TI POWER

# Fundamentals of battery gauging algorithms

Battery Management Deep Dive Training

October 2020

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# Agenda

- Introduction to gauging
- Lithium ion battery models
- Fundamentals of gauging algorithms – CEDV and Impedance Track™ (IT)
- IT gauging configuration

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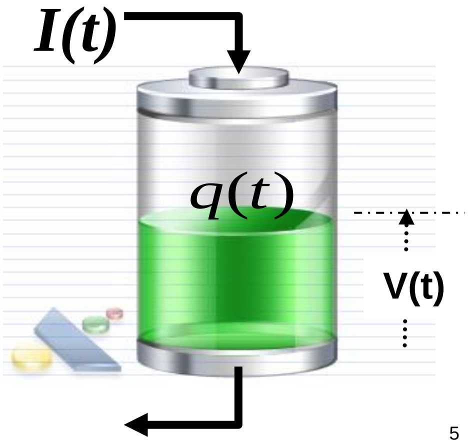
# What is fuel gauging technology

- It is the technology that predicts battery capacity under all system conditions and reports battery operational status
- **Key benefit –** ***Provides extended RUN TIME***
  - Confidently use all available battery capacity with no surprises
  - No unused capacity due to over-cautious shutdown conditions
  - Enable a controlled system shutdown, prevent any data loss and electronics damage
- A fuel gauge measures, calculates and reports:
  - Voltage
  - Charging or discharging current
  - Temperature
  - Remaining battery capacity information
    - *Capacity percentage (SOC)*
    - *Run time to empty/full*
  - Battery state of health
  - Battery safety diagnostics

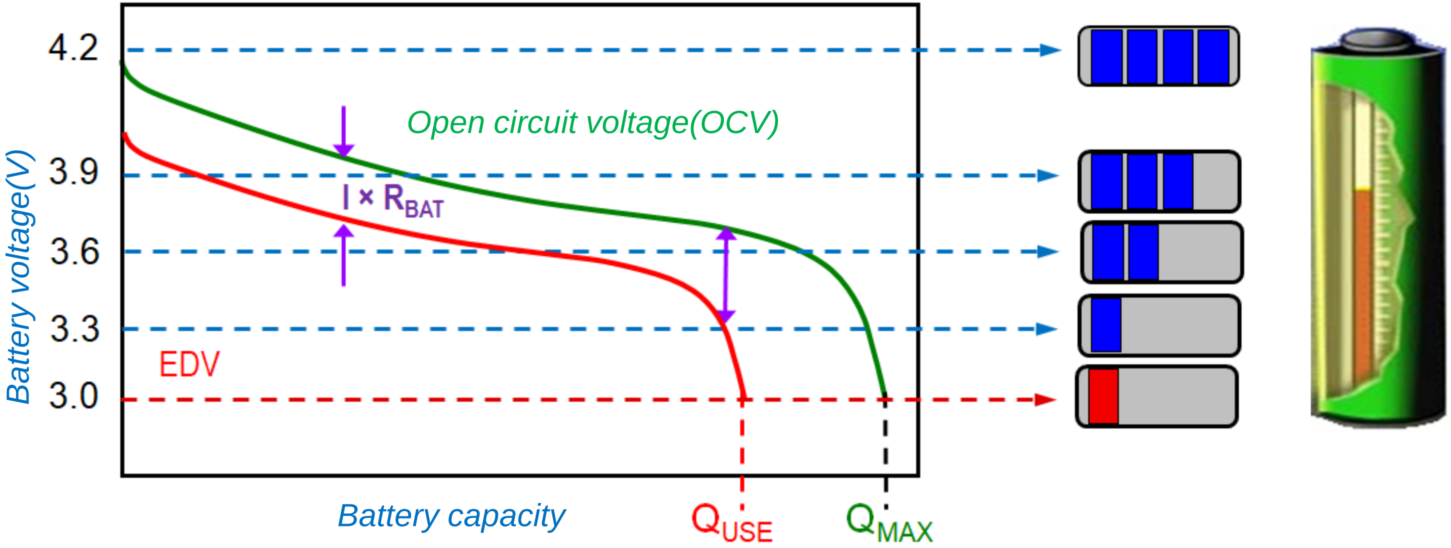
# Voltage based gauging

- One can tell how much water is in a glass by reading the water level
  - Accurate water level reading should only be made after the water settles (no ripple, etc.)

- One can tell how much charge is in a battery by reading well-rested cell voltage
  - Accurate voltage should only be made after the battery is well-rested (stops charging or discharging)



# Voltage based gauging issues




- Granularity: One bar represents over 50% capacity between 3.9 V and 3.6 V
- Pulsating load causes capacity bar to jump up and down
- Accurate only at very low current
- No compensation for cell age

# Coulomb counting based gauging

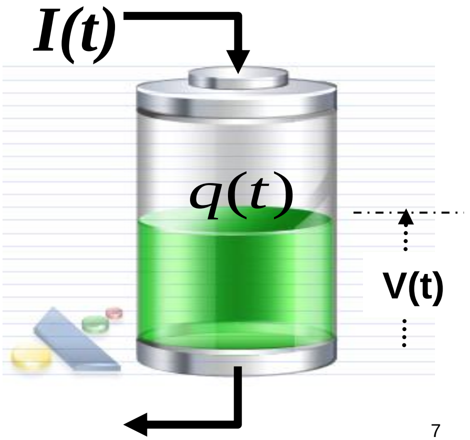
- One can also measure how much water goes in and out

- In batteries, battery capacity *changes* can be monitored by tracking the amount of electrical charges going in/out

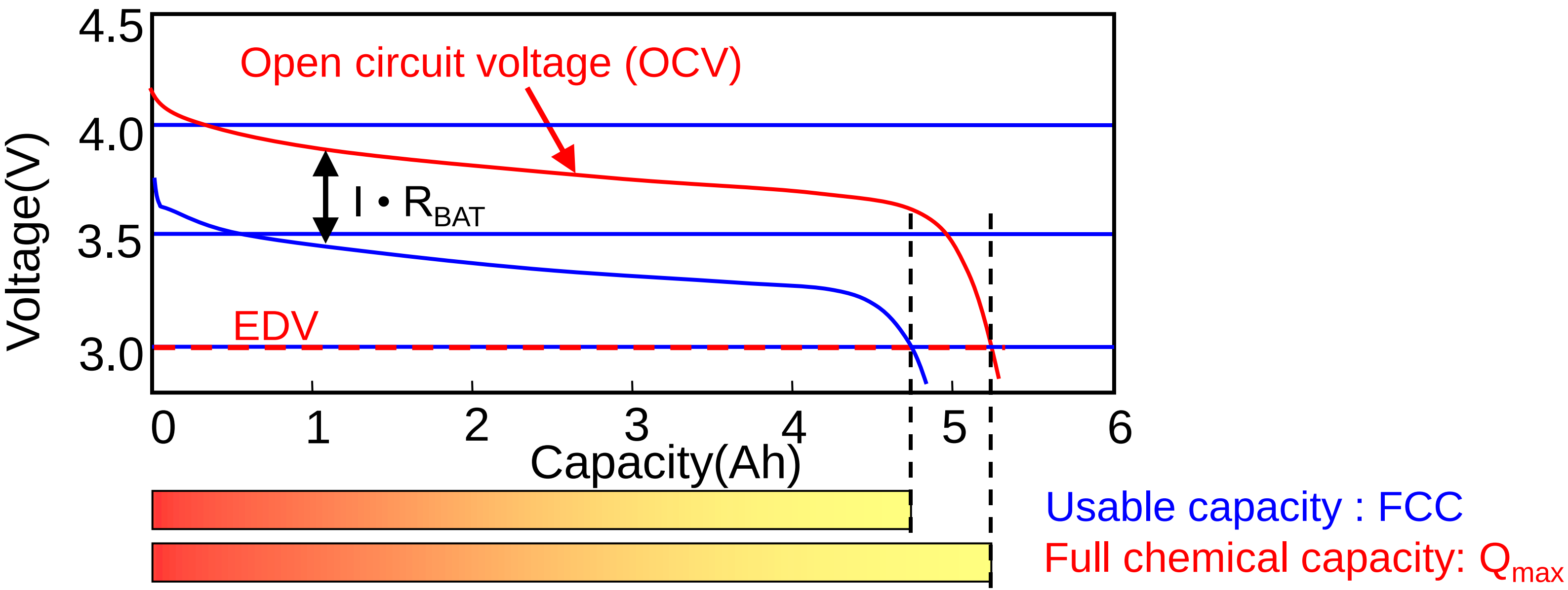
$$q(t) = q_0 + \int I(t) \cdot dt$$

$$q_k = q_0 + \Delta t \cdot \sum_k I_k$$

- But how do you know the amount of charge, $q_0$, already in the battery at the start?

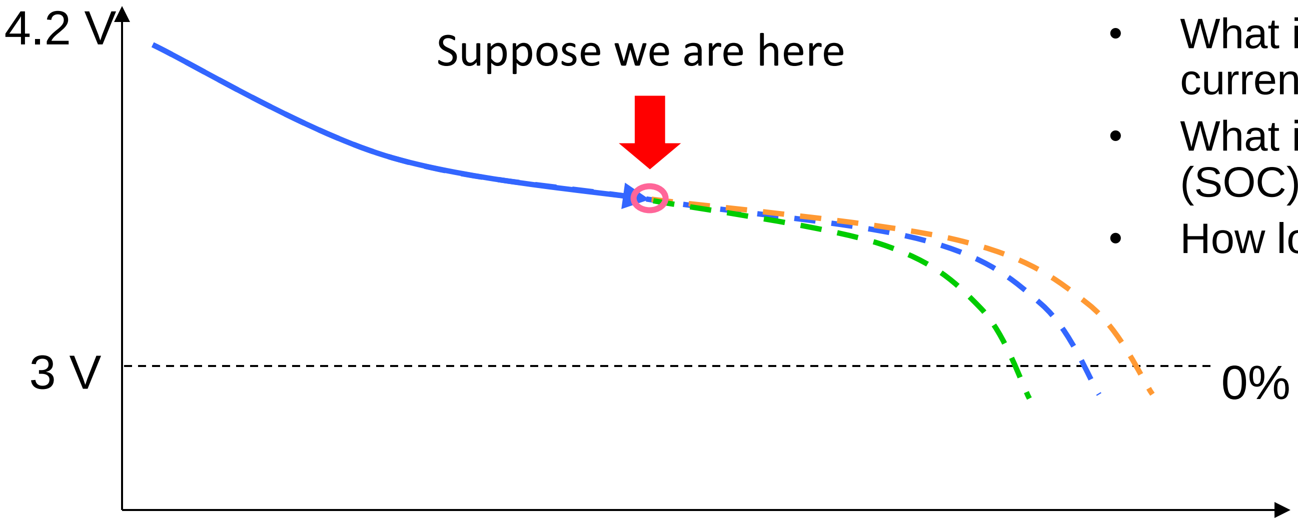


# How much capacity is really available?




- External battery voltage (blue curve), $V = V_{0CV} – I * R_{BAT}$
- Higher C-rate → EDV is reached earlier (higher $I * R_{BAT}$)

# What does a fuel gauge do?




## Which route is the battery taking?

- What is the remaining capacity at current load?
- What is the state of charge (SOC)?
- How long can the battery run?

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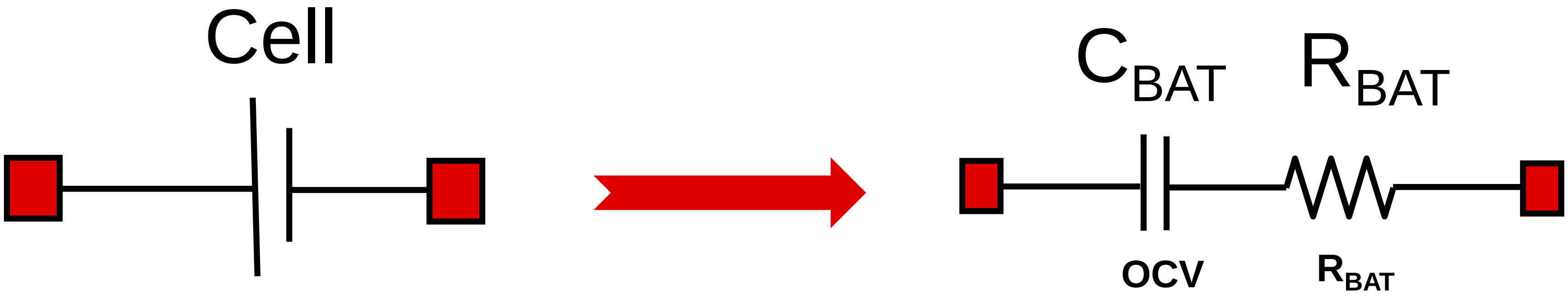
# Simple battery model

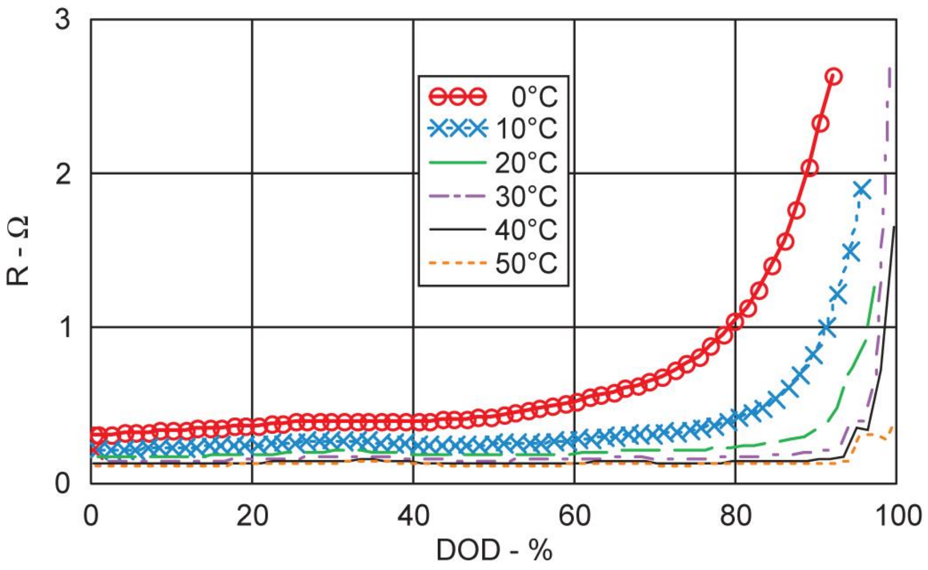
- A battery is a complex electrochemical system
- A simple steady state model can be used to determine full charge capacity (FCC)

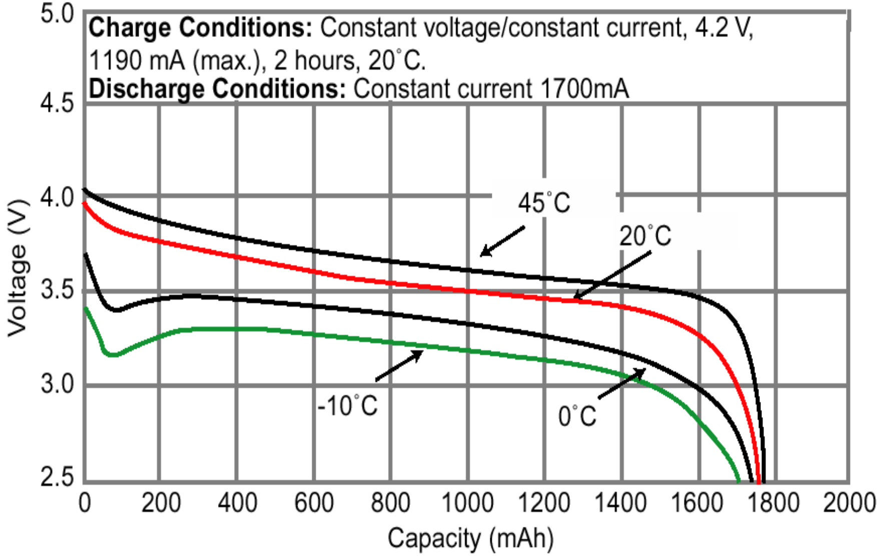



$V = OCV - I*R_{BAT}$

# Battery impedance strongly depends on temperature

Impedance decreases about 1.5 times per 10°C increase



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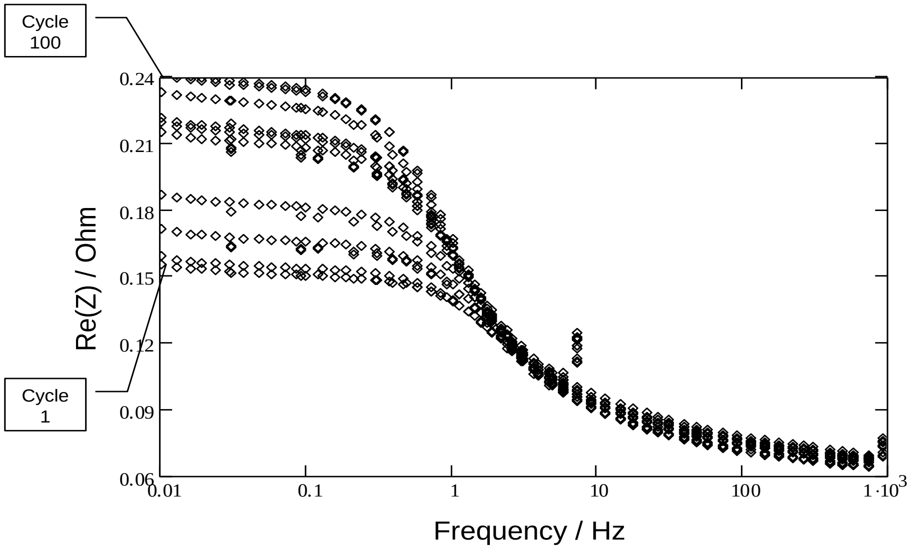
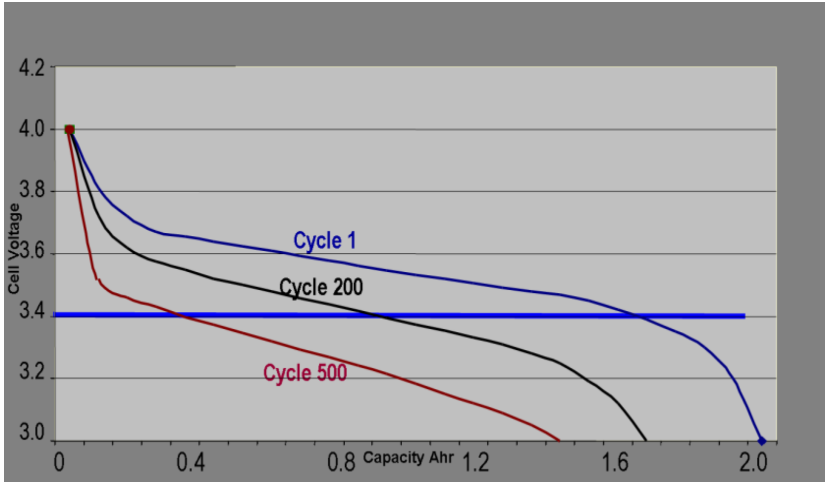
# Battery impedance strongly depends on age

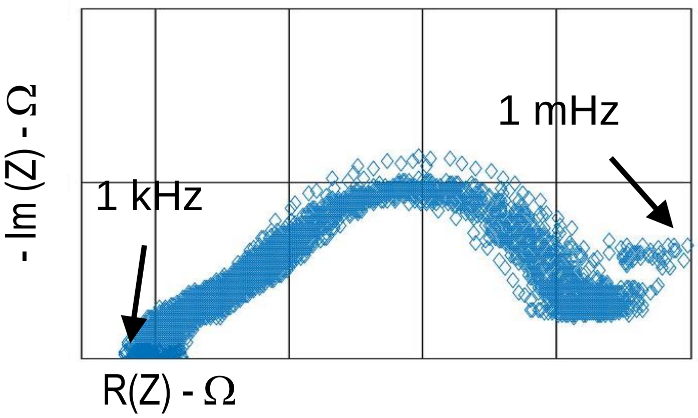
Impedance doubles after approximately 100 cycles



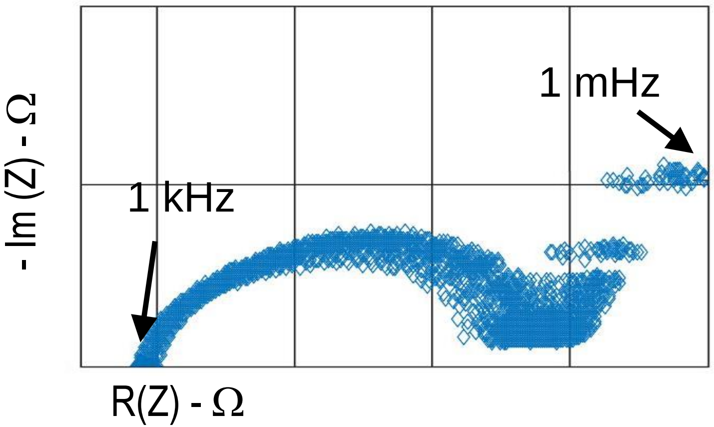



# Cell to cell variation of battery impedance

Manufacturer 1

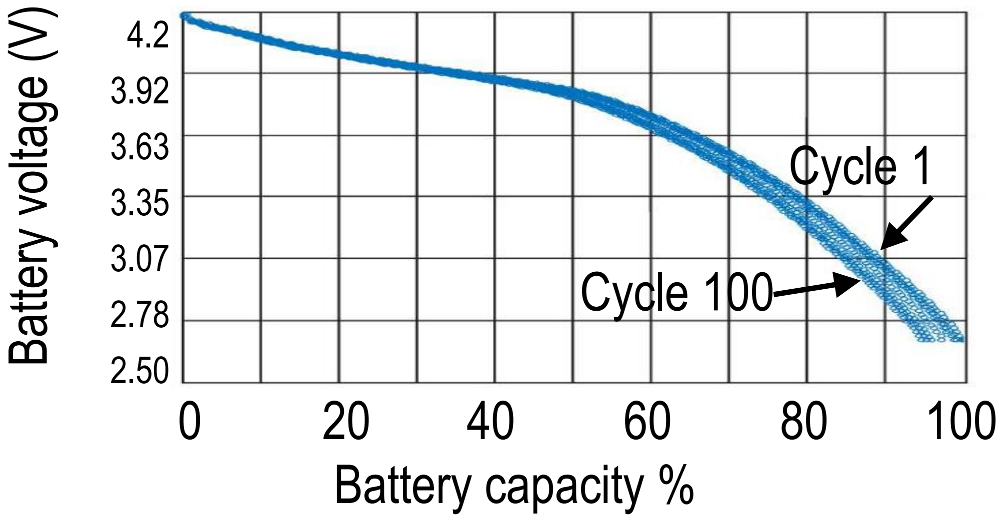



Manufacturer 2




- Low frequency (1 mHz) impedance variation 15%

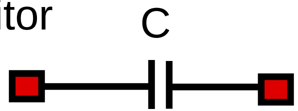
# $Q_{max}$ decreases with age



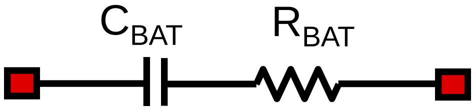

- Chemical capacity reduces by 3-5% after 100 cycles
- Hence, it is very important to update $Q_{max}$

# Transient response

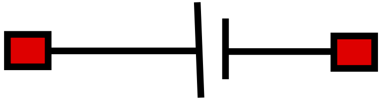
Capacitor

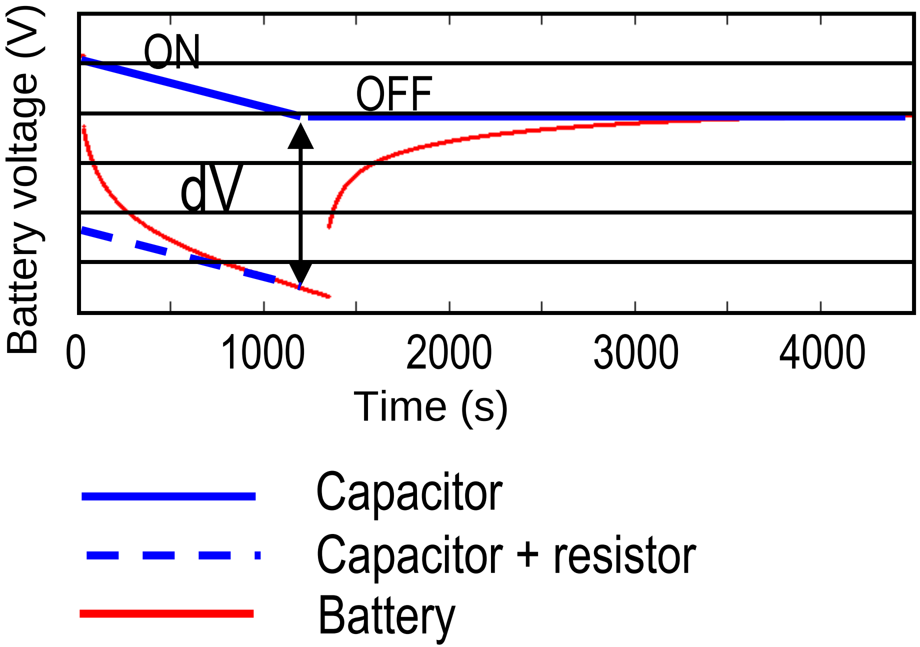



Capacitor + resistor

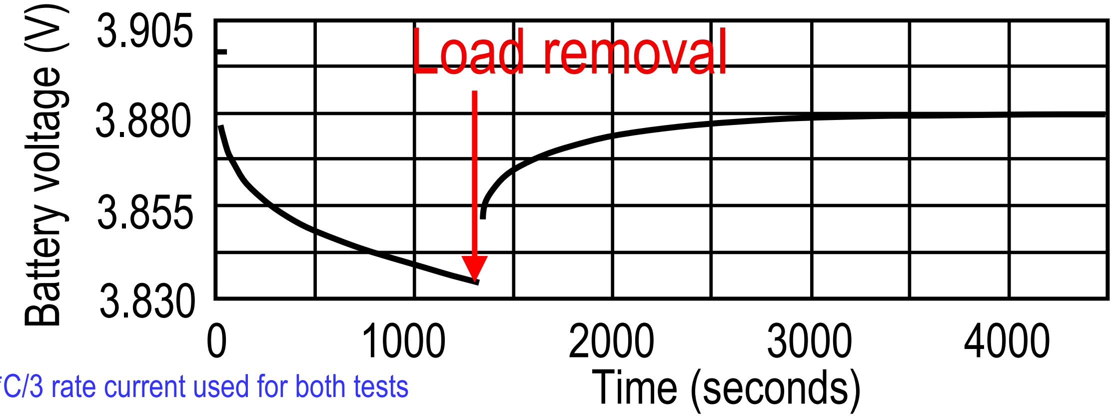



Battery

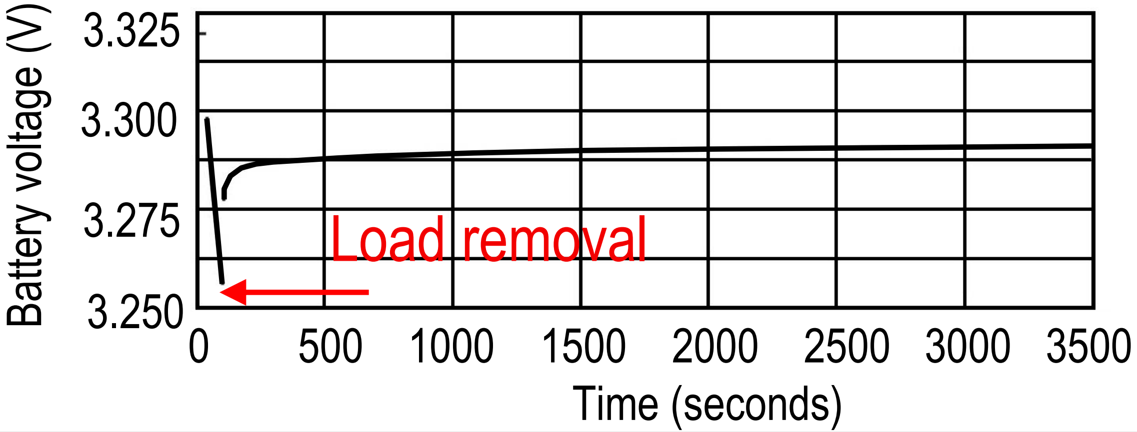




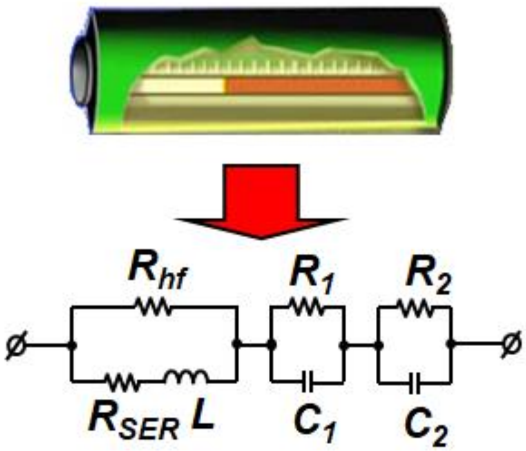
# Transient response




*C/3 rate current used for both tests




- Complete relaxation takes about 2000 seconds
- Different voltage at different instants
- Voltage difference between 20 and 3000 seconds is over 20 mV



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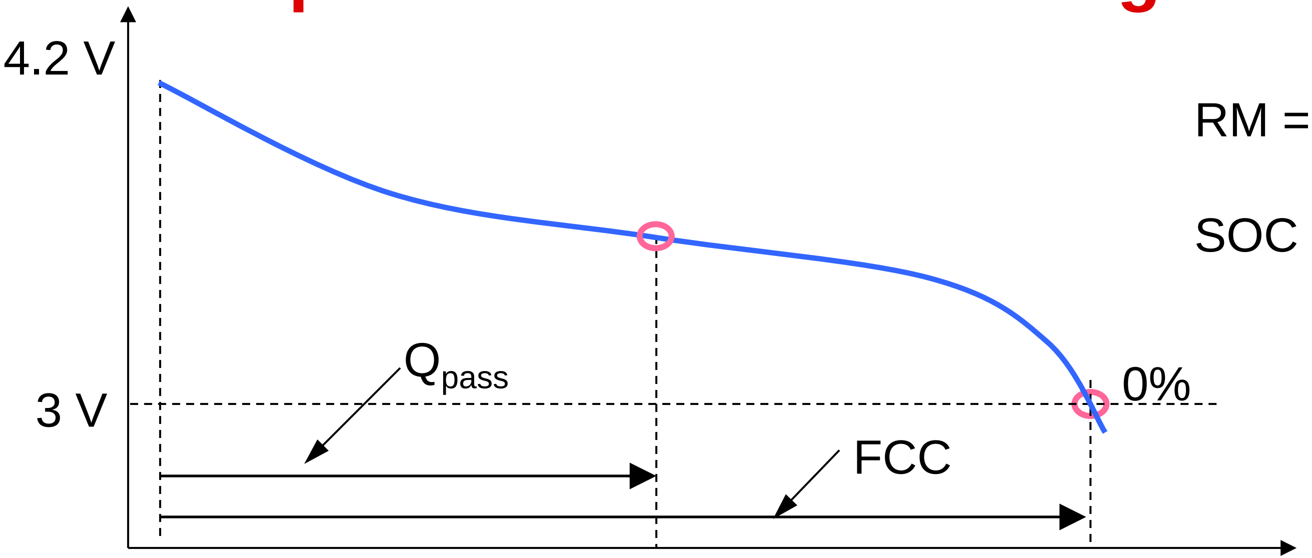
# CEDV – Compensated end of discharge voltage

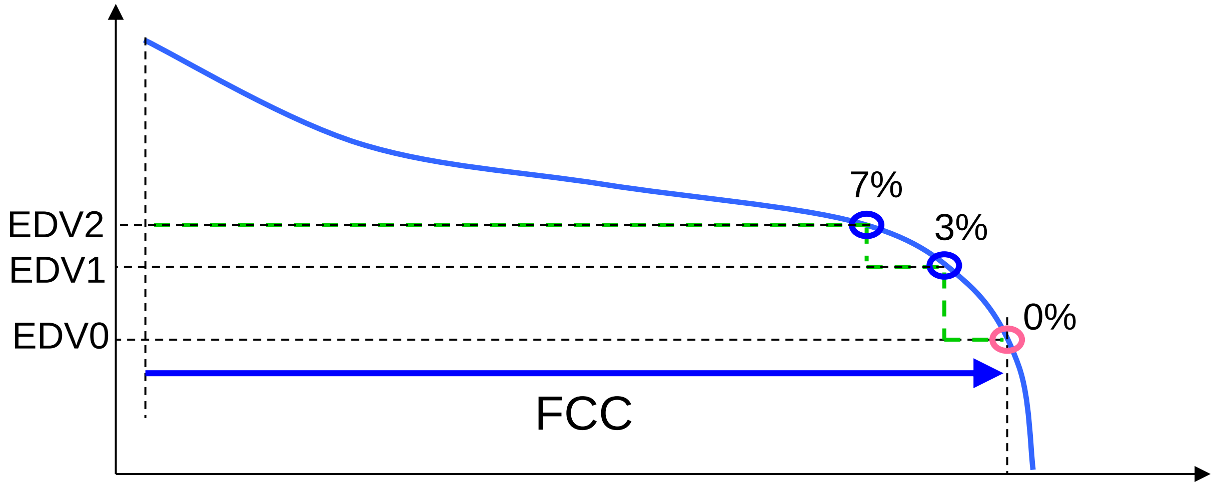



$RM = FCC - Q_{pass}$

$SOC = RM/FCC$

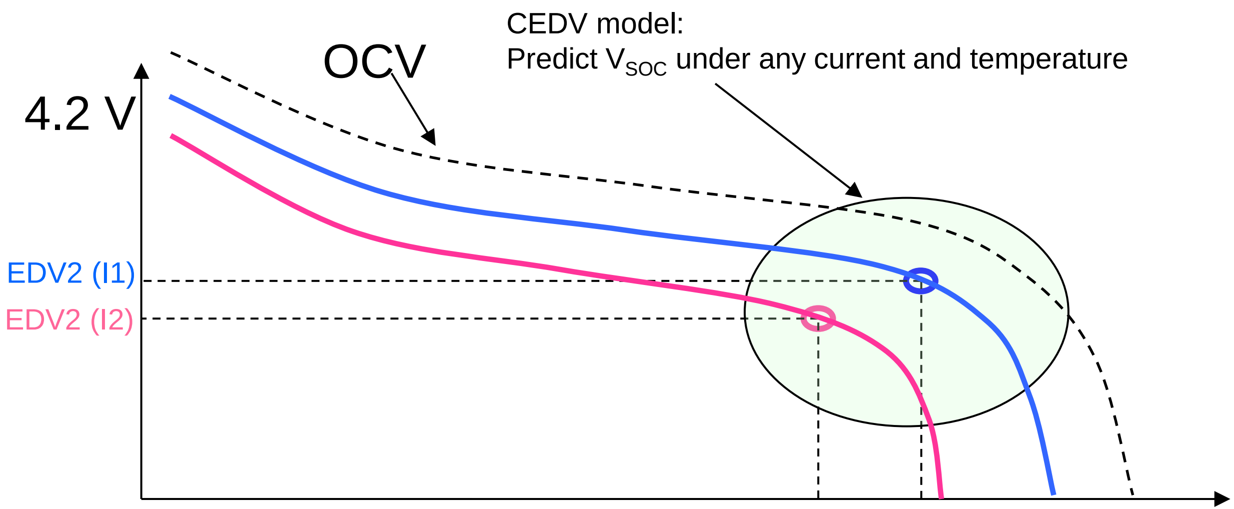
- A coulomb counting based gauging
- State of charge (SOC) at each moment is RM/FCC
- FCC is updated every time full discharge occurs

# Learning FCC before fully discharged




- It is too late to learn when 0% capacity is reached → learning FCC before 0%
- We can set voltage thresholds that correspond to given percentage of remaining capacity
- EDV1 and EDV2 are the voltages that correspond to 3% and 7% respectively
- However, EDV1 and EDV2 depend on current and temperature

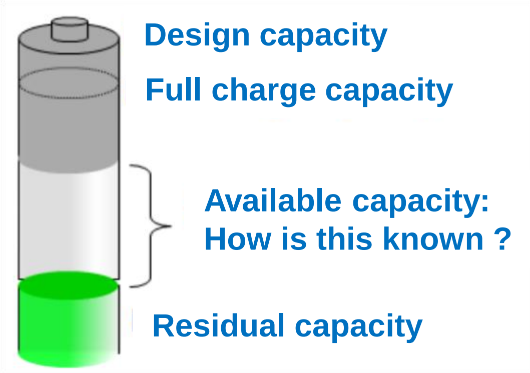
# Learning FCC before fully discharged



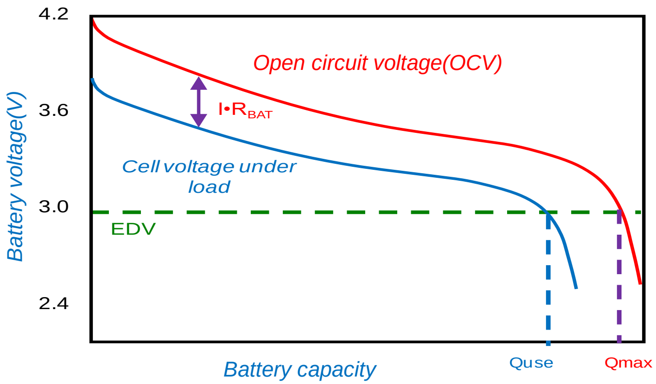

- Modeling last part of discharge allows calculation of EDV2 and EDV1 as a function V(SOC, I, T)
- Substituting SOC = 7% allows calculation in real time of CEDV2 threshold that corresponds to 7% capacity at any current and temperature

# IT – Impedance Track™

- The Impedance Track algorithm incorporates
  - *Voltage based gauge: accurate gauging under no load*
  - *Coulomb counting: accurate gauging under load*
  - *Real time impedance update*
  - *Remaining run time calculation*
  - *State of health calculation*




- Uses **impedance, discharge rate** and **temperature** to calculate the usable capacity, also known as FCC *(full charge capacity)*



# What are the main characteristics of Impedance Track™?

1. *Chemistry table* in data flash

   $OCV = f(DOD,T); R = g(DOD,T)$

2. *Update max chemical capacity* for each cell

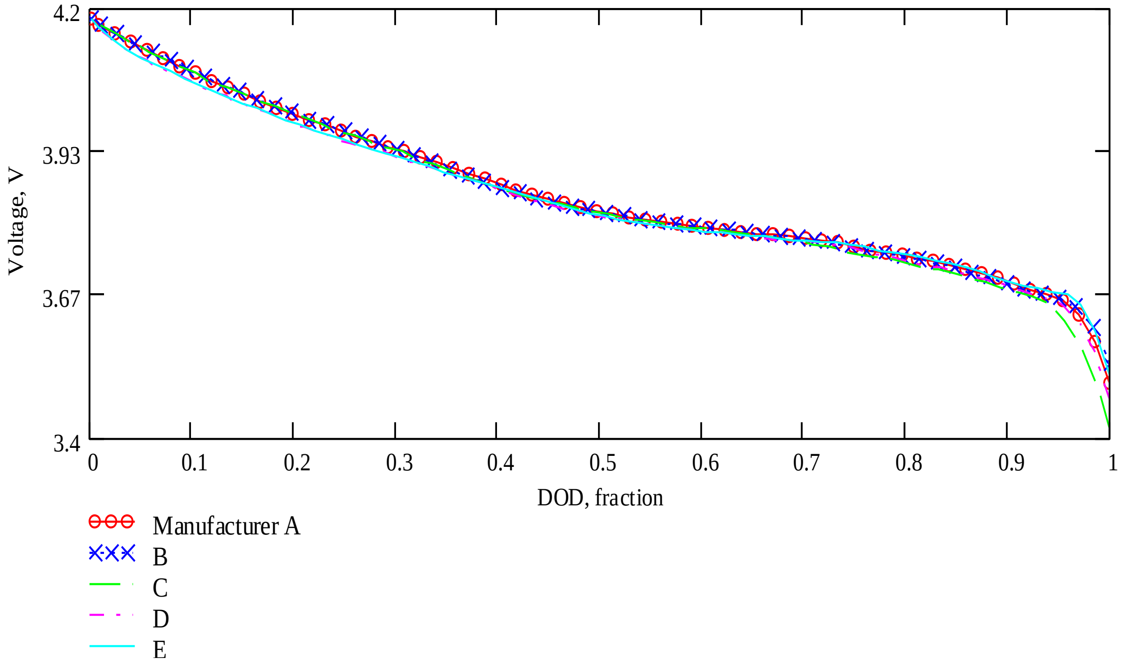
   $$Q_{max} = \frac{PassedCharge}{(DOD1 - DOD2)}$$

3. *Impedance learning* during discharge

   $$R = \frac{V - OCV}{I}$$

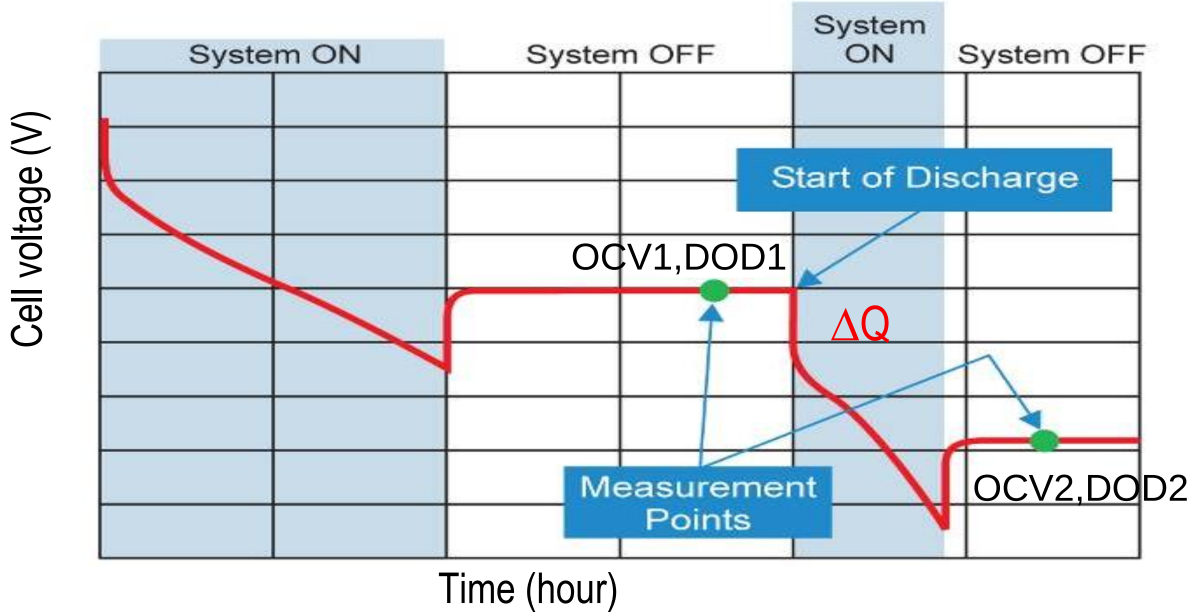
4. Run periodic *simulations* to update predictions of remaining and full charge capacity

# OCV (open circuit voltage)




- Data flash contains the OCV tables
- OCV profiles can be very consistent if base cathode electrode chemistry is the same, such as LCO, NMC, LFP, etc.
- Same OCV database can be used with batteries produced by different manufacturers if base chemistry is same

# Measuring OCV and updating $Q_{max}$

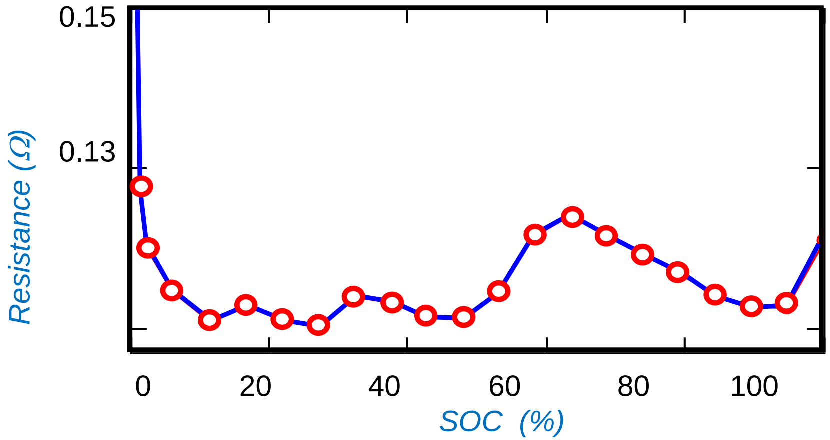



- Passed charge is determined by coulomb counting
- DOD1 and DOD2 computed from the measured OCV

$$Q_{max} = \frac{\Delta Q}{DOD2 - DOD1}$$

# Measuring and updating resistance

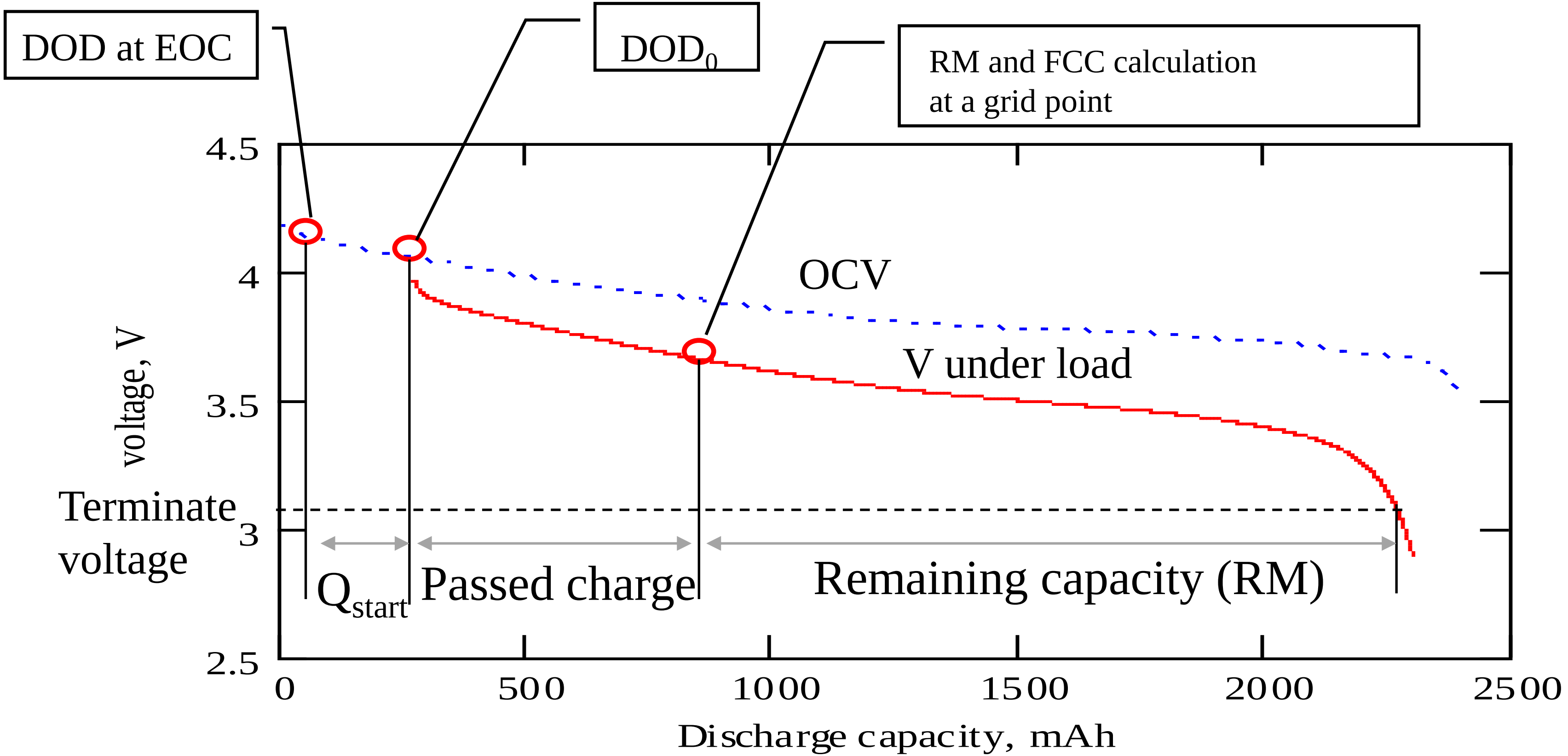
- Data flash contains a fixed table: $R_a = f\,(SOC,\ T)$




- Resistance is measured real time and the $R_a$ tables are updated

$$R_{BAT} = \frac{OCV - V_{BAT}}{I_{AVG}}$$

# Simulation to find RemCap and FCC



# What are the main advantages of Impedance Track™ (IT)?

- **Dynamic (learning) ability**
  - **Temperature variability in applications**
    - IT considers cell impedance changes due to increase/decrease in temperature
    - IT incorporates thermal modeling to adjust for self heating
  - **Load variation**
    - IT will keep track of voltage drops due to high load spikes
- **Aged battery**
  - IT can adjust for changes in useable capacity due to cell aging
- **Increased run time**
  - A lower terminate voltage can be utilized with an IT based gauge
- **Flexibility**
  - Cell characterization
  - Host system does not need to perform any calculations or gauging algorithms

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# Impedance Track™ (IT) configuration

The best performance from IT gauges can be obtained via correct configuration:

- Determine and program the correct ChemID
  - Create relax-discharge-relax logs and use the GPC Chemical ID Selection tool to identify a close match
  - If no match, send cells to TI to characterize and create a new ChemID
- After programming the ChemID, perform learning cycle (optimization cycle) to learn the $R_a$ and $Q_{max}$ values and finalize the golden image

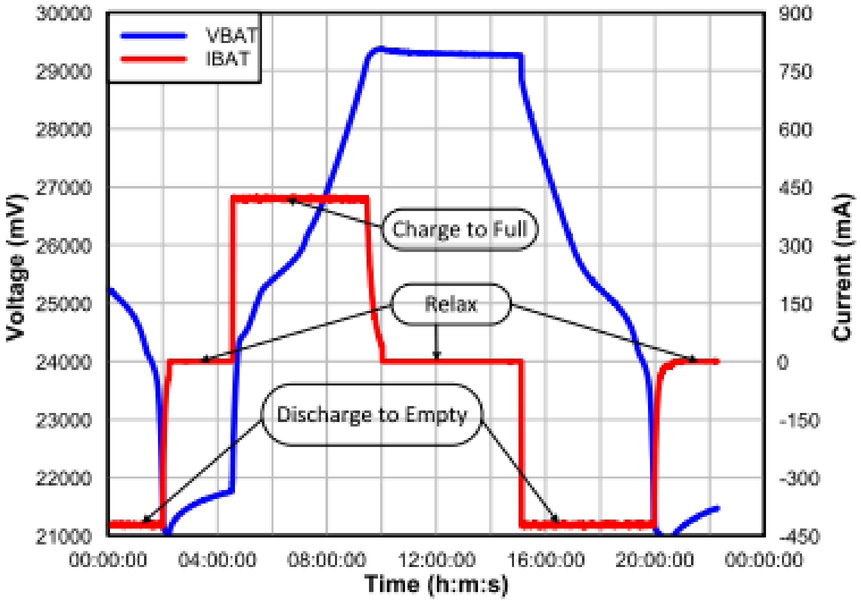
# Before performing the learning cycle

Make sure to enter the correct values for the following parameters:

- *Design Capacity*
- *Design Voltage*
- *Charge Term Taper Current*
- *Discharge (Dsg) Current Threshold*
- *Charge (Chg) Current Threshold*
- *Quit Current*
- *Term Voltage*

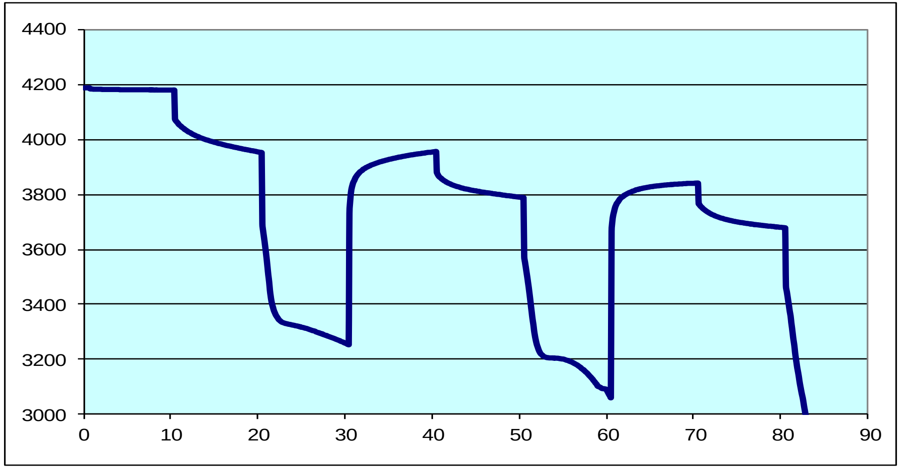
# Learning cycle procedure

- Discharge battery to empty
- Relax for at least 5 hours
  - *Enable IT(0x21)*
  - *Update Status Changes from 00 to 04*
- Charge battery to full
- Relax for at least 2 hours
  - *$Q_{max}$ updates at this point*
  - *Update Status Changes to 05*
- Discharge battery to empty using rate between C/10 and C/5
  - *Resistance tables are updated during the discharge cycle*
- Relax for at least 5 hours
  - *Update Status Changes to 06*




http://www.ti.com/lit/an/slua903/slua903.pdf

# How to improve performance for dynamic loads




- **Symptom**
  - Gauge jumps to 0% when load current suddenly increases
- **Possible causes**
  - Voltage dropped below Terminate Voltage with heavier current
  - Gauge updated prediction with new heavier load and expects "empty" will be reached immediately

# Fuel gauge configuration: *Load Mode*

- Do NOT increase Terminate Voltage as further guard band!
- If possible, lower Terminate Voltage.  Trust Impedance Track™!
- **Change Load Mode and Load Select to another option**

***Load Mode*** = 0

- Gauge will use a constant current load for simulations

***Load Mode*** = 1

- Gauge will use a constant power load for simulations
- As the battery voltage decreases, the current draw will increase to maintain a constant power (P = I*V)

# Fuel gauge configuration: *Load Select*

- ***Load Select*** tells the gauge what load to assume for simulations

***Load Mode = 0: (constant current)***

- 0 = Avg I Last Run
- *<u>1 = Present average discharge current</u>*
- 2 = Current
- *<u>3 = AverageCurrent</u>*
- 4 = DesignCapacity/5
- 5 = AtRate (mA)
- 6 = User-Rate-mA
- 7 =  Max Avg I Last Run

***Load Mode = 1:  (constant power)***

- 0 = Avg P Last Run
- *<u>1 = Present average discharge power</u>*
- 2 = Current x Voltage
- *<u>3 = AverageCurrent x Voltage</u>*
- 4 = DesignEnergy/5
- 5 = AtRate (cW)
- 6 = User-Rate-cW
- 7 = Max Avg P Last Run

# How to improve performance at low temperatures

## Symptom:

- SOC jumps to 0% at low temperatures

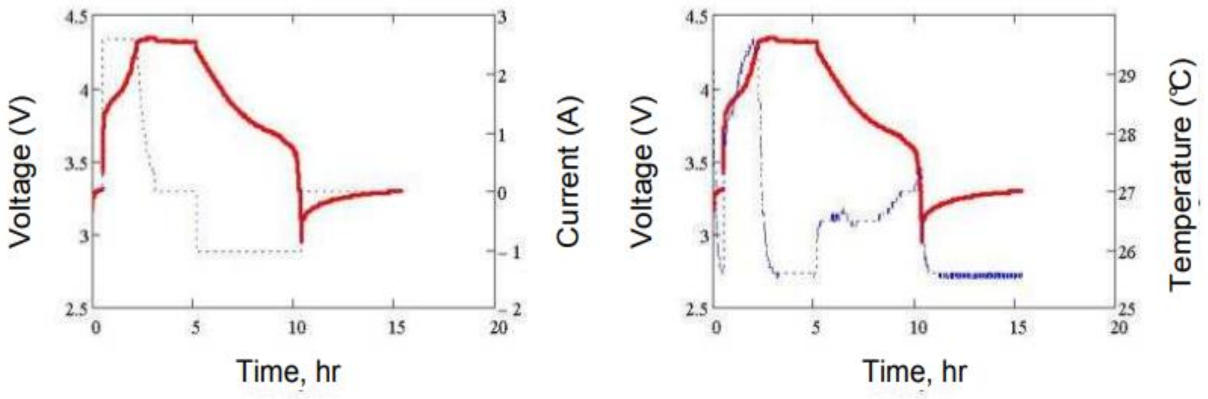
## Possible causes:

- Incorrect $R_b$ lo values and/or thermal model parameters

## Resolution:

- Perform an $R_b$-tweak test to get the correct $R_b$ and thermal model parameters using the online GPC tool

# $R_b$-tweak test procedure




1. Perform the charging at room temperature and let the battery relax for 2 hrs
2. Set discharge temperature to 25°C and wait for 1 hr until pack reaches thermal equilibrium
3. Discharge the battery at system typical high rate until the minimal voltage and let the battery relax for 5 hrs to reach full equilibrium OCV
4. Go to step 1, and repeat all steps with temperature set to 0°C in step 2

*More details can be found here: [http://www.ti.com/lit/ug/sluubd0/sluubd0.pdf](http://www.ti.com/lit/ug/sluubd0/sluubd0.pdf)*

# Summary

- Gauging is extremely important for extended battery run time
- Accurate modeling of the battery, particularly the battery resistance enables accurate prediction of the usable capacity (FCC)
- Impedance Track™ gauges have the capability of handling a wide variety of battery operating conditions, such as varying temperature, varying loads and age
- Correct configuration is essential in obtaining the best performance from the gauges

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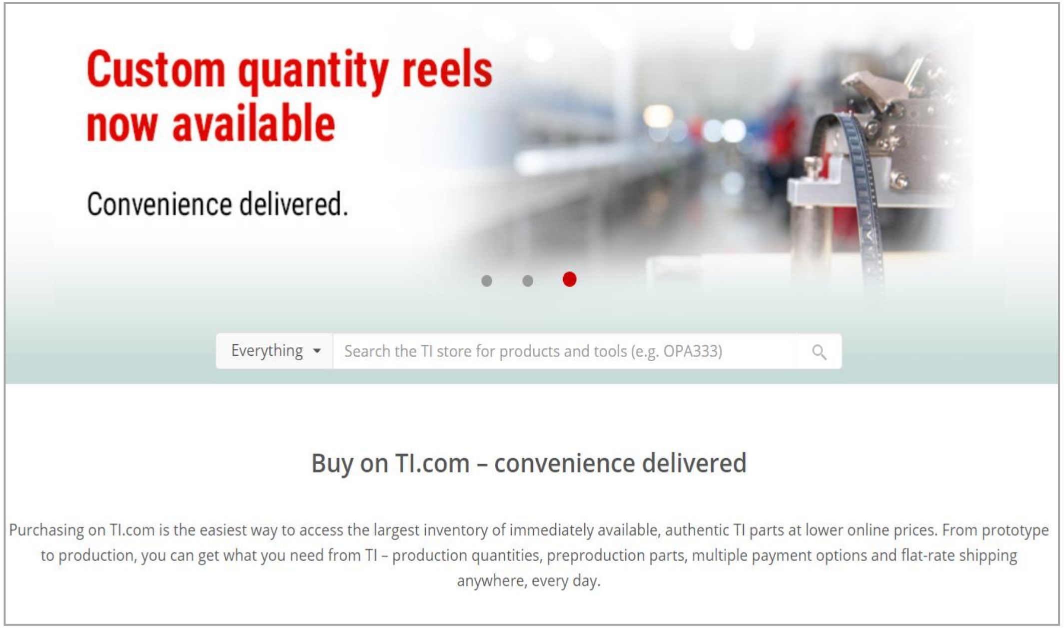


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