Real-time optimal energy management strategy for range-extended electric bus in Harbin urban bus driving cycle

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Abstract
Developing electric driving powertrain technology is the core of national strategies for Chinese electric vehicles. Range-extended electric vehicles, an important configuration, are focused by more and more automobile manufacturers and consumers. The energy management strategy is a key technology to develop range-extended electric vehicles. DP strategy can achieve the optimal energy management. However, it cannot be used in the real-time as the heavy computational burden. This paper establishes the simulation model of the range-extended electric bus which is developed independently by Tsinghua University. The model is simulated using the DP control strategy in the Harbin urban bus driving cycle. Minimum energy consumption is regarded as the optimization target. According to the simulation result, δSOC control strategy is put forward on the basis of the relationship between the SOC change per second and the motor power. This strategy can guarantee the fuel saving rate and be applied in the real time simultaneously. The simulation results show that when the range-extended electric bus runs 189km in the Harbin urban driving cycles, the fuel saving rate can exceed 30% with DP and δSOC strategies. The energy consumption difference between these control strategies is no more than 2%, but the δSOC strategy improves the computational efficiency significantly.

Keywords: DP strategy, Energy management strategy, Range-Extended Electric Bus; Real-time control

1 Introduction
The transport sector, a major oil consumer and greenhouse gas emitter, accounted for 26% of the world’s energy use and 23% of the energy-related greenhouse gas emissions (GHG) in 2004. Road transportation is responsible for over 90% of these emissions [1] [2]. To overcome the resulting air pollution and energy crisis, governments are encouraging automobile manufacturers to develop electric vehicles (EVs) and hybrid electric vehicles (HEVs). However, the battery cycle life and the travel range of such vehicles continue to hinder their development. Therefore, for now, range-extended electric vehicles seem to be the most promising among renewable energy vehicles [3].

Given that the energy required by range-extended electric vehicles is supplied mainly by range extenders and the electric power grid, optimal strategies should be applied to such vehicles’ energy management systems to minimize their energy consumption [4]. At present, these optimal strategies can be classified into three categories.
[5]: ruled-based strategies, modern control theory–based intelligent strategies, and optimal strategies. He et al. [6] presented several rule-based control strategies such as constant-voltage control, out-line control, and on-line control. Wei et al. [7] devised a model-based fuel optimal control for HEVs. The rule-based control strategy is easy to understand and realize. However, it lacks any rigorous mathematical basis, and it cannot extract the full performance potential of a hybrid system [8]. Schouten et al. [9] and Gong et al. [10] designed control rules for energy management systems by using fuzzy logic and neural network. The methods achieved better results than the traditional rule-based control strategy, but its results still have difference to those achieved with the optimal strategies. The dynamic programming (DP) algorithm is widely used in the optimal strategies. DP is one of the best methods for dealing with constrained non-linear optimal problems [11]. It is suitable for optimizing the control strategy of an energy management system when the driving cycle is known in advance. Geng et al. [12] and Barsali et al. [13] presented an equivalent consumption minimization strategy based on the DP algorithm. However, this strategy cannot be applied to real-time control because of its heavy computational burden. Given that the rule-based control strategy can be applied easily to real-time control, the DP algorithm can be combined with the rule-based control strategy. The resulting hybrid control strategy would not only have the global optimal feature of DP strategy but would also be easily applicable to real-time control. He et al. [14] used an optimal control strategy for a specified driving cycle to control long-distance driving cycle for a plug-in series-parallel hybrid electric bus. The strategy reduces the computational time significantly, while maintaining the desired precision. Chen et al. [15] designed a DP algorithm–based energy management strategy for range-extended electric vehicles. Then, a rule-based control strategy was designed considering the global optimal solution and driving cycle recognition. Peng et al. [16] considered energy consumption and GHG emissions to design an energy management strategy by using the DP algorithm and presented an adaptive rule-based control strategy based on the DP solution. Bianchi et al. [17] established a rule-based control strategy for HEVs by using the DP strategy. The corresponding simulation result was close to the optimal result.

We present a DP and rule-based hybrid control strategy for a range-extended electric bus (REEB) running the Chinese typical urban bus driving cycle. This strategy retains the advantages of the DP and the rule-based strategies, while reducing the computational burden.

![REEB powertrain system structure](image)

Figure 1: REEB powertrain system structure

2 REEB powertrain model

A schematic of the typical REEB powertrain is shown in Figure 1. The powertrain consists of a range extender, battery, traction motor, transmission, and the main reducer. The battery and the range extender provide power to the traction motor through electrical connections. The traction motor drives the wheels directly through the transmission and the main reducer. The entire power system is connected in series. One feature of the REEB is their large battery capacity, which provides greater power to the REEB, thus reducing fossil fuel consumption and emissions [18]. The range extender module of REEB mainly includes an engine, generator, and rectifier. The generator is mechanically coupled to the output shaft of the engine. The range extender can convert diesel power into electric power for direct use by the traction motor or for charging the on-board battery, thus extending the vehicle’s driving range. Moreover, when the power demand of the bus is higher than what the battery can supply, the range extender provides the insufficient power, thus ensuring dynamic performance.

2.1 Powertrain system modelling

We establish a backward simulation model considering the features of the DP strategy as well as the objective of analysing fuel consumption. The relative speed $u_i$ at each discrete time point $(k)$ can be calculated using Eq.1 by the driving cycle data.

$$u_i(k) = \frac{v(k)}{3.6} \quad (1)$$

where $v$ is the driving speed (km/h).
To fulfil the requirements of the DP strategy, the vehicle’s longitudinal dynamics model is expressed as the following state equation:

\[
\dot{u}_r(k) = \frac{1}{\delta(m_v + m_p)} \left( \frac{1000P_{req}(k)\eta_T}{u_r(k)} - \frac{u_r(k)}{\eta_T(k)}(F_r + F_w(u_r(k)) + F_s) \right)
\]

where \(\delta\) is the conversion coefficient of the vehicle rotation quality, \(m_v\) is the bus mass, \(m_p\) is the passenger mass, \(P_{req}\) is the demand power of the transmission, \(\eta_T\) is the efficiency of the transmission and the main reducer, \(F_r\) is the rolling resistance, \(F_w\) is the air resistance and the function of \(u_r\), and \(F_s\) is the slope resistance. The parameters of the REEB are shown in Table 1.

The drive power of the vehicle \(P_{motor}\) is provided by the battery \(P_{bat}\) and/or the range extender \(P_{re}\), as expressed by Eq. 3.

\[
P_{motor} = \frac{P_{req}}{\eta_{motor}} = P_{re} + P_{bat}
\]

where \(\eta_{motor}\) is the efficiency of the traction motor. Given the computational burden of the DP strategy, the dynamic characteristics of traction motor are ignored. The 2D look-up table is used for the traction motor model, as shown in Figure 2.

Table 1: Powertrain parameters of range-extended electric bus

<table>
<thead>
<tr>
<th>Bus</th>
<th>Size (Length×Width×Height)/mm</th>
<th>11980×2550×3200</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus Mass/kg</td>
<td>13400</td>
<td></td>
</tr>
<tr>
<td>Passenger Mass/kg</td>
<td>2760</td>
<td></td>
</tr>
<tr>
<td>Windward Area/m²</td>
<td>7.83</td>
<td></td>
</tr>
<tr>
<td>Air Resistance Coefficient (C_D)</td>
<td>0.75</td>
<td></td>
</tr>
<tr>
<td>Rolling Resistance Coefficient (f)</td>
<td>0.0076+0.00056(u_a)</td>
<td></td>
</tr>
<tr>
<td>Rolling Radius (r/m)</td>
<td>0.512</td>
<td></td>
</tr>
<tr>
<td>Speed Ratio of Main Reducer (i_0)</td>
<td>6.2</td>
<td></td>
</tr>
<tr>
<td>Speed Ratio of Transmission (i_g)</td>
<td>2.18</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Motor</th>
<th>Continuous Power/kW</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Power/kW</td>
<td>180</td>
<td></td>
</tr>
<tr>
<td>Maximum Torque/N·m</td>
<td>860</td>
<td></td>
</tr>
<tr>
<td>Maximum Speed/r/min</td>
<td>4500</td>
<td></td>
</tr>
<tr>
<td>Operating Voltage/V</td>
<td>300–450</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Engine</th>
<th>Displacement/L</th>
<th>1.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power/kW</td>
<td>82/4000r/min</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Generator and Generator Controller</th>
<th>Rated Power/kW</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Torque/N·m</td>
<td>220</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Power Battery</th>
<th>Capacity</th>
<th>180Ah</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Voltage/V</td>
<td>350–460</td>
<td></td>
</tr>
</tbody>
</table>
Generally, the equivalent battery models include Rint, PNGV, and GNL. The Rint model focuses on the charge/discharge resistance and the open circuit voltage of the battery, and it has a simple structure. What is more, it meets the demand of the DP strategy. Considering the features of the DP strategy, the following form of the state equation is used in the battery model [19].

\[ \dot{SOC} = \frac{I(k)}{Q_{bat}} \]

where \( I \) is the battery current, \( Q_{bat} \) is the battery capacity, \( \eta_{soc} \) is the Coulomb efficiency, \( U_{ocv} \) is the open circuit voltage of the battery, \( R_{int} \) and \( R_t \) are the internal resistance and thermal resistance, respectively. \( R_{int} \) and \( U_{ocv} \) are functions of the SOC. The equivalent circuit of the simplified battery model is shown in Figure 3.

![Figure 3: Equivalent circuit of simplified battery model](image)

As in [20], the charging \( \eta_{chg} \) and discharging \( \eta_{dis} \) efficiencies are calculated using Eq. 6.

\[ \eta_{chg} = \frac{U_{ocv} - IR_{dis}}{U_{ocv}} = \frac{1}{2} \left( 1 + \frac{4R_{dis}P_{bat}}{U_{ocv}^2} \right) \]

\[ \eta_{dis} = \frac{U_{ocv} - IR_{chg}}{U_{ocv}} = \frac{1}{2} \left( 1 + \frac{4R_{chg}P_{bat}}{U_{ocv}^2} \right) \]

where \( R_{dis} \) and \( R_{chg} \) are the discharging resistance and the charging resistance, respectively.

The dynamic characteristics of the engine and generator models in the range extender are also ignored to reduce the computational burden of the DP strategy. Their models are the MAPs, which are generated by using the data from the bench tests. Because the generator is mechanically coupled to the output shaft of the engine, the generator and engine are in the same working points. The optimal fuel economy curve of the range extender is developed by the method described in [15], as shown in Figures 4 and 5.

3 Driving cycle

As driving cycles are an important factor to affect the energy consumption of electric vehicles, this paper conducts the simulation on the basis of the Harbin urban bus driving cycle, as shown in Figure 5. Considering investigation results on typical cities of electric buses main running lines, the driving distance is about 200km per day. Therefore, given the large battery capacity of the REEB and the one-charge-per-day operation mode, the driving cycle for the simulation is 20 Harbin urban bus driving cycles, which spans 189.8km.

![Figure 4: BSFC map of engine](image)

![Figure 5: Efficiency map of generator](image)

![Figure 5: Harbin urban bus driving cycle](image)
4 Energy management strategy

4.1 DP strategy

In the horizon \([t_0, t_f]\), the state variables of the REEB powertrain system include the SOC of the battery and the bus speed. As the bus speed can be determined from the driving cycle, the state variable is \(x(t) = [\text{SOC}(t)]^T\). According to the optimal objective of minimum equivalent fuel consumption, the range extender is regarded as the control variable, \(u(t) = [P_{\text{el}}(t)]\). The powertrain system of the REEB in the discrete form is shown as follows:

\[
\dot{x} = f(x(k), u(k))
\]

where \(f\) represents this activity, this paper expresses the optimal conditions of the state space by Eq. 8.

\[
P_{\text{bat}} \in [U_{\text{bus,max}} - U_{\text{bus,min}}] / R_{\text{chg}},
\]

\[
U_{\text{bus,min}} - U_{\text{bus,min}} / R_{\text{dis}}
\]

\[
0 \leq P_{\text{ele}} \leq P_{\text{ele, max}}
\]

\[
\text{SOC}_0 < \text{SOC} < \text{SOC}_1
\]

\[
T_{\text{m,min}} < T_m(t) < T_{\text{m,max}}
\]

where \(U_{\text{bus,max}}, U_{\text{bus,min}}, U_{\text{ocv}}, R_{\text{chg}},\) and \(R_{\text{dis}}\) represent the maximum voltage, minimum voltage, open circuit voltage, and charging resistance and discharging resistance, respectively. \(P_{\text{ele, max}}\) represents the maximum power of the range extender. \(\text{SOC}_0\) and \(\text{SOC}_1\) represent the maximum and minimum values of the SOC, respectively. \(T_m\) denotes the traction motor torque; \(T_{\text{m,min}}\) and \(T_{\text{m,max}}\) represent the maximum torque and the minimum torque of the traction motor, respectively.

The key to the DP strategy is the reasonable cost function. In this paper, the electric power is equivalent to the fuel consumption, and achieving the minimum fuel consumption is regarded as the objective for reducing the fuel consumption and emissions. The cost function \(J\) is shown as follows:

\[
J = \sum_{k=0}^{n} \left[ C_{\text{ele},k} + k_k C_{\text{bat,k}} \right]
\]

where \(C_{\text{ele},k}\) is the fuel consumption of the range extender in the \(k\)-th state, \(C_{\text{bat,k}}\) is the equivalent fuel consumption of the battery in the \(k\)-th state, and \(k_k\) is the coefficient for constraining the SOC. The fuel consumption of the range extender, equivalent fuel consumption of the battery, and \(k_k\) can be calculated as follows:

\[
C_{\text{ele}} = P_{\text{eng}} / \eta_{\text{eng}} C_{\text{avg}} \Delta t
\]

\[
k_k = 1 - 2\mu \text{SOC} - 0.5(\text{SOC}_0 - \text{SOC}_1) / (\text{SOC}_0 - \text{SOC}_1)
\]

where \(P_{\text{eng}}\) is the output power of the engine in the \(k\)-th state, \(be\) is the specific fuel consumption, \(C_{\text{avg}}\) is the average fuel consumption of the range extender, \(P_{\text{ele, avg}}\) is the average output power of the range extender, \(\mu\) is the balance coefficient required to maintain the SOC within the reasonable range [21].

4.2 δSOC strategy

With the DP strategy to achieve minimizing the energy consumption, this paper analyses the optimal result features on the basis of the Harbin urban bus driving cycle. An obvious rule appears that the SOC changes per second are gathering at different motor output power. The δSOC strategy is formulated according to the relationship between the SOC changes per second and the motor power, which are fitted in a curve, as shown in Figure 6. This curve is regarded as the control rule for the battery SOC dropping.

5 Results and analysis

In order to verify the effect of δSOC strategy as mentioned above, the REEB is simulated to analyse the energy efficiency on the basis of the CTUDC. Drop curves of the battery SOC with 2 kinds of control strategies are shown in Figure 7.
In Figure 7, δSOC-RB strategy which are revised from the DP strategy have similar SOC dropping curves with the DP strategy. Figure 8 shows the relationship among the demand power of the motor, the output power of the range extender and the battery in different control strategies. When the battery output power is negative, the range extender is charging the battery. Because the driving cycle duration is long, a segment of 5000 s is extracted from the entire cycle.

Figure 8: Relationship among power of components based on the DP strategy

As shown in Figure 8, comparing δSOC strategy with the DP strategy, the output power features of the range extender are similar. The demand power of the motor and the battery output power have the same features in 2 kinds of control strategies. It means that the performance of the DP strategy can be approximated by the δSOC strategy effectively.

5.1 Comparative analysis on fuel and energy saving

Comparing to conventional bus in the same level, the energy saving effect and fuel economies of the REEB are analysed with the δSOC strategy. As the comparison results shown in Figure 9, fuel saving rates can reach 32.04% and 30.87% in the DP and δSOC strategies, respectively.

5.2 Comparison of computational efficiencies

Comparing to the DP strategy, the δSOC control strategy improve the computational efficiency significantly. It is more responsive with almost 0 time delay, which can be used in real-time to control the REEB.

6 Conclusion

In order to present an energy management strategy which can improve the energy efficiency and apply in real-time for the REEB, this paper design a rule-based control strategy from the SOC dropping rule of the DP strategy. The simulation is conducted to analyse the control effect of different strategies on the basis of the Harbin urban bus driving cycle. Conclusions are as follows.

1. On the aspect of energy efficiency optimization to the REEB, the δSOC control strategy derived from the DP strategy can achieve similar optimization effects as the DP strategy. The fuel saving rate can exceed 30% with DP and δSOC strategies. The energy consumption differences among these control strategies are no more than 2%.
2. The δSOC strategy not only keep the energy efficiency of the powertrain, but also improve the computational efficiency significantly. It can achieve real-time energy management for the REEB with 0 time delay control.

From the analysis shows above, the optimal performance of the δSOC strategy is in a high level. Considering the real-time performance, the δSOC strategy is ideal energy management strategy for the REEB in this paper.

Acknowledgments
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References


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