Energy Optimization and Simulation of CJY6470PHEV with Mild Hybrid Strategy

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Abstract

This paper mainly focuses on the energy management system of CJY6470 parallel hybrid electric vehicle (CJY6470PHEV) with the mild hybrid strategy. The energy controller is designed, and the optimum method of the throttle angle and vehicle gear shift, as well as the energy distributing strategy is presented, too. Moreover, the energy management system is simulated according to ECE-EUDC cycles. The results indicate that the energy can be distributed as expected in the system.

Keywords

parallel hybrid electric vehicle (PHEV), energy optimization, the energy management system, the mild hybrid strategy

1. INTRODUCTION

There are both the engine drivetrain and electrical motor drivetrain in PHEV. The power driving PHEV is provided by both of the engine and electrical motor separately or together. Thus, it is absolutely essential to study the energy distributing strategy and the way to control the vehicle with the energy management system [Chan, 2002; Massimo, 2006; Antoni et al., 2001; Zhang et al., 2008]. The energy management system of CJY6470PHEV is studied in the paper, mainly including the design of the controller, decision of the control strategy, as well as the energy optimization and system simulation.

2. STUDY ON THE ENERGY MANAGEMENT SYSTEM OF CJY6470PHEV

CJY6470PHEV is an off-road vehicle designed on the basis of CJY6470G off-road vehicle. Its drivetrains, or rather, the parallel hybrid drivetrains with the combination of traction forces [Deng, 2005], developed by the authors, are showed in Figure 1. The figure tells that, the rear wheels are driven by the engine with a gearbox, while the front wheels by the electrical motor with a reducer. Both the engine and electrical motor can provide power to the vehicle separately or together. The electrical motor can also operate energy regenerative braking in the course of decelerating.

2.1 Design of the CJY6470PHEV energy controller

In terms of requirements and characteristics of CJY6470PHEV, the energy controller is designed and showed in Figure 2 [Deng et al., 2006]. The figure indicates that the controller includes following parts:

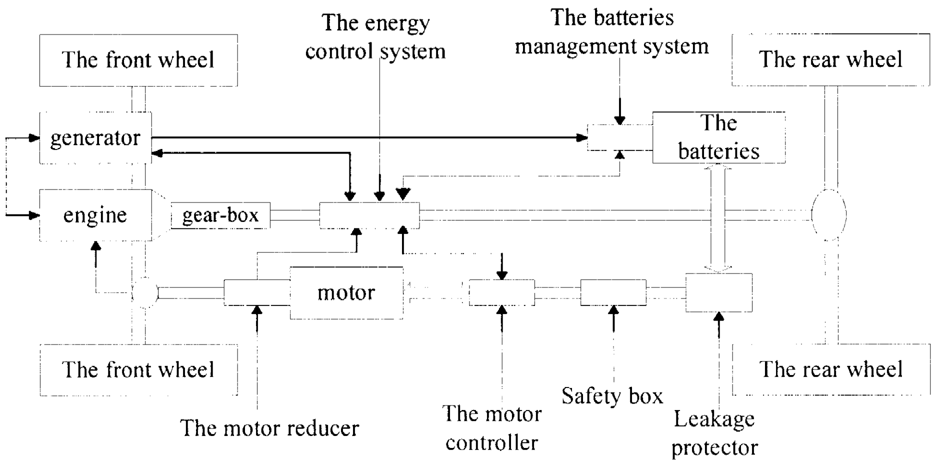

Fig. 1 The drivetrains configuration of CJY6470PHEV

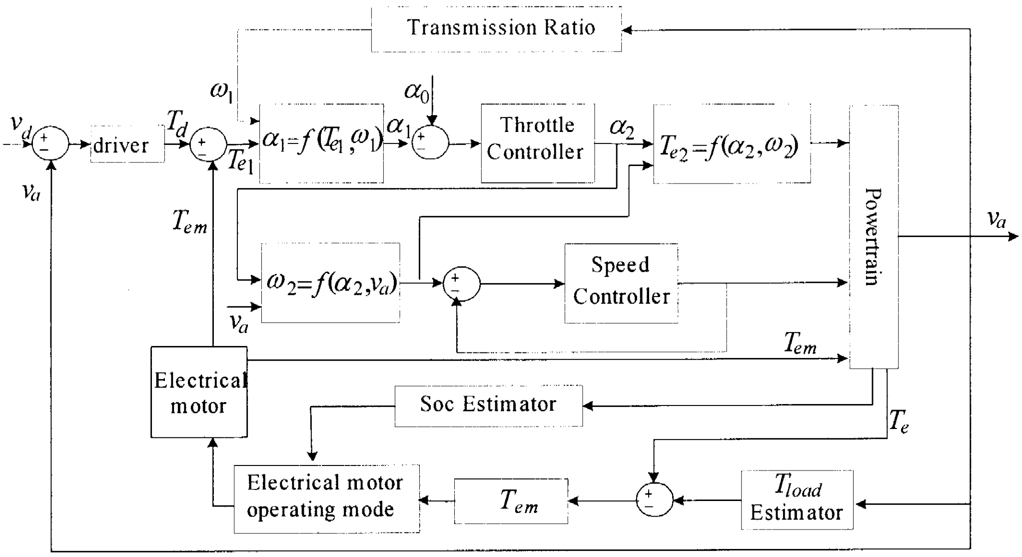

Fig. 2 The energy management system of CJY6470PHEV

(1) The driver module, whose main function is that, after the actual vehicle speed v_a has been compared with the anticipative vehicle speed v_d, the position of the accelerating pedal and braking pedal can be decided. Thereby, the vehicle running anticipative torque T_d can be settled too.

(2) The engine part, whose basic idea is that the engine output torque is adjusted with the engine throttle, which needs to calculate the throttle angle, i.e. $\alpha_1 = f(T_{e1}, n_1)$,along with the control of the engine in the optimum cycles (Throttle controller) and the engine actual output torque, i.e. $T_{e2} = f(\alpha_2, n_2)$.

(3) The vehicle speed part, which includes the adjustment of the engine output speed and control of the vehicle gear shift.

(4) The electrical motor part, which needs to estimate the electrical motor torque T_{em} based on the calculation of the vehicle torque (T_{load} Estimator) and the engine torque T_{e2}, and decide the electrical motor operating modes (Motor operating mode).

(5) The Soc of battery pack module (Soc estimator), which is used to estimate the Soc of battery pack.

2.2 Energy distribution of CJY6470PHEV with the mild hybrid strategy

After the engine optimum cycles has been determined, the vehicle minimum speed $v_{a,min}$, corresponding to the engine minimum speed in the optimum cycles can be gained [Deng et al., 2005]:

$$v_{a,\min} = 0.377 \frac{n_{opt,\min}}{i_0 i_{g,\max}} \qquad (1)$$

Here, $n_{opt,min}$ is the engine minimum speed in the optimum cycles, i_0 is the ratio of the single final drive, while $i_{g,max}$ is the maximum gear shift of the vehicle.

The basic idea of the mild hybrid strategy with a big hybrid ratio is that, when the vehicle speed v_a is lower than the required lowest speed $v_{a,min}$ in the optimum cycles, the engine separately drives the vehicle and provides power to the electrical motor by adjusting the engine throttle and the electrical motor operates in terms of the generator mode in order to make vehicle perform well, namely,

$$P = P_e - P_{em1}\,(v_a < v_{a,\min}) \qquad (2)$$

Here, P denotes the vehicle running power, P_e refers to the engine power, P_{em1} means the electrical motor generating power.

When the engine speed is high enough, the engine provides separately the vehicle running power. Moreover, when the battery pack needs to be charged, the engine also can provide the electrical motor power and make it operate as the generator mode charging the battery pack, namely,

$$P = P_e \text{ or } P = P_e - P_{em1}\,(v_a \geq v_{a,\min}) \qquad (3)$$

When the vehicle needs a great deal of running power or a higher speed, the electrical motor will operate as the electromotor mode, and provide the vehicle running power together with the engine, namely,

$$P = P_e + P_{em2} \qquad (4)$$

In this equation, P_{em2} denotes the electrical motor driving power.

CJY6470PHEV will operate energy regenerative braking in the course of decelerating. Assuming that the vehicle minimum speed is $v_{b,min}$ demanded by the energy regenerative braking. When the vehicle speed satisfies the equation: $v_a \geq v_{b,\min}$, the electrical motor will do the energy regenerative braking, namely,

$$P = P_b + P_{em1}\,(v_a \geq v_{b,\min}) \tag{5}$$

Here, P_b denotes the mechanical braking power.
Otherwise, the electrical motor will not operate the energy regenerative braking, namely,

$$P_{em1} = 0 \text{ and } P_b = P_{load}\ (v_a < v_{b,\min}) \tag{6}$$

In this equation, P_{load} is the vehicle braking power.

2.3 Exploration on optimum method of the throttle angle and vehicle gear shift

In the energy management system, the engine cycles are controlled mainly by the electronic throttle, while the vehicle speed is adjusted by the gear-box. Therefore, it is indispensable to explore the optimum method of the throttle angle and vehicle gear shift.
Assuming that the electrical motor actual torque is T_{em}, the vehicle running anticipative torque can be calculated as follows:

$$T_d = T_{e1} i_0 i_g \eta_e + T_{em} i_{em} \eta_{em} \tag{7}$$

In Eq. (7), η_e is the efficiency of the drivetrain including engine; ς_{em} is the efficiency of the drivetrain including electrical motor. Thus, the engine anticipative torque can also be gained:

$$T_{e1} = \frac{T_d - T_{em} i_{em} \eta_{em}}{i_0 i_g \eta_e} \tag{8}$$

The engine speed can be calculated with the actual vehicle speed as follows:

$$n_1 = 0.377 i_0 i_g v_a / r \tag{9}$$

Here, r denotes the wheel radius. Consequently, the throttle angle can be calculated as follows:

$$\alpha_1 = f(T_{e1}, n_1) \tag{10}$$

α_1 is optimized in the range of α_0 in the engine optimum cycles, which can be expressed as follows:

$$\min f(\alpha), f(\alpha) = \alpha_1 - \alpha_0 \tag{11}$$

In the light of the optimum results, the throttle angle α_2 is calculated as follows:

$$\alpha_2 = \alpha_0 + k f(\alpha) \tag{12}$$

Here, k is a constant value.
In the course of optimizing the throttle angle, the engine speed must also be adjusted. Assuming that the adjusted speed is n_2, then

$$|n_1 - n_2| \leq \varepsilon \tag{13}$$

Here, ε is a constant value.
The actual output torque of engine can be calculated with the throttle angle and speed [Markolf et al., 2006]:

$$T_{e2} = f(\alpha_2, n_2) \tag{14}$$

Assuming that the vehicle anticipative speed is v_d, thereby, according to Eq. (13), the ideal gear shift in the vehicle running can be gained:

$$i_d = \frac{n_2 r}{0.377 i_0 v_d} \tag{15}$$

The vehicle gear shift is expressed with the following equation:

$$I = [I_{-1}, I_1, I_2, I_3, I_4, I_5] \tag{16}$$

In this equation, I_{-1} denotes reverse gear, I_1 to I_5 respectively denote gear shift one to five.
Then, i_d is compared with the gear shifts of I, namely,

$$\Delta I = |I - i_d| \tag{17}$$

When ΔI reaches min(ΔI), the gear shift of I is the vehicle gear shift. Using the gear shift to adjust the vehicle or engine speed can make the vehicle perform well.
The electrical motor torque can be calculated with the vehicle running load T_{load} and engine torque T_{e2}:

$$T_{em} = \frac{T_{load} - T_{e2} i_g i_0 \eta_e}{i_{em} \eta_{em}} \tag{18}$$

The electrical motor operating modes which mainly include the generator mode and electromotor mode are determined by the vehicle running state and the Soc of battery pack. The Soc of battery pack can be showed with [$Soc_{\min}$, $Soc_{\max}$], $Soc_{\min}$ and $Soc_{\max}$ respectively denotes the minimum and maximum values in the available range.
Through the above analysis, the optimum control of the engine throttle angle and vehicle gear shift can be expressed:

$$\begin{aligned} &\min f(\alpha) \\ &s.t.\ |n_1 - n_2| \leq \varepsilon,\ i_d \in I. \end{aligned} \tag{19}$$

This is a constrained, optimum issue. The throttle angle, engine speed and gear shift can be calculated by settling the equation.

3. SIMULATION OF CJY6470PHEV ENERGY MANAGEMENT SYSTEM

The CJY6470PHEV energy management system mainly consists of the models of the engine, electrical motor and Soc of battery pack. There has been a detailed analysis on the models of the engine and electrical motor in the paper [Antoni, 2001]. A model estimating the Soc of battery pack has been created in accordance with the energy conservation principle by the authors [Deng et al., 2006].

Based on the economical requirement of the engine, the engine optimum cycles showed in Figure 3 [Deng et al., 2005] indicate the relationship of the torque and speed, when the fuel consumption ratio of CJY6470PHEV engine is 275g/(kW×h).

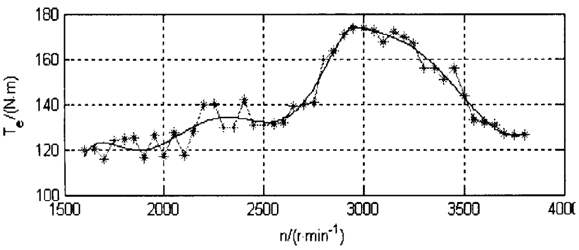

Fig. 3 Region of the engine optimum cycles

When the vehicle runs according to the ECE-EUDC cycles, the power P and torque T_w can be calculated through the vehicle parameters. The results are presented in Figure 4 and Figure 5.

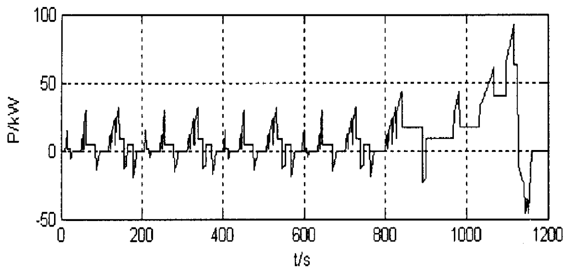

Fig. 4 The vehicle power in the running

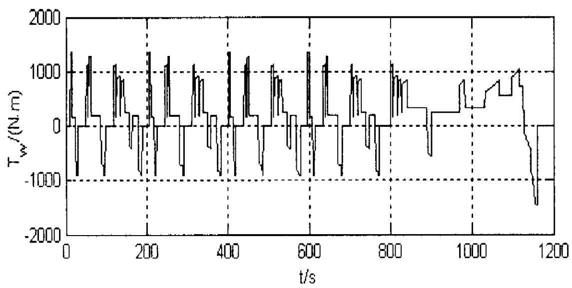

Fig. 5 The vehicle troque in the running

Supposing the vehicle speed is the function of time: $v=v(t)$. v_a, the actual vehicle speed, changes according to ECE-EUDC cycles ,while the vehicle anticipative speed of the driver v_d, changes based on the Eq. : $v_d(t)=v_a(t+3)$. When the energy management system is employed in Figure 2, the power, torque and gear shift of CJY6470PHEV can be obtained in the vehicle running in line with the above decided energy management strategies. The running state of the engine and changing rule of its throttle angle also can be concluded. So can the power and torque of the electrical motor, along with the Soc of battery pack. The results are stated as follows.

(1) The power P_d, torque T_{wd} and gear shift of the vehicle in the course of running are showed in Figure 6, Figure 7 and Figure 8. Compared with the power and torque of the vehicle displayed in Figure 4 and Figure 5, in condition of the vehicle actual speed, all of the power and torque of the vehicle are changed. The figures imply that, if the changing frequency of the gear shift increases, so does fluctuation of the power and torque in the vehicle running. When the vehicle speed is high enough, the

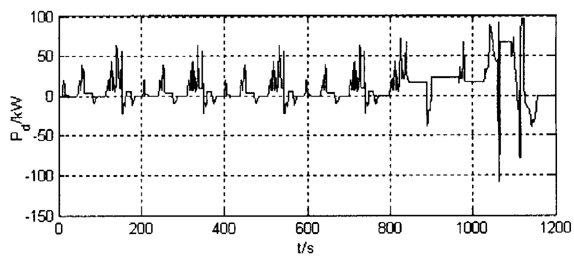

Fig. 6 The vehicle power with the mild hybrid strategy

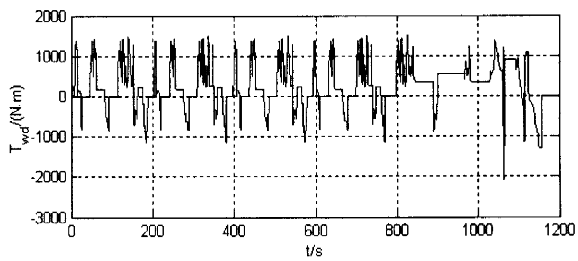

Fig. 7 The vehicle torque with the mild hybrid strategy

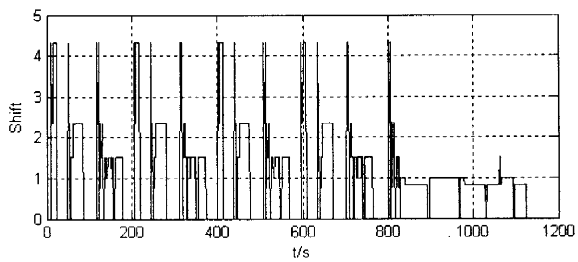

Fig. 8 The gear shift with the mild hybrid strategy

power and torque will sharply vary with the changes of the gear shift, and the vehicle will run unsteadily.

(2) In the course of vehicle running, the changing rules of the engine speed, torque, power and throttle angle respectively in Figure 9, Figure 10, Figure 11 and Figure 12 indicates that the throttle angle is optimized in the range of the optimum cycles, and controlled by the electrical throttle. Thus, it can be got from the figures that, the throttle angle changes within the range corresponding to the optimum cycles. When the engine throttle is adjusted in line with the changing rule in Figure 12, the engine speed mainly concentrates between 1500r×min-1 and 3000r×min-1. Or rather, the speed lower than 1000r×min-1 hardly occur, and the maximum speed is about 3800r×min-1, so the engine speed is basically controlled in the required range. The engine torque mainly fluctuates between 100N×m and 150N×m. More exactly, the minimum torque exceeds 50N×m, and the maximum torque is about 180N×m, which satisfies the range of the required torque. However, it can be got from the change of the engine power that, it locates in the range of middle power. The result conforms to the conclusion that the engine optimum fuel consumption ratio locates in the range of the middle speed and torque gained from the engine universal characteristics. It can be also got from the figures that, when the throttle angle continuously changes, so do the engine speed and torque and influence on the engine steadily works.

(3) The changing principle of the electrical motor power and torque in the vehicle running is showed in Figure 13 and Figure 14. The electrical motor power consists of three parts: the generating power of the energy regenerative braking, the generating power to charge the battery pack in the vehicle normal running, and the driving power when the vehicle needs a great deal of power or speed up. In the figures, the minus part is the generating power; the plus part is the driving power. According to ECE-EUDC cycles, since the vehicle speed in the front part is lower, the electrical motor is mainly used to do energy regenerative braking, and hardly provide the driving power to the vehicle. In the rear parts of ECE-EUDC cycles, an abnormal situation occurs

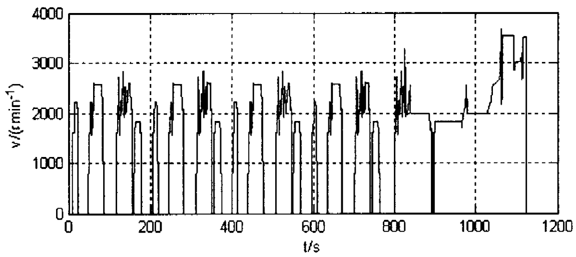

Fig. 9 The engine speed with the mild hybrid strategy

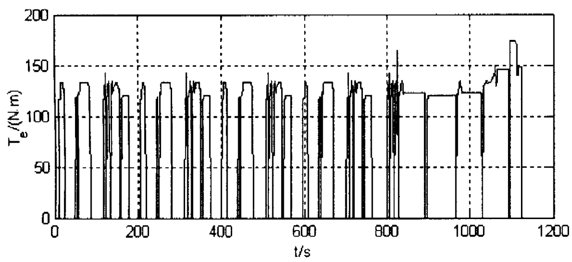

Fig. 10 The engine torque with the mild hybrid strategy

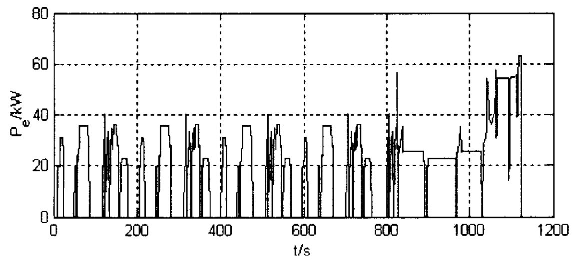

Fig. 11 The engine power with the mild hybrid strategy

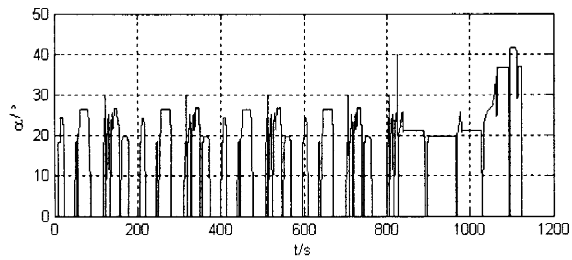

Fig. 12 The throttle angle with the mild hybrid strategy

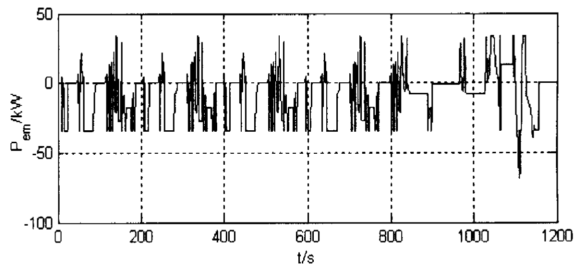

Fig. 13 The motor power with the mild hybrid strategy

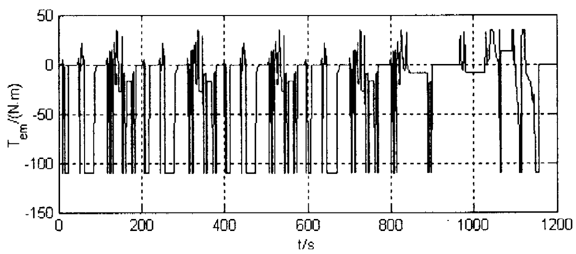

Fig. 14 The motor torque with the mild hybrid strategy

that the energy regenerative braking power is more than the maximum power of the electrical motor, which may be caused by some unreasonable designs of the program. In the same way, the torque can be demonstrated through Figure 14.

(4) The Soc of battery pack in the vehicle running is showed in Figure 15, which implies that, in the front part of ECE-EUDC cycles, since the vehicle needs a few power, in order to make the engine operate in the optimum cycles, the electrical motor may be used as a generator mode to supply the deficiency of the vehicle power. However, when the vehicle decelerates, the electrical motor may do energy regenerative so that the Soc of battery pack continuously increases. In the rear part of ECE-EUDC cycles, since the vehicle speed is high, when the vehicle speeds up, the electrical motor needs to provide the driving power to supply the deficiency of the engine power. Therefore, the Soc of battery pack will be decreased. Nevertheless, when the vehicle decelerates and brakes, the electrical motor may do energy regenerative braking and make the Soc of battery pack increase.

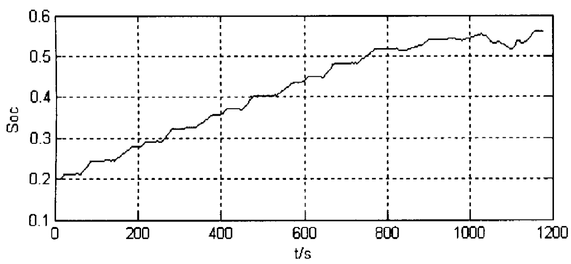

Fig. 15 Soc of battery pack with the mild hybrid strategy

4. ANALYSIS AND DISCUSSION

(1) In the course of distributing the energy of CJY6470P HEV, the engine output power and torque are mainly controlled by the engine throttle. The engine throttle is adjusted according to the changing principle of the throttle angle in the optimum cycles. The electrical motor operating modes are relative to the vehicle load and Soc of battery pack. Thus both the vehicle load and Soc of battery pack must be estimated in the energy management system.

(2) The reason for selecting the torque as the control variable is that, CJY6470PHEV employs the parallel hybrid drivetrains with the combination of traction forces, while the engine and electrical motor drivetrains have different transmission ratios. Thus, despite the vehicle power is the sum of both, the vehicle torque, besides both the torques, is relative to the both transmission ratios.

(3) In the view of the control strategy, it has something to do with the vehicle minimum speed in running. However, the vehicle minimum speed decided is relative to the engine optimum cycles. The gear shift will be adjusted more frequently with the mild hybrid strategy. The power and torque will also fluctuate so strongly with the mild hybrid strategy. Because the control strategy and engine optimum cycles are decided by the designer according to the vehicle using requirements, it is influenced by the man.

(4) There is more difficulty in controlling the engine on the line cycles. It can be concluded from the changing rules of the engine speed, torque, power and throttle angle, the engine can not operate stably.

(5) The Soc of battery pack augments so much in condition of the mild hybrid strategy, while it consumes a little. When the vehicle speed is high, the electrical motor has more chance of providing the vehicle torque and operating with the electrical motor mode, which can keep the Soc of battery pack in balance.

5. CONCLUSION

(1) The energy management system of CJY6470PHEV has been designed, which includes adjusting the engine output torque, controlling the engine speed, estimating the vehicle running load and the Soc of battery pack, as well as selecting electrical motor operating modes.

(2) The optimum method on the energy management system is presented with the throttle angle and gear shift, while the energy distributing strategy is also demonstrated on the basis of the mild hybrid strategy.

(3) The model estimating the Soc of battery pack is introduced in terms of the energy conservation principle, which is applied in the energy management system of CJY6470PHEV. The results prove that the model is appropriate.

(4) The simulating results indicate: (1) the energy can be distributed as expected in the system. The engine and electrical motor can also operate as the anticipative modes. The Soc of battery pack is controlled in the required range; (2) the vehicle gear shift with the mild hybrid strategy needs more adjustment. The power and torque are bound to fluctuate more frequently. The engine with the mild hybrid strategy can not operate very freely. Therefore, the operation is not very stable and there will be more difficulty in controlling; (3) because of the engine's effect, fluctuation of the power and torque of the electrical motor also increases with the mild hybrid strategy; (4) when the vehicle runs at the low

vehicle speed, the Soc of battery pack increases little by little, whereas at the high speed the Soc of battery pack can keep in balance

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