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Short communication

Test of a PEM fuel cell with low voltage static converter

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Abstract

This paper presents a test of a 500 W polymer electrolyte membrane (PEM) fuel cell connected with a power electronic converter. The aim of this device is to develop fuel cell dynamic models and to study converter structure and control to adapt fuel cell to an electrical power train. The design of the converter is first discussed before presenting different experimental results involving thermodynamic and mechanical phenomena of the PEM fuel cell.

Keywords: Fuel cell; Polymer electrolyte membrane; Automotive system; Power train; Supercapacitor

1. Introduction

Presently, fuel cells are one of the most promising alternative sources of electric power. Scientists are developing many different types of fuel cells, but the most promising for use in automobiles is the lightweight, relatively small polymer electrolyte membrane fuel cell (PEMFC), first used by NASA in the 1960s as part of the Gemini space program. PEMFC low-temperature operation lets it start quickly and increases its durability [1,2]. Fuel cells vehicles have already proven much more efficient than similar internal combustion vehicles. Toyota and GM have also announced that their fuel cells prototypes running on hydrogen have twice the efficiency of their conventional gasoline vehicles [3].

The study of electrical power train needs test to study the interaction between powered electronic devices and fuel cells. Two methods we are developed, the first one to establish fuel cell dynamic models which can be later used in the modeling of the whole system, the second one to define static converter structures and control the output voltage of the fuel cell to the 42 V standard automotive electrical system (power net) as shown in Fig. 1 [4,5].

This paper presents the design and the implementation of a 500 W PEMFC test made up of a low voltage static converter associated with a PEM fuel cell. Different results show the PEMFC characteristics when connected power electronics converter.

2. Fuel cell converter

2.1. Converter operation

Fuel cell operates giving direct current, and at a low voltage; thereby, the boost converter, presented in Fig. 2, is selected to adapt the low dc voltage delivered by the fuel cell, which is around 12.5 V at its rated power, to the 42 V standard automotive dc bus.

The fuel cell converter is composed of a high frequency inductor L_1, an output filtering capacitor C_1, a diode D_1, and a main switch S_1. Switch S_2 is a shutdown device for test security to prevent the fuel cell stack from short circuits in case of accidental destruction of S_1, or faulty operation of the regulator.

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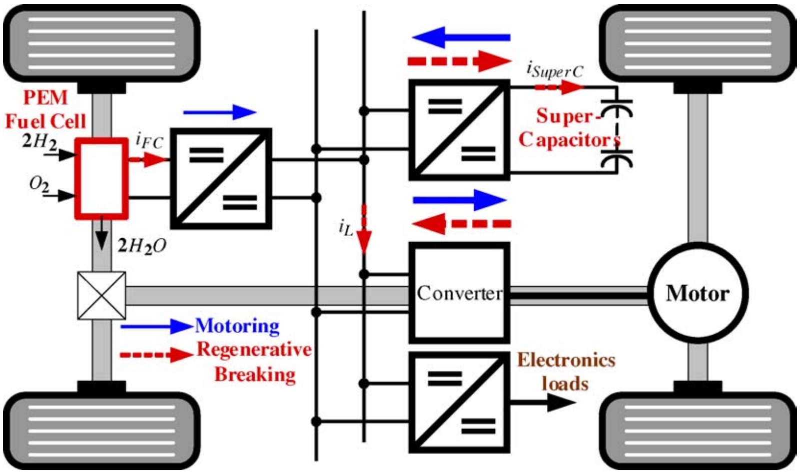

Fig. 1. Power train for a hybrid fuel cell vehicle.

The boost converter can operate in continuous or discontinuous modes. The fuel cell converter is designed to operate in continuous mode because the discontinuous mode has the following disadvantages: firstly, a load regulation problem when the output voltage depends on load; secondly, a high peak inductor current which can lead to magnetic saturation; thirdly, the tendency of the output voltage to increase at low power levels can add reliability problems for the load [6].

2.2. Power circuit design

The output power and current are linked to the fuel cell specifications and to the dc bus voltage by:

$$\begin{aligned} P_{\text{in}} &= V_{\text{FC}} I_{\text{FC}} \\ P_{\text{out}} &= P_{\text{in}} \eta \end{aligned}, \qquad I_{\text{out}} = \frac{P_{\text{out}}}{V_{\text{Bus}}} \tag{1}$$

where P_{in} is input power or fuel cell power, P_{out} the output power or dc bus power, V_{FC} the fuel cell voltage, I_{FC} the fuel cell current, I_{out} the load current at dc bus, and η is the efficiency.

And the duty cycle of pulse width modulation (PWM) is given by:

$$D = 1 - \frac{V_{\text{FC}}}{V_{\text{Bus}}} \tag{2}$$

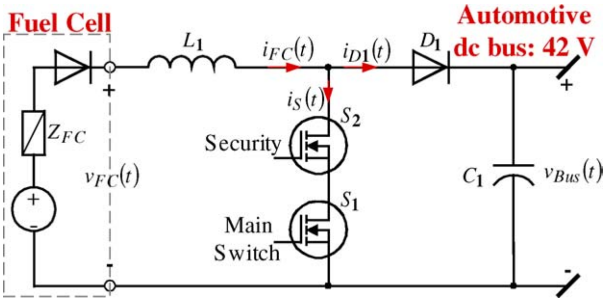

Fig. 2. Fuel cell boost converter.

At the rated duty cycle of 0.70, the rms current rating in the switches is:

$$\begin{aligned} I_{\text{S,rms}} &= I_{\text{FC}} \sqrt{D} \\ I_{\text{D}_1\text{,rms}} &= I_{\text{FC}} \sqrt{1-D} \end{aligned} \tag{3}$$

where $I_{\text{S,rms}}$ is rms current of power switches and $I_{\text{D}_1\text{,rms}}$ is rms current of power diode.

Selecting a proper output capacitor C_1 contributes to the reduction in output voltage ripple. Considering that all the current harmonics delivered by the converter are filtered by the capacitor leads to the rms capacitor current, $I_{C_1\text{,rms}}$:

$$I^2_{C_1\text{,rms}} = I^2_{\text{D}_1\text{,rms}} - I^2_{\text{out,rms}} = \left(1 - \frac{V_{\text{FC}}}{V_{\text{Bus}}} \eta^2\right) \frac{V_{\text{FC}}}{V_{\text{Bus}}} I^2_{\text{FC}} \tag{4}$$

The value of the capacitor C_1 depends on the capacitor ripple amplitude voltage, ΔV_{Bus}:

$$C_1 = \frac{I_{\text{out}} D}{\Delta V_{\text{Bus}} f} = \frac{\eta P_{\text{in}} D}{V_{\text{Bus}} \Delta V_{\text{Bus}} f} \tag{5}$$

where f is PWM switching frequency.

The input filter current, ripple (ΔI_{FC}) and peak ($I_{\text{FC,peak}}$), determine the size of the inductor L_1:

$$L_1 = \frac{V_{\text{in}} D}{\Delta I_{\text{FC}} f} \tag{6}$$

With a 12.5 V, 40 A fuel cell rated and assuming an efficiency of 90% with a switching frequency (f) of 25 kHz, a dc bus voltage ripple of 2%, and an input ripple current of 12% of the rated value leads to:

$$\begin{aligned} &P_{\text{out}} = 450\,\text{W} && I_{\text{S,rms}} = 33.5\,\text{A} \\ &I_{\text{out}} = 10.7\,\text{A} && I_{\text{D}_1\text{,rms}} = 21.9\,\text{A} \\ &I_{C_1\text{,rms}} = 19.1\,\text{A} && C_1 = 357\,\mu\text{F} \\ &L_1 = 72.9\,\mu\text{H} \end{aligned} \tag{7}$$

Worst-case scenarios determine device ratings; therefore, the blocking voltage is equal to 42 V. STE180NE10 (100 V-

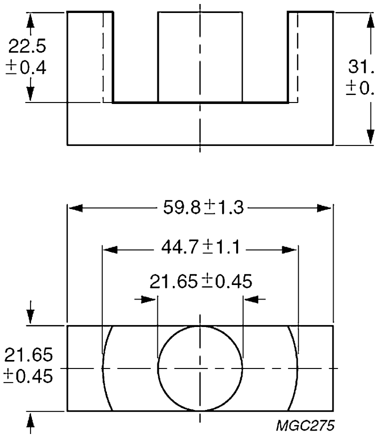

Fig. 3. Half core geometry of the ETD59-3C90.

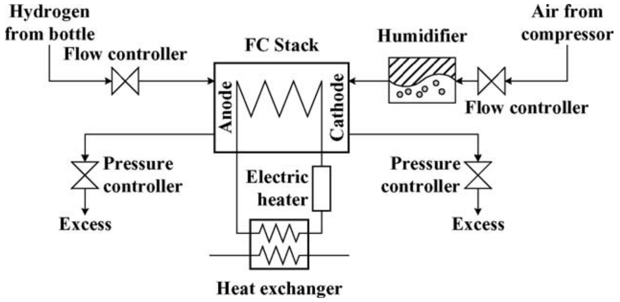

Fig. 5. Simplified diagram of the 500 W PEM fuel cell [7].

4.5 mQ-180 A Isotop, ST Microelectronics MOSFET with two devices in series, was chosen for switches S_1 and S_2. STPS80H100TV (100 V, 40 A) Power Schottky, ST Microelectronics, was selected. Based on the rated ripple current, Panasonic aluminum electrolytic capacitors 10,000 μF, 100 V, 7.32 A, were chosen. The necessity to use three devices in parallel will, in fact, lead to a lower voltage ripple which comes from the rms capacitor current value.

Inductor L_1 has to be built following the two main parameters, which are the inductance value and the peak current. The value of the inductance is given by a relation the form [6]:

$$L_1 = \frac{\mu_0 A}{2d} N^2 \tag{8}$$

where μ_0 is the permeability of air, A the area of the magnetic path, d the air gap length, and N is the number of turns.

Considering the Ferroxcube soft ferrites ETD59-3C90 core represented in Fig. 3, one obtains with a 2 mm air gap and 26 turns for the desired inductance and one can verify that the ampere-turn does not lead to exceed the saturation limit (B_{Sat}) equal to 0.33 T:

$$N I_{\mathrm{FC,Peak}} \frac{\mu_0}{2d} < B_{\mathrm{Sat}} \tag{9}$$

2.3. Control structure

The control structure of the PEM fuel cell converter is shown in Fig. 4. PID and PI regulators are implemented for fuel cell current and dc bus control, respectively. The voltage controller demands dc bus power instead of current because, in future work, the fuel cell will work with secondary sources, and for this reason, power conditioning is necessary.

Additionally, i_{FCREF} is sent to fuel cell processor to obtain hydrogen and oxygen in order to generate the desired electrical current.

3. Experimental results and discussion

Fig. 5 shows a diagram of the PEMFC, which is used for this research. Constructed by Zentrum für Sonnenenergie und Wasserstoff-Forschung (ZSW), Ulm, Germany, the fuel cell stack is composed of 23 cells of 100 cm^2 (Fig. 6). The rated output power is 500 W for a rated current of 40 A, and approximately 12.5 V.

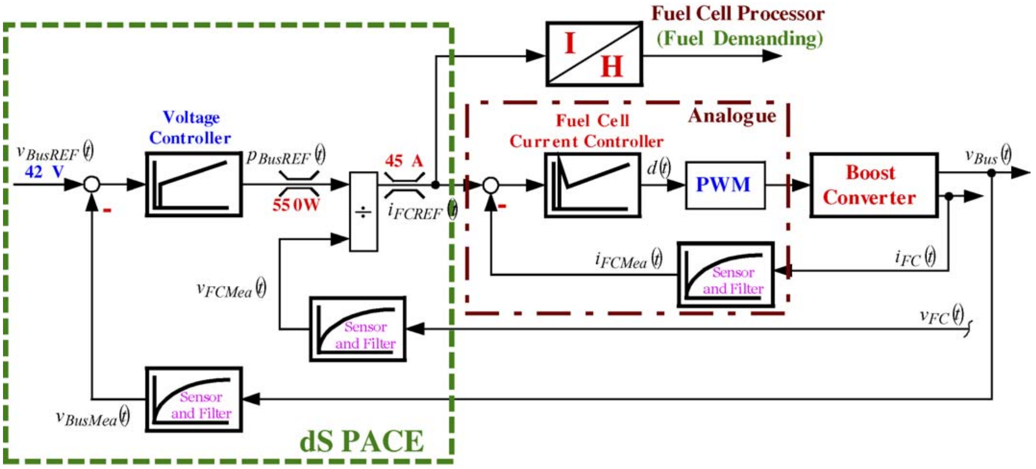

Fig. 4. Cascade voltage and average-current control structure of PEMFC converter.

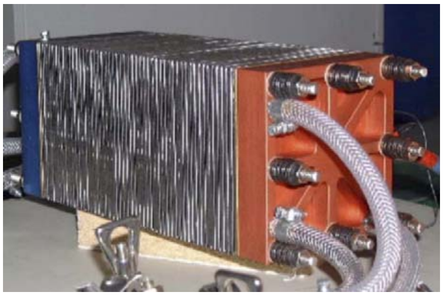

Fig. 6. ZSW 500 W PEMFC.

3.1. Fuel cell converter testing with an ideal power supply

Initial testing was performed using an ideal 12.5 V power supply, which has the same rated voltage as the fuel cell, in order to confirm that the boost converter can operate correctly and to compare fuel cell and ideal power supply characteristics.

Fig. 7 shows the input current response with a stepped current command. It shows that the current response has high dynamics with optimum response by the current controller (PID). Moreover, Fig. 8 presents the voltage loop test with a load disturbance. This result shows that the regulation of the fuel cell converter correctly works.

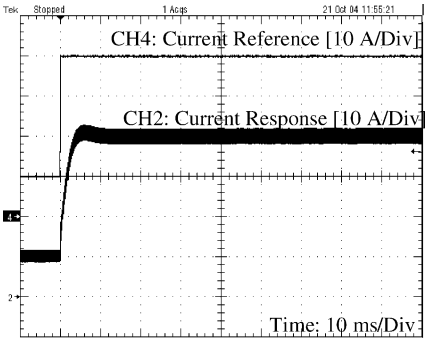

Fig. 7. Current response to a 10–40 A step.

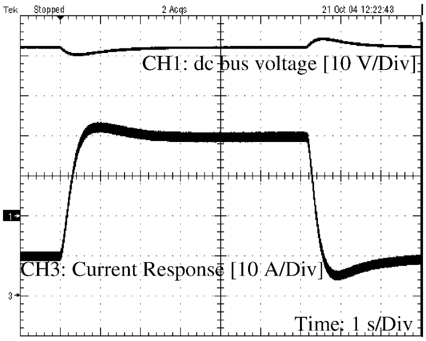

Fig. 8. Converter response to a stepped load disturbance.

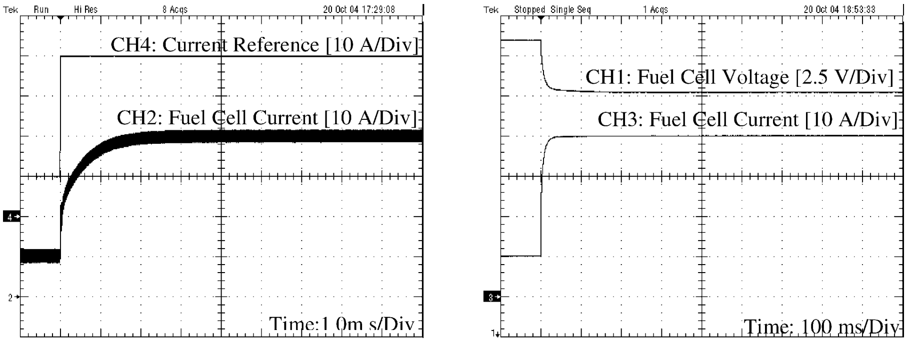

Fig. 9. Fuel cell current response for a 10–40 A step at constant fuel flow for 50 A.

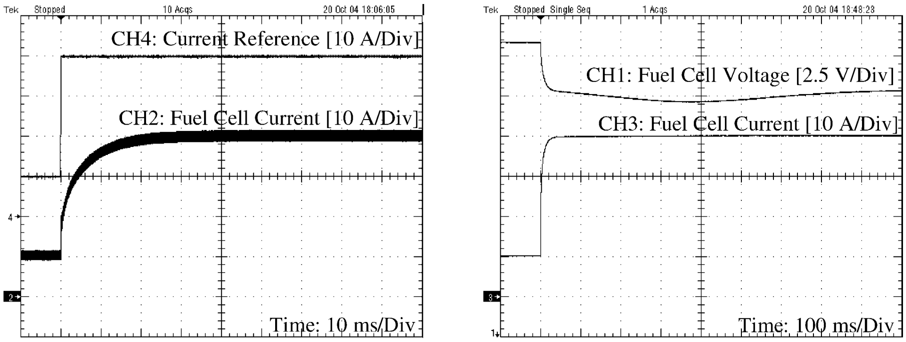

Fig. 10. Fuel cell current response for a 10–40 A step at variable fuel flow.

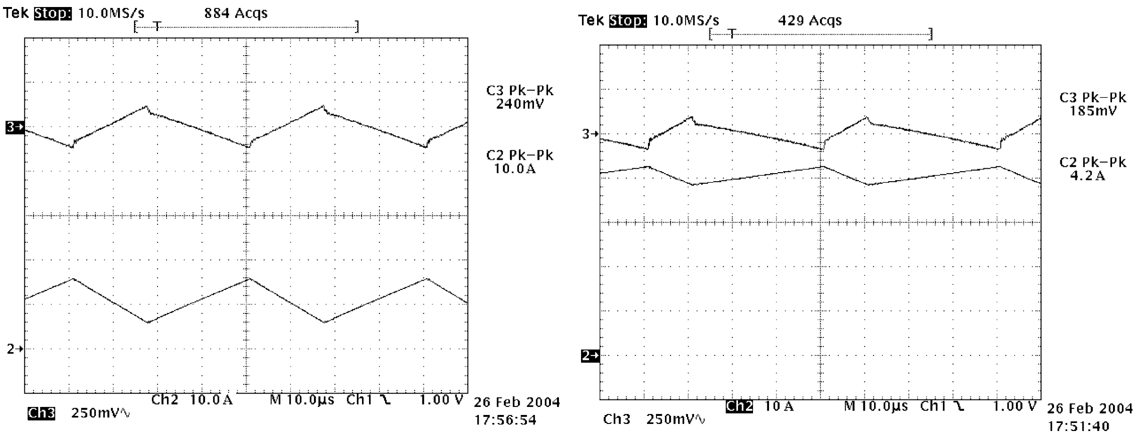

Fig. 11. PEM fuel cell characteristics at steady-state (top: FC voltage ripple (250 mV/div); bottom: FC current (10 A/div)): (a) at fuel cell current 10 A and (b) at rated power (40 A).

3.2. Fuel cell converter testing with a PEM fuel cell

When fuel cell is operated, its fuel flow is controlled by the fuel cell processor, which receives current demand from the current reference as shown in Fig. 4.

To present the fuel cell characteristics, the test bench is operated in two different ways:

- firstly, the fuel cell works at constant fuel flow corresponding to the maximum available current of 50 A. In this case, the fuel cell has always enough hydrogen and oxygen;
- secondly, the fuel flow varies depending on the current reference.

As shown in Fig. 9, the dynamic response of the fuel cell current is different from Fig. 7. There are two ways to explain this phenomenon. Firstly, the electrical fuel cell model is different from an ideal power supply. Secondly, the phenomenon is due to the slowness of its electrochemic operation.

Fig. 10 shows the effect of mechanical problems. It can be seen from the fuel cell voltage that it drops lower than in Fig. 9. This means that the fuel supply and delivered electrical current do not coincide. Fuel flow is not enough for the converter current. This condition of operating is hazardous for the fuel cell stack [8–10].

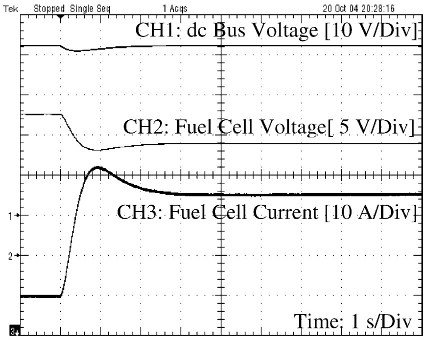

Fig. 12. Fuel cell converter response to a stepped load disturbance at constant fuel flow for 50 A.

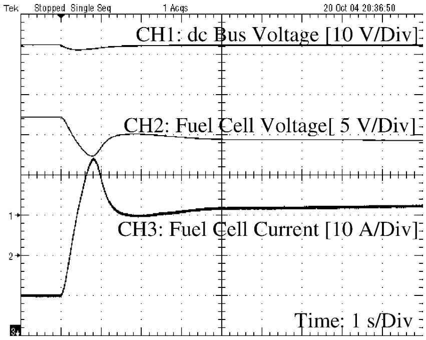

Fig. 13. Fuel cell converter response to a stepped load disturbance at variable fuel flow.

Characteristics of the PEMFC at steady-state when connecting with a converter are presented in Fig. 11. It can be seen that the PEMFC contains a complex impedance component, which it is not purely resistive at a switching frequency of 25 kHz.

Furthermore, the voltage loop test is presented in Figs. 12 and 13. Compared with the current response of Fig. 8, it also shows the slowness of the fuel cell response. The fuel cell current has a high overshoot and delay time.

These tests clearly confirm the slowness and complicated model of the fuel cell system [7,11,12].

4. Conclusion

The main objective of this work was to design, implement, and test a low voltage static converter for a PEM fuel cell, in order to understand the PEM fuel cell behavior when operating in an environment of power electronics for an automotive electrical system.

The experimental results obtained with the 500 W PEM fuel cell confirm the relative slowness of this device, which will require an auxiliary power source, such as a battery or supercapacitor, in order to operate with high dynamics.

This fuel cell model can be used for the simulation of a whole system including fuel cell, converters, storage element, and electrical loads.

Acknowledgements

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