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A measurement method for determination of dc internal resistance of batteries and supercapacitors

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ABSTRACT

Internal resistance is an importance parameter determining the power performance of a battery or supercapacitor. An 8.5 Ah Li-ion battery and a 350 F supercapacitor were tested as examples to validate the measurement method of dc internal resistance. Voltage data were taken at 10 ms, 2 s and 30 s after the current interruption or pulse. The ac resistances at 1 kHz of the battery and supercapacitor were also measured for comparison with the dc values. Based on these tests, it is proposed that the dc internal resistance of the battery and supercapacitor be obtained from $\Delta V/\Delta I$ where the ΔV is the voltage change after the current interruption, and ΔI means current change from I to 0. When the voltage change at 10 ms or less is selected, the resistance corresponds to the Ohmic resistance of the device.

1. Introduction

Internal resistance of an energy storage device, either a battery or a supercapacitor, is an importance parameter that determines their power performance. For commercial products, the manufacturers usually provide two types of internal resistance, i.e. dc internal resistance and ac internal resistance. For ac resistance, typically the parameter is measured at 1 kHz frequency, namely Rs at 1 kHz. For dc resistance, there has been no standard regarding the method of measurement. In the battery test manual of USABC 1996, appendix I [1], the internal resistance of the battery is measured by $R = (V_2 - V_1)/(I_2 - I_1)$, where the V_2 is measured at 30 s after a pulse current (from I_1 to I_2) is provided, and V_1 is the voltage before current pulse. This method of determination of dc resistance has been adopted by some battery manufacturers, and it has been widely regarded as "the" standard of dc resistance measurement.

For a battery or supercapacitor, the internal resistance is dependent on many factors, such as conductivity of electrolyte, electrode material, and current collectors, as it was also discussed in literature [2,3]. The Ohmic internal resistance should be distinguished from the influence of electrode processes, such as voltage changes due to electrochemical double layer charge/discharge and faradaic reactions (polarization in the battery) [4–7]. Ideally internal resistance should be measured by instantaneous voltage change after a current pulse or interruption. However when it comes to practical measurements, time resolution regarding to how the dc resistance from iR drop is determined has become an issue.

In this work, we propose a realistic measurement approach to determine the dc resistance of batteries and supercapacitors. Two storage device samples, an 8.5 Ah capacity Li-ion battery and a 350 F supercapacitor, were tested to illustrate the validity and effectiveness of the proposed method. Two measurement methods of current interruption or pulse were performed, i.e. $I \to 0$ and $0 \to I$, and the cell voltage changes were measured at 10 ms intervals. The dc resistance was calculated from the voltage change over the value of current I. It is suggested that the dc resistance be determined from a current interruption method, i.e. $I \to 0$, and the voltage change be taken at short times after the current interruption.

2. Experimental

The dc resistance tests were performed on an 8.5 Ah capacity $LiFePO_4$/graphite Li-ion battery (from Headway, China) and a 350 F commercial carbon/carbon supercapacitor (from Maxwell USA). The battery and supercapacitor are first charged to 100% SOC (state of charge). In $I \to 0$ tests, the cells are charged or discharged at selected currents for 2 s from the open circuit voltage. The charge or discharge current is then set to zero instantaneously.

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In the $0 \rightarrow I$ tests, the cells are rested for 2 s at open circuit voltage, then a charge or discharge current pulse at a selected current is applied. The voltages after the current interruption or pulse are measured at 10 ms intervals for 30 s. Internal resistance is calculated from

$$Rs = (V_2 - V_1)/(I_2 - I_1) \quad (1)$$

where V_1 is the voltage before the current change ($I \rightarrow 0$ as interruption or $0 \rightarrow I$ as pulse), V_2 is the voltage taken at 10 ms or 2 s or 30 s after the current change. I_1 and I_2 are the current values before and after the current change, either interruption or pulse.

The equipment for the testing was a Maccor Series 4000 battery tester. The ac impedance tests were performed using a Zahner IM6ex electrochemical workstation. The Maccor tester is capable of 10 ms sampling rate, which is the fastest data acquisition rate available with reliability.

3. Results and discussion

In the test procedure of electric vehicle battery test procedure manual [1], the internal resistance measurement method is discussed in appendix I, where a 'dynamic' resistance determined from a measurement of $\Delta V/\Delta I$ between a base current and a high current step. The changes in voltage and current are measured from a point in time just before the beginning of a 30 s current pulse to a point near the end of the 30 s pulse. The resulting resistance value is calculated from $R = \Delta V/\Delta I = (V_1 - V_2)/(I_1 - I_2)$. However this method of measuring voltage change at 30 s will over-estimate the value of internal resistance for most applications, since in the 30 s response time the voltage change will include contributions from double layer charge or discharge and faradaic electrode reactions.

3.1. Batteries

In Fig. 1a, the battery is first charged at 0.5C and 1C rates for 2 s, and followed by current interruption to 0 A, or $I \rightarrow 0$. The discharge test is shown in Fig. 1b. In each case, the cell voltage response is recorded for 30 s after the current interruption at 10 ms intervals, which is the data acquisition limit of the equipment. The dc internal resistances for the current interruption tests are calculated from $(V_2 - V_1)/(I_2 - I_1)$ with V_2 taken at 10 ms, 2 s and 30 s. The results are shown in Table 1, where it is seen that there are significant differences of Rs from V_2 at 10 ms, 2 s and 30 s. At 0.5C charge rate, the Rs (10 ms) = 7.5 mΩ, Rs (2 s) = 9.8 mΩ, and Rs (30 s) = 10.8 mΩ. At higher 1C charge rate, the Rs values at corresponding times are similar to those measured at 0.5C rate. The internal resistance inferred from the measurement of voltage at 30 s is 44% higher than that from 10 ms, and the resistance at 2 s is 31% higher than at 10 ms. The ac resistance is lower than the dc resistance for all cases, which is possibly due to the short time response of ac measurement at 1 kHz or 1 ms time frame. The dc internal resistance at 10 ms is primarily the Ohmic resistance. The resistance at 2 s includes some effects of concentration gradients (diffusion) and faradaic reactions in the battery.

Fig. 1c shows the response of the battery cell to 30 s charge and discharge pulses ($0 \rightarrow I$). The dc resistances were calculated accordingly and shown in Table 1. The Rs values at 10 ms for the $0 \rightarrow I$ case are close to those obtained by current interruption method $I \rightarrow 0$. However, it is apparent that in the long time domain especially taking V_2 at 30 s, the Rs is significantly higher from the $0 \rightarrow I$ test than from the $I \rightarrow 0$ test. This is due to the involvement of electrochemical reactions at electrodes when charge or discharging current is applied over the long time periods, which leads to an over-estimation of the dc internal resistance. Note from Table 1 that the pulse and current interruption methods yield close to the same resistance values for 10 ms and 2 s.

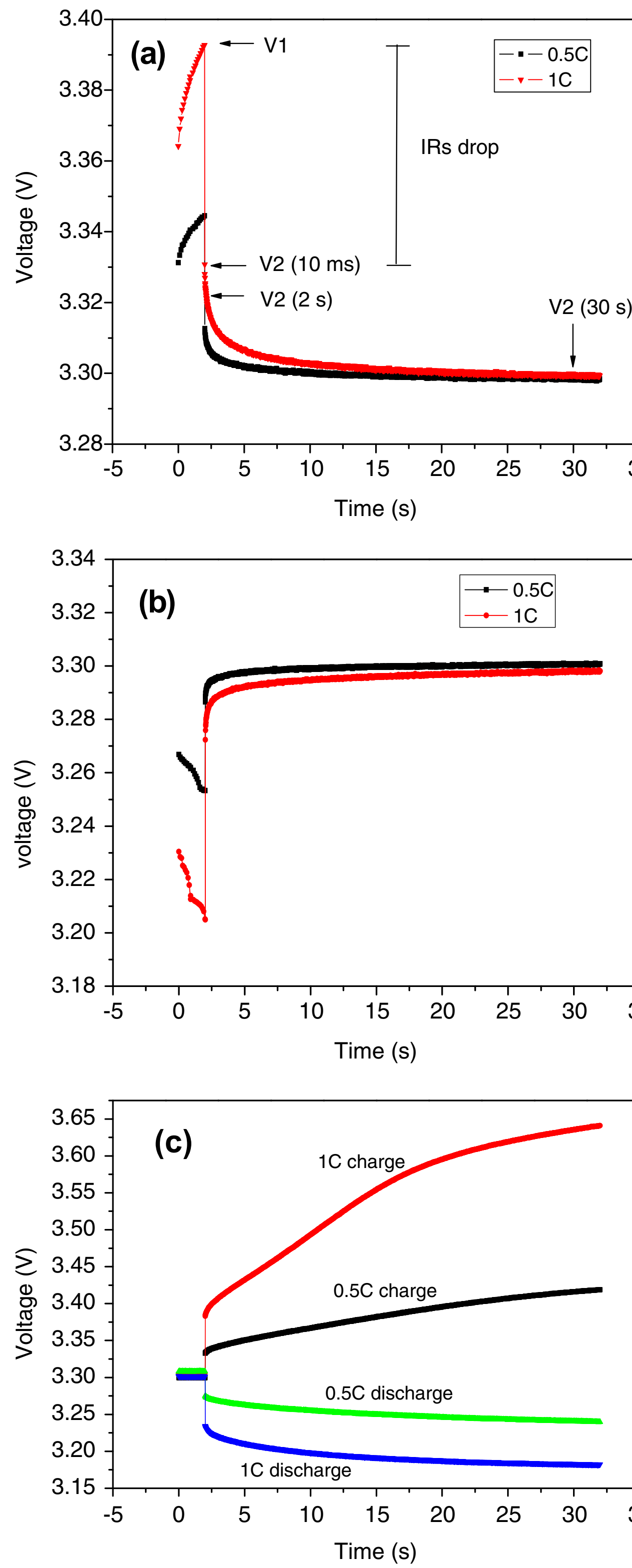

Fig. 1. Voltage time response of an 8.5 Ah $LiFePO_4$/GC Li-ion battery. (a) The battery was first charged at 0.5C (I_1 = 4.25 A) and 1C (I_1 = 8.5 A) for 2 s, and followed by current interruption to I_2 = 0 A, rested for 30 s. (b) The battery was first discharged at 0.5C (I_1 = 4.25A) and 1C (I_1 = 8.5A) for 2 s, and followed by current interruption to I_2 = 0 A, rested for 30 s. (c) The battery was rested for 2 s (I_1 = 0 A), then a discharge or charge current pulse of 0.5C (I_2 = 4.25 A) and 1C (I_2 = 8.5 A) was supplied for 30 s. Data acquisition was taken at 10 ms interval.