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A NOVEL POWER MANAGEMENT IN A PLUG-IN HYBRID ELECTRIC VEHICLE WITH A HYBRID ENERGY STORAGE SYSTEM

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ABSTRACT

In this paper, a novel hierarchical power management strategy is proposed for a plug-in hybrid electric vehicle with multiple energy sources. In the first level, dynamic programming is used to distribute the power between the energy storage system and the engine. Then, the hybrid energy storage system is composed by adding a supercapacitor to the energy storage system. In the second level, the low-pass filtering algorithm is researched to distribute power between the battery and the supercapacitor of the hybrid energy storage system. To control the battery and the supercapacitor working within the energy range, the limit management approach is proposed to redistribute power among the battery, the supercapacitor and the engine. Simulink results show that the final distributed powers of battery, supercapacitor and engine are within the reasonable power and energy ranges.

Keywords: Plug-in hybrid electric vehicle; Hybrid energy storage system; Power management strategy; Dynamic programming; Low-pass filtering

NONMENCLATURE

Abbreviations

PHEVs	Plug-in hybrid electric vehicles
SC	Supercapacitor
HESS	Hybrid energy storage system
DP	Dynamic programming
ESS	Energy storage system
ICE	Internal combustion engine
SOC	State of charge
SOE	State of energy
CTUDC	Chinese typical urban driving cycle

1. INTRODUCTION

Plug-in hybrid electric vehicles (PHEVs) are becoming more and more popular because of longer driving range and excellent fuel economy [1]. Owing to a large capacitor battery pack loaded, PHEVs can charge from grid. However, battery pack will be frequently charged and discharged due to the power demand of the vehicle, which will accelerate the battery aging [2]. Because the supercapacitor (SC) has high power density and cycle-life, it can be used to meet the instantaneous high power and frequent charging and discharging power requirements of the vehicle. The hybrid energy storage system (HESS) is composed by combining a battery pack and a SC group [3, 4]. Ref.[5-7] confirm that HESS with SC will greatly inhibit battery aging.

In previous works, lots of approaches have been applied to distribute the power between the battery and the engine or the battery and the SC. Currently, widely studied strategies are rule-based strategies and optimization-based strategies. Considering the advantages of easy implementation and high calculation efficiency, rule-based strategies are wildly used in practice. Optimization-based strategies such as dynamic programming (DP) [8], particle swarm optimization (PSO) [9] and model predictive control (MPC) [10] have been greatly developed in recent years. However, few energy management methods have been applicated to allocate the power between more than two energy sources.

In this paper, a hierarchical power management strategy is proposed to distribute the power for a PHEV with multiple energy sources. In the first level, DP is used to distribute the power between the engine and the energy storage system (ESS). In the second level, the low-pass filtering algorithm is researched to distribute power between the battery and SC inside HESS. To control the battery and SC working within the energy ranges, the limit management approach is proposed to redistribute power between the battery, the SC and the engine.

2. HIERARCHICAL POWER MANAGEMENT STRATEGY

2.1 PHEV configuration

In this paper, a single-axis series-parallel PHEV is selected as the research target. As shown in Fig.1, the series-parallel hybrid powertrain configuration mainly includes a conventional internal combustion engine (ICE), an integrated starter generator (ISG), a traction motor (TM), a SC group and a battery pack. In this paper, two configurations based on the Fig.1 are studied. Powertrain configuration (a) loads single ESS only. Powertrain configuration (b) loads HESS. Except for the energy storage unit, the two configuration parameters are the same.

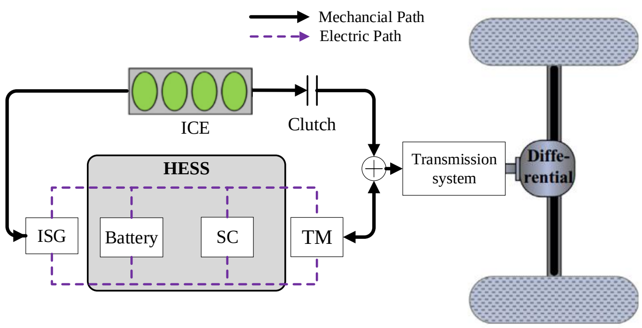

Fig.1 Topology of the series-parallel powertrain

2.2 The first level control strategy

DP is used to solve multi-stage decision problems. In this paper, it is used to allocate the power between engine and ESS of powertrain configuration (a).

The state of charge (SOC) of ESS is selected as state variable, and the ICE torque T_{ICE}, the ISG torque T_{ISG}, the TM torque T_m, the clutch state S_{clu}, and the braking torque T_b are selected as the control variables of the system.

As shown in Fun. (2), the power system of the PHEV is described as a nonlinear and time-discrete system.

$$\begin{cases} x(k+1) = f(x(k),u(k)) \\ x(0) = x_0 \end{cases} \tag{2}$$

Where, $x(k)$ and $x(k+1)$ are SOC of the battery of step k and k+1, respectively; $u(k)$ is the control variable acting on the vehicle at step k, which includes T_e, T_{ISG}, T_m, S_{clu}, T_b; f is the transfer function of SOC.

Then, the objective function of equivalent fuel consumption of PHEV is described as follows:

$$J = \sum_{k=0}^{N-1} L[x_k, u_k] \tag{3}$$

Where, $L[x_k, u_k]$ is equivalent fuel consumption at step k, which includes electricity consumption and fuel consumption. J is total equivalent fuel consumption.

As shown in Fun. (4), the ICE, ISG, TM and battery are constrained to ensure that the power system can operate normally

$$\begin{cases} SOC_{\min} \le SOC_k \le SOC_{\max} \\ n_{e\_\min} \le n_{e\_k} \le n_{e\_\max} \\ T_{e\_\min}(n_{e\_k}) \le T_{e\_k} \le T_{e\_\max}(n_{e\_k}) \\ n_{ISG\_\min} \le n_{ISG} \le n_{ISG\_\max} \\ T_{ISG\_\min}(n_{ISG\_k}, SOC_k) \le T_{ISG\_k} \le T_{ISG\_\max}(n_{ISG\_k}, SOC_k) \\ n_{m\_\min} \le n_{m\_k} \le n_{m\_\max} \\ T_{m\_\min}(n_{m\_k}, SOC_k) \le T_{m\_k} \le T_{m\_\max}(n_{m\_k}, SOC_k) \\ T_{d\_k} = T_{e\_k} + T_{ISG\_k} + T_{m\_k} + T_{b\_k} / i_0 \\ n_{m\_k} = n_{e\_k} = n_{ISG\_k} \quad if \quad clutch = 1 \\ n_{e\_k} = n_{ISG\_k} \quad if \quad clutch = 0 \\ T_{e\_k} + T_{ISG\_k} = 0 \quad if \quad clutch = 0 \end{cases} \tag{4}$$

2.3 The second level control strategy

In the second level, the power of ESS obtained in the first-level is specified as the power of HESS. As shown in Fig.2, in order to redistribute the power between ICE, battery and SC efficiently, the power allocation frame is proposed, which is consisted of two parts: Low-pass filtering algorithm and Limit management approach. The low-pass filtering algorithm is used to distribute the power between battery and SC of HESS. The limit management approach is proposed to control the SC and battery to work within the energy range.

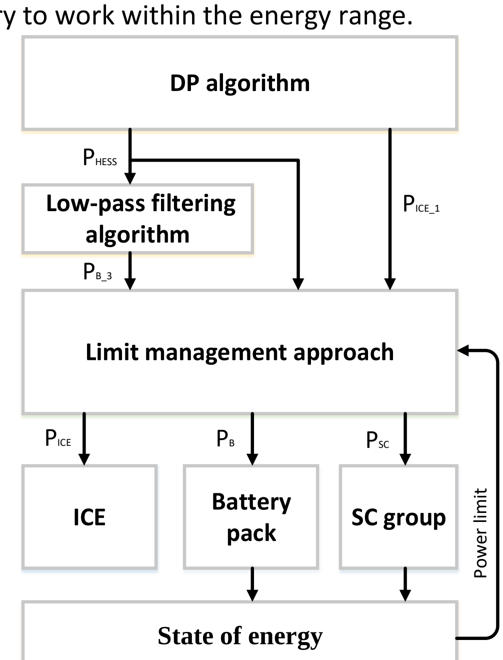

Fig.2 Power allocation frame

2.3.1 The low-pass filtering algorithm

The power can be efficiently allocated between the battery and the SC of HESS based on the low-pass filtering algorithm.

The battery power $P_{Bat}(t)$ and SC power $P_{SC}(t)$ at time t can be obtained by the following functions:

$$P_{Bat}(t) = (1-k(t)) \times P_{Bat}(t-1) + k(t) \times P_{HESS}(t) \quad (5)$$

$$P_{SC}(t) = P_{HESS}(t) - P_{Bat}(t) \quad (6)$$

Where, $k(t)$ is the filtering coefficient.

2.3.2 The limit management approach

The battery and SC are easy to be over-charged and over-discharged because their power cannot be controlled in real time, which will result in poor robustness of the power system. Aiming at this issue, the limit management approach is proposed, which can implement two functions: On one hand, it can limit the maximum or minimum output power of the battery and the SC. On the other hand, when the battery or the SC has insufficient energy, it is used to distribute the power between ICE and HESS. In the limit management method, there are three limit modules, namely limit module 1, module 2 and module 3. The power of battery is limited by limit module 1 and 3, and the power of SC is limited by limit module 2. Note that P_{Bat_3} is the battery power obtained by the low-pass filtering algorithm, P_{Bat_2} is the battery power obtained by the limit module 1, P_{SC_1} is the SC power which is equal to the difference between the power of HESS P_{HESS} and P_{Bat_2}, P_{Bat_1} is the battery power which is equal to the difference between P_{HESS} and P_{SC_1}. The limit management approach is implemented by the following steps:

Step 1: Limit module 1 controls P_{Bat_3} to realize the battery works within the energy range.

Step 2: Limit module 2 controls P_{SC_1} to realize the SC working within the energy range.

Step 3: The tracking error of the charging and discharging power of the battery will occur because of the difference between P_{SC_1} and P_{SC}. Limit module 3 can control P_{Bat_1} working within the energy range.

Step 4: The final allocated battery power P_{Bat}, SC power P_{SC} and ICE power P_{ICE} can be obtained by redistributing the power between ICE and HESS when the sum of P_{Bat} and P_{SC} don't meet HESS requirements.

3. SIMULATION RESULTS AND DISCUSSION

The selected model is a plug-in hybrid electric bus, which drives in city condition. As shown in Fig.3, during simulation, the Chinese typical urban driving cycle (CTUDC) is chosen. The vehicle model is in operation continuously for twelve CTUDCs.

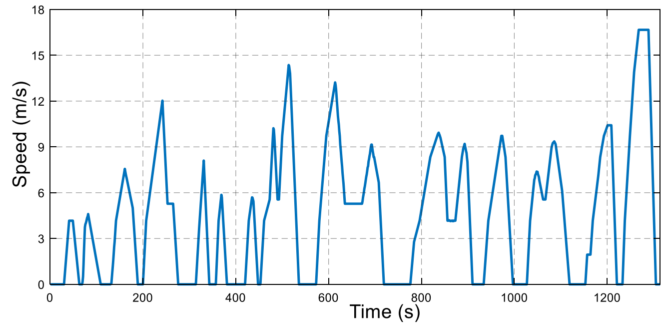

Fig.3 The CTUDC driving cycle

As shown in Fig.4, comparing with the battery power obtained by DP, low-pass filtering results in less battery power fluctuations, which is able to protect the battery from aging.

Fig.4 Comparison of the battery power obtained by DP and low-pass filtering

As shown in Fig.5, comparing with the battery SOC obtained by DP, the number and amplitude of the battery charging and discharging cycles are significantly reduced based on the low-pass filtering algorithm, which can effectively inhibit battery aging.

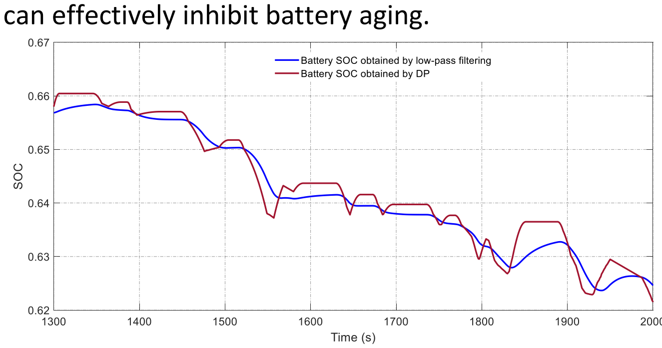

Fig.5 Comparison of the battery SOC obtained by DP and low-pass filtering

Because the SOE of the battery and the SC cannot be monitored in real time, they are prone to be over-charged or over-discharged. To solve this issue, the limit management approach is proposed to redistribute the power between the battery, SC and ICE. Upper and lower limit of SOE of the SC is set to be 0.9 and 0.1, respectively. Upper and lower limit of SOC of the battery is set to be 0.9 and 0.2, respectively. As shown in Fig.6, the battery and SC work within the energy range based on limit management approach.

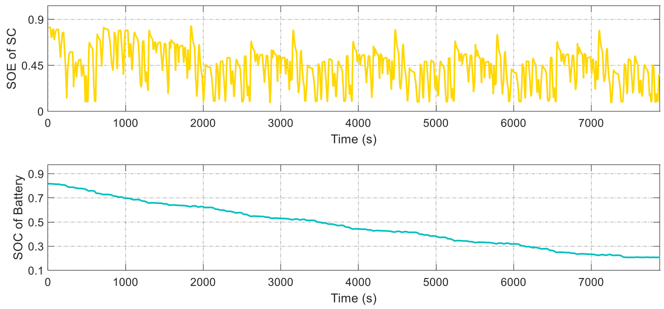

Fig.6 The remaining energy of the battery pack and the supercapacitor group

As shown in Fig.7, the final allocated battery power, SC power and ICE power are within reasonable power ranges.

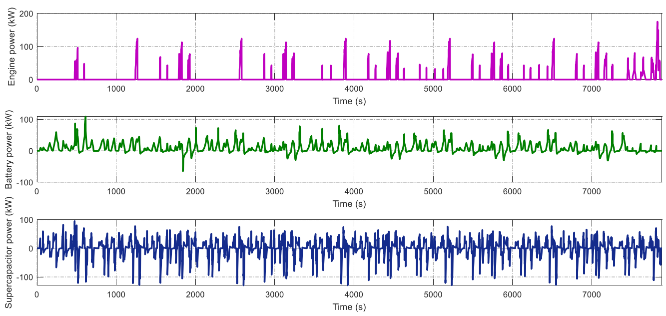

Fig.7 Final allocated power of engine, battery and SC

4. CONCLUSIONS

A novel hierarchical power management strategy is proposed for a PHEV with multiple energy sources. In the first level, DP is used to distribute the power between the ESS and engine, which guarantees the best fuel economy of the vehicle. In the second level, the low-pass filtering algorithm is researched to distribute power between the battery and SC of HESS, which results in the number and frequency of charge and discharge cycles of the battery to be effectively reduced. The limit management approach is proposed to redistribute power between the battery, SC and engine, which controls the battery and SC working within the energy range in real-time.

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