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Adaptive Real-Time Energy Management of a Multi-Mode Hybrid Electric Powertrain

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Abstract

Meticulous design of the energy management control algorithm is required to exploit all fuel-saving potentials of a hybrid electric vehicle. Equivalent consumption minimization strategy is a well-known representative of on-line strategies that can give near-optimal solutions without knowing the future driving tasks. In this context, this paper aims to propose an adaptive real-time equivalent consumption minimization strategy for a multi-mode hybrid electric powertrain. With the help of road recognition and vehicle speed prediction techniques, future driving conditions can be predicted over a certain horizon. Based on the predicted power demand, the optimal equivalence factor is calculated in advance by using bisection method and implemented for the upcoming driving period. In such a way, the equivalence factor is updated periodically to achieve charge sustaining operation and optimality. To verify the performance of the adaptive strategy, simulation has been conducted under city and highway driving cycles. Optimal solutions of the equivalence factor and the control outputs, i.e., engine speed and torque, are presented. Results show that the adaptive strategy can maintain battery charge sustaining operation, although there is a drawback that engine activation sometimes happens when vehicle is decelerating or braking. A comparative study is also conducted to verify the fuel economy of the proposed strategy. It is shown that with adaptive strategy, fuel consumption is increased by 9.737% in city driving and 2.409% in highway driving.

Introduction

Hybrid electric vehicles (HEVs) have attracted widespread public attention over the past few decades and are considered as the mid-term solution to pure electric vehicles (EVs) [1]. Along with the emergence and application of HEVs, significant fuel economy improvement and greenhouse gas reduction has been witnessed compared to conventional internal combustion engine vehicles (ICEVs) [2]. In recent years, multi-mode power-split powertrains have been proposed and explored by major automotive manufacturers. Multiple modes are realized by adding clutches or brakes to the transmission and are expected to improve both fuel economy and drivability [3].

As there are multiple power sources in HEVs, efficient power distribution among power sources is one of the most important research topics [4]. Vehicle energy management strategy (EMS) is designed to optimally split the power demand between engine and battery in a sense of fuel reduction. The effectiveness of EMS has great and direct influence on vehicle performance [5, 6]. Over the years, extensive control strategies have been investigated to exhibit better fuel economy and emission behaviors [7], and these can be mainly classified into three categories: rule-based EMS [8, 9, 10], optimization-based EMS [11, 12], and learning-based EMS [13, 14]. Optimization-based EMS is to employ optimization algorithms to minimize a defined cost function and find the optimal control sequence. It can be further divided into off-line strategies and on-line strategies based on the need for a prior knowledge of driving cycles [15]. Off-line strategies ensure a global optimal control policy but require the knowledge of the driving cycle in advance. Plus, the computational burden of global optimization approaches is usually heavy, and it is therefore hard to apply in real-time controls. By contrast, on-line strategies define an instantaneous

TABLE 3 Statistics of eFlite® transmission with basic ECMS simulated under UDDS and HWFET driving cycle.

Statistics	Variable	UDDS	HWFET
Mechanical & electrical energy loss [kJ]	EMA loss	312.512	426.494
	EMB loss	420.877	673.261
	Auxiliary Loss	657.120	367.200
	Friction brake loss	0	0
	Road loads	3615.003	7880.408
	Battery loss	83.996	114.404
	Total energy loss	5089.508	9461.767
Engine statistics	Total fuel consumption [grams]	$Fuel_{ECMS\_UDDS}$	$Fuel_{ECMS\_HWFET}$
	Total mechanical energy [kJ]	5121.415	9427.649
Battery statistics	Net battery energy consumption [kJ]	-31.907	34.118
	SOC at the beginning of trip [%]	40	40
	SOC at the end of trip [%]	40.050	39.9465
Unbalanced energy: Total energy loss - (Total mechanical energy + Net battery energy consumption)		0	0

FIGURE 14 Fuel consumption of adaptive ECMS vs. basic ECMS under UDDS driving cycle.

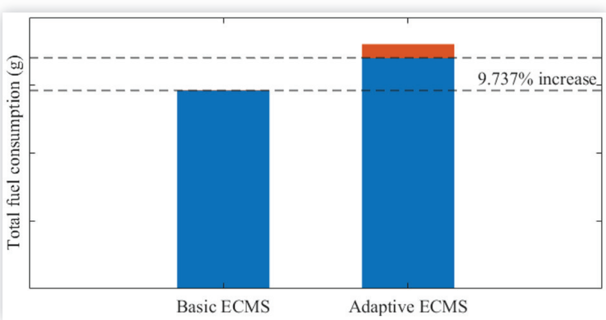
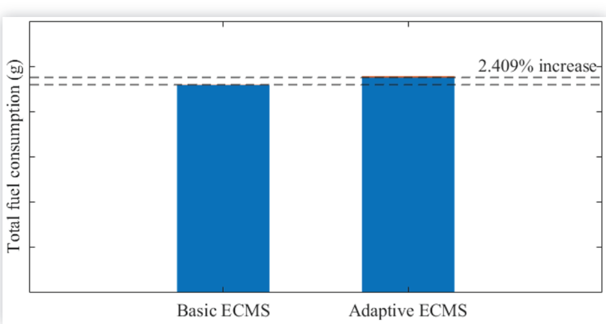


FIGURE 15 Fuel consumption of adaptive ECMS vs. basic ECMS under HWFET driving cycle.



increases fuel consumption by 9.737% in UDDS cycle and 2.409% in HWFET cycle.

Conclusions

In this paper, an adaptive real-time ECMS control strategy is proposed for a multi-mode hybrid electric powertrain, the eFlite® transmission. With the help of road recognition and vehicle speed prediction techniques, future driving conditions over a certain horizon can be predicted. Based on the predicted driving conditions and power demand, the optimal equivalence factor is determined for the next driving period by using bisection method. The predicted equivalence factor is then implemented on the upcoming driving conditions. In such a way, the equivalence factor is updated periodically to achieve battery charge sustaining operation. To test the performance of the proposed adaptive ECMS, simulation has been conducted under UDDS and HWFET driving cycles. Optimal solutions of the equivalence factor and the control outputs, i.e., engine speed and torque, are presented and discussed in detail. Results show that the adaptive ECMS exhibits great charge sustaining capabilities, although there is a minor drawback that engine activation sometimes happens when the vehicle is decelerating or braking. A comparative study is also conducted with basic ECMS to verify the fuel economy performance. It is shown that with adaptive ECMS, fuel consumption is increased by 9.737% in city driving and 2.409% in highway driving.

Future work can be done on exploring other improved methods, such as improved shooting method, for EF searching to improve the computational efficiency of adaptive ECMS. Moreover, the proposed adaptive ECMS can be implemented on other powertrain architectures such as range-extended electric vehicles.

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