Texas Instruments

TI POWER

TI *Live!* BATTERY MANAGEMENT SYSTEMS SEMINAR

DOMINIK HARTL

BATTERY GAUGING FUNDAMENTALS

Agenda

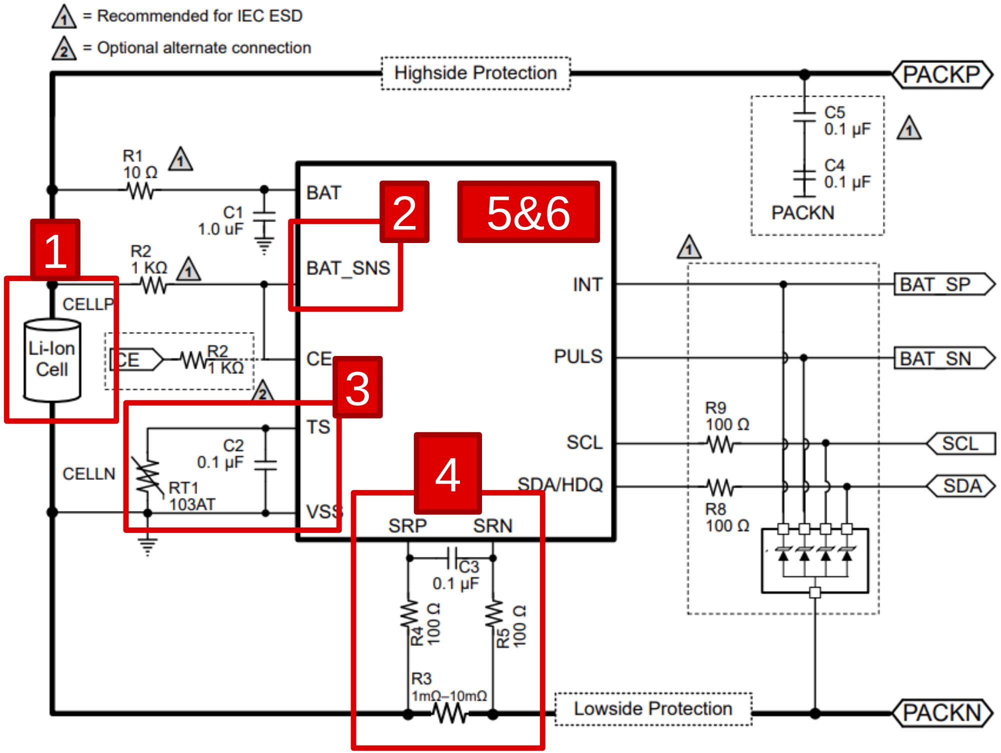
- What is a gauge & what can it do?
- Battery basics
- How to make a gauge
- Gauging algorithm types
- Gauging challenges

What is a gauge

Custom microcontroller with an accurate ADC and coulomb counter!

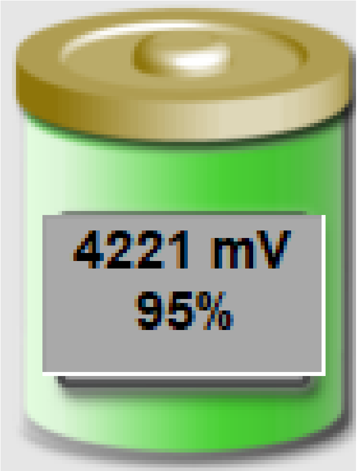
It needs…

1. Battery
2. Voltage measurement
   - Ideal at least 1 mV accurate
3. Temperature measurement
   - Battery temperature
4. Current measurement
   - Integrating ADC
   - Accumulating passed charge
   - Current measurements
5. CPU/RAM
6. Non-volatile memory
   - Flash or EEPROM and/or ROM



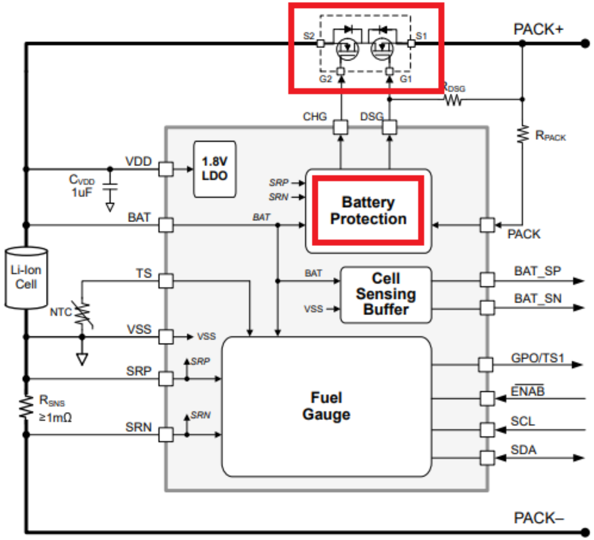
What can a gauge do?

- Predict the future
  - capacity (% or mAh or mWh)
  - run-time predictions (in minutes)
  - what-if predictions
  - charge time predictions
- Enhance safety
- Be a “black box”
- Extend run-time
- Extend lifetime of a battery



What can a gauge do?

- Predict the future
- Enhance safety
  - controls protection functions inside the battery pack
- Be a “black box”
- Extend run-time
- Extend lifetime of a battery



What can a gauge do?

- Predict the future
- Enhance safety
- Be a “black box”
  - record usage conditions
  - assist with warranty analysis and troubleshooting
  - assist with supplier quality improvement
- Extend run-time
- Extend lifetime of a battery

What can a gauge do?

- Predict the future
- Enhance safety
- Be a “black box”
- Extend run-time
  - confidently use all available battery capacity with no surprises
  - no unused capacity due to over-cautious shutdown conditions
- Extend lifetime of a battery

What can a gauge do?

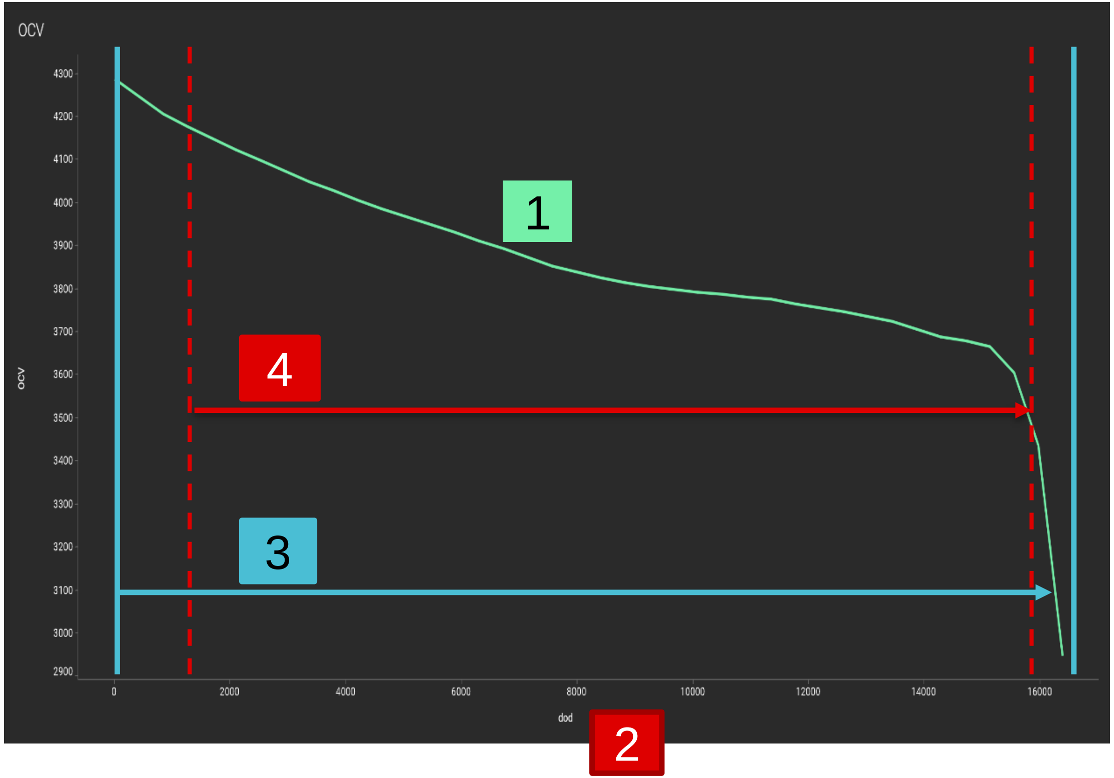
- Predict the future
- Enhance safety
- Be a “black box”
- Extend run-time
- Extend lifetime of a battery
  - get more cycles from a battery
  - uses dynamic learning and battery modeling to control healthy, safe, and fast charging

What else can a gauge do…

- Authentication
  - Ensure only safe/authorized packs are used
- State of health
  - Objectively tell user when a battery is at end of life
- Traceability
  - Store serial numbers, production information, and more inside gauge’s flash memory
- Instrumentation in system
  - Highly accurate voltage, current, and temperature measurements
  - Useful for system characterization and production tests
- Assist with power management
  - Recommend maximum current that won’t crash battery
  - Allow host to remain in low power state and wait for interrupts

(1) Battery - terms

1. Open circuit voltage (OCV)
    - Unloaded battery voltage
2. Depth of discharge (DOD)
    - Internal factor to give the gauge more resolution (2^{14})
    - 0 = 100% state of charge
    - 16384 = 0% state of charge
3. QMax
    - Maximum battery capacity under no load
    - Never achievable in real application
4. Full charge capacity
    - Usable capacity
    - Not charged to battery max
    - Not discharged to min cell V
    - FCC = [Qmax - IR(load) – application]

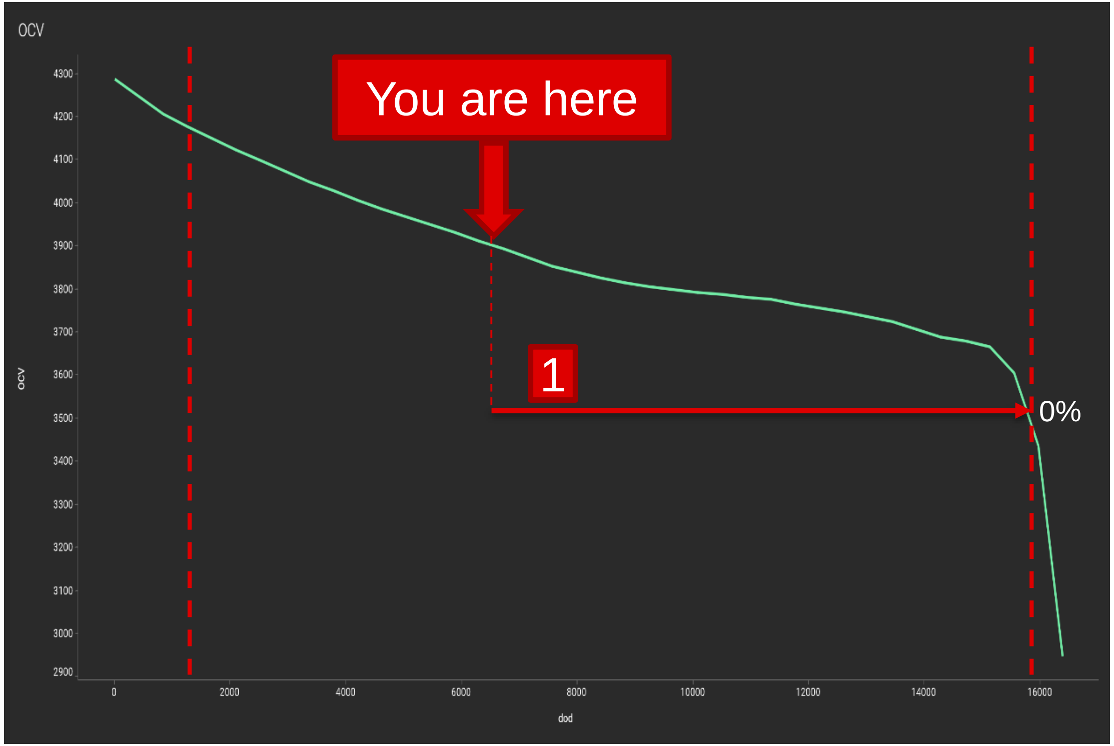


(1) Battery - terms

1. Remaining capacity
   - Capacity until 0%

2. State of charge
   - 100% - 0%
   - Based in application range
   - = RemCap / FCC

3. State of health
   1. 100% - 0%
   2. Degradation of battery

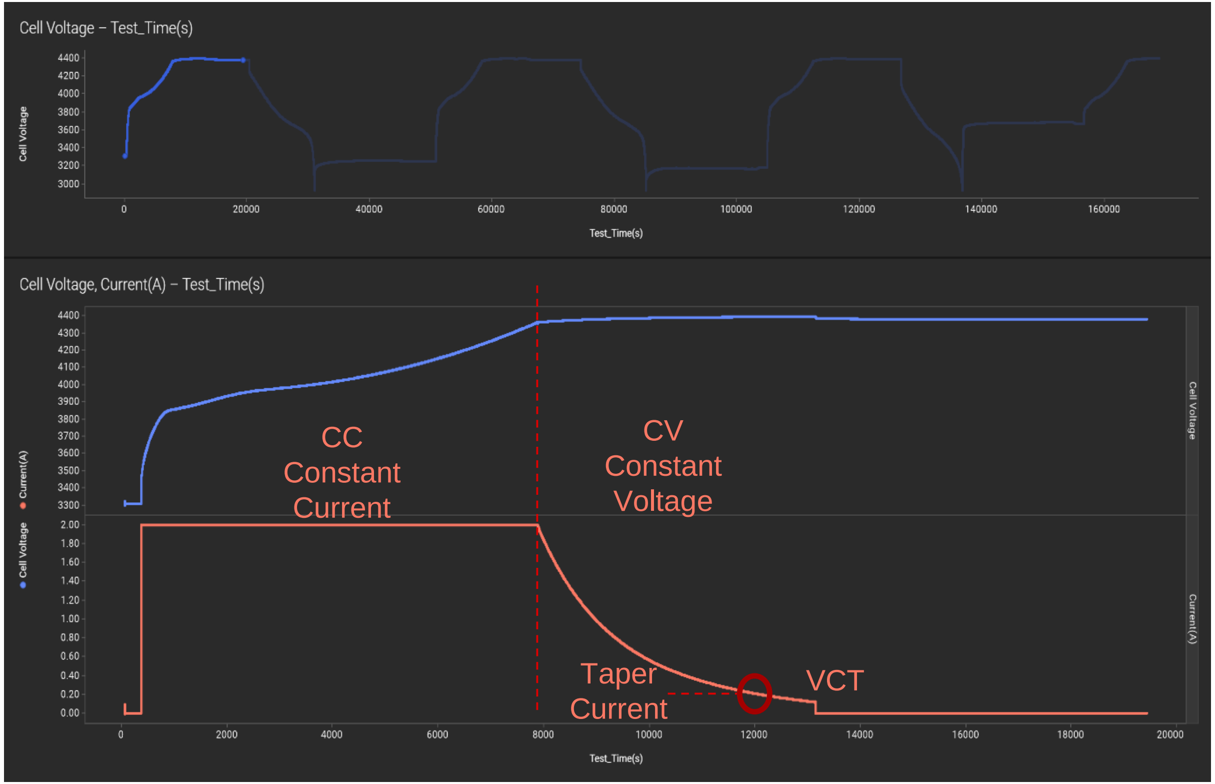


(1) Battery basics - charging

Constant current
- Current stable at adapter power
- Often C/2, but increasing in recent years

Constant voltage
- Voltage stable at charge voltage
- Current reduces until taper current
- Taper often C/20

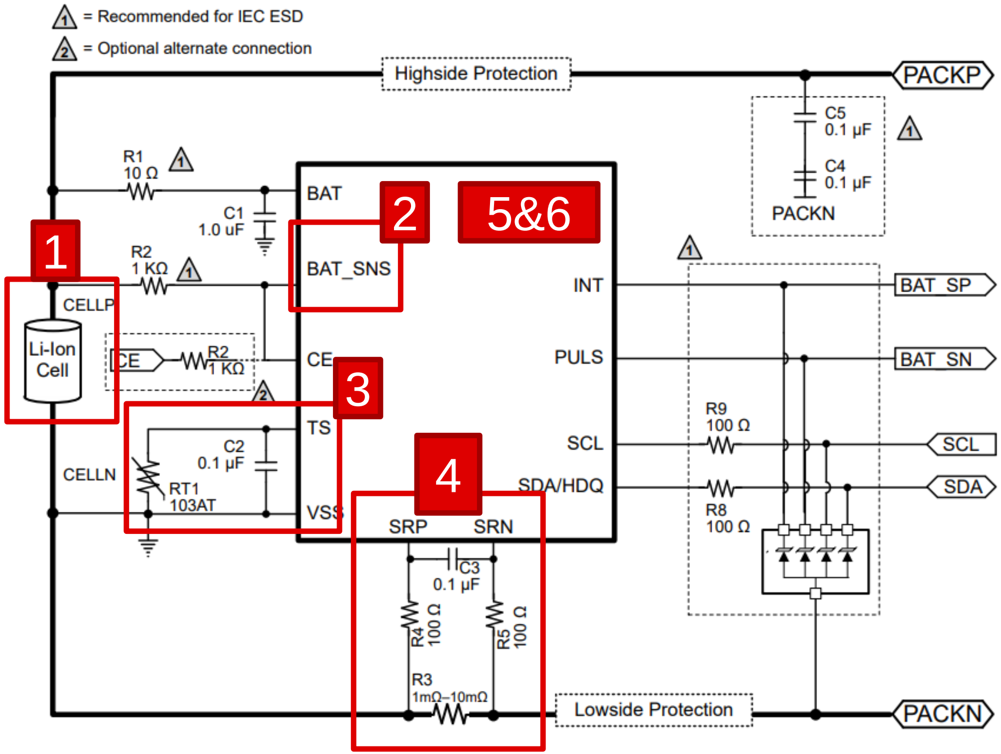
Valid charge termination
- Current below taper for window of time
- Sync point, gauge knows it is 100%



Texas Instruments

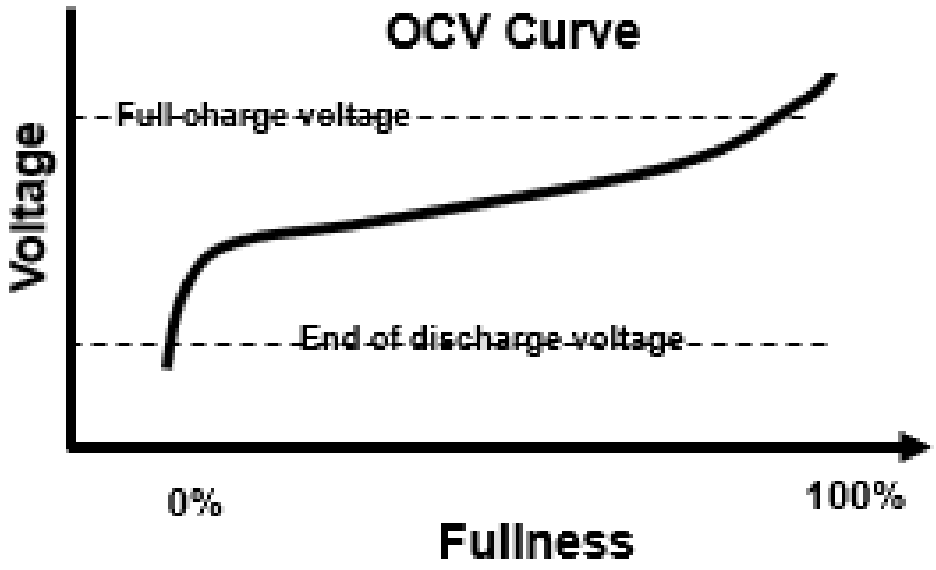
How to gauge a battery

1. Battery
2. Voltage measurement
   - Ideal at least 1 mV accurate
3. Temperature measurement
   - Battery temperature
4. Current measurement
   - Integrating ADC
   - Accumulating passed charge
   - Current measurements
5. CPU/RAM
6. Non-volatile memory
   - Flash or EEPROM and/or ROM



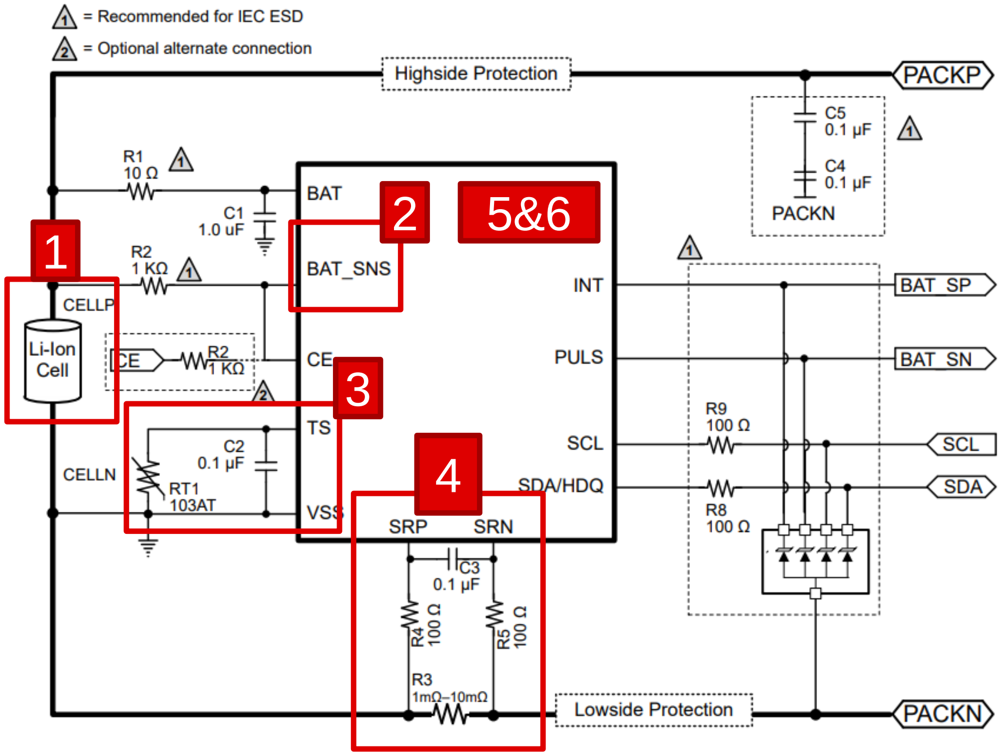
(2) Voltage gauging

- Measure battery voltage & correlate to state of charge



How to gauge a battery

1. Battery
2. Voltage measurement
   - Ideal at least 1 mV accurate
3. Temperature measurement
   - Battery temperature
4. Current measurement
   - Integrating ADC
   - Accumulating passed charge
   - Current measurements
5. CPU/RAM
6. Non-volatile memory
   - Flash or EEPROM and/or ROM



(2) Current gauging

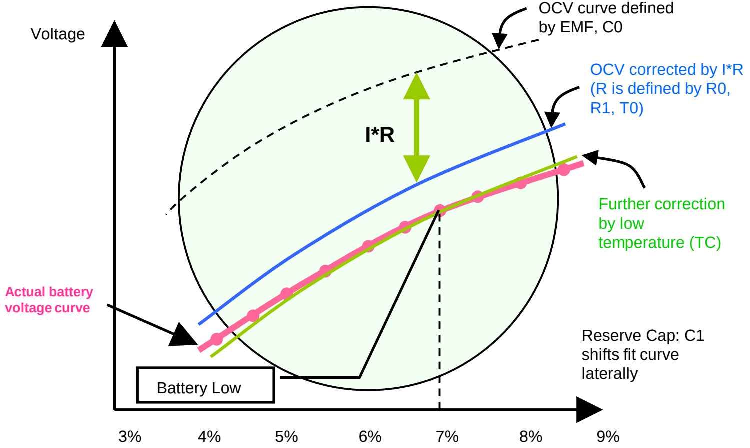
- Count and keep track of charge in and out

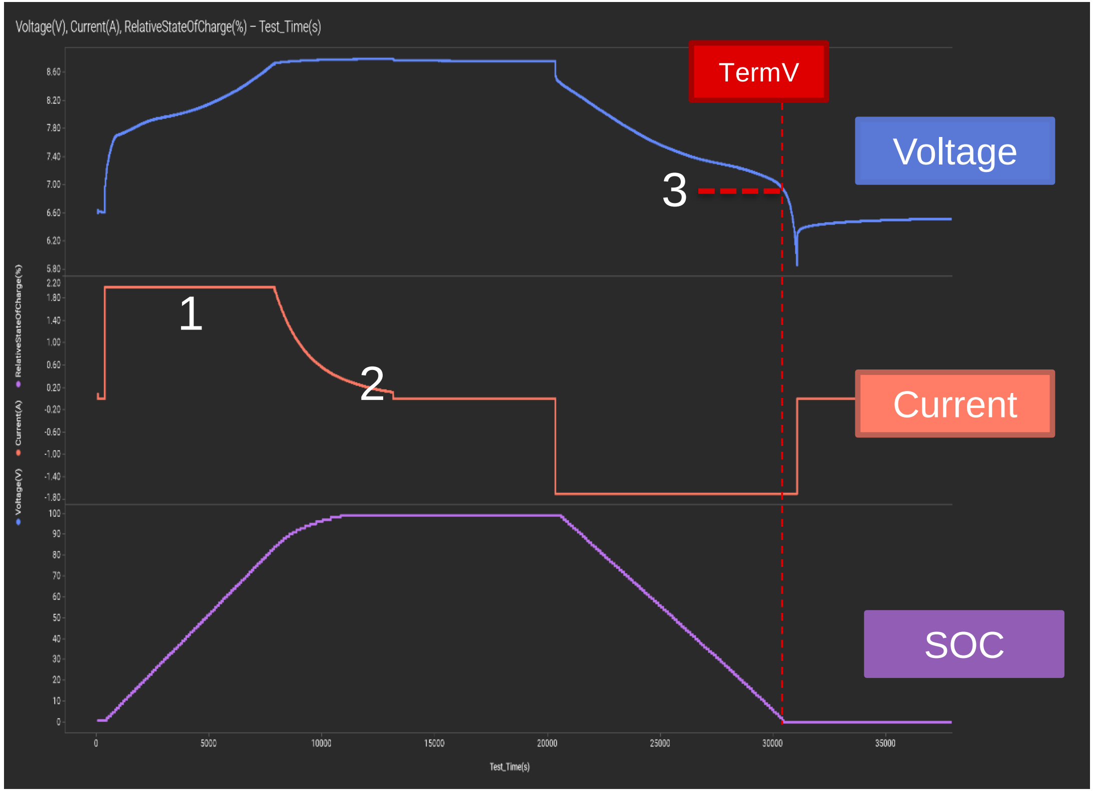
Challenges

1. Unknown starting point
2. Coulomb counting error
3. Unknown leakage
4. No idea if glass size changes

TI gauging method - CEDV

1. Coulomb counting
2. Sync to 100% at full charge
3. Capacity learning threshold adjusts for
   - Discharge rate
   - Temperature
   - Age





TI gauging method - CEDV

- Compensated end of discharge voltage (CEDV)

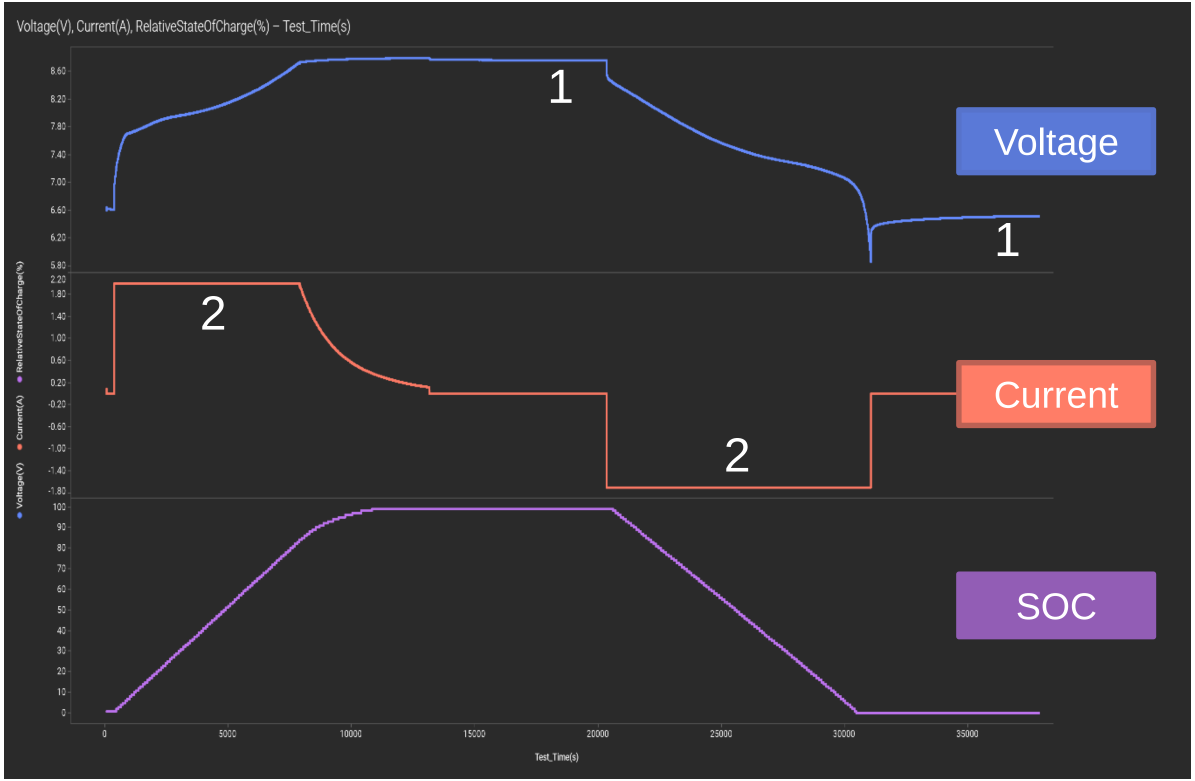
- Everything done through TI online web tool
  - https://www.ti.com/tool/GAUGEPARCAL

- Requires 6 discharge cycles
  - 2x Discharge rate (Avg application discharge rate & Max application discharge rate)
  - 3x Temperature (cold, room, hot)

- Expected setup time: Less that 1 week

TI gauging method – Impedance Track™ technology

1. Voltage while battery stable
2. Coulomb counting while active
3. Thermal model prediction
   - Self-Heating
   - Ambient temperature changes
4. Constant capacity simulations
   - Up to 14 times while discharging
   - Start of chg/dsg
   - OCV readings
   - Charge termination
   - Temperature change
5. Learns the battery over the life of the device



Impedance Track - ChemID

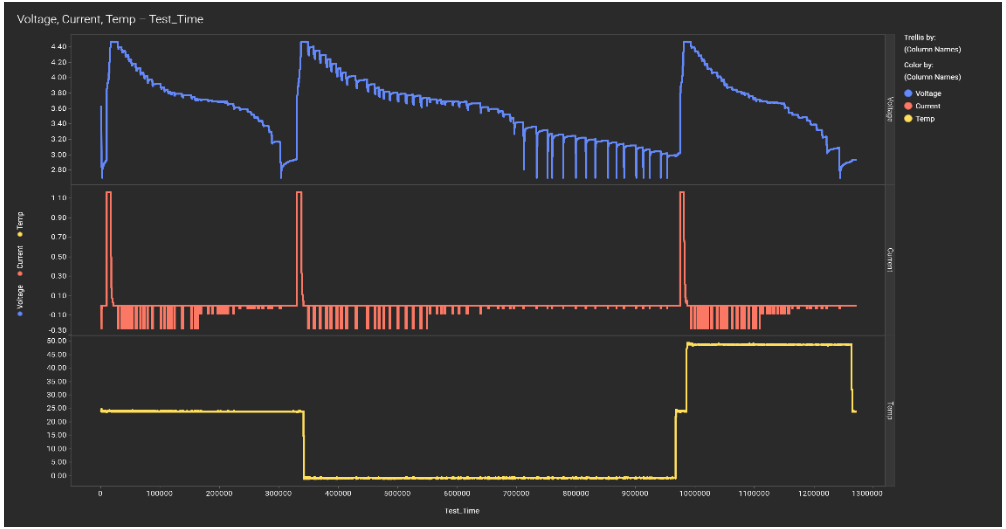
What is it:

- Series of proprietary tests to establish the characteristics and behavior of a given battery

What does it contain:

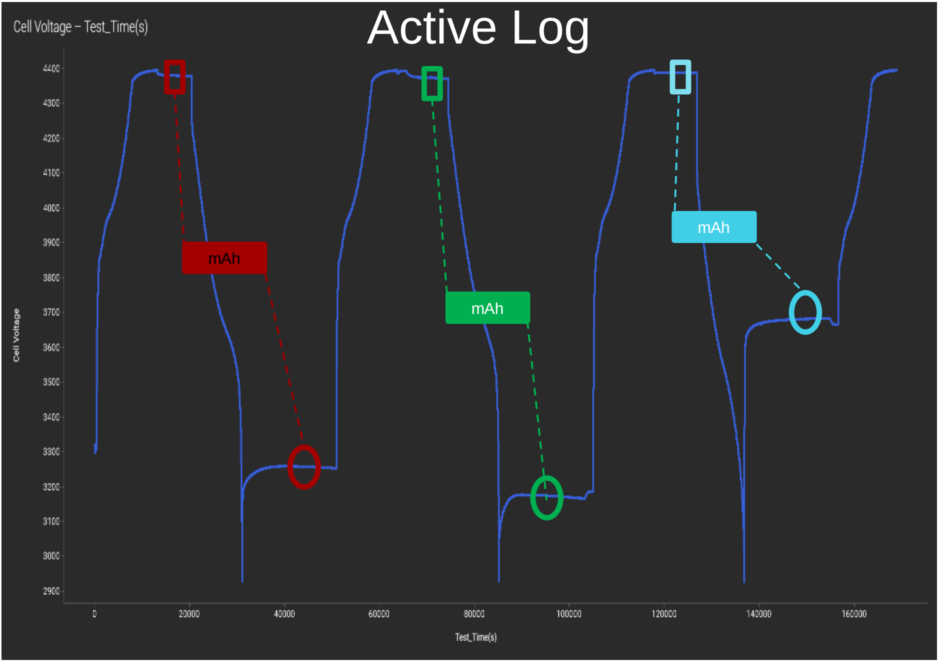
- OCV
- Resistance
- High frequency resistance
- Chemical “Flat Zone”

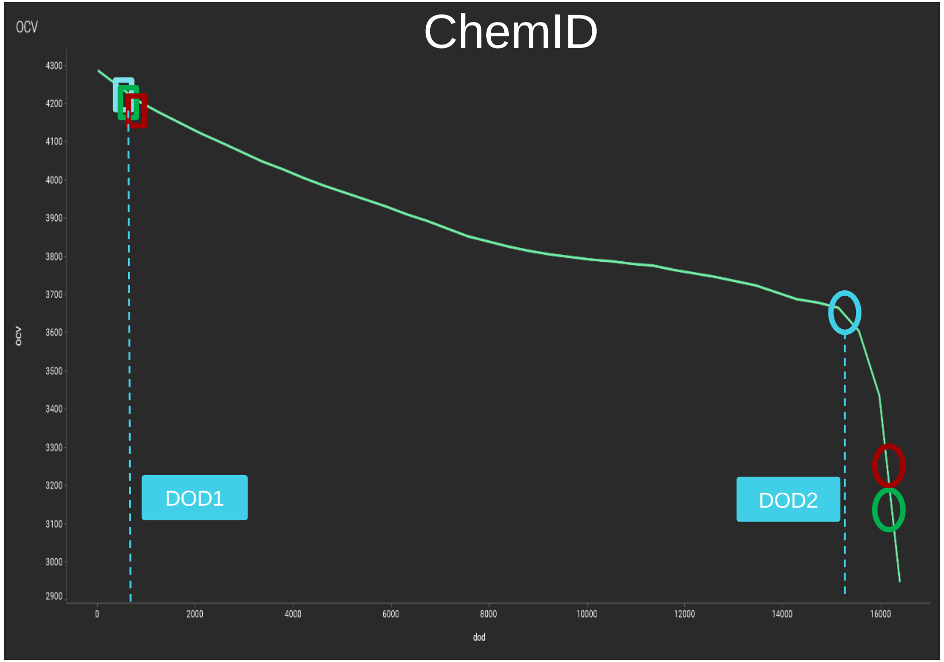
- All modeled across temperature



Texas Instruments

Impedance Track - QMax





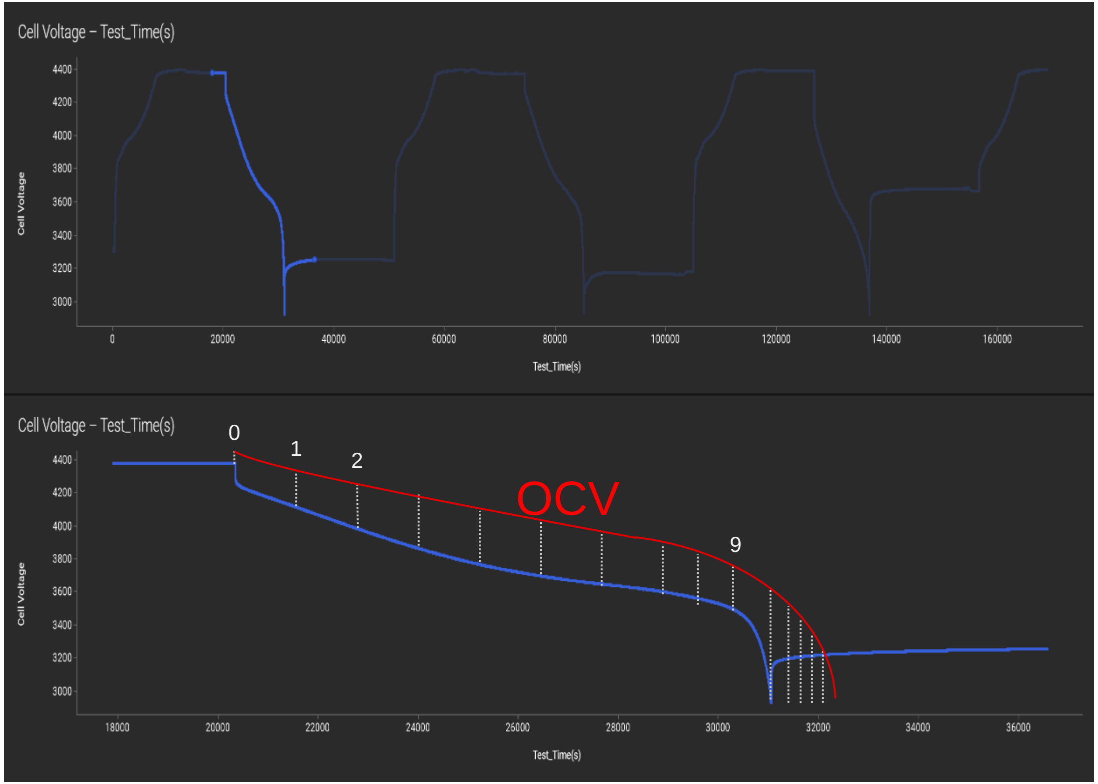
$$\frac{QMax}{16384} = \frac{\Delta Q}{DOD1 - DOD2}$$

Some additional rules

1. DOD points must be at least [37%] apart, [90%] on first QMax
2. DOD reading must not be disqualified (Flat zone, Temperature)
3. Qmax has a max change amount (protection)
4. Qmax has an upper limit (protection)

Impedance Track - resistance

1. Resistance update points are called [Grid Points]
2. 15 grid points over a full discharge
3. Grids not distributed evenly
4. Resistance only updated in discharge direction
5. Must be discharging for an amount of time before resistance update can happen
6. Resistance updates are heavily filtered
7. Updates are stored in flash in the Ra & RaX table
    - Two tables to avoid flash wear out
8. Simultaneous voltage and current measurement needed



TEXAS INSTRUMENTS

TI gauging method – Impedance Track

- Everything can be done through TI online web tool
  - https://www.ti.com/tool/GAUGEPARCAL
  - ChemID match, initial golden learning, & cold temp resistance tuning

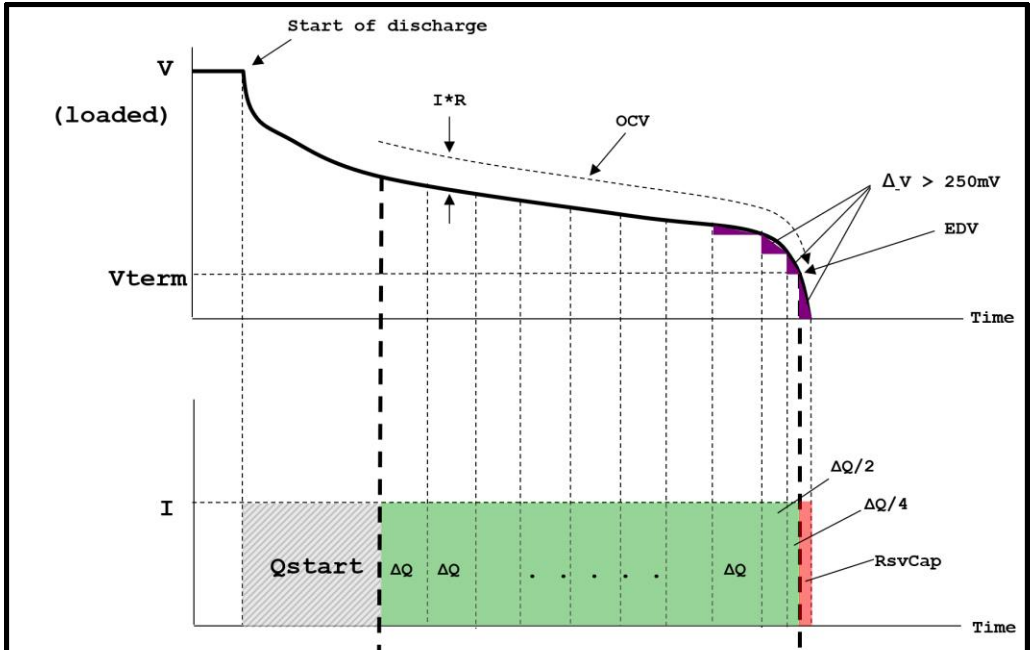
- Requires 3 discharge cycles
  - Nominal discharge rate & room temperature
  - Nominal discharge rate & cold temperature
  - Application charging and discharge rate

- Expected setup time: 2 months
  - ChemID: Match (3 Days), Custom (3-4 Weeks)
  - Learn Cycle: 1 Week
  - Tuning for application: 3 Weeks
    - Load select, Load mode, charge profile, reserve capacity, thermal model, resistance learning, ect….

Impedance Trace - simulation

1. PresentDOD keeps track of where you are

2. Simulations are triggered
   - Grid points
   - Temp change
   - Start of charge
   - Start of discharge
   - Every hour in relax
   - Valid charge termination
   - OCV reading



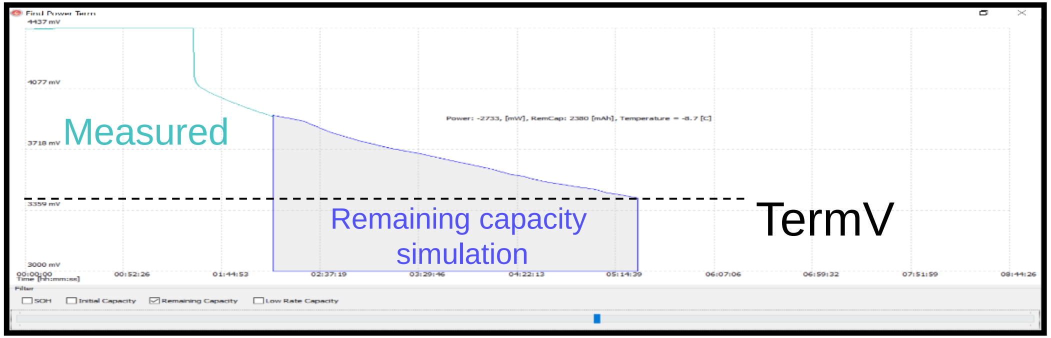
Constant Load Example

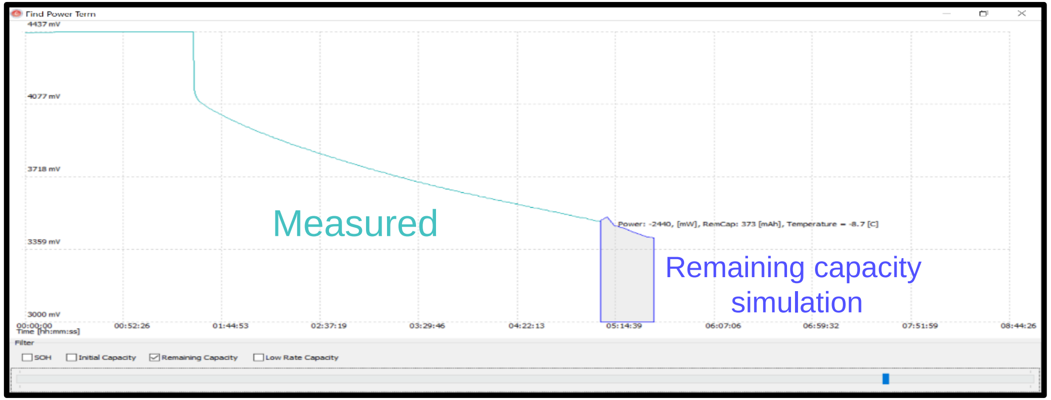
Impedance Trace – simulation

Example:

1. Temperature = -10 °C

2. Constant C/5 discharge





Impedance Track - FAQ

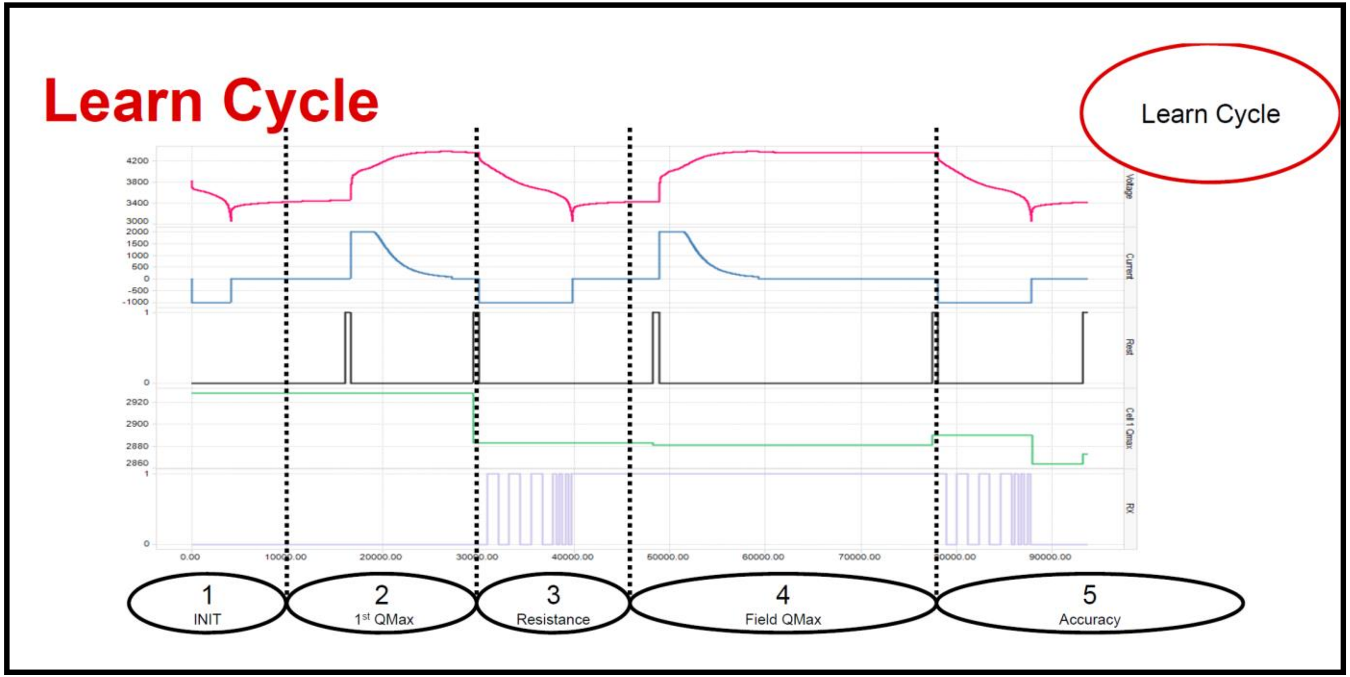
Notes

1. First QMax needs 90% change in DOD

2. Resistance learning should be done a C/5 – C/10 rate until min battery voltage

3. Step 4 should be charged to application max charge voltage to learn derated 100% point

4. Learning should be done on multiple packs to average cell to cell variation



Impedance Track – common challenges

1. Extreme cold temperatures (-10 °C or lower)
   - Issue: Battery impedance across temperature is non-linear with greater cell to cell variation
   - Recommendation: Should be tuned at slightly less extreme temperature (eg. -10 C for -20 C needs)
2. High rate discharge 1.5 C+
   - Issue: Battery termination could be happening within the “Flat Zone”. Flat zone calculation errors increase due to mV delta per capacity delta
   - Recommendation: Lower termination voltage to increase accuracy
3. High termination voltage
   - See #2
4. Rarely used, battery always “topped” off
   - Issue: Increase degradation with no resources to learn
   - Recommendation: Force a shallow discharge to allow for learning
5. No rest periods, constantly cycling
   - Issue: Gauge build coulomb counter error with no correction spot
   - Recommendation: Utilize specialized gauge features to assist with learning and location reset
     - FastQMax, valid charge termination, FastOCV…

Gauging algorithm comparison

Algorithm	IT	CEDV
	Impedance Track™ (IT)	Compensated end of discharge voltage+
Accuracy	Typical accuracy ~ 1%	Typical accuracy ~ 5%
Chemistry characterization	Characterize battery to generate chemID Estimated time: 2 weeks ~ 6 weeks Need TI's assistance	Characterize battery to generate parameters Estimated time: 1 week Customers can self-tune the parameters without TI's assistance
State of charge	SOC learning uses current measurement during chg/dsg and voltage correlation during rest	SOC learning uses current during discharge and voltage correlation at the end of discharge
Full charge capacity	FCC learning does NOT require full discharge	FCC learning requires discharge to <7% (Application must be capable of occasionally discharging to <7% ~ once a month)
End equipment profile	Suitable for end equipment with chg/dsg current and some rests Suitable for end equipment with extended rest periods and short chg/dsg bursts	Suitable for end equipment with chg/dsg current and some rests Suitable for end equipment with continuous chg/dsg current and no rests
Initialization	SOC at power up uses voltage correlation	SOC at power up uses voltage correlation
Intel Turbo Mode feature	Supported	Not supported
LiFeP04	Possible	Preferred
Ease of use	Large number of algorithm parameters	Very few algorithm parameters

Impedance Track advantages

- ✓ Combines advantages of voltage correlation and coulomb counting methods
- ✓ Accounts for cell impedance/aging, temperature and variable current loading
- ✓ Doesn’t require full charge-discharge learning cycle for FCC (usable capacity)
- ✓ Best accuracy (~1%)
- ✓ Dynamically updates the gauge data flash as it fully characterizes the parameters of each cell
- ✓ Parameters learning on-the-fly:
  - ➢ Learn impedance during discharge
  - ➢ Learn total capacity (Qmax) without full charge or discharge
  - ➢ Adapt to spiky loads (delta voltage)
- ✓ Host system does not need to perform calculations or gauging algorithm

TI battery electronics options

Protector

- Simple hardware-based protection to respond to unsafe conditions like over-voltage, under-voltage, over-current, over-temperature, under-temperature, over-current, or short circuit.

Lowest complexity

Monitor

- Measures individual cell voltages
- Measures current (coulomb counting)
- Measures die temperature and external thermistors
- Cell balancing to extend battery run-time and battery life
- Protections with flexible thresholds
- Communicates data and status to MCU or stand-alone gauge

Highest Flexibility

Gauge

- Reports capacity, run-time, state-of-charge
- Enhanced protections
- Black box features to diagnose battery failure
- Extends run-time of battery due to accurately determining how much capacity is remaining
- Extends lifetime by dynamically controlling healthy, safe, fast charging
- Authentication, state-of-health, traceability…

Highest Integration

How can you extend run-time with an accurate gauge?

APPENDIX A

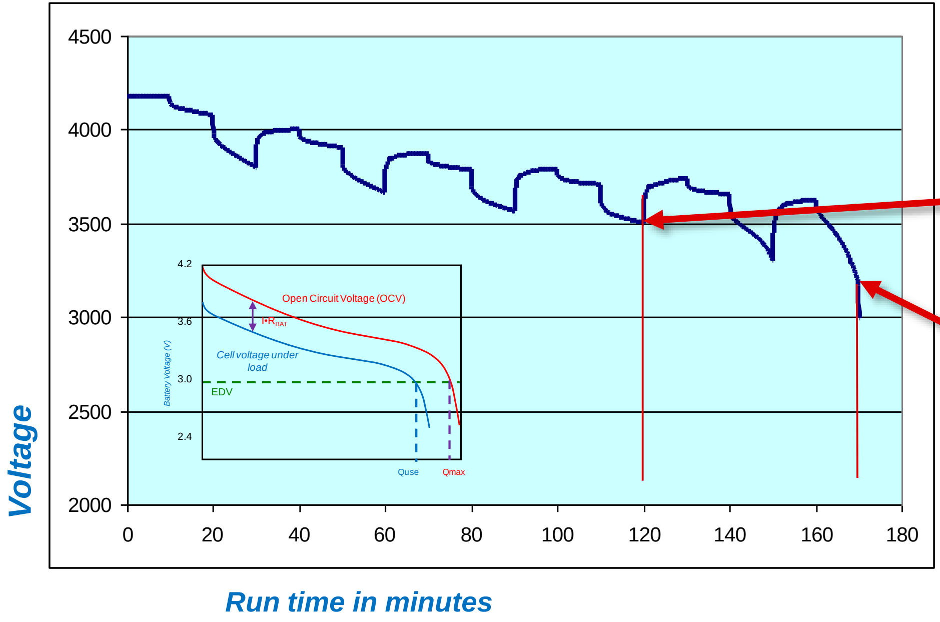
Run time comparison example

Impedance Track™ gauge shutdown vs. OCV shutdown point

- Systems without accurate gauges simply shutdown at a fixed voltage
- Smartphone, tablets, portable medical, digital cameras etc… need reserve battery energy for shutdown tasks
- Many devices shutdown at 3.5 or 3.6 volts in order to cover worst case reserve capacity
  - *3.5-volt shut down used in this comparison*
  - *Gauge will compute remaining capacity and alter shutdown voltage until there is exactly the reserve capacity left under all conditions*
  - *10-mAH reserve capacity is used*
  - *Temperature and age of battery are varied*

Fuel gauging

OCV vs. IT Use Case exp – NEW battery w/ variable load mix



Conditions:

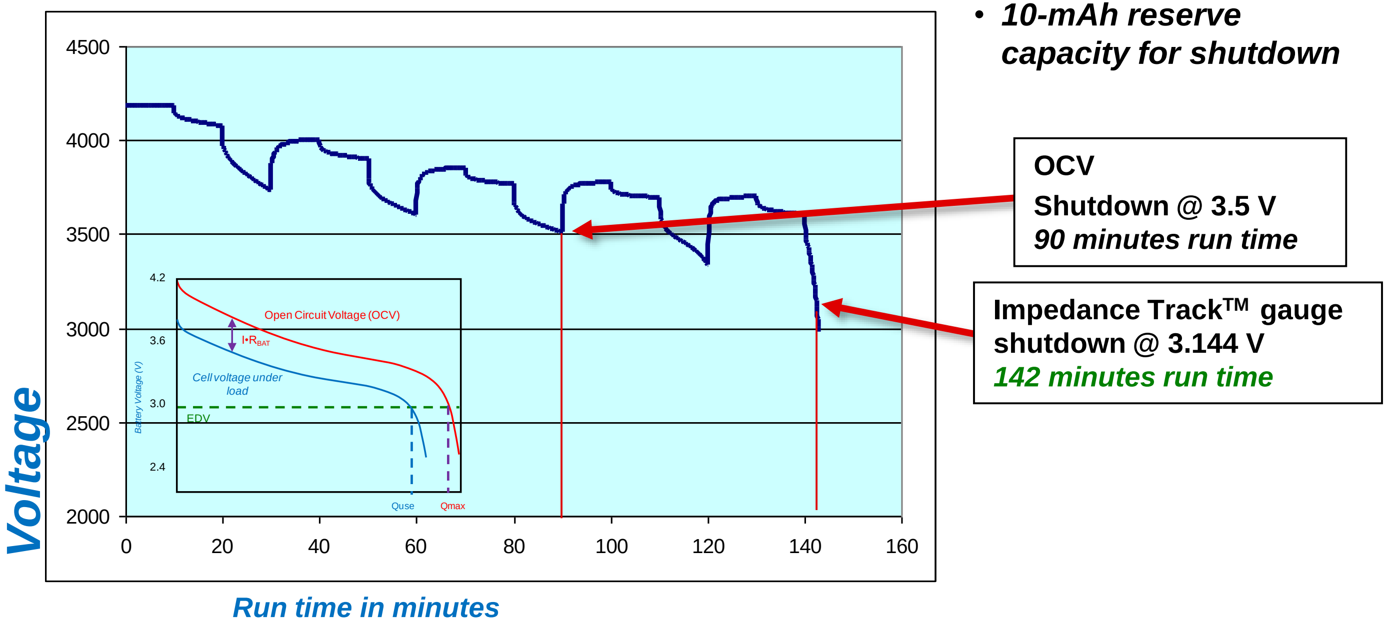
- *New battery*
- *Room temp (25 °C)*
- *10-mAh reserve capacity for shutdown*

OCV
Shutdown @ 3.5 V
120 minutes run time

Impedance Track™ gauge shutdown @ 3.295 V
168 minutes run time

Fuel gauging

OCV vs. IT Use Case Exp – OLD battery w/ variable load mix

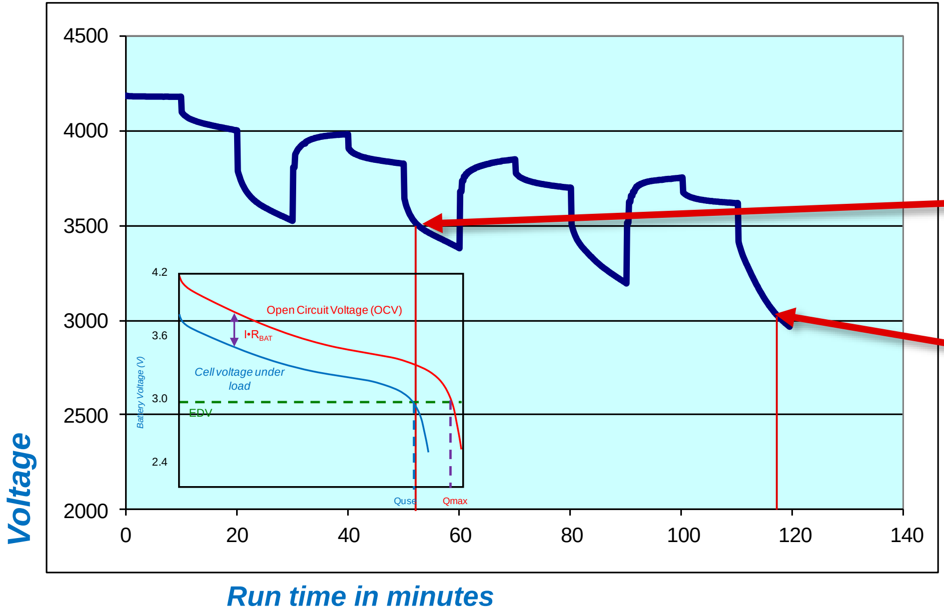


Conditions

- *Room temp (25 °C)*
- *10-mAh reserve capacity for shutdown*

Fuel gauging

OCV vs. IT Use Case Exp – NEW battery COLD w/ variable load mix



Conditions ***Batty***

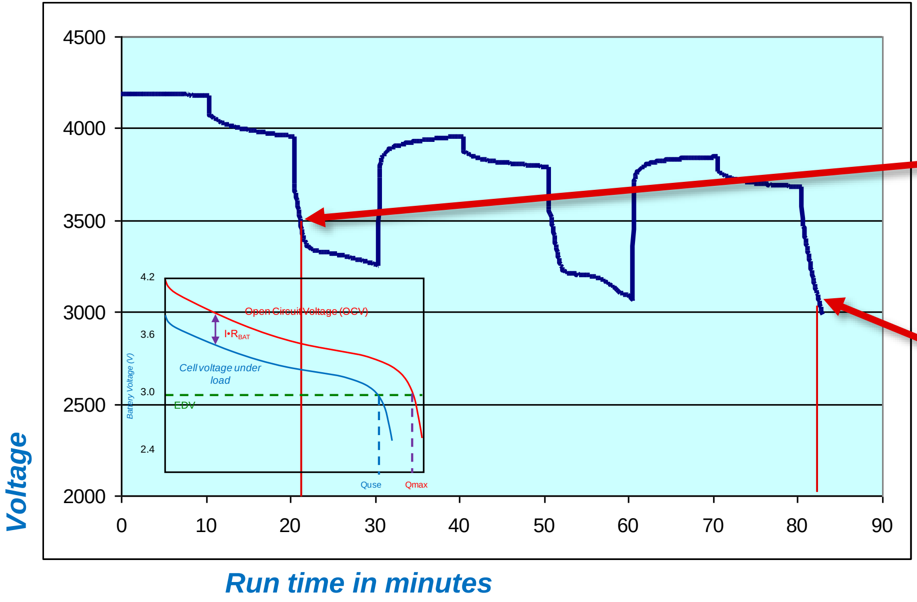
- ***Cold (0 °C)***
- ***10-mAh reserve capacity for shutdown***

OCV
Shutdown @ 3.5 V
53 minutes run time

Impedance Track™ gauge shutdown @ 3.020 V
117 minutes run time

Fuel gauging

OCV vs. IT Use Case Exp – OLD battery COLD w/ variable load mix



Conditions *(0 °C)*

- ***Cold (0 °C)***
- ***10-mAh reserve capacity for shutdown***

OCV
Shutdown @ 3.5 V
21 minutes run time

Gauge shutdown at 3.061 volts:
82 minutes run time

SLYP847