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Study on energy management strategy and dynamic modeling for auxiliary power units in range-extended electric vehicles ☆

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HIGHLIGHTS

- The limit of APU power changing rate significantly affects the fuel consumption.
- The dynamic characteristic of APU is better when engine speed keeps constant.
- Two types strategies are proposed to track the demand power of APU.

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ABSTRACT

Range-extended electric vehicles (REEVs) are becoming a development trend of new vehicles. Energy management is one of the core problems in REEVs. The structure and control method of the auxiliary power unit (APU) is determined based on the configuration analysis in this paper. An energy management optimization problem is proposed to solve the power distributions of APUs and batteries in the charge-sustaining (CS) stage of REEVs, which are determined by dynamic programming and pseudo-spectral optimal control, respectively. The results show that different limits of the APU power changing rate significantly influence fuel consumption. To obtain the power changing rate of APUs and to evaluate the energy management optimization method of REEVs, a model of the APU control system is built and verified by a platform test; the dynamic response characteristics and control parameters of the APU are obtained by step-changing conditions. Two types of strategies for tracking APU power are proposed for different power changing rates, and the fuel consumption of REEVs is analyzed in four types of driving cycles. The effect on fuel consumption caused by the power changing rate of the APU is verified.

1. Introduction

Compared with a pure electric vehicle (PEV), a REEV is equipped with an APU and possesses both an electric mode and a hybrid mode. Thus, REEVs can solve the "range anxiety" problem in PEVs, and they are gradually becoming a development trend in new vehicles. In REEVs, the engine is decoupled from the vehicle velocity, and the application of lithium-ion batteries can meet the power requirements for most vehicle driving conditions [1]. Consequently, the APU is mainly used to promote endurance mileage and to improve power following in heavy load conditions.

Energy management is one of the core problems for REEVs, and the key task of energy management is to coordinate the power distribution between the APU and the battery [2]. In the charge-sustaining (CS) stage of REEVs, the output power should meet the demand of the work condition. In addition, the SoC of the battery should be maintained within a reasonable range. On this basis, fuel economy is the main objective of energy management.

1.1. Literature review

Power management problems for PHEVs are usually solved by two types of ideas: rule-based solutions or optimization-based solutions. The rule-based strategy is the most direct and widely used method due to its easy implementation and high calculation efficiency. The rules are predefined to ensure that the vehicle is working at its highest efficiency point without any prior information about the work condition. In contrast, the performance of rule-based strategies may be far from optimal as they do not use

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prior information to optimize the whole cycle. Optimization-based control strategies find the optimal distribution between power sources to minimize a control objective, which is usually fuel consumption. Global optimization is a non-causal method because it requires previous driving cycles to find the minimum fuel consumption. This method is also highly computationally demanding, and the processing power it requires cannot be facilitated by standard onboard processors in real vehicles [3]. Therefore, it cannot be implemented as a real-time controller, but it can be used to design rules for rule-based control strategies. Therefore, this method is a good benchmark for evaluating the performance of other control strategies.

As global optimization algorithms, particle swarm optimization (PSO), genetic algorithm (GA) [4,5], dynamic programming (DP) [6,7], model predict control (MPC) [8], pseudo-spectral optimal control (PSOC) and minimum principle (MP) [9–11] are widely applied in the solution process of the energy management problem of hybrid electric vehicles. Sorrentino et al. [12] compared DP and GA for the energy management of plug-in HEVs. Hegazy and Van Mierlo [13] and Caux et al. [14] optimized the power distributions for APUs and fuel cells using PSO. Fard and Khajepour [15] sought to develop a real-time control strategy for the power management system; they employed a fast DP technique to find an SOC trajectory for the whole trip, which operates based on extracted features of available a priori knowledge and addresses the issue of the high computational burden of DP. Cheng-ning et al. [16] realized that the online energy management of REEVs by MP. Zhou et al. [17] presented a novel pseudo-spectral HEV power management algorithm capable of optimizing the power management; they showed that this algorithm is numerically more efficient than DP and is able to achieve a solution very close to that of DP. Hou et al. [18] proposed an optimal energy management strategy based on the approximate pontryagin's minimum principle algorithm for parallel plug-in HEVs to achieve the best fuel economy.

DP-based methods have the ability to settle the global optimal problem in energy management based on known driving cycles. The computational demands of DP are relatively large, requiring significant time. PSOC is an optimal control method that has been developed in recent years [19–21]. It is a direct method for solving optimal control problems that transcribes an optimal control problem into a nonlinear programming problem (NLP) by parameterizing the state and control variables using global polynomials at a set of collocation nodes. Then, the NLP problem could be solved by well-developed NLP solvers, such as GPOPS-II [22], a software package that contains the machinery for transcribing a trajectory optimization problem into a NLP and incorporates two optional well-developed NLP solvers. PSOC possesses the advantages of small computational requirements and fast convergence.

Suitable models for APUs and batteries are essential for the verification of energy management. To evaluate the control strategy in a real vehicle, a precise model is needed to reflect the vehicle characteristics. However, an excessively detailed model will require too much resources and time, which is not always necessary. Based on experimental data, data-based models take fewer system resources in the operation process, but the accuracy is relatively lower. To balance the prediction accuracy and calculation time, we can add the inertial elements for the critical components on the basis of a data-based model [23]. For the battery, the estimation of the battery SoC and the battery model have been researched extensively and been highly developed [24–26]; it is possible to accurately estimate the SoC with the RC battery model in the working process of electric vehicles. However, the RC model requires a high calculation demand in the solution process of the optimization problem. In this paper, the battery works within a narrow range of SoC in the CS stage of the vehicle, which means that a simplified model is also capable of meeting the precision of the SoC estimation. According to the literature [17], compared with a first-order RC impedance model, the terminal voltage predictions of the Rint model are fairly accurate, which shows the rationality of the Rint model in the energy management problem.

1.2. Motivation and innovation

The purpose of this study is to propose an optimization problem for the energy management of REEVs and then to solve the optimization problem by dynamic programming and pseudo-spectral optimal control. Finally, this study verifies the solutions using an APU model built in Matlab/Simulink. In proposing the optimization problem, the changing rate of the APU power is set as one of the limits, which was not considered in most past studies. The changing rate of APU power represents the dynamic response of the APU, which significantly affects the fuel consumption. In addition, the energy management results are not verified in most past studies due to neglecting the dynamic response of APUs. There is a large difference in the dynamic response between the engine and generator, so coordination control is essential for ensuring stable APU work. In this paper, by analyzing the APU configuration, the APU scheme is obtained. Based on specific driving cycles, the distributions of APU power and battery power are optimized. A speed control strategy for the engine and a torque control strategy for the generator are proposed as the APU control strategy. Through experiments, the control strategies are confirmed to be reliable. Thus, the energy management results presented in this paper are verified. This paper shows the optimization of the fuel consumption in REEVs and the dynamic characteristics of APUs, and it can provide a reference for the establishment of rule-based control strategies on energy management in REEVs.

1.3. Organization of this paper

This paper is organized as follows: Section 2 describes the configuration of the power drive system of REEVs and representative APU configurations. Section 3 presents the energy management problem and solves the problem using global optimization method. Section 4 shows the APU modeling process and proposes two types of strategies to achieve the coordination control of the APU. In Section 5, the APU model is validated experimentally, and the verification of the energy management results is given by a simulation. Conclusions are drawn in Section 6.

2. Configuration of the power drive system and the REEV control method

The power drive system of a REEV mainly consists of an APU, a power battery, a driving motor and a mechanical driving mechanism. All of the demand driving force in the vehicle travel process is provided by the motor drive system. The engine runs only to drive the generator instead of providing the driving force directly. Consequently, engine speed is not coupled with vehicle velocity, which ensures that the engine can continuously work in a high frequency zone to reduce fuel consumption. The power battery provides power output, power compensation and storage of braking energy.

Based on previous studies, some representative APU configurations are summarized in Table 1.

Among the schemes above, the first scheme appeared the earliest, and the gearbox was applied to match the low speed engine and high speed generator (No. 1). With the development of permanent magnet synchronous generators (PMSGs), the excitation generator was gradually substituted due to the low efficiency and power density (No. 2). Along with the rapid development of high

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