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Longevity-conscious dimensioning and power management of the hybrid energy storage system in a fuel cell hybrid electric bus

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HIGHLIGHTS

- Hybrid energy storage system is optimally sized and controlled for a hybrid bus.
- Dynamic battery health model is incorporated in the optimization.
- Convex programming is efficient for optimizing hybrid propulsion systems.
- Optimal battery replacement strategy is explored.
- Comparison to the battery-only option is made in the health-aware optimization.

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ABSTRACT

Energy storage systems (ESSs) play an important role in the performance and economy of electrified vehicles. Hybrid energy storage system (HESS) combining both lithium-ion cells and supercapacitors is one of the most promising solutions. This paper discusses the optimal HESS dimensioning and energy management of a fuel cell hybrid electric bus. Three novel contributions are added to the relevant literature. First, efficient convex programming is used to simultaneously optimize the HESS dimension (including sizes of both the lithium-ion battery pack and the supercapacitor stack) and the power allocation between the HESS and the fuel cell system (FCS) of the hybrid bus. In the combined plant/controller optimization problem, a dynamic battery State-of-Health (SOH) model is integrated to quantitatively examine the impact of the battery replacement strategy on both the HESS size and the bus economy. Second, the HESS and the battery-only ESS options are systematically compared in the proposed optimization framework. Finally, the battery-health-perceptive HESS optimization outcome is contrasted to the ideal one neglecting the battery degradation (assuming that the battery is durable over the bus service period without deliberate power regulation).

1. Introduction

Automobiles are currently responsible for a considerable part of the word's primary energy consumption, mostly fossil fuels, leading to serious public concerns over energy sustainability and environmental benignity [1]. Improvement of the fuel economy of vehicle propulsion systems hence has become a top priority. As an important technology, electrified vehicles, such as battery electric vehicles (BEVs) and hybrid electric vehicles (HEVs), are being intensively investigated and developed by almost all the automotive companies over the world [2–4]. The performance, reliability, and cost effectiveness of these electrified vehicles are significantly influenced by the selection, integration, and control of energy storage systems (ESSs, onboard electricity carrier).

Lithium-ion battery and supercapacitor technologies are among the most appropriate ESS options for electrified vehicles [5,6]. Lithium-ion batteries often exhibit good energy/power characteristics, whereas their lifetime may need further improvement. Despite a very low energy density, supercapacitors typically have an extremely high power density and sufficient durability. By combining these two ESSs, a hybrid energy storage system (HESS) can be built up. It has been demonstrated in [7–9] that a synergistically enhanced overall performance could be expected for this type of dual buffer, owing to the prospect of mutually compensating deficiencies. HESS, nevertheless, results in an increased complexity that poises a heavy challenge for energy-buffer system integration and power management in electrified powertrains.

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The power coordination between an HESS and a prime mover (i.e., an internal combustion engine) of an HEV was simulated in ADVISOR, Advanced Vehicle Simulator [10]. Energy management of an HESS for a BEV was evaluated based on the simulation of urban driving schedules in MATLAB/SIMULINK environment [11]. A fuzzy-logic-based energy management strategy for an HESS of a BEV was also discussed in hardware-in-the-loop (HIL) experiments [12]. These studies illustrated that HESS can successfully meet the vehicular energy/power requirements, while reducing the battery stress with the load-leveling aid of supercapacitors. These strategies, however, were heuristic rule-based control algorithms that cannot realize the optimum power allocation between multiple energy sources with respect to some criterions, e.g., energy-consumption minimization. The consequent non-optimal power management may not make the most of the HESS potential and benefits, which in the worst case incurs incorrect decisions in the product planning.

The advantages of optimization-based energy controls over conventional rule-based ones have been indicated in [13–16]. Optimal energy management strategies are often used for benchmarking those online implementable algorithms, e.g., rule-based methods. In other words, the optimized control law informs designers of the potential of improving vehicle performance and guides them to refine existing causal/implementable strategies. Powertrain optimization has become a vast area of intensive research, as a result of great motivations for pursuing maximum system benefits. An optimal power management strategy, for example, was obtained by dynamic programming (DP), in order to minimize the fuel consumption of a parallel HEV equipped with an HESS [17]. The foregoing articles, however, did not involve the HESS dimensioning problem, an additional instrumental factor influencing the drivability and economy of electrified powertrains. First insights have been provided in [18–20] that the optimal supervisory energy control law is strongly coupled with the powertrain component sizing, and a framework of simultaneously optimal sizing and energy management is thereby needed for achieving an “exactly” optimal solution. An integrated optimization approach was applied to derive the optimal HESS size and control strategy for a BEV [21]. In this approach, a bi-loop optimization topology was used, where the optimal HESS size was searched in the outer loop, while a three-mode rule-based power distribution strategy is optimized in the inner loop. Although the parameters of the rule-based control algorithm are tuned in the inner loop, the control policy/feedback was not inherently optimal, since the controller structure was decided by the rules. Moreover, the bi-loop optimization may be very computationally expensive. A nonlinear programming problem was also formulated to simultaneously solve the optimal HESS size and energy management for minimizing the total cost of ownership of a BEV [22]. Although the solver on the basis of the interior-point algorithm could quickly solve this problem, the solution was highly prone to getting stuck in local minima, since the combined plant/controller optimization problem was quite complicated and nonlinear. Therefore, the nonlinear-programming-based method lacked a guarantee of global optimality. In our prior work [23], the innovative convex programming was employed to accomplish the simultaneously optimal HESS size and power management strategy for a series hybrid powertrain. It has been verified that the convex optimization can rapidly and efficiently yield a globally optimal solution.

All of the aforementioned papers regarding the HESS optimization overlook the potential implications of the battery health. In other words, the existing formulations of the HESS optimization were unconscious of the State-of-Health (SOH) of the battery that is actually closely tied to the HESS sizing and the supervisory control strategy design of electrified powertrains. As a consequence, a quantitative examination of the battery replacement strategy over vehicle service period was lacked. Some interesting questions also remained unaddressed. For instance, how large should the optimized HESS be if no battery replacement is required? What if the battery is replaced twice? And what is the preferred replacement strategy?

This paper is concerned with the optimal HESS dimensioning and energy management of a fuel cell hybrid electric bus. Its main purpose is to attempt to explore solutions to the above interesting questions. The convex optimization for HEVs/PHEVs energy management and sizing was firstly proposed in our previous work [16,20,23–25] for various vehicle configurations and driving cycles. The emphasis of this article is to utilize convex programming for optimization of a fuel cell/HESS bus, and to the best of our knowledge, this is the first time that convex programming extends to fuel cell/HESS vehicles. To sufficiently demonstrate the efficacy of the approach and to showcase the value of the obtained results, three prominent important contributions are delivered to the relevant literature: (1) battery-health-aware optimization of the HESS dimension and the power distribution between the HESS and the fuel cell system (FCS) via convex programming; (2) a comparison of the HESS and the battery-only ESS options in the context of battery degradation; and (3) a comparison between the battery-health-conscious HESS optimization result and the ideal counterpart neglecting the battery capacity fading.

The remainder of the paper is outlined as follows: Section 2 elaborates the modeling of the propulsion system of the fuel cell hybrid bus; the battery SOH model is described in Section 3; the convex-programming-based framework is formulated in Section 4 for the combined HESS size and power management optimization taking the battery SOH into account; Section 5 illustrates the optimization results with different battery replacement strategies; a comparison with the battery-health-unaware scenario (the ideal case neglecting the battery wear) is carried out in Section 6 followed by further discussion in Section 7 and conclusions presented in Section 8.

2. Modeling of fuel cell hybrid bus powertrain

The architecture of the propulsion system of a fuel cell hybrid electric bus operated in Gothenburg, Sweden, is shown in Fig. 1. The bus is impelled by an electric machine (EM) with a power rating of 220 kW. A 100 kW unpressurized proton-exchange-membrane (PEM) FCS and an HESS constitute the main power sources of the bus. A DC–DC converter is applied to regulate the FCS

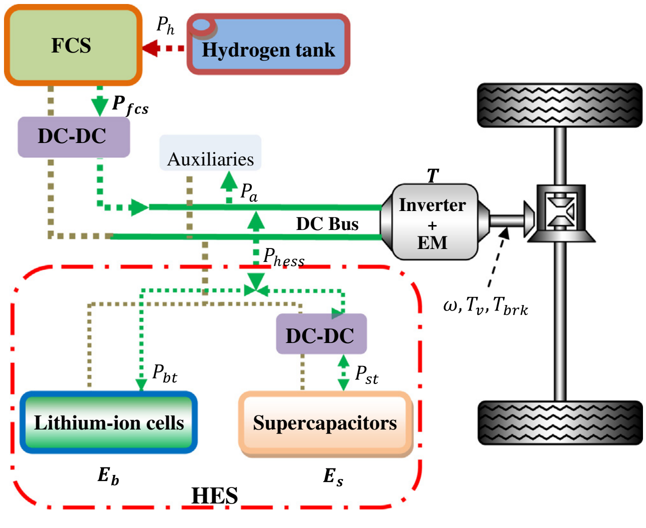

Fig. 1. Architecture of the fuel cell hybrid bus propulsion system.

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