Energy 144 (2018) 393–403

Contents lists available at ScienceDirect

Energy

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

Component sizing optimization of plug-in hybrid electric vehicles with the hybrid energy storage system

Ziyou Song [a], Xiaobin Zhang [a], Jianqiu Li [a, b], Heath Hofmann [c], Minggao Ouyang [a], Jiuyu Du [a, *]

[a] State Key Laboratory of Automotive Safety and Energy, Tsinghua University, Beijing 100084, PR China
[b] Collaborative Innovation Center of Electric Vehicles in Beijing, Beijing 100081, PR China
[c] Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, MI 48109, USA

ARTICLE INFO

Article history:

Keywords:
Plug-in hybrid electric vehicle
Hybrid energy storage system
Sizing optimization
Pontryagin's minimum principle
Battery degradation
Operating cost

ABSTRACT

The Pontryagin's minimum principle is utilized in this paper to determine the best solution of component sizing and energy management strategy for a plug-in hybrid electric vehicle which is equipped with a hybrid energy storage system. The hybrid energy storage system, including batteries and supercapacitors, is an effective solution to extend battery life span and reduce the vehicle operating cost. The operating costs of different hybrid energy storage system candidates, including fuel cost, electricity cost, and battery degradation cost over 6 consecutive China bus driving cycles, are minimized by using a 2-dimensional Pontryagin's minimum principle algorithm proposed in this paper. The proposed Pontryagin's minimum principle algorithm not only determines the optimal energy management strategy, but also globally finds the optimal battery and supercapacitor sizes. It is shown that the operating cost strictly decreases with increasing battery and supercapacitor sizes. In addition, simulation results show that the operating cost is reduced by up to 28.6% when compared to a conventional hybrid powertrain without supercapacitors. Thus the effectiveness of adopting supercapacitors in plug-in hybrid electric vehicles is verified.

1. Introduction

Hybrid electric vehicles (HEVs) are being actively developed by automotive companies worldwide to pursue higher fuel economy than conventional internal-combustion-engine (ICE) vehicles without inducing range anxiety [1]. Owing to vehicle-to-grid services, plug-in hybrid electric vehicles (PHEVs) can potentially take advantage of renewable energy sources [2], and thus are an effective solution to reduce carbon dioxide emissions in the transportation sector [3]. Lithium batteries are widely used in PHEV applications due to their high energy density. However, batteries used in PHEVs often encounter significant instantaneous power demand [4]. Under such conditions, batteries perform frequent charge and discharge operations, which tend to have an adverse effect on battery life [5].

The PHEV demands both high energy and high power densities of the onboard energy storage system. Therefore, the hybrid energy storage system (HESS), which combines the functionalities of supercapacitors (SCs) and batteries, is an effective solution to extend battery life span and reduce the operation cost [6]. Chau et al. put forward the concept of hybridization of energy sources in 2001 [7]. The HESS utilizes the unique properties of SCs, which offer high power density, yet low energy density, when compared to lithium batteries. Therefore, this combination (SCs and batteries) in HESSs inherently offers better performance in comparison to the use of either of them alone [8]. Capasso et al. presents experimental evaluations on the performance of a hybrid energy storage system to supply urban electric vehicles to increase the vehicle performance [9]. Wei et al. designed a battery/SC HESS for HEVs when considering mass, efficiency, and the cost of HESS [10]. It has been verified that HESS can be effectively used as a peak power buffer for HEVs [11]. A similar conclusion can also be found in Ref. [12] based on experimental test results.

To effectively protect the battery by using the SC, the HESS topology, the component (battery and SC) sizes, and the energy management strategy (EMS) should be optimized [13]. For the HESS

* Corresponding author.
E-mail addresses: ziyou.song@qq.com (Z. Song), dujiuyu@tsinghua.edu.cn (J. Du).

https://doi.org/10.1016/j.energy.2017.12.009

topologies, the semi-active HESS, which only employs one DC/DC converter, has a good balance of performance and system cost [14]. The effectiveness of the semi-active topology was verified by an experimental analysis performed via a laboratory 1:1 scale test bench [15]. More than 6000 plug-in hybrid electric buses (PHEBs) with the semi-active HESS, in which the DC/DC converter is used to interface the battery with the DC bus, have been produced as of the end of 2015 [16]. Furthermore, the SC from Maxwell® is adopted in this study since it has been widely used in industrial applications [17].

The EMS optimization for PHEVs with a single electric energy source (battery or SC) has been extensively studied in the last decade [18]. An optimal EMS can either reduce the battery size required to maintain performance, or improve the fuel economy using the same components [19]. Yu et al. proposed a novel real-time EMS for a fast-charging electric urban bus with HESS [20]. Li et al. proposed a droop control algorithm for HESS [21]. Two off-line methods, Dynamic Programming (DP) [22] and Pontryagin's minimum principle (PMP) [23], are commonly used because they can find the globally optimal solution. Thus these methods can be employed to determine the maximum potential fuel economy and optimal component sizing for hybrid powertrains [24]. Moura. et al. used a stochastic DP to optimize PHEV fuel economy [25] based on the velocity distribution of typical driving cycles [26]. Koot. et al. applied DP to HEVs and achieved a 2% fuel reduction [27]. Gong. et al. developed a two-scale DP, a macro-scale and a micro-scale, which are solved using historical data and on-line traffic data of the driving cycle, respectively [28]. The PMP transforms the global optimization problem described by DP into an instantaneous Hamiltonian optimization problem, even though it is only a necessary condition for the original problem [29]. Serrao. et al. made a comparative analysis of EMS and unveiled the substantial equivalence between DP and PMP [30]. Hou. et al. proposed an on-line EMS based on the approximate PMP algorithm for parallel plug-in HEVs, which reduced the fuel consumption by 6.96% compared with the “All-Electric, Charge-Sustaining” (AE–CS) strategy [31]. The PMP is more flexible than DP due to its low computational effort, thus PMP makes real-time control possible. In addition, this paper focuses on the optimization of HESS size, which requires running significant amount of DP or PMP. Based on the simulation results, the simulation time of DP to optimize each HESS candidate is more than 10 h while the simulation time of PMP is only 20–30 min, while they have almost the same simulation results. Thus the PMP is adopted in this paper to optimize the HESS size.

The HESS optimization for the EV application, which is crucial for saving energy, reducing cost, reaching high overall efficiency, and enhancing system dynamics, has also been extensively studied [32]. In Ref. [33], it was verified that the optimization of SC size and EMS should be simultaneously considered since these two issues are integrated. In addition, the DP algorithm was used to minimize the HESS operating cost, including the electricity cost and the battery degradation cost, over a specific driving cycle. In previous studies, the optimization of battery size was not considered because the battery size of EVs is mainly determined by the requested minimal mileage. And the computational cost of DP, which is adopted in previous studies, is large for the HESS sizing of PHEV because 1) the engine characteristics should be considered and 2) the DP must be conducted many times in the size optimization process.

There are few papers in the literature studying the optimal potential of the three-source powertrain (engine, battery, and SC) under optimal EMS. Vinot. et al. proposed an optimal EMS for the HEV with a HESS and compared it to a rule-based parameterized control strategy [24]. However, battery degradation is not accurately considered in the optimization process. The typical PHEV with two power sources has one degree of freedom in the EMS design process. In terms of the PHEV with a HESS, an additional degree of freedom is introduced because a third power source is integrated [24]. The optimization process for determining the best solution of component sizing and EMS for a PHEV with a HESS is therefore more complex. To the best of our knowledge, this is the first paper focusing on the optimization of battery and SC sizes in PHEV applications.

In this paper, a 2-dimensional PMP algorithm is proposed to determine the optimal strategy for the instantaneous power split between engine, battery, and SC, based on a dynamic battery degradation model. A preset cost function is employed to evaluate the powertrain operating cost including fuel cost, electricity cost, and battery degradation cost over a China bus driving cycle (CBDC). By conducting the PMP for different HESS candidates, the optimal sizes of battery and SC packs are globally found. Simulation results show that the operating cost is reduced over 20% when compared with the typical hybrid powertrain which only includes the engine and the battery. This paper is organized as follows: In section 2, the dynamic model of the PHEB with HESS is illustrated. Section 3 presents a 2-dimensional PMP algorithm to reduce the powertrain operating cost. In section 4, the optimal EMS and component sizing results are analyzed. Conclusions are presented in section 5.

2. System modeling

The modeling of PHEB equipped with HESS is presented in this section.

2.1. The hybrid powertrain description

As shown in Fig. 1 (a), the topology of the studied PHEV is series-parallel, which is composed of a diesel ICE, an integrated starter generator (ISG), a traction motor, a clutch, an SC pack, a battery pack, a bidirectional DC/DC converter, and the control system. Compared with the series and parallel powertrains, the series-parallel powertrain needs a more complex EMS since more operation modes can be achieved. Both ICE and traction motor may deliver power to the vehicle wheels. The ISG may also be used to charge the battery or SC by absorbing the excess power from the ICE when its power is greater than that required to drive the wheels. In order to evaluate the performance of the PHEB with an HESS, the typical PHEV, which only includes engine and battery pack, is also optimized and compared in this paper. As shown in Fig. 1 (b), the typical PHEV has the same components except the SC pack and the DC/DC converter.

To be specific, the series-parallel powertrain with a HESS works in several modes:

1) The manufacturer presets a rule that when the vehicle speed is below 20 km/h and the state of charge (SOC) of the battery is high, the clutch is disengaged and only the traction motor drives the vehicle. The engine is turned off, which means that the bus operates in pure electric mode.
2) When the vehicle speed is below 20 km/h and the battery SOC is low, the engine is turned on and drives the ISG to charge the HESS. The engine also supplies power to the wheels through the traction motor in this mode, meaning that the bus operates in series mode.
3) When the vehicle speed exceeds 20 km/h and the battery SOC is high, the clutch may get engaged. The engine and the traction motor directly drive the bus together or independently, which depends on the on-line EMS. The system switches to the parallel mode.