Research on the energy management of composite energy storage system in electric vehicles

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Abstract: To solve the problem of power allocation of battery and super capacitor in the composite energy storage system of electric vehicles, we propose the logic threshold and fuzzy control strategy to arrange battery and super capacitor to supply the average and peak power to the load, respectively. Based on the simulation software of electric vehicles, we perform simulation modelling to analyse the current of the battery, the SOC of battery and the current of the super capacitor. For verifying the feasibility of the control strategy, we set up an experimental platform to study pure electric vehicles during driving and braking. Simulation and experimental results indicate that the composite energy storage system can reduce the charging and discharging times and the current amplitude of the battery, and improve the utilisation ratio of regenerative braking energy and the mileage of electric vehicles.

Keywords: electric vehicles; composite energy storage; control strategy; test platform.


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1 Introduction

Environmental and resource protection are highly valued worldwide, because of the increasingly severe environmental and natural resource problems. Therefore, electric vehicles enter a new era of rapid development (Ephrem et al., 2016). At present, the development of electric vehicles with the battery as the power supply is limited by its large volume, heavy weight and short service life (Lei et al., 2008). In order to solve these problems, the super capacitor is used as the auxiliary power supply, which has advantages of large current charge and discharge and long service life during acceleration, climbing and braking (Shen and Khaligh, 2016; Valentin et al., 2014). The power allocation of battery and super capacitor in the composite energy storage system is controlled by the control strategy, making the battery and super capacitor assume the average and peak power to the load, respectively (Wang et al., 2010; Li et al., 2005; Lu et al., 2013). Therefore, the composite energy storage system can improve the mileage of electric vehicles and the service life of the battery.

At present, many research institutes have done a lot of researches on the composite energy storage system of electric vehicles. An intelligent regenerative power management controller based on fuzzy logic was presented to optimise the distribution of the braking power between the regenerative and the hydraulic parts. This helped to save the ratings of the power units of hybrid electric vehicles system (Abdelsalam and Cui, 2011). An optimisation framework for computing the sub-optimal current flow of the hybrid energy storage system in electric vehicles was presented. It can efficiently minimise the magnitude of the battery current in electric vehicles (Choi and Seo, 2012). An adaptive optimisation method of power management was used to compensate the output power of the battery and improve the efficiency of the composite power system (Wang et al., 2015). An adaptive filter power splitting control strategy was proposed to realise the power allocation of battery and super capacitor in reason. It minimised the magnitude and fluctuation of the current of battery effectively, so the battery was protected (Wang and Sun, 2014).

In this research, we adopt the logic threshold and fuzzy control strategy to study the composite energy storage system, and analyse the SOC and current in a single battery and a composite power supply. We perform a theoretical study using MATLAB and CRUISE joint simulation and build an experimental platform to verify and test the single and composite power supply. The simulation and experimental results demonstrate the feasibility and benefits of the energy control strategy.

2 Composite energy storage system

2.1 Composite power supply topology

In this research, we adopt the topology that the super capacitor is paralleled with the battery via a bidirectional DC/DC converter. It has advantages of large current charge and discharge of the super capacitor, and improves energy conversion rate of the composite
power supply (Mamadou et al., 2008; Chen et al., 2017). The topology is shown in Figure 1. In the process of driving, the composite energy storage system can rationally allocate the energy of the super capacitor and the battery according to the road conditions and control strategy.

Figure 1  Composite power supply system

2.2 Working mode of composite energy storage system

According to the demand of pure electric vehicles, the working mode of composite energy storage system is mainly divided into the following three kinds:

- **Mode one**: When the demand power of pure electric vehicles is low, the battery drives motor alone. The working conditions of the composite energy storage system are shown in Figure 2.

- **Mode two**: When the demand power of pure electric vehicles is high, the super capacitor and battery drive motor together. At this point, bi-directional DC-DC converter works in the boost mode. The working conditions of the composite energy storage system are shown in Figure 3.

- **Mode three**: When the pure electric vehicles are during deceleration or braking, the driving motor works in the generator mode, which can make the braking energy return to the energy storage device. At this point, bi-directional DC-DC converter works in the buck mode. The working conditions of the composite energy storage system are shown in Figure 4.

Figure 2  Battery drives motor alone
Figure 3 Super capacitor and battery drive motor together

![Figure 3](image1)

Figure 4 Mode of recycling braking energy

![Figure 4](image2)

2.3 Logic threshold control strategy

The basic idea of logic threshold control strategy is that the battery provides the average demand power during driving and the super capacitor provides the power beyond the average power to give full play to the advantages of super capacitor and battery.

When the composite energy storage system operates in the discharging mode, the demand power of the electric vehicle \( P_{\text{req}} \) is more than zero. The working mode of the composite energy storage system is as follows:

- When \( P_{\text{req}} \) is less than the average power \( P_{\text{av}} \), the demand power of motor is low, the battery provides the power alone, so the power of battery \( P_{\text{bat}} \) is equal to \( P_{\text{req}} \), if the SOC of the super capacitor \( S_{\text{SOC}} \) is low, in order to avoid the battery charges for the super capacitor leading to energy loss, the bi-directional DC-DC converter does not work, so the energy of battery will not flow to the super capacitor.

- When \( P_{\text{req}} \) is more than \( P_{\text{av}} \), the demand power of the motor is high. If \( S_{\text{SOC}} \) is less than the minimum value of SOC of the super capacitor \( S_{\text{SOC}_{\text{min}}} \), the battery provides the total energy during driving. Because the battery discharge for a long time with large current will shorten its life, so we set the maximum output power of battery \( P_{\text{bat}_{\text{max}}} \), if \( P_{\text{req}} \) is more than \( P_{\text{bat}_{\text{max}}} \), the output power of battery will be defined in \( P_{\text{bat}_{\text{max}}} \); if \( S_{\text{SOC}} \) is more than \( S_{\text{SOC}_{\text{min}}} \), the super capacitor has sufficient energy to provide for the load.
When the composite energy storage system operates in the charging mode, \( P_{\text{req}} \) is less than zero. If \( S_{\text{SOC}} \) is less than \( S_{\text{SOC}_{\text{min}}} \), the super capacitor recycles the braking power alone, so the power of super capacitor \( (P_{\text{SC}}) \) is equal to \( P_{\text{req}} \); if \( S_{\text{SOC}} \) is more than the maximum value of SOC of super capacitor \( (S_{\text{SOC}_{\text{max}}}) \), the battery recycles the braking power alone, so the power of battery \( (P_{\text{bat}}) \) is equal to \( P_{\text{req}} \); if \( S_{\text{SOC}} \) is between \( S_{\text{SOC}_{\text{min}}} \) and \( S_{\text{SOC}_{\text{max}}} \), the battery and the super capacitor recycle the braking power together.

According to the above rules, the control strategy of composite energy storage system is shown in Figure 5.

**Figure 5** Control strategy diagram of composite energy storage system

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### 2.4 Fuzzy control strategy

Fuzzy control strategy adopts the structure of three inputs and one output (Lv et al., 2010). Its structure is shown in Figure 6. The inputs of fuzzy control are \( P_{\text{req}} \), the SOC of battery \( (B_{\text{SOC}}) \) and \( S_{\text{SOC}} \), the output is the distribution factor of battery power \( (K_{\text{bat}}) \).

Due to the difference of the demand power during driving and braking in the electric vehicles, we design two fuzzy controllers respectively in the two modes. The inputs and output are the same, but the universe and fuzzy sets of demand power and output are different, and the fuzzy control rules of the two controllers are also different.

When \( P_{\text{req}} \) is more than zero, the electric vehicles are during driving. The universe of \( P_{\text{req}} \) is on the interval \([0, 4] \). The universe of \( B_{\text{SOC}} \) is on the interval \([0.2, 1] \). The universe of \( S_{\text{SOC}} \) is on the interval \([0.1, 1] \). The universe of \( K_{\text{bat}} \) is on the interval \([0, 1] \). The fuzzy sets of the inputs and output for the discharging fuzzy controller are respectively defined as equation (1).

\[
\begin{align*}
P_{\text{req}} &: S, MS, M, MB, B \\
B_{\text{SOC}} &: S, M, B \\
S_{\text{SOC}} &: S, M, B \\
K_{\text{bat}} &: S, MS, M, MB, B
\end{align*}
\]

The membership functions of inputs and output are shown in Figure 7.
When $P_{req}$ is less than zero, the electric vehicles are during feedback braking. The universe of $P_{req}$ is on the interval $[-1, 0]$. The universe, fuzzy sets and membership functions of $B_{SOC}$ and $S_{SOC}$ are the same as $P_{req}$ is more than zero. The universe of $K_{bat}$ is on the interval $[0, 1]$. The fuzzy sets of $P_{req}$ and $K_{bat}$ for the charging fuzzy controller are respectively defined as (2).

$$
\begin{align*}
\text{If } P_{req} & : B, M, S \\
K_{bat} & : S, M, B
\end{align*}
$$

(2)

The membership functions of $P_{req}$ and $K_{bat}$ are shown in Figure 8.
Figure 8  (a) The membership functions of $P_{req}$ and (b) the membership functions of $K_{bat}$

2.5 Simulation and analysis

The logic threshold control and fuzzy control strategy model of composite energy storage system is built in MATLAB. We build the whole vehicle model in the CRUISE, and embed the sub file of the logic threshold control strategy in MATLAB into the MATLAB_DLL module of CRUISE. The whole vehicle model is shown in Figure 9. The typical cycle conditions of NEDC are selected to test, as shown in Figure 10. The parameters of electric vehicles simulation model are shown in Table 1. The single battery power supply and composite power supply are simulated in CRUISE, the current curve of battery and super capacitor are shown in Figure 11(a) and (b). The SOC curve of the battery is shown in Figure 12.

Figure 9  The simulation model of electric vehicles in CRUISE (see online version for colours)
Figure 10  The typical cycle conditions of NEDC (see online version for colours)

![Graph showing speed vs time](image1)

Table 1  Parameters of electric vehicles

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curb weight/kg</td>
<td>1200</td>
<td>Gross weight/kg</td>
<td>1580</td>
</tr>
<tr>
<td>Capacity of battery/Ah</td>
<td>50</td>
<td>Capacity of super capacitor/F</td>
<td>150</td>
</tr>
<tr>
<td>Battery nominal voltage/V</td>
<td>320</td>
<td>Super capacitor Nominal voltage /V</td>
<td>260</td>
</tr>
<tr>
<td>Battery initial charge/%</td>
<td>95</td>
<td>Super capacitor Initial charge/%</td>
<td>90</td>
</tr>
<tr>
<td>Converter efficiency/%</td>
<td>90</td>
<td>Frontal area/m²</td>
<td>1.97</td>
</tr>
</tbody>
</table>

Figure 11  (a) The current curve of battery and (b) the current curve of super capacitor (see online version for colours)

![Current curves](image2)
As can be seen from Figure 11, when the battery is used as the single energy source of electric vehicles, the discharge current is large and the amplitude varies greatly; in the composite energy storage system, the current amplitude of the battery is relatively small. Therefore, it can be considered that the super capacitor plays an important role in limiting large charge and discharge current of battery; the current of the battery is larger in the logic threshold control strategy than that in the fuzzy control strategy, and the current amplitude of super capacitor is smaller, illustrating that the fuzzy control strategy is better than the logic threshold control strategy in improving charge and discharge effect of the battery.

As can be seen from Figure 12, the SOC of the battery of fuzzy control, logic threshold control and single battery power supply decline 5.3%, 7.6% and 8.1%, respectively. Therefore, compared to the single battery power supply, the composite energy storage system can save the energy of the battery, and the fuzzy control strategy can save more, illustrating that fuzzy control strategy can give full play to the advantages of the super capacitor and increase the mileage of pure electric vehicles.

3 Dynamic analysis of electric vehicles

The force analysis of electric vehicles is shown in Figure 13. In Figure 13, $F_v$, $F_f$, $F_w$, $F_m$ are the driving force of the motor, the rolling friction forces, the air resistance and the force of gravity along the inclined plane.

The formulas for calculating the forces of electric vehicles are shown in equations (3)-(6):
In the above expressions, $T_e$, $i_g$, $i_o$, $\eta_T$, $r$, $C$, $\rho$, $s$, $V$, $mg$, $\delta$, $\beta$ are the torque of motor output, the transmission ratio, the main drive ratio, the transmission efficiency, the radius of wheel, the air drag coefficient, the air density, the windward area of electric vehicles, the speed, the weight of electric vehicles, the rolling friction coefficient and the angle between the chassis and the ground.

**Figure 13** Force analyses of electric vehicles

In the process of electric vehicles driving, the formulas of the output torque and speed of the motor are shown in equations (7) and (8):

\[ T_e = \frac{T_e \cdot i_g \cdot i_o \cdot \eta_T}{r} \quad (3) \]
\[ F_u = \frac{C_o \cdot S \cdot V^2}{2} \quad (4) \]
\[ F_f = mg \cdot \delta \cdot \cos \beta \quad (5) \]
\[ F_{n} = mg \cdot \sin \beta. \quad (6) \]

In the above expressions, $T_e$, $i_g$, $i_o$, $\eta_T$, $r$, $C$, $\rho$, $s$, $V$, $mg$, $\delta$, $\beta$ are the torque of motor output, the transmission ratio, the main drive ratio, the transmission efficiency, the radius of wheel, the air drag coefficient, the air density, the windward area of electric vehicles, the speed, the weight of electric vehicles, the rolling friction coefficient and the angle between the chassis and the ground.

In the process of electric vehicles driving, the formulas of the output torque and speed of the motor are shown in equations (7) and (8):

\[ T_e = \frac{9.55P}{n} \quad (7) \]
\[ n = 2.653 \frac{V \cdot i_g \cdot i_o}{r}. \quad (8) \]

In the above expressions, $P$ and $n$ are the output power and the rotational speed of a motor.

The acceleration formula of electric vehicles in acceleration state is shown in equation (9):

\[ a = \frac{F_e - F_u - F_f - F_m}{m}. \quad (9) \]

In the above expression, $a$ represents the acceleration of electric vehicles.
4 Experimental verification

4.1 Experimental platform

In order to verify the feasibility of the control strategy, we build a test platform of the composite power supply of electric vehicles for experimental verification. Based on the existing laboratory conditions, we adopt the logic threshold control strategy to control the composite power supply. The test platform is shown in Figure 14.

Figure 14  Test platform (see online version for colours)

The composite energy storage system adopts the topology that the super capacitor is paralleled with the battery via the DC/DC converter. In Figure 14, the parameters of the super capacitor are 48V/165F, the battery is composed of two lithium iron phosphate batteries connected in series which parameter is 53V/50Ah, the model of the electric dynamometer is Z4-112, and brushless DC motor is selected as the drive motor. The experimental platform adopts the form that the load motor and the measured motor drive each other for simulating the load resistance during driving. It can carry out the no-load test, load test, performance test and regenerative braking feedback test. The parameters of the electric dynamometer and drive motor are shown in Table 2. Due to the rated torque and speed of the drive motor is relatively small, so the experimental test platform simulates the operation of small electric vehicles during braking, climbing and acceleration. The basic parameters are shown in Table 3.

Table 2  The parameters of the electric dynamometer and drive motor

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Rated voltage/V</th>
<th>Rated current/A</th>
<th>Rated power/kW</th>
<th>Rated torque /N·m</th>
<th>Rated Speed/r·min⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drive motor</td>
<td>48</td>
<td>180</td>
<td>5</td>
<td>14</td>
<td>3500</td>
</tr>
<tr>
<td>Dynamometer</td>
<td>440</td>
<td>19.6</td>
<td>7.5</td>
<td>16.5</td>
<td>3000</td>
</tr>
</tbody>
</table>
Table 3  Basic parameters of electric vehicles

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission ratio</td>
<td>2.16</td>
<td>Frontal area/m²</td>
<td>1.97</td>
</tr>
<tr>
<td>Transmission ratio of main retarder</td>
<td>5.01</td>
<td>Curb weight/kg</td>
<td>400</td>
</tr>
<tr>
<td>Transmission efficiency/%</td>
<td>90</td>
<td>Air density/kg·m⁻³</td>
<td>1.29</td>
</tr>
<tr>
<td>Rolling friction coefficient</td>
<td>0.01</td>
<td>The radius of wheel/cm</td>
<td>30</td>
</tr>
<tr>
<td>Air resistance coefficient</td>
<td>0.30</td>
<td>Gravity acceleration /m·s⁻²</td>
<td>10</td>
</tr>
</tbody>
</table>

4.2  Regenerative braking feedback test

When electric vehicles are during deceleration or braking, the motor is transferred from the motor state to the generator state, and the regenerative braking energy is fed back to the energy storage device. By simulating partial braking road conditions of NEDC, we study the status of energy recovery in the single and composite power supply. When the drive motor is during braking, the electric dynamometer drives the drive motor to simulate the braking state. The test speeds of electric vehicles reduce from 30 km/h to 2 km/h. The speed of drive motor reduces from 2870 r/min to 190 r/min by formula (6). The experimental results are shown in Figure 15.

In Figure 15, the output power is negative, and the value is taken as a positive value for visual analysis. As shown in Figure 15(a) and (b), the speed of drive motor gradually decreases, and DC bus current and the energy of feedback also gradually reduce during regenerative braking. As shown in Figure 15(a), when the battery power of the single power supply reaches saturation at 50 s, the battery no longer continues to recycle the regenerative braking energy. As shown in Figure 15(b), the composite power supply can recycle more regenerative braking energy, so the energy recovery efficiency of the composite power supply is higher.

4.3  Climbing test

Experimental platform simulates the uniform climbing process of electric vehicles from the slope of 0 degrees to 5.4 degrees, and the corresponding load torque of the electric dynamometer increases from 2.4 N·m to 14 N·m. The speed of electric vehicles is set to 9.4 km/h, and the corresponding motor speed is 900 r/min. In the experiment, the load torque of the electric dynamometer is gradually increased from 2 N·m to 14 N·m, and 1 Newton force is increased every 6 s. In this research, the battery, the super capacitor and the composite power supply provide the required power of drive motor, respectively. The experimental results are shown in Figure 16.

As shown in Figure 16(a), when the battery as the single power supply provides energy for electric vehicles during climbing, the DC bus voltage decreases slowly with the increase of the slope. It illustrates that the battery has the advantage of high specific energy. As shown in Figure 16(b), when the super capacitor as the single power supply provides energy for electric vehicles during climbing, the DC bus voltage decreases sharply with the increase of the slope, illustrating that the super capacitor has the disadvantage of low specific energy. We can also see that the current of super capacitor increases rapidly with the increase of the slope, illustrating that the super capacitor can discharge quickly with high power. As shown in Figure 16(c), when the composite power
supply provides energy for electric vehicles during climbing, the DC bus voltage decreases slowly with the increase of the slope, illustrating that the composite power supply plays an important role in improving the stability of electric vehicles.

Figure 15 (a) The braking state of the single power supply and (b) the braking state of the composite power supply (see online version for colours)

4.4 Accelerating test

The experiment platform simulates electric vehicles with the acceleration of 0.12 m/s², and the speed of drive motor increases from 9.4 km/h to 22 km/h within 30 s, the corresponding motor speed also increases from 900 r/min to 2100 r/min. The experimental results are shown in Figure 17.
Figure 16  (a) The climbing state of battery used as the single power supply; (b) the climbing state of super capacitor used as the single power supply and (c) the climbing state of the composite power supply (see online version for colours)
As shown in Figure 17, when electric vehicles are speeding up evenly, the input power provided by the composite energy storage system increases evenly and the efficiency of electric vehicles increases gradually. It illustrates that the composite power supply can provide stable energy for electric vehicles. From 16 s to 21 s, the acceleration of electric vehicles suddenly increases and the efficiency of electric vehicles suddenly reduces, indicating that the efficiency of electric vehicles decreases in the state of sudden change.

**Figure 17** The test curve of accelerating test (see online version for colours)

5 Conclusion

In this paper, the composite energy storage system is studied and two control strategies are designed. The simulation experiments are carried out under NEDC operating conditions in CRUISE, and we built the experimental platform of the composite energy storage system to test. The following conclusions are obtained.

- The composite energy storage system composed of the battery, the super capacitor and the bi-directional DC-DC converter can improve the mileage and the dynamic performance of pure electric vehicles.
- The super capacitor can provide instantaneous high power for the load during driving, so that the power output of the battery is relatively stable; the super capacitor can recycle the braking energy and improve the energy utilisation rate during braking.
- The logic threshold and fuzzy control strategy can realise the power distribution between the super capacitor and battery, decrease the charge and discharge current of the battery and prolong the service life of the battery. And the fuzzy control strategy is better than the logic threshold control strategy.
Acknowledgements

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References


