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Battery durability and longevity based power management for plug-in hybrid electric vehicle with hybrid energy storage system

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HIGHLIGHTS

- A novel procedure for developing an optimal power management strategy was proposed.
- Efficiency and durability were considered to improve the practical performance.
- Three control rules were abstracted from the optimization results with DP algorithm.
- The proposed control strategy was verified under different SoC and SoH conditions.
- The proposed strategy could further improve the energy efficiency obviously.

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ABSTRACT

Efficiency and durability are becoming two key issues for the energy storage system in electric vehicles together with their associated power management strategies. In this paper, we present a procedure for the design of a near-optimal power management strategy for the hybrid battery and ultracapacitor energy storage system (HESS) in a plug-in hybrid electric vehicle. The design procedure starts by defining a cost function to minimize the electricity consumption of the HESS and to optimize the operating behavior of the battery. To determine the optimal control actions and power distribution between two power sources, a dynamic programming (DP)-based novel analysis method is proposed, and the optimization framework is presented accordingly. Through analysis of the DP control actions under different battery state-of-health (SoH) conditions, near-optimal rules are extracted. A rule based power management is proposed based on the abstracted rules and simulation results indicate that the new control strategy can improve system efficiency under different SoH and different SoC conditions. Ultimately, the performance of proposed strategy is further verified under different types of driving cycles including the MANHATTAN cycle, 1015 6PRIUS cycle and UDDSHDV cycle.

1. Introduction

The depletion of oil resources and growing problems in haze pollution have greatly encouraged the development of electric vehicles [1,2]. As one of key technologies and components in electric vehicles, studies on the energy storage systems (ESSs) have drawn increasing attention. Unfortunately, although many technological breakthroughs have been made in battery-only ESSs, they still have some obvious drawbacks, such as short battery life, high cost and low power density [3–5]. Especially for plug-in hybrid electric vehicles (PHEVs), these systems require both high specific energy capacities for long driving distances and high specific power capacities for acceleration, braking, climbing, etc. Current battery technologies cannot fully satisfy both requirements. High discharge-charge current rates will lead to short calendar life or excessively loaded battery cells [6,7]. On the other hand, ultracapacitors could provide high power, and their life cycles are much longer than those of batteries. However, their energy densities are much lower than those of batteries. In order to improve calendar life and ensure safe application of batteries in PHEV, a combination of batteries and ultracapacitors seems to be an effective method to meet the dual requirements of power density and energy density at the same time. In this hybrid battery and ultracapacitor energy storage system (HESS), batteries are preferred for providing the total electricity energy of the PHEV, while the ultracapacitors are required to serve as power buffers [8–11].

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With the development of HESS, researchers have developed a variety of topologies as well as optimal sizing and power management methods to promote the performance of the HESS. Refs. [8,12–17] have made significant contributions to the development and analysis of six typical HESS topologies. These typologies attempt to combine batteries and ultracapacitors differently by flexibly applying DC/DC converters and diodes. Based on our previous research experience in Ref. [18], the topology of connecting battery pack with a bidirectional DC/DC converter in series before connecting with an ultracapacitor pack in parallel has been selected for this study.

To fully realize the potential of the ultracapacitor, the power management function of the HESS must be carefully designed. An optimal power management system should not only minimize the electricity consumption of the HESS and extend the driving range but also determine the proper power level for regulating the power distribution between the two power sources and avoid the current impact on the battery pack for improving its calendar life. To achieve it, a number of power management strategies have been developed [8,19–22]. In Ref. [8], a power management strategy for a PHEV based on a fuzzy logic algorithm was proposed and verified by a dynamic driving cycle, and its energy efficiency was improved compared with traditional rule-based strategies. However, the determination of the fuzzy rules is based on the engineering experience, and there is no systematic method to determine thresholds, which makes this strategy difficult to adjust when the driving conditions or system parameters are changed. Ref. [22] proposed a control strategy based on neural networks for a HESS and the application of the HESS with the proposed strategy could increase the driving range by 8.9% in city cycles. However, the performance of neural network based power management highly depends on the training data, and if the neural network is not well trained, its performance can't be guaranteed.

On the other hand, many studies have optimized the control strategy based on the known environment [23–25]. In these works, the dynamic programming algorithm (DP) is applied to locate an optimal control strategy based on the provided driving cycles. However, for practical applications, the road information is usually unknown and different from the original driving cycles. When these optimized strategies are applied to different driving conditions, the performance may be quite different and may even be much worse than the original strategy. To overcome this drawback, the stochastic dynamics programming (SDP) algorithm has been proposed [26,27]. However, due to its high computational cost, the application of the SDP algorithm in real vehicle energy management units is limited [20].

The performance of the control strategy may be affected by the change of battery state-of-health (SoH). Because when the battery is aging, the internal resistance and capacity will change. Lots of valuable works have been done about the aging mechanisms and aging models [28], but precisely describing the SoH is still an open problem [29]. In the power management design process, the consideration of different SoH conditions is very important to guarantee the excellent control performance.

The above analysis demonstrates that the power management performance of the HESS depends on three aspects. The first is an effective analysis method for extracting near-optimal power management strategies from optimization results. The second is that the power management can be applied in real time application. The third is that the power management can guarantee excellent performance in different conditions (different battery SoH, different driving patterns or different battery SoC). Most of above research can't deal with the three aspects very well. In this study, an optimization procedure for designing the power management of the HESS was constructed under different battery SoH. The control strategy of the HESS under different SoH conditions will be optimized by DP algorithm. Then an innovative analysis method was proposed for extracting the control rules from the optimization results. Through further classification of the operation points in the Chinese Bus Drive Cycle (CBDC), the thresholds of the rule-based control strategy were obtained. Three general control regulations were extracted from the optimization results and an improved control strategy was developed. Simulation results validated the effectiveness of the proposed procedure.

The organization of this paper is as follows. Section 2 illustrates the configuration of the HESS. Section 3 describes the construction of the models and the formulation of the dynamic optimization problem. Then, the optimization results and the optimized control strategy are presented in Section 4. The conclusions are finally presented in Section 5.

2. Configuration and preliminary rule-based control strategy

2.1. Structure of the hybrid energy storage system

The configuration of the HESS used in this study is presented in Fig. 1. The battery pack connects with a DC/DC converter in series before it connects in parallel with the ultracapacitor pack. The required energy/power of the PHEVs is jointly provided by the battery pack and the ultracapacitor pack according to the vehicular power requirement strategy. The vehicle controller can regulate and monitor the state of voltage (SoV) of the ultracapacitor pack and the state of charge (SoC) of the battery pack in real time. The drawbacks of this topology are that as the DC bus is connected with the ultracapacitor directly, its voltage will vary with the ultracapacitor. The change of the voltage can increase the control complexity and controller cost of the motor driving system or affect its output torque especially in the high speed and high torque conditions. As this paper mainly focused on the power management of the HESS, we assume that the motor driving system can deal with the voltage variation and do not consider detailed control process of motor driving system. The basic parameters of the target vehicle are listed in Table 1.

2.2. Original rule-based energy management strategy

Compared with the electrical energy stored in traditional PHEVs with a single energy source, power management for PHEV with a

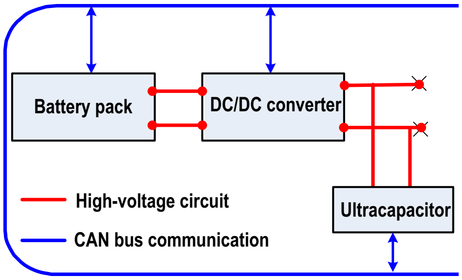

Fig. 1. Configuration of the hybrid energy-storage system.

Table 1
Basic parameters of the PHEVs.

Item	Value	Unit
Vehicle mass – M	16,500	kg
Efficiency of the transmission system – η_0	0.90	Null
Rolling resistance coefficient – f	0.011	Null
Windward area – A_{air}	6.60	m^2
Air resistance coefficient – C_{ar}	0.55	Null
Gravitational acceleration – g	9.81	m/s^2
Correction coefficient of rotating mass – δ	1.03	Null