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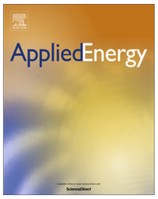

Energy management of a plug-in fuel cell/battery hybrid vehicle with on-board fuel processing

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HIGHLIGHTS

- Model-based simulator for energy management of parallel fuel cell/battery vehicle.
- Fuel processor optimization for on-board hydrogen production and storage.
- Electrochemical model of a HT-PEMFC for performance curves determination.
- Design of real time Pontryagin's Minimum Principle-based adaptive controller.
- Results comparison against the same vehicle with conventional and hybrid powertrain.

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ABSTRACT

This paper describes the energy management controller design of a mid-sized vehicle driven by a fuel cell/battery plug-in hybrid powertrain, where an experimentally validated hight temperature polymer electrolyte membrane fuel cell model is used. The power management strategy is derived by the application of the Pontryagin's Minimum Principle, where the control parameter is adapted by using feedback information on the state of charge and total trip length forecast as a function of a moving average of past information about the driving cycle speed. The strategy we propose aims at achieving a real time sub-optimal solution of the control problem which is cast into the minimization of the consumed fuel. The vehicle is also equipped by an auto-thermal reformer and, in order to minimize the hydrogen buffer size, the control algorithm is subject to constraints on the maximum hydrogen buffer level. A comparative analysis of the proposed strategy against the optimal one is conducted and results are reported. The obtained fuel consumptions are also compared to those obtained by the same vehicle, powered by an internal combustion engine and by a plug-in hybrid electric powertrain.

1. Introduction

Road transportation and, particularly, road vehicles are nowadays proved to be one of the main contributors to pollutant and global green-house gas emissions [1]. This, together with the rising of fuel price, is striving the automotive sector research towards innovative solutions, aimed at reducing costs and emissions [2]. Electric Vehicles (EVs) are still too far from being a valid solution for the problem, both for reduced driving range and long charging time. Promising solutions - already widely proposed and analyzed - are plug-in hybrid electric vehicles (PHEVs), characterized by high overall efficiency, short transients, long range and low road-load-dependency [3,4]. The same advantages apply for fuel cell vehicles (FCVs), which generally make use of polymer electrolyte membrane fuel cells (PEMFCs), with the possibility of further reducing pollutant emissions, giving a satisfactory range without the need of an internal combustion engine (ICE) [5]. In fact, when compared to ICE-propelled vehicles, both conventional or hybrid electric ones, FCVs are, locally, zero-emission vehicles and, in principle, if the fueling hydrogen could be derived from renewable energy sources, these vehicles could allow for zero pollutant emissions also at a global level. Therefore, these vehicles can give a valid contribution to make the transportation sustainable in the long term and governments are strongly striving towards these solutions [6,7]. Nonetheless, even being a relatively mature technology, there are still some disadvantages related to the use of fuel cells for vehicles, such as high costs, low power density, and lack of

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hydrogen infrastructures [6]. The latter issue could be solved by using an on-board fuel processor for on-site hydrogen production from hydrocarbon fuels. This solution has been often investigated for the use of hydrogen-enriched fuel directly in internal combustion engines [8,9]. Early prototypes for fuel processors to be used directly in vehicles were obtained by scaling down already existing industrial technologies. In this case, gasoline, ethanol and other automotive fuels could be successfully processed, but the prototypes still required volume and mass not suitable for automotive applications. In the US, on 2004, these issues and the competition with more mature technologies, such as gasoline/battery hybrid vehicles, have convinced the DOE On-Board Fuel Processing Go/NoGo Decision Team to terminate the research on on-board fuel processing for FCVs [10]. In Europe, in the early 2000s, Daimler Chrysler started testing methanol processors for the fueling of fuel cell vehicle prototypes. NeCar 5, based on the A-Class Mercedes design, was the last launched prototype, which used a 75-kW Ballard fuel cell showing impressive performance [11]. In 2004, Renault/Nuvera presented a four-year project for a fuel processor for on-board hydrogen production small enough and powerful enough for use on a vehicle, but also this program ended in 2008 with no further developments [12]. In these early projects, on-board fuel processing had been considered for fuel cells providing 100% of vehicle traction power, with reformer size and system costs which made this solution unworthy. Afterwards, on-board fuel processing was investigated again for coupling with fuel cells used as auxiliary power units (APUs). In fact, when a fuel cell is used as APU, its power is reduced, the system can be more compact and hydrogen storage unit is not required. Technological features and challenges of on-board reforming of heavy hydrocarbon fuels to feed solid oxide fuel cells (SOFCs) as APUs have been summarized by [13], underlining the benefits of autothermal reforming (ATR) over partial oxidation (POX) and steam reforming (SR). ATR has been again coupled to SOFCs by [14], who evaluated the effect of off-gas recycle on overall system efficiency. Albeit the lower efficiency and poorer fuel quality [15], ATR is recognized to be the best solution for transportation applications. In fact, reactions are considered to be thermally self-sustaining, and therefore, they do not produce or consume external thermal energy, unlike POX or SR.

In the automotive sector, though, polymer electrolyte membrane fuel cells are preferred to SOFCs being more reliable and having faster transients. On-board fuel processing for an APU based on a low temperature polymer electrolyte membrane fuel cell (LT-PEMFC) has been investigated by [16]. However, these devices are affected by CO poisoning [15,17–19] and require high-purity hydrogen, which can ask for more than one water gas shift units and for a preferential oxidation reactor or separation membranes. Such a complex and space consuming system is rather unsuitable for applications like small or medium-size cars. Instead, high temperature PEM fuel cells (HT-PEMFCs) are more tolerant to carbon monoxide and may cope with an increased CO level in the syngas [20], avoiding the need of water gas shift units and preferential oxidation reactor. HT-PEMFCs can also be operated without external gas humidification - further simplifying system complexity and management - and have the advantage of a more efficient heat dissipation and of a better integration in the system thermal management [21]. Moreover, the increased electrode kinetics resulting from the higher operating temperatures allow using alternative catalysts for the electrodes, thus reducing costs [22]. The result is a significant reduction in system complexity, size and cost. An extensive review of HT-PEMFC-based auxiliary power units has been proposed by [22] for diesel-powered road vehicles, showing their great potential.

Beside these applications, recent developments in autothermal reactors are justifying the comeback to the use of on-board processors in vehicles where the fuel cell is used for traction purposes [23,24]. In particular, as mentioned above, early projects failed because they focused on the on-board fuel processing for fuel cells providing 100% of vehicle traction power. Nevertheless, the cooperation with an energy storage system, such as a battery, can reduce the fuel cell size and, consequently, the reformer size. Fuel cell size can be further reduced by employing a plug-in solution, which gives the possibility of charging the battery by means of an external source, extending its operating range. However, the real benefits of such a solution can only be emphasized with a proper energy management of all the in-vehicle power sources [25].

Several energy management control strategies have been already proposed for fuel cell vehicle, such as heuristic strategies [26–28], equivalent consumption minimization strategy (ECMS) [29,30] and strategies based on optimal control theory [31–35]. Nonetheless, these analyses are all applied to fuel cell vehicles with hydrogen produced offline and stored on board, while the energy management of vehicles with on-board fuel processing is usually based on operation of the fuel cell at constant power, derived from the stand-alone optimization of the ATR/FC system efficiency. A system efficiency of 25.1% has been evaluated for a methanol based on-board reformer for PEM fuel cell by [23], while [36] obtained a system efficiency up to 41%, for a fuel cell system with autothermal ethanol reformer. Even claiming the possibility of using the system on-vehicle, those results were obtained with a stand-alone system. Also in [24], a stand-alone hydrogen production unit from reforming of ethanol for LT-PEMFC is simulated for on-board purposes. There is no evidence of studies on the energy management of fuel cell vehicles with an on-board processor and variable fuel cell load. Constraints derived from the hydrogen availability must be considered in the energy management in this case.

In this paper, the design of a controller for the energy management of a parallel fuel cell/battery vehicle with an on-board fuel processor is proposed. The application is a vehicle equipped by an autothermal reformer producing a syngas from isooctane, considered as gasoline surrogate. Aspen Plus™ has been used for the fuel processor modeling, in order to find the operating point which maximizes the conversion efficiency and properly evaluates the syngas composition. The fuel cell is a HT-PEMFC, whose performance as a function of the syngas composition have been carefully evaluated by means of a self-made semi-empirical code, realized by the authors and presented in [37,38]. As the fuel cell load can vary, the fuel processor can not satisfy the hydrogen demand in real time and, therefore, a syngas buffer is placed between the fuel processor and the fuel cell.

The strategy derives from the application of the framework proposed in [39] to fuel cell vehicles and considers the dynamic of the syngas buffer and the constraints derived from the hydrogen availability. Moreover, the adaptation law proposed in the previous algorithm has also been improved by using the information on the driving cycle average speed, averaged on past driving conditions, for pattern typology recognition.

In order to demonstrate the effectiveness of the proposed algorithm, a comparative analysis of the algorithm against the optimal one is conducted and main results are reported. The model has been validated by comparing the results to the fuel consumption of the original conventional vehicle, namely the Chevrolet Malibu, and to a plug-in hybrid electric powertrain implemented on the same vehicle chassis in a past work [40].

2. Vehicle model

The simulator used for the study is a quasi-static forward-looking simulator, developed in Matlab Simulink and derived from a past study [40]. The driver model is based on a PID controller,