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Experimental validation of an optimized power allocation strategy for multi-stack fuel cell

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Abstract— Hydrogen is more and more considered for the decarbonization of energy uses, especially for transport applications. To reach a power range of several hundred kilowatts usually met in high power applications, an association of fuel cells in multi-stack is necessary. An adapted control must therefore be designed to share the requested power among the fuel cells. This paper presents an optimized power allocation strategy based on the minimization of the consumption of the stacks. The polarization curves are considered to take the fuel cell characteristics and its state of health into account. The proposed control strategy is experimentally validated thanks to a computation in real-time on a test bench, emulating four stacks of fuel cells with different states of health. The results show the effectiveness of the developed strategy, allowing the consumption to be reduced by 1.2 % compared to a strategy based on a fair distribution. Moreover, the reconfigurability of the power allocation is validated by considering the unavailability of some of the stacks.

Keywords—Fuel cell, hydrogen, multi-stack, power allocation, Hardware-In-the-Loop

I. INTRODUCTION

In recent years, hydrogen has been increasingly considered for the decarbonization of energy needs. For example, hydrogen can be an interesting energy vector for the industry and transport sectors [1], and it could be associated with renewable energy sources in a multi-source system. Hydrogen can be used as an energy source for different means of transport such as cars, buses or vessels, thanks to the use of a hydrogen fuel cell coupled or not to other storage solutions [2]. Among the different technologies of fuel cells existing on the market, the Proton Exchange Membrane (PEM) fuel cell is currently the most developed one, as the advantages are numerous, such as the fast start-up speed, the low operating temperature and the high power density [3]. Thus, this technology is more and more considered in transport applications, for example for maritime mobility [4]. However, these transport applications often involve high power requirements, as the load power can reach several hundreds of kilowatts [4]. Thus, multi-

stack architectures have been investigated over the last years, by considering an assembly of fuel cell in series and/or parallel so as to reach desired voltage and current requirements and also to bring modularity and fault tolerance [5]. Moreover, it allows the replacement of only faulty modules instead of the whole system.

However, the association of fuel cells in series and/or parallel requires an appropriate control and energy management system to ensure the reliability, the durability and the cost-effectiveness of the solution. The load power must be allocated among the modules, which can present mismatches due to different state of health (ageing) or operating conditions (temperature, relative humidity...). Several authors have recently investigated the control of multi-stack fuel cell by considering different criteria to define how the modules must operate. The control can be done according to the ageing and the durability, by considering the degradation of stack performance [6]–[8]. In [9], the authors proposed a control strategy based on consensus allowing the modules to reach the same lifetime. Moreover, the operating decisions can be defined in order to minimize the hydrogen consumption [10], [11]. In [12], the management of fuel cells is done according to a maximum power point tracking algorithm. Moreover, economic criteria can be considered. In [13], the authors proposed an economic optimization taking into account the operating cost of fuel cells and the hydrogen cost. It can be highlighted that the control of multi-stack fuel cell can be done by coupling these technical and economic criteria, as in [14]. These control methods can be designed as rule-based oriented strategies or as optimization problems [15]. Nevertheless, the literature survey shows that the studies experimentally validating their control strategies as in [16] are more scarce, particularly for those considering multi-criteria strategies, as the design of multi-stacks is recent.

Thus, we propose in this article a multi-criteria power allocation strategy for a multi-stack fuel cell association. The operating decisions are defined thanks to an on-line optimization problem, consisting in the minimization of the multi-stack consumption while considering the ageing of the

modules. A Power Hardware-in-the-Loop (PHIL) experimental validation is carried out to show the effectiveness of the proposed control, considering an emulation of a set of fuel cell stacks. A comparison with a classical non-optimized strategy based on the equalization of the power allocation is also proposed. This paper is organized as follows: the modelling of the multi-stack fuel cell is presented in Section II. Then, a power allocation method based on an optimization problem is proposed in Section III. The PHIL test bench is described in Section IV and some experimental results are proposed. Section V concludes the paper by giving some perspectives.

II. MULTI-STACK FUEL CELL DESCRIPTION

The topology of the system considered in this article is presented in Fig. 1. The studied multi-stack is made of four stacks of hydrogen fuel cells, but an extension to a larger number of stacks could be easily considered. Each stack is connected to a DC/DC boost converter allowing the voltage to be increased. These power converters supply a DC load connected to a DC bus voltage, on which a capacitor is also connected.

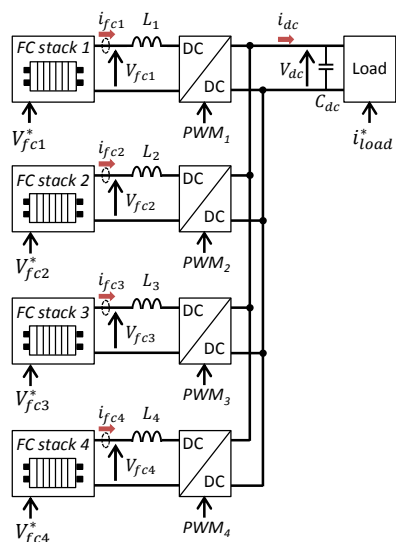


Fig. 1. Overview of the considered multi-stack fuel cell system

The behaviour of each fuel cell stack is assessed according to the static polarization curve of the fuel cells, following the detailed model presented in [17]. The operating voltage of the stack V_{fc} [V] is defined from the current I_{fc} [A], the state of health SoH and several fuel cell parameters such as the operating temperature, the chemical and geometrical characteristics, etc. The state of health represents the degradation of the fuel cell voltage compared to the initial voltage, with $SoH = 1$ at the beginning of the lifetime [7]. The power P_{fc} of the fuel cell stack [W] is defined as

$$P_{fc} = V_{fc} i_{fc} \quad (1)$$

An example of fuel cell stack polarization curves is given in Fig. 2. for two SoH values (1 and 0.8), considering for each stack a connection in series of 50 cells with the same SoH . These curves show that for a given power value, the most degraded fuel cell stack presents a higher current. As the hydrogen consumption depends directly on the fuel cell current [13], this ageing means that more hydrogen will be consumed for a same output power.

The system is controlled according to the command diagram presented in Fig. 3. The outer loop of the control allows the DC bus voltage V_{dc} to be regulated to the reference value V_{dc}^* thanks to a PI controller, by defining the reference value of the DC load current (i_{dc}^*). This value is then used as input data of the power allocation algorithm, which determines the reference current of each fuel cell stack (i_{fc1}^* to i_{fc4}^*) according to an optimization problem, as described in the next section of this article. These references are used as input data of the control loop of DC/DC converter input current. PI controllers are implemented in these inner loops for the regulation of the currents, so as to define the pulse width modulated (PWM) signals controlling the transistors of the power converters.

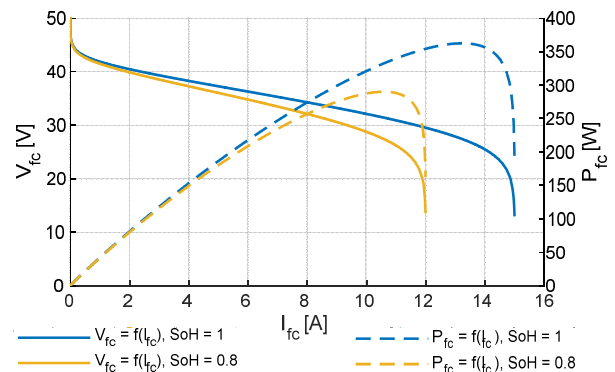


Fig. 2. Example of polarization curves for two fuel cell stacks with different SoH values

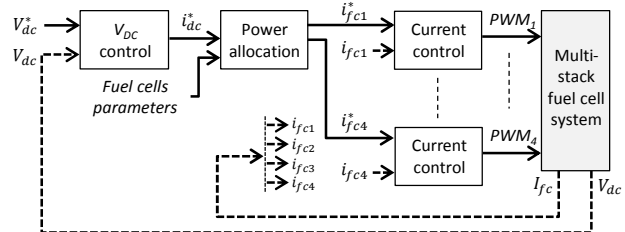


Fig. 3. Control scheme of the system

III. POWER ALLOCATION STRATEGY

A power allocation strategy is necessary so as to spread the supply of the load over the fuel cell stacks. Assuming that all the fuel cells behave identically, the simplest strategy would be to equally distribute the requested power between the stacks. However, this strategy may not be optimal in terms of efficiency, as the fuel cell stacks may not be identical, especially because of their ageing. As shown in Fig. 2, a degradation of fuel cell characteristics leads to a higher current, thus to a higher hydrogen consumption. Thus, an optimized power allocation strategy taking the degradation of fuel cells into account has to be designed to maximize the efficiency and to avoid hydrogen overconsumption. Moreover, it must allow the reconfigurability of the system so as to ensure the load supply whatever the situation, including in the event of a stack fault. The power allocation strategy proposed in this article is made of several steps as shown in the flowchart of Fig. 4, resulting in an optimized distribution of the current over the fuel cell stacks, thus an optimized distribution of the power.

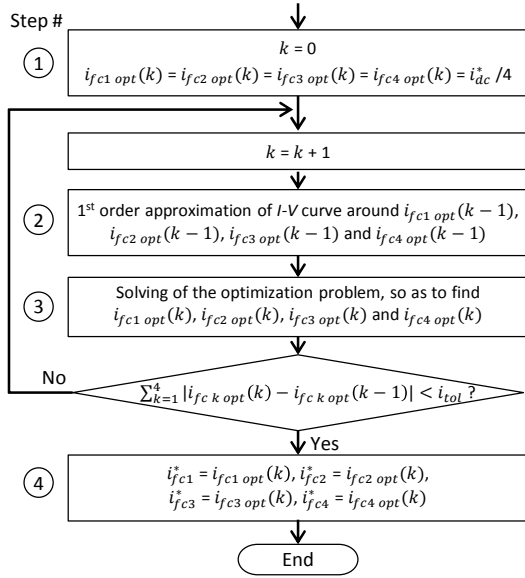


Fig. 4. Flowchart of the proposed power allocation strategy

The main steps of the method presented in the flowchart of Fig. 4 are described hereafter.

Step 1: the optimized current values ($i_{fc1\ opt}$ to $i_{fc4\ opt}$) are initialized considering an equally distribution of the demanded current i_{dc}^* .

Step 2: a linear approximation of the I-V characteristic of each fuel cell stack is computed around the last calculated current setpoint, to make the solving of the linear optimization problem of the next step easier. Thus, the fuel cell stack voltage V'_{fc} is approximated by the following linear expression (Thevenin model):

$$V'_{fc} = -r'_{fc} i_{fc} + V'_{fc,0} \quad (2)$$

with r'_{fc} the approximated resistance of the ohmic polarization region [Ω] and $V'_{fc,0}$ the open circuit voltage obtained when i_{fc} is zero. It must be noted that in this work, the online identification is not considered but it could be easily implemented through a small perturbation method.

Step 3: the optimization problem is solved in order to calculate the reference current of each fuel cell stack ($i_{fc1\ opt}$ to $i_{fc4\ opt}$) allowing the total hydrogen consumption to be minimized, while ensuring the load power is met. Thus, the decision variables of the optimization problem correspond to the current of each fuel cell stack, gathered in a vector I_{fc} such as:

$$I_{fc} = [i_{fc1} \quad i_{fc2} \quad i_{fc3} \quad i_{fc4}]^T \quad (3)$$

The aim of the optimization problem is to minimize the hydrogen consumption, which is related to the value of the fuel cell stack current. Thus, the objective function f consists in the minimization of the sum of the fuel cell currents:

$$f(I_{fc}) = i_{fc1} + i_{fc2} + i_{fc3} + i_{fc4} = \sum_{k=1}^4 i_{fc\ k} \quad (4)$$

The optimal solution must ensure that the load power P_{dem} is met, thus the following equality constraint must be verified:

$$P_{dem} = \sum_{k=1}^4 V'_{fc\ k}(i_{fc\ k}) i_{fc\ k} \quad (5)$$

The voltage V'_{fc} of each fuel cell stack is determined thanks to the linear approximation considered in the step 2 of the proposed algorithm, according to the equation (2).

Thus, this optimization problem corresponds to a linear optimization problem with quadratic constraint, which can be written according to the following classical matrix formalism:

$$I_{fc\ opt} = \operatorname{argmin}(f(I_{fc})) = \operatorname{argmin}(C^T I_{fc}) \quad (6)$$

s.t.:

$$0.5 I_{fc}^T A I_{fc} + B^T I_{fc} + D = 0 \quad (7)$$

where $I_{fc\ opt}$ is the vector containing the optimal solution and A, B, C and D are the matrices integrating the optimization input data of equations (2), (4) and (5) for each stack:

$$A = \begin{bmatrix} -2r'_{fc1} & 0 & 0 & 0 \\ 0 & -2r'_{fc2} & 0 & 0 \\ 0 & 0 & -2r'_{fc3} & 0 \\ 0 & 0 & 0 & -2r'_{fc4} \end{bmatrix} \quad (8)$$

$$B^T = [V'_{fc1,0} \quad V'_{fc2,0} \quad V'_{fc3,0} \quad V'_{fc4,0}] \quad (9)$$

$$C^T = [1 \quad 1 \quad 1 \quad 1] \quad (10)$$

$$D = -P_{dem} \quad (11)$$

To obtain a solution as fast as possible, this optimization problem is solved iteratively by Newton's method. It can be noted that a reformulation is done in a way to get a Lagrangian function. Moreover, the reconfigurability of the system is integrated in this step by considering in the optimization problem only the available fuel cell stacks (the current of non-available fuel cell stacks is set to zero).

Step 4: if the sum of the absolute values of the differences between the currents of the two last iterations is lower than a predefined tolerance (example: 10 mA), the algorithm is stopped and the current values of the last iteration are considered to be the new reference currents for the fuel cell stacks (i_{fc1}^* to i_{fc4}^*). Otherwise, the steps 2 and 3 are computed until the stopping criterion is met.

IV. EXPERIMENTAL VALIDATION

The optimized power allocation strategy proposed in the previous section is experimentally validated on a PHiL test bench. The experimental platform and the characteristics of the fuel cell stacks are described in the following subsections. Several experimental results are also given and discussed.

A. Test bench description

An overview of the test bench used for the experiments is given in Fig. 5. The four fuel cell stacks are emulated by DC voltage sources (ref. PSI 9200-15 from Electro-Automatik manufacturer), which are controlled by the fuel cell stack models computed in real-time in the Opal-RT target (OP4510). Each voltage source is connected to a DC/DC

boost converter through a 4 mH inductance and supplies a DC current load. This load is connected to the DC voltage bus, on which a 880 μF capacitor is connected. The nominal voltage of the DC bus is set to 100 V. The power allocation algorithm, the regulation of the DC voltage and the control of the boost converters are implemented using the MATLAB SIMULINK software and computed in real-time in the Opal-RT target, which is equipped with an Intel Xeon E3 3.5 GHz processor. The model is computed with a 60 μs time-step. As the power allocation algorithm can require more than one time step to provide optimized results, it is considered that this algorithm is computed every 300 ms to ensure the optimization convergence and no overrun. Thus, until the optimized results are available, the last values of the current references are used to adapt the theoretical setpoint values based on an equally shared distribution of the demanded power. The monitoring of the experiments and the visualization of signals are done thanks to a host computer connected to the Opal-RT target via the TCP/IP protocol.

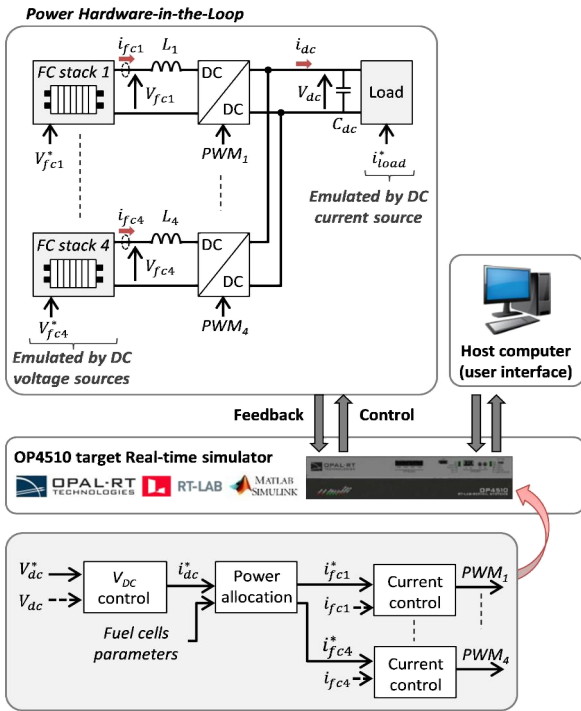


Fig. 5. Overview of the PHIL test bench

B. Emulated fuel cells characteristics

In order to validate the efficiency of the proposed power allocation algorithm, four different fuel cell stack characteristics have been considered, assuming different SoH values. The voltage versus current and power versus current static curves of these stacks are given in Fig. 6 and 7. It has been assumed that the stack 1 presents the best state of health value ($SoH = 1$), while the stack 4 is the most degraded one ($SoH = 0.7$). The nominal power of the considered fuel cell stack at the beginning of its lifetime ($SoH = 1$) is 360 W. So as to illustrate how the choice of these SoH values can influence the results of the power allocation optimization, an example of optimized allocation is shown on the curves of Fig. 6 and 7, considering a load power of 880 W under $V_{dc} = 100$ V. Moreover, the linear I-V characteristic around the optimal solution is plotted for each stack. It can be seen

that the higher the SoH value, the higher the current, as a less aged fuel cell can provide more power than a more aged one.

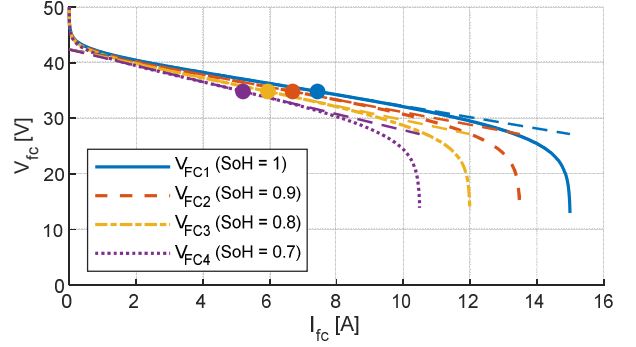


Fig. 6. I-V characteristics of the four considered fuel cell stacks (markers indicate an example of optimized solution for power allocation)

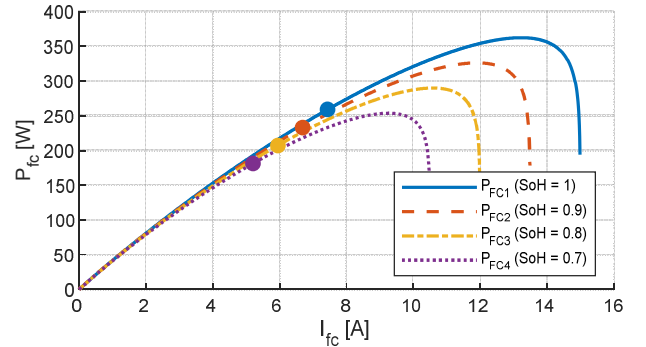


Fig. 7. I-P characteristics of the four considered fuel cell stacks (markers indicate an example of optimized solution for power allocation)

C. Experimental results

The designed control algorithm is validated for several load current values, considering the variable current load profile shown in Fig. 8, for a 20 s period.

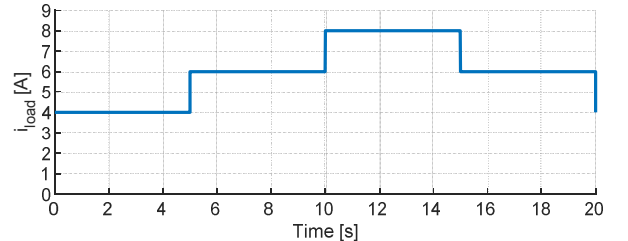


Fig. 8. Profile of load current i_{load} considered in the experiments

The obtained output current of each emulated fuel cell stack is plotted in Fig. 9 for two allocation strategies: the first one is without optimization (i.e. an equally distribution of the demanded power over the stacks) and the second one corresponds to the proposed algorithm based on an optimized sharing. The power profile of each fuel cell stack for both strategies is presented in Fig. 10. The obtained results show that for the non-optimized strategy, the power is equally shared between the stacks but the currents present slight differences. This phenomenon is due to the fact that the fuel cells polarization curves are not the same. For a same value of power, the current of the most aged fuel cell will be higher than the less aged fuel cell, as the voltage decreases with the ageing. Thus, this sharing strategy is not optimal in terms of hydrogen consumption.

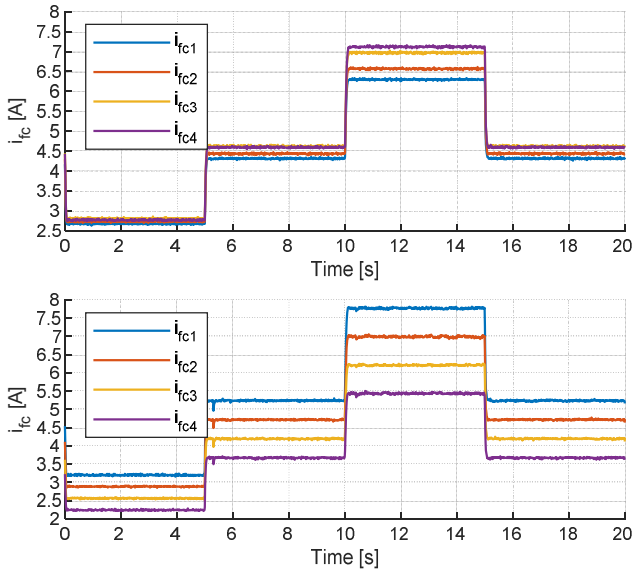


Fig. 9. Output current profiles of the emulated fuel cell stacks (top: non-optimized energy management, bottom: optimized energy management)

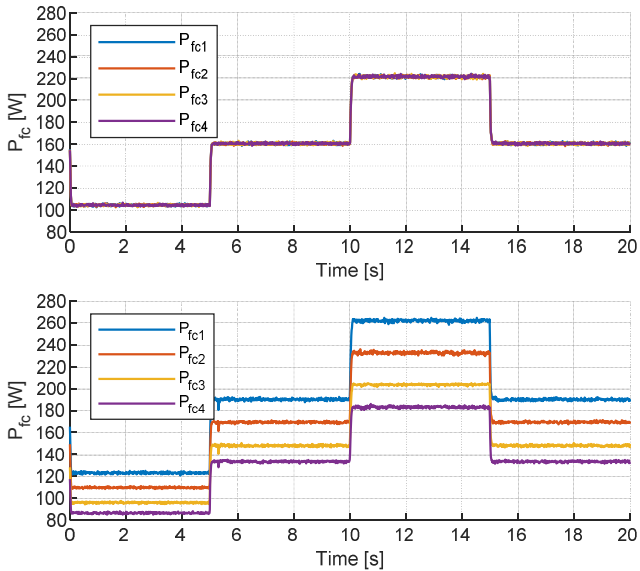


Fig. 10. Power profiles of the emulated fuel cell stacks (top: non-optimized energy management, bottom: optimized energy management)

For the optimized strategy, the obtained results show the effectiveness of the proposed control algorithm as the power and currents are shared to reduce the solicitation of the most aged fuel cells (FC stacks 3 and 4) and to request more power from the less aged fuel cells (FC stacks 1 and 2). The sharing obtained for the period between 10 s and 15 s corresponds to the optimized distribution presented in Fig. 6. It can be noted that even if the power allocation algorithm is computed every 300 ms, the distribution of the currents is kept optimized according to the *SoH* values, by conserving the ratios between the currents. Also, these profiles show the ability of the proposed control to maintain the stability of the system during the transients.

So as to show the benefits brought by the proposed algorithm, the difference $\Delta I_{fc\ tot}$ between the total current $I_{fc\ tot}$ of the optimized strategy (Fig. 9 bottom) and the non-optimized strategy (Fig. 9 top) is plotted in the Fig. 11, with $I_{fc\ tot} = \sum_{k=1}^4 i_{fc\ k}$. This profile shows that the optimized

control allows the total current to be decreased, up to -0.5 A for the highest load current value and even -2A during a transient. A comparison of the consumption of the stacks for both strategies is given in Table I, for the period of 20 s presented in Fig. 9. The results show that the total consumption is reduced by 1.2 % when using the optimized strategy rather than the non-optimized strategy. Thus, a similar hydrogen reduction can be expected thanks to the optimized power allocation strategy. Thanks to the proposed control, a longer durability of multi-stack can be expected as the less efficient and the more aged modules are less stressed. Moreover, more savings can be expected by increasing the load power. An analysis of the computation time of the power allocation algorithm during the tests shows that the algorithm takes between 30 and 50 μ s to provide results, which means that the power can be allocated efficiently in a short time.

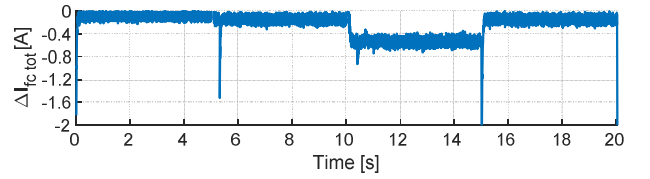


Fig. 11. Difference between the total current of the two strategies

TABLE I. COMPARISON OF EXPERIMENTAL RESULTS

Fuel cell stack	Consumption without optimized allocation [mAh]	Consumption with optimized allocation [mAh]
1	24,4	29,8
2	25,2	26,8
3	26,4	23,8
4	26,5	20,9
Total	102,5	101,3

Finally, the reconfiguration capability of the multi-stack in case of fault has been experimentally validated by switching off some of the stacks, considering a constant load current i_{load}^* of 6 A during the 30 s of the test. The obtained current and power profiles are given in Fig. 12. The stack 4 has been switched off between 8.6 s and 15.3 s, then the stack 3 between 21.1 s and 27.8 s.

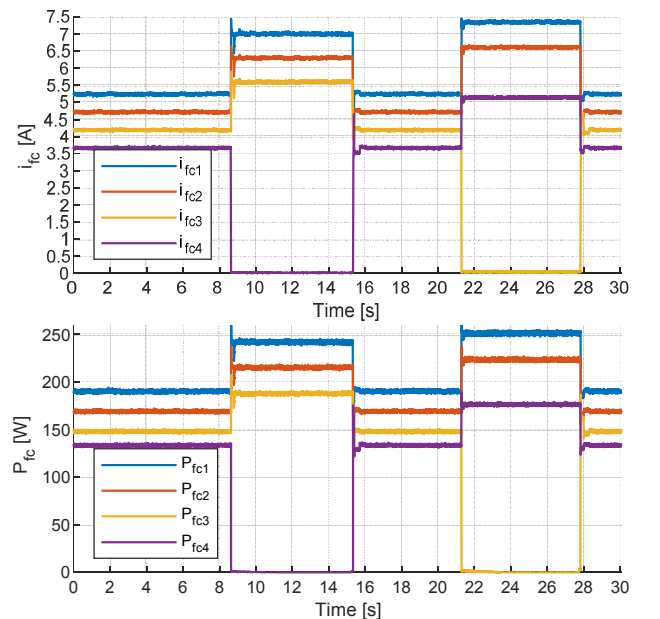


Fig. 12. Output current (top) and power (bottom) profiles of emulated fuel cell stacks with occurrences of stack fault

These profiles show that the dispatch of the requested power has been updated when the fault occurs while maintaining the sharing rules observed previously according to the state of health of the fuel cells (the less aged fuel cells take most of the power). Thus, the power allocation algorithm ensures the reconfigurability of the multi-stack in case of stack fault.

V. CONCLUSION

In this article, an optimized power allocation strategy has been proposed, so as to minimize the consumption of a multi-stack fuel cell system. The proposed optimization problem allows the operating setpoint of each stack to be defined by taking into account the polarization curves, and therefore some possible mismatches between the fuel cells such as the ageing. This strategy has been validated experimentally by considering different *SoH* values, leading to a lower solicitation of the most degraded fuel cells thus to a lower hydrogen consumption. The proposed allocation strategy performs better than a classical strategy based on an equally sharing of the requested power. The developed strategy has been applied to a small number of stacks and to a low voltage due to constraints related to the experimental test bench, but it can be applied to any number of stacks and any voltage level. As an extension of the presented work, several perspectives could be explored. For example, others criterions could be integrated in the power allocation strategy, such as the operating cost, the ageing in terms of operating hours, the number of operating fuel cells, etc. The estimation of the polarization curve parameters during the operation could also be investigated, by an online identification of the characteristics of a real fuel cell. Thus, the *SoH* could be estimated online during the operation, allowing the power sharing to be updated according to the ageing of the stacks. Finally, the use of real fuel cells instead of emulated ones could be considered.

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