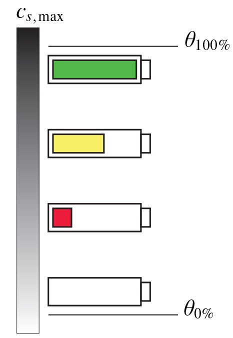
A careful definition of state of charge

- Course 1 introduced an electrochemical definition of SOC
- Defined lithium concentration stoichiometry: $\theta = c_{s,\text{avg}}/c_{s,\text{max}}$
- Stoichiometry is intended to remain between $\theta_{0\%}$ and $\theta_{100\%}$
- Then, cell SOC is computed as: $z_k = (\theta_k - \theta_{0\%})/(\theta_{100\%} - \theta_{0\%})$
- Issue: there is (presently) no direct way to measure concentrations that allow calculating SOC
- So, we must infer or estimate the SOC using measurements of only cell terminal voltage and cell current
- We've already noticed that while cell OCV is closely related to SOC, the terminal voltage is a poor predictor of OCV unless the cell is in electrochemical equilibrium (and hysteresis is negligible)

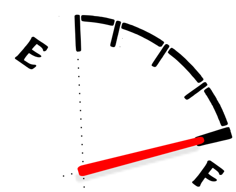


"Fully charged"

- So, how can we know true cell SOC to evaluate estimators?
- How can we know true SOC for any other purpose?

KEY POINT: Some definitions can calibrate our lab tests

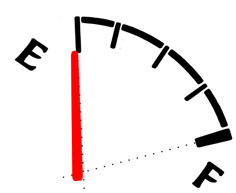
DEFINITION: A cell is fully charged when its OCV equals $v_h(T)$, a manufacturer-specified voltage (may be function of T)



- *e.g.*, $v_h(25\,°\text{C}) = 4.2$ V for LMO; $v_h(25\,°\text{C}) = 3.6$ V for LFP
- To bring cell to fully charged state: execute CC charge until terminal voltage reaches $v_h(T)$, followed by CV until charging current becomes infinitesimal
- We define the SOC of a fully charged cell to be 100 $\%$

"Fully discharged"

DEFINITION: Cell is fully discharged when OCV equals $v_l(T)$, a manufacturer specified voltage (may be function of T)



- *e.g.*, $v_l(25\,°\text{C}) = 3.0$ V for LMO; $v_l(25\,°\text{C}) = 2.0$ V for LFP
- To bring cell to fully discharged state: execute CC discharge until terminal voltage equals $v_l(T)$, followed by CV until discharge current becomes infinitesimal
- We define the SOC of a fully discharged cell to be 0 $\%$

“Total capacity”

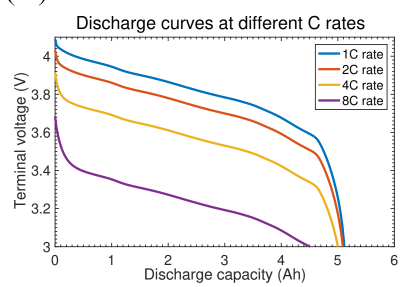
DEFINITION: Cell <u>total capacity</u> Q is quantity of charge removed as cell is brought from fully charged state to fully discharged state

- SI unit for charge is coulombs (C), but more common to use units of ampere hours (Ah) or milliampere hours (mAh) to measure the total capacity of a battery cell
- The total capacity of a cell is not a fixed quantity: it generally decays slowly over time as the cell degrades

“Discharge capacity”

DEFINITION: <u>Discharge capacity</u> $Q_{[\text{rate}]}$ is quantity of charge removed as cell discharged at constant rate from fully charged state until terminal voltage $v(t)$ reaches $v_l(T)$

- Since based on loaded terminal voltage rather than OCV, is strongly dependent on cell's internal resistance, and so also rate and temperature
- Unless $i(t) \to 0$, discharge capacity is less than total capacity
- Likewise, cell SOC is nonzero when terminal voltage reaches $v_l(T)$ when $i(t) > 0$



- The discharge capacity of a cell at a particular rate and temperature is not a fixed quantity: it also generally decays slowly over time as the cell degrades

“Nominal capacity”

DEFINITION: Cell <u>nominal capacity</u> Q_{nom} is manufacturer-specified quantity intended to be representative of 1C-rate discharge capacity Q_{1C} of a particular manufactured lot of cells at room temperature, 25 °C

- The nominal capacity is a constant value
- Since nominal capacity is representative of a lot of cells and discharge capacity is representative of a single individual cell, $Q_{\text{nom}} \neq Q_{1C}$ in general, even at beginning of life
- Also, since Q_{nom} is representative of a discharge capacity and not a total capacity, $Q_{\text{nom}} \neq Q$

“Residual capacity” and “state of charge”

DEFINITION: Cell residual capacity is quantity of charge that would be removed from cell if it were brought from its present state to a fully discharged state

DEFINITION: Cell state-of-charge is ratio of residual capacity to total capacity

- These definitions are consistent with the relationships

$$z(t) = z(0) - \frac{1}{Q}\int_0^t \eta(t) i(t)\,\mathrm{d}t, \quad \text{and} \quad z_{k+1} = z_k - \eta_k i_k \Delta t / Q$$

that you have already seen

Summary

- Careful definitions of important quantities important for remainder of the specialization
- Have defined what is meant by “fully charged”, “fully discharged”, “total capacity”, “discharge capacity”, “nominal capacity”, “residual capacity”, and “state of charge”
  - In particular, definition of state of charge is consistent with the equations you learned in course 2 of the specialization
- Can now build on these definitions to build estimators for any of the above

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