DEVELOPMENT AND EXPERIMENTAL EVALUATION OF THE CONTROL SYSTEM OF A HYBRID FUEL CELL VEHICLE

Carlos Bordons[a], Miguel A. Ridao[a], Eduardo López[b], David Marcos[a], F. Isorna[b] and F. Rosa[b]

[a]*Escuela Técnica Superior de Ingenieros, Universidad de Sevilla. Camino de los descubrimientos s/n, 41092 Sevilla, Spain*

[b]*Instituto Nacional de Técnica Aeroespacial (INTA)*
Ctra. S. Juan-Matalascañas, km.34
21130 Mazagón (Huelva) – Spain

Abstract:

This work presents the development and experimental evaluation of a Fuel Cell Hybrid Vehicle, focusing on the control system. The main objective of this paper is to present a real vehicle which has been designed in order to demonstrate the feasibility of the use of hydrogen as an energy source for automotive applications.

The paper describes the components that are integrated in the vehicle and presents several experimental results obtained during normal operation. A control system is designed and tested in order to perform all the operations related to the coordinated operation of the fuel cell, the intermediate electrical storage and the power train. Its main task is to compute the power that must be demanded to the fuel cell in real time. This computation is done in order to satisfy the power demand of the electric motor taking into account the state of charge of the batteries and the operating regime of the fuel cell. This is accomplished by manipulating the electronic converter which regulate the current that the fuel cell supplies to the batteries.

Keywords: Fuel Cells, Hybrid Vehicles, Control Systems, Power Management

1. Introduction

Fuel cells have been considerably developed in the last decade because of the social energy concern. They are considered as good candidates in the future of conventional energy resources, provoking an energy revolution in stationary and mobile applications. In recent years, with the problems of energy shortage and air-pollution becoming more and more serious, interest in alternative automotive power train has increased steadily. The research on Fuel Cell Vehicles (FCV) is considerably increasing in the area of clean vehicle technology, as good candidates for substituting traditional vehicles.

Accordingly with [1], vehicles cannot be driven only by fuel cells because such systems need energy storage in order to support the fuel cell during the start-up and acceleration peaks, also storing energy during regenerative braking. There are many papers which analyze storage systems and the possibilities presented are twofold: firstly, conventional batteries, remarking Lithium-ion batteries [2]; and secondly, ultracapacitors. Batteries generally have high energy density but less power density compared to ultracapacitors. The principal weakness of battery technologies are cycle life and cost. So power

Corresponding author: Carlos Bordons. E-mail: bordons@esi.us.es. +34 954487348.

batteries are usually applied in FCVs, which are so-called fuel cell hybrid vehicles (FCHV). Most major vehicle manufactures have developed prototype FCHVs for technology evaluation and demonstration purposes [3,4].

Academic research groups are also actively working on this emerging technology. Guezennec et al. [5] solved the supervisory control problem of a FCHV as a quasi-static optimization problem and found that hybridization can significantly improve the fuel economy of FCVs. Mohsen Mohammadian et al. [6] proposed a control strategy developed for optimizing the energy flow by using evolutionary algorithms implemented on a fuel cell hybrid vehicle to reach the best performance, fuel economy, emission and acceptable operation of this hybrid structure. Haitao et al. [7] presented an integrated procedure for math modeling and power control strategy design for a fuel cell hybrid vehicle that takes into account the performance and economy characteristics of components.

The main objective of this paper is to present a real vehicle which has been designed in order to demonstrate the feasibility of the use of hydrogen as an energy source for automotive applications. The operation strategy is based on many state-of-the-art works about power management in fuel cell hybrid vehicles such as [8], [9], [10], which apply several control techniques for the power management. The main contribution of the paper is the implementation of a simple control strategy and the tests performed on the real vehicle.

This work has been done in the framework of a joint research project between the University of Seville and the Instituto Nacional de Técnica Aeroespacial (INTA), in Spain. Notice that these two research institutions have a background on the design of hybrid FCVs, including the production of hydrogen from renewable sources [11]. The objective of this research project is to demonstrate the feasibility of the use of hydrogen as an energy source for automotive applications. This paper focuses on the development and evaluation of the control system.

The paper is organized as follows: in section 2, the vehicle and its components are described. Section 3 presents the control system and the experimental results of the tests carried out in the real vehicle are shown in section 4. Finally, conclusions and future work are discussed in section 5.

2. Vehicle and Components description

A market electric vehicle (GEM eL, from Global Electric Motocars) has been used as the experimental platform, where a PEM fuel cell, a hydrogen storage system and a power converter have been integrated, as shown in figure 1. Additionally, a control system has been developed in order to guarantee a safe operation of the vehicle.

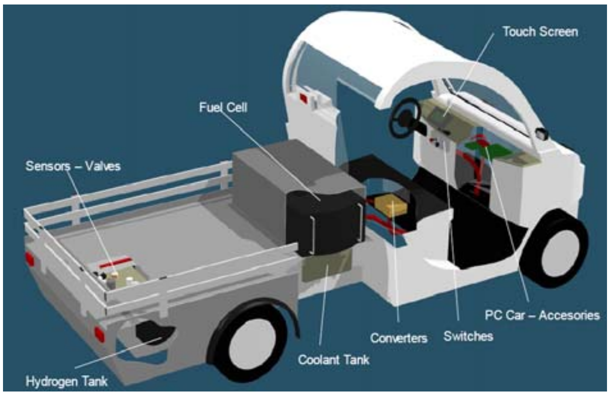

Figure 1. Vehicle components

The original power train of the vehicle has been used, although in the next stage a modification is foreseen. The power of the D.C. electric motor is 3.72 kW at 72 Volts, with 6 gel batteries of 12 V each one. The PEM fuel cell is the HyPM-12XR, supplied by Hydrogenics, whose main characteristics are:

- Maximum output power: 12.5 kW
- Otuput voltaje range: 37-57 V
- Maximum current: 350 A
- Dimension: 96 x 50 x 32 cm.
- Volume: 153.6 l
- Weight: 90 kg

Notice that the fuel cell is oversized, the reason for this is that the electrical power supplied can be used for other loads in the vehicle that will depend on its use (surveillance, telecommunication, UPS, etc.).

Hydrogen is stored on board at 200 bar using a tank supplied by Dynetek (model L033), with a capacity of 5.8 Nm^3, equivalent to 476.25 grams of hydrogen (see figure) and 33 litres of volume. The hydrogen storage system includes pressure sensors, electro valves, regulators and the outlet connection for refuelling. Notice that there exists a pilot plant in our facilities that generates hydrogen from solar energy which can be connected to this vehicle, achieving as a second objective a refuelling plant with hydrogen coming from renewable energy. Figure 2 shows the current state of the prototype.

Figure 2. Rear view of the prototype showing the fuel cell.

3. Control System and integration

The controller must determine how to operate the different power units (fuel cell, batteries and converters) to fulfil the power demanded by the motor in the most convenient way. Also, the most important parameters of the system are monitored and historical data are stored.

The control system is based on an embedded controller (PC-104) located in the dashboard of the car. Figure 3 shows a scheme with the different modules of the system and communication among them. CANBus protocol (CAN 2.0A) has been implemented for linking the control system and the fuel cell, allowing the operation of the fuel cell and the reception of its status and parameters for control and monitoring purposes, with a communication speed of about 250 kbits/s. Communication between the control system and the power converter is performed using a RS-232 protocol.

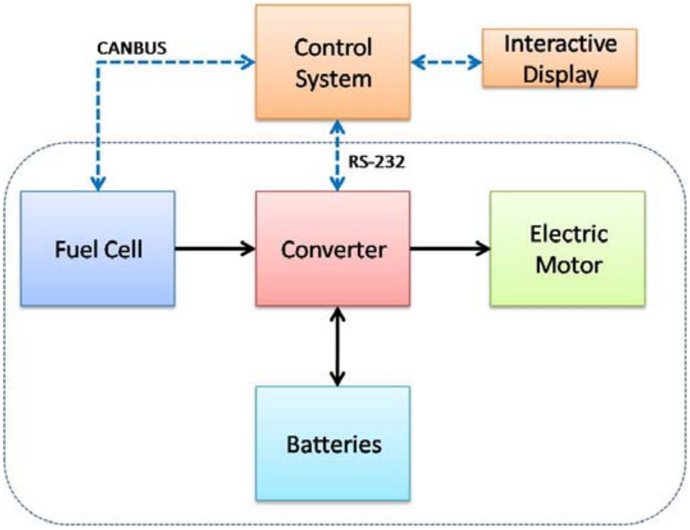

Figure 3. Control system scheme.

The main tasks of the control system are:

- **Start-up and shut-down procedures:**
  The start-up procedure has been designed to efficiently start up the different units in an ordered way, taking into account security aspects. That includes the hydrogen storage system, power converter and, in communication with the electronic control unit (ECU) of the fuel cell, switch among the different states of the fuel cell. Also, procedures have been implemented to shut-down the system.

- **Power management:**
  Power management is an important task. It consists of computing the power that must be demanded to the fuel cell in real time. This computation is done in order to satisfy the power demand of the electric motor taking into account the state of charge of the batteries and the operating regime of the fuel cell. This is accomplished by manipulating the electronic converter which demands the power that the fuel cell supplies to the batteries. Several control strategies can be used in

power management of fuel cell hybrid vehicles [8]. The maintenance of the battery state of charge is the one used in this application. The fuel cell is used to maintain the charge in batteries while the vehicle is powered mainly by the battery system.

- **Monitoring:**
  The control system monitors fuel cell and other systems operating conditions. Most of the variable of the system (voltages, currents, temperature and hydrogen pressure) are shown under user request and historical data are stored and are available for studying the vehicle performance. Also the operator is informed of any critical system condition to facilitate user intervention when needed.

- **HMI:**
  Control actions can be executed and the system status is displayed in a touch screen. Figure 4 shows one of the screens, where it can be seen the general status of the vehicle, including alarms in different subsystems and buttons to launch start-up and shut-down procedures.

Figure 4. Driver's display

4. Experimental results

The control system has been tested under several driving conditions and it has shown that it is able to fulfil the requested objectives, showing useful information to the driver about system functioning. The software stores a sort of data, useful for the developers: converter input and output current, voltage of the batteries, hydrogen pressure, etc. Analyzing this information it is possible to see the performance of the system, previewing hypothetical problems, and correcting possible developing mistakes.

Figure 5 shows a graphic that represents some of the stored variables.

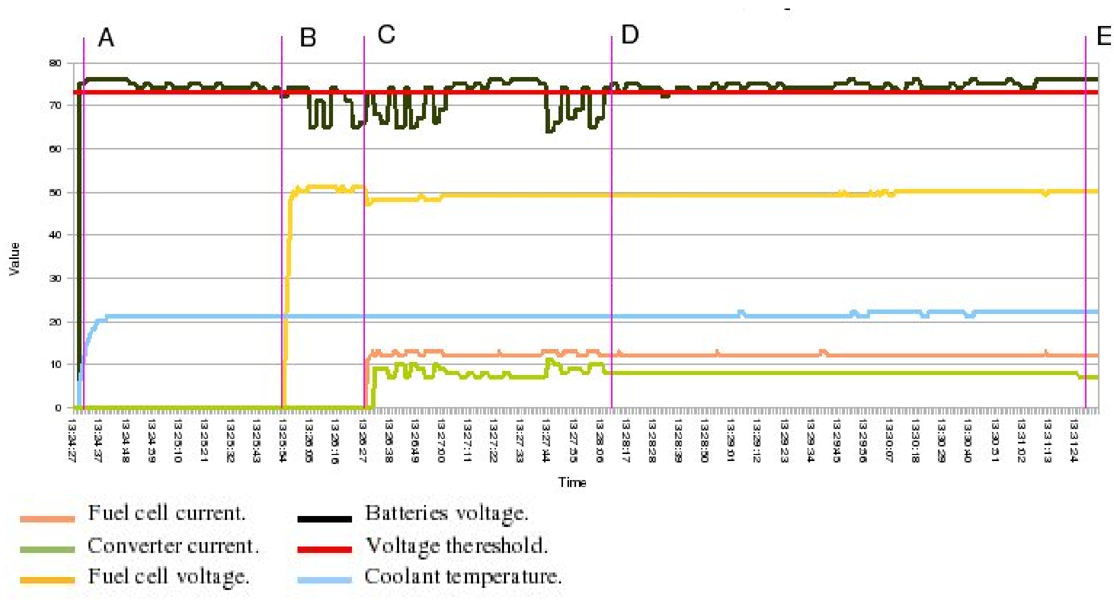

Figure 5. Evolution of electrical variables.

The graphic shows the first minutes of operation of the car. Several time windows can be identified that correspond to different situations:

- Window A-B: The system has been started. The car is stopped until the driver/passengers are ready, or it is running at low speed.
- Window B-C: At 'B' the batteries voltage reaches the threshold. The fuel cell enters run mode; therefore its voltage increases fast from 0 to 52 volts. The system waits some time for the fuel cell to stabilize before requesting any power, so the fuel cell current is still zero. The oscillations of the batteries voltage are produced by the driving cycle. The driver may be accelerating and braking the car continuously.
- Window C-D: At 'C' The converter starts requesting power to the fuel cell, so its current experiences a fast increase, until it reaches 12-14 A approximately. The oscillations of the current correspond to the ones of the voltage, caused by the aggressive driving mode. The falling of the voltage means that the motor requires more power; therefore the current from the fuel cell must increase. The electronic power converter turns the fuel cell voltage from about 50 volts to more than 70, so its current is lower than the output current of the fuel cell as it's shown in the graphic.
- Window D-E: Everything is still the same but the driving. The batteries voltage has very little oscillation, which means that the car is set to a constant and moderated speed. Consequently, current suffer very low variations. Despite the voltage keeps higher than the threshold for a period of time, the fuel cell continues running and power is still being required for charging the batteries. Actually, the fuel cell will work until the batteries voltage reaches a higher threshold; and it won't be stopped until the voltage falls again lower than the threshold shown in the figure, as previously explained.

Coolant temperature: During the time that the fuel cell is running, the coolant temperature increases about two degrees. However, the fuel cell wouldn't get damaged unless the temperature reaches 75º C, and it's not supposed to happen. Nevertheless, if the limit temperature is exceeded the fuel cell would automatically be stopped by the controller. The following figure shows the evolution of the coolant temperature in a longer experiment (about five hours long).

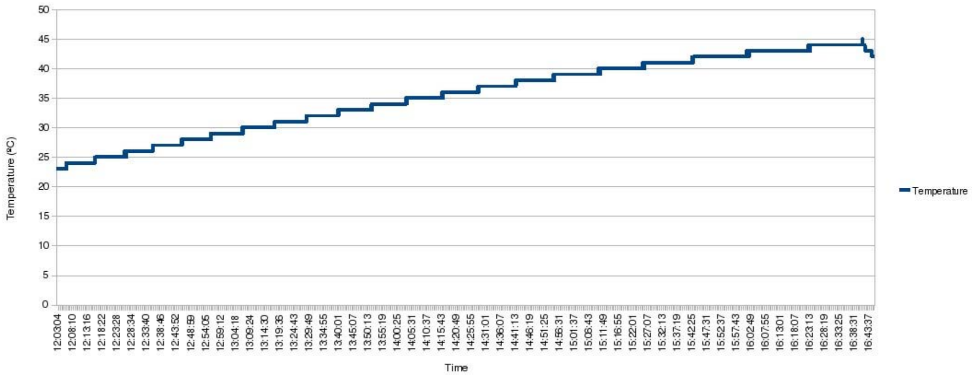

Figure 6. Temperature evolution.

In the same test it is possible to see how the batteries voltage increases from about 73 to 77 volts. Figure 7 shows the oscillations of the first minutes caused by a testing driving (accelerating and braking continuously), and a constant evolution when the car is running at cruise speed.

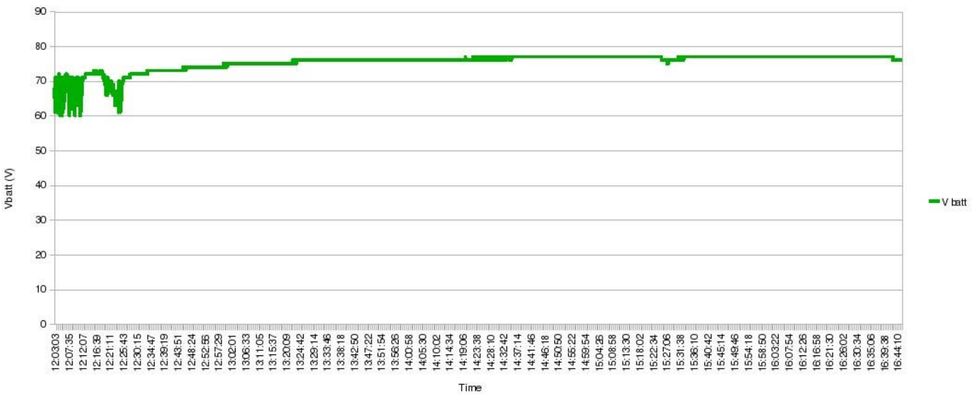

Figure 7. Battery voltage evolution.

Other interesting variable is hydrogen consumption. Figure 8 shows the evolution of the tank level, that decreases at 0.625 g/min average. Assuming that the tank capacity is 476.25 grams, the system could be working for more than twelve hours.

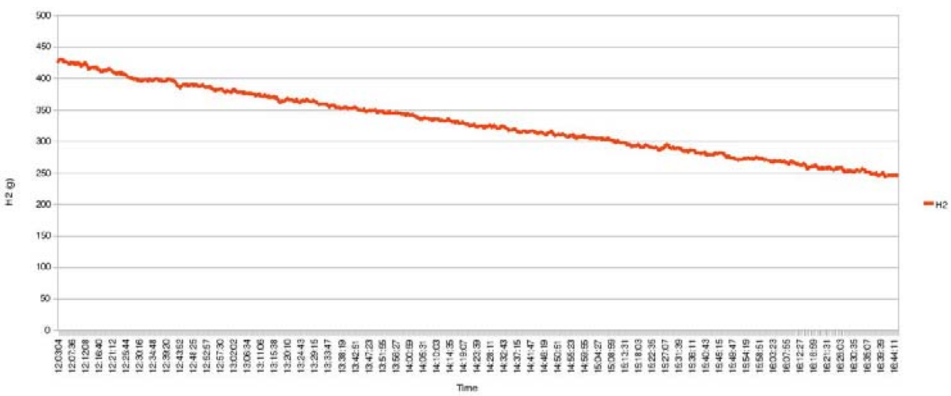

Figure 9. Hydrogen consumption.

5. Conclusions and Future Work

This work has presented the development and experimental evaluation of a Fuel Cell Hybrid Vehicle, focusing on the control system. A market electric vehicle has been used as a platform to demonstrate the feasibility of the use of hydrogen as an energy source for automotive applications. A control system has been designed and tested in order to perform all the operations related to the coordinated operation of the fuel cell, the intermediate electrical storage and the power train. Experimental results obtained during the operation of the vehicle show that the power demanded by the driver is supplied in a coordinated manner using the fuel cell and the battery.

As a future work, the prototype is being re-designed using a smaller fuel cell and a bigger converter that can manage all the current that the fuel cell can deliver, making it work in the most efficient operating point. Also, the authors of the paper are also working on a bigger prototype, a SUV vehicle with a 68 kW electric motor and lithium-ion batteries.

6. Acknowledgements

The authors want to acknowledge Manuel R. Halcon and Carlos Montero for their collaboration. This work was supported in part by the Spanish Ministry of Science and Technology under Grant DPI2007-66718-C04-01.

7. References

[1] C. Chan, The state of the art of electric hybrid and fuel cell vehicles, in: Proceedings of the IEEE, Vol. 95, 2007, pp. 704–718.

[2] A. Burke, Batteries and ultracapacitors for electric, hybrid and fuel cell vehicles, in: Proceedings of the IEEE, Vol. 95, 2007, pp. 806–820.

[3] T. Ishikawa, et al., Development of next generation fuel cell hybrid system—consideration of high voltage system, SAE paper, No.2004-01- 1304.

[4] A. Ohkawa, Electric power control system for a fuel cell vehicle employing electric double-layer capacitor, SAE paper, No.2004-01-1006.

[5] Y. Guezennec, T.-Y. Choi, G. Paganelli, G. Rizzoni, Supervisory control of fuel cell vehicles and its link to overall system efficiency and low-level control requirements, in: Proceedings of the American Control Conference, Denver, CO, 2003.

[6] Mohsen Mohammadian, et al., Neuro-genetic energy management for hybrid fuel cell power train, in: Proceedings of the 2006 IEEE Conference on Cybernetics and Intelligent Systems, Singapore, 13 December 2006.

[7] Yun Haitao, Zhao Yulan, Sun Zechang , Wan Gang, Model-based power control strategy development of a fuel cell hybrid vehicle. Journal of Power Sources 180 (2008) 821–829.

[8] L. Guzella, A. Sciarretta, Vehicle Propulsion Systems: Introduction to Modeling and Optimization, Springer, 2005.

[9] J. Bernard, S. Delprat, F. Buechi, T. Guerra, Global optimization in the power management of a fuel cell hybrid vehicle (FCHV), in: Proceedings of 2006 Vehicle Power and Propulsion Conference, 2006.

[10] M. Gielniak, Z. Shen, Power management strategy based on game theory for fuel cell hybrid electric vehicles, in: Proceedings of 2004 Vehicular Technology Conference, Vol. 6, 2004, pp. 4422–4426.

[11] M. Arxer, L. M. Calleja, Hercules project. Contributing to the development of hydrogen infrastructure, Journal of Power Sources 171 (1) (2007) 224–227.