A four stage energy control strategy and fuel economy simulation for extended-range electric city bus

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Abstract

Because of the high cost of battery, lack of charging infrastructure and limitation of range, EVs are hard to be accepted by ordinary customers recently. Compared with EVs, range extender EVs should allow vehicle weight reduction, manufacturing cost reduction, and dramatic range extension. For most driving conditions, the range of E-REVs subjected to the same limitation as traditional internal combustion engine vehicles. Recently, our research group designed the power train and vehicle energy control strategy for an electric city bus which has a range extender composed of a gasoline engine and a generator. In this paper, a four stage energy control strategy applied to the bus is introduced. Based on the driving distance is fixed or can be forecasted, the strategy aims to optimize vehicle equivalent fuel economy by controlling APU output power to let the battery work on high discharge and charge efficiency state during the most time of driving process, and the battery SOC should maintain a low level at the end of the driving cycle. The vehicle equivalent fuel consumption is simulated by using a real time vehicle simulation platform. The simulation results show that four stage control strategy can make the bus save 0% to 2.7% of fuel consumption compared to CDCS strategy according to different mileage.

Keywords: E-REV, Energy Management, Four Stage Energy Control, Power Track

1 Introduction

Extended-range electric vehicle (E-REV) has an auxiliary energy supply, and the vehicle can function as a full-performance battery electric vehicle [1]. Because of the high cost and short life cycle of battery, EVs are hard to be accepted by ordinary customers recently. However, E-REVs are promising to fill the commercial vacancy during the transition period from traditional vehicles to pure electric vehicles.

Since 1992, some research institutes and companies have engaged in E-REV research. Keller and Whitehead [2] worked at Electrotek Concepts tested the performance of an extended-range electric vehicle, which was based on an electric G Van, and a 7-kW gasoline engine/generator (E/G) unit was retrofitted into the Van. Their research shows that the gasoline price, electricity price and driving distance can affect vehicle energy cost. Delphi's researchers, Jean, Grieve and MacBain [3] added a fuel cell auxiliary power unit (APU) to a battery electric vehicle to recharge the battery pack. They think that E-REV allows much cost and weight reduction, and extends the range up to 400 ~ 650 km according to the size of the tank, compared with EV. GM is also developing E-REV, and they have introduced a product that the Chevrolet Volt E-REV [4][5]. In paper [1], Tate, Harpster and Savagian compared the electrification and operating strategy of Hybrid, Plug-in Hybrids and Extended-Range Electric Vehicles.

Our research group are designing a range-extended electric city bus, and its full quality is 18 tons. Figure1 shows the bus power train architecture. The battery capacity of the bus is 100Ah, and the auxiliary power unit is composed of a gasoline engine and a permanent magnet synchronous generator.

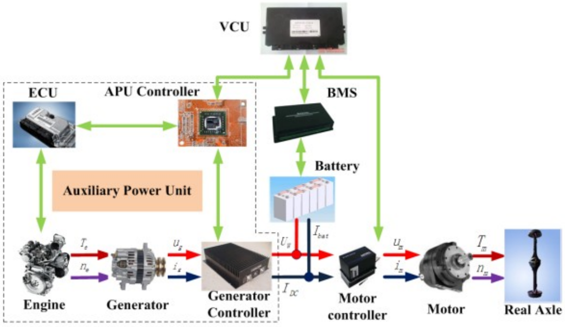

Figure1: Power train architecture of the extended-range electric city bus

2 Strategy description

Compared with private car, city bus has relatively fixed route. So the bus driving distance can be known or predicted. In addition, the experiment shows that the lithium iron phosphate battery owns higher efficiency when the SOC is between 0.5 and 0.8. Based on the above advantages, the four stage energy control strategy aims to make the battery work on the high efficiency condition that SOC between 0.5 and 0.8 during the most time of driving course. Because of the electricity use-cost is cheaper than fuel, so we hope the bus use battery charge as much as possible when one driving cycle is finished. Figure2 gives an example illustration of the strategy.

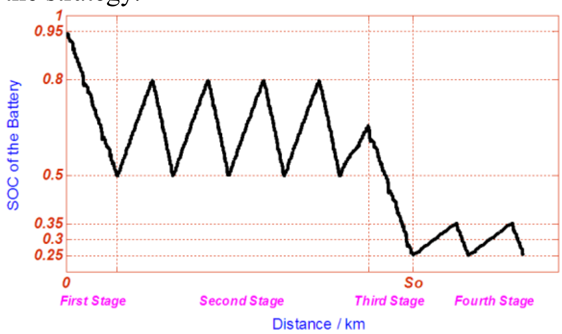

Figure2: Example illustration of four stage energy control strategy

First stage, the vehicle functions as a full-performance electric vehicle. Before driving, the battery starts at its maximum state of charge (we assume 0.95). During the driving process, the charge is depleting. And energy control switches to the second stage when the SOC is lower than 0.5.

Second stage, the auxiliary power unit (APU) engages in power output. The vehicle works on hybrid mode, and the APU can work on either power track mode [6] or fixed point mode. In the former mode, the APU output power can be calculated by formula (1) (2). In the other mode, the character of APU is constant output power. The control objective in this stage is to maintain the battery SOC between 0.5 and 0.8. Based on the mileage prediction value S_0, the controller can justify whether battery energy is enough to support for the remaining mileage. And if the answer is true, the vehicle stops the APU and enters the third control stage.

Third stage, the APU is off. The vehicle works on the pure electric mode in order to consume the rest charge for the forecasted remaining distance. Because of the mileage estimation error, maybe the real driving distance is longer than prediction value. In that case or when the SOC is lower than 0.25[7], the controller switches to the fourth stage,

Fourth stage, the SOC is very low, so the APU engages in power providing, which is similar to the second stage. But the power splitting proportional coefficient k_2 is replaced by k_4. To reduce the discharge current of the battery relatively and maintain the vehicle dynamic performance, the factor k_4 is greater than k_2, and the objective is to maintain the SOC between 0.25 and 0.35. During this stage, the vehicle works on the blend mode for the rest mileage and the SOC can maintain a low state when the driving cycle is over,

$$P_{cal} = P_f + P_i + P_w + k_2 \cdot P_j \tag{1}$$

$$P_{APU} = \begin{cases} 0, & if \ P_{cal} < P_{e,min} \\ P_{e,max}, & if \ P_{cal} > P_{e,max} \\ P_{cal}, & others \end{cases} \tag{2}$$

Table1: Symbol description

P_f	rolling resistance power
P_i	grad resistance power
P_w	aerodynamic drag power
P_j	acceleration power
P_{cal}	calculation power
P_{APU}	APU output power target
$P_{e,min}$	minimum APU power
$P_{e,max}$	maximum APU power
k_2	power splitting proportional coefficient in the second stage
k_4	proportional coefficient in the fourth stage
S_0	prediction value of mileage

3 Simulation model

Our group developed a real time and hardware in the loop vehicle simulation platform, which can be used to simulate vehicle dynamic performance and equivalent fuel economy, and test the performance of the vehicle controller unit. In the platform, the vehicle simulation model can be defined by users. Figure3 shows the structure of extended-range electric city bus mathematical model. The cycle data used in the model is china city bus driving cycle.

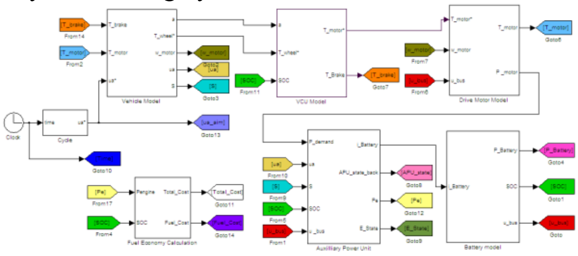

Figure3: Vehicle fuel economy simulation model

4 Simulation results

4.1 Comparison of CDCS strategy and four stage control strategy

The CD-CS strategy applied to the vehicle is defined as following.

Charge depleting (CD) stage, the vehicle works on the pure electric mode. And at the beginning of the cycle, SOC is also assumed to 0.95. The energy control stage enters to CS stage when SOC is lower than 0.25.

Charge sustaining (CS) stage, the vehicle works on the hybrid mode. The APU starts when SOC is lower than 0.25 and stops when SOC is higher than 0.35.

Table2 gives equivalent fuel consumption of the bus when APU works on fixed power mode and power track mode by using CD-CS strategy and four stage control strategy individually.

Table2: Vehicle equivalent fuel consumption for different strategies

	CD-CS		Four stage control	
Mileage [km]	200		200	
APU work mode	Fixed power	Power track	Fixed power	Power track
APU output power [kW]	45.24	2.5~61.58	45.24	2.5~61.58
k_2	-	1.50	-	1.50
k_4	-	1.75	-	1.75
Equivalent fuel consumption [L/100km]	36.7395	37.9591	36.2248	37.7397

Figure4 and Figure5 show the APU and battery output power sequence when APU works on fixed power mode and power track mode of four stage control strategy individually.

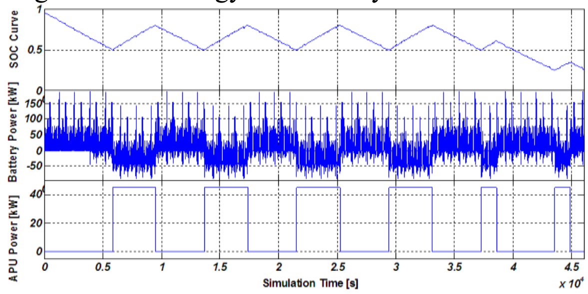

Figure4: The battery and APU output power sequence under fixed power mode of 4 stage strategy

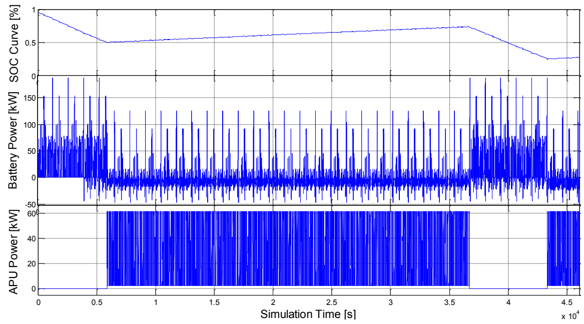

Figure5: The battery and APU output power sequence under power track mode of 4 stage strategy

Fig.6 is a partial enlarged drawing of Fig.5, and the simulation time is from 5500 seconds to 7000 seconds.

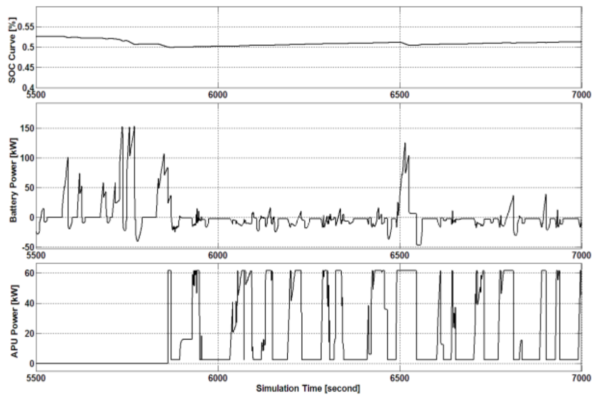

Figure6: Partial enlarged drawing of the battery and APU output power sequence

According to the simulation data, APU works on either fixed power mode or power track mode, the fuel economy of applying four stage control strategy to the vehicle is better than CD-CS strategy. And under the same strategy, APU works in fixed mode can save more fuel than power track mode, but APU works in power track mode can reduce the noisy power of battery relatively, which is very important for battery lifetime.

4.2 Relationship between fuel economy and mileage

E-REVs' fuel economy performance decreases with mileage increasing. Figure7 shows the simulation results of equivalent fuel cost per 100km with mileage change trend by applying different energy control strategies, and APU works on fixed power mode. The data indicates that four stage control strategy can save 0% to 2.7% of fuel consumption compared to CDCS strategy according to different mileage.

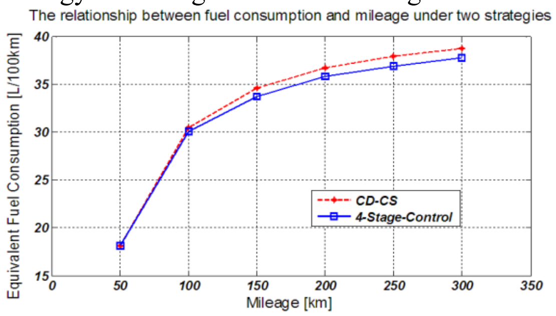

Figure7: The relationship between fuel consumption and mileage for two strategies

Figure8 gives detailed description, in which fuel cost and electricity cost can be known.

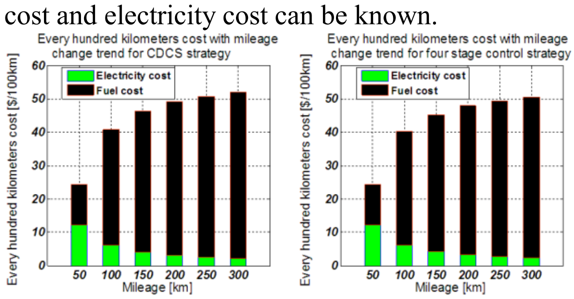

Figure8: Every hundred kilometers cost with mileage change trend for two strategies

4.3 Parameter sensitivity analysis

In this part, the parameter sensitivity on coefficients of k_2 and k_4 is analysed when APU works on power track mode (Mileage is 200km, S_0 is 190km), as is shown in Figure9.

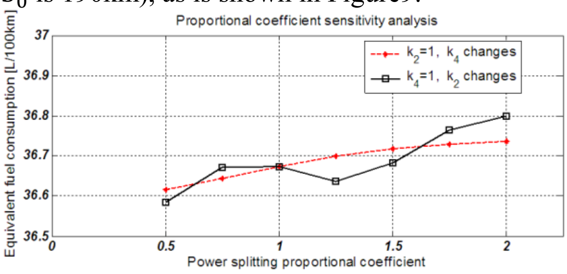

Figure9: Sensitivity analysis on power splitting proportional coefficients

5 Conclusions

Based on the simulation results, the four stage control strategy can provide better fuel economy than CDCS strategy. And APU works on power track mode is better for battery lifetime. In addition, the following factors are important for the E-REV fuel economy.

1) mileage,

2) the system configuration of energy size ratio of APU and battery,

3) APU starts and stops times,

4) efficiency of braking energy recovery.

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Authors

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I am majoring in Mechanical Engineering for a doctor's degree. And my main research field is multiple energy source system optimal control strategy. Recently, our research group are engaging in designing power train and vehicle energy control strategy for the extended-range electric city bus.