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HEV power management control strategy for urban driving

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HIGHLIGHTS

- The conventional DP method is modified with the consideration of SOC balance.
- Rules of torque slip behaviors have been found in DP results.
- Rules of torque slip behaviors are utilized to design the fuzzy controller.
- An urban driving pattern recognition method is proposed base on similarity degree.
- The proposed strategy is combined with the driving pattern recognition method.

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ABSTRACT

The aim of this paper is to further improve the fuel efficiency and keep the balance of battery SOC simultaneously during urban driving. A dynamic programming (DP)-optimized HEV power management control strategy is proposed. The DP algorithm is applied to obtain the optimal engine/motor power distribution and utilized for the design of the fuzzy control strategy. The traditional DP algorithm is modified with the consideration of SOC balance for HEVs. In the analysis of DP simulation results, rules of torque slip behaviors have been found, which are directly utilized in the design of fuzzy control strategy. In order to improve the practicality of the control strategy to meet the diversities of city driving patterns, an urban driving pattern recognition method is presented. To evaluate the control performance, the proposed control strategy is also compared with the conventional rule-based strategy. The simulation results indicate that by adopting the proposed strategy the fuel efficiency of HEV is improved, and the SOC of the battery is kept in balance during different urban driving cycles.

1. Introduction

As the energy crisis increases severely, cleaner and more fuel-efficient vehicles have become the hotspot of automotive technology research. However, conventional ICE (internal combustion engine) vehicles suffer from poor fuel economy during urban driving due to the low efficiency of engine under the stop-and-go urban driving situation. Battery-powered electric vehicles (EV), on the other hand, have some advantages over conventional ICE vehicles, such as high energy efficiency and less pollution. However, due to the lower energy content of the battery compared gasoline, the operation range per battery charge, is far less than ICE vehicles, which is the major disadvantage of EV. Hybrid electric vehicles (HEVs) are widely considered as one of the most viable solutions to the world's need for cleaner and more fuel-efficient vehicles. In order to overcome the drawbacks of the conventional gasoline vehicles, HEVs encompass two power sources (ICE and electric motor) to generate the power to drive the vehicle, which have the advantages of both ICE vehicles and EV and overcome their disadvantages [1,2]. However, the joining of the secondary power source also brings another layer of complication to the power management control system. A proper power management control strategy is thus a critical issue in the implementation of HEVs, which should be able to distribute the drive power between the engine and the motor reasonably to realize efficient energy saving and balance of battery SOC at the meantime.

The conventional rule-based control strategy is widely adopted in the modern HEVs due to the advantages of strong robustness, high operation efficiency and being easy to implement [3,4]. However, the tuning of the rule-based strategy mainly relies on human experiences and the threshold values are fixed. In order to solve the problems of the rule-based strategy, some researchers focused on global optimization strategies such as DP [5–8]. Global optimization strategy can achieve optimal fuel efficiency; however,

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Nomenclature

a	vehicle acceleration	R	battery internal resistance
$\overline{a_a}$	average acceleration	S	similarity degree
$\overline{a_d}$	average deceleration	T_c	torque coupler output rotational torque
F_g	grading resistance	T_e	engine torque
F_r	wheel rolling resistance	T_m	motor torque i_e is
F_t	vehicle tracking force	TSR	torque slip ratio
F_w	aerodynamic drag force	SOC	state of charge
i_e	engine gear ratio	V	vehicle speed
i_m	motor gear ratio	$\overline{v}$	vehicle average speed
L	instantaneous fuel consumption	α	weight factor of penalty function
M	vehicle mass	δ	rotational inertia factor
P	vehicle demanded power	η	idle ratio
P_{bat}	battery power	λ	weight factor similarity degree
P_e	engine power	ω_c	torque coupler output rotational speed
P_m	motor power	ω_e	engine rotational speed
P_r	vehicle required power	ω_m	motor rotational speed
P_{opt}	optimal engine power		
Q	battery capacity		

it is based on a priori knowledge of scheduled driving cycles. Although the DP algorithm cannot be directly implemented in real-time, the theoretical optimal solutions are widely utilized to design real-time control strategies and act as benchmarks for evaluation of the control performance. Hence, the new control strategy is supposed to combine the merits of both control methods.

Simulation results from previous work indicate that those control strategies can achieve excellent fuel efficiency for the individual given driving cycle; however, in real case the driving pattern varies with time, weather or other urban driving conditions, therefore the applicability of the existing DP-based control strategies needs to be improved for real time implementations. In this paper an optimized DP-based HEV power management control strategy is proposed, including the optimization and implementation of the DP-based control strategy for different urban driving patterns. In the literatures [5–7], in order to maintain the balance of the battery SOC, normally a penalty function of battery SOC is added to the cost function of DP algorithm to ensure the final SOC gets as close to the initial SOC as possible. However, the factor of different initial SOC is not investigated. In this paper, due to the employment of fuzzy controller, the initial SOC can be utilized as an input variable for the control of power split ratio. To set different initial SOC, the SOC available domain is meshed instead, and the penalty function is thus removed.

To improve the applicability of the DP-optimized control strategy for practical application of urban driving, an urban driving pattern recognition method is proposed. The driving pattern recognition method is used to classify the tested driving cycle into one of the saved urban driving patterns. For each driving pattern, the proposed DP-optimized control strategy is applied to obtain the optimal control strategy.

The remainder of this paper is organized as follows. The vehicle model is established in Section 2, followed by the investigation of conventional rule-based strategy in Section 3. The traditional dynamic programming algorithm is modified for urban driving in Section 4. The design procedures of the proposed fuzzy control strategy for urban driving are expressed in Section 5. The simulation results under different conditions are compared in Section 6. Finally, conclusions are made in Section 7.

2. Parallel HEV modelling

In order to verify the performance of different control strategies, a parallel HEV model is first established. The configuration of the parallel hybrid electric drivetrain mainly consists of an internal combustion engine, a motor/generator, a torque coupling mechanism, a transmission and a battery packs [9]. Fig. 1 shows the structure of a typical torque-coupling HEV adopted in this paper.

The target of this paper is to study the fuel economy of HEVs; hence vehicle stability and lateral dynamics are not taken into consideration. For longitudinal dynamics, the dynamic equation is expressed by:

$$F_t = M\delta\frac{\mathrm{d}V}{\mathrm{d}t} + F_r + F_w + F_g \tag{1}$$

where F_t is the vehicle tracking force; M is the vehicle mass; δ is the rotational inertia factor; V is the vehicle speed; $\mathrm{d}V/\mathrm{d}t$ is the vehicle acceleration; F_r is the wheel rolling resistance; F_w is the aerodynamic drag force, and F_g is the grading resistance, which equals to zero when on flat road.

In order to simplify the vehicle model to reduce the simulation time for DP, the equation is expressed as:

$$F_t(k) = M\delta\frac{V(k+1) - V(k)}{t_s} + F_r + F_w \tag{2}$$

The SOC is calculated as [10]:

$$SOC(k) = SOC(k+1) + \frac{E - \sqrt{E^2 - 4RP_m}}{2RQ}t_s \tag{3}$$

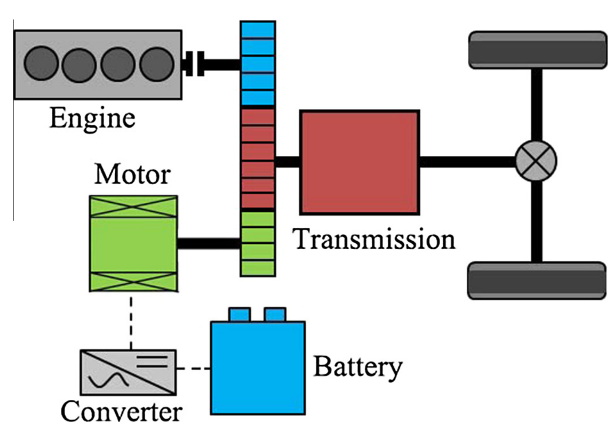

Fig. 1. Powertrain of torque-coupling parallel HEV.