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Lumped Parameter Modeling as a Predictive Tool for a Battery Status Monitor

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***Abstract*— The Advanced Technology Development Program is currently evaluating the performance of the second generation of lithium-ion cells (i.e., Gen 2 cells). Both the Gen 2 Baseline and Variant C cells are tested in accordance with the cell-specific test plan, and are removed at roughly equal power fade increments and sent for destructive diagnostic analysis. The diagnostic laboratories did not need all test cells for analysis, and returned five spare cells to the Idaho National Engineering and Environmental Laboratory (INEEL). INEEL used these cells for special pulse testing at various duty cycles, amplitudes, and durations to investigate the usefulness of the lumped parameter model as a predictive tool in a battery status monitor. The lumped parameter model is a simplified linear model that accurately predicts the voltage response during certain pulse conditions. A database of parameter trends should enable dynamic predictions of state-of-charge and state-of-health conditions during in-vehicle pulsing. This information could be used by the battery status monitor to provide accurate information to the vehicle control system.**

Keywords*— *Advanced Technology Development; lithium-ion batteries; lumped parameter model; battery status monitor

I. Introduction

The U.S. Department of Energy (DOE) initiated the Advanced Technology Development (ATD) Program in 1998 to address the outstanding barriers that limit the commercialization of high-power lithium-ion batteries, specifically for hybrid electrical vehicle applications. As part of the program, 18650-size cells are aged using calendar- and cycle-life tests developed under the Partnership for a New Generation of Vehicles (PNGV) Power Assist goals. [Note: PNGV was superceded by the formation of a new program between the U.S. Government and the U.S. Council for Automotive Research, dubbed FreedomCAR (Freedom Cooperative Automotive Research)]. Reference [1] provides additional information about the ATD Program.

II. Cell Chemistry and Testing

Testing of the second generation of ATD cells (referred to as Gen 2 cells) is performed in accordance with the *PNGV Battery Test Manual* [2] and the cell-specific test plan [3]. Quallion, LLC, manufactured the Gen 2 cells, which consist of a baseline cell chemistry and one variant chemistry (referred to as Variant C). The Baseline cells were built to the following specifications, as developed by Argonne National Laboratory [4]:

- **Positive Electrode:**
  - 84 wt% $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$
  - 4 wt% carbon black
  - 4 wt% SFG-6
  - 8 wt% PVDF binder
- **Negative Electrode:**
  - 92 wt% MAG-10
  - 8 wt% PVDF binder
- **Electrolyte:**
  - 1.2 M $LiPF_6$ in EC/EMC (3:7 wt%)
- **Separator:**
  - 25 μm thick PE Celgard

The Variant C cell chemistry is the same, except for an increased quantity of aluminum dopant, and a subsequent decrease to the cobalt dopant to the positive electrode (i.e., $LiNi_{0.8}Co_{0.1}Al_{0.1}O_2$). This was done to increase the cell structural integrity, thereby providing longer life and improved abuse tolerance. However, this also resulted in a 20% drop in rated capacity (0.8 Ah) at beginning of life (BOL) compared to the Baseline cell rated capacity of 1.0 Ah.

The Gen 2 cells were aged at various temperature (25, 35, 45, and 55°C) and state-of-charge (SOC) (60, 80, and 100% SOC) conditions. Reference [5] provides additional information on the Gen 2 test matrix and performance results. The Idaho National Engineering and Environmental

Laboratory (INEEL) cycle-life tested the Baseline and Variant C cells using the standard PNGV 25-Wh Power Assist cycle-life profile defined in [2] and shown in Figure 1. It consists of a constant power discharge and regen pulse with interspersed rest periods. The cumulative length of a single profile is 72 s and constitutes one cycle. For standard Gen 2 testing, the pulses were centered around 60% SOC and were repeated continuously during life testing.

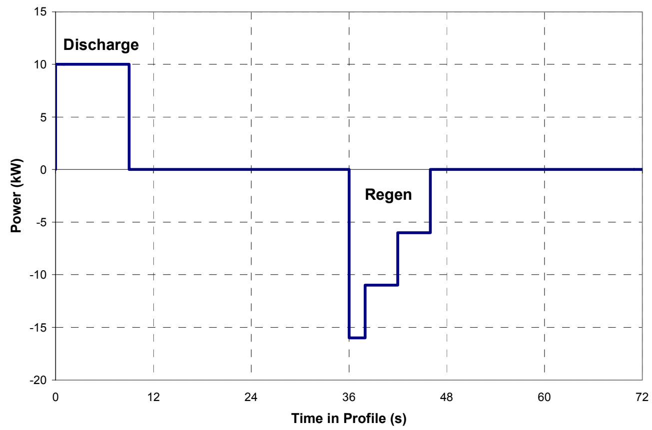

Figure 1. PNGV 25-Wh Power Assist cycle-life profile.

At BOL, and every 4 weeks thereafter (i.e., 33,600 cycles), life testing was interrupted for reference performance tests (RPTs) to quantify changes in capacity, resistance, and power. The low-current hybrid pulse power characterization (L-HPPC) test is regularly included as part of the RPTs. The test profile is defined in [2] and shown in Figure 2. It consists of a constant current 18-s discharge (normally at a 5C rate) and 10-s regen pulse with a 32-s rest in between, for a total duration of 60 s. The profile is repeated at every 10% depth-of-discharge (DOD)[1] increment, with a 1-h rest at open circuit voltage (OCV) at each DOD increment to ensure that the cells have reached electrochemical and thermal equilibria [2].

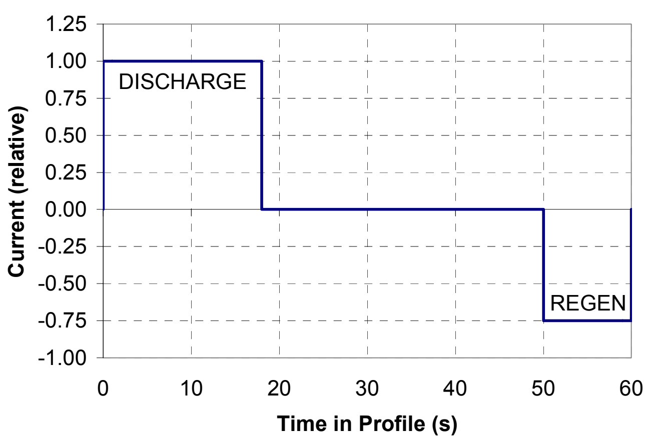

Figure 2. Hybrid pulse power characterization profile.

[1] DOD is based on capacity removed, whereas SOC is based on discharging to a specified OCV.

The BOL L-HPPC test is used to calculate a battery size factor (BSF), which is the minimum number of cells required to meet the PNGV goals at end of life (assuming a 30% power margin at BOL) [2]. All cycle-life test profiles and subsequent L-HPPC power and energy curves are scaled by the BSF for direct comparison with the PNGV goals. The standard measure of cell degradation is the percent-fade of the power at 300 Wh, normalized by the BOL power at 300 Wh.

The primary objective of ATD cell testing is to provide the diagnostic laboratories with cells that have been conditioned in a methodical way. The INEEL cycle-life cells were organized into groups of fifteen. Once cell from each group was sent to a diagnostic laboratory following the BOL RPT. The remaining fourteen cells were removed at roughly equal power fade increments such that the penultimate pair of cells are sent for destructive diagnostic analysis when the power fade reaches 30%. The last pair of cells will continue testing until the power fade reaches 50% [5].

III. LUMPED PARAMETER MODEL

The lumped parameter model (LPM) is a simplified linear battery model that can be used to predict the voltage response of a battery under certain pulse conditions (e.g., during a L-HPPC or cycle-life pulse). The LPM is based on the circuit diagram shown in Figure 3 [2]. The parameters (i.e., R_o, R_p, C, OCV, 1/OCV', and τ) are obtained through multivariable linear regression, where the load voltage (V_L) is the dependent variable; the load current (I_L), the integral of the load current [$\Sigma(I_L\Delta t)$], and the polarization current (I_p) are the independent variables. The load voltage and current (V_L and I_L) are the measured voltage and current response of the battery during a pulse. The ohmic resistance (R_o) is the result of electrical conductivity, and the polarization resistance (R_p) is controlled by mass transfer. The measured and estimated voltage responses during a L-HPPC and cycle-life pulse for a representative Baseline cell at 40% DOD and 60% SOC, respectively, are shown in Figures 4 and 5. These results show excellent fits, both with coefficients of determination (R^2) values of 0.9996.

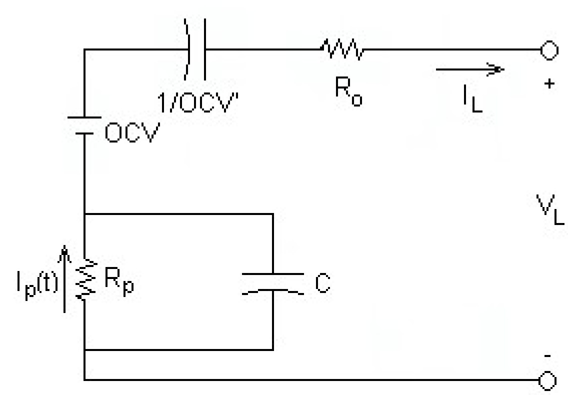

Figure 3. Lumped parameter model circuit.

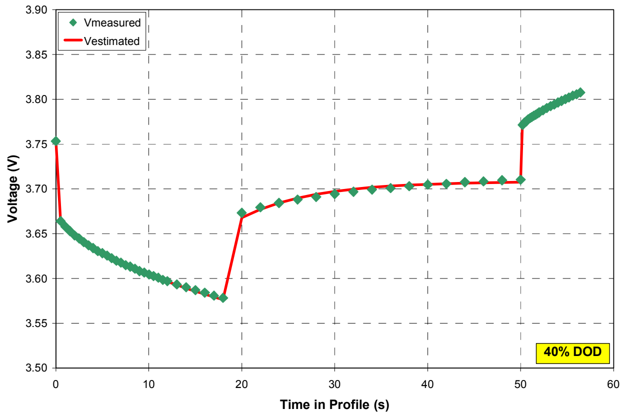

Figure 4. LPM voltage response estimation for a L-HPPC pulse.

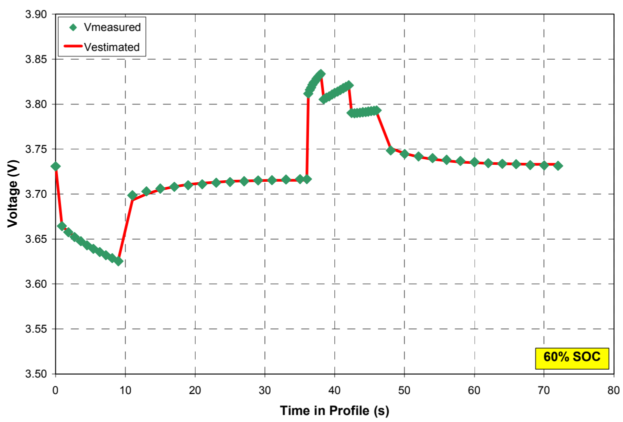

Figure 5. LPM voltage response estimation for a cycle-life pulse.

IV. Predictive Tool

INEEL is conducting special pulse testing on five ATD Gen 2 spare cells (two Baseline and three Variant C cells). These cells have already met the specified end-of-test criteria, but were not needed for destructive diagnostic analysis. One Baseline cell was tested for 16 weeks and showed a power fade of 17%; the other tested for 20 weeks, with a power fade of 20%. The three Variant C cells were tested for 8, 24, and 28 weeks, and showed power fades of 18, 25, and 27%, respectively.

The intent of this special pulse testing is to investigate the usefulness of the LPM as a predictive tool for an in-vehicle battery status monitor (BSM), and begin developing a database of parameter trends. The BSM is an instrumentation system that interfaces the battery with the vehicle control system in a hybrid electric vehicle. The primary objectives of the BSM are to provide SOC, state-of-health, available energy, available power, and warnings of impending failure. The LPM could be used to assess these features through regressing pulses performed during actual driving cycles, compare them to a database of known parameter trends, and dynamically predict battery performance capabilities.

Initial LPM validation testing on the 5 spare cells was performed at 45°C. Several 25-Wh Power Assist cycle-life profiles (Figure 1) were repeated at each 10% SOC increment with changes to the duty cycle, amplitude, or duration. INEEL has also began investigating the L-HPPC pulse profile (Figure 2) at each 10% DOD increment with changes in duration. Additional testing, including changes in duty cycle and amplitude on the L-HPPC pulse, as well as temperature-dependent trends, could not be performed since most of the spare cells reached end-of-life and were no longer able to maintain a control voltage.

A. *Duty Cycle*

The duty cycle of the cycle-life test profile was changed by adding more time to the 26-s rest period at the end of the regen pulses. Five cycle-life pulses were consecutively performed at each 10% SOC increment, with an additional 7.5, 30, and 60-min rest between each pulse. Figure 6 shows the resulting ohmic (solid lines) and polarization (dashed lines) resistances as a function of SOC. The ohmic resistances are consistently higher than the polarization resistances. Resistance increases at 90% SOC since the cells are generally voltage limited during the 9-s discharge pulse (i.e., the cells reached the minimum voltage before completing the discharge pulse). Both ohmic and polarization resistances show similar magnitudes at different duty cycles, but are slightly higher than the normal duty cycle pulsing. The small offset is primarily due to the longer rest interval between pulses, giving the cells more time to reach electrochemical equilibrium (as opposed to normal pulsing, which only has a 26-s rest prior to the next pulse). Therefore, the LPM results are very sensitive to the rest step immediately prior to the start of a pulse. Similar trends are observed for the Variant C cells.

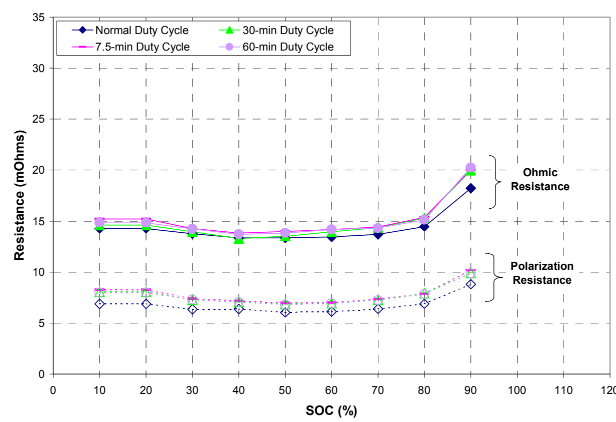

Figure 6. Baseline cell average cycle-life ohmic and polarization resistance with duty-cycle changes.

B. *Amplitude*

The cycle-life pulse amplitude is normally scaled by the BSF. For special pulse testing, the amplitude was additionally scaled in increments of 25% over a range of a quarter to double the normal amplitude. For each amplitude increment, ten cycle-life pulses were consecutively performed at every 10% SOC with a 1-h rest at OCV prior to each set of pulses.

Figure 7 shows the resulting average ohmic and polarization resistances at each amplitude increment for the Baseline cells. Although ten pulses were performed at each

SOC increment, the first pulse was not included in the average. The initial rest step immediately prior to the pulse was following a 1-h rest at OCV; the rest step prior to the other nine pulses was following the 26-s rest from the previous pulse (see above). The ohmic resistance generally increases with increasing amplitude. The two outliers (the half and normal amplitude pulses) show lower ohmic resistances due to test conditions. Figure 8 shows the average Baseline cell temperature during pulsing at each amplitude increment. As expected, cell temperature increases with increasing amplitude. However, the half and normal amplitude levels show temperature jumps, primarily attributable to a higher average chamber temperature during those particular tests. The double amplitude pulses also show some unusual behavior because the first 2-s regen pulse was improperly scaled to one and three-quarter amplitude. The polarization resistances follow the same trends as the ohmic resistances, but they are much closer together (except the normal, half, and double amplitude, as discussed above). Therefore, the LPM is also sensitive to temperature fluctuations during pulsing. The three spare Variant C cells also show similar results, but with a much smaller spread in the data. This is consistent with Variant C cell degradation behavior during standard Gen 2 testing [5].

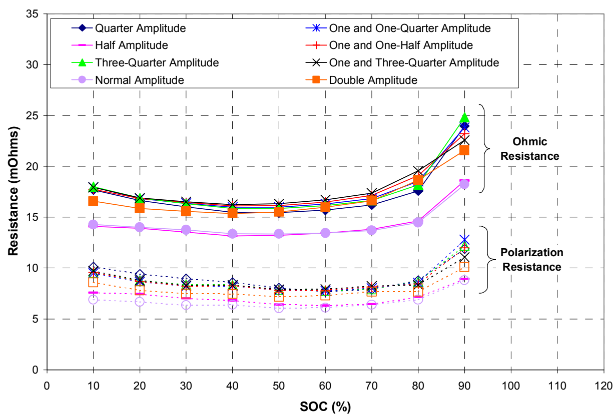

Figure 7. Baseline cell average cycle-life ohmic and polarization resistance with amplitude changes.

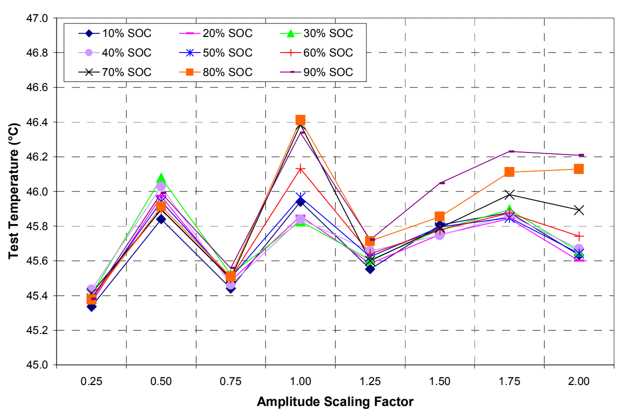

Figure 8. Average Baseline cell cycle-life temperature during amplitude changes.

C. *Duration*

The cycle-life pulse duration (normally 72-s) was also adjusted in increments of 25% over a range of a quarter to double the normal duration. Figure 9 shows the average ohmic and polarization resistances at each duration change for the Baseline cells. The magnitude of the resistances is similar to the changes in amplitude (Figure 7). As seen with amplitude adjustments, the ohmic and polarization resistances generally decrease with decreasing durations, with the same outliers (i.e., the half, normal, and double duration pulses were also affected by temperature fluctuations). A notable difference from the amplitude adjustments, however, is the increased spread in polarization resistance as a function of pulse duration. This is expected since the polarization resistance is controlled by mass transfer, which is time dependent. Similar results are also seen with the Variant C cells.

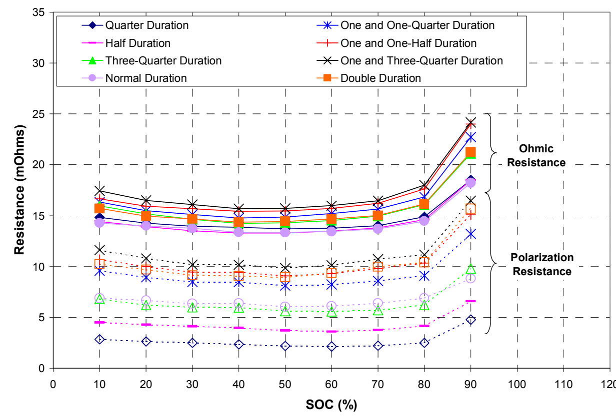

Figure 9. Baseline cell average cycle-life ohmic and polarization resistance with pulse duration changes.

Figure 10 shows the relationship between amplitude and duration adjustments (excluding the half, normal, and double pulses) for the Baseline (solid symbols) and Variant C (open symbols) cells. The ohmic and polarization resistances are shown in the diamond and square symbols, respectively. The Baseline cell ohmic impedance increases with both amplitude and duration. The Variant C cells, however, appear to decrease in ohmic resistance as pulse amplitude increases. But, the difference between the highest and lowest resistance (15.8 and 15.5 mΩ) is insignificant. The ohmic resistance, therefore, changes minimally as a function of amplitude and duration. The polarization resistance does not change much with amplitude adjustments, but changes significantly with pulse duration adjustments. This relationship is useful for a BSM in predicting optimal amplitude and duration pulses when queried by a vehicle control system.

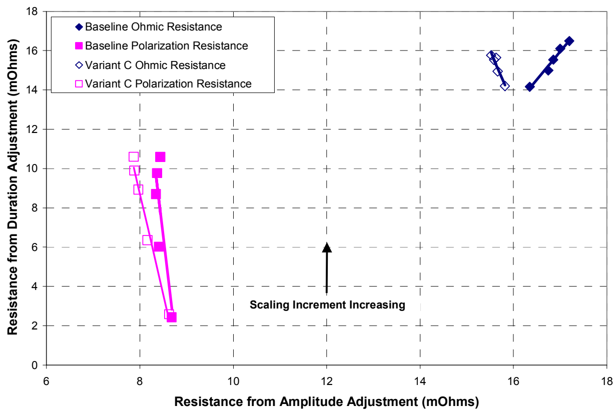

Figure 10. Relationship between amplitude and duration changes for the Baseline and Variant C cells.

Figure 11 shows the average ohmic and polarization resistances for the L-HPPC pulses (Figure 2) that were performed at half, normal, and double duration. The resistances are higher than the cycle-life results, but the trends are similar, with the ohmic resistance showing a very minor dependency whereas the polarization resistance is changing as a function of duration length.

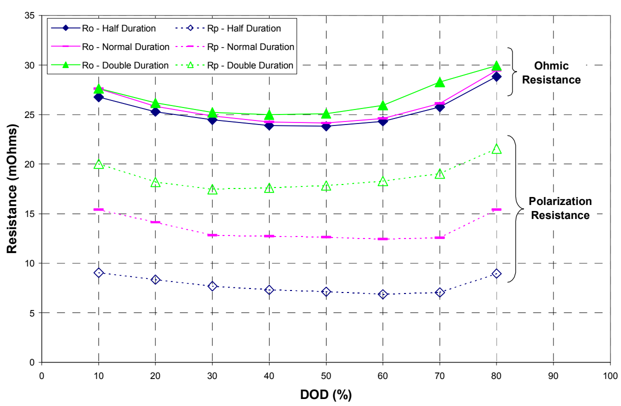

Figure 11. Baseline cell average L-HPPC ohmic and polarization resistance with pulse duration changes.

V. Conclusion

INEEL performed special pulse testing on five ATD Gen 2 spare cells to investigate the usefulness of the lumped parameter model as a predictive tool in a battery status monitor. The LPM is very sensitive to changes in duty cycle, amplitude, and pulse duration. Fluctuations in temperature will also affect parameter results. Multiple tests are still required to establish a reliable database of parameter trends that incorporates sensitivities to temperature, SOC, and pulse characteristics. However, from the data already collected, it appears that the LPM will be useful in accurately predicting state-of-charge, state-of-health, and pulse power behavior of a battery based on pulses observed during in-vehicle use.

VI. Acronyms and Abbreviations

The following acronyms and abbreviations were used in this paper:

ATD	Advanced Technology Development
BOL	beginning of life
BSF	battery size factor
BSM	battery status monitor
DOD	depth-of-discharge
DOE	Department of Energy
Freedom CAR	Freedom Cooperative Automotive Research
INEEL	Idaho National Engineering and Environmental Laboratory
L-HPPC	low-current hybrid pulse power characterization
LPM	lumped parameter model
OCV	open circuit voltage
PNGV	Partnership for a New Generation of Vehicles
RPT	reference performance test
SOC	state-of-charge

Acknowledgment

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