EVTC

Electric Vehicle Transportation Center

Electric Vehicle Battery Durability and Reliability Under Electric Utility Grid Operations

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EVTC Project 8 – Electric Vehicle Battery Durability and Reliability Under Electric Utility Grid Operations

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The objective of the Electric Vehicle Battery Durability and Reliability Under Electric Utility Grid Operations project was to determine the impact of electric vehicle use on battery life including charging cycles and vehicle-to-grid (V2G) applications. The work identified conditions that improve battery performance and durability with focus on providing battery data for system engineering, grid modeling and cost-benefit analysis. The work was conducted by Dr. Matthieu Dubarry, of the University of Hawaii under a subcontract from the University of Central Florida.

Final Research Project Report

Electric Vehicle Battery Durability and Reliability Under Electric Utility Grid Operations

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1.0 Abstract

Battery degradation is extremely important to EV technologies and is a function of several factors, such as electrode chemistries, operating temperatures, and usage profiles (i.e. vehicle-only vs. vehicle-to-grid (V2G) applications). The goal of this research was to assess such impact. Laboratory testing of commercial "18650" Li-ion cells was conducted in Hawaii Natural Energy Institute's Battery Testing Laboratory. The battery test plan used two separate experiments: a cycling experiment to assess the impact of both V2G and grid-to-vehicle (G2V) charging strategies and a calendar aging experiment to assess the impact of temperature and State of Charge (SOC). The results have shown an impact of V2G, temperature and SOC on the battery capacity loss and indicate that V2G use can double the capacity loss when performed twice daily.

2.0 Research Results

The research results are presented in three journal publications and four HNEI reports that have been completed and posted on the EVTC and HNEI websites. The research also resulted in the filing of a U.S Patent listed as number 8 below. The citations for the publications, reports and patent are as follows:

1. Dubarry, M., Truchot, C., Devie, A., Liaw, BY. "State-of-Charge Determination in Lithium-Ion Battery Packs Based on Two-Point Measurements in Life" Journal of Electromechanical Society, 162 (6) A877-A884 (2015).
2. Dubarry, M., (2015). Test Plan to Assess Electric Vehicle Cell Degradation under Electric Utility Grid Operations (HNEI Project No. HNEI-03-15). Honolulu, HI: Hawaii Natural Energy Institute, University of Hawaii at Manoa.
3. Dubarry, M. and Devie, A., (2015). Initial Conditioning Characterization Test and Other Preliminary Testing (HNEI Project No. HNEI-06-15). Honolulu, HI: Hawaii Natural Energy Institute, University of Hawaii at Manoa.
4. Dubarry, M. and Devie, A., (2016). Cell Emulation and Preliminary Results (HNEI Project No. HNEI-11-16). Honolulu, HI: Hawaii Natural Energy Institute, University of Hawaii at Manoa.
5. Dubarry, M. and Devie, A., (2016). Battery Cycling and Calendar Aging: Year One Testing Results (HNEI Project No. HNEI-12-16). Honolulu, HI: Hawaii Natural Energy Institute, University of Hawaii at Manoa.

6. Devie, A. and Dubarry, M. Durability and Reliability of Electric Vehicle Batteries under Electric Utility Grid Operations. Part 1: Cell-to-Cell Variations and Preliminary Testing, Batteries, 2016, 2(3), 28 doi:10.3390/batteries2030028.
7. Dubarry, M., Devie, A. and McKenzie, K., "Durability and Reliability of Electric Vehicle Batteries under Electric Utility Grid Operations: Bidirectional Charging Impact Analysis", Journal of Power Sources, 358 39-49, (2017).
8. Dubarry, M., Devie, A. "Methods and Apparatus for Updating a Fuel Gauge and Estimating State of Health of an Energy Storage Cell," US Publication 15/444.163 filed February 27, 2017.

A summary of the findings from the project follows.

A test plan was developed to optimize the battery cell testing to determine degradation, as measured by battery capacity loss, resistance increase and kinetic hindrance. Two synergistic experiments were used, cycling and calendar aging. A cycling experiment was conducted to assess the impact of both grid-to-vehicle (G2V) charging and vehicle-to-grid (V2G). A calendar aging experiment was used to separately assess the impact of temperature and State of Charge (SOC) on degradation.

Development of the test plan and methodology is covered in the reports listed above, with preliminary testing in reports 3 and 4. Journal publication 6 encompasses results from reports 3 and 4, and they are summarized below in Figure 1 and Figure 2. In this study, researchers tested a batch of 100 cells of commercial graphite/NCA cells in order to assess the quality of the cells before the start of the main experiment. The aim of this preliminary testing was to verify two critical requirements for the V2G and G2V impact study: (1) the use of cells with a low intrinsic variability; and (2) the ability to perform advanced diagnosis of these cells without the need for post mortem studies. It is essential to distinguish differences in intrinsic variability from degradation outcomes resulting from duty cycles. It is also critical to establish a systematic operando diagnosis method because the sheer volume of cells to analyze makes relying on postmortem techniques impractical.

In this study the developed methodology [1] was used to address the variations in maximum capacity, resistance and rate capability. See Figure 1(a). The researchers also introduced a new methodology to characterize the cell further and study the thermodynamic electrode matching variability. The cell-to-cell variation analysis revealed that the test cells were of high quality with similar thermodynamic properties as well as less than 0.5% variation in rate capability and capacity ration (maximum capacity/100), and less than 3% variation in resistance. Thus, the selected cells were found suited for long term studies of cells tested under a range of aging scenarios such as V2G and G2V. As a result, 36 cells were selected for the cycle aging experiment and 16 cells for the calendar aging experiment.

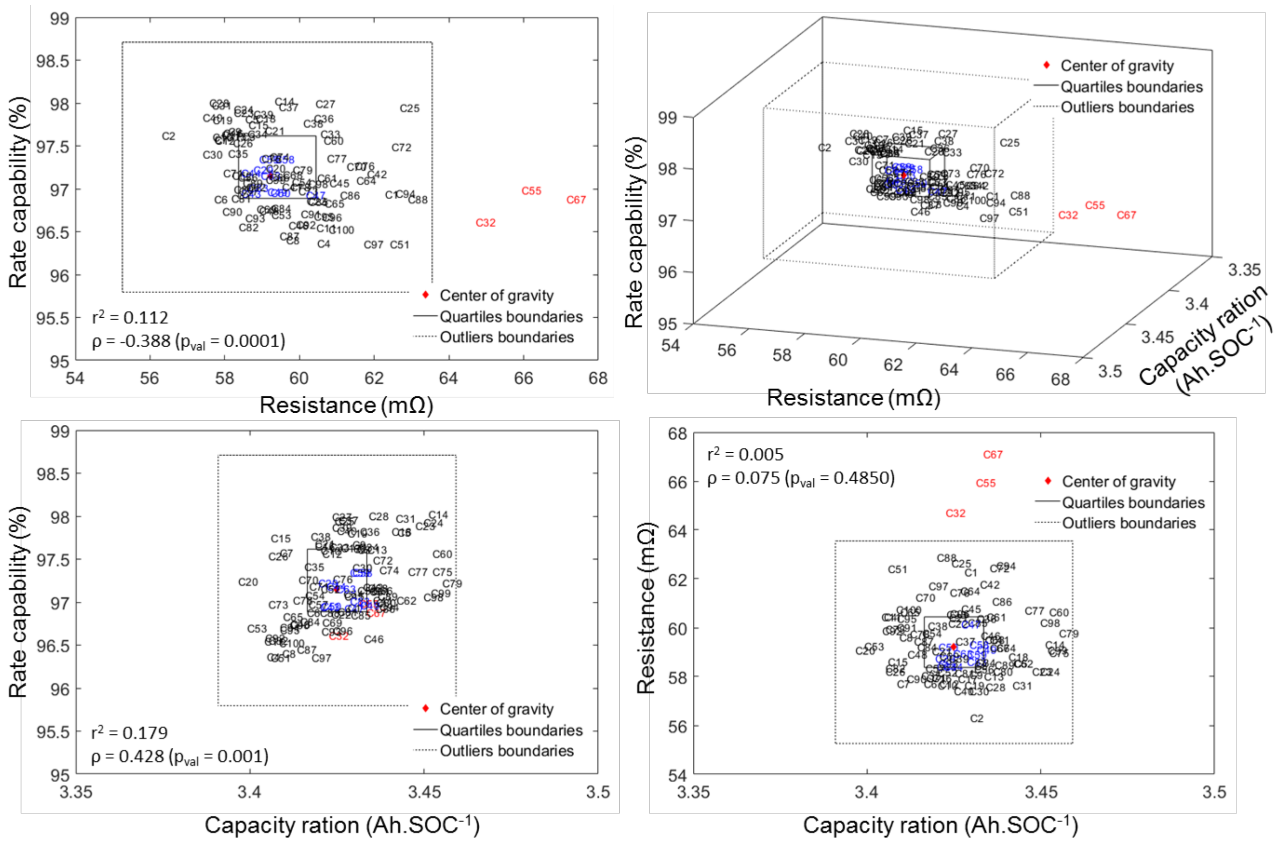

Figure 1: 3D map and top/side/front projections of the measured rate capability, capacity ration and ohmic resistance highlighting cell-to-cell variations

In order to accelerate the analysis of the degradation data and perform advanced diagnosis without resorting to post-mortem analysis, the recent developed methodology called the 'Alawa toolbox [2] was used. This emulation approach creates a virtual representation of the cell from its individual electrode data. The virtual cell can then be degraded at different degradation modes to highlight the changes in voltage response. In order to build the virtual cell, the diagnosis methodology requires harvesting the electrodes of a fresh cell to cycle them against a lithium reference/counter electrode. This harvesting and the subsequent testing and emulation were successful since the emulated cell is matching the experimental one (top left of Figure 2). Battery degradation can be summarized in seven degradation modes, the loss of lithium inventory, the loss of active material on the positive and negative electrodes, lithiated or not, and the kinetics of the positive and the negative electrode. The impact of the degradation modes is different enough to enable accurate diagnosis of cell degradation and permit comparison of cells following different degradation paths. Indeed, as highlighted by the arrows on Figure 2, every degradation mode induces different changes on the voltage response of the cells.

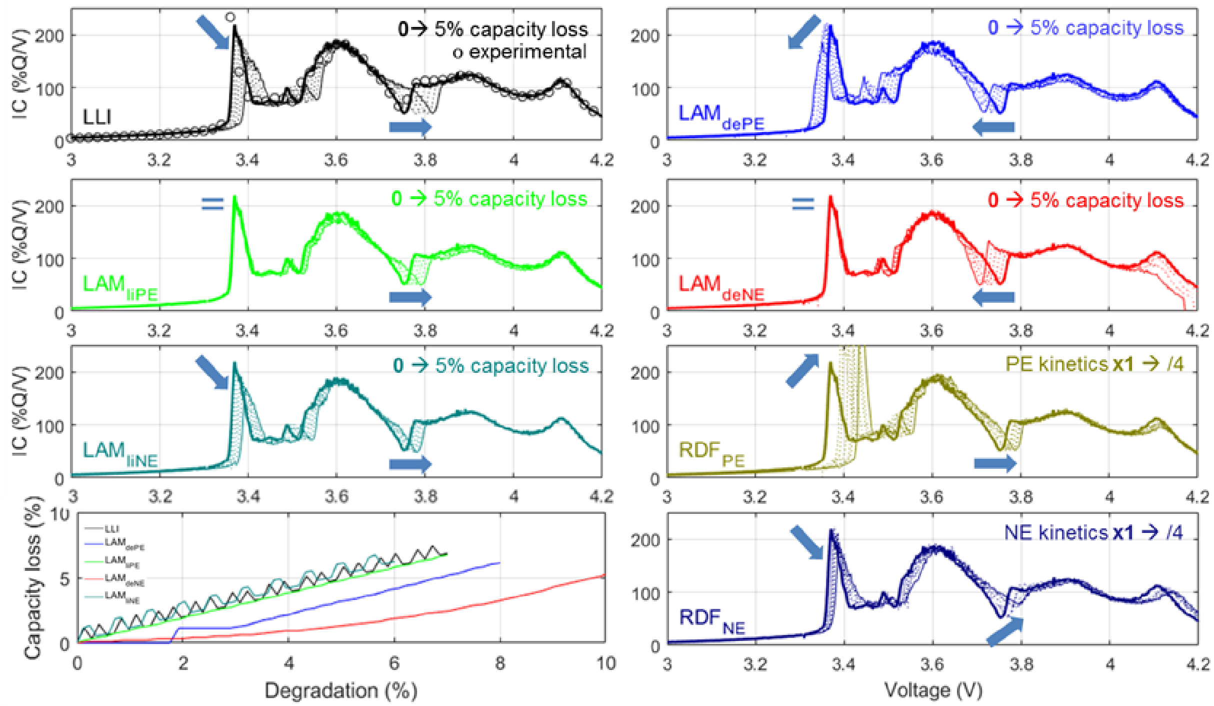

Figure 2. Cell emulation and degradation table for the selected cell.

Next the effect of V2G and G2V on battery durability was investigated. In addition, the effects of calendar aging on capacity loss, resistance increase, and rate capability were identified. Results were reported in report numbers 2, 4 and 5 (as listed above). These results were summarized in journal publication 7 and are shown in Figure 3 and Figure 4. In order to optimize testing time, a design of experiment methodology was applied to both experiments. The cycle aging experiment was designed to study combined effects shown in Figure 3(a) and the calendar aging experiment shown in Figure 4(a) was designed to focus on the high SOC/high temperature region.

This study focused on testing the impact of V2G discharging the battery twice a day to the power grid for a total of 2 hours per day at the maximum possible power to maximize potential electricity savings or revenues for the EV owner. See Figure 3(a). Results showed that such a V2G step twice a day increased the capacity loss by 75% and the resistance by 10% as shown in Figure 3(b). Reducing the V2G usage by half (to one discharge cycle lasting 1 hour per day) degraded the cell less but the result was still found to accelerate the capacity loss by 33% and the resistance increase by 5% over no V2G at all. Thus, a detrimental impact of V2G under these aggressive conditions was clearly established for these cells. Translating these results to the entire life of the cells using the model developed for this project showed that participating in V2G programs could decrease the lifetime of the battery packs below 5 years as a result of a capacity loss of more than 20%. See Figure 3(c).

In contrast, delaying the G2V charge rather than charging immediately after driving (to help the grid to spread the load) had no significant effect (<1%) on capacity retention and was found to limit the resistance growth (5% less increase). It was noted that this experiment was performed at room temperature where the SOC exercised very little influence on calendar aging.

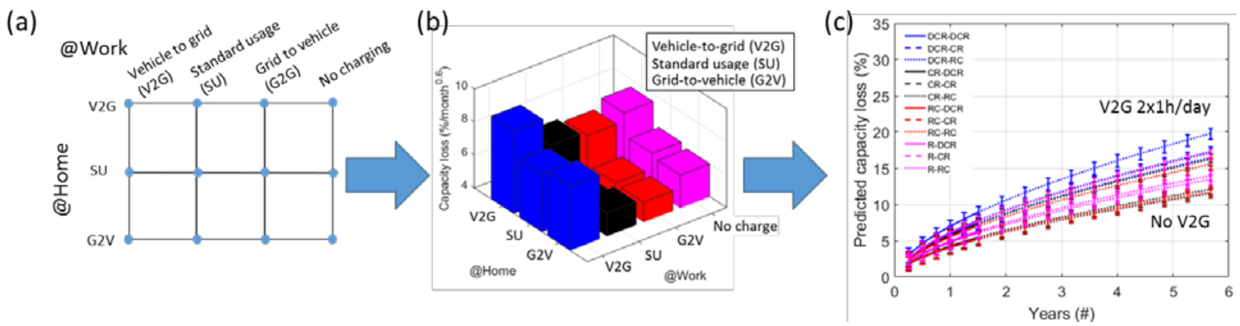

Figure 3. Summary of the cycle aging experiment with the experimental design, the resulting induced capacity loss and the capacity loss prognosis at 6 years.

The calendar aging experiment showed that the storage SOC has a much higher impact at higher temperature. See Figure 4(b). This suggests that delayed G2V should induce less degradation and be beneficial in warmer climates. Looking closer at calendar aging, shown in Figure 4(b), aging was found to influence the cells and that, at room temperature, charging the cells twice a day instead of once lowered the rate of capacity loss by 5%. See Figure 3(b). However, since the capacity loss increases with temperature and SOC, this will not be the case in warmer climates. The capacity loss associated with time, temperature and SOC was modeled with a double-quadratic equation. This modeling allowed for the prediction of the capacity loss induced by time, temperature and SOC. See Figure 4(c). Looking at the individual effect analysis, storage temperature was found to have the biggest impact on capacity loss and rate capability. However, the SOC had more influence on the resistance increase.

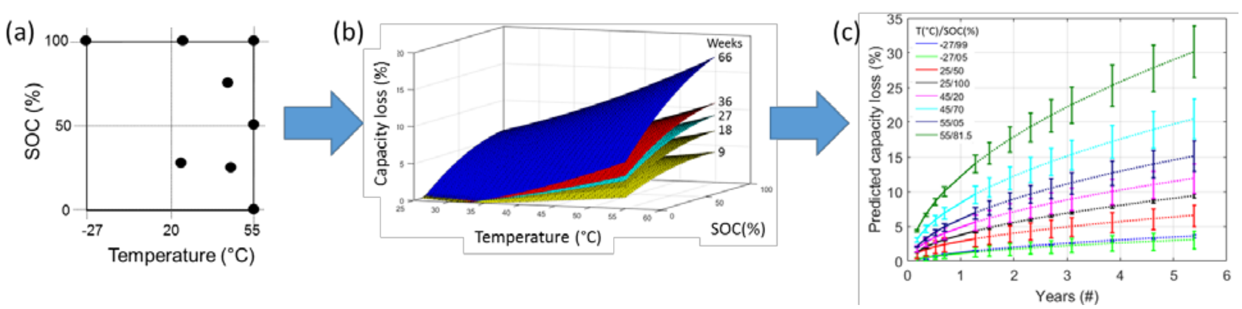

Figure 4. Summary of the calendar aging experiment with the experimental design, the resulting induced capacity loss and the capacity loss prognosis at 6 years.

Overall, this project was successful in determining the battery stress levels associated with calendar aging and V2G/G2V strategies. V2G use had a significant deleterious impact on the cell performance, possibly diminishing the lifetime of battery packs to less than 5 years. In contrast, delayed G2V charging profiles were found to have a negligible effect on cell performance at room temperature, which could be advantageous in warmer climates. Moreover, the study showed that EVs using these cells should not be left fully charged in warmer climates because of accelerated calendar aging.

A study of the different degradation mechanisms in the cells as a function of duty cycle at 5 % capacity loss (cycle aging and calendar aging) was presented at the Electrochemical Society 230th meeting in Honolulu in October 2016. Results were published in report 5 and are summarized in Figure 5.

In performing the forecasting analysis for capacity loss (journal publication 7), it was assumed that the degradation mechanism of the battery remains consistent and that neither a second stage of degradation, where the capacity loss is accelerated, nor parasitic reactions will occur. However, the literature suggests that these cells might experience accelerated fading through their lifespan [3]. A detailed electrochemical analysis, with the emulated cell presented in publication 6, was therefore needed to refine the aforementioned forecast model which represents the best case scenario (journal publication 7). At 5% capacity loss (red line on left curves, Figure 5), V2G testing (①, Figure 5) degraded the cells slightly differently than G2V testing (②, Figure 5) as a higher degradation was observed on the negative electrode capacity and kinetics with V2G (Figure 5, right). These difference should not induce any major change in the cycle-ability between cycling duty cycles but the presence of loss of active material on the negative electrode opens the possibility for lithium plating to occur and therefore for the overall life forecast to be potentially reduced.

Significant deviation in terms of degradation paths were also observed between the cycling and the calendar aging experiments, see Figure 3. With calendar aging, substantial fading of the positive electrode was observed at high temperatures (③, ④ Figure 5). The SOC also seems to play a role, since low SOC seems to induce some additional degradation on the negative electrode (③, Figure 5). For the calendar aging, and at 5% capacity loss, no plating concern was detected and therefore the forecast in journal publication 6 could be accurate. The forecast of the impact of degradation mechanisms on the cell life is in progress under other funding.

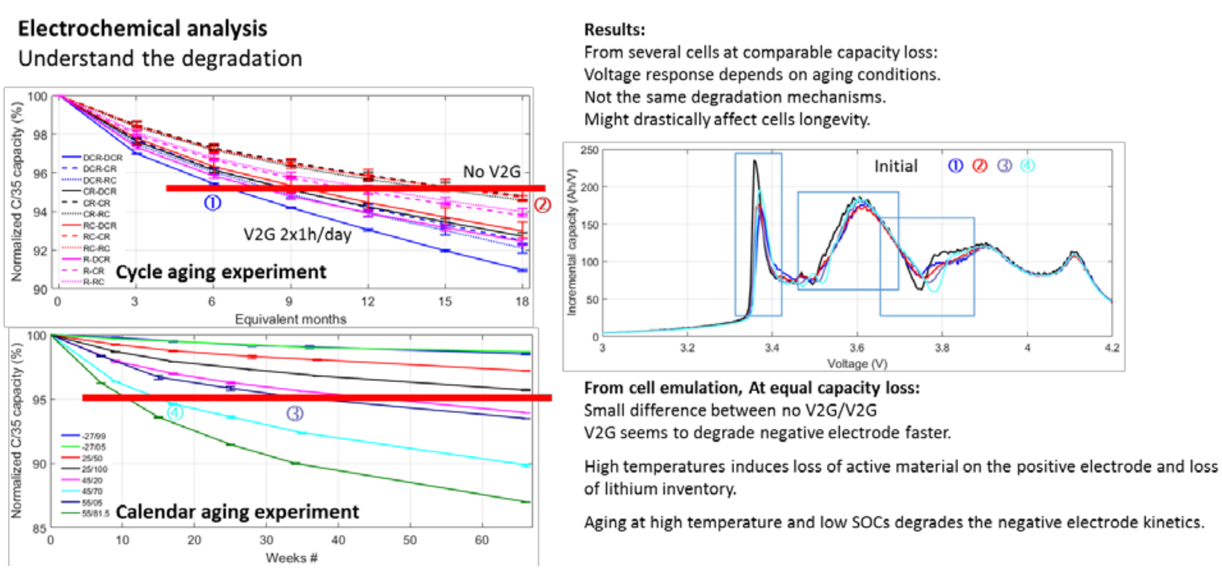

Figure 5. Graphical summary of the path dependence of battery degradation (Report 5) illustrating how different duty cycles led to different changes in the voltage response of the cells. The left curves relates the capacity loss as a function of the different duty cycles in the cycling experiment (top) and calendar aging experiment (bottom). Red lines indicate a 5% capacity loss.

Finally, while working to automate the analysis of the data, a new method to track battery State of Health (SOH) was invented. It should provide a significant leap forward compared to methods currently used in battery management systems. A provisional patent, “Apparatus & Method for Estimating the State of Health of a Battery via updating the OCV and SOC relationship” was filed on February 29th 2016 (EFS25057001, application #62301447). The full patent, “Methods and Apparatus for Updating a Fuel Gauge and Estimating State of Health of an Energy Storage Cell,” was filled on February 27th 2017, reference 8.

Further validation is in progress under other funding. The researcher’s invention addresses and solves the two main problems associated with SOC estimation: the gradual loss of accuracy with aging and the difficulty to diagnose cell aging without maintenance cycles. Table 1 presents a comparison of the method compared to recent patents and literature.

Table 1: SOH estimator comparison

US pat. #	First Filing Date	Assignee	Uses Coulomb counting	Infers SOC from OCV meas.	Estimates Q' as a result	Estimated Q' is accurate	1st principles method	Uses simple algebra	Does not restricts SOC range validity	Generates OCV = f(SOC) curves	Updates OCV = f(SOC)	Correlates Q' to LLI, LAMPE, LAMNE
US 6,892,148 B2	May 2, 2003	Texas Instruments	Y	Y	Y	N		N		N	N	N
US 2015/0268309 A1	Mar 20, 2014	Hyundai	Y	Y	Y[1]	N[1]	N	N	N[2]	N	N	N
US 9,081,068 B2	Jul 13, 2015	Apple	Y	Y	Y	N			N	N	N	N
US 8,046,181 B2	Aug 8, 2008	LG Chem	Y	Y	Y	N	N	Y	Y	N	N	N
Tong2015	Oct 30, 2014	In JPS	Y	Y	Y	Y	N[3]	N[3]				
Wang2016	May 16, 2015	In JPS	N	N	N		Y[4]	N[4]	N	N		Y[4]
Our invention		UH	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

[1] The Hyundai patent estimates the new no-load capacity Q' as the average value of a number of Qr measurements. However the OCV = f(SOC) does not appear to be updated. Meaning the estimate for Q' is likely to be wrong.

[2] The Hyundai patent restricts the applicability of the method to a range of SOC from 0 to 50%.

[3] The UC Davis method uses Extended Kalman Filter, Recursive Least Square and Parameter Varying Approach. Heavy on computation and not physics based.

[4] The Harbin Institute of technology method uses emulated battery voltage from active materials and tracks specific markers at end of charge and discharge. More of a visual approach as popularized by Dr. Dubarry.

3.0 Conclusions

This research performed laboratory testing of commercial "18650" Li-ion cells in Hawaii Natural Energy Institute's Battery Testing Laboratory. For the battery tests, the cells were first determined to be suitable for long term studies by testing under a range of aging scenarios giving a selection of 36 cells for the cycle aging experiment and 16 cells for the calendar aging experiment. The battery tests used two separate experiments: a cycling experiment to assess the impact of both V2G and G2V charging strategies and a calendar aging experiment to assess the impact of temperature and SOC. The results for the battery degradation were summarized in seven degradation modes -- the loss of lithium inventory, the loss of active material on the positive and negative electrodes, lithiated or not, and the kinetics of the positive and the negative electrode. The results also showed the impact of the degradation modes is different enough to enable accurate diagnosis of cell degradation and permit comparison of cells following different degradation paths.

Next the effect of V2G and G2V on battery durability was investigated. The study focused on testing the impact of V2G discharging the battery twice a day to the power grid for a total of 2 hours per day at the maximum possible power. These test results showed that the life of the cells using the developed model could decrease the lifetime of the battery packs below five years as a result of a capacity loss of more than 20%. The results have shown an impact of V2G, temperature and SOC on the battery capacity loss and indicate that V2G use can double the capacity loss when performed twice daily. Finally, a new method to track battery (SOH) was invented and is being patented. This method will provide a significant leap forward compared to methods currently used in battery management systems.

4.0 Impacts/Benefits

Battery degradation is extremely important to EV technologies. Batteries can be sensitive to temperature, SOC and other factors leading to concerns over battery durability and longevity, especially under adverse conditions such as hot climates. Additionally, with the integration of more and more renewables on the power grid, there is a push to use EV batteries as energy storage systems which may stress the batteries even more. The outcome of this project is to determine the battery stress levels associated with calendar aging, G2V and V2G usage, and to help identify the potential for mutually beneficial grid usage of EV batteries.

5.0 References

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