Energy Management of Plug-in Hybrid Electric Vehicle Based on Fuzzy Logic Control

FUXING YAO

ABSTRACT

In order to optimize the energy distribution of plug-in hybrid electric vehicle (PHEV) and improve the fuel economy and discharge performance of PHEV, a double fuzzy controller composed of two sets of input variables which are accelerator opening and change rate, torque requirement and state of charge (SOC) is designed. Particle swarm optimization algorithm is used to optimize the fuzzy control strategy to obtain the global optimal. The simulation results show that the energy management strategy with optimized fuzzy logic control can effectively reduce the fuel consumption and exhaust emissions.

INTRODUCTION

Air pollution, global warming and the rapid decline in oil resources have become the constraints of the sustainable development of the automotive industry. The traditional technology for Energy-saving & Emission-reduction has been unable to meet the needs of sustainable development, thus the development of efficient, clean and safe new energy vehicles become the primary task of the automotive industry.

Plug-In Hybrid Electric Vehicle (PHEV) is a new hybrid electric vehicle derived from the traditional hybrid electric vehicle (HEV), and it is equipped with a large-capacity battery pack which can be charged with the home energy grid. The biggest feature of PHEV is the combination of drive System for Hybrid Electric and pure electric, and this can greatly improve fuel economy of the traditional HEV and driving range of the pure electric vehicle. Therefore, PHEV as one of the most promising hybrid vehicles is increasingly concerned by automotive companies, research institutions and governments, and has gradually become the research hotspot on the field of new energy automotive [1].

Energy management strategy (EMS) is one of the core technologies of PHEV, and its core problem is to control the size and flow of energy between components such as motor, engine and battery to realize the reasonable distribution of energy.

EMS can improve fuel economy and emissions performance of PHEV in the condition of meeting the dynamic performance of vehicle. Therefore, the quality of energy management strategies directly affects the fuel economy, exhaust emissions.

Fuxing Yao . Department of Mechanical and Aerospace Engineering, Polytechnic of Turin, 10129 Turin, Italy
In recent years, researchers have optimized PHEV energy management strategies from different perspectives. A supervisory control strategy for plug-in hybrid electric vehicles based on energy demand prediction and route preview is proposed to optimally distribute the energy between the engine and the motor on a global range and achieve an optimal torque split on a local range [2]. YANG Chao et. Al proposed an equivalent grade estimation method and the relevant battery state of charge correction approach, and optimally distributed the energy in one city bus route by the employed equivalent consumption minimization strategy [3]. A corrected stochastic model predictive control (MPC) based Markov-chain was built for the statistic of city bus driving cycles to reduce unnecessary mode transitions and take advantage of multiple operation modes [4]. A blended rule-based energy management system for PHEV which was formulated over driving information and vehicle trip energy and not over vehicle speed profiles is proposed [5]. A driving pattern recognition based adaptive energy management approach which uses a fuzzy logic controller to classify typical driving cycles into different driving patterns and to identify the real-time driving pattern has been proposed to realize the adaptive energy management for real-time driving cycles [6]. A traffic data-enabled predictive energy management framework for PHEV is developed to rapidly generate battery SoC trajectories that are utilized as final-state constraints in the model predictive control level [7].

In this paper, a dual fuzzy logic controller composed of two sets of input variables which are accelerator opening and change rate, torque requirement and SOC is designed, and the particle swarm optimization algorithm is used to optimize the fuzzy logic controller. The simulation shows that the optimized energy management strategy has significantly lower fuel consumption and exhaust emissions.

ENERGY SYSTEM OF PHEV

The structure of PHEV powertrain is shown in Fig. 1. The system is mainly composed of vehicle controller, engine, integrated starter/generator (ISG) motor, wet multi-disc clutch, continuously variable transmission (CVT), electric oil pump, battery pack, charger and other components.
The vehicle controller controls the combination and separation of wet multi-disc clutch to achieve starting the engine by ISG motor and mode switch of vehicle. The establishment between Oil Pressure of accumulator and CVT is realized by controlling the operation of the electric oil pump under low speed. The CAN bus is used for the communication among vehicle controller, engine controller, motor controller, battery management system and CVT controller to monitor the operation status of the vehicle and control torque, speed, operating mode of motor and engine.

ENERGY MANAGEMENT STRATEGY BASED ON FUZZY LOGIC CONTROL

To improve energy consumption economy, the energy management strategy in this paper is shown in Fig. 2. First, using the torque requirement $T_r$ and SOC as input, the fuzzy logic controller 1 is designed, and the output of controller 1 multiplied by the scale factor $\beta$ as the main part of motor output torque; secondly, using the accelerator opening and change rate as input, the fuzzy logic controller 2 is designed, and the output of controller 2 multiplied by the scale factor $1 - \beta$ as the modification part of motor output torque; finally, in order to overcome the shortcoming of the fuzzy controller, the particle swarm optimization algorithm is used to optimize the fuzzy logic control and obtain the global optimal value.
THE DESIGN OF FUZZY LOGIC CONTROL

The fuzzy logic control is shown in Fig. 2. The total torque requirement and SOC are the input of the fuzzy logic controller 1, accelerator opening and its change rate are the input of the fuzzy logic controller 2. The output of fuzzy logic controller 1 and fuzzy logic controller 2 is weighted to obtain the motor output torque.

The fuzzy subset and the membership function of the input and output of fuzzy logic controller 1 are shown in Fig 3. For easy calculation, the triangular and trapezoidal function is used as membership functions.

The input variable Tr and output variable Tm can be divided into five fuzzy subsets. The main reason is as follows: when Tr is very small and the battery is not saturated, the motor is in energy generation state to provide negative torque; when Tr is small, the motor decides whether to actively charge to increase the load depending on the size of the SOC; when the vehicle is running normally, try to ensure that the engine is in a high-efficiency state and the motor is in energy or no-working state; when Tr is very high, Motor energy is used to reduce the load; when Tr is high, try to meet the torque requirements and no longer consider the engine economy.
The energy density of the Ni-MH battery is not high, thus the SOC can be divided into three fuzzy subsets. The main reason is as follows: it is considered to be a loss state when SOC is below 0.5, and the motor mainly generate energy at this time; it is considered to be a ideal state when SOC is between 0.5 and 0.8, and the motor is mainly in no-working or electric state at this time; it is considered that the battery exceeds the upper limit of use performance when SOC above 0.8, and the motor is mainly in electric state at this time.

The 0-120N•m range of input variable Tr can be averagely divided into 10 intervals with the corresponding domain is \{0,1,2,3,4,5,6,7,8,9,10\}, the 0-100% range of another input variable SOC can also be averagely divided into 10 intervals with the corresponding domain is \{0,1,2,3,4,5,6,7,8,9,10\}, and the 0-100N•m range of output variable motor torque can be averagely divided into 10 intervals with the corresponding domain is \{0,1,2,3,4,5,6,7,8,9,10\}. Five fuzzy subsets denoted by \{VS, S, M, B, VB\} is defined for the total torque requirement; three fuzzy subsets denoted by \{VS, M, VB\} is defined for SOC; five fuzzy subsets denoted by \{VS, S, M, B, VB\} is defined for engine output torque.

After determining the fuzzy subsets and membership function of the input and output variables, the control rules of fuzzy logic control 1 is shown in Table 1.

The fuzzy logic control rules are as follows: (1)Tr is approximately the optimal torque at current speed, the motor does not work and the vehicle is driven by the engine alone; (2) Tr is certain value less than or greater than the optimal torque, the operating point of engine is located near the optimal torque curve, and the remaining part of the positive/negative torque is provided by the motor; (3)when SOC is high, motor torque can be increased appropriately, otherwise, it is reduced.

The fuzzy subset and the membership function of the input and output variables in fuzzy logic controller 2 are shown in Fig. 4. For easy calculation, the triangular function is used as the membership function. The accelerator opening and change rate can be averagely divided into five fuzzy subsets. After determining the fuzzy subsets and membership function of the input and output variables, the fuzzy logic control rules can be given as shown in Table 2.

<table>
<thead>
<tr>
<th>SOC</th>
<th>Tr</th>
<th>VS</th>
<th>S</th>
<th>M</th>
<th>B</th>
<th>VB</th>
</tr>
</thead>
<tbody>
<tr>
<td>VS</td>
<td>S</td>
<td>M</td>
<td>B</td>
<td>B</td>
<td>VB</td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>S</td>
<td>M</td>
<td>M</td>
<td>B</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>VB</td>
<td>VS</td>
<td>VS</td>
<td>S</td>
<td>M</td>
<td>B</td>
<td></td>
</tr>
</tbody>
</table>
Fuzzy reasoning uses Mamdani method. Firstly, the minimum value of the membership of two input variables in the same rule is selected as the membership of the rule antecedent. Secondly, the conclusions of each rule is obtained by calculating the membership of the rule consequent. Then, the result of the fuzzy reasoning is obtained by maximizing the conclusions of each rule. Finally, the result of the fuzzy reasoning is transformed into the actual control quantity using anti-fuzzification which adopts the centroid method.

**PARTICLA SWARM OPTIMIZATION**

Particle swarm algorithm is a kind of intelligent optimization algorithm which evolved from the foraging of birds. In the particle swarm optimization algorithm, the solution is the particle in the search range. During each iteration, each particle changes its current position and speed by continuously searching for two extremes. One of the
extremes is the individual extremum $P_{id}^k$, and the other is the global extremum $P_{gd}^k$.

The formula for updating the speed and position is as follows:

\[
V_{id}^{k+1} = \omega V_{id}^k + c_1 r_1 (P_{id}^k - X_{id}^k) + c_2 r_2 (P_{gd}^k - X_{id}^k)
\]

\[
X_{id}^{k+1} = X_{id}^k + V_{id}^{k+1}
\]

where $V_{id}^{k+1}$ and $X_{id}^{k+1}$ are the speed and position of the d-th component of particle i at the kth generation. $V_{max}$ and $V_{min}$ are the maximum and minimum speed of the particles, $X_{max}$ and $X_{min}$ are the maximum and minimum positions of the particles; $r_1$ and $r_2$ are the random number between 0 and 1, $c_1$ and $c_2$ are learning factors which are usually set as $c_1 = c_2 = 2$, $w$ is the inertia weight. The algorithm has a strong local search capability when $w$ is smaller, and the algorithm has more tend to global search when $w$ is larger. In order to better balance the local optimal and global optimal capabilities, the inertia weight is generally not set as a fixed value, but rather as a function which linear decreases over time. The inertia weight $w$ is given as follows:

\[
\omega = \omega_{max} - k \frac{\omega_{max} - \omega_{min}}{k_{max}}
\]

The total equivalent fuel economy and emissions are important indicators of the hybrid electric vehicle, thus the weighted value of total equivalent fuel consumption and emissions is used as the Fitness value in the particle swarm optimization to comprehensively optimize the fuel economy and emissions.

The steps to optimize the fuzzy logic controller using the particle swarm algorithm are as follows:

Step1: Encoding the control rules of all membership function and fuzzy logic controller, and determining the maximum speed and search range of particles.

Step2: After Initializing each particle, the membership function and control rule is added to the initialized particle group.

Step3: After initializing the speed, the speed of the particle is updated s according to equations (1) and (2), and the position of the particle is updated according to equations (3) and (4).

Step4: Inputting the decoding of the membership function parameters and the control rules to the designed Advisor fuzzy controller, simulating using the parallel hybrid electric vehicle model, and updating $P_{id}^k$ and $P_{gd}^k$ - or not, as the case may be.

Step5: Iterating Step 3 until the number of iterations reaches the maximum, or the improved value of $P_{gd}^k$ is less than the set value. At this time, the decoding of $P_{gd}^k$ is performed and the membership function parameter and its control rules are output.

**SIMULATION RESULTS AND ANALYSIS**

The vehicle model is built using Matlab/Simulink, and the energy management strategy based on fuzzy logic control is researched under new European driving cycle (NEDC) condition.
Fig. 5 shows the curve of SOC in NEDC. As we can see, the overall SOC is in a downward trend. In the acceleration and cruise phase of cycle block a and b (low speed), the total torque requirement is small or the vehicle is in the initial stage, and the vehicle is in pure electric mode with ISG motor as the energy source, thus the SOC in the descending stage at this time. In the acceleration and cruise phase of cycle block c, d and e (medium speed), the total torque requirement is medium, and the vehicle is in driving charge, hybrid drive or engine alone drive mode with engine as the main energy, thus the SOC fluctuates up and down, and overall in maintenance stage. In the acceleration and cruise phase of cycle block f, g and h (high speed), the total torque requirement is large, and the vehicle is in hybrid drive or engine alone drive mode, thus the SOC is in descending or maintenance stage. In the deceleration phase of each cycle block, the vehicle is in coasting or regenerative braking mode, ISG is in the energy generation mode to recovery the energy, and the SOC is in the rising stage.

Fig. 6 shows a comparison of the fuel consumption and exhaust emissions between pre-optimization and post-optimization. After optimization, the fuel consumption is reduced from 6.26 L (100 km) to 4.03 L (100 km), the CO emissions is reduced from 1.15 g km-1 to 0.67 g km-1, HC emissions is reduced from 0.38 g km-1 to 0.24 g km-1, NOx emissions is reduced from 0.16 g km-1 to 0.11g km-1. The decline of fuel consumption, CO emissions, HC emissions and NOx emissions are all about 30%.
CONCLUSION

In this paper, a double fuzzy logic controller composed of two sets of input variables which are accelerator opening and change rate, torque requirement and state of charge (SOC) is designed. The fuzzy logic controller reasonably distributes the energy of the PHEV to improve the fuel economy and reduce the emission. The fuzzy control strategy is optimized by particle swarm optimization algorithm to realize the global optimal. The simulation shows that the energy management strategy based on optimized fuzzy logic control can effectively reduce fuel consumption and exhaust emissions.

REFERENCES