INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 40 (2015) 15052–15066

Available online at www.sciencedirect.com

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

Energy flow modeling and real-time control design basing on mean values for maximizing driving mileage of a fuel cell bus

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ARTICLE INFO

Article history:
Received 1 June 2015
Received in revised form
8 July 2015
Accepted 26 August 2015
Available online 1 October 2015

Keywords:
Fuel cell electric vehicle
Energy flow
Driving mileage
Energy management
Mean values

ABSTRACT

This paper proposes an energy flow model and an optimal energy management strategy based on mean values for maximizing driving mileage of a fuel cell bus (FCB), which is powered by a polymer electrolyte membrane (PEM) fuel cell system and a lithium battery. Firstly, an energy flow model describing the relations between vehicle performance and power flow parameters is quantitatively established. An optimization problem for maximizing driving mileage on a predetermined route is defined, and an analytical solution with clear physical meanings is derived. Next, a practical real-time supervisory Energy Management strategy basing on Mean Values (EMMV) is proposed. The strategy, which doesn't require a priori knowledge of the driving trip, is then compared with several well-known strategies, e.g. charge depleting and charge-sustaining (CDCS), Blended, dynamic programming (DP), and Pontryagin's Minimum Principle (PMP). Simulation results show that, the proposed strategy achieves a near-optimal effect, and converges after one driving cycle on a predetermined bus route. Finally, on-road testing is carried out. The proposed strategy achieves an average endurance mileage on a real bus route of 162 km with a usable battery state of charge (SOC) of 90% and 20 kg hydrogen gas for a fully loaded fuel cell city bus.

Introduction

Studies involving electric vehicles (EVs) are of significant interest because of concerns about limited fossil fuel energy, global warming, and exhaust emissions. Generally speaking, EVs include battery electric vehicles (BEVs), fuel cell electric vehicles (FCEVs), and hybrid-electric vehicles (HEVs). Polymer electrolyte membrane (PEM) FCEVs are favored in automotive applications, because they are highly efficient, zero emission, and low-noise. And the driving mileage of an FCEV can be equivalent to a traditional vehicle. However, fuel cell durability and hydrogen infrastructure are major bottlenecks that prevent its commercialization [1,2]. Although Toyota and Hyundai have released two FCEVs, Mirai and i35, respectively,

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http://dx.doi.org/10.1016/j.ijhydene.2015.08.104

commercialization of FCEVs still appears to be an arduous task.

A plugin fuel cell city bus is preferable to prolong the working lifetime and preserve the merits of long driving mileage. In such a vehicle, the fuel cell system provides a stationary output power to partly fulfill powertrain requirements [3–7]. The output power of the fuel cell system determines the working modes of the battery, i.e., in a charge-depleting (CD) mode, or in a charge-sustaining mode (CS). An energy management (EM) strategy is required to determine the power split ratio between two power sources. There have been numbers of paper in literature on EM strategies. They can be generally classified into two kinds, rule-based strategies and optimization-based strategies [8–12].

Rule-based strategies

Rule-based strategies are suitable for real-time control applications [13,14]. Rules can be designed according to powertrain characteristics, or extracted from optimized algorithms. Chen et al. [15] proposed a global optimization strategy based on dynamic programming (DP) for range extended EVs. They subsequently developed a rule-based multi-mode strategy, and applied it to real-time operations. Fuzzy logic (FL) is popular in designing control rules for complex powertrain systems [16]. Caux et al. [17] designed an online FL strategy, in which the parameters are optimized using a genetic algorithm (GA). Li et al. [18] developed an FL strategy for fuel cell/battery/UC systems. Hemi et al. [19] studied a fuzzy logic controller (FLC) for FCEVs.

Optimization-based strategies

Optimization-based strategies have been widely studied. They can be classified according to the time horizon or the optimized objectives [8,9].

Optimization strategies according to time horizon

Basing on length of the time horizon during which performance of an alternative powertrain is optimized, optimal energy management strategies can be categorized into global optimizations (GO), instantaneous optimizations (IO), and real-time optimizations (RO).

Dynamic programming. Dynamic programming (DP) is a powerful tool for solving GO problems, in which the optimized matrices are minimized for a predetermined driving trip [20]. Even though it cannot be directly applied into an embedded controller, it is regarded as a benchmark for other real-time strategies. Sundstroem and Guzzella [21] presented a generic DP MATLAB function named ***dpm*** for GO problems. Rizzo et al. [22] developed FL and DP-based energy management strategies for Mild-Solar-Hybridization vehicles.

Some researchers focused on how to reduce algorithm complexity and avoid the curse of dimensionality. Fares et al. [23] proposed a weighted improved dynamic programming (IDP) algorithm for FCEVs. Zhang et al. [24] investigated a near-optimal strategy for rapid component sizing of power split hybrid vehicles. The strategy is based on analysis of the efficiency of powertrain components. It has accuracy similar to that of DP, but is orders of magnitude faster.

DP algorithm can also be utilized in cloud-computing systems as a background algorithm. Ozatay et al. [25] designed a DP-based optimized velocity profile for a cloud-computing platform. The driving signals are transmitted to the cloud platform, and optimal results are generated by the DP algorithm, and sent to the real-time controller.

In some situations, a multi-dimensional dynamic programming (MDDP) algorithm is required to solve EM problems with more than one degree of freedom (DOF). Ansarey et al. [26] described a dual-storage (a battery and a super capacitor) MDDP strategy for FCEVs. Additionally, convex optimization can also be used to solve GO problems. Hu et al. [27] presented a blended strategy based on convex optimization.

Equivalent consumption minimization and Pontryagin's minimum principle strategies. Equivalent consumption minimization strategy (ECMS) is suitable for IO problems. Performance indexes are optimized for one control cycle in an ECMS. The optimized result can be calculated offline and stored as a lookup table, or online. A critical parameter called the equivalent coefficient α, which represents the equivalent power ratio between two power sources, needs to be defined. In most cases, parameter α is a fixed value which can be calculated in accordance with on-road data. When it changes with driving conditions, it becomes an adaptive ECMS (A-ECMS) [28,29].

A Pontryagin's Minimum Principle (PMP) strategy utilizes a forward iteration method by introducing an extra co-state λ. The initial value of the co-state λ_0 is difficult to determine, because it is related to the information of the whole driving cycle [30,31]. When an optimized λ_0 is found and all the constraints are fulfilled, the PMP strategy is equivalent to the DP algorithm. In other words, by using the PMP algorithm, a DP problem can be converted into an ECMS problem with an additional co-state. The PMP strategy is formally similar to A-ECMS [9].

Sciarretta et al. [32] studied a benchmark control problem for the IFAC Workshop E-COSM 12. In this workshop, the objective was for the participants to develop an online EM strategy for a plugin hybrid-electric vehicle which is similar to the GM Voltec powertrain. Several metrics, including fuel economy, dynamic performance, and computational performance, were evaluated, and nine strategies were proposed. Sivertsson et al. [33] presented a map-based ECMS for this PHEV benchmark problem. Based on the PMP idea, a co-state λ was introduced to ECMS. A method for estimating the optimized initial value of λ was introduced, and the control algorithm was extended to make use of traffic information such as GPS signals. This strategy achieved the best performance among the nine strategies in Ref. [32].

Stockar et al. [34] studied the PMP strategy for a GO EM problem, and analyzed the influence of environmental factors and geographic scenarios on the control parameters. Mura et al. [35] deduced an approximate analytical solution to the PMP problem, which minimizes fuel consumption based on nonlinear system theories. Guardiola et al. [36] studied the PMP strategy for HEV/PHEV, and developed a λ-plot method for obtaining a real-time strategy based on ECMS or PMP. Simmons