The Fuel Economy Analysis of Series Hybrid Electric Bus with Different Energy Storage Devices

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Abstract

Two kinds of energy strategy devices of series hybrid electric bus, Ni-MH battery and super-capacitor, are used in this paper. The influence of using different energy storage devices on fuel economy of the series hybrid electric system is analyzed by power flow method. The simulation results show that the system with super-capacitor can effectively improve the efficiency of the braking energy recovery, in condition of a certain Chinese city driving cycle and the average power of the electric auxiliary power unit is 5kW.

Keywords: Series Hybrid Electric Bus, Energy Storage Device, Fuel Economy, Potential, Comparative Analysis.

1. Introduction

The series hybrid electric system has a large proportion in the amount of the new hybrid electric bus. Although the parts of the series hybrid electric system (for example: generator, battery, traction motor) add the weight of the bus, the series configuration will not influence the dynamic performance observably for the bus is already heavy enough. Meanwhile, the series hybrid electric system with APU can effectively recover the braking energy.

The configuration of the series hybrid electric system is shown in Figure 1.

Figure 1. Series hybrid electric system

Engine is integrated with the generator to be named as Auxiliary Power Unit (APU) and the APU output is transferred directly to energy storage device or traction motor. Traction motor works to drive the bus in motoring mode or recover the braking energy into electric energy in generating mode. In general, the energy of the series hybrid electric system is distributed by vehicle controller. The vehicle controller determines

the distribution between the APU and energy storage device through the power requirement of the driving cycle and conditions of different parts. This research is based on powertrain of the series hybrid electric bus (as is shown in Figure 1) The APU is constituted of diesel engine, electric excitation generator and three-phase uncontrollable rectifier (as is shown in Figure 2). The APU output power is transmitted to connect energy storage device and load [1-2].

Figure 2. APU configuration

Now the studies of the series hybrid electric bus mainly focus on configuration analysis and energy management strategy. In configuration analysis, literature [3] made optimization design for the traction motor and energy storage device of the army's suspension, using super-capacitor and battery as energy storage devices to improve the battery life. Literature [4] put forward a system of diesel engine, generator, lead-acid-battery, and super-capacitor and made the study by power follow energy management algorithm for the four-wheel driving series hybrid electric bus. Both literature [5] and [6] studied the designs of DC/DC power converter and control method for the configuration of battery and super-capacitor. Literature [7] put forward a configuration using GT (Gas Turbine) as APU prime motor for series hybrid electric min-bus. In energy management strategy, the mainly algorithms are instantaneous optimization algorithm based on the minimum fuel consumption, fuzzy logic algorithm based on complex rules, global optimization algorithm based on established driving cycle. Literature [8] put forward an optimization algorithm based on the minimum fuel consumption rule. The efficiency is improved by 1.6%~5% compared with conventional thermostat control method. Literature [9-10] studied the change of engine working points and optimization efficiency area based on sliding mode controller and improved the energy efficiency of the series hybrid electric bus for High Mobility Multipurpose Wheeled Vehicle. Literature [11] put forward an algorithm of engine-generator torque and speed based on optimization track for the series hybrid electric bus. Literature [12-13] improved the energy efficiency of the series hybrid electric system by new control method based on equivalent consumption minimization strategy. Literature [14] put forward a selection and control method and studied the minimum fuel consumption strategy in determined condition for the series tracked vehicle. Literature [15] put forward an energy management strategy that using fuzzy logic algorithm to confirm battery condition and make sure that the engine is working at high fuel efficiency area to avoid battery over discharged for plug-in series hybrid vehicle. Literature [16] used improved dynamic programming to optimize the APU of the series hybrid electric system and power battery output power. The operation time is reduced as well as the fuel consumption.

In energy management strategy, most studies focus on optimizing the engine working points and efficiency area of engine. But the fuel economy analysis of the series hybrid electric bus is seldom reported in Chinese city driving cycle. Although literature [17] analyzed and compared the system efficiency in the public transit driving cycle, braking energy recovery, idle shutdown and the electric auxiliary system of the series hybrid electric system using 75Ah lead-acid battery. The fuel economy of different energy storage devices has never been analyzed.

This paper compares the economy influence of series hybrid electric bus with different energy storage devices of super-capacitor and Ni-MH battery. The fuel economy improvement of the series hybrid vehicle using the super-capacitor compared with conventional fuel bus and the series hybrid electric bus that using Ni-MH battery is also obtained.

2. Operation Condition Analysis and Formulating Energy Management Strategy

This paper uses a certain Chinese city driving cycle (as is shown in Figure 3) to analyze the economy of the series hybrid electric system.

Figure 3. Certain Chinese city driving cycle

As is shown in Table 1, the driving cycle duration is 2010s, covering 10.56km, the maximum speed is 50.55km/h, the average speed is 18.91km/h (considering idle), idle proportion is 12.64%.

Table 1. The characteristic value

Duration time/s	2010
Trip mileage/km	10.56
Maximum speed/km/h	50.55
Average speed/km/h	18.91
Maximum acceleration/m/s ⁻²	1.26
Maximum deceleration/m/s ⁻²	-2.75
Average acceleration/m/s ⁻²	0.27
Average deceleration/m/s ⁻²	-0.37
Idle time/s	254
Parking times/times	22

Energy management strategy may increase the fuel economy of the series hybrid electric system. As mainly studying the fuel consumption influence of the energy storage device, this paper chooses power follow algorithm based on rules. As Ni-MH battery is in the best working condition with 40%~70% SOC, the energy distribution curve based on SOC is mainly in this interval.

In the process of energy distribution, APU, energy storage device and traction motor fit formula (1). The objective power of APU is determined after the power provided by energy storage device is determined.

$$P_{APU} = P_{mot} - P_{bat} + P_a \quad (1)$$

Where, P_{APU} is the APU output power, P_{mot} is the traction motor controller inlet power, P_{bat} is the energy storage device power, P_a is the auxiliaries consumption power, auxiliaries include air condition, battery heat management system, interior heating system, lighting and control system, steering and braking consumption.

3. Simulation Results and Analysis

To effectively analyze the economy of the series hybrid electric bus, this paper analyzes the influence of different energy storage devices on the fuel economy.

The model data used in simulation is shown in Table 2.

Table 2. Series hybrid electric bus simulation model data

Length, width and height(mm)	11980×2550×3180
Mass(kg)	12900
Engine type	ISDE160-30
Engine rated power(kW)	118
Engine rated power rotary speed(r/min)	2500
Engine maximum torque (N·m)	600
Engine maximum torque rotary speed(r/min)	1300
Generator type	UC274C/D
Generator maximum rotary speed(r/min)	1500
DC output voltage with full-wave rectification(V)	360 ~ 460
Energy storage device	Super-capacitor11.7F Ni-MH battery60Ah
Traction motor type	JD147A
Traction motor maximum rotary speed(r/min)	4500
Traction motor highest/rated power(kW)	160 /80
Traction motor maximum torque	≥1300 N.m
Transmission main reduction ratio	6.333

It is assumed that air condition, power steering and other auxiliaries worked in electric auxiliary mode, and the average power is 5kW. To further accurately calculate the fuel economy, the simulation sets the same SOC value in both start and stop point.

Figure 4 is the parts working condition of the hybrid system with Ni-MH battery. Figure 4 shows that, in one driving cycle, APU output power changing follows the power demands. The charge and discharge ratio of Ni-MH battery is controlled below 3.5C, the fuel consumption in simulation is 31.42L/100km.

Figure 4. Parts of the series hybrid electric system changing curve with Ni-MH battery

Figure 5 shows the distribution of the engine working points. The engine mainly works in the trajectory that is given in the power follow energy management.

Figure 5. The engine working points distribution with Ni-MH battery

The energy flow in simulation is shown in Figure 6.

Figure 6. The hybrid system energy flow chart with Ni-MH battery

Figure 6 shows that, the charge and discharge resistance is relatively higher that of using Ni-MH battery. The system energy efficiency of the device can only reach 89.1%.

Figure 7 is the parts working condition of the energy storage device with super-capacitor and APU using load following control method. Figure 7 shows that, as using super-capacitor, the charge and discharge ratio reaches above 4C and the fuel consumption is 29.52L/100km.

Figure 7. Parts of the series hybrid electric system changing curve with super-capacitor

Figure 8 is the distribution of the engine working points with super-capacitor. The energy flow is shown in Figure 9. The system energy efficiency of the device is improved and can reach 99.1%. The fuel energy is reduced and the fuel economy of the hybrid electric system is improved.

Figure 8. The engine working points distribution with super-capacitor

Figure 9. The hybrid system energy flow chart with super-capacitor

Based on simulation results, the power flow characteristics of components are analyzed (as is shown in Table 3).

Table 3 shows that, the loss of the energy storage device of the series hybrid electric bus using super-capacitor is reduced by 0.8%. The fuel economy is increased by 6.05% compared with the series hybrid electric system with Ni-MH battery. The fuel economy

is increased by 16.14% compared with the conventional fuel bus (the auxiliary average power of the conventional bus is 4kW).

Table 3. The energy and loss of the parts of the series hybrid electric system with different energy storage devices

Bus(Energy storage device) type	Ni-MH batter	Super-capacitor	Conventional fuel bus
Fuel energy	400.42%	391.2%	519.89%
Feedback energy in theory	52.1%	52.09%	
Braking feedback recovery energy	32.84%	32.84%	
Engine loss	271.65%	266.35%	380.21%
Generator and rectifier loss	11.02%	10.6%	
Energy storage device loss	3.47%	0.28%	
Generating loss	5.73%	5.73%	
Generator driving loss	17.54%	17.54%	
Auxiliary loss	28.45%	27.54%	33.04%
Vehicle driving energy	100%	100%	100%
Fuel consumption L/100km	31.42	29.52	35.2
Fuel saving ratio compared with conventional fuel bus	10.74%	16.14%	

4. Conclusion

The actual test data of certain Chinese city is chosen as the driving cycle of the simulation in this paper. The load following method is used as energy management strategy. Two different energy strategy devices, Ni-MH battery and super-capacitor, can be used in the system. The device has two kinds of energy recovery methods, idle shutdown and braking energy recovery. The fuel economy potential of series hybrid electric system is analyzed.

Based on the simulation results, it can be concluded that if using the super-capacitor as energy storage device, the fuel economy is increased by 6.05% compared with the hybrid system with Ni-MH battery, the fuel economy is increased by 16.14% compared with the conventional fuel bus.

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