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Intelligent energy management strategy based on hierarchical approximate global optimization for plug-in fuel cell hybrid electric vehicles

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ABSTRACT

The energy management strategy (EMS) is a key to reduce the equivalent hydrogen consumption and slow down fuel cell performance degradation of the plug-in fuel cell hybrid electric vehicles. Global optimal EMS based on the whole trip information can achieve the minimum hydrogen consumption, but it is difficult to apply in real driving. This paper tries to solve this problem with a novel hierarchical EMS proposed to realize the real-time application and approximate global optimization. The long-term average speed in each future trip segment is predicted by KNN, and the short-term speed series is predicted by a new model averaging method. The approximate global optimization is realized by introducing hierarchical reinforcement learning (HRL), and the strategy within the speed forecast window is optimized by introducing upper confidence tree search (UCTS). The vehicle speed prediction and the proposed EMS have been verified using the collected real driving cycles. The results show that the proposed strategy can adapt to driving style changes through self-learning. Compared with the widely used rule-based strategy, it can evidently reduce hydrogen consumption by 6.14% and fuel cell start-stop times by 21.7% on average to suppress the aging of fuel cell. Moreover, its computation time is less than 0.447 s at each step, and combined with rolling optimization, it can be used for real-time application.

Introduction

Fuel cell hybrid electric vehicle (FCHEV) is the promising solution to the environmental issues aggravated by traditional vehicles for its zero emission. Compared with traditional FCHEV, the initial cost of plug-in FCHEV equipped with downsized fuel cell stack is lower [1,2], and the system operation efficiency increases with the decrease of hybrid ratio because battery with larger capacity improves the power dynamic response and recovers more braking energy [3]. To reduce the operation cost of plug-in FCHEV, energy management strategy (EMS) for the power distribution between battery and fuel cell has become a key issue. Compared with the EMS for hybrid electric vehicle (HEV) and plug-in HEV (PHEV), the EMS for plug-in FCHEV is more complicated, because the degradation and dynamic characteristics of fuel cells are very different from those performances of internal combustion

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engines [4] in HEVs or PHEVs, which will lead to more complex optimization goals and constraints.

The energy management optimization goals for FCHEVs include reducing the equivalent hydrogen consumption and extending the fuel cell service life. Frequent start-stop, high power operation and power fluctuation of the fuel cell stack should be avoided because they are the main causes of the fuel cell degradation [5–7]. Previous studies show that global optimal control of FCHEV is the guarantee of lowest energy consumption in a trip [8,9]. It reduced the hydrogen consumption by 7.7% on average and the most up to 10% relative to the commonly used rule-based (RB) strategy developed based on the efficiency-map [10], and suppressing the aging of the fuel cell and battery effectively [11] [12]. To enhance system durability and improve energy economy, many methods have been proposed, such as fuzzy logic control strategy, equivalent consumption minimization strategy (ECMS) and predictive control strategy. Researchers developed RB or fuzzy logic control strategy based on minimum loss power algorithm, genetic algorithms and system characteristics [13–15]. C.H. Zheng et al. [16] found the fuel-saving potential of ECMS is around 4% relative to RB. The RB or fuzzy logic strategy is suitable for online control, but lacks adaptability to variations in driving conditions and in vehicle characteristics [9] and the energy economy is far from optimal [17]. Adaptive ECMS has been studied [18], it has some adaptability to the above-mentioned variations, but since it may lead to frequent fluctuations in fuel cell power, fuel cell degradation is shown to be accelerated. In order to smooth the fuel cell power, predictive EMS based on model predictive control (MPC) [19] is carried out. Other adaptive EMS based on intelligent learning algorithms can adjust the strategy online to adapt to different driving styles [20,21]. However, these EMS mainly focuses on local optimization, the energy economy is also far from global optimal. Many researches have obtained the global optimal results from dynamic programming (DP) or stochastic dynamic programming [12], but since these methods require the detailed trip information in advance and consume much time (e.g. 8 h or so for a trip), they are unrealistic to be implemented in vehicle real-time application.

In order to realize real-time application, avoid complex vehicle model identification and improve the strategy adaptability to model changes, some studies proposed EMS based on reinforcement learning (RL). Previous work, such as in Refs. [22–25], shows that RL can be used to update the control strategy and component operation points adaptively during driving. However, this basic RL method can only be used in local optimization due to the limitation of dimensionality. The global optimization of energy management is still open. We note, the hierarchical reinforcement learning (HRL) is not limited by dimensions because it decomposes the learning task into multiple levels to reduce state space dimension. HRL is commonly used in path planning and computer games [26,27] as an approximate global optimal algorithm. The HRL is introduced into the EMS for FCHEV in this paper.

Considering the fuel cell characteristics mentioned above, approximate global optimization should be combined with predictive algorithms to smooth the fuel cell power fluctuation. We note, upper confidence tree search (UCTS) is a multi-step decision searching algorithm which combines the upper confidence boundary (UCB) and the random method, and researchers have applied UCTS in several domains, including Go game and receding-horizon planning in nonlinear systems [28,29]. The vehicle speed prediction and UCTS are introduced into the HRL-based EMS as a predictive controller in this paper. As for the vehicle speed prediction, existing algorithms include Autoregressive Integrated Moving Average Model, Gray Model, Markov Chain and exponential smoothing [30,31]. As no single model alone can apply to all cases as shown in Section Verification of short-term vehicle speed forecast of this paper, it needs a new algorithm to predict the vehicle speed.

The main contribution of this paper is that, concerning the challenge of global energy consumption minimization and real-time application, a novel hierarchical EMS based on HRL, UCTS and vehicle speed prediction is proposed for plug-in FCHEV. The vehicle speed is predicted by a feature-based model averaging algorithm. It fuses the traffic information and various prediction models to improve the prediction accuracy. Combined with accurate vehicle speed prediction, the proposed real-time EMS based on HRL and UCTS approximates the global optimal strategy by decomposing the optimization problem into two levels, thus reducing the hydrogen consumption. The EMS also optimizes multi-step strategy within the speed forecast range to slow down fuel cell performance degradation. The collected real-world trip database is used to verify the accuracy of the proposed vehicle speed prediction algorithm. The proposed EMS is also simulated using driving cycles with different characteristics, and the results show much better energy economy, fuel cell durability and adaptability to the change of driving cycles when compared with the commonly used EMS.

The rest of this paper is organized as follows. Section Vehicle model describes the vehicle configuration and mathematical model. Section Vehicle speed prediction algorithm presents the vehicle speed prediction algorithm including average speed forecast and short-term speed prediction. Section Hierarchical energy management strategy introduces the combined control strategy, including the HRL-based approximate global optimal control strategy and the UCTS-based short-term local optimal control strategy. Section Simulation results evaluates the proposed method. Conclusions are drawn in section Conclusion.

Vehicle model

Vehicle structure

The EMS is developed based on the powertrain configuration shown in Fig. 1. It consists of fuel cell stack, DC-DC converter, lithium battery, motor/generator and final drive.where P_{fc} and P_{dcf} are output power of fuel cell stack and DC-DC converter, respectively, Pbp is electric power supplied by the battery pack, $P_{M,e}$ is electric power required by the motor, P_{acs} is accessory power, T_M is motor torque, ω_M is motor speed, T_{fd} is final drive output torque and ω_{fd} is final drive speed.

P_{fc} is fed into the DC-DC to supply appropriate voltage for motor input. The lithium battery pack is in parallel with the fuel cell and is served as a power source to store excess power