporal mission profile to satisfy: this analysis makes possible to understand how the electrical power has to be supplied by the sources in terms of amplitude and frequency.

Step 2 - Choice of a filtering frequency (key point of the methodology): after having analysed the FFT diagram, a filtering frequency is chosen to obtain two new power profiles for the fuel cell and the storage device. This choice is not easy and depends on several criteria, mainly:

- time response of the fuel cell system in general limited by the time responses of certain auxiliaries like air compressor (a few seconds), reformer (a few tens of seconds)…
- authorized frequencies to assure a satisfying life time of the fuel cell system, particularly the fuel cell itself.

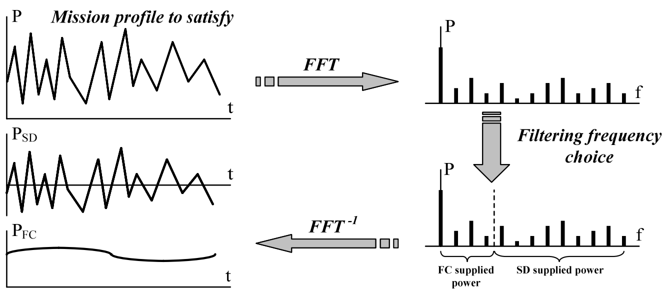

Fig. 5. Power sharing method between fuel cell and storage device.

These values are badly known to date. The current tendency is to limit the use of the fuel cell at low frequencies (< 1 Hz).

Step 3 - Return to a temporal power consumption profile for each component: an inverse Fourier transformation is thus applied for each part of the harmonic spectrum selected for each component. The output is two temporal power profiles, one for the fuel cell stack and another one for the storage device. These curves are afterwards used to dimension the fuel cell and the storage device.

The developed global sizing procedure is presented in Fig. 6. This procedure is iterative to take into account the impact of the system losses (in the storage device and in the electrical architecture) and the energy management in order to respect the sizing requirements. The methods to size the storage and the fuel cell are not detailed here (see [18]). Each time a sizing is realized, a simulation of the global system is achieved thanks to an electrical circuit simulator. If the sizing criteria are respected, the procedure stops. If not, a new sizing of the fuel cell and the storage is tried, etc.

Two examples of final sizing results are given in Fig. 7 and Fig. 8, respectively, for a direct hybridization between a fuel cell and supercapacitors and the hybridization through two power converters. For both cases, we assume an auxiliaries consumption of 20 % of the total power supplied by the fuel cell and we take into account the power converter losses. These last points explain a mean power for the fuel cell higher than the mean power of the load.

The direct hybridization presents the big interest of an energy self-management, but it is difficult to size in an optimized way without the previous procedure. The power is well shared between both sources: the fuel cell is well protected against the rapid load variations. However, one can observe that the fuel cell power shows a lot of little "power drops" due to the electrical resistors of the fuel cell and the supercapacitors; in other words, the filtering by the supercapacitors cannot be ideal due to internal ohmic losses of both sources [16-18].

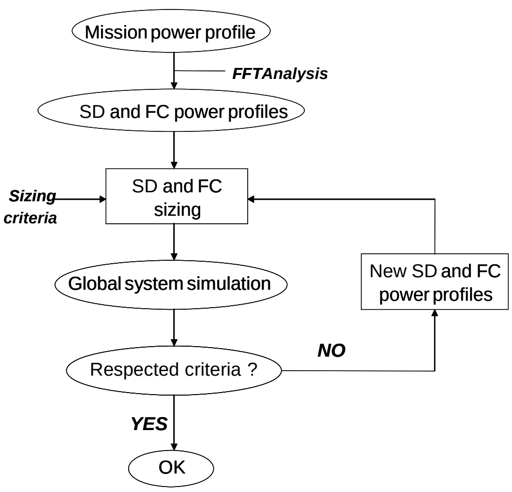

Fig. 6. Global sizing procedure of the hybridization between a fuel cell and a storage device.

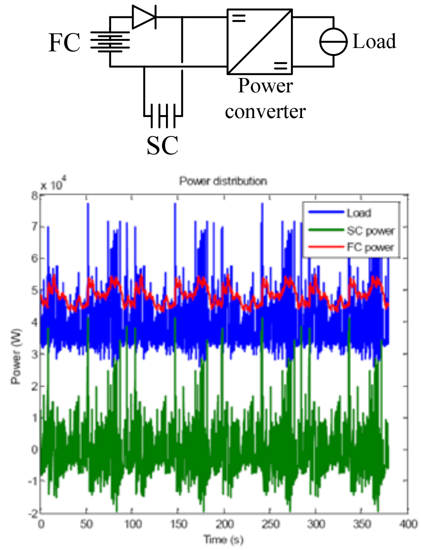

Fig. 7. Example of sizing results for direct coupling of a fuel cell and supercapacitors [16, 18].

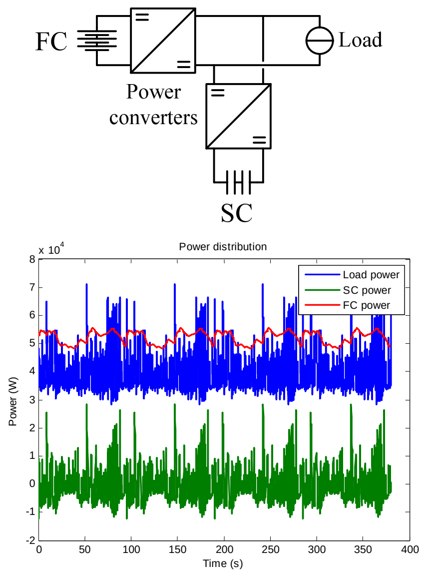

Fig. 8. Example of sizing results for an architecture with two power converters [18].

For the second example, the hybridization being achieved through two power converters, an energy management is required to obtain the desired power sharing. An example of possible control is proposed in Fig. 9: the DC bus is imposed by the fuel cell power converter. The frequential power sharing is achieved rather easily: a high-pass filter is applied to the measured load current and constitutes the current reference to reach for the supercapacitors. In [16, 18, 19], it was proved that it was necessary to add a control loop assuring the recharge of the ultracapacitors in any conditions, particularly to enforce the fuel cell to deliver the system losses instead of the superpacitors. The final sizing results shown in Fig. 8 takes into account the impact of all the energy management. The perturbations on the fuel cell power are less compared to the previous case.

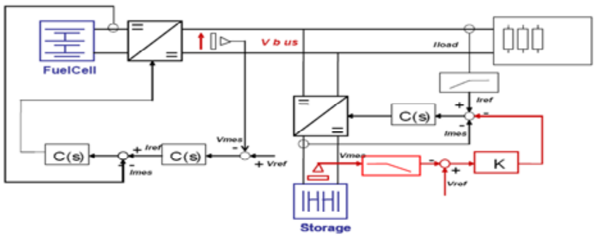

Fig. 9. Control strategy with the DC voltage imposed by the fuel cell converter.

B. Energy management

Energy management must allow the hybrid power system to satisfy the load power requirement while, on the one hand minimizing the fuel consumption and on the other hand assuring the integrity of each component.

Different control strategies have been described for hybrid system power management. Most important strategies are based on the evolution of the state of the system [20], on fuzzy control [21, 22], on voltage regulation of DC links [13, 23], or on passivity and flat systems [15, 24, 25].

Control strategy is generally based on regulation of the DC link voltage. As a matter of fact the fuel cell is a voltage generator with a strong internal linked impedance due to its three major irreversibility losses (activation voltage drop, ohmic voltage drop and concentration voltage drop) [26].

Hence, control of the DC link voltage allows indirectly controlling the current delivered by the fuel cell. Fuel cells dynamics is quite low especially because of its own compressor time response. Therefore, it seems clear that, to guarantee good fuel cell behaviour, the DC link voltage value must evolve in a controlled and slow way. This control will be managed by supercapacitor pack which has a great capacity compared to the DC bus one. At the same time, this device will absorb the differential of power which will result from this management. One must underline that the only degree of freedom is the 2-quadrant chopper duty cycle; that is the reason why the control structure is organised around this only control device in several cascaded loops. Fig. 10 gives an example of strategy synoptic associated to “Direct Parallel Structure”.

Fig. 11 presents such a structure composed of a fuel cell as the main source and a supercapacitor as an auxiliary one which is connected to a DC bus through a reversible DC/DC converter. Maximum voltage of this main source is 43 V in no load situation. This hybrid power source supplies two independent loads through unidirectional buck converters while having different output voltages (5 V and 12 V). Total power of the fuel cell is about 27 W. As the electrical boards consume 10 W approximately, the 5V and 12V converters can totally receive about 17 W from the fuel cell. The super-capacitor voltage is considered as a time-varying parameter since the capacitance value is high and its voltage variation in time is slow. Fig. 12 gives some experimental results during intensive load variations of the 5 V output. The flat outputs correspond to the electrostatic energy stored in the capacitors. During the load variation y_0 represents the stored electrostatic energy on C_0, and follows perfectly its reference.

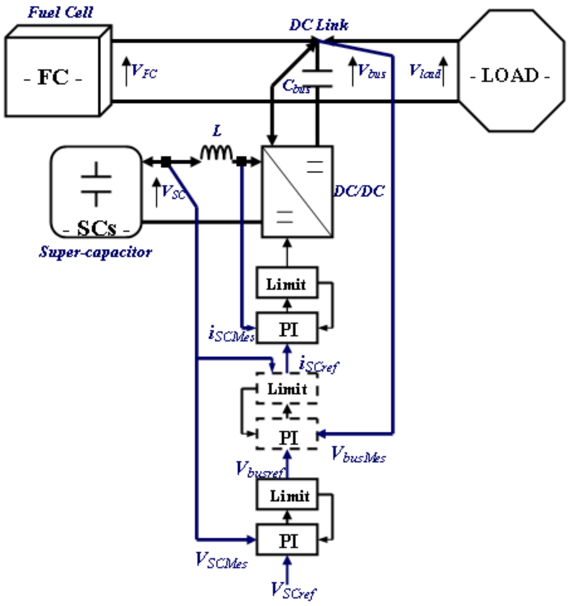

Fig. 10. Hybrid Power Source, FC and SC. Example of control strategy block diagram for a Direct Parallel Structure.

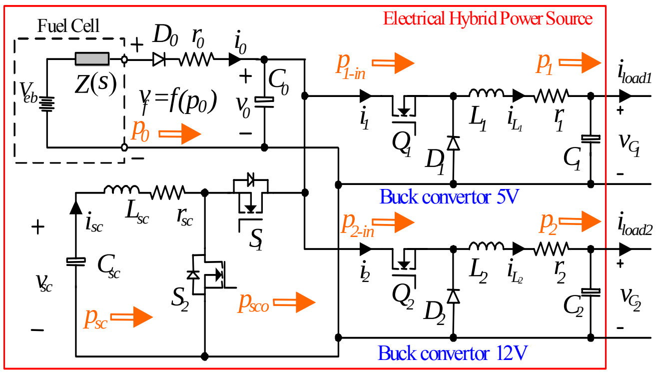

Fig. 11. Hybrid system with two independent loads [27].

Since the supercapacitor compensates the low dynamic response of the fuel cell, the output voltage v_1 stays constant during load variation. It helps also the fuel cells to supply the loads when the load power is greater than the fuel cells power. On Fig. 12, the maximum load power which is imposed to the system is 32 W which is about 180 % of the maximum power provided by the fuel cell.

III. Fuel Cell Multi-Stack Power Sources

The challenge and technological feasibility for power delivering with only one single fuel cell stack is not viable yet for high power applications. As a matter of fact, running a long stack is difficult as operating conditions for a high number of cells can hardly be achieved. Furthermore, as all cells are in series, the failure of a single cell leads to the unavailability of the whole power. Then, in order to increase the power required by applications and adequate for fuel cells development, an interesting solution consists in associating several elementary fuel cell stacks, building fuel cell multi-stack power architecture.

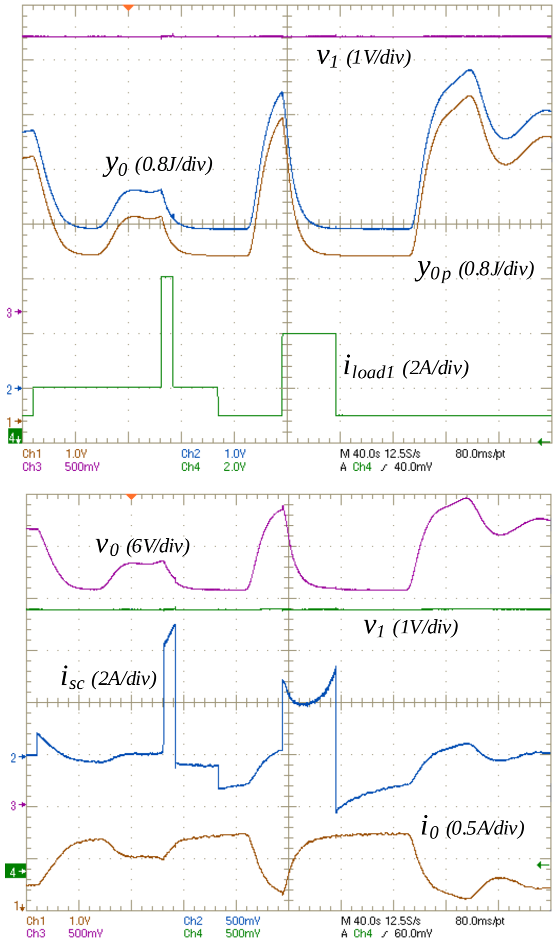

Fig. 12. Hybrid system with two independent loads, experimental results during load variations [27].

However fuel cell multi-stack association appears as a real technical challenge. It faces to some critical constraints and limitations. Some are linked to the fuel cell itself like the range of voltage and its variation with load. The association of elementary stacks needs to manage the partition of the power and to take into account the possible gap between the performances. Some constraints can also be issued from the power electronic interface and the auxiliaries' devices and to the load constraints as load cycles or fast transient dynamic. Thus, FC stacks have to be interfaced with power electronic converters, which is mostly the case when the voltage level has to be adapted between the fuel cell generator and the DC bus of the vehicle. Moreover, following criteria have to be considered when designing a FC multi-stack generator: compactness of the power system, easy integration, high reliability degree, high efficiency, availability and degraded working modes of the assembly PEFC multi-stack generator - power converter architecture [28].

Two multi-stack power architectures are presented hereafter. The first one uses a high frequency planar technology transformer to connect two fuel cell modules to a DC bus. The second one presents a fault tolerant PEMFC/ battery hybrid source developed for transportation applications.

A. *Fuel cell multi-stack power architecture*

According to the previous criteria, the structure of a converter is proposed in order to allow an independent power regulation for each fuel cell stack in order to increase the global output power level, taking into account the small unbalances of each stack. It is presented for two stacks but it can be easily extended to several stacks [29-30]. It is based on the use of a high frequency planar technology transformer which offers a better integration and compact structure for the power system than using a conventional HF transformer. A working frequency of 50 kHz appears as a good compromise between power losses and volume of the transformer. The power converter is composed of two conversion stages linked by the HF transformer. The first stage is a DC-AC inverter and the second one is an AC-DC rectifier with an associated boost converter.

The first stage converter structure is composed of an inverter which generates square shaped voltage from both fuel cell sources. It is based on the use of two separated half bridges using SK 300MB075 (SEMITOP®3) MOSFET integrated Trench technology. This converter structure is able to associate the two fuel cell modules (FC_1 and FC_2) either in parallel or in series (Fig. 13).

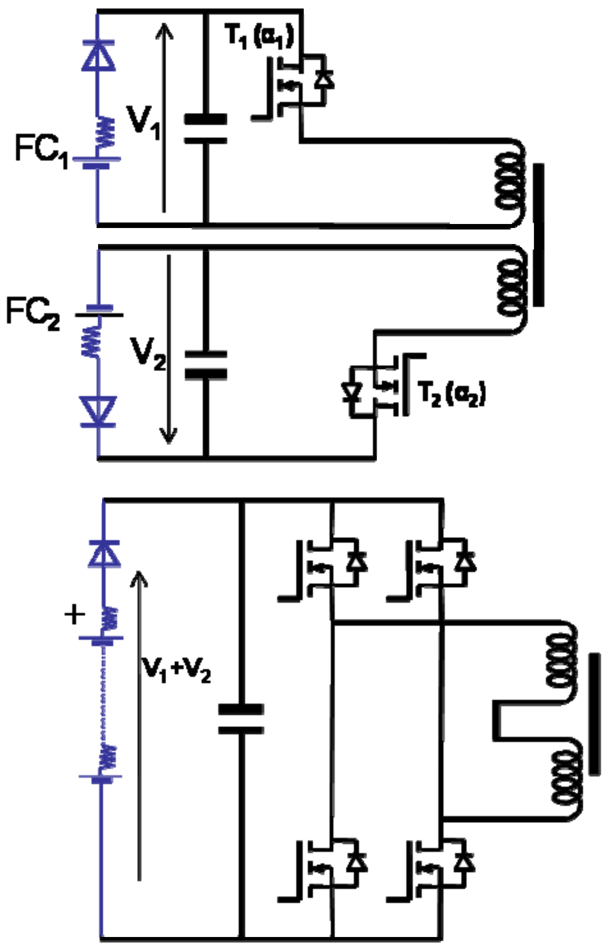

Fig. 13. Multi-stack power architectures, first stage converter topology, "pseudo-parallel" association (top), and series association (bottom).

The parallel coupling is in fact a "pseudo-parallel" connection mode which consists in operating both stacks separately. A closed magnetic coupling between windings allows using only two MOSFETs (T_1 and T_2) in order to switch alternatively each fuel cell power. Moreover, the "pseudo-parallel" topology can lead to an asymmetric power control of the stacks, as the duty cycles (α_1 and α_2) of the two MOSFETs can be different or even not complementary.

When two fuel cell stacks are connected in series, a transformer with only one primary winding can be used. This second topology can be obtained using the same planar technology transformer by connecting both primary windings and allowing a practical switch from one transformer topology (series) to the other (pseudo-parallel) thanks to the use of dedicated contactors.

The second stage is composed of a 2-diode rectifier connected to an adaptive static converter. Different topologies for the adaptive power converter can be chosen; like sinusoidal, square shaped multi-level converters or simply a boost converter. Here a classical boost converter is presented Fig. 14). The inductance L (50µH) limits the I_L current and allows controlling its amplitude through a current regulator.

Fig. 15 shows experimental results with two WBzU 500W PEMFC stacks used as power sources, in order to balance the power delivering of each PEMFC stack. Different current balance tests for the two PEMFC have been performed on both stacks allowing observing a step by step evolution of the current and voltage variations and for different load current.

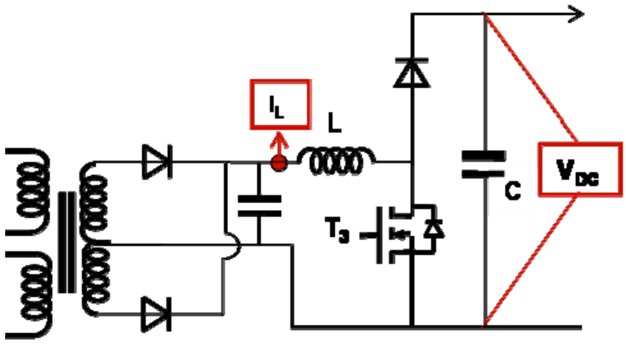

Fig. 14. Multi-stack power architectures, second stage adaptative booster.

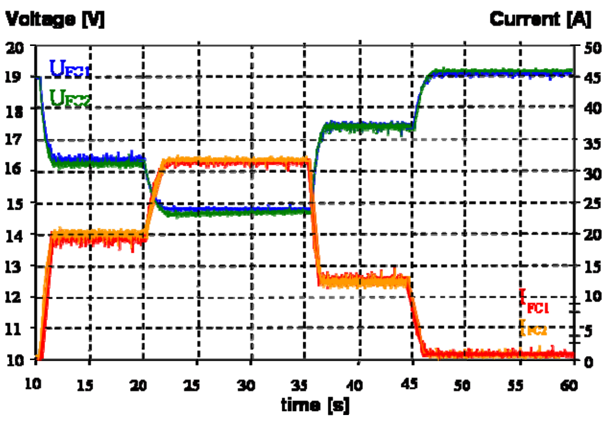

Fig. 15. Multi-stack power architectures. Experimental balance current tests performed on 2 PEFC stacks for different load current steps.

For the different tests on the stacks, the control signals (duty cycles α_1 and α_2) were calculated in order to maintain equal current amplitudes (I_{FC1} and I_{FC2}) delivered by the fuel cells. Experimental results demonstrate a good performance of the control strategy for current balancing. The voltage gap ($\Delta V_{FC} = U_{FC1} - U_{FC2}$) observed on the 2 fuel cells stacks can be adjusted thanks to a reactant gas flow variation.

In the proposed architecture, the stacks are electrically coupled but are fed with reactants independently and their temperature is controlled with separated cooling circuits as well. Future work will be oriented towards the coupling of the stacks on the fluidic and thermal aspects.

B. *Fault tolerant PEMFC/ battery hybrid source*

In the objective of making hybrid PEM fuel cell systems commercially viable in the transportation sector, it is fundamental to propose some technical concepts which counteract the fault and authorize degraded working modes. Certain redundancy can notably be achieved through the use of multi-stack fuel cell generators and well-suited control strategies for the continuation of operation even if one stack fails [31, 32]. Indeed, strengthen reliability and high power availability is naturally considered as very important targets particularly for the vehicle end-users. As a first approach, the problematic of fault tolerance for multi-stack PEMFC systems dedicated to hybrid FC/battery transportation engines will be considered from both sides which closely interact: the FC generator in case of faulty working and the power converter interface. For the first case, the use of anti-parallel by-pass diodes has proved to be a solution and has already been tested in the laboratory on a series assembly of 2-cell PEMFC stack and extrapolated to a twenty cell one [32, 33]. For the second one, the technological choice of an interleaved boost converter with backup strategies and fault tolerance management will be detailed [34]. In fact, one of the important issues of these power converter architectures is also to give new possibilities for power management and coordination with the battery in the hybrid system. The battery plays also a significant role in the global power management strategy as a transient power buffer.

Fault tolerance has also to be considered from the point of view of the power electrical interface which interacts with the FC generator. This approach is studied by numerical simulation for a high power twin-stack PEMFC system dedicated to railway application (60 to 120 kW). Both fuel cell stacks are electrically connected in series (2x220 V at no load, 2x107 V full load). A lead-acid battery is connected to the on-board DC-Link which imposes the 540 V_{DC} nominal voltage and delivers the transient power as necessary (Fig. 16). Among a multitude of possible candidates of power converter structures, the authors have focused their study on an interleaved multi-phase boost converter for the power converter interface between the FC generator and the on-board DC bus [35, 36]. The converter should meet objectives linked to the transportation environment: compactness, reliability, high efficiency, adaptability for degraded working modes.

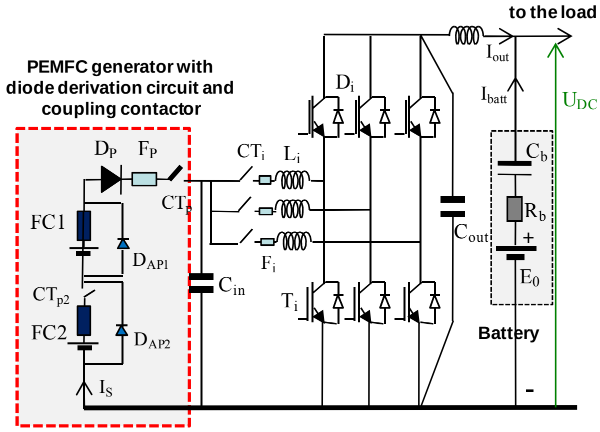

Fig. 16. Fault tolerant hybrid PEMFC/battery architecture for power transport application.

In addition, it should be fault tolerant in case of one FC stack is defective or even if a converter fault appears. The N-phase interleaved boost converter structure has been chosen mainly because of its simplicity (it uses only a few standard components) and redundancy (if a converter phase is out of work, the others can still be used as a backup system avoiding any power delivery interruption). The choice of 3 phases is justified by a severe specification on the FC stack current ripple (1% of the FC rated current) [34]. Two additional reasons which confirm this technological choice could be the cancellation of the current ripple near the rated power and the use of an appropriate integrated IGBT technology. It can be seen that the power semi-conductor technology could be an important parameter for the design of the converter; it can impose different architectures for the converter.

The model adopted for the fuel cell is basically composed of an electrical voltage source E in series with a pure resistance R_m, which represents the high frequency impedance of the fuel cell (the resistance of the membranes). Such an (E, R_m) simplified model is representative to analyze the switching behavior of the anti-parallel diode. Since the value of the membrane resistance is always lower than the total polarization resistance, the (E, R_m) model can be considered as the “worst-case” for the triggering of the anti-parallel diode conduction. When the fuel cell voltage equals zero or tends to reach negative values, the fuel cell behaves like a pure resistance (R_m) and the current amplitude delivered by the stack is dependent on the resistance R_m and on the conducting threshold V_F of the Diode AP [32].

The battery connected to the DC-Link is modeled as an (E_0, R_b, C_b) series assembly, E_0 is the no-load potential, R_b and C_b respectively the internal resistance and battery capacity.

Sharing the overall input current (I_s) in N phases leads to smaller individual inductances per phase, but their total ratio size/volume remains identical [35]. For a 3-phase interleaved boost converter, the input current ripple can be significantly reduced [35, 36]. The inductance value is $L_{i=1,2,3}$ = 220 µH. The input and output capacitors are set to C_{in} = 500 µF and C_{out} = 800 µF. In the studied application, the FC stack voltage varies according to the power level and the DC link voltage is almost constant (around 540V).

The fuel cell current I_s is controlled in a closed-loop by a classical PI controller. The output of the controller is compared to a generated PWM signal at f_s frequency, and then the signals are shifted to generate the gate driver signals for the transistors T_i. For a 3-phase interleaved boost converter the gate control signals are shifted by $T_s/3$ and $2T_s/3$, whereas for a 2-phase boost converter the phase shift is $T_s/2$. The control strategy switches automatically between 3 and 2 phases when a failure appears depending on the phase contactor status.

The following two degraded working modes have been considered: one FC stack fails and one converter phase leg is out of work. The simulations are based on MATLAB™ /Simulink™ . In case of one FC stack failure (e.g. decrease of the FC voltage as a consequence of a sudden break in the gas reactant feeding), the system must deliver the power with the help of the battery during the transition phase (Fig. 17).

If one converter phase is out of work, the converter continues to supply the full power thanks to an automatic shift of the IGBT gate control signal from 3 to 2 phases (Fig. 18). The sudden opening of the phase contactor (CT_i) or error in the gate signal emission which becomes zero lead to the shutdown of one converter phase. Just after the fault detection, the 2-phase currents remain controlled; however the current ripple has increased. After the localization of the fault, the corresponding phase leg is isolated and the converter continues to operate with only two active phases.

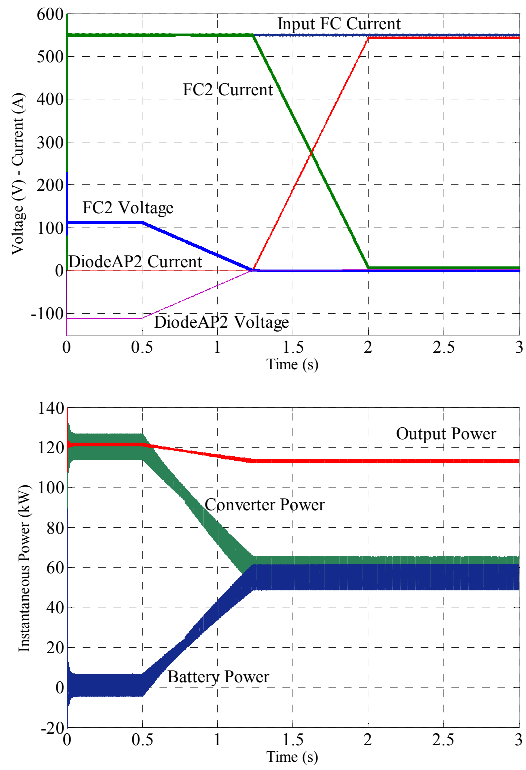

Fig. 17. FC2 stack out of work and power compensation (simulation results). Transient phase during fuel cell failure (top) and power compensation by the battery (bottom).

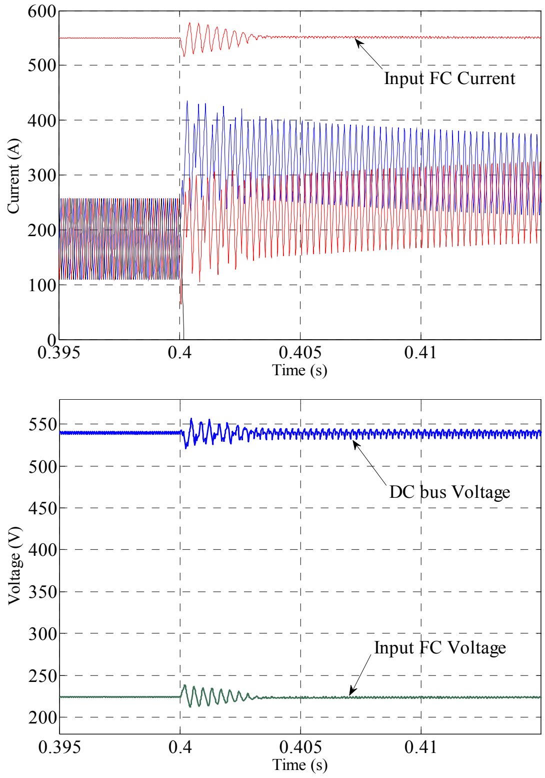

Fig. 18. Boost converter phase-leg out of work. Boost converter currents after fault detection (top) and DC bus and FC voltages during transient (bottom).

This fault causes two important changes: first, the IGBTs control shift is modified from $1/(3.f_s)$ to $1/(2.f_s)$, and second, the power is transferred through only two IGBTs increasing the current amplitude. Thus, the IGBT ratings and the switching frequency have to be adjusted from the beginning according to this constraint. A short-circuit identification and the leg isolation take time, but the battery supplies the necessary power during this transition.

The design of a fault-tolerant electrical power architecture to associate multi-stack fuel cells inside a hybrid on-board system is rather complex. However technological solutions exist to face up to the constraints relating to fuel cell generator composed of several stacks and its power converter interface. Anti-parallel diodes towards each fuel cell stacks allow to by-pass the stack in case of a fault. Moreover an adequate control strategy linked with power management permit to build a fault-tolerant power electronics interface. The battery plays a significant role in the global power management as a transient power buffer. As a perspective, the fuel cell/battery hybrid system should be optimized via a RAMS (Reliability, Availability, Maintainability, and Safety) approach and the study completed with an experimental validation.

IV. HPS FOR DISTRIBUTED GENERATION

In distributed generations, Hybrid Power System (HPS) is a possible solution to design active generators based on intermittent renewable energy sources. Here, one presents a HPS consisting of a wind generator, fuel cells, electrolyzers and supercapacitors [37]. Fuel cells have been previously used as an alternative generation system to deal with intermittent availability of renewable energy sources [7, 8, 38]. In this study, fuel cells are used with electrolyser cells to make up a long-term storage system. The active generator receives power references from a grid operator and is able to supply smooth powers against the fluctuant wind power. The challenge of the study is to control the power flows from the different sources by taking into account the characteristics of each power source.

HPSs can generally be classified into AC-coupled and DC-coupled structures. In AC-coupled HPSs, all sources are connected to a main AC-bus before being connected to the grid otherwise, or are directly connected to the grid [39]. In a DC-coupled HPS, all sources are connected to a main DC-bus before being connected to the grid through a main inverter [40]. The frequency and the voltage of the grid are independent from those of each source by using the common DC link and the source-side converters. In this study a DC-coupled structure is used (Fig. 19).

The studied HPS has five sources: wind generator (WG), fuel cells (FC), electrolyzers (EL), super-capacitors (SC) and grid connection (GC) [41, 42]. They are connected to the DC bus through five power converters, which are able to regulate the exchanged powers. A control system has been developed, which is organized in three different levels:

- *Switching Control & Modulation Technique (SCMT)*, which generates the transistor signals *T* from the ideal states {0, 1}, via drivers and opto-couplers;
- *Control Algorithm (CA)*, where algorithms calculate the duty ratio to perform the control of some physical quantities;
- *Power Tracking of Sources (PTS)*, whose main task is to control the power flows among the different sources.

The Switching Control & Modulation Technique and Control Algorithm are dedicated for each source and the common Power Tracking of Sources for the whole HPS is designed to manage power flows (Fig. 20).

The Power Tracking of Sources is organized into two levels: the "power conversion" (between the powers and other quantities) and the "power management" (to control the power flows, which are assigned for each source). For a simpler presentation of the PTS, losses in filters and in power converters are not presented in Fig.20.

According to the operating point of each source (SOC of the supercapacitor, H_2 components, power availability of the wind generator…), several operating modes exist. In a normal mode all sources can be used to generate the required reference powers. Hence for this mode, the power management strategy is organized as following. The grid-side inverter controls the choke currents to supply required powers (p_{gc_ref} and Q_{gc_ref} =0). Then the different sources should be coordinated in order to supply the required grid power p_{gc_ref} and the necessary power P_{dc_ref} to maintain the DC-link voltage ($p_{sour} = p_{gc\_ref} + P_{c\_ref}$). The wind generator works in MPPT mode to extract the maximal available wind power p_{wg_ref}.

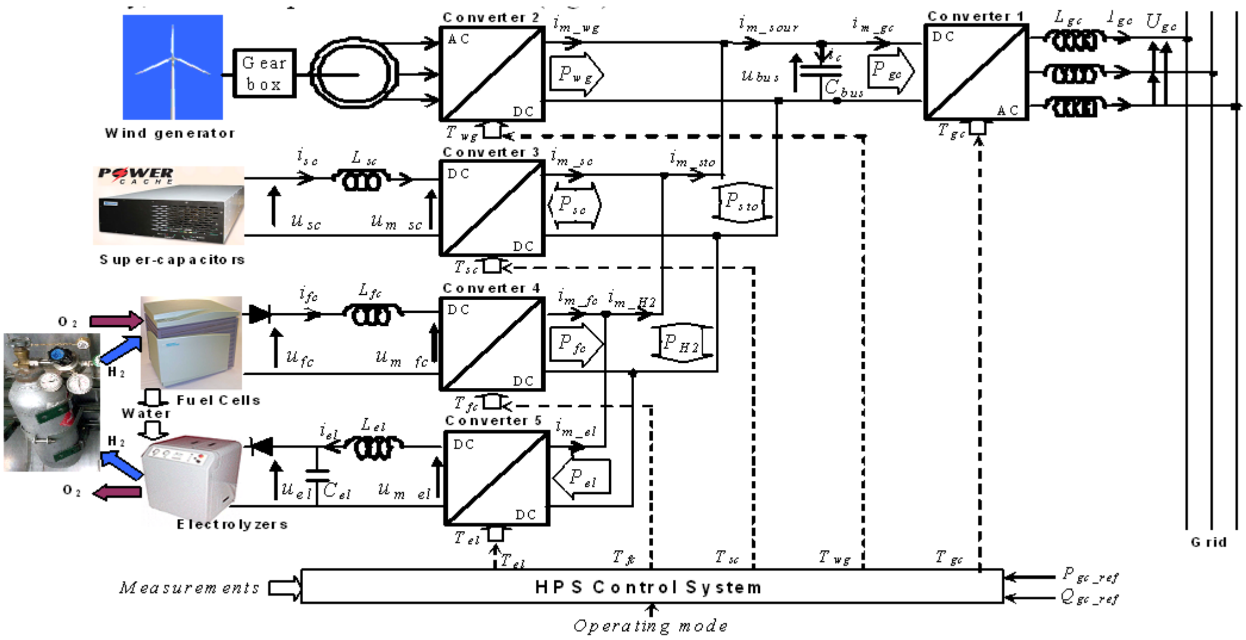

Fig. 19. Structure of the multi-source hybrid power system.

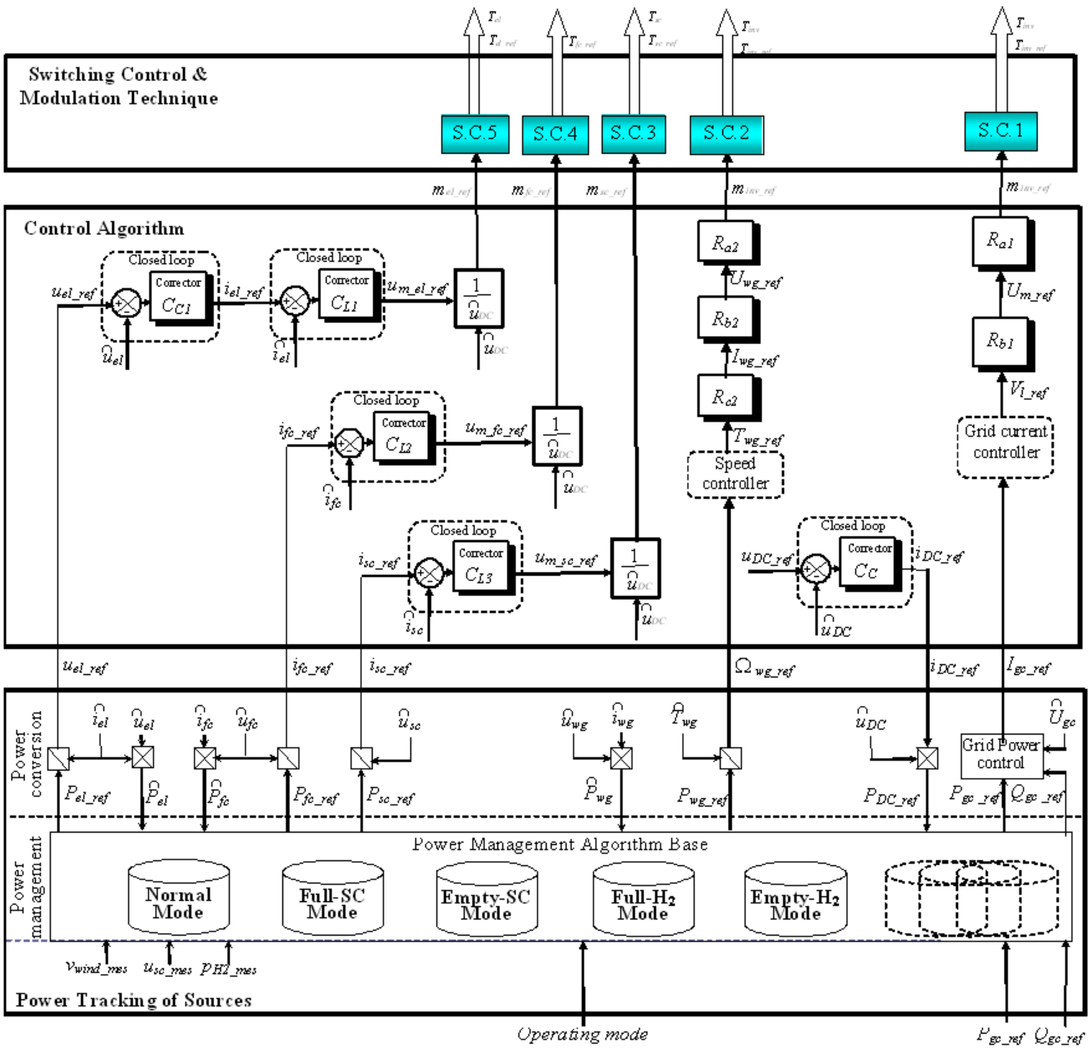

Fig. 20. Control system of the hybrid power system.

The storage units should compensate the complement (p_{sto_ref}=p_{sour_ref}-p_{wg}, Fig. 21). Since the fuel cell and the electrolyser have relative slow dynamics, the slope of their power reference should be limited by a low-pass filter ($P_{H2\_ref} \approx P_{sto\_ref}$). When P_{H2_ref} is negative, the electrolyser is activated to absorb the excess power (P_{el_ref}=P_{H2_ref}) and to produce H_2, which is stored in the H_2 tank for future use. When P_{H2_ref} is positive, the fuel cell is activated to compensate the needed power (p_{fc_ref}=$|p_{H2\_ref}|$) by using the stored hydrogen. During the transients, the supercapacitors are used to compensate the difference between the required storage power p_{sto} and the power, which is produced or consumed by the H_2 chain p_{H2} (P_{sc_ref}=P_{sto_ref}–P_{H2}).

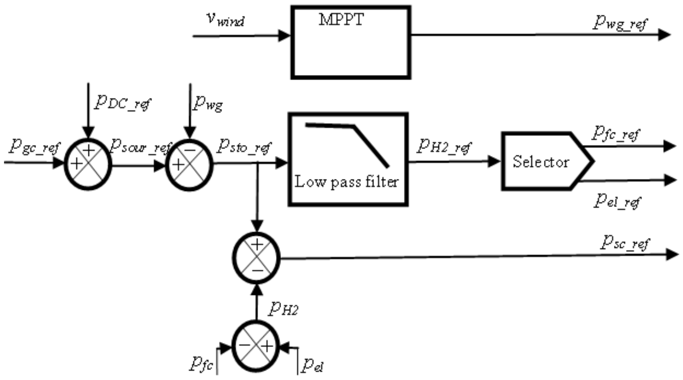

Fig. 21. Power management in "normal mode".

V. Conclusion

Different applications of fuel cell based hybrid systems have been presented in this paper. They illustrated the variety of systems where the association of fuel cell, battery, supercondensator, wind generator… improves the characteristics of the whole system. To realize such systems different ways are followed by the authors: sizing methodology to define each element of the hybrid source, control techniques to optimize energy flows, power electronics architectures to allow degraded working modes. Besides these theoretical developments many test benches have been developed to verify good agreement between analysis, simulation and experimental results.

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