A Control Strategy to Reduce Fuel Consumption of APU for Range-extended Electric Vehicle

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Abstract. To reduce fuel consumption, a simulation model of range-extended electric vehicle for city bus drive cycle is established and a fuzzy control strategy to maintain battery SOC is put forward. The fuzzy controller’s input parameters are battery SOC and the change rate of SOC. Confirmed by the experimental results in MATLAB/Simulink, this strategy reduces 5\% fuel consumption and maintains SOC of battery nearby 30\%, which showes it’s an effective strategy.

Introduction

Range-extended electric vehicle has two power sources, the main one is the battery and the auxiliary one is the engine-generator unit, which allows it work in pure electric mode and hybrid mode [1]. In hybrid mode, a better control strategy decides less fuel consumption [2]. In this paper, theoretical model is combined with experimental datas to build the simulation model of range-extended electric vehicle sample A in MATLAB/Simulink. According to this simulation model, fuzzy control strategy of constant battery SOC (named S1 below) is compared with control strategy of constant engine speed (named S2 below) to see which one gets less fuel consumption.

Structure of power system and simulation model

Range-extended electric vehicle is a kind of series hybrid vehicle. Fig. 1 shows the structure of the power system, the APU (auxiliary power unit) is structured by high-speed diesel engine, permanent magnet synchronous generator and three-phase uncontrollable rectifier bridge. The motor adopts torque control and the gearbox is two-speed.

| Table 1 Parameters of vehicle |
|-------------------------------|-----------------|
| Parameter                     | Value           |
| Vehicle total mass            | 14500 kg        |
| Transmission ratio of main reducer | 6.5            |
| Tire radius                   | 0.432 m         |
| Frontal surface               | 6.7 m$^2$       |
| Rolling friction factor       | 0.012           |
| Battery capacity              | 35×4 Ah         |
| Driving range in pure electric mode | 50 km          |

![Fig. 1 Structure of power system](image1.png)

The parameters of vehicle are shown in Table 1 and the simulation model in MATLAB/Simulink is shown in Fig. 2 (take S1 for example).

![Fig. 2 Simulation model of range-extended electric vehicle](image2.png)
Fuzzy control strategy of constant battery SOC

Range-extended electric vehicle’s main power is battery, mostly works in pure electric mode. According to its pure electric driving range, it switches to hybrid mode only when battery SOC is low. The goal of APU controller is reducing fuel consumption while battery SOC maintaining on a suit level. In this paper, battery SOC is controlled around 0.3.

Structure of fuzzy controller

Fuzzy controller is adopted to maintain battery SOC in this paper (Fig. 3). The input parameters of fuzzy controller are battery SOC (named SOC), the change rate of SOC (named △SOC), and the output parameter is the expected current of battery (named CoefIb). As SOC reflects the DC bus voltage and △SOC reflects the change of battery current, battery SOC can maintain by the fuzzy controller’s output CoefIb.

Fig. 3 Structure of fuzzy controller

APU is the controlled object and the load current I_L is a disturbance. First, obtain the expected current of generator I_gexp by the expected current of battery I_bexp, which is the fuzzy controller’s output (Eq. 1). Second, calculate the expected power of APU P_gexp by DC bus voltage (almost equals to the battery voltage V_b), shown in Eq. 2. Combine battery SOC and P_gexp, the goal speed of engine n_goal is determined. The power system adjusts the generator current by controlling the engine speed, with the load demand, it also controls the battery current [3].

\[
I_{gexp} = I_L + I_{bexp} \\
P_{gexp} = V_b \times I_{gexp}
\]

Membership functions and control rules of fuzzy controller

A first-rate fuzzy controller requires good control rules, proper quantization factors for inputs and scale factors for outputs [4].

The membership functions of inputs SOC, △SOC and output CoefIb are shown in Fig. 4-6, all of them are triangle. SOC has five fuzzy states: NB, NS, Z, PS, PB, and its domain is [0.25, 0.275, 0.3, 0.325, 0.35]. The quantization factor Kc=1. △SOC has three fuzzy states: N, Z, P, and its domain is [-1, 0, 1]. The quantization factor Ke=1000. CoefIb has five fuzzy states: BC, SC, Z, SD, BD, and its domain is [-0.5, -0.25, 0, 0.5, 1]. The scale factor Ku=400.

Fig. 4 Membership function of SOC

Fig. 5 Membership function of △SOC

The control rules are shown in Table 2 and the inference method adopts Mamdani method, which can be expressed by if-then form below.

if SOC and △SOC, then COEF

As fuzzy controller with center of gravity method can export ideal results, it is used to make the output clear in this paper. This method is widely used when real-time is guaranteed.
The goal speed of engine \( n_{\text{goal}} \) is determined by \( SOC \) and the expected power of APU \( P_{\text{exp}} \), the control flow is shown in Fig. 7. The goal speed of engine has three levels and each level covers a range of \( P_{\text{exp}} \). Fig. 8 shows the hysteresis comparator for speed level switches. The step for speed raising or falling is 0.2 \( \text{r/min} \). Multi-point control of engine speed can make the engine easily follow the dynamic goal power [5].

**Control strategy of constant engine speed**

In fuzzy control strategy of constant battery SOC, the engine speed is adjusted by engine power demand. The fluctuation of engine speed leads to noise and poor engine performance. Control strategy of constant engine speed aims on a constant engine speed.

For the APU works in the whole driving cycle, the working time of APU equals to the driving cycle time \( T \). The average power that load demand is

\[
P_{da} = \frac{1}{T} \int_0^T P_d(t) \, dt
\]

The power ripple factor is

\[
R_{eq} = \frac{1}{\sqrt{T}} \int_0^T (P_d(t)-P_{da})^2 \, dt
\]

The energy consumption on battery’s internal resistance is

\[
E_R = \int_0^T \frac{R}{V_b^2} (P_d(t)-P_{da})^2 \, dt = \frac{R}{V_b^2} R_{eq}^2 \cdot T
\]

The total energy consumption on both battery and load is

\[
E_{\text{total}} = (P_{da} + \frac{R}{V_b^2} R_{eq}^2) \cdot T
\]

The DC bus voltage is expressed in the equation below

\[
V_b \approx U_{dc} = K_{n_{\text{g}}} \cdot K_{x} \cdot n_{\text{g}} \cdot I_{\text{g}}
\]

Assume APU equivalents to a constant voltage source during \( T \), and the equivalent voltage \( V_b \) almost equals to battery open circuit voltage \( U_{dc} \). The average power of APU \( P_{ga} = E_{\text{total}} / T \). According to Eq. 7, the goal speed of generator is
The goal speed of engine equals to the generator’s, which is determined on 2520r/min by equations above [3].

**Simulation Results**

NurembergR36 driving cycle for city bus is adopted in this paper. As is shown in Fig. 9, the vehicle speed can be well followed in both S1 and S2. The driving range of this cycle is 4.29km and the driving time \( T \) is 1084s.

The engine speed in S1 is shown in Fig. 10, mostly maintains 2500 r/min and well followed when raise and fall. In S2, the engine speed maintains 2520 r/min.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>SOC(_{\text{init}})</th>
<th>SOC(_{\text{end}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>0.3</td>
<td>0.2972</td>
</tr>
<tr>
<td>S2</td>
<td>0.3</td>
<td>0.2977</td>
</tr>
</tbody>
</table>

Table 3 Initial value and end value of SOC

Compare generator current with battery current in S1, the engine speed is adjusted by load demand, so the generator current’s wave range is larger than the battery current’s (shown in Fig. 12). In S2, the engine speed is constant, the battery follows the load demand, so the battery current’s wave range is larger than the generator current’s (shown in Fig. 13).
The operating points of engine is shown in Fig. 14. In S1, engine speed is adjusted by load demand, which leads to economy fuel consumption condition. In S2, some working points deviate economy fuel consumption condition. Table 4 shows S1’s fuel consumption is 5.1% less than S2’s.

Summary

With the same initial value and end value of battery SOC in the driving cycle, fuzzy control strategy of constant battery SOC gets less fuel consumption, smaller wave range of battery current and larger lifetime than control strategy of constant engine speed. Although engine speed wave leads to noise and poor engine performance, fuzzy control strategy of constant battery SOC is adoptable for range-extended electric vehicle, which is main powered by battery.

References