Using Rapid Impedance Measurements for Cell Screening and Qualification

Jon P. Christophersen
Dynexus Technology
Troy, ID 83871, USA
jon.christophersen@dynexustech.com / 1-208-521-2537

Abstract

The inline Rapid Impedance Spectroscopy (iRIS) system enables multispectral AC impedance measurements during a battery screening and qualification process. A set of single-cell packs were screened using standard metrics such as voltage, capacity, pulse resistance, and self-discharge. From the batch of qualified cells, 120 packs were subjected to 5-s iRIS measurements. The captured impedance spectra revealed two distinct groups, with 20 packs having a smaller mid-frequency semicircle compared to the rest. An aging study is presently underway to evaluate pack degradation as a function of cycling. The first set of tests consists of mild abuse conditions (denting and dropping). The packs with smaller impedance spectra show higher capacities and lower pulse resistances through 860 cycles.

Keywords

Screening; qualification; rapid; impedance spectroscopy.

Introduction

Energy storage demand is continuing to increase for multiple industries, including consumer electronics, automotive, and telecommunications. As a result, several new gigafactories are being planned in the US and abroad [1]. However, increased battery utilization also comes with an increased risk of catastrophic failure during operation. A critical step towards mitigating field failures is cell screening and only qualifying the batteries that fall within specific acceptance criteria. Multiple screening tests can be conducted at several locations to ensure faulty cells are removed before integrating batteries into a field-deployed application. Initial screenings can be very extensive and require multiple hours or days to evaluate charge retention and/or discharge capacity. Other screening applications can also include safety considerations such as the battery response to abuse conditions [2]. Once the manufacturer ships cells to the battery assembler, they will likely be screened again (sometimes using extensive methods [2], other times with quick checks such as open-circuit voltage) to properly qualify cells and, where feasible, match them for module and/or pack assembly. The screening process must also be repeated when certifying batteries in second use applications.

Electrochemical impedance spectroscopy (EIS) provides unique insights into battery chemical, physical, and structural attributes as a function of time and use [3-4]. However, a standard EIS measurement can take minutes to hours depending on system settings, making it impractical as an in-situ sensor for rapid decision-making processes. Thus, inline EIS research has generally focused on single frequencies or a subset of targeted frequencies. The data acquired from the targeted frequencies have been used for various predictive applications such as safety/stability [5], and state-of-charge (SOC) or state-of-health (SOH) estimations [4].

Dynexus Technology has developed a fast EIS method known as inline Rapid Impedance Spectroscopy (iRIS) that can yield broadband measurements within seconds [6]. The iRIS system is also scalable so that it can be used to monitor battery characteristics from inception to recycling. High-voltage systems (50V and a 100+V prototype) have been developed for end-of-line assessment and/or battery second-use applications. High-resolution iRIS systems have been developed for battery cell assembly, screening, qualification, and matching applications.

A consumer electronics (CE) Fortune 500 company is presently evaluating an iRIS-based screening and qualification process for their batteries in collaboration with Dynexus. The batteries sent to Dynexus had been fully qualified for product use based on the specific CE company requirements and metrics. The first qualification stage was at the cell level. Screening tests at the manufacturer site included open circuit voltage (OCV), alternating current internal resistance (ACIR), a full discharge capacity, and a self-discharge test. The cells that met the acceptance criteria were sent to the pack assembler where battery management "gas gauges" were connected. The single-cell packs were then subjected to a second round of qualification testing using the same metrics plus an additional direct-current internal resistance (DCIR) measurement. The packs that met the acceptance criteria were sent to the CE customer for integration into their devices. Thus, extensive qualification testing was conducted over several hours at two different locations to ensure consistent, repeatable cells were delivered to the end user.

Dynexus received 120 fully qualified single-cell packs for iRIS screening. Upon receipt, each pack was subjected to a 5-s iRIS measurement using galvanostatic excitation at 470 mA_{RMS} with 14 frequencies over a range of 0.2 to 1638.4 Hz. The iRIS measurement was conducted through the gas gauge terminals (i.e., through the battery management electronics and not directly on the cell tabs). Figure 1 shows the impedance spectra for all 120 packs; the data have been normalized by the pack weight per the customer's request.

For this cell screening, lower frequencies were not considered to ensure rapid measurements (i.e., mass transport effects were not considered), but the mid-frequency semicircle was clearly defined. Results from the 5-s iRIS screen revealed two distinct groups of packs; 20 of the packs (shown in red) had a smaller mid-frequency semicircle compared to the other 100 packs (shown in blue).

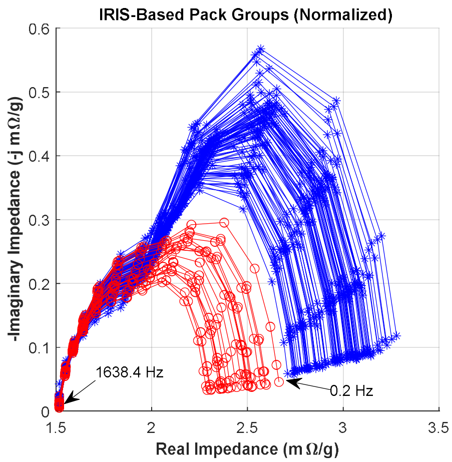

Figure 1. Screening results from 120 qualified packs.

Experimental

To determine the long-term effects of the observed differences in Figure 1 (i.e., how SOH is affected between the two groups), the packs have been assigned to an aging matrix. The full test matrix consists of standard cycle-life aging at 25, 55, and 5°C and some abuse conditions. The abuse conditions include high-temperature, high SOC calendar aging and some mild damage scenarios such as cell bending and dropping. The test conditions include packs from both groups. The first stage of aging at 25°C with packs damaged by bending and dropping is presently underway. There are 10 packs in each condition, three of which are from the smaller iRIS impedance group.

Characterization and reference testing consisted of a DCIR pulse every 10% SOC with 0.2C-rate discharges down to each 10% increment. IRIS measurements were then conducted at full discharge, 50% SOC, and full charge. For this aging study, a broader frequency range from 12.5 mHz to 1638.4 Hz was used (i.e., an 80-s measurement with 18 frequencies at 470 mA_{RMS}) to fully capture mass transport effects at lower frequencies.

Pack aging was initiated with eight discharge cycles at a 1C-rate, followed by two discharges at a 0.2 C-rate. The penultimate cycle was used to measure the discharge capacity; the final cycle included a DCIR pulse sequence every 10% SOC increment down to full discharge based on the measured capacity. Following these initial 10 cycles, the packs were removed from the thermal chamber and subjected to abuse. Ten packs were placed on an angled jig. When pressure was applied, the bottom portion of the pack was bent by the jig. The other ten packs were gently affixed to a piece of foam core and connected to vacuum cups at a 4-ft height. Once the suction was released, the packs were dropped, resulting in damage to the bottom right corner.

After damage, the packs were placed back in thermal chambers and reconnected to the tester for continued cycling at 25°C. Reference tests were conducted every 50 cycles. Within each cycle set, 48 discharges were at a 1C-rate, and the other two were at a 0.2C-rate. The final cycle included the DCIR pulse sequence as part of the reference test.

Results

Discharge Capacity: To date, the packs have completed 860 cycles. Figure 2 shows the discharge capacity for the packs subjected to bend damage normalized by the overall maximum measured capacity. The three packs with smaller mid-frequency semicircles are shown in red lines; they consistently have higher discharge capacities compared with the other seven packs. The same is generally true for the packs subjected to drop failure, as shown in Figure 3. These results suggest that the packs with smaller impedance spectra should have longer cycle-life capability.

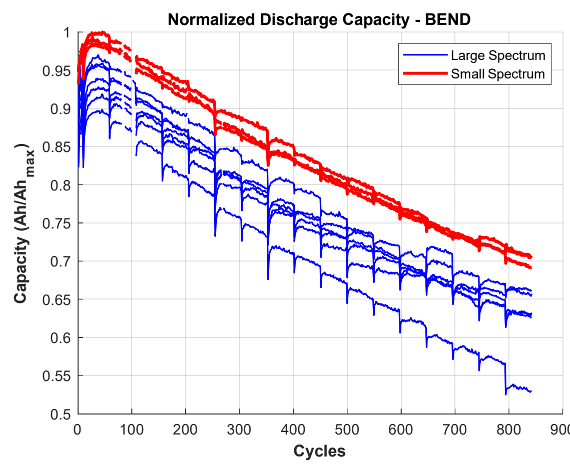

Figure 2. Discharge capacity for the BEND packs (1C rate).

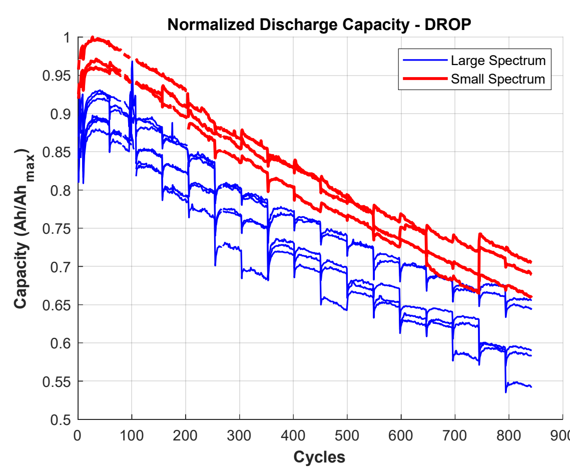

Figure 3. Discharge capacity for the DROP packs (1C rate).

The periodic drops observed in Figures 2 and 3 correspond with the reference tests every 50 cycles, in which the packs are subjected to a DCIR sequence and iRIS measurements. When cycling resumes at a 1C rate, the discharge capacity requires a few cycles to stabilize again. The packs with the smaller mid-frequency impedances generally have lower capacity drops at these intervals, indicating faster stabilization times.

DCIR Pulse Resistance: Every 50th cycle, the packs were subjected to a DCIR pulse test sequence at every 10% SOC condition. Figures 4 and 5 show the DCIR pulse resistance normalized by the overall minimum calculated resistance over 860 cycles at 100% SOC for the bend and drop packs, respectively. In all cases, the pulse resistance is lower for the packs that have smaller impedance spectra. This observation is true for each 10% SOC condition, but is the most pronounced at 100% SOC. These results suggest that the packs with smaller impedances have a better overall SOH condition as a function of age.

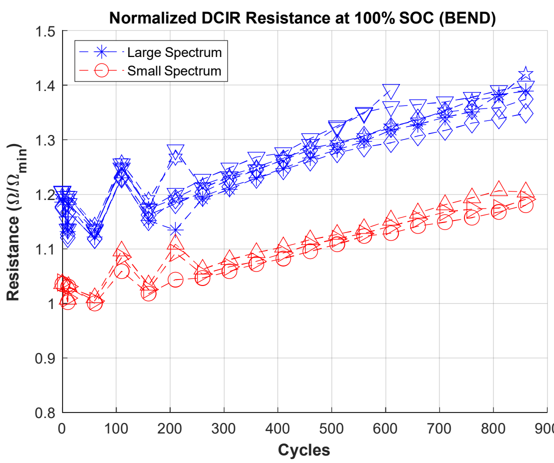

Figure 4. DCIR at 100% SOC for the BEND packs.

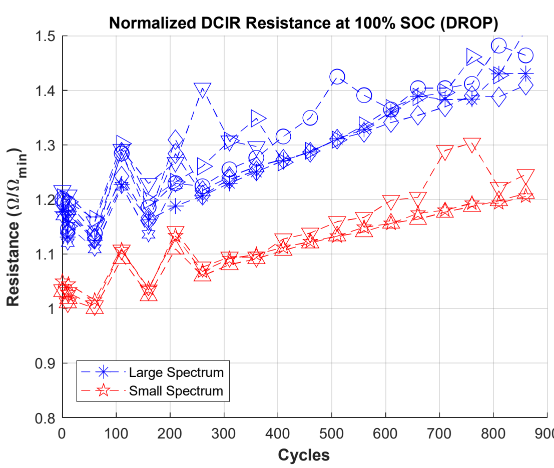

Figure 5. DCIR at 100% SOC for the DROP packs.

IRIS Measurements: As part of the reference test, iRIS measurements were also conducted at full discharge, 50% SOC, and full charge. Figure 6 shows representative impedance spectra (normalized by the pack weight) for a large and small charge transfer resistance group after 860 cycles for the bend packs (the spectra are similar for the drop packs as well). With an 80-s measurement, the impedance spectra now include a good representation of the low-frequency Warburg tail (on the right side of the spectrum). As shown, the observed differences between spectra from Figure 1 are still present out to 860 cycles.

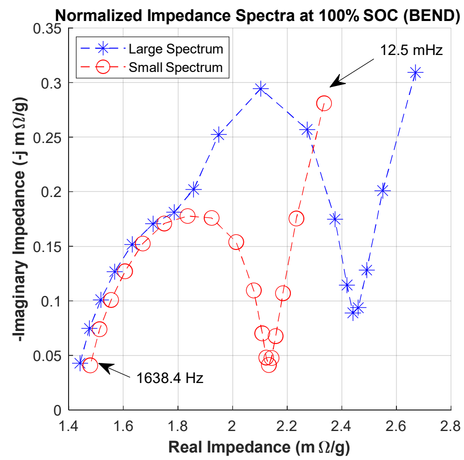

Figure 6. Representative impedance spectra after 860 cycles for the BEND packs.

The impedance spectra were modeled using the apparent equivalent circuit in Figure 7, which is based on a distribution of relaxation times (DRT) analysis [7]. It consists of an ohmic resistance (Ro) in series with an inductor and three parallel RC circuits representing the cell tabs and current collectors (R1), effects from the solid electrolyte interphase (SEI) with R2, and the charge transfer resistance (R3). Diffusion is modeled with a Warburg element (W). From the model fit, the growth in the mid-frequency semicircle is primarily dominated by R2 (i.e., SEI resistance growth). Figures 8 and 9 show the SEI resistance (normalized by the overall minimum resistance) for the bend and drop packs, respectively, over 860 cycles. As with the DCIR results, the smaller group (shown in red) consistently had lower overall SEI resistances during aging. These results also indicate a stronger SOH condition for these packs.

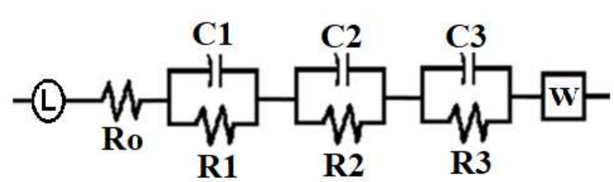

Figure 7. Equivalent circuit model for the packs.

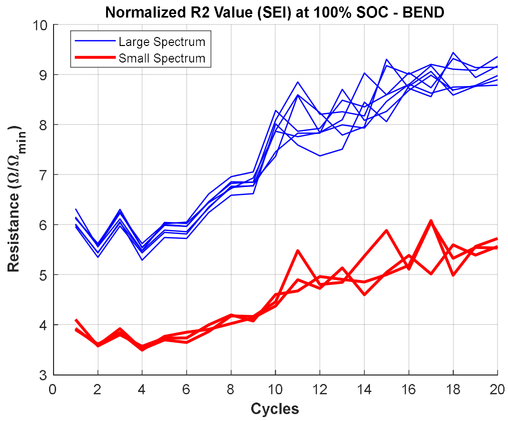

Figure 8. R2 value for BEND packs.

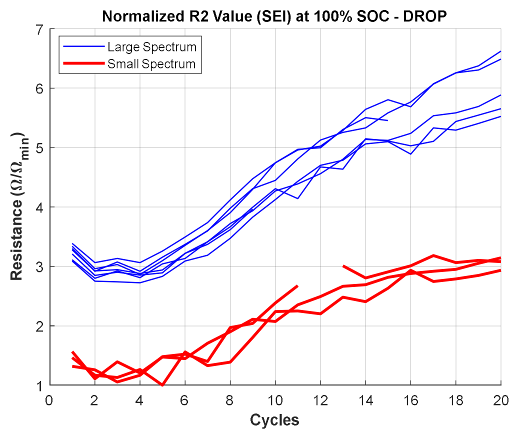

Figure 9. R2 value for DROP packs.

Discussion

The cells were manufactured in March 2021 and assembled into single-cell packs in April 2021. Within that initial month of battery life, the standard screening metrics (e.g., capacity and DCIR resistance) did not reveal any obvious difference between the packs. Pack cycling at Dynexus was initiated in October 2022 (i.e., a year and a half later, in which the packs were placed in cold storage). After this extended rest period, there was a clear distinction between the packs based on both capacity (Figures 2 and 3) and DCIR (Figures 4 and 5). However, calendar aging for an extensive period is not a practical solution for battery screening.

By way of contrast, the initial 5-s iRIS measurements were conducted at Dynexus in May 2021 (i.e., one month after the standard screening was completed). It immediately revealed a difference between pack groups which has remained through 860 cycles (see Figure 6). Additionally, equivalent circuit modeling of the impedance spectra can help provide some explanations for the differences. In this case, the packs with the lower mid-frequency semicircles primarily show lower resistances in the SEI layer (i.e., R2 in Figure 7), as demonstrated by Figures 8 and 9. Lower SEI resistances indicate reduced electrolyte consumption which can come from better cell construction in the manufacturing process and/or a more stable SEI development in the formation process. Thus, cell manufacturing quality control is critical for improved battery SOH and extended cycle-life capability. This study demonstrates that iRIS-based impedance measurements could be used as an effective screening tool for cell qualification.

Conclusion

A set of 120 consumer electronics single-cell packs were subjected to 5-s iRIS measurements to evaluate an alternative screening process. The batteries had been extensively screened and qualified using standard metrics such as discharge capacity and DCIR. These metrics did not reveal any obvious differences between the packs, but the iRIS measurements identified two distinct groups of packs; 20 had a smaller charge transfer resistance compared to the other 100. The packs have been assigned to a test matrix; mild abuse testing is presently under way. One set of packs was bent and the other was dropped from a 4-ft height. The packs having smaller impedance spectra generally show higher capacities and lower DCIR resistances through 860 cycles. These results indicate that the packs with smaller impedances may have extended cycle life, improved SOH, and better charge retention during extended calendar aging. Equivalent circuit modeling of the impedance spectra has indicated that the primary difference between the two pack groups is the resistance growth in the SEI layer, which is developed during the manufacturing and formation process. Cycle life aging for the mild abuse conditions will be completed soon, and then the groups cycling at different temperatures will be initiated for continued performance evaluation between the two groups of single-cell packs.

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