Internal resistance measurements of Li-ion batteries using AC methods

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Abstract. The internal resistance of Li-ion cells is a quantity for determining the performance such as energy efficiency and state of health (SoH). To combine Li-ion cells as a battery for the solar cell industry as well as electric vehicle (EV), the internal resistance of each cell needs to be consistent otherwise the lifetime will be shortened. However, the internal resistance of Li-ion cells depends on variables such as operating temperature and state of charge (SoC). In this work, we carried out the internal resistance measurements of individual Li-ion cells based on AC methods. According to an equivalent circuit of Li-ion battery, the measurement frequency was varied to study the effects of influence quantities such as the battery’s capacitance and inductance. Two AC methods were compared and discussed for the internal resistance values of Li-ion cells.

1. Introduction
In an electric vehicle (EV), the Li-ion battery plays a vital role to provide the source of driving power. Normally, the cost of battery accounts for about half of the EV’s price. Inspection of the quality of batteries is therefore crucial in the EV [1] as well as the solar cell industry [2]. To combine Li-ion cells as a battery, the internal resistance of the Li-ion cells needs to be consistent to provide the maximum efficiency and state of health (SoH) [3-4]. The internal resistance of the battery can be measured by several methods [5-6]. The AC method in comparison with the DC method has several advantages such as online measurement, avoiding the accumulated damage and reducing the costs [7].

Some equivalent circuits have been introduced to describe the characteristics of the Li-ion battery such as the Rint model, the RC model and the Thevenin model [8-9]. In this work, we use an RLC model to simulate the influence of capacitance and inductance on the internal resistance measurement by two AC methods of the Li-ion cells.

2. Experiments
A battery is considered to be a voltage source because they are used to store and deliver energy with a fixed voltage across it. However, the battery is not an ideal voltage source because of some internal resistance and reactance. Figure 1 shows an RLC equivalent circuit of the battery where \( V_{oc} \) stands for open-circuit voltage of the battery and \( V_t \) for the terminal voltage of the battery. The internal resistance of the battery consists of the ohmic resistance (\( R_s \)) and polarized resistance (\( R_p \)). The reactance components include inductance (\( L \)) and polarized capacitance (\( C_p \)).
If the frequency of the AC signal injected into the battery is $\omega$, the internal impedance of the battery according to the RLC equivalent circuit is

$$
\begin{align*}
\zeta &= R_s + \frac{R_p}{\omega^2 C_p^2 R_p^2 + 1} j \left( \frac{\omega^2 C_p R_p^2}{\omega^2 C_p^2 R_p^2 + 1} - \omega L \right)
\end{align*}
$$

(1)

\[ \text{Figure 1. An RLC equivalent circuit of battery.} \]

At low frequency, the impedance deduces to an internal resistance as

$$
\begin{align*}
r &= R_s + R_p
\end{align*}
$$

(2)

In general, we can calculate the internal impedance as an example shown in figure 2. We assume the values of the quantities in the RLC model as $R_s = 0.05 \, \Omega$, $R_p = 0.05 \, \Omega$, $C_p = 1 \, \text{nF}$ and $L = 1 \, \text{nH}$. The magnitude of $\zeta$ is calculated by

$$
|\zeta| = \left( \left( R_s + \frac{R_p}{\omega^2 C_p^2 R_p^2 + 1} \right)^2 + \left( \frac{\omega^2 C_p R_p^2}{\omega^2 C_p^2 R_p^2 + 1} - \omega L \right)^2 \right)^{1/2}
$$

(3)

The calculated results show the total magnitude value of $\zeta$ with the real and imaginary components of the impedance where $\omega = 2\pi f$ and $f_0 = 1 \, \text{Hz}$. The value of $r$ is almost constant up to the frequency of 10 kHz before diverging due to the imaginary part of $\zeta$ that influencing the magnitude value of $\zeta$ beyond 1 kHz.

\[ \text{Figure 2. A calculation of the magnitude value of } \zeta \text{ with the real and imaginary components.} \]
We carried out two AC methods to measure the internal resistance of 18650 Li-ion cells. The first method uses the AC voltmeter and AC ammeter to measure both AC voltage and current. The experimental setting is shown in figure 3(a). The excitation signal is generated by an AC current source. A capacitor with the value of 1000 \( \mu \text{F} \) is used to block the DC current of the battery to protect the AC current source. The AC current is

\[
i = i_{\text{max}} \sin(\omega t)
\]

and the AC voltage respond of the battery is

\[
v = v_{\text{max}} \sin(\omega t + \varphi)
\]

Hence, the impedance is

\[
z(\omega) = \frac{v_{\text{max}}}{i_{\text{max}}} e^{j\varphi}
\]

Then, the impedance modulus is

\[
|z(\omega)| = \frac{v_{\text{max}}}{i_{\text{max}}} = \frac{v_{\text{rms}}}{i_{\text{rms}}}
\]

The second method uses two AC voltmeters to measure the voltage of the Li-ion cell and the voltage of a resistance. The experimental setting is similar to the first method except changing the ammeter to another voltmeter measuring across the resistance as shown in figure 3(b).

The voltage across the resistance, \( R_c \), is

\[
v_1 = iR_c
\]

and the voltage across the Li-ion cell is

\[
v_2 = iz
\]

Hence, the impedance is

\[
z(\omega) = \frac{R_cv_2}{v_1}
\]

Then, the impedance modulus is

\[
|z(\omega)| = \frac{R_cv_{2\text{max}}}{v_{1\text{max}}} = \frac{R_cv_{2\text{rms}}}{v_{1\text{rms}}}
\]

Figure 3. The first (a) and second (b) methods to measure the impedance modulus of Li-ion batteries.

3. Results and discussion

The impedance of Li-ion battery samples was measured by the AC methods with frequencies ranging from 10 Hz to 150 kHz. The results of the first and second methods are shown in figure 4. The first method shows the modulus impedance of 37 m\( \Omega \) at 10 Hz and gradually decreases to the minimum value of 18.8 m\( \Omega \) at 1.8 kHz and exponentially increases to 200 m\( \Omega \) at 60 kHz before diverging. The second method shows the modulus impedance of 28 m\( \Omega \) at 10 Hz and gradually decreases to 5 m\( \Omega \) at about 150 kHz. The modulus impedance of the two AC methods was closest at 1.5 kHz with the value of about 19 m\( \Omega \). The different results between the two methods could be influenced by the ohmic contact
and the parasitic reactance of $R_c$. For the first method, the RLC model describes quite well for the modulus impedance by assuming $R_s = 10 \, \text{m} \Omega$, $R_p = 10 \, \text{m} \Omega$, $C_p = 1 \, \mu \text{F}$ and $L = 1 \, \mu \text{H}$. However, for the frequency ranging from 1 kHz to 2 kHz, both methods can be used to measure the internal resistance with the minimum influence of the battery’s reactance. For convenience, it is practical to select a measurement frequency such as 1 kHz for the internal resistance measurement of Li-ion batteries by AC methods.

![Figure 4](image.png)

**Figure 4.** Impedance modulus of Li-ion cells measured by two AC methods.

### 4. Conclusion

We measured the modulus impedance of Li-ion cells using two AC methods. The first method uses both voltmeter and ammeter to measure AC voltage and current while the second method uses two voltimeters to measure AC voltage across the resistant and the Li-ion cell respectively. The frequency of the AC source is ranging from 10 Hz to 150 kHz. The modulus impedance measured by the two AC methods were different due to ohmic contact resistance as well as parasitic reactance. However, at the frequency ranging from 1 kHz to 2 kHz, both methods can be used to measure the internal resistance of Li-ion batteries consistency.

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