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Adaptive power management control of range extended electric vehicle

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Abstract

Range extended electric vehicle can extend the cruising distance of the electric vehicle by using the range extender which consists of engine and generator, i.e. genset, without using a larger and more expensive battery pack. Equivalent fuel consumption minimization is used to design the proposed adaptive power management control strategy, such that fuel consumption is effectively reduced lower than that of the thermostat control strategy. Driver only needs to provide the approximate estimation of the traveling distance to plan the reference trajectory of SOC for discharging the battery. In order to track the reference, self-organizing fuzzy controller adaptively adjusts the equivalence factor which is used to convert the electric power usage to equivalent fuel consumption. A cost function of instantaneous fuel consumption is minimized to obtain the optimum power split between the genset and battery. Simulation results show that the proposed algorithm can improve the fuel economy and reduce the average charging/discharging power of the battery.

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Keywords: range extended electric vehicle; engine and generator; equivalent fuel consumption minimization; equivalence factor; adaptive power management control

1. Introduction

The increase of oil price has become a global long-term trend. Major automotive manufactures have been investigating new energy vehicles. Electric vehicle (EV) has the advantage of zero missions. However, its cruising distance is often limited due the insufficient battery energy density. Range extended electric vehicle (REEV) can extend the cruising distance of EV by using the range extender which consists of engine and generator, i.e. genset, without using a larger and more expensive battery pack. REEV can be viewed as one kind of the series hybrid electric vehicle (HEV) with the plug-in capability to recharge the battery.

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Genset and battery can be used to supply electric power to drive the tractor motor. Genset can also be used to charge the battery when necessary.

The power management strategies (PMS) of REEV can be classified into three types. The first type is thermostat control strategy (TCS) [1] which utilizes battery as the main power source. The vehicle is operated as the pure battery EV (EV mode) until the state of charge (SOC) is less than the lower bound. Genset is then turned on and operated at the most efficient operating point to supply electric power until the SOC reaches the upper bound. It can be referred as charge sustaining (CS mode) to maintain SOC within the bounds. The second type is power follower control strategy (PFCS) [2-4] which utilizes genset as the main power source to satisfy the driver's power demand. If the maximum genset power is not enough, battery is used to supply the rest of power demand. The third type is the equivalent consumption minimization strategy (ECMS) [5-7]. Equivalence factor is used to transform battery power into the equivalent fuel consumption and is often selected to be a predetermined function of SOC. A cost function of instantaneous fuel consumption which consists of the fuel consumption of genset and the equivalent fuel consumption of battery is minimized to obtain the optimum power split between genset and battery. However, the predetermined function might not be optimal for different driving cycles.

2. Modeling

The system configuration of the target REEV is shown in Fig. 1 (a). Component parameters are obtained from the experiments of subsystems. In order to simply the analysis, regenerative braking is assumed not available in this paper. A point mass model is used to represent the longitudinal vehicle dynamics with tire dynamics, load transfer, rolling resistance, and air dynamic drag. Engine and generator is coupled on the same axle without the reduction gear. Internal resistance model is used to describe the SOC dynamics. Steady-state maps with proper first order dynamics are used to represent genset and motor dynamics.

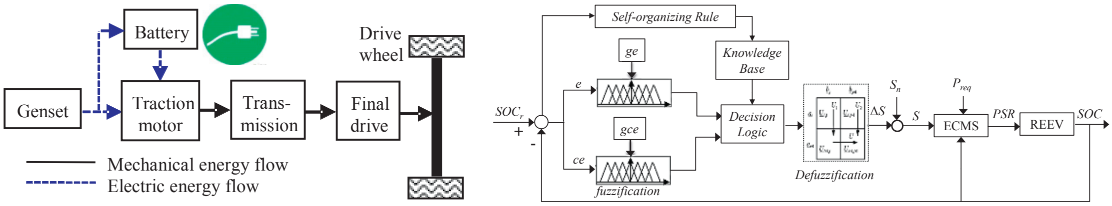

Fig. 1. (a) system configuration of the target REEV; (b) proposed adaptive power management strategy

3. Control Strategy

In order to develop a power management strategy which is adaptive to different driving cycles, a charge depleting problem according to the energy-to-distance ratio [8] is formulated in this paper. The SOC-distance curve behaves like a straight line with a constant slope for the optimal solutions. Driver only needs to provide the approximate estimation of traveling distance to plan the reference trajectory of SOC for discharging the battery. Chen et al. [9] proposed an adaptive power split control for a hybrid electric scooter to adjust the equivalence factor according to the SOC deviation, such that SOC is regulated around the desired constant level. In order to investigate the universality of the SOC control configuration in [5], an adaptive power management strategy as shown in Fig. 1 (b) is proposed to track the reference trajectory of SOC for REEV in this paper. A self-organizing fuzzy controller (SOFC) is designed to adaptively adjust the equivalence factor S according to the SOC tracking error.

An instantaneous cost function J_{ECMS} which represents the total equivalent fuel consumption rates is established as follows.

$$J_{ECMS} = \dot{m}_g(P_g) + \dot{m}_b(P_b) \tag{1}$$

where $\dot{m}_g$ is the fuel consumption rate of the genset power P_g; $\dot{m}_b$ is the equivalent fuel consumption rate of the battery power P_b. $\dot{m}_b$ can be obtained from the following equation.

$$\dot{m}_b(P_b) = \gamma \frac{SP_b g_e}{\eta_b(P_b, SOC)} + (1-\gamma)SP_b g_e \eta_b(P_b, SOC) \tag{2}$$

where η_b is the efficiency of the battery; g_e is the minimum brake specific fuel consumption (BSFC) of the engine; $\gamma = 0.5(1+\text{sign}(P_b))$ is equal to 1 and 0 for discharging and charging, respectively. The summation of P_g and P_b is equal to the driver's power demand P_{req}. If the equivalence factor $S = S_n + \Delta S$ is large, battey power is more expensive than genset power. If S is small, battery power is cheaper than genset power.

4. Simulation Results

Simulation results of SOC for running 12 NEDC driving cycles with a total distance of 130.8 km are shown in Fig. 2 (a). TCS operates the vehicle in EV mode from the beginning and changes to CS mode when SOC is less than the lower bound. By setting the upper bound of SOC as the desired SOC trajectory, PFCS can track the desired SOC in a satisfactory manner. ECMS has the best SOC tracking performance among these controls. The engine operating points of three control strategies on the BSFC map are shown in Fig. 2 (b). TCS only operates at the optimal operating point with the minimum BSFC. The operating region of PFCS is larger than the TCS due to its nature to use genset as the main power source. The proposed control has the largest region with operating points which are determined to be efficient for the driver's power demand, SOC, and adjusted equivalence factor at the sample time.

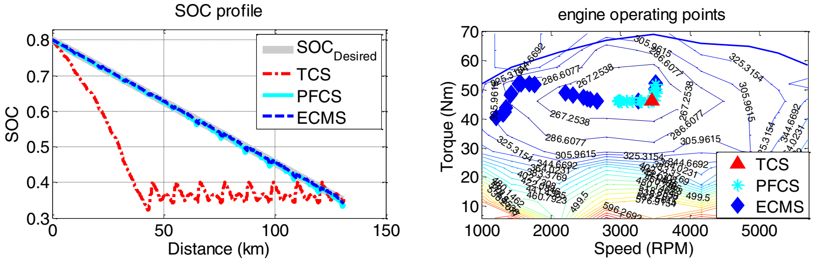

Fig. 2. (a) responses of SOC; (b) engine operating points

Table 1. Fuel economies and averaged battery charge/discharge powers for 12 NEDC driving cycles

Strategy	Fuel / SOC_{final}	Corrected Fuel / SOC_{final}	Fuel economy	Improvement	Averaged charge/discharge power
TCS	5109 g / 0.353	5065 g / 0.34	19.56 km/l	0%	10.425 kw / 7.798 kw
PFCS	4963 g / 0.339	4858 g / 0.34	20.39 km/l	4.25%	8.798 kw / 6.994 kw
Proposed	4618 g / 0.341	4617 g / 0.34	21.45 km/l	9.69%	8.648 kw / 5.870 kw

The fuel economies and averaged battery charge and discharge powers are shown in Table 1. The final SOCs of PFCS and the proposed control are different from that of the TCS. The SOC differences are taken into account for a fair comparison of fuel economy. The associated fuel consumptions are corrected using the SAE standard J1711. After correction, PFCS can improve the fuel economy of TCS by 4.25%. The proposed control has the largest improvement of 9.69%. Meanwhile, the averaged battery charge and discharge powers of the PFCS and the proposed control are less than those of TCS. If the battery power usages are reduced for the same given driving cycle, it is possible to extend the battery life [6].

5. Conclusion

An adaptive power management control strategy is designed based on ECMS with the equivalent factor adjusted using SOFC. Approximate traveling distance is used to plan the reference trajectory of SOC for discharging the battery. The proposed control has the largest region with operating points which are determined to be efficient for the driver's power demand, SOC, and adjusted equivalence factor at the sample time. Simulation results show that the proposed algorithm can achieve better power split between genset and battery than TCS and PFCS with improved fuel economy and reduced battery power usage.

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