The cell delta filters

- The quantities that we are most interested in estimating at the individual cell level are: SOC, resistance, and capacity
- These all factor into determining pack available energy, available power, and lifetime (state-of-health) estimates
- Have seen how to create "bar"-filter models for all of these
- Will now consider "delta"-filter approach to determining cell SOC

Delta-filter state equation for SOC

- Recall, $\Delta z_k^{(i)} = z_k^{(i)} - \bar{z}_k$. Then, using prior equations for dynamics of $z_k^{(i)}$ and $\bar{z}_k$, we find ($\Delta Q_{\text{inv},k}^{(i)} = Q_{\text{inv},k}^{(i)} - \bar{Q}_{\text{inv},k}$)

$$\begin{aligned}\Delta z_k^{(i)} &= z_k^{(i)} - \bar{z}_k \\ &= \left(z_{k-1}^{(i)} - (i_{k-1} - i_{k-1}^b)\Delta t\, Q_{\text{inv},k-1}^{(i)}\right) - \left(\bar{z}_{k-1} - (i_{k-1} - i_{k-1}^b)\Delta t\, \bar{Q}_{\text{inv},k-1}\right) \\ &= \Delta z_{k-1}^{(i)} - (i_{k-1} - i_{k-1}^b)\Delta t\, \Delta Q_{\text{inv},k-1}^{(i)}\end{aligned}$$

- Because $\Delta Q_{\text{inv},k}^{(i)}$ tends to be small, state $\Delta z_k^{(i)}$ does not change quickly, and can be updated at a slower rate than the pack-average SOC by accumulating $(i_{k-1} - i_{k-1}^b)\Delta t$ in-between updates

Delta-filter output equation for SOC

- An output equation suitable for combining with this state equation is

$$y_k^{(i)} = \text{OCV}(\bar{z}_k + \Delta z_k^{(i)}) + M\bar{h}_k - \sum_j R_j \bar{i}_{R_j,k} - (\bar{R}_{0,k} + \Delta R_{0,k}^{(i)})(i_k - i_k^b) + v_k$$

- To estimate $\Delta z_k^{(i)}$, an SPKF is used with these two equations.
  - Since it is a single-state SPKF, it is very fast

Delta-resistance model

- As preview of param estimation (Course 4), can similarly make state-space models of delta-resistance and capacity states
- A simple state-space model of the delta-resistance state is:

$$\begin{aligned} \Delta R_{0,k}^{(i)} &= \Delta R_{0,k-1}^{(i)} + n_{k-1}^{\Delta R_0} \\ y_k &= \text{OCV}(\bar{z}_k + \Delta z_k^{(i)}) - (\bar{R}_{0,k} + \Delta R_{0,k}^{(i)})(i_k - i_k^b) + v_k^{\Delta R_0}, \end{aligned}$$

  where $\Delta R_{0,k}^{(i)} = R_{0,k}^{(i)} - \bar{R}_{0,k}$ and is modeled as a constant value with a fictitious noise process $n_k^{\Delta R_0}$ allowing adaptation, y_k is a crude estimate of the cell's voltage, and $v_k^{\Delta R_0}$ models estimation error
- Dynamics of delta-resistance state are simple and linear enough to use single-state EKF rather than SPKF

Delta-capacity model

- To estimate cell capacity using an EKF, we model

$$\begin{aligned} \Delta Q_{\text{inv},k}^{(i)} &= \Delta Q_{\text{inv},k-1}^{(i)} + n_{k-1}^{\Delta Q_{\text{inv}}} \\ d_k &= (z_k^{(i)} - z_{k-1}^{(i)}) + (i_{k-1} - i_{k-1}^b)\Delta t \left(\bar{Q}_{\text{inv},k-1} + \Delta Q_{\text{inv},k-1}^{(i)}\right) + e_k \end{aligned}$$

- Second equation is reformulation of the SOC state equation such that expected value of d_k is equal to zero by construction
- As EKF runs, computation for d_k in second equation is compared to known value (zero, by construction), and difference used to update inverse-capacity estimate
- Note that good estimates of present and previous SOCs are required
  - Here, they come from the pack SPKF combined with the cell SPKF

Summary

- Have now derived models to use with "delta" filters for estimating all cell SOCs, resistances, capacities
- Outputs of bar filter and delta filters combined to create individual cell estimates

$$\begin{aligned} z_k^{(i)} &= \bar{z}_k + \Delta z_k^{(i)} \\ R_{0,k}^{(i)} &= \bar{R}_{0,k} + \Delta R_{0,k}^{(i)} \\ Q_k^{(i)} &= \frac{1}{\bar{Q}_{\text{inv},k} + \Delta Q_{\text{inv},k}^{(i)}} \end{aligned}$$

- Overall computation complexity can be reduced from N_s to 1^+