Journal of Power Sources 220 (2012) 31–41

Contents lists available at SciVerse ScienceDirect

Journal of Power Sources

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

Proton exchange membrane fuel cells cold startup global strategy for fuel cell plug-in hybrid electric vehicle

Nilson Henao [a], Sousso Kelouwani [b,*], Kodjo Agbossou [a], Yves Dubé [b]

[a] Hydrogen Research Institute and the Department of Electrical and Computer Engineering of Université du Québec à Trois-Rivières, Trois-Rivières, Québec G9A 5H7, Canada
[b] Hydrogen Research Institute and the Department of Mechanical Engineering of Université du Québec à Trois-Rivières, Trois-Rivières, Québec G9A 5H7, Canada

HIGHLIGHTS

► The design and the experimental validation of a supervisory architecture for FC-PHEV energy management.
► The design of a global strategy for the fuel cell cold startup.
► A time optimal heating method based on the Pontryagin minimum principle.

ARTICLE INFO

Article history:
Received 23 May 2012
Received in revised form
28 July 2012
Accepted 30 July 2012
Available online 7 August 2012

Keywords:
Electric vehicles
Energy efficiency
Energy management
Fuel cells cold startup
Nonlinear optimal control
Vehicle dynamics

ABSTRACT

This paper investigates the Proton Exchange Membrane Fuel Cell (PEMFC) Cold Startup problem within the specific context of the Plugin Hybrid Electric Vehicles (PHEV). A global strategy which aims at providing an efficient method to minimize the energy consumption during the startup of a PEMFC is proposed. The overall control system is based on a supervisory architecture in which the Energy Management System (EMS) plays the role of the power flow supervisor. The EMS estimates in advance, the time to start the fuel cell (FC) based upon the battery energy usage during the trip. Given this estimation and the amount of additional energy required, the fuel cell temperature management strategy computes the most appropriate time to start heating the stack in order to reduce heat loss through the natural convection. As the cell temperature rises, the PEMFC is started and the reaction heat is used as a self-heating power source to further increase the stack temperature. A time optimal self-heating approach based on the Pontryagin minimum principle is proposed and tested. The experimental results have shown that the proposed approach is efficient and can be implemented in real-time on FC-PHEVs.

1. Introduction

The hydrogen fuel cell is emerging as one of the best power sources for the sustainable transportation due to its low greenhouse gas emission and its high power density [1,2]. Different types of fuel cell technologies are being investigated for Hybrid Electric Vehicle (HEV). However, the Proton Exchange Membrane Fuel Cell (PEMFC) is one of the most selected power sources for electric mobility [3]. In some vehicle applications involving fuel cells, the batteries are being used primarily to capture the regenerative power, secondary to absorb the rapid and high power transient originating from the vehicle dynamics and finally to provide power to the vehicle motion [4]. These vehicles are designated as Fuel Cell Plug-in Hybrid Electric Vehicle (FC-PHEV). The energy efficiency of an FC-PHEV is thoroughly related to the power flow management between all components that contribute to the vehicle propulsion. So, a lot of work is being done on the specific problem of the on-board energy management and power splitting [5].

When the fuel cell is operating, there is a production of water and water vapor. Although a systematic purge is performed during the PEMFC shutdown process, the remaining water vapor could frost when the temperature drops below 0 °C (in regions with long and very cold winter seasons). To preserve the fuel cell life, a specific attention is required before restarting the fuel cell during the periods of sub-freezing and freezing ambient temperatures [6–8]. Thus, Ref. [9] reported that an irreversible degradation in the fuel cell components occurs during sub-freezing and freezing operating temperatures. The volume expansion of the cell materials in the freezing conditions is one of the reasons for this degradation

* Corresponding author. Tel.: +1 819 376 5011; fax: +1 819 376 5210.
E-mail addresses: Nilson.Henao@uqtr.ca (N. Henao), sousso.kelouwani@uqtr.ca (S. Kelouwani), kodjo.agbossou@uqtr.ca (K. Agbossou), yves.dube@uqtr.ca (Y. Dubé).

0378-7753/$ – see front matter
http://dx.doi.org/10.1016/j.jpowsour.2012.07.088

[10]. Among the proposed recommendations in Refs. [9,10] is the water purge operation during the fuel cell shutdown. The research reported in Refs. [11,12] showed that heating the stack has a great positive impact on the fuel cell transient thermal model. In Ref. [13], the catalytic oxygen/hydrogen reaction heat is used to increase the stack temperature.

In physics and in electrochemistry, several studies regarding the stack self-heating when the stack temperature belongs to a subfreezing range, have been reported. The cell membrane water content and the ice formation in the cathode catalyst layer are extensively studied and identified as the main performance limiting factors. In Ref. [21], an analytical model describing the heat balance, the ice formation in the catalyst layer, and the water transport characteristic throughout a fuel cell at very low temperatures is presented. In Ref. [22], numerical studies were conducted using a monotonically increasing current for a fuel cell cold start from $-30\,^{\circ}$C. It was shown that using a moderate current increasing rate or using a large initial current density in combination with a small current increasing rate, can lead to a successful stack self-start. In the experimental study presented in Ref. [23], the ice accumulation in a frozen PEMFC was measured at sub-freezing temperatures and the time to voltage failure for various current densities under isothermal operation at $-20\,^{\circ}$C was also measured.

Although these reported studies demonstrated that it is possible to achieve a fuel cell self-start from a sub-freezing temperature, we propose in this paper a different approach which focuses only on the stack thermodynamic and electric aspects. This approach allows us to consider the PEMFC global electrothermal behavior without focusing on the electrochemistry detail equations. In addition, the electrothermal behavior model permits a simple and effective formulation of the global optimization problem that can be solved in real-time in the context of the FC-PHEV. To avoid complicated water management issues and potential irreversible damages in the fuel cell components, an external heating system is used to heat the stack and let the cell temperature to belong to its normal operating range from a sub-freezing starting point.

Two different methods have been reported for the fuel cell heating [7]. The internal heating which is the first method, consists in providing an electric current to a resistance embedded directly into the stack. The heat generated from the resistance Joule effect is transferred to the stack structure. Often, this method is used by the fuel cell manufacturers. The second method is related to the external fluid based warm-up system which uses a heat exchanger and an antifreeze fluid (mixture of glycol and water). The exchanger allows the heat transfer from the fluid to the stack components. This method is more accessible to our research than the previous one. However, the main problem is to determine the heating energy (heating power and duration) that will allow rising the stack temperature whilst minimizing the heat loss through the natural convection with the environment.

This paper investigates the PEMFC temperature management for the vehicle application, especially for the FC-PHEV vehicles. On such a vehicle, the batteries have the energy to propel the vehicle over a portion of the travel distance and the fuel cell, which plays the role of range extender, is started to recharge the batteries through a serial topology [14].

We assume that the fuel cell has an appropriate heat exchanger embedded into the cells to allow the warm-up process using an external fluid heating system. Two contributions are presented: the first one is related to the design and to the experimental validation of a two layer supervisory architecture for FC-PHEV energy management. The second contribution consists in designing a global strategy for the fuel cold startup by considering the cells initial temperature, the ambient temperature, the thermal operating range of the cells and the amount of energy available for heating the stack. The vehicle Energy Management System (EMS) is part of the upper layer whereas the global strategy for the fuel cell cold startup belongs to the lower layer. Knowing the trip length and the average power requirement for the vehicle motion, this EMS estimates the amount of fuel cell energy required to complete the trip. It also estimates in advance the appropriate time to start the fuel cell. The global strategy for the fuel cell cold startup uses these two data as constraints and provides the appropriate heating timing that will allow the fuel cell to comply with them.

The rest of the paper is organized in 7 sections. The FC-PHEV supervisory architecture is presented in section 2. The cold start problem overview and the startup strategy are discussed in sections 3 and 4, respectively. The self-heating method based on the Pontryagin minimum principle is investigated in section 5, whereas the high temperature regulation and the experimental results are discussed in sections 6 and 7, respectively. Finally the conclusion is presented in section 8.

2. FC-PHEV supervisory architecture

Fig. 1 represents a typical FC-PHEV serial topology where the solid and dashed arrows represent the power flow and the control signal, respectively. The driver power demand is sent to the Energy Management System (EMS) which generated the corresponding power command P_{m} for Electric Propulsion System. The bi-directional converter allows the Battery Pack to be charged and discharged and P_{b} represents the power flowing through this converter. In this architecture the EMS supervises the Fuel Cell Power Controller and the battery pack energy E_{b}. The power from the Fuel Cell P_{fc} is used to recharge the batteries.

To prevent the Battery Pack to be over discharged, a minimum energy threshold $E_{\mathrm{b}}^{\mathrm{min}}$ is usually defined [15]. So the Battery Pack is operating in a depleting mode until E_{b} reaches $E_{\mathrm{b}}^{\mathrm{min}}$. Knowing the initial Battery Pack energy E_{b}^{0}, the amount of energy available for the trip and the stack heating is represented by:

$$E_{\mathrm{b}}^{\mathrm{a}} = E_{\mathrm{b}}^{0} - E_{\mathrm{b}}^{\mathrm{min}} - E_{\mathrm{he}}^{\mathrm{max}} \tag{1}$$

where $E_{\mathrm{he}}^{\mathrm{max}}$ is the maximum energy that can be used to heat the stack.

We assume that the whole trip duration t_{td} and the average traction power $\tilde{P}_{\mathrm{m}}$ are known; thus, it is possible to approximate the total energy required to drive the vehicle to the destination using the following equation:

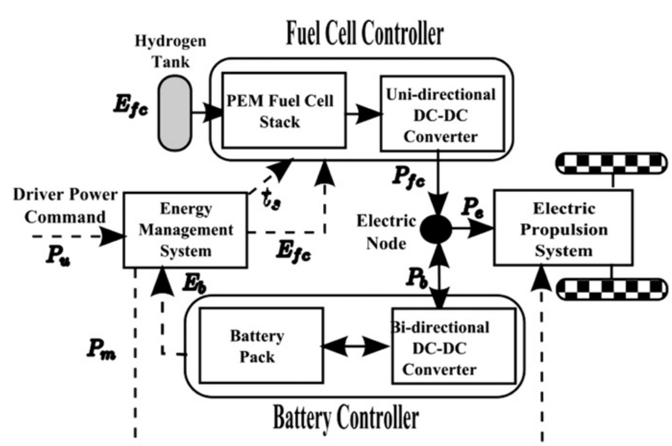

Fig. 1. Fuel cell hybrid electric Vehicle: the arrows with solid lines represent energy flows; the arrows with dashed lines represent control and measured signals.