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Simulation research of energy management strategy for dual mode plug-in hybrid electrical vehicles *

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Abstract: In this paper, a plug-in hybrid electrical vehicle (PHEV) is taken as the research object, and its dynamic performance and economic performance are taken as the research goals. Battery charge-sustaining (CS) period is divided into power mode and economy mode. Energy management strategy designing methods of power mode and economy mode are proposed. Maximum velocity, acceleration performance and fuel consumption are simulated during the CS period in the AVL CRUISE simulation environment. The simulation results indicate that the maximum velocity and acceleration time of the power mode are better than those in the economy mode. Fuel consumption of the economy mode is better than that in the power mode. Fuel consumption of PHEV during the CS period is further improved by using the methods proposed in this paper, and this is meaningful for research and development of PHEV.

Keywords: plug-in hybrid electrical vehicle; power mode; eco mode; energy management strategy; model and simulation

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1 Introduction

The dual mode hybrid power system can be divided into three classes. The typical examples of the first category are General Motors, Daimler Chrysler and BMW dual-mode hybrid system, which consist of two or three modes among input power split mode, output power split mode [1-5], composite power split mode, and series mode [6].

The second kind of dual mode hybrid power system is called an electromechanical transmission system (EMT) [7-8], which was proposed by Beijing Institute of Technology. EMT connects many electrical machines together by planetary gears [9-10]. If the engine power input to EMT is fixed, EMT can change the output power by controlling planetary mechanism components [11-12]. As a result, a different vehicle power can be satisfied.

The example of the third kind of dual mode plug-in hybrid power system comes from BYD Company and Shanghai Automotive Industry Corporation. This kind of dual mode hybrid power system refers to pure electric mode (EV) and hybrid mode, and two modes can be switched by a manual button. In the pure electric mode, electrical machine drives the vehicle all

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the time. The engine is used to charge the battery when the battery stands at a low state of charge (SOC); this is similar to the extended range electrical vehicle. But it is a pity that the engine cannot drive the vehicle directly in this mode. In the hybrid mode, the engine and the motor can drive the vehicle separately or together according to the control strategy.

The power flow between the power sources and the performance of PHEV in fuel consumption are determined significantly by the energy management strategy [13-15]. In order to further improve the fuel consumption of PHEV during the CS period, this paper proposes a new method, which divides the CS period into the power mode and the economy mode according to the torque requirement of the driver. And the design methods of the two-mode energy management strategy are also proposed in this paper. The methods are verified based on the AVL CRUISE and Simulink simulation environment.

This paper is organized as follows: the second part introduces the configuration of PHEV, and the main parameters of models also are introduced. The third part introduces the energy management strategy of power mode and economy mode during the CS period, which include the required torque calculation method, mode switch strategy and torque distributed strategy. In this part, the simulation model is also built. The fuel consumption of the CS period, maximum velocity and acceleration time are simulated in the fourth part, and the simulation results are analyzed in this part. The fifth part summarizes the research contents and conclusions of this paper.

2 Configuration of PHEV

In this paper, the structure of the plug-in hybrid electric vehicle is a single-shaft parallel hybrid powertrain. The 2.0 liter turbocharged gasoline engine, permanent magnet synchronous motor (PMSM), and dual clutch transmission (DCT) are included in the powertrain. There is a clutch between the engine and the motor, which is used to interrupt the power delivery between the engine and the motor. The energy management strategy of this paper is verified in the AVL CRUISE and Simulink environment. Therefore, the control strategy model is built in Simulink, and the powertrain model of vehicle is built in the AVL CRUISE. All the parameters are included in the powertrain model, such as vehicle basic parameters (Table 1), engine parameters (Table 2), motor parameters, battery parameters, DCT parameters, clutch parameters, final ratio parameters, differential parameters, brake parameters, wheel parameters and driver model parameters.

Table 1 Vehicle basic parameters

Parameter	Value
Wheel base	2 807 mm
Curb mass	1 869 kg
Gross mass	2 244 kg
Frontal area	2.69 m^2
Drag coefficient	0.4

Table 2 Engine parameters

Parameter	Value
Engine displacement	2 L
Number of cylinders	4
Maximum speed	6 000 r/min
Maximum torque	253.4 N m
Maximum power	133.6 kW

Engine fuel consumption can be obtained by engine fuel consumption ratio, which is shown in follow formula. And engine fuel consumption ratio can be obtained from experimental data.

$$B_e = f(n_e, T_e)\,, \tag{1}$$

where B_e is the engine fuel consumption ratio, n_e represents the engine speed, and T_e represents the engine torque.

In this paper, the PMSM is adopted, and the motor parameters are listed in Table 3.

Table 3 Motor parameters

Parameter	Value
Maximum speed	7 000 r/min
Maximum torque	241 N m
Maximum power	69 kW
Nominal speed	3 000 r/min
Nominal torque	115 N m
Nominal power	32 kW

The efficiency of PMSM during the motor mode or the generation mode can be got from experimental data by the following formula.

$$\eta_m = f(n_m, T_m), \tag{2}$$

where η_m represents the motor efficiency, n_m represents the motor speed, and T_m represents the motor torque.

The following formula is used to calculate the vehicle resistance force, which includes rolling resistance and air resistance. This formula is fitted by experimental coasting data. As a result, this formula is only suitable to certain vehicles, and this is not an experienced formula.

$$F = Au^2 + Bu + C, \tag{3}$$

where u represents the velocity, F represents the driving resistance force, and A, B, and C are fitting parameters.

3 Energy management strategy research

3.1 Vehicle required torque

In this paper, the power mode means that if the acceleration pedal travel is 100%, the vehicle maximum drive torque or the vehicle drive torque is calculated through the composite maximum torque between the engine and the motor. In contrast, the economy mode means that if the acceleration pedal travel is 100%, the vehicle maximum drive torque or the vehicle drive torque is calculated only through the engine maximum torque. Based on this definition, the input torque of the hybrid control unit (HCU) is designed between the power mode and the economy mode.

3.1.1 Power mode required torque

The engine maximum torque characteristic curve and motor maximum torque characteristic curve are indicated in Figs. 1 and 2.

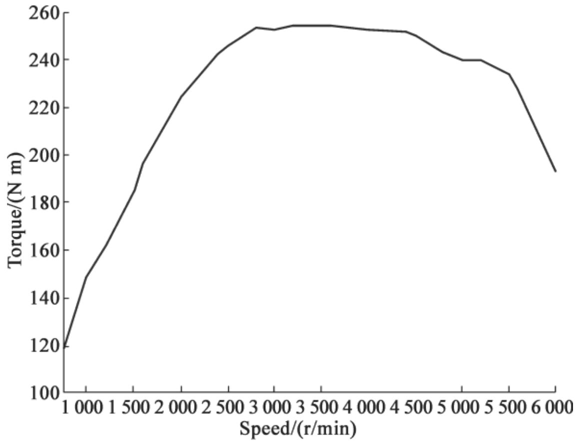

Fig. 1 Engine maximum torque curve

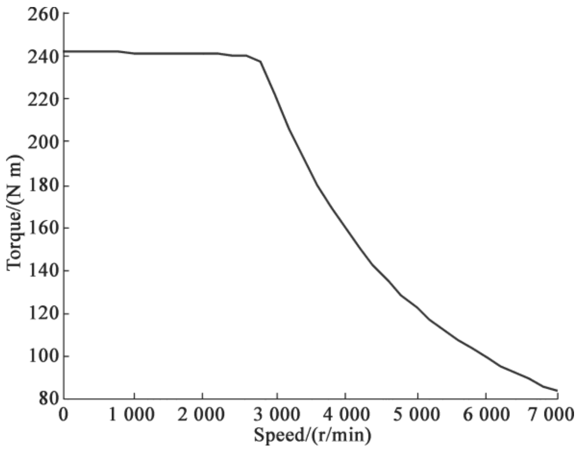

Fig. 2 Motor maximum torque curve

The composite maximum torque curve between the engine maximum torque characteristic curve and the motor maximum torque characteristic curve is obtained and it is shown in Fig. 3.

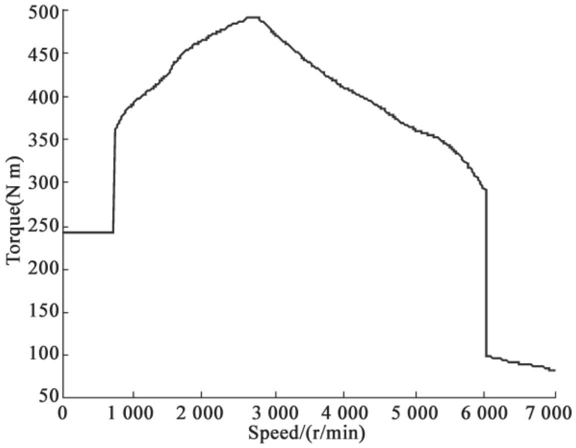

Fig. 3 Composite maximum torque

When the acceleration pedal travel is 100%, based on the composite maximum torque between the engine and the motor, taking the transmission gear ratio, the final drive ratio and the mechanical transmission efficiency into consideration, the maximum drive torque is obtained, which is shown in Fig. 4, and the envelope curve of maximum drive torque is also obtained, which is shown in Fig. 5.

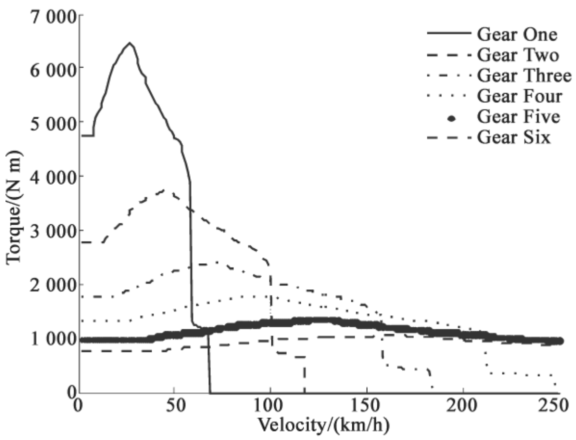

Fig. 4   Power mode maximum drive torque

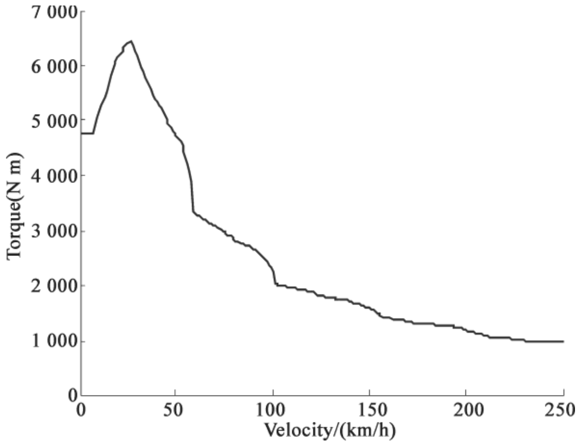

Fig. 5 Power mode drive torque envelope curve

In order to get the HCU input required torque conveniently, interpolation method is used to get driving torque in the case of certain velocity and certain acceleration pedal travel, which is shown in the follow formula.

$$T_{\mathrm{r}} = f(\alpha, v), \tag{4}$$

where T_{r} represents the HCU input required torque, α represents the acceleration pedal travel, and v represents the velocity.

By the interpolation method, the required torque map also can be obtained, which is shown in Fig. 6.

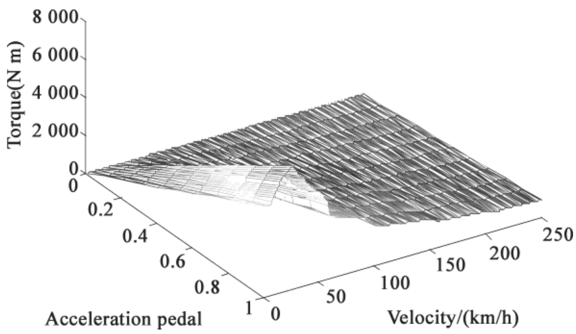

Fig. 6 Power mode required torque map

3.1.2 Economy mode required torque

Based on the engine maximum torque, taking the transmission gear ratio, final drive ratio and mechanical transmission efficiency into consideration, the maximum drive torque is obtained when the acceleration pedal travel is 100%, as shown in Fig. 7. The envelope curve of maximum drive torque is also obtained, which is shown in Fig. 8.

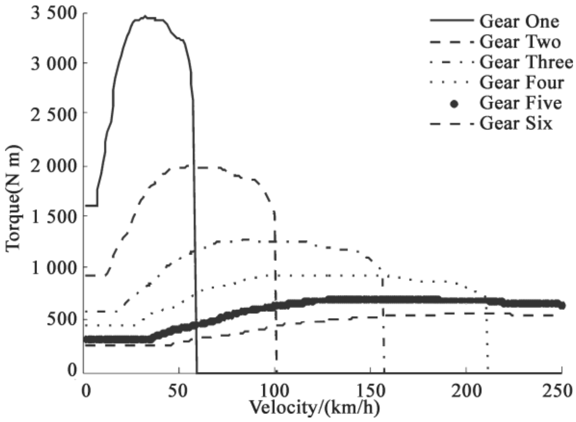

Fig. 7 Economy mode maximum drive torque

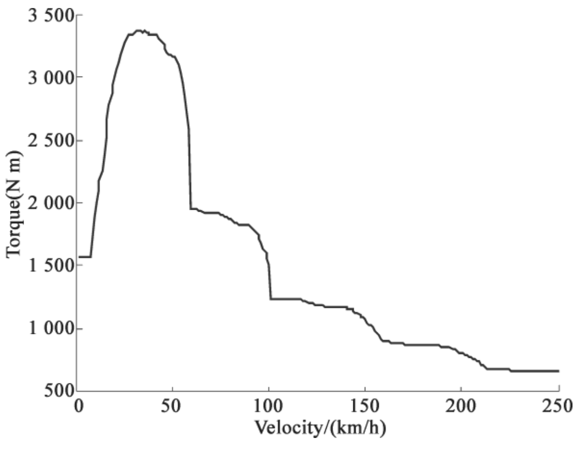

Fig. 8 Economy mode drive torque envelope curve

In order to get the HCU input required torque conveniently, the interpolation method is used to get the driving torque in the case of certain velocity and certain acceleration pedal travel, which is given by Formula (4).

Through the interpolation method, the required torque map can be also obtained, as shown in Fig. 9.

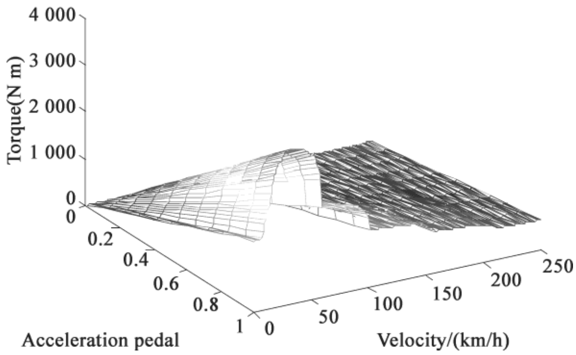

Fig. 9 Economy mode required torque map

3.2 Mode switch strategy

The engine maximum torque characteristic curve, engine optimal torque characteristic curve and motor maximum torque characteristic curve are shown in Fig. 10. According to the HCU required torque and battery SOC, the mode switch strategy can be obtained. The main idea of the energy management strategy is to keep the SOC in the suitable charge or discharge arrangement. If the battery SOC stands at high level, in order to improve the fuel consumption, motor drive mode or hybrid drive mode are used as much as possible. By the contrast, when the SOC close to the low limitation level, engine drive mode and charge mode are used, according to the required torque.

According to the engine and the motor torque characteristic curves, the mode switch strategy is designed as shown in Table 4.

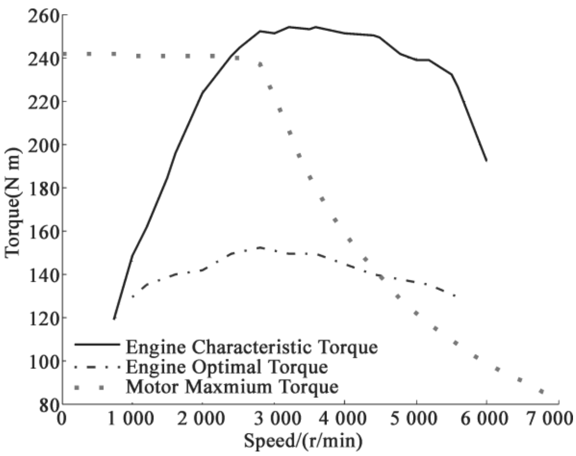

Fig. 10 Engine and motor torque characteristic curve

Table 4 Mode switch strategy

Mode	Conditions
EV mode	$0<T_r<T_{mmax}$, and $SOC_{low}<SOC_{obj}$
Engine mode	$T_r>T_{eopt}$, and $SOC<SOC_{obj}$
Hybrid mode	$T_r>T_{mmax}$, and $SOC_{low}<SOC<SOC_{obj}$
Charge mode	$T_r<T_{eopt}$, and $SOC<SOC_{low}$
Regeneration mode	$T_r<0, SOC<SOC_{max}, V>V_{min}$, and $a<a_{ref}$

Notes: T_r is the HCU input required torque; α is the acceleration pedal travel; v is the velocity; T_{mmax} is the motor maximum torque; T_{eopt} is the engine torque in the case of the lowest fuel consumption rate; SOC_{low} is the lowest limitation level of battery; SOC_{obj} is the expected SOC value of battery; SOC_{max} is the highest limitation level of battery; a is the current vehicle acceleration; and a_{ref} is the reference vehicle acceleration.

3.3 *Torque distributed strategy*

According to the aforementioned plug-in hybrid electrical vehicle modes, the required torque distributed strategy between the engine torque and the motor torque is proposed, as shown in Table 5. The motor provides all the required torque in the EV mode. The engine provides all the required torque in the engine mode. In the hybrid mode, the engine provides the torque which is corresponding to the optimal fuel consumption ratio, and the other required torque is provided by the motor. In the charge mode, the relationship between the engine optimal torque and the torque which is equal to the sum of the required torque and the maximum generation torque should be judged. If the latter one is larger than the former one, then, the engine provides the optimal toque, and the redundant torque is used to charge the battery. If the latter one is smaller than the former one, then the engine provides the total torque of the required torques and the maximum generation torque, and the generator provides the maximum generation torque. In the regeneration mode, the generator provides all brake torque.

Table 5 Torque distributed strategy

Mode	Torque distributed strategy
EV mode	$T_e=0,\ T_m=T_r$.
Engine Mode	$T_e=T_r,\ T_m=0$.
Hybrid mode	$T_e=T_{eopt},\ T_m=T_r-T_e$.
Charge mode	If $T_r+T_{gmax}>T_{eopt}$, $T_e=T_{eopt},\ T_m=-(T_{eopt}-T_r)$; else, $T_e=T_r+T_{gmax},\ T_m=-T_{gmax}$.
Regeneration mode	$T_e=0,\ T_m=T_r-T_b$.

Notes: T_e is the engine current torque; T_m is the motor torque; T_r is the HCU input required torque; T_{eopt} is the engine torque in the case of the lowest fuel consumption rate; T_{gmax} is the motor maximum generating torque; and T_b is the brake torque of vehicle.

3.4 *Construction of simulation model*

According to the aforementioned energy management strategy of PHEV, the HCU model is built in the Simulink environment, as shown in Fig. 11.

The vehicle simulation model is built in the AVL CRUISE environment, as shown in Fig. 12. The HCU model is compiled into a DLL format file and connected with the AVL CRUISE software.

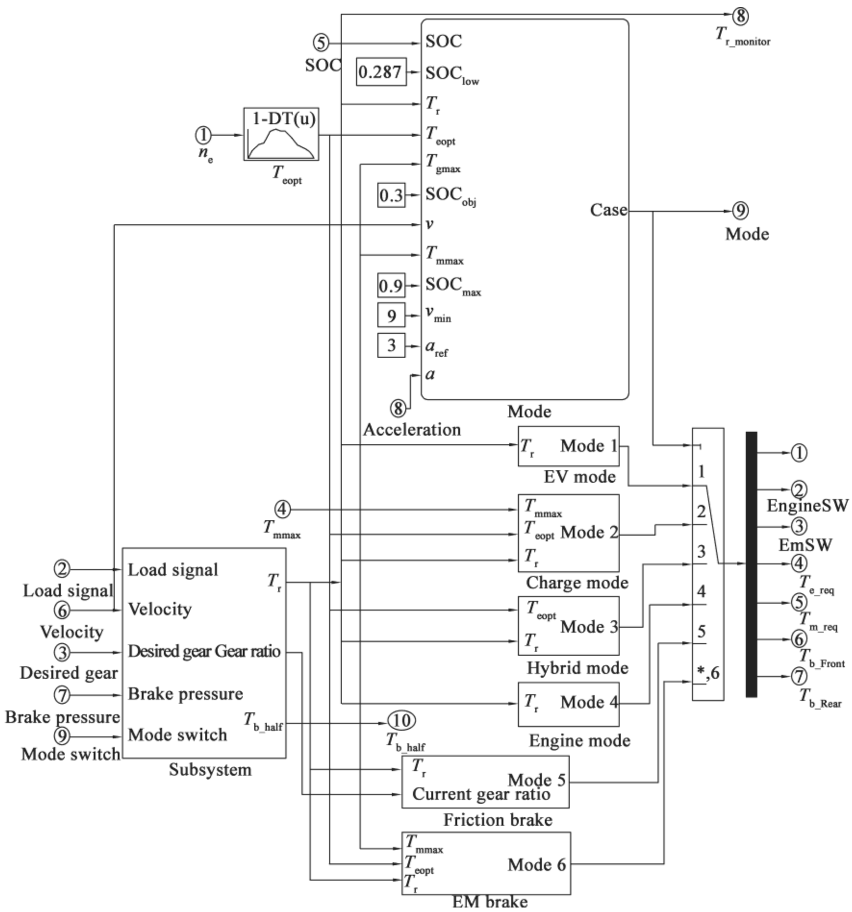

Fig. 11 HCU model

4 Simulation and results analysis

4.1 Power mode simulation results

The maximum acceleration time from 0 to 100 km/h, maximum velocity and fuel consumption of CS period base on NEDC cycle run are simulated. The simulation results are shown in the table 6. Battery SOC simulation curve of power mode is shown in the figure 13. The initial SOC of battery is 0.3, and the end SOC of battery is 0.291248. Therefore, the change ratio between initial SOC and end SOC is within 3%.

Velocity curve between desired velocity and current velocity is shown in the figure 14. It is clear from the figure that the vehicle's driving and braking torque are satisfied.

Table 6 Power mode simulation results

Task	Result
Fuel consumption	5.831 L/100 km
Acceleration time	9.04 s
Max velocity	217 km/h

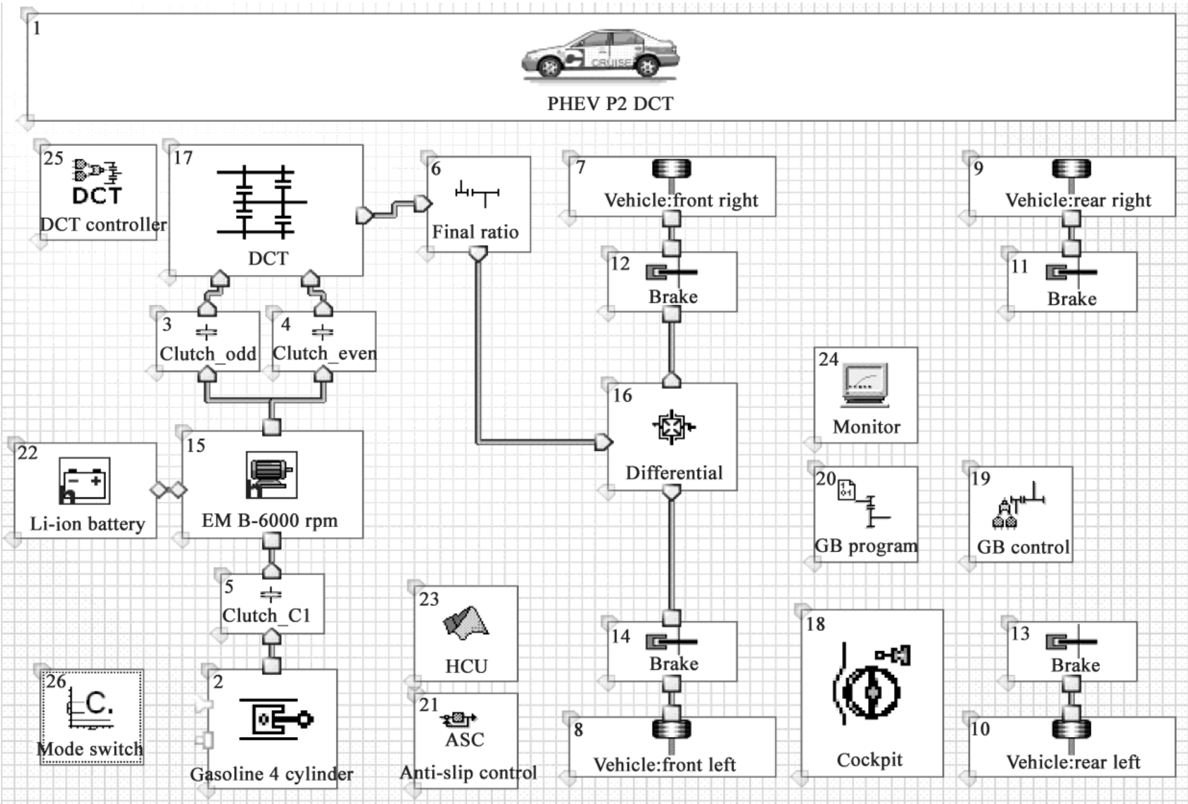

Fig. 12 Vehicle simulation model

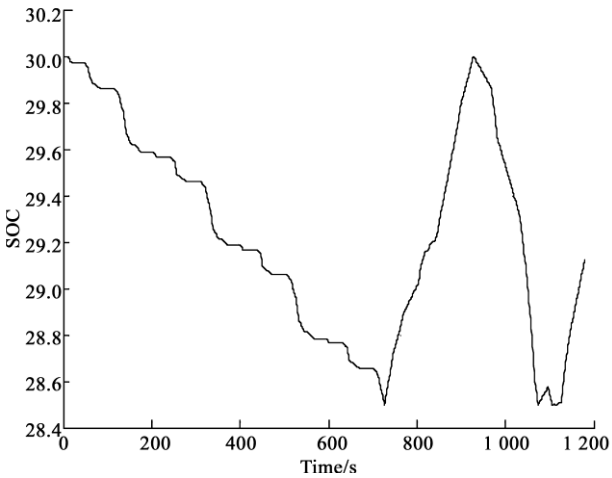

Fig. 13 Power mode SOC curve

The engine speed and torque curves are shown in Fig. 15. By the contrast, the motor speed and torque curves are shown in Fig. 16. We can see from the figures that the engine and the motor are all working within the reasonable range. As a result, the effectiveness of energy management strategy of the power mode is verified.

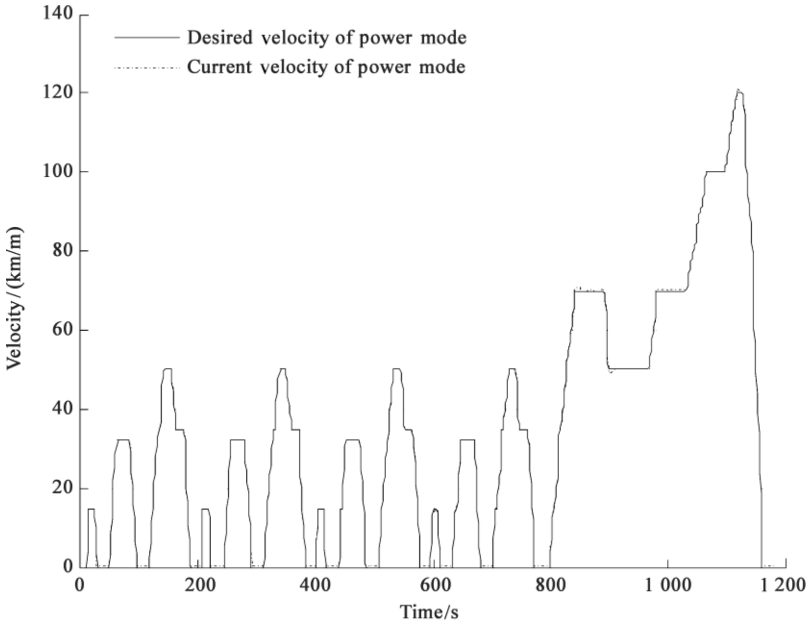

Fig. 14 Power mode velocity curve

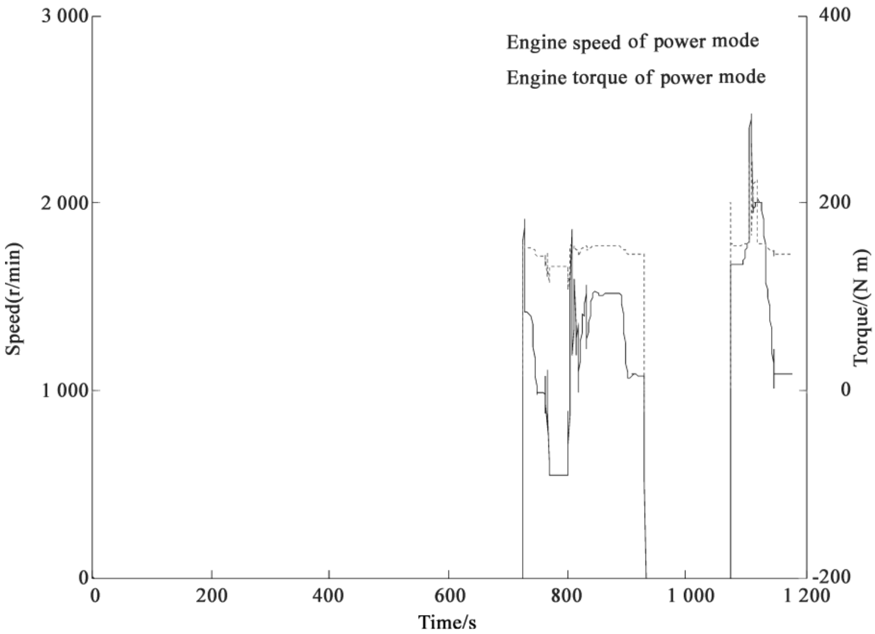

Fig. 15 Power mode engine characteristic curve

4.2 Economy mode simulation results

The maximum acceleration time from 0 to 100 km/h, maximum velocity and fuel consumption of CS period base on the NEDC cycle run are also simulated. The simulation results are shown in Table 7. The battery SOC curves of economy mode are shown in Fig. 17. The initial SOC is 0.3, and the end SOC of battery is

0.291 227. Therefore, the change ratio between the initial SOC and the end SOC is within 3%.

The velocity curve between the desired velocity and current velocity is shown in Fig. 18. We can see from the figure that the driving and braking torques of the vehicle are satisfied.

Table 7 Economy mode simulation results

Task	Results
Fuel consumption	5.729 L/100 km
Acceleration time	12.77 s
Maximum velocity	198 km/h

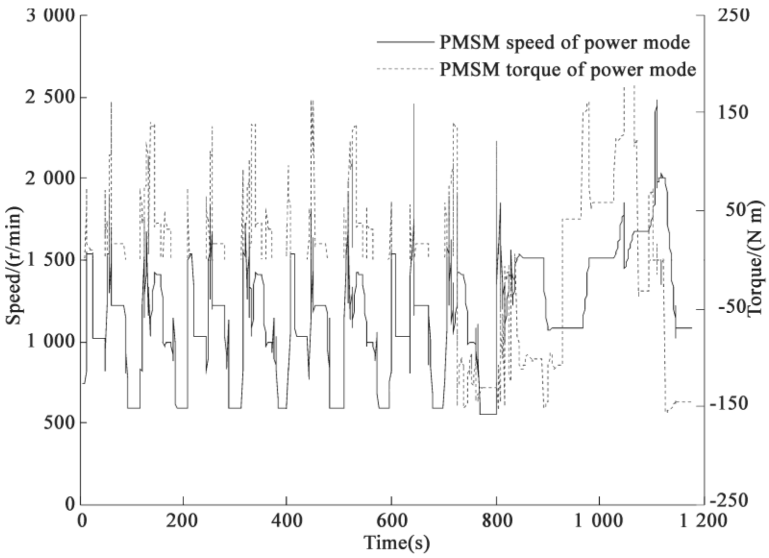

Fig. 16 Power mode electrical machine curve

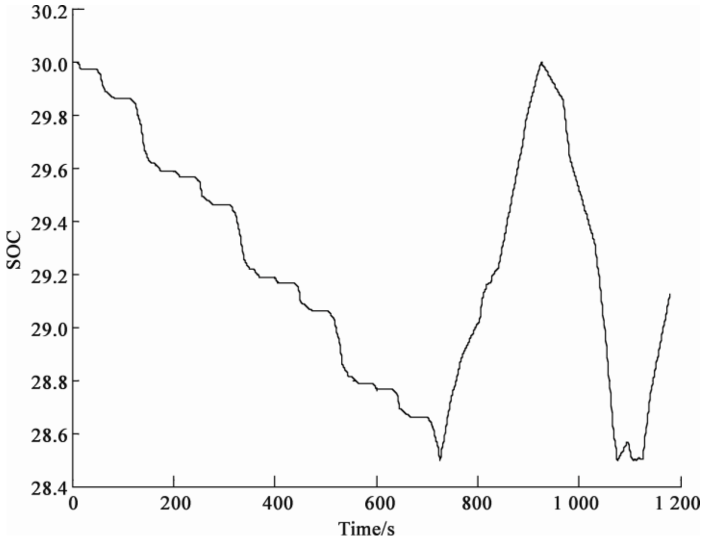

Fig. 17. Economy mode SOC curve

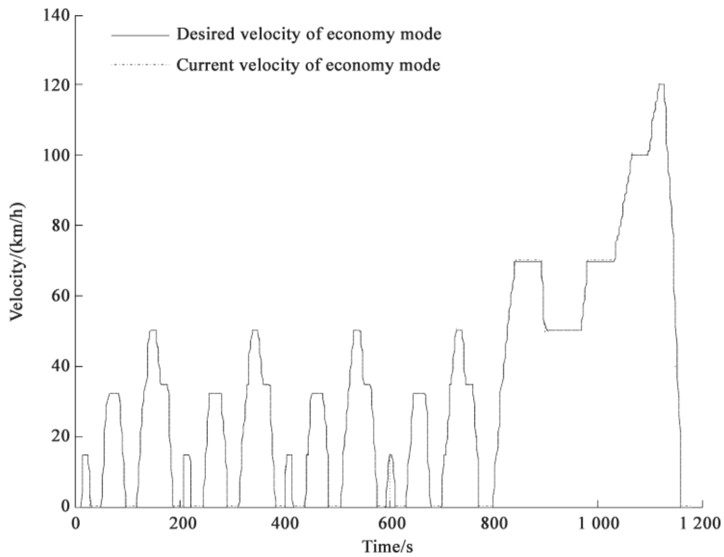

Fig. 18 Economy mode velocity curve

The engine speed and torque curve are shown in Fig. 19. The motor speed and the torque curve are shown in Fig. 20. It is clear from the figures that the engine and the motor are all working within the reasonable range. We can see from Figs. 16 and 20 that the motor is used more often in the economy mode than in the power mode. By the contrast, we can see from Figs. 15 and 19 that the engine is used more often in the power mode than in the economy mode.

4.3 Simulation results analysis

Based on the NEDC cycle run, the fuel consumptions of PHEV power mode and economy mode during the CS period are 5.831 L and 5.729 L, respectively. Fuel consumption is improved by 1.75%. Compared with the economy mode, the acceleration time of power mode declines by 29.2%, and at the same time, the maximum velocity increases by 9.6%. As a result, PHEV can work in the power mode or the economy mode according to the required torque during the CS period. The economy mode is suitable to a low load cycle run, and the power mode is suitable to a high load cycle run or a high way cycle run. This paper proposed the idea of dividing the PHEV battery charge sustaining period into the power mode and the economy mode, to further improve the fuel consumption, which is meaningful to the research and development of PHEV.

5 Conclusion

In order to further improve the PHEV fuel consumption during the CS period, this paper divides the CS period into the power mode and the economy mode, and at the same time, energy management strategies of the two modes are proposed. The energy management strategy is verified in the AVL CRUISE and Simulink simulation environment. Simulation results indicate that fuel consumption of economy mode is improved by 1.75% compared with the power mode. Compared with the economy mode, the power mode acceleration time decreases by 29.2%, and the maximum velocity increases by 9.6%. The idea of dividing the CS period into the power mode and the economy mode can further improve the fuel consumption of PHEV. This is meaningful to the research and development of PHEV.

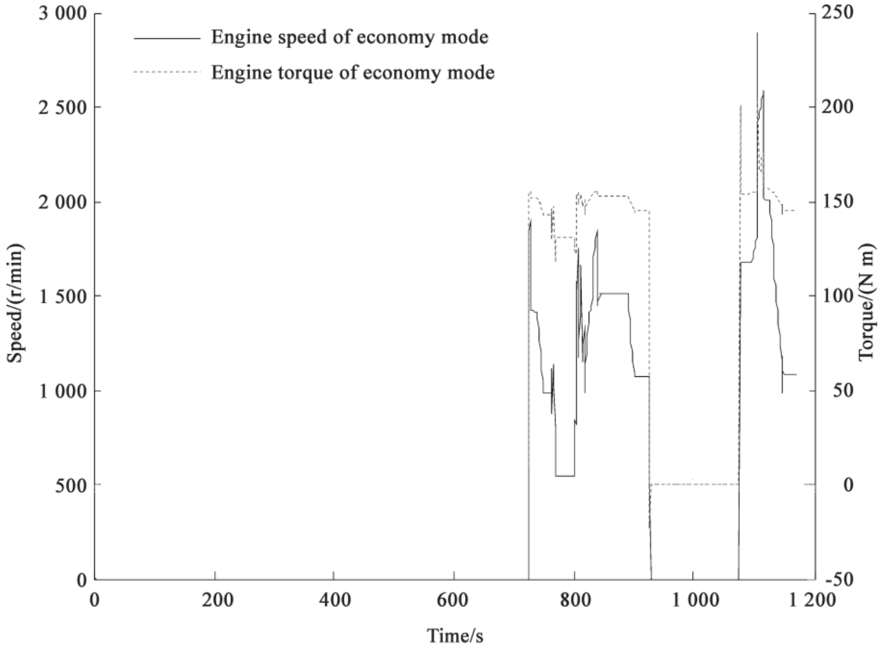

Fig. 19 Economy mode engine characteristic curve

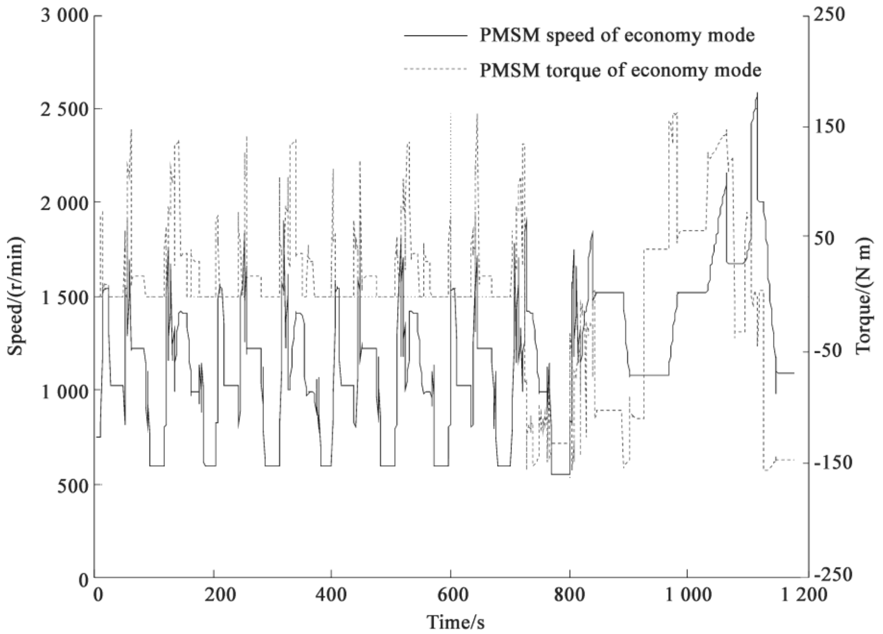

Fig. 20 Economy mode electrical machine curve

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