Research on the Combined Control Strategy of Low Temperature Charging and Heating of Lithium-Ion Power Battery Based on Adaptive Fuzzy Control

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Abstract: A low temperature environment will lead to the decrease of chemistry reaction rate and increase of the internal resistance of the lithium battery. In addition, the excessive charging current will cause the lithium to separate out and even the permanent attenuation of battery capacity. In order to solve these problems, this paper proposes a low-temperature charging heating combined control strategy, which takes the temperature acceptable charging current of the battery at low temperature as the charging current constraint and the maximum output power of the system as the power constraint. Firstly, a scheme of combined charging and heating control system is put forward. Secondly, the low temperature charging control strategy based on adaptive fuzzy control is established and then the model is simulated and analyzed in MATLAB software. At last, a Chroma 72,001 charge and discharge tester is used to conduct a low temperature test on 18,650 lithium iron phosphate battery monomers. The results show that the low-temperature charging control strategy proposed in this paper has a more stable temperature control effect on the battery, the constant current charging time of the battery is reduced by 14% compared with the traditional threshold control method, and the overall charging energy consumption is reduced by 5.6%.

Keywords: low-temperature charging; Li-ion battery; combined control strategy; temperature-acceptable charging current curve; adaptive fuzzy control strategy

1. Introduction

Electric vehicles (EV) have many competitive edges, such as quietness, pollution-free, high energy efficiency, energy diversification, and so on. The EV has become one of the key developments and research fields in the automobile industry [1]. The lithium-ion battery has become one of the main power sources of EV and the factors that underpin its dominance today are high energy density, high specific power, long life, and environmental friendliness [2–4]. Charging is a necessary part in the daily use of electric vehicles. Whether its comprehensive characteristics can meet the user’s expectation of charging performance is directly related to the user experience of EVs. When the temperature is low in winter, the charge and discharge performance of the battery obviously decline [5,6]. The decrease of temperature will lead to the reduction of the constant current charging capacity of the power battery, so that the constant voltage is mainly used for charging. However, a long time of constant voltage charging under low temperature will lead to a long charging time, low charging efficiency, and will induce the side reaction performance attenuation of power batteries [7]. Therefore, a reasonable heating and charging strategy can not only maximize the charging performance of the battery, but also
avoid additional damage to the battery. A product of Beijing-Hyundai Automobile Company adopts preheating–charging low temperature charging strategy, which recharge the battery after heating it to a threshold temperature. This strategy, being simple to operate, increases the rate of charging and can guarantee security, but this charging method has not made full use of an acceptable charging current charge below the threshold temperature [8]. In reference [9], the whole low-temperature charging process is divided into three modes, namely pure heating, heating while charging and pure charging, which shortens the heating–charging time under low temperature. In reference [10], a similar three-stage low temperature charging control strategy is adopted, in which the charging current is further adjusted in real time according to the battery temperature in the charging and heating stage, so as to make fully advantage of the acceptable charging current of the battery and improve the charging speed. However, in this method, the heating power is not controlled in real-time according to the state of the battery. On one hand, the charging power of the charger cannot be fully utilized in the early stage of heating; on the other hand, the battery temperature will continue to rise after reaching the heating temperature threshold, resulting in the loss of energy efficiency. In reference [11], the battery heating film is powered by the battery’s own energy, which made the best use of the large internal resistance of the battery’s low-temperature discharge, can effectively improve the temperature rise speed of the battery and save the charging time. The disadvantage is that if the initial battery power is low, it is easy for the battery to over discharge or become unable to reach the desired temperature. Remmlinger [12,13] put forward a charging control strategy by using the information obtained from proposed reduced anode potential model. Since anode potential is an indicator for lithium deposition, the charging current is controlled in real time in the strategy such that the anode potential never drops below 0V, therefore preventing degradation during charging from lithium plating and improves charging time significantly at low temperatures. However, the charging control strategy still need more experimental verification. Ruan [14] proposed a method of stepwise segmented charging technique, which uses the internal resistance heat generation principle in the process of battery charging and discharging to realize the heating of the battery by continuously charging and discharging the battery. The battery temperature rose to 0 °C in 15 min under the environment of −10 °C. At the same time, the control mode of “shallow charging and shallow discharging” did not significantly shorten the battery life. Based on the equivalent circuit of the battery, Zhang [15] analyzed the working characteristics of the battery in the frequency domain and proposed the AC heating control strategy of the battery. The results show that the temperature of the battery can be increased from −20 °C to 5 °C in 15 min. Wei [16] analyzed the influence of frequency and amplitude of charging current on the heating effect and service life of battery by means of model calculation and analysis. The results demonstrate that properly reducing the frequency of charging current and increasing the amplitude of charging current can effectively improve the heating speed of battery without additional attenuation of battery life. Although the above methods of self-heating through battery charging and discharging cycle or AC charging are effective, in the actual use process, the complex operation process and the expensive equipment cost make it difficult to put into use temporarily. Wang [17] made a comparative study of several common external and internal heating methods. The results show that the fastest heating speed can be obtained by covering the heating device on the outside of the battery and using the battery’s own discharge to power the heating device.

Through the above research on the low-temperature charging control strategy of lithium-ion batteries, it can be found that the low-temperature charging is mainly a reasonable combination of the low-temperature preheating process and the normal temperature charging process of the battery through different ways. In this paper, a combined control strategy of low-temperature charging and heating based on adaptive fuzzy control is proposed. This strategy takes the temperature acceptable charging current curve of the battery as the charging current constraint and the maximum power of the system as the power constraint. Then, the effectiveness and feasibility of the proposed strategy are verified by simulations and experiments. The results show that the strategy can shorten charging time and reduce energy consumption. In addition, the limited system power is fully and reasonably
utilized so that charging and heating power are optimally distributed. As another contribution of this paper, factors such as ambient temperature, system power, and battery insulation are discussed.

The paper is organized as follows. Section 2 establishes the mathematical model, its control scheme, as well as the corresponding control strategy. Section 3 introduces the simulation results and the influences of temperature, power, and insulation on charging are discussed. Then, experiments are carried out to verify the performance of the proposed strategy. Finally, Section 4 summarizes the conclusions.

2. Study on Control Strategy of Low Temperature Charging

2.1. Mathematical Model of Low Temperature Charging and Heating

At present, the common method to study the battery power characteristics is using the battery model. In order to ensure the real-time estimation of the model parameters, weighing the calculation amount and identification effect of the model, the first-order RC model is selected to simulate the battery terminal voltage change under the operating condition. The circuit structure is shown in Figure 1. $U_{oc}$ is the battery open circuit voltage (OCV); $U_i$ is the battery terminal voltage; $I_L$ is the battery load current (assumed negative for discharging and positive for charging) and $I_P$ is the outflow current of $C_P$. $R_r$ is the ohmic resistance; $R_P$ is the polarization resistance; and $C_P$ is the polarization capacity. The RC network consisted with $R_P$ and $C_P$ describes the mass transportation effects and dynamic voltage performance of the battery. The polarization voltage on $R_r$ and $C_P$ is represented as $U_P$.

![First order RC-branch equivalent circuit model.](image)

According to the equivalent circuit model, we know:

$$
\begin{align*}
\dot{U}_P &= -\frac{1}{C_P R_P} U_P + \frac{1}{C_P} I_L \\
U_i &= U_{oc} - I_L R_r - U_P
\end{align*}
$$

(1)

All the parameters of the battery model are the function of SOC, which is defined as

$$
SOC_t = SOC_0 - \int_0^t \eta \dot{I}(\tau) d\tau / C_Q
$$

(2)

where SOC$_t$ denotes battery SOC at time $t$, SOC$_0$ denotes the initial value of battery SOC (defined as 0 in this paper for the charging condition), $C_Q$ is the rated capacity of the battery, and $\eta$ is the current efficiency (assumed to be 1 in this paper), $\tau = C_P R_P$ is the time constant of the circuit.

In the process of battery charging and heating, the heat generation and dissipation of the battery can be regarded as an unsteady process of time varying heat source. The heat generation of the battery mainly includes the heat generated by the battery during charging and the heat generated by the electric heating film outside the battery. In this paper, the heat dissipation of the battery ignores the
radiation heat dissipation and is mainly the convection heat transfer between the battery surface and the air. Therefore, the charging and heating process of the battery can be expressed by the following heat balance equation:

$$Q_{\text{batt}} = Q_C + Q_H - Q_a$$  \hspace{1cm} (3)

where $Q_{\text{batt}}$ is the net change of battery heat (W), $Q_{\text{batt}} = m_{\text{batt}} \cdot C_{\text{h,batt}} \frac{dT}{dt}$, $m_{\text{batt}}$ is the battery mass (g), $C_{\text{h,batt}}$ is the heat capacity of the battery (J/g·°C), and $T$ is battery temperature (°C). $Q_C$ is the heat generated by charging inside the battery (W). $Q_H$ is the heat generated by electric heating film (W). $Q_a$ is the heat transferred from the battery surface to the external environment (W).

Thomas and Newman’s research [18] on the heat generation mechanism of the battery shows that the heat generation of the battery in the process of charging and discharging is mainly generated by Joule heat generation and entropy heat generation. In this paper, the charging current of the cylindrical battery is small, so the entropy heat generation is ignored, and only Joule heat generation is considered, as shown in the following formula [19]:

$$Q_C = I^2 R_s + U^2 p / R_p$$  \hspace{1cm} (4)

As for internal heat generation, since the 18,650 battery has a winding structure, it can be approximately considered that the internal heat generated is evenly distributed throughout the battery monomer. The heat generated by the electric heating film is mainly transferred to the inside of the battery by means of heat conduction, while the heat exchange between the battery and the environment is mainly by convection.

Since the electric heating film is a flexible material and is closely pasted on the battery surface, the contact thermal resistance between the heating film and the battery is ignored in the calculation of convection and heat transfer. The electric heating film is taken as a part of the battery surface and the part covered by the heating film is replaced. Because there is no forced air flow in the whole system, the convection heat transfer is mainly natural convection. The rate of convection heat transfer can be calculated by Newton’s formula:

$$Q_a = A \cdot h (T_{\text{bw}} - T_a)$$  \hspace{1cm} (5)

where, $A$ is the battery surface area ($m^2$), $h$ is the surface heat transfer coefficient, $T_{\text{bw}}$ is cell surface temperature (°C), and $T_a$ is ambient temperature (°C).

The heat transfer process of the electric heating film to the battery is carried out through heat conduction. The heat conduction in the heating process of the battery is calculated by Fourier law. According to the Fourier law, in the isotropic continuous medium, the heat passing through the section at any position in unit time is numerically proportional to the temperature gradient of the point, and the direction is opposite to the temperature gradient of the point. The formula is as follows:

$$\vec{q} = -\lambda \text{grad}T = -\lambda \frac{\partial T}{\partial n} \vec{n}$$  \hspace{1cm} (6)

where $\text{grad}T$ is the temperature gradient of a point in space, $\vec{q}$ is the heat flux density vector (W/m²), $\lambda$ is the thermal conductivity (W/(m·°C)), and $T$ is the temperature (°C).

In the process of heat transfer calculation, it is considered that the specific heat capacity of the same material in the same direction is the same regardless of the different density and specific heat capacity of different materials inside the battery, and the battery is regarded as a lumped parameter model. Three coordinate systems are established to decompose the heat flux introduced in each direction of the parallelepiped micro element according to the Fourier law, which can be expressed as follows:

$$\begin{align*}
\Phi_x &= -\lambda \frac{\partial T}{\partial x} dydz \\
\Phi_y &= -\lambda \frac{\partial T}{\partial y} dxdz \\
\Phi_z &= -\lambda \frac{\partial T}{\partial z} dxdy
\end{align*}$$  \hspace{1cm} (7)
where, $\Phi_x$, $\Phi_y$, $\Phi_z$ is the heat flux ($W$) in $x$, $y$ and $z$ directions respectively.

For the microelements, according to the law of conservation of energy, in any time interval, the total heat introduced into microelements + the heat generation of the heat source in the microelements = the total heat derived from microelements + the increment of the thermodynamic energy of the microelements. Then, there is the following expression:

$$\rho C \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \lambda \frac{\partial T}{\partial z} \right) + \Phi$$ (8)

where $\rho$ is the average density of the battery ($kg/m^3$), $T$ is the temperature of the battery cell (°C), $C$ is the average specific heat capacity of the battery ($J/(kg\cdot°C)$); $t$ is the time (s); $K$ is the thermal conductivity of the battery cell ($W/(m\cdot°C)$); $\Phi$ is the heat generation rate per unit volume of the battery ($W/m^3$).

2.2. Charging-Heating Combined Control Scheme

In reference [13], the author used the battery reduced model to get the degradation map and then by evaluating the map, the maximum non-harming charging current can be obtained. In this paper, the same method is used to get the battery temperature-acceptable charging current curve as shown in Figure 2. It can be seen that the battery can be charged at a current ratio of 1 °C above 10 °C, while the acceptable charging current of the battery is reduced to 0.2 °C when the temperature drops to 0 °C, i.e., the lower the temperature, the lower the charging rate.

![Figure 2. Temperature-acceptable charge current curve.](image_url)

Therefore, in the low temperature environment, the acceptable charging current of the battery corresponding to different charging temperatures is different, and the curve reflects the maximum safe charging current of the battery at different temperatures. In order to ensure the safety of charging and prevent the irreversible loss of battery capacity due to low-temperature charging, the charging current should meet the acceptable charging current curve constraint:

$$I(t) \leq I_W(T_i)$$ (9)

where $I(t)$ is the charging current at time $t$, $T_i$ is the battery temperature at time $t$, and $I_W(T_i)$ is the lossless charging current corresponding to the temperature $T_i$. For the charging heating combined control system, due to the limited total output power, the following constraints must be met for the charging power $P_c$ and the heating power $P_H$:

$$P_{\text{max}} \geq P_c + P_H$$ (10)
The control strategy block diagram of the low-temperature charging heating combined control system is shown in Figure 3. During charging, the expected charging current is calculated according to the charging demand, and then the safe charging temperature required by the expected charging current is calculated by the temperature acceptable charging current curve. Through comparing the expected temperature with the actual temperature of the battery, the temperature difference and the change of the difference are obtained, which are used as the input of the adaptive fuzzy control system, and the desired heating power is achieved through the calculation of the fuzzy controller. Meanwhile, according to the temperature feedback of the battery, the acceptable charging current of the battery can be obtained through the temperature-acceptable charging current curve. By comparing the acceptable charging current with the expected charging current, the minimum value can be taken to calculate the expected charging power. Due to the limitation of the maximum power of the system, it may not be able to meet the requirements of expected heating power and expected charging power at the same time. Therefore, it is necessary to decouple the charging power and heating power. In this paper, the priority method is used to set the charging power as the highest priority. Then, the heating power is adjusted according to the maximum output power of the system, so as to obtain the final charging power and heating power.

**Figure 3.** Schematic diagram of low-temperature charging and heating combined control scheme.

### 2.3. Charging-Heating Combined Control Strategy Based on Adaptive Fuzzy Control

Due to the complexity and non-linear characteristics of the heating–charging model of the battery, the adaptive fuzzy control method based on the scale factor self-adjustment is adopted to enhance the control performance in this paper. A fuzzy system can be divided into four parts: fuzzification, fuzzy rule base, fuzzy inference engine and defuzzification [20,21]. The proposed fuzzy system is described in detail below.

As shown in Figure 4, the adaptive fuzzy control system in this paper consists of two parts: basic fuzzy controller and scale factor adjusting fuzzy controller. For the basic fuzzy controller, the error \( e \) between the actual expected temperature of the battery and its derivative \( \Delta e \) are used as the system input, and the increment of the heating power of the charging subsystem \( \Delta P \) is used as the system output. \( \Delta p \) is the product of \( \Delta P \) times scale factor \( k_f \). \( k_e \) and \( k_{\Delta e} \) are quantization factors. \( E \) and \( \Delta E \) are quantized input. \( k_{\Delta k_f} \) is the scale factor of \( \Delta k_f \).

For the fuzzy controller of scale factor adjustment, its input is the same as that of the basic fuzzy controller, and its output is the scale factor increment of the basic fuzzy control system \( \Delta k_f \). \( K_e \) and \( K_{\Delta e} \) are quantization factors. \( E' \) and \( \Delta E' \) are quantized input. In addition, \( r \) is the set value, \( y \) is the feedback value, \( \eta \) is the output value.
2.3.1. Fuzzification of Input and Output

After determining the input and output of the fuzzy controller, in order to realize the conversion between the accurate and fuzzy quantity, 7 fuzzy subsets are selected for the input and output quantity, and the corresponding language values are NB (negative big), NM (negative middle), NS (negative small), O (Zero), PS (positive small), PM (positive middle), PB (positive big). The basic domain of the control error \( e \) between the battery temperature and the target temperature is set as \([-1,1]\), the fuzzy domain is set as \([-3,-2,-1,0,1,2,3]\), and the quantization factor is \( k_e = 3 \); The basic domain of battery temperature control error increment is set as \([-0.2,0.2]\), the fuzzy domain is set as \([-3,-2,-1,0,1,2,3]\), and the initial quantization factor is \( k_{\Delta e} = 15 \); the basic domain of the heating power output from the heating subsystem is \([-3,3]\), and the corresponding fuzzy domain is set as \([-3,-2,-1,0,1,2,3]\), and the initial scaling factor is 1. The output basic domain of the fuzzy controller is set as \([-1,1]\), and the fuzzy domain is set as \([-3,-2,-1,0,1,2,3]\). Input and output membership functions are shown in Figures 5 and 6.

![Figure 4. Schematic diagram of adaptive fuzzy system.](image)

![Figure 5. Input membership function. (a) Temperature error membership function, (b) temperature error change membership function.](image)
2.3.2. Fuzzy Control Rules

The making of fuzzy rules is the core of the fuzzy controller. According to the temperature performance of the battery under different heating power in the process of low-temperature charging and heating, the fuzzy rule table as shown in Table 1 is developed based on summarizing the results of multiple simulations and tests. Figure 7 shows the surface diagram of fuzzy control rules obtained by the above fuzzy rules.

Table 1. Heating power fuzzy control rules.

| Heating Power $\Delta P$ | Battery Temperature Error $E$ |
|--------------------------|-------------------------------|
|                          | NB | NM | NS | O  | PS | PM | PB |
| Chang in battery         | NB | NB | NB | NM | NM | NS | PS |
| temperature error $\Delta e$ | NM | NM | NM | NS | NS | PS | PB |
|                           | NS | NS | NS | MS | O  | PS | PM |
|                           | O  | NM | NM | NS | O  | PS | PM |
|                           | PS | NM | NS | O  | PS | PS | PB |
|                           | PM | NS | O  | PS | PM | PM | PB |
|                           | PB | O  | O  | PS | PM | PM | PB |

Table 2 shows the fuzzy control rules for scaling factors and the regular surface of these rules is shown in Figure 8.
Table 2. Scale factor fuzzy control rules.

| Change in battery temperature error $\Delta e$ | Battery Temperature Error $E$ | $\Delta k_f$ |
|-----------------------------------------------|-------------------------------|--------------|
| NB                                           | NB                            | NB           |
| NM                                           | PB                            | NB           |
| NS                                           | PB                            | NB           |
| O                                            | PS                            | PS           |
| PS                                           | O                             | PS           |
| PM                                           | PS                            | PS           |
| PB                                           | PS                            | PS           |

Figure 8. Fuzzy control surface of scale factor.

2.3.3. Defuzzification

In this paper, the centroid method is used to realize defuzzification. The output of the fuzzy controller can be defined by the algebraic expression below:

$$u^* = \frac{\sum_{i=1}^{n} \mu_C(u_i) \cdot u_i}{\sum_{i=1}^{n} \mu_C(u_i)} \tag{11}$$

where $\mu_C(u_i)$ is the membership degree of the domain element; $u_i$ is the element in the domain; $n$ is output quantized series; $u^*$ is the fuzzification of the output.

3. Simulation and Experiments

The experimental setup includes: (1) a LiFePO$_4$ test battery (Bak, Shenzhen, China); (2) a Chroma 72,001 battery (Chroma ATE, Taoyuan, China) test system; (3) a host computer. The nominal voltage of the battery is 3.2 V, the recommended charging voltage is 3.65 V. The nominal capacity is 2.5 Ah. The weight is no more than 45 g. The Chroma 72,001 battery is used to charge and discharge the battery with a maximum voltage of 5 V and a maximum current of 20 A with an accuracy of 1 mV voltage and 10 mA current. It has 8 independent testing channels as well as 8 temperature acquisition sensors. The experimental data such as current and voltage are saved in real time by the host computer through TCP/IP interface. The experimental setup is shown in Figure 9.
For the first order RC-branch equivalent circuit model, the estimated battery parameter is set as follows according to the pulse current charging: \( R_p = 0.08 \, \Omega \), \( R_r = 0.035 \, \Omega \), \( C_p = 525 \, F \). The OCV curve is shown in Figure 10:

![Battery parameter of OCV](image)

**Figure 10. Battery parameter of OCV.**

### 3.1. The Influence of Ambient Temperature on Low Temperature Charging

The control strategy of low-temperature charging in this paper is simulated and analyzed with 1 °C constant current as the expected charging rate at -30 °C, -20 °C, -10 °C, and 0 °C respectively. The maximum power of the system used in the simulation is 15 W and the heat exchange coefficient of battery surface \( h = 5 \). The charging characteristic curves of the battery at the above different ambient temperatures are shown in Figure 11. In the initial heating stage, the temperature of the battery rises rapidly. When approaching the target temperature, the battery temperature rises slowly and finally stabilizes at the target temperature.

At different ambient temperatures, the temperature rise curves of the battery are similar, which indicates that the adaptive fuzzy control strategy can work stably. In the initial stage of charging, the battery charging current is limited by the temperature-acceptable charging current curve due to the low temperature of the battery.

Due to the large difference between the actual battery temperature and the expected charging temperature corresponding to the 1 °C ratio, the heating power of the system increases rapidly, and the overall output power of the charging–heating system reaches the maximum rapidly. With the heating process, the battery temperature increases rapidly, as well as the charging current of the battery.

Since the charging power priority of the system is higher than the heating power and the total system power is certain, the heating power of the system gradually decreases with the increase of battery charging current. When the temperature of the battery is close to the target temperature, the decrease rate of heating power increases, and the temperature rise rate of the battery slows down and gradually stabilize.
By comparing the charging–heating characteristics at different temperatures, it can be found that the system works at the maximum power at the beginning of charging. When the battery temperature reaches the expected temperature, the total system power decreases with the increase of the ambient temperature.

For the condition of −30 °C, due to the low ambient temperature, the heating process lasts the whole charging stage, and the system power is always maintained at the maximum value. For the condition of −20 °C, the heating power is reduced to 0 W in the later stage of charging and the battery can maintain its temperature depending on its own charging heating; for the condition of −10 °C and 0 °C, the heating power of the system quickly reduces to 0 W after the battery reaches the target temperature.

Figure 11 shows the error between the actual temperature of the battery and the expected temperature during charging. In the early stage of charging, the temperature error of the battery drops rapidly and reaches stability after a short period of overshoot. For the condition of −30 °C, the battery temperature remains almost the same and its fluctuation is within ±0.5 °C, while for the other three conditions, since the heat power generated from battery charging is greater than the heat dissipation power, the battery temperature still keeps rising although the heating power has been reduced to 0 W.
Figure 12. Error between actual battery temperature and expected charging temperature.

Figure 13 shows the performance of battery charging time and charging system energy consumption at different ambient temperatures. With the decrease of ambient temperature, the battery temperature rise time and the total charging–heating time increase slightly, while the heating energy consumption and the total energy consumption of the system increase obviously, which shows that the impact of the ambient temperature on the energy consumption of the system is significantly higher than that of the charging time.

3.2. The Influence of System Power on Low Temperature Charging

The maximum power of the system is set at 10 W, 15 W, 20 W, and 25 W respectively, and the influence of the different maximum output power of systems on the low temperature charging is
analyzed. The working condition adopted is the expected charging current ratio 1 °C, the ambient temperature −30 °C, and the convective heat transfer coefficient h = 5.

Figure 14 shows the performance of the system at different maximum power. Through analyzing the performance of the battery charging current ratio, it is found that when the maximum power of the system is greater than 15 W, the battery charging current can reach the expected current, while when the maximum power of the system is 10 W, the maximum charging current can only reach about 0.7 °C. By analyzing the battery temperature curve, it is found that the higher the maximum power of the system, the faster the battery heating rate. However, when the maximum power exceeds 20 W, the increase of the temperature rising rate obviously decreases. In the constant temperature stage, except for the maximum power of 10 W, the heating power performance of the battery of the other three systems is almost the same. When the 25 W and 20 W systems make temperature adjustment, the heating power peak value is higher than the 15 W system.
At the end of charging, except for the 10 W system, the heating power of the other three systems is close to 0 W, while the 10 W system still needs a certain heating power to maintain the battery temperature.

By analyzing the total system power, it can be found that 10 W system has been working at maximum power since the system power cannot meet the expected charging demand. For the other three systems, they work with full power output in the temperature rise stage and when the battery enters the constant temperature charging stage, the total power of the system is maintained at about 14 W.

During charging, due to the system power constraint and the system has priority to satisfy the charging power, the heating power often fails to meet the output power requirement. In order to further analyze the factor of system power, the difference between the expected output power of the adaptive fuzzy control system $P_{\text{need}}$ and the actual heating power $P_h$ is defined as $\Delta P$.

Figure 15 shows the change of $\Delta P$ during charging in systems of different maximum power. It can be found that, for the maximum power of 20 W and 25 W, the power limitation of the system mainly occurs at the end of the heating stage. The battery temperature is low at this stage. In order to heat the battery quickly, the control system will generate a large output control power. However, due to the rapid increase of battery temperature, the battery charging current rises rapidly and the charging power increases, which limits the actual heating power of the system.

If the maximum power is 15 W, the power limit is mainly distributed in the temperature rising stage. When the battery enters the constant temperature charging process, there are several peaks of $\Delta P$ that disappear quickly, which shows that 15 W power can meet the constant temperature charging demand. If the maximum power is 10 W, $\Delta P$ stabilizes around 9 W after a rapid rise in the early stage of charging. The continuous limitation of the system on charging power indicates that the system power cannot meet the requirement of 1 °C current charging.

Figure 16 shows the performance of battery charging time and charging energy consumption of different maximum system power. It can be found that the charging time of 10 W system is significantly higher than that of the other three systems, while for the 15 W, 20 W and 25 W systems, the charging time is almost the same. The results show that when the system power cannot meet the charging current demand of the system, the overall charging time will be significantly extended, while the shortening of the charging time is limited when the system power continues to increase on the basis of meeting the charging demand. In terms of system energy consumption, as the maximum system power increases, the heating energy consumption decreases, mainly because a larger system power can accelerate the temperature rise of the battery, thereby shortening the overall charging time and reducing the total heating time.

Figure 14. Low temperature charging characteristics of different system power. (a) Charging current, (b) battery temperature, (c) heating power, (d) total system power.
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Figure 15 shows the change of $\Delta P$ during charging in systems of different maximum power. It can be found that for the maximum power of 20 W and 25 W, the power limitation of the system mainly occurs at the end of the heating stage. The battery temperature is low at this stage. In order to heat the battery quickly, the control system will generate a large output control power. However, due to the rapid increase of battery temperature, the battery charging current rises rapidly and the charging power increases, which limits the actual heating power of the system.

If the maximum power is 15 W, the power limit is mainly distributed in the temperature rising stage. When the battery enters the constant temperature charging process, there are several peaks of $\Delta P$ that disappear quickly, which shows that 15 W power can meet the constant temperature charging demand. If the maximum power is 10 W, $\Delta P$ stabilizes around 9 W after a rapid rise in the early stage of charging. The continuous limitation of the system on charging power indicates that the system power cannot meet the requirement of 1 °C current charging.

Figure 16 shows the performance of battery charging time and charging energy consumption of different maximum system power. It can be found that the charging time of the 10 W system is significantly higher than that of the other three systems, while for the 15 W, 20 W and 25 W systems, the charging time is almost the same. The results show that when the system power cannot meet the charging current demand of the system, the overall charging time will be significantly extended, while the shortening of the charging time is limited when the system power continues to increase on the basis of meeting the charging demand. In terms of system energy consumption, as the maximum system power increases, the heating energy consumption decreases, mainly because a larger system power can accelerate the temperature rise of the battery, thereby shortening the overall charging time and reducing the total heating time.

Figure 15. Comparison between the actual heating power and the demand power.

Figure 16. Cont.
3.3. The Effect of Battery Insulation on Low Temperature Charging

The power battery of EV is placed in the battery box during actual use. In order to reduce the heat loss of the battery at low temperature, the battery box is usually coated with thermal insulation material to insulate the battery. In this section, the influence of the battery insulation performance on the low temperature charging is analyzed. The expected charging current is 1 °C, the ambient temperature is ~30 °C, and the maximum power of the system is 15 W. Generally, the natural convection heat transfer coefficient of air is 5–25 W/m²·°C. In this paper, the value of $h$ is set to 1, 5, 10, and 20 to represent different insulation effects. Figure 17 shows the charging performance of the system with different convective heat transfer coefficients.

**Figure 16.** Comparison of charging time and energy consumption of different maximum system power.
(a) Charging time, (b) energy consumption.

**Figure 17.** Low temperature charging performance with different convective heat transfer coefficient.
(a) Charging current ratio, (b) battery temperature, (c) heating power, (d) system power.
By analyzing the charging current ratio, when the convection heat exchange coefficient $h = 1$ and $h = 5$, the expected 1 °C charging current can be achieved, while when $h = 10$ and $h = 20$, the system power cannot meet the charging requirement. It can be seen from the temperature curve that in the initial charging stage, the battery temperature rising rate of different convective heat exchange coefficient is almost the same, while in the end stage of temperature rising, with the increase of convective heat transfer coefficient, the temperature rising rate of the battery slows down rapidly. In the case of $h = 1$, when the battery is in the stage of constant temperature charging, the temperature of the battery starts to rise continuously after charging for a period, indicating that the heat generation rate of the battery is already higher than its heat dissipation rate.

Through analyzing the temperature curve of $h = 5$, it can be found that, although the battery temperature is very close to that of $h = 1$, the charging current difference between them is obvious, because the temperature acceptable charging current curve of the battery drops sharply below 10 °C so that small temperature drop will cause a larger charging current drop. The heating power and total system power are also analyzed. It is found that for $h = 1$ and $h = 5$, the total system power is relatively low because of better insulation of the battery. Especially for $h = 1$, when the system reaches 10 °C, the heating power is always kept at 0 W. When $h = 10$ and 20, the system always maintains the maximum power output; when $h = 20$, nearly 1/3 of the system power is used for battery heating.

As shown in Figure 18, the total energy consumption and heating energy consumption of the system vary with the convective heat transfer coefficient.

![Graphs showing total system energy consumption and heating energy consumption with different convective heat transfer coefficients.](image)

**Figure 18.** Energy consumption with different convective heat transfer coefficient. (a) System energy consumption, (b) heating energy consumption.

Since the system always works at the maximum power when $h = 10$ and $h = 20$, the total energy consumption curve of the two systems is exactly the same, and its rising rate is higher than that when $h = 1$ and $h = 5$. Although the total energy consumption is the same, the heating energy consumption
when \( h = 20 \) is much higher than that when \( h = 10 \). When \( h = 1 \) and \( h = 5 \), there is little difference in total energy consumption between them, but the heating energy consumption when \( h = 5 \) is much higher than that when \( h = 1 \). The reason is that the battery insulation effect is good, and the system energy consumption is mainly used to charge the battery, so the difference in charging energy consumption between them is not obvious in total energy consumption. In terms of charging time, the charging time of \( h = 20 \) is significantly higher than that of other three conditions, while the difference of charging time of the other three working conditions is not obvious, especially for \( h = 1 \) and \( h = 5 \), the charging time of these two is almost the same. The results above show that improving the insulation effect of battery can effectively reduce the total energy consumption and charging time, but when it is reduced to a certain extent, the further reduction of convective heat transfer coefficient has a limited effect on the improvement of the energy consumption and charging time.

### 3.4. Analysis and Comparison of Experimental Results

The experimental environment is outdoor environment in winter, and the ambient temperature is measured as \(-17.5^\circ\text{C}\). During the experiment, the battery is in a natural convection state with the air, and no additional insulation measures are set outside the battery. The maximum power of the system is set to 15 W, and the target charging current is \(1^\circ\text{C}\). According to the actual insulation effect of the battery, the convection heat transfer coefficient is set as \( h = 10 \). Figure 19 shows the battery temperature change curve obtained through simulation and experiment respectively.

![Simulation and test curve of battery temperature.](image)

It can be found that when the charging process starts, the temperature of the battery increases rapidly under the heating subsystem. At about 300 s, the battery temperature reaches the expected temperature \(10^\circ\text{C}\), which is the expected temperature of \(1^\circ\text{C}\) charging current. As the charging process continues, the battery temperature is always stable at about \(10^\circ\text{C}\), and the fluctuation is no more than \(0.2^\circ\text{C}\). The duration of the whole low temperature charging–heating process is about 2400 s. Through comparing the temperature curve obtained by simulation with that obtained by experiment, it is found that the two curves are in good agreement. Then the local amplification of the two temperature curves indicate that there is still a certain error between the simulated and the actual battery temperature, but the error margin is small, no more than \(0.2^\circ\text{C}\). In terms of charging time, the actual charging time obtained through the experiment is slightly less than the simulation time, which is caused by the model error of the battery.

Figure 20 shows the temperature curve of the battery under the charging control strategy based on adaptive fuzzy control in this paper and the traditional threshold controlled low temperature charging method. By comparing these two curves, it can be found that the temperature curve under
threshold control presents a zigzag fluctuation, while the proposed method in this paper can keep the temperature near the target temperature stably. At the same time, the constant current charging time of the battery is reduced by 14% compared with the traditional method, and the comprehensive energy consumption is reduced by 5.6%, which proves the effectiveness and superiority of the low temperature charging control strategy in this paper.

![Figure 20. Comparison of low temperature charging under conventional method and adaptive fuzzy control method.](image)

### 4. Conclusions

Aiming at the low temperature charging problem of the lithium-ion battery, this paper proposes a low-temperature charging–heating combined control strategy based on adaptive fuzzy control, which takes the temperature-acceptable charging current curve of the battery as the charging current constraint and the maximum output power of the system as the power constraint. The battery equivalent circuit model is adopted, and the battery parameters are estimated through a pulse current charging experiment.

In addition, the relevant simulation analysis of the low-temperature charging and heating model is carried out. The results show that: (1) With the decrease of ambient temperature, the time of battery temperature rise and the total charging heating time increase slightly, while the heating energy consumption and the total system energy consumption increase obviously, which shows that the influence of ambient temperature on the system energy consumption is significantly higher than that on the charging time; (2) When the system power fails to meet the charging current demand of the system, the overall charging time will be significantly extended. However, if the system power continues to increase when the charging demand is satisfied, the effect of shortening charging time is limited. In terms of system energy consumption, with the increase of the maximum system power, the heating energy consumption decreases. (3) Improving the battery insulation can effectively reduce the overall energy consumption and charging time of the system, but when it is reduced to a certain extent, the further reduction of the convection heat transfer coefficient has limited effect.

Furthermore, the battery temperature rise under different control strategies is compared using an experimental platform. The results show that the low-temperature charging control strategy proposed in this paper has a more stable effect on the temperature control of the battery than the traditional method. At the same time, the constant current charging time of the battery is reduced by 14% compared with the traditional method, and the overall charging energy consumption is reduced by
5.6%, which proves the effectiveness and superiority of the low-temperature charging control strategy in this paper. Finally, another contribution of this paper is that the limited system power is fully and reasonably utilized so that charging and heating power are optimally distributed. Therefore, this strategy can help to charge the battery with a shorter time and less energy consumption within a possible power constraint.

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