Electronic Device for the Control and Energy Management of a PEM Fuel Cell Stack/Supercapacitors Hybrid System

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Abstract

This work shows the development of an electronic system for the control and the management of a hybrid configuration of generation of energy, based on the use of a PEMFC fuel cell stack (50W) and a supercapacitors module. In order to achieve this aim, a Buck DC-DC converter and an electronic control unit (ECU) based on a microcontroller have been set in the electronic system. The ECU controls the DC-DC converter by adapting the voltage given by the fuel cell to the voltage required by the electronic speed regulator of the truck. Moreover, it limits the extraction of energy from the fuel cell according to its electrochemical behaviour. Two digital PID regulators in closed loop are used for the control. They keep the power extracted from the fuel cell constant and limited by regulating the converter, either at constant voltage (CV) or at constant current (CC). Finally, the ECU regulates the fan speed according to the current which is extracted from the fuel cell, in order to provide enough amount of oxygen inside the cell. A supercapacitors module (7.5V, 66.6F) has been installed between the DC-DC converter and the electronic speed regulator of the truck so as to provide the necessary energy during the load peaks required in the start-up or in the acceleration. The supercapacitors will be recharged by the fuel cell stack as soon as the demand of the vehicle decreases and there is an excess of energy. In order to identify faults in the system, as well as to refine and optimize the control algorithm, the ECU keeps a record of all the variables of the system, such as the temperature of the fuel cell stack and the room temperature, the voltage of all the cells, the voltage and current extracted form the stack, the voltage and the current given by the DC-DC converter, the speed of the fan which provides the stack with air, and the activation of the hydrogen purge valve with respect to time.

Keywords

PEM fuel cell, hybrid system, DC-DC converter, supercapacitor

1. INTRODUCTION

Nowadays electric and electronic toys are powered by R6, button, R14 and R20 cells, or by batteries of lead / acid, Ni-Cd, and Ni-Mh. The toxicity of the cells and batteries used is different according to the kind of battery which is considered. All their components do not have the same degree of toxicity regarding their effects on health and the environment. In this respect, those which have mercury, cadmium and lead are those which present the highest risk. In order to imagine the magnitude of the pollution that these cells and batteries produce, it is enough to know that they cause the 93% of the mercury in waste, as well as the 47% of the zinc, the 48% of the cadmium, the 22% of the nickel, and so on. These cells undergo the corrosion of their cases, which internally, are affected by their components, and externally, are affected by the climatic corrosion and the fermentation process of waste, especially of the organic matter, which, as it increases its temperature up to 70°C, acts as a reactor of pollution. When the spilling of the internal electrolytes of the cell occurs, it drags the heavy metals. These metals flow through the ground polluting any kind of living being (plant and animal assimilation). Bearing in mind the health and environment problems which the use of the cell and batteries currently used implies, the development of this project is intended to eliminate all these problems by using fuel cells. Among the most important advantages we can point out the following ones:

(1) High energy efficiency

Fuel cells are not thermal machines, so their performance is not limited by the Carnot cycle, being able to approach 100% theoretically. Only the limitations in the exploitation of the generated energy and in the materials used in their construction prevent reaching this value.

(2) Nil loading times

The amount of electric energy that fuel cells are able to give is not set in advance. This is why, as long as a sufficient number of reagents is provided, the cell will always produce electricity.

(3) Low level of environment pollution

Since the high-temperature combustion of fossil fuels is substituted for an electrochemical reaction catalyzed between the hydrogen and the oxygen, there is no emission of pollutant gases (nitrogen oxides and sulphur oxides, unsaturated hydrocarbons, etc.), so the impact on the environment is minimal.

Some important limitations of the fuel cells are the sudden increases of loading and the delivery of large current peaks, which makes necessary a gradual acceleration from the resting stage. We solve the problem by introducing supercapacitors and a control electronics into the system, without introducing pollutant agents (batteries).

The purpose of this work is to develop a radio controlled electric vehicle, powered by a hybrid electrical system, based on fuel cells and supercapacitors. In order to do that, a PEMFC fuel cell stack (50W), a supercapacitors module, a DC-DC converter, and an electronic control unit (ECU) based on a DSP microcontroller have been integrated. By using this electronic control unit, similar to the switchboard that modern cars incorporate, it is possible to keep the fuel cell at the maximum performance point, optimizing the consumption of hydrogen and keeping the system controlled to face faults.

2. EXPERIMENTAL

2.1 Electric characterization of the vehicle

The electric characterization was necessary in order to gauge the new alternative power system. In order to carry it out, the power, which the speed regulator extracted from the original Ni-Mh battery, was monitored versus the time. We can see the representation of the instant power consumed during an acceleration in Figure 1. The acceleration area, in which peaks up to 150W can be observed, appears from the 2.5 seconds to the 7.2 seconds. The area of constant speed, in which the electric consumption returns to normal around 25W, appears from the 7.2 seconds to the 13.5 seconds.

2.2 Components of the hybrid system

Now we will explain the main components selected in the incorporation of the power system based on hybrid configuration using fuel cells and supercapacitors.

2.2.1 Supercapacitors

The supercapacitors were gauged and selected with the aim of making up for the power peaks which appear during the start-up (up to 150W) for 10 seconds. Three supercapacitors in a series, of 200F and 2.5V, and with an ESR of 3.5 mΩ, were incorporated. They are able to provide peaks up to 1.3kW according to the following equation (1).

$$P_{Peak} = \frac{V^2}{4 \cdot ESR} \quad (1)$$

Where P_{Peak}, V, ESR, are peak power, voltage of the supercapacitor, and internal resistance of the supercapacitor respectively. The final characteristics of the supercapacitors module are 66F at 7.5V. So as to keep the supercapacitors in a correct working order, a stage which limits the output current of the supercapacitors during the charge and discharge has been introduced [Jeong et al., 2002].

2.2.2 Fuel cell stack

A fuel cell stack with a rated power above the average

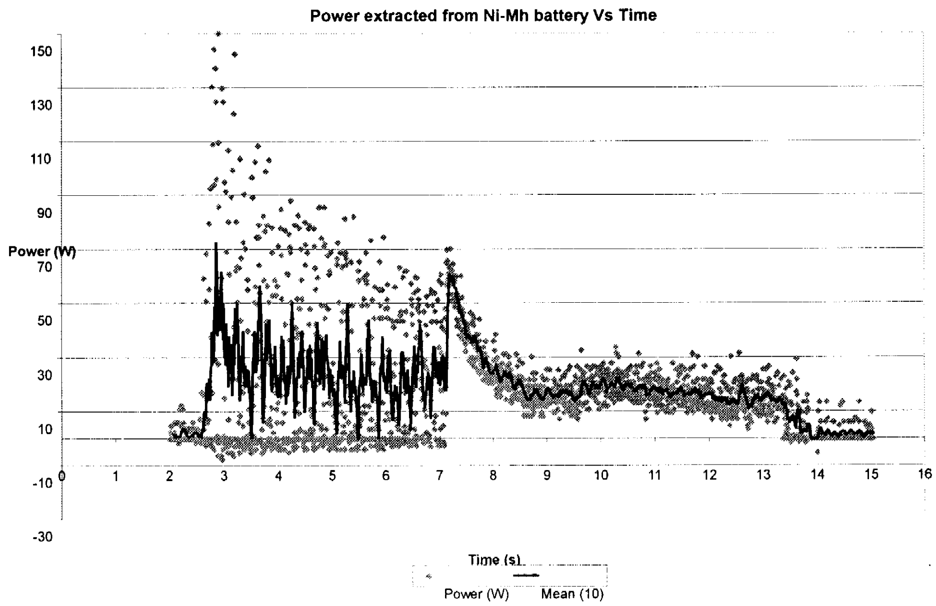

Fig. 1 Record of the power consumed by the truck during an acceleration in a straight line

consumption of the truck (25W) was selected in order to be able to reload the supercapacitors with the surplus of energy production when the vehicle is not demanding power peaks. To be precise, a PEMFC fuel cell stack of 20 cells was selected, with AirBreathing configuration, which uses hydrogen gas and room air as reagents, with self-humidified MEA's, and with a rated power of 50W and an output voltage of 12V.

2.2.3 Tanks of metallic hydrides

In order to store the hydrogen, we used tanks of metallic hydrides with a capacity of 20 litres and a volume of flow of 0.16sl/min (in normal conditions). In order to calculate the flow rate of hydrogen demanded by the fuel cell, Faraday's law is used. (2)

$$\frac{\partial m}{\partial t} = \frac{I \cdot n}{e^{-} \cdot F} \tag{2}$$

Where $\delta m/\delta t$, I, n, e, F are molar rate of flow in hydrogen moles per second, demanded current in amperes, number of cells of the fuel cell stack, number of electrons in the electrochemical reaction (2 electrons), and Faraday constant (96480 F). In order to have a maximum power of 50W and 80% of use of hydrogen (λ=1.25), we calculated a maximum volume of flow of 0.73sl/min. That way, it is necessary to install 5 tanks in parallel so as to fulfil such maximum volume of flow. Supposing an average consumption of 30W, an average flow tamks rate of 0.435sl/min is calculated. That is why, since we have 100 litres of hydrogen, we obtain an autonomy of 3.8 hours.

2.3 Interconnection of the components of the alternative hybrid power system

The interconnection of the hybrid system based on fuel cells, supercapacitors, a DC-DC converter, and an electronic control unit (ECU) is shown in Figure 2 [Thounthong et al., 2005; U.S. Department of Energy,

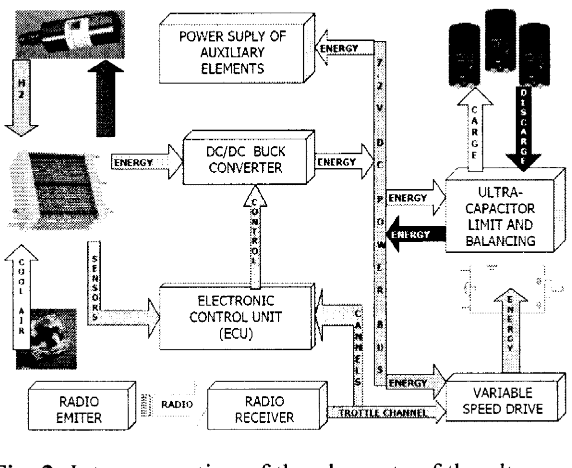

Fig. 2 Interconnection of the elements of the alternative hybrid feed system

2004]. We can see how the thermal energy which gets out of the cell is used to heat the bottles of metallic hydrides, increasing this way its output flow rate. Figure 3 shows a picture of the radio controlled truck. It shows the complete assembly of the hybrid power system set on the trailer.

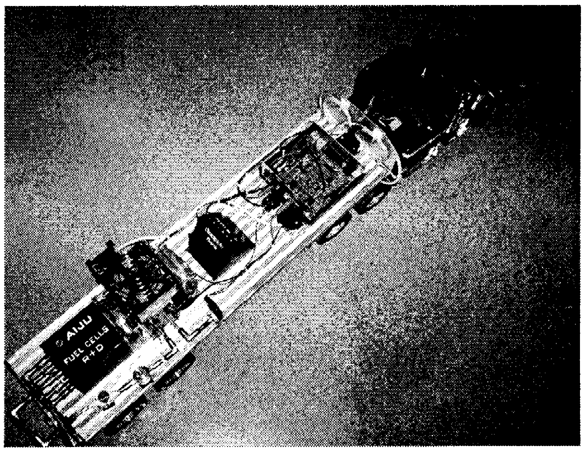

Fig. 3 Interconnection of the elements of the alternative hybrid power system

2.4 Electronic control

Figure 4 shows the control loop of the DC-DC converter. All the boxes represent software processes inside the microcontroller. We can observe two PID controllers [Microchip Technology, 2004]. Each of them generates a PWM control signal to control the converter, one of them does so at constant voltage and the other one at constant current. In order to keep the output power constant and limited according to the quality of the electrochemical reaction, a controller selector is used. It regulates the switching between modes (CV↔CC) by applying a temporal and value histeresis.

The output power is proportional to the input with a 72% of performance of the DC-DC converter. The limitation of the power extracted from the fuel cell through the electric management allows keeping the cell inside the optimum working area. Apart from controlling the power, the electronic control unit is in charge of regulating the revolutions per minute of the fan which introduces air into the channels of the fuel cell stack, so as to guarantee a sufficient amount of oxygen and that it does not dry the membranes.

3. RESULTS

Figure 5 shows the real behaviour of the DC-DC converter limited to 7.2W, when a demand of energy which exceeds the fixed limit is applied to it. When this demand is lower than the fixed maximum, it is regulated in constant voltage mode at 7.2V. On the other hand, when the demand is higher than the limit, it is regulated in

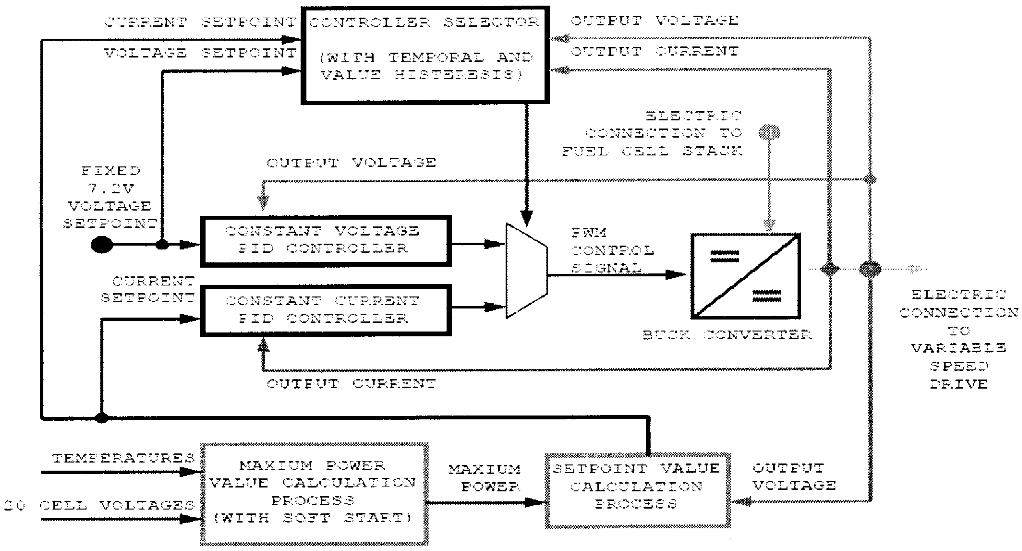

Fig. 4 Control loop of the DC-DC converter, with automatic CV-CC switching which keeps the output power controlled and limited according to the electrochemical reaction inside the fuel cells stack

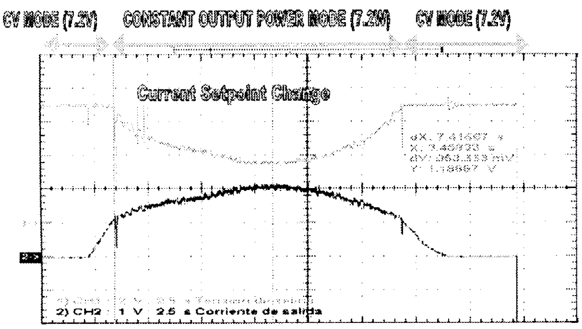

Fig. 5 Real behaviour of the DC-DC converter when the power setpoint is higher than 7.2W

constant power mode. In order to regulate at constant power, the current setpoint is recalculated.

When the power setpoint is lower than the ideal output power, the variation of the power setpoint, (inside the "Maximum Power Value Calculation Process (with soft start)") follows a straight acceleration line until it reaches the ideal output power. When the power setpoint is equivalent to or higher than it, it matches the ideal output power, as we can see in Figure 6. The ideal output power is recalculated according to the voltages of the cells and the temperature of the fuel cell stack. The values are stored in the look up tables inside the microcontroller.

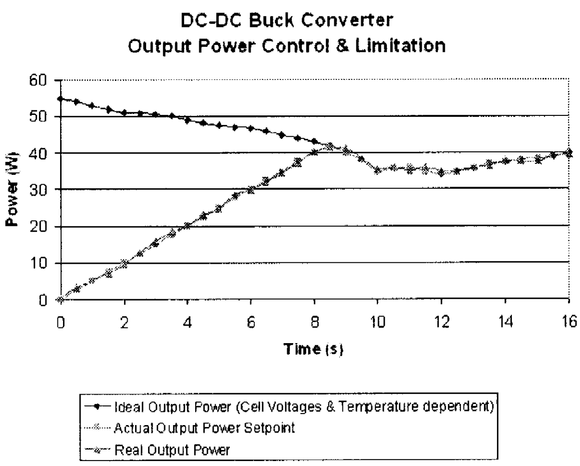

Fig. 6 Real test of how the power setpoint increases until it reaches the ideal output power

4. CONCLUSIONS

This work shows the technical viability of integrating a hybrid system based on fuel cells and supercapacitors into a R/C electric toy vehicle and therefore, in electrical toys in general. Hybrid systems based on fuel cells and supercapacitors are an alternative which respects the environment, in opposition to batteries. The electronic control and management of the system maximize the performance of the fuel cell, minimize the consumption of hydrogen, and guarantee the correct working order of the hybrid vehicle. The use of supercapacitors together with fuel cells in hybrid systems allows reducing the size of the fuel cell, providing the power peaks needed for the start-up and the acceleration, and stabilizing the energy given to the motor by the fuel cell stack. As regards the economic viability, nowadays it is far from being competitive concerning the current power systems in this kind of vehicles or in electric toys. However, this situation is changing, and the cost of the technology is decreasing exponentially. According to the guidelines of the European Hydrogen And Fuel Cell Technology Platform which appear in its document "Strategic Research Agenda (July 2005)" [European Hydrogen & Fuel Cell Technology Platform, 2005], it is urged to do research into specific critical areas, which allows discovering new materials that are more economical and light, and new production methods that allow a mass production of the fuel cells. This way, the systems which use hydrogen and fuel cells as power supplies will become much cheaper.

As a future work, we will develop hybrid systems using the same concepts, fuel cell stack and supercapacitors, but reducing it size.

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(Received June 11, 2007; accepted June 27, 2007)