Fuel cell system integration into a heavy-duty hybrid vehicle : preliminary experimental results

J. Mulot [1], F. Harel [1], S. Begot [1], D. Hissel [1], *Senior Member IEEE*, I. Rodel [2], S. Boblet [3], M. Amiet [4]

[1] FEMTO-ST, UMR CNRS 6174, University of Franche-Comte, Rue Thierry Mieg, 90010 Belfort, France

[2] Panhard General Defense, Z.A Pralong, 42260 Saint Germain Laval, France

[3] Helion Fuel Cells, Domaine du petit Arbois, 13545 Aix en Provence, cedex 04, France

[4] Direction Générale de l'Armement (DGA), 7-9 Rue des Mathurins, 92221 Bagneux Cedex, France

Abstract – This paper is the second paper dealing with the evaluation of different power sources and hybridization strategies in a heavy-duty vehicle. It focuses on the physical integration of a fuel cell system (FCS) into the vehicle as well as the preliminary experimental results obtained with the FCS coupled to batteries. The vehicle considered here is a mobile research platform (ECCE) dedicated to the integration and characterization of various hybridization technologies and architectures in real operating conditions. The installation of the FCS into ECCE required some heavy modifications of the vehicle structure and architecture. Prior to moving toward extensive development and testing of energy management algorithms, a validation stage was necessary. The objective of the present paper is to describe this first stage. The first step was the functionality validation of the embedded FCS in term of communication with ECCE's controller and electrical performance in static vehicle operation. The second step of the validation process was to proceed to a slow displacement of the vehicle powered by the FCS and batteries. This research activity was initiated within the framework of the SPACT-80 program and is now continued under a new project called ECCE 2, supported by the DGA (Technology & Procurement Agency of the French Ministry of Defense).

Keywords: Fuel Cell System (FCS), battery, heavy-duty hybrid vehicle, power management

I. INTRODUCTION

At present, we observe an important growth of the worldwide research activity on electric vehicles. However, because of some weaknesses such as autonomy and dimensions, electric vehicles have not reached the point yet where it can fit all needs and be envisioned as a global solution for the mass market. A more progressive hybridization of a classical vehicles powered by internal combustion engine appears as an appropriate path to reduce the energy consumption and the emissions of pollutants [1]. In this context, the ECCE 2 project has been initiated to characterize different energy technologies and architectures for hybrid vehicles in the real conditions of the transportation application. This project represents the continuation of the SPACT-80 program that aimed at designing, developing and testing a Polymer Electrolyte Membrane Fuel Cell (PEMFC) power generator for transportation applications. The SPACT-80 program ended in February 2010 with the successful integration of the FCS developed by HELION into a mobile test platform named ECCE ("Electrical Chain Component Evaluation"). This vehicle is being used for the evaluation of various electric components such as power sources, power electronics as well as their associated control strategies.

II. THE ECCE 2 PROJECT

A. *Description of the project*

The ECCE 2 project, funded by the DGA gathers a public laboratory (FEMTO-ST), a fuel cell manufacturer (HELION, a division of AREVA) and a military vehicle manufacturer (PANHARD). The ECCE test platform (Fig. 1) will be used as a mobile laboratory to accomplish the following tasks:

- Onboard characterization of different energetic solutions: batteries, FCS, ICE-based generators, ultracapacitors and flywheels.
- Testing of different hybrid configurations: FCS/batteries, FCS/batteries/ultracapacitors, batteries/ICE generator, batteries/ ICE-based generators/flywheel…etc.
- Development of specific energy management algorithms corresponding to the specificities of each configuration.

From a general perspective, this project will allow the partners to acquire in-depth knowledge and know-how on the use, control and integration of high power energy components in real scale transportation vehicle.

Fig. 1: The ECCE mobile test platform

978-1-4244-8218-4/10/$26.00 ©2010 IEEE

B. Descrition of the ECCE vehicle

The ECCE platform was designed for testing in real conditions the different components of a heavy-duty military vehicle (Fig. 1). An important amount of work was accomplished between 1997 and 2005 for the conception, modeling, and simulation of this real scale multi-physics system [2, 3, 4, 5]. The structure of the ECCE vehicle in its original configuration has already been detailed in the literature [6, 7]. In order to make the FCS fit into ECCE, the structure of the vehicle has received some heavy modifications. The complete study for this integration was detailed by Jeuvrey *et Al.* in VPPC 2009 [8]. This study included the electric section (power and control/command), the so-called "process" (balance of plant and fuel cell stacks), and the hydrogen storage. Following the FCS integration study, all the mechanical and electrical modifications of the vehicle were accomplished in 2009-2010 (Fig. 2 and 3). The FCS integrated into ECCE is provided by HELION. It features two 110-cell PEMFC stacks with an active surface area of 760 cm². Their normal operating temperature is in the 65 to 75°C temperature range. The two stacks are electrically connected in series and are fed with pure hydrogen and ambient air with a gas distribution in parallel. As shown in Fig. 4, a DC-DC converter connects the FCS to the DC-bus and is in charge of interfacing the energy distribution between the FCS and DC-bus.

The control of the vehicle is handled by a Programmable Logic Controller (PLC) and an AutoBox (Dspace) in charge of the start/run/shutdown sequences, steering and torque calculations, energy management, and safety supervision.

In its new configuration, ECCE is a 14-ton, 4-wheel drive vehicle. The DC-bus of the vehicle is directly connected (i.e. with no power converter) to a pack of lead-acid batteries, maintaining its voltage at a level of about 552 VDC (+10% and -20%). These batteries constitute an electrical source buffer fed by the FCS in a hybrid-series electrical vehicle topology. This DC-bus feeds the 4-electrical traction motors and also the vehicle's auxiliaries (Fig. 4).

Fig. 2: Integration of the fuel cell process unit and air-water heat exchanger

Fig. 3: Integration of the hydrogen bottle rack

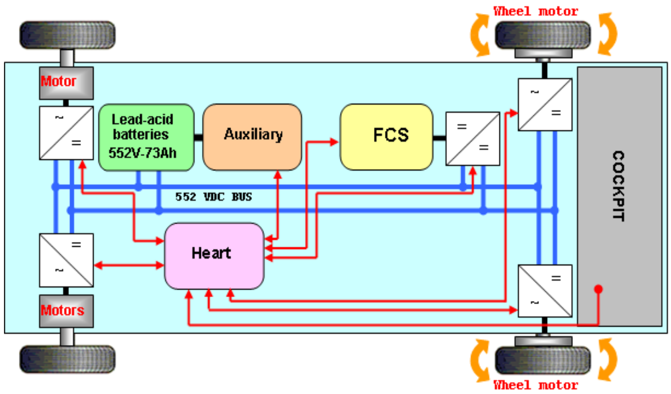

Fig. 4: ECCE powerflow schematic (configuration as of april 2010) [5]

III. EXPERIMENTAL RESULT

A. Static FCS operation validation

After completion of the FCS integration into ECCE and prior to moving on to a vehicle driving phase with the test of different energy management solutions, it was essential to go through a static validation of the FCS in its final vehicle environment. This stage consists in, first, the verification of the FCS capability to communicate both ways with the vehicle controller (also referred as "Heart"), second, the validation of the fuel cell stack and subsystem functionalities (air compressor, valves, pressure regulators, pumps, exchangers…etc) and, third, the electrical performance characterization of the FCS. It is important to note that the FCS is seen as a black box by ECCE's controller. Consequently, only a limited number of parameters are exchanged by ECCE's controller and the FCS (i.e. stop and start orders, current request, FCS operating states, and default alarms…etc). The other parameters that are specific to the FCS such as the algorithm variables and the internal signals are strictly managed by the FCS controller itself.

In the case of a static test of the FCS (vehicle parked), the total electric consumption of the vehicle was limited to its accessories as the electric motors could not be used to dissipate the power supplied by the FCS to the DC-bus of the vehicle. For this purpose, a 100 kW resistive DC-load was connected to the DC-bus of the vehicle. It was used as an external power consumer preventing any overvoltage on the DC-bus and consequently potential damages to the battery pack. This test was carried out in complete automatic operation of the FCS. A start order is initially transmitted to the FCS from the vehicle controller. The start up procedure of the FCS is then launched. Once the FCS is ready to operate and deliver power, the FCS controller informs the vehicle controller and a current request can be sent to the FCS and progressively increased.

In these conditions, the FCS demonstrated a maximum net power of 35 kW (Fig. 5). The net current sent onto the DC-bus by the FCS power converter was about 65A at a mean voltage of 545 V. This performance appears to be slightly below the 50kW-range that was initially targeted [8]. The main explanations to this performance level are reviewed hereafter.

During this test, a careful monitoring of the stack voltages and individual cell voltages was required in order to prevent any damage to the stacks. Fig. 6 shows the average cell voltages of each fuel cell stack. At peak power, the average cell voltages of the stacks n°1 and n°2 were respectively of 0.693 and 0.667 V. These voltage levels did not represent the limiting factors for reaching higher power levels. However, some individual cells exhibited overly low voltages which represented a real limit.

The other limiting factors that have been identified during this test are a normal ageing of the stacks, a pressure regulation problem of the cathodic and anodic sides of the stacks, a limitation related to the control algorithm of the FCS air blower, as well as a very cold ambient temperature. Of course, the regulation and control difficulties will be addressed before proceeding to any extensive dynamic testing of the vehicle.

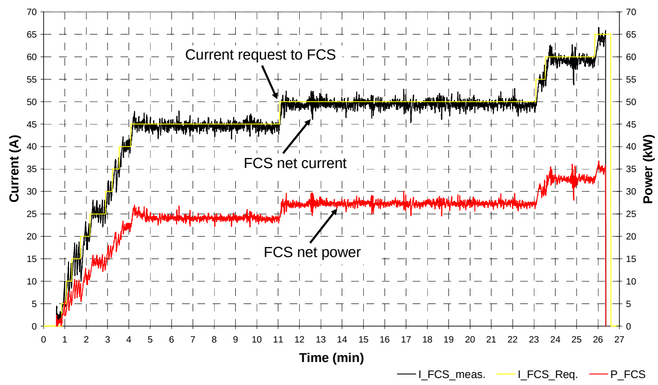

Fig. 5: Peak power reached by the FCS in static vehicle operation

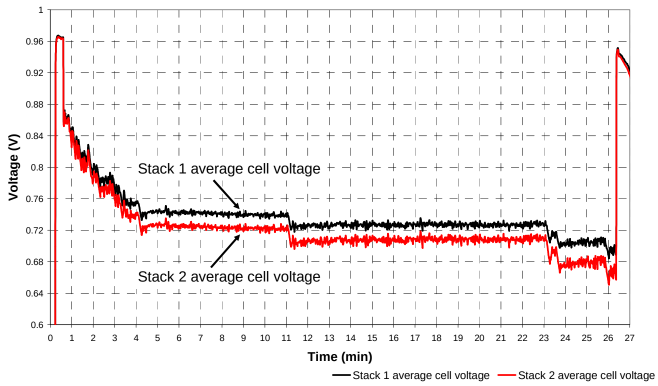

Fig. 6: Fuel cell stack average cell voltage in static vehicle operation

B. FCS operation with slow vehicle displacement

The second and final stage of the validation process consisted in a slow displacement of the vehicle while running on the batteries and FCS. During this operation, no energy management algorithm was implemented in the vehicle controller yet. Our objective was limited to the validation of the vehicle's capability to operate the multiple components of the energy chain (from the power sources to the motors) altogether. In this operating mode, the batteries provided most of the power to enable the displacement of the vehicle. The current supplied by the FCS onto the DC-bus is adjusted in order to regulate the bus voltage and prevent any damage to the batteries. The FCS current was increased during the acceleration periods in order to limit the drop of the bus voltage. Alternatively, the current request was decreased when the vehicle was slowing down in order to prevent rapid jumps of the bus voltage.

The variation of the DC-bus voltage throughout the vehicle displacement test is shown on Fig. 7. The major voltage drops correspond to the vehicle acceleration phases when the vehicle starts moving forward or backward from a parked position. Indeed, the important weight of the vehicle imposes a massive energy peak, and consequently a drop in the bus voltage, in order to initiate the displacement. Thus, the bus voltage variation was comprised between 519 and 576 V.

Fig. 8 shows the battery and FCS currents throughout the vehicle displacement test. The maximum currents delivered by the battery and FCS were respectively of 42 and 21A. The major part of the total current appears to be supported by the battery. The profile of this test based on small displacements of the vehicle with only acceleration and deceleration phases clearly explains the limited contribution of the FCS. Indeed, Helion's FCS is purposely not designed for high dynamic operations and its controller imposes current ramps in order to let the air blower increase its rotational speed, and therefore avoid operation of the stack cathode at low stoichiometric ratio. In addition, the FCS current has to be carefully controlled because of the high internal resistance of the battery pack which is composed of 45 individual 12V lead-acid modules arranged in electrical series. In consequence, a small variation of the FCS current supplied to the DC-bus creates an important variation of the bus voltage which can potentially damage the battery.

The negative values of the battery current that can be seen on figure 8 show the recharging phases of the batteries. The batteries are then recharged thanks to the energy recovery and the additional current supplied by the FCS.

In term of power, the batteries and FCS supplied to the DC-bus respectively up to 18 kW and up to 36 kW throughout the test (Figure 9).

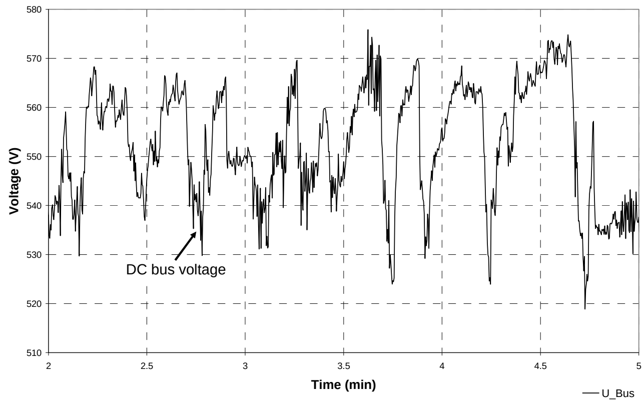

Fig. 7: DC-Bus voltage in slow dynamic vehicle operation

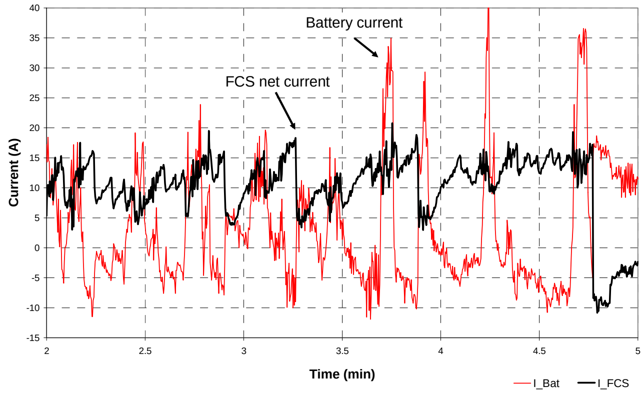

Fig. 8: FCS and battery current in slow dynamic vehicle operation

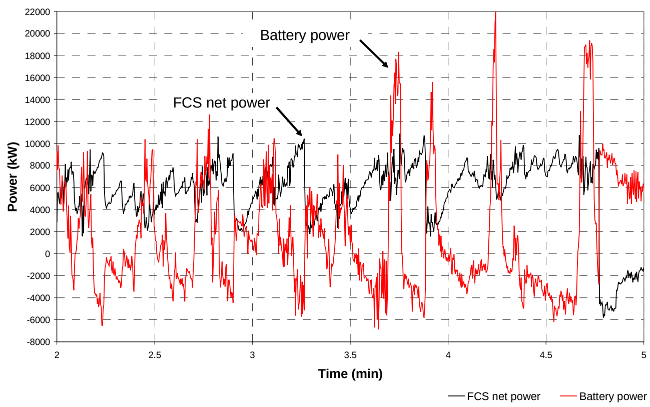

Fig. 9: FCS and battery power in slow dynamic vehicle operation

In this configuration, the control of the FCS/battery coupling appears quite challenging for several reasons. The first one is inherent to the high internal resistance of the battery, related to the association of several module of lead-acid battery that imposes a close monitoring of the bus voltage, associated with a careful control of the delivered FCS current. The second one is inherent to the dynamic limitations implemented in the FCS control strategy. Thus, rapid current jumps are internally limited by the FCS controller and a more progressive ramp is then applied while the blower rotational speed is progressively increased.

These remarks tend to demonstrate that the role of the FCS in ECCE's current configuration has to be limited to the support and/or recharge of the battery when the vehicle is operated in steady state conditions or idled. This present limitation was indentified prior to this test, but it is important to keep in mind that this test was carried out as the last stage of a component validation process. The objectives were the validation of the FCS operation in the vehicle as well as its interactions with the other components of the vehicle (i.e.: controller, DC-bus…etc). In consequence, this test can be considered as a success and authorizes to move on to the next stages of the ECCE 2 project.

The basic control software implemented in ECCE's controller and used for the validation process will become the corner stone for the future integration and test of energy management algorithms. Some of these algorithms have already been developed in previous works [8, 9, 10, 11, 12] and some others are still under active development [13].

CONCLUSIONS

This paper presents the major achievements of the ECCE 2 project to-date. The fuel cell system developed by HELION within the framework of the SPACT-80 program has been successfully integrated and validated into the heavy-duty mobile test platform named ECCE. A maximum net power of 35kW was reached with the FCS in static vehicle operation and some driving experiments were also accomplished.

Some of the limitations of the FCS / battery coupling have been highlighted in this paper. The upcoming vehicle testing with extended vehicle displacement will obviously help the FCS to reach higher current levels and will provide a more detailed vision of the interest and limitations of the FCS/ battery coupling. The future stages of the project will also consist in the integration of an energy management algorithm dedicated to the FCS/battery coupling. Some new hybridization architectures based on other energy sources such has ultracapacitors, flywheels and ICE-based generators as well as their associated energy management algorithms will also be integrated into the vehicle Thus, the limitations of the current configuration should be at least partially overcome by the integration of highly dynamic power sources. Of course, new energy management constraints will appear and will have to be addressed. These next stages of the ECCE 2 projects will lead to additional papers.

AKNOWLEDGMENT

This work was initiated under the SPACT-80 program and sponsored by the French National Research Agency (ANR). This program gathered CEA, HELION, INRETS, UTBM-FCLAB, SNCF, and DGA. It is now continued under the ECCE 2 project and sponsored by DGA. The project partners are FEMTO-ST/ENYSIS (University of Franche-Comté), PANHARD, and HELION.

REFERENCES

[1] Boulon, L.; Hissel, D.; Bouscayrol, A.; Pera, M.C.; Delarue, P., "Multi physics modelling and representation of power and energy sources for Hybrid Electric Vehicles," *Vehicle Power and Propulsion Conference, 2008. VPPC'08. IEEE,* pp. 1-6, 3-5 Sept. 2008, doi: 10.1109/VPPC.2008.4677665

[2] Espanet, C.; Tekin, M.; Bernard, R.; Miraoui, A.; Kauffmann, J.-M., "A new structure of an high torque in-wheel motor", S*ixth International Conference on Electrical Machines and Systems, 2003. ICEMS 2003* , vol. 1, pp. 158-162, 9-11 Nov. 2003, doi: 10.1109/ICEMS.2003.1273835

[3] Pusca, R.; Ait-Amirat, Y.; Berthon, A.; Kauffmann, J.M., "Modeling and simulation of a traction control algorithm for an electric vehicle with four separate wheel drives," *Vehicular Technology Conference, 2002. Proceedings. VTC 2002-Fall. 2002 IEEE 56th* , vol. 3, pp. 1671-1675, 2002, doi: 10.1109/VETECF.2002.1040500

[4] Pusca, R.; Amirat, Y.A.; Berthon, A.; , "Fuzzy logic speed estimator to drive a four electric wheels truck," *The 4th International Power Electronics and Motion Control Conference, 2004, IPEMC 2004* , Vol. 3, pp. 1448- 1453, 14-16 Aug. 2004

[5] Espanet, C.; Kauffmann, J.-M.; Bernard, R., "Comparison of Two In-Wheel Permanent Magnet Motors for Military Applications", *Vehicle Power and Propulsion Conference, 2006, VPPC '06. IEEE*, pp. 1-6, 6-8 Sept. 2006, doi: 10.1109/VPPC.2006.364300

[6] El Kadri, K.; Djerdir, A.; Berthon, A., "Hybrid Energy Sources for Heavy Truck: Simulation and Behavior", *Power Electronics and Motion Control Conference, 2006. EPE-PEMC 2006. 12th International*, pp. 1395-1400, Aug. 30 2006-Sept. 1 2006, doi: 10.1109/EPEPEMC.2006.4778598

[7] El Kadri, K.; Berthon, A., "Simulation of a dual hybrid generator for heavy vehicle application," *IEEE Industrial Electronics, IECON 2006, 32nd Annual Conference on*, pp. 2642-2647, 6-10 Nov. 2006 doi: 10.1109/IECON.2006.347255

[8] Jeuvrey, J.; Harel, F.; Begot, S.; Hissel, D.; Rodel, I.; Faure, V.; Boblet, S., "Fuel cell system integration on a heavy-duty vehicle and development of a control strategy with real time simulation", *Vehicle Power and Propulsion Conference, 2009. VPPC '09. IEEE*, pp. 704-710, 7-10 Sept. 2009, doi: 10.1109/VPPC.2009.5289780

[9] El Kadri, K.; Berthon, A., "Energy Management Operating Modes Concerning a Hybrid Heavy Vehicle", *EUROCON, 2007, The International Conference on "Computer as a Tool"*, pp. 1587-1593, 9-12 Sept. 2007, doi: 10.1109/EURCON.2007.4400566

[10] Bernard, J.; Delprat, S.; Buechi, F.; Guerra, T.M., "Global Optimisation in the power management of a Fuel Cell Hybrid Vehicle (FCHV)," *Vehicle Power and Propulsion Conference, 2006. VPPC '06. IEEE* , pp. 1-6, 6-8 Sept. 2006, doi: 10.1109/VPPC.2006.364289

[11] Tekin M.; Hissel D.; Pera M.C.; Kauffmann J.M., "Energy-Management Strategy for Embedded Fuel-Cell Systems Using Fuzzy Logic," *Industrial Electronics, IEEE Transactions on*, vol. 54, no.1, pp.595-603, Feb. 2007, doi: 10.1109/TIE.2006.885471

[12] Chen, K.; Bouscayrol, A.; Berthon, A.; Delarue, P.; Hissel, D.; Trigui, R.; , "Global modeling of different vehicles using Energetic Macroscopic Representation," *Vehicle Power and Propulsion Conference, 2008. VPPC '08. IEEE*, pp. 1-7, 3-5 Sept. 2008, doi: 10.1109/VPPC.2008.4677728

[13] Solano-Martinez, J.; Boulon, L.; Hissel, D.; Pera, M.-C.; Amiet, M.;, "Energetic macroscopic representation of a multiple architecture heavy duty hybrid vehicle," *Vehicle Power and Propulsion Conference, 2009. VPPC '09, IEEE*, pp. 1322-1329, 7-10 Sept. 2009, doi: 10.1109/VPPC.2009.5289445