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 (naemd 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 geerbox is two-speed.

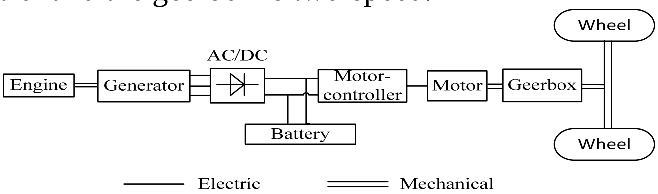

Fig. 1 Stucture of power system

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).

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 ㎡
Rolling firction factor	0.012
Battery capacity	35×4 Ah
Driving range in pure electric mode	50 km

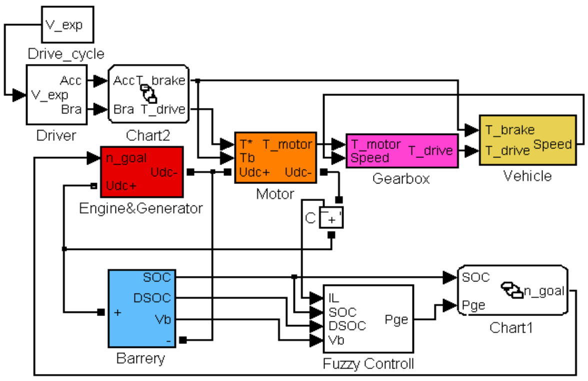

Fig. 2 Simulation model of range-extended electric vehicle

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*.

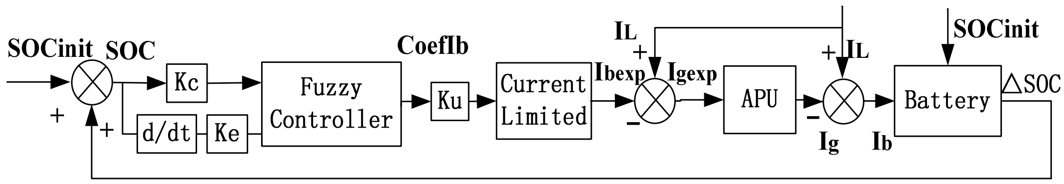

Fig. 3 Structure of fuzzy controller

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].

$$I_{gexp} = I_L + I_{bexp} \tag{1}$$

$$P_{gexp} = V_b \times I_{gexp} \tag{2}$$

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 mebership 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.

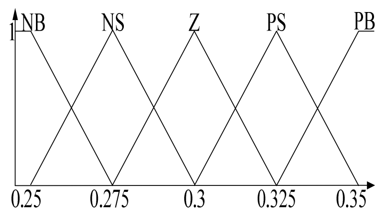

Fig. 4 Membership function of *SOC*

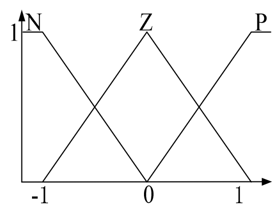

Fig. 5 Membership function of *△SOC*

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.

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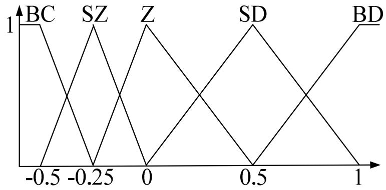

Fig. 6 Membership function of *CoefIb*

Table 2 Fuzzy control rules

△SOC \ SOC (COEF)	NB	NS	Z	PS	PB
N	BC	SC	Z	Z	SD
Z	BC	SC	Z	SD	BD
P	SC	Z	Z	SD	BD

Control flow of engine speed

The goal speed of engine *n_goal* is determined by *SOC* and the expected power of APU P_{gexp}, the control flow is shown in Fig. 7. The goal speed of engine has three levels and each level covers a range of P_{gexp}. Fig. 8 shows the hysteresis comparator for speed level switches. The step for speed raising or falling is 0.2 r/min. Multi-point control of engine speed can make the engine easily follow the dynamic goal power [5].

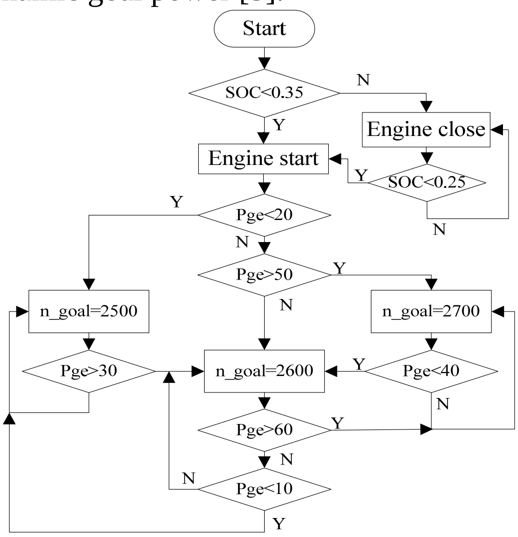

Fig. 7 Control flow of engine speed

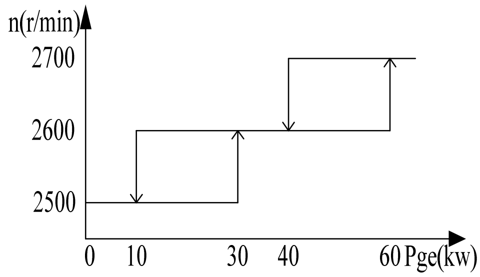

Fig. 8 Hysteresis compartor

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 dmand is

$$P_{da} = \frac{1}{T}\int_0^T P_d(t)dt \tag{3}$$

The power ripple factor is

$$R_{eq} = \sqrt{\frac{1}{T}\int_0^T (P_d(t)-P_{da})^2 dt} \tag{4}$$

The energy consumption on batterry's internal resistance is

$$E_R = \int_0^T \frac{R}{{V_b}^2}(P_d(t)-P_{da})^2 dt = \frac{R}{{V_b}^2}{R_{eq}}^2 \cdot T \tag{5}$$

The total energy consumption on both battery and load is

$$E_{total} = (P_{da} + \frac{R}{{V_b}^2}{R_{eq}}^2) \cdot T \tag{6}$$

The DC bus voltage is expressed in the equation below

$$V_b \approx U_{dc} = K_e n_g - K_x n_g I_g \tag{7}$$

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 $P_{ga}=E_{total} / T$. According to Eq. 7, the goal speed of generator is

$$n_g^* = \frac{30}{\pi}\frac{V_b^2}{K_eV_b\text{-}K_xP_{ga}} = \frac{30}{\pi}\frac{V_b^2}{K_eV_b\text{-}K_x(P_{da}+\frac{R}{V_b^2}R_{eq}^2)} \quad (8)$$

P_d - Load power demand

K_x - Equivalent resistance coefficient of generator

R - Battery internal resistance

n_g - Generator speed

K_e - Equivalent electromotive force coefficient of generator

I_g - Generator current

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.

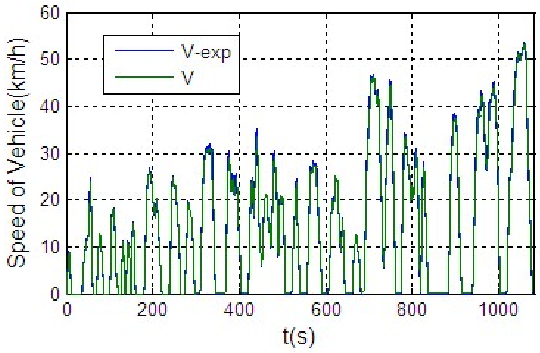

Fig. 9 Drive cycle

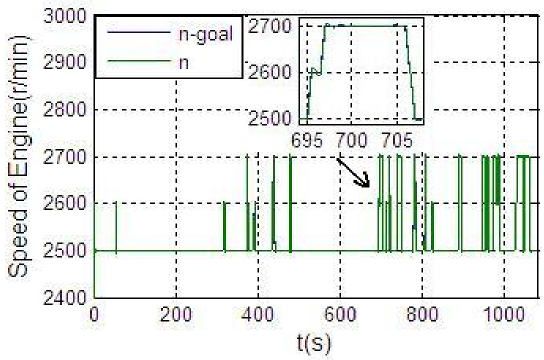

Fig. 10 Speed of Engine

Battery SOC can well maintain nearby 0.3 in S1, while the battery SOC has a little bigger wave range in S2 (shown in Fig. 11). Table 3 shows that the initial value and the end value of SOC in S1 and S2 are almost the same.

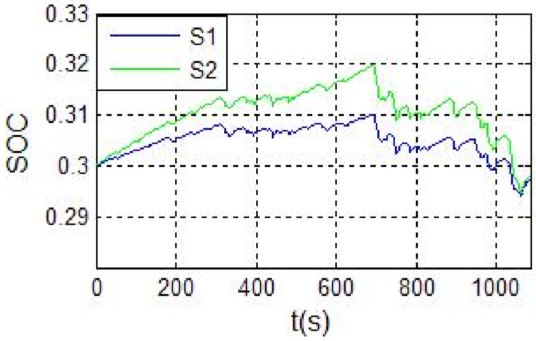

Fig. 11 Battery SOC

Table 3 Initial value and end value of SOC

Strategy	SOC_{init}	SOC_{end}
S1	0.3	0.2972
S2	0.3	0.2977

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).

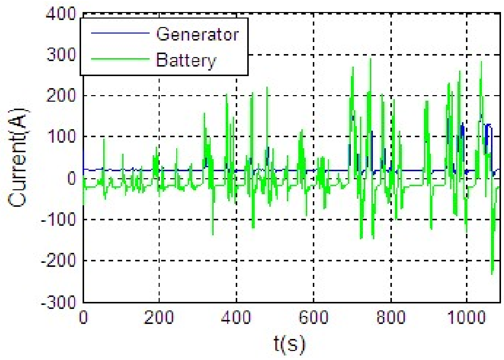

Fig. 12 Generator and battery currents in S1

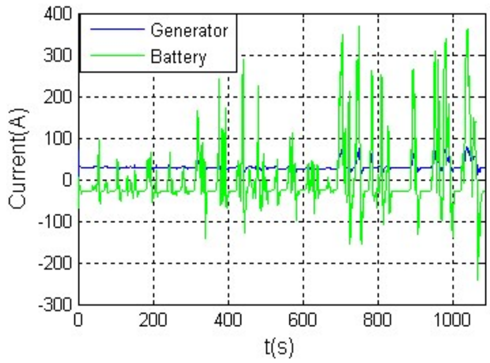

Fig. 13 Generator and battery currents in S2

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.

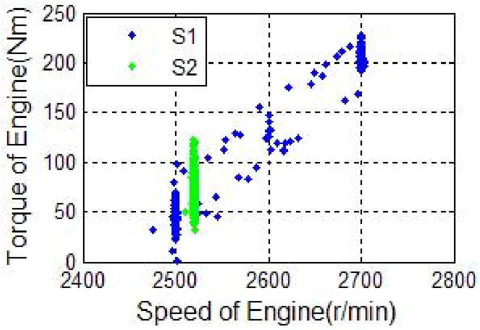

Fig. 14 Operating points of engine

Table 4 Fuel consumption

Strategy	Fuel consumption
S1	1320g
S2	1391g

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.

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