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AN OPTIMAL CRD-REFLEX CHARGING STRATEGY FOR LI-ION BATTERY

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Abstract. *This paper proposed a CRD-Reflex (Charge-Rest-Discharge Reflex) optimal charging strategy. First, this study used Fourier series to calculate harmonic current component of CRD-Reflex charge current, and then applied AC impedance under each harmonic frequency of Li-ion battery to calculate out battery's charge power loss. Finally, this work took battery's minimum charge power loss as objective and used Particle Swarm Optimization (PSO) algorithm to derive optimal charge-discharge pulse width of charge current. After testing, the results showed that, compared to constant-current charging strategy, the CRD-Reflex optimal charging strategy proposed in this paper has better charge temperature rise, charge capacity, discharge capacity, and efficiency.*
Keywords: Li-ion battery, CRD-Reflex charging strategy, Constant-current charge, Particle Swarm Optimization (PSO) algorithm

1. Introduction.

Because traditional cars would consume tremendous oil resources, and the emitted exhaust gases also cause global warming, electric cars using electricity as power source have been increasingly flourishing. In the meantime, along with the advance of electronic technology, various 3C electronic products are also increasingly increased, and their electricity mostly uses secondary batteries, which mainly are Li-ion batteries [1-3]. Currently, there are many battery charging strategies, such as Constant-Trickle (CT), Constant-Current (CC) and Constant-Current Constant-Voltage (CC-CV) charging strategies [4]. Although circuit structure of CT charging strategy is simple, charge time is too long due to small current charge; CC charging strategy has the problem that battery cannot be fully charged; while CC-CV charging strategy first uses constant current to charge, and then uses constant voltage to charge after waiting for that battery voltage has been charged to reach set full-charge voltage, but under constant voltage charge, this charging strategy takes a longer charge time [4]. Therefore, subsequent scholars have proposed various current charge technologies, such as genetic algorithm, neural network, gray prediction method, ant algorithm and other charge technologies [5]. However, the above-mentioned charging strategies must use multiple microprocessors to implement algorithm charging strategy, so their circuit structures are certainly complex and costly [4-7].

The sequence of CRD-Reflex charging strategy proposed in this paper is that the battery is first applied with a forward current for charging, plus after a rest time, and then applied with a reverse current for discharging. The rest time in between can just allow the battery to obtain a buffer time for uniform distribution of electrolyte ions in order to achieve not only slowing battery polarization, and decreasing battery temperature rising during battery charging process, but also extending battery life [8-11]. This paper mainly used Fourier series to calculate harmonic current component of CRD-Reflex charge current, and then applied AC impedance to calculating out battery's total charge loss. Finally, this work took battery's minimum charge power loss as objective, and used PSO algorithm to derive battery's optimal charge-discharge pulse width [12-15].

This study used optimal charge-discharge pulse width to conduct real charge test on Li-ion battery. Because constant-current charging has a fast charging feature, currently it is the most conventional and widely used charging strategy. The results of the test showed that, compared to CC charging strategy under the same charge-discharge conditions, the CRD-Reflex charging strategy proposed in this paper has a lower charge temperature rise of 24.75%, a higher charge capacity of 1.55%, a higher discharge capacity of 1.77%, and a higher charge-discharge conversion efficiency of 0.222%.

2. **CRD-Reflex Charging Strategy Analysis.**

Figure 1 shows the current waveform schematic diagram of CRD-Reflex charging strategy proposed in this paper, in the figure T_C is charge time, T_R is rest time, and T_D is discharge time.

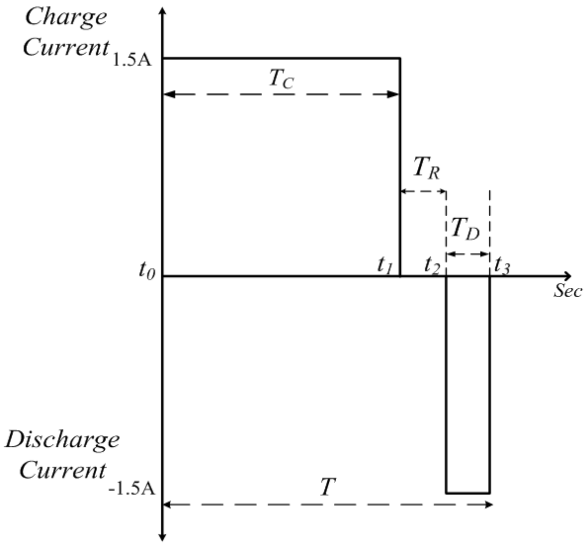


FIGURE 1. Charge current waveform of CRD-Reflex charging strategy

This study used Fourier series to calculate harmonic current component of CRD-Reflex charge current in Figure 1. The Fourier series of CRD-Reflex charge current $I(t)$ can be expressed as

$$I(t) = a_0 + \sum_{n=1}^{\infty} a_n \cos\frac{2\pi n}{T}t + \sum_{n=1}^{\infty} b_n \sin\frac{2\pi n}{T}t \tag{1}$$

where T: charge period as shown in Figure 1.

$$a_0 = \frac{1}{T}\int_{-T/2}^{T/2} I(t)dt \tag{2}$$

$$a_n = \frac{2}{T}\int_{-T/2}^{T/2} I(t)\cos\frac{2\pi n}{T}tdt \tag{3}$$

$$b_n = \frac{2}{T}\int_{-T/2}^{T/2} I(t)\sin\frac{2\pi n}{T}tdt \tag{4}$$

From Figure 1 it can be known, $T_C = (t_1 - t_0)$, $T_R = (t_2 - t_1)$ and $T_D = (t_3 - t_2)$. Setting t_0, t_1, t_2, and t_3 as variables to be solved in solving optimal charge-discharge pulse width, and bringing t_0, t_1, t_2, and t_3 into Equations (2) to (4), Fourier series equations can be derived in closed-form expressions as

$$a_0 = \frac{1}{t_3 - t_0}[1.5 \times (t_1 - t_0) + (-1.5) \times (t_3 - t_2)] \tag{5}$$

$$\begin{aligned} a_n = \frac{2}{t_3 - t_0} \Bigg[& 1.5 \times \frac{t_3 - t_0}{2\pi n} \left(\sin \frac{2\pi n}{t_3 - t_0} t_1 - \sin \frac{2\pi n}{t_3 - t_0} t_0 \right) \\ & + (-1.5) \times \frac{t_3 - t_0}{2\pi n} \left(\sin \frac{2\pi n}{t_3 - t_0} t_3 - \sin \frac{2\pi n}{t_3 - t_0} t_2 \right) \Bigg] \end{aligned} \tag{6}$$

$$\begin{aligned} b_n = \frac{2}{t_3 - t_0} \Bigg[& 1.5 \times \frac{t_3 - t_0}{2\pi n} \left(\cos \frac{2\pi n}{t_3 - t_0} t_1 - \cos \frac{2\pi n}{t_3 - t_0} t_0 \right) \\ & + (-1.5) \times \frac{t_3 - t_0}{2\pi n} \left(\cos \frac{2\pi n}{t_3 - t_0} t_3 - \cos \frac{2\pi n}{t_3 - t_0} t_2 \right) \Bigg] \end{aligned} \tag{7}$$

The n-order harmonic current amplitude I_n can be obtained from Equations (6) and (7).

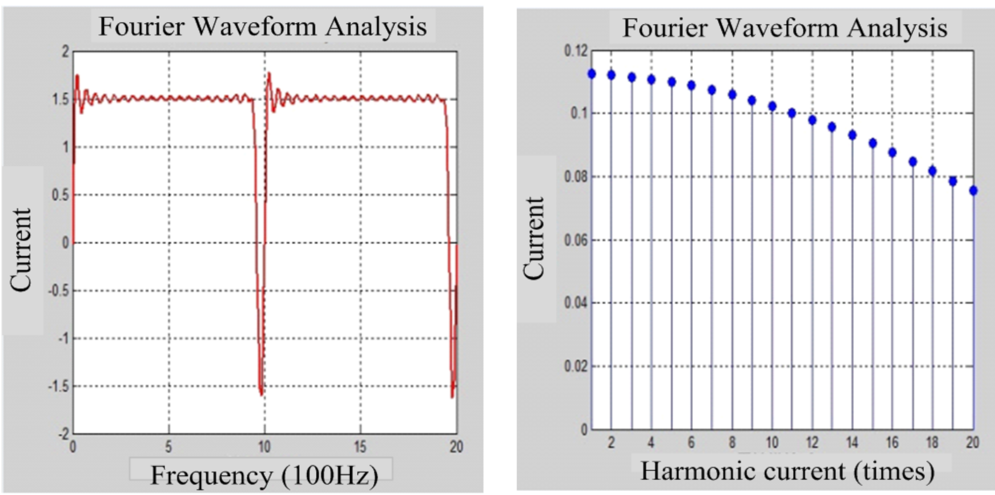
$$I_n = \sqrt{an^2 + bn^2} \tag{8}$$

Using harmonic currents and battery AC impedance, the battery charging power loss P_{loss} can be calculated as

$$P_{loss} = \sum_{n=1}^{\infty} \frac{I_n^2}{2} R_n \tag{9}$$

In Equation (9), I_n is the n-order harmonic current amplitude under nkHz harmonic frequency, and R_n is battery's resistance value under nkHz harmonic frequency. Since harmonic current amplitude will greatly decrease with the increase of harmonic order, this study took only first 20-order harmonic currents for actually calculating battery charging power loss. Through above Fourier series analysis, charge loss under CRD-Reflex charging strategy can be accurately calculated. Finally, this work minimized Equation (9), battery charging power loss, as objective function, and used PSO to search for t_0, t_1, t_2, and t_3. The optimal charge-rest-discharge pulse widths T_C, T_R, and T_D then can be obtained.

Through derivation of Fourier series, this study obtained battery's harmonic current $I(t)$ of CRD-Reflex charge current, took battery's minimum charge power loss as design objective, and applied PSO algorithm to deriving the optimal charge-discharge pulse width



(a) (b)

FIGURE 2. (a) Optimized pulse width and (b) current harmonic component derived from PSO

of charge-discharge current waveform. Figure 2 shows the tested battery's optimized pulse width and 20 times current harmonic component derived from PSO, and the optimized pulse width result is $T_C = 0.975$ms, $T_R = 0.0125$ms, and $T_D = 0.0125$ms. Using Equation (9) the battery's total charge power loss is 0.030469W.

3. **Measurement Process.** The measurement processes are as follows. First, this study used a battery AC impedance analyzer to measure out Li-ion battery's AC impedance Bode plot, and then to obtain battery's corresponding AC impedance values under various frequencies from Bode plot. Next, this study used lowest battery AC impedance frequency $f_{Z_{\min}}$ corresponding to lowest current AC impedance $Z_{\min}$ as charge frequency of the experiment, and gave a preset value to charge waveform pulse width, and the Fourier series of CRD-Reflex charging strategy can be calculated through this preset pulse width. Then, this study analyzed and tracked optimized pulse width of CRD-Reflex charging strategy through using PSO algorithm. This study conducted the same charge process for both CC charging strategy and CRD-Reflex charging strategy. First, conduct charge process on a battery with an initial voltage 2.8V. The charge current for both charging strategies is 1.5A, charge process was stopped after battery voltage reached 4.2V for five seconds, and the battery charge capacity Q_{in} can be derived from the following equation

$$Q_{in} = \int_0^{t_x} I_C(t)dt \tag{10}$$

where t_x is the charge time required for making battery voltage reach 4.2V for 5 seconds, $I_C(t)$ is charge current. The fully charged battery was quietly placed for 30 minutes, and then conducted discharge process to discharge the battery to 2.8V. Finally, this study measured temperature rise on battery surface, charge capacity, discharge capacity, and calculated charge-discharge conversion efficiency in order to verify that the used charge pulse width is the optimized charge pulse width.

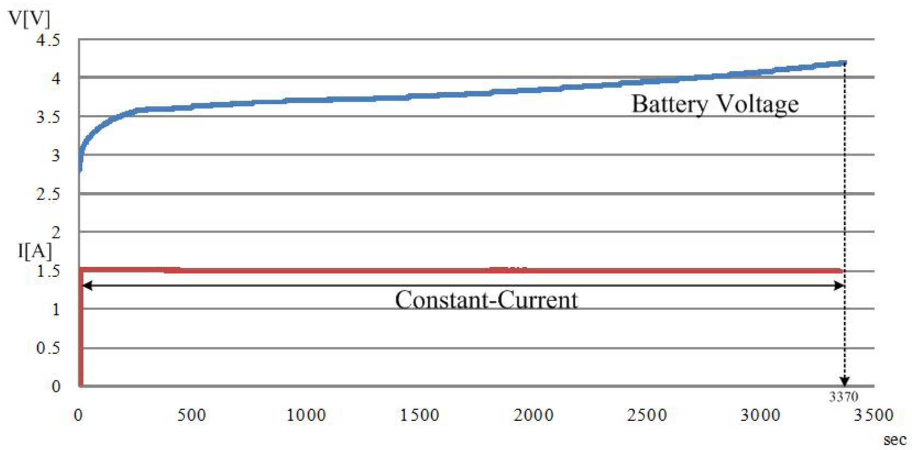
4. **Measurement Results and Discussions.** In order to obtain more reliable battery charge measurement results data during charge test experimental process, the battery was placed inside a compartment thermostat in order to prevent charge process from environmental temperature effect throughout the entire test process for charge experiments. In the meantime, the rises in temperature on battery body surface during real measurement process were recorded by temperature recorder, and battery's current signals and voltage signals were detected through using current clamp meter and voltage probe, and then presented and recorded by digital oscilloscope. A brand new Li-ion battery produced by E-ONE MOLI ENERGY CORP. was used as tested battery in this study, and its specification is IBR18650BC 1500mAh high power battery. The CRD-Reflex optimal charging strategy proposed in this study was used to conduct charge on the Li-ion battery with 1kHz as charge frequency, and compared with constant-current charging strategy.

4.1. **Constant-current charging strategy.** Figure 3(a) shows the curve graphs of charge voltage and charge current, and Figure 3(b) shows battery temperature of the battery under using constant-current charging strategy.

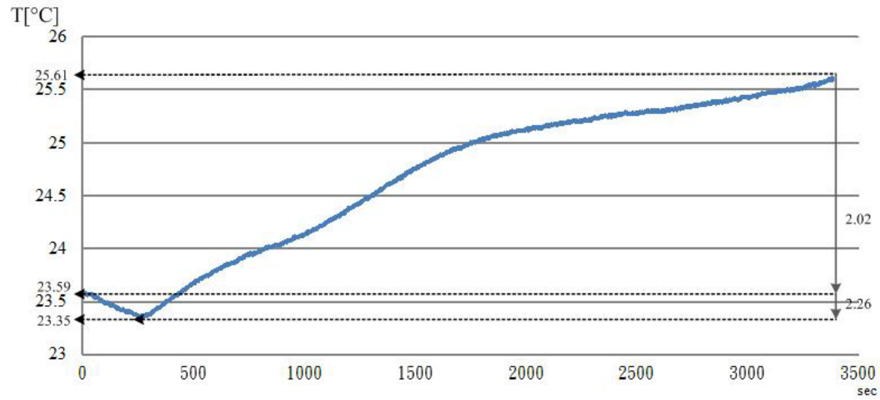
Figure 4 shows battery discharge voltages and discharge currents of three-step discharge. It can be seen that in the first step, discharge time is 3178 sec and discharge current is 1.5A; in the second step, discharge time is 655sec and discharge current is 0.5A, and in final third step, discharge time is 1096sec and discharge current is 0.1A.

4.2. **CRD-Reflex charging strategy.** Figure 5 shows the curve graphs of battery charge voltage, average charge current and battery temperature under using proposed CRD-Reflex charging strategy.

Figure 6 shows battery voltages and discharge currents of three-step discharge. It can be seen that in the first step discharge time is 3212sec and discharge current is 1.5A, in



(a)



(b)

Figure 3. Constant-current charging strategy: (a) charge voltage and charge current, (b) battery temperature

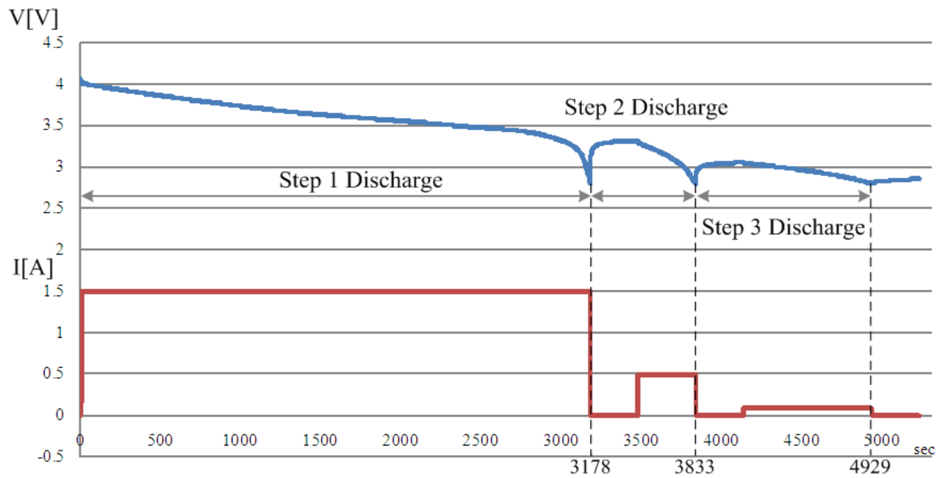
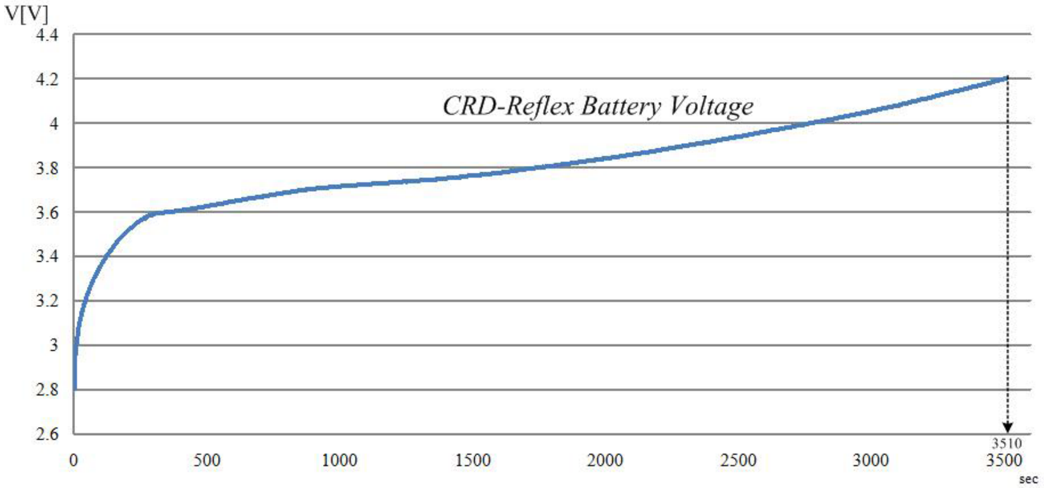


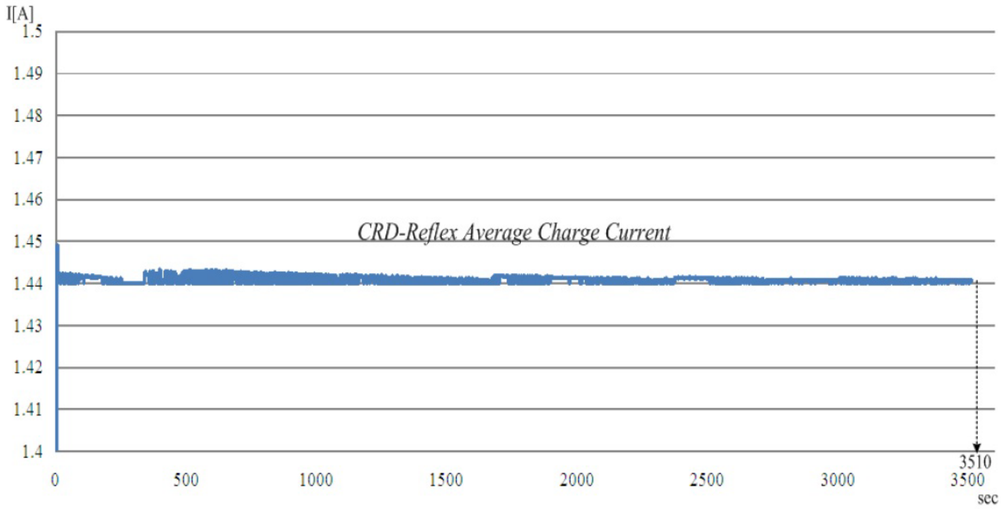
Figure 4. Three-step discharge voltages and discharge currents under constant-current charging strategy

the second step discharge time is 683sec and discharge current is 0.5A, and in the final third step discharge time is 1369sec and discharge current is 0.1A.

Table 1 shows the comparison of battery measurement result between constant-current charging strategy and CRD-Reflex charging strategy. It can be seen that charge temperature rise, total charge capacity, total discharge capacity and efficiency of CRD-Reflex



(a)



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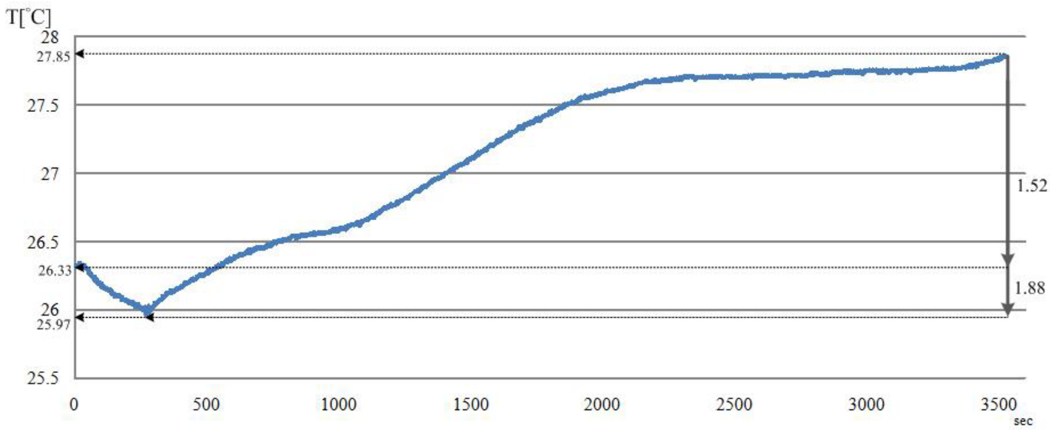

(c)

FIGURE 5. CRD-Reflex charging strategy: (a) battery voltage, (b) average charge current, (c) battery temperature

charging strategy are all better than those of constant-current charging strategy. Charge temperature rise is 24.75% lower, total charge capacity is 1.55% higher, total discharge capacity is 1.77% higher, and conversion efficiency is 0.222% higher.

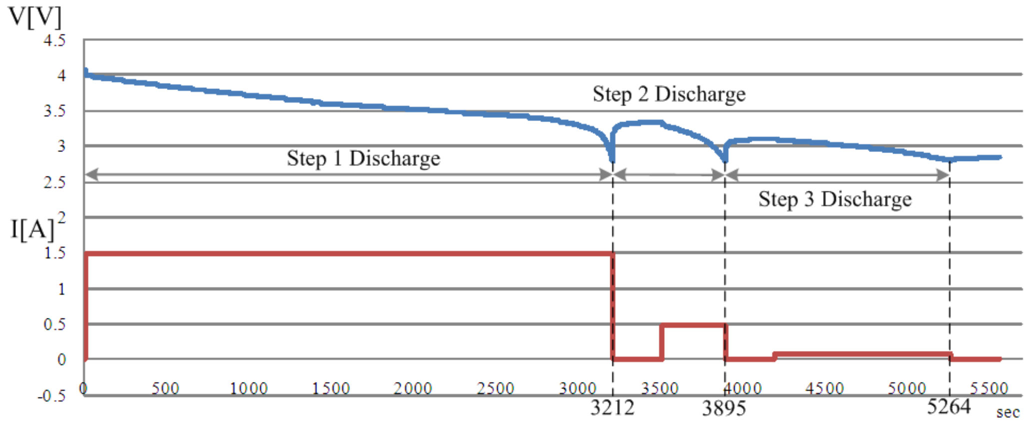

FIGURE 6. Three-step discharge voltages and discharge currents under CRD-Reflex charging strategy

TABLE 1. Comparison of battery measurement results with different charging strategy

Charging strategy	Charge time (sec)	Charge temperature rise (°C)	Total charge capacity (mAh)	Total discharge capacity (mAh)	Conversion efficiency (%)
Constant-current	3370	2.02	1406.25	1379.61	98.106
CRD-Reflex	3510	1.52	1428.44	1404.56	98.328

5. **Conclusion.** This paper conducted a study on high-efficiency charging strategies of Li-ion battery, and used Fourier series, battery AC impedance analysis, and PSO algorithm to propose the CRD-Reflex optimal charging strategy. Compared to constant-current charging strategy, the proposed charging strategy has better charge temperature rise, charge capacity discharge capacity, and charge-discharge conversion efficiency. After testing, the results showed that charge temperature rise is 24.75% lower, total charge capacity is 1.55% higher, total discharge capacity is 1.77% higher, and charge-discharge conversion efficiency is 0.222% higher.

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