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Control strategy and parameter optimization of compound energy storage device for pure electric vehicle

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Abstract: In order to solve the problem of insufficient power of battery of pure electric vehicle, we study the energy storage system of electric vehicle. According to the characteristics and objectives of the complex energy storage device, we design its working mode, and propose a fuzzy control strategy based on speed and current limitation. In order to further improve the vehicle performance and reduce the output current of the battery, the key parameters of the composite energy storage device are linearly optimized. The simulation results show that: The acceleration time of pure electric vehicles equipped with composite energy storage devices is shortened by 12%, the braking energy recovery efficiency is increased by 39%, the power consumption of 100 kilometers is reduced by 8.55%, and the output current of the battery is significantly reduced, effectively extending the service life of the battery and the driving range of the vehicle.

Keywords: Supercapacitor; Compound energy storage device; Control strategy; Optimize.

1. Introduction

The domestic economic growth rate is running at a high level, the automobile industry is developing rapidly, and the demand for automobiles is growing at the same time. The number of motor vehicles in China reached 319 million by the end of June 2018. According to the statistics of Xu Changming, deputy director of the State Information Center, the number of motor vehicles in the country will reach 630 million in 2020, which may be the first in the world. However, the rapid development of the automobile industry and the rapid increase in car ownership have brought about two problems that are the most concerned in today' s society: one is the increasingly serious environmental pollution, and the other is the massive consumption of natural resources. From the perspective of environmental pollution, automobile pollution has become a worldwide public nuisance, according to the survey, the traditional fuel vehicle exhaust emissions is the main source of air pollution nitrogen oxides, hydrocarbons, carbon monoxide, the above dirty gas not only aggravate the impact of the greenhouse effect, but also make the human living environment under great threat; From the perspective of resource consumption, the automobile is a high energy consumption industry, at present, China's oil reserves have been seriously insufficient, resources are facing the threat of exhaustion, in the face of the increase in automobile demand, China's external dependence on oil will be more and more serious, China's economic development is also limited to a certain extent.

Pure electric vehicles are one of the development directions of new energy vehicles, but the insufficient performance of power batteries has become an important reason to hinder the marketization process of pure electric vehicles [1-2]. At present, domestic and foreign scholars have conducted relevant studies on composite energy storage devices. Moren et al. [3] loaded supercapacitors onto pure electric vehicles and carried out road tests under different cycle conditions and low temperature conditions. Viot et al. [4] have optimized the energy management strategy of the composite energy storage device used for hybrid electric vehicles, and the simulation results show that the composite energy storage device can effectively improve the output current of the battery. Hwng et al. [5] studied the compound energy storage device of fuel cell and battery, and the results of bench test and road test showed that the compound energy storage device system had high efficiency. The research group of Jilin University also studied the parameter matching and energy management strategies of hybrid electric buses with vehicle-mounted composite energy storage devices [6-8]. However, current research is mainly focused on composite energy storage devices for hybrid electric vehicles. Specifically, in the field of control strategies for these composite energy storage devices, many adopt logical threshold control methods, which have limited adaptability and limit the optimal power allocation.

To enhance the power performance and lifespan of pure electric vehicles, we opt for a composite energy storage solution comprising supercapacitors and battery packs. By strategically positioning each energy storage unit and fine-tuning their parameters, we employ a fuzzy logic control strategy grounded in speed and current constraints to optimize performance effectively.

2. Working principle and structure selection of composite energy storage device

Because the supercapacitor has the advantages of high specific power and long life, it can withstand large current in the charge and discharge process, and can "cut the peak and fill the valley" of the battery, so it can extend the life of the battery pack and improve the power performance of pure electric vehicles. At present, the structure of the composite energy storage device is summarized as shown in Figure 1 [9-11]. Structure (b) is selected as the structure of the composite energy storage device because of its simple structure, the terminal voltage of the battery changes gently than that of the supercapacitor, and the control is easy.

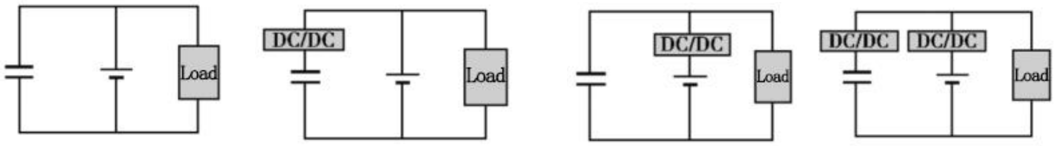


Fig.1 Different structure of the hybrid energy storage device

3. Working mode and control strategy of composite energy storage device

3.1. Working mode of composite energy storage device

The average power demand of the motor of the composite energy storage device composed of a supercapacitor and a battery is borne by the battery, and the difference above the average power is supplemented by the supercapacitor, and the braking energy is first recovered by the supercapacitor during braking. Based on the basic working principle of the composite energy storage device and the driving condition of pure electric vehicles, we can divide the working mode of the composite energy storage device into the following five modes.

(1) Starting/accelerating/climbing conditions.

In this condition, the required power of the motor is usually large, and if only the battery is used to provide the required power, the current output of the battery will be larger, or even exceed the endurance limit, resulting in a sharp rise in the temperature of the battery and a decrease in its life . Therefore, the combined output power of the supercapacitor and the battery should meet the needs of the motor, as shown in Figure 2(a).

(2) Constant speed driving, and the supercapacitor energy storage state is moderate conditions.

In this condition, the power demand of the motor is often small, and only the battery can meet the power required by the motor, as shown in Figure 2(b).

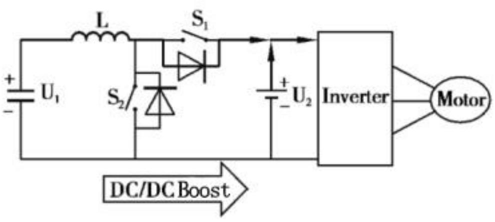
(3) When the speed is constant and the supercapacitor energy storage state is low.

In this working condition, the required power of the motor is also small. Due to the low energy storage state of the supercapacitor at this time, the battery drives the pure electric vehicle and can supplement energy to the supercapacitor to meet the demand of the pure electric vehicle under high-power output conditions such as overtaking acceleration, as shown in Figure 2(c).

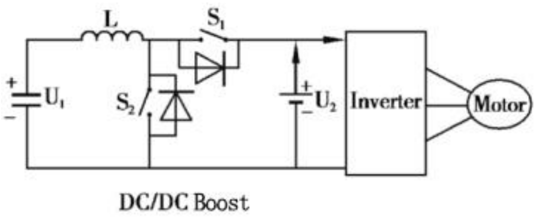
(4) When the braking energy is recovered, and the supercapacitor has energy storage space. In this working condition, since the supercapacitor has energy storage space and has the advantage of high current charging, the supercapacitor is preferred to recover the braking energy. If and only when the supercapacitor no longer has storage space, the battery is used to recover the braking energy, as shown in FIG. 2(d) and 2(e) respectively.

(5) When the pure electric vehicle is at rest, the working condition of the battery for supplementary charging of the supercapacitor.

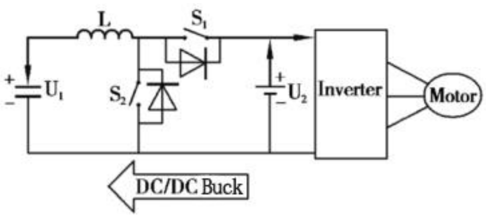
In this working condition, since the energy stored by the supercapacitor cannot meet the energy demand of the pure electric vehicle for a start acceleration, the battery can supplement the energy of the supercapacitor by using the depressurization effect of DC/DC to avoid the impact of large current output on the battery at the next start, as shown in Figure 2 (f).



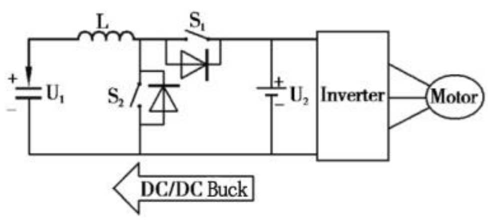
(a)High power output (acceleration, climbing)



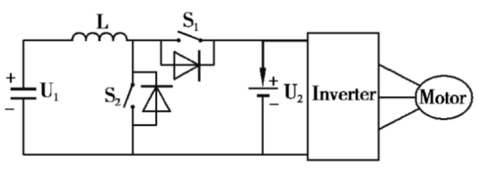
(b)At constant speed I



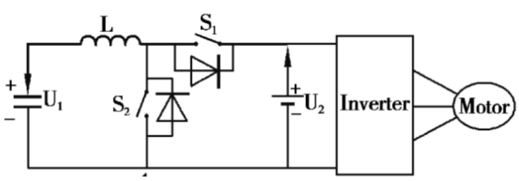
(c)At constant speed II



(d)Braking energy recovery time rainbow I



(e)Braking energy recovery II



(f)At rest

Fig.2 Different work modes of the hybrid energy storage device

3.2. Control strategy of composite energy storage device

On the basis of determining the working mode of the compound energy storage device, it is necessary to formulate the control strategy of the compound energy storage device to rationally distribute the energy and power between the battery and the supercapacitor. Usually let the battery meet the average power required in the motor drive process to ensure the basic performance of pure electric vehicles, and the supercapacitor is mainly to meet the peak power of the motor minus the additional part of the average power, in order to play its high specific power, large current charging and discharging characteristics, so as to make full use of the respective characteristics of the supercapacitor and the battery. The control strategy of the composite energy storage device is as follows.

(1) Speed constraint control strategy

The speed constraint control strategy mainly makes the supercapacitor store appropriate energy according to the actual driving condition of pure electric vehicle. When the car is in the starting state, the supercapacitor discharge is required to give power assistance, so as to ensure the power performance of the electric vehicle, so the supercapacitor should store relatively more energy. When the car is driving at a lower speed, the supercapacitor should also store more energy to ensure the acceleration of pure electric vehicles; When the car is driving at a higher speed, it is obvious that there will be no more high-power output request for the energy storage device, so the energy storage state of the supercapacitor should be lower at this time, which is conducive to recovering more energy during braking.

According to the matching principle of the supercapacitor, when it can recover the maximum braking energy, there is a relationship of formula (1) for the supercapacitor group.

$$0.5C\left(V_{max}^2 - V_{min}^2\right) N = 0.5mv_{max}^2 \quad (1)$$

For other speeds, formula (2) should be satisfied:

$$0.5C\left(V_{max}^2 - V^2\right) N = 0.5mv^2 \quad (2)$$

By combining formula (1) and (2), the relationship between the vehicle speed and the voltage value of the supercapacitor can be obtained (3):

$$\frac{V}{V_{max}} = \sqrt{1-(1-k^2)*(\frac{v}{v_{max}})} \quad (3)$$

N indicates the total number of supercapacitors. Vmax indicates the maximum usable voltage of the supercapacitor. Vmin indicates the minimum usable voltage of the supercapacitor. V indicates the current voltage of the supercapacitor. m stands for the quality of the car; vmax stands for the maximum speed of the car; v is the current speed of the car.

Since formula (1) ~ (3) only considers the ideal driving state of the vehicle, and does not consider the energy loss caused by the motor efficiency and driving resistance of the pure electric vehicle during the braking energy recovery, there is a certain deviation in the voltage storage state in the actual application. In order to facilitate the modification and optimization of the status value of the supercapacitor, The author determines the charging state of the supercapacitor according to the current vehicle speed and the charging state of the battery, as shown in Figure 3.

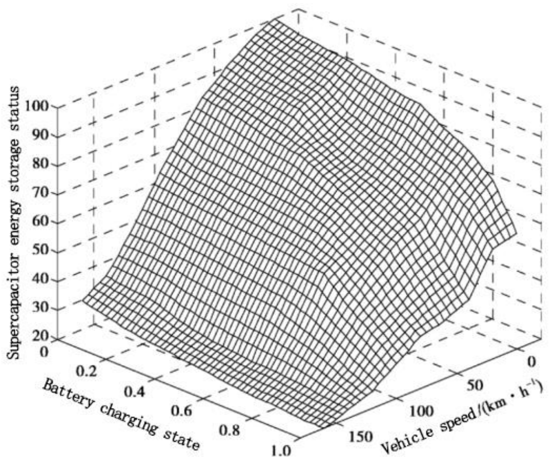


Fig.3 Relationship between vehicle speed and ultra-capacitor SOC under different battery SOC

(2) Current constraint control strategy

When electric vehicles accelerate, decelerate or drive up and down hills frequently, the load power demand fluctuates greatly. When the load current reaches the peak or trough, it usually exceeds the withstand range of the battery, resulting in a shortened battery life and a rapid reduction in the energy that can be released. The supercapacitor is introduced into the compound energy storage device to reduce the output current of the battery. The structure diagram of the composite energy storage device is shown in Figure 4.

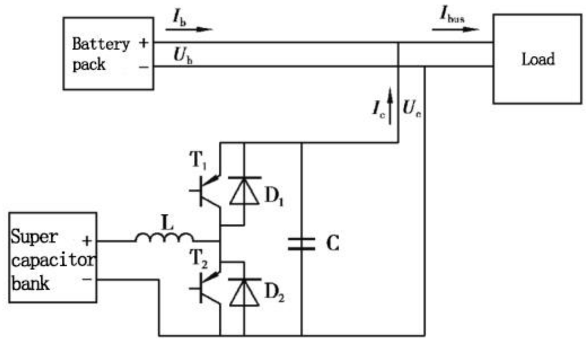


Fig.4 Scheme of the hybrid energy storage device

The current relationship of composite energy storage device is as follows:

$$I_{bus} = I_b + I_c \quad (4)$$

Where: Ibus is the load current; Ic is the current generated after the supercapacitor is boosted by DC/DC. Ib is the operating current of the battery pack, and its limitations are:

$$-I_{bN} \leqslant I_b \leqslant I_{bP} \quad (5)$$

$$I_{bN} = k_1 C_{rate} \quad (6)$$

$$I_{bp} = k_2 C_{rate} \quad (7)$$

Where: Ibn represents the maximum charging current of the battery pack; Ihp represents the maximum discharge current of the battery pack. Crate Indicates the nominal capacity of a battery pack. k1 and k2 represent the maximum charge rate and maximum discharge rate of the battery respectively.

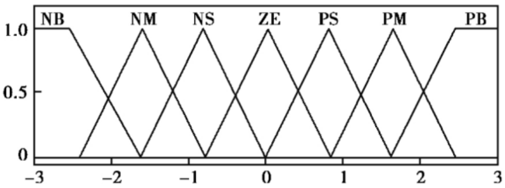
Formula (8) is obtained from formula (4), (5), (6) and (7):

$$I_{bus} - k_2 C_{rate} \leqslant I_c \leqslant I_{bus} + k_1 C_{rate} \quad (8)$$

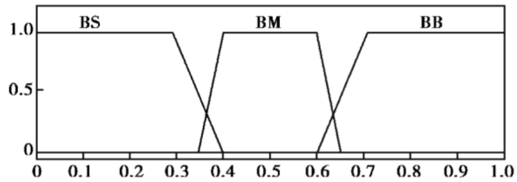
Current restraint control is to improve the current output of the battery by bidirectional DC/DC control.

(3) Fuzzy control strategy based on velocity constraint and current constraint

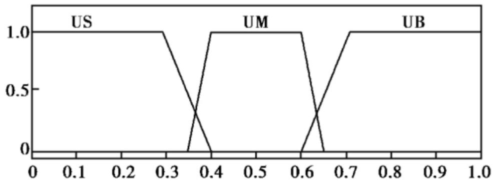
In the current constraint control strategy, although the output current of the battery is controlled to prevent the damage to the battery set by the large current, the value of the battery is usually large in the process of IbN and IbP, which will shorten the life of the battery. Based on the speed and current constraint strategy, this strategy uses the fuzzy control idea to better manage the charge and discharge process of the ultracapacitor-assisted battery pack according to the energy storage state of the battery and the supercapacitor and the required power parameters, so as to ensure that the battery pack can reduce the large current impact without affecting the power performance of the vehicle. The fuzzy controller adopts the Mamdani structure with three inputs and one output. The input includes the required power Pe, SOCbat and SOCuc of the battery and supercapacitor, and the output is the power distribution ratio of the battery Kbat, which is defined as the ratio of the output power of the battery to the required power of the motor.The domain of the required power is {negative large, negative medium, negative small, positive zero, positive small, median, Zhengda}, which can be expressed as {NB,NM,NS,ZE,PS,PM,PB}. The battery charge state discourse domain is {small, medium, large}, which can be expressed as {BS, BM, BB}. The ultracapacitor's charged state discourse domain is {small, medium, large}, which can be expressed as {US, UM, UB}. The domain of the battery power distribution ratio is {small, small, medium, large, large}, which can be expressed as {TS, S, M, B, TB}. The membership function of the input and output variables is shown in Figure 5.



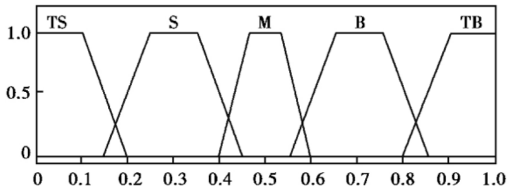
(a)Required power P_e



(b)Charging status of the battery SOC_{bat}



(c)The supercapacitor is charged $S0C_{uc}$



(d)Battery output power distribution ratio K_{bat}

Fig.5 Membership functions of input and output variables

Based on engineering experience and defined fuzzy domain, 63 fuzzy control rules are formulated by IF-THEN rules. Limited by space, only the fuzzy control rule table is listed when the discourse domain of supercapacitor SOCuc in charge state is UM (middle), as shown in Table 1.

Table 1. Fuzzy rule table when SOCuc is UM

p_e	BS	SOC_{bat} BM	BB
NB	M	S	TS
NM	B	S	TS
NS	B	TS	TS
ZE	TS	TS	TS
PS	S	M	B
PM	TS	M	TB
PB	S	B	TB

4. Simulation Analysis

In order to verify the advantages of installing a composite energy storage device on pure electric vehicles and the effectiveness of the control strategy adopted, we used Matlab/Simulink simulation software to establish a vehicle model for simulation experiments. After the composite energy storage device is installed, the total mass of the pure electric vehicle is 1420kg, the windward area is 2m2, the rolling resistance coefficient is 0.012, and the air resistance coefficient is 0.335. Other major parameters are shown in Table 2.

Table 2. Main parameters of the pure electric vehicle with the hybrid energy storage device

Device name	Performance name	Parameter value
Permanent magnet synchronous motor	Rated power/kW Rated speed($r\cdot min^{-1}$)	35 3600
Lithium-ion battery	Monomer content($A\cdot h$) Specific energy($W\cdot h\cdot kg^{-1}$)	50 100
supercapacitor	Monomer content/F Specific energy($W\cdot h\cdot kg^{-1}$)	3000 6.0

Device name	Performance name	Parameter value
Permanent magnet synchronous motor	Peak power/kW Voltage level/V	75 336
Lithium-ion battery	Cell voltage/V Specific power($W\cdot kg^{-1}$)	3.2 200
supercapacitor	Cell voltage/V Specific power($W\cdot kg^{-1}$)	2.7 5900

4.1. Acceleration performance simulation

The power performance of pure electric vehicle is an important evaluation index. In order to verify the performance of the proposed control strategy and the compound energy storage device, a simulation study of starting acceleration to 100km/h for pure electric vehicles was carried out. As shown in Figure 6, the acceleration time of vehicles equipped with composite energy storage devices is 12% lower than that of vehicles using only batteries due to the power assistance of supercapacitors.

Figure 7 shows the current output characteristics of each energy storage unit when the pure electric vehicle accelerates from 0 to 50km/h. From the simulation results, it can be concluded that the maximum output current exceeds 140A when only the battery is used. When the composite energy storage device is used, the output current of the battery is reduced to 17.5A, but the output current of the supercapacitor is 400A, giving full play to the advantages of the supercapacitor to charge and discharge with large current.

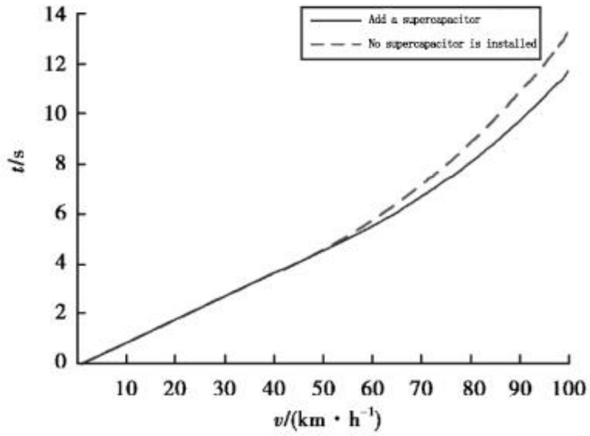
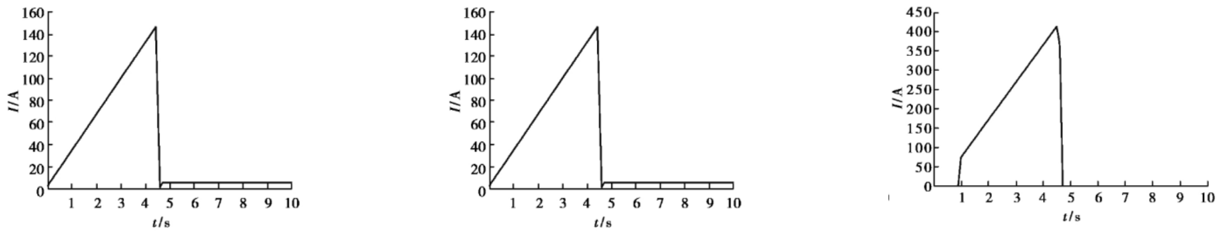


Fig.6 Comparison of the curve chart about the acceleration



(a) (b) (c)

Fig.7 Output current of energy storage units

4.2. Cycle working condition simulation

In order to further evaluate the output power, current output state of battery and vehicle energy consumption of pure electric vehicles equipped with composite energy storage devices under urban road driving conditions, NYCC cycle conditions were selected as vehicle simulation driving conditions to simulate the performance of pure electric vehicles under urban road driving conditions. The simulation results are shown in FIG. 8-12.

As shown in FIG. 8 and 9, when only batteries are used, due to their limited output power capacity, the actual speed cannot follow the target speed well in some local high-power demands, while the actual speed of pure electric vehicles using compound energy storage devices can follow the target speed well.

As can be seen from FIG. 10-12, for pure electric vehicles that only use batteries, the output current peaks at points A,B and C, which cannot meet the needs of pure electric vehicles. However, after the composite energy storage device is adopted, the output current at points A',B' and C' corresponding to the battery is ideal because the supercapacitor plays the role of "peaking and valley filling". And due to the addition of supercapacitors, the output capacity of the energy storage unit increases, which better meets the power demand of pure electric vehicles in cycling conditions.

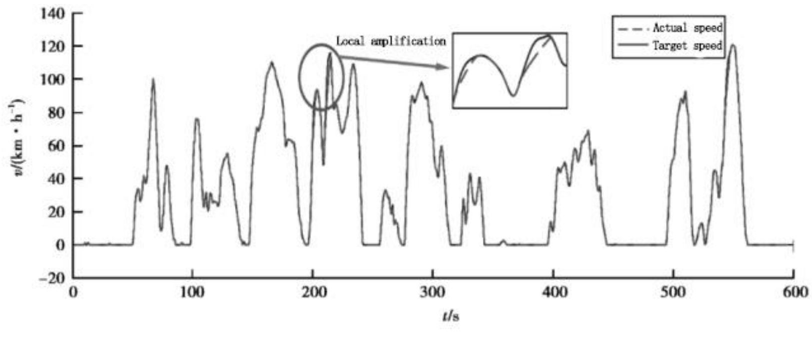


Fig.8 Actual velocity and target velocity when the vehicle equipped with battery only

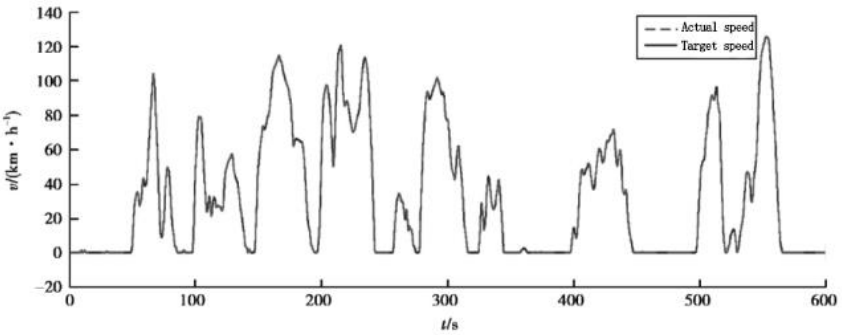


Fig.9 Actual velocity and target velocity when the vehicle equipped with the hybrid energy storage device

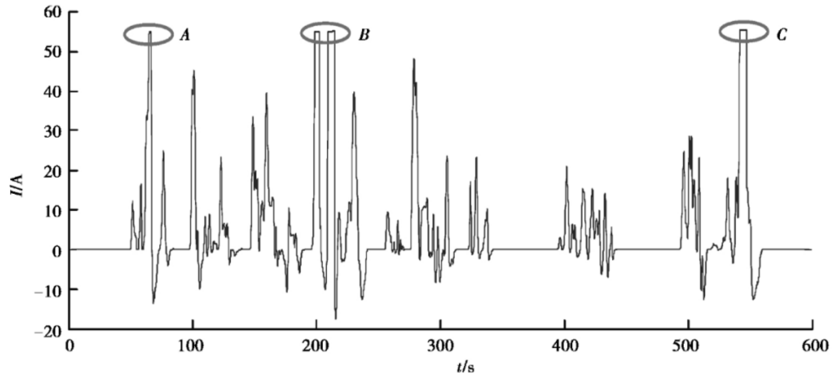


Fig.10 Output current of battery when the vehicle equipped with battery only

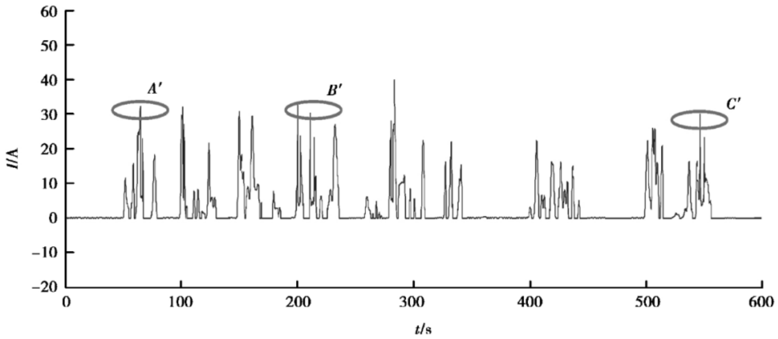


Fig.11 Output current of battery when the vehicle equipped with the hybrid energy storage device

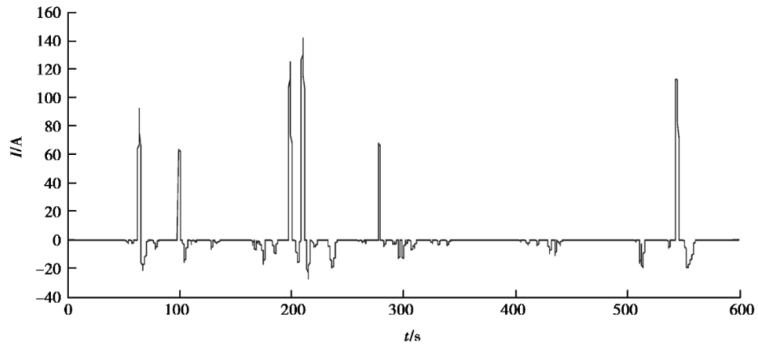


Fig.12 Output current of ultra-capacitor when the vehicle equipped with the hybrid energy storage device

Table 3 Simulation results equipped with different energy device kW.h

Project name	100 km power consumption	Battery charge capacity	Braking energy recovery
Rechargeable battery	15.56	0	3.82
Compound energy storage device	14.23	2.46	5.31
Increase rate/%	8.55	—	39.00

Under NYCC cycle conditions, the energy consumption simulation results of the two energy storage devices are shown in Table 3.For pure electric vehicles equipped with composite energy storage devices, although the battery adds 2.46kW·h of electric energy to the supercapacitor during the whole cycle, compared with the battery, the supercapacitor has higher energy conversion efficiency and fast charging characteristics, so the brake recovery energy of the composite energy storage device increases by 39%. Finally, the 100 km power consumption of pure electric vehicles equipped with composite energy storage devices is reduced by 8.55% than that of vehicles using only batteries, effectively extending the range of pure electric vehicles.

5. Conclusions

1) According to the characteristics of the composite energy storage device and its control objectives, different working modes are determined, and a fuzzy control strategy based on speed and current constraint control is proposed.

2) Based on the optimized composite energy storage device, the performance simulation under acceleration and urban road conditions is carried out. The results show that the device can effectively improve the power performance and braking energy recovery of pure electric vehicles, reduce the output current of the battery and the power consumption of the whole vehicle 100 km, extend the service life of the battery and increase the driving range of pure electric vehicles.

3) Further research will focus on bench tests of the hybrid energy storage device for pure electric vehicles. Bench tests of dynamic and energy consumption characteristics, including acceleration time, maximum climb and driving range, will be conducted to verify the effectiveness of the proposed control strategy.

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