



Lifetime Failure and Degradation Analysis of Grid-Connected Battery Energy Storage Systems

PI: Atri Bera

Team Members: Dilip Pandit, Cody Newlun, Tim Wilcox, Yuliya Preger, Tu Nguyen

Email: dpandit@sandia.gov

Project Objective

Develop a probabilistic model for grid-connected battery energy storage systems that accounts for cell degradation and failures

Why This Work Is Needed

- Integration of battery energy storage systems (BESS) has been increasing in recent years to support grid flexibility and reliability
- As BESS deployment scales, grid-level impacts of BESS degradation and failures must be modeled accurately
- Existing works in this domain:
 - Generalize cell level degradation to overall BESS degradation
 - Do not quantify impacts of cell and module level failures on system reliability

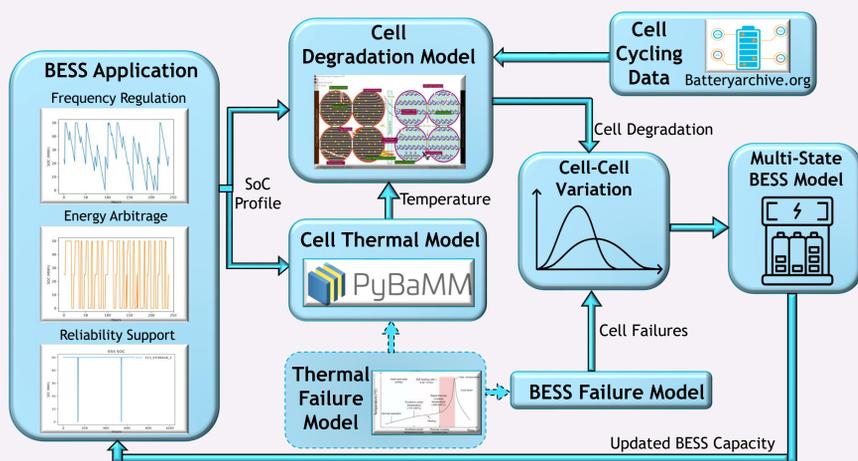
What We Do

- Develop enhanced probabilistic model of BESS for long-term revenue and reliability analysis
- Capture the impact of cell-level dynamics and failures on system-wide performance, economics, and reliability
- Key modeling considerations for this work:**
 - BESS application (arbitrage, frequency regulation, reliability support)
 - Cell Degradation
 - Cell chemistry (LMO, LFP, NMC, etc.)
 - Cell and Module failures
 - Cell-Cell variation
 - Battery topology

Progress

- Developed a stress-factor-based degradation formulation on the Sandia LFP and NMC cell cycling data
- Using the degradation model and market participation strategies, performed BESS degradation and revenue assessment
- A abstract accepted to EESAT conference 2026 – conference paper is in progress
- Individual modules for cell-cell variation and BESS capacity model have been developed – ready to be tuned with experimental data

Model Overview & Features



Degradation figure: Edge, Jacqueline S., et al. "Lithium ion battery degradation: what you need to know." *Physical Chemistry Chemical Physics* 23,14 (2021): 8200-8221.
 PyBaMM ref: Sulzer, V., Marquis, S. G., Timms, R., Robinson, M., & Chapman, S. J. (2021). "Python Battery Mathematical Modelling (PyBaMM)". *Journal of Open Research Software*, 9 (1), 14.

Cell Degradation and Thermal Model

Degradation model

- Considers cyclic ageing. Critical stress factors:
 - Depth-of-discharge
 - Temperature
 - C-rates
- Different cell types considered: LMO, LFP, NMC
- Real-world data to fine tune the degradation models

Thermal model

- Provide SoC and cell details to PyBaMM, returns temperature profile

Probabilistic Cell and BESS Capacity Model

Cell-Cell Variation

- Outputs from degradation and failure models used to form cell probability distribution
- Cell energy levels are discretized to form universal generating functions (UGF)
- Real-world cell-cell variation data used to tune the model

BESS Capacity Model

- BESS capacity is obtained using cell pdfs and UGF
- Updated capacity is provided to the BESS application model

Cell Failure Model

Base Failure Model

- Random sampling to obtain module/sub-assembly failure
- Failed module updates the probabilistic cell model

Failure Model with Thermal Runaway

- Random sampling to obtain cell thermal runaway (TR)
- TR cell:** Update the cell pdf
- Cells near the failed cell:**
 - Increased temperature
 - Increased degradation rate
- TR propagation dependent on cell spacing, topology, SoC

Degradation Model Formulation and Results

- Stress factor-based degradation model is used
- LFP and NMC cell cycling data obtained from Batteryarchive.org and [1]
- Least squares optimization used for curve fitting on a representative cell

LFP Cells

- Important characteristics to model:
 - The DoD model must account for large cycle life
 - Higher dependence on temperature than DoD and C-rates
- Parameter with larger degradation effect has an accelerating factor.

Mathematical model is expressed as follows:

$$\text{Overall cell degradation: } L = 1 - \alpha^{SEI} e^{(-\beta^{SEI} f_d)} - (1 - \alpha^{SEI}) e^{-f_d}$$

$$\text{Aggregated stress factor: } f_d = \sum_{i=1}^N f_{DoD}(DoD_i) * f_c(C_i) * f_T(T_i) * n_i$$

stress factors are expressed as:

$$\text{Depth of Discharge stress factor: } f_{DoD}(DoD_i) = k_1^{DoD} * e^{k_2^{DoD}(DoD_i - DoD^{ref})}$$

$$\text{Temperature stress factor: } f_T(T_i) = e^{k_3^T(T_i - T^{ref})} * T^{ref}/T_i + k_4^T * n_i^{k_5^T} (T_i - T^{ref}) * T^{ref}/T_i$$

$$\text{C-rate stress factor: } f_c(C_i) = e^{k_6^C(C_i - C^{ref})}$$

NMC Cells

- Important characteristics to model:
 - Despite having much smaller cycle lives than LFC, NMC cells have good lifetime discharge capability
 - Higher dependence on DoD than temperature and C-rates
- Other stress factor equations are same as LFC except:

$$f_{DoD}(DoD_i) = k_1^{DoD} * e^{k_2^{DoD}(DoD_i - DoD^{ref})} + k_3^{DoD} * n_i^{k_4^{DoD}} (DoD_i - DoD^{ref})$$

$$f_T(T_i) = e^{k_5^T(T_i - T^{ref})} * T^{ref}/T_i$$

$$f_c(C_i) = e^{k_6^C(C_i - C^{ref})}$$

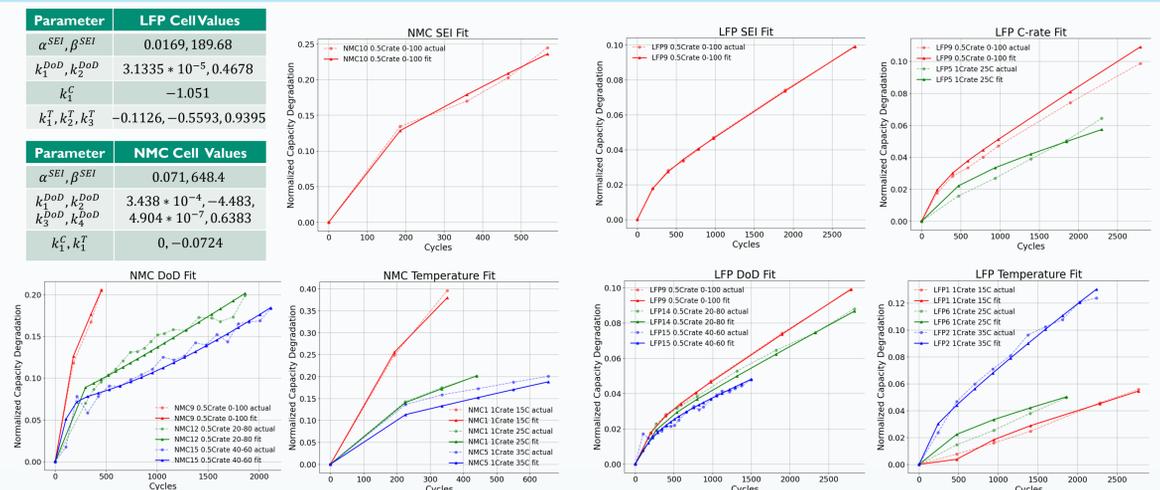
Notations:
 $k_{1,2,3}^{factor}$: denotes stress factor coefficients
 $\alpha^{SEI}, \beta^{SEI}$: denotes SEI factor coefficients
 ref : superscript denotes reference parameter
 n_i, n_i : Total number of cycles and current cycle

Parameter LFP Cell Values

$\alpha^{SEI}, \beta^{SEI}$	0.0169, 189.68
k_1^{DoD}, k_2^{DoD}	$3.1335 * 10^{-5}, 0.4678$
k_3^C	-1.051
k_4^T, k_5^T, k_6^C	-0.1126, -0.5593, 0.9395

Parameter NMC Cell Values

$\alpha^{SEI}, \beta^{SEI}$	0.071, 648.4
k_1^{DoD}, k_2^{DoD}	$3.438 * 10^{-4}, -4.483,$
k_3^{DoD}, k_4^{DoD}	$4.904 * 10^{-7}, 0.6383$
k_5^T, k_6^C	0, -0.0724



- Results show good agreement between experimental and simulation data for both cell chemistries

Next Steps

- Complete integration of cell-cell variation and BESS capacity model with the existing degradation model
- Integrate the BESS model with the ProGRESS tool and evaluate overall system reliability impacts of BESS degradation and failures
- Write a journal article summarizing the reliability results
- Formulate and integrate the thermal runaway failure model

[1] Preger, Yuliya, et al. "Degradation of commercial lithium-ion cells as a function of chemistry and cycling conditions." *Journal of The Electrochemical Society* 167,12 (2020): 120532.