

Research on the Four-State Control Strategy Based on the Specific Condition

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Abstract: The Four-State control strategy based on the original CD-CS strategy has been designed by using a plug-in hybrid electric vehicle (PHEV) as the research object. The disadvantage of the CD-CS strategy is that when the driving distance is more than the maximum pure electric driving range, vehicle enters prematurely into the charge sustaining mode, resulting in the battery in a low SOC state for a long time. The software GT-drive was used to model and simulate the PHEV. The analysis results show that the Four-State control strategy is more fuel-efficient than CS-CD control strategy in the case of mileage known. The fuel consumption per 100km is reduced by 10.4% and SOC remains at high values.

Introduction

Because the PHEV has two power source and a variety of operating modes, the hybrid control strategies must be a reasonable allocation of energy in order to achieve the best dynamic performance of the vehicle.

At present, the control strategies of hybrid electric vehicle are divided into rule based control strategy and optimal control strategy. The rule based control strategy is widely used because of its simple control and good effect. The optimal control strategy is mainly applied in model optimization and calculation. At any time, the vehicle is in the optimum condition [1]. The power following control strategy [2] and on-off control strategy [3] are mainly applied to the traditional hybrid electric vehicle. Peng [4] pointed that fuel economy of power following strategy is better than that of on-off strategy. Most of rule based control strategies used by PHEV are composed of three kinds of modes, which are CD (Charge Deplete) Mode, CS (Charge Sustaining) Mode and EV (Electric Vehicle) Mode [5].

In this paper, the PHEV control strategy research was studied relying on the National Natural Science Foundation of China. Overall vehicle model was established by GT-drive software. Using virtual simulation technology, system performance can be improved, and the control strategy can be optimized.

Construction of the PHEV

The powertrain of the PHEV we discuss was modified based on the traditional platforms. Automatic transmission was replaced with a CVT. In addition, traction motor and auxiliary drive motor were added. The vehicle details are shown in the following Table.

Table 1 Vehicle Details

items	value
Curb Weight (kg)	1670
Effective aerodynamic drag surface (m ²)	2.759
Air Drag Coefficient	0.414
Tire size(m)	0.307
Battery capacity(kWh)	13
Engine power(Kw)	75
Traction Motor Max Torque(Nm)	250
Traction Motor Peak Power(Kw)	70
Traction Motor Nominal Voltage (V)	355
Traction Motor Required Peak Current(A)	225
Traction Motor Working Temperature (°C)	-30~125
Auxiliary Driver Moto Max Torque(Nm)	27
Auxiliary Driver Moto Peak Power(Kw)	5
Auxiliary Driver Moto Continues Power(Kw)	3
Auxiliary Driver Moto Nominal Voltage (V)	355

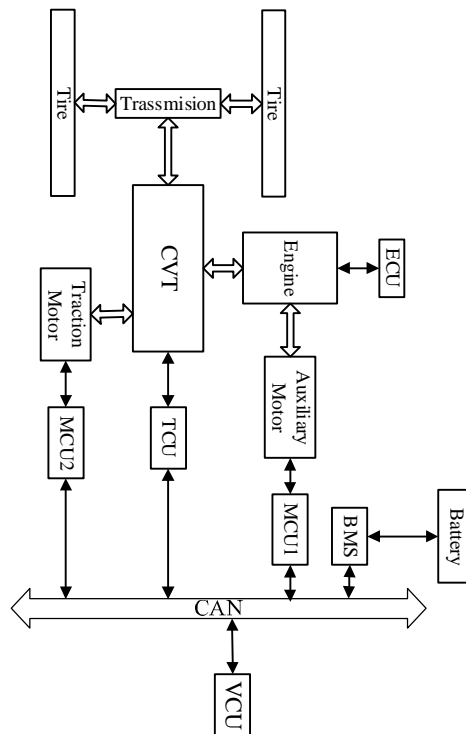


Fig. 1 Auxiliary Driver Motor Details

The PHEV uses a parallel hybrid system, both engine and motor may deliver power to the vehicle wheels. The motor may also be used as a generator to charge the battery by either

regenerative braking or absorbing excess power from the engine when its output is greater than required to move the wheels. The overall construction is shown in Fig.1.

The vehicle controller, located in the top level of the vehicle construction, is responsible for receiving signals from other controllers and electric appliances. Those signals are processed and relevant conclusion are drawn by calculation. The resultant orders are sent to corresponding modules via CAN bus, according to which other controllers and electric appliances would take proper actions. The functions such as drive force control, energy management control and security control are realized by this way.

CD-CS control strategy

The PHEV has three operating modes: pure electric mode (EV), hybrid mode (HEV), and brake mode. The HEV mode can be divided into auxiliary mode and power generation model based on the role of the motor. The CD-CS control strategy was developed based on the SOC value and the demand torque as the reference value.

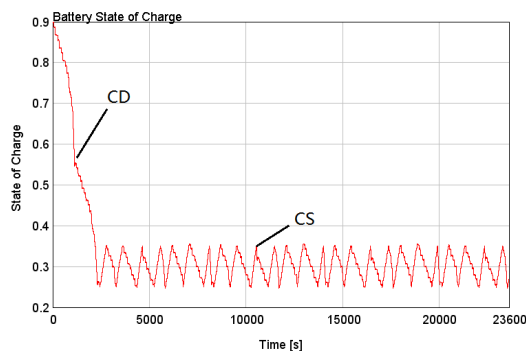


Fig. 2 CD-CS control strategy

As shown in Fig.2, when the vehicle is started, the SOC is high. When the demand torque is less than the maximum torque of the motor, the vehicle priorities in EV mode, relying on the power provided by a battery. While regenerative braking energy causes the SOC value fluctuations, but the overall SOC presents a downward trend, which is called the CD mode. When the SOC falls to 0.25, in order to avoid SOC value continues to drop to dangerous area, the vehicle enters the HEV mode. The engine provides the driving force. At the same time, the power battery is charged, such that SOC is maintained within a certain range, the stage belongs to the CS mode.

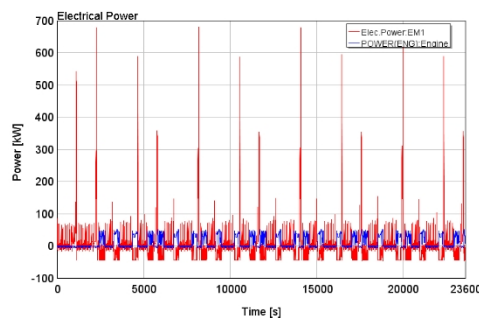


Fig. 3 Engine power and motor power

As shown in Fig.3, the traction motor provides most of the energy and the engine start only in a few cases. The disadvantage of the CD-CS strategy is that when the driving distance is more than the maximum pure electric driving range, vehicle enters prematurely into the charge sustaining mode, resulting in the battery in a low SOC state for a long time. Studies have shown that LFP battery charge and discharge efficiency decreases as the SOC declines.

Four-State control strategy

The Four-State control strategy is based on the CD-CS control strategy. The purpose is to enable the power battery to be in a high efficiency area for a long time. At the end of the trip, the SOC value is low.

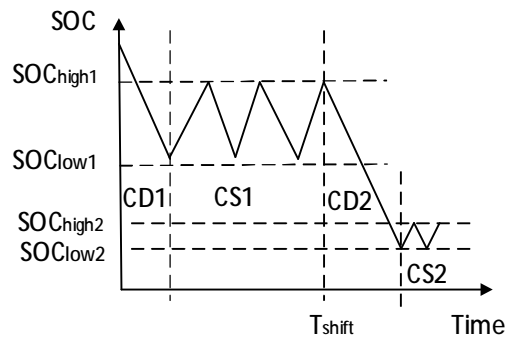


Fig. 4 Four state control strategy

As shown in Fig.4, the Four-State control strategy consists of four models: CD1, CD2, CS1, and CS2. The vehicle starts with high SOC, the battery provides the required power which is called the CD1 mode. When the SOC falls below SOC_{low1} , the vehicle enters CS1 mode and the SOC is maintained between SOC_{low1} and SOC_{high1} . The battery charging and discharging efficiency is high. When the vehicle is running to T_{shift} , the system detects the remaining energy of the battery. If the vehicle can finish the rest of the trip in EV mode, the vehicle enters CD2 mode. When the actual mileage is greater than the estimated mileage, the vehicle enters CS2 mode. At the end of the trip, the SOC is as low as possible.

Determination of T_{shift} is the key point of the research of Four-State control strategy under the condition of known driving condition. The system needs to calculate the pure electric driving range according to the current driving cycle. In this paper, based on the principle of conservation of energy [6-7], the pure electric driving range is estimated

The battery voltage in the selected cell model decreases with the SOC. As shown in Eq.1 and Eq.2, the remaining energy of battery is W_b .

$$W_b = \frac{V_t + V_d}{2} Q \quad (1)$$

$$Q = \Delta SOC \times C \quad (2)$$

Where V_t =the battery voltage of t ; V_d =the battery voltage of termination time; Q =the remaining battery power of t ; ΔSOC =the SOC variation.

According to automobile theory, the consumption power can be calculated by Eq.3.

$$P = \frac{Gf v_a + G i v_a}{3.6} + \frac{C_D A v_a^3}{76.14} + \partial m v_a \frac{du}{dt} \quad (3)$$

Where G = vehicle gravity; v_a = vehicle; f = friction coefficient; i = Climbing slope; A = frontal area; C_D = drag coefficient; ∂ = mass conversion factor.

The research of Four-State control strategy is based on the known driving conditions. Taking a NEDC cycle as an example, its motion trajectory is shown in Fig.5.

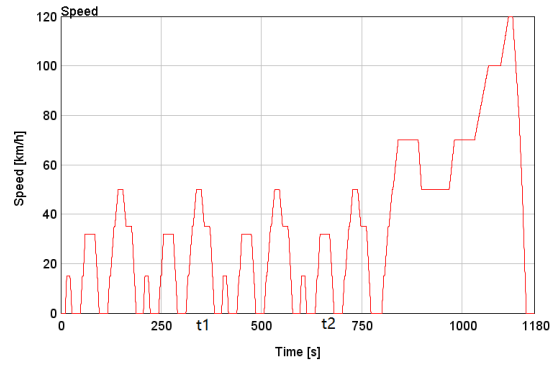


Fig. 5 Vehicle speed

Fig.6 shows the required power (P) at any moment in a NEDC cycle. As shown in Eq.4, the energy (W_v) required from t_1 to t_2 can be obtained by integrating the power of the period.

$$W_v = \int_{t_1}^{t_2} P d_t \quad (4)$$

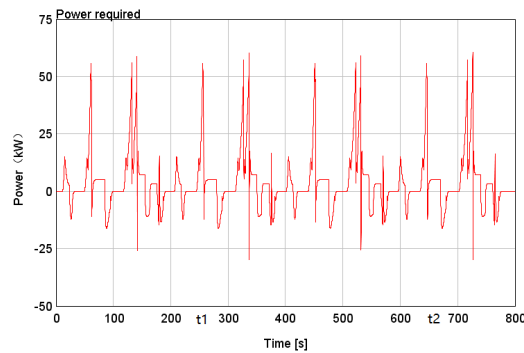


Fig. 6 The required instantaneous power

Based on the principle of conservation of energy, Eq.5 is established.

$$W_b = W_v \quad (5)$$

In the process of calculating T_{shift} , t_2 is obtained according to the cyclic condition and t_1 is T_{shift} .

Simulation analysis

In order to compare the effects of CD-CS control strategy and Four-State control strategy on fuel economy, the vehicle simulation model is established by using GT-drive.

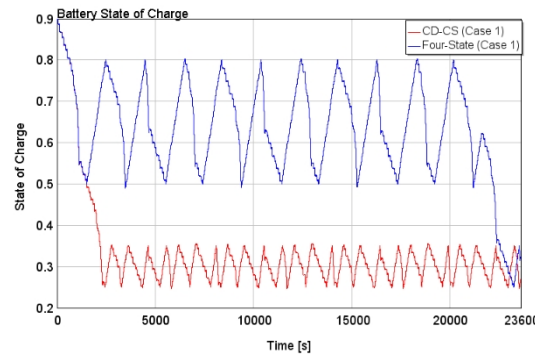


Fig. 7 SOC change chart

As shown in Fig 7, under different control strategies, the SOC values are changed with different trends. When the mileage is greater than that of pure electric vehicle mileage, The SOC in the CD-CS control strategy will be in a low state for a long time, and the SOC in the Four-State control strategy will be in a high state for a long time. Table 2 shows that fuel economy gets a certain increase. The fuel consumption per 100km is 6L, 10.4% lower than the CD-CS control strategy.

Table 2 Simulation results

control strategy	Fuel consumption per hundred kilometers of 20 NEDC (L)	Improved
CD-CS	6.7	-
Four State	6	10.4

Summary

The simulation results show that under the condition of known driving condition, that fuel economy of Four-State strategy is better than that of CD-CS strategy. In the actual operation of the vehicle, driving conditions are often unknown. How to connect Four-State strategy and real-time traffic is the next content to be researched.

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References

- [1] H.M. Xie, H. Yong, W. Jing, et al. Review of Energy Management Strategies for Plug-in HEVs. Journal of Chongqing University of Technology: Natural Science, Forum Vol. 29 (2015) , pp. 1-9.

- [2] C. Anderson, E. Pettit. The effects of APU characteristics on the design of hybrid control strategies for hybrid electric vehicles. Training, Forum Vol .4(2010), pp. 10-29.
- [3] C.G. Hochgraf, M.J. Ryan, H.L. Wiegman. Engine control strategy for a series hybrid electric vehicle incorporating. SAE Technical Paper, Forum Vol .18(1996), pp.11-24.
- [4] W. Peng, J.Z.Zhang, Q.C.Lu. Simulation on the Control Strategy of Hybrid Electric Bus. Journal of Highway and Transportation Research and Development, Forum Vol 20 (2003), pp.10-29.
- [5] J. Gonder, T. Markel, Energy management strategies for plug-in hybrid electric vehicles, SAE World Congress, Forum Vol 6(2007), pp.5656-5675.
- [6] G.M. Liu, M.G. Ouyang, L.G. Lu. Driving Range Estimation for Electric Vehicles Based on Battery Energy State Estimation and Vehicle Energy Consumption Prediction. Automotive Engineering, Forum Vol 36 (2014), pp. 1302-1310.
- [7] Y. Chen, F.C. Shun. Study on Range and Its Related Factors of Electric Vehicles, Forum Vol 21 (2011), pp. 578-581.