INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (2017) 1–13

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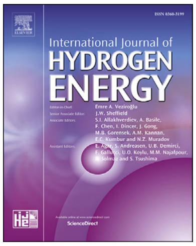

Energy management control design for fuel cell hybrid electric vehicles using neural networks

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ARTICLE INFO

Article history:
Received 21 June 2017
Received in revised form
28 September 2017
Accepted 29 September 2017
Available online xxx

Keywords:
Fuel cell hybrid electric vehicle
Energy management system controller
Dynamic PEM fuel cell model
Hydrogen consumption minimization
Neural networks

ABSTRACT

The design and optimization of hybrid electric vehicle powertrains can take a great benefit from mathematical models which include auxiliary management and control strategies of the energy fluxes: the use of virtual platforms reduces the expensive and time-consuming experimental activity. In this work the authors developed an online Energy Management System (EMS) controller for a FCHEV, designed to employ the same energy management over a wide range of driving style types. The controller was designed by using neural networks (NN), which were trained with the optimal power flux distribution between a fuel cell system and a battery system that minimizes the overall equivalent energy consumption. The optimal solution was obtained by carrying out a gradient-based method minimization over eight different driving cycles, and using a dynamic lumped parameter mathematical model of a FCHEV fed by hydrogen and Li-ion batteries. A quantitative and qualitative analysis was made showing the networks performances over different type of cycles. Through this analysis, a suitable classification into two cycle categories is provided, covering most of the possible driving styles with two of the developed controllers.

Introduction

Currently, new and rapidly emerging hydrogen based technologies are being extensively used for propulsion systems of hybrid electric vehicles. Fuel Cell System (FCS) could become the main power source of electric vehicles in the forthcoming decades, not only in terrestrial systems but also in air and naval systems [1,2]. There are several potential advantages for using such a power source ranging from environmental to performance and operability aspects.

Among the various types of fuel cells currently available, due to their performance characteristics, Proton Exchange Membrane Fuel Cells (PEMFC), which work around 70 °C and with pressures close to atmospheric pressure, are at present the most suitable for use in transportation systems. Because

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https://doi.org/10.1016/j.ijhydene.2017.09.169

Please cite this article in press as: Muñoz PM, et al., Energy management control design for fuel cell hybrid electric vehicles using neural networks, International Journal of Hydrogen Energy (2017), https://doi.org/10.1016/j.ijhydene.2017.09.169

the FCS dynamic response is relatively low, PEMFC-powered vehicles could be unstable at the sudden load change [3]. For vehicular use, these systems should be complemented by electrochemical energy storage devices, such as advanced rechargeable batteries, to guarantee the immediate delivery of the necessary power for the propulsion at any moment when required.

There are many motivations for introducing the hybridization in FCS for vehicular applications: decouple the fuel cell from the current demanded by the traction motor to allow the FCS to be used as close as possible to its optimum operating range. Energy recovery by decelerating and braking through regenerative brakes. Reduce FCS size and save the overall weight of the system. The transient FCS response observed in dynamic analysis is not instantaneous and typical transient phenomena such as overshoot effects can be visualized, that can be solved with the use of a complementary battery [4,5]. But the benefits are not limited to it, the use of a second source of energy could even work as an emergency power source, in the case of the failure of the fuel cell. On the other hand, the extra degree of freedom offered by the hybrid topology and the complex power flow, introduces the need for an energy management control strategy [6]. The Fuel Cell Hybrid Electric Vehicle (FCHEV) needs an Energy Management systems to distribute electrical power among the load and distinct power sources. The strategy must satisfy powertrain component constraints while trying to achieve some system-level performance objective such as maximizing fuel economy or maintaining the battery state-of-discharge (SoD).

In the specific literature, there are mainly two types of control approaches: rule-based and optimization-based [7]. Several studies have been performed on this technology, with the aim to attain improved performance and the contributions from the literature on FCHEV control techniques are numerous [8–16]. In the study done by Simmons [17], an onboard EMS with an optimal control based on Pontryagins Minimum Principle (PMP) is implemented to find the global optimal solution which minimizes fuel consumption. They developed a practical controller suitable for on-board implementation, in the form of an Auto-Regressive Moving Average (ARMA) regulator. Cipollone et al. [18] have proposed a method that considers a propulsion strategy where the fuel cell can be completely switched on or off, in order to achieve the best fuel cell efficiency. Many power management algorithms were designed by rule-based or heuristic methods. Those rule-based methods are simple and easy to understand because they come from engineering intuition [19,20]. However, they often lack optimality or cycle-beating. Ideally, fuel consumption minimization of hybrid vehicles can be achieved only when the driving scenario is known a priori. For instance, many authors implement online control through the Pontryagins Minimum Principle, but this method ensures optimality only when the driving cycle is known a priori. In particular, once the vehicle characteristics are defined, the optimal solution strictly depends on the speed trace and the total traveled distance [21–25]. Delprat and Bernard [26,27] develop the global optimization algorithm where the driving cycle needs to be a priori known.

In the present work, a full hybrid structure for a FCS/battery electric vehicle, with a lithium ion battery pack as secondary source is proposed. The FCS was selected as the main power supplier to minimize the usage of the battery. The dynamic behavior of a PEMFC system is a crucial factor to ensure the safe and effective operation of FCHEV [28]. Because water and thermal management are critical to stabilize the performance of the PEMFC during severe load changes, the model used in this work will include the fulfilled lumped capacitance model of the thermal management subsystem. This was developed to describe the temperature dynamics of the system based on the system inputs (power required and ambient temperature) [29]. Although in the FC the dynamic behavior of the Temperature is much slower than most of the electrochemical processes that take place inside the FC, the difference of H_2 consumptions between a stack model coupled to an accurate thermal model and a Model of FC without thermal is about 4%. The great majority of the research published on the subject carry out optimizations adopting static models that use polarization curves and efficiency tables [30,31]. As the performance of the hybrid vehicles (e.g., FCHEV) vary dramatically from driving patterns [32], in this work eight light duty vehicle driving cycles for urban, suburban and highway settings were considered: UDDS, LA92, NYCC, NEDC, HWFET, WLTP and CADC in its urban and rural road variants [33]. As the optimization process of the complex dynamic model requires a significant computational effort, simplified models were used to carry out the optimization process of each cycle, as shown in Fig. 1. A gradient-based method was employed to obtain the optimal energy management strategies, instead of methods such as PMP or DP, which cannot be used here because of the nature of the models.

These optimal strategies were used to train a particular NN for each cycle. Additionally, every NN was run over the rest of the cycles, showing different performances.

The aim of this paper is the development of an EMS capable of supervising the power flux from the fuel cell, obtaining a solution that minimizes the equivalent energy consumption of an a priori unknown cycle.

This work is organized as follows: in Section Vehicle model specifications and powertrain description a comprehensive description of the used vehicle parameters and the mathematical models of the vehicle, battery and the PEMFC systems is done. Also, a simplified model of the PEMFC is introduced to reduce the computational cost on the optimization stage. In Section Optimization method a minimization of the hydrogen consumption was carried out by the gradient-based method over the different driving cycles. Both the used algorithm and numerical results are also included in this section, showing the reliability of the obtained solutions. Section Neural network EMS describes the on-line control strategy based on neural networks as well as its training, using the ideal fuel cell power of Section Optimization method. Finally in Section Results, a quantitative and qualitative analysis of the behavior of the networks over the different types of cycles was made, classifying the administration strategies into two categories. Finally, it is shown the degree in which EMS improves the performance in terms of equivalent consumption by contrasting both the on-line neural network strategy and the ideal a priori known cycle optimization with the baseline case.

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