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A Rule-Based Energy Management Strategy for a Light-Duty Commercial P2 Hybrid Electric Vehicle Optimized by Dynamic Programming

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Abstract

An appropriate energy management strategy can further reduce the fuel consumption of P2 hybrid electric vehicles (HEV) with simple hybrid configuration and low cost. The rule-based real-time energy management strategy dominates the energy management strategies utilized in commercial HEVs, due to its robustness and low computational loads. However, its performance is sensitive to the setting of parameters and control actions. To further improve the fuel economy of a P2 HEV, the energy management strategy of the HEV has been re-designed based on the globally optimal control theory. An optimization strategy model based on the longitudinal dynamics of the vehicle and Bellman's dynamic programming algorithm was established in this research and an optimal power split in the dual power sources including an internal combustion engine (ICE) and an electric machine at a given driving cycle was used as a benchmark for the development of the rule-based energy management strategy. Then, a novel rule-based real-time energy management strategy was proposed on the basis of the nonlinear relation between the output torque of the ICE and the torque demanded by the HEV, and then was used in a commercial P2 HEV. The experimental results show that the equivalent energy consumption of the HEV can be reduced around 6.1% in the world- harmonized light-duty vehicle test cycle (WLTC) when the energy management strategy is altered from the original strategy to the optimization strategy.

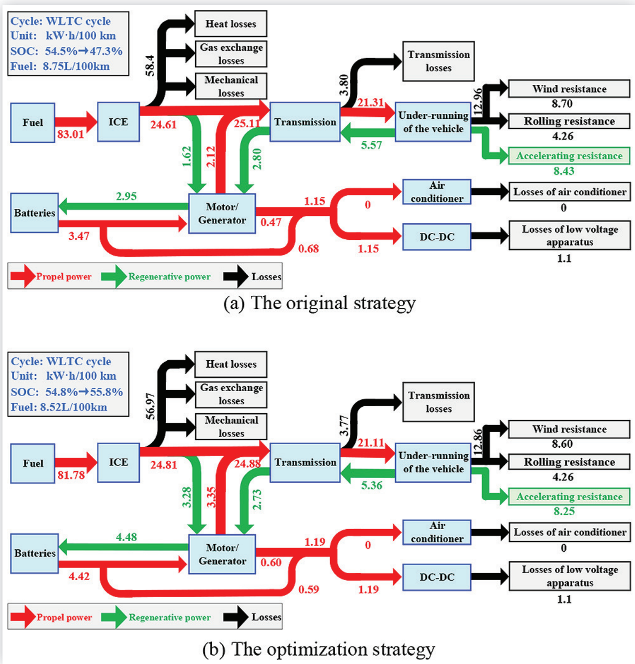
Introduction

The power sources of the vehicles have been dominated by the internal combustion engines (ICE) for a long time due to the relatively high thermal efficiency, good durability and high energy density of the ICE fueled with gasoline or diesel [1]. However, the vehicles powered by the ICEs have poor fuel economy and emissions especially operating at the urban conditions with low power demand. The main reason is that the operating points of an ICE with high efficiency occur only at a narrow region of medium engine speeds and medium-high loads [2], while the ICE is required to be operated in a wide region in order to satisfy the drivers' demands in a real time [3]. Therefore, a vehicle with an ICE only is hard to reach high overall efficiency in most driving conditions.

The powertrain of a hybrid electric vehicle (HEV) takes full advantages of the ICE and the electric motor (EM), which can obviously improve the overall efficiency of the vehicle since the ICE can operate in the loads with high thermal efficiency with the help of the EM. Therefore, the HEV provides an effective method to overcome the relatively low efficiency of a conventional vehicle. Generally, the energy management strategies for the operation of an ICE and/or EM at different loads and speeds have obvious effect on the overall efficiency of HEVs [4].

The energy management strategies for HEVs have been investigated by many research institutes and universities around the world [5, 6, 7, 8]. The optimal energy management strategies can be achieved through control methods [9], such as Pontryagin's minimum principle (PMP) [10], equivalent consumption minimization strategy (ECMS) [11,12], dynamic programming (DP) [13,14], model predictive control (MPC) [15]. However, a priori knowledge of the trajectory of vehicle speed should be known before optimizing. The DP method based on the globally optimal control theory can obtain the globally optimal energy management strategy with the lowest fuel consumption, while its real-time application to commercial HEVs is limited by a lot of computational requirements of the DP algorithm. Thus, it can be used as a benchmark to investigate the fuel economy potential and redesign the rule-based energy management strategy offline [16].

FIGURE 10 The energy flow of the vehicle loaded with the original and optimization energy management strategies at the WLTC cycle



under the same cycle with the same HEV loaded with the original and optimization strategies, respectively. It can be seen that the output energy from the ICE in the case of the original strategy is close to that of the optimization strategy, while the input energy of the ICE is around 1.2 kW·h/100 km lower at the optimization strategy than at the original strategy. The mainly reason is that compared to the original strategy, the EPG and EMA modes appear more frequently with longer time in the optimization strategy (Figure 9), which increases the overall efficiency of the ICE operating at its medium-high loads with high thermal efficiency. It can also be seen that the input energy and output energy of the EM and batteries are much higher with the optimization strategy than with the original strategy, indicating that the reasonable processes of charging the batteries, discharging the batteries, generating electricity, and the vehicle driven by the EM only could offset the losses from the EM and batteries through improving the overall thermal efficiency of the ICE.

From Figure 10, the fuel consumption of the HEV is 8.75 L/100km with the SOC reducing from 54.5% to 47.3% in the case of original strategy. The HEV loaded with the optimization strategy has a fuel consumption of 8.54 L/100km with the SOC increasing from 54.8% to 55.8%. Furthermore, the equivalent energy consumption including fuel and electricity is around 287.8 MJ/100 km in the original strategy, and is 270.3 MJ/100 km in the optimization strategy. It can be seen that the energy consumption is reduced around 6.1% when the energy management strategy is switched from the original version to the optimization version. Therefore, the proposed rule-based energy management strategy optimized by the optimization strategy model is an effective method to improve the fuel economy of HEVs.

Conclusions

A novel rule-based energy management strategy is proposed to approximate the optimal energy consumption of a commercial P2 HEV operating at the WLTC cycle, in which the trajectory of SOC and the torque demand of the vehicle relative to engine speed are used to as the conditions enabling the EPG, EMA, and ICE_O modes. An optimization management strategy based on DP algorithm and the simplified mode of the HEV is used to guide the design of the trajectories of SOC and the calibration of the mapping relation between the T_{ICE} and T_{Veh} at different engine speeds.

According to the results of optimization strategy model, there exist almost optimal linear relations between the T_{ICE} and T_{Veh} in the EMA mode, except for some operating points. As a result, the re-designed mapping relationship in the EMA mode is relatively flat except for an obvious peak at a certain engine speed. In the mode of EPG, the optimal relationship is almost linear at the relatively low T_{Veh} less than 45 Nm, while it is nonlinear at higher T_{Veh}. Therefore, several peaks and valleys exist in the re-designed mapping relationship in the EPG mode. Furthermore, the amount of the electricity generated from the EM driven by the ICE can be higher at the optimization strategy than at the original strategy, resulting in higher electrical power consumed in the EMA mode at the former strategy.

The effects of the original strategy and optimization strategy on the energy consumption of the P2 HEV were experimentally investigated on a chassis dynamometer. The experimental results show that compared to the original strategy, the amount of electricity generated from the ICE and that used to drive the vehicle obviously increases in the optimization strategy, which increases the overall efficiency of the ICE. The energy consumption of the vehicle at the WLTC cycle is reduced around 6.1% when the strategy is changed from the original version to the optimization version, indicating that the proposed rule-based energy management strategy optimized by the optimization strategy model can further improve the fuel economy of the vehicle.

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Definitions/Abbreviations

C_{Max} - The Maximum value of the SOC enabled the EPG mode

C_{Min} - The Minimum value of the SOC enabled the EMA mode

ICE - Internal Combustion Engine

EM - Electric Machine

EMA - Electric Machine Assist