Study on Energy Management Strategies for Series-parallel Plug-in Hybrid Electric Buses

Jiankun Peng, Hongwen He, Rui Xiong

Abstract

The power flow between the power sources and the performance of plug-in-hybrid electric vehicles (PHEV) significantly in fuel economy are mainly determined by energy management strategy. To research the energy management of the PHEV, the control strategy of a plug-in series-parallel hybrid electric bus (PHEB) is studied in this paper. Firstly, the simulation model of the PHEB is built with CRUISE software. Secondly, to explore the fuel-saving potential of the PHEB, the global optimal control strategy which adopts dynamic programming (DP) algorithm is studied and built with MATLAB software, although the minimum fuel consumption of certain driving cycle can be a benchmark for evaluating the energy management strategy of PHEB, the global optimal control strategy based on DP is rarely directly applied in real vehicle due to its long online computation time. At last, to ensure control timely, a rule-based control strategy is calibrated according to the computation results of global optimal control strategy. The simulation results show that, the fuel consumption per 100km decreased by 9.11% and the electric power consumption per 100km decreased by 6.27%.

Keywords: Energy management; Dynamic programming (DP); rule-based; Plug-in hybrid electric bus (PHEB)

Introduction

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The Plug-in hybrid electric vehicle (PHEV), which consumes less fuel than conventional vehicles and hybrid electric vehicles (HEV), can not only decrease the dependence on petroleum resources, but also reduce the emissions from vehicles. The energy management strategy significantly affects the performance of the PHEV, so many research institutes and colleges all over the world have performed lots of research on the energy management strategy of the PHEV. The paper [1] studied the rule-based energy management strategy for plug-in Prius by using the existed Prius model in the ADVOSOR software. The paper [2] studied the optimization of energy management strategy for parallel PHEB by using genetic algorithm. The paper [3] researched the rule-based energy management strategy for parallel-series PHEB.

In this paper, the energy management strategy research is carried out for a plug-in series-parallel hybrid bus (PHEB), and the possible working modes of PHEB in rule-based control strategy are analyzed, the dynamic programming (DP) algorithm is utilized to explore the global optimization of energy management strategy. At last, rule-based control strategy which can be applied in real vehicle is optimized according to the simulation result of the DP.

**Powertrain of Plug-In Series-Parallel Hybrid Electric Bus**

The schematic of the PHEB powertrain is shown in Fig. 1. The power system is consisted of diesel engine, integrated starter generator (ISG) motor, main drive motor and power battery pack. The maximum power of diesel engine is 147 kW, and the maximum torque is 730 Nm. The maximum power and the maximum torque of the ISG motor are 55 kW and 500 Nm. The maximum power and the maximum torque of the drive motor are 166 kW and 2080 Nm. The capacity of the power battery is 60 Ah, and the nominal voltage is 580 V. The main parameters of the PHEB are listed in Table 1. And the facing-forward simulation model of the PHEB is built in AVL Cruise software.

![Schematic of the PHEB powertrain](image)

**Table 1. Main parameters of the PHEB**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final drive ratio</td>
<td>6.17</td>
</tr>
<tr>
<td>Curb weight (kg)</td>
<td>12500</td>
</tr>
<tr>
<td>Gross weight (kg)</td>
<td>18000</td>
</tr>
<tr>
<td>CD</td>
<td>0.55</td>
</tr>
<tr>
<td>Facing area (m²)</td>
<td>6.6</td>
</tr>
<tr>
<td>Tire dynamic radius(mm)</td>
<td>473</td>
</tr>
</tbody>
</table>

**Rule-based energy management strategy for PHEB**

The rule-based energy management strategy of PHEB is more complicated than that of HEV. Generally, the PHEB works in three modes under rule-based control: electric vehicle (EV) mode, charge-depletion (CD) mode and charge-sustaining (CS) mode [4].
When the PHEB works in EV mode, the drive motor drives the bus alone, the energy comes from the power battery pack, the state of charge (SOC) decreases fast. When the PHEB works in CD mode, the engine and the drive motor drives the bus together, both fuel and power battery pack supply the energy, and the SOC decreases slower than that of in EV mode. While the bus works in CS mode, the engine, ISG and drive motor works together, the fuel supply energy alone to drive the bus and the SOC sustains in a proper range.

When the SOC is very high, the regenerative breaking is forbidden for protecting the power battery, so the SOC decreased to the specific lower state through EV mode for taking full use of the regenerative energy. In CS mode, the engine drives the bus directly and it also drives the ISG to generate electricity, the working condition of engine is very complicated, and the engine is inefficient than that in CD mode, so the PHEB usually works in EV+CD+CS mode under rule-based control strategy. The components’ working condition of each working mode was described in paper [4].

Global optimal energy management strategy based on dynamic programming

Rule-based control strategy just makes sure that the components work in their own efficient working areas, and didn’t take the system as a whole. And some driving cycles would also limit the performance of the rule-based control strategy, so the rule-based control strategy cannot take full use of the advantage of the PHEB. Global optimization methods optimize the energy distribution between the components for the whole trip to achieve the optimal comprehensive performance of the bus, and dynamic programming (DP) algorithm is effective to solve such problems.

According to the optimization target, we should build the cost function first. We considered the fuel consumption only, and the cost function can be expressed as:

$$ J = \sum_{k=0}^{N-1} fuel(k) $$  

where $N$ is the duration of the driving cycle, $fuel(k)$ is the instantaneous fuel consumption of each stage.

To avoid the situation that the components can’t supply the sufficient torque when the SOC may drop below the lower threshold value, another cost should be added to the cost function, so the cost function become as following form:

$$ J = \sum_{k=0}^{N-1} \left[ fuel(k) + \alpha \left( T_{req}(k) - T_{eng}(k) - T_{ISG}(k) - T_{m}(k) - T_{b}(k) / i_o \right)^2 \right] $$

where $\alpha$ is a positive weighting factor, $T_{req}$ is the required torque of the input side of the final drive, and $T_{eng}$, $T_{ISG}$, $T_{m}$, $T_{b}$ is torque of engine, ISG motor, drive motor and hydraulic brake, respectively, $i_o$ is the final drive ratio.

If we want the SOC to turns out to be the desired value at the final time, a terminal constrain on SOC is needed, so the cost function is rewrite as follows:

$$ J = \sum_{k=0}^{N-1} \left[ fuel(k) + \alpha \left( T_{req}(k) - T_{eng}(k) - T_{ISG}(k) - T_{m}(k) - T_{b}(k) / i_o \right)^2 \right] + \beta \left( SOC(N) - SOC_f \right)^2 $$

where $\beta$ is a positive weight factor, $SOC_f$ is the desired SOC value at the end of driving cycle.

Then we can build the DP recursive equation for PHEB based on Bellman optimal principle [5]. At last, the global optimal control path can be found by solving the DP recursive equation and finding the optimal control forward. The detail method to solve the DP problem can be found in [6].

Calibrating the rule-based control strategy using the DP

The PHEB studied in this paper doesn’t have the transmission, so the working point of the engine is related to the driving cycles closely. As shown in figure 2, the working area of the engine is narrow, and the working points are scattered. So it’s very hard to get the ideal PSR line.
Fig. 2. Power split ratio line of the PHEB

The figure 3 shows the torque demand at the final drive input, and the figure 4 shows the torque and speed allocation between the engine and the main drive motor under the optimal control.

Compared with the figure 3 and figure 4, we can see that the working area of the engine is centralized and the engine always work in efficient areas under the optimal control. So we can optimize the engine working area of the rule-based control strategy using the working area under the optimal control.

The engine working area before optimization is shown in figure 5, and the figure 6 shows the working area of the engine after optimization. Before the rule-based control strategy is optimized, set the initial SOC to be 0.6, and the fuel consumption and variation of SOC for 15 consecutive driving cycles are shown in
Figure 7. The PHEB consumed 22.52L diesel in 15 driving cycles under the rule-based control which hasn’t been calibrated. The trip distance is about 88.455km, so the fuel consumption per 100 km is about 25.46L/100km. The bus came to work in CS mode at the time of about 5000s of the trip, and the SOC at the final trip is 0.313. Compared with the optimal control, the fuel consumption per 100 km increased by 27.94%, while the electric consumption decreased by 2.71%. So there is great room for the rule-based control strategy to improve the fuel economy of the PHEB.

The working points of the engine in the CD mode are shown in figure 8. The working speed of the most points is higher than 1000r/min, the engine participate in driving the bus late, the drive motor supplies most of the desired torque, thus the SOC drops fast, and the bus comes into the CS mode earlier.

After the rule-based control strategy is calibrated, the fuel consumption and variation of SOC for the same driving cycles are shown in figure 9. The initial SOC is set to be 0.6 too.
According to the comparison of figure 7 and figure 9, the engine working area after the control strategy was calibrated is larger than that before calibration, which is more in accordance with the optimal control. The PHEB comes to work in CS mode at the time of about 9000s, the bus can work longer in the CD mode, the total fuel consumption decreased, and the SOC drops slower during the trip, which is in keeping with the variation of SOC under optimal control.

After the rule-based control strategy was calibrated, the working points of the engine in the CD mode under are shown in figure 10. The working areas mainly concentrate in the speed range higher than 800r/min. The engine comes into work earlier, and the drive motor supplies less power to the bus, so the SOC decreases slower. The working area which is larger than that before being calibrated is more in line with the optimal control.

**Conclusion**

The SOC of the PHEB is nearly decreases evenly from the initial SOC to the terminal SOC under the optimal control based on DP, and the bus works in CD mode during the whole trip. The optimal control is hardly used in real bus directly because of the limitation of the DP, and it is used to calibrate the rule-based control strategies usually. After the rule-based control strategy was calibrated, the simulation shows that the PHEB works longer in CD mode, and the fuel consumption decreased by 9.11%, and the electric power consumption decreased by 6.27%.

**References**


**Biography**

Hongwen He is currently a Professor with the National Engineering Laboratory for Electric Vehicles, Beijing Institute of Technology and a researcher with the Beijing Co-innovation Center for Electric Vehicles. His research interests include power battery modeling and simulation on electric vehicles, design, and control theory of the hybrid power train.