Monitoring of lithium-ion cells using a microcontroller

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Abstract

Safe and efficient operation of batteries is always desired but batteries with a high energy density pose a threat to the system causing thermal breakdown, reduced performance and rapid ageing. To reduce such vulnerabilities, an optimum environment with controlled parameters is required. Four parameters have been considered for analysis, i.e. state of charge, current, voltage and temperature. The module makes a detailed analysis of the above-mentioned parameters and suggests a microcontroller-based prototype that is capable of monitoring the external factors in real time and generating relevant warnings.

Keywords: lithium ion; battery-management system; thermal runaway; battery temperature; battery current; battery voltage; microcontrollers

Introduction

Lithium-ion batteries (Fig. 1) have found their application in various industries ranging from miniscule electronics to huge smart grids, thanks to their high charge-holding capacity, high charging-discharging efficiency and ability to handle currents of huge magnitudes. Interestingly, important factors such as the charge-holding capacity, battery life, coulombic efficiency and charging-discharging current...
are dependent on temperature and the internal chemistry of the batteries. Therefore, it is very important to monitor and, if possible, control these external factors for optimal performance and the prevention of adverse situations [1, 2]. Attempts have been made to monitor lithium-ion cells using application-specific integrated circuits (ICs) or specialized IC chips [3]. Simulation efforts have also been carried out using Simulink (a MATLAB-based graphical programming environment for modeling, simulating and analyzing dynamical systems) [4], but monitoring using an affordable general-purpose microcontroller like Arduino to carry out the monitoring of temperature, current and voltage has not been realized.

1 Coulombic efficiency

The coulombic efficiency of a lithium-ion cell is defined as the amount of charge leaving the cell divided by the amount of charge stored in the cell at a fixed temperature, multiplied by 100. Mathematically, this is:

$$\eta_c = \frac{Q_{\text{discharge}}}{Q_{\text{charge}}} \times 100 \%$$

(1)

Since the temperature does not remain constant under real conditions, neither does the efficiency. This problem is solved by performing a soak test in a laboratory to obtain the efficiencies of various parameters at different possible temperatures. Although the discharging coulombic efficiency of lithium-ion cells remains always at ~99.9%, the charging coulombic efficiency is temperature-dependent and determines the amount of energy to be provided for charging the cell [5, 6].

1.1 Soak test

Soak tests are performed to calculate various parameters such as the coulombic efficiency and total capacity of the cell using open-circuit voltage-test data. In these tests, cells are first discharged and charged to certain state of charge levels at different temperatures and a generalized equation to compute the coulombic efficiency is derived, which is mathematically represented as:

$$\eta(T) = \frac{Q_{\text{discharge}}}{Q(T)_{\text{charge}}} - \eta(25 \degree C) \times \frac{Q(25 \degree C)_{\text{charge}}}{Q(T)_{\text{charge}}}$$

(2)

where \(\eta(T)\) is the coulombic efficiency at temperature \(T\), \(Q_{\text{discharge}}\) is the total magnitude of the outgoing charges, \(Q(T)_{\text{charge}}\) is the magnitude of incoming charges at temperature \(T\), \(\eta(25 \degree C)\) is the coulombic efficiency at 25°C and \(Q(25 \degree C)_{\text{charge}}\) is the magnitude of incoming charges at 25°C. The above-mentioned equation is used to calculate the coulombic efficiency at various temperatures.

1.2 Dependence of coulombic efficiency on temperature

Charge coulombic efficiency is dependent on the temperature of the cell. It is usually ~96% to ~98% at negative temperatures and reaches 100% at ~20°C. On the other hand, the discharge coulombic efficiency is always 100% and is visually depicted in Fig. 2 [7].

This implies that cells should be charged at >20°C for optimal charging and to minimize the loss of energy [8–10].

2 Usable capacity

The usable capacity is the magnitude of that energy which can be extracted from the cell. It is also

![Fig. 1: A lithium-ion 18650 cell, which is ~18 mm wide and 65 mm long, hence the name.](https://example.com/image1)

![Fig. 2: Coulombic efficiency vs temperature. The red line represents the charging coulombic efficiency and the blue line represents the discharging coulombic efficiency. It may be noted that the discharging coulombic efficiency is always ~100%, whereas the charging coulombic efficiency increases with increase in temperature and reaches ~100% at >15°C [7].](https://example.com/image2)
temperature-dependent as the rate of the chemical reactions increases with an increase in temperature and vice versa. Mathematically, it is represented using an Arrhenius equation:

\[ k = Ae^{\frac{E_a}{RT}} \]  

(3)

where \( k \) represents the rate constant, \( T \) represents the temperature in Kelvin, \( A \) is the constant for each chemical reaction, \( E_a \) is the activation energy and \( k_B \) is the Boltzmann constant [11].

Another explanation for more capacity argues that the ions have more mobility and energy at higher temperatures, and hence more charges get extracted from the cell as compared to at lower temperatures. But higher temperatures also bring a drawback to lithium-ion cells, as they also accelerate the rate of degradation of the cell. This is due to the fact that the number of collisions taking place inside the cell increases and this significantly harms the internal chemistry, which is evident from Figs 3 and 4 in which high temperature levels have >100% of usable capacity, thereby reducing the average lifespan of the cell [13-15]. Meanwhile, negative temperatures correspond to <90% of usable capacity at –1°C, which drops down to 50% at ~30°C and the cell fails to perform due to sluggish electrochemistry, as is visible in Figs 3 and 4 [12, 16].

3 C-rating

The C-rate of a cell is defined as the level of constant current charge or discharge that can be sustained by the cell. C-rates also determine how quickly a battery can be charged or discharged and even the amount of power that can be extracted in a short span of time. A cell of 1-Ah capacity with a 1C rating can be charged or discharged in 1 hour using maximum of 1 A of constant current. The charge time declines when the C-rate is increased and vice versa, as shown in Table 1 [17].

Usually, for applications in which huge power in a short span of time is required while charging or discharging, as smartphones or drones, batteries with high C-rates are preferred whereas if the application does not need huge power in a short span of time, lower C-rates are preferred [18].

C-rates are not limited to lithium-ion cells, but are also used with different chemistries such as nickel-cadmium or lead-acid. Since lead-acid batteries can only have lower C-rates, they are preferred in day-to-day applications such as home inverters and car batteries. But lithium-ion cells possess high C-rates and this has made them the norm in high-power applications such as smartphones and electric vehicles.

Even though high C-rates reduce the time to charge and a huge amount of energy can also be extracted in a short period, this comes with the demerit of a reduction in the average lifespan of the cell [19, 20].

The lifespan of a cell is defined as the number of times it can be charged completely and then completely discharged; this is also termed as a single cycle. The lifespan of a cell is determined using the average cycles for which it can function. But if a cell is charged or discharged at higher

![Usable capacity vs temperature](image)

**Fig. 3:** Usable capacity vs temperature. The usable capacity hits 100% at -20°C, and even exceeds 100%. On the other hand, it may go as low as 50% at around -30°C [12].

![Discharge power vs temperature](image)

**Fig. 4:** Discharge power vs temperature. The optimal operating range for lithium-ion cells ranges from 10°C to 30°C; at <10°C, sluggish electrochemistry is experienced and the cell might not be able to provide the necessary power for the application, whereas at >30°C, the cell will experience degradation and a reduction in the average lifespan [16].

| C-rate | Maximum current (C-rate × capacity) | Discharge-charge time |
|--------|-----------------------------------|-----------------------|
| 10C    | 10 × 100 A = 1000 A              | 6 minutes             |
| 5C     | 5 × 100 A = 500 A               | 12 minutes            |
| 3C     | 3 × 100 A = 300 A               | 20 minutes            |
| 2C     | 2 × 100 A = 200 A               | 30 minutes            |
| 1C     | 1 × 100 A = 100 A               | 1 hour                |
| C/2    | 100 A/2 = 50 A                  | 2 hours               |
| C/3    | 100 A/3 = 30 A                  | 3 hours               |
| C/5    | 100 A/5 = 20 A                  | 5 hours               |
| C/10   | 100 A/10 = 10 A                 | 10 hours              |

The higher the C-rate, the less time it takes to completely charge the cell and vice versa.
C-rates, then this reduces the average number of cycles and, if the C-rates are lower, this reduces the average lifespan. This is due to the damage made to the internal structures of the cells because of charging and discharging, although it is bound to happen even if lower C-rates are used, but higher C-rates cause more damage and the overall capacity of a cell reduces rapidly, as is clearly visible in Fig. 5 [18].

4 Charging and discharging
A cell was charged and discharged to obtain the respective curves for better understanding of the performance of a cell.

4.1 Discharging
The cell was discharged three times by connecting three different loads of resistance 10, 15 and 20 Ω. The voltage of the cell and the discharging current were measured using a multimeter and the data have been compiled in Table 2 (Fig. 6).

It can be noted from the readings of Table 2 that the magnitude of the current decreases proportionally to the voltage of the cell and the amount of current also depends on the load resistance.

4.2 Charging
A TP4056 module was used to charge the cell linearly. The TP4056 can be easily connected to a smartphone charger of 5-V output using a USB cable and additional wires can be used to charge a 2600-mAh 18650 lithium-ion cell. The readings were recorded and compiled in Table 3 (Fig. 6).

Table 2: Sample readings of discharging current and cell voltage recorded while discharging a 2600-mAh 18650 lithium-ion cell using different loads

| Load resistance | 20 Ω | 15 Ω | 10 Ω |
|----------------|------|------|------|
| Voltage (V)    | Current (A) | Voltage (V) | Current (A) | Voltage (V) | Current (A) |
| 4.2            | 0.20  | 4.2   | 0.27  | 4.2      | 0.41  |
| 4.0            | 0.18  | 4.0   | 0.26  | 4.0      | 0.40  |
| 3.8            | 0.17  | 3.8   | 0.25  | 3.8      | 0.38  |
| 3.6            | 0.16  | 3.6   | 0.23  | 3.6      | 0.37  |
| 3.4            | 0.15  | 3.4   | 0.22  | 3.4      | 0.34  |
| 3.2            | 0.14  | 3.2   | 0.21  | 3.2      | 0.32  |
| 3.0            | 0.14  | 3.0   | 0.20  | 3.0      | 0.30  |
| 2.8            | 0.13  | 2.8   | 0.18  | 2.8      | 0.28  |
| 2.6            | 0.12  | 2.6   | 0.16  | 2.6      | 0.26  |

Fig. 5: Capacity vs number of cycles of different lithium-ion cells discharged–charged at various C-rates. A discharging cell with a 3C rating dies very quickly at ~300 cycles, whereas 2C and 1C cells work for >300 cycles and even retain better capacity than a 3C cell [21].

Fig. 6: A 2600-mAh 18650 lithium-ion cell being (L) discharged using two 10-Ω resistors connected in series (R) and being charged using TP4056. A multimeter is also used to measure the discharging and charging currents.
It can be noted that after 3.8 V in Table 3, the magnitude of the current drops significantly. This is due to the CC–CV (constant current–constant voltage) charging algorithm of lithium-ion batteries [22].

5 Need for monitoring
As discussed earlier, temperature, current and voltage are parameters that determine whether the cell can perform efficiently or not. Lithium-ion cells have high energy density, which means that they are volatile and can be dangerous to their surroundings in the case of thermal breakdown. Therefore, constant monitoring is required [23–25].

5.1 Temperature factor
Lithium-ion cells can achieve a long lifespan if they are operated within the temperature range of 10–30°C. If the operating temperature is <10°C, sluggish electrochemistry drops the performance of the cell and the required output current cannot be obtained, whereas at >30°C, ageing of the cell accelerates and the lifespan decreases rapidly [14, 18, 25].

Temperature also determines the capacity of the cell, as at low temperatures the electron mobility drops and at high temperatures it increases [15, 19].

5.2 Current factor
C-rates determine how quickly a cell can be charged or discharged. Usually, high C-rates can provide high currents to the load, but they also contribute to ageing of the cell. High electron flow damages the internal chemistry of the cell [26, 27].

The charging and discharging currents and C-rates are usually defined by the manufacturer in the data sheet of the cell.

Table 3: Sample readings of charging current and cell voltage recorded while charging a 2600-mAh 18650 lithium-ion cell using a TP4056

| Voltage (V) | Charging current (A) |
|------------|----------------------|
| 2.6        | 0.70                 |
| 2.8        | 0.78                 |
| 3.0        | 0.90                 |
| 3.2        | 0.91                 |
| 3.4        | 0.92                 |
| 3.6        | 0.88                 |
| 3.8        | 0.83                 |
| 4.0        | 0.68                 |
| 4.2        | 0.00                 |

Fig. 7: Block diagram of the in which an Arduino Mega is interfaced with a current sensor (ACS712), temperature sensor (LM-35) and organic light-emitting diode screen. The discharging apparatus includes resistors of various resistances and the charging apparatus includes a TP4056. All of the sensors are connected to a 18650 cell to measure the temperature and current, while the voltage is measured using an analogue-to-digital converter (ADC). The ADC is an internal feature of the microcontroller that can be used to measure voltages below the input voltage of the microcontroller, which in this case is 5 V. The Arduino is powered using a laptop through a USB cable.
5.3 Voltage factor

Voltages in lithium-ion cells correspond to the state of the charge of the cell. Voltages of <2.5 V in a lithium-ion cell increase the probability of the cell being dead. Hence, they should never be discharged to <2.5 V and charged to >4.2 V. Exceeding these limits might lead to overcharging and an inevitable thermal breakdown [10].

Exceeding the limits of the above-discussed parameters may lead to overcharging, overvoltage or rapid degradation of the cell. It might also lead to thermal breakdown or death of the cell. In order to prevent the cell from exceeding the limits, a continuous monitoring solution is required.

6 Prototype

6.1 Principle

A temperature sensor (LM-35) and a current sensor (ACS712) were interfaced with an Arduino Mega. An organic light-emitting diode (OLED) screen was also interfaced, to display the real-time readings of current, voltage and temperature. An ADC (analogue-to-digital controller) was used to measure the voltage; since the input voltage of the Arduino is 5 V, it can easily measure the voltage of a single 18650 cell (Figs 7 and 8).

The Arduino was programmed to show the respective warning when either the voltage, current or temperature exceeded the decided limits, which are defined in Table 4.

6.2 Results

The cell was again charged and discharged (using different load resistances) using the method explained in Section 4. Whenever any warning was displayed on the OLED screen, the voltage, current and temperature readings were noted and compiled into Table 5.

6.3 Results discussion

As discussed in the previous sections, it is important to monitor the parameters such as temperature, current and voltage to enhance the life and performance of lithium-ion cells. Initially, the cell was discharged and charged without any monitoring apparatus, which might result in overcharging, over/under voltage or high/low temperature. These extreme conditions are usually responsible for thermal breakdown and the ageing of the cell.

Hence, monitoring apparatus developed using an Arduino Mega board and some sensors was able to...
monitor the real-time readings as well as show warnings whenever any limit of temperature, voltage or current was violated. This mechanism helps in detecting anomalies in the early stage as well as making the user aware whenever the cell is not operating under optimal conditions.

Results from Table 5 show that whenever the current exceeds the 900-mA mark, the voltage exceeds the 4-V mark or the temperature is >35°C or <25°C, the respective warning is flashed on the OLED screen interfaced with the Arduino.

7 Conclusion

Lithium-ion cells have found their application in various industries because of their high energy density and 99% efficiency. But if they are not operated within an optimal operating range that is determined by parameters such as temperature, charging-discharging current and voltage, they are bound to fail and age quickly, and this may even lead to thermal breakdown.

Therefore, it is important to monitor these parameters and whenever the cell exceeds the prescribed limits, a warning should be generated. This problem is solved using the prototype that monitors current using an ACS712 current sensor, temperature using an LM-35 sensor and voltage using the inbuilt ADC of the Arduino. All of the warnings are shown on an OLED screen, as well as the real-time readings from external sensors.

A microcontroller as basic as an Arduino is capable of monitoring lithium-ion cells with a few enhancements and can provide a real-time solution that is required for extracting energy from lithium-ion cells efficiently and safely (Fig. 9).

Conflict of interest statement

None declared.

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