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# Research on PHEV logic threshold energy management strategy based on Engine Optimal Working Curve

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**Abstract.** The main purpose of energy management strategy design is to satisfy the requirements of power performance; to make sure that the engine can work in the high-efficiency working area as far as possible; to optimize the economic performances and environmental performance of the vehicle, and to avoid overcharging and discharging of battery packs. The advantages and disadvantages of energy management strategy directly determine the economy and environmental protection of parallel hybrid electric vehicles. In this paper, a logic threshold energy management strategy based on the engine's most working curve is designed, and then a real-time optimal energy management strategy is proposed based on the equivalent fuel consumption minimization algorithm. The strategy is correct and has good real-time performance.

## 1. Introduction

The development of automobiles has brought comfort and prosperity to mankind, but at the same time, it also emits a large number of harmful gases, polluting people's living environment and consuming valuable oil resources. Therefore, the development of new energy vehicles has become an inevitable choice for automobile production enterprises. Hybrid vehicle technology is the most mature, the best comprehensive performance, has been favored by automobile manufacturers. The research of energy management strategy is the key part of parallel hybrid vehicle simulation, and also the focus of this paper.

## 2. Energy management strategy

### 2.1 Analysis of PHEV working mode

Parallel hybrid electric vehicle (PHEV) Parallel hybrid electric vehicle is a structural type of hybrid electric vehicle. The parallel hybrid electric vehicle studied in this paper adopts the mechanism of double-axle and double-transmission. The working state of engine, motor and mechanical brake device is considered and the feasibility analysis is made. There are eight working modes of parallel hybrid electric vehicle, namely, engine driving mode, motor driving mode, hybrid driving mode and driving mode. Charging mode, regenerative braking mode, mechanical braking mode, hybrid braking mode and parking mode [1], as shown in Table 1.

Table1. Work mode of PHEV.

NO.	Mode	Engine status	Motor status	Brake status
1	Engine drive	Open	Shut	Not working
2	Motor drive	Shut	Motor	Not working
3	Hybrid drive	Open	Motor	Not working



4	Driving charge	Open	Generator	Not working
5	Regenerative brake	Shut	Generator	Not working
6	Mechanical brake	Shut	Shut	working
7	Hybrid brake	Shut	Generator	working
8	Stop	Shut	Shut	Not working

### 2.2 Calculation of vehicle demand torque

The calculation of vehicle demand torque is mainly based on the driver's acceleration pedal signal and brake pedal signal to determine the vehicle demand torque, which provides the premise for the identification of working mode and the distribution of demand torque.

The driver's input signals, i.e. acceleration pedal and brake pedal signal, are defined and standardized as shown in Form (1):

$$\begin{cases} \lambda_A = \max\left\{\frac{S_A - S_{\min}}{S_{\max} - S_{\min}}, 0\right\} \\ \lambda_B = \max\left\{\frac{S_B - S_{\min}}{S_{\max} - S_{\min}}, 0\right\} \end{cases} \quad (1)$$

$\lambda_A$ —standardized accelerator pedal signal, range 0-1;  $\lambda_B$ —standard brake pedal number, range 0-1;

$S_A$ —accelerating pedal stroke;  $S_B$ —braking pedal stroke;  $S_{\max}$ —maximum pedal stroke;

$S_{\min}$ —free pedal stroke;

The required torque of the system can be determined by the acceleration pedal signal, the brake pedal signal and the running state of the vehicle, as shown in Form (2):

$$T_{req} = \sigma_1 \lambda_A T_{\max}(u, \Gamma_{AMT}) + \sigma_2 \lambda_B T_{B\max} \quad (2)$$

$T_{req}$ —Vehicle demand torque;  $T_{\max}(u, \Gamma_{AMT})$ —maximum output torque;  $u$ —Current speed;

$\Gamma_{AMT}$ —Stall;  $T_{B\max}$ —maximum braking torque;  $\sigma_1, \sigma_2$ —Represented the coefficient state;

### 2.3 Energy management strategy for optimal engine working curve

The logic threshold energy management strategy is mainly based on the optimal engine working curve. This strategy determines the working mode of parallel hybrid electric vehicle mainly through the demand torque, vehicle speed and battery *SOC*, and distributes the torque of engine and motor reasonably. By adjusting the motor, the engine can work in the optimal working curve as far as possible, thus achieving better fuel economy [2-4]. At the same time, the controller of parallel hybrid electric vehicle should detect battery *SOC*, avoid permanent damage to battery caused by deep discharge when battery *SOC* is too low, and avoid overcharging when battery *SOC* is too high. The method of determining the optimal engine working curve is found in document [5].

When the demand torque is negative, it can be divided into two cases according to whether the battery pack can be recharged. When *SOC* is less than  $SOC_{hi}$ , the motor shall first brake, and when the maximum braking torque of the motor can not meet the required torque, the mechanical brake shall supplement it; when *SOC* is greater than  $SOC_{hi}$ , the mechanical brake device shall provide all the braking force, as shown in Formula (3).

$$\begin{cases} T_{brake\_m} = \max \left\{ \frac{T_{req} \eta_m}{i_m}, T_{brake\_m\_max}(n_m, P_{bat\_max\_chr}) \right\} \\ T_{brake\_m} = \max \left\{ T_{req} - \frac{T_{brake\_m} i_m}{\eta_m}, 0 \right\} \end{cases}, \text{if } SOC \leq SOC_{hi} \quad (3)$$

$$\begin{cases} T_{brake\_m} = 0 \\ T_{brake\_mec} = T_{req} \end{cases}, \text{if } SOC > SOC_{hi}$$

$T_{brake\_m}$ —Braking torque provided by motors,  $N_m$ ;  $\eta_m$ —System efficiency of electric drive chain;

$T_{brake\_mec}$ —Braking torque provided by mechanical braking devices,  $N_m$ ;

$i_m$ —System drive ratio of electric drive chain;  $n_m$ —Speed of the motor,  $r/\min$ ;

$T_{brake\_m\_max}$ —Maximum braking torque provided by motors,  $N_m$ , Which related to motor speed and battery state;  $P_{bat\_max\_chr}$ —Maximum permissible charging power of battery pack in current state,  $kW$ ;

$SOC_{hi}$ —Upper limit of battery working area;

And when the demand torque is positive, according to the battery pack SOC and the speed, it can be divided into four situations:

(1)  $SOC$  is less than  $SOC_{low}$ . At this time, the battery pack can not discharge, mainly driven by the engine vehicle, specific demand torque distribution see formula (4):

$$\begin{cases} T_e = (T_{req} - T_{g\_max} i_m \eta_m) / i_e \eta_e, \text{if } T_{req} < T_{limit1} \\ T_m = T_{e\_max} \end{cases}$$

$$\begin{cases} T_e = T_{e\_opt} \\ T_m = (T_{req} - T_{e\_opt} i_e \eta_e) / i_m \eta_m, \text{if } T_{limit1} \leq T_{req} \leq T_{e\_opt} i_e \eta_e \end{cases}$$

$$\begin{cases} T_e = T_{req} / i_e \eta_e, \text{if } T_{e\_opt} i_e \eta_e \leq T_{req} < T_{e\_max} i_e \eta_e \\ T_m = 0 \end{cases}$$

$$\begin{cases} T_e = T_{e\_max} \\ T_m = (T_{req} - T_{e\_max} i_e \eta_e) / i_m \eta_m, \text{if } T_{req} \geq T_{e\_max} i_e \eta_e \end{cases} \quad (4)$$

$T_e$ —Engine torque required,  $Nm$ ;  $T_m$ —Torque required by motors,  $Nm$ ;

(2) When  $SOC$  is greater than  $SOC_{tar}$ , but less than  $u_{low}$ , the battery pack can be discharged. Because of the low speed and low efficiency of the engine, the vehicle is mainly driven by the motor. The specific demand torque distribution equation (5):

$$\begin{cases} T_e = 0 \\ T_m = T_{req} / i_m \eta_m, \text{ if } T_{req} < T_{m\_max} i_m \eta_m \end{cases} \\
\begin{cases} T_e = (T_{req} - T_{m\_max} i_m \eta_m) / i_e \eta_e, \text{ if } T_{m\_max} i_m \eta_m < T_{req} < T_{limit3} \\ T_m = T_{m\_max} \end{cases} \\
\begin{cases} T_e = T_{e\_max} \\ T_m = (T_{req} - T_{e\_max} i_e \eta_e) / i_m \eta_m, \text{ if } T_{req} \geq T_{limit3} \end{cases} \quad (5)$$

(3) The battery pack can be charged and discharged when bound  $SOC$  is between  $SOC_{tar}$  and  $SOC_{low}$ , but  $u$  is larger than  $u_{low}$ . Specific torque distribution is shown in formula (6):

$$\begin{cases} T_e = 0 \\ T_m = T_{req} / i_m \eta_m, \text{ if } T_{req} < T_{limit1} \end{cases} \\
\begin{cases} T_e = T_{e\_opt} \\ T_m = (T_{req} - T_{e\_opt} i_e \eta_e) / i_m \eta_m, \text{ if } T_{limit1} \leq T_{req} < T_{e\_opt} i_e \eta_e \end{cases} \\
\begin{cases} T_e = T_{e\_opt} \\ T_m = (T_{req} - T_{e\_opt} i_e \eta_e) / i_m \eta_m, \text{ if } T_{e\_opt} i_e \eta_e \leq T_{req} \leq T_{limit2} \end{cases} \\
\begin{cases} T_e = (T_{req} - T_{m\_max} i_m \eta_m) / i_e \eta_e, \text{ if } T_{limit2} \leq T_{req} < T_{limit3} \\ T_m = T_{m\_max} \end{cases} \\
\begin{cases} T_e = T_{e\_max} \\ T_m = (T_{req} - T_{e\_max} i_e \eta_e) / i_m \eta_m, \text{ if } T_{req} \geq T_{limit3} \end{cases} \quad (6)$$

(4) When  $SOC$  is greater than  $SOC_{tar}$ , and  $u$  is greater than  $u_{low}$ , the battery pack can only discharge and can not be charged, mainly driven by motor vehicles, the specific torque distribution can be seen in formula (7):

$$\begin{cases} T_e = 0 \\ T_m = T_{req} / i_m \eta_m, \text{ if } T_{req} < T_{m\_max} i_m \eta_m \end{cases} \\
\begin{cases} T_e = (T_{req} - T_{m\_max} i_m \eta_m) / i_e \eta_e, \text{ if } T_{m\_max} i_m \eta_m \leq T_{req} < T_{limit3} \\ T_m = T_{m\_max} \end{cases} \\
\begin{cases} T_e = T_{e\_max} \\ T_m = (T_{req} - T_{e\_max} i_e \eta_e) / i_m \eta_m, \text{ if } T_{req} \geq T_{limit3} \end{cases} \quad (7)$$

Based on the above analysis, the flow chart of the energy management strategy based on the optimal operating curve of the engine can be determined, as shown in Figure 1. The relevant parameters in the simulation are shown in Table 2.

Table 2. Variables and simulation parameters of logic threshold energy management strategy

Variable	Instructions	Parameter
$SOC_{hi}$	Battery SOC Upper limit	0.8

$SOC_{low}$	Battery SOC Lower limit	0.2
$SOC_{tar}$	Target value of SOC	0.6
$u_{low}$	Minimum engine speed	20km/h

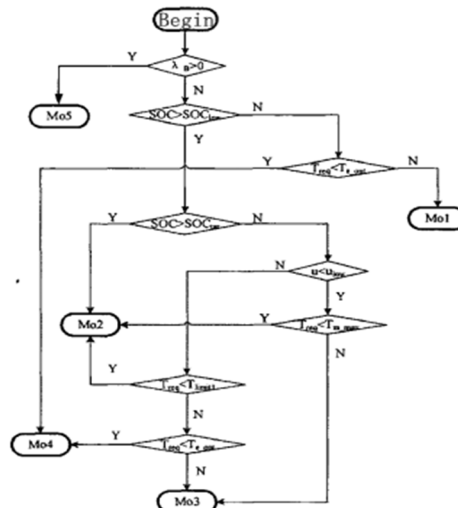


Figure 1. Flow chart of logic threshold energy management strategy

Mo1—Engine driving mode; Mo2—Motor drive mode; Mo3—Hybrid driving mode;

Mo4—Traffic charging mode; Mo5—Regenerative braking mode;

### 3. Modeling and simulation

Computer simulation is an important means of annual research on energy management of hybrid electric vehicles. Through computer simulation technology, it is helpful to reduce unnecessary prototype manufacturing and vehicle test, shorten development time and save development cost. The accuracy of simulation model directly affects the accuracy of computer simulation.

#### 3.1 Energy management strategy model

Energy management strategy model is the core of forward simulation model of parallel hybrid electric vehicle. The main task is to reasonably determine the torque distribution between engine and motor, including two sub-modules: demand torque calculation, pattern recognition and torque distribution. The energy management strategy model is shown in Figure 2. The input of the model is acceleration pedal signal A, brake pedal signal B, actual speed  $u$  and the battery  $SOC$ , and the output of the model is engine torque command  $T_e$  and motor torque command  $T_m$ .

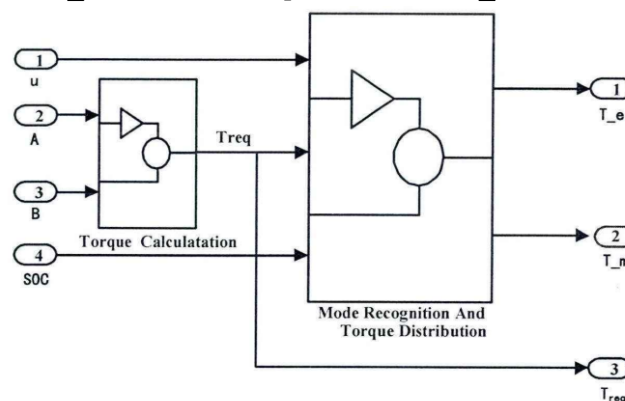


Figure 2. Model of energy management strategy

Using MATLAB/Simulink/Stateflow, the energy management strategy and the optimized energy management strategy model based on the optimal operating curve of the engine are established, as shown in Figures 3 and 4.

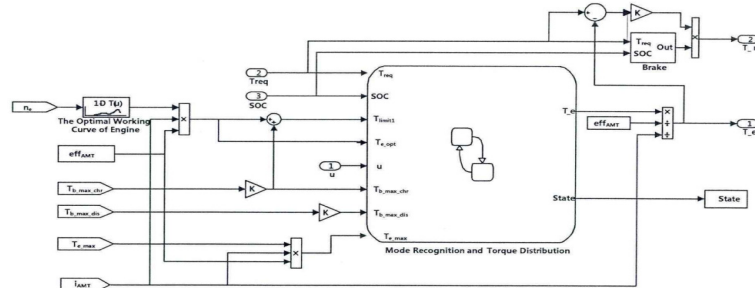


Figure 3. Model of logic threshold energy management strategy

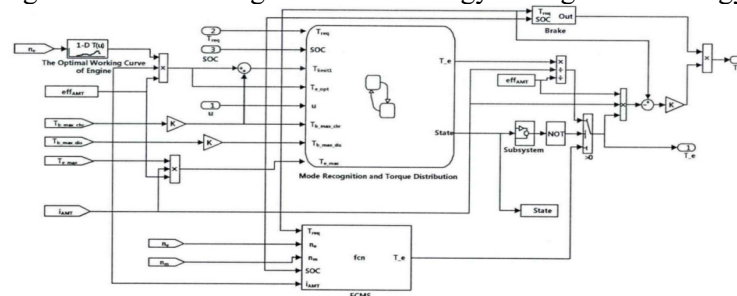


Figure 4. Model of logic threshold energy management strategy

### 3.2 Introduction of simulation working condition

In order to verify the feasibility of the energy management strategy, the standard driving cycle must be chosen as the simulation condition. In this paper, US06 standard driving cycle is selected as the simulation condition. In order to verify the universality of the simulation, ARB02 cycle and HWFET cycle are selected as two conditions. Among them, US06 is mainly used to evaluate the operation of vehicles at high speed and extreme conditions, taking into account road changes, running time is 601s, running distance is 12.88 km; ARB02 is developed by the California Environmental Protection

Agency based on tracking vehicle operating conditions, including cold start and formation end, mainly used to evaluate vehicles. Emission performance, running time is 1640 s, running distance is 31.9 km; HWFET working condition is mainly used to evaluate the fuel economy of passenger vehicles running on the highway, running time is 866 s, running distance is 16.5 km [7].

### 3.3 Analysis of simulation results

The data files of the above three working conditions are imported into the simulation model, and the simulation algorithm is set as the fixed step ode3(Bogacki-Shampine) method with the simulation step of 0.1s. Considering the factors such as vehicle weight and total power of power source, TOYOTA PRIUS is chosen as the corresponding reference vehicle.

Table 3. Parameters comparison between PHEV and Prius

Parameter	PHEV	PRIUS
Weight(kg)	1400	1368
Engine power( $kW$ )	43	43
Engine torque( $N_m$ )	79	102
Motor Power( $kW$ )	49	30
Motor torque( $N_m$ )	275	305

At the end of the simulation, the simulation results under US06 condition are shown in Figures 5, 6, 7.

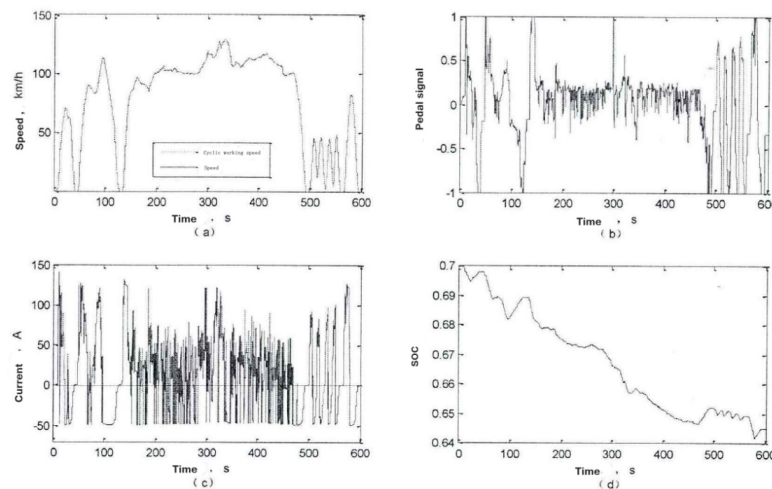


Figure 5. Simulation results of logic threshold energy management strategy (1)

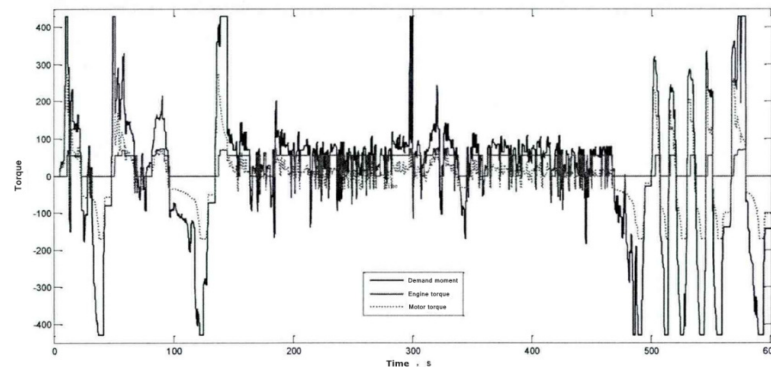


Figure 6. Simulation results of logic threshold energy management strategy (2)

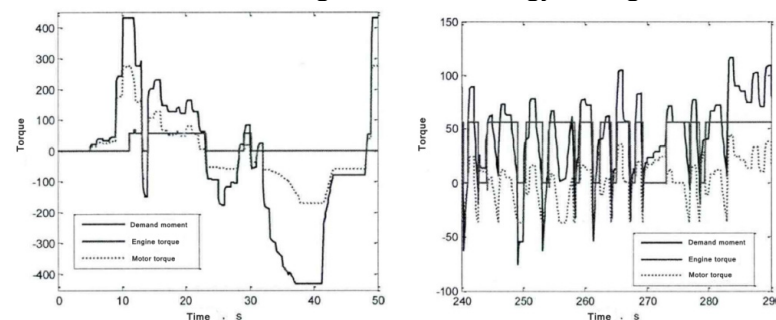


Figure 7. Simulation results of logic threshold energy management strategy (3)

As shown in Figure 5., when the pedal signal is negative, the motor current is negative, and the battery SOC rises, so the motor is charging the battery. After the end of the whole cycle, the SOC of the battery pack decreased little, indicating that the vehicle has a strong endurance. Figures 6. and 7. show that when the speed is low, the engine does not work, and the motor provides all the required torque; when the demand torque is small, the engine operates in the optimal operating curve, and the rest of the torque is supplemented by the motor; when the demand torque is large, the engine provides the maximum torque, and the rest of the torque is provided by the motor; when the demand torque is negative. The motor provides braking torque, and the engine does not work. Thus, the engine provides steady-state load in the whole working condition. The main function of the motor is to balance power and provide dynamic load.



#### 4. Conclusion

In this paper, eight operating modes of PHEV are introduced, and the energy flow in different operating modes is analyzed. Then, based on the optimal operating curve of the engine, a logic threshold energy management strategy based on the optimal operating curve of the engine is designed. ECMS algorithm is used to optimize the energy management strategy of the hybrid electric vehicle (HEV) when it operates in hybrid drive mode and charging mode.

A simulation model is built in Matlab/Simulink, and the two strategies are simulated offline under the three standard driving cycles of US06, ARB02 and HWFET. Simulink results prove that the proposed logic threshold energy management strategy is reasonable and effective, and can achieve good fuel economy. Comparing with the results of real-time optimization curves, we can see that although the logic gate strategy can not achieve the optimal, it is very close to the optimal.

The working point of the engine is concentrated between the optimum working curve and the exterior characteristic curve of the engine. It is known that the instantaneous fuel consumption of the vehicle directly driven by the engine is generally less than that of the vehicle driven by the motor when the engine drives the generator to charge the battery pack. This is because the energy management strategy stipulates that the vehicle has a lower speed or needs to turn. When the torque is small, the motor drives the vehicle. When the vehicle works, the torque is usually large. At this time, there are more intermediate links in the second drive mode, and the energy loss is greater. The energy management strategy is more inclined to use the engine.

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