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Implementation of an SOC-based four-stage constant current charger for Li-ion batteries

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ABSTRACT

This study implements a possible use of the state of charge (SOC) instead of the charge voltage limit (Vlimit) to control the charging process for a four-stage constant current charging strategy. To determine the charging current in each stage, an iterative optimization procedure based on Taguchi method is employed to find near-optimal values. To control the change of the charging stage and terminate the charging process, the Coulomb counting method combined with battery's open circuit voltage estimation is adopted for SOC estimation. Tests of Sanyo 840 mA h, 3.6 V lithium-ion (Li-ion) batteries have been conducted with a Keithley 2230-30-1 triple power supply and a Prodigit 3332 F dual electronic load. The implemented charger has an input voltage of 12 V, output currents of 1.176 A, 0.840 A, 0.588 A, and 0.336 A, as well as an output voltage ranged from 0.168 V to 0.588 V. By performing the experiments, the proposed charging strategy has shorter charging time than the equivalent constant current constant voltage (CCCV) and the Vlimit-based charging methods. However, it yields a slightly lower charging efficiency than the equivalent CCCV and pulse current charging methods.

1. Introduction

The standard charging strategy for lithium-ion (Li-ion) batteries consists of constant current-mode (CC) followed by constant voltage-mode (CV), namely the CCCV method. However, this algorithm may not be suitable for fast charging since the CV charging process will significantly extend the charge time [1,2]. Thus, the double-loop control charger and the boost charger were developed to improve the charging performance of the CCCV method [3,4]. Moreover, a combination of time-to-charge (TTC), energy losses (EL), and a temperature rise index as the objective function was proposed to find the analytical solution to the problem of optimally charging a Li-ion battery for the CCCV method with the value of the current in the CC stage being a function of the ratio of weighting on TTC and EL and of the resistance of the battery [5,6].

With regard to its implementation, control techniques, such as fuzzy logic, grey prediction and phase locked loop, have been utilized to optimize the CV-mode charging current [7–10]. Nevertheless, integrating these techniques into a commercial battery charger is not currently available due to requiring more complicated control algorithms.

Alternatively, a multi-stage constant current (MSCC) charging strategy has been shown to have many advantages such as long cycle life, high charge/discharge energy efficiency and short charging time [11–17]. However, there are two issues raised in conducting this algorithm. One is what is the transition point condition when the charging process switches from one stage to another. This has been solved by setting a charge cutoff voltage (i.e., charge voltage limit, V_{limit}). The other is how to determine the appropriate charging current in each stage, which is regarded as a combinatorial optimization problem. This has been solved by using several algorithms such as fuzzy logic, ant colony systems, Taguchi approach, and consecutive orthogonal arrays [14–19]. Nevertheless, it is difficult to obtain a precise model that determines the optimal charging current value in each stage due to the complex electrochemical properties of Li-ion batteries. Moreover, such a model requires many parameters that are generally difficult to be determined by inexperienced users.

In this study, the state of charge (SOC) is employed as the transition point condition instead of V_{limit} to govern the MSCC charging process. The SOC-based charging method has been demonstrated with four stages and the SOC values at 25%, 50% and 75% are set as the transition points. The experimental results obtained with the proposed charging method are based on the integration of an L_9 orthogonal array (OA) of the Taguchi method (TM) to find a near-optimal charging current pattern, and the Coulomb counting method is combined with

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battery's open circuit voltage (i.e., V_{oc}) estimation in SOC estimation. Possible advantages and disadvantages using SOC as the transition point condition in this study are outlined below [13,19–21]:

(1) Although the proposed charging method is demonstrated by using four stages with each individual stage of the SOC to be set as 25%, the optimal number of charge stages and the setting range of the SOC in each stage have not yet been proven. Moreover, since the final stage current of the optimal charge current is 0.4 C rate in the demonstrated example, the battery may not have a fully charged capacity with this large current due to the resistance of the battery inside. Nevertheless, it can successfully charge Li-ion batteries with different initial SOCs and has shorter charging time and narrower temperature variation than the equivalent CCCV charging method.
(2) Unlike evolutionary computation techniques, such as genetic algorithms, particle swarm optimization and ant colony systems that require many parameters that are generally difficult to be determined by inexperienced users, TM offers a scientifically disciplined methodology to explore the search space and select near-optimal values for the parameters.

2. Procedure of searching for the four-stage optimal charging current pattern based on Taguchi's method

2.1. Selecting a proper OA

The first step in TM is to select a proper OA. According to the most commonly used standard OAs for experimental design [14], this study selects the $L_9(3^4)$ OA to perform a search to find the optimal charging current pattern. The $L_9(3^4)$ OA means that only nine experimental runs of searching for the optimal charging current are performed in a 3-level design of charging currents with a 4-stage charging strategy as illustrated in Table 1. With these nine experiments selected on the basis of the TM method, the interactions between the current levels are quasi-uniformly distributed between the columns of Table 1 and are nearly independent [19].

2.2. Assigning each level with a parameter value

To conduct the experiments, the levels in the OA require to be assigned with parameter values. Manufacturers of Sanyo Li-ion battery (UR14500 P) used in this study recommend charging at 0.7 C for the CCCV mode to prolong battery life. However, this study takes a higher charge C-rate with the goal of maintaining the temperature under control during the charge since there is no information about the maximum charge current. To simplify the process of searching for the optimal charging current pattern, the medium level of charging current candidates at Stage 1 (i.e., S_1) in the first iteration is set as two times as much as the nominal charge current for the CCCV mode (i.e., 1.4 C)

Table 1
Illustrative $L_9(3^4)$ OA with the Measured Responses and Their Corresponding SN Ratios.

Exp. no.	Stage name Stage 1	Stage 2	Stage 3	Stage 4	Measured responses (j = 1, 2, 3)	SN ratio
1	H	H	H	H	y_{1j}	SN_1
2	H	M	M	M	y_{2j}	SN_2
3	H	L	L	L	y_{3j}	SN_3
4	M	H	M	L	y_{4j}	SN_4
5	M	M	L	H	y_{5j}	SN_5
6	M	L	H	M	y_{6j}	SN_6
7	L	H	L	M	y_{7j}	SN_7
8	L	M	H	L	y_{8j}	SN_8
9	L	L	M	H	y_{9j}	SN_1

Note: H stands for High, M stands for Medium, and L stands for Low.

Table 2
Current Setting Values for the First Iteration.

Stage name	Selected charging current candidates (unit in C rate) H	M	L
Stage 1, S_1	1.5	1.4	1.3
Stage 2, S_2	1.2	1.1	1.0
Stage 3, S_3	0.9	0.8	0.7
Stage 4, S_4	0.6	0.5	0.4

with the difference between a high-level and low-level of 0.1 C as shown in Table 2. In addition, the current between two charging stages at the same level has a standardized difference of 0.3 C that the values at the present stage are smaller than those of previous stages. For instance, the charging current pattern represented by M, L, H and M in experiment no. 6 as tabulated in Table 1 stands for the current sequence of 1.4 C, 1.0 C, 0.9 C and 0.5 C, respectively. In any iteration, the levels of charging currents at each stage are distributed by subtracting a value of 0.05 C. This update is necessary to test a new set of values in the following iterations and therefore cover the full optimization range.

2.3. Applying TM to formulate charging current patterns

In any iteration, the required experiments of a full factorial charging pattern for the four stages at three levels are 81 runs. Based on L_9 OA for the experimental design, nine tests have been performed on 840 mA h Li-ion batteries at a room temperature to search for the optimal charging current pattern. After completing each experiment, such results are considered as the numerical responses of the charging system denoted as y_{ij}. The subscript i is used to reference a particular experiment, while the subscript j is used to reference the battery charging performance where the indices take on values 1, 2 and 3 corresponding to charging efficiency, charging time and temperature variation, respectively.

During the test, the battery's SOC is estimated based on the current integration and V_{oc} estimation. The charging process will move on to the next stage with the charging current at a new preset constant current when the estimated SOC at stages S_1, S_2 and S_3 is equal to 25%, 50% and 75%, respectively. However, the charging process is terminated as the estimated SOC reaches 100%. After the process of complete charging, the battery is discharged at a constant current of 0.84 A (i.e., 1 C = 0.84 A) until the battery voltage reaches the threshold of 2.6 V. Then, charging efficiency associated with the charging time and temperature variation over the charging process is determined. The charging efficiency of a battery, η, is defined as below:

$$\eta = \frac{I_{discharge} \times T_{discharge}}{I_{charge} \times T_{charge}} \times 100\% \tag{1}$$

where $I_{discharge}$ is the discharging current, $T_{discharge}$ is the discharge duration until a specified cut-off voltage is reached, I_{charge} is the charging current in T_{charge} charging duration at each stage.

The experimental results related to the responses of charging efficiency, charging time and temperature variation in the first iteration of the selected charging currents are shown in Table 3. For example, the experiment no. 8 (i = 8) of the second iteration has three responses: charging efficiency (j = 1) of 96.38%, charging time (j = 2) of 4760 s and temperature variation (j = 3) of 2.45 °C. To solve a multi-response optimization problem in the TM, the following steps are suggested and outlined [19]:

Step1: After conducting all the experiments, TM converts the measured responses to the so-called signal-to-noise (SN) ratios, β_{ij}. Since the aim is to maximize the measured responses y_{ij}, the target value of the three responses is classified into two types. One is the larger-the-better (LTB) which is the charging efficiency; the other is the-smaller-the-better (STB) which includes the charging time and temperature