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

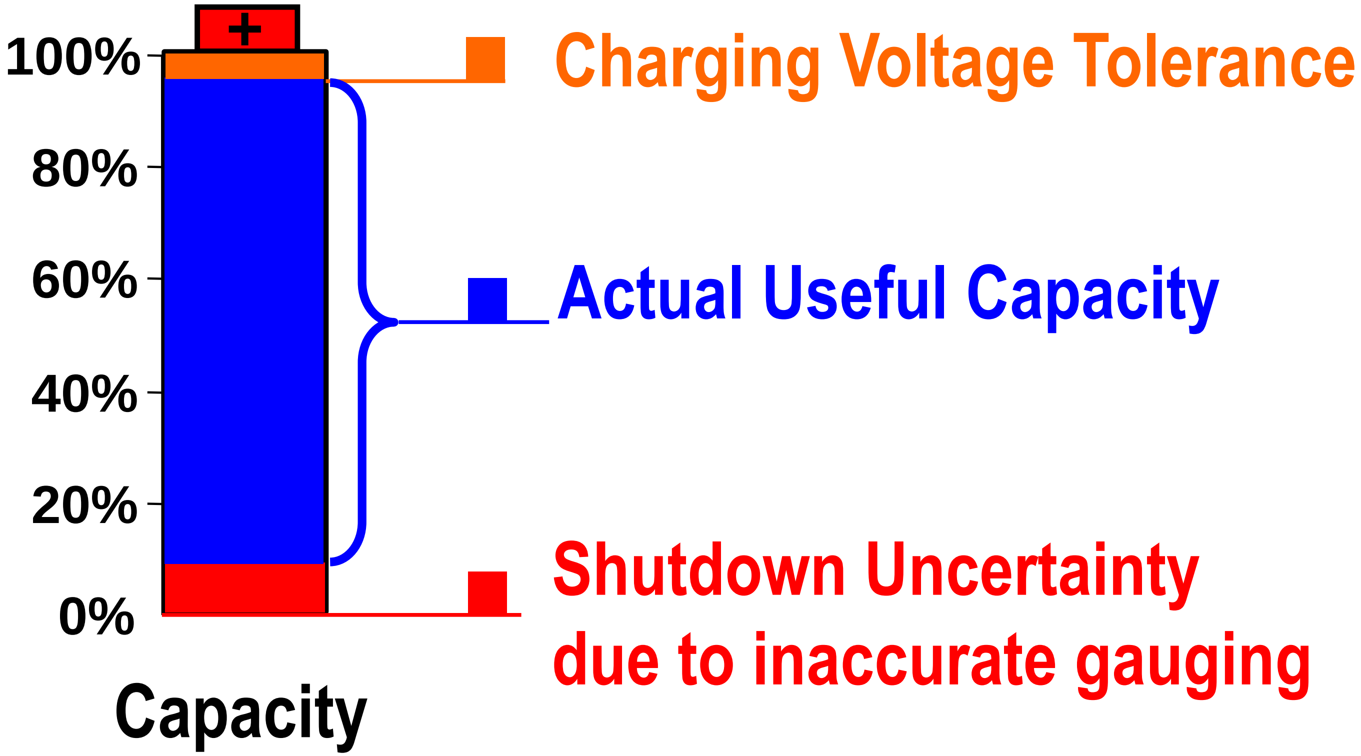
Outline

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

Single-Cell Gauging 101

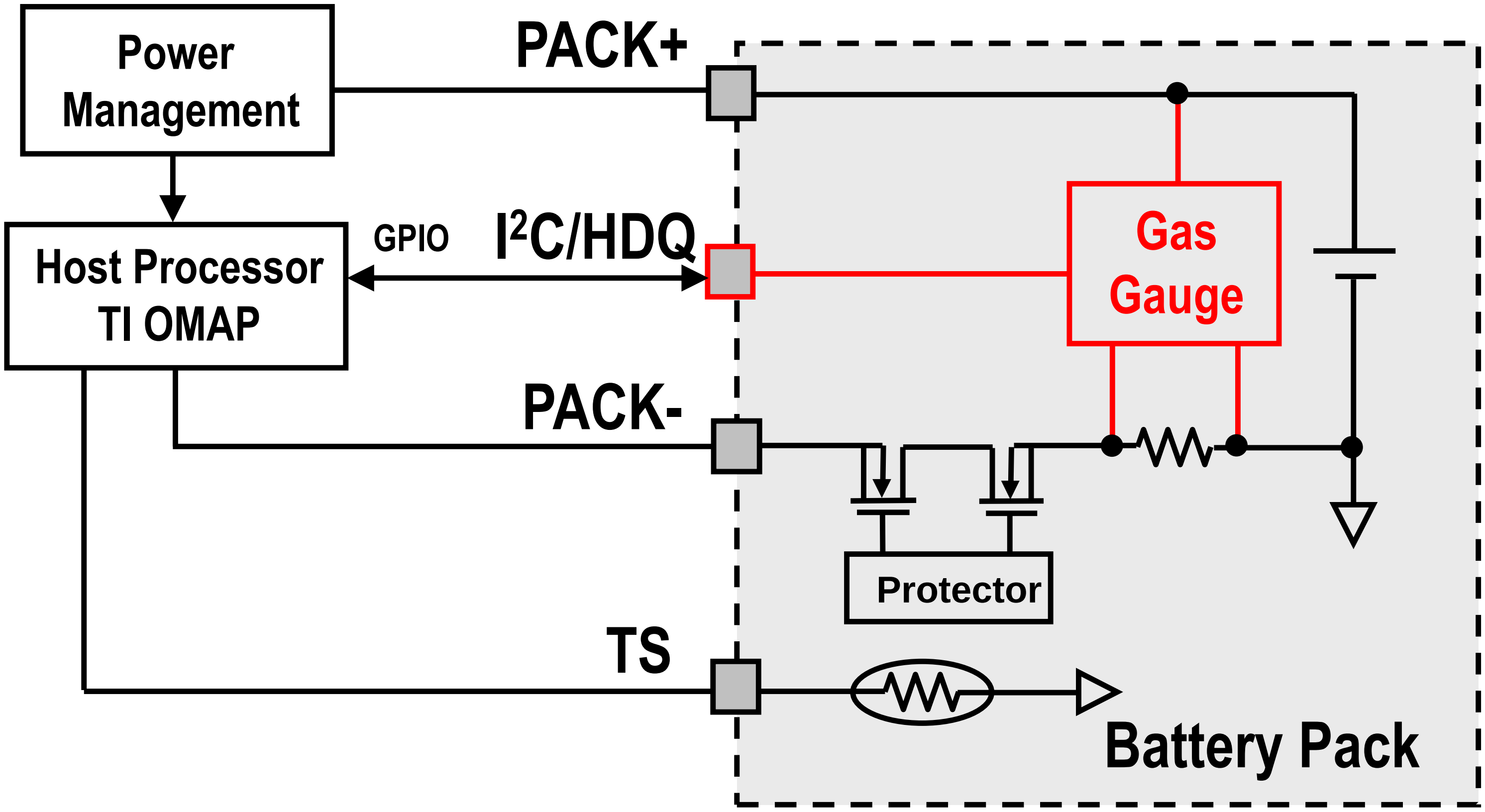
Part 2: Classic fuel gauging approaches

Goal: Full Use of Available Battery Capacity

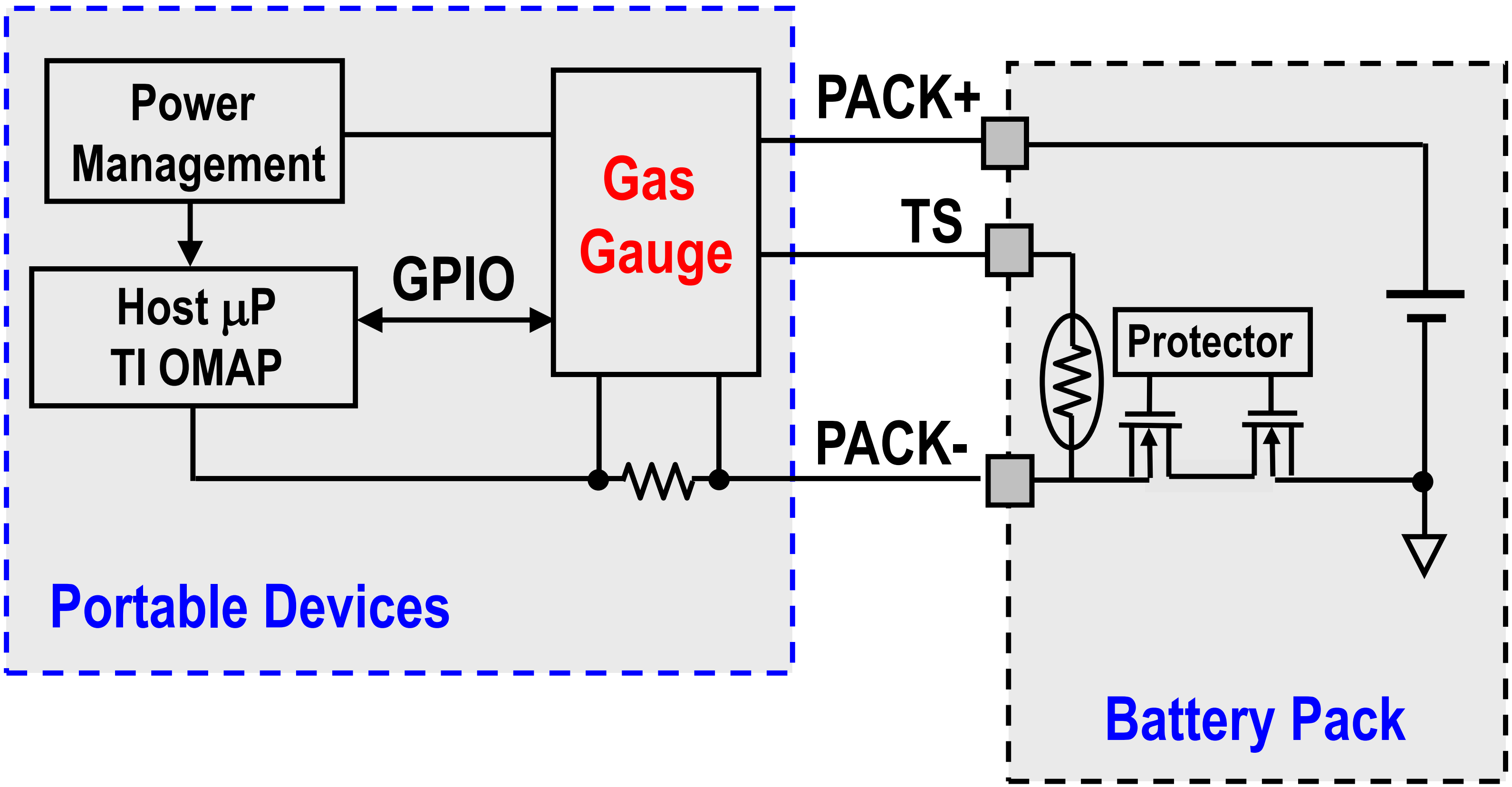


- Only 80-90% of Available Capacity may actually be used!
- High Accuracy Gas Gauge Increases the Battery Run-time

Traditional Battery Pack-Side Gas Gauge



System-Side Impedance Track Fuel Gauge



What does the Fuel Gauge do?

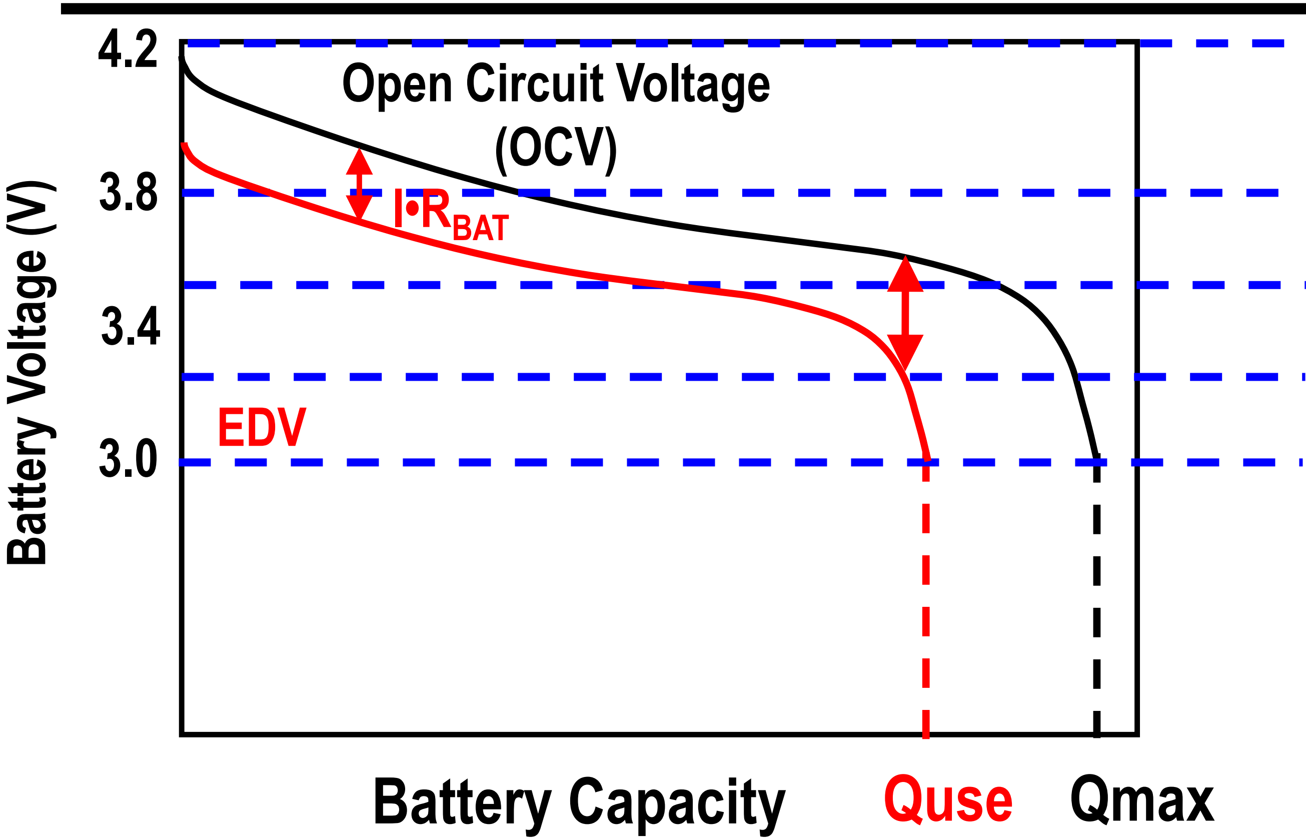
- Communication between battery and user
- Measurement:
  - Battery voltage
  - Charging or discharging current
  - Temperature
- Provide:
  - Battery Run Time and Remaining Capacity
  - Battery health information
  - Overall battery power management (Operation mode)

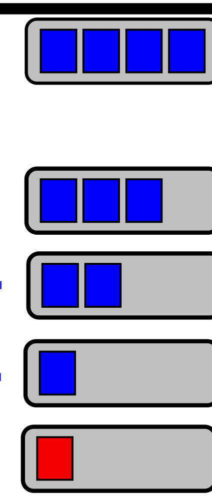
How to Implement a Fuel Gauge?

- **Voltage Based: SOC = f (VBAT)**
- **Coulomb Counting:** $$Q = \int i \, dt$$
- **Impedance Track: Real time resistance measurement**

$$V = V_{OCV} - I \bullet R_{BAT}$$

Voltage Based Fuel Gauge





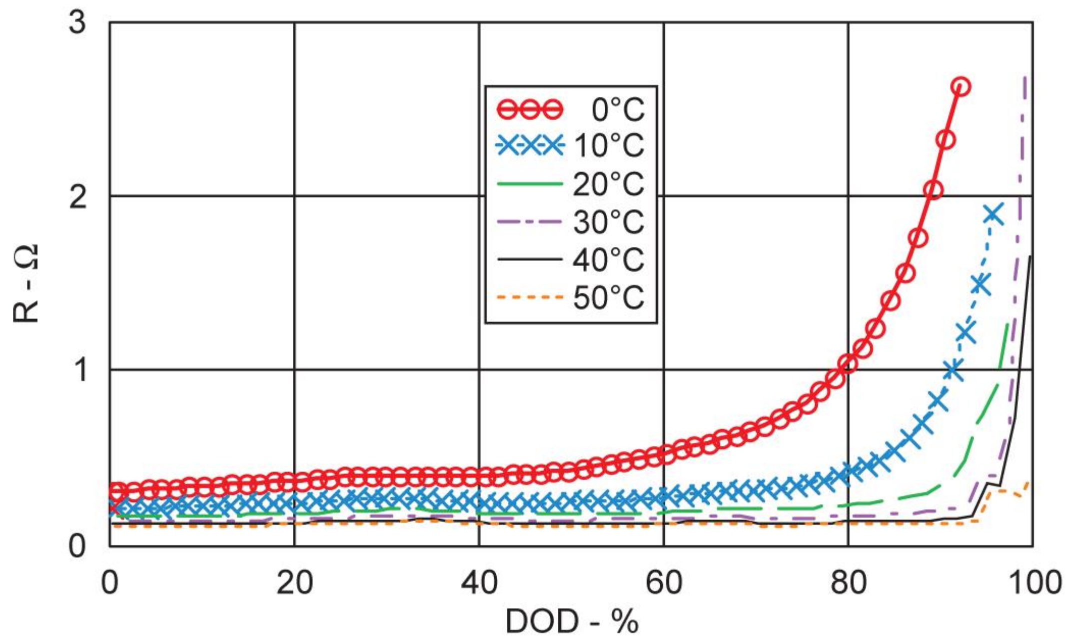
- Applications: low end cellular phone, DSC,…
- Pulsating load causes capacity bar up and down
- Accurate ONLY at very low current $V = V_{OCV} - I \bullet R_{BAT}$?

Battery Resistance

$$V = V_{OCV} - I \bullet R_{BAT}?$$

- Impedance = f(Temperature, State of Charge, and Aging)
- Resistance doubles after 100 cycles
- 10-15% cell-cell resistance variation
- 10-15% resistance variation from different manufacturers

Impedance Dependent on Temperature and DOD



Full Charged **Fully Discharged**

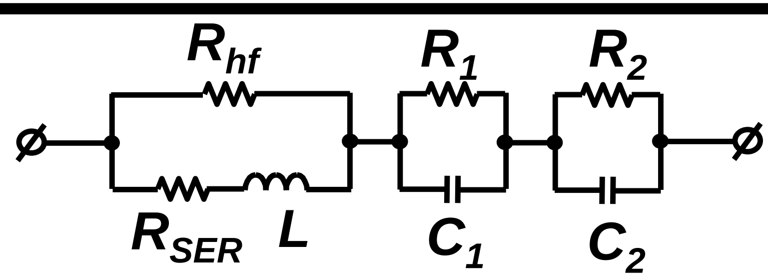
Impedance is strongly dependent on temperature, State of Charge and aging

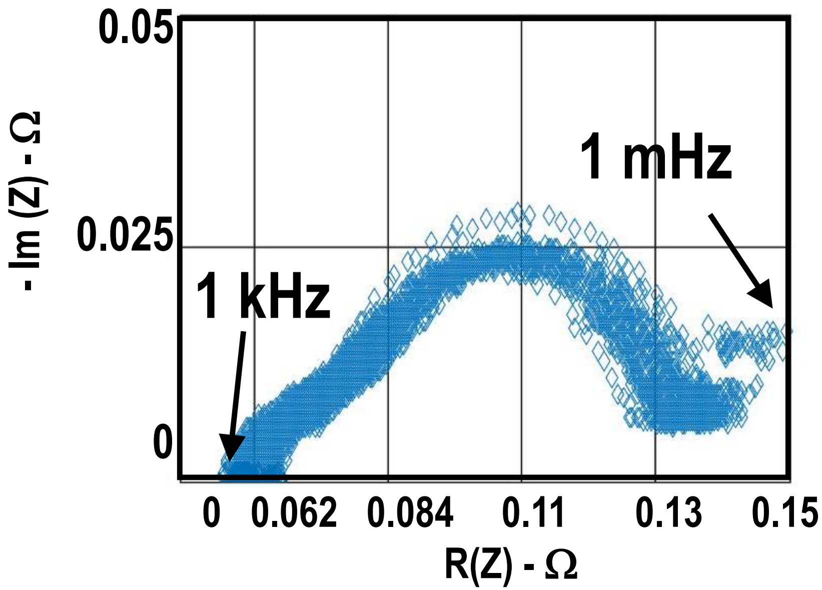
$$SOC = \frac{Q}{Q_{max}}$$

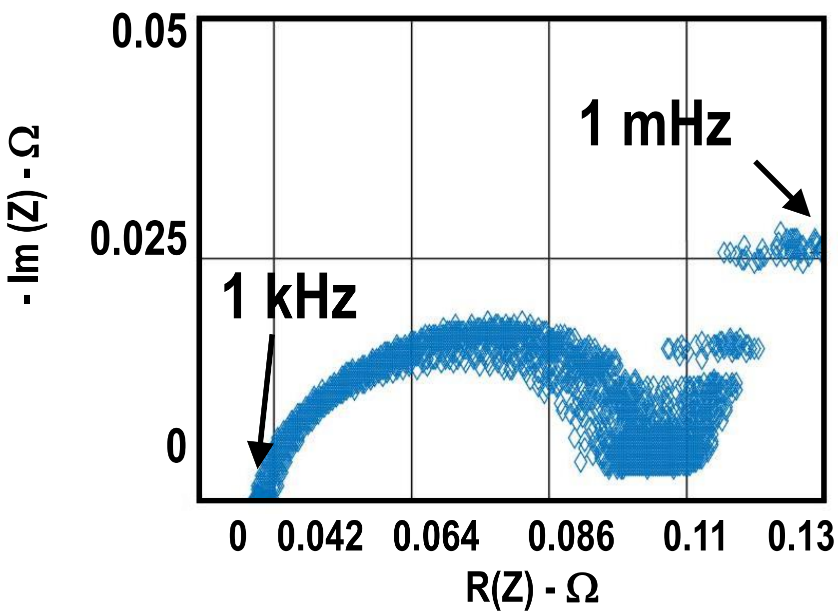
DOD=1-SOC (State of Charge)
SOC=1 (Full charged battery)
SOC=0 (Full discharged battery)

SOC: State of Charge
DOD: Depth of Discharge

Impedance Differences for New Cells

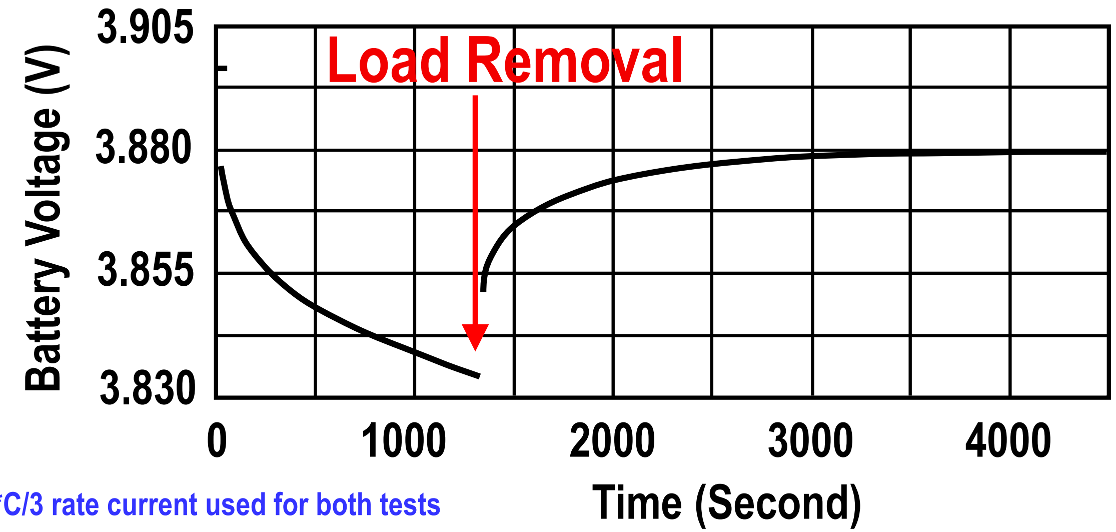




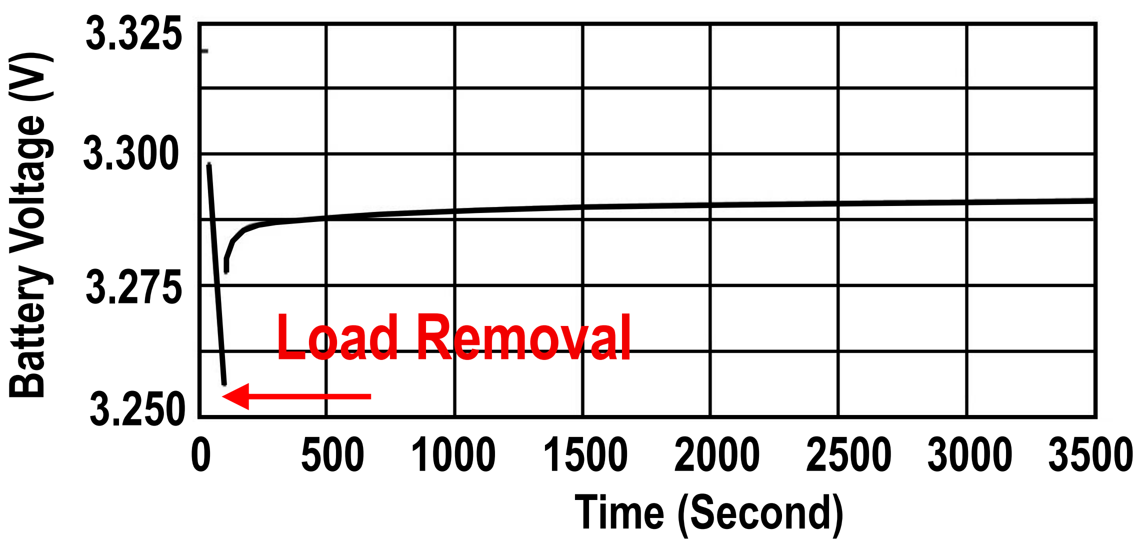


- Low-frequency (1 mHz) impedance variation 15%
- At 1C rate discharge, 40-mV difference, causes maximum SOC error of ±26%

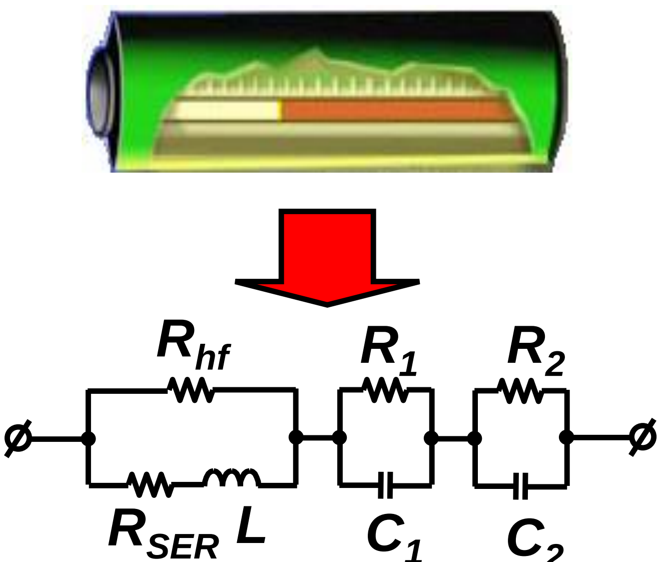
Battery – Transient Response



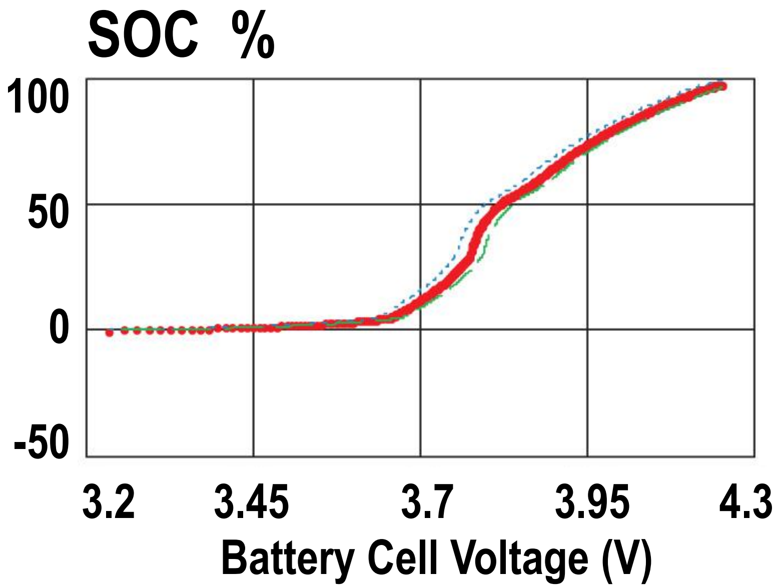
*C/3 rate current used for both tests

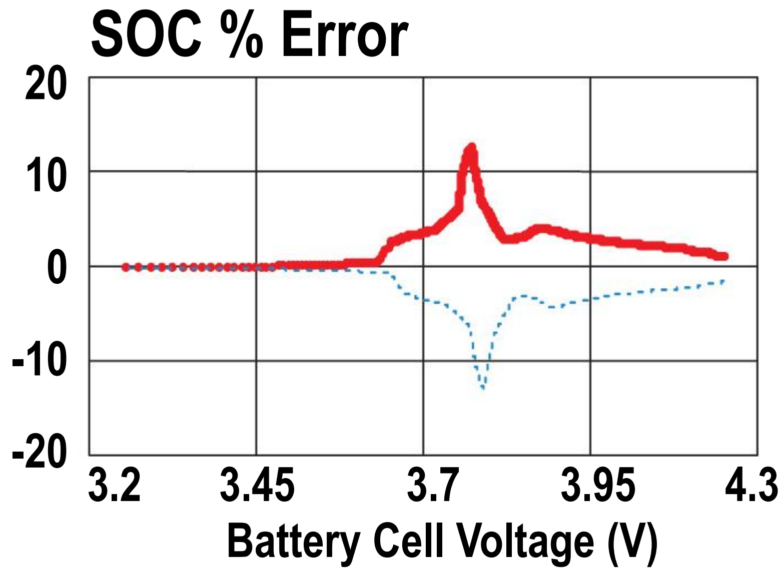


- Complete relaxation takes about 2000 seconds
- Different voltage at different instants
- Voltage difference between 20 and 3000 seconds is over 20 mV



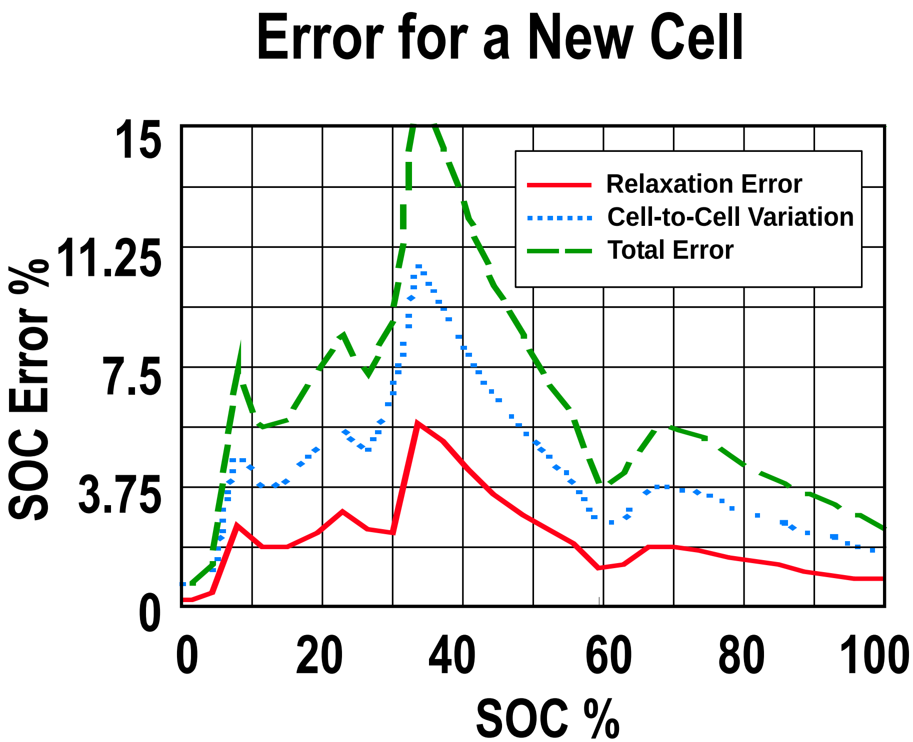
Voltage Relaxation and State of Charge Error

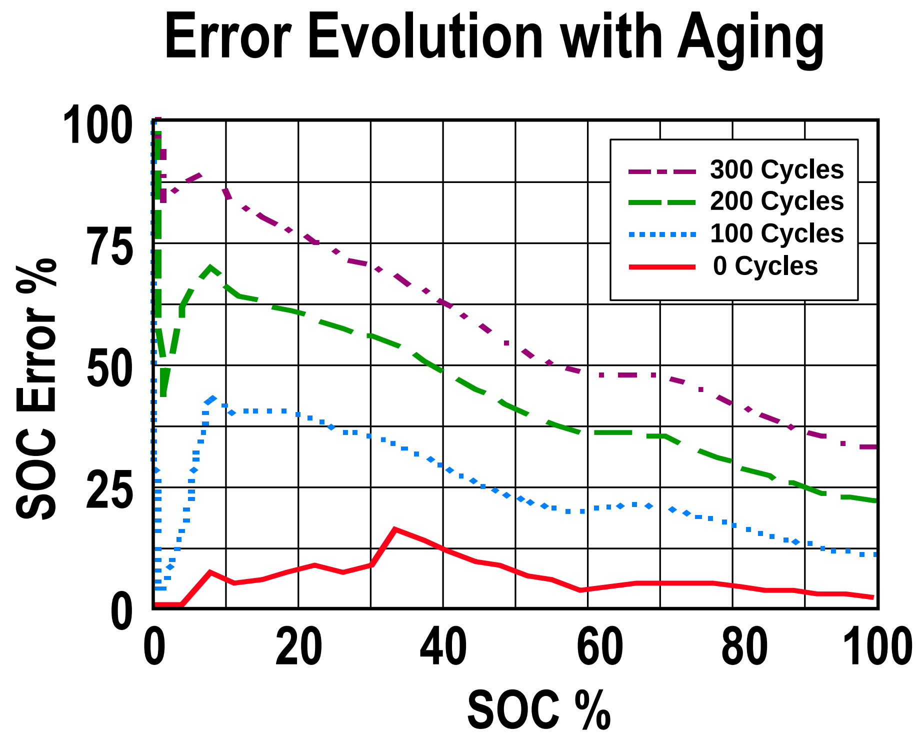




- ±20mV difference
- Error depends on particular voltage at the moment of estimation
- Maximum error reaches 15%, average error 5%

SOC Error of Voltage-Based Fuel Gauging





$$V = V_{OCV} - I \cdot R_{BAT}\ ?$$

- 20-mV relaxation measurement error
- 15% cell-to-cell resistance tolerance
- Battery resistance doubles every 100 cycles

Voltage-Based Fuel Gauge

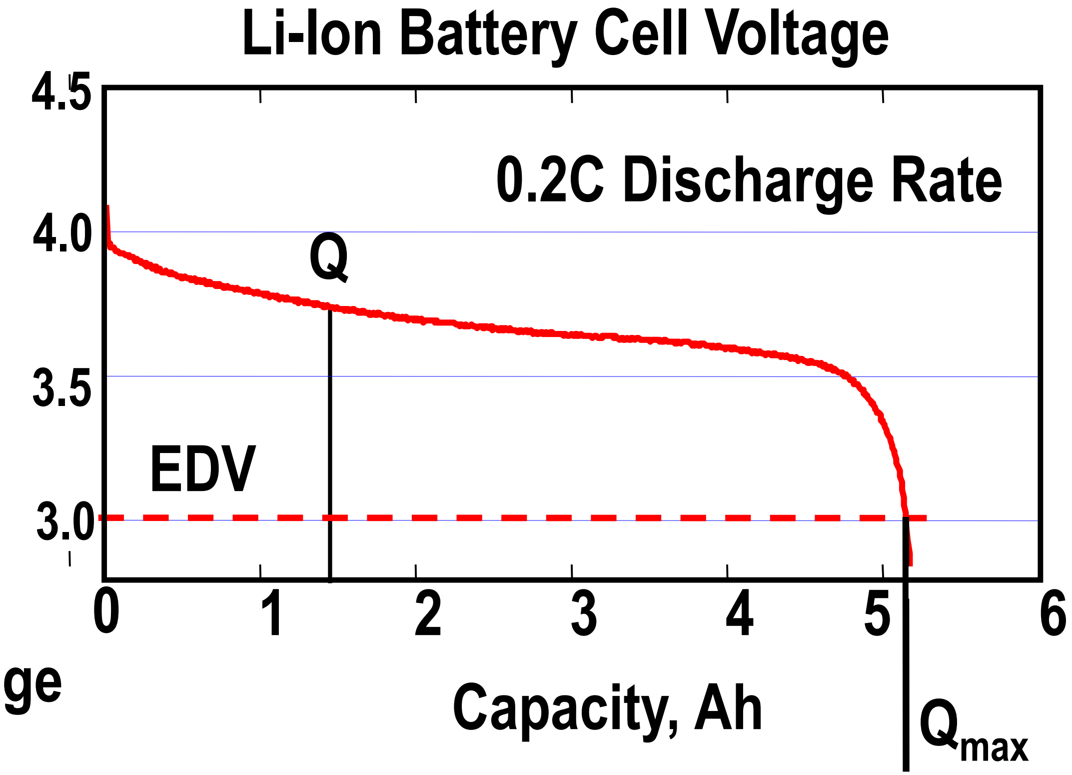
- Advantages
  - Learning can occur without full discharge
  - No correction needed for self-discharge
  - Very accurate with small load current

- Disadvantages
  - Inaccurate due to internal battery impedance
  - Impedance is function of temperature, aging, and State of Charge

Coulomb Counting Based Gauging

- Battery is fully charged
- During discharge capacity is integrated
- Q_{max} is updated every time full discharge occurs

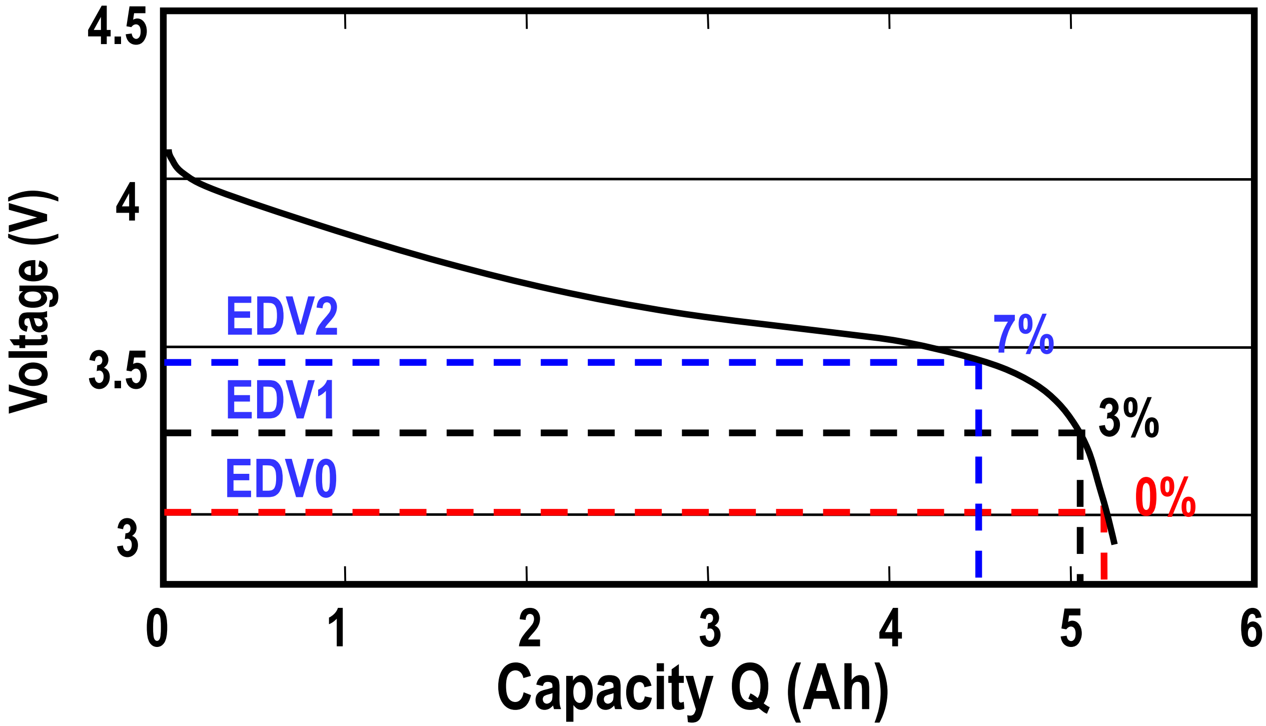
$$Q = \int i \, dt$$



EDV: End of Discharge Voltage

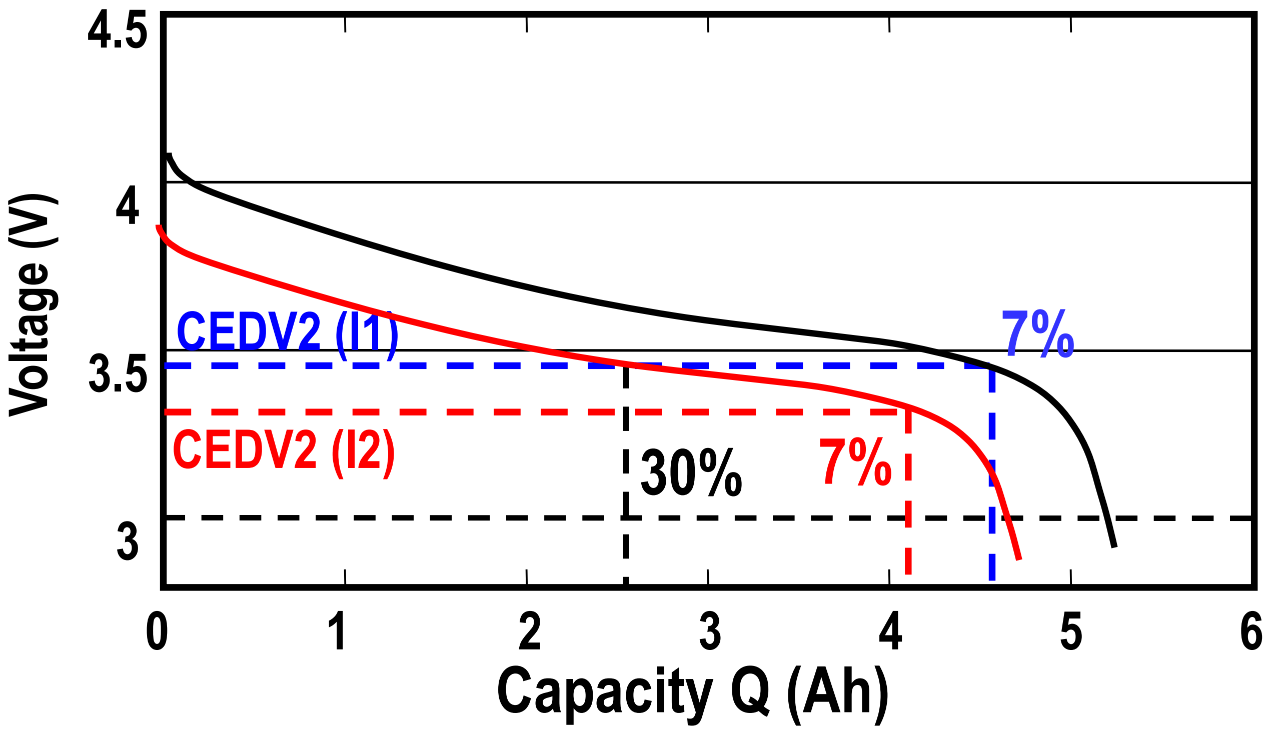
Example: bq27010, bq27210

Learning before Fully Discharged



- Too late to learn when 0% capacity is reached
- Set voltage threshold for given percentage of remaining capacity
- True voltage at 7%, 3% remaining capacity depends on current, temperature, and impedance

Compensated End of Discharge Voltage (CEDV)



CEDV = OCV(T,SOC) - I*R(T,SOC)

- Modeling: R(SOC,T), good for new battery
- Calculate CEDV2 (7%) and CEDV1 (3%) threshold at any I and T.
- Not Accurate for Aged battery

Coulomb Counting Based Gauging

Advantages

- Not influenced by distortions of voltage measurement
- Accuracy is defined by current integration hardware
- Gauging error: 3-10% depending on operation conditions and usage

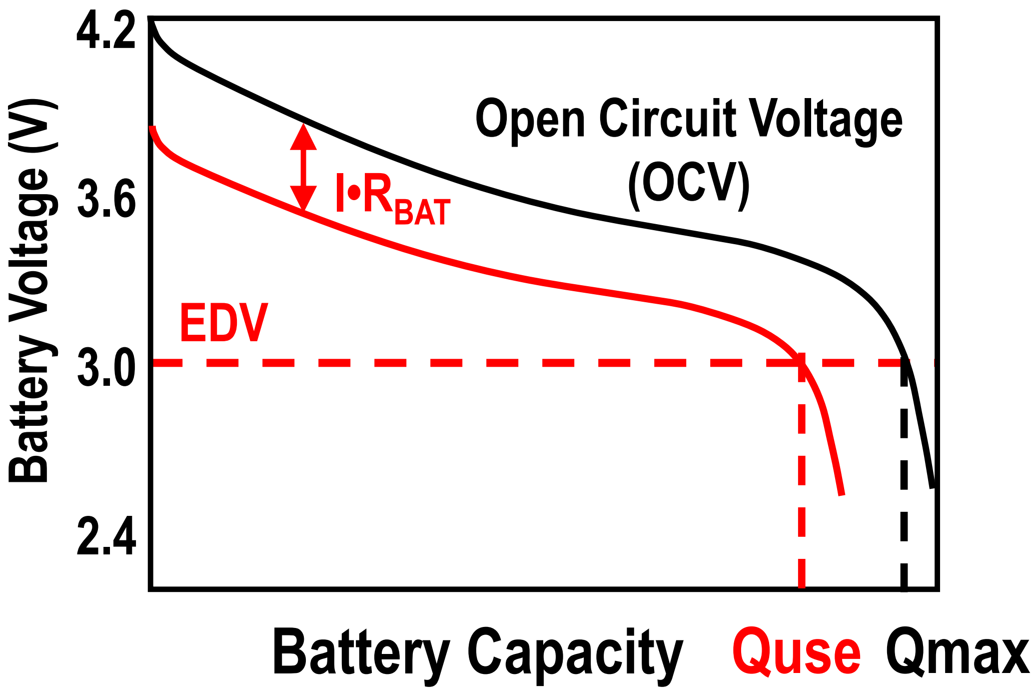
Disadvantages

- Learning cycle needed to update Q_{max}
  - Battery capacity degradation with aging
    - Qmax Reduction: 3-5% with 100-cycles
  - Gauging error increases 1% for every 10-cycles without learning
- Self-discharge has to be modeled: Not accurate

Key Parameter related to Aging: Impedance

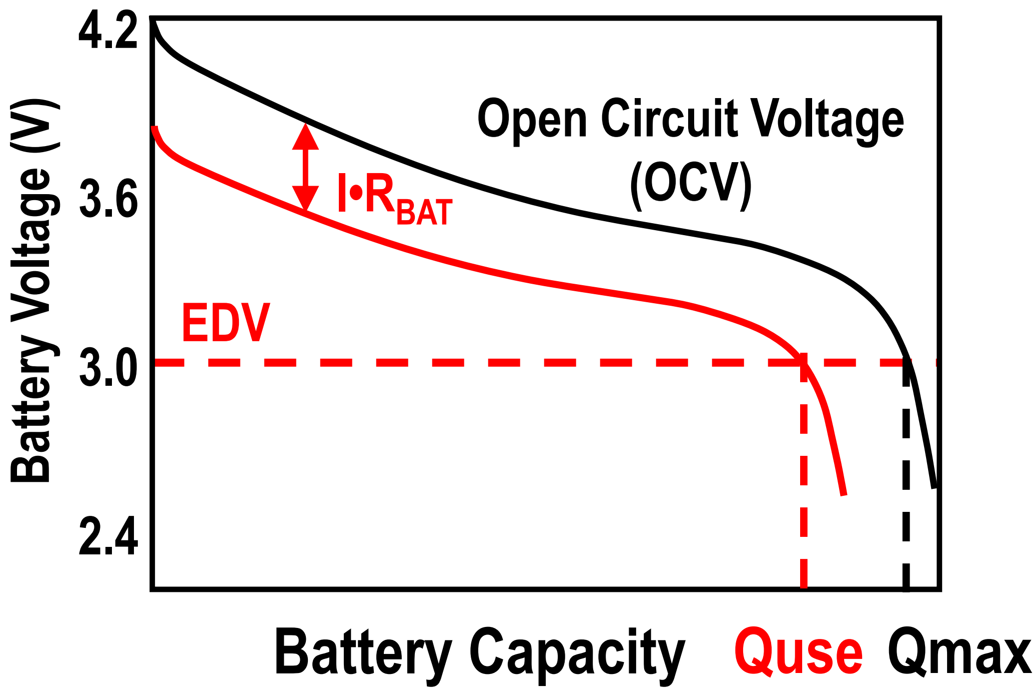
$$V = V_{OCV} - I \bullet R_{BAT}\,?$$

Advantages for typical gas gauges



- Very accurate gauging from OCV without load (relaxation)
- Very accurate gauging with Coulomb Counting with load

Issue Review



- Voltage Based gas Gauge: V = OCV(T,SOC) - I×R(T,SOC, Aging)
- Current integration gas gauge: CEDV = OCV(T,SOC) - I×R(T,SOC, Aging)

Problem: Battery Impedance

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

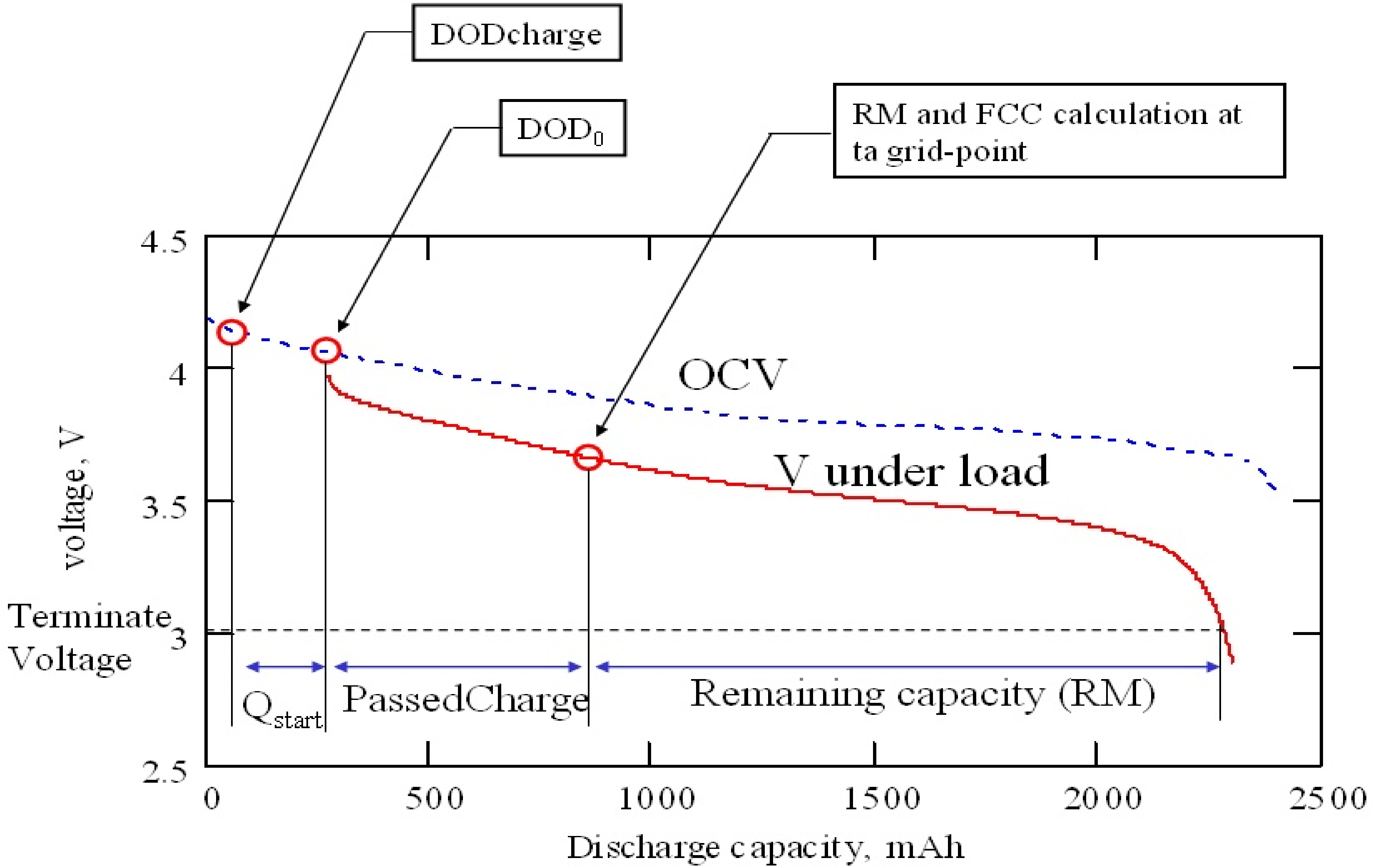
- **FCC – Full Charge Capacity is the amount of charge passed from a fully charged state until the system terminate voltage is reached at a given discharge rate**

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

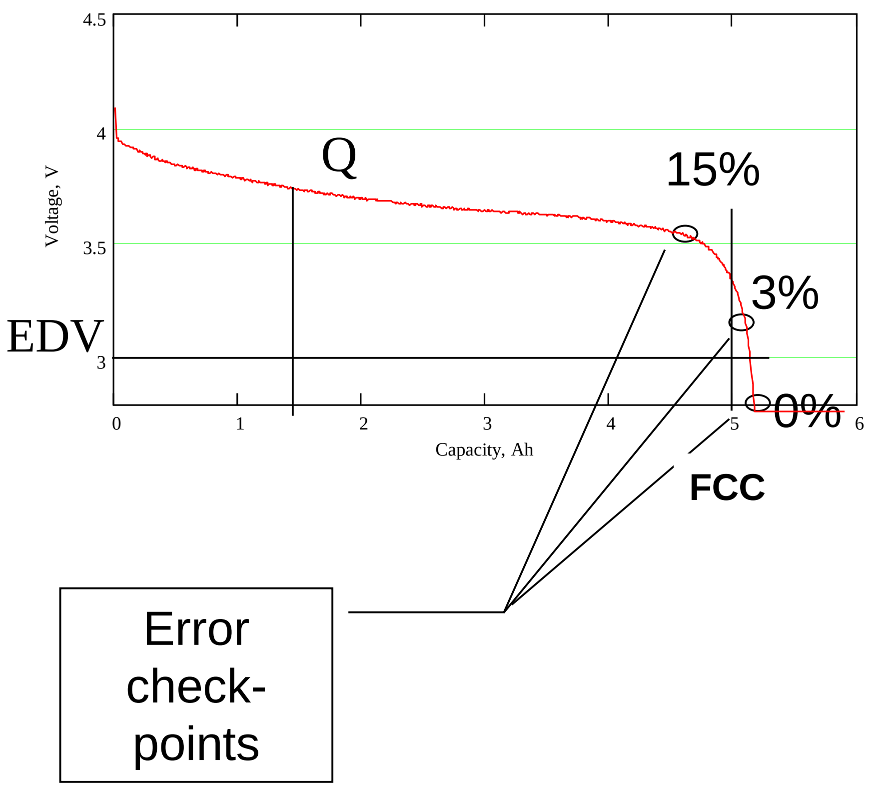
- **RSOC – Relative State of Charge**

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

Single Cell Impedance Track (IT) Fuel Gauge Introduction



Gauging Error definition



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

- **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.**

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**

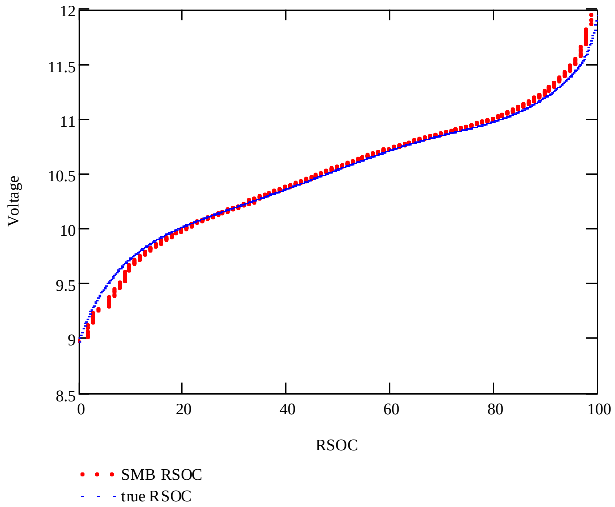
$$RM\ Error = \frac{RM_{calculated} - RM_{reported}}{FCC}$$

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

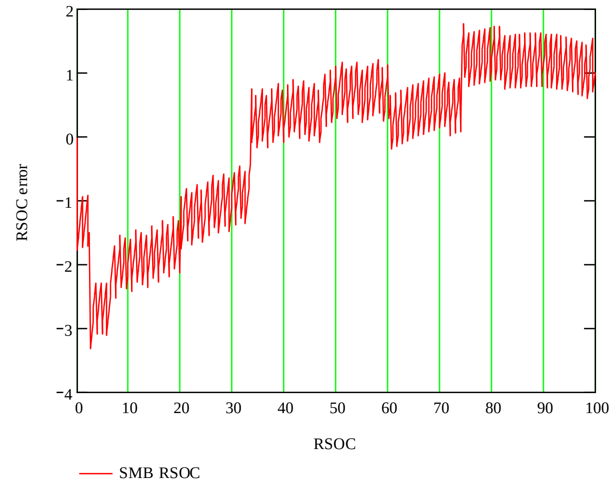
($RM_{reported}$ is the RM reported by bq275xx Impedance Track™ algorithm)

Example error plots

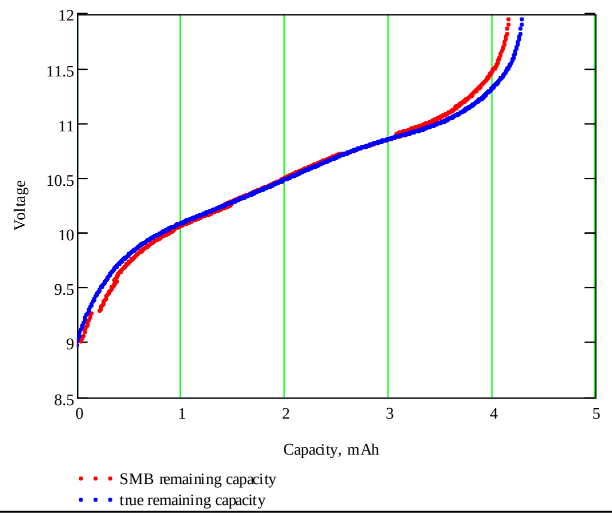
True vs reported RSOC



RSOC error



Remaining capacity test



Relative RemCap error