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Implementation of Coulomb Counting Method for Estimating the State of Charge of Lithium-Ion Battery

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Authors' contributions

This work was carried out in collaboration between both authors. Author KCN designed and constructed the hardware, wrote the software code and performed the analysis, under the supervision of author SOE. Author KCN wrote the first draft of the manuscript. Author SOE performed critical revision of the manuscript. All authors read and approved the final manuscript.

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ABSTRACT

An accurate estimate of the state of charge, which describes the remaining percentage of a battery's capacity, has been an important and ever existing problem since the invention of the electrochemical cell. State of charge estimation is one of the important function of a battery management system which ensures the safe, efficient and reliable operation of a battery. In this paper, the coulomb counting method is implemented for the estimation of the state of charge of lithium-ion battery. The hardware comprises an Arduino based platform for control and data processing, and a 16-bit analog to digital converter for current and voltage measurement. The embedded algorithm initializes with a self-calibration phase, during which the battery capacity, coulombic efficiency and initial state of charge are evaluated. The initial state of charge is determined at the fully charged state (100% state of charge) or the fully discharged state (0% state of charge). The cumulative error of this method was addressed by routine recalibration of the capacity, coulombic efficiency and state of charge at the fully-charged and fully-discharged states. The algorithm was validated by charging/discharging a lithium-ion battery through fifty complete cycles and evaluating the error in the estimated state of charge. The result shows a mean absolute

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error of 0.35% in the estimated state of charge during the test. Further analysis, considering prolonged battery operation without parameters recalibration, suggests that error in the coulombic efficiency term contributes the most to the increasing error in the estimated state of charge with each cycle.

Keywords: State of charge; SOC; coulomb counting; coulombic efficiency; lithium-ion battery; recalibration; Arduino.

1. INTRODUCTION

Presently, among the various choices of energy storage technologies, the most popular method is the electrochemical cell. It is utilized in most energy storage applications especially portable electronics, electric vehicles and renewable energy systems [1]. The electrochemical cell (battery) offers the advantage of portability and energy efficiency, and its use is promoted by increasing concern over global warming and climate change [2-3]. Among all existing battery technologies, the lithium-ion battery is the most improved and efficient battery technology. It offers the highest energy density and efficiency in addition to other advantages such as low self-discharge rate, long life span, no memory effect, and a high number of charge-discharge cycles. This prompted its increasing use in consumer electronics such as mobile phones, tablets and laptop computers [4-5].

However, lithium-ion battery is sensitive to over-charge and over-discharge, which can cause permanent damage to the battery cells and may also lead to fire or explosion [6]. This necessitates the implementation of a battery management system, which guarantees the safe, reliable, efficient and long-lasting operation of the lithium-ion battery [7-8]. The battery management system has, among many other functions, the important task of estimating the state of charge (SOC) of the battery [9-10]. The state of charge of a battery is defined as the ratio of the available capacity to the maximum capacity (when the battery is fully charged) [7], [11]. It describes the remaining percentage of the battery capacity and serves as a sort of fuel gauge of the battery [12]. The lithium-ion battery is a highly complex and non-linear electrochemical system. It is a chemical energy storage system, and this chemical energy cannot be directly accessed or measured [13]. This makes SOC estimation complex and difficult to implement [11].

Accurate and precise SOC estimation has been a long standing problem since the invention of the electrochemical cell [1], [8]. Various methods, models and algorithms for SOC estimation have been proposed and developed over the years, with each having its own advantages and disadvantages [3]. Among all, the coulomb counting method is the most used method for SOC estimation [14]. This is because it is relatively easy to implement and requires relatively low computational resources [8]. In the coulomb counting method, the remaining capacity of the battery is determined by accumulating the charge transferred in and out of the battery [15-16], and the SOC is estimated using equation 1.

$$SOC(t) = SOC(t_0) + \frac{1}{C_n}\int_{t_0}^{t} \eta I(t)dt \qquad (1)$$

Where $SOC(t_0)$ is the initial SOC, C_n is the nominal capacity, η is the coulombic efficiency, and $I(t)$ is the battery current [11]. The coulomb counting method is the most accurate technique for short term estimation. However, in the long term small error will accumulate, due to its open loop nature and lack of error correction ability, leading to significant inaccuracy. Jeong et al [17]. reported an SOC error of 0.5% after 40 minutes of estimation using the coulomb counting method. Ng et al [15]. reported that without correction, the SOC error increases gradually with operating cycle, with an error of 2.43% at the 6th cycle and 8.93% at the 21th cycle. However, by considering the operating efficiency correction and by re-evaluating the state of health (SOH), the estimation error can be reduced to 1% in the next operating cycle. Another drawback is the requirement of an auxiliary method to determine the initial SOC, also any error in the initial SOC is propagated throughout subsequent estimates [7].

In this paper, the coulomb counting method was implemented using an Arduino based platform. In the software, a self-calibration procedure which evaluates the battery capacity, coulombic efficiency and initial SOC was devised. In addition, to improve accuracy, routine parameter recalibration at the fully charged and fully discharged states was incorporated. Finally, the error in the estimated SOC and the contribution of each parameter to the SOC error was analysed.

2. MATERIALS AND METHODS

The algorithm was implemented on a battery management system (BMS), which was designed and constructed using the following components: Arduino Nano, TP4056 battery charging module, ADS1115 ADC module, SSD1306 OLED display, MT3608 boost converter module, and IRF3205 N-MOSFET. Fig. 1 shows a block diagram of the hardware setup.

2.1 The Hardware

Current and voltage measurements were performed by the ADS1115 module; a 16-bit, four-channel analog-to-digital converter. During voltage measurement, the programmable gain amplifier (PGA) of the ADS1115 module is configured to provide a full scale range of ±6.144 V with a corresponding resolution of 0.1875 mV. The high-side current sensing method was applied for current measurement. Here, the ADS1115 module measures the voltage across a 0.1 Ω sense resistor connected in series to the positive terminal of the battery, and the current is calculated using Ohm’s law. During current measurement, the PGA is configured to provide a full scale range of ±0.512 V with a resolution of 15.625 μV. This configuration enables current measurement in the range of ±5.12 A with a resolution of 0.15625 mA, the sign of the current indicates the direction of current flow. The charging current and voltage are regulated by the TP4056 charging module. The module charges the battery using the constant current/constant voltage procedure. The battery is determined to have reached its fully charged state when the battery voltage is 4.2 V and the charging current falls below a threshold (100 mA). When this condition is satisfied the Arduino disables the charging module, thereby terminating the charging process and preventing overcharge. The battery is considered to be fully discharged when the battery voltage falls below a threshold (2.75 V). Consequently, the discharge current is terminated via a MOSFET switch controlled by the Arduino, thereby preventing over discharge. A DW01 battery protection IC, which is incorporated into the TP4056 charging module, provides an added level of protection from overcharge, over discharge and overcurrent. The SOC and other battery parameters are displayed on an SSD1306 OLED display. The control unit consist of an Arduino Nano microcontroller module. It serves as the “brain” of the hardware and controls all other units, as dictated by the embedded algorithm.

2.2 The Software

The embedded algorithm controls the hardware and performs the actual SOC estimation. Upon installing a new battery, the system is initialized by a system format followed by a system calibration. The system format involves clearing and initializing all memory location in the Arduino EEPROM. The initial SOC, battery capacity and coulombic efficiency are evaluated during the initial system calibration which has to be completed before SOC estimation can commence. During the system calibration, the battery is charged and discharged through one complete cycle. During the cycle, the initial SOC is set to 0% at the fully discharged state and 100% at the fully charged state. At the end of the cycle, the battery capacity is evaluated as the net capacity discharged during the cycle, and the coulombic efficiency is evaluated as the ratio of the discharged capacity to the charged capacity during the cycle. Once these parameters are evaluated, the calibration is complete and SOC estimation can commence.

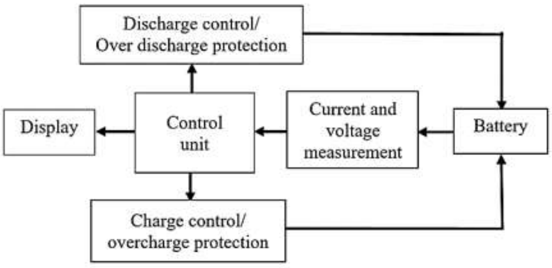

Fig. 1. Block diagram of the hardware

It is essential that the battery capacity is calibrated rather than utilizing the rated capacity, because the rated capacity is likely to be inaccurate due to cell-to-cell variation, difference in the operating condition from the manufacturer's testing condition, and battery ageing. The capacity is more accurately quantified during the initial system calibration. However, it is still prone to error due to the dependence of the discharged capacity on the discharge rate and temperature. The discharge rate which gives the maximum capacity is a low discharge rate below which there is no significant capacity increase. However, this does not necessarily depict the normal operating condition of the battery. Thus, to maximize accuracy, it is essential that the condition during the initial system calibration is representative of the subsequent operating conditions of the battery.

During the battery operation, the battery current and voltage are continuously sampled every 100 ms. The charge, discharge and net capacities are accumulated and utilized in estimating the SOC. The estimation was done using equation 1. However, the maximum releasable capacity (capacity stored at 100% SOC) was used rather than the rated capacity, also the coulombic efficiency was utilized only during the charging process (η = 1 during discharge and η < 1 during charge). Equation (1) describes the coulomb counting method. However, digital systems work with discrete time, therefore the equation utilized is equation (2), which is the discrete time version of equation (1)

$$SOC_k = SOC_{k-1} - \frac{1}{C}\eta i_k \, \Delta t \qquad (2)$$

Where SOC_k is the SOC in the present time step, SOC_{k-1} is the SOC in the previous time step, i_k is the battery current in the present time step, Δt is the duration of each time step (100 ms) and η is the coulombic efficiency (utilized only during charge). The current and voltage sampling and capacity accumulation are performed by a timer interrupt service routine.

In addition to the initial system calibration, recalibration is performed routinely in order to improve accuracy. At the fully discharged state, the SOC is reset to 0% and the battery capacity is recalibrated as the mean of the net discharge capacities in the previous five cycles. At the fully charged state, the SOC is reset to 100% and the coulombic efficiency is reevaluated as the mean of the coulombic efficiencies evaluated in the previous five cycles. The embedded algorithm, in addition to SOC estimation, also controls other units of the battery management system.

3. RESULTS AND DISCUSSION

In order to ascertain the accuracy of the algorithm, the battery (Panasonic NCR18650B) was charged/discharged through 50 complete cycles (100 half-cycles). The SOC error was evaluated at the fully charged state as the discrepancy between the estimated SOC and 100%, and at the fully discharged state as the discrepancy between the estimated SOC and 0%. The result of the test is shown in Fig. 2. The scatter plot shows only the error at the fully charged and fully discharged states (before recalibration), since these are the only states where the true value of the SOC is certain. The SOC error throughout the cycles is estimated by a linear interpolation between points, as shown in Fig. 3. The justification for this interpolation is the fact that the SOC is a linear function of all its variables. Thus, it is assumed that the SOC error increases linearly from zero, immediately after an SOC reset, to its value just before the next reset.

The mean absolute error (MAE) over the 100 half-cycles is 0.35%. This result is for the case where there are opportunities for recalibration; the battery is discharged only when it attains the fully charged state and charged only when it attains the fully discharged state. However, this may not be the case during normal battery operation. Thus, to determine the SOC error profile in cases where the battery undergoes prolonged operation without parameter recalibration, the SOC was recalculated (without recalibration).

The SOC is estimated from the initial SOC, current, time step duration, capacity and coulombic efficiency. Errors in each of these terms will contribute to the overall SOC error. By setting the initial SOC to 0% at the fully discharge state and 100% at the fully charged state, the uncertainty in the initial SOC is zero (by definition and calibration). Error in the measured current can be minimized by making use of an ADC of high resolution and fidelity. However, even the best ADC will still incur a quantization error. The ADC used (16 bit) incurred a quantization error of ±0.15625 mA, which will result in an error of ±0.15625 mAh per hour in the accumulated capacity, and will contribute an error of 0.000078% per hour to the estimated SOC of a 2000 mAh battery. This contribution is relatively negligible. Similarly, any contribution from measurement noise, which usually have a Gaussian distribution, will tend to cancel out in the long run. The datasheet of ADS1115 [18] indicates a typical offset error of ±1 LSB (least significant bit). This will contribute an error, of the same magnitude as that contributed by the quantization error, to the overall SOC error. Also, the datasheet states that the typical gain error of ADS1115 is 0.01%. This will contribute an error of 0.01% (per cycle) to the SOC error. However, unlike the quantization error, the offset error and gain error can be eliminated by proper calibration and by making use of a high fidelity ADC. The timing is handled by a timer interrupt, which uses one of the Arduino timers. The Arduino timer utilizes a 16MHz crystal oscillator. A typical standard crystal oscillator has an accuracy in the order of 20 to 50 parts per million [19]. This corresponds to an uncertainty of (considering the worst case) 0.00005% in the time step duration which results in an SOC error of the same order of magnitude. Short term instability in the oscillator frequency is effectively removed by the integration over time.

To ascertain the influence of an error in the coulombic efficiency term on the SOC error, three cases with different value of coulombic efficiency were considered. In the first case, the coulombic efficiency was set at 1.000000 (the maximum value evaluated during the test). In the second case, it was set at 0.983538 (the minimum value evaluated during the test), and in the third case, it was set at 0.992372 (the mean of all the values of coulombic efficiencies evaluated during the test). In all three cases, the battery capacity was set at 2312.42 mAh (the capacity evaluated during the initial system calibration). The SOC error of the three cases and that of the test are shown in Fig. 4.

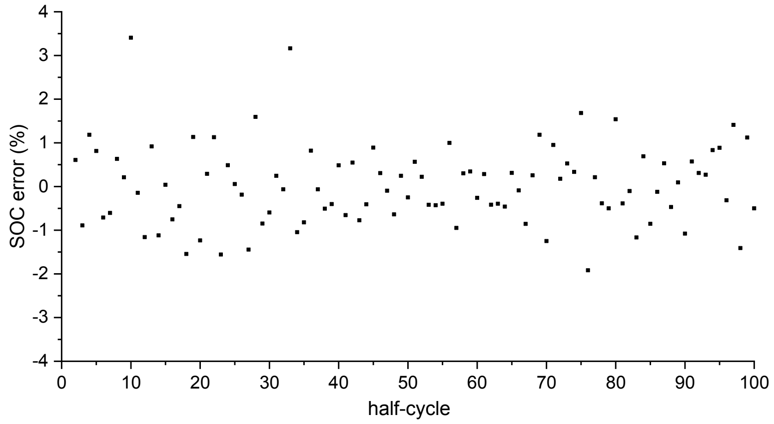

Fig. 2. Scatter plot of SOC error

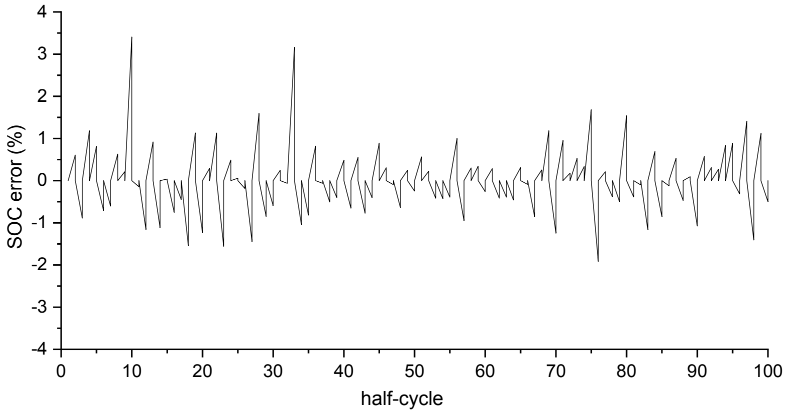

Fig. 3. Error in the estimated SOC

The graph shows that a sight difference in the value of coulombic efficiency can result in a significant discrepancy in the estimated SOC after prolonged operation, with the discrepancy increasing with each cycle.

To ascertain the contribution of an error in the battery capacity to the SOC error, three cases with different value of battery capacity were considered. In the first case, the battery capacity was set at 2312.42 mAh (the capacity evaluated during the initial system calibration). In the second case, the battery capacity was set at 2289.21 mAh (the minimum value that was evaluated as the capacity during the test), in the third case, the capacity was set at 2333.93 mAh (the maximum value that was evaluated as the capacity during the test). In all three cases, the coulombic efficiency was set at 0.992372 (the mean of all coulombic efficiency values evaluated during the test). The error in the estimated SOC of the three cases are shown in Fig. 5. The SOC error in the three cases differ by less than 2%. In addition, the graph shows that although the SOC error for the three cases are different, in the long run (over many cycles) the accumulated SOC error follows the same trend, which is determined by the coulombic efficiency term. This suggest that an inaccurate value of coulombic efficiency is responsible for the increasing SOC error with each cycle.

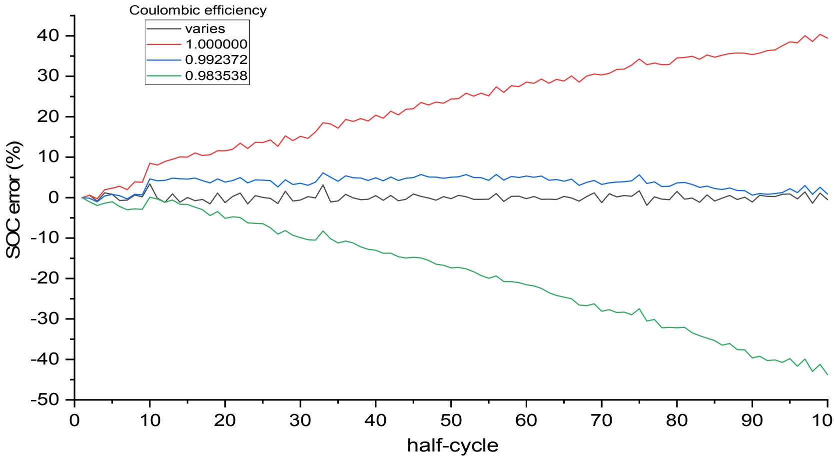

Fig. 4. Error in estimated SOC (coulombic efficiency = varies, 1.0, 0.992372, and 0.983538; capacity = 2312.42 mAh)

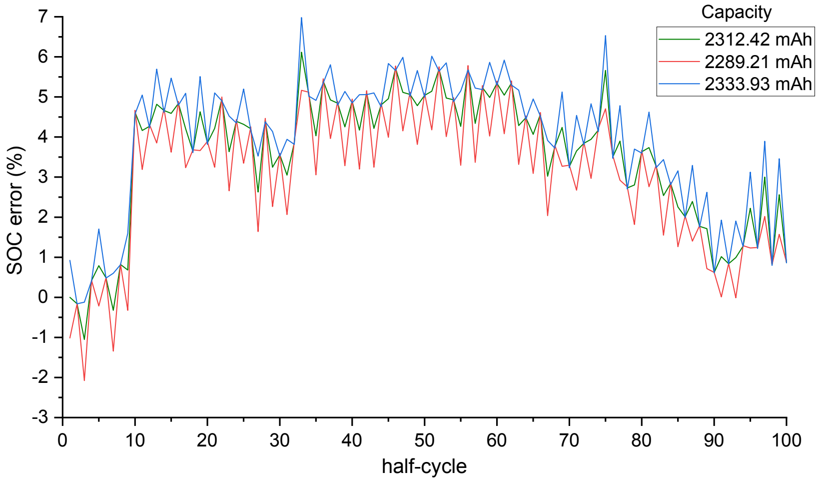

Fig. 5. Error in estimated SOC (Capacity = 2312.42 mAh, 2289.21 mAh and 2333.93 mAh; coulombic efficiency = 0.992372)

4. CONCLUSION

Although the coulomb counting method requires relatively low computational resources to implement, it can provide an accurate SOC estimate. However, the accuracy of the estimated SOC is dependent on the accuracy of the measured current, initial SOC, time step duration, coulombic efficiency and capacity. The test carried out suggests that the coulombic efficiency has the greatest influence on the increasing error in the SOC estimate during prolonged operation without recalibration. The coulomb counting method provides its best estimate when there are opportunities for routine recalibration.

DISCLAIMER

The products used for this research are commonly and predominantly use products in our area of research and country. There is absolutely no conflict of interest between the authors and producers of the products because we do not intend to use these products as an avenue for any litigation but for the advancement of knowledge. Also, the research was not funded by the producing company rather it was funded by personal efforts of the authors.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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