Y9.ET5.3: Battery Degradation Model for Real-Time Levelized Cost Calculation

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1. Project Goals

The objective of this task is develop (or adopt from literature) a model that estimates the battery degradation as the function of the DESD use profile. The off-line degradation model supports system cost-benefit studies while the on-line implementation resides on the DESD ARM board (BeagleBoneBlack), and supports the IEM application. The on-line model will be implemented on the newly-developed AC DESD platform, which uses the new Lithium Titanate ($Li_4Ti_5O_{12}$ or LTO) batteries. The on-line battery degradation model will expand the capabilities of the standardized DESD communication and control platform developed in past years, which already contains safety (voltage, current and temperature monitoring) and battery management functionalities. Therefore, the main goals of the project are (1) redesign the FREEDM AC DESD unit to use SCiB batteries and associated battery management and protection features, and (2) develop and implement an on-line battery degradation model that determines the instantaneous cost of use of the DESD.

2. Role in Support of Strategic Plan

The proposed work addresses two issues brought up by the SVT. First, we will use the LTO chemistry, which the team determined in the past years to be best suited for the FREEDM application from in terms of performance and safety. Toshiba LTO batteries boast a long cycle life, are less volatile than other Li-ion chemistries (such as the Boeing 787 Dreamliner batteries that caught fire, which used the lithium cobalt oxide chemistry), and integrate the latest state of the art battery monitoring and protection functions. Second, the development work on the battery degradation modeling aims to address SVT concerns that the effects of battery use and the resulting battery degradation are not considered in the cost-benefit analysis, and in developing strategies for optimal DESD dispatch.

3. Fundamental Research, Technological Barriers and Methodologies

The vision of FREEDM to have a very high renewable penetration while maintaining extremely high power quality and availability, is enabled by the availability of the DESD. The work in this project aims to address the optimal sizing question for the FREEDM DESD. Since the DESD use profile is a strong function of the distributed generation and load mix, optimal storage sizing is very case-specific. Many studies have dealt with solving this sizing problem, given a known load and generation mix, while trying to minimize a given cost or maximize revenue. The FREEDM cost-benefit team is doing this in their cost-benefit analysis. In this work, we try to give these studies more fidelity by considering the battery degradation as it serves the application. Given the battery capacity loss and resistance growth as the battery degrades, the battery has to be sized to serve the application over the entire service life. In this work we determine the changes in battery performance over the battery life, evaluating the resulting performance, losses, and eventual failure. The battery degradation model will be introduced in the next section.

4. Achievements

High Efficiency AC DESD: This year the team has embarked on developing and deploying a new AC DESD which integrates the Toshiba LTO batteries as the energy storage system. This work demonstrates recent DESD integration efforts including control, communication, and protection functionalities developed in past years. The resulting system topology is shown in Fig. 1. The new system employs a commercialized three-leg SiC MOSFET module, where one leg is used as a boost converter to while the other two legs are controlled as a full-bridge inverter. The boost converter boosts the battery nominal voltage of 135V to 200V required by the full-bridge inverter, which delivers 120Vac to the grid.

In the new AC DESD implementation, the team makes use of the standardized DESD communication and control platform, shown in Fig. 1. At the lowest level, a TI TMS320F28335 digital signal processor (DSP) implements control loops for the power electronics, which actuate the real and reactive power commands from the DGI. The DSP communicates via the MODBUS protocol to the local Beagle Bone Black ARM Board, which links to the FREEDM distributed grid intelligence (DGI) via the MQTT protocol. The DSP receives power and relay status commands from the DGI via the ARM Board and reports the actuated power and relay status. The Toshiba battery modules have an integrated battery management system (BMS). The BMS measures the battery voltage, current, temperature; estimates the battery state-of-charge (SOC); and communicates this information to the local ARM board using CAN communication. The BMS monitors all five LTO battery modules, and autonomously controls two additional relays if a fault condition is detected (overvoltage, overcurrent, temperature rise, or leakage current). The ARM board collects the information from the battery and the DSP and uses this information to implement higher-level applications, such as calculating round trip efficiencies, and running the on-line battery degradation model.

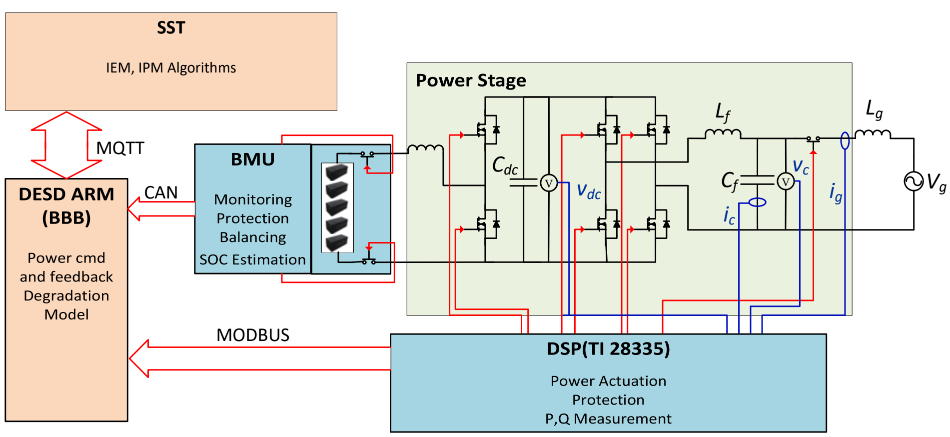

Figure 1: DESD System Configuration

Battery Degradation Model: The team has adopted a semi-empirical model developed by researchers at National Renewable Energy laboratory (NREL) and described in [1]. The model details and the dataset used was presented in Year 8 report. In our initial evaluation, the model is developed to represent the degradation of the NCA chemistry from [2]. The NCA chemistry is selected due to the fact that the chemistry is mature, well-understood, and that substantial experimental data is available in the literature.

The model uses Rainflow algorithm [3] to assess the battery stress due to cycling. Rainflow algorithm is used to break up a complex depth of discharge history into individual marco- and micro-cycles,

ΔDOD_i. The algorithm also tracks whether each cycle was a full or a single-ended charge/discharge cycle and stores this information as N_i. N_i equals to 1.0 for a full cycle and 0.5 for a single-end cycle. To model the battery behavior, we use a simple equivalent circuit model, shown in Fig 2(a). In this model, the voltage source V_0 represents the open circuit voltage (OCV) of the battery, and Q_c represents the battery capacity. R_{in} represents the total cell resistance and can be considered as a function of both cell aging and battery SoC. This resistance model is a simplification of the well-established battery capacity fade model of lithium-ion cells [4], which considers the battery impedance as a resistor R_1 in series with a parallel R_2C branch of resistance R_2. The resistance term R_1 refers to the ohmic resistance and R_2C presents all the faradic non-linear components, with its parameters varying with the battery SOC and age. In steady state, the battery impedance can be represented as $R_{in} = R_1+R_2$. In degradation model, the dynamic response of the cell is intentionally ignored. The relation of V_{oc} to SOC, and R_1 are intrinsic to the cell, while R_2 and Q_c vary as the battery degrades.

To model the changes in temperature during the charge-discharge cycles of the ESS we use a simple thermal model:

$$q_{heat} = I^2 R_{in} = \frac{\theta_{battery} - \theta_{ambient}}{R_{SA}} + C.\frac{d\theta_{battery}}{dt} \tag{1}$$

q_{heat} represents the heat generated by battery; $\theta_{battery}$ and $\theta_{ambient}$ represent battery temperature and ambient temperature respectively; R_{in} is the internal resistance; R_{SA} is the thermal resistance of the battery casing; C is the thermal capacity of the battery. Referring to [5], the thermal model parameters for an 18650 cell are set to $R_{SA} = 2\,K/W$ and $C = 670\,J/K$. Fig. 2(b) shows the equivalent circuit diagram.

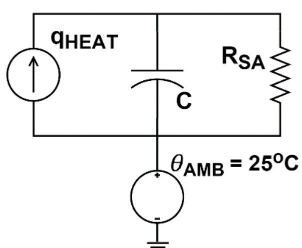

Figure 2a: Equivalent Circuit Battery Model

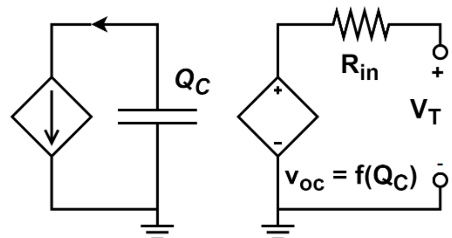

Figure 2b: Equivalent Thermal Model

Effects of Battery Degradation on Economic Viability of Energy Storage Systems Participating in Regulation Markets

Given that the use profile of the FREEDM storage system will be highly dependent on the use case considered, as well as the load mix assumption, the team wanted to run the degradation model through a use profile that was well established. The purpose of this work was to *demonstrate the importance of including high fidelity battery degradation information in making decisions on how to use the battery*. We selected to look at the use case where the energy storage system participates in the regulation market.

FERC Order 755 requires transmission system operators to provide performance-based payment for ancillary services. Battery Energy Storage Systems (BESS) have the capacity to play a more vital role in regulation market because of their ability to provide an accurate and fast response to automatic generation control (AGC) dispatch signals. However, since batteries are complex electrochemical systems, it is difficult to understand how the battery degradation phenomena will affect the total revenue from BESS providing the regulation service. We showed that bid-in strategies that consider the battery degradation as a function of the service provided have a substantial effect on the total revenue for the BESS operators.

In our work, we assumed that BESS operator bids only in the day-ahead frequency regulation market. 'Mileage' measurement is used to evaluate BESS's performance. Mileage is defined as the absolute sum of power difference between each adjacent AGC dispatch signals sent to BESS. We assume that BESS follows the AGC dispatch signals perfectly, and that BESS's lifetime can be divided into several bid-in intervals, which could be days or months. BESS would remain at a constant bid-in capacity within each bid-in interval and update its bid-in capacity at the end of each interval. We assumed that that it is not feasible to influence revenue based on the mileage payment alone, and the mileage revenue can be increased, on average, by increasing the bid in capacity in each bid-in interval. Since the mileage differentials caused by daily variations is not of interest, for simplification, we selected a single-day use cycle for the investigations that follow. The selected daily use profile is published by PJM [6] and is shown in Fig 1.

In our study, an energy neutral signal was used to ensure a stable battery state-of-charge over the extended use cycles. To generate an energy neutral signal for the purposes of this study, the selected test duty cycle form the PJM dataset is closest to being energy neutral over the 24h period. A constant offset is introduced to each regulation interval to generate an energy neutral profile. Since all command points are shifted equally, no mileage deviation is introduced into the modified test duty cycle.

We considered three different bid in strategies: *Conventional Bid-in Strategy*: bid its rated capacity every day in the day-ahead market until it reaches its end of life (EOL). *Aggressive Bid-in Strategy*: bid in the highest sustainable capacity without violating battery voltage limits, or thermal constraints. *Degradation Aware Bid-in Strategy*: bid in a constant capacity that maximizes normalized sum of the bid-in capacities. *Smart Bid-in Strategy*: bid in the capacity determined using the Aggressive Bid-in Strategy (while the battery impedance is low), and periodically evaluate which bid in capacity maximizes throughput at any given time, adjusting the bid accordingly.

Based on the four proposed bid in strategies our work shows that the sub-optimal smart bid-in-strategy results in a 24% revenue gain over the conventional bid-in strategy.

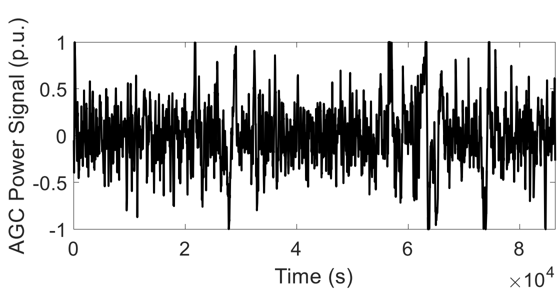

Figure 3. Selected Test Duty Cycle

Table 1. Different Bid-in Strategies Comparison

Bid-in Strategy	Time to EOL	Normalized Sum of Bid-in Capacity
Conventional	90 months	1 p.u.
Aggressive	56 months	0.876 p.u.
Degradation Aware	126 months	1.017 p.u.
Smart	116 months	1.124 p.u.

Other Relevant Work Being Conducted Within and Outside of the ERC

The degradation model used in this work was developed by researchers at NREL. We will build on the work done by these entities to complete our goals.

5. Milestones and Deliverables

This year, the team focused on integrating center-developed DESDs into the GEH and HIL testbeds. This completes the migration of technology from the enabling plane to the demonstration plane. To that end, the team demonstrated a unified messaging protocol for the DESD to deliver the necessary information to the DGI to optimally use these resources. The team also adopted degradation model from the literature and implemented the algorithm to run in real-time on an ARM platform.

6. Plans for Next Five Years

The team will continue the integration and standardization of commercial and center developed DESDs using the described integration platform. The work done this year shows that the center is able to quickly integrate new DESDs, which will allow for commercial and second party DESDs to be integrated into the GEH. The degradation modeling work will continue, with the ultimate goal of providing real-time cost estimation of using the DESD to support the FREEDM System. Having this real-time cost data will allow for system-level cost or efficiency optimization in real-time, thus allowing DESD optimal dispatch in the context of the defined cost function.

7. Member Company Benefits

The LTO batteries used by the center are developed by a member company, Toshiba. The company has provided battery test data and has helped the center procure the batteries. Another member company Pos-En is using the same LTO battery modules in their products, and joint development on battery integration has benefited both institutions.

8. References

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