Research on energy control strategy of PHEV

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Abstract. According to the characteristics of Plug-in hybrid electric vehicle, PHEV optimal fuzzy control is proposed. The engine operating points are controlled on optimal fuel consumption curve. Based on the power request and SOC, the fuzzy controller can distribute the engine given power and the condition of SOC drop with insufficient of energy recovery is improved to realize constant SOC control. Furthermore, ADVISOR is developed by Fuzzy control model embedding, and make simulation experiment under different driving cycle. The studies on case prove that PHEV optimal fuzzy control can realize the constant SOC control under road conditions, so that it has the well robustness.

Keywords: Plug-in hybrid electric vehicle, simulation, control strategy, fuzzy control.

1. Introduction
With the progress of society and the development of science and technology, the hybrid electric vehicle (HEV), which has the advantages of improving fuel consumption and reducing emissions, has begun to be popularized in large scale. However, HEV still depends on petroleum fuel, and the prospect is not optimistic. On this basis, plug-in hybrid electric vehicle (PHEV) was born. The key technology of PHEV is to ensure the power performance of the vehicle, improve the fuel economy, reduce emissions, and maintain the balance of battery charge and discharge, and reasonable energy distribution control.

In order to solve this problem, this paper proposes an optimal fuzzy logic control strategy for PHEV based on the design goal of PHEV. In terms of fuzzy input, the battery power, the output torque of vehicle driving demand and the motor speed are comprehensively considered. The situation of insufficient energy recovery and SOC decline is improved, and the electric vehicle simulation software based on Simulink is used for the second time. Develop ADVISOR for simulation test verification.

2. Working mode
As plug-in hybrid electric vehicle can be charged through the external power grid, the power and energy of its battery are larger than that of ordinary hybrid electric vehicle, and the driving range of pure electric vehicle is longer. Therefore, priority should be given to the driving of vehicle driven by battery alone. According to a certain value of SOC consumption of battery pack, PHEV is divided into two working modes: power consumption mode and power holding mode. The control strategies of these two working modes are quite different [1]:

1) Power consumption mode with electric energy as the main energy: after the battery system is fully charged, the vehicle starts in pure electric mode, and the electric energy obtained by the battery from the power grid can meet the vehicle driving demand in a short distance. If the demand of high-power
conditions, continue pure electric driving need to use expensive high-power motor and battery, so the cost is too high. So, we adopt the Electric energy is the main energy source of hybrid control strategy, the motor provides most of the power, the engine provides a small part of auxiliary power.

2) Power holding mode based on engine: when battery pack When the energy consumption reaches a certain level, the battery cannot meet the driving needs of the vehicle, so it needs to be driven by the engine and the motor.

3. Optimal fuzzy control strategy for plug in HEV

When the speed or torque demand of PHEV reaches a certain switching value, the vehicle will switch from pure electric mode to engine-based hybrid drive mode. In this mode, the engine usually works on the optimal curve to provide most of the power, and the difference between the output torque and the vehicle driving torque depends on electricity Only when the battery SOC is insufficient and the motor's supplementary capacity cannot meet the vehicle's driving demand, the engine's working point will deviate from the optimal curve, and the SOC balance should be controlled. According to the above, the optimal fuzzy control strategy of PHEV is composed of power distribution according to the optimal curve of engine and SOC balance control [2].

3.1. Optimal interval fuzzy control of engine

Fuzzy control is a kind of computer digital control based on fuzzy set theory, fuzzy linguistic variables and fuzzy logic reasoning [3]. Advisor fuzzy control strategy takes the engine torque and SOC of battery state of charge as the basis to calculate the engine output torque, but does not consider the efficiency of the motor. In fact, the loss of energy secondary conversion of hybrid power is mainly the energy loss of motor when working, so the efficiency of motor should be considered when controlling the output torque of engine. According to the design goal of fuzzy controller and the efficiency of engine map, the main torque is provided by the engine as the main power source. The motor buffers and compensates the difference of residual torque. The input of fuzzy controller is determined as the difference Δt between the required torque of the whole vehicle and the actual torque of the engine working in the optimal working range, SOC of battery and current motor speed Nm.

Considering the load characteristics of the engine, the input variable Treq is divided into five fuzzy sets \{lower, low, optimal, high, higher\} in the universe \[0,1\]. According to the characteristics of battery internal resistance, the input variable SOC is divided into five fuzzy sets \{lower, low, mid, high, higher\}. According to the characteristics of the motor, the motor speed is divided into two fuzzy sets \{low, high\}. The fuzzy set of engine output torque can be divided into \{small, small, optimal, big, bigger\}, in which "optimal" represents the best engine torque. The trapezoidal membership function is adopted for fuzzy input language variable and output language variable, which is convenient for parameter adjustment. According to the membership function of fuzzy control input and output in MATLAB simulation toolbox [4], as shown in Figure 1.
In fuzzy reasoning, the and operation is small, the implication operation is Mamdani method, and 50 rules are established. The conclusion synthesis uses the cumulative addition method, and the area barycenter method is used for non-fuzzification. The control rule is shown in Table 1, and the control rule surface is shown in Figure 2.

**Table 1. Fuzzy Control Rules**

| SOC  | SOC  | ΔT   | lower | low  | mid  | high  | higher |
|------|------|------|-------|------|------|-------|--------|
| Lower| Opti | Opti | Smaller| Smaller| Smaller| Smaller| Smaller|
| Low  | Big  | Opti | Small | Opti | Big  | Opti | Opti |
| Opti | Bigger | Big | Opti | Big | Opti | Big | Opti |
| High | Bigger | Bigger | Opti | Bigger | Opti | Big | Opti |
| higher | Bigger | Bigger | Opti | Bigger | Opti | Big | Opti |

**Motor low speed**

| SOC  | Trq  | lower | low  | mid  | high  | higher |
|------|------|-------|------|------|-------|--------|
| Lower| Opti | Opti | Smaller| Smaller| Smaller| Smaller|
| Low  | Big  | Opti | Small | Opti | Opti | Opti |
| Opti | Big  | Big  | Opti | Opti | Opti | Opti |
| High | Bigger | Big | Bigger | Opti | Opti | Opti |
| Higher| Bigger | Bigger | Opti | Bigger | Opti | Opti |

**Motor high speed**

Several rules are listed as follows: (1) If Try = lower & SOC = lower & Nm = high, then TE = optimal. It means that the request torque is very small and the SOC is very low, so it needs to be charged in time. At this time, the motor acts as a generator to generate electricity and is in a high efficiency state. The torque output by the engine is used to drive driving and to drive the generator to generate electricity.
If $\text{Try} = \text{Higher} \& \text{SOC} = \text{Higher} \& \text{Nm} = \text{high}$, then $\text{TE} = \text{optimal}$. It means that the required torque is large, the SOC is high, and the motor is in high efficiency state, and the output torque is large. The motor can be used to provide part of the power to make the engine in the optimal torque state.

Figure 2. Fuzzy controlling surface of input and output parameter

In order to make the fuzzy control more accurate, the fuzzy rules are feedback adjusted. When the deviation $\delta$ between the actual response and the expected response is fed back to the controller, the controller corrects the fuzzy output of the engine based on $\delta(\Delta T) \ \delta(\text{SOC}) \ \delta(N_m)$, and then the required correction $p(n)$ of the controller output is transformed into the output correction $r(n)$ applied to the controller:

$$p(n) = \Pi( \ \delta(\Delta T) \ \delta(\text{SOC}) \ \delta(N_m) )$$

$$r(n) = H^{-1} p(n)$$

$H$ is the process incremental model matrix in the formula.

By fuzzing the inputs $\delta \ \Delta T(nt - mt) \ \delta \ \text{SOC}(nt - mt) \ \delta N_m(nt - mt)$ and expected output $T_e'(nt - mt) + r(n)$ of the controller, the corresponding fuzzy subsets $\Delta T(nt - mt) \ \text{SOC}(nt - mt) \ N_m(nt - mt)$, $T_e'(nt - mt)$ are obtained. Then the relation matrix of the modified control rules is:

$$R(n) = \Delta T(nt - mt) \times \text{SOC}(nt - mt) \times N_m(nt - mt) \times T_e'(nt - mt)$$

3.2. Battery SOC balance control

The optimal curve control strategy can basically achieve the control goal of PHEV in the power holding stage, but when the energy recovered from braking is not enough to meet the power supply of the motor, if the engine is not used for power generation, the battery’s SOC value at the end of the cycle is lower than that at the beginning of the cycle. Therefore, it is necessary to develop a battery SOC balance fuzzy control strategy to assist the engine optimal interval control to achieve better control effect.

The fuzzy control unit also adopts Mamdani method. The two input parameters are the difference SOC$_1$ of battery power and the change SOC$_2$ of battery power. The difference of battery power refers to the difference between the battery power value and the target control value at the end of driving cycle. Its fuzzy sets are: SOC value of battery at the end of driving cycle is lower, normal and higher than the target control value. The variation of battery power refers to the difference between the battery charge value at the end of driving cycle and that at the beginning of driving cycle. Its fuzzy sets are, respectively,
indicating that the SOC value of battery at the end of driving cycle and at the beginning of driving cycle is decreased, balanced and increased.

The fuzzy sets of Tec are \{smaller, small, optimal, big, bigger\}, in which "smaller" greatly reduces the output torque of the engine, "small" slightly reduces the output of engine torque, "big" slightly increases the output of engine torque, "bigger" represents a substantial increase of engine output torque. The membership function of fuzzy control output in the simulation toolbox is used, as shown in Fig. 3.

![Figure 3. SOC balance control membership function of output parameter](image)

3.3. Simulation of fuzzy control strategy
After the design of fuzzy logic controller is completed, the fuzzy control strategy module can be built in Matlab/Simulink environment according to the input and output of the control strategy module in advisor. As shown in Figure 4, the established model is embedded into advisor to carry out secondary development of advisor [5]. According to the ratio of the torque and the motor speed, the motor torque is converted into the maximum value according to the ratio of the motor torque and the motor speed Actual output torque.

![Figure 4. Fuzzy control strategy model](image)

4. Comparison of simulation results
The energy control strategy of plug-in hybrid electric vehicle is simulated by the secondary developed advisor [6]. Under the conditions of sufficient energy recovery in Beijing and insufficient energy
recovery in New York City, the advantages of PHEV optimal fuzzy control strategy over traditional electric auxiliary control strategy are verified, and SOC balance fuzzy control is added to assist optimal interval fuzzy control strategy to achieve better control effect.

4.1. Performance comparison between optimal interval fuzzy control and electric assistant control

Under the Beijing cycle, PHEV can adopt two control strategies: optimal interval fuzzy control and electric auxiliary control, and the control results of the two controllers are different. Under the electric auxiliary control, it can be seen from figure 5 that the engine starts and stops frequently. After adopting the optimal interval fuzzy control, it can be seen from Figure 6 that the working state of the engine is relatively stable.

In the case of insufficient energy recovery of New York cycle, PHEV is simulated. Under the optimal operating range fuzzy control, the fuel economy of PHEV decreases, and the battery SOC is in a state of decline (Fig. 8). Because the battery power is relatively low, there is not enough discharge capacity. At this time, the engine first provides the energy required by the external load, but also sends out more power to charge the battery. Therefore, the engine inevitably works in the low efficiency area. However, with the increase of SOC balance fuzzy control, the SOC of battery decreases slightly, but the change is not big, and it is always in the state of sufficient electricity (Fig. 7), which can effectively assist the engine to work in the appropriate working mode, so the engine can still work well in the high efficiency area.

![Figure 5. Electric auxiliary control torque output](image1)

![Figure 6. Optimal control interval fuzzy control torque output](image2)
4.2. Economic analysis

Table 2 is the economic comparison between the traditional electric auxiliary control and the optimal interval fuzzy control. From the simulation results, it can be seen that for the energy recovery sufficient cycle of Beijing cycle, the fuzzy control can fuzzify the control parameters, realize the reasonable distribution of power, and achieve better control effect. Compared with the electric auxiliary control strategy, the fuel economy is improved, the fuel consumption rate decreased by 2.1%. But for the New York cycle with insufficient energy recovery, the fuel economy of fuzzy control strategy is lower than that of electric auxiliary control strategy.

| Driving cycle  | Fuel economy L/100km | Economy          |
|----------------|----------------------|------------------|
|                | Electric auxiliary control | fuzzy control |
| Beijing        | 25.7                 | 20.2             | Increase 2.3% |
| New York       | 39.2                 | 43.1             | Reduce 4.5%   |

After adjusting the fuzzy control strategy of the New York cycle under the condition of insufficient energy recovery, the fuzzy control strategy of battery SOC balance was formulated. Table 3 shows that under the New York cycle condition, when the energy recovery is insufficient, through the battery SOC balance control to assist the engine optimal interval control, the battery efficiency, braking energy recovery efficiency and fuel consumption changes before and after adjustment, the braking energy recovery efficiency has been improved, and the fuel economy has also been greatly improved.

| Battery efficiency | Braking energy recovery rate | Fuel consumption (L/100km) |
|--------------------|------------------------------|-----------------------------|
| Optimal interval fuzzy control before adjustment | 86   | 25   | 45   |
| Plus, SOC balance fuzzy control                      | 91   | 31   | 39   |
| Improvement rate (%)                                   | 5    | 24   | 14   |

5. Conclusion

The key of PHEV control is the reasonable distribution of engine and motor torque. In this paper, an optimal fuzzy control strategy is designed, which takes into account the fuel economy of the engine and the battery SOC balance.

The simulation of the control strategy depends on a certain road condition, and the simulation of the control strategy depends on a certain road condition. For the case of sufficient energy recovery, the fuel economy of the engine optimal interval control strategy is better than that of the electric auxiliary control.
strategy. However, in the case of insufficient energy recovery, it needs to be improved through different control strategies. Simulation analysis shows that the improved optimal fuzzy control can control the engine near the optimal fuel line and realize the battery SOC change in a reasonable range.

The optimal fuzzy control strategy has certain robustness and is more efficient than the basic power auxiliary control strategy.

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