TI POWER

Battery management for pulsed load applications

Battery Management Deep Dive Training

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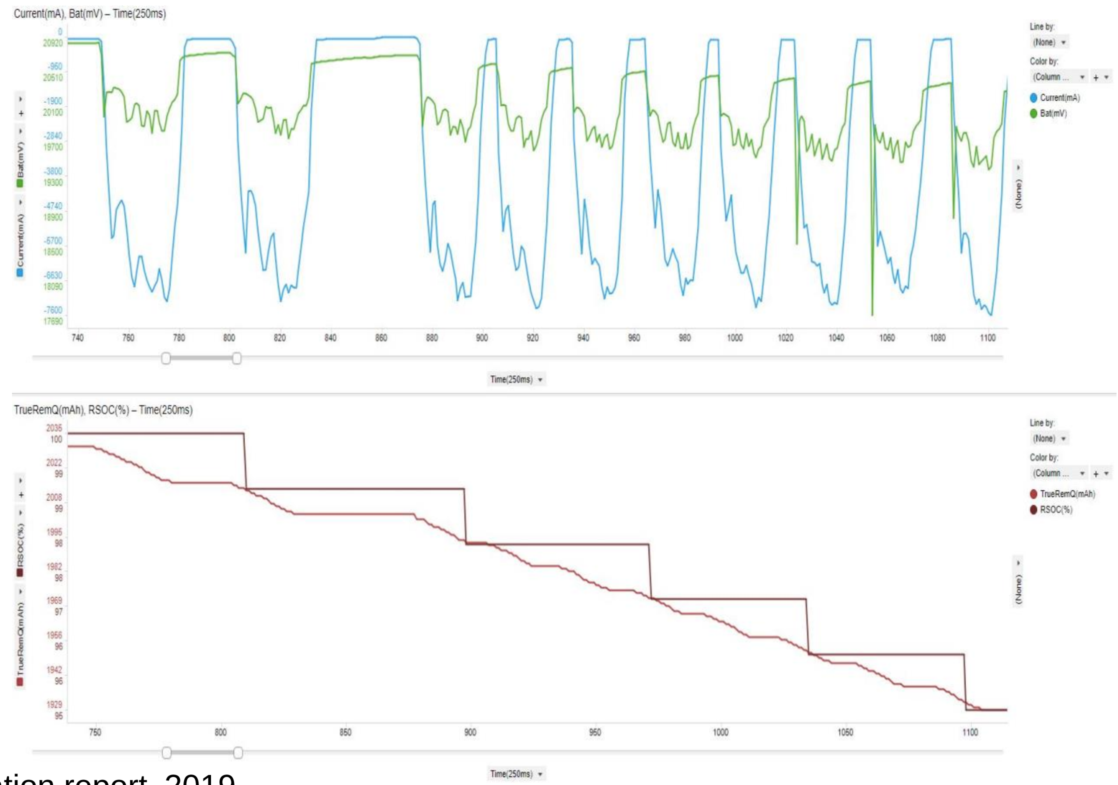
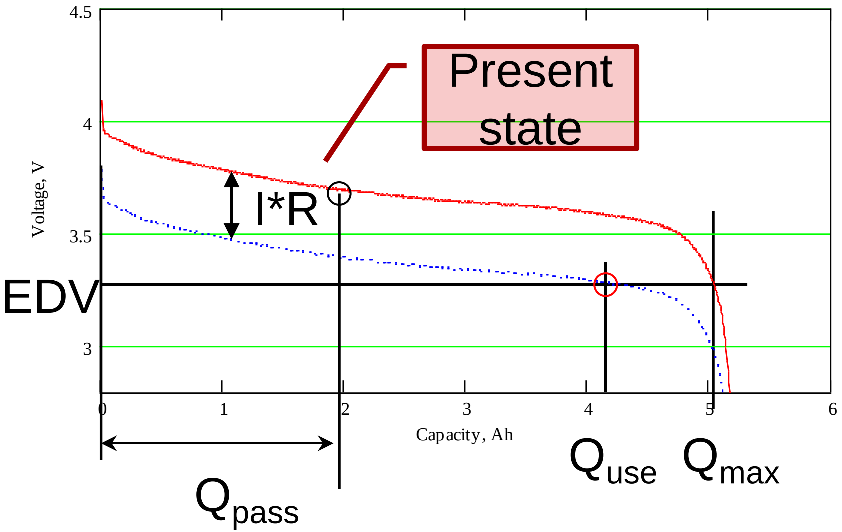
  - State of power health (SOPH) – how max power compares to system min power and new battery max power

Example current and voltage profile during power tool operation



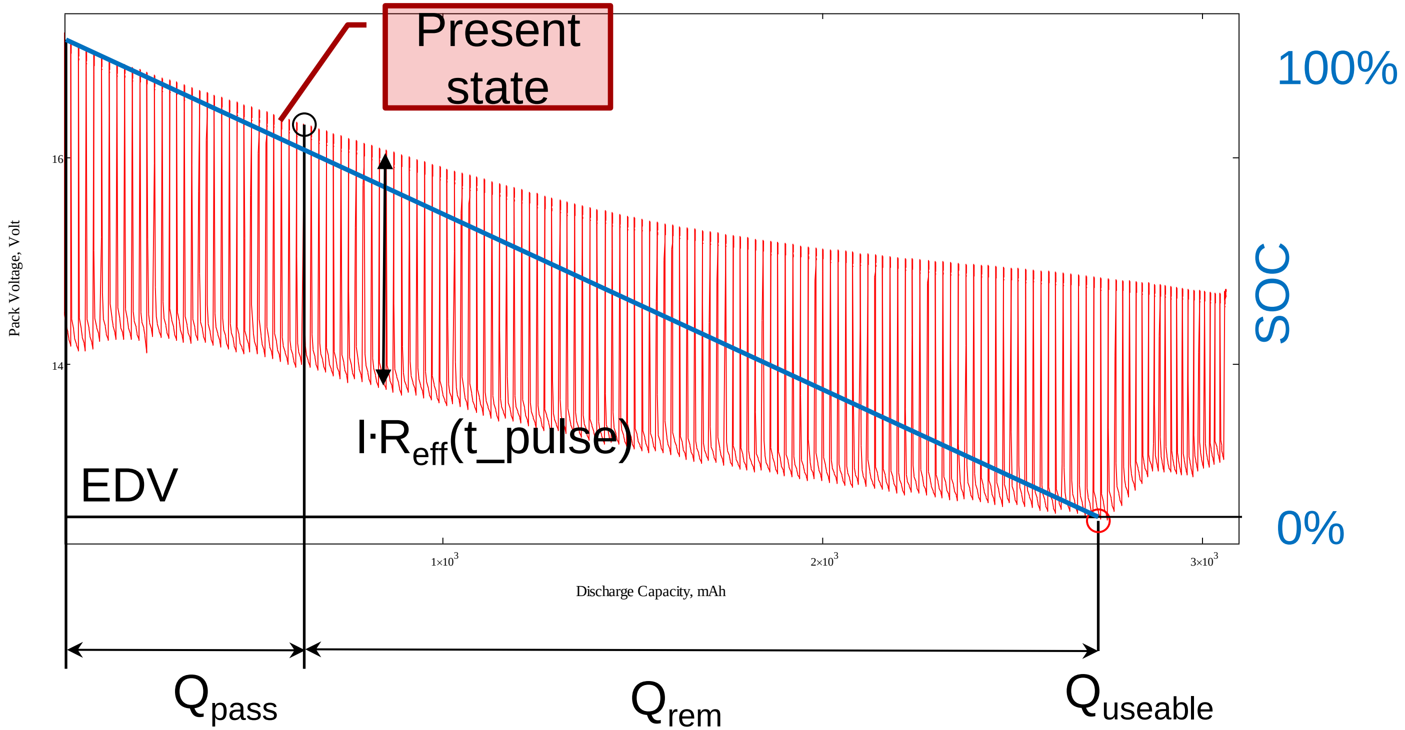
*Kang,Kang, TI application report, 2019

Useable capacity at steady-state discharge / useable SOC



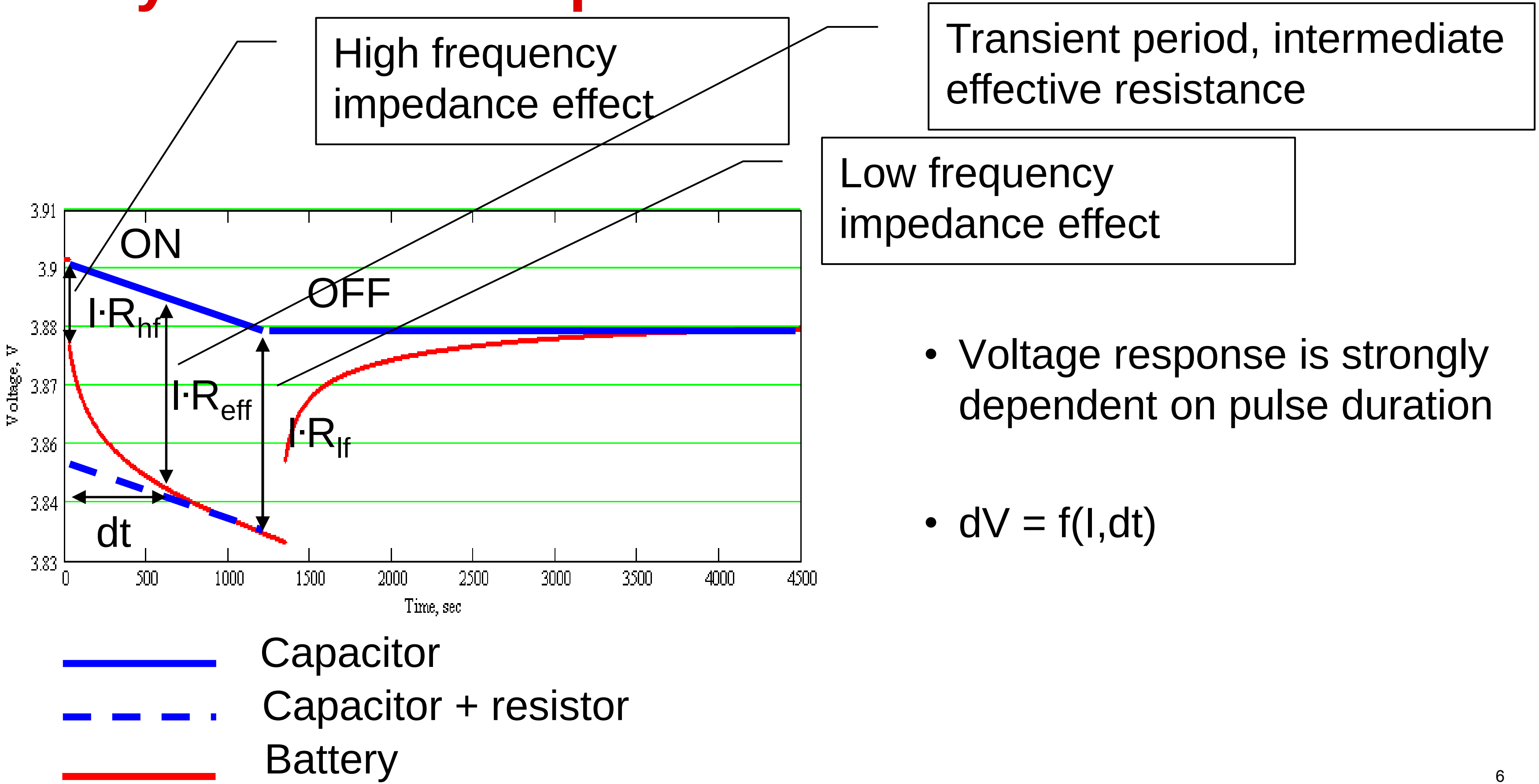
- If high current is flowing through the battery, EDV will be reached earlier because of I*R voltage drop
- External battery voltage can be roughly modeled as V=V0-I*R, where R is low frequency internal impedance of battery
- Useable capacity, Q_{use}, of battery is capacity at given load I
  - Q_{use} is less than Q_{max}
- $SOC_{use} = (Q_{use} - Q_{pass}) / Q_{use}$
- Impedance changes with age: update is critical for Q_{use} accuracy!

Useable capacity at pulsed discharge



$$SOC = (Q_{rem} * 100) / Q_{useable}$$

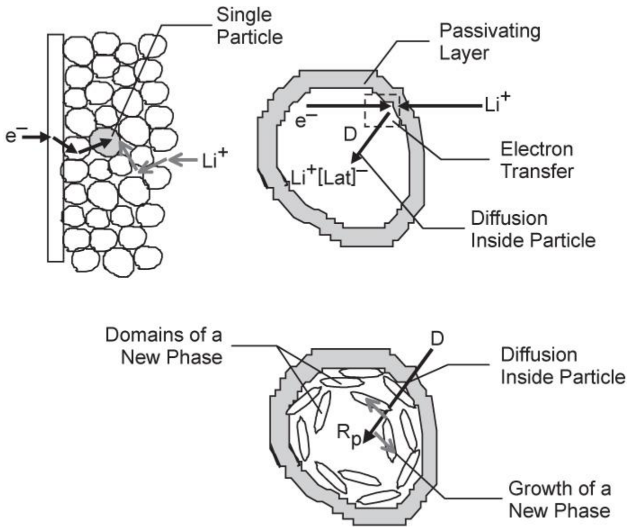
Battery transient response



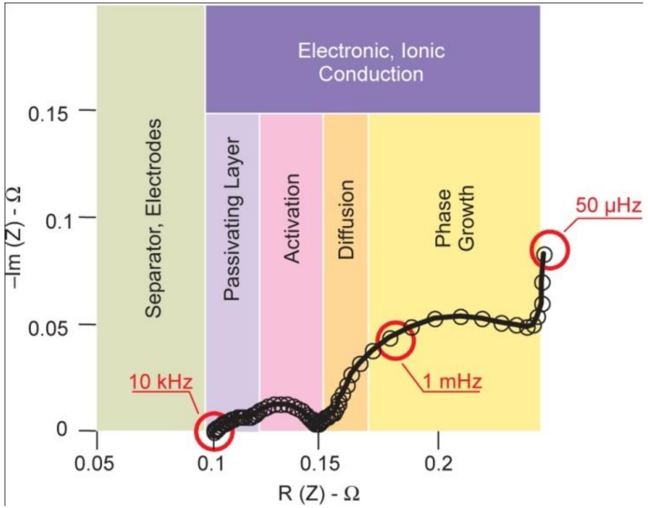
- Voltage response is strongly dependent on pulse duration
- dV = f(I,dt)

Components of battery impedance

Kinetic steps in Li-ion battery*

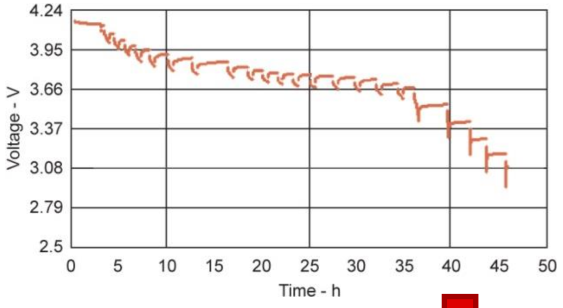


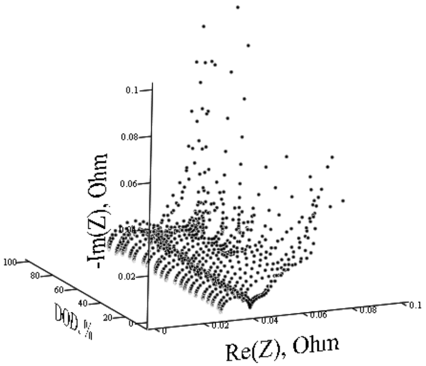
Corresponding impedance spectrum

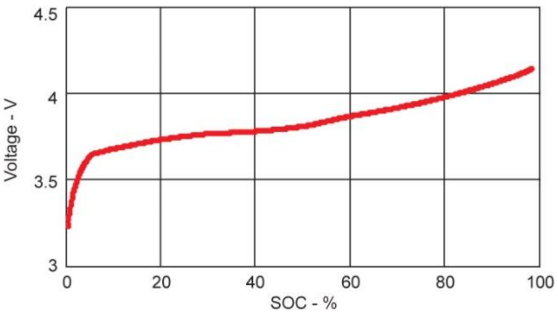


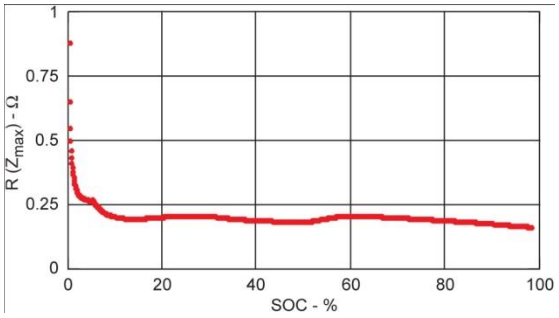
*E. Barsoukov et al., J. New Materials for Electrochem. Sys., 3, (2000) 301

Offline characterization to obtain OCV and impedance information

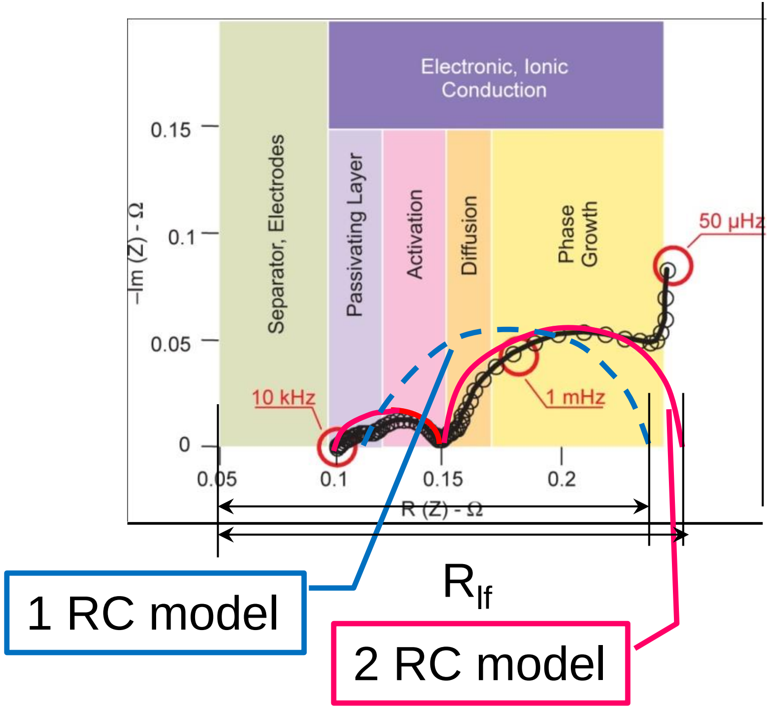








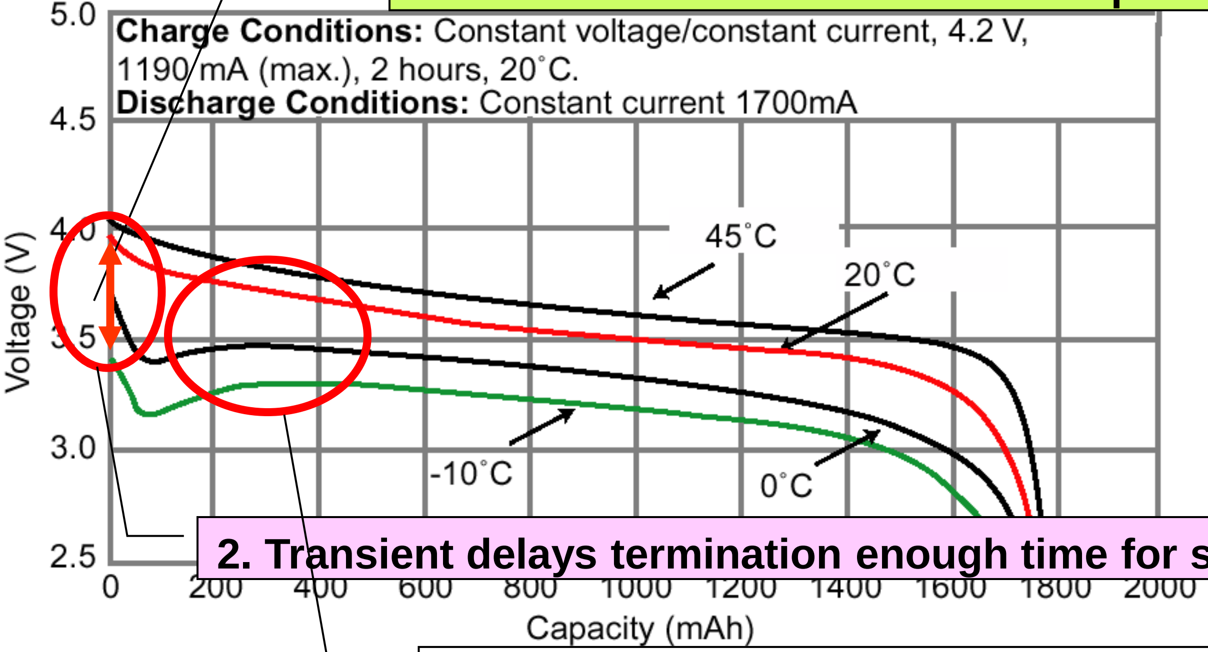
Equivalent circuit model errors



- 2 RC or higher equivalent circuit is needed to model both R_{hf} and R_{lf} correctly
- 1 RC models used in some gauging systems result in drastic error in R_{lf}
- Since R_{lf} is used in IR correlation for OCV estimation, this model error results in additional DOD error

Need for thermal modeling

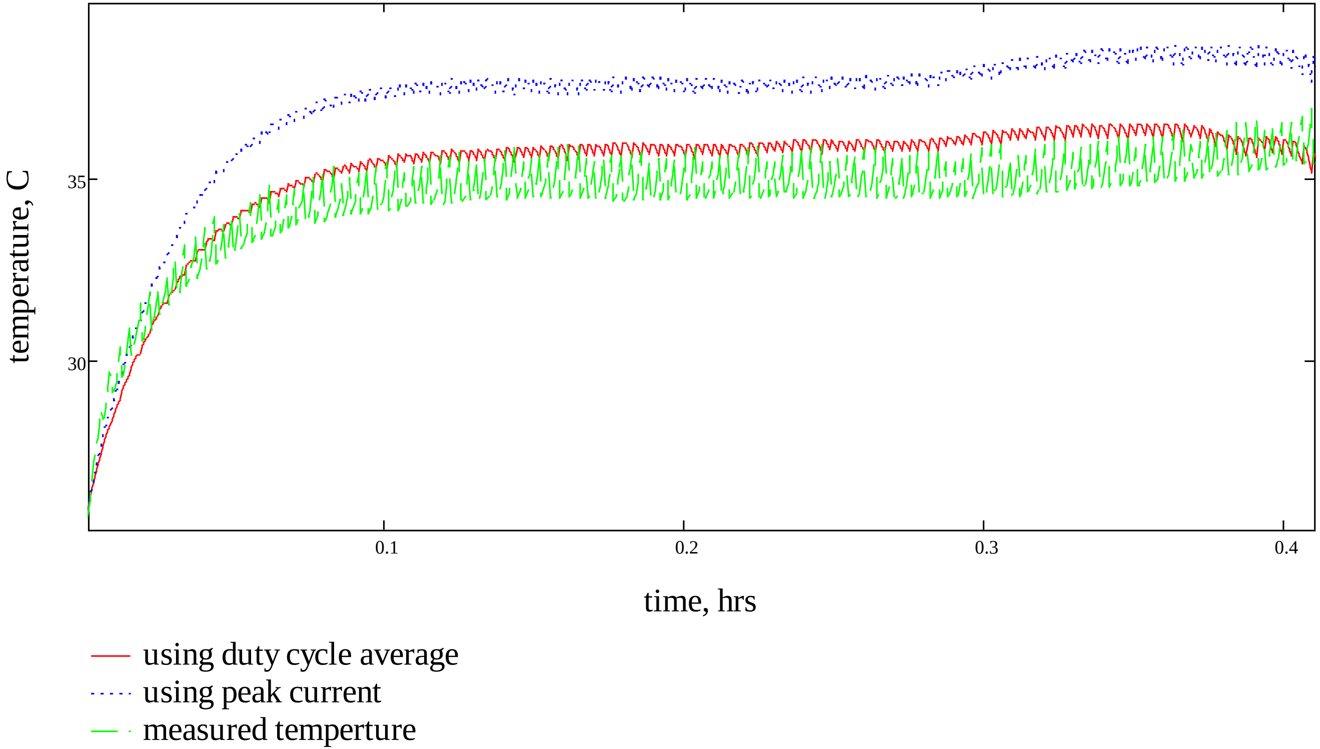
1. Resistance increases at low temperature



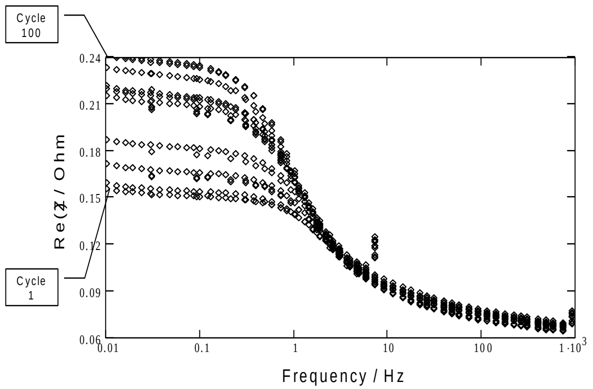
2. Transient delays termination enough time for self-heating

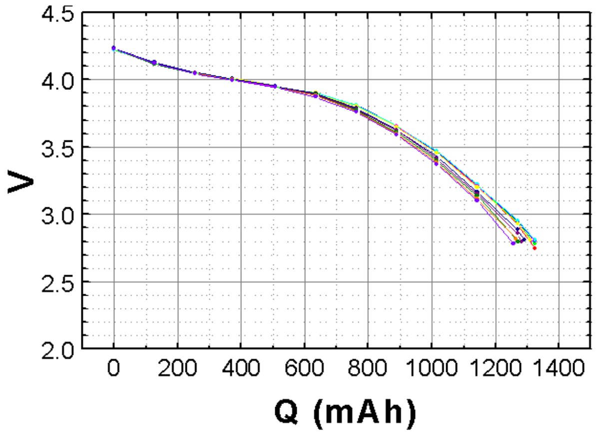
3. Self-heating allows cell voltage to be kept above termination

Thermal modeling for pulsed applications



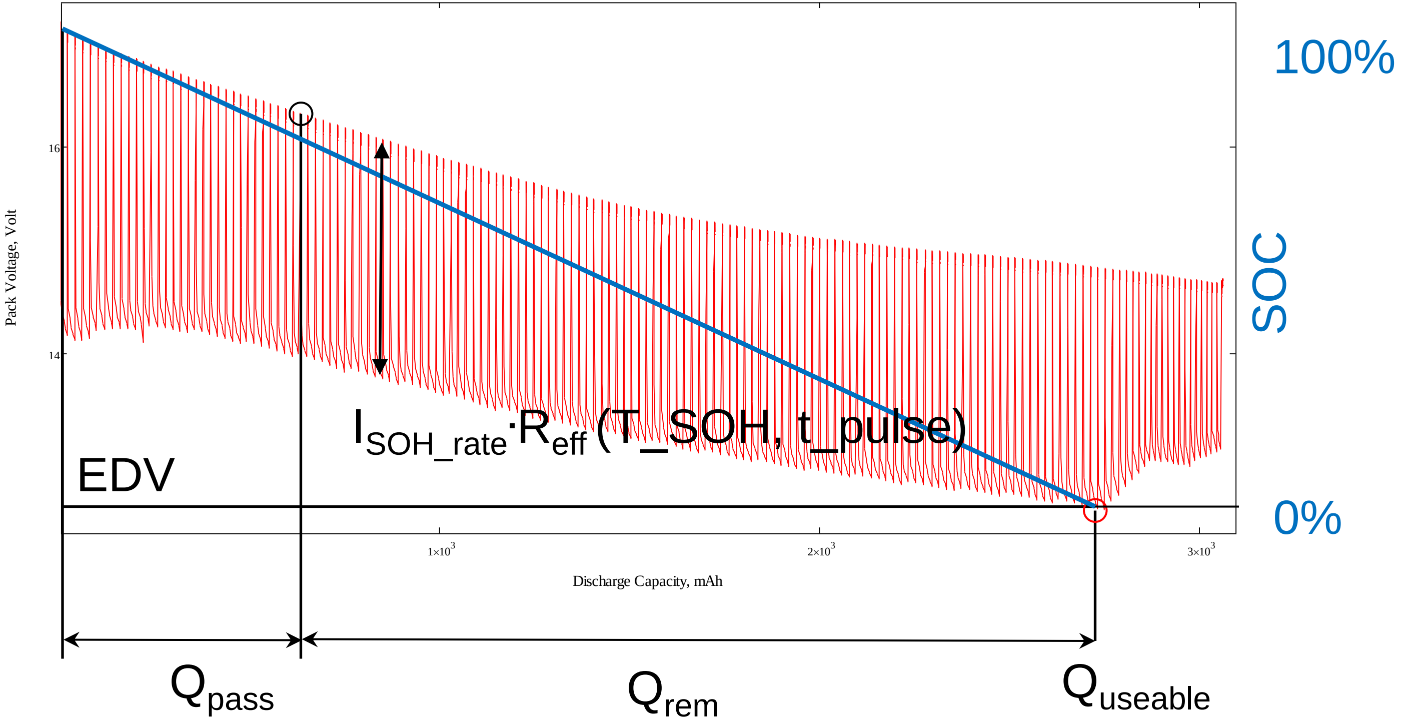
Impedance increase with aging – Update of R_{lf} is most critical





- Impedance important for DC performance is low frequency (1 mHz and below) impedance
- Low frequency impedance increases much faster than 1 kHz impedance often reported by battery manufacturers
- Impedance increase is much faster than decrease of base (low-rate) capacity
  - Usual rate is 60% impedance increase in 100 cycles
- This results in about 60 mV error in voltage estimation at 1C rate discharge – this is equivalent to $\pm$30% error in SOC estimation after only 100 cycles

State of health under pulsed discharge conditions

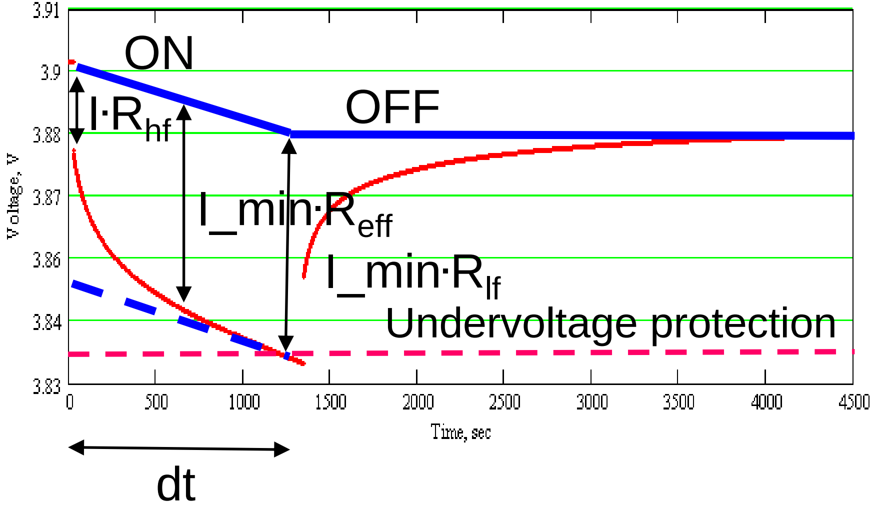


$$SOC = (Q_{rem} *100) / Q_{useable}$$

Battery health indication for pulsed applications

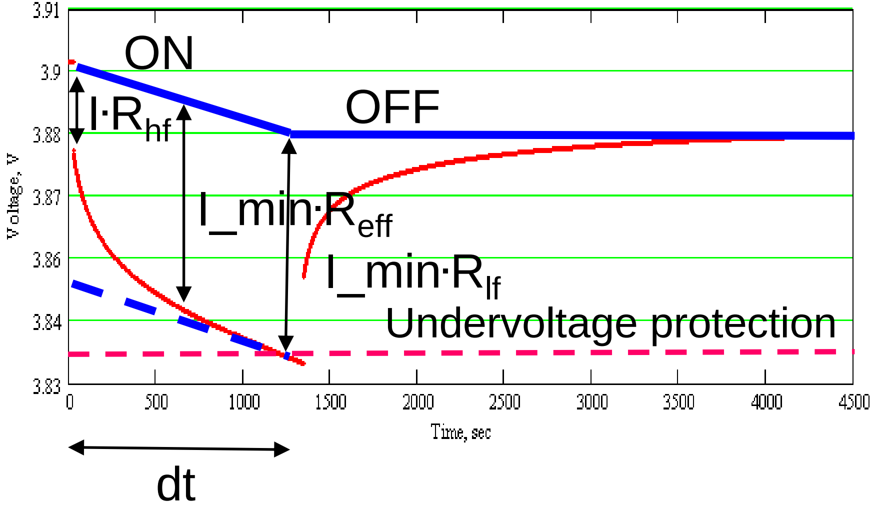
- Cycle count and time alone are not representative because usage conditions such as temperature, voltage, charge and discharge rates and depth of cycling significantly affect aging
- Battery useable capacity degradation consists of:
  - Impedance increase
  - Chemical capacity decrease
- Impedance increase needs to be accounted for with periodic measurements when load is present
- Chemical capacity, Q_{max}, decrease is less significant (5% per 100 cycles) and can be updated by combining voltage correlation and passed charge information
  - Measured discharge capacity alone can be misleading as an indication
  - At high rates or low temperatures, state of health indicated is too high because impedance increase effect becomes dominant
- State of health as ratio of useable capacity normalized to room temperature and typical rate to design capacity includes both impedance and capacity effects
- For pulsed applications additional factors, such as pulse duration and duty cycle, affect voltage and thermal modeling
- SOH = Q_{use}(25C, I_{av}, $I_{max,}$ dt_pulse, duty cycle) *100% / Q_{design}

Minimum device power requirement – Can we drill one hole?



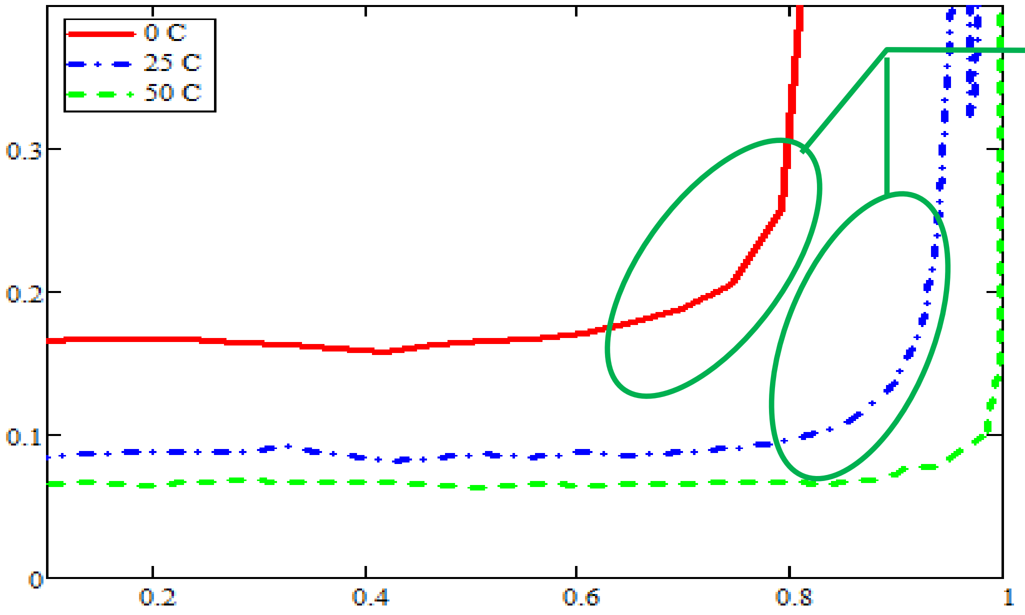
- Power tool becomes useless if it can not deliver even a single tool action, such as "drill one hole", even if battery has significant capacity left
- Drilling one hole requires **minimum power over a pulse duration (P_{min})**, for example 25 W over 1 sec pulse
- Failure to deliver given power means voltage drops **below undervoltage protection** level before time dt
- Other pulsed load applications have similar requirements
  - A drone needs minimum power to take off
  - A hybrid car battery has minimum power to crank the engine

State of power for the battery – SOP



- Battery **state of power** is power delivered for pulse duration *dt* that causes voltage of the battery to reach undervoltage protection level or EDV (whichever comes first)
- Increased dt results in decreased SOP, because effective resistance increases with the duration of pulse application.
- **State of power** depends on state of charge and temperature, and R_{eff} increases at <u>low temperature and low state of charge</u>
- State of power will also decrease with battery age
- One example use of state of power is **intel turbo-mode** sustained peak power SPP (dt = 10 sec) and max peak power MPP (dt = 10 msec)
- System can use SOP to keep the power use below this level, those <u>avoiding unexpected termination and extending device run-time</u>

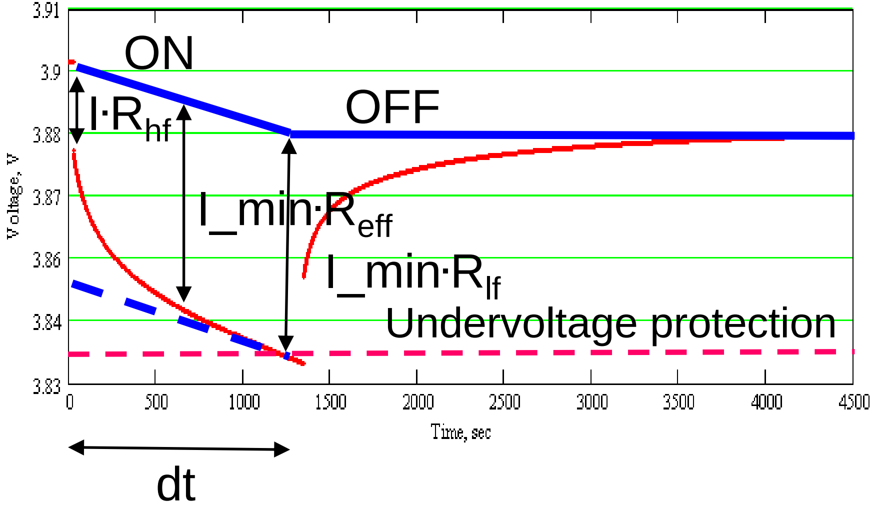
Temperature effect on 10 sec effective resistance



Onset of higher resistance with DOD is much earlier at low temperature

- 10 sec resistance starts increasin at DOD of 60% at 0C vs 80% and 25C
- This shows a need for temperature compensation for this value in order to correctly predict maximal power at 10 sec pulse.

State of power health for given device – SOPH



- Device **minimum pulse power** (P_{min}) – minimal power that needs to be sustained for duration dt for single device action, such as drilling a hole
- Battery **max peak power** (P_{max}) – power delivered *under standard conditions* for pulse duration dt that causes voltage of the battery to reach **undervoltage protection level**
  - Different from SOP, **max peak power** is intended to reflect state of degradation of the battery, but not present conditions as such
  - While SOP changes with SOC and T conditions, $\mathbf{P_{max}}$ is computed for fixed temperature and fully charged sate SOC conditions
- **New battery maximum pulse power:** P_{max_new}
- State of power health definition:

  $$SOPH = (P_{max} - P_{min})*100 /(P_{max\_new} - P_{min})$$

- This definition assures SOPH = 100% for new battery and 0% when P_{max} degrades to device P_{min} value

Summary

- Power tools profile challenges
  - Pulsed load, very high currents
  - State of charge for constant and pulsed discharge cases
- Modeling of pulsed load
  - Elevated effect of impedance
  - Impedance characterization and RC modeling
  - Effect of pulse duration
  - Thermal modeling and duty cycle
- Battery state of health
  - State of health (SOH) – useable capacity compared to new battery for given pulse duration and duty cycle
  - Min system power for given pulse duration (P_{min}) – can we drill one hole?
  - Battery state of power (SOP) – power to reach undervoltage during fixed pulse duration
  - State of power health (SOPH) – how max power compares to system min power and new battery max power

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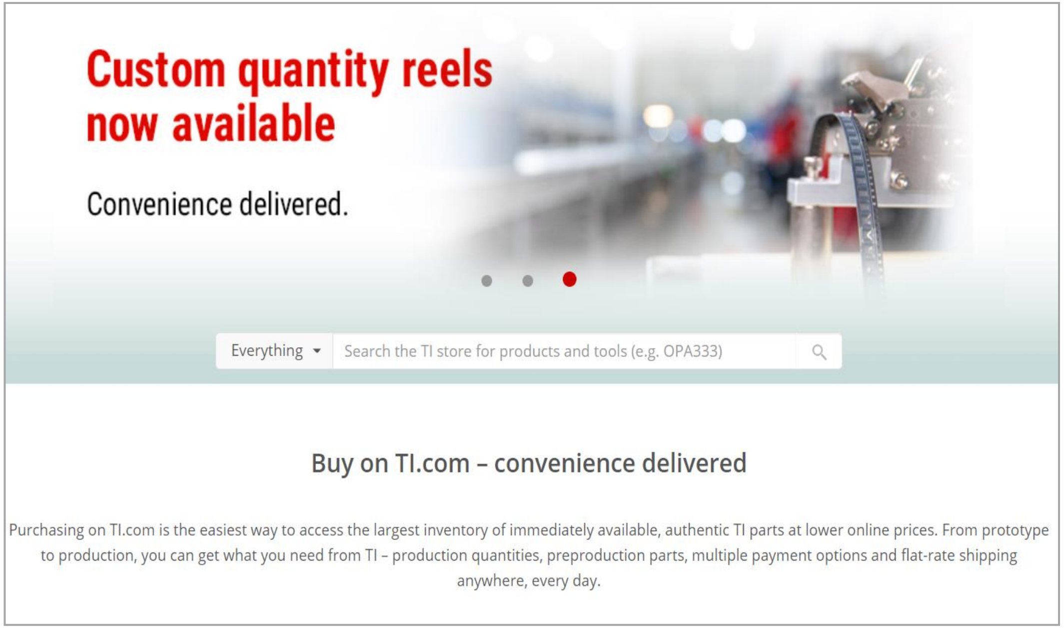

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