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ANALYSIS AND OPTIMIZATION OF POWER FLOW FOR HYBRID ELECTRIC VEHICLE WITH DUAL-PLANETARY GEAR

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ABSTRACT

Sustained environmental pollution and energy crisis are constantly promoting the development of hybrid electric vehicles. Among many configurations, the power-split ones based on planetary gear have special advantages of energy saving potential and velocity conversion characteristics.[1] Thus it has attracted considerable attention in related fields. Power-split system based on dual-planetary gear provides a variety of energy flow modes,[2] so it is suitable for constructing a multi-mode hybrid power-system for hybrid electric commercial vehicles. In this paper, a power flow model for the vehicle with such configuration is constructed; the energy flow relationship is analyzed and optimized. The optimal power flow relationship can be used to guide the division of working modes of hybrid electric vehicles and also provided a model basis for further study of related energy management strategies.

Keywords: power-split hybrid electric vehicle, dual-planetary gear, power flow model, energy management strategy

NONMENCLATURE

Abbreviations	
HEV	Hybrid Electric Vehicle
ICE	Internal combustion engine
Symbols	
m	mass(kg)
r	rolling radius(m)
i_g	main reduction ratio(/)
C_d	Air drag coefficient(/)
A	Windward area(m^2)
g	Gravity acceleration(m/s^2)
k_1,k_2	Coefficient of planetary-gear
P_e	ICE's output power(kW)
P_d	Vehicle's demand power(kW)
P_{m1}	M1's output power(kW)
P_{m2}	M2's output power(kW)
W_b	Equivalent total energy of batteries(J)

1. INTRODUCTION

Planetary gear is the core component of hybrid electric vehicle to reach the power diversion function. Power-split hybrid electric vehicle based on single-planetary structure has been perfectly applied in passenger vehicles. Those vehicles like Toyota Prius can perform excellently in fuel economy under urban environment.[3] However, the working mode provided by single-planetary gear configuration is not enough to meet the requirement of commercial vehicles under complex conditions, so developing hybrid electric commercial vehicles with dual-planetary gear has becoming necessary[4].

In principle, energy flow modes provided by dual-planetary gear is more than that by single planetary gear, which is helpful to design multi-mode hybrid system. The power flow relationship in such system is complex, but not each flow relationship is energy efficient enough. Therefore, the power flow modes are analyzed and optimized in this paper, which could provide important guidance for building and optimizing corresponding energy management strategies.

2. VEHICLE CONFIGURATION

2.1 Dual-planetary gear structure

As is shown in fig 1, the power-split device consists of two single planetary gears, two motors, one ICE and one pack of battery with converter. Through coordinated control of three brakes and one clutch, the power-split device can achieve the following different working modes as table 1 shows.

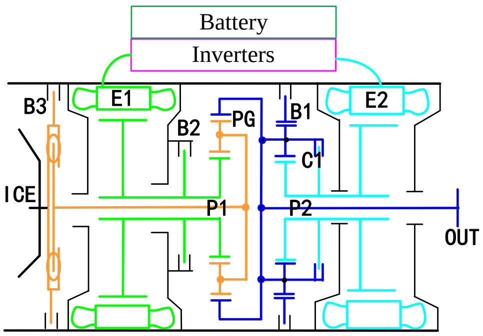


Fig 1 Configuration of dual-planetary gear

Tab 1 Possible working modes of dual-planetary gear

B2	B3	B1	C1	Mode	Power unit
0	1	0	1	EV	E1 and E2(low gear)
		1	0		E1 and E2(high gear)
1	0	0	1	Parallel	ICE and E2(low gear)
		1	0		ICE and E2(high gear)
0	0	0	1	Power-split	ICE,E1 and E2(low gear)
		1	0		ICE, E1 and E2(high gear)

Remarks: 1/0 indicates that clutch/brake is in/no in a combination state.

2.2 Basic parameters

The basic parameters of the hybrid system and the vehicle are shown in tab 2.

Tab 2 basic parameters of the vehicle

parameters	Values	parameters	Values
m	11200	f	0.0063
r	0.5	δ	1.13
i_g	4.88	g	9.81
C_d	0.65	k_1	2.63
A	7	k_2	2.11

3. POWER-FLOW MODEL

3.1 Power balance relationship

Equation 1 shows the power balance relationship.

$$P_e + P_d + P_{m1} + P_{m2} = 0 \quad (1)$$

Battery power can be calculated by equation 2.

$$P_b = P_{m1} + P_{m2} \quad (2)$$

The SOC of battery can be calculated by equation 3.

$$S\dot{O}C(t) = \frac{\int P_b dt}{W_b} \quad (3)$$

The actual power consumption of the engine, motors and battery can be defined as the following formulas.

$$\begin{cases} P_e = \eta_e P_e \\ P_b = \eta_b P_b \\ P_{m1} = \eta_{m1} P_{m1} \\ P_{m2} = \eta_{m2} P_{m2} \end{cases} \quad (4)$$

3.2 Calculation of engine's efficiency

Assuming that the engine always works on the optimal fuel economy curve, the relationship between efficiency and output power of ICE can be established as the following figure shows.

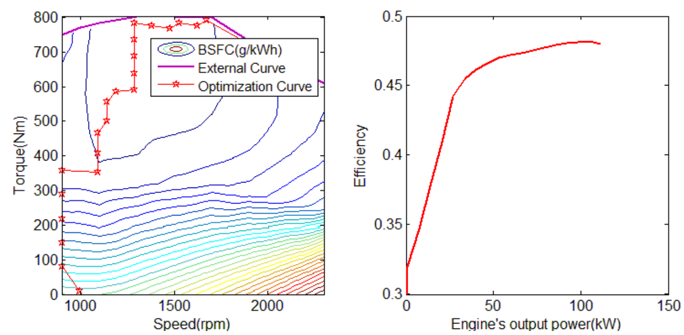


Fig 2 Relation between engine's efficiency and output power

3.3 Calculation of battery's efficiency

Based on the internal resistance model, the power loss of batteries can be attributed to the heat generated by the internal resistance. Therefore, an efficiency map based on experimental data can be constructed as fig 3 shows.

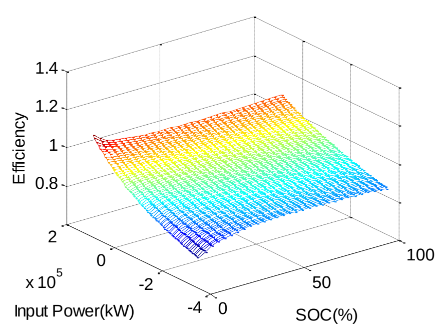


Fig 3 Battery's efficiency

3.4 Calculation of motor's efficiency

Compared with ICE, both the overall and average operating efficiency of the driving motor are much higher. Therefore, motor's efficiency can be defined as a constant value for preliminary calculation. In this study, motor's efficiency is defined as η =1.1(driving mode) and η =0.9(generating mode).

4. OPTIMIZATION OF POWER FLOW

4.1 Definition of vehicle's demand power

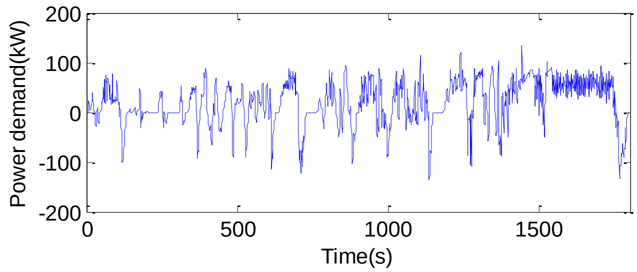


Fig 4 Power demand of CWTVC

Vehicle's demand power is calculated by CWTVC driving cycle, with the maximum power being 130kW and the average driving power being 27.87kW.

4.2 Establishment of the optimization problem

The optimization problem for power flow process can be defined in the following form.

$$J(SOC,t)=\min\{\int_{t_0}^{t_f} P_e dt\}$$

$$s.t.\begin{cases} 0\le P_e \le P_{e\_\max} \\ P_{m1\_\max}\le P_{m1}\le P_{m2\_\max} \\ P_{m2\_\max}\le P_{m2}\le P_{m2\_\max} \\ SOC_{f1}\le SOC(t_f)\le SOC_{f2} \\ SOC(t_0)=\mathrm{SOC}_0 \\ \text{equation (2)} \\ \text{equation (3)} \\ \text{equation (4)} \end{cases}$$

Besides, additional constraints should also be added according to actual requirement, including the maximum power limit of motor at low speed and the maximum charge/discharge power limit of battery, which is helpful to improve the universality of this power flow model.

4.3 Optimization results

By discretizing the above problems and solving them by dynamic programming algorithm, the power flow relationship which satisfies the optimal fuel economic performance under CWTVC can be obtained.

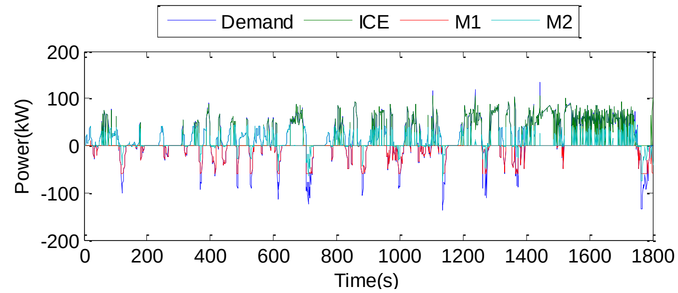


Fig 5 Optimal power allocation

As is shown in fig 5, vehicle's demand power under driving mode is mainly supplied by ICE and M2; under braking mode, vehicle's demand power is mainly supplied by M1 and partly supplied by M2.

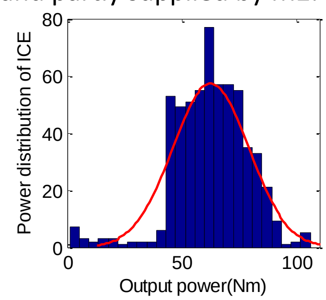
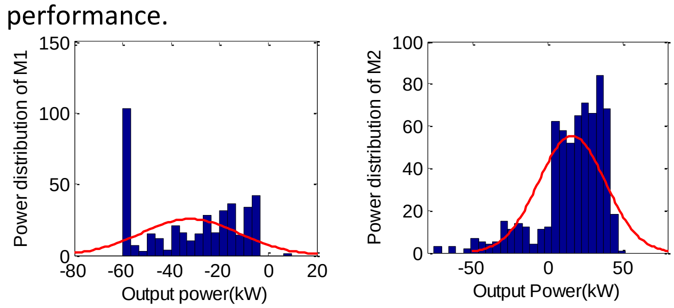


Fig 6 Distribution of working points of the motors

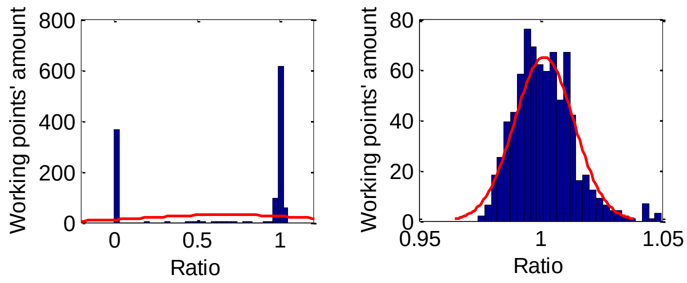
Fig 6 shows that ICE's output power is mainly upper 50kW, which corresponds to a better fuel economy performance.



(a) M1 (b) M2

Fig 7 Distribution of motors output power

Fig 7 further validates the main working state of two motors under optimal control conditions. Because ICE is required to achieve better fuel economy performance under high power output condition, the main output power of M2 are mostly below 50kW.



(a) whole ratio (b) local ratio

Fig 8 Ratio of ICE's output power to total driving power

Fig 8(a) shows the ratio of ICE's output power to total driving power. The proportion of ICE's output power is mainly concentrated in two positions: 0.0 and 1.0. The former state corresponds to pure electric mode because ICE does not work; the latter corresponds to several modes with ICE outputting power.

As shown in fig 8(b), the output ratio of ICE is roughly between 0.97 and 1.05, which suggests that the demand power of the vehicle is mainly supplied by ICE when it participates in driving. In order to achieve an efficient power transmission process, ICE is more suitable to work in a power-split mode than in a parallel mode to provide driving power for vehicles.

If the vehicle works as the requirement of plug-in hybrid power system, in order to make full use of energy offered by power battery, the optimal power flow mode may be different; the probability of parallel driving mode may increase as well. Besides, the driving cycle which represents different driving conditions may also have an impact on the optimal power flow mode, so related works are being further carried out.

5. CONCLUSITIONS

In this paper, a power-flow model for a hybrid electric vehicle with dual-planetary gear is constructed; the corresponding efficiency calculation method is given. In the discrete state, the optimal power allocation relationship is obtained by dynamic programming method. The results suggest that, in order to achieve the best power flow mode, the working mode of the hybrid electric vehicle is more suitable to be switched between pure electric mode and power-split mode. ICE is recommended to start working when the demand power exceeds 50kW, in such case the fuel consumption will be relatively low.

In addition, if the vehicle with this configuration works as the requirement of a plug-in hybrid electric vehicle, the above conclusions may change and need a further study.

ACKNOWLEDGEMENT

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