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Battery durability and reliability under electric utility grid operations: Representative usage aging and calendar aging

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ABSTRACT

Battery energy storage systems (BESS) are often viewed as solution to mitigate the intermittency of renewable energies in electric grids. However, battery degradation associated with grid-tied BESS usage has never been investigated in detail. This work was aimed at understanding the impact of a BESS representative usage profile on the degradation of commercial Li-ion cells. It was found that the cell temperature history had the strongest impact on battery degradation followed by the C-rate and the state of charge (SOC). Also, batteries lost capacity faster at low SOCs during calendar aging and under small SOC swings while cycling.

1. Introduction

With the Hawai'i Clean Energy Initiative [1], the state of Hawai'i is committed to reach 100% clear energy by 2045. A high penetration level of renewables, such as wind and solar, is necessary to reach that goal, but this shift in electricity generation scheme poses numerous challenges for grid operations. To mitigate these challenges, grid storage is necessary and battery energy storage systems (BESS) have been proven to be a promising solution [2–6]. Unfortunately, very few literature studies report detailed results on battery usage under grid utilization [7–11].

The Hawai'i Natural Energy Institute (HNEI), at the University of Hawai'i at Mānoa, has been assessing the benefits of grid-scale BESS for various ancillary service applications for the past five years [12]. Since the beginning of the program, HNEI has procured and installed three grid-scale (≥ 1 MW) fast-response BESS on Hawaii's island grids at both the transmission and distribution levels. The objective includes an assessment of the battery performance on the grid, an optimization of the BESS closed-loop control algorithms to maximize grid support while minimizing battery cycling, and laboratory testing of cells for a better understanding of cell aging and degradation.

In previous work [13], three years of battery usage were studied. Data was acquired from a 1 MW/250 kWh Li-ion titanate BESS designed to perform either frequency response or wind smoothing control schemes [12,14]. This data was used to assess the influence of several factors, such as C-rate, state of charge (SOC) swing range, and temperature on cell aging. This study aimed to understand cell aging patterns, reproduce real-life aging, and accelerate the degradation to enable end-of-life prognosis. In other words, the aim was to relate grid usage and laboratory testing of titanate batteries for the first time.

Due to the path dependency of battery degradation [15], it was only by reproducing the real-life aging that an accurate evaluation of BESS cell durability was obtained. To the best of our knowledge, the few studies on this particular topic [16,17] did not use a duty cycle representative of realistic usage. Moreover, although some modeling studies [18] proposed the hypothetical influence of some stress factors, no experimental validation was published. To gather experimental validation of the impact of several different factors, a thorough design of experiments was needed [19,20]. Such a methodology was proposed and successfully applied to battery testing [21–25].

In this work, the cell-to-cell variations [26–28] of two batches of Generation 1 Altairnano cells, similar to the ones that composed the BESS system, were analyzed to select cells for the cycle aging and the calendar aging experiments. The cycle aging experiment involved a computer-optimized custom design to determine the impact on cycle aging of several factors at the same time. The calendar aging experiment was designed to investigate the influence of the entire temperature and SOC ranges using a surface response methodology. The results from both experiments were analyzed with respect to the real usage data from the field.

2. Materials and methods

Fifty Altairnano Generation 1 $Li_4Ti_5O_{12}$ (LTO)//{$LiCoO_2$ (LCO) + $LiNi_xAl_yCo_{1\text{-}x\text{-}y}O_2$ (NCA)} pouch cells were purchased for this work. Thirty of them were 11 Ah cells, and the remaining 20 were

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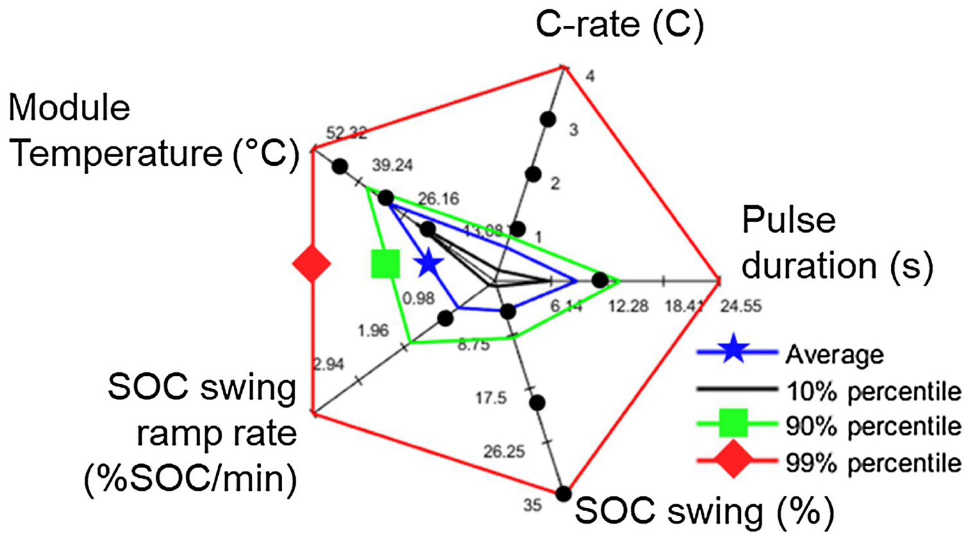

Fig. 1. Representative usage with selected data points (black circles).

50 Ah cells. They were designated ALT1S and ALT1L, respectively. The large cells, ALT1L, were the same cells in the BESS whose usage was reported in a previous work [13]. The BESS, rated at 1MW/250kWh, comprised 2688 ALT1L cells in a 384S7P topology meaning 384 modules, each containing 7 cells in parallel, were arranged in series.

The smaller ALT1S single cells had the same electrode chemistry and architecture as the ALT1L single cells but in a smaller form factor. According to the specification sheets, the performance and durability of both types of cells were similar.

Upon initial survey, the cells were weighed and their open circuit voltages (OCV) were recorded. One ALT1L 50 Ah cell was found to be leaking and was discarded. All non-leaking cells were subjected to a conditioning process using a series of C/2 discharge regimes to a 1.5 V cutoff, which was terminated when the capacity stabilized within ± 0.2% between two consecutive cycles. All cells were recharged according to manufacturer specifications using a constant current (CC) step at C/2 rate to the cut off voltage of 2.8 V. The capacity typically stabilized within three to six cycles.

After completion of the capacity stabilization process, the cells were subjected to the initial conditioning and characterization test (ICCT) [26] which consisted of two discharge regimes at C/5 and C/2. A 4-h rest between charge and discharge regimes was imposed to determine the cells' rest cell voltages (RCV) at the beginning of each regime. The polarization resistance of the cells was estimated from the IR drop induced by the C/2 discharge using Ohm's law; i.e., $\Delta V = R^*\Delta I$. The rate capability was estimated by dividing the C/2 capacity by the C/5 capacity. Following these tests, the cells were recharged to 50% SOC for storage at −27 °C in a freezer until the main experiments began.

Out of the cells that were deemed consistent using the parameters outlined in the Results section, 16 were selected for a cycling experiment and 8 for a calendar aging experiment. The specific duty cycles will be detailed in Section 3.2. The testing was interrupted to perform a reference performance test (RPT) every four weeks for the cycling experiment and every eight weeks for the calendar aging experiment. All RPTs were performed at 25 °C and consisted of C/25, C/5 and C/2 full cycles that included 4-h rests before and after residual capacity measurements at C/50. The resistance and the rate capability were calculated employing the same methods as in the ICCT utilizing the data from the C/25 and C/5 cycles. OCV curves were calculated by averaging the C/25 charge and discharges.

All tests were carried out on a calibrated 20-channel ARBIN LBT-5V-100A instrument (± 0.01 FSR accuracy on voltage and current) with 3D printed cell holders designed to minimize tab teardown. Prior to the testing, current and voltage were calibrated on all channels against a common reference (NIST-traceable Keithley 2700 source meter unit) to ensure consistency across the experiment.

The temperature chambers used in the experiment were the following:

- A Norlake Scientific LF201WWW/0 freezer for the −27 °C test,
- Amerex IC500-R chambers with ± 0.1 °C temperature accuracy and a microprocessor PID temperature controller for the 25 °C (calendar, RPTs for calendar aging experiments and cycling), 35 °C and 45 °C tests.
- An Espec BTZ475 chamber with ± 0.5 °C temperature accuracy and a microprocessor PID temperature controller for the 55 °C evaluation.

The Design of Experiment (DOE) implementations, as well as the statistical analysis, were executed using the Design Expert® 9 software, Stat-Ease Inc., USA.

3. Experimental

3.1. Definition of the design of experiment

From the analysis performed in a previous work [13], it was suggested that the representative BESS usage in the field could be described with five parameters: pulse duration, pulses C-rate, SOC swing range, SOC swing ramp rate, and temperature, Fig. 1(a). Indeed, the usage was shown to consist of "SOC events" where the SOC was mostly increasing, decreasing, or stable. These SOC events comprised a multitude of short pulses, both charge and discharge, that had a specific C-rate and duration. Depending on the pulses characteristics and distribution, the SOC events were shown to have different ΔSOC (SOC swing) and slope (SOC swing ramp rate).

In a controlled experiment methodology, to assess the effect of any parameter, it was important to test at least three values for each parameter, typically low/medium/high, and analyze the data for a bell-shape effect. When examining multiple parameters at once, it was also important to test every possible combination to identify any catalytic combined effects. To consider all these aspects, testing the impact of the five parameters would add up to 243 (3^5) experiments. Knowing that each experiment was scheduled to last more than six months and that only 22 channels were available, this study could not be completed in a manageable amount of time. To reduce the number of experiments to be performed, a computer-generated optimal custom design [19,20,29] was required. The design was generated by the Design Expert® 9

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