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Airport electric vehicle powered by fuel cell☆

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Abstract

Nowadays, new technologies and breakthroughs in the field of energy efficiency, alternative fuels and added-value electronics are leading to bigger, more sustainable and green thinking applications. Within the Automotive Industry, there is a clear declaration of commitment with the environment and natural resources. The presence of passenger vehicles of hybrid architecture, public transport powered by cleaner fuels, non-aggressive utility vehicles and an encouraging social awareness, are bringing to light a new scenario where conventional and advanced solutions will be in force.

This paper presents the evolution of an airport cargo vehicle from battery-based propulsion to a hybrid power unit based on fuel cell, cutting edge batteries and hydrogen as a fuel. Some years back, IBERIA (Major Airline operating in Spain) decided to initiate the replacement of its diesel fleet for battery ones, aiming at a reduction in terms of contamination and noise in the surrounding environment. Unfortunately, due to extreme operating conditions in airports (ambient temperature, intensive use, dirtiness, ...), batteries suffered a very severe degradation, which took its toll in terms of autonomy. This reduction in terms of autonomy together with the long battery recharge time made the intensive use of this fleet impractical in everyday demanding conditions.

Keywords: PEMFC; Hydrogen; Airport; Vehicle; Hybrid system

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1. Introduction

Fuel cells are systems that can produce electricity from fuel continuously and much more efficiently than the combustion systems used until now, which have a Carnot limitation in the maximum efficiency reached. Moreover, with the use of fuel cells the CO_2 emission (coming from the hydrogen production, if not renewable) is reduced considerably compared with the internal combustion motors, at the same time that the emissions of other contaminants such as NO_x, SO_2, hydro carbons, etc. are removed completely.

The fuel cells are expected to play, in the short and long term, an important role in the sustainable supply of energy, since it allows an important energy saving as well as a diversification of energy sources.

Fuel cells have characteristics that make them suitable for their application in the propulsion field, one of the most important sources of contamination emissions and greenhouse effect nowadays. The most adequate fuel cells for this application are the so-called polymer proton exchange membrane (PEMFC) used widely in research and demonstration projects led by several automobile manufacturers.

Focusing on the airport sector, one of the main aviation impacts are the atmospheric emissions of the motors, in a local level in the airport surrounding areas, as well as globally, due to the emissions generated in crossing. The aviation industry is

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Nomenclature

A_{PEM}	regime variation capacity of the fuel cell
C_{BAT}	capacity of the batteries system
$C_{\mathrm{H_2}t}$	hydrogen consumption in a period of time (t)
$\mathrm{CO_2}$	carbon dioxide
$C(P_{\mathrm{SS}},T_{\mathrm{SS}})$	correction coefficient in normal conditions
DC	discharge coefficient of the batteries
E_{SS}	energy contained in the hydrogen storage system
I_{BAT}	current of the batteries
I_{EL}	current demanded by the electronic charge
I_{M}	current demanded by the electric motor
I_{PEM}	current supplied by the fuel cell
I_{PS}	current supplied by the power source
$\mathrm{LHV}_{\mathrm{H_2}}$	lower heating value of the hydrogen in normal conditions
NO_x	oxide of nitrogen
$P_{\mathrm{FC}t}$	power supplied by the fuel cell and DC/DC converter system during the period of time (t)
$P_{\mathrm{N_{PEM}}}$	nominal power of the fuel cell
$P_{\mathrm{PEMmax}t}$	maximum power that the fuel cell can supply in the period of time (t)
$P_{\mathrm{PEM}t-1}$	power that the fuel cell was supplying during the period of time $t-1$
P_{SS}	hydrogen storage pressure
$\mathrm{SO_2}$	sulfur dioxide
SOC_t	state of charge of the batteries during the period of time (t)
SOC_{t-1}	state of charge of the batteries during the period of time $t-1$
T_{SS}	hydrogen storage temperature
Δt	time step considered
V_{BAT}	voltage of the batteries system
V_{PEM}	voltage of the fuel cell
V_{SS}	volume of the hydrogen storage system
$z_{\mathrm{H_2}}$	hydrogen compressibility factor

Greek symbols

η_{c}	efficiency of the batteries charge process
$\eta_{\mathrm{DC/DC}}$	efficiency of the DC/DC converter
η_{FC}	efficiency of the fuel cell
$\rho_{\mathrm{H_2}}$	hydrogen density under normal conditions in the gaseous state

permanently searching for alternatives to reduce these emissions by means of research, developments and collaborations.

The emissions generated by vehicles in the ground support operations also influence the air quality in the surrounding areas of the airport, as well as in the emissions of installations linked above all to airplane maintenance operations. One of the solutions proved until now to reduce contaminant emissions of land vehicles has been to replace diesel vehicles by electric vehicles. However, these vehicles are heavy and have low autonomy.

IBERIA, as responsible for an important fleet of land vehicles in operation in the main Spanish airports, decided to carry out a project to develop an airport vehicle with a hybrid power system. This project is based on the hydrogen fuel cell technology to solve the operation problems detected in the airport handling operations. The designer and integrator of this system is BESEL, with the collaboration of the electrical engineering department of the Carlos III University, in Madrid.

The main objective of the project is to design and build a prototype of a hybrid electric vehicle for the airport sector, which includes a new propulsion system based on electric motor and hydrogen fuel cell, offering advantages over the existing vehicles regarding autonomy, charging time, efficiency and emissions.

There are several types of transport systems with electric motor associated to the handling activities of IBERIA. Specifically, due to its singular characteristics and its possibility of extrapolation, an electric conveyor, which transports the cargo from the loading vehicle (pallet-carriers, containers) to the aerial platform, which elevates the load to the storage compartment of the aircraft, was selected.

The main scientific and technological goals of the project are:

- Autonomy improvement of existing electric vehicles.
- Definition of the ideal configuration of the system, adjusted to the general characteristics that the vehicle will require, regarding the location of components, security requirements, etc.
- Development of power electronics specifically designed, with the necessary requirements to manage the power given by the cell and the batteries charge/discharge process.
- Development of a control system, based on a microprocessor, that must monitor and control all power systems (generators, protections and batteries), as well as other important variables of the propulsion and vehicle systems.
- Reduction of the refuelling time of the vehicles, with the incorporation of immediate spare hydrogen storage system and high energy density.
- In a long term, elimination of the contaminants emissions of the current vehicles that use internal combustion motors since they will be replaced progressively by systems based on fuel cells.

There is much literature on the description of fuel cell performance and the development of electric vehicles. We shall highlight Refs. [1–3] for the first one, and Refs. [4,5], among several others, for the second one. However, the literature about the hybrid fuel cell and batteries is not as extensive, although in the last years several interesting publications in this field have been written, such as Refs. [6,7].

2. Theory and calculation

2.1. Computer simulation of the hybrid system

When designing a hybrid vehicle, the simulation of its performance is an essential tool, which will provide us information that we shall use during the system measuring and optimization processes.

Table 1
Hydrogen compressibility factor (source: Spanish Hydrogen Association)

Pressure (bar)	1	50	100	150	200	250	300	350	400	500	600	700	800	900	1000
z_{H_2}	1	1032	1065	1089	1132	1166	1201	1236	1272	1344	1416	1489	1560	1632	1702

The simulation program must have two main characteristics: the versatility to face different situations that may take place during the operation of a hybrid vehicle, and the precision of the results obtained, which will be mainly determined by the accuracy percentage of the first data and the calculations done. To improve these two characteristics of the simulation program, specific software was developed according to project requirements, which takes the real consumption of the vehicle, measured with a monitoring system, as a starting point of the calculation process.

Once the consumption of the electric motor of the vehicle is known, the supply of the power needed was distributed between the fuel cell and batteries, as will happen in the hybrid system, that is, the fuel cell will be in charge of all the power demand of the motor that is below its nominal power, giving the batteries the power over this value.

The simulation of the hybrid system was carried out mathematically modelling the performance of the different components involved.

- Hydrogen storage system:

  The hydrogen storage system is determined by its volume and storage conditions (pressure and temperature). The calculation of the energy contained in the storage system was done through the expression (1), considering besides these parameters the lower heating value LHV_{H_2} and the density ρ_{H_2} of the gaseous hydrogen, as well as the compression factor of the same z_{H_2}, which value is included in Table 1.

$$E_{SS} = V_{SS}\frac{C(P_{SS}, T_{SS})}{z_{H_2}(P_{SS})}\rho_{H_2}\mathrm{LHV}_{H_2} \tag{1}$$

  where

$$C(P_{SS}, T_{SS}) = \frac{P_{SS}}{1.01325\,\mathrm{bar}}\frac{298.15\,\mathrm{K}}{T_{SS}} \tag{2}$$

- Fuel cell + DC/DC converter system:

  The fuel cell and the DC/DC converter system will transform the energy contained in the hydrogen of the storage system in electric power with a constant voltage. The main characteristics of this system are the efficiency of both equipments, the nominal power of the fuel cell $P_{N_{PEM}}$ and its variation availability of regime A_{PEM}, which will make the maximum power that the fuel cell can generate at a given moment depend on the one that had been generated previously, always without exceeding the nominal power of the fuel cell, as shown in the following expression (3).

$$P_{\mathrm{PEM\,max}_t} = \begin{cases} P_{\mathrm{PEM}_{t-1}} + A_{\mathrm{PEM}}\Delta t, & \text{if} \quad P_{\mathrm{PEM}_{t-1}} + A_{\mathrm{PEM}}\Delta t \le P_{N_{\mathrm{PEM}}} \\ P_{N_{\mathrm{PEM}}}, & \text{if} \quad P_{\mathrm{PEM}_{t-1}} + A_{\mathrm{PEM}}\Delta t > P_{N_{\mathrm{PEM}}} \end{cases} \tag{3}$$

  On the other hand, once we know the work profile of this system, we can calculate the hydrogen consumption in every time step through expression (4).

$$C_{H_2} = \frac{P_{\mathrm{FC}_t}\Delta t}{\eta_{\mathrm{FC}}\eta_{\mathrm{DC/DC}}} \tag{4}$$

- Batteries system:

  The batteries will be discharged when supplying energy to the propulsion system of the vehicle and will be charged by the fuel cell + DC/DC converter system when it is considered necessary. The batteries system is defined by the nominal voltage, the capacity, depth of discharge, charge efficiency, and the curve of discharge, which determines the amount of energy that can be extracted from the battery according to the current we are supplying. These values usually are provided by the manufacturer of the battery modules.

  In the simulation program, the charge state of the batteries is calculated as indicated in expression (5).

$$\mathrm{SOC}_t = \begin{cases} \mathrm{SOC}_{t-1} + \eta_c\dfrac{I_{\mathrm{BAT}}\Delta t}{C_{\mathrm{BAT}}}, & \text{if} \quad \text{Charge} \\ \mathrm{SOC}_{t-1} + \mathrm{DC}\dfrac{I_{\mathrm{BAT}}\Delta t}{C_{\mathrm{BAT}}}, & \text{if} \quad \text{Discharge} \end{cases} \tag{5}$$

  The performance of battery charging is estimated at 90%, usual value for lead-acid batteries.

- Vehicle propulsion system:

  The performance of the vehicle propulsion system does not need to be modelled in the simulation program, since we have its electric consumption as initial data item.

3. Experimental materials and methods

3.1. Monitoring system

When measuring the hybrid system through the simulation software, it is necessary to know the consumption of the vehicle, which can be divided into the electric motor consumption and its hydraulic pump. To obtain the data, we designed a measurement sensor system that will send the data measured to a National Instruments USB 6009 acquisition card with a 1 kHz frequency. After doing so, the data is treated with a program in Labview.

In the scheme of the system (Fig. 1) we can see the position of the current sensors (LEM DK100B10 y LEM DK400B10) monitoring the current consumed by the hydraulic pump and by the complete system, respectively, the two voltage sensors (printed circuit designed by BESEL) that monitor the voltage of

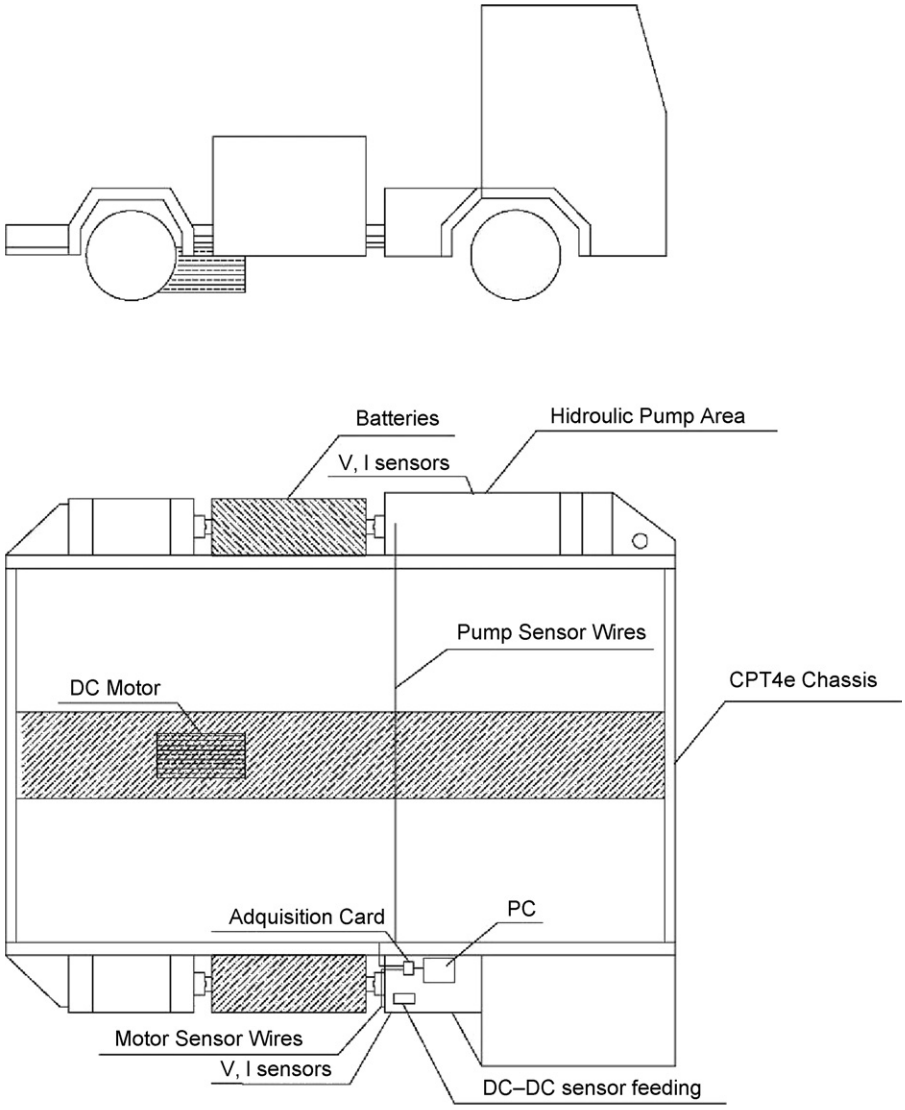


Fig. 1. Monitoring System.

the bus and the pump, and the Databox magnetic speed sensor connected to the axis of the vehicle. All sensors are fed through a DC/DC Sun power SDS-100D24 converter, which changes the voltage of the batteries to the voltage required by the sensors (24 V). In Figs. 2 and 3 the data obtained this way are presented.

In Fig. 2, we can see a representation of the power consumed by the hydraulic pump of the vehicle during the test, having considered it as the product of the current and the voltage, which are monitored by the sensors it includes. Fig. 3 shows the power consumption of the global system, that is, the sum of the consumption of the hydraulic pump and the

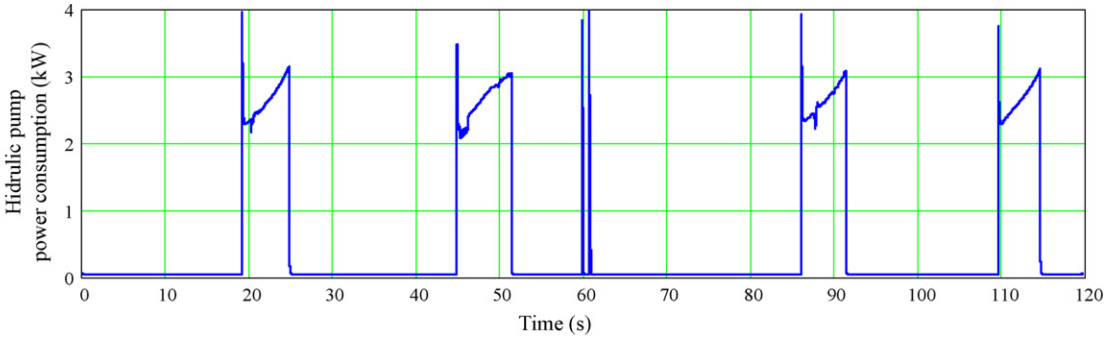


Fig. 2. Vehicle hydraulic pump consumption.

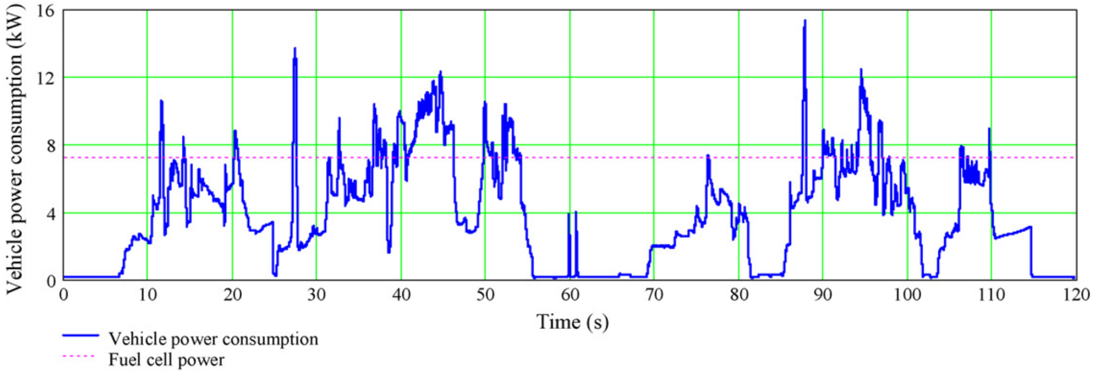


Fig. 3. Hydraulic pump system consumption + traction motor.

electric motor, obtaining a maximum consumption closed to 15 kW.

3.2. Power scaled system

Once we had identified the consumption of the electric vehicle with the monitoring system during the field tests, an assembly was done in the laboratory simulating the running of the hybrid system, schemed in Fig. 4. This figure shows a hybrid system with configuration in parallel, in which the fuel cell will be in charge of the base of the power demand of the electric motor and the batteries of the consumptions peaks to which the fuel cell cannot reach, the whole system will be controlled by the control subsystem. Once the batteries have a state of charge below the one defined previously in the control subsystem, the fuel cell will charge the batteries when the power requirements of the motor are inferior to what the fuel cell can supply, hence charging the batteries during the continuous operation of the vehicle.

In the assembly done in the laboratory, schemed in Fig. 5, the collection fuel cell and DC/DC converter was replaced by a Sorensen DCS-E power source and the motor by a DS3612 Höcherl&Hackl electronic charge model, inserting in the system one of the battery modules that the hybrid vehicle will have, this way we will pass from 84 V in the hybrid vehicle to 12 V in the test of the laboratory, scaling down the power of the system. The test was controlled and monitored through a PC and a National Instrument USB 6009 acquisition card.

The test entailed inserting the consumption profile monitored in the vehicle in the electronic charge and programming the power source to follow the energy demand of the charge until a maximum value that will be limited by the power of the fuel cell, so that the module of batteries will supply the current demanded by the charge situated over this value. The main goal of the test is to characterize the performance of the batteries towards the real cycle of work that the batteries will suffer during the operation of the hybrid vehicle, providing this way an easy comparison between different types of batteries under controlled conditions to find the most adequate batteries in order to achieve the requirements of the hybrid system.

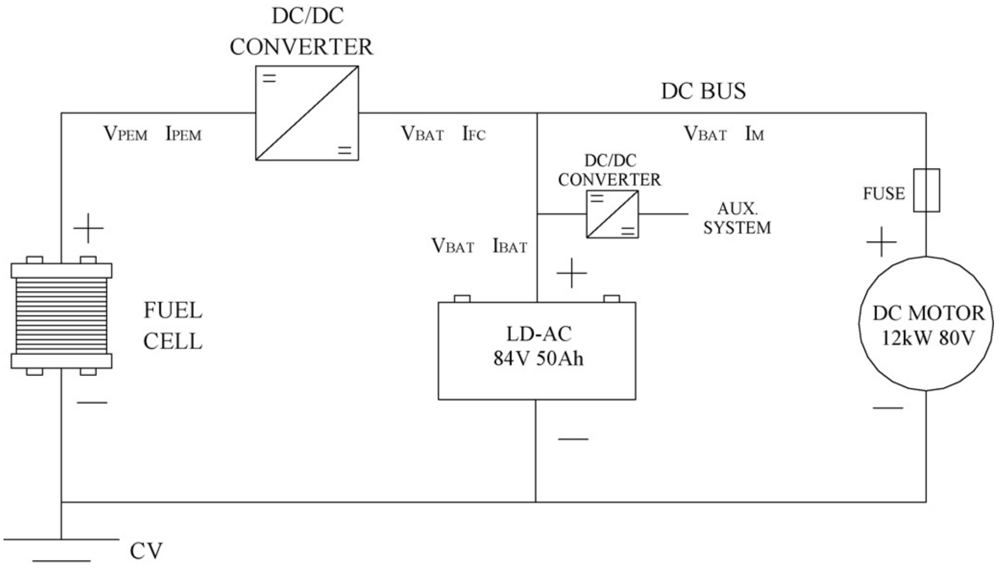


Fig. 4. Operation scheme of the hybrid system.

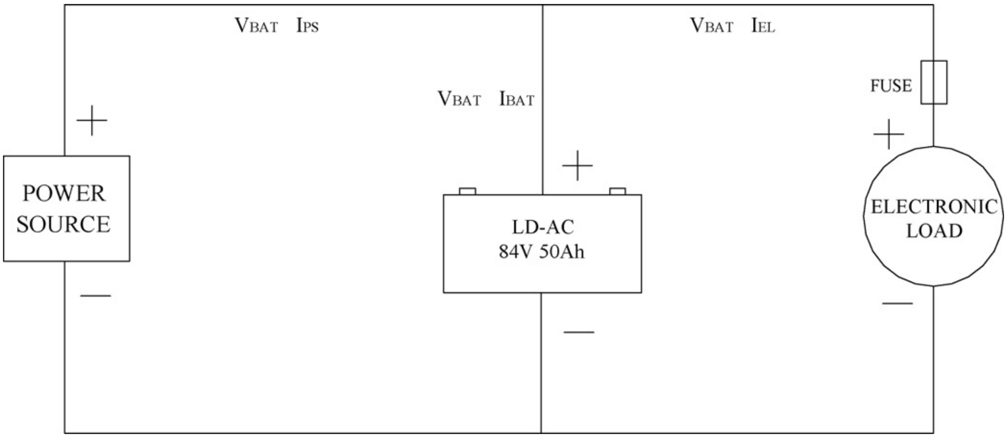


Fig. 5. Scheme of the assembly done in the laboratory.

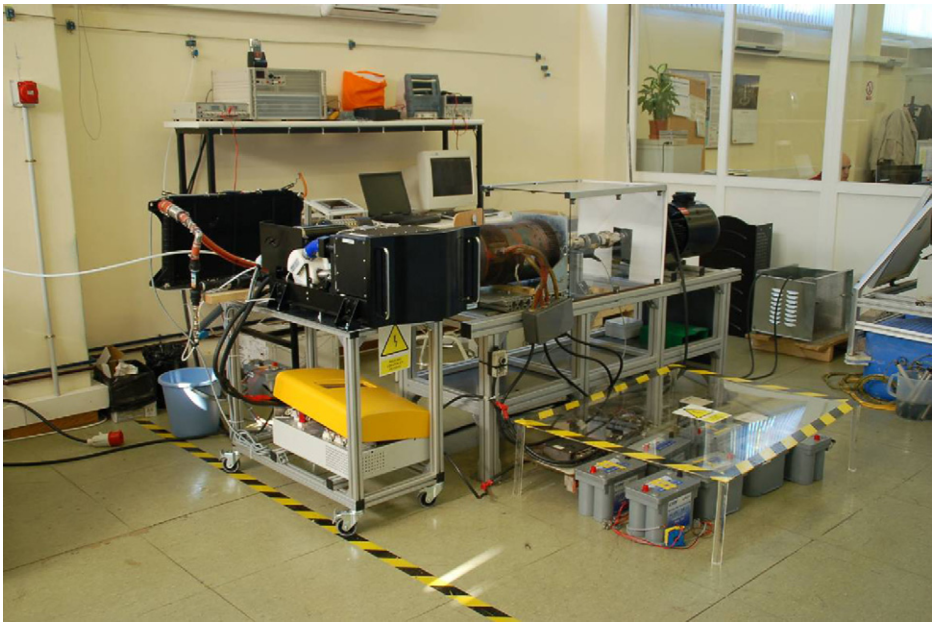


Fig. 6. Tests bank.

3.3. *Characterization of the system in a test bank*

In order to get a controlled environment when doing the tests prior to the integration phase of components, a hybrid modules test bank was installed in the laboratory. The bank has the following elements:

- Leroy Sommer 15 kW brake motor software controlled through its converter, whose function is similar to the resistance charge from the real work cycle of the electric motor of the vehicle.
- Bedplate medium with Bosch profiles to support the elements of the test bank.
- Motor to test, in this case, the original motor of the vehicle.
- Magtrol torque sensor to monitor the torque and the speed in the connection axis between both motors.
- Bank control PC and software programmed in Labview.
- Hydrogen storage system in the laboratory to feed the fuel cell.
- Sensor to monitor the main parameters of the system.

With the bank control program, the resistant torque that the axis must apply is sent to the motor that acts as a brake, reproducing this way the real conditions of the vehicle. A photograph of the test bank is presented in Fig. 6, where it is possible to see the assembly between the motor to test and the brake, the battery modules, the fuel cell and the control system.

4. Results

4.1. *Results of the simulation program*

The simulation software is a very useful tool that mainly allows to know the performance of the hybrid system towards variations in the measuring of each of the systems that form part

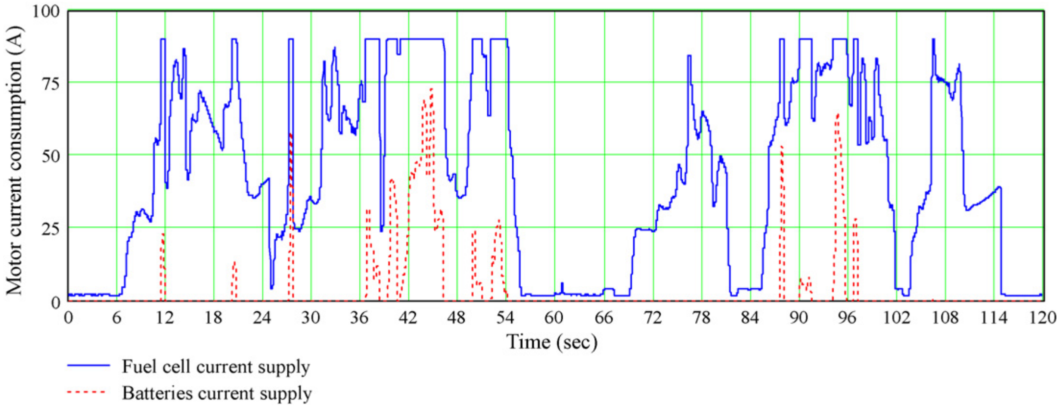


Fig. 7. Distribution of the power demand of the motor between the fuel and the batteries.

of it (fuel cell and batteries), facilitating the obtaining of the ideal degree of hybridization. Likewise, this enables us to calculate the capacity of the hydrogen storage system to achieve a given autonomy and optimize the control strategy of the vehicle.

Since the functioning of the vehicle is cyclical, the monitored consumption of the electric motor in the vehicle was inserted and considered for the hybrid system to repeat this cycle as many times as possible until the hydrogen of the storage system has been totally consumed. Fig. 7 shows the portion of the current required by the motor that the fuel cell in charge of base demand, as well as the batteries system in charge of the peaks, will supply.

Taking into account that our hybrid system has a fuel storage subsystem capable of containing 15 N m^3 of hydrogen and with modules of batteries with a capacity of 50 Ah at 84 V, we will be able to do our work cycle for almost more than 6 h, as is shown in Fig. 9.

Fig. 8 shows the variation of the amount of hydrogen present in the storage system. It is advisable to analyze the figure jointly with Fig. 9 that shows the energy that the batteries have. Initially, each of the subsystems faces its part of the current demand present in Fig. 7, so the hydrogen amount that the storage system contains, as well as the energy in the batteries experiment a linear fall, to the point where the batteries have a charge state inferior to the one in the beginning of the charge (point A). This is when the charge of the batteries by the fuel cell starts, which logically entails an increase of hydrogen consumption (see in Fig. 8 a sharper fall in the amount of hydrogen available from point A). The process of charging the batteries will end when the state of charge of these exceeds end of charge (point B), which is when the fuel cell will stop supplying energy to the battery system. So in Fig. 8 we will detect hydrogen consumption inferior to the one we had during the charge process.

When reaching the initial state of charge of the charge process (point C) we will start the charging again and this process will be repeated, maintained with a relatively high state of charge, until the vehicle has consumed all hydrogen available in the beginning (point D). From this moment on, the movement of the vehicle will be exclusively carried out with the batteries (as you may see in Fig. 9, a sharper fall in the energy contained in the batteries than on the case where we had hydrogen and the fuel cell, was in charge of the base of the motor consumption). In the simulation program, we consider that the vehicle continues with its usual operation, without filling up with hydrogen, until the batteries reach their maximum depth of discharge (point E) and the vehicle stops definitively.

4.2. Characterization of the system in a test bank

The control software of the test bank, as we can see in Fig. 10, allows the characterization of the DC motor current that the vehicle currently has.

In Fig. 10 we can see the torque signals in the axis, bus voltage and the current consumed by the motor consuming it from the power bus. The entry signs to the data acquisition card are fil-

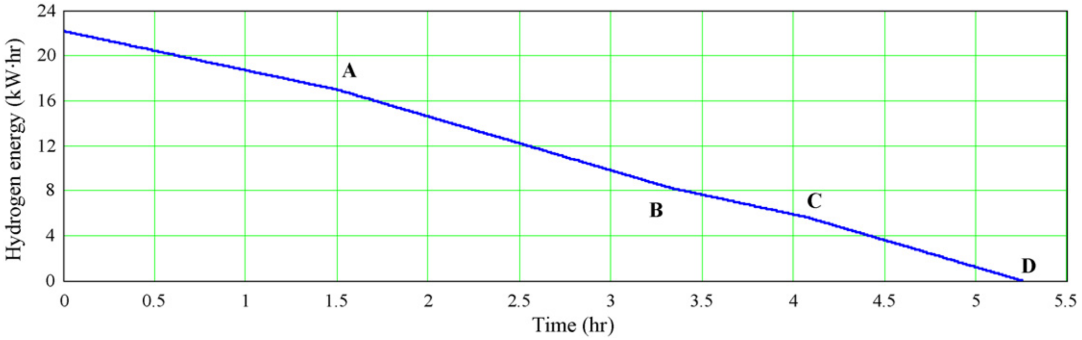


Fig. 8. Hydrogen available in the storage system.

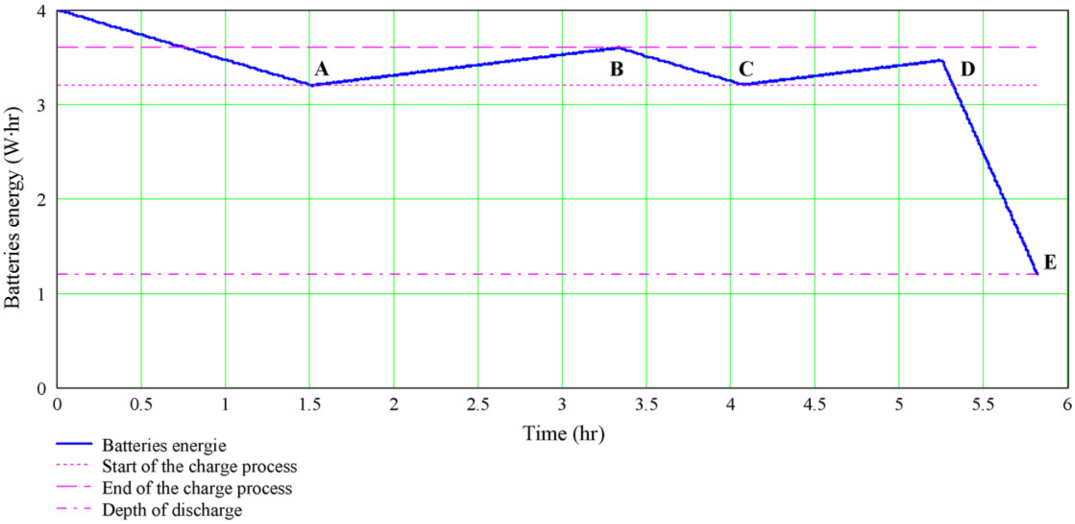
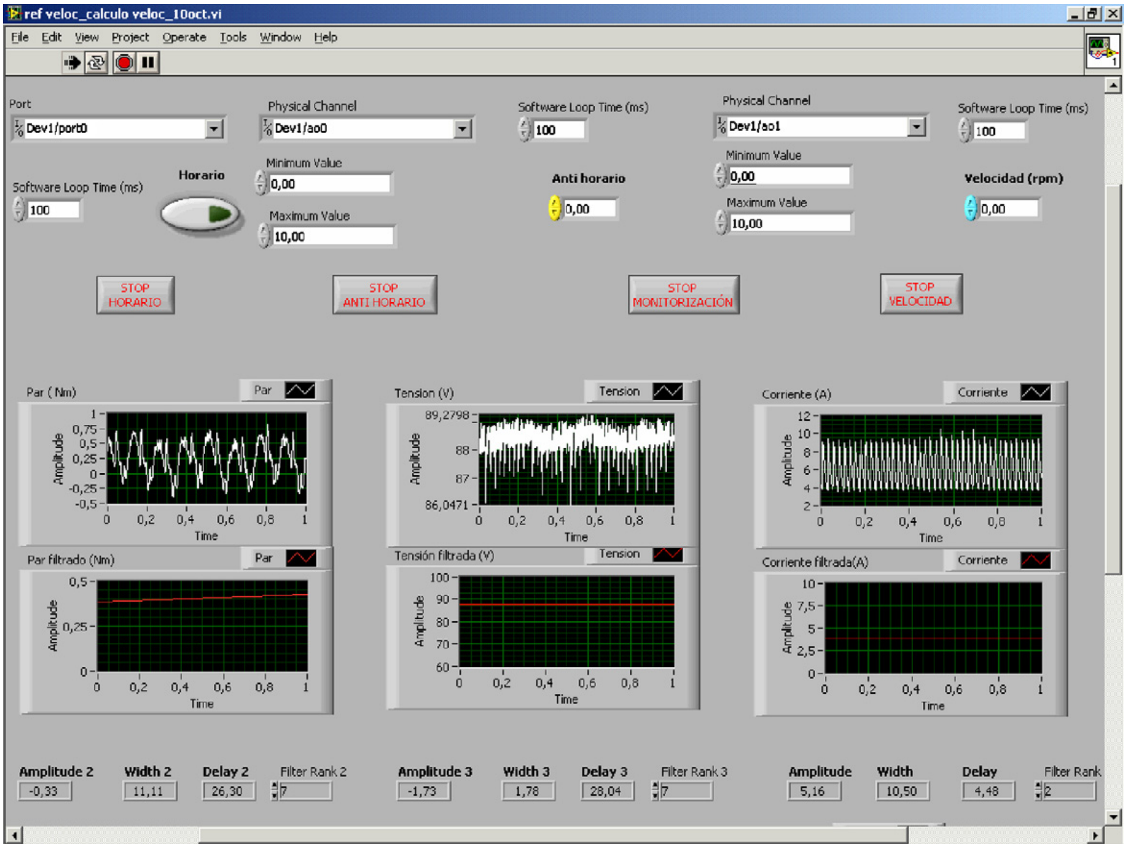


Fig. 9. Energy available in the batteries system.

tered through software so the measurement noise is eliminated, as we can see in the graphs of the lower part of the image. In the upper part of the image shows the parameters of the brake fitted in the motor, which during the experiment was disconnected, executing only the resistant charge derived form its inertia.

Fig. 11 represents a monitoring of the battery power flow as a function of the energy requirements, both the batteries current "represented by a blue line under the acronym of Ibat" and fuel cell current (red line) are plotted against the time.

From 0 to second 40, the fuel cell is feeding the battery whilst non-energy demand exists. At second 40, a 30 A current is required from the hybrid transmission, leading the battery to provide a current of 10 A. It can be also appreciated that the fuel cell's current output is simultaneously tapered off to 20 A by the control strategy.



Port: Dev1/port0
Physical Channel: Dev1/ao0
Software Loop Time (ms): 100
Physical Channel: Dev1/ao1
Software Loop Time (ms): 100
Software Loop Time (ms): 100
Horario
Minimum Value: 0,00
Maximum Value: 10,00
Anti horario: 0,00
Minimum Value: 0,00
Maximum Value: 10,00
Velocidad (rpm): 0,00

Amplitude 2	Width 2	Delay 2	Filter Rank 2	Amplitude 3	Width 3	Delay 3	Filter Rank 3	Amplitude	Width	Delay	Filter Rank
-0,33	11,11	26,30	7	-1,73	1,78	28,04	7	5,16	10,50	4,48	2

Fig. 10. Control software of the tests bank.

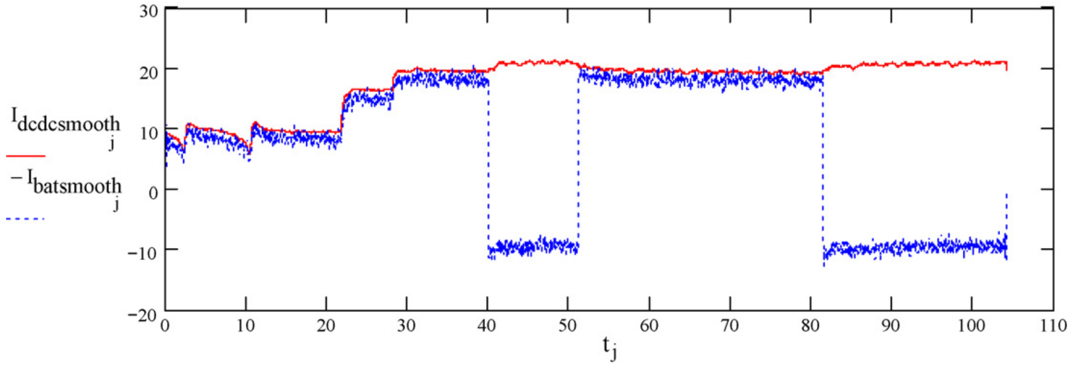


Fig. 11. Batteries and fuel cell currents.

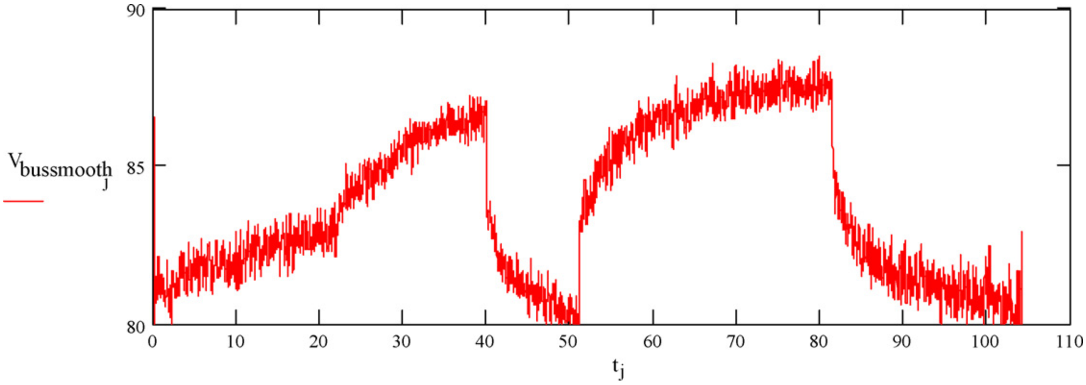


Fig. 12. Bus voltage.

In Fig. 12, the bus voltage variation is shown by smoothing the datum trace by a median interpolation each 69 points.

4.3. Integration of the equipments of the power module in the vehicle

After the monitoring and analyses phases of the grade of hybridization, the next step was to design the hybrid and integration system on the vehicle. The system has a fuel cell, a battery module, a direct current converter (in order to transform the variable voltage level at the outlet of the fuel cell into a constant voltage in the power bus of the vehicle), the control system, the hydrogen storage system and the cooling system. The main components are described as follows:

- Fuel cell: Hydrogenics HyPM8 of polymer membrane type (PEMFC) and 8 kW of net power.
- DC–DC converter: SMA to condition the power outlet of the fuel cell.
- Batteries system: composed by seven modules of Pb-Ac batteries with a nominal voltage of 12 V and a 50 Ah capacity. The Batteries used were specifically designed to withstand high charge and discharge rates.

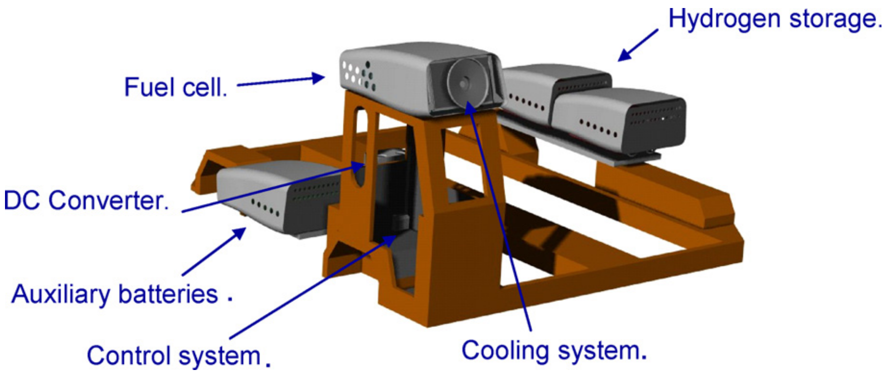


Fig. 13. Components integration.

- Cooling system: It has a Behr Hella radiator with a SPAL VA18-AP70/LL86A fan controlled by the Electronic Control Unit (ECU) of the fuel cell. Its function is to evacuate the thermal power generated by the fuel cell in the course of its operation and maintain the temperature of the stack of this one within the operation limits.
- Control system: based on an IFM controller with integrated Human Machine Interface (HMI). Its function is to control the whole system on the basis of the previously set up control algorithms.
- Hydrogen storage system: it has four B20 bottles of Air Liquide at 200 bar pressure.

In Fig. 13 we can see a 3D scheme regarding the integration of the different components on the vehicle. We can see that the integration does not reduce in any case the charge capacity of the vehicle, which is an essential requirement regarding its function, since none of the components will be installed in the charge zone of the vehicle.

5. Conclusions

Once the simulations of the hybrid system are done with the computer program and after ending the initial tests in the laboratory, it was proved that the optimum configuration to develop a hybrid power module based on the fuel cell is the topology in parallel (see Fig. 4). This topology allows the charging of the batteries during the movement of the vehicle, providing that the power consumed by the electric motor is less than the maximum power of the fuel cell, calculated with expression (3).

The execution of the characterization test of the performance of the batteries has proved that it is possible to reach greater global efficiency by charging and discharging the batteries between two limits of the state of charge compared to a charge that depends exclusively on the power availability of the fuel cell (it means we charge the batteries as soon as the motor consumption is lower than the fuel cell nominal power). Moreover, this way we avoid having to expose batteries to charge/discharge microcycles, and thus extend its useful life.

Until now, we have achieved the initial goals of the phases prior to the integration and prototype tests, which will be done during the last quarter of the year 2006.

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