Control method for the improvement of the efficiency of a fuel cell

Radu C. DONCA[1], Radu BĂLAN[1], Vistrian MĂTIEŞ[1], Olimpiu HANCU[1]

[1] Department of Mechanisms, Precision Mechanics and Mechatronics
Faculty of Mechanics, Technical University of Cluj-Napoca
Cluj-Napoca, Romania
Phone/Fax number: +0040 264 401682, e-mail: DoncaRadu@yahoo.com, RaduBalan@yahoo.com,
MatiesVistrian@yahoo.com, OHancu@netscape.net

Abstract

The major breakthroughs that have recently brought fuel cells to the fore-front include the development of low resistance membranes, highly diffusive electrodes, and reduced use of noble metal catalysts. However, in order to obtain the maximum efficiency out of a fuel cell, some parameters like flow control, temperature, water flow and load must be controlled. This paper is focused on the load control. A three-stage SMPS converter is proposed and analyzed. The fuel cell operation and the types of fuel cells are also described. An experimental setup was made using a toy vehicle powered by a fuel cell in order to experimentally prove the theoretical approaches of load control.

Keywords

fuel cell, control theory, SMPS converter, mechatronics, hydrogen car

1. Introduction

Even if the fuel cell principle dates back to 1839 (Schoenbein), only with recent researches have fuel cells become a promising alternative to internal combustion engines and thus are considered for transportation (automotive, marine and aerospace) applications and distributed power generation [1]. The major breakthroughs that have recently brought fuel cells to the fore-front include the development of low resistance membranes, highly diffusive electrodes, and reduced use of noble metal catalysts. It is the application of mechatronics concepts, however, that will allow the fuel cells to move from laboratories to every day's use, powering electric automobiles, domestic appliances and even industrial plants [1]. Studies have been made in order to precisely control the reactant flow and pressure, stack temperature, and membrane humidity in order to maximize the efficiency of the fuel cell. However, one aspect is forgotten or left aside very often. Being a power supply, the fuel cell is not affected only by its internal operation but also by the load conditions. A typical PEM fuel cell produces a voltage from 0.6V to 0.7V at full rated load. Voltage decreases as current increases, due to several factors:

1) Activation loss
2) Ohmic loss
3) Mass transport loss [2][3]

A technique and control strategy is provided in this article in order to overcome the above mentioned factors. This technique is implemented on a small-scale fuel cell powered vehicle, in order to prove its efficiency.

2. Fuel cell operation

A fuel cell is an electrochemical energy conversion device. It produces electricity from external supplies of fuel (on the anode side) and oxidant (on the cathode side). These react in the presence of an electrolyte. Generally, the reactants flow in and reaction products flow out while the electrolyte remains in the cell (Figure 1). Fuel cells can operate virtually continuously as long as the necessary flows are maintained. [3][4]

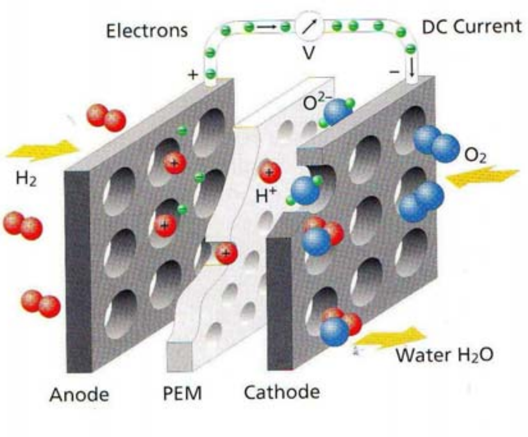

Fig. 1. Operating principle

The processes by which the electric current is produced are electrochemical, rather than thermochemical, in nature. Since no combustion reactions are involved in these processes fuel cells gain two main advantages over the combustion engines: 1 - they do not produce any of the undesirable products normally associated with the oxidation of fossil fuels such CO_2, SO_2, oxides of nitrogen, or particulate matter; [6] 2 – their operation is not constrained by the maximum Carnot cycle efficiency as combustion engines are, because they do not operate with a thermal cycle. At times, this is misrepresented when fuel cells are said to be exempt from the laws of

https://doi.org/10.24084/repqj06.373

thermodynamics, as most people think of thermodynamics in terms of combustion processes (enthalpy of formation). The Laws of Thermodynamics hold for chemical processes (Gibb's free energy), like fuel cells, also but the maximum theoretical efficiency is much higher (83% efficient at 298K) than the Carnot cycle (21% for a car with TL=293K and TH=373K), the most efficient combustion cycle. [5][6]

In the original hydrogen–oxygen proton exchange membrane fuel cell (PEMFC) design, a proton-conducting polymer membrane, (the electrolyte), separates the anode and cathode sides. This was called a "solid polymer electrolyte fuel cell" (SPEFC) in the early 1970s. [3]

On the anode side, hydrogen diffuses to the anode catalyst where it later dissociates into protons and electrons. The protons are conducted through the membrane to the cathode, but the electrons are forced to travel in an external circuit (supplying power) because the membrane is electrically insulating. On the cathode catalyst, oxygen molecules react with the electrons (which have traveled through the external circuit) and protons to form water — in this example, the only waste product, either liquid or vapor. [3]

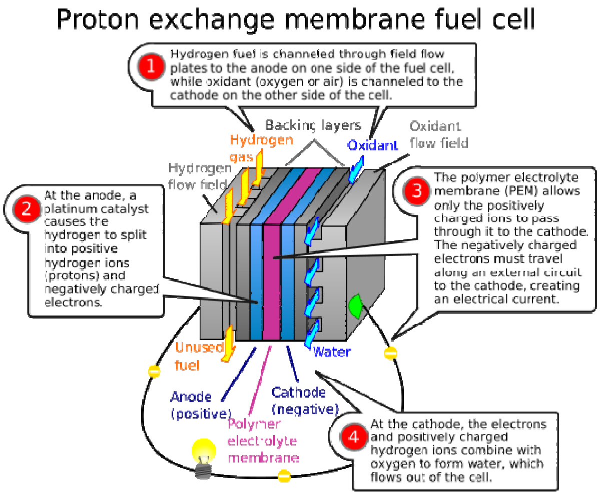

Fig. 2. Main components

Construction of a low temperature PEMFC (Figure 2): Bipolar plate as electrode with in-milled gas channel structure, fabricated from conductive plastics; Porous carbon papers; reactive layer, usually on the polymer membrane applied; polymer membrane. The materials used in fuel cells differ by type. The electrode–bipolar plates are usually made of metal, nickel or carbon nanotubes, and are coated with a catalyst (like platinum, nano iron powders or palladium) for higher efficiency. Carbon paper separates them from the electrolyte. The electrolyte could be ceramic or a membrane.

In addition to this pure hydrogen type, there are hydrocarbon fuels for fuel cells, including diesel, methanol and chemical hydrides. The waste products with these types of fuel are carbon dioxide and water. [7][8]

Depending upon the manner in which the electrodes and the electrolyte are configured and the nature of the ionic species transported through the electrolyte, fuel cells can be grouped into six basic designs: (1) phosphoric acid fuel cells (PFAC) in which the electrolyte is phosphoric acid (H_2PO_4); (2) alkaline fuel cells (AFC) in which the electrolyte is a base such as potassium hydroxide (KOH); (3) proton exchange membrane fuel cells (PEMFC) in which a polymer membrane serves as the electrolyte; (4) molten carbonate fuel cells (MCFC) in which molten carbonate, primarily in the form of potassium carbonate (K_2CO_3), serves as the electrolyte transporting carbonate ions rather than protons; (5) solid oxide fuel cells (SOFC) in which the electrolyte is a solid such as yttria (Y_2O_3)-stabilized zirconia (ZrO_2) that transports oxygen ions rather than protons; and (6) direct methanol fuel cells which are similar to PEMFC in that a polymer membrane serves as the electrolyte but the methanol/hydrogen reformer is built in to the anode. [3]

In order to get the best efficiency, some factors must be controlled:

1) Water management (in PEMFCs). In this type of fuel cell, the membrane must be hydrated, requiring water to be evaporated at precisely the same rate that it is produced. If water is evaporated too quickly, the membrane dries, resistance across it increases, and eventually it will crack. If the water is evaporated too slowly, the electrodes will flood, preventing the reactants from reaching the catalyst and stopping the reaction. [12]
2) Flow control. Just as in a combustion engine, a steady ratio between the reactant and oxygen is necessary to keep the fuel cell operating efficiently. [1][2]
3) Temperature management. The same temperature must be maintained throughout the cell in order to prevent destruction of the cell through thermal loading. [2][7]
4) Power management. The power drawn by the load must be maintained between two limits in order to get the maximum efficiency out of the fuel cell.

3. Load control strategy

As stated before, the voltage of the cell decreases as current increases. In order to maximize the efficiency of the fuel cell, the current (and indirectly the voltage) of the cell must be controlled. A three stage converter is used in order to achieve this goal (figure 3).

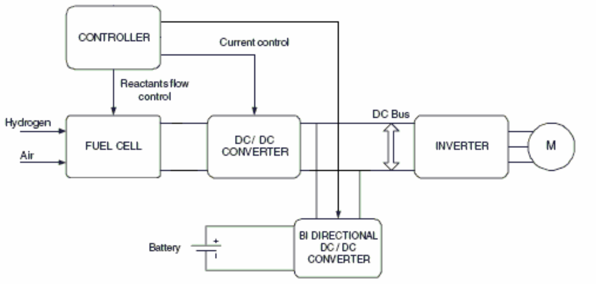

Fig. 3. Functional Diagram

The first DC/DC converter stage is the main component. Its main purpose is to regulate the current drawn from the fuel cell, regardless of the load condition. This will lead to a fluctuating voltage on the dc bus, depending on the load conditions (suggested by the motor in figure 3).
It is based on a boost converter SMPS. The output dc voltage is always greater than its input dc voltage. It is composed of two semiconductor switches – a transistor and a diode, and two energy storage elements – a bobbin and the output condenser (figure 4). [11][13]

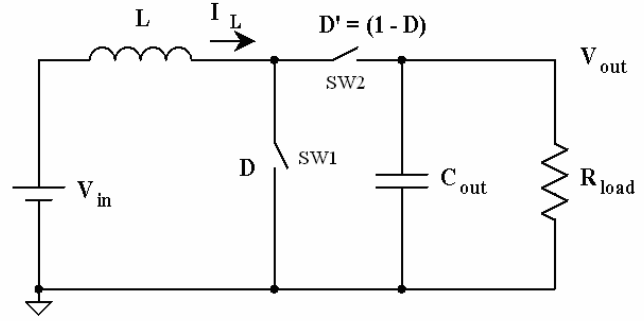

Fig. 4. Boost converter components

In the basic boost topology shown in Figure 5, the input voltage (VIN) is always less than the output voltage (VOUT). Initially, energy is stored in inductor L1 when SW1 is turned on. From the electrical characteristics of the inductor, the current ramps up linearly according to Equation 1 (assuming inductor series resistance and switch on resistance are negligible).

$$V_{in} = L_1 \frac{di_L}{dt} \rightarrow \frac{V_{in}}{L_1} t = i_L \qquad (1)$$

The peak current is achieved the moment before SW1 turns off. Equation 2 shows the peak current, where D is the duty cycle and T is the period for Pulse-Width Modulation (PWM).

$$\frac{V_{in}}{L_1} DT = I_{peak} \qquad (2)$$

The current in an inductor cannot change instantaneously. When SW1 is switched off, the current in L1 continues to flow through D1 to the storage capacitor, C1. Thus, the current in the inductor decreases linearly in time from the peak current. Equation 3 shows this relationship.

$$\frac{di_L}{dt} = \frac{V_{in} - V_{out}}{L_1} \rightarrow i_L = \frac{V_{in} - V_{out}}{L_1} t + I_{peak} \qquad (3)$$

During this linear decrease in current, the energy stored in the inductor is transferred to C1. The result is a simple relationship between input and output voltage shown in Equation 4. This equation is derived from the simple concept: power in equals the power out. [10][13]

$$V_{out} = V_{in} \sqrt{\frac{R_L DT}{2L_1}} \qquad (4)$$

The second component in figure 3 is the bi-directional DC/DC converter. It is used to keep the voltage on the DC bus between two imposed limits. When the voltage increases, the converter uses the extra energy generated by the fuel cell to charge an auxiliary battery. On the contrary, if the load increases, the first DC/DC converter will not be able to keep up leading to a voltage drop on the DC bus. When the voltage drops under a threshold value, the bi-directional DC/DC converter will switch its operation from the first quadrant to the third, putting the energy already stored in the battery back on the DC bus.
The inverter will convert the DC energy from the bus to whatever form of current is needed by the motor (tri-phase, sinus, square wave, trapezoidal or even chopped DC). It must operate correctly with large fluctuation of the input voltage.

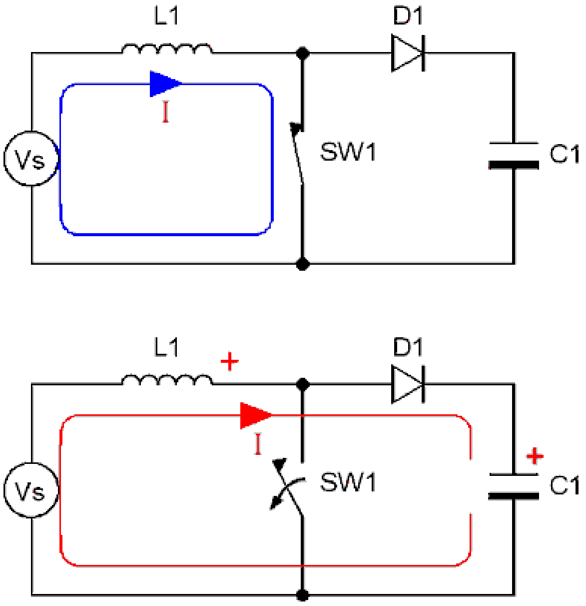

Fig. 5. Boost converter functionality

The controller (figure 3) was designed to accomplish the following tasks:

1) Maintain the current drawn from the fuel cell at a constant value to use the cell at maximum efficiency
2) Detect "on the fly" the MPP of the fuel cell
3) Regulate the flows of oxygen, hydrogen and water in and out of the cell
4) Monitor the value of DC bus in order to control the charge/discharge of the battery
5) Change the quadrant in which the bi-directional DC/DC converter is operating
6) Detect the power demand of the motor and drive the motor accordingly

4. Experimental set-up

In order to practically test the concept described above a “Thames & Kosmos - Fuel Cell car & experiment kit” was used. The kit contains a mobile platform with a dc motor, a fuel cell and all the needed cables, connectors, oxygen and hydrogen tanks in order to operate the fuel cell. [4]

A circular hilly route was build to test the car. With both the hydrogen and oxygen tanks full, the car runs for 418 seconds with an average speed of 5.47m/s. The calculated fuel to wheel efficiency is 9.27%.

The fuel cell volt/ampere characteristic was also plotted in figure 6. The measured short-circuit current is 1.3A.

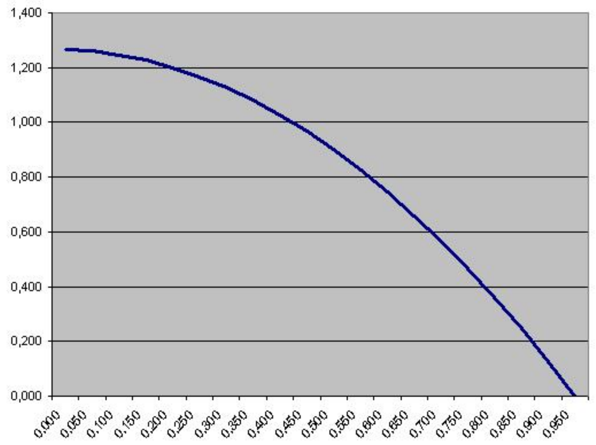

Fig. 6. Voltage vs. current

The power was also plotted (figure 7). The determined MPP is 0.455W at 0.827A.

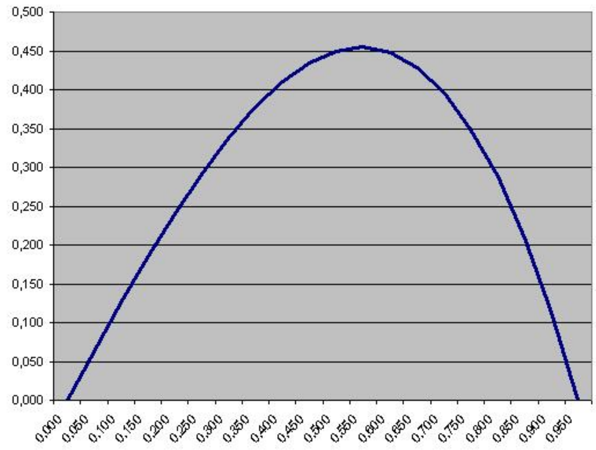

Fig. 7. Power vs. output voltage

A simplified three stage converter was built. The bi-directional converter and the battery were replaced with a large electrolytic capacitor. Because the motor is a DC motor, the inverter is replaced by a buck converter. The microcontroller used is an AVR ATMEGA128. Two PID regulators were implemented in software, one for the boost DC/DC converter and one for the motor buck converter. A hysteresis controller was used as DC voltage bus monitor. If the voltage exceeds a certain limit, the boost converter is shut down.

With the new control strategy, the car runs on the same circuit for 723 seconds, with an average speed of 6.13m/s. The new calculated efficiency is 14.49%, representing more than 50% increase from the original efficiency.

5. Conclusions

This paper presents a strategy to maximize the efficiency of the fuel cell by means of controlling the load. A new three stage SMPS topology was proposed in order to achieve this goal. Two of the three stages were experimentally validated on a 0.5W fuel cell powered toy car. The original efficiency was increased by more than 50%. Even if a more powerful fuel cell stack is required to test the full potential of this load control strategy, the goal of this article was achieved.

Acknowledgement

This work was supported by the Ministry of Education and Research grants CEEX 112 INFOSOC and ID_1072 CNCSIS.

References

[1] “Mechatronics in fuel cell systems”, Anna G. Stefanopoulou, Kyung-Won Suh
[2] Larminie, James (May 2003). Fuel Cell Systems Explained, Second Edition.
[3] en.wikipedia.org/wiki/Fuel_cell
[4] http://www.thamesandkosmos.com/products/fc/fc2.html
[5] www.worldenergy.org/focus/fuel_cells/377.asp
[6] www.fuelcells.org/basics/benefits.html
[7] auto.howstuffworks.com/fuel-cell.htm
[8] en.wikipedia.org/wiki/Water_fuel_cell
[9] www.bigs.de/en/shop/htm/bz01.html
[10] www.coilgun.eclipse.co.uk/electromagnetic_pistol_voltage_converter_design.html
[11] http://www.geocities.com/CapeCanaveral/Lab/9643/rhpzero.htm
[12] http://microfluidics.asu.edu/fcells.html
[13] http://en.wikipedia.org/wiki/Boost_converter