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Rule based energy management strategy for a series–parallel plug-in hybrid electric bus optimized by dynamic programming

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HIGHLIGHTS

- A rule-based energy management strategy is calibrated by dynamic programming.
- Hardware-in-loop experiment bench for energy management system is designed.
- Comparisons among typical energy management strategies are performed.
- The fuel consumption is decreased by 10.45% with the improved strategy.

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ABSTRACT

An appropriate energy management strategy is able to further improve the fuel economy of PHEVs. The rule-based energy management algorithms are dominated in industry due to their fast computation and ease of establishment potentials, however, their performance differ a lot from improper setting of parameters and control actions. This paper employs the dynamic programming (DP) to locate the optimal actions for the engine in PHEVs, and more importantly, proposes a recalibration method to improve the performance of the rule-based energy management through the results calculated by DP algorithm. Eventually, an optimization-based rule development procedure is presented and further validated by hardware-in-loop (HIL) simulation experiments. The HIL simulation results show that, the improved rule-based energy management strategy reduces fuel consumption per 100 km from 25.46 L diesel to 22.80 L diesel. The main contribution of this study is to explore a novel way to calibrate the existed heuristic control strategy with the global optimization result through advanced intelligent algorithms.

1. Introduction

Plug-in hybrid electric vehicle (PHEV) takes the advantages of low emission and low fuel consumption by combing the typical driving modes of pure electric vehicle and conventional hybrid electric vehicle. PHEV integrates a large-capacity battery pack, which can be charged from power grid, and covers a certain pure electric driving mileage [1–3]. The power distribution flexibility of PHEV brings a more complex energy management problem, and more studies have been concentrated on it in the literature [4–7]. The energy management strategy of hybrid electric vehicle can be divided into two categories, namely rule-based and optimization-based [8,9]. The optimization-based energy management strategy regulates the control variables based on numerical computation results, by minimizing a predefined cost function within feasible constraints. Optimization-based approaches can be further divided into the global optimization control and real-time optimization control [10,11].

Nonlinear programming, genetic algorithm and dynamic programming (DP) are frequently used in global optimization control [12]. Especially, DP is based on the optimal control theory, and can always generate the most fuel efficient results while dealing with the PHEV energy management problem. DP is able to solve the powertrain control problem for most of the HEV/PHEV structures

Abbreviations: PHEV, plug-in hybrid electric vehicles; PHEB, plug-in hybrid electric bus; DP, dynamic programming; HIL, hardware-in-loop; CTUDC, Chinese typical urban driving cycle; ECMS, equivalent consumption minimization strategy; MPC, model predictive control; EV, electric vehicle; CD, charge-depletion; CS, charge-sustaining; ISG, integrated starter generator; PSR, power split ratio; BSFC, brake specific fuel consumption.

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developed currently. However, for global optimization control approaches, the overall driving power demand is required to be known a prior, which is extremely difficult in real applications. Global optimization algorithms, such as DP, are also trapped in the 'curse of dimension' and cost too much computation effort from the controller. Therefore, global optimal control is normally implemented offline and serves as a benchmark to explore the fuel economy potential [13,14].

For real-time optimization control manner, the equivalent consumption minimization strategy (ECMS) and model predictive control (MPC) are two most representative methods, yet both have not been massively used to practical application. The equivalence factor of ECMS influences its energy management performance greatly, but the optimal value needs to be determined offline by 'trial and trivial' according to a specific driving cycle [15]. For MPC, it is able to maintain the computational burden within an acceptable range. However, the powertrain control effect depends a lot on the future driving information prediction accuracy, which remains an open question for now [16–18].

Rule-based energy management strategy is widely used in practice, because it can be easily developed and is able to operate quite reliably [19]. Generally, the PHEV works in three modes under rule-based control strategy, namely electric vehicle (EV) mode, charge-depletion (CD) mode and charge-sustaining (CS) mode [20]. The fuel consumption comparison of EV + CS, CD + CS, EV + CD + CS rule-based control and global optimization control is shown in Fig. 1. It can be seen that, the EV + CD + CS control mode with proper control parameters produces the lowest fuel consumption among the rule-based ones [20], and is employed in this paper.

The rule-based control strategies include deterministic rule-based methods and fuzzy logic rule-based methods [21]. A deterministic rule-based controller operates on a set of rules that have been defined prior to actual operation, and state machines are proposed as a viable method to implement it. This control approach has been successfully applied to Toyota Prius and Honda Insight [21]. A rule-based control is implemented by finite-state machine, which has eight states switches among the possible driving situations according to event-triggered rules that depend on the brake and accelerator pedal angle, the state-of-charge (SOC) of the battery and the request of torque, this control approach has been validated in simulation on FT-SIM, but difficult to evaluate the potential improvement [22]. A novel rule-based control strategy for the PHEVs that focuses on all electric range and charge depletion range operations is presented in Ref. [23], and it has been validated by simulation of passenger car driving in FTP75 driving cycle. An engine on–off rule-based control strategy with consideration on position of acceleration pedal is proposed in Ref. [24], but the author still doesn't discuss the fuel saving effort and potential.

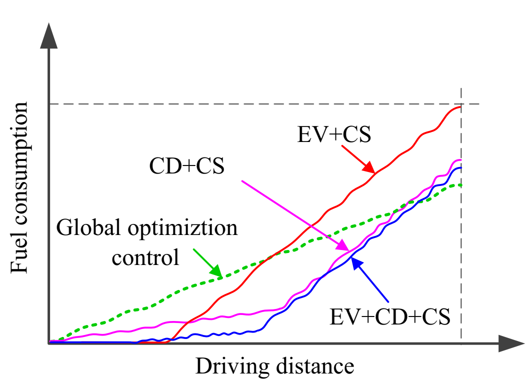

Fig. 1. The fuel consumption under typical rule-based energy management strategy.

A heuristic solution is improved by that of ADVIOSOR software, the results of this heuristic control were compared to the Prius control strategy, and the comparative results shows that the gas mileage of the PHEV increased by 16% over the Prius control strategy [25]. Jalil et al. have proposed a rule-based strategy to determine the power split between the battery and engine for a series hybrid electric vehicle, this 'Thermostat' strategy bring the fuel economy with an improvement of 11% in the urban cycle and of 6% in the highway cycle [26]. However, all these traditional deterministic rule-based controllers hardly can implement the optimization operation. In a fuzzy logic rule-based controller, fuzzy rules are required to be established based on some 'expert' knowledge of the powertrain, which requires long development period [27]. An adaptive fuzzy logic controller selects the operating points with the least impact on fuel economy and the key parameters evolves according to the driving cycles, as implemented by literature. However, it is very difficult to develop appropriate adaptive fuzzy rules when the power system has two or more control variables [28,29].

Practically, deterministic rule-based energy management strategy is the mostly implemented approach in resolving the PHEV powertrain control problems. The target of this study is to further improve the effectiveness and performance of deterministic rule-based energy management algorithms. The main contribution of this paper is the development and validation of an optimization-based rule energy management strategy. By constraining the engine operating points to an optimized working area based on the offline optimal results, the new control logic is able to better adapt to the target driving cycle online. Typically, this optimization-based rule development method is more suitable to fixed-pattern driving circumstances. Hardware-in-loop (HIL) simulation is one of the key steps of "V" cycle development process to verify the effectiveness of the developed control system [30], and is employed in this paper for verification.

The paper structure is arranged as following, the traditional EV + CS + CD rule-based energy management strategy is developed for a plug-in series–parallel hybrid bus in Section 2. Dynamic programming algorithm for PHEV energy management is presented and analyzed in Section 3. Then, in Section 4, the rule-based energy management strategy is calibrated and optimized according to the optimal results calculated by the DP. In Section 5, the HIL simulation experiment is carried out to verify the improved rule-based management strategy over the Chinese typical urban driving cycle. Several conclusions are drawn in Section 6.

2. Rule-based energy management strategy for a series–parallel plug-in hybrid electric bus

2.1. Powertrain of a series–parallel plug-in hybrid electric bus

The PHEB powertrain is shown in Fig. 2, which is consisted of diesel engine, integrated starter generator (ISG), traction motor and power battery pack.

The peak power of the diesel engine is 147 kW, and the peak torque is 730 N m. The peak power and the peak torque of the ISG motor are 55 kW and 500 N m. The peak power and the peak torque of the traction motor are 166 kW and 2080 N m. The battery pack is 60 A h capacity with the nominal voltage of 580 V. The main parameters of the PHEB are listed in Table 1.

2.2. Series–parallel PHEV model

2.2.1. Engine model

To analyze and evaluate the engine fuel economy, a static model [31,32] is used based on the net efficiency data from the bench experiment. The engine net efficiency is defined as

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