Power distribution strategy based on fuzzy controller and Savitzky-Golay selective filtering in hybrid energy storage system

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Abstract. Lithiumion batteries, as the power of electric vehicles, are facing challenges due to their intrinsic defects. The hybrid energy storage system with the combination of high power supercapacitor and lithium-ion battery are better promising solution. The peak current output by the lithium battery would be reduced greatly, which would result in great heat reduce and further enhancement of life cycle and safety of the lithium-ion battery. In considering their different charge and discharge behaviors, a high efficient control strategy is necessary for better performances. Here, an intelligent energy control strategy that combines fuzzy controller and Savitzky-Golay selective filtering is studied for HESS controlling. The fuzzy controller has good robustness and is suitable for nonlinear control, while the Savitzky-Golay filter can effectively smooth the waveform, and by selecting the output of both can effectively improve cell performance index. The simulation results show that compared with ESS under the tested cycle conditions, the proposed control strategy reduces the maximum current of the battery by 8.5% and the maximum temperature is reduced by 7.98%; when compared with a single fuzzy controller used by HESS, the proposed strategy can reduce the maximum battery current and maximum temperature by 7.02% and 1.50%, respectively.

1. Introduction

Although the performance of lithium batteries has been greatly improved in the past decades of development, the existing batteries have many limitations and cannot meet the kinetic energy demand of electric vehicles[1].For example, electric vehicles still face problems such as high initial cost and reliability of energy storage[2]. And there is also a concern that it has safety issues, which mainly refers to when the demand power of electric vehicles is too large, the lithium battery will output excessive current to meet the demand power, and in order to release the high current lithium battery, the chemical reaction will be accelerated, and the system will release a lot of heat at this time, which may cause the battery to explode. When the violent chemical reaction time is too long, the cycle life of the lithium battery will be reduced. At present, the most common solution is to use super capacitors as auxiliary equipment and lithium batteries to form a hybrid energy storage system (HESS), which can use the advantages of supercapacitors to reduce the peak current of lithium batteries, and greatly reduce the heat generated when the lithium battery is working. In view of the non-linear characteristics of the power demand of electric vehicles, this paper chooses fuzzy logic for control, and then adds...
Savitzky-Golay filter for selective filtering. Through simulation and comparison, it is found that this strategy can effectively reduce the energy consumption rate of electric vehicles, and reducing the temperature of the battery when the electric vehicle is running.

In order to make full use of the performance of the hybrid energy storage system, researchers have proposed various energy management strategies. The proposed strategies are mainly divided into two types, rule-based strategies and optimization-based strategies. The rule-based strategy is to select the operating mode according to the defined rules[3, 4]. It is mainly divided into the strategy based on the deterministic rule and the strategy based on fuzzy logic[4]. Rule-based strategies are widely used because of their simplicity, practicality and low computational complexity. In order to make the hybrid energy storage system achieve better performance in terms of economy, researchers have done a lot of research on optimization-based strategies in recent years, including real-time power optimization strategies and offline optimization strategies. Real-time optimization strategies such as consumption minimization (ECMS), For example, Amir et al.[5] used ECMS cost function derives estimations for the upper and lower bounds of the optimal equivalent factor to obtain better economic fuel performance. Offline optimization strategies are based on evaluation indicators to obtain global optimal solutions, such as dynamic programming(DP)[6], particle swarm optimization(PSO)[7], genetic algorithm(GA)[8], simulated annealing(SA)[9]. However, these strategies have high requirements on the computing power of the device.

2. Coupling mode of hybrid energy storage system

There are four topological structures in the HESS coupling system: passive topology, two semi-active topologies and fully active topologies. The semi-active topology of HESS uses only one DC/DC converter. The converter selected in this paper is in the semi-active topology of the supercapacitor side, because the output voltage and current of the supercapacitor are more difficult to control than the battery. This is also the topology selected by most papers, which can well balance cost and performance. The topology used in this paper is shown in Figure 1.

![Figure 1.Semi-active topology.](image)

3. Hess modeling

3.1. Dynamic model of battery

This article uses the PNGV equivalent circuit model. This model is based on the Thevenin model and adds a capacitor to describe the open circuit voltage change caused by the accumulated load current time. As shown in Figure 2.
Figure 2. PNGV equivalent circuit model of the battery.

Where $U_{oc}$ represents an ideal voltage source, which is used to represent the open circuit voltage of the battery; $R_p$ is ohmic resistance; polarization resistance $R_p$ and polarization capacitance $C_p$ are used to describe the overvoltage $U_p$ of the battery; $U_{bat}$ and $I_{bat}$ represent battery load voltage and current, respectively. The basic parameters of the battery used are shown in Table 1.

Table 1. Basic parameters of the battery.

| Parameters          | Value | Unit |
|---------------------|-------|------|
| Battery Type        | Lithium-ion battery |       |
| Nominal pack voltage| 322   | V    |
| Nominal pack capacity| 40    | Ah   |
| Number of cells     | 174   |      |
| Parallel number     | 2     |      |
| Normal cell voltage | 3.7   | V    |
| Normal cell capacity| 20    | Ah   |

Based on the equivalent circuit, the voltage state equation is established as follows:

$$U_{oc} = U_L - R_s I_s - \frac{1}{C_p} \left( \int I_{bat} dt \right) - I_{bat} R_p \quad (1)$$

The remaining SOC at time $t$ is calculated based on the SOC at the initial time. The percentage of remaining SOC is calculated by integrating the current over time $t$. Which is defined by

$$SOC(t) = SOC_0 \frac{1}{Q_N} \int_0^t \eta I(t) dt \quad (2)$$

Among them, $Q_{loss}$ is the rated capacity of the battery; $I(t)$ is the current of the battery at time $t$, and $\eta$ is the coulomb efficiency of the battery. The actual power loss caused by charging and discharging in time $\lambda$ in the battery pack is:

$$Q_{loss} = \sum_{\lambda=0}^{\lambda} \left( I(t)^2 R/m - U(t) I(t) (1 - Q_c) \right) \quad (3)$$

$I(t)$ is the output current of the battery pack at time $t$, $R$ is the total impedance of the battery pack, $U(t)$ is the instantaneous terminal voltage of the battery pack at time $t$, $Q_c$ is the Coulomb efficiency of the battery, $m$ is the number of parallel branches in the battery pack.

3.2 Dynamic model of supercapacitor

The supercapacitor uses RC equivalent circuit for dynamic modeling, as shown in Figure 3. The model includes a large capacitor $C_b$ and a characteristic small capacitor $C_s$. The large capacitor $C_b$ is usually used to simulate the static state of the super capacitor, and the capacitor $C_s$ is used to describe the dynamic state of the supercapacitor. The resistance $R_s$ is used to simulate the resistance of the super capacitor. The resistance $R_s$ and the surface resistance $R_s$ are used to reflect the storage capacity and dynamic characteristics of the supercapacitor, respectively.
Figure 3. RC equivalent circuit model of the supercapacitor.

According to the RC equivalent circuit of the battery, the mathematical model of each parameter in the circuit can be written:

\[
\begin{align*}
\frac{dU_b}{dt} + \frac{dU_s}{dt} &= \left[ \begin{array}{c}
-1 \\
1
\end{array} \right] U_b + \left[ \begin{array}{c}
-R_s \\
-C_b(R_e + R_s)
\end{array} \right] \cdot [I_{sc}] \\
U_s &= \frac{R_e - R_t}{R_e + R_s} U_b + \frac{R_e + R_t}{R_e + R_s} U_s + \left( \frac{R_e R_t - R_e R_s}{R_e + R_s} \right) I_{sc}
\end{align*}
\]

(4)

(5)

The basic parameters of supercapacitors are listed in Table 2.

| Parameters               | Value | Unit |
|-------------------------|-------|------|
| Battery Type            | Supercapacitor |       |
| Nominal pack voltage    | 297   | V    |
| Nominal pack capacity   | 24    | F    |
| Number of cells         | 110   |      |
| Parallel number         | 1     |      |
| Normal cell voltage     | 2.7   | V    |
| Normal cell capacity    | 2500  | F    |

The SOC of the super capacitor at the current moment can be expressed as

\[
SOC = \frac{Q_{\text{remaining}}}{Q_{\text{total}}} = \frac{C \times (U_{sc} - U_{min})}{C \times (U_{max} - U_{min})} = \frac{U_{sc} - U_{min}}{U_{max} - U_{min}}
\]

(6)

4. Energy management strategy

Since the power demand of an electric vehicle is related to the acceleration and speed of the vehicle at the current moment, the power demand analysis is performed on the existing cyclic operating conditions. Figure 4 shows the demand power analysis under the same vehicle type and under different cycle conditions. We can see from the figure that more than 80% of the power demand is below 20,000W. Then the proposed control strategy takes 20,000W as the baseline and is processed under two different control strategies. This can better handle the demand power. The general flow chart and specific processing block diagram of the proposed energy management strategy are shown in Figure 5.
According to the following conditions, the control strategy selectively outputs the power processed by the fuzzy controller and Savitzky-Golay filter:

• When the battery power output by the fuzzy controller is less than or equal to 0, and the battery power output after the Savitzky-Golay smoothing filter is greater than or equal to 0, the output power of the fuzzy controller will be selected for the battery.

• When the difference between the battery power output by the fuzzy controller and the previous time is less than 1, and the output value after the Savitzky-Golay smoothing filter and the output of the fuzzy controller are greater than 1, the power output of the fuzzy controller will be used for the battery.
• When the product of the battery power output by the fuzzy controller and the output power smoothed and filtered by Savitzky-Golay smoothing filter is less than 0, the output power of the fuzzy controller will be selected for the battery.

The membership functions of the fuzzy controllers used are shown in Figure 6(a)-(b) and (e)-(h), where (a)-(b) are fuzzy11, (e)-(h) It is fuzzy22.

![Membership function of P<sub>req</sub>](image1)
![Membership function of SOC<sub>bat</sub>](image2)
![Membership function of SOC<sub>dc</sub>](image3)
![Membership function of K<sub>bat</sub>](image4)

(a) Membership function of P<sub>req</sub>  
(b) Membership function of SOC<sub>bat</sub>  
(c) Membership function of SOC<sub>dc</sub>  
(d) Membership function of K<sub>bat</sub>

According to the fuzzy optimal control strategy, the fuzzy rules are shown in Table 3 and Table 4.

5. Simulation results and analysis
The control strategy proposed in this paper is implemented in Matlab/simulink environment, and the effectiveness of the proposed control strategy is verified. We chose the driving schedule (CYC_NYCC + CYC_UDDS) as the test driving cycle, and its figure are shown in Figure 7.
The energy loss of the hybrid energy storage system is an important indicator of the coordinated working efficiency of the battery and supercapacitor. When the battery and supercapacitor are charged and discharged within the allowable capacity, the energy loss of the energy storage system is smaller than other system (under agreed cycling conditions), which shows that the strategy can effectively allocate the required power. The energy loss of the energy storage system in this paper is based on formula (3). Table 5 shows the energy loss of battery bank and supercapacitor bank in the energy storage system under four conditions. (Strategy A, Strategy B, and Strategy C respectively represent traditional fuzzy control strategies, with two modes of fuzzy control strategy and B strategy combined with Savitzky-Golay selective filtering.)

Table 5. Energy loss of energy storage system.

| Mixed types or strategies | $Q_{\text{bat-loss}}$ (kJ) | $Q_{\text{sc-loss}}$ (kJ) | $Q_{\text{loss}}$ (kJ) |
|---------------------------|-------------------------|----------------------|------------------|
| Single ESS                | 420.17                  | 0                    | 420.17           |
| Strategy A                | 343.81                  | 10.84                | 354.65           |
| Strategy B                | 338.46                  | 11.21                | 349.67           |
| Strategy C                | 321.93                  | 18.18                | 340.11           |

Compared with Single ESS, the energy loss of the hybrid energy storage system under the three strategies was reduced by 15.60%, 16.78%, and 19.05%, respectively.

The data image obtained by the simulation is shown in Figure 8.
Figure 8. Performance comparison of ESS and HESS based on different strategies

Figure (a) shows the battery current, after being selectively filtered by the Savitzky-Golay filter, the battery current is smoother than other strategies. When the maximum discharge current of the battery in the ESS is 118.7A, the maximum current of the hybrid energy storage system based on Strategy A, Strategy B and Strategy C is 116.8A, 115.7A, and 108.6A respectively; Compared with Single ESS, the maximum current of the three strategies is reduced by 1.6%, 2.5% and 8.5% respectively; Figure (b) shows that the power fluctuation of Strategy C is relatively gentle; In Figure (c), the final SOC of Single ESS is 0.68712, and the final SOCs of HESS based on three different strategies are 0.688591, 0.696687 and 0.69730498 respectively. Compared with the SOC of Single ESS, the SOC based on the three strategies has increased by 0.21%, 1.39% and 1.48% respectively; Battery temperature is an important indicator of battery safety. Shown as Figure (d), the maximum temperature of the battery in Single ESS is 30.6897°C, and the maximum temperature based on three different strategies in HESS is 28.659002°C, 28.4278905°C and 28.24126656°C, respectively. Compared with Single ESS, the maximum temperature in HESS is reduced by 6.62%, 7.37% and 7.98% respectively; When the test cycle is completed, the temperature of Single ESS is 29.83108°C, and the temperature of HESS in the three cases is 27.95278°C, 27.78254°C and 27.57719°C. The temperature of HESS under the three strategies is lower than that of ESS by 6.30%, 6.87% and 7.56%. Figure (e) shows the battery voltage change during the cycle of working conditions. The battery voltage change range of the Strategy C based HESS is smaller than the other three. Figure (f) shows the current change of the supercapacitor in HESS. It can be seen that the current of the supercapacitor in Strategy C covers the current of the supercapacitor in the other two cases, and the SOC of the supercapacitor in Figure (g) is the lowest in Strategy C. This is mainly because the Savitzky-Golay filter reduces the peak power of the battery after selective filtering, and the supercapacitor will absorb more peak power.

6. Conclusion

An intelligent energy management strategy based on fuzzy logic control and Savitzky-Golay selective filtering for electric vehicle demand power classification is studied, which aims to improve various performance indicators of the battery by optimizing power allocation of HESS. By using Savitzky-Golay selective smoothing filter, the peak power of the battery can be effectively reduced, and the current fluctuation of the battery can be reduced. The improvement of these performance indicators helps reduce the degradation of the battery due to high current.

In order to evaluate the performance of the proposed control strategy, a simulation test was performed by MATLAB/Simulink. The results show that this method can effectively improve various performance indexes of the battery. For instance, compared with the traditional single ESS, the maximum current of the batteries in the HESS dropped by 1.60%, 2.53%, and 8.51% under the three strategies. In terms of the maximum temperature, compared with Single ESS, they were reduced by 6.62%, 7.37% and 7.98%.

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