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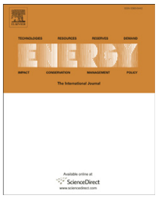

Battery degradation minimization oriented energy management strategy for plug-in hybrid electric bus with multi-energy storage system

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ABSTRACT

The potential of reducing fuel consumption, harmful emission and cost benefit for plug-in electric hybrid buses depended largely on the power management strategy for specific hybrid electric powertrain configuration, especially for those with compound energy storage system. Hybrid energy storage system in this research comprise high energy lithium iron phosphate batteries and super-capacitors, therefore, the key of improving the life cycle cost-benefit is to extend the cycle life for lithium battery. This paper presents an optimal control strategy for the serial-parallel plug-in hybrid electric buses based on the lithium battery degradation model to minimize life cycle operating cost. To derive the globally optimal strategy, an algorithm based on two-dimensional Pontryagin's minimum principle is proposed. With the optimal strategy, the battery degradation is significantly reduced, and the total cost is reduced by 21.7% compared with a plug-in hybrid electric bus with single type energy storage. Further embodies the advantages of hybrid energy storage systems and optimization algorithms.

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1. Introduction

Plug-in hybrid electric buses (PHEBs) can reduce fuel consumption and emissions by substituting electricity for fuel. They have been in service in major markets including China, the USA, Japan, and Europe for more than a decade [1,2]. China has become the largest market for electric buses, with 23,000 PHEBs produced in 2015. Compared with range-limited battery electric buses, plug-in hybrid electric buses can adapt to different bus routes with low cost and high operational efficiency. Compared with their diesel counterparts, they provide life-cycle economic advantages [3].

PHEBs have a certain charge-depletion range that demands both high energy and power capacities for the onboard energy storage system (ESS), which plays a critical role in the performance of electric buses [4–6]. The ESS must meet various demands regarding safety, energy density, power density, cycle life, and charging rate. Lithium-ion batteries (LIBs) (e.g., lithium iron phosphate ($LiFePO_4$) batteries (LFP batteries), or LIBs with $Li_4Ti_5O_{12}$ anodes (LTO batteries)) and super-capacitors (SCs) are the main ESSs currently used in electric buses. Each type of ESS has its advantages and limitations. LFP batteries have comparatively high energy density but low power density, so they can be used in electric buses and PHEBs; however, LFP batteries suffer more severe capacity degradation when applied in PHEBs [6,7]. They need to be replaced during the bus life, resulting in significant maintenance costs. There are two major reasons for this. First, the batteries on PHEBs are smaller than those on electric buses; therefore, the propulsion and regenerative power induce higher discharge/charge rates in the former. Second, frequent charging/discharging operations of batteries are needed to adjust the engine power. Therefore, the high discharge/charge rate and frequent charging/discharging operations contribute to battery degradation in PHEBs [8–10]. Different from LFP batteries, LTO batteries can tolerate discharge/charge rates up to 10 C, work over a wide temperature range (−35°C–+55 °C), and have good cycle life (>20,000 cycles). However, LTO batteries have relatively low energy density and are more expensive [11–13]. Therefore, electric buses with LTO batteries

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Abbreviations

PHEBs	Plug-in hybrid electric buses
ESS	Energy storage system
LFP	$LiFePO_4$
LTO	$Li_4Ti_5O_{12}$
SC	super-capacitors
LIB	Lithium-ion batteries
PMP	Pontryagin's minimum principle
DP	Dynamic programming
HESS	hybrid energy storage system
DC	direct current
ECMS	the equivalent fuel consumption minimization strategy
SOH	the state of health
1D	one-dimensional
2D	two-dimensional
CCBC	The China City Bus Cycle
DOD	depth of discharge for battery
OCV	open circuit voltage

always have limited electric mileage. Compared with LIBs, SCs have higher power density and longer cycle life but lower energy density (3.5–4.5 Wh/kg) and higher price for the same energy content [14]. Therefore, they can be used only in conventional hybrid electric buses.

A hybrid energy storage system (HESS) comprising LIBs and SCs achieves long battery life and good power and energy performance when there are significant power swings and energy regeneration, which is true for buses operating in urban environments [15,16]. The batteries can be charged from the grid and provide sufficient energy for electric drives, whereas the SCs can store the peak power to extend the battery life. There are many designs for HESS configurations, including passive, active, and semi-active configurations with different power electronics [8]. In actual use, an HESS with a bidirectional DC/DC converter connected to an LFP battery is applied in PHEBs, and more than 6000 buses equipped with such an HESS had been put into operation by the end of 2015 [9].

The configuration and control of the battery/SC HESS have been studied intensively [13–17]. In those studies, the HESS is used either as the main energy source on electric buses or as an auxiliary energy source on series or parallel hybrid electric buses. Considering the degree of freedom of the powertrain, one-dimensional (1D) or two-dimensional (2D) algorithms including dynamic programming, Pontryagin's minimum principle (PMP), and the equivalent (fuel) consumption minimization strategy (ECMS) are used to derive an optimal strategy [15,16]. The control objective focuses on the energy consumption of the powertrain (fuel consumption for hybrid electric buses, electricity for PHEBs, and hydrogen for fuel-cell buses). To extend the battery life, the state of health (SOH) of batteries is also considered in the control objective [18–20]. However, battery degradation still lacks consideration in the evaluation and design of buses with an HESS, meaning that neither can the operating cost of the HESS be evaluated accurately nor can optimal component sizing be achieved [21,22]. In addition, cloud computing-based energy optimization control method is used to solve the problem of traffic flow in city bus route and the nonlinear vehicle dynamics. The driving condition is classified in offline part and the current driving conditions are recognized [23,24].

Optimal control of a PHEB with an HESS is challenging. At the control level, three energy sources (the engine, battery, and SC) are coupled in power and corresponding costs, and the trade-off between fuel and electricity consumption as well as battery degradation should be considered. This represents a multidimensional and multi-objective optimal control problem. At the operational level, unlike electric buses, PHEBs use both fuel and electricity; therefore, the energy consumption and battery degradation are intensively dependent on the operation and charging patterns.

This study explores a method for minimizing battery degradation and the life-cycle economic cost of a PHEB with an HESS comprising LFP batteries and SCs. A battery-degradation model is adopted to assess the battery-degradation cost. A 2-dimensional PMP algorithm is proposed to derive the optimal strategy to manage the three energy sources. To the best of our knowledge, there are few papers focusing on battery degradation as well as the comprehensive cost of hybrid electric powertrain including engine, battery and super-capacitor. Furthermore, the 2D PMP algorithm proposed can reduce the calculation time significantly. Therefore, this study provides some new insights in terms of the operating control strategy of PHEB.

This paper is organized as follows. In Section II, both a series–parallel hybrid electric powertrain with the HESS and single LFP batteries are modeled based on a typical bus product. The driving and charging patterns are also specified. In Section III, a 2D PMP algorithm is developed considering battery degradation and the comprehensive economic cost. The optimal results for both the HESS and single-battery buses are presented in Section IV.

2. Vehicle modeling

2.1. Powertrain configuration

The series-parallel hybrid electric bus is the mainstream PHEB in the Chinese market owing to its adaptability to Chinese urban driving conditions, simple configuration, simplified control strategy and excellent cost-effectiveness. Two typical configurations are studied and compared, which have the same components except for the ESS.

2.1.1. Configuration A: electric powertrain with single type batteries

LFP batteries are the common ESS used in PHEBs. Configuration A is a series–parallel hybrid powertrain with LFP batteries. As shown in Fig. 1, the powertrain consists mainly of a diesel engine, a generator, a traction motor, LFP batteries, and the control system.

2.1.2. Configuration B: electric powertrain with HESS

Because LFP batteries experience severe degradation when used in configuration A, they are replaced by an HESS comprising LFP batteries and an SC in the improved configuration B, which is shown in Fig. 2. The powertrain has all the same components as configuration A except for the SC and DC/DC converter.

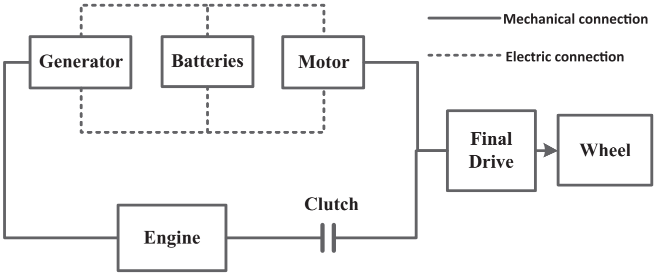

Fig. 1. Configuration A: series–parallel hybrid electric powertrain with single batteries.

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