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Two-step optimal energy management strategy for single-shaft series-parallel powertrain

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A B S T R A C T

The series-parallel architecture of the plug-in hybrid electric powertrain has attracted wide attentions in recent years for its flexible and highly efficient operating modes. However, despite the improvement of the vehicle fuel economy, it has been gradually facing more challenges on the design of the optimal controller due to the complex structure and the fast depletion of the battery. In this paper, a two-step optimal energy management strategy is proposed for a novel single-shaft series-parallel powertrain. In the first step, an equivalent method is adopted, in which two motors are equivalently regarded as one. After detailed analysis of the operating modes, various objective functions are established to pre-optimize the power split between engine and motor or two motors. In the second step, a stochastic dynamic programming (SDP) is adopted to optimize the power split between the engine and the equivalent motor, and the optimal combination of the operating modes. Then coupled with the pre-optimized results of the first step, the optimal power split among the engine and two motors could be obtained and then constructed as simple lookup-tables, which have great potential for practical applications. Finally, the preliminary test about the real-time performance of the optimal results is developed on the hardware-in-the-loop (HIL) system.

1. Introduction

With increasing public awareness of environmental pollution and the shortage of energy sources, new energy technologies used in automobiles have attracted more and more attentions for manufactures. Of them, the plug-in hybrid buses (PHEB) have been well-developed for their larger electrical capacity and better fuel economy in public transport in recent years [1]. Generally, three types of architectures, namely, series, parallel and series-parallel are available for the powertrain of PHEB. Of them, the series-parallel architectures have shown superiority for its flexible operating modes and good adaptabilities for the driving cycles. The multi-operating modes and the special structural features of the powertrain provide a significant benefit in improving the fuel economy and drivability of the vehicles compared with traditional architectures. However, at the same time it also brings more challenges to obtain an applicable optimal control strategy considering the fast depletion of the battery and the complex driving situations of buses.

Unlike the vehicle stability of traditional cars [2], more attentions are paid on the energy management control especially for PHEB or HEB. To improve the fuel economy as much as possible, numerous efforts in the research areas on optimal energy management have been made in the last decade. The equivalent consumption minimization strategy (ECMS) [3,4], the Pontryagin's minimum principle (PMP)-based strategy [5], and Dynamic programming (DP) [6,7] all could obtain the global or approximate global optimal control strategy if all of the future driving information is known in advance. Thus, these methods all suffer from their own difficulties in being put to practice. Other methods have been proposed to improve fuel economy, which include the rule-based strategies on the basis of offline optimization results [8], improved instantaneous optimization strategies [9,10], model predictive control strategies [11–13], and stochastic dynamic programming (SDP) [14,15]. Of them, the SDP, which could obtain the stationary full-state feedback strategies, could be directly applied in actual despite its complexity in offline process [16]. Furthermore, considering the high regularity of the bus driving cycle due to its fixed route, the SDP may be a nice choice for this paper to obtain an applicable strategy.

Moura *et al.* obtained the optimal energy management for the PHEV with power-split architecture and discussed the tradeoff

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between battery capacity and energy management based on SDP [17]. Opila *et al.* derived the optimal control strategies together with the vehicle drivability and discussed its real-time application based on the algorithm of SP-SDP [18,19]. Johannesson *et al.* fully explored the potential of SDP to reduce fuel consumption with three-level of information access to the route [20]. Liu and Peng modeled the powertrain with the Toyota Hybrid system and compared the performance of SDP and ECMS [21]. Jiao *et al.* constructed various stochastic models on different segments of a certain route, and obtained a position-based optimal strategy [22].

All researches mentioned above provide a good background for this paper to study the energy management of the hybrid powertrain. In this paper, a novel single-shaft series-parallel powertrain is studied. An extra motor is added to the output-shaft of the automated mechanical transmission (AMT) of the single-shaft parallel powertrain in [23,24]. Different from the general single-shaft series-parallel configuration in [25], where the two motors are equipped on the both sides of clutch, the two motors of this novel architecture are assembled on the both sides of AMT. And the driver power demand will be satisfied by the engine and two motors. There are two control variables in one equation (e.g. the power of engine and motor 1) according to the vehicle longitudinal dynamics equation. With the improvement of discrete precision for control variables, there will be large number of possible solutions. Thus, it will highly increase the calculation burden for SDP to find the optimal decisions by traversing all possible solutions. Therefore, it's necessary to propose an improved method to simplify the optimization without sacrificing the final optimal results. Note a fact that both fuel and electricity consumptions are directly related to economy of PHEB, and the operating modes of two motors jointly determine the final electricity consumption. This provides a potential solution to simplify the design of the controller using SDP. Therefore, a two-step method is developed to optimize the energy management for PHEB in this paper. For the first step, all the possible operating modes of the architecture are analyzed in detail and the equivalent method is adopted to treat the two motors as an equivalent motor (E-motor). Then various objective functions are established to find the optimal control strategies for the engine in series mode and for motors in non-series mode based on the pre-defined state grids of E-motor. On the basis of the pre-optimized results, SDP is adopted in the second step to determine the optimal operating modes and the power split between engine and E-motor. Then combined with pre-optimized results obtained in the first step, the final control strategies are established.

This paper is organized as follows. In Section 2, the mathematical models of the PHEB are established. And the proposed method is described in detail in Section 3. Section 4 presents the simulation results about the optimal strategy and then the preliminary test about the real-time performance of the optimal results is developed on the hardware-in-the-loop in Section 5. Finally, conclusions are presented in Section 6.

2. Configuration and simulation model

The prototype of the novel series-parallel powertrain is shown in Fig. 1. The main advantages of this architecture is that it can partially, even completely resolve the problem of power interruption in the gearshift process caused by the discontinuous transmission of AMT, and significantly improve the passenger's comfort experience. During the gearshift process, motor 2 continues to supply the power for the vehicle. And motor 1 would adjust the rotation speed of the AMT input shaft to shift the gear. While in other situations, motor 1 would act as the auxiliary equipment to supply the power for the vehicle. Therefore, the power of motor 2 is much larger than that of motor 1. And some parameters about the main components are listed in Table. 1.

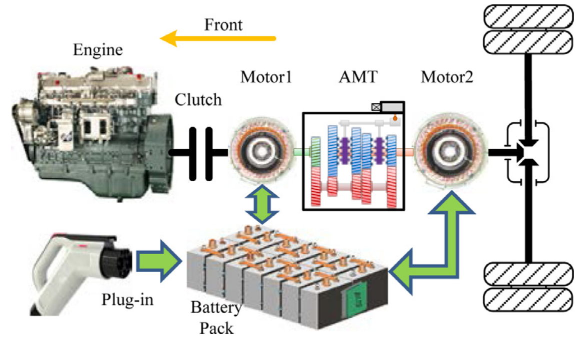

Fig. 1. The prototype of the single-shaft series-parallel powertrain.

Table 1
Main parameters of the components.

Components	Description
Engine	YC6G230N,CNG, 6.454 L, nominal power:170kW
Motor 1	Permanent magnet, max torque: 500Nm, nominal power :40 kW,peak power:60kW
Motor 2	Permanent magnet, max torque: 750Nm, nominal power :94 kW,peak power:121kW
Battery	Lithium titanate, capacity: 50Ah
Transmission	4-speed AMT, gear ratio: 2.92/1.63/1/0.73
Final Drive	Ratio: 5.571

The main operating modes of this configuration include engine mode, electrical vehicle (EV) mode, series mode and parallel mode. The detailed descriptions of these modes are shown as follows.

(1) **Engine Mode:** Engine is on, clutch engaged and both motors are off.
(2) **EV Mode:** Engine is off, clutch disengaged, at least one motor is on.
(3) **Series Mode:** Engine is on, clutch engaged, motor 1 operates as generator, AMT is on neutral gear, and motor 2 is on.
(4) **Parallel Mode:** Engine is on, clutch engaged, and at least one motor is on.

Note that the situation in series mode may also happen in parallel mode during the gearshift process. However, the transient processes, such as the gearshift and half-linkage of the clutch etc., are not considered in this paper. Thus, the control-oriented model is established. According to the vehicle longitudinal dynamics equation, the balance equation on the wheel can be established as (1).

$$(P_e \cdot \eta_T + P_{m1} \cdot \eta_T^{\mathrm{sgn}(P_e+P_{m1})} + P_{m2}) \cdot {\eta_0}^{\mathrm{sgn}(P_e+P_{m1}+P_{m2})} + P_{mech} = (mgf_r\cos\alpha + mg\sin\alpha + \frac{1}{2}C_D A\rho v^2 + \delta m\frac{dv}{dt}) \cdot v \quad (1)$$

where P_e, P_{m1} and P_{m2} are power of engine, motor 1 and motor 2 respectively. And P_{mech} is the braking power on the wheel. η_T and η_0 are efficiency of transmission and final drive respectively. m is the vehicle mass, g is the acceleration of gravity,f_r is the rolling resistance coefficient, α is the road slope. C_D is the aerodynamic drag coefficient, v is the vehicle speed, and δ is the rotary mass coefficient. From (1), the discrete vehicle speed is described as (2).

$$v_{k+1} = v_k + [(P_{e,k} \cdot \eta_T + P_{m1,k} \cdot \eta_T^{\mathrm{sgn}(P_e+P_{m1})} + P_{m2,k}) \cdot {\eta_0}^{\mathrm{sgn}(P_{e,k}+P_{m1,k}+P_{m2,k})} + P_{b,k} - mgf_r v_k\cos\alpha_k - mgv_k\sin\alpha_k - \frac{1}{2}C_D A\rho v_k^3]/(\delta m v_k) \quad (2)$$

where k is the discrete instant time, and Δt is the discrete time step.

The main concern about the engine and the motor are their fuel consumption and operating efficiency. Therefore, the quasi-