Real-world issue: Current-sensor bias

- KF theory assumes that all noises are zero mean: unknown current-sensor bias can introduce permanent SOC error
  - Accumulated ampere-hours of bias tend to move SOC estimate faster than measurement updates can correct
- Best solution would be to design sensing hardware to eliminate current-sensor bias, but this can be done only approximately
- So, we can also attempt to correct for the (unknown, time-varying) bias algorithmically by estimating the bias

Real-world issue: Current-sensor bias

- Augment the pack state with current-sensor bias state

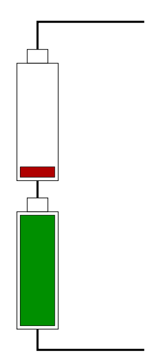
$$
\begin{aligned}
z_k &= z_{k-1} - (i_{k-1} - i^b_{k-1} + w_{k-1})\Delta t/Q \\
i_{R_j,k} &= A_{RC} i_{R_j,k-1} + B_{RC}(i_{k-1} - i^b_{k-1} + w_{k-1}) \\
A_{h,k} &= \exp\left(-\left|(i_{k-1} - i^b_{k-1} + w_{k-1})\gamma\Delta t/Q\right|\right) \\
h_k &= A_{h,k} h_{k-1} + (1 - A_{h,k})\,\mathrm{sgn}(i_{k-1} - i^b_{k-1} + w_{k-1}) \\
i^b_k &= i^b_{k-1} + n^b_{k-1},
\end{aligned}
$$

  where n^b_k is a fictitious noise source: allows SPKF to adapt bias state
- Output equation is also modified (where v_k models sensor noise)

$$
y_k = \mathrm{OCV}(z_k) + M h_k - \sum_j R_j i_{R_j,k} - R_0(i_k - i^b_k) + v_k
$$

Real-world issue: Speed, solved by “bar-delta”

- We consider again a philosophical question with very important practical implications
- Consider the picture to the right: What is the pack SOC?
  - SOC cannot be 0 % because we cannot charge
  - SOC cannot be 100 % because we cannot discharge
  - SOC cannot be the average of the two, 50 %, because we can neither charge nor discharge
- So, battery “pack SOC” is not a helpful concept, by itself
- The example is an extreme case, but it is important to estimate the SOC of all cells even in the typical case



Important observation

- The problem is that the SPKF is computationally complex
  - Running SPKF for one cell is okay, but
  - Running 100 SPKFs for 100 cells in series is probably not okay
- In this section we talk about efficient SOC estimation for all individual cells in a large battery pack

  OBSERVATION: While "pack SOC" does not make sense, concept of "pack-average SOC" is a useful one

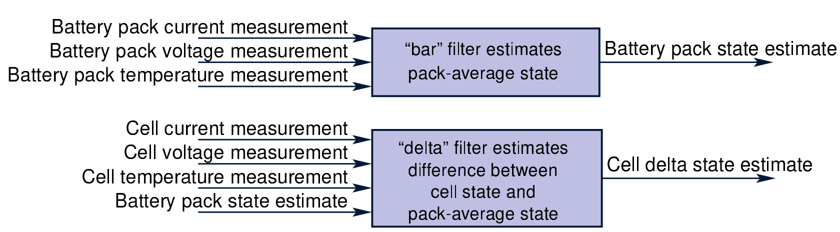
- Since all cells in series experience same current, their SOC values will
  1. Move in the same direction for any given applied current, by
  2. A similar amount (but different because of unequal cell capacities)

Defining the pack-average state

- We take advantage of this similarity by creating:
  - One algorithm to determine the composite average behavior of all cells in battery pack, and
  - Another algorithm to determine the individual differences between specific cells and that composite average behavior
- We define pack-average state "x-bar" as $\bar{x}_k = \frac{1}{N_s}\sum_{i=1}^{N_s} x_k^{(i)}$
  - Note that $0 \le \min_i(z_k^{(i)}) \le \bar{z}_k \le \max_i(z_k^{(i)}) \le 1$; therefore, its range is within the standard SOC range

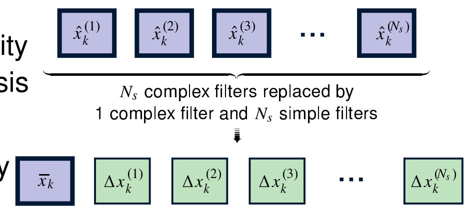
Defining the cell-difference states

- Can then write an individual cell's state vector as $x_k^{(i)} = \bar{x}_k + \Delta x_k^{(i)}$ where $\Delta x_k^{(i)}$ ("delta-x") is difference between state vector of cell i and pack-average state vector
  - Name "bar-delta filtering," inspired by the "x-bar" and "delta-x" naming convention
- Use one xKF to estimate pack-average state, N_s xKFs to estimate delta states:



Considering complexity

- Have we replaced complexity N_s with complexity $N_s + 1$?
- No! The three different types of estimator are not of identical computational complexity
  - Bar filter *is* of same computational complexity as individual state estimators used as a basis
  - But, delta filters can be made very simple
  - Also, delta states change much more slowly than average state, so delta filters can be run less frequently, down to $1/N_s$ times rate of bar filter
  - Overall complexity can be reduced from order N_s to order 1^+



Summary

- We have started to investigate some real-world concerns with implementing xKF to estimate battery-cell-model state vector
- First concern is when there is current-sensor bias
  - Not an ideal scenario, but we can attempt to estimate sensor bias so that it won’t in turn bias state estimate
- Second concern is with computational complexity
  - Using bar-delta filtering, can implement xKF very efficiently for multi-cell battery packs
- Will continue to investigate bar-delta filtering this week