Research on Optimizing Fast Charging Strategies Using Super Capacitors

Yu Zhang, Si Xu and Wanwan Zeng *
School of Hubei University of Technology, Wuhan, China

*Corresponding author e-mail: zengwanwan@hbut.edu.cn

Abstract. One of the important factors affecting the rapid charging of lithium-ion batteries is polarization, the current commonly used depolarization method is the positive and negative pulse method. In the charging process, the resistance discharge method is used to consume the high-energy negative pulses emitted during the charging process, but the energy utilization rate of this method is low. This article proposes a method of using super capacitors to absorb and store high-energy negative pulses, when the stored power of the super capacitor reaches the set value, the stored power will be used to charge the battery at a constant voltage. After analysis and verification, compared with the traditional positive and negative pulse method, the energy utilization rate of this method is increased by 19.3%.

1. Introduction
With the rapid development of electric vehicles, power batteries, as an important system for storing energy, are very important to the development of vehicles. Lithium-ion batteries are widely used with the advantages of long service life, high specific energy, low self-discharge rate, and high cost performance. However, the long charging time brings inconvenience to the driver, so how to improve the charging rate of lithium-ion batteries is still the focus of the moment [1].

At present, the traditional lithium-ion battery charging methods include constant current charging, constant voltage charging and segmented constant current and constant voltage charging, etc. However, the above methods have problems such as long charging and discharging time, poor battery stability, and low charging and discharging efficiency. Literature [2] proposed a reflective pulse charging method, that is, a discharge pulse is added in the process of pulse charging, by discharging the battery during the charging process, the maximum acceptable charging current of the battery is increased. Literature [3] proposed a pulse charging method, which can reduce the polarization effect, shorten the charging time, and achieve the purpose of fast charging.

This paper proposes a supercapacitor to absorb the high-energy negative pulses released during positive and negative pulse charging, because supercapacitors have excellent charging and discharging characteristics. When the super capacitor absorbs the power to a given value, the stored power is then charged to the lithium-ion battery at a constant voltage. Compared with the traditional positive and negative pulse charging method, this method improves the energy utilization rate during the charging process.
2. Lithium-ion battery equivalent model

In the process of charging and discharging, the phenomenon that the battery terminal voltage deviates from the circuit voltage when the current flows is called the polarization effect. The polarization effects of lithium-ion batteries can be divided into three categories: ohmic polarization, electrochemical polarization and concentration polarization. Among them, ohmic polarization exists in the whole battery charging process and the change is small, with the progress of charging and the occurrence of chemical reactions inside the battery, the electrochemical polarization changes significantly in the middle and late stages, and the concentration polarization changes the most in the later stages. According to the different characteristics of the three polarization voltages, this paper selects the first-order RC equivalent circuit model of the battery for analysis.

\[ U_{p}(t) = U_{p}(0)e^{-\frac{t}{\tau}} + IR_{p} \left( 1 - e^{-\frac{t}{\tau}} \right) \]  
\[ \tau = C_{p}R_{p} \]

Where \( U_{OCV} \) is the electromotive force of the battery, and its value is approximately equal to the open circuit voltage; \( U_{0} \) is the terminal voltage; \( U_{p} \) is the polarization voltage; \( R \) is the ohmic resistance; \( R_{p} \) is the equivalent concentration polarization internal resistance and electrochemical polarization internal resistance; \( C_{p} \) is the equivalent polarization capacitance.

3. Super capacitor optimization method

3.1. Positive and negative pulse method

In the positive and negative pulse method, the lithium-ion battery is charged with a constant current with a set current at the initial stage of charging. As the charging process progresses, the polarization voltage gradually increases and the charging efficiency decreases. Then, the lithium-ion battery is temporarily charged or discharged with a certain current. After a short period of charging or discharging, the polarization effect is alleviated, and then the lithium-ion battery is continuously charged with a constant current [5].

In the positive and negative pulse charging cycle, under the condition that the width and amplitude of the positive pulse current and the width and amplitude of the negative pulse current remain
unchanged, set the positive pulse charging current to $I_{in}$, the charging time is $t_{in}$; the negative pulse discharge current is $I_{out}$, the discharge time is $t_{out}$; the total capacity of the battery to be charged is $C_o$.

According to the ampere-hour method, it can be known that in the traditional positive and negative pulse method, the amount of electricity $C_{all}$ that the battery can charge in one cycle is:

$$C_{all} = I_{in}t_{in} - I_{out}t_{out}$$  \hspace{1cm} (5)

The charge and discharge cycle $T_{all}$ required to fully charge the battery is:

$$T_{all} = \frac{C_o}{C_{all}} = \frac{C_o}{I_{in}t_{in} - I_{out}t_{out}}$$  \hspace{1cm} (6)

The total energy $Q_{all}$ released by the charging power source when the battery is full is:

$$Q_{all} = I_{in} \cdot t_{in} \cdot T_{all}$$  \hspace{1cm} (7)

The energy utilization rate $\delta_{all}$ at this time is:

$$\delta_{all} = \frac{Q_{all}}{C_{all}} = \frac{C_o}{I_{in}t_{in}T_{all}}$$  \hspace{1cm} (8)

The traditional positive-negative pulse method uses resistance to consume the negative pulse emitted by the battery, and the energy of the negative pulse emitted is completely wasted, resulting in low energy utilization in the entire charging process.

### 3.2. Optimization method

Divide each charging cycle into two phases. The first stage is the positive and negative pulse charging stage. In this stage, the negative pulse discharge is performed at a certain frequency, which better suppresses the polarization effect and can accept a larger charging current. At this stage, the voltage of the lithium-ion battery rises rapidly, and the lithium-ion battery is discharged the negative pulse is absorbed and stored by the super capacitor and used in the next stage. The second stage is constant voltage charging. When the super capacitor is fully charged by the negative pulse from the previous stage, the super capacitor charges the lithium-ion battery at a constant voltage through a DC/DC converter. In this stage, the charging current is small and the charging speed is slower. However, due to the capacity of the supercapacitor, the charging time in the constant voltage charging phase is very short compared to the charging time in the positive and negative pulse phase, and has little effect on the charging time. When the capacity of the super capacitor drops to a certain value, it enters the next charging cycle and continues to charge the lithium-ion battery. The current and voltage curves of the proposed charging method are shown in Figures 2 and 3.

![Figure 2. Optimized current diagram](image)

![Figure 3. Optimized voltage diagram](image)

The specific work flow chart of the method proposed in this paper is shown in Figure 4. The lithium-ion battery is charged with a constant current first. After time $t_1$, it switches to negative pulse discharge. At this time, the lithium-ion battery is discharged to the super capacitor through a bidirectional DC/DC
After the discharge is carried out for $t_2$, the lithium-ion battery is continuously charged with constant current. At the end of each lithium-ion battery charging and discharging cycle, the SOC of the super capacitor is detected. When the SOC of the super capacitor reaches the set upper limit SOC1, the DC/DC converter is controlled to make the super capacitor charge the lithium-ion battery at a constant voltage alone; When the super capacitor is lower than the set lower limit SOC2, stop the super capacitor to charge the lithium-ion battery, and repeat the above charging process, until the lithium-ion battery reaches the charging cut-off voltage.

\[
\text{Begin} \quad \text{Constant current charging} \quad \text{Pulse discharge} \quad \text{If Super capacitor SOC=SOC1?} \quad \text{N} \quad \text{N} \quad \text{Y} \quad \text{Y} \quad \text{End}
\]

Supercapacitors charge lithium-ion batteries at constant voltage

\[C_{in} = I_{in} t_{in} - I_{out} t_{out} + I_{out} t_{out} \beta^2 \gamma_1 \gamma_2\]  \hspace{1cm} (9)

Where $\beta$ is the power transmission efficiency of the bidirectional DC/DC converter; $\gamma_1$ is the charging efficiency of the super capacitor; $\gamma_2$ is the discharge efficiency of the super capacitor.

Comparing formula (5) and (9), it can be seen that the method proposed in this paper stores and reuses the electrical energy consumed by the resistance. In this process, only the charging and discharging of the lithium-ion battery and the supercapacitor during the transmission of the DC/DC converter are considered Most of the energy loss generated can be recovered and utilized. Compared with the traditional positive and negative pulse method, the energy utilization rate of the entire charging process is improved.

The number of cycles $T_n$ required to fully charge the battery is:

\[T_n = \frac{c_0}{c_{in}} = \frac{c_0}{I_{in} t_{in} - I_{out} t_{out} + I_{out} t_{out} \beta^2 \gamma_1 \gamma_2}\]  \hspace{1cm} (10)

Comparing formula (6) and formula (10), it can be seen that $T_n < T_{all}$, which shows that the method proposed in this paper can charge more power for the battery in one charging cycle than the traditional positive and negative pulse method. Therefore, when the battery is fully charged, the number of charge and discharge cycles in the method proposed in this article is less.

The total energy $Q_n$ released by the charging power source when the battery is full is:

\[Q_n = I_{in} \cdot t_{in} \cdot T_n\]  \hspace{1cm} (11)

Comparing formula (7) and (11), we can get $Q_n < Q_{all}$, which shows that when the battery is fully charged, the method proposed in this paper is compared with the traditional positive and negative pulse method.
method. Due to the reduction in the number of charge and discharge cycles, lithium-ion battery discharges is reduced, so the total amount of power released by the charging power supply is smaller.

The energy utilization rate $\delta_n$ of the charging method proposed in this paper is:

$$\delta_n = \frac{C_0}{Q_n} = \frac{C_0}{I_{in} \cdot t_{in} \cdot T_n}$$  \hspace{1cm} (12)

Suppose the duty cycle of positive pulse charging in one charging cycle is 58%, and the charging current is 1C; the duty cycle of negative pulse discharge in one charging cycle is 15%, and the discharge current is 1.5C; the super capacitor charging efficiency is 0.98 , The discharge efficiency of the supercapacitor is 0.99, and the efficiency of the bidirectional DC/DC converter is 0.9 (the above data is currently the most common experimental data). It is calculated that the energy utilization rate of the traditional positive and negative pulse method is about 72.8%; the energy utilization rate $\delta_n$ of the improved method proposed in this paper is about 93.6%. Compared with the traditional positive and negative pulse method, the energy utilization rate of the method proposed in this paper is increased by about 20.8%.

4. Analysis of simulation results

It can be seen from Figure 5 that during the pulse charging phase, the SOC of the supercapacitor also rises with the increase of the number of negative pulses, indicating that the supercapacitor absorbs the high-energy negative pulses emitted by the lithium-ion battery during the pulse charging phase, avoiding energy loss.

![Figure 5. Pulse charging stage](image)

Figure 6 shows the change of the constant voltage charging stage under the simulation conditions. In this stage, as the SOC of the super capacitor decreases, the charging current of the lithium-ion battery gradually increases. When the SOC of the supercapacitor rises to the threshold, the lithium-ion battery changes from the pulse charging stage to the constant voltage charging stage. At this time, the charging current changes are shown at the forefront of the curve in Figure 6 (a). The circuit can realize the constant voltage charging of the supercapacitor to the lithium-ion battery, which improves the energy utilization rate.
In order to verify the optimization effect of the positive and negative pulse method proposed in this article, a comparative experiment was carried out with the traditional positive and negative pulse method under the same simulation conditions. The experimental results are shown in Table 1. The simulation results show that compared with the traditional positive and negative pulse method, the energy utilization rate of the method proposed in this paper is increased by 19%, which is not much different from the theoretically calculated energy utilization rate of about 21%. The feasibility of the charging method proposed in this paper is verified.

**Table 1. Comparison of effects of different charging methods**

| Method                      | Battery capacity when charging is complete/% | Charging time /s | Energy utilization/% |
|-----------------------------|---------------------------------------------|-------------------|----------------------|
| Positive and negative pulse method | 100                                         | 2230              | 70.6                 |
| Optimization method         | 100                                         | 2489              | 89.9                 |

5. Conclusion

This paper proposes a method based on supercapacitors to optimize the recovery and utilization of high-energy negative pulses in the rapid charging of lithium-ion battery positive and negative pulses, and conducts theoretical analysis and simulation experiments on this method. The verification results show that compared with the traditional resistance discharge method, this method can improve the energy utilization rate during the charging process while ensuring a shorter charging time.

**References**

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