Laplace transform and pressurized SOC tests

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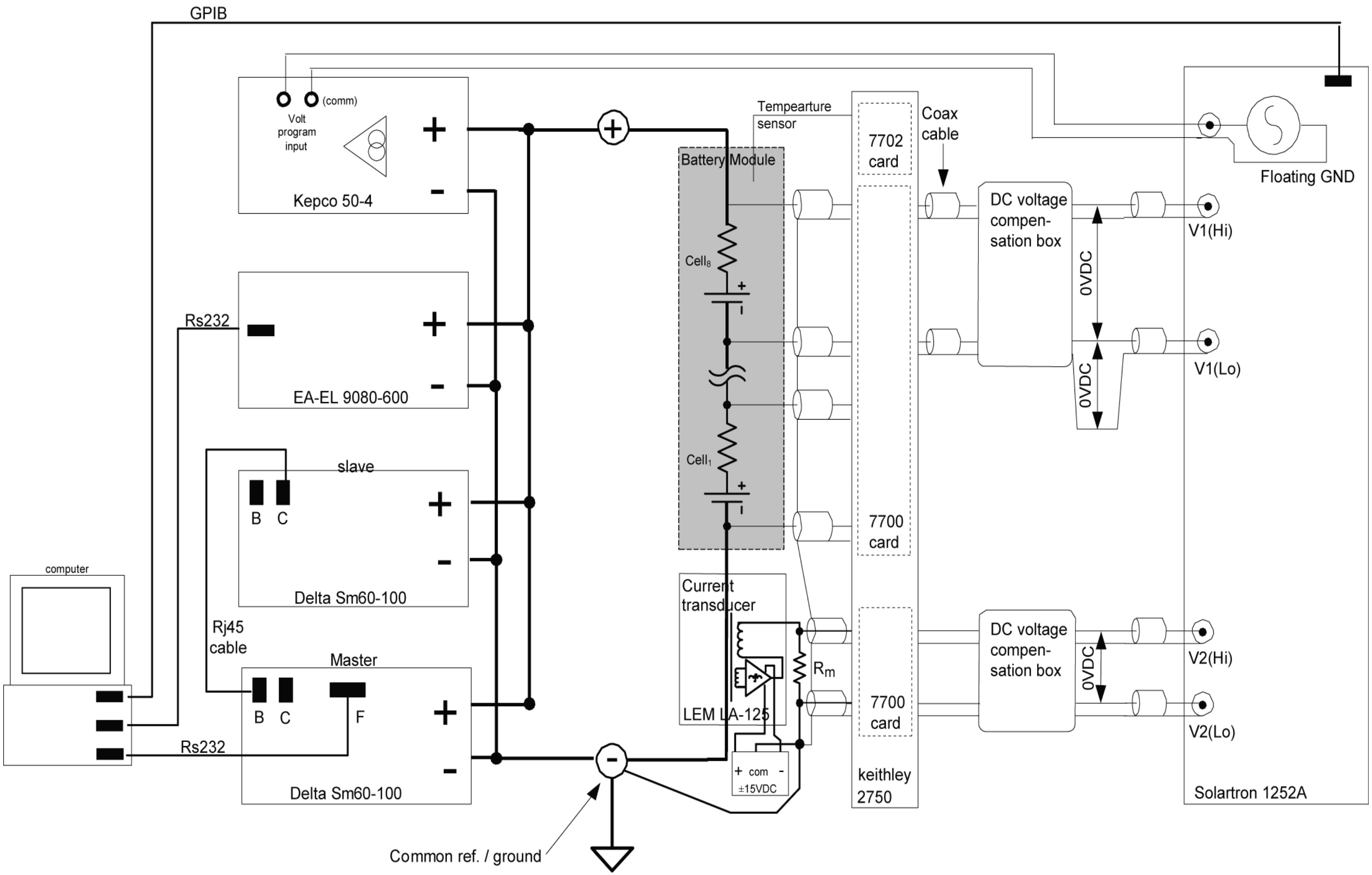
Battery Module Test Setup



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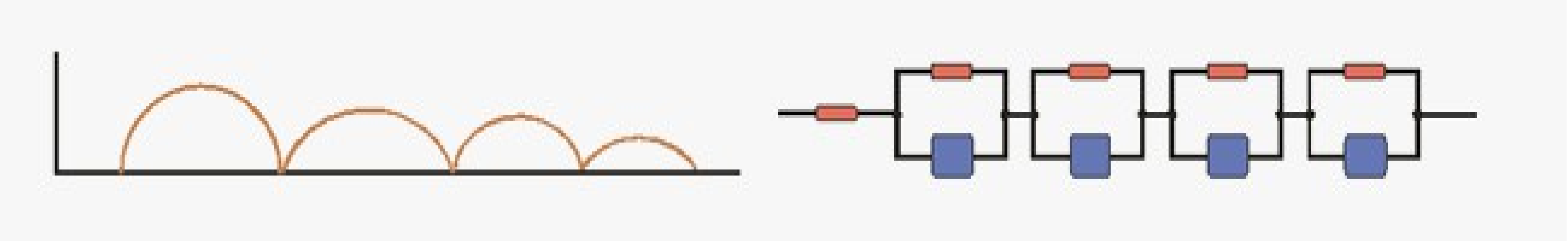


Impedance Spectroscopy

Ph.D. Course 45105 (2011)
MR 4. B779, Risø Campus
30/11/2011

Module 11: Step response and integral transforms

Fourier Transform

- Fourier transform

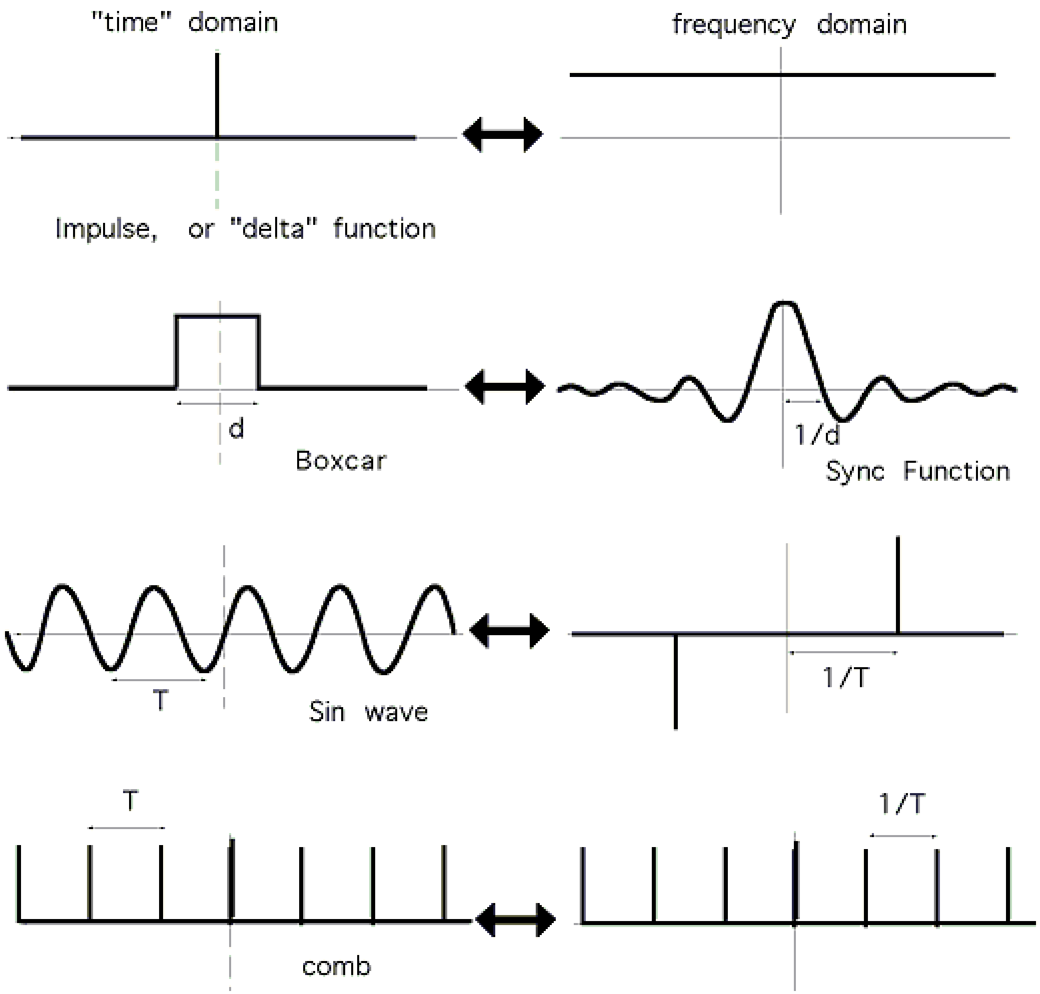
$$\hat{f}(\xi) = \int_{-\infty}^{\infty} f(x)\ e^{-2\pi i x \xi}\, dx,$$

$$\mathcal{F}(f(x)) = F(\omega) = \int f(x) e^{-2\pi i \omega x} dx.$$

- Inverse Fourier transform

$$f(x) = \int_{-\infty}^{\infty} \hat{f}(\xi)\ e^{2\pi i x \xi}\, d\xi,$$

Fourier Transform



Laplace Transform

- *Two Different Impedance Measurement Techniques:*
  - First technique:

    Apply a sinousidal (AC) voltage (or current) and measure the resulting AC current (or voltage)

  Strengh: Very good noise rejection, if measured over several cycles

  Weakness: Very long data acquisition time at low frequencies

Laplace Transform

- *Two Different Impedance Measurement Techniques:*

  - Second technique:

    Apply a step voltage (or current) and measure the resulting current (or voltage) as a function of time

Strengh: Very fast measurements at low frequency

Weakness: Difficult to get good precision at high frequencies. Less noice rejection

Laplace Transform

- What is the Laplace transform?

$$F(s) = \int_0^\infty e^{-s \cdot t} \cdot f(t) dt$$

- The transformation is essentially bijective for the majority of practical uses
- Common pairs of $f(t)$ and $F(s)$ can be found in look-up tables

- *Various functions and their laplace transform:*

Time domain	Laplace domain
$u(t)$	$\frac{1}{s}$
$e^{-\alpha t} \cdot u(t)$	$\frac{1}{s+\alpha}$
$(1 - e^{-\alpha t}) \cdot u(t)$	$\frac{\alpha}{s(s+\alpha)}$
$t \cdot u(t)$	$\frac{1}{s^2}$

$$s = \delta + \omega \cdot i$$

Laplace Transform

How to measure the impedance?

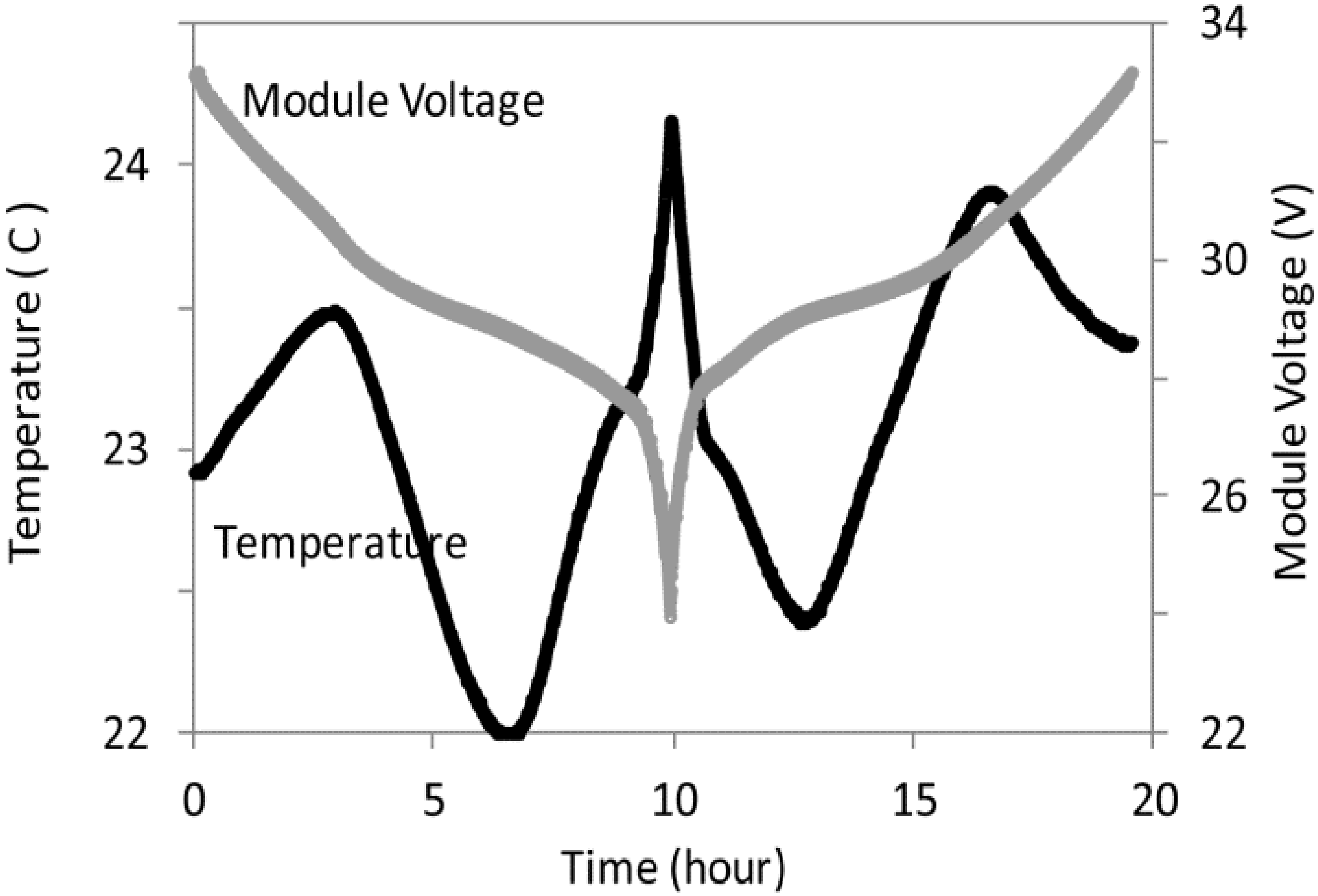
- Apply a step current $I(t) = Io \cdot u(t)$ to the cell
- Laplace transform $I(t)$ to obtain $I(s)$
- Measure $V(t)$
- Model $V(t)$ with a sum of exponential decay-functions
- Laplace transform the sum of exp. decay-functions to get $V(s)$
- $Z(s) = V(s)/I(s)$

Laplace Transform

How to calculate V(t) from Z(s) and a current step function I(t) = Io·u(t) ?

- I(s)=Io/s
- Multiply Z(s) with I(s) to get V(s)
- Model V(s) with a sum of Laplace transformed exponetial functions
- Inverse laplace transform the sum of Laplace transformed exponentials to obtain V(t)

Charge Discharge Curve of KOKAM Battery Module: 75 Ah, 29,6V (8S) NMC



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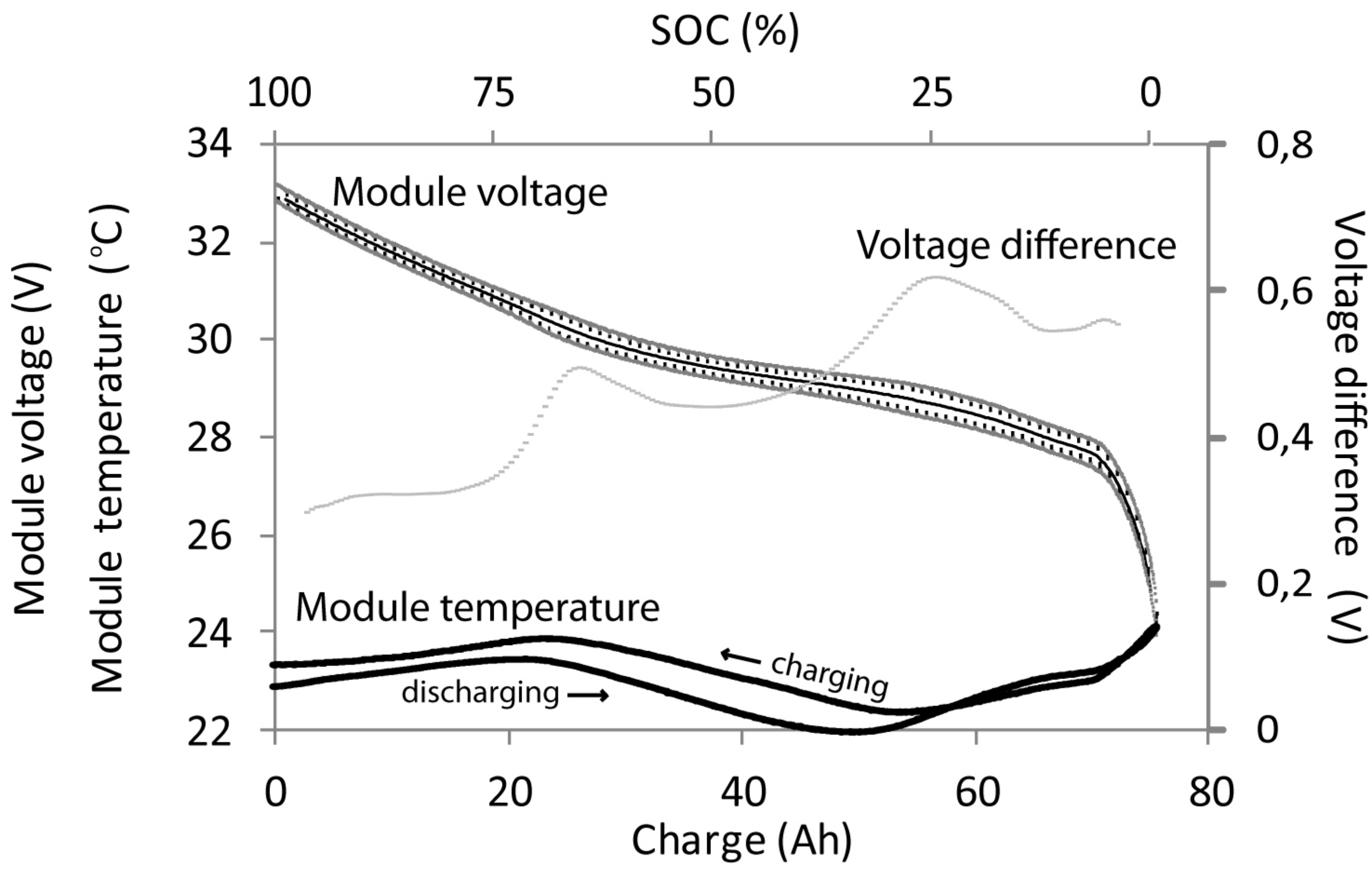
U, T vs SOC



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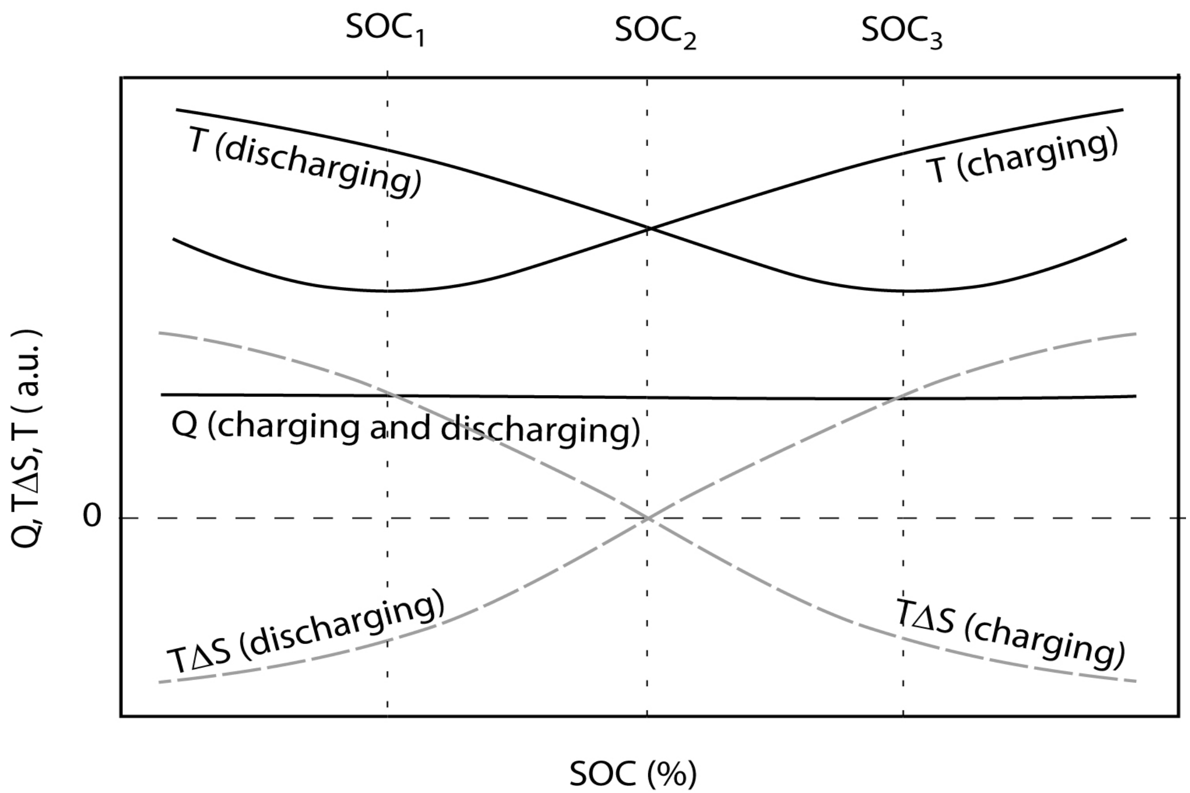
Endothermic/Exothermic Reaction Heat and Joule Heat

SERC

$$P_e = \frac{I}{nF} \cdot T \Delta S \qquad P_J = R_i I^2 \qquad \frac{dT}{dt} = (P_e + P_J)/C_p$$



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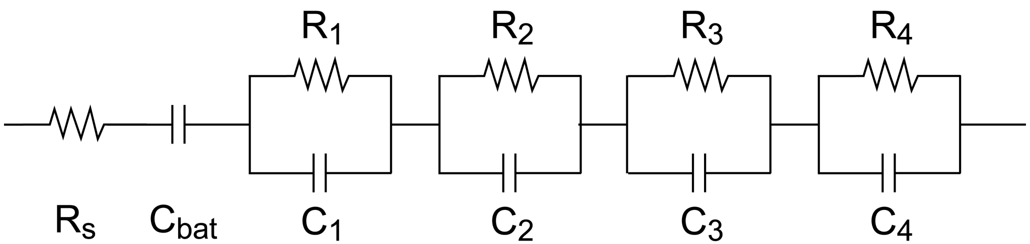
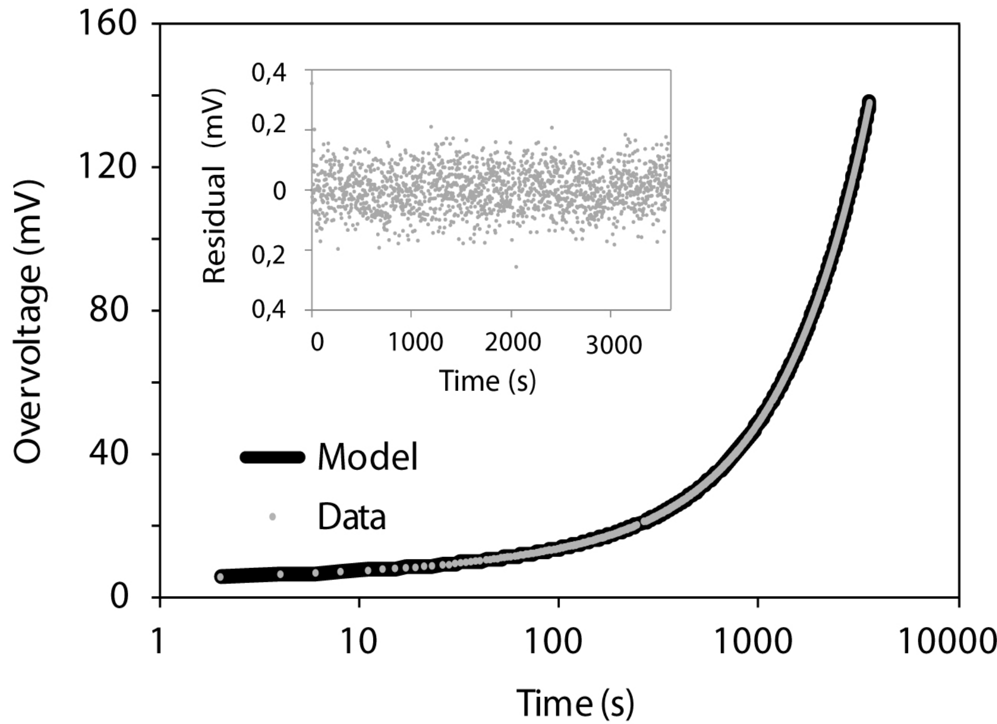
Overvoltage vs time after onset of 1A step-current



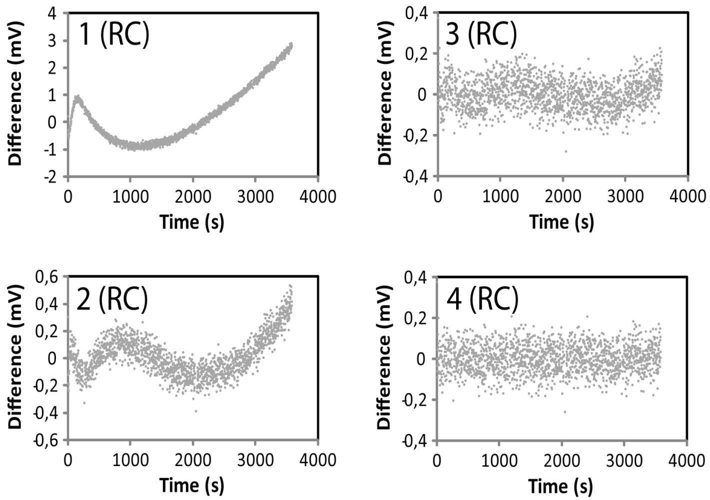
$$U_m(s) = I(s) \cdot Z_m(s) = \frac{I_0}{s} \cdot \left(R_s + \frac{1}{sC_{bat}} + \frac{R_1}{1 + sR_1C_1} + \frac{R_2}{1 + sR_2C_2} + \frac{R_3}{1 + sR_3C_3} + \frac{R_4}{1 + sR_4C_4} \right)$$

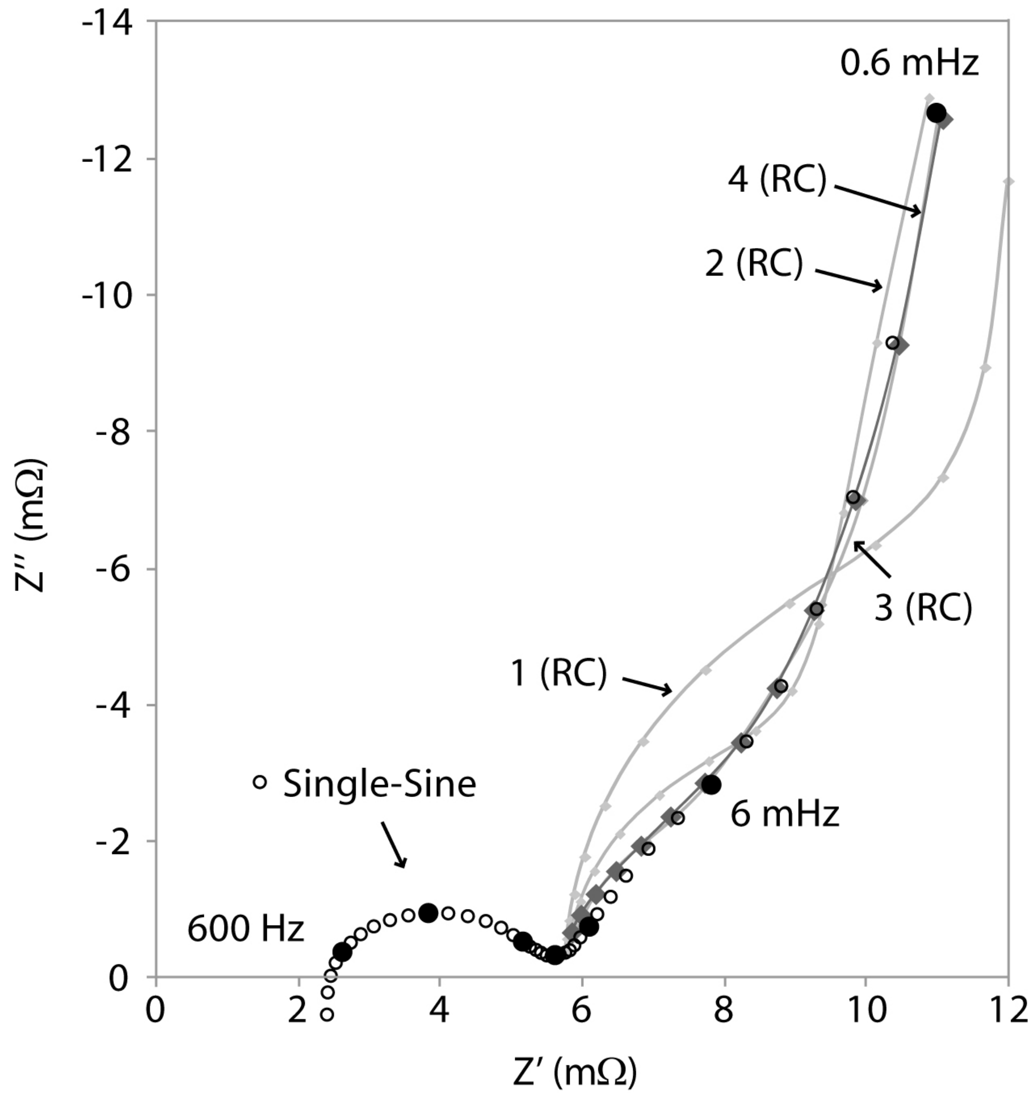


$$U_m(t) = u(t) \times I_0 \left[R_s + t \times C_{bat} + R_1\left(1 - e^{\frac{-t}{R_1C_1}}\right) + R_2\left(1 - e^{\frac{-t}{R_2C_2}}\right) + R_3\left(1 - e^{\frac{-t}{R_3C_3}}\right) + R_4\left(1 - e^{\frac{-t}{R_4C_4}}\right) \right]$$

Impedance spectra - Module

- Residuals





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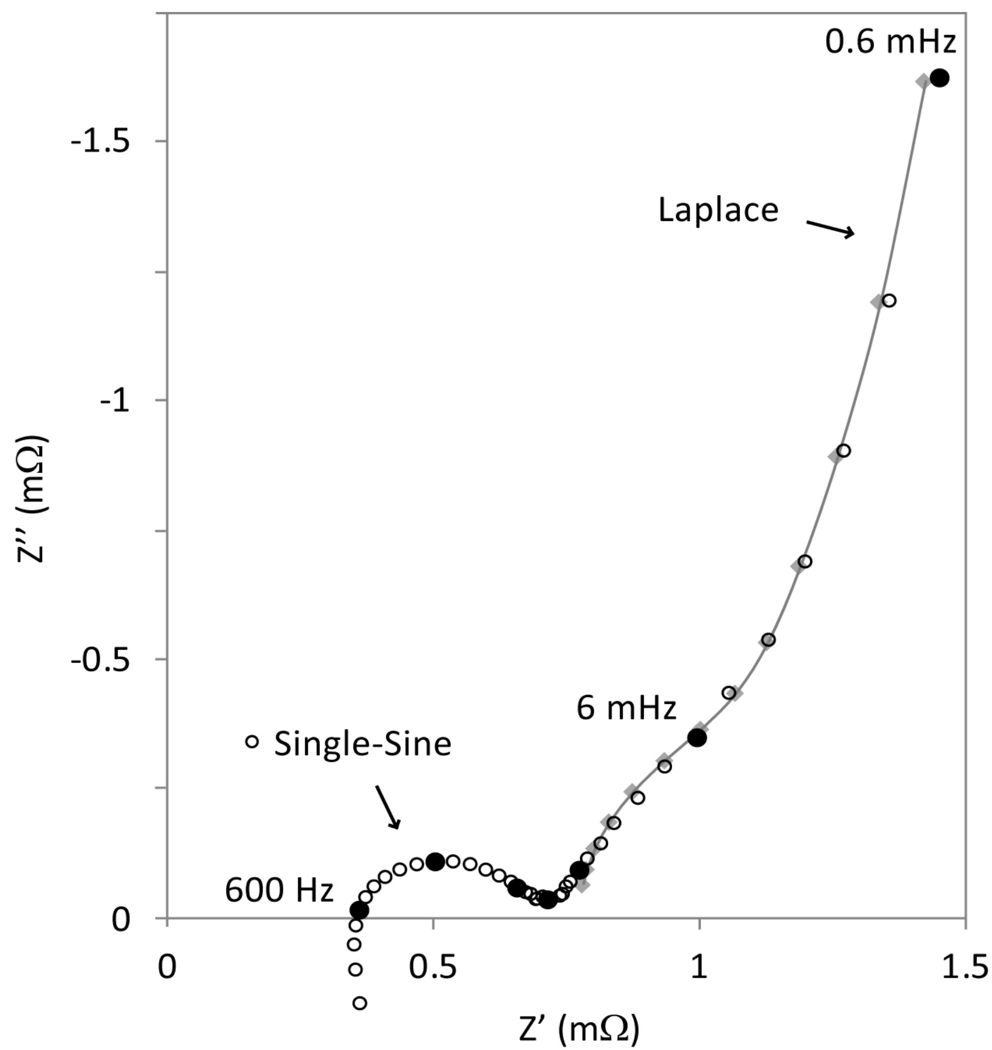
Impedance spectra – Single Cell



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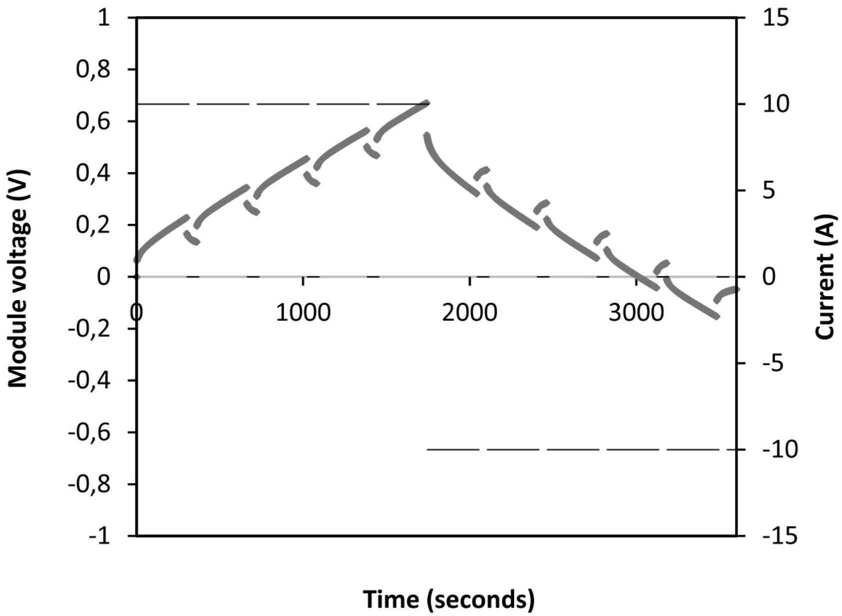
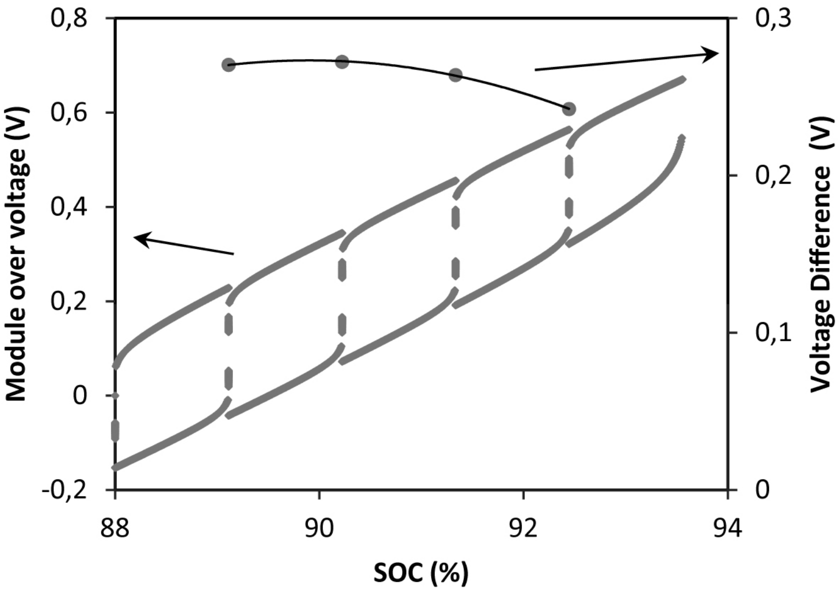
Calculated Voltage Difference





Thank You