Exploring Secondary Uses of "Spent" King County Metro Batteries

Matthew D. Murbach and Daniel T. Schwartz (dts@uw.edu)
Clean Energy Institute, University of Washington, Seattle.

Background

Batteries are used in hybrid buses to assist in acceleration and capture energy from regenerative braking – both very high power applications. As the batteries are operated, they age, losing power and energy capacity until the on-board battery management system (BMS) triggers a flag to replace a particular module. This maintenance trigger is dictated by the time that the module spends below a cut-off voltage. Voltage dwell time is a simple proxy for the battery's power capability (*a.k.a.*, state-of-function, SoF) and energy capacity (*a.k.a.*, state-of-health, SoH). King County Metro (KCM) operates a large hybrid and electric bus fleet, including about 200 BAE Systems (HybriDrive) buses purchased in 2010.[1-3] Each HybriDrive bus contains approximately 12 kWh of battery storage in 16 modules. Each module contains a series of 12 submodules with eight 2.3 Ah $LiFePO_4$ cells from A123 Systems[4] in parallel. Approximately 60 modules/month become waste, per Cathy Johnson at KCM on 12/5/16.

Preliminary Capacity Testing

A complete teardown of a typical spent BAE module allowed the capacity of the 96 individual cells to be explored (Figure 1). While not enough modules have been analyzed cell-by-cell to draw statistical conclusions, our preliminary results indicate an interesting distribution of cell capacities in the module. First, the average cell capacity is 1.75 Ah or 76% SoH. This means that after the battery is removed from a hybrid bus, there is a significant amount of energy storage capability remaining. Secondly, the batteries at the top of the battery module show consistently higher capacity, which likely reflects a temperature gradient across the module. Lastly, there is a single highly degraded cell (#64); this bad cell likely caused the BMS to flag the module for maintenance.

Several other modules have been tested at the submodule-level (eliminating the time consuming tear-down) and they are consistent with Figure 1. We find an average submodule capacity of 77% SoH with an average standard deviation of 2.1% SoH amongst submodule groups.

Advanced Diagnostics

Measuring the capacity of a battery gives an accurate measure of the batteries state-of-health, but the measurement takes hours and does not indicate the remaining useable lifetime (RUL) of the cells A second-use battery with 77% capacity that is used in a new application and runs for years is great, but if it fails in weeks, that is problematic. More advanced diagnostics are important for getting at information that can predict RUL.

One widely utilized method of noninvasive diagnostics for batteries is electrochemical impedance spectroscopy (EIS). EIS is an alternating current technique which probes the underlying physical response of a system at different

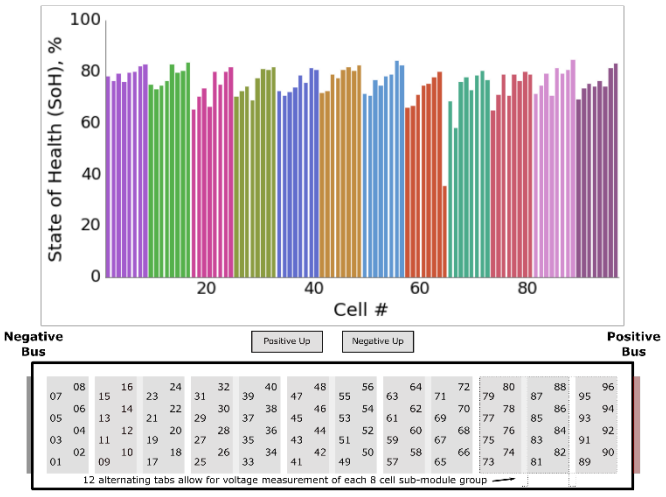

Figure 1. Measured individual capacities of a King County Metro battery module and the schematic showing the location of each cell.

frequencies in order to generate insight into the internal state of the system.[5,6] The two EIS spectra in Figure 2 clearly show the difference between a “good” and “bad” cell. Performance parameters can be extracted from these spectra, providing much more information about the battery state, including battery safety and indicators of remaining usable lifetime.

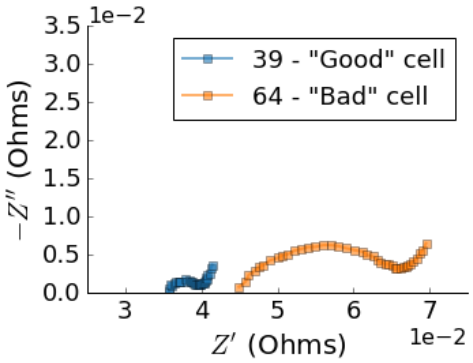

Figure 2. EIS spectra for cells 39 and 64. The distinction between a "good" and "bad" cell provides important information about SoF and SoH that can be used to predict remaining life. EIS measurements take about a minute, whereas each capacity measurement in Fig 1 takes hours.

Experimental Testing at Off-Grid ISP Twin Comm

In Autumn 2017, we designed a set of new battery management boards for an experimental 9.2 kW-h storage system using KCM spent batteries. The system has been operating at a test site provided by off-grid internet service provider Twin Comm. Twin Comm is an ideal partner, with good data connectivity for battery monitoring, and an owner that has worked closely with the UW team. The past year of cycling data is shown in Figure 3. In this second-use scenario, the pack saw about a 2% net degradation over the last calendar year of operation. Seasonal temperature variations (˚C) account for the seasonal performance changes seen in the data. This initial use case suggests spent Metro batteries have the potential to maintain their second-use capacity for many years, when coupled to the right application.

Looking Forward

We see great promise for second-use of waste KCM batteries in low power applications, with two key paths for partnering with the UW Clean Energy Institute to further develop applications of these batteries.

- Further battery testing of cells and sub-modules using advanced diagnostics to gain a statisitically-significant understanding of SoH, SoF, and use-case durability is desired. A deeper supply analysis is needed. This could enable commercial or KCM-related second-use applications (Chintan Pathak).
- A predictive SoH and SoF analytic framework to support cost effective KCM management of electric hybrid or all-electric buses, with the potential to minimize battery maintenance and maximize the value for second-use applications (Erica Eggleton)

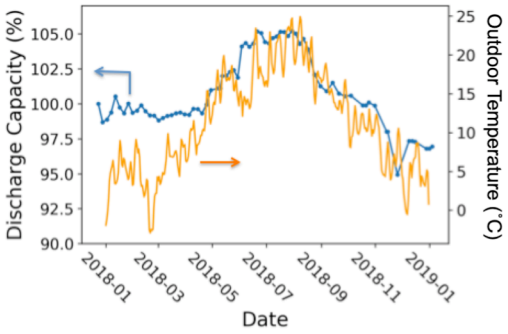

Figure 3. Capacity and temperature data for one year of experimental second-use battery operation at Twin Comm’s off-grid solar+storage ISP tower.

References

1. King County Metro, (2015) http://metro.kingcounty.gov/am/sustainability/pdf/sustainability-facts-081715.pdf.
2. A. Roman, *Metro Mag.* (2016) http://files.metro-magazine.com/pdfs/top1002016.pdf.
3. Canadian Public Transit Discussion Board, *CPTDB Wiki* https://cptdb.ca/wiki/index.php/King_County_Metro.
4. A123 Systems, https://www.buya123products.com/uploads/vipcase/844c1bd8bdd1190ebb364d572bc1e6e7.pdf.
5. E. Barsoukov and J. R. Macdonald, Eds., *Impedance spectroscopy: theory, experiment, and applications*, 2nd ed., p. 595, Wiley-Interscience, Hoboken, N.J, (2005).
6. M. E. Orazem and B. Tribollet, *Electrochemical impedance spectroscopy*, p. 523, Wiley, Hoboken, N.J, (2008).

.