A Soft-Switching Four-Port DC-DC Converter for Segmented PEM Fuel Cell Power Management in Vehicle Application

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***Abstract*—In transport application, long high power PEM fuel cell stacks could suffer from voltage discrepancy between cells due to severe constraints or appearance of localized faults in case of bad water management, moreover the output power of the stack is limited by the weakest group of cells. This article proposes a three-part segmented fuel cell associated with an isolated four-source DC/DC converter which makes possible a power sharing between the fuel cell segments according to their state-of-health. This topology allows an enhanced utilization of the stack as well as fault tolerance. ZVS operation is achieved to improve global converter efficiency.**

Keywords- PEM Fuel cell, isolated DC-DC converter, multi-source converter, zero voltage switching, power conditioning

I. Introduction

The application of power fuel cells (FC) in transport is still a technical challenge. High power stacks with a large number of cells (more than a hundred of cells) are complex to manage. Moreover transport applications face up some severe constraints (mission profiles and stop and start cycles) whereas they require an enhanced reliability. Nevertheless preindustrial examples of PEM (Polymer Electrolyte Membrane) fuel cells realizations in transport domain already exist, mainly concerning demonstrators and which are able to provide a feedback experience on the PEM technology for transport. Fuel cells with a power range of about 150 to 250 kW have been tested and evaluated for busses direct and hybrid propulsion (CUTE and ECTOS European projects, but also bus programs running in California and Canada) [1-3]. In France, the GENEPAC technology developed by CEA and PSA has been evaluated for automotive applications [4,5] and in the marine domain within the “Zero CO2” sailboat as a component of the hybrid electric propulsion chain, supplying the electrical motor [6]. Meanwhile, the 80kW “SPACT-80” PEM fuel cell technology from the French company Helion has been evaluated and integrated in heavy-duty hybrid military truck [7] and hybrid electric locomotive demonstrators [8,9]. These projects focus on the development of a compact fuel cell stack technology with high output dynamic performances, compactness and facilitated system integration. As other examples of the application of FC in the railway area, a fuel cell hybrid locomotive is presented in [10]. Powered by two FC stacks which deliver a continuous power of 250kW, the locomotive can produce a transient power up to 1MW thanks to the hybridization. In Japan, a test running of a railway vehicle equipped with 100-kW fuel cells has been also performed [11].

Some of these industrial FC generators, composed of a high number of cells in series are divided into multi-stack FC, in order to share the constraints. The segmented approach using a split FC stack into reduced number of cells associated with a dedicated power electronic interface can also be a solution for the power management of the system.

In a vehicle the FC power generator has to be reliable and with a high availability. In order to achieve this objective, it is essential to control FC state-of-health thanks to on-line fault detection. Many techniques exist based on the fuel cell impedance measurement thanks to electrochemical impedance spectroscopy (EIS) analysis, cyclic voltammetry (CV) and current interruption (CI) [12-16]. They provide accurate information about the FC state-of-health but are long to perform. For very fast fault detection, a voltage based detector can be a good agreement. Indeed, some faults can occur in localized areas of the stack. Thus, a judicious monitoring using only a few numbers of cells allows the detection of the fault. The authors propose in [17, 18] fault detection thanks to localized voltage measurements. With this technique, named the differential technique, it is possible to quickly detect a fault. This technique can be monitored on-line, uses only a few sensors and has the property to be non-intrusive.

These diagnosis techniques can be used as input information for a fault handling strategy. In [19], authors propose a corrective action performed by the power converter for a multi-stack FC association. Such a fault management can also be adapted to a single or segmented stack.

The segmented concept for FC stack has already been investigated in a US patent on method and apparatus for monitoring fuel cell or group of cells performance [20]. An improved concept, using a power converter interface is proposed by Palma et al. in [21]. The presented three-section FC stack and DC-DC topology based on push-pull modules allow modularity, isolation, as well as fault tolerance. However, some counter-arguments can be underlined. Indeed push-pull converter modules are rather dedicated to low power applications and the use of multiple single transformers may lead to a bulky implementation.

The principle of power coupling presented in [21] is based on a series DC node. Another idea is to consider an isolated AC node as a link between low voltage FC segments and a high voltage DC load. Indeed, it permits to use an N-windings transformer and has two main advantages. First, it minimizes the number of leg closings the magnetic core. Secondly, it reduces the power transfer losses since the power split is directly achieved through the magnetic circuit. This idea has been explored by Mariéthoz et al. and Zhao et al. [22-24].

In [22] Mariéthoz et al. propose to employ a multisource DC-DC converter to interconnect energy sources, it employs a single magnetic core with multiple windings and a three-level inverter dedicated to each source. Zhao et al. develop a control strategy to manage the power flow between the ports based on the phase shift control and utilizing the duty cycle for optimizing the system behavior and the control laws ensuring the minimum overall system losses [24].

Anyway, these different control strategies proposed by authors [22-24] impose a strong coupling between the input variables (phase shifts), and the output ones (power sources). This approach leads to a complex control algorithm and particularly because the considered system is non linear.

In this paper, we introduce a new control strategy which enables to decouple the input and output power fluxes and thus simplify the control strategy. Moreover, the power losses are all the more critical since traction application involves high power. Heat sinks may be voluminous in embedded application; thus it is important to minimize the size of the components. A solution, regarding power losses minimization, is to guarantee soft switching in power converter. Our strategy makes possible to obtain ZVS (Zero voltage switching) switching on any converter.

The article is organized as follow; firstly a segmented fuel cell with its 4 port DC-DC converter is presented. Control principle is explained allowing a ZVS operating mode. Then 2 scenarios are introduced: the normal operating mode, and one stack failure case. Finally the regulation of the output voltage is described. Article ends with some perspectives on the potential applications of the proposed converter topology to multi-stack or electrical hybrid systems [25].

II. Segmented Fuel Cell Stack and Control Strategy of 4-Source Converter

A. Control strategy of the four-source converter

A single FC cell delivers only about 1V at no load and near 0.6V at nominal current. Thus in high power applications, very long stack have to be used. A huge number of cells makes the fuel cell control more difficult, and could imply a non uniform gas distribution between different cells. Because of the series association, the output power of the stack is limited by the weakest cell. Moreover, many studies [26,27] point out thermal discrepancy between the center cells and the extremity ones that could lead to appearance of local faults owing to bad water management. In [18] authors suggest that three key-parts of the stack are instrumented: the extremity areas (border cells) at input and output of the stack, where a cell flooding may occur, and the center region which is generally hotter and where a membrane drying is susceptible to appear.

In order to apply this detection and identification methodology and be able to electronically manage a possible localized fault occurring in one of the stack segments, an isolated DC-DC multiple input / single output converter for a fuel cell is proposed. The converter and the 3 parts segmented fuel cell are presented in figure 1.

Segmented fuel cell consists in a fuel cell split in 3 parts. Hence, it virtually creates a series multi-stack association of 3 fuel cells, with the advantage to have the same fluidic circuits. This allows space saving and compactness compared to a real 3 FC association.

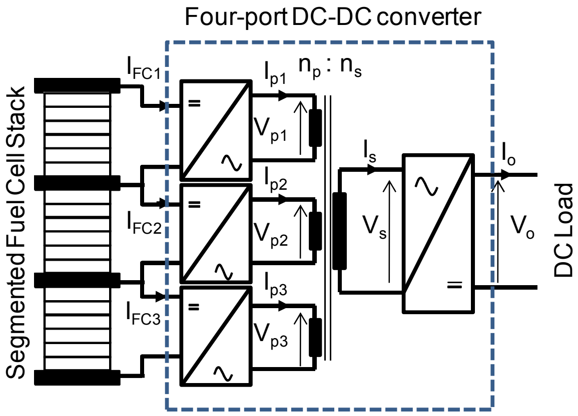

Figure 1. Principle of power conditioning for 3-part segmented fuel cell stack

In the proposed converter topology a four-winding transformer is used. Its equivalent circuit is given figure 2. L1, L2, L3 and Ls are the transformer leakage inductances, Lm is the magnetizing inductance. Power flow between the input and output ports is determined by a phase displacement between the different converters thanks to leakage inductance.

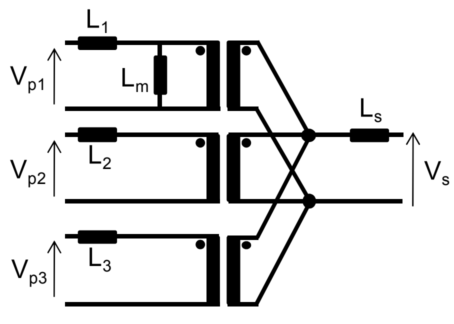

Figure 2. Equivalent circuit of the four-winding transformer

The objective of the control methodology is to decouple the energy fluxes issued from each converter. In order to achieve this properly, output AC voltage (Vs) and current (Is) are set in phase. Moreover one objective of the converter is to manage power transfer between the different inputs according to the appearance of a FC fault. Output rectifier is then set as the master, while input inverters are slaves. This choice should allow the loss of one input while allowing a minimal output power.

Most of the power is carried by the fundamental component, thus only fundamental is considered in the regulation. Theoretical phase shift angle and maximal amplitude of the input fundamental voltage are deduced from the rotating vector phasor diagram (Fig. 3):

$$\alpha_i = \arctan\left(\frac{L_{i,s}\,\omega I_{i,s}}{V_s}\right) \tag{1}$$

$$\hat{V}_{p,i} = \frac{V_s}{\cos\alpha_i} \tag{2}$$

With i = 1, 2, 3 : the primary port number, αi the phase shift between input voltage Vpi and output voltage Vs, and Li,s leakage inductance between primary port i and output.

Nevertheless, the input FC voltage will vary according to current solicitation and in order to maintain the voltage amplitude to the calculated theoretical value (Eq. 2), it will be necessary to modify impulse width of the input primary voltage. This is achieved by the following procedure:

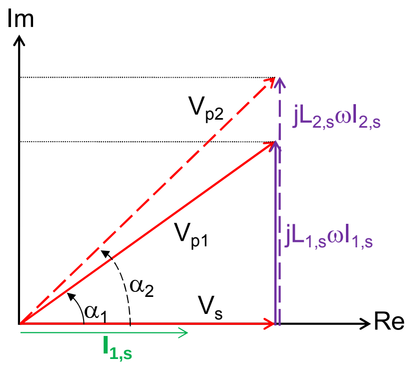

Figure 3. Phasor diagram for the system voltages and currents.

The Fourier series development of the rectangular input primary voltage shown in figure 4 is:

$$V_{p,i} = \frac{4}{\pi} V_{FC\,i} \sum_{n=0}^{+\infty} \frac{1}{(2n+1)} \cos((2n+1)\delta_i)\sin((2n+1)(\omega t + \delta_i))$$

With δi the control impulse width, VFC i the fuel cell voltage and (2n+1) the harmonic rank.

Reduced to the first harmonic, its expression is given by:

$$V_{p,i} = \frac{4}{\pi} V_{FC\,i} \cos(\delta_i)\sin(\omega t + \delta_i)$$

Then the voltage amplitude is given by (3):

$$\hat{V}_{p,i} = \frac{4}{\pi} V_{FC\,i} \cos(\delta_i) \tag{3}$$

The problem is decoupled port by port and the voltage amplitude at the primary side is only depending on the impulse width and input voltage.

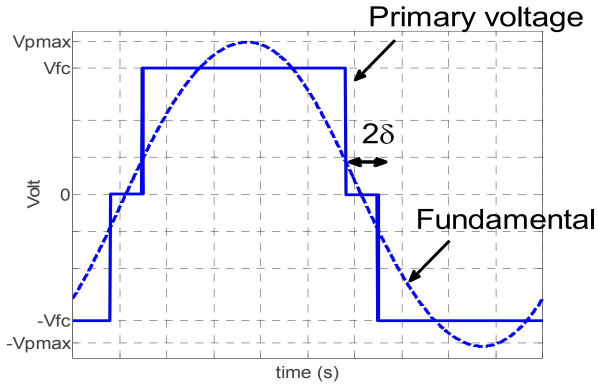

Figure 4. Principle of voltage magnitude control.

B. *Principle of soft switching : ZVS mode for all converters*

In order to reduce switching losses, and taking into account the proposed control strategy, a soft switching ZVS mode is possible. Figure 5 shows converters switch configuration, and Figure 6 shows transformer input and output voltage with output current. Fundamental of current is also plotted and is in phase with output voltage. Switches involved in the converters are bi-directional IGBT/Diode or MOSFET/Diode.

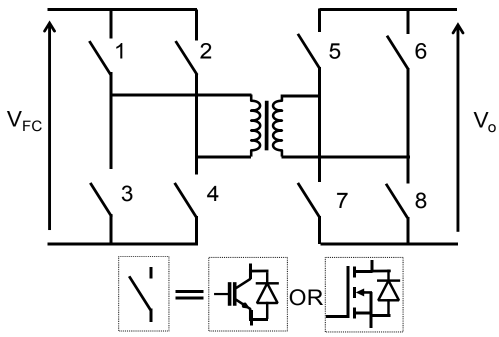

Figure 5. Converters switch configuration between input and output ports

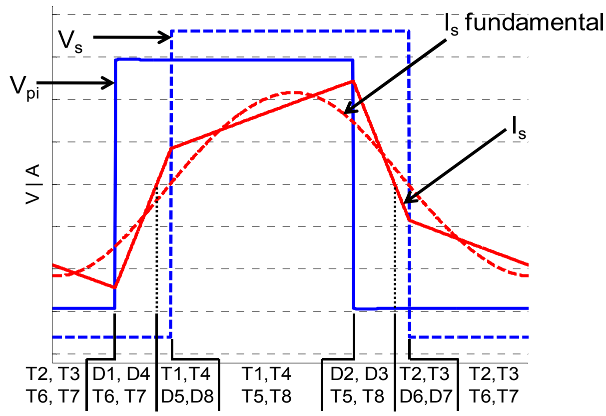

Figure 6. Voltages and currents in one primary and secondary winding.

Input and output converters can operate in ZVS mode. Figure 6 points out when input voltage changes from –Vpi to +Vpi, current is negative, then transistors are switched on conducting diode (i.e. transistor are switched on a zero voltage). The same behavior occurs with output converter. Switching losses occurs only on the transistors switch-off instants. EMC pollution is reduced during natural switching of the diodes and parasitic capacitors assist the transistors during the switched-off sequence. The condition to have a ZVS mode in primary side is:

$$\frac{V_s}{L_{i,s}} \frac{2\alpha_i}{\omega} < \hat{I}_{i,s}$$

With $\hat{I}_{i,s}$ the peak current equal to:

$$\hat{I}_{i,s} = \frac{V_{p,i}(\pi - 2\delta_i) + V_s(2\alpha + 2\delta - \pi)}{2L_{i,s}\omega}$$

The choice of the leakage inductance Li,s remains essential in the control methodology, and a compromise should be found on its value. In fact a low inductance imposing high dynamic current transition should facilitate the ZVS mode. On the contrary, for low power working, the inductance value should be higher to minimize the current ripple, but slow down the global current dynamic.

Moreover depending on the inductance value Li,s, the transformer can be designed with the required leakage inductance [24] thus no additional inductance is required.

C. PEM fuel cell modeling

FC voltage is highly dependent on its current. It varies by half from no load to nominal load. Then a fuel cell model is required to analyze its behavior. The same model than [17] is used and is based on the static voltage equation for one cell.

The cell voltage equation is given by (4):

$$V_{cell} = E - \eta_{act} - \eta_{ohm} - \eta_{conc.} \quad (4)$$

With E the electromotive force given thanks to the Nernst equation:

$$E = 1.229 - 8.5\times10^{-4}\,(T_{fc} - 298.15) + 4.3085\times10^{-5} \times T_{fc}\,(\ln(P_{H2}) + 0.5\,\ln(P_{O2})) \quad (5)$$

Tfc is the fuel cell stack temperature; PH2 and PO2 are the partial pressures of hydrogen and oxygen respectively.

The activation voltage losses represent the fact that some energy is needed to generate a reaction product. They are obtained by the Tafel equation:

$$\eta_{act} = (R\,T_{fc}) / (2\,\alpha\,F).\ \ln((J+J_n)/J_0) \quad (6)$$

J is the fuel cell current density, Jn the leakage current density, J0 the exchange current density, R the perfect gas constant, Tfc the cell temperature, α the charge transfer coefficient and F the Faraday's constant.

The ohmic voltage loss is due to the resistance for both electronic and ionic currents. They result in a slow and linear voltage drop with increasing current. The main parameter of this voltage drop is the membrane resistance Rmem:

$$\eta_{ohm} = R_{mem}\,.\ J \quad (7)$$

The concentration voltage losses are due to internal inefficiencies at high levels of reactive consumption. They occur at very high current density and are obtained empirically:

$$\eta_{conc} = m.\ \exp(n\,J) \quad (8)$$

m and n are constant depending of the construction of the cell.

III. SIMULATION FOR DIFFERENT SCENARIOS

A. Healthy stack: Equilibrated power

In the case where FC is healthy the system regulation will ensure that every fuel cell parts deliver the same power. It is the normal operating scenario. Figure 7(upper plot) shows the current and the voltage in one primary port of the transformer. All the different primary electrical inputs are the same, and then only one port is plotted. Figure 7(lower plot) shows the output of the transformer. The fundamental of Is current is also plotted and is in phase with the secondary voltage Vs. Inputs and output converters are operating in ZVS mode.

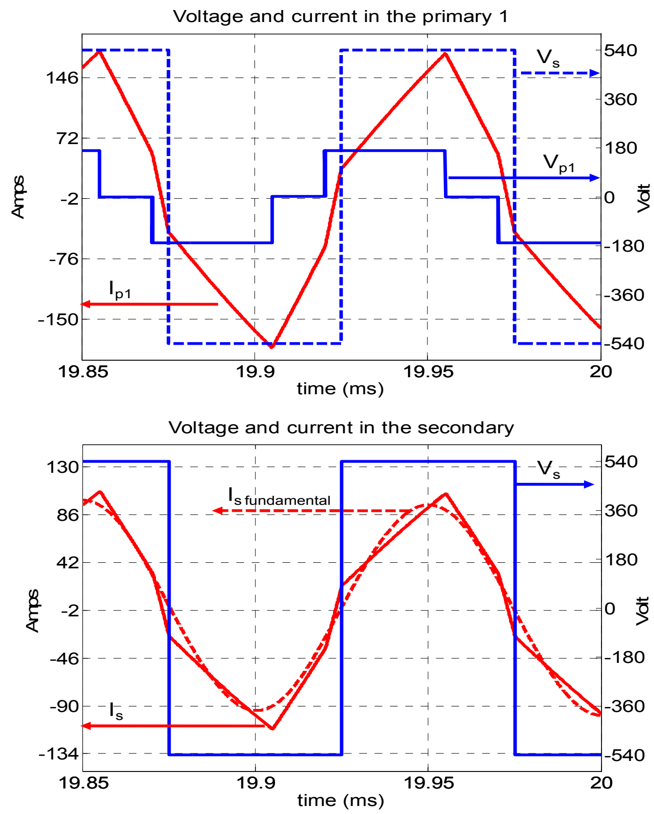

Figure 7. Voltages and currents in one primary (upper plot) and secondary winding (lower plot).

B. Malfunctioning stack: Unbalanced power

A reversible fault occurring in the fuel cell due to bad water management affects only some localized cells or groups of cells. As already mentioned, flooding mainly affects extreme parts (linked to port 1 and 3) and drying the center part (port 2). As a consequence, power is unbalanced. When a fault is detected, then the regulation strategy will reduce the power delivered by the faulty part of the stack and report it on the healthy others. This action should allow a restore of the fault without output power loss.

In the case of a drying, faulty cells are diagnosed in the center of the stack [17, 18]. Thus converter associated with input port 2 will reduce its power and report it on the others. This scenario is illustrated in figure 8. Power is shared between the three inputs. Input 1 and 2 deliver 2/5 of full power (Figure 8 upper plot) while input 2 delivers only 1/5 (Figure 8 middle plot). Figure 8 (lower plot) depict the output current and voltage. The output variables are almost the same during the balance power strategy and the unbalanced power strategy (Figure 7 and figure 8 lower plots).

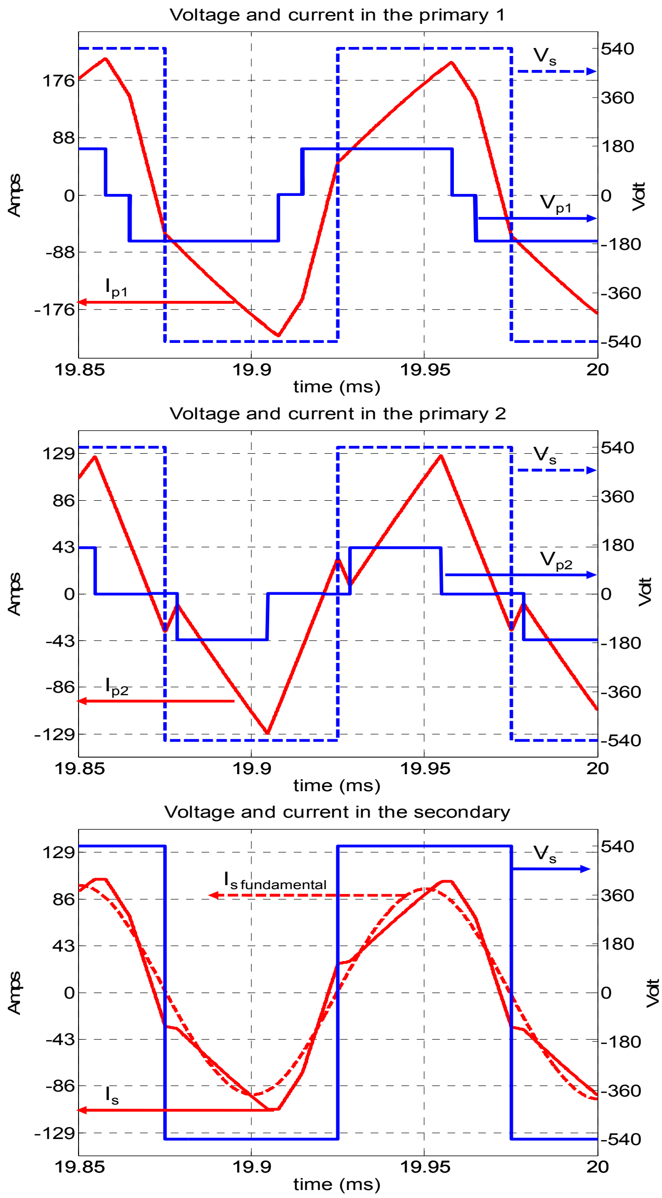

Figure 8. Voltages and currents in primary 1(upper plot), primary 2 (middle plot) and secondary winding (lower plot).

Figure 8 shows that input 1&3 and output are operating in ZVS mode, but input 2 affected by reduced power (Figure 8 middle plot), has lost the soft-switching mode. Indeed, the soft-switching mode is possible up to a given power level which should be compatible with the power specifications of the fuel cell.

IV. REGULATION OF THE OUTPUT DC VOLTAGE

Output voltage regulation is performed thanks to 2 regulation loops. The outer loop, for the voltage regulation, is common to all the system. The reference calculated by this regulation is shared between the 3 input converters. Then each input converter has its own inner loop for fuel cell current regulation. Figure 9 shows the global synoptic of the system. In addition to the voltage regulation system, the supervisor's role is to manage power distribution between inputs according to the FC parts state of health.

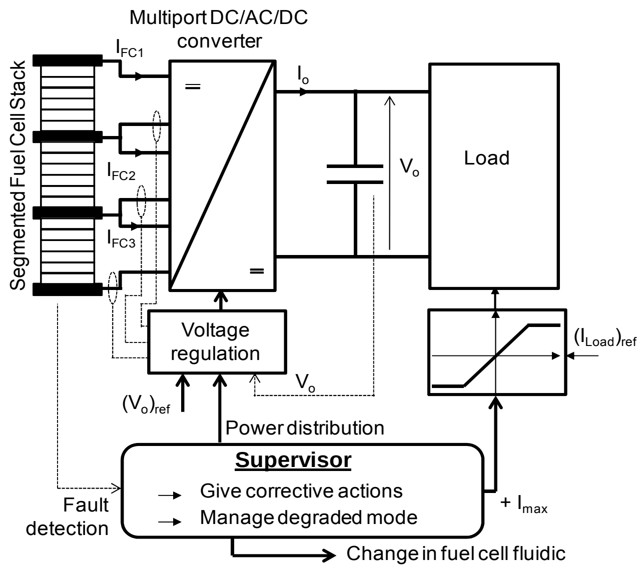

Figure 9. Overall synoptic of the system regulation

Each converter can be controlled independently. In figure 10 the synoptic of the regulation loop is shown.

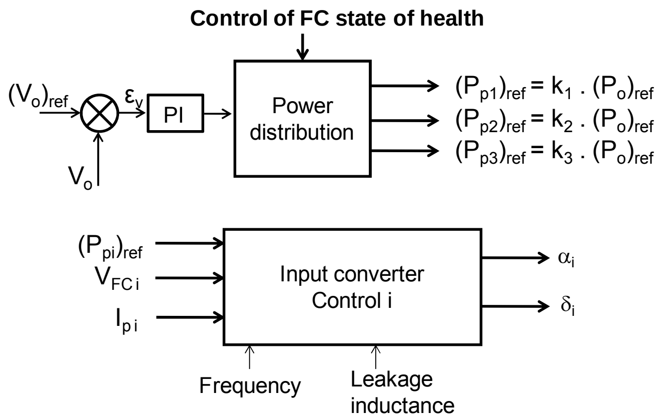

Figure 10. Synoptic of the regulation loop.

V. CONCLUSION AND PERSPECTIVES

An isolated four-source DC-DC converter has been presented. The particularity of this study is that the three converter inputs are connected to three parts of one fuel cell. This allows a power regulation of the three key parts of the FC according to their state of health. Indeed flooding or drying faults only occur in some localized cells or areas of the stack which can then be less stressed. This allows an optimal utilization of the fuel cell and should increase its availability in particular in a vehicle traction application for example.

Power flow between different static converters is done thanks to voltage phase shift. In our case a particular strategy is used which consists in setting in phase secondary voltage and current, this allows a decoupling of the energy flux, a possible soft switching in order to reduce semiconductor losses.

It will be interesting in a future work to compare this topology (which consists of an AC parallel link) to a DC series coupling. AC links are more complex than DC, but they allow galvanic isolation.

The three-source converter has been presented for one segmented fuel cell, but the proposed topology will work with multiple fuel cells too or extended to a FC hybrid system including energy storage components.

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