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Adaptive energy management of a plug-in hybrid electric vehicle based on driving pattern recognition and dynamic programming

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HIGHLIGHTS

- The hierarchical control strategy has been proposed for the multiple energy sources.
- Three typical driving patterns have been classified with the fuzzy logic controller.
- A driving pattern recognition method was developed with the fuzzy logic controller.
- DP was used to develop suboptimal control strategies for different driving blocks.
- Adaptive energy management method for a plug-in HEV has been proposed and verified.

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ABSTRACT

To achieve the optimal energy allocation for the engine-generator, battery and ultracapacitor of a plug-in hybrid electric vehicle, a novel adaptive energy management strategy has been proposed. Three efforts have been made. First, the hierarchical control strategy has been proposed for multiple energy sources from a multi-scale view. The upper level is for regulating the energy between the engine-generator and hybrid energy-storage system, while the lower level is for the battery and ultracapacitor. Second, a driving pattern recognition based adaptive energy management approach has been proposed. This approach uses a fuzzy logic controller to classify typical driving cycles into different driving patterns and to identify the real-time driving pattern. Dynamic programming has been employed to develop optimal control strategies for different driving blocks, and it is helpful for realizing the adaptive energy management for real-time driving cycles. Third, to improve the real-time and robust performance of the energy management, the previous 100 s duration of historical information has been determined to identify a real-time driving pattern. Finally, an adaptive energy management strategy has been proposed. The simulation results indicate that the proposed energy management strategy has better fuel efficiency than the original and conventional dynamic programming-based control strategies.

1. Introduction

Energy shortages, environmental concerns over air pollution, and the prospect of the global warming support the need for further development of plug-in hybrid electric vehicles (HEVs). Plug-in HEVs have become more and more popular due to their excellent fuel economy and relatively low cost [1,2]. However, possessing both a highly specific energy density for long driving ranges and a highly specific power for deep and shallow discharge/charge cycles is difficult for current batteries [3]. Because an ultracapacitor has a high power density and can be used as a power buffer during climbing, braking or acceleration, the combination of lithium-ion batteries and ultracapacitors is an efficient solution to prolong the battery service life by optimizing its operating range [4–7].

1.1. Literature review

A few topologies of a hybrid battery/ultracapacitor energy-storage system (HESS) have been proposed and can be roughly classified into four types from the control perspective.

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They include directly connecting the battery and ultracapacitor in parallel [4], connecting the battery with a DC/DC converter in series before connecting with the ultracapacitor in parallel [5], connecting the ultracapacitor with a DC/DC converter in series before connecting with the battery in parallel [7–9], and connecting the battery and the ultracapacitor each with a DC/DC converter in series before they are connected in parallel [7]. In addition to these types, Ali Emadi has proposed a new HESS topology in which the battery does not provide power unless its terminal voltage is higher than that of the ultracapacitor [8]. However, the required voltage level of the ultracapacitor is twice as much as that of the battery, which is unsupportable in some applications. Based on our previous research experience on the systematical evaluation results for the four HESS topologies in Ref. [9], the second topology that the battery pack connects with a DC/DC converter in series before it is connected with the ultracapacitor pack in parallel has been selected for this study. This type has the potential to fully exert the dynamic performance of the ultracapacitor by avoiding the current/power impact of the battery and to extend the calendar life of the HESS.

To achieve optimal energy/power management for HEVs and plug-in HEVs, a number of strategies have been developed [10–12]. The rule based strategy is the most direct and widely used method due to its easy implementation and high calculation efficiency [13–15]. Jalil N et al. have proposed a rule-based strategy to determine the power split between the battery and engine for a series hybrid electric vehicle [15]. To further improve the performance of the energy management system for hybrid electric vehicles, several optimal energy/power management methods have been proposed, such as methods based on a fuzzy logic approach [16] and an equivalent consumption minimization strategy [17]. However, with the development of intelligent algorithms, multiple advanced algorithms such as neural network [18], particle swarm optimization [19], simulated annealing [20], model predictive control [21], and dynamic programming (DP) [22,23] have been widely employed to develop various advanced adaptive/online energy management systems and optimal strategies. With a prior knowledge of the driving cycle, DP-based methods have the ability to locate the global optimal control strategy. However, the actual future driving cycles can hardly be known in advance. In this case, the DP-based strategies cannot be used for an online energy management.

Few energy management methods have been conducted for more than two energy sources [13–28]. Most publications have investigated control strategies for EVs and HEVs powered by the battery and engine or the battery and ultracapacitor [24–28]. Specifically, for a series plug-in HEV with HESS, the optimization allocation problem for electricity energy among the battery, ultracapacitor and engine-generator has not been solved effectively.

1.2. Motivation and innovation

The purpose of this study is to propose an adaptive energy management approach via driving pattern recognition and dynamic programming and to improve the energy management efficiency for a plug-in HEV with a HESS. To avoid the adverse effects of the optimal result against unknown cycles, the driving pattern recognition (DPR) method has been employed to classify and train the typical driving patterns. With the DP algorithm, the micro-control strategies for different classified driving patterns can be developed in a systematic way. Using the fuzzy control algorithm-based predictive approach, the current driving pattern can be recognized with a period of historical driving information. To realize the optimal energy allocation between the engine-generator and HESS with less computational cost, a hierarchical control strategy has been proposed for three energy sources from a multi-scale view. The proposed energy management strategy has been verified and evaluated by a combined driving cycle and Japanese 10–15 mode driving cycles.

1.3. Organization of the paper

This paper is organized as follows. Section 2 describes the configuration of the plug-in HEV and the original control strategy. Then, the classification of driving blocks, construction of DPR, subsystem modeling, DP formulation and energy management system are illustrated in Section 3. The verification and evaluation of the proposed method are reported in Section 4, and conclusions are drawn in Section 5.

2. Plug-in hybrid electric vehicle configuration

2.1. Vehicle configuration

The structure of the researched target is illustrated in Fig. 1. The electricity power of the plug-in HEV comes from two parts: the HESS and assistance power unit (APU). The APU consists of an 80 kW permanent magnetic generator and a 1.9 L gasoline engine, and the rated power of the APU is 75 kW. Detailed modeling of the APU and HESS are introduced in Section 3.2. The target vehicle is an electric bus and its essential parameters are presented in Table 1.

2.2. Hierarchical energy management for the plug-in HEV

The energy management system of the plug-in HEV can be divided into two layers. The upper level is for controlling the energy between the APU and HESS, and the lower level is for controlling the energy between the battery and ultracapacitor.

2.2.1. Upper level control strategy

The main objective of the energy management is to minimize the operation cost of the plug-in HEV. For optimizing the allocation of energy/power between the HESS and APU, a systematic energy management strategy is necessary. The original control strategy of the researched plug-in HEV is a typical charge depleting (CD) and charge sustaining (CS) method. It first operates the plug-in HEV with the CD mode, which is similar to a pure electric vehicle, and then operates the plug-in HEV with the CS mode once its state-of-charge (SoC) level hit the lower threshold, which is similar to a traditional hybrid electric vehicle. The detailed original control rules in the CS model are identified by the required power of the plug-in HEV-P_n and they are described by the following conditions.

Condition I: $P_n < 0$.

The HESS absorbs as much energy as possible, and the excess energy is consumed by the traditional mechanical braking system. It is noted that the APU is turned off in condition I.

Condition II: $P_n \geqslant 75$ kW.

The output power of APU−P_{APU} will maintain to its rated power (75 kW), and the insufficient power will be supported by the HESS.

Condition III: $0 \leqslant P_n \leqslant 75$ kW

- If the SoC of the battery pack (z_b) is bigger than its lower threshold ($z_{b,min}$), the HESS will provide the total required power and the APU will be in the off stage.
- If the SoC of the battery pack (z_b) is smaller than its lower threshold ($z_{b,min}$), the APU will work in the rated power condition and the redundant power will be used to charge the HESS to its predetermined level.