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Experimental Study of Multistage Constant Current Charging with Temperature Awareness Control Method

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ABSTRACT- Temperature and charging time are critical parameters during charging period of a battery as temperature rise affects battery life. In a particular charging method, setting high current minimizes charging time but raises temperature. In this study attention is given to multistage constant current charging approach to shorten charging time while maintaining battery temperature below preset range. Battery charging characteristics of various methods are studied, and their performance is compared. The proposed multistage charging method is compared with constant current constant voltage and traditional multistage charging method. The experimental results obtained show that, the proposed method reduces the charging time by 42.22 % and 9.3 % as compared to the constant current constant voltage and conventional multistage charging method respectively, while limiting the rise in battery's temperature to 5°C above room temperature. Further in the proposed method, battery temperature is reduced by 20% as compared to the conventional multistage method.

General Terms: Lithium-ion battery, Charging methods, control algorithm.
Keywords: Battery Wired Charging, Constant Current, Temperature, Multistage, Electric Vehicles.

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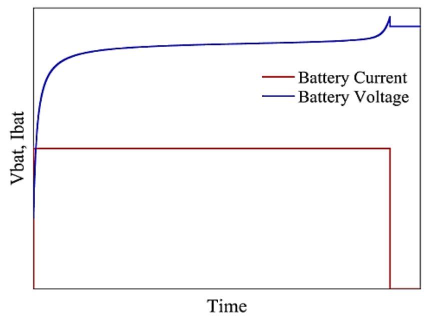
1. INTRODUCTION

Electronics devices like digital cameras, mobile phones, laptops, electronic toys and many other uses Lithium-ion battery as a main power source due to its advantages like high durability, high energy density, low maintenance requirement etc. Due to these advantages, they are also used in electric vehicles in which very high-capacity battery is required. It takes several hours to charge the battery using traditional/onboard chargers. Lack of charging infrastructure and long charging time are major reasons for the low demand of electric vehicles. A lot of research has been underway on battery charging methods to improve the performance of battery.

Battery charging time, energy efficiency, State of Charge (SoC) and temperature are all significant parameters of the battery. Charging time of battery is a critical factor that must be minimized to overcome the problem of driving range anxiety in case of electric vehicles. Energy efficiency of the battery is the measure of amount of power delivered by the battery in a charge cycle. SoC is the measure total amount of charge present in the battery to the total charge capacity. Charging time, energy efficiency, SoC as well as temperature of the battery depends on charging current. Pumping large current into battery has demerits like- increased battery temperature; reduced SoC; reduced energy efficiency; and reduced battery life [1]. On the contrary, low charging current maintains battery temperature under threshold value and improves charging efficiency and SoC but it prolongs charging time. Therefore, the charging current should be selected properly, so that the battery will be charged fast and safely [2].

1.1 Battery Charging Methods

The various charging methods [3] are: Constant Current (CC); Constant Voltage (CV); Constant Current Constant Voltage (CCCV); Pulse charging; and Multistage Constant Current (MSCC). Each of these methods has its merits and demerits. In CC method a constant current is applied to the battery as shown in *figure 1 (a)*. Charging time of battery can be minimized by setting high current during charging time. In constant current charging method, battery may get overcharged. Battery overcharging increases battery temperature drastically and it may damage the battery permanently.



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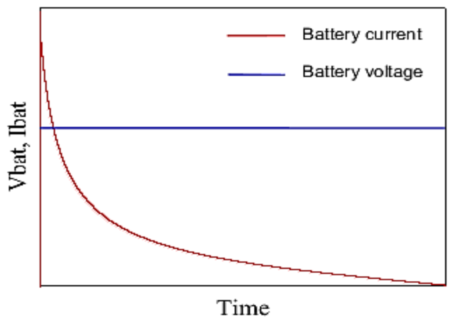

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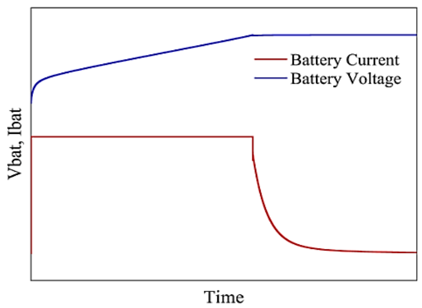

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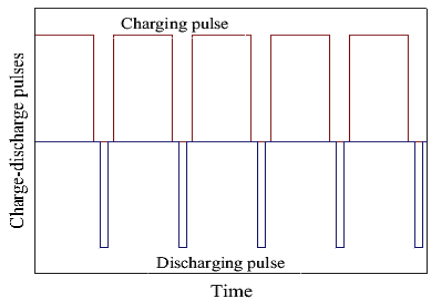

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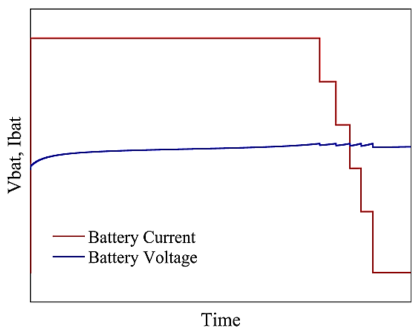

(e)

Figure 1: Charging characteristics: (a) CC charging method; (b) CV charging method; (c) CCCV charging method; (d) Pulse charging method; (e) MSCC charging method

In CV method the battery is subjected to a constant voltage equal to maximum charging voltage as shown in *figure 1 (b).*

Since the charging voltage is constant it avoids the problem of overcharging, but the battery draws an excessive amount of current when SoC of battery is low [4]. CV charging method is suitable for charging the battery having SoC more than 80%. Moreover, when SoC of battery reaches above 80%, the battery charging current progressively reduces thereby increasing the charging time.

CCCV method is the combination of CC and CV methods as shown in *figure 1 (c).* In CCCV method, the battery is first charged by a constant current till battery voltage reaches to threshold voltage, thereafter battery is fully charged by applying a constant voltage. In this method, constant current stage reduces charging time but increases temperature while constant voltage stage prolongs the battery charging time.

In pulse charging method as shown in *figure 1 (d)*, high frequency and high-power charging pulse is applied to the battery for certain duration of time. Then the charging pulse is removed, and large negative discharge pulse is applied during relaxation time. Moreover, the values of pulse charging parameters like duty cycle, pulse frequency, and temperature are needs to be properly selected to obtain better performance [5-6]. When compared to CC and CCCV methods, in pulse charging method SoC increases but battery temperature increases greatly.

In the traditional MSCC charging method as shown in *figure 1 (e)*, initially large current is applied and maintained constant. After the battery voltage is reached to preset value the current flowing through battery is reduced to next level and held constant. This sequence is repeated 3 to 5 times during a charging period [7]. MSCC method reduces charging time, increase energy efficiency and reduce energy losses effectively [8-9]. However, in traditional MSCC battery temperature increases to great extent, this leads to degradation or permanent damage of the battery.

Thus, to improve battery lifetime, reliability and performance [10-11] there is a need to take precaution that battery temperature should not exceed beyond prescribed limit. This paper is organized in five sections. The proposed MSCC charging method and control algorithm are explained in *Section 2*. The steps used in the experimental work are discussed in *Section 3* and experimental results are discussed in *Section 4*. In *Section 5* concluded the paper.

2. PROPOSED WORK

As discussed in the introductory section, in traditional MSCC method battery temperature is measured initially, but it is not taken into consideration while charging the battery, therefore battery temperature increases significantly. In the proposed MSCC approach, focus is given to shorten charging time at the same time maintaining battery temperature within limits. The proposed MSCC technique is similar to traditional MSCC method with some modification in control approach. In the proposed method, in addition to battery voltage, the temperature is also monitored continuously and not allowed to exceed preset limit. Battery current is switched to next lower value when either voltage or temperature reaches to preset value. In this technique the battery voltage may not reach to upper cut-off voltage level as depicted in *figure* 2 in the initial charging stages like traditional MSCC method.

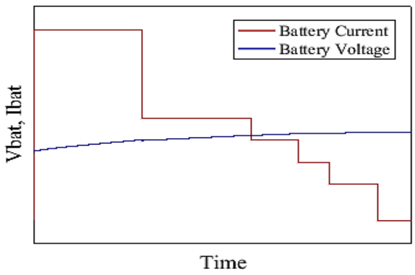

Figure 2: Battery voltage and current characteristics

Control algorithm of proposed MSCC charging method is depicted in the *figure 3*. Initial SoC of the battery is measured first and recorded. The battery temperature as well as battery voltage both are measured and compared with their preset values continuously. When either of these parameters exceed preset limit, battery current is decreased to next level. Battery SoC is also measured continuously, when SoC reaches to 100% charging process is terminated. Coulomb's counting method discussed in [12] is used to measure battery SoC. The coulombs counting equation for estimation of the SoC of the battery is given by,

$$SoC = SoC(initial) + \frac{\int_{t0}^{t0+\tau} Ib*\Delta\tau}{Ah} \qquad (1)$$

Where, *SoC(initial)* is initial value of battery SoC, *Ib* is battery current during charging and *Ah* is total charge capacity of the battery in ampere-hour.

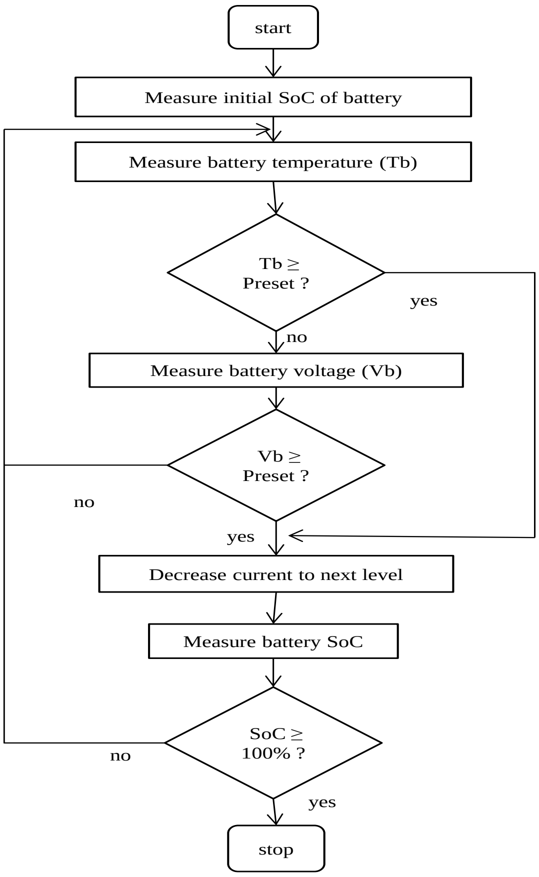

Figure 3: Control algorithm of proposed battery charging

3. EXPERIMENTATION

In this work a cylindrical ICR-18650 rechargeable Lithium-ion battery is used. Specifications of the battery used for experimentation are given in the *Table 1*.

Table 1: Specifications of battery

Battery parameter	Value
Nominal voltage	3.7V
Maximum charging voltage	4.2V
Maximum charging current	1C
Nominal battery capacity	2600mAh
Discharge capacity	3C/ 7.8A
Size (cylindrical)	65x18mm

Figure 4 depicts the experimental setup used to study battery characteristics. The real time experiments were conducted at room temperature (@30ºC). The charging current is limited below maximum permissible charging current of magnitude 1C (i.e. 2.6 A) for each charging method. CCCV tests were performed at different charging rates as 0.4C and 0.6C and 1C. The traditional and proposed MSCC tests were performed by progressively decreasing current from 1C to 0.2C. After each charge cycle the battery is relaxed for two hours and then discharged at constant current until battery reaches to lower cut-off voltage.

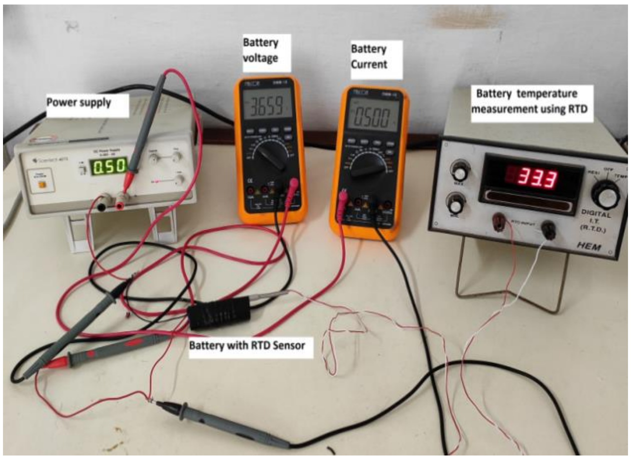

Figure 4: Experimental setup of battery charging

Before running new test, first the battery is charged slowly until the SoC reaches 5%. Following steps were used in each experiment:

1. Discharge the battery at constant current (0.25C) until lower cut-off reached.
2. Record total discharge time.
3. Let the battery relax for two hours.
4. Charge the battery at low current until SoC = 5%.
5. Apply next charging method.
6. Record the battery voltage, current, temperature and SoC after every minute.
7. Let the battery relax for two hours after test is over.
8. Go to *step 1*

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The impact of CCCV, traditional and proposed MSCC charging methods on SoC, temperature and energy efficiency of battery is observed and compared. Results of different charging methods and their comparison are presented in result and discussion section.

4. RESULT AND DISCUSSION

The experimental battery voltage and current charging characteristics of CCCV and MSCC mode are shown in *Figure 5 and 6* respectively. *Figure 5* shows CCCV test results when battery is charged at three different rates 0.4C, 0.6C and 1C in constant current phase. When charging rate is 0.4C, it took 135 minutes to charge the battery up to 4.2V. When charging rate is 0.6C, it took 70 minutes to charge the battery up to 4.2V. When charging rate is 1C, it took 35 minutes to charge the battery up to 4.2V. After constant current phase the battery took a long time to charge in constant voltage phase. In constant voltage phase it is found that first battery current decreased exponentially and then it decreased slowly.

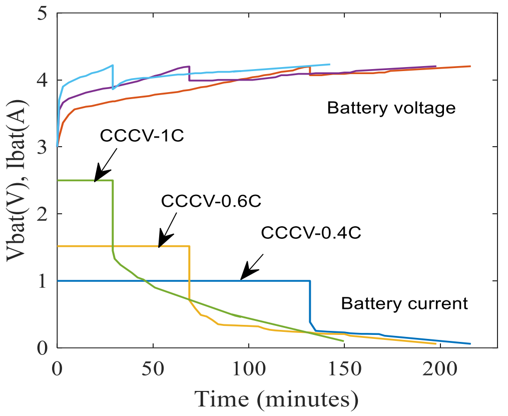

Figure 5: Battery voltage and current in CCCV method

Figure 6 shows battery voltage and current characteristics of MSCC mode. In proposed MSCC method, the battery is charged in 8 constant current steps and the results are compared with 5 step traditional MSCC method. The battery voltage and temperature both are monitored in the proposed method. It is found that, in proposed method charging time is reduced while maintaining battery temperature under preset limit and performs equally well as traditional MSCC method.

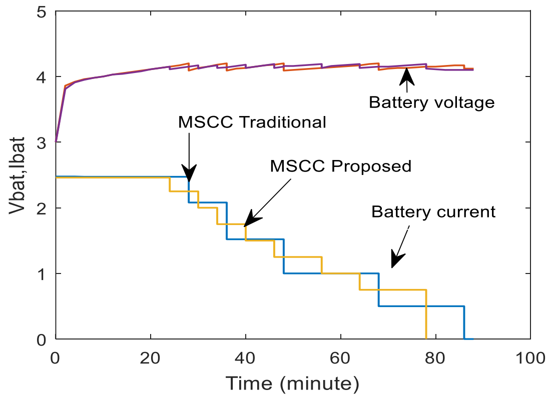

Figure 6: Battery current and voltage in MSCC method

Resulting SoC characteristics for different modes of operation are shown in the *Figure 7*. In CCCV charging mode with 0.4C, 0.6C and 1C charging rate the battery SoC is increased up to 90%, 73% and 54% in 135, 70 and 35 minutes respectively in constant current phase. Constant voltage phase prolongs charging time, so it is not considered for comparison with MSCC method. In traditional MSCC charging mode with initial maximum charging rate of 1C, the battery SoC is 90% in 86 minutes, while in the proposed MSCC charging mode it is 90% in 78 minutes.

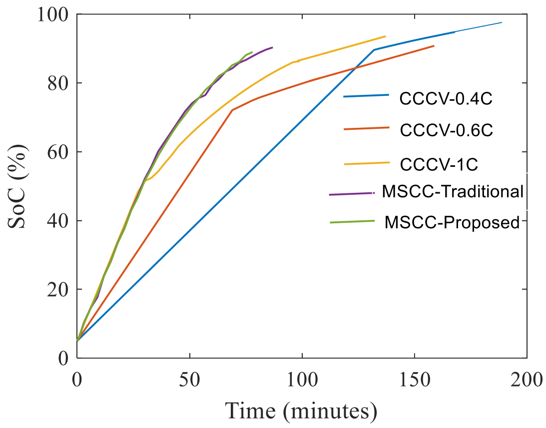

Figure 7: SoC of battery for different charging methods

The variation of battery temperature over room temperature for CCCV and MSCC charging mode is shown in the *figure 8*. In CCCV charging mode using 0.4C, 0.6C and 1C charging rate, the battery temperature is increased by 1.6ºC, 2.8ºC and 6.2ºC respectively in constant current phase. In traditional MSCC charging mode with initial maximum charging rate of 1C the battery temperature is increased by 6.3ºC, while in the proposed method the battery temperature rise is limited to 5ºC.

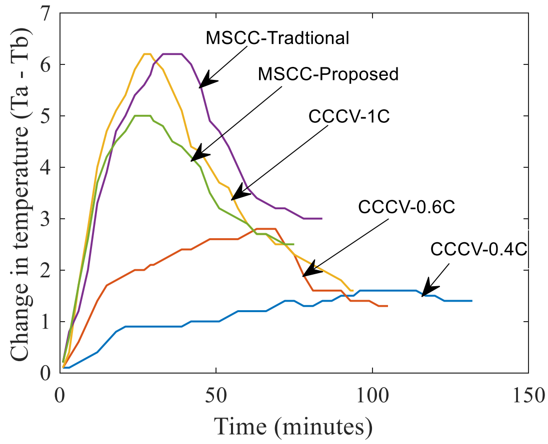

Figure 8: Temperature variation of battery for different charging methods

The results of the various charging schemes are given in the *table 2*. In CCCV method, high energy efficiency is obtained at low charging current, but charging time is too large. In the conventional MSCC charging method, the charging time is reduced by 36.29% as compared to CCCV (1C) charging method, while the energy efficiency is improved by 4.44%.

However, temperature of the battery was found increased by 6.2°C above room temperature. In the proposed MSCC charging method, the charging time is reduced by 42.22% as compared to CCCV (1C) charging method while retaining same energy efficiency and SoC as in traditional MSCC. In the proposed MSCC method the battery temperature is reduced by 20% and charging time is reduced by 9.3% as compared to traditional MSCC method. The experimental results are summarized in *table 2.*

Table 2: Experimental results

Charging method		Charging time in minutes	Energy efficiency (%)	SoC (%)	Temperature rise (°C)
CCCV method	0.4C	190	97	96	1.6
	0.6C	160	96	90	2.8
	1C	135	90	90	6.1
Traditional MSCC method		86	94	90	6.2
Proposed MSCC method		78	94	90	5

5. CONCLUSION

Battery performance and its usable life depends on charging as well as discharging pattern. Temperature and charging time are very important parameters of the battery. Frequently charging the battery at high temperature affect battery life but charging times should also be minimized. The major goal of this research was to find the scope of MSCC method to shorten charging times while maintaining battery temperature within a certain range. The experimental results obtained in this study show that the proposed MSCC method inherits advantages of the conventional MSCC charging method over CCCV charging scheme. In the proposed MSCC method battery temperature is not allowed to exceed 5°C above room temperature. The charging time is reduced by 42.22% as compared to CCCV (1C) charging method while retaining same energy efficiency and SoC like in traditional MSCC. When compared to traditional MSCC method the battery temperature is reduced by 20% and charging time is reduced by 9.3% as compared to traditional MSCC method.

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