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Enhanced coulomb counting method for estimating state-of-charge and state-of-health of lithium-ion batteries

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ABSTRACT

The coulomb counting method is expedient for state-of-charge (SOC) estimation of lithium-ion batteries with high charging and discharging efficiencies. The charging and discharging characteristics are investigated and reveal that the coulomb counting method is convenient and accurate for estimating the SOC of lithium-ion batteries. A smart estimation method based on coulomb counting is proposed to improve the estimation accuracy. The corrections are made by considering the charging and operating efficiencies. Furthermore, the state-of-health (SOH) is evaluated by the maximum releasable capacity. Through the experiments that emulate practical operations, the SOC estimation method is verified to demonstrate the effectiveness and accuracy.

1. Introduction

State-of-charge (SOC) estimation is one of the most important issues in battery applications. Precise SOC estimation of the battery power can avoid unpredicted system interruption and prevent the batteries from being over-charged and over-discharged, which may cause permanent damage to the internal structure of batteries [1,2].

Many SOC estimation methods have been proposed in the literatures [3–7]. Among which, the terminal voltage and the internal resistance of a battery are two parameters that can easily be obtained and thus are convenient for SOC estimation. However, these two parameters not only change irregularly with the depth-of-discharge (DOD), the charging/discharging rate and the ambient temperature, but also depend highly on the state-of-health (SOH) of the batteries. The complex interrelationship of these factors causes the difficulties in the pursuit of a precise SOC estimation method.

On the other hand, the coulomb counting method calculates the remaining capacity simply by accumulating the charge transferred in or out of the battery. This method, requiring long time monitoring and memorizing, was thought to be impractical for real-time SOC estimation but critical in verifying the accuracy of estimated results from other methods. Nevertheless, the recent applications of battery power in many portable devices and electric vehicles [8,9] essentially consist of computable hardware and a large size of memory such as vehicle powertrain control module (PCM) [10], facilitating the realization of the coulomb counting method.

The accuracy of the coulomb counting method resorts primarily to a precise measurement of the battery current and accurate estimation of the initial SOC. With a pre-known capacity, which might be memorized in the memory or initially estimated by the operating conditions, the SOC of a battery can be calculated by integrating the charging and discharging currents over the operating periods. However, the releasable charge is always less than the stored charge in a charging/discharging cycle. In other words, there are losses during charging and discharging. These losses in addition with the self-discharging cause accumulating errors. For more precise SOC estimation, these factors should be taken into account. In addition, measurement instruments should be re-calibrated and the declination of the releasable capacity should be considered for more precise estimation [11].

This paper proposes an SOC estimation method for lithium-ion batteries on the basis of coulomb counting. The initial capacities of the tested batteries are obtained from the open-circuit voltages or the loaded voltages. The charging and discharging efficiencies are used for compensation of the coulombic losses. With dynamically re-calibration on the maximum releasable capacity of an operating battery, the SOH of the battery is evaluated at the same time. This in turn leads to a more precise SOC estimation.

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For safe usage, the battery operating current and voltage are specified by manufacturers [12]. However, the proposed SOC method depends merely on the charges flowed into and out from the battery within the safe operating range. Obviously, the accuracy of the SOC estimation method is affected by discharging and charging efficiencies under different ambient temperature. This paper focuses on the most favorable charging regime, constant-current–constant-voltage (CC–CV) method, which is suggested by the manufacturer [12].

The presented method is demonstrated and verified on the small capacity lithium-ion batteries. To exclude error caused by the imbalance problems of the series-connected batteries, single-cell lithium-ion batteries are used for the experiments [13]. It is noted that the operating voltages and currents are measured by programmable DC power supply and electronic load. These instruments are calibrated periodically to ensure the accuracy of the measurements.

2. Measurement and data acquisition system

Fig. 1 shows the measurement and data acquisition system. The batteries are charged by a DC power source and discharged by a programmable electronic load. The operating currents, voltages, and periods are monitored by data acquisition modules, and then processed by a personal computer.

In this research, the lithium-ion batteries, CGR 18650D from Panasonic Co., are used for all experiments. The battery voltage and capacity are rated at 3.6 V and 2.35 A h. The *C* rate for the charging and discharging current of the tested batteries is 2.35 A. In fact, the average of maximum releasable capacities of tested batteries is 2.283 A h. In accordance with the data sheet from the manufacturer, the maximum charging and discharging rates are limited to 0.6 and 1 C, respectively. In practice, however, a discharging rate greater than 0.8 C will cause an excessive heat resulting in drastic increase in the battery temperature. Since, the temperature effect is not within the scope of the paper, all experiments are carried out under the room temperature of 25 °C. To prevent from over-charging and over-discharging, the batteries are operated within a voltage range from 3 to 4.2 V.

3. Coulomb counting method

A battery is thought to be completely exhausted when it is discharged by a small rate of 0.1 C to the preset cut-off voltage.

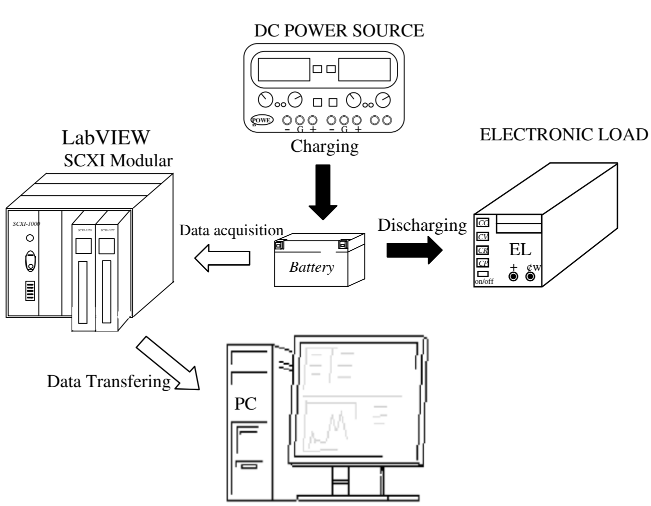


Fig. 1. Measurement and acquisition system.

The releasable capacity, $Q_{\text{releasable}}$, of an operating battery is the released capacity when it is completely discharged. Accordingly, the SOC is defined as the percentage of the releasable capacity relative to the battery rated capacity, Q_{rated}, given by the manufacturer.

$$S_{\text{OC}} = \frac{Q_{\text{releasable}}}{Q_{\text{rated}}} \times 100\% \tag{1}$$

A fully charged battery has the maximal releasable capacity, Q_{MAX}, which can be different from the rated capacity. In general, Q_{MAX} is to some extent different from Q_{rated} for a newly used battery, and will decline with the used time. It can be used for evaluating the SOH of a battery.

$$S_{\text{OH}} = \frac{Q_{\text{MAX}}}{Q_{\text{rated}}} \times 100\% \tag{2}$$

When a battery is in discharging, the DOD can be expressed as the percentage of the capacity that has been discharged relative to Q_{rated}.

$$D_{\text{OD}} = \frac{Q_{\text{released}}}{Q_{\text{rated}}} \times 100\% \tag{3}$$

where Q_{released} is the capacity discharged by any amount of current.

With a measured charging/discharging current I_b, the difference of the DOD in an operating period τ can be calculated by

$$\Delta D_{\text{OD}} = \frac{-\int_{t_0}^{t_0+\tau} I_b(t)\mathrm{d}t}{Q_{\text{rated}}} \times 100\% \tag{4}$$

In (4), I_b is positive for charging and negative for discharging. As time elapsed, the DOD is accumulated.

$$D_{\text{OD}}(t) = D_{\text{OD}}(t_0) + \Delta D_{\text{OD}} \tag{5}$$

Without considering the operating efficiency and the battery aging, the SOC can be expressed as

$$S_{\text{OC}}(t) = 100\% - D_{\text{OD}}(t) \tag{6}$$

To improve the accuracy of estimation, the operating efficiency denoted as η is considered, (5) then becomes

$$D_{\text{OD}}(t) = D_{\text{OD}}(t_0) + \eta\Delta D_{\text{OD}} \tag{7}$$

η is equals to η_C during charging stage and equal to η_d during discharging stage.

Fig. 2 shows the flowchart of the proposed SOC estimation method. At the start, the historic data of the used batteries are retrieved from the associated memory. Without any information for a newly used battery, the SOH is assumed to be healthy and have an SOH of 100%. The tested batteries are suggested to be fully charged before starting the estimation. If possible, the SOC is preset at 100%. When a fully charged battery is not available, the SOC is initially estimated by testing either the open-circuit voltage or the loaded voltage depending on the starting conditions.

The estimation process is based on monitoring the battery voltage, V_b, and current, I_b. The battery operation mode can be known from the amount and the direction of the operating current. When the battery is open-circuited with zero current, a compensation of self-discharging loss is made. The DOD is adding up the drained charge in the discharging mode, and counting down with the accumulated charge into the battery for the charging mode. After a correction with the charging/discharging efficiency, a more accurate estimation can be achieved.

The battery is exhausted when the loaded voltage V_b becomes less than 3 V during the discharging. In this case, the battery can no longer be used and should be recharged. At the same time, a re-calibration to the SOH can be made. On the other hand, the tested battery is fully charged if V_b reaches the upper limit and I_b

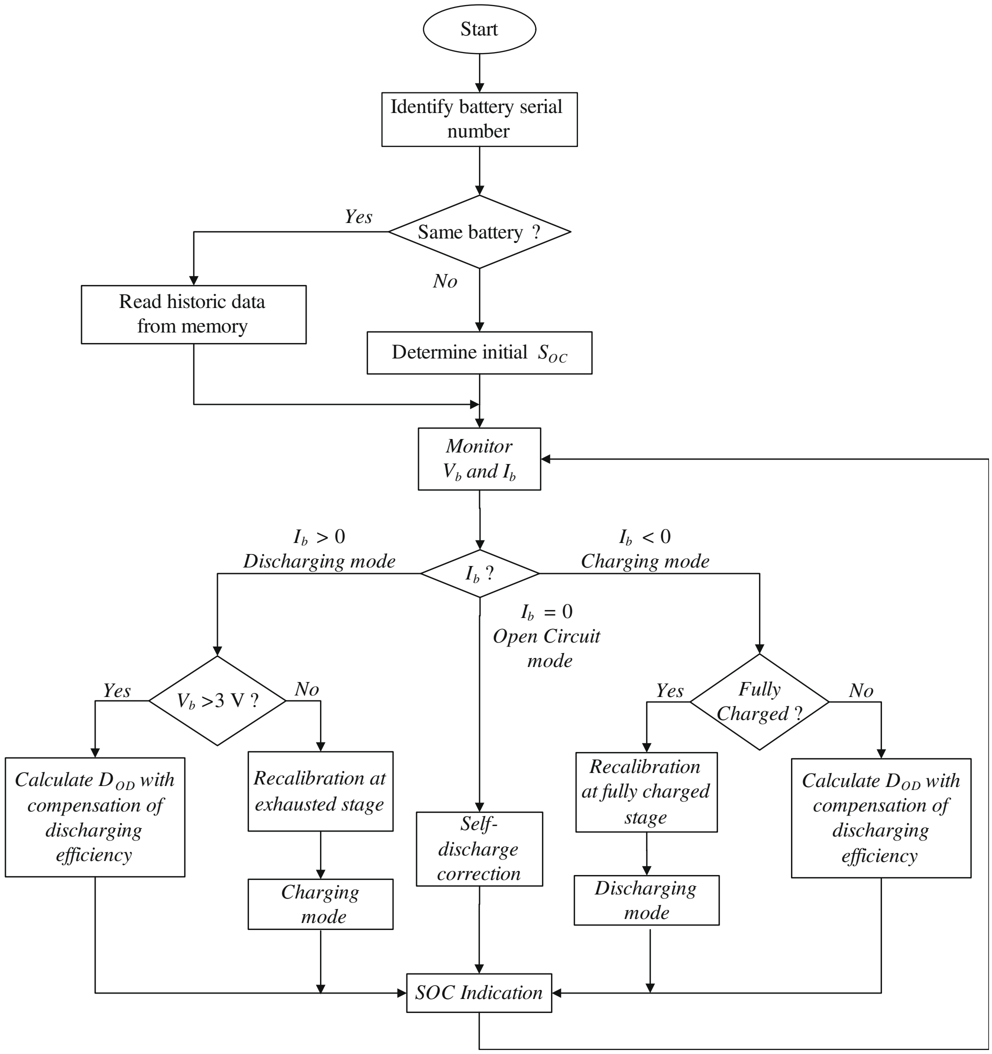


Fig. 2. Flowchart of the enhanced coulomb counting estimation method.

declines to the lower limit. A new SOH is obtained by accumulating the sum the total charge put into the battery.

Considering the SOH, the SOC is estimated as

$$S_{OC}(t) = S_{OH}(t) - D_{OD}(t) \tag{8}$$

As shown in (2), SOH is proportional to Q_{MAX}, which is equal to D_{OD} when the battery is exhausted. In other words, the SOH of battery should be re-evaluated by the accumulative D_{OD} at the exhausted state. It is noted that the SOH can be re-evaluated when the battery is either exhausted or fully charged. If the SOH is underestimated, D_{OD} would become negative at the next fully charged state. Conversely, D_{OD} will be positive at the next fully charged state if the SOH is overestimated. These errors can be eliminated by setting the sum of S_{OC} and D_{OD} to S_{OH} at the fully charged state.

$$S_{OH} \Leftarrow S_{OC} - D_{OD} \tag{9}$$

In practice, the fully charged and exhausted states occur occasionally. The accuracy of the SOH evaluation can be improved when the battery is frequently fully charged and discharged.

4. Determination of initial SOC

A battery can be operated at one of the three modes, charging, discharging, and open-circuit.

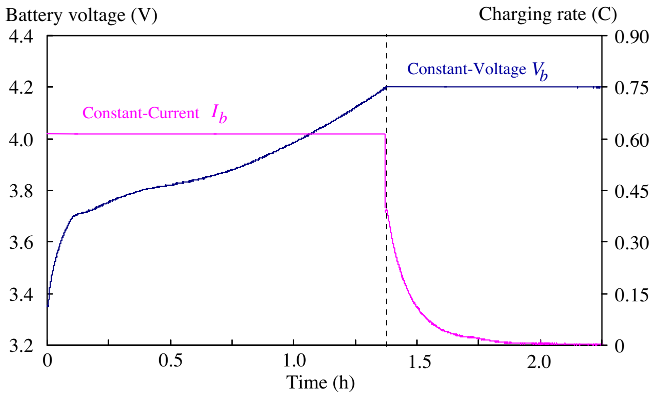
4.1. Charging stage

Fig. 3a shows the variations of the battery voltage and current when a battery is charged by the CC–CV mode. In this experiment, the tested battery is first charged by a constant rate of 0.6 C to a threshold voltage of 4.2 V, and then by a constant-voltage of 4.2 V to its full capacity. With a constant charging current, the battery voltage increases gradually and reaches the threshold after 1.275 h. Once has the battery been charged by the constant-current mode, the charging current drops first rapidly, and then slowly. Eventually, the current declines to almost zero when it has been fully charged.

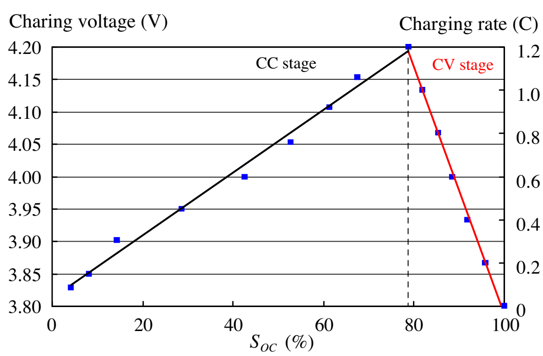
Fig. 3a can be converted into the relationship between the SOC and the charging voltage during the constant-current stage and the relationship between the SOC and the charging current during the constant-voltage stage are shown in Fig. 3b. The battery voltage increases approximately linearly to the amount of charge delivered to the battery. As a result, the SOC can be obtained by

$$S_{OC} = (198.5V_b - 755.590)\% \tag{10}$$

At the end of the constant-current stage, the battery has been charged to 78% of the rated capacity. During the constant-voltage stage, the charging current decreases linearly with the increasing of the battery capacity. As a result, the SOC can be obtained by



(a) Charging current and voltage



(b) Estimation lines with experimental results

Fig. 3. The charging voltage, current, and estimation curves

$$S_{OC} = (-17.402 I_b + 99.377)\% \quad (11)$$

In accordance with (12), the battery can be fully charged to an SOC of 99.377 when the charging current drops to zero.

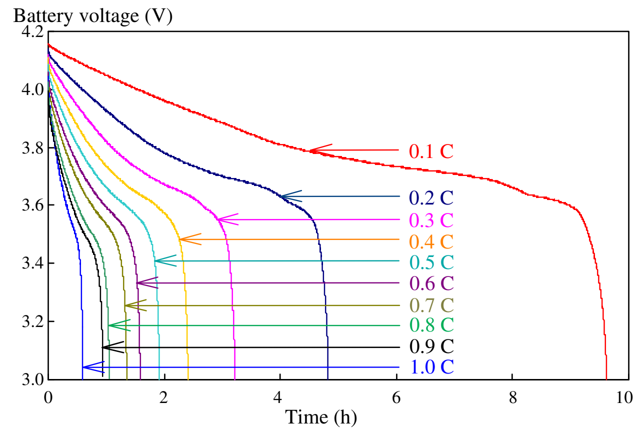
4.2. Discharging stage

Fig. 4a shows the typical voltage curves when a lithium-ion battery is discharged by different currents. The terminal voltage declines as the operating time elapses. A higher current causes faster decline in the terminal voltage, leading to a shorter operating time. As shown in Fig. 4a, the battery can sustain for 582 min when discharged by 0.1 C, but only 57 min for a high discharging rate of 1 C. However, only insignificant differences, 1.8% of the rated capacity, in the total released capacities are found in Fig. 4b. Fig. 4c illustrates the relationship between SOC and the discharging voltage at different currents. The initial SOC during discharging stage can be obtained by

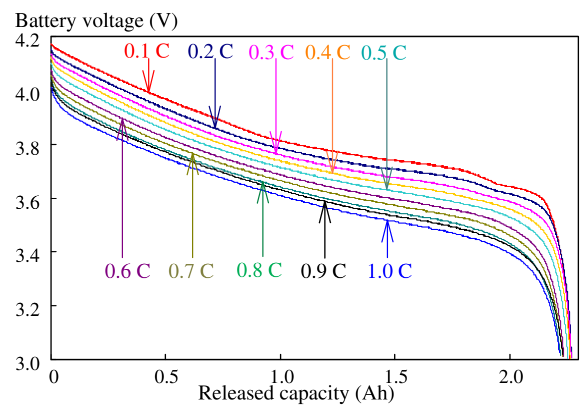
$$S_{OC} = 41.5882 I_b + 831.8838 V_b - 0.5720 I_b^2 - 88.9639 V_b^2 - 1833.0557 \quad (12)$$

4.3. Open-circuit stage

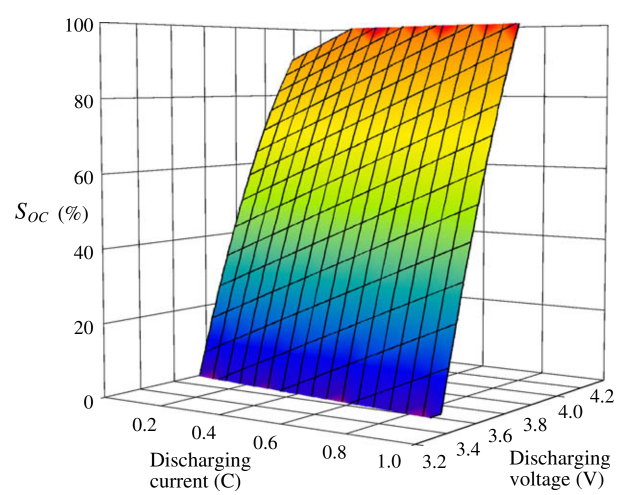
Fig. 5 shows the relationship between the open-circuit voltage and the SOC when a battery is open-circuited for 120 min. The battery is discharged by different currents before disconnecting from load. The experimental results reveal that open-circuit voltage can be used to estimate SOC if a long period rest time is available. For simplicity, the experimental curve is divided into two regions, the estimation curves are shown in Fig. 5. The SOC is linearly proportional to the open-circuit voltage which is within a range between 3.0 and 3.7 V.



(a) Discharging voltage with respect to time



(b) Discharging voltage with respect to released capacity



(c) Estimation curve

Fig. 4. The discharging curves and SOC estimation surface.

$$S_{OC} = 39.862 V_{OC} - 128.13 \quad (13)$$

When the open-circuit voltage is greater than 3.7 V, the SOC can be expressed as

$$S_{OC} = -229.14 V_{OC}^2 + 1973.5 V_{OC} - 4148 \quad (14)$$

5. Charging and discharging efficiencies

The operation efficiency of a battery can be evaluated by the coulombic efficiency, which is defined as the ratio of the number

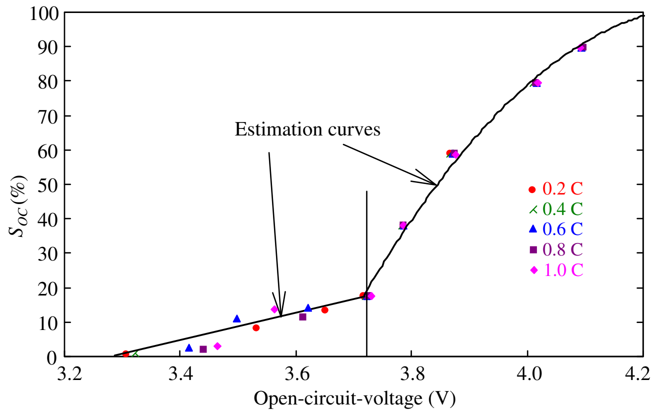


Fig. 5. Estimation curves at open-circuit stage.

of charges that enter the battery during charging compared to the number that can be extracted from the battery during discharging. It is noted that the coefficients of the charging and discharging efficiencies are obtained from the average values of ten batteries.

$$\eta_{\mathrm{Ah}} = \frac{Q_{\mathrm{discharge}}}{Q_{\mathrm{charge}}} \times 100\% \tag{15}$$

Both Q_{charge}, and $Q_{\mathrm{discharge}}$ are denoted by ampere-hour (A h).

5.1. Charging stage

Fig. 6 shows the charging efficiencies at different charged capacities. All tested batteries are charged by a constant rate of 0.6 C to the designated capacities, Q_{C}, which is the product of the charging rate and charging duration, and then discharged by a constant rate of 0.1 C to the cut-off voltage 3 V. The charging efficiency is defined as

$$\eta_{\mathrm{C}} = \frac{Q_{\mathrm{discharge,0.1\,C}}}{Q_{\mathrm{charge,0.6\,C}}} \times 100\% \tag{16}$$

The experimental results show that the battery with a lower Q_{C} has a higher charging efficiency. Approximately, the charging efficiency is inversely proportional to Q_{C}.

$$\eta_{\mathrm{C}} = (-0.4192Q_{\mathrm{C}} + 100)\% \tag{17}$$

For the purpose of SOC estimation, the relationship between the charged capacity and the Q_{C} is converted into the relationship between the charging efficiency and the SOC, as shown in Fig. 6. As a result, the charging efficiency can be expressed in terms of SOC.

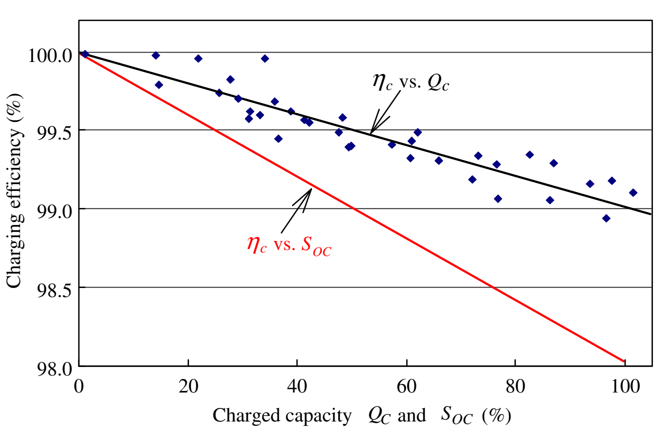


Fig. 6. Charging efficiency vs. Q_{C} and SOC.

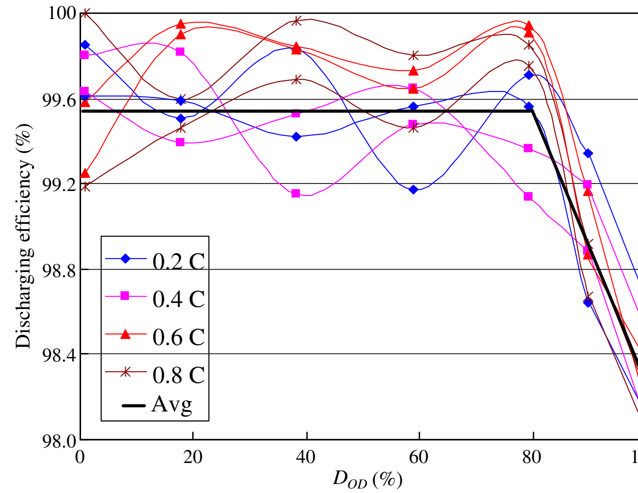


Fig. 7. Discharging efficiency under different currents.

$$\eta_{\mathrm{C}} = (-0.0197S_{\mathrm{OC}} + 100)\% \tag{18}$$

5.2. Discharging stage

The discharging efficiency, η_{d}, is the ratio of the released capacity of two-stages to Q_{MAX} in one discharge cycle. In the experiments, all tested batteries are fully charged before discharging and then discharged by the two-stage current profile, first by a specified current to a designated D_{OD}, and then by 0.1 C to the cut-off voltage, 3 V. The discharging efficiencies are calculated by

$$\eta_{\mathrm{d}} = \frac{I_1T_1 + I_2T_2}{Q_{\mathrm{MAX}}} \times 100\% \tag{19}$$

where I_1, I_2, T_1, and T_2 are the discharging currents and periods during the first and second stages, respectively.

The experimental results in Fig. 7 show that the discharging efficiency is irrelevant to the discharging rate. The discharging efficiency is always higher than 99% when D_{OD} is less than 80%. Even though the coulombic loss is trivial, the discharging efficiency is roughly approximated to 99.52% or further accurate estimation. On the other hand, the discharging efficiency decreases considerably for a deeper discharged battery

$$\eta_{\mathrm{d}} = (-0.0668D_{\mathrm{OD}} + 104.9)\% \tag{20}$$

where the coefficients are obtained from Fig. 7.

6. Verification of proposed SOC estimation method

Fig. 8 illustrates the process of the verification experiment to calculate the accuracy of the proposed estimation method. The voltage, current, and operating time are monitored every 2 s. The battery current is positive for charging and negative for discharging. The estimated SOC accumulates during the charging period, and declines in the discharging mode. The examined point can be made during either the charging or discharging stage. The battery is discharged with 0.1 C to the cut-off voltage. Consequently, the measured cumulative capacities are compared to the estimated SOCs at the examined points to verify the accuracy of estimation method. The estimation error is

$$\varepsilon(\%) = \frac{S_{\mathrm{OC(estimated)}} - S_{\mathrm{OC(measured)}}}{S_{\mathrm{OC(rated)}}} \times 100\% \tag{21}$$

where $S_{\mathrm{OC(estimated)}}$, $S_{\mathrm{OC(measured)}}$, and $S_{\mathrm{OC(rated)}}$ are the estimated, measured and rated S_{OC} in percentage, respectively.

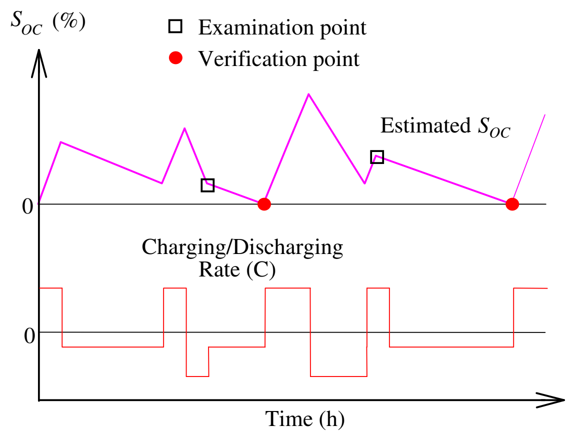


Fig. 8. Sketch map of verified experiment.

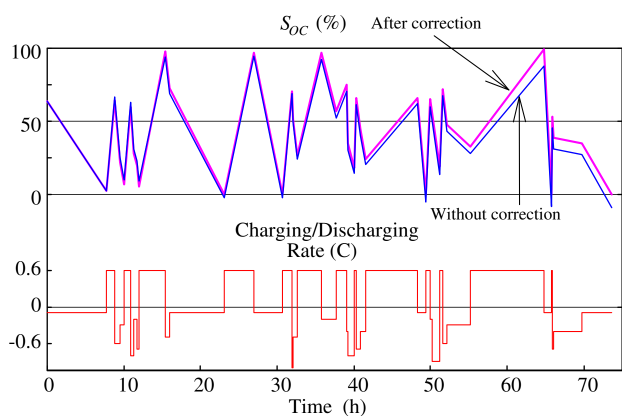


Fig. 9. Verified experiments.

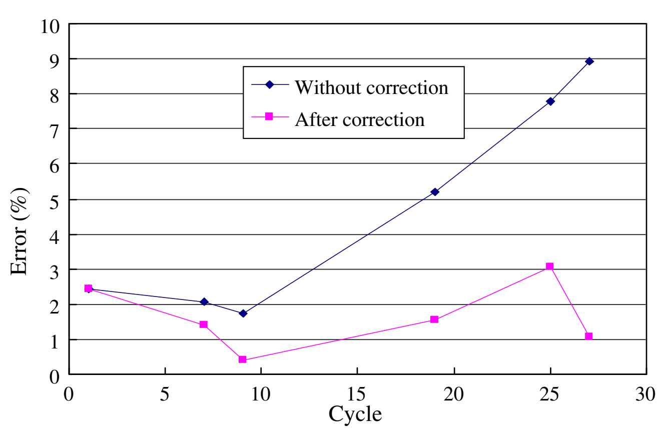


Fig. 10. Estimation errors of various coulomb counting methods.

The proposed SOC estimation method is verified by several experiments. Fig. 9 shows one of the experimental results. The tested battery is charged by a constant rate of 0.6 C and discharged by different currents. The total operating time is 73.68 h with 28 charging and discharging cycles. At the start, the SOC is initially pre-estimated to be 63.85% with a loaded voltage of 3.87 V at a discharging rate of 0.1 C. The There are six examination points at the 1st, 7th, 9th, 19th, 25th, and 27th cycles, at which the battery is discharged by 0.1 C to the cut-off voltage.

The estimation errors are shown in Fig. 10. Without correction, the estimation errors of the coulomb counting method increase gradually with the operating cycle. The error at the 6th cycle is 2.43%, but can be enlarged to 8.93% at the 21st cycle. By introducing the correction of operating efficiency and considering the declination of SOH, the estimation error is effectively reduced to 1.08% at the 28th cycle.

7. Conclusion

An enhanced coulomb counting method for estimating SOC and SOH is proposed for lithium-ion batteries. The charging and discharging characteristics of lithium-ion batteries were studied carefully. To improve the estimation accuracy, the correction of the operating efficiency and the evaluation of the SOH were both considered. Through the investigation, some noteworthy conclusions are concluded as the following:

1. The battery can be regarded as completely exhausted when its voltage drops to the cut-off voltage, so that S_{OC} can be reset to zero at this point. On the other hand, the calculated D_{OD} can be reset to zero at the fully charged state.
2. Once has a battery been completely discharged, the cumulative D_{OD} is equal to the current maximum releasable capacity and can be used to evaluate the S_{OH}.
3. When a battery in fully charged, the cumulative D_{OD} can be used to examine the evaluation of the S_{OH}.
4. The estimation error increases with the charging and discharging cycles. The S_{OC} can be preset to the current S_{OH} when the battery is fully charged.
5. The accuracy of proposed S_{OC} estimation method depends critically on the time for examination. The estimation error can be reduced to 1% at the operating cycle next to the re-evaluation of the S_{OH}.

Thanks to the simple calculation and the uncomplicated hardware requirements, the proposed method can be easily implemented in all portable devices as well as electric vehicles.

References

[1] Garche J, Jossen A, Döring H. The influence of different operating conditions, especially over-discharge, on the lifetime and performance of lead/acid batteries for photovoltaic systems. J Power Sources 1997;67(1–2):201–12.
[2] Ball RJ, Kurian R, Evans R, Stevens R. Failure mechanisms in valve regulated lead/acid batteries for cyclic applications. J Power Sources 2002;109:189–202.
[3] Aylor JH, Thieme A, Johnson BW. A battery state-of-charge indicator for electric wheelchairs. IEEE Trans Ind Electron 39(5): 398–409.
[4] Huet F. A review of impedance measurements for determination of the state-of-charge or state-of-health of secondary batteries. J Power Sources 1998;70(1):59–69.
[5] Sabine P, Marion P, Jossen A. Methods for state-of-charge determination and their applications. J Power Sources 2001;96(1):113–20.
[6] Pop V, Bergveld HJ, Notten PHL, Regtien PPL. State-of-charge indication in portable applications. Proc Int Symp on Ind Electron 2005;3:1007–12.
[7] Pei F, Zhao K, Luo Y, Huang X. Battery variable current–discharge resistance characteristics and state-of-charge estimation of electric vehicle. Proc IEEE World Congress Intell Control Automat 2006;2:8314–8.
[8] Affanni A, Bellini A, Franceschini G, Guglielmi P, Tassoni C. Battery choice and management for new generation electric vehicles. IEEE Trans Ind Electron 2005;52(5):1343–9.
[9] Roth EP, Doughty DH. Development and characterization of Li-ion batteries for the freedom car advanced technology development program. In: Proc IEEE Veh Tech Conf Stockholm, Sweden, September 2005, vol. 4, p. 2362–66.
[10] Munday FC. Electronic engine management reference manual. Graffiti Publications; 2004.
[11] Coleman M, Lee CK, Zhu C, Hurley WG. State-of-charge determination from EMF voltage estimation: using impedance, terminal voltage, and current for lead-acid and lithium-iron batteries. IEEE Trans Ind Electron 2007;54(5):255–2557.
[12] Panasonic lithium ion batteries technical handbook '03/'04.
[13] Hsieh YC, Chen WC, Ng KS, Moo CS. Investigation on operating characteristics of individual cells in a lead-acid battery pack. In: Power Convers Conf, April 2007, p. 745–50.