Single-Cell Gauging 101

What is Fuel Gauging Technology?

- **Fuel Gauging is a technology used to <u>predict battery capacity</u> under all system active and inactive conditions.**
- **<u>Battery capacity</u>**
  - **Percentage**
  - **time to empty/full**
  - **milliamp-hours**
  - **Watt-hours**
  - **talk time, idle time, etc.**
- **<u>Other data</u> can be obtained for battery health and safety diagnostics.**
  - **State of Health**
  - **Full Charge Capacity**

73%

Run Time 6:23

Outline

- **Battery chemistry fundamentals**
- **Classic fuel gauging approaches**
  - **voltage based**
  - **coulomb counting**
- **Impedance Track and its benefits**

Single-Cell Gauging 101

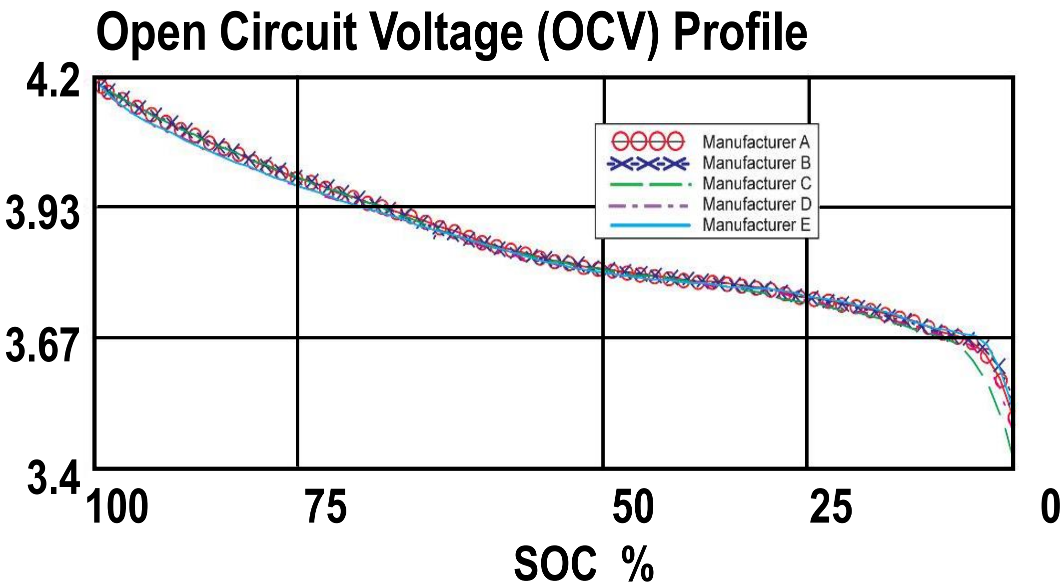
Part 3: Impedance Track Benefits

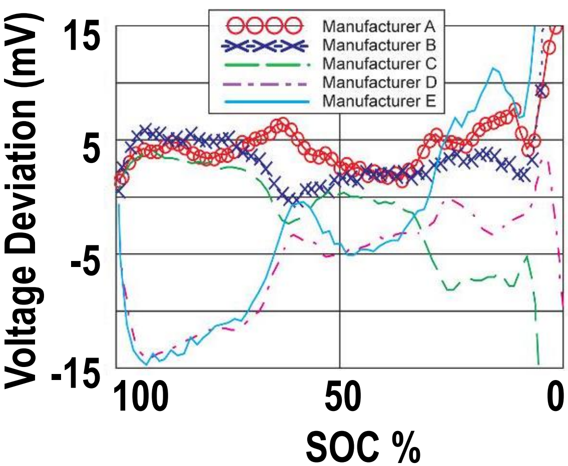
Impedance Track^{TM} Gas Gauge

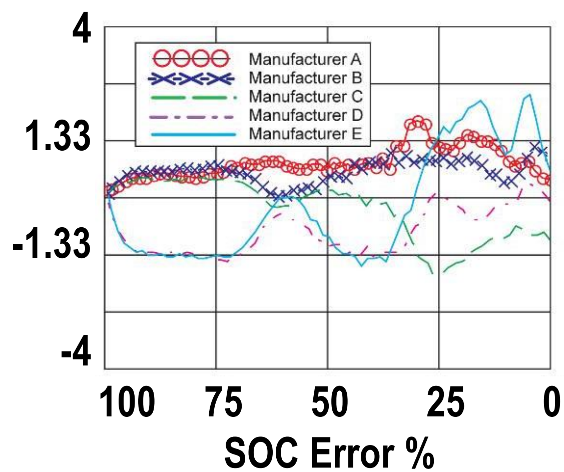
- Voltage based gas gauge: Accurate gauging under no load
- Coulomb counting based gauging: Accurate gauging under load
- Combines advantages of voltage and current based methods
- Real-time impedance measurement
- Calculate remaining run-time at given average load using both open circuit voltage and impedance information.

$$V = OCV(T,SOC) - I*R(T,SOC, Aging)$$

Comparison of OCV=f (SOC, T) profiles

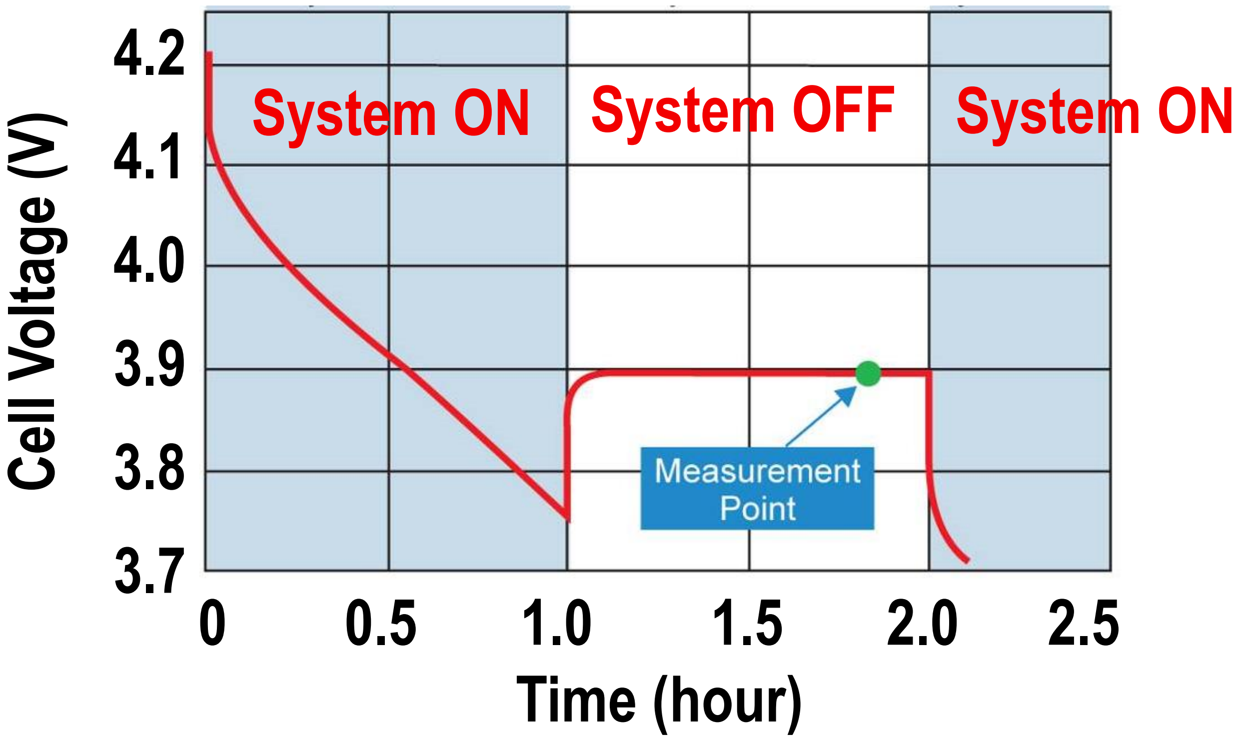






- OCV profiles similar for all tested manufacturers
- Most voltage deviations < 5 mV
- Average SOC prediction error < 1.5%
- Same database can be used for batteries from different manufacturers for the same chemistry

How to measure OCV ?



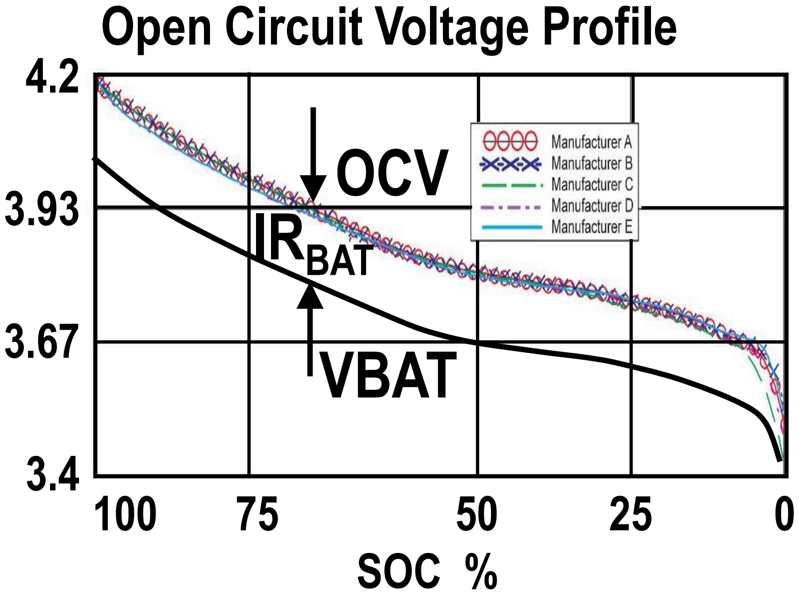
- OCV measurement allows SOC with 0.1% max error
- Self-discharge estimation is eliminated

How to measure impedance?

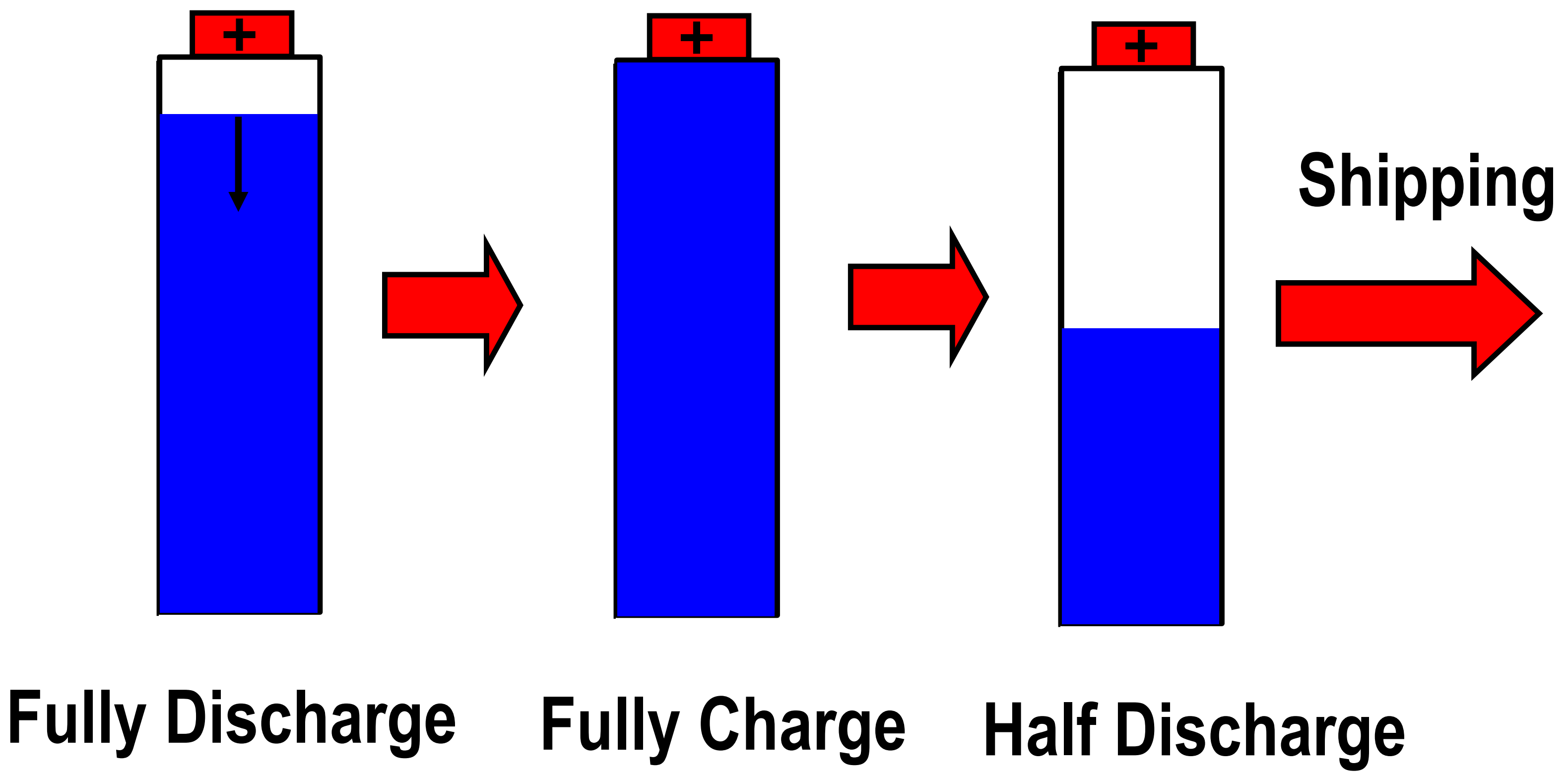
- Data flash contains a fixed table: *OCV = f (SOC, T)*
- IT algorithm: Real-time measurements and calculations during charge and discharge.

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

V = OCV(T,SOC) - I*R(T,SOC, Aging)

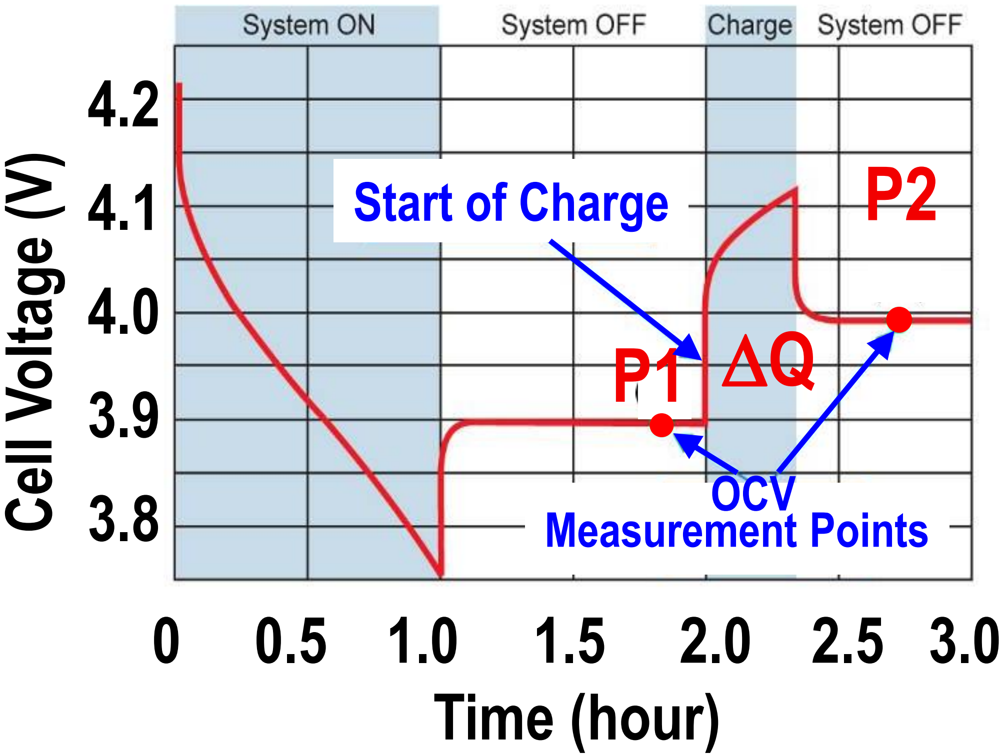


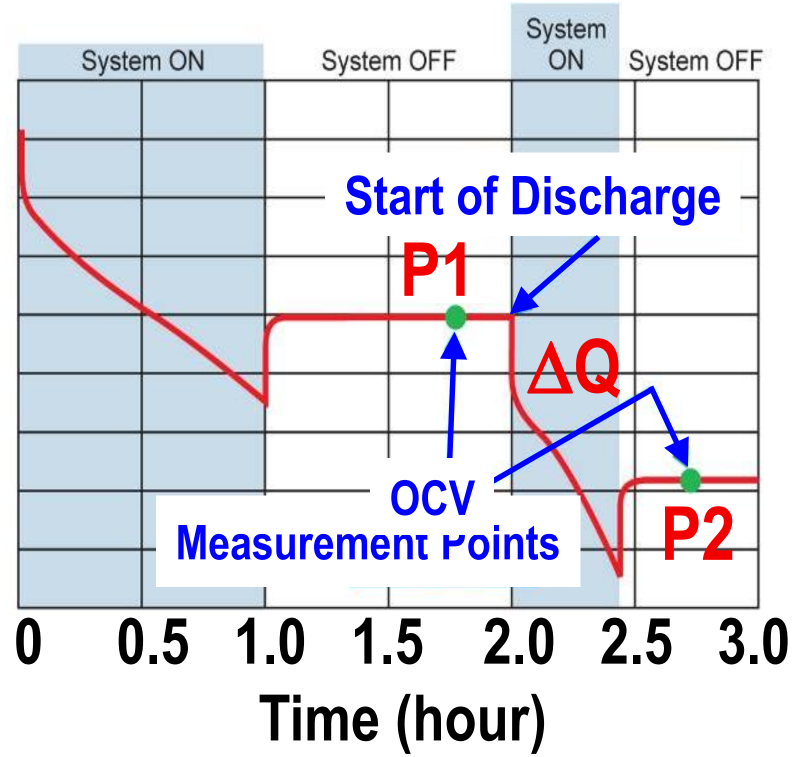
Issue for Traditional Battery Capacity Learning



- Involve a lot of test equipment and time
- User may never fully discharge battery to learn capacity
- Gauging error increase 1% for every 10 cycles without learning

Learning Qmax without Full Discharge

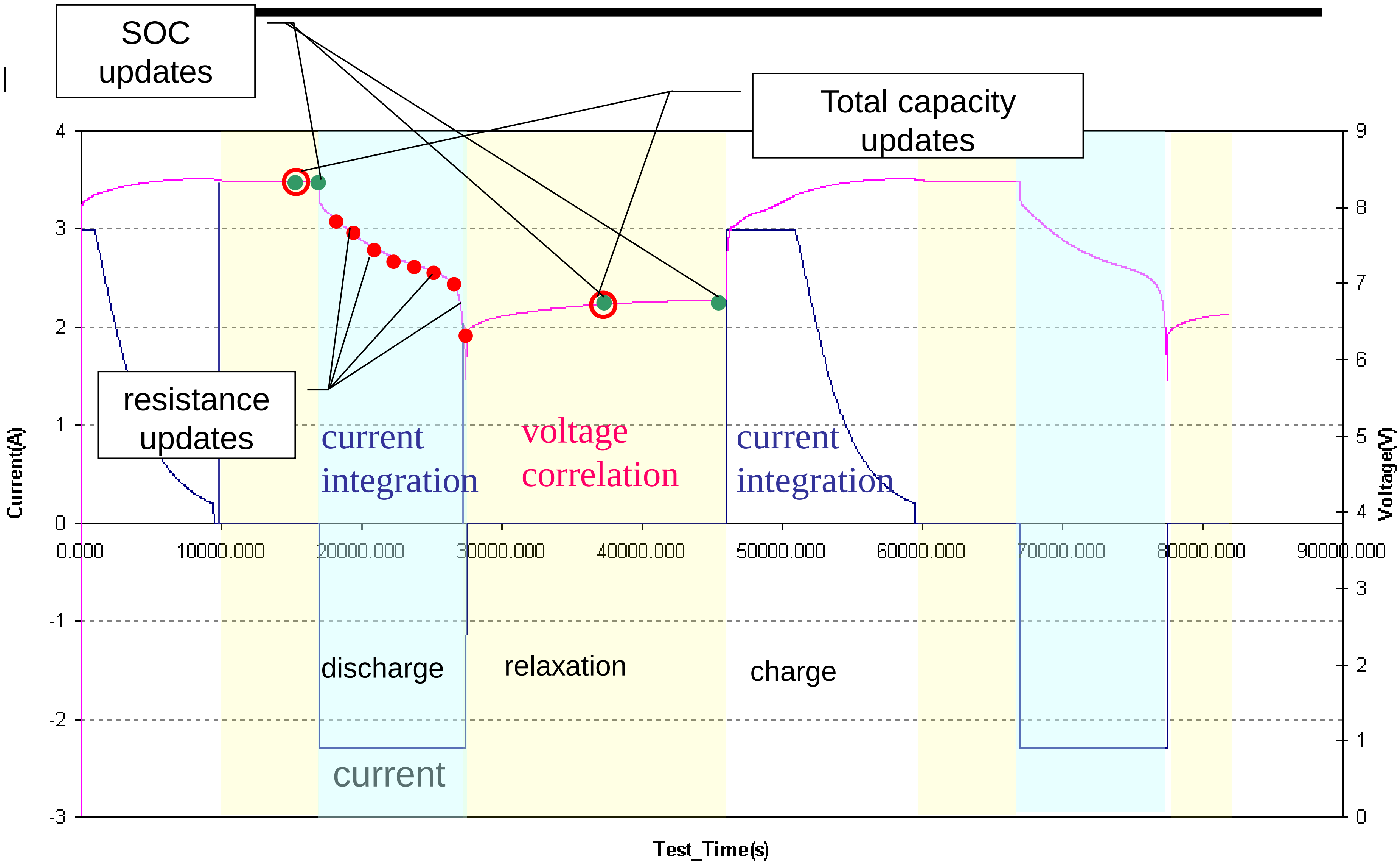




- Charge passed is determined by exact coulomb counting
- SOC1 and SOC2 measured by its OCV
- Method works for both charge or discharge exposure

$$Q_{max} = \frac{\Delta Q}{SOC1 - SOC2}$$

Cooperation between integration and correlation modes



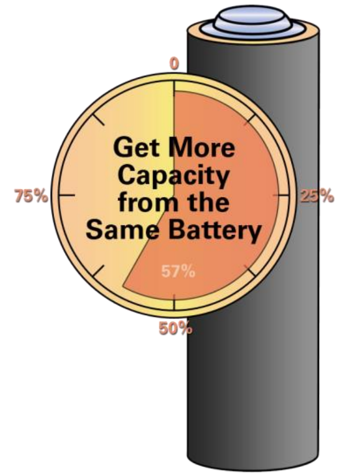
Impedance Track Fuel Gauge

Advantages

- Combine advantages from both voltage based and coulomb counting
- Accurate with both small current (OCV) and large load current
- Throw out inaccurate self-discharge models (use OCV reading)
- Very accurate with new and aged cells
- No need for full charge and discharge for capacity learning

Fuel Gauging Benefits

- **Accurate report of remaining run time**
- **Better Power Management**
- **Longer Run Time**
  - **Power management**
  - **Accuracy: less guard band needed for shutdown**
  - **Variable shutdown voltage with temperature, discharge rate, and age based on impedance**



Extend Operating Time Using Impedance Track™ Technology

- **Orderly shutdown**
  - **Automatically save data to flash with reserve energy when battery dies**
- ***Fuel gauging enables mobile applications***

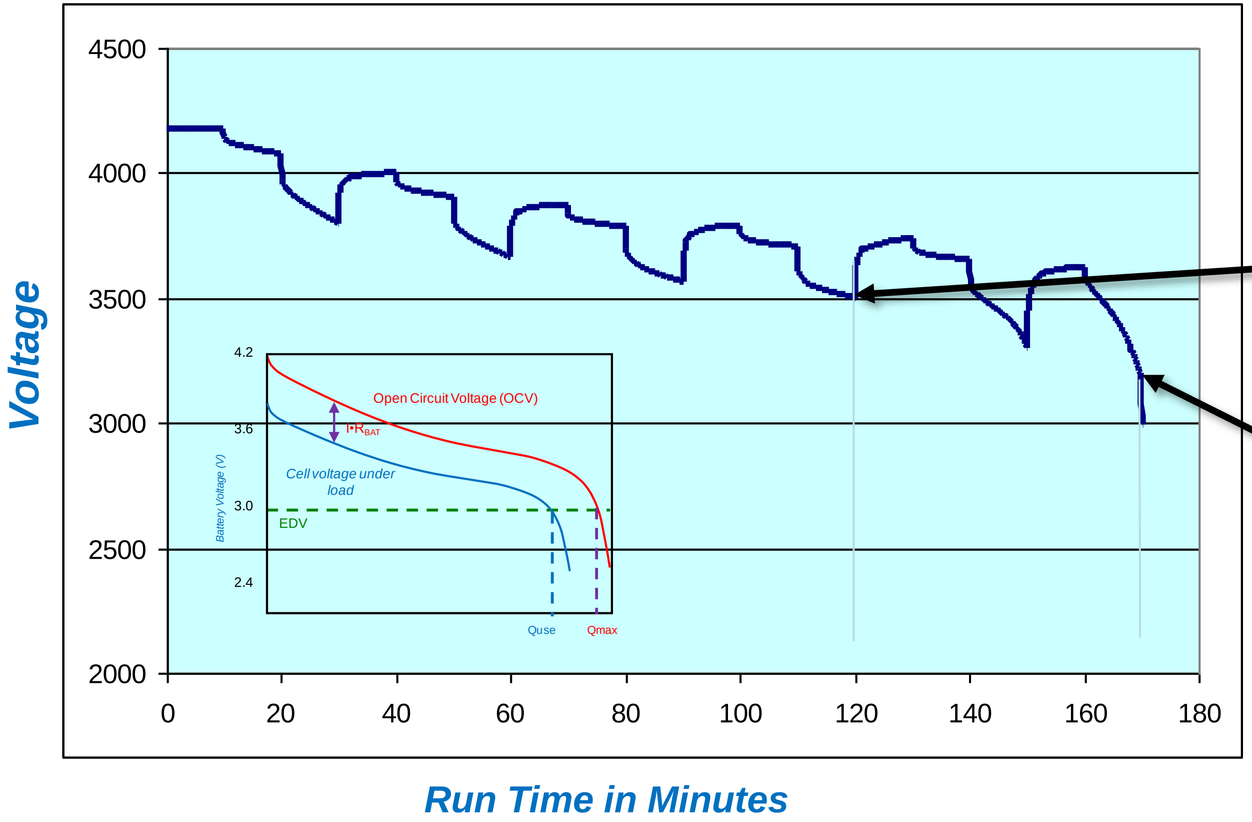
Run Time Comparison Example

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***

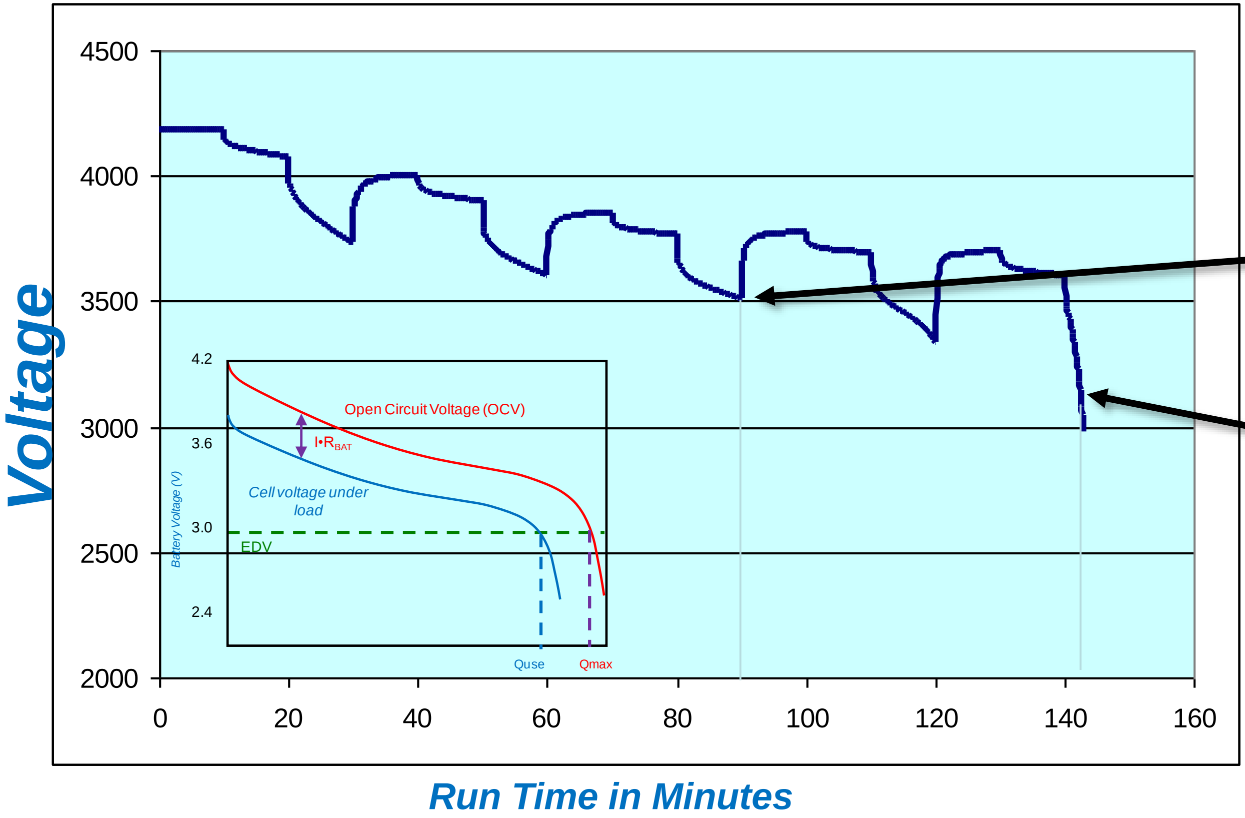
OCV
Shutdown @ 3.5V
120 minutes run time

Impedance Track™ Gauge
Shutdown @ 3.295V
168 minutes run time

Extended runtime with TI Gauge: +40%

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*

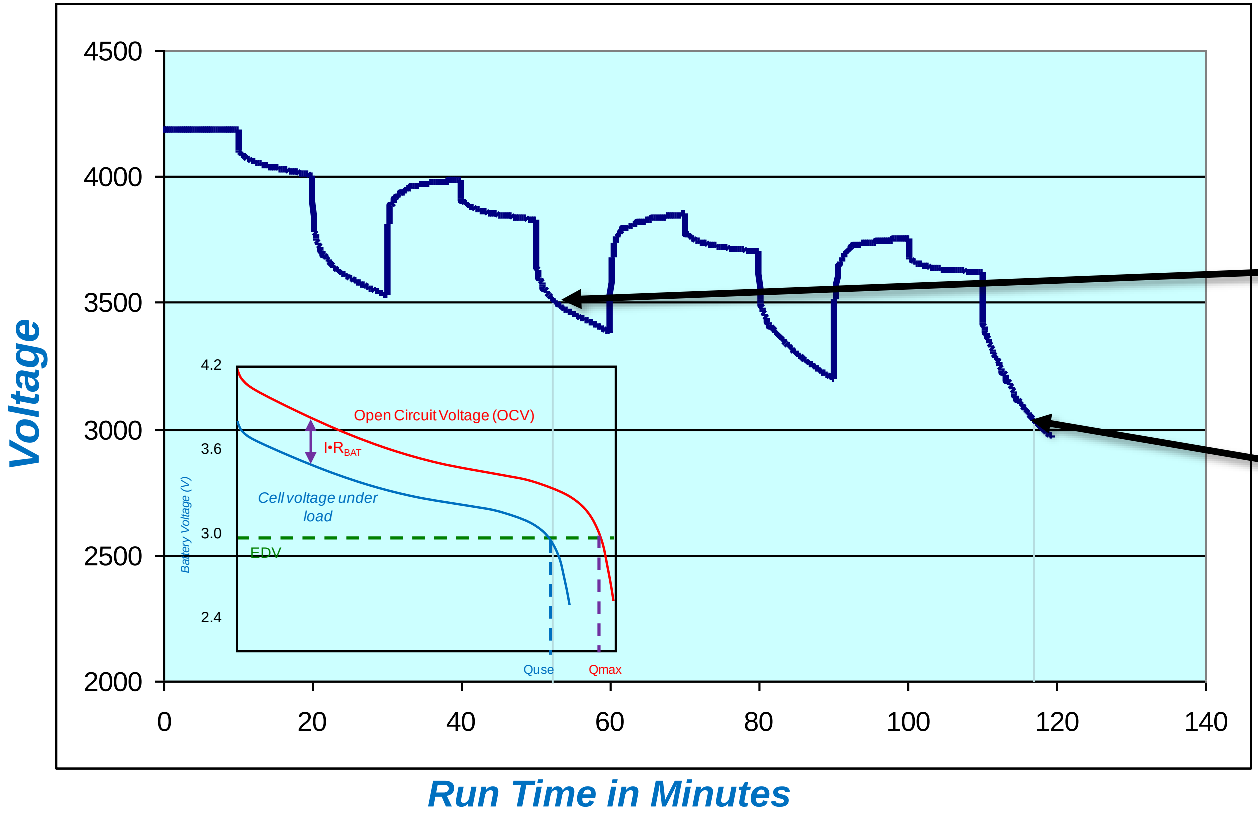
OCV
Shutdown @ 3.5V
90 minutes run time

Impedance Track™ Gauge
Shutdown @ 3.144V
142 minutes run time

Extended runtime with TI Gauge: +58%

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***

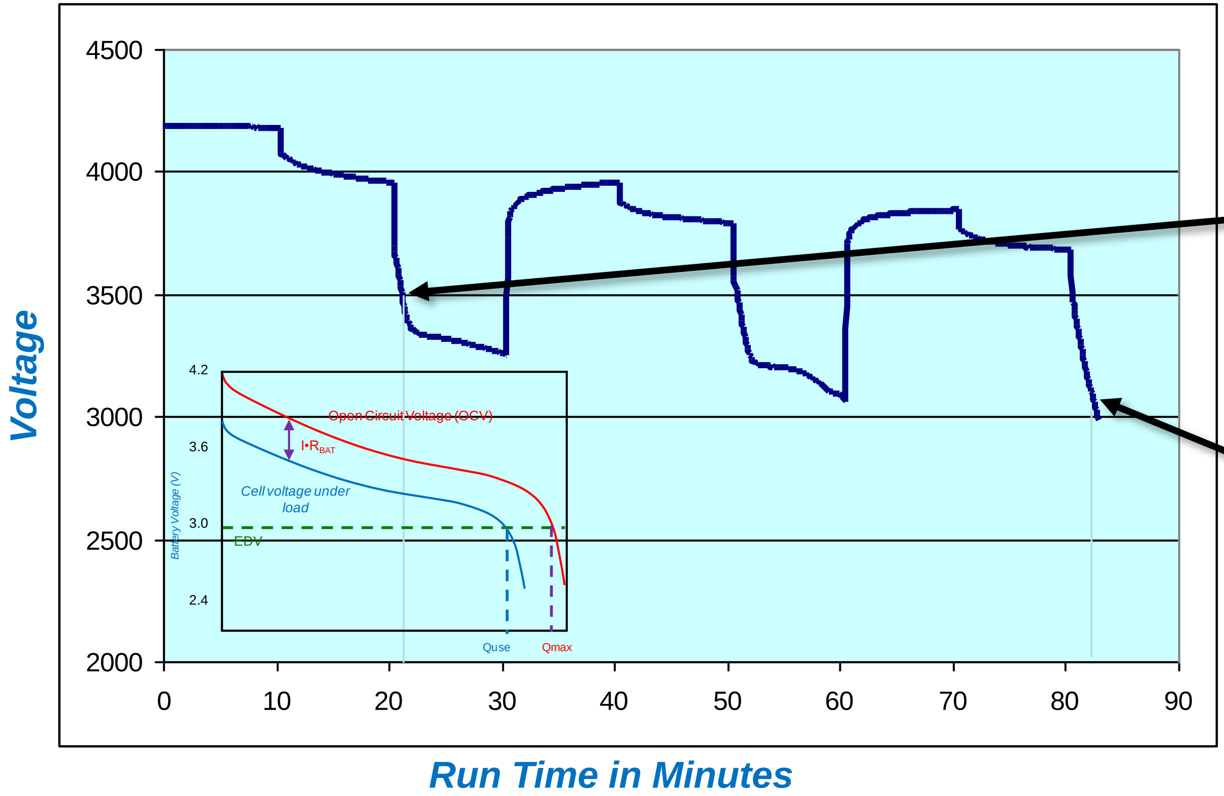
OCV
Shutdown @ 3.5V
53 minutes run time

Impedance Track™ Gauge
Shutdown @ 3.020V
117 minutes run time

Extended runtime with TI Gauge: +121%

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 @ 3.5V
21 minutes run time

Gauge shutdown at 3.061 volts:
82 minutes run time

Extended runtime with TI Gauge: +290%

Fuel Gauging – Impedance Track™ Advantages

- **Dynamic (learning) Ability**
  - Temperature variability in applications
    - IT takes into account 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 has the ability to 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

Unused Battery Capacity implications

- **Cell cost: avg $0.15 for every 100mAh**
- **Lower Terminate Voltage (TV) = Larger Battery Capacity**
- **500mV lower of TV ~ 5% increase on capacity for new battery → save ~$0.10 for 1500mAh battery**
- **500mV lower of TV ~ around 50% increase on capacity for aged battery → save ~$1.00 for 1500mAh battery and extend run time!**
- ***Money saving opportunity for manufacturer while still extending end-user runtime***

Cost of an inaccurate gauge

- Assuming customer discharge and charge once every day → three month use time = 90 day ~ 90 cycles → Battery internal impedance almost doubled → Aged battery scenario
- Non-Impedance Track based gauge → inaccurate gauging results due to battery aging→ much shorter run time or even system crash
- Battery warranty by operators could be one year or even two years.
- Customer return entire units due to faulty gauging results → Returns within warranty period cost company money
- Impedance Track based gauge can extend the battery run time and eliminate some costly return due to faulty gauging results

Summary

- Accurate gauges for portable electronics are as critical to long run-time as reducing your design’s power and having a beefy battery.
- A variety of gauges are available with different approaches and different trade-offs.

Finish

Back Up Slides:
Impedance Track Reference

Single Cell Impedance Track (IT)

Basic Terminology and Relationships

- **OCV – Open Circuit Voltage**
- **Q_{max} – Maximum battery chemical capacity**

$$Q_{max} = \frac{PassedQ}{|SOC_1 - SOC_2|}$$

(SOC_1/SOC_2 is correlated from *OCV* table after OCV_1/OCV_2 measurement)

- **SOC – State of Charge**

$$SOC = 1 - \frac{PassedQ^*}{Q_{max}}$$

  - (* From Full Charge State)

- **RM – Remaining Capacity**

$$RM = (SOC_{start} - SOC_{final}) \times Q_{max}$$

  - (SOC_{start} is present *SOC*, SOC_{final} is *SOC* at system terminate voltage)

Single Cell Impedance Track (IT)
Basic Terminology and Relationships

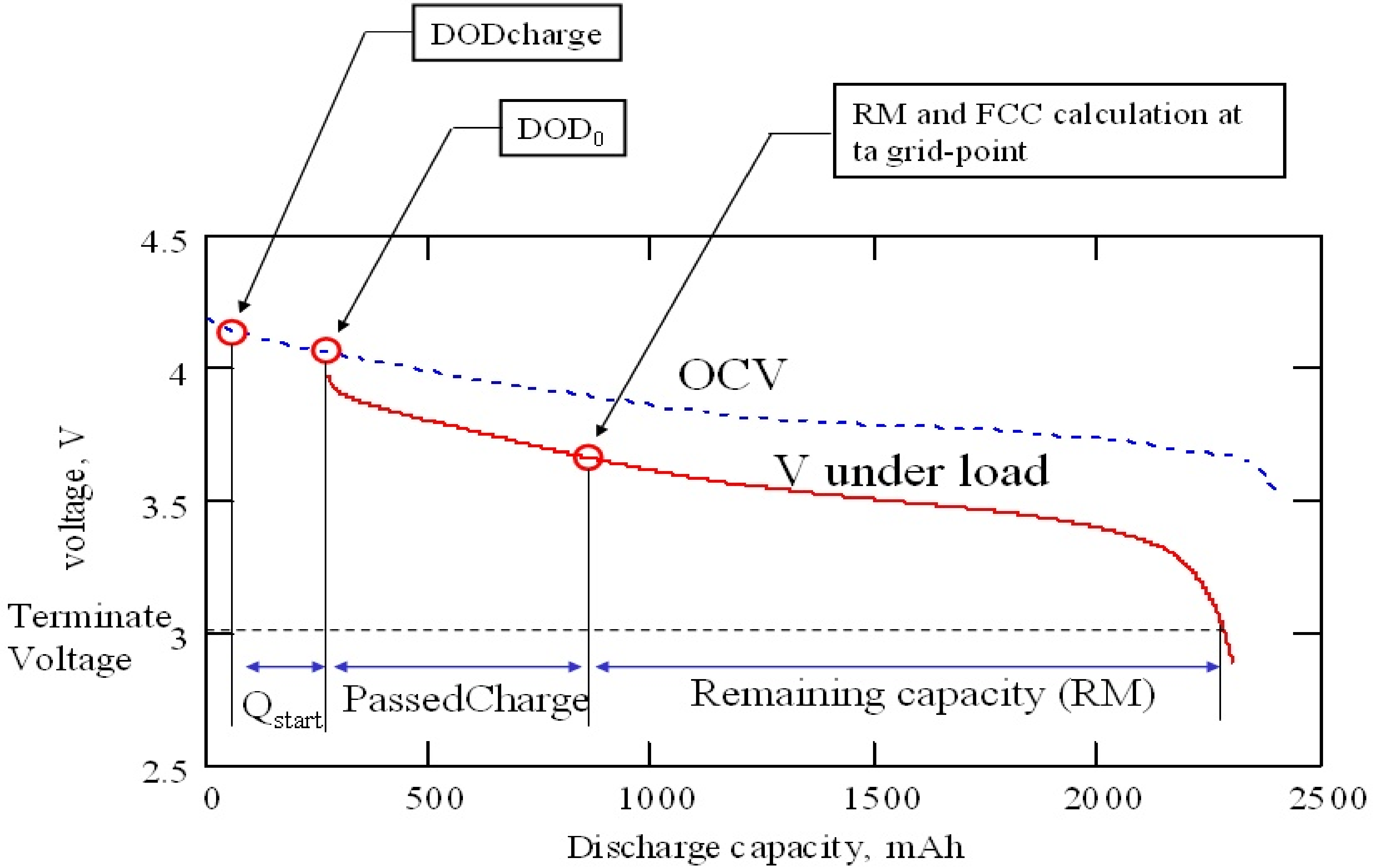
- **FCC – Full Charge Capacity is the amount of charge passed from a fully charged state until the system terminate voltage is reached at a given discharge rate**

  - $FCC = Q_{start} + PassedQ + RM$

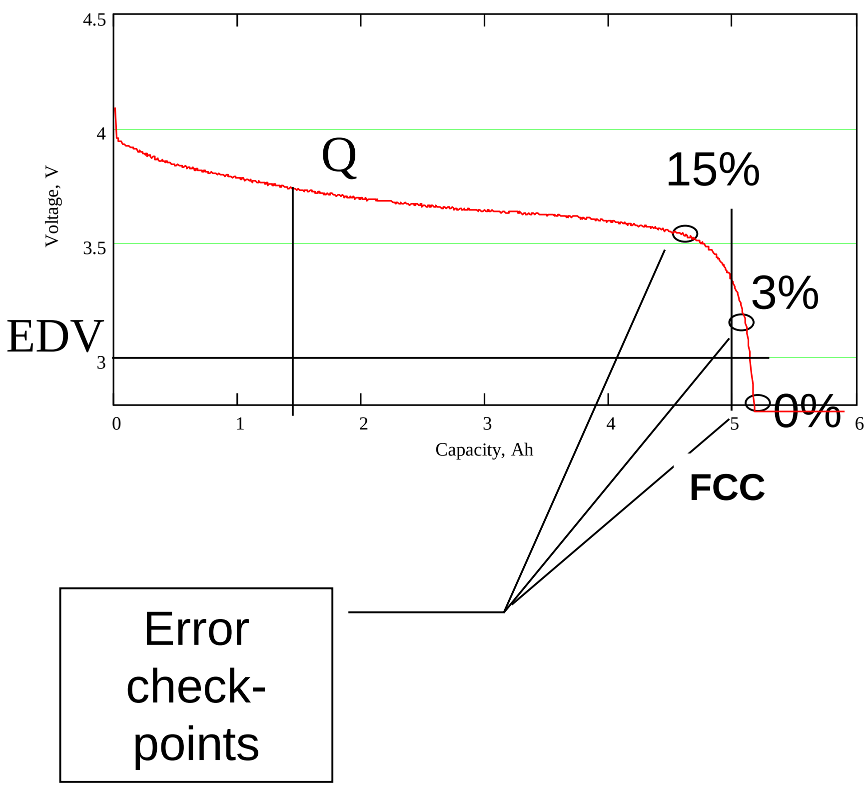
- **RSOC – Relative State of Charge**

$$RSOC = \frac{RM \times 100}{FCC}$$

Single Cell Impedance Track (IT) Fuel Gauge Introduction



Gauging Error definition



- Reference points
  - at charge termination SOC = 100%
  - at EDV SOC=0
  - Charge integrated from fully charged to EDV is FCC_{true}
- From these reference points, true SOC can be defined as

  $SOC_{true}= (FCC_{true}-Q)/FCC_{true}$
- Reported SOC at all other points can be compared with true SOC.
- Difference between reported and true SOC is the error. It can be defined at different check points during discharge.

Check point at 0% is not meaningful – EDV is the voltage where system crashes!

Single Cell Impedance Track (IT)

Error Definition and Calculation

- **Relative State of Charge (RSOC) Error**

$$RSOC\ Error = RSOC_{calculated} - RSOC_{reported}$$

$$RSOC_{calculated} = \frac{FCC - Q_{start} - PassedQ}{FCC} \times 100$$

($RSOC_{reported}$ is the RSOC reported by bq275xx Impedance Track ™ algorithm)

Single Cell Impedance Track (IT)
Error Definition and Calculation

- **Remaining Capacity (RM) Error**

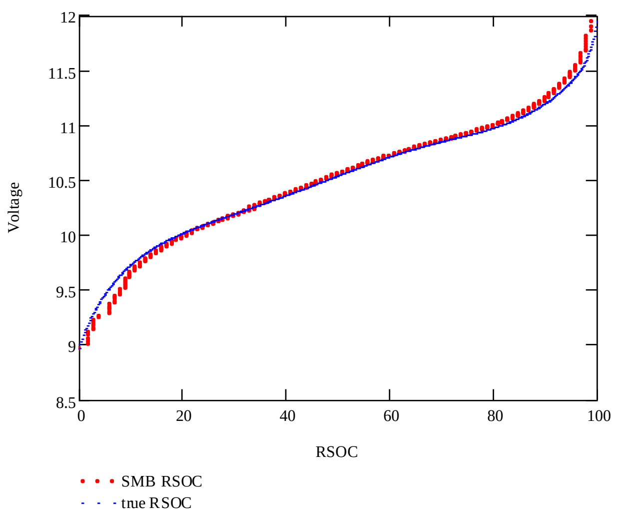
$$RM\ Error = \frac{RM_{calculated} - RM_{reported}}{FCC}$$

$$RM_{\ calculated} = FCC - Q_{start} - PassedQ$$

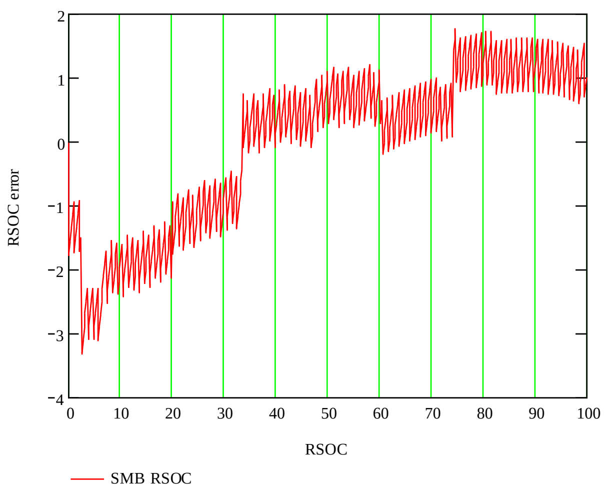
(*$RM_{\ reported}$* is the RM reported by bq275xx Impedance Track ™ algorithm)

Example error plots

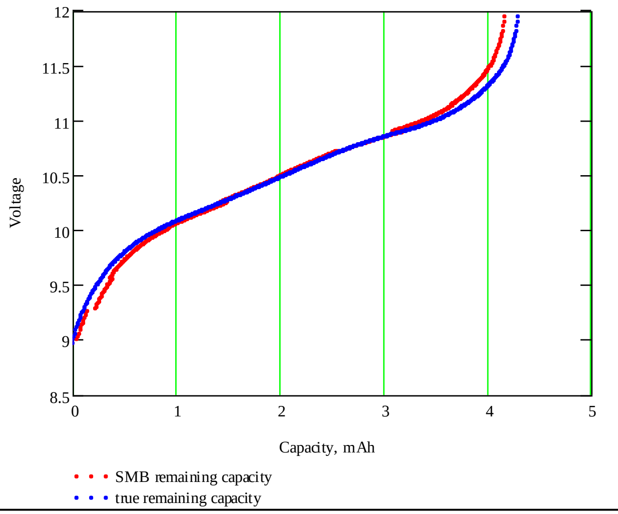
True vs reported RSOC



RSOC error



Remaining capacity test



Relative RemCap error