Battery Model Summary

Jules Pare

Arrhenius Correlation Amp-hour Throughput Model

$$Q_{loss} = A \exp\left[\frac{-E_a + BC_{rate}}{RT}\right] Ah_{th}^{z}$$

- Q_{loss} $-$ $Capacity\ Loss$
- C_{rate} $-$ $Mean\ C - Rate$
- R $-$ $Ideal\ Gas\ Constant$
- T $-$ $Temperature$
- Ah_{th} $-$ $Amp\text{–}\ hour\ Throughput$
- A, B, D, z $-$ $Fitting\ Coefficents$

L. Chen, Y. Tong, and Z. Dong, “Li-Ion Battery Performance Degradation Modeling for the Optimal Design and Energy Management of Electrified Propulsion Systems,” *Energies*, vol. 13, no. 1629, p. 1629, Apr. 2020, doi: 10.3390/en13071629.

Second-Order Arrhenius Amp-Hour Throughput

$$Q_{loss} = (aT^2 + bT + c)\exp[(dT + e)I_{rate}]\,Ah_{th} + ft^{0.5}\exp\left[-\frac{E_a}{RT}\right]$$

Coefficient values and units			
a	8.61E-6, 1/Ah-K^2	I_{rate}	C-rate
b	−5.13E-3, 1/Ah-K	t	Days
c	7.63E-1, 1/Ah	E_a	24.5, kJ mol^{-1}
d	−6.7E-3, 1/K-(C-rate)	R	8.314, J mol^{-1} K^{-1}
e	2.35, 1/(C-rate)	T	K
f	14,876, 1/day$^{1/2}$		

J. Wang et al., "Degradation of lithium ion batteries employing graphite negatives and nickel–cobalt–manganese oxide + spinel manganese oxide positives: Part 1, aging mechanisms and life estimation," J. Power Sources, vol. 269, pp. 937–948, Dec. 2014, doi: 10.1016/j.jpowsour.2014.07.030.

Deshpande-Bernardi Model

$$Q_{loss} = Q_{loss}^{SEI\ growth} + Q_{loss}^{SEI\ crack}$$

$$Q_{loss} = Kt^{y} + a\left\{\sum_{i}^{n}(\mathrm{DOD_i})^2\right\}$$

- Q_{loss} – *Capacity Loss*
- t – *Time*
- DOD – *Depth of Discharge*
- n – *Number of Cycles*
- K, y, a – *Fitting Parameters*

R. D. Deshpande and K. Uddin, "Physics inspired model for estimating 'cycles to failure' as a function of depth of discharge for lithium ion batteries," *J. Energy Storage*, vol. 33, p. 101932, Jan. 2021, doi: 10.1016/j.est.2020.101932.

Quadradic Approximation Model

$$\ln\left[-ln\left(\frac{C(t)}{C_0}\right)\right] = \ln(k_c) + \alpha\ln(t)$$

$$\ln(k_c) = \beta_0 + \beta_T\left(\frac{1}{T}\right) + \beta_S(SOC) + \beta_C(I_C) + \beta_D(I_D) + \beta_{TC}\left(\frac{I_C}{T}\right) + \beta_{TD}\left(\frac{I_D}{T}\right) + \beta_{TT}\left(\frac{1}{T^2}\right) + \beta_{SS}(SOC^2)$$

- $C(t) - Present\ Capacity$
- $C_0 - Inital\ Capacity$
- $k_c - Stress\ Factor\ Fitting\ Parameter$
- $t - Time$
- $T - Ambient\ Temperature$
- $SOC - Average\ SOC$
- $I_C - Charge\ Current$
- $I_D - Discharge\ Current$
- $\beta_i - Set\ of\ fitting\ parameters$
- $\alpha - Fitting\ parameter\ for\ time$

D. Galatro, C. D. Silva, D. A. Romero, O. Trescases, and C. H. Amon, "Challenges in data-based degradation models for lithium-ion batteries," *Int. J. Energy Res.*, vol. 44, no. 5, pp. 3954–3975, 2020, doi: https://doi.org/10.1002/er.5196.

Nonlinear model with linear stress factors

Cycling: $L = 1 - \alpha_{sei} \exp[-N\beta_{sei} f_d] - \alpha_{sei} \exp[-N f_d]$
Calendar: $L = 1 - \alpha_{sei} \exp[-t\beta_{sei} f_d] - \alpha_{sei} \exp[-t f_d]$

- $L - Degradation\ in\ form\ (1 - SOH)$
- $N - Number\ of\ cycles$
- $t - time$
- $\alpha_{sei}, \beta_{sei}, f_d - Fitting\ parameters$

$$f_d^1 = \big(S_\delta(\delta) + S_t(t_c)\big) S_\sigma(\sigma) S_T(T_c)$$
$$f_d^t = S_t(t) S_\sigma(\sigma) S_T(T_c)$$

$\delta - DOD$
$t - time$
$\sigma - SOC$
$T_c - chamber\ temperature$
$S(i) - Linear\ stress\ models$

B. Xu, A. Oudalov, A. Ulbig, G. Andersson, and D. S. Kirschen, “Modeling of Lithium-Ion Battery Degradation for Cell Life Assessment,” IEEE Trans. Smart Grid, vol. 9, no. 2, pp. 1131–1140, Mar. 2018, doi: 10.1109/TSG.2016.2578950.

Model with EC and Thermal Model

$$\frac{C(t)}{C_0} = 1 + c_a c_v^{V-V_0} c_t^{T-T_0} \sqrt{t}$$

$V - Voltage$
$V_0 - Nominal\ Voltage$
$T - Temperature$
$T_0 - Nominal\ Temperature$
$c_a, c_v, c_t - Fitting\ parameters$
$t - time$