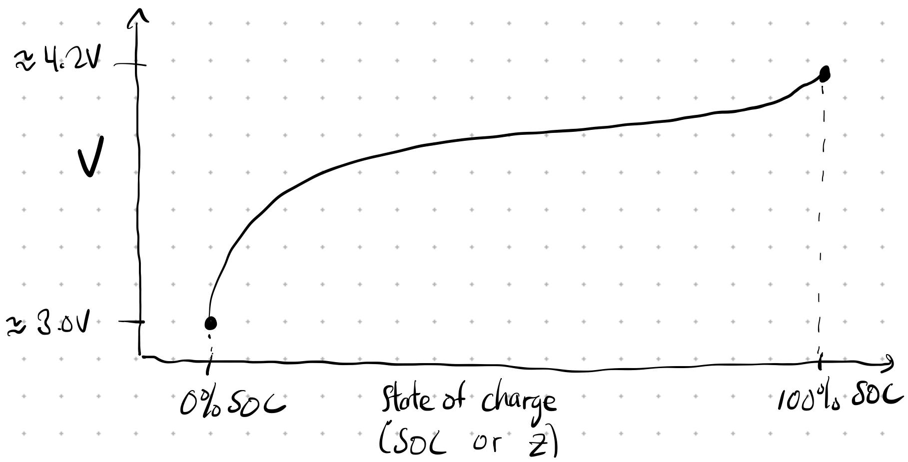
Battery Performance Metrics

Oct 12, 2021

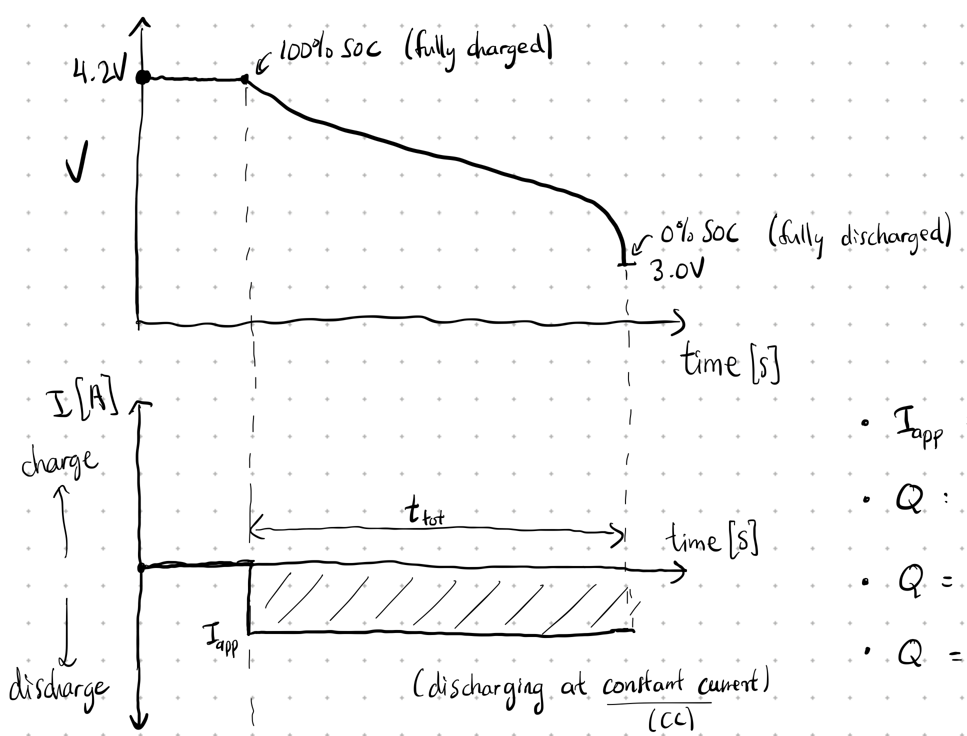
Start with the open-circuit voltage (OCV) curve: (a.k.a open circuit potential (OCP) or V_{oc})



→ Voltage limits depend on chemistry and are set by the manufacturer.

→ OCV = $f(z)$ is usually <u>measured</u>; it is a characteristic curve of a battery.

⇒ Consider a fully charged cell. Start discharging it using a constant current:



- I_{app} : Applied current [A]
- Q : Capacity [Ah] (Amp-hours)
- $Q = \int I_{app}(\tau)\, d\tau$
- $Q = I_{app} \cdot t_{total}$ (for constant current operation)

When dealing with batteries, we speak alot about capacity and energy, so let's get familiar with these units:

Capacity

- Capacity is usually measured in [Ah]
- Other common metrics include gravimetric capacity [Ah/g]
  volumetric capacity [Ah/L]
- $1\,[A] = \frac{1[\text{Coulomb}]}{1[\text{second}]} \Rightarrow 1[Ah] = 1\,\frac{[\text{coulomb}]}{[\cancel{\text{second}}]}[\cancel{\text{hour}}] \times \frac{3600[\cancel{\text{seconds}}]}{[\cancel{\text{hours}}]}$

$$\Rightarrow \quad 1\,[Ah] = 3600\,[\text{coulombs}].$$

Energy

- Energy is obtained by considering $E = \int P(\tau)\,d\tau$

energy [Wh] power [W]

- $P = I^{*}V \Rightarrow E = \int I(\tau)\,V(\tau)\,d\tau$

For constant current operation, $E = I_{app} \times \int V(\tau)d\tau \times \frac{t_{tot}}{t_{tot}}$

$$E = \underset{[A]}{I_{app}} \times \underset{[h]}{t_{tot}} \times \underset{[V]}{V_{avg}}$$

$$1\,[W] = 1\,\frac{[\text{Joule}]}{[\text{Second}]} \Rightarrow 1[Wh] = 1\,\frac{[J][\cancel{h}]}{[\cancel{S}]} \times \frac{3600[\cancel{S}]}{[\cancel{h}]}$$

$$1\,[Wh] = 3600\,[J].$$

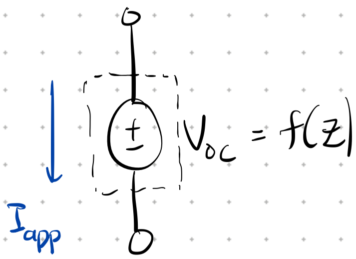
- Gravimetric energy ⇒ [Wh/kg]
- Volumetric energy ⇒ [Wh/L]

"C-rate": a convenient way to talk about current.

$$1C\,[h^{-1}] \triangleq \frac{\text{Current }[A]}{\text{Capacity }[Ah]}$$

Eg. for a 5Ah cell: 1C = 5A
2C = 10A
0.5C = 2.5A

So far, our battery model looks like this:



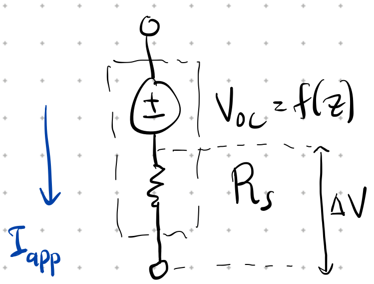
V_{OC}: open circuit voltage

z : state of charge. $z \in [0,1]$

I_{app} : Applied current.

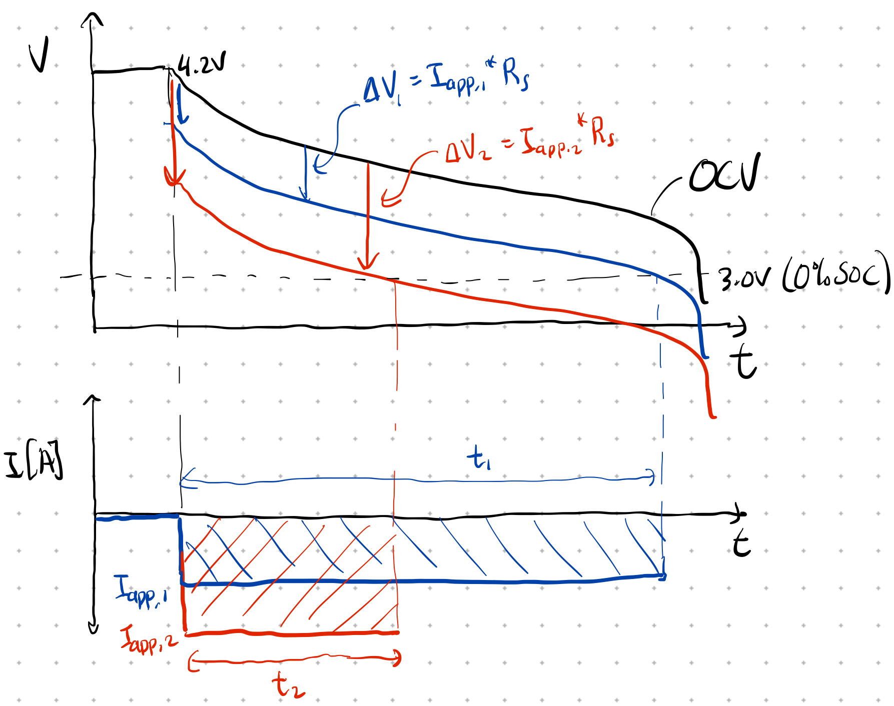
Here, a battery is simply a voltage source.

Let's add another element to make the model more realistic.



R_s: a series resistance: represents the internal resistance of the battery.

ΔV : an additional voltage drop due to R_s. ΔV will cause the cell to finish discharging more quickly.

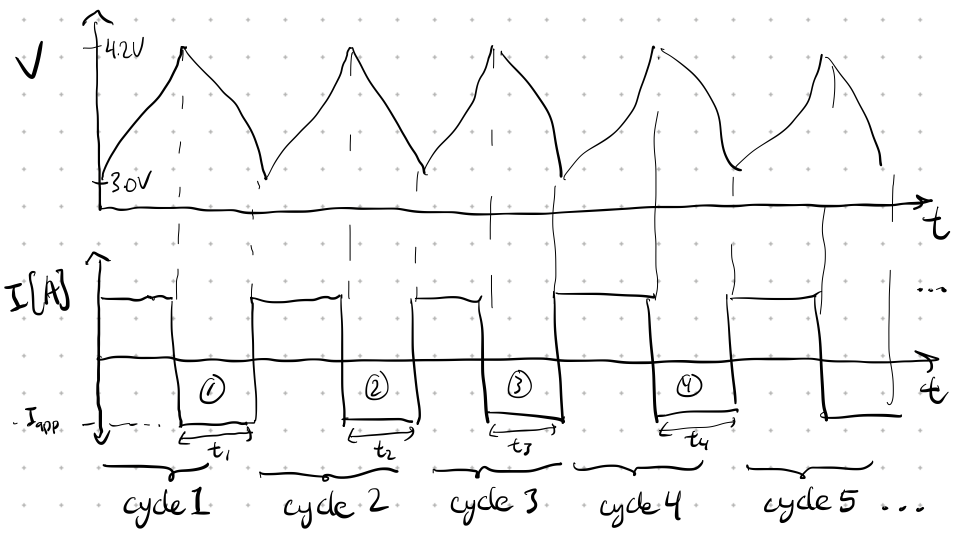


$Q_1 = I_{app,1} * t_1$

$Q_2 = I_{app,2} * t_2$

Cycle Life Characterization

1 cycle $\triangleq$ 1 charge and 1 discharge

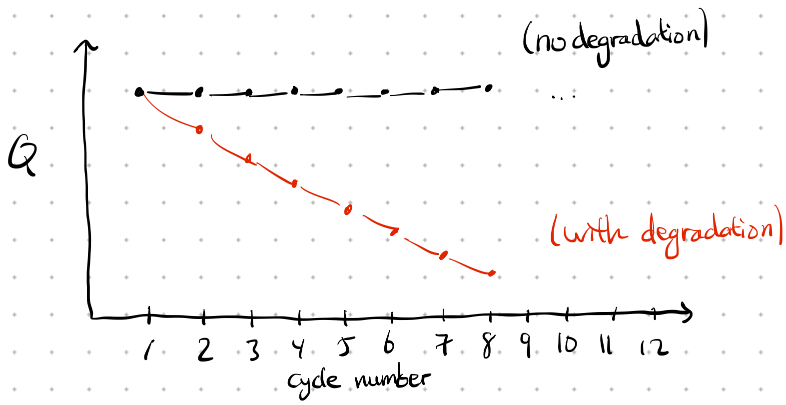


①: $Q_1 = |I_{app}| * t_1$

②: $Q_2 = |I_{app}| * t_2$

⋮

↳ plot the Q's against cycle number



"Units" Cheat Sheet

Current — Absolute Capacity — normalizations: (Gravimetric) (Volumetric)

m: mass
V: volume

$$\begin{tikzcd} I(t)\ [A] \arrow[r, "\int_0^{t_f} dt"] \arrow[d, bend right, "\times V(t)"'] & Q\ [Ah] \arrow[r, "/m"] & {[Ah/g]} \arrow[r, "/V"] & {[Ah/L]} \arrow[d, bend left, "\times V_{avg}"] \\ P(t)\ [W] \arrow[r, "\int_0^{t_f} \cdot\, dt"] & E\ [Wh] \arrow[r, "/m"] & {[Wh/kg]} \arrow[r, "/V"] & {[Wh/L]} \end{tikzcd}$$

$[Ah] = (3600\,[C])$ (SI)

$[Wh]$ " $(3600\,[J])$ (SI)

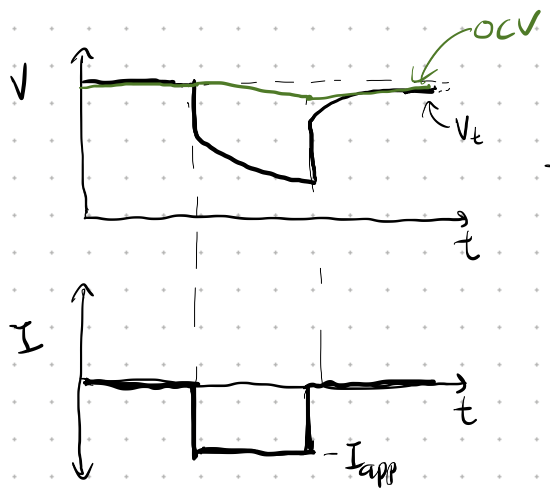
Power — Absolute Energy

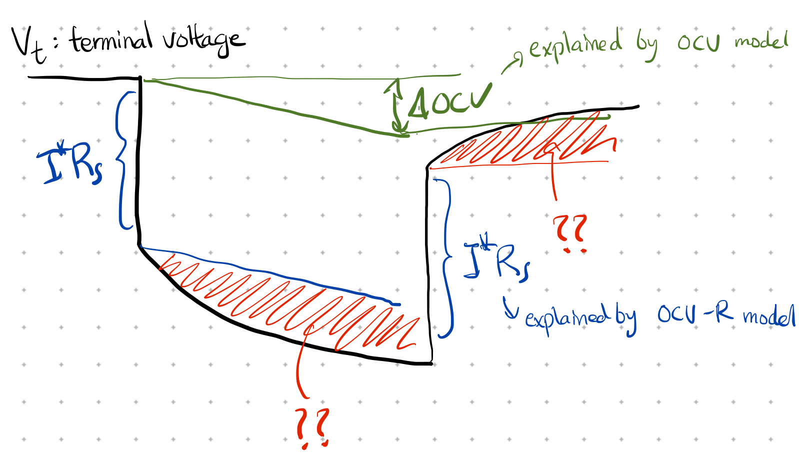
- State of charge : $z = \dfrac{1}{\underset{[Ah]}{3600\,Q}} \int_0^{t_f} I(\tau)\, d\tau \xrightarrow{\text{constant current}} \dfrac{\overset{[A]}{I} \cdot \overset{[s]}{t_f}}{3600 \cdot \underset{[Ah]}{Q}}$

- C-rate : $[h^{-1}] = \dfrac{I}{Q}$ (for constant-current (CC) operation)

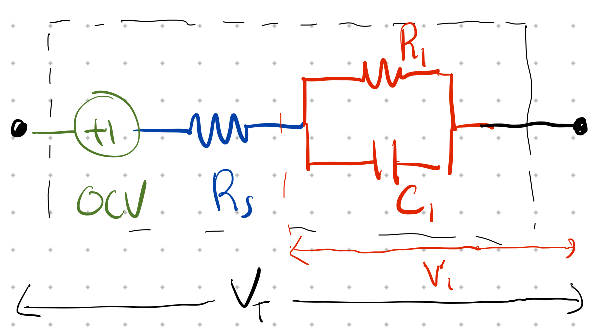
- E-rate : $[h^{-1}] = \dfrac{P}{E}$ (for constant-power (CP) operation)

Let's look at the battery voltage response slightly more carefully.





OCV-R-RC model



To be continued...