INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 41 (2016) 5378–5388

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/he

Integration of electrochemical impedance spectroscopy functionality in proton exchange membrane fuel cell power converter

Daniel Depernet [a,b,*], Abdellah Narjiss [c], Frédéric Gustin [a,d], Daniel Hissel [a,d], Marie-Cécile Péra [a,d]

[a] FCLAB Research Federation, FR CNRS 3539, FEMTO-ST/Energy Department, UMR CNRS 6174, UBFC, France
[b] University of Technology of Belfort-Montbéliard, 90010 Belfort Cedex, France
[c] ElecSys France, Engineering and Innovation Consulting, 25460 Etupes, France
[d] University of Franche-Comté, 90010 Belfort Cedex, France

ARTICLE INFO

Article history:
Received 9 June 2015
Received in revised form
4 February 2016
Accepted 7 February 2016
Available online 27 February 2016

Keywords:
Online EIS
PEMFC
Electric vehicle
DC/AC/DC converter
DFT
Real time implementation

ABSTRACT

This paper presents a solution of implementation of electrochemical impedance spectroscopy (EIS) functionality in the power converter used for Proton Exchange Membrane Fuel Cell (PEMFC) power management. The fuel cell is electrically coupled to an electric vehicle DC bus using a DC/AC/DC converter based on an inverter stage, a high frequency power transformer stage, and a rectifier stage. The EIS is achieved by the power converter in order to be performed without additional hardware, cost and volume. The proposed EIS process is integrated in the power control to allow real time using of EIS results for embedded diagnosis or control improvement. An experimental platform developed in the laboratory has validated the online EIS method on a 750 W 20-cell-stack. Experimental validation tests presented in this paper illustrate spectral impedance monitoring for variations of requested current, air humidification rate and hydrogen flow rate.

Introduction

The conversion of hydrogen into electricity allows considering electric vehicles with an acceptable autonomy thanks to embedded storage of hydrogen [1], while enjoying all the benefits of powertrain electrification: greater energy efficiency, lower maintenance costs, zero emissions at the vehicle level. The PEMFC is one of the innovative key components of this energy conversion architecture. Its operating conditions are quite suitable for this type of application. Its efficiency, its cost and its reliability are decisive to the commercial growth of this technology and have not yet reached sufficient levels to make it profitable and competitive. Nowadays, considering the use of a PEMFC in an electric vehicle under actual operating conditions, it is possible to achieve a lifespan of about 2500 h, while 5000 h is classically the requirement for personal vehicles. Thus, among the

* *Corresponding author*. University of Technology of Belfort-Montbéliard, 90010 Belfort Cedex, France. Tel.: +33 (0) 3 84 58 36 10; fax: +33 (0) 3 84 58 36 36.
E-mail address: daniel.depernet@utbm.fr (D. Depernet).
http://dx.doi.org/10.1016/j.ijhydene.2016.02.010

different ways to solve this technological bolt, the development of efficient real-time observation methodologies for the state-of-health of the fuel cell stack is key possibility. This could offer a better understanding of the phenomena causing internal damage and aging. Moreover, these technologies, if featuring real-time ability, should eventually help correcting the electrical and fluidic management of fuel cell system in order to minimize the degrading effects.

The use of PEMFC in automotive vehicles also makes diagnostic and maintenance operations very expensive and difficult to implement without the intervention of a specialist. These operations can then become very restrictive for the user. The development of smart characterization methods that are online, incorporated and low cost is essential for in situ diagnosis of PEMFC system. Therefore, the vehicle should be able to ensure its diagnosis autonomously, generating the lowest possible downtime. In addition, the extra cost and integration constraints implied by the implementation of these features should remain low since these two properties already appear as penalizing factors whose impact needs to be reduced [2].

Accurate identification of the parameters of the fuel cell stack & system will supply diagnostic algorithms with more reliable data and will help facilitating decision in the case of a default event [3]. It will also achieve an optimal management of control leading to increased service life of the fuel cell stack.

After describing the principle of the PEMFC connection to the DC bus of the vehicle, the structure of the power converter based (here) on a HF transformer will be described. Then, the power converter control principle will be presented. The constraints of implementation of the PEMFC characterization by EIS will also be given. The integration principle of EIS ability thanks to power converter control will then be shown. Finally, the experimental system developed in the laboratory and experimental results illustrating the online characterization of PEMFC will be highlighted before concluding.

PEMFC coupling to electrical vehicle DC bus

PEM fuel cells have the property of being low voltage and high current power sources. Indeed, the cell voltage depends on the required current. The experimental single-cell voltage is classically comprised between 0.4 V and 1 V. The 20-cell experimental stack UBZM 750 used in this study has a voltage that remains between approximately 20 V (no-load) and 13 V (for rated current). The specification of the intended application defines a vehicle DC bus voltage about 8 times higher than the voltage of our considered PEMFC stack (note that this elevation ratio is quite classical on embedded applications). The experimental DC output voltage of the converter is set at 110 V to keep this specified voltage boost from UBZM-750 stack voltage. Power increasing may then be obtained by coupling several stacks, thereby also increasing the power availability on-board the vehicle in case of failure of one of the fuel cell stacks.

The power converter coupling the fuel cell stack to the vehicle DC bus must perform this high voltage elevation ratio while minimizing also the energy losses due to power conversion. Electronic topology of the power converter is shown in Fig. 1a and discussed in Ref. [4]. The first stage consists of a full bridge MOSFET inverter coupled to the PEMFC via a high frequency capacitor filter. This capacitive input filter reduces the harmonic content of the requested current which may be harmful for the PEMFC [5]. A temporized charge circuit allows the capacitor C to be connected to PEMFC without current overload. The high switching frequency of the transistors implies the need for special attention to the quality of MOSFET switching to limit their losses. The second stage includes a PLANAR technology high frequency transformer. Its main asset is its very small size (high power density) mainly due to the use of high frequency (i.e. up to 150 kHz) voltage and current combined with its low eddy current loss level (its efficiency is typically 98%). This property helps converter integration constraints in the vehicle to be minimized [6]. The transformer also provides galvanic isolation which may be useful in some applications. It performs a high voltage elevation ratio by simple design of the ratio between turn numbers of primary and secondary windings. PLANAR transformers may be used for powers up to 20 kW, which is an acceptable limit for applications in hybrid electric traction when the power is correctly segmented (i.e. the use of multiple low-power fuel cell power generation units). The third stage consists in a diode rectifier and a LC low-pass filter which reduces the harmonic content before connection to the vehicle DC bus. Limiting losses in this stage can be met by choosing diodes characterized by a low voltage drop. Efficiency improvement according power domain of this converter including Silicon Carbide components is discussed in Ref. [7].

Control of energy transfer is performed by a motor control Digital Signal Processor (DSP). This microcontroller supports control of power semiconductors, measurements and regulations. It is also used to perform the characterization of the PEMFC by EIS presented in this paper, as shown in Fig. 2. Using of a single microcontroller for control and characterization allows size and cost to be minimized. Furthermore, the entire dynamic of the control and of the sampling may be used by real time algorithms to perform EIS measurements. The curves of Fig. 1b illustrate the control signals of the inverter MOSFET and the electrical waveforms. The principle is to drive the transistors to achieve a symmetrical AC waveform across the primary of the transformer V_p. The switching frequency F_{PWM} is chosen equal to 50 kHz, which is the lowest limit considering the HF technology of the transformer. The increase in PWM frequency would facilitate the design of the filters and increase the accuracy of the EIS, but at the expense of increased losses in the inverter.

Frequency of primary voltage V_p is fixed while its RMS value is controlled by acting on the conduction duration of the transistors which is modeled by the duty cycle α. Gates of transistors Q_1 and Q_2 are controlled with identical signals in order to perform the adjustment of the conduction time during the positive halfwave of the transformer primary voltage V_p. Transistors Q_3 and Q_4 are controlled identically, but for adjustment of the conduction time during the negative halfwave of V_p. The average value of the output voltage of the converter V_{BUS} is linked to the PEMFC voltage V_{FC} by the voltage ratio m of the transformer and the duty cycle α according to the following expression:

$$V_{BUS} = 2m\alpha V_{FC} \quad (1)$$