Research on Fuzzy Control Strategy and Genetic Algorithm Optimization for Parallel Hybrid Electric Vehicle

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Abstract. In this paper, the fuzzy control strategy for parallel hybrid electric vehicle (HEV) is proposed. Based on fuzzy logic theory, SOC and torque demand scale factor are taken as the input, a fuzzy logic controller is designed. Combining with the rule-based control strategy (RBCS), the engine and motor output torque are gotten, so the whole energy control strategy is proposed. Then the genetic algorithm (GA) is used to get the optimal results: fuel consumption and emission level, to verify the accuracy of fuzzy control strategy.

1. Introduction
Energy control strategy plays an important role in the HEV design. It has an obviously impact on the HEV’s fuel consumption and emission level [1-3]. Salmasi [4] proposed a power following control strategy, it means the engine provides the most power and motor provides the rest. Banvait [5] proposed a rule-based energy management strategy for plug-in hybrid electric vehicle. Sciarretta [6] proposed a model-based strategy for the real-time load control of parallel HEV. It designs a system just rely on the current operation. Sun [7] is aimed at the heavy hybrid vehicle and proposed a configuration consisting of hydraulic/electric synergy system.

In this paper, the fuzzy logic theory is adopted to design a fuzzy logic control strategy (FLCS) because of its good robustness and adaptability. According to fuzzy controller, the scale factor is calculated to get the motor target torque. And combining with the rule-based control strategy, the torque can be distribution between engine and motor. Then the accuracy is verified by simulation and the optimal results based on GA.

2. Energy Control Strategy Design
The structure of rule-based control strategy is simple and easy to realize, but it ignores the efficiency of the energy conversion and is lack of robustness. HEV energy control system is a high complex non-linear system so that it is difficult to express the variables. The energy control strategy based on fuzzy logic theory can avoid using the precise mathematical model. Therefore, the fuzzy control strategy is adopted in this paper to solve the problems above.

2.1. Component Selection
Based on the existing vehicle, the external parameters are unchanged. Then the power system is transformed into a parallel hybrid drive, under the requirements of vehicle power, selecting the approximate parameters to achieve the power distribution.
2.2. Torque Distribution
The aim of the HEV energy control strategy is using the motor with high work efficiency to compensate engine output power to make the engine work in the high efficiency area. According to this, the rule of torque distribution can be defined: 1. When the required torque is small, the motor output positive torque to drive HEV with engine; 2. When the required torque is large, the motor output negative torque to optimize the engine work efficiency.

2.3. Fuzzy Controller Design
There are lots of variables in the energy control strategy, which variables should be chosen is very important for fuzzy controller design. Considering with the torque requirements, SOC and scaling factor (required torque divided by engine optimal torque) are selected as the input of fuzzy controller. The aim of the fuzzy controller design is get the motor target torque. Therefore, the scaling factor of motor target torque k is selected as the output. The fuzzy controller is shown in Fig.1.

It should be noted that only positive torque flows into the fuzzy controller. When the torque is negative, the energy will flow into the recovery module. Then according to energy recovery strategy, distributing the braking torque to recover the energy.

Then the membership function should be built. Based on the fuzzy logic theory, initialing the membership function to describe the input and output variables. According to the simulation analysis and theory, the membership function is adjusted to make it adapt to energy control strategy.
Based on the torque distribution rule to build the rule base. Under the condition with the stable SOC, making the corresponding rules to meet the power requirement and make engine work in the high efficiency area. The rule base of fuzzy controller is shown in Tab.2.

| Motor target torque $k$ | Torque require scaling factor $u$ |
|------------------------|----------------------------------|
| LL                     | LL                               |
| L                      | L                                |
| M                      | M                                |
| H                      | H                                |
| HH                     | HH                               |

Table 2. Rule Base

2.4. Energy control system design
Because of the motor work efficiency is much higher than the engine, the appropriate motor torque should be selected to optimize the engine work efficiency, make the engine torque close to its optimal torque. When required engine torque is too small to make it work in the low efficiency area, the engine should be closed.

Combining with the fuzzy controller, the whole system is shown in Fig.3.

The output of the fuzzy controller is expressed by $k$, and the target torque of the motor is $T_{mot \_obj}$:

$$T_{mot \_obj} = kT_{mot \_max}$$  \hspace{1cm} (1)

In equation (1), $T_{mot \_max}$ is the maximum torque of the motor. Through the distribution module, in the ordinary, the engine output torque $T_{eng}$ and motor torque $T_{mot}$ are expressed below:

$$T_{eng} = T_{req} - T_{mot}$$
$$T_{mot} = T_{mot \_obj}$$  \hspace{1cm} (2)

In order to improve the engine efficiency, when required torque $T_{req}$ is very low, the engine should be closed. So the engine closing torque is set to avoid engine work in the low efficiency area.

When the engine output torque is lower than closing torque, engine should be closed and motor provides the whole torque.

$$T_{eng} = 0$$
$$T_{mot} = T_{req}$$  \hspace{1cm} (3)
When the required torque is larger than the engine maximum out torque $T_{\text{eng\_max}}$, engine outputs maximum torque and the rest is provided by motor.

$$ T_{\text{eng}} = T_{\text{eng\_max}} $$
$$ T_{\text{mot}} = T_{\text{mot\_obj}} $$  \hfill (4)

3. Simulation Results

In order to verify the strategy designed in this paper, comparison between with the RBCS and FLCS, simulating in ADVISOR with UDDS drive cycle to find out whether the fuel consumption and emission level of FLCS is better than RBCS. The simulation results are shown in Fig.4.
Fig. 4 Simulation results: (a) speed follow curve; (b) engine speed; (c) battery SOC change curve; (d) engine and motor torque of RBCS; (e) engine and motor torque of FLCS; (f) engine working area of RBCS; (g) engine working area of FLCS

Fig. 4(a) shows the speed curve of both strategies are well fit that of UDDS drive cycle. Fig. (b) shows the engine speed curves are almost same because of transmission and speed of drive cycle keep unchanged in the process of simulation. And Fig. (c) shows the SOC value is stability in the whole drive cycle. According to these, HEV meets the power demand.

Comparing with (d) and (e), in 180s-300s, the required torque increases, the motor of FLCS output more positive torque than that of RBCS so that battery of RBCS provides more torque. Therefore, the SOC value curve of FLCS is higher. And in the whole drive cycle, the motor of FLCS output more negative torque so that it can recover more energy. Therefore, as shown in (f) and (g), it is obviously to see that engine efficiency of FLCS is higher than that of RBCS so that FLCS has lower fuel consumption and emission level. It is well fits the data of Tab.3.
Table 3  Fuel Consumption and Emission Level

|                | RBCS | FLCS |
|----------------|------|------|
| Fuel consumption (L/100km) | 8.5  | 7.1  |
| CO             | 1.579| 1.032|
| HC             | 0.416| 0.231|
| NOX            | 0.284| 0.147|

4. Genetic Algorithm Optimization

4.1. Optimization target

Optimization target can be written in equation (5).

\[
\begin{align*}
\min_{X} F(X) &= [\text{Fuel}(X), \text{CO}(X), \text{HC}(X), \text{NOx}(X)] \\
\text{s.t. } & g_j(X) \geq 0, j = 1, 2, \ldots, m
\end{align*}
\] (5)

The equation (5) expresses a multi-objective optimization problem. \(X\) are the variables in the energy control system. \(\text{Fuel}(X)\) represents the fuel consumption function. \(\text{CO}(X), \text{HC}(X)\) and \(\text{NOx}(X)\) are the emission level function, represent \(\text{CO}, \text{HC}\) and \(\text{NOX}\) respectively.

The multi-objective problem is hard to optimize so that weight factors are used to represent each variable. Therefore, the optimization problem is transformed into single-objective problem and written in equation (6).

\[
F(X) = \alpha_{\text{Fuel}} \int \text{Fuel}(t)dt + \alpha_{\text{CO}} \int \text{CO}(t)dt + \alpha_{\text{HC}} \int \text{HC}(t)dt + \alpha_{\text{NOx}} \int \text{NOx}(t)dt
\] (6)

According to the standard, 100% short-circuit current was applied to the three phases in turn for three times, and a total of nine tests were carried out on the three phases. In this test, the waveform was abnormal during the phase B 1-tap test, and the test was stopped for a total of 4 times. The test current waveform is shown in Figure 6-9.

Table 4  Standard Values

| Symbol       | Value |
|--------------|-------|
| \(\text{HC}/\text{g}\cdot\text{km}^{-1}\) | \(\text{HC}_{\text{tar}}\) | 0.16 |
| \(\text{CO}/\text{g}\cdot\text{km}^{-1}\) | \(\text{CO}_{\text{tar}}\) | 2.11 |
| \(\text{NOX}/\text{g}\cdot\text{km}^{-1}\) | \(\text{NOX}_{\text{tar}}\) | 0.25 |
| \(\text{Fuel consumption}/\text{L}\cdot(100\text{km})^{-1}\) | \(\text{Fuel}_{\text{tar}}\) | 5.88 |

It is noted that the fuel consumption and emission level of HEV are non-negative so that the equation (6) can be used as the fitness function.

4.2. Coding and initial population

There are lots of variables in the energy control system, the most important parts of these are motor power, engine power, battery power and SOC value. So the four variables are chosen to be optimized.

Table 5  Optimized Variables

| Variables |                  |
|-----------|------------------|
| X1        | Engine power     |
| X2        | Motor power      |
| X3        | Battery power    |
| X4        | SOC upper limit  |
| X5        | SOC lower limit  |
In this paper, using binary code to optimize the target, and the optimization problem can be expressed as below.

\[ X = (X_1, X_2, X_3, X_4, X_5) \]  

(7)

Considering the calculation efficiency, the population size is 50 and generated by random population generation method.

4.3. Coding and initial population

The proportional selection is adopted in this paper, the chosen probability of each individual is proportional to its fitness. It can be expressed as equation (8).

\[ p_{i} = \frac{F_{i}}{\sum_{i=1}^{\text{popsize}} F_{i}} \quad (i = 1, 2, \ldots, \text{popsize}) \]  

(8)

For crossover, randomly select a segment of the gene of an individual and exchange with other individual, then detecting the both individuals whether have the duplicated genes, if they have, change the duplicated genes until they do not have duplicated genes.

In order to increase the diversity of population, mutation of each gene according to probability.

4.4. Operating parameters and constraints

Table 6 Main Parameters

| Parameter               | Value  |
|-------------------------|--------|
| Iterative generation    | 80     |
| Population size         | 50     |
| Coding length           | 55     |
| Generation gap          | 0.9    |
| Crossover probability   | 0.7    |
| Mutation probability    | 0.01   |
| Maximum speed (km/h)    | $\geq 140$ |
| Acceleration time: 0-100km/h (s) | $\leq 11.5$ |
| Maximum grade (%)       | $\geq 30$ |

4.5. Simulation results

According to Tab.6, the simulation based on GA optimization is shown below.
Comparison between with Fig.4(e) and Fig.5(b), the engine output torque is similar because of the same torque required. For motor output torque, although, the motor of GA provides a little more positive and negative torque. It just has a little improve on engine work efficiency as shown in Fig.5(c). And the extra torque always charges the battery so that the SOC battery curve of GA is higher.

Combining with the Tab.7, comparing with the optimal results, the fuel consumption and emission of FLCS is similar with the optimal results. So the energy control strategy based on fuzzy logic designed in this paper is suit for HEV.

**5. Conclusion**

This paper aims at the energy control strategy based on fuzzy logic for HEV. Following conclusion could be made:

1. The fuzzy logic theory is suit for HEV energy control strategy design because of its good robustness and adaptability.
2. Comparing with the RBCS and FLCS, the FLCS can improve the engine work efficient, fuel consumption and emission level.

3. After GA optimized, the optimal results are similar with the FLCS, the fuzzy controller designed in this paper is suit for HEV.

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