## Finding SOC for every data sample

- To compute OCV vs. SOC, must first compute SOC
- DOD (in Ah) at every point in time is calculated as

$$\begin{aligned}\text{depth of discharge}(t) &= \text{total Ah discharged until } t\\ &\quad - \eta(25\,^\circ\text{C}) \times \text{total Ah charged at } 25\,^\circ\text{C until } t\\ &\quad - \eta(T) \times \text{total Ah charged at temperature } T \text{ until } t\end{aligned}$$

- Likewise, SOC corresponding to every data sample is then

$$\text{state of charge}(t) = 1 - \text{depth of discharge}(t)/Q$$

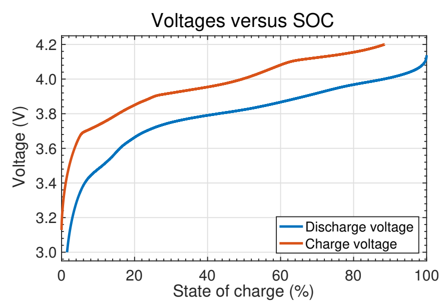
- Check: SOC at end of step 4 must be 0 %, and SOC at end of step 8 must be 100 %





## Challenge in finding OCV

- Figure plots discharge voltage from step 2 vs. SOC and charge voltage from step 6 vs. SOC
  - Same data as shown before, but now plotted vs. SOC rather than time
- Example illustrates that there is a challenge in determining OCV at all SOCs:
  - Missing discharge voltages at low SOC because test encountered cutoff voltage $v_{\min}$ in step 2 before 0 % SOC was reached;
  - Missing charge voltages at high SOC because test encountered cutoff voltage $v_{\max}$ in step 6 before 100 % SOC was reached.

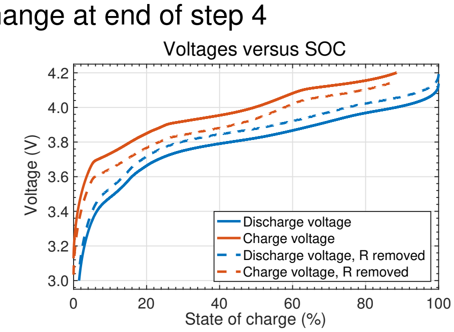






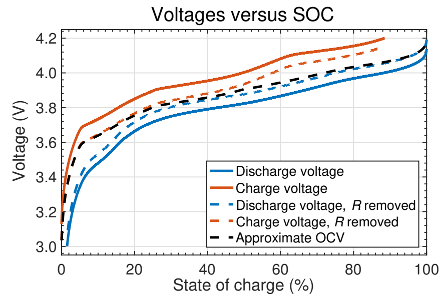

## Overcoming missing-data challenge (1)

- Estimate 100 % SOC discharge resistance $R_0$ via instant voltage change when test moves from step 1 to step 2
- Estimate 0 % SOC resistance $R_0$ via voltage change at end of step 4
- Estimate 0 % SOC charge resistance $R_0$ via voltage change when moving from step 5 to 6
- Estimate 100 % SOC charge resistance $R_0$ at end of step 8
- Assume $R_0$ changes linearly from 0 % SOC value to 100 % SOC value
- Adjust voltage curves by removing $R_0 i(t)$



## Overcoming missing-data challenge (2)

- Approximate mid-SOC steady-state resistance by considering voltage difference between adjusted curves at 50 % SOC
- Blend linearly between modified charge-voltage and discharge-voltage curves so that blend is halfway between curves at 50 % SOC
  - Follows charge curve for low SOC and discharge curve for high SOC
  - Overcomes "missing data" problem
- Figure shows OCV estimate as black dashed line








## Modeling temperature dependence

- At any given SOC, OCV variation is nearly linear in $T$
- Combine individual approximate single-temperature OCV results to make a final model of the form

$$\text{OCV}(z(t), T(t)) = \text{OCV0}(z(t)) + T(t) \times \text{OCVrel}(z(t)),$$

  where $\text{OCV0}(z(t))$ is the OCV relationship at 0 °C , and $\text{OCVrel}(z(t))$ (V/°C) is the linear temperature-correction factor at each SOC
- Once $\text{OCV0}(z(t))$ and $\text{OCVrel}(z(t))$ are determined, $\text{OCV}(z(t), T(t))$ can be computed via two computationally efficient 1D table lookups





## Computing OCV0 and OCVrel

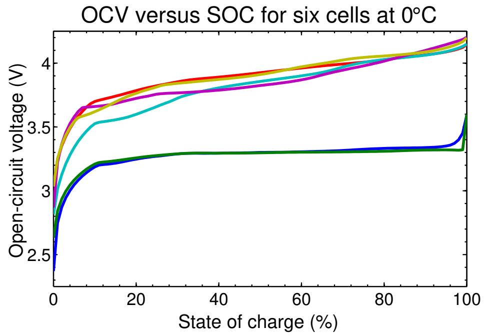
- To make $\text{OCV0}(z(t))$ and $\text{OCVrel}(z(t))$, note we can write

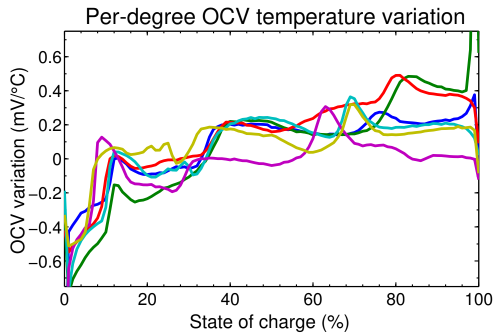
$$\underbrace{\begin{bmatrix} \text{Approx. OCV at SOC } z, \text{ temp. } T_1 \\ \text{Approx. OCV at SOC } z, \text{ temp. } T_2 \\ \vdots \\ \text{Approx. OCV at SOC } z, \text{ temp. } T_n \end{bmatrix}}_{Y} = \underbrace{\begin{bmatrix} 1 & T_1 \\ 1 & T_2 \\ \vdots & \vdots \\ 1 & T_n \end{bmatrix}}_{A} \underbrace{\begin{bmatrix} \text{OCV0}(z) \\ \text{OCVrel}(z) \end{bmatrix}}_{X}$$

  at $m$ SOC values $z$ for each of $n$ temperatures ($Y$ is $n \times m$; $A$ is $n \times 2$; $X$ is $2 \times m$)
- One way to find $X$ from $A$ and $Y$ is to use the least-squares solution, which is computed in Octave/MATLAB as `X=A\Y;`
  - We tend to use data only from tests above 0 °C because accuracy degrades at low temperatures due to high cell resistances

## Sample results

- The figures plot the outcome of this overall process for six different lithium-ion cells








## Summary

- Encounter problem of "missing data" at high and low SOC
- First, extract dis/charge voltages at every available SOC
- Find $R$ at 0 $\%$, 50 $\%$, and 100 $\%$ SOC—linearly interpolate for other SOCs
- Approximate OCV as *charge* voltage plus *charge* current times $R$ at low SOCs and as *discharge* voltage plus *discharge* current times $R$ at high SOCs
- Assemble approximate OCVs at each temperature into matrix $Y$, put temperatures in matrix $A$, compute OCV0 and OCVrel as as `X=A\Y;`
- Two 1D table lookups used to compute OCV at any given SOC and temperature as

$$\text{OCV}(z(t), T(t)) = \text{OCV0}(z(t)) + T(t) \times \text{OCVrel}(z(t))$$