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Particle swarm optimization-based optimal power management of plug-in hybrid electric vehicles considering uncertain driving conditions

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ABSTRACT

This paper proposes a novel optimal power management approach for plug-in hybrid electric vehicles against uncertain driving conditions. To optimize the threshold parameters of the rule-based power management strategy under a certain driving cycle, the particle swarm optimization algorithm was employed, and the optimization results were used to determine the optimal control actions. To better implement the power management strategy in real time, a driving condition recognition algorithm was proposed to identify real-time driving conditions through a fuzzy logic algorithm. To adjust the thresholds of the rule-based strategy adaptively under uncertain driving cycles, a dynamic optimal parameters algorithm has been further established accordingly, and it is helpful for avoiding the problem that the thresholds of the rule-based strategy are very sensitive to the driving cycles. Finally, in combination with the above efforts, a detailed operational flowchart of the particle swarm optimization algorithm-based optimal power management through driving cycle recognition has been proposed. The results illustrate that the proposed strategy could greatly improve the control performance for different driving conditions. Especially for the uncertain driving cycles, the reduction in energy loss can be up to 1.76%.

1. Introduction

The plug-in HEV (hybrid electric vehicle) provides a platform to reduce fuel consumption and energy loss through a reliable and efficient power management system [1]. It has attracted a lot of attention from researchers and engineers recently. For example, Hedegaard [2] investigated the influence of large-scale plug-in HEVs and pure EVs (electric vehicles) implementation to power system of five European countries in 2030. Amjad [3] proposed an evaluation of electrical power requirement of plug-in HEV with various all-electric driving range, the influence of battery cycle life was also investigated in this study. The plug-in HEV has the advantages of both HEVs and EVs [4]. Considering that two types of energy sources, gasoline and electricity, have been installed in a plug-in HEV, the key issue for efficiently utilizing the two sources and achieving the best fuel economy is to develop a reliable and efficient power management system [5].

1.1. Review of the existing optimization approaches

With the development of the HEVs, many approaches have been proposed for developing power management strategies. To name a few, a comparative study of energy management used in the full HEVs and power-split HEVs has been presented in Ref. [6], the energy management study for a testbed HEV has been presented in Ref. [7], and an intelligent energy management method for plug-in HEVs has been developed and evaluated in Ref. [8]. Generally, these existed methods for vehicular energy management can be divided into three types: **(1) Heuristic methods**. Early research focused on the development of rule-based strategies and FLC (fuzzy logic control) strategies. For example, Sorrentino [9] proposed a rule-based strategy for a hybrid solar vehicle with a series structure. Ferreira [10] proposed a fuzzy logic

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algorithm for an electric vehicle to control the power allocation among the fuel cell, battery pack, and ultracapacitors. This type of method has been widely used for its simple structure. Easy implementation in real-time control is the other most remarkable advantage. **(2) Instantaneous minimization methods**. ECMS (Equivalent Consumption Minimization Strategies) is a typical realization. Based on the ECMS, the fluctuation of the energy level in the secondary power source will be compensated by the replacement of the equivalent fuel power [11]. Kim [12] and Xiong [13] proposed a PMP (Pontryagin's minimum principle) –based strategy for a power-split hybrid electric vehicle and dual-motor-driven electric bus to achieve a near-optimal control performance, respectively. Musardo [14] proposed an adaptive ECMS algorithm for HEV power management that can achieve a slightly suboptimal performance compared with the global optimal control effect. **(3) Optimization methods**. To better optimize the control performance of the power management strategy, more and more advanced optimization algorithms have been utilized. Kim [12] implemented the DP (dynamic programming) algorithm to obtain the global optimal performance for a power-split HEV. Xiong [15] proposed an adaptive energy management strategy using DP combined with fuzzy logic to improve the managing efficiency of the Plug-in HEV. Additionally, Perez [16] used DP to obtain the optimal result as a benchmark for the optimal control problem, Abido [17] described the application of PSO (particle swarm optimization) in power flow control. Chen [18] proposed an improved PSO algorithm for HEVs and compared it with other algorithms. Poursamad [19] described a GA (genetic algorithm)-fuzzy control strategy for a parallel HEV. Kumari [20] presented an enhanced GA (genetic algorithm) to solve the multi-objective optimal energy management problem. According to the optimization horizon, optimal strategies could be categorized into local optimal strategies and global optimal strategies. Local optimal strategies employ the optimization algorithm on a short-time optimization horizon. For example, Moura [21] proposed a stochastic DP for plug-in HEVs, and Xiong [22] built up a MPC (model predictive control) scheme for plug-in HEV with a hybrid energy storage system. On the other hand, global optimization approaches use optimization algorithms to solve the power flow control problem on the time horizon of the entire driving cycle. Kum [23] proposed a DP-based optimal strategy for a parallel HEV, and S.R. Spea [24] proposed a DE (differential evolution) algorithm to solve the optimal power management problem.

1.2. Contribution of the paper

Although these approaches have their own advantages, several problems remain regarding better use of the multiple power sources of the plug-in HEVs. First, the benefits from any rule-based strategy are quite limited and generally sub-optimal, so researchers have turned their research efforts to optimization theory, which theoretically guarantees optimality and can be employed to develop new control actions and rules for improving the rule-based methods. Second, the huge instantaneous computational task is a drawback of the second type. Moreover, the co-state in PMP and the equivalent factor in ECMS are quite sensitive to the driving cycles. Third, theoretically, the implementation of the local optimization strategy does not rely on the priori driving cycle. However, the local optimal strategies are implemented based on a prediction of future driving patterns, and the way to generate reliable and precise predictions remains a big problem. On the other hand, global optimization approaches are useful for finding the optimal policy; however, they cannot directly be used in real-time control due to their requirement of a priori driving cycle that can hardly be known in practice [25].

In our previous research, a PSO-based optimal power management system has been implemented on the rule-based strategy [26]. The results showed that combining offline global optimization with a real-time heuristic method is a viable solution for implementing the global optimization-based strategy. However, the influence of driving cycles adopted for the offline optimization process on the real environment has not been well investigated; moreover, when implemented online, the real-time driving conditions may be different from the offline driving cycle, which could further aggravate the influence. So far, few investigations have considered the optimal power management problem. Serrao [5] indicated that the driving distance has an impact on the rule-based strategies of plug-in HEVs, but the specific influence has not been specifically discussed. Maclean [27] analyzed the impacts of driving conditions on the energy efficiency based on multiple driving cycles. However, the driving conditions have not been analyzed in combination with the optimal power management strategy.

The main purpose of this study is to investigate a PSO-based power management strategy for plug-in HEVs considering uncertain driving conditions. The optimization objective of the PSO algorithm is to minimize the energy cost during the vehicle use. To solve the problem of how to implement the PSO-based algorithm in a real-time manner, a rule-based strategy is proposed in combination with the PSO algorithm. Several contributions have been made in this study. First, a novel power management scheme for a plug-in HEV is proposed. The control parameters of the proposed scheme are optimized by the PSO algorithm under different driving conditions. Second, the influences of driving conditions, including the speed profile and driving distance, on the optimal control parameters are analyzed. Third, to generalize the optimal performance on unknown cycles, a driving cycle recognition algorithm is developed to identify the real-time driving conditions based on a fuzzy logic control system. Finally, the optimal power management strategy has been evaluated.

1.3. Organization of the paper

The remainder of the paper is organized as follows: the optimal control problem of the power management for a plug-in HEV is formulated in Section 2. The PSO-based power management approach, an analysis of the driving conditions and optimization results, driving cycle recognition and the power management strategy are proposed in Section 3. The evaluation of the power management strategy is carried out in Section 4, and conclusions are given in Section 5.

2. Formulation of the power management

2.1. Configuration of the plug-in HEV

The target vehicle is a plug-in HEV with a series topology, as illustrated in our previous research [26]. The power system of the vehicle mainly contains an 86 kW electric motor driving system, a 26 kWh lithium-ion battery pack, a 60 kW APU (assistance power unit), which is made up of an engine and a permanent magnetic generator, and several converters. The vehicle is propelled by an electric motor and its electric power is supplied by the battery and APU. Some basic parameters of the vehicle are listed in Table 1.

2.2. Power management

Power management for the plug-in HEV can be formulated as an optimal control problem because it can be described as finding an optimal policy to minimize a cost function during a period of