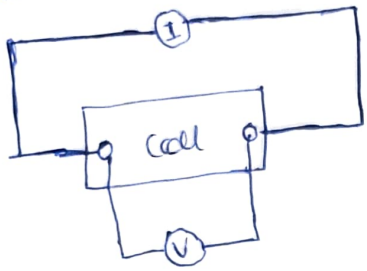
BMS2: ECM Simulation

* Week 2: Parameterization of Static Model

#1 Lab equipment for cell characterization

A cell's OCV is a static function of SOC and temperature. Separate cell tests are performed to collect data for the OCV versus SOC relationship in the lab

- Physical test setup: 4-wire connection



It is critical to use 4-wire or kelvin connection in test setup. When the battery is connected using 4-wires, the circuit sensing the cell voltage through the third wire draws essentially zero current hence zero voltage drop.

- Equipment:

Lab equipment known as battery cell cyclers or battery cell test equipment is used. An example, is one Colorado Spring manufactured by Arbin Instruments.

- Controlling Ambient Temperature

In addition to controlling the input current or power to a battery cell, the ambient temperature also should be controlled.

Example of an environmental chamber is heat, manufactured by Cincinnati Sub-Zero that can maintain constant temperatures between -45°C & 190°C.

#2 Cell test to determine OCV

The cell should be slowly discharged, then slowly charged between specified cut-off voltage by manufacturer. The test equipment will continuously measure voltage, accumulated ampere-hours discharged, and accumulated ampere-hours charged per second (1s)

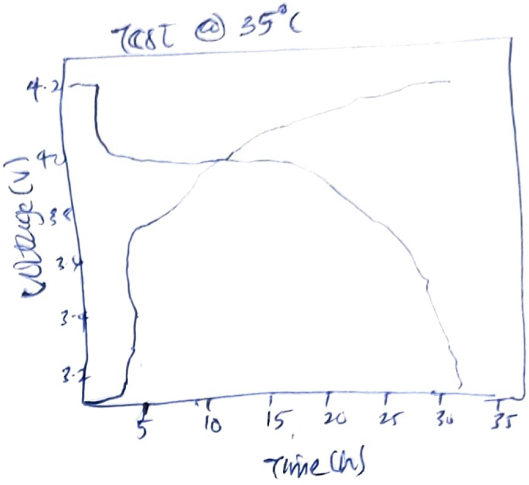
Since OCV is a function of temperature, the test is done at the number of temperature spread over cell's operational range. Also, used very low current for negligible heat generation.

* Discharge portion of test

Assuming you want to carry out OCV test @ 35°C test temperature follow this steps:

i Soak fully charged cell at test temperature (35°C) for at least 2hrs to ensure uniform temperature

ii discharge cell at a constant-current C/30 rate until terminal voltage equal Vmin



→ Test @ 25°C ; follow d same step

* Charge portion of test

i Soak cell at test temperature (35°C) for at least two hours to ensure uniform temperature throughout

ii charge the cell at constant-current rate C/30 until cell terminal voltage equal Vmax

test 1 @ 35°C
100% SOC → Vmin

Test 3 @ 35°C
0% SOC → Vmax

test 2 @ 25°C
Vmin → 0% SOC

Test 4 @ 25°C
Vmax → 100% SOC

} calibration

N.B: OCV is diffrnt frm equilibrium terminal voltage due to hysteresis, so set point SOC is not truly achieved.

Summary

i To determine OCV relationship, we generally want to average discharge and charge curves

ii Calibration tests by starting with fully charged cell and ensuring that SOC is OK after discharge and 100% after charge.

iii Record of accumulated ampere hours discharged will be used to determine total capacity, coulombic efficiency, and discharge voltage at every point in the test

iv the voltages will be processed to compute OCV

#3 Determining cell's Coulombic Efficiency

* How to process the OCV test data to compute coulombic efficiency and total capacity

- Processing data for 25°C

- Discrete time equation of SOC

$$z[k] = z[0] - \frac{1}{Q}\sum_{j=0}^{k-1} \eta[j]\, i[j]$$

k = time step
k = final data point
① time k = 100% SOC
k = 0 = 100% SOC

$$z[k] - z[0] = 1 \text{ (cancels out)}$$

- Multiply by $-Q$, split summation into

$$z[k] - z[0] = \frac{-1}{Q}\sum_{j=0}^{k-1} \eta[j]\, i[j]$$

$$0 = \frac{-1}{Q}\sum_{j=0}^{k-1} \eta[j]\, i[j]$$

$$0 = \sum_{j=0}^{k-1} \eta[j]\, i[j]$$

Split summation into discharging & charging sets

$$0 = \sum_{\text{discharge}} i[j] + \sum_{\text{charge}} \eta[k]\, i[j]$$

- Since temperature is constant; $\eta[k] = \eta(25°C)$ in all steps, the coulombic efficiency at 25°C =

$$\eta(25°C) = \frac{\text{total absolute amperehours discharge in all steps at } 25°C}{\text{total absolute ampere-hour charged in all steps @ } 25°C}$$

- Processing data for other temperatures

Once efficiency in 25°C is known, η at other temperature can be calculated.

- $z[k] = z[0] =$, but now

$$0 = \sum_{\text{discharge}} i[j] + \sum_{\text{charge at } T} \eta[k]\, i[j] + \sum_{\text{charge @ } 25°C} \eta[k]\, i[j]$$

$$= \sum_{\text{discharge}} i[j] + \eta(T) \sum_{\text{charge at } T} i[j] + \eta(25°C) \sum_{\text{charge at } 25°C} i[j]$$

- Compute Coulombic efficiency at test temperature T:

$$\eta(T) = \frac{\text{total absolute ampere-hours discharged}}{\text{total absolute ampere-hours charged at temperature } T}$$

$$= -\eta(25^\circ C)\,\frac{\text{total absolute ampere-hours charged at } 25^\circ C}{\text{total absolute ampere-hours charged at temperature } T}$$

* Capacity estimation for $25^\circ C$

Theoretically, total capacity Q is not a function of temperature, but it can be verify experimentally as well.

SOC is 100% at start of test and 0% at the end of step 4. Use SOC relationship

$$z[k] = 0 \text{ and } z[0] = 1$$

$$z[k] = z[0] - \sum_{j=0}^{k-1} \frac{\eta[j]\, i[j]}{Q}$$

- Summing over all data in step 1-4 gives Q in ampere-seconds

$$Q(25^\circ C) = \sum_{j=0}^{k-1} \eta[j]\, i[j]$$

* Capacity estimation for other temperature

- SOC is still 100% at start of test and 0% at the end of step 4
- Again, use SOC relationship where $z[k] = 0$ and $z[0] = 1$

$$z[k] = z[0] - \sum_{j=0}^{k-1} \frac{\eta[j]\, i[j]}{Q}$$

- Summing over all data in step 1-4 gives Q in ampere-seconds

$$1 = \sum_{\text{data @ } 25^\circ C} \frac{\eta(25^\circ C)\, i[j]}{Q(25^\circ C)} + \sum_{\text{data } T} \frac{\eta(T)\, i[j]}{Q(T)}$$

NoB: Assumed $Q(25^\circ C) = Q(T)$ when computing $\eta(T)$, but can solve simultaneous equations for $Q(T)$ and $\eta(T)$ if not convinced this is true.

* Summary

To determine a cell's Coulombic efficiency and total capacity:

i) Calculate absolute sum of ampere-hours discharged
ii) Calculate absolute sum of ampere-hours charged @ 25°C
iii) Calculate absolute sum of ampere-hours charged at all other temperatures
iv) Compute $\eta(25°C)$, $\eta(T)$ for other temperature of interest
v) Compute $Q(25°C)$, $Q(T)$ for other temperature of interest

NB: While total capacity is not a function of temperature, there is a strong temperature dependence on discharge capacity & charge capacity.

↳ Total capacity is the maximum number of ampere-hours that can be removed from a fully charged cell before fully discharged.

- discharge capacity: no of ampere-hours that can be extracted from a fully charged cell at some constant current rate before encountering minimum voltage limit.
- Total capacity: 100 → 0% SOC
- Discharge capacity: 100 → V_{min}

Total capacity needed for SOC estimation

#4 Determine a cell's temperature-dependent OCV

To compute OCV vs SOC, you need to compute state of charge SOC for every single data point. Instead of computing SOC, you can compute DOD

- DOD (in Ah) at every point in time is calculated as:

depth of discharge (t) = total Ah discharge until t
$-\eta(25°C) \times$ total Ah charged at 25°C until t
$-\eta(T) \times$ total Ah charged at temperature T until t

- Likewise, SOC corresponding to every data sample is then:

$$SOC(t) = \frac{1 - DOD(t)}{Q}$$

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

* Modeling temperature dependence

At any given SOC, OCV remains ~ nearly linear in T - combining individual approximate single-temperature OCV results to make a final model of the form:

$$OCV(z(t), T(t)) = OCV_0(z(t)) + T(t) \times OCV_{rel}(z(t))$$

- $OCV_0(z(t))$ is the OCV relationship at 0c and OCV_{rel} is the linear temperature correction factor at each SOC
- Once $OCV_0(z(t))$ and $OCV_{rel}(z(t))$ are determined, $OCV(z(t), T(t))$ can be computed via two computationally efficient 1D table lookups.

- To make $OCV_0(z(t))$ and $OCV_{rel}(z(t))$, note we can write:

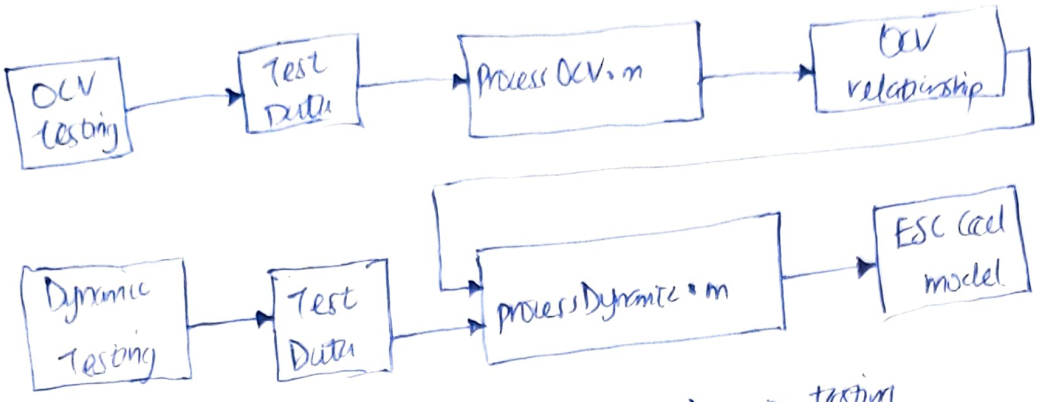
$$\underbrace{\begin{bmatrix} \text{Approx. OCV at } SOC_z, \text{ temp. } T_1 \\ \text{Approx. OCV at } SOC_z, \text{ temp. } T_2 \\ \vdots \\ \text{Approx. OCV at } SOC_z, \text{ temp. } T_n \end{bmatrix}}_{Y} = \underbrace{\begin{bmatrix} 1 & T_1 \\ 1 & T_2 \\ \vdots & \vdots \\ 1 & T_n \end{bmatrix}}_{A} \underbrace{\begin{bmatrix} OCV_0(z) \\ OCV_{rel}(z) \end{bmatrix}}_{X}$$

at m SOC value z for each of n temperatures (Y is $n \times m$; A is $n \times 2$; X is $2 \times m$)

- One way to solve/find X from A and Y is to use the least-squares solution, which is computed in Octave/MATLAB as $\boxed{X = A \backslash Y}$;
- Two 1D table lookups used to compute OCV at any given SOC and temperature as:

$$OCV(z(t), T(t)) = OCV_0(z(t)) + T(t) \times OCV_{rel}(z(t))$$

#5: Octave code to determine Static Part of an ECM



- Laboratory processes: OCV testing, Dynamic testing
- Data files: Test data, OCV relationship, ESC cell model
- Octave/MATLAB function: processOCV.m, processDynamic.m

ESC - Enhanced Self-correcting

The processOCV.m computes OCV relationship from lab-test data
↳ the code first computes $\eta(25°C)$ and $Q(25°C)$
- then adjust discharge curve to compensate for estimated R_0
- Computes approximate OCV vs SOC, compensating for steady-state resistance
- Repeat for all other test temperature
- Finally, computes OCV0 and OCVrel, combining data from all temperature
- Results saved to a model file

* Summary

This week, how to determine a cell's static OCV relationship as a function of SOC, and temperature
- Lab-test equipment
- Test required to collect the necessary data
- How to process the data to determine coulombic efficiency, total capacity, OCV

Octave/MATLAB code to produce the static model.