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# Battery Parameter Estimation using Electrochemical Impedance Spectroscopy

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# Battery Parameter Analysis Through Electrochemical Impedance Spectroscopy at Different State Of Charge Levels


Rohit Sengar (First MASc Seminar)
110044638

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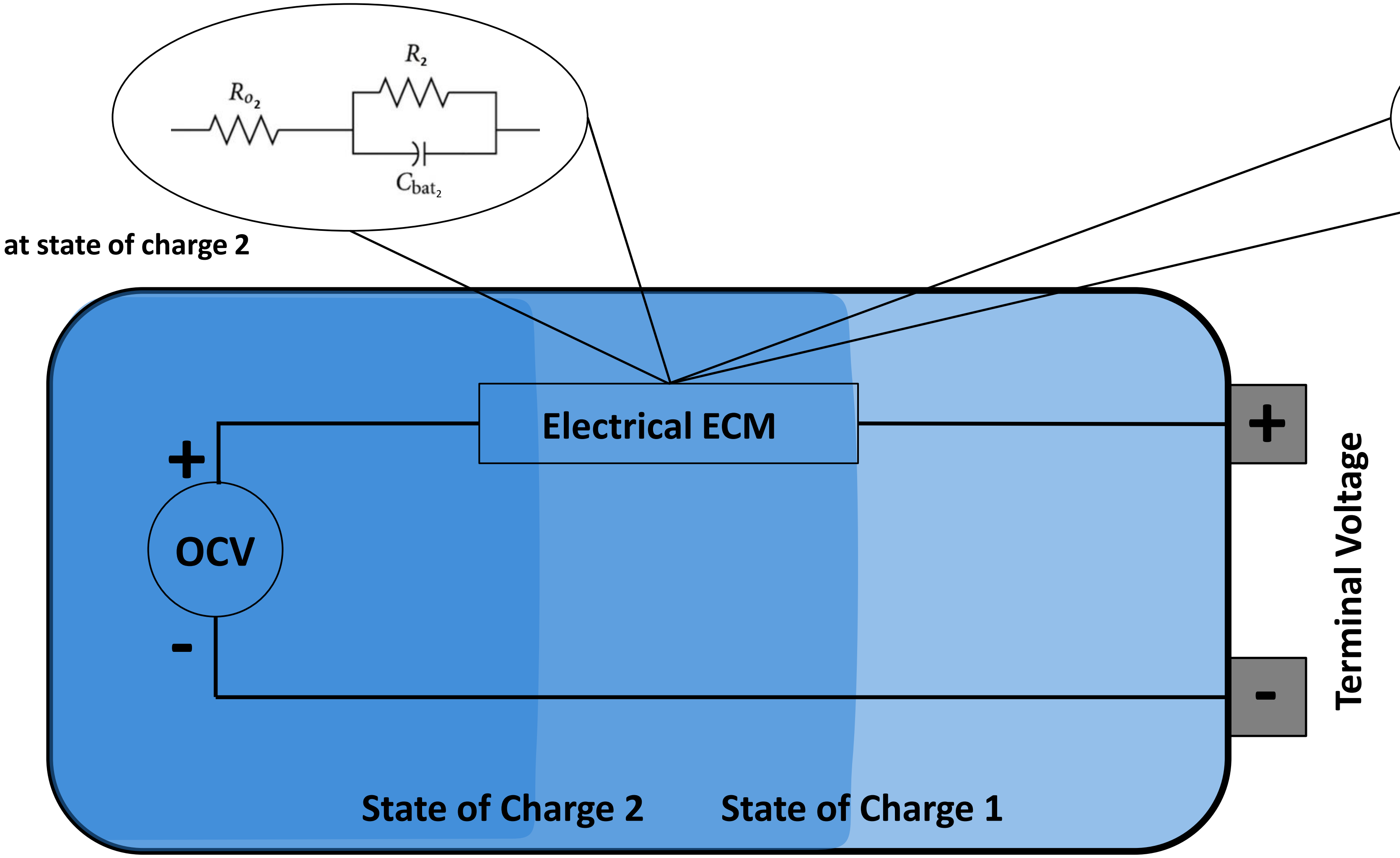
Dr. Sreekanta Das (Outside Program Reader)

# Outline

- Introduction
- Literature review
- Limitation of existing work
- Proposed solution
- Result
- Timeline
- Publications
- References

# Introduction

# Battery and its parameters

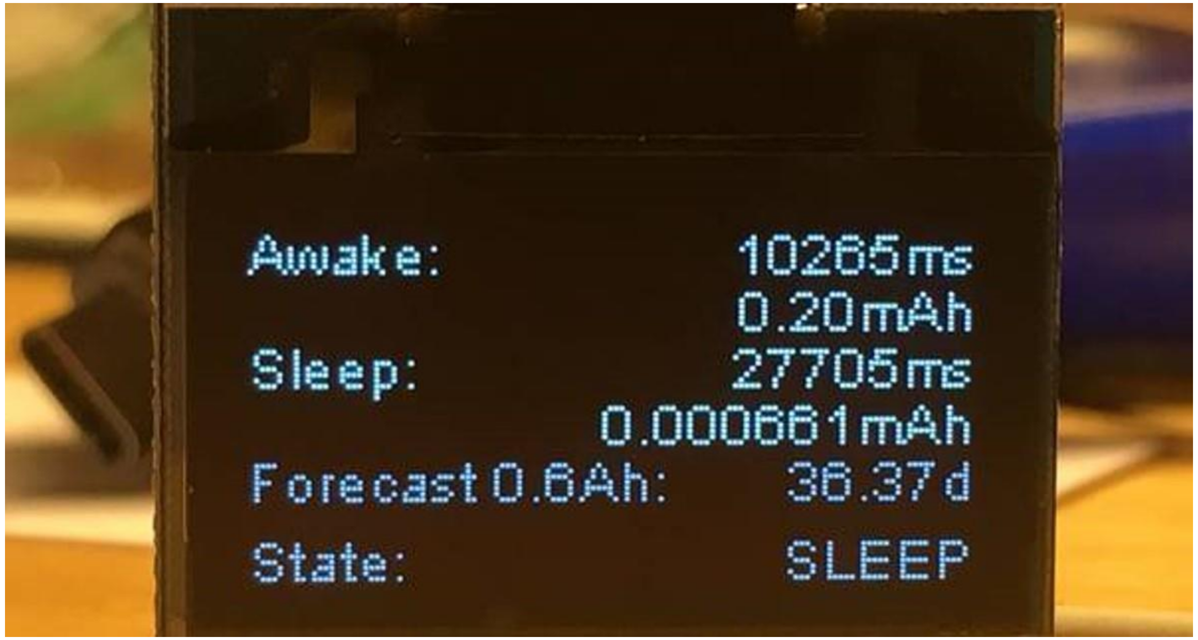



**(OCV)**
Open Circuit Voltage

**(ECM)**
Equivalent Circuit Model

# Why battery parameter estimation is important

To estimate available power in the battery [3]




To estimate available run time [3]

# Literature Review

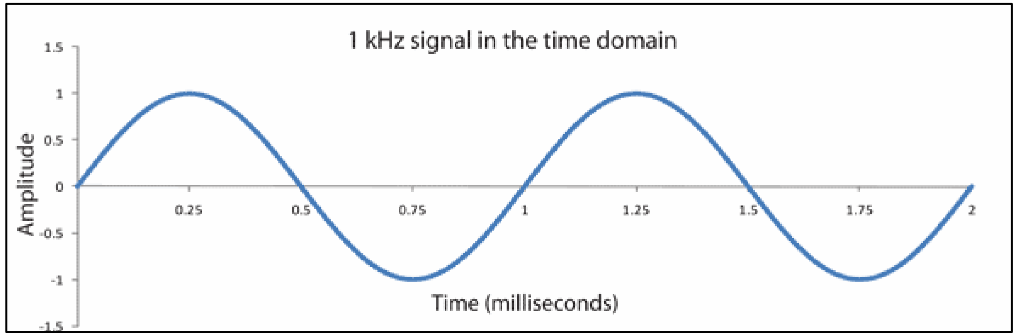
# Methods to estimate parameters

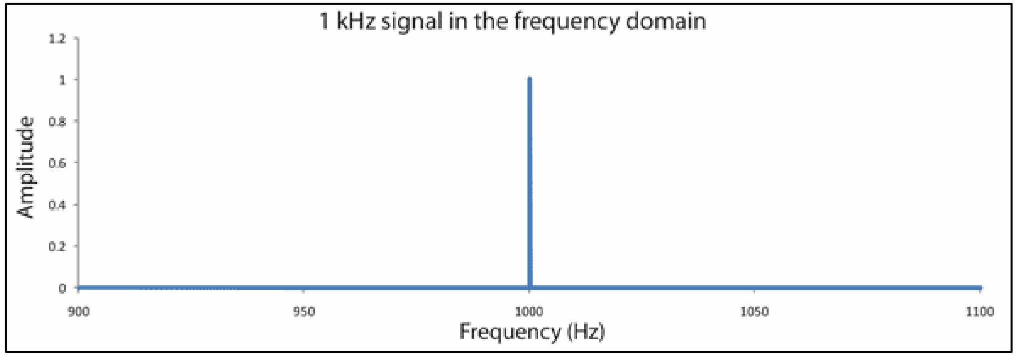
**Time domain**

- Suitable for real time applications
- Comparatively fast
- Not very accurate

**Frequency domain**

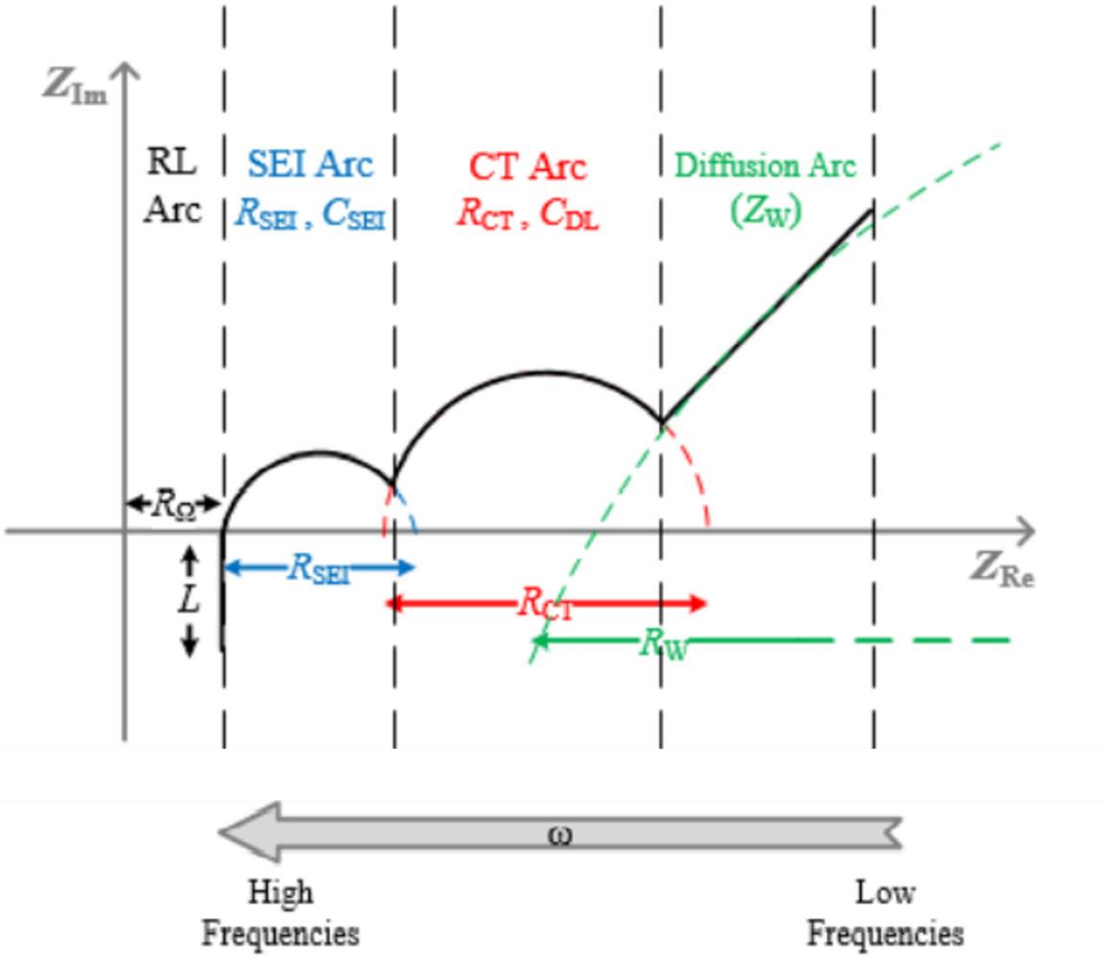
- High precision instruments required
- Slow to be implemented real time
- Very accurate

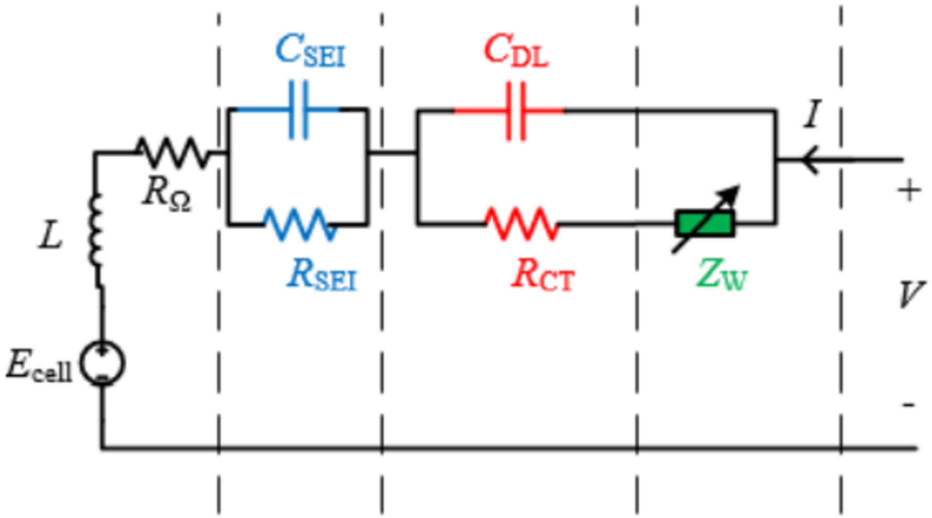


# Nyquist Plots [1]






| | |
|---|---|
| $R_\Omega$ | - Ohmic resistance |
| L | - Stray inductance |
| $R_{SEI}$ | - Solid electrolytic interface (SEI) resistance |
| $C_{SEI}$ | - Solid electrolytic interface (SEI) capacitance |
| $R_{CT}$ | - Charge transfer resistance |
| $C_{DL}$ | - Double layer capacitance |
| $Z_W$ | - Warburg impedance |

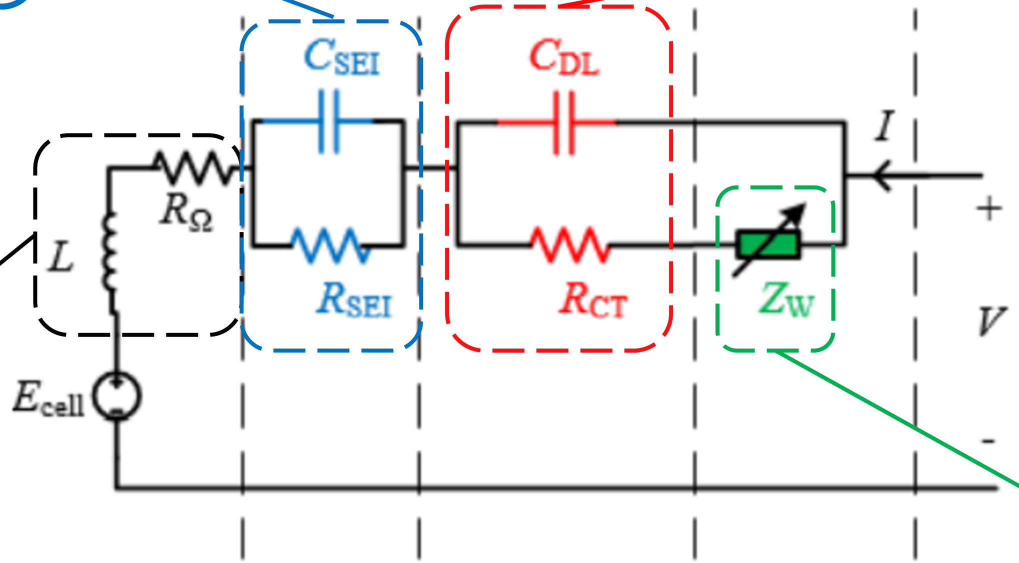
# Adaptive Randles ECM

$$Z_{\mathrm{SEI}}(\omega) = \frac{1}{\frac{1}{R_{\mathrm{SEI}}} + j\omega C_{\mathrm{SEI}}}$$

SEI arc

$$Z_{\mathrm{F}}(\omega) = \frac{1}{\frac{1}{R_{\mathrm{CT}}+Z_{\mathrm{w}}(j\omega)} + j\omega C_{\mathrm{DL}}}$$

CT arc




$$Z_{\mathrm{RL}}(j\omega) = j\omega L + R_{\Omega}$$

RL arc

$$Z_{\mathrm{w}}(j\omega) = (1-j)\frac{\sigma}{\sqrt{\omega}}$$

Warburg impedance

# Estimation of Warburg coefficient

$$z_r(0) - z_r(k_1) = \sigma\left(\frac{1}{\sqrt{\omega_0}} - \frac{1}{\sqrt{\omega_{k_1}}}\right)$$

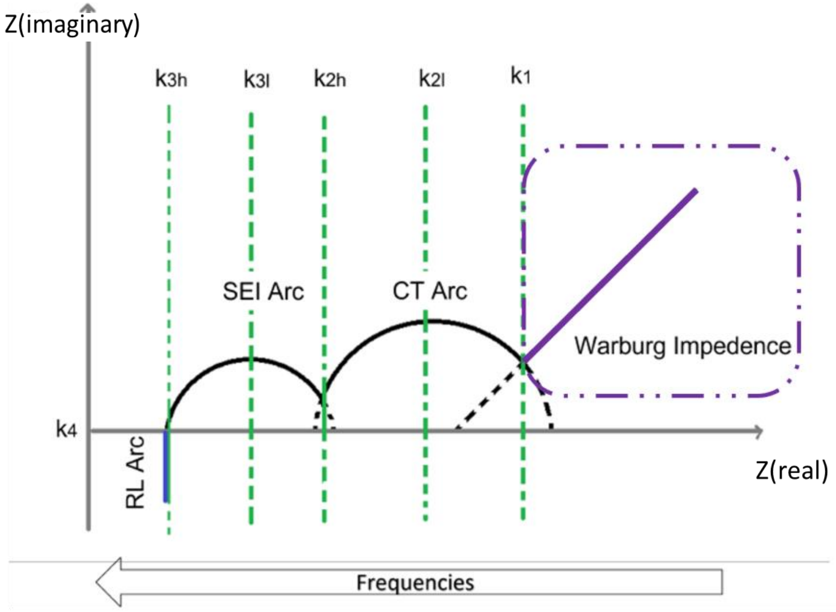
$$z_r(1) - z_r(k_1 - 1) = \sigma\left(\frac{1}{\sqrt{\omega_{k_1}}} - \frac{1}{\sqrt{\omega_{k_1 - 1}}}\right)$$

$$\vdots$$

$$z_r(n) - z_r(k_1 - n) = \sigma\left(\frac{1}{\sqrt{\omega_n}} - \frac{1}{\sqrt{\omega_{k_1 - n}}}\right)$$

$$\tilde{\mathbf{z}} = \begin{bmatrix} z_r(0) - z_r(k_1) \\ z_r(1) - z_r(k_1 - 1) \\ \vdots \\ z_r(n) - z_r(k_1 - n) \end{bmatrix}, \quad \mathbf{b} = \begin{bmatrix} \left(\frac{1}{\sqrt{\omega_0}} - \frac{1}{\sqrt{\omega_{k_1}}}\right) \\ \left(\frac{1}{\sqrt{\omega_{k_1}}} - \frac{1}{\sqrt{\omega_{k_1 - 1}}}\right) \\ \vdots \\ \left(\frac{1}{\sqrt{\omega_n}} - \frac{1}{\sqrt{\omega_{k_1 - n}}}\right) \end{bmatrix}$$

$$\hat{\hat{\sigma}} = \frac{(\mathbf{b}^T \tilde{\mathbf{z}})}{(\mathbf{b}^T \mathbf{b})}$$

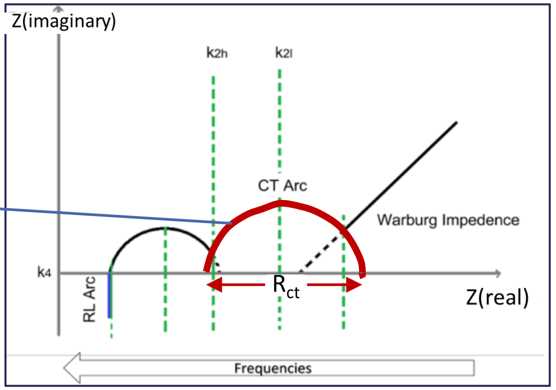


# Estimation of $R_{CT}$ and $C_{DL}$



$$Z_r^2 + Z_i^2 + aZ_r + b = 0$$

**Equation of circle**




$$\underbrace{\begin{bmatrix} -(Z_r(k_{2l}+1)^2 + Z_i(k_{2l}+1)^2 \\ -(Z_r(k_{2l}+2)^2 + Z_i(k_{2l}+2)^2 \\ \vdots \\ -(Z_r(k_2)^2 + Z_i(k_{2h})^2 \end{bmatrix}}_{\mathbf{z}} = \underbrace{\begin{bmatrix} Z_r(k_{2l}+1) & 1 \\ Z_r(k_{2l}+2) & 1 \\ \vdots & \\ Z_r(k_{2l}) & 1 \end{bmatrix}}_{\mathbf{B}} \underbrace{\begin{bmatrix} a \\ b \end{bmatrix}}_{\mathbf{x}} + \underbrace{\begin{bmatrix} n_v(1) \\ n_v(2) \\ \vdots \\ n_v(n) \end{bmatrix}}_{\mathbf{n}}$$

Z = Bx + n

$$\hat{\mathbf{x}} = (\mathbf{B}^T\mathbf{B})^{-1}(\mathbf{B}^T\mathbf{z})$$

$\hat{x}(1) = a$
$\hat{x}(2) = b$

$$\hat{R}_{CT} = 2\sqrt{\frac{a^2}{4} - b}$$

$$\text{Im}\left(\frac{1}{Z_F(\omega)}\right) = \frac{\frac{\sigma}{\sqrt{\omega}}}{\left(R_{CT} + \frac{\sigma}{\sqrt{\omega}}\right)^2 + \frac{\sigma^2}{\omega}} + \omega C_{DL}$$

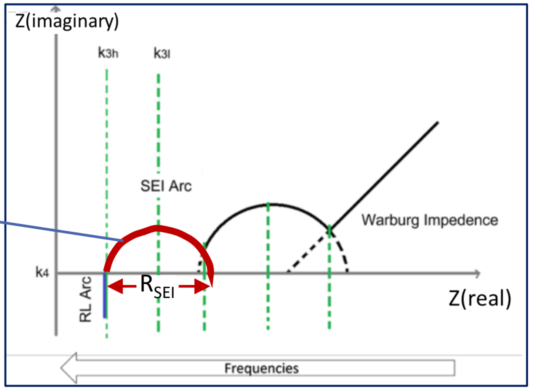
$$\tilde{C}_{DL} = \frac{1}{\omega_k}\left(\text{Im}\frac{1}{Z_F(\omega_k)} - \frac{\frac{\sigma}{\sqrt{\omega_k}}}{(\hat{R}_{CT} + \frac{\sigma}{\sqrt{\omega_k}})^2 + \frac{\sigma^2}{\omega_k}}\right)$$

$$\hat{C}_{DL} = \frac{1}{k_{2h} - k_{2l}} \sum_{k=k_{2l}+1}^{k_{2h}} \tilde{C}_{DL}(k)$$

# Estimation of $R_{SEI}$ and $C_{SEI}$

$$\left(Z_r + \frac{c}{2}\right)^2 + Z_i^2 = \frac{c^2}{4} - d$$

**Equation of circle**




$$\underbrace{\begin{bmatrix} -(Z_r(k_{3l}+1)^2 + Z_i(k_{3l}+1)^2 \\ -(Z_r(k_{3l}+2)^2 + Z_i(k_{3l}+2)^2 \\ \vdots \\ -(Z_r(k_{3h})^2 + Z_i(k_{3h})^2 \end{bmatrix}}_{\mathbf{z}} = \underbrace{\begin{bmatrix} Z_r(k_{3l}+1) & 1 \\ Z_r(k_{3l}+2) & 1 \\ \vdots & \\ Z_r(k_{3l}) & 1 \end{bmatrix}}_{\mathbf{B}} \underbrace{\begin{bmatrix} c \\ d \end{bmatrix}}_{\mathbf{y}} + \underbrace{\begin{bmatrix} n_v(1) \\ n_v(2) \\ \vdots \\ n_v(n) \end{bmatrix}}_{\mathbf{n}}$$

Z = By + n

$$\hat{\mathbf{y}} = (\mathbf{B}^T\mathbf{B})^{-1}(\mathbf{B}^T\mathbf{z})$$

$\hat{y}(1) = c$

$\hat{y}(2) = d$

$$\hat{R}_{\text{SEI}} = 2\sqrt{\frac{c^2}{4} - d}$$

$$\frac{1}{Z_{\text{SEI}}} = \frac{1}{R_{\text{SEI}}} + j\omega C_{\text{SEI}}$$

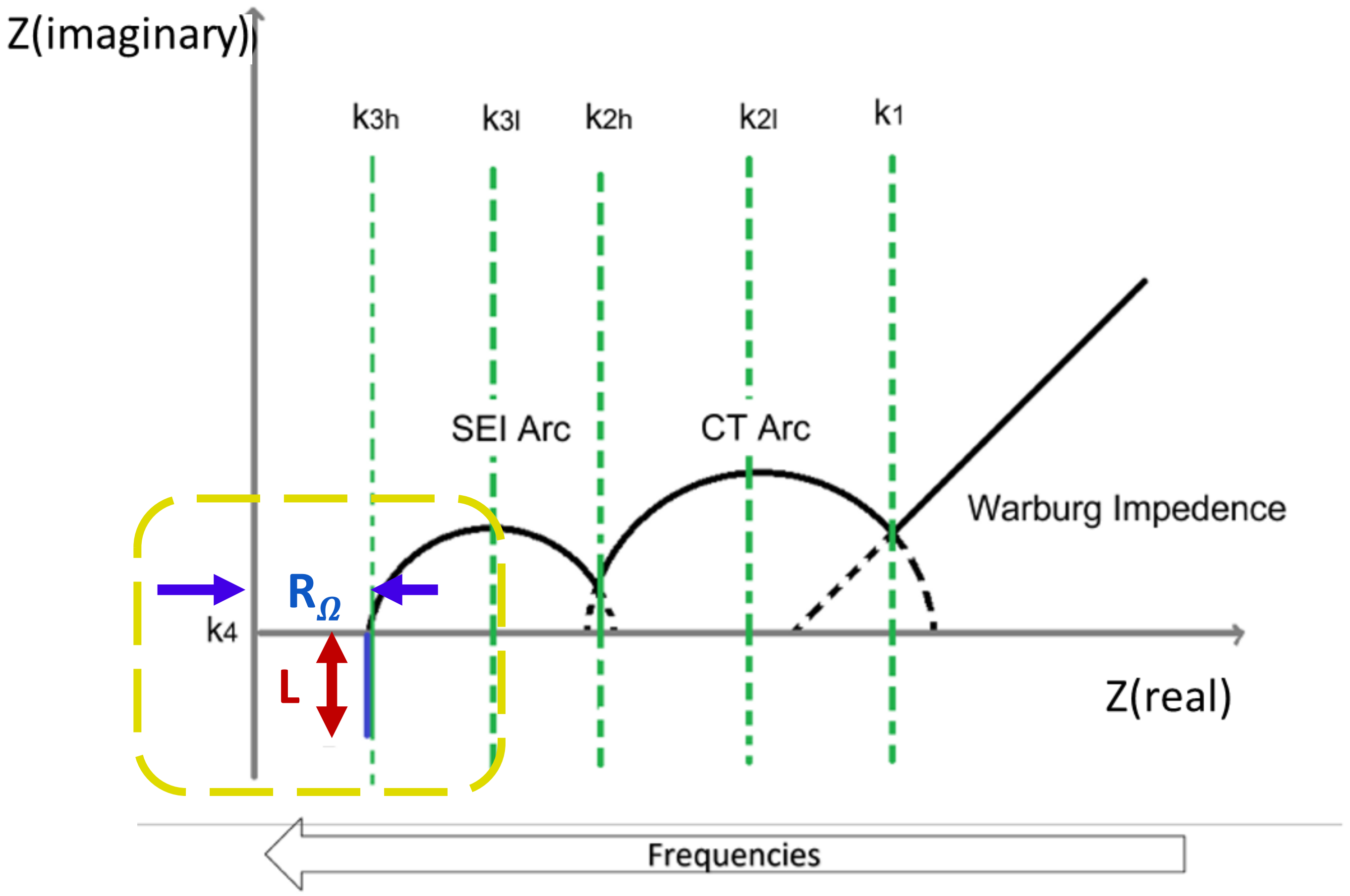
$$\tilde{C}_{\text{SEI}} = \left(\frac{1}{\omega_k}\right) \text{Im}\left(\frac{1}{Z_{\text{SEI}}(\omega_k)}\right)$$

$$\hat{C}_{\text{SEI}} = \frac{1}{k_{3h} - k_{3l}} \sum_{k=k_{3l}+1}^{k_{3h}} \tilde{C}_{\text{SEI}}(k)$$

# Estimation of $R_\Omega$ and L

$$\hat{R}_\Omega = \frac{1}{k_4 - k_{3h}} \sum_{k=k_{3h}+1}^{k_4} Z_r(k)$$

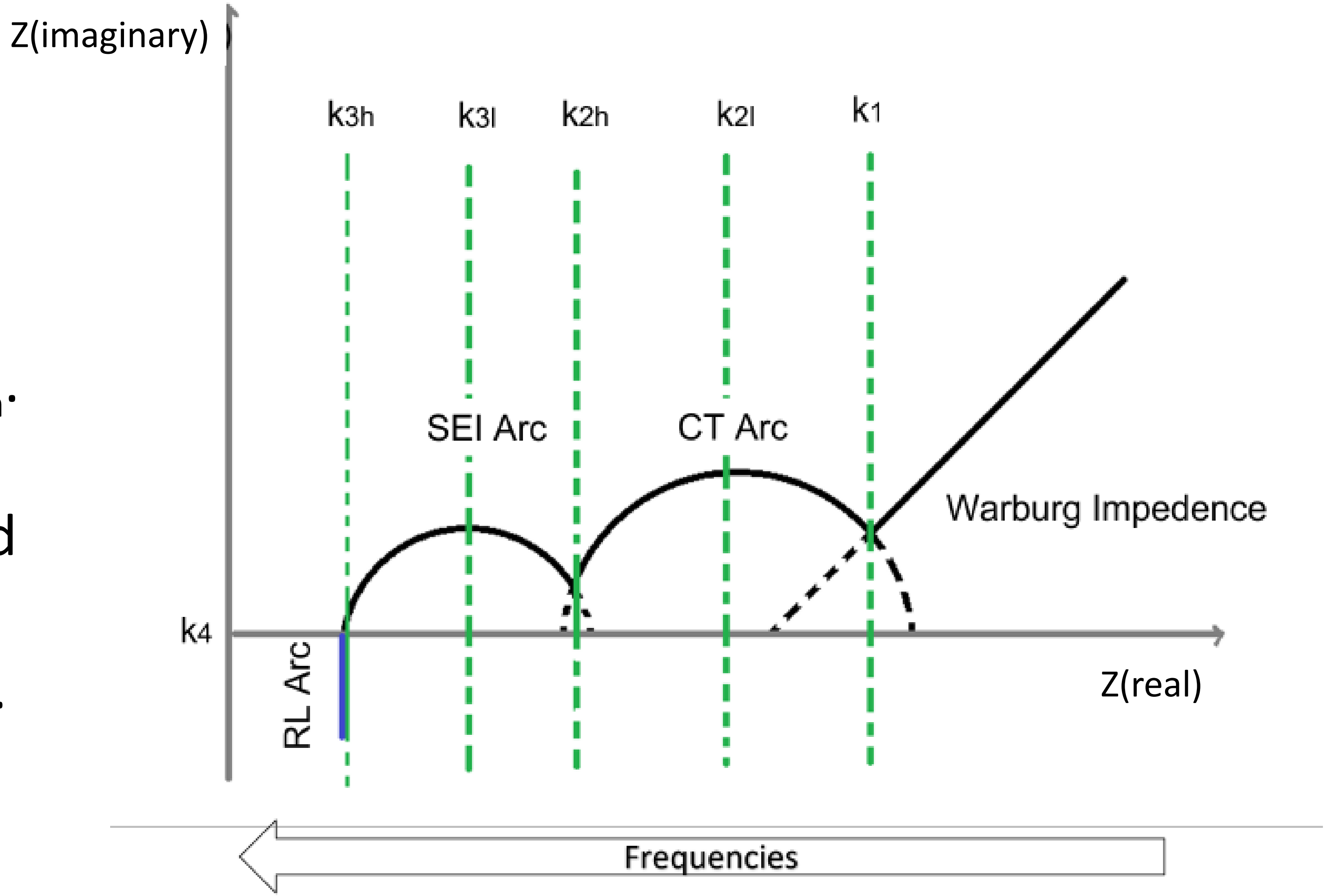
$$\hat{L} = \frac{1}{k_4 - k_{3h}} \sum_{k=k_{3h}+1}^{k_4} Z_i(k)$$



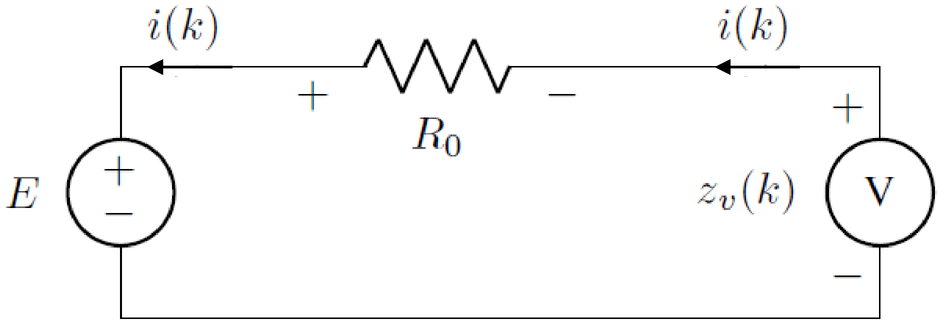
# Feature points



- Warburg impedence is estimated upto $k_1$.
- $R_{CT}$ and $C_{DL}$ are estimated between points $k_{2l}$ and $k_{2h}$.
- $R_{SEI}$ and $C_{SEI}$ are estimated between the points $k_{3l}$ and $k_{3h}$.
- $k_4$ is at the max frequency.



# Parameter estimation in time domain

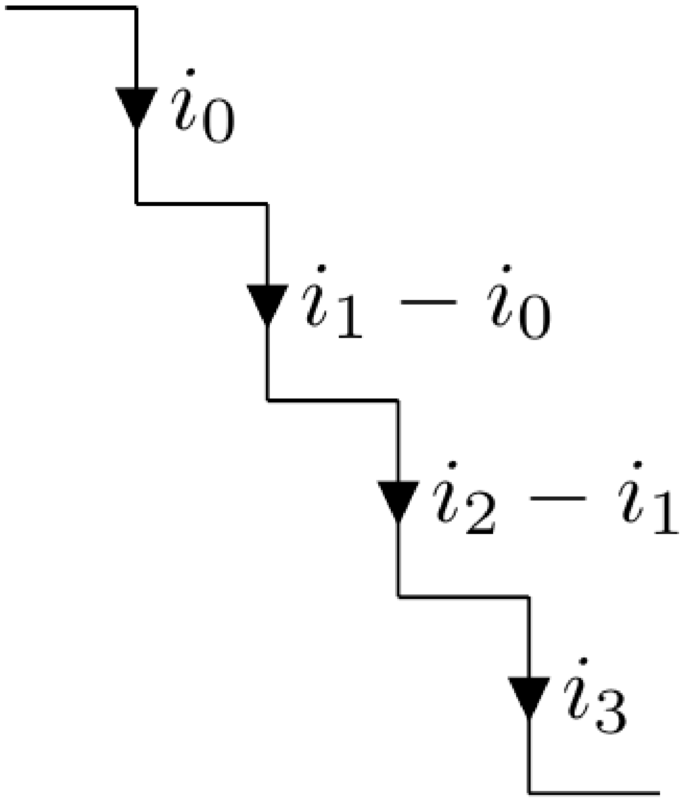



$$z_v(k) = E + i(k)R_0 + n_v(k)$$

$$\underbrace{\begin{bmatrix} z_v(1) \\ z_v(2) \\ \vdots \\ z_v(n) \end{bmatrix}}_{\mathbf{z}} = \underbrace{\begin{bmatrix} 1 & i(1) \\ 1 & i(2) \\ \vdots & \\ 1 & i(n) \end{bmatrix}}_{\mathbf{P}} \underbrace{\begin{bmatrix} E & R_0 \end{bmatrix}}_{\mathbf{k}} + \underbrace{\begin{bmatrix} n_v(1) \\ n_v(2) \\ \vdots \\ n_v(n) \end{bmatrix}}_{\mathbf{n}}$$

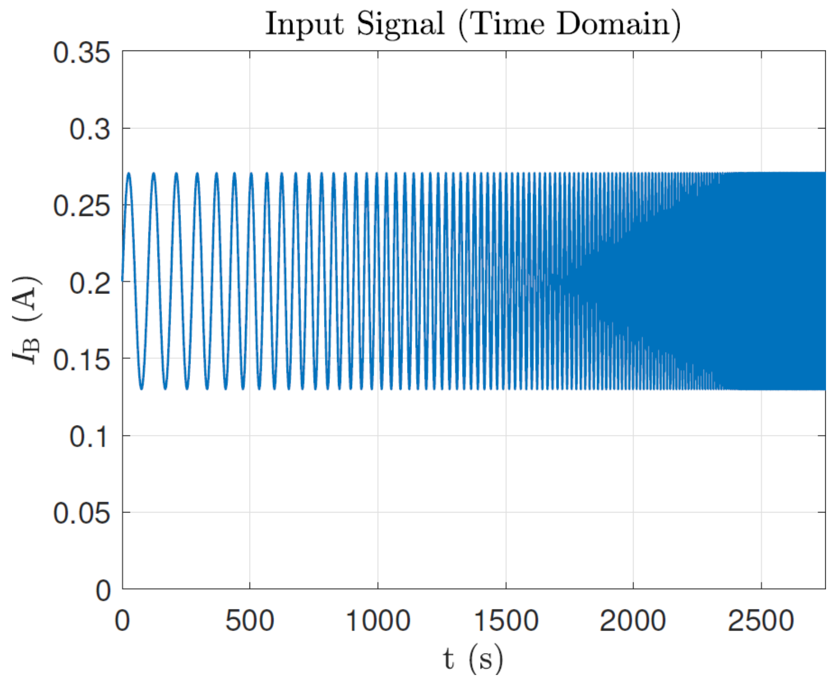
$$\hat{\mathbf{k}} = (\mathbf{P}^{\mathrm{T}}\mathbf{P})^{-1}(\mathbf{P}^{\mathrm{T}}\mathbf{z})$$

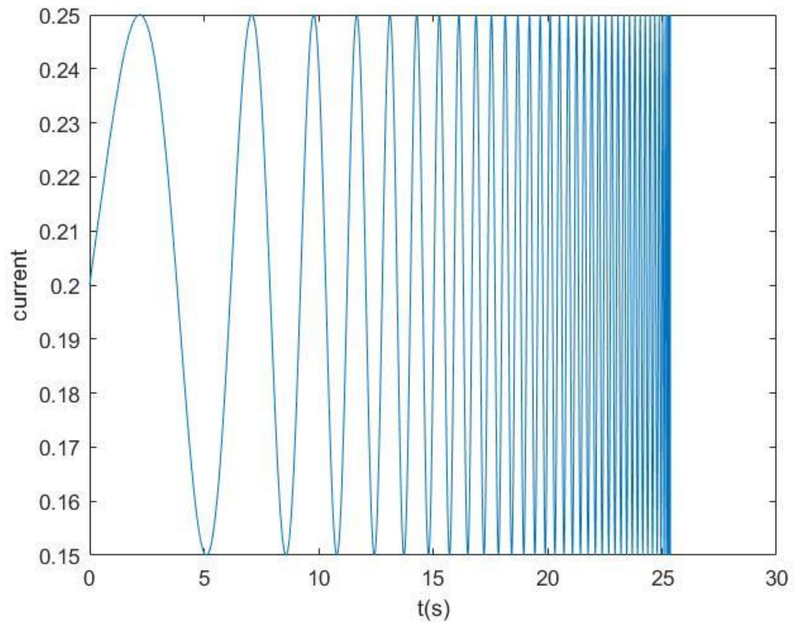
$$\hat{k}(1) = E$$
$$\hat{k}(2) = R_0$$




Time domain current stair

# Limitation of existing work




- Parameters estimation algorithm, developed in [1] was not verified using real-world data.
- Time taken is much greater to be implemented real time.

# Proposed Solution

## Real time validation

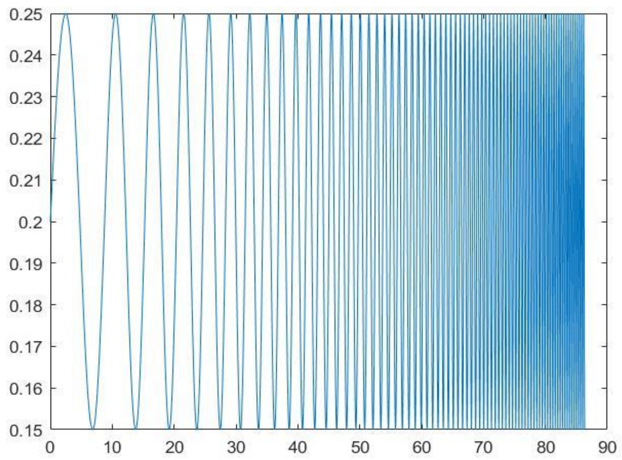
- The algorithms are tested using real data collected from three different cells.
- The battery ECM parameters are estimated in frequency domain.
- The parameters are then validated using time domain experiment.
- Several small experiments are combined together in a grand experiment which includes both time and frequency domain experiments.

## Speeding up parameter estimation

- A signal similar to chirp signal with varying frequency is made.
- Our goal is to simulate the signal to obtain Nyquist plot.

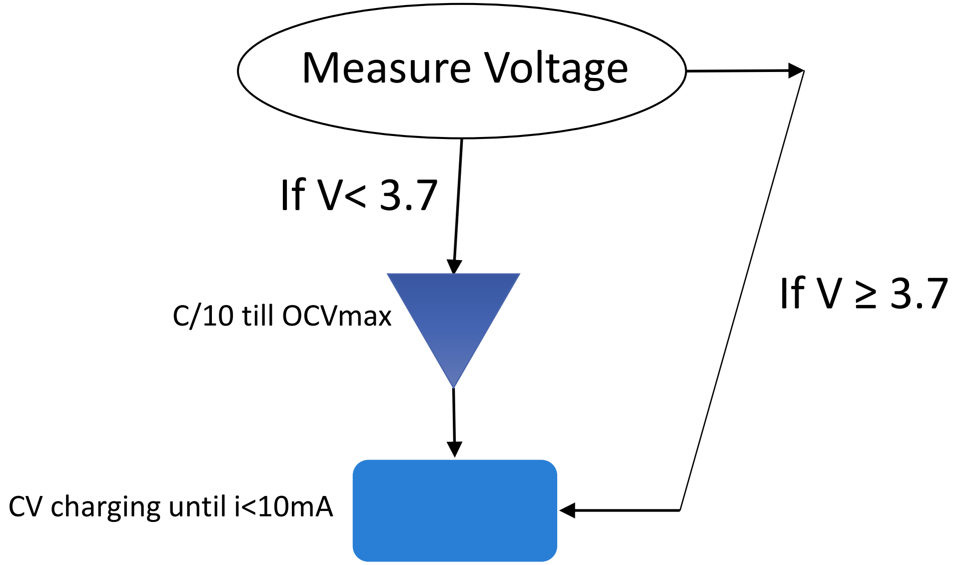
# Tests performed in the experiment

## EIS test with charge/discharge current



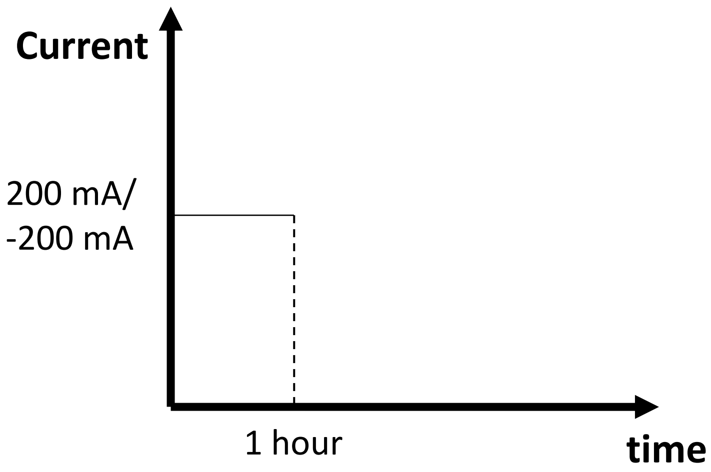

Perturbation current of 200mA DC (charging or discharging) with 50mA sinusoid superimposed on it.

## Fully charge the battery



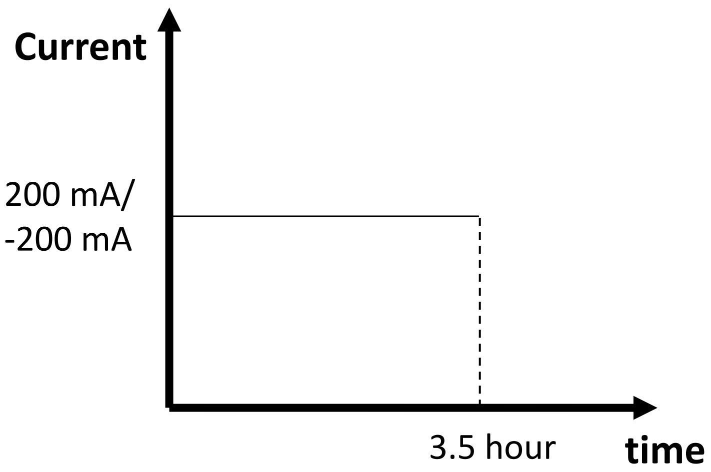
# Tests performed in the experiment

## Compensate for the SOC gained/lost during EIS test




Charge/discharge with 200 mA for 1 hour (sampling 1 Hz) or until voltage reaches $OCV_{max}/OCV_{min}$

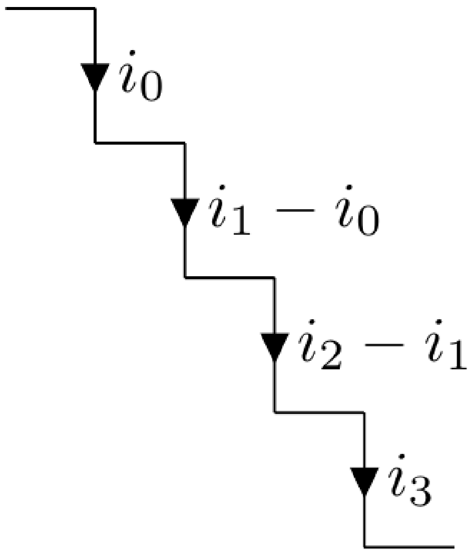
## Increase/reduce SOC by 20%




Charge/discharge with 200 mA for 3.5 hour

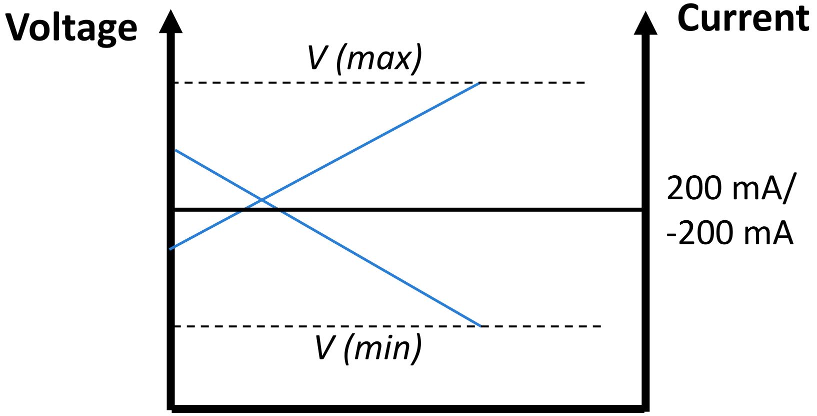
# Tests performed in the experiment

## Staircase profile (charge/discharge) with sampling (200Hz)




$$i_0 = 40mA/-40mA$$
$$i_1 = 80mA/-80mA$$
$$i_2 = 120mA/-120mA$$
$$i_3 = 160mA/-160mA$$

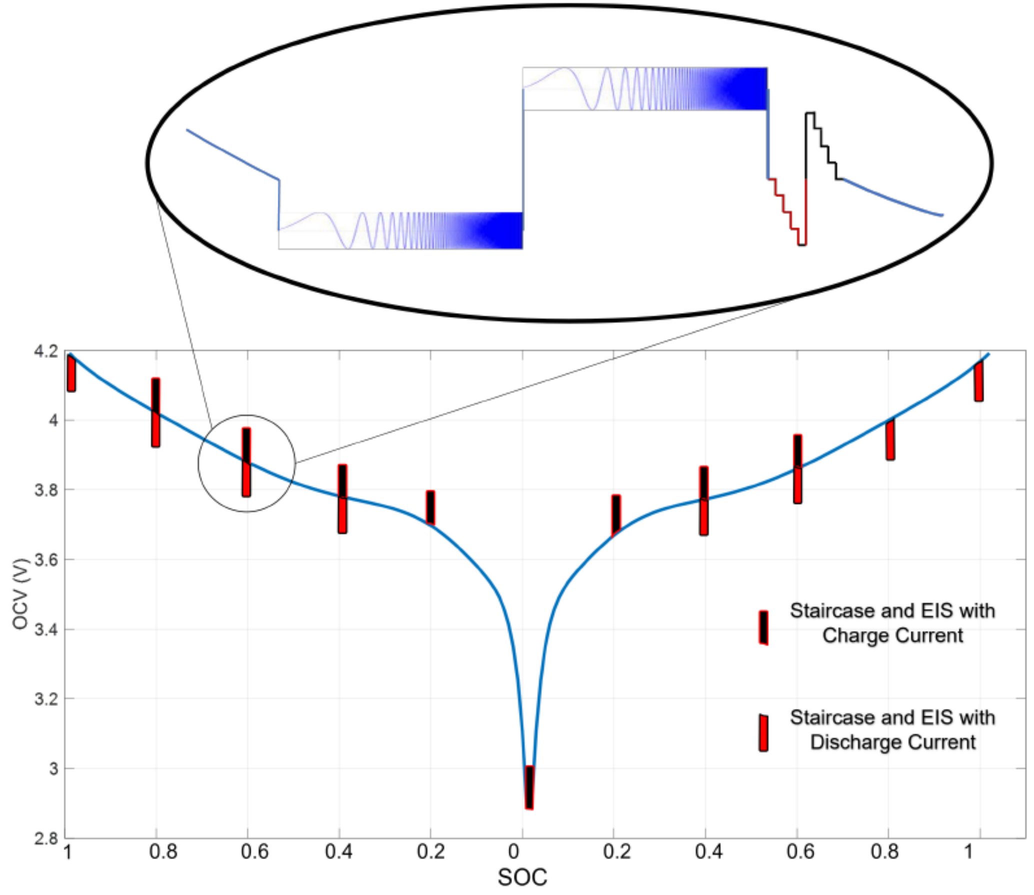
## Bring SOC to 100% or 0%



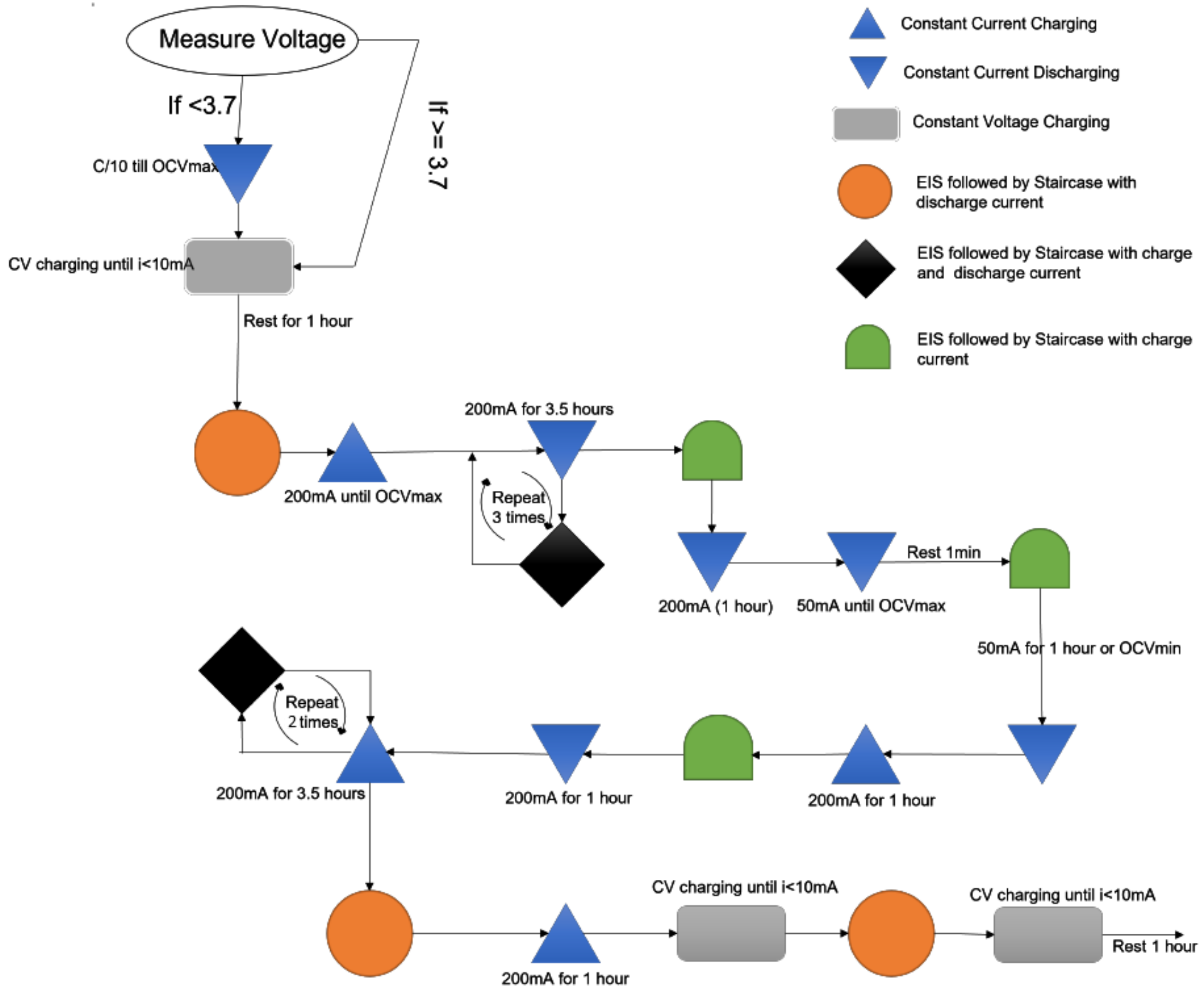

Charge/discharge until V(min) or V(max)

# Experimental procedure



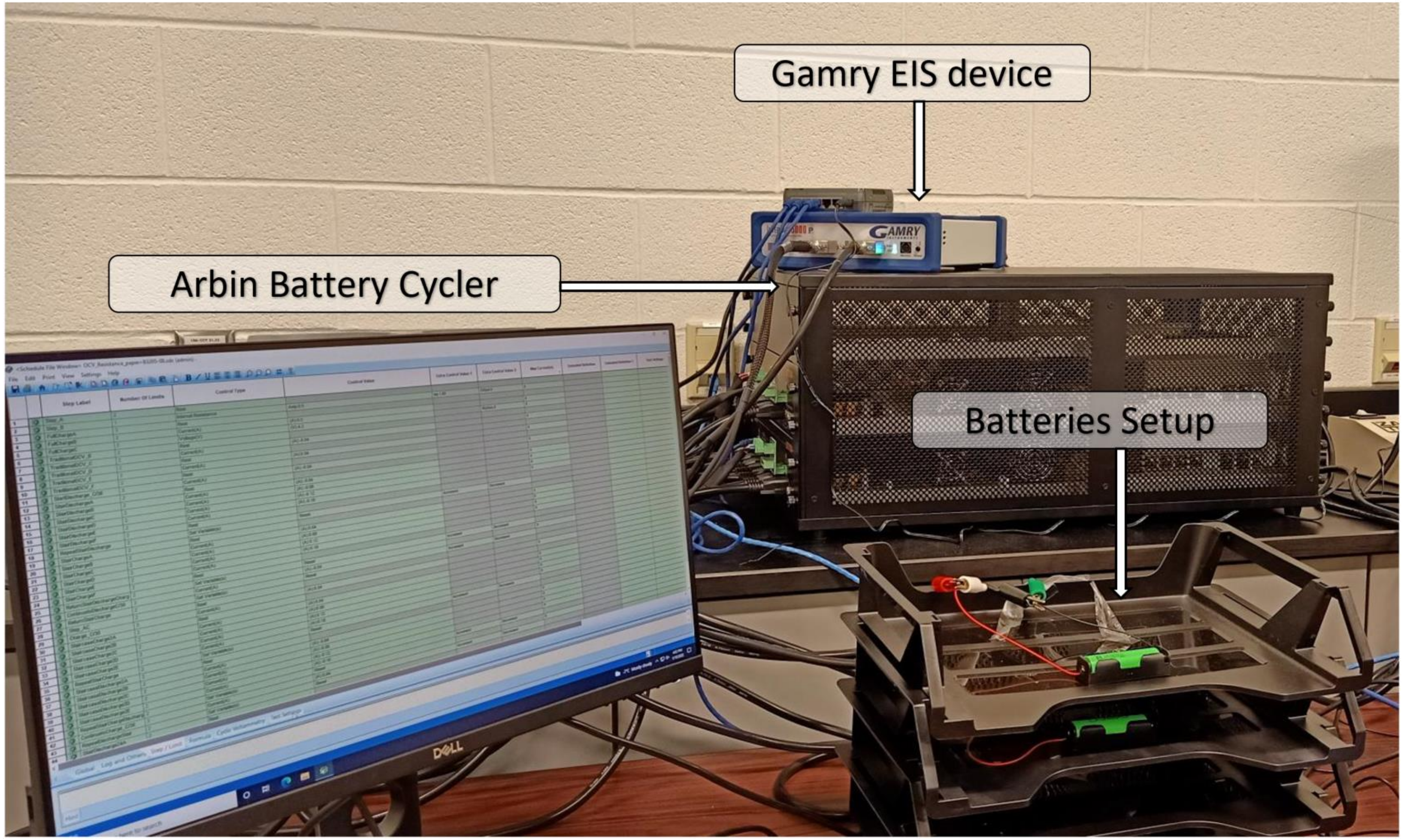



**Bird eye view**




**Detailed view**

# Experiment Setup



# Battery used for the experiment

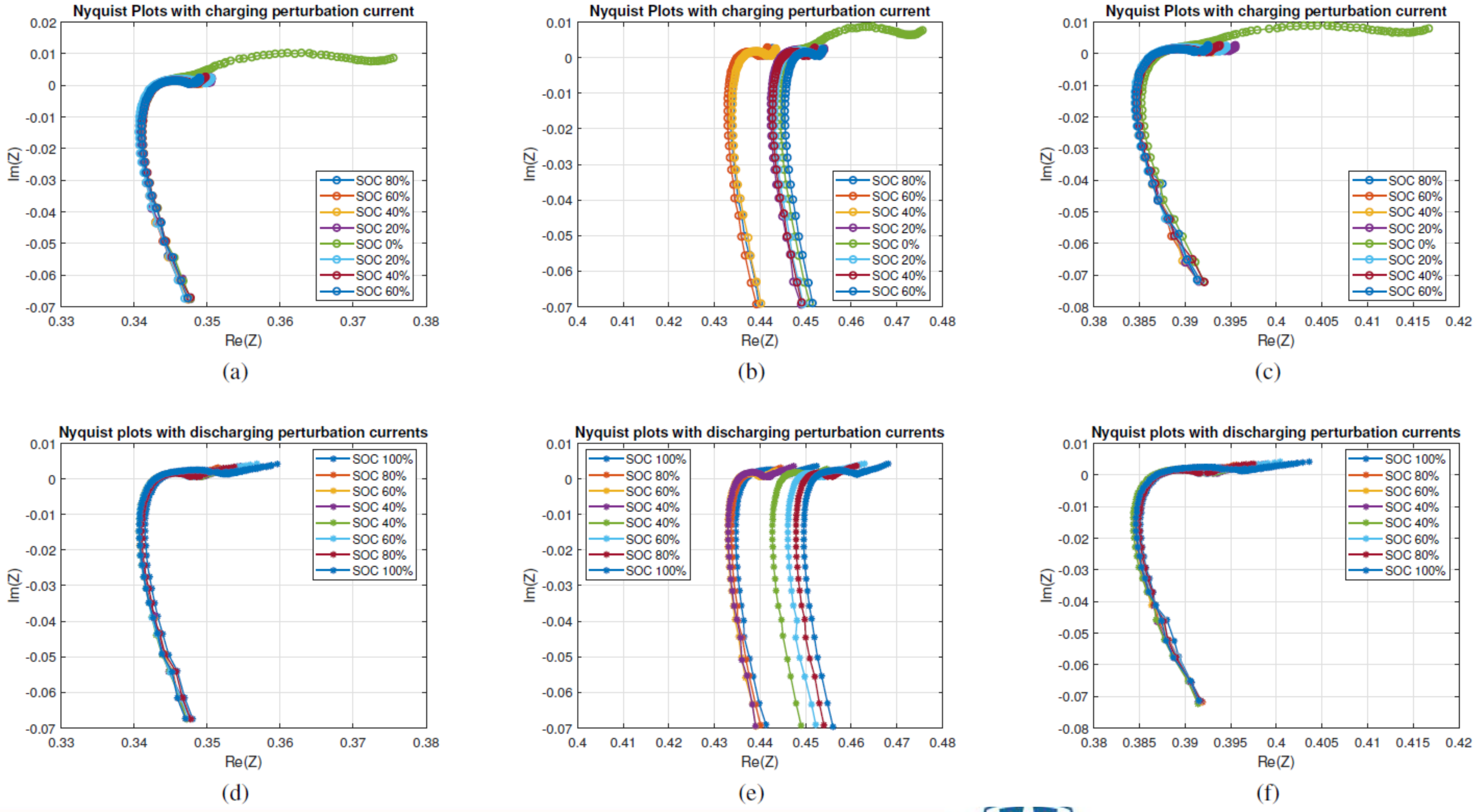
| Specification | Value (unit) |
|---|---|
| Nominal capacity | 3500 mAh |
| Max.current | 10 A |
| Nominal voltage($V_{nom}$) | 3.7 V |
| Height | 65 mm |
| Diameter | 18 mm |
| Weight | 46.5 g |


LG – INR18650MJ1

# Results

# Nyquist plots after the experiment

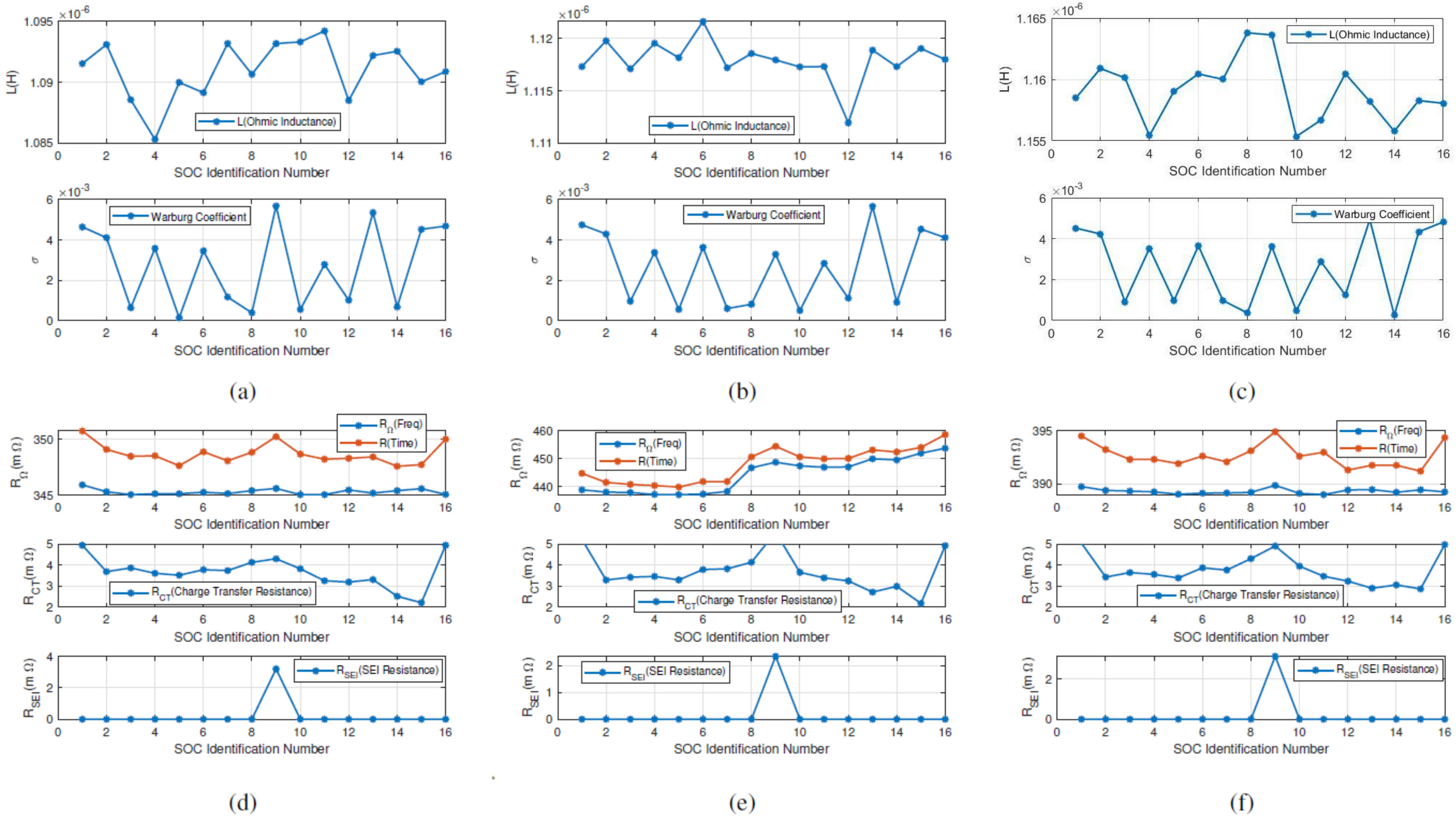
- The results after EIS of batteries at different SOC during charging and discharging at room temperature.
- The data is collected on Gamry – Interface 5000P



# Estimated Parameters

| x-axis | SOC | x-axis | SOC |
|---|---|---|---|
| **1** | 100 | **9** | 0 |
| **2** | 80 | **10** | 20 |
| **3** | 80 | **11** | 40 |
| **4** | 60 | **12** | 40 |
| **5** | 60 | **13** | 60 |
| **6** | 40 | **14** | 60 |
| **7** | 40 | **15** | 80 |
| **8** | 20 | **16** | 100 |

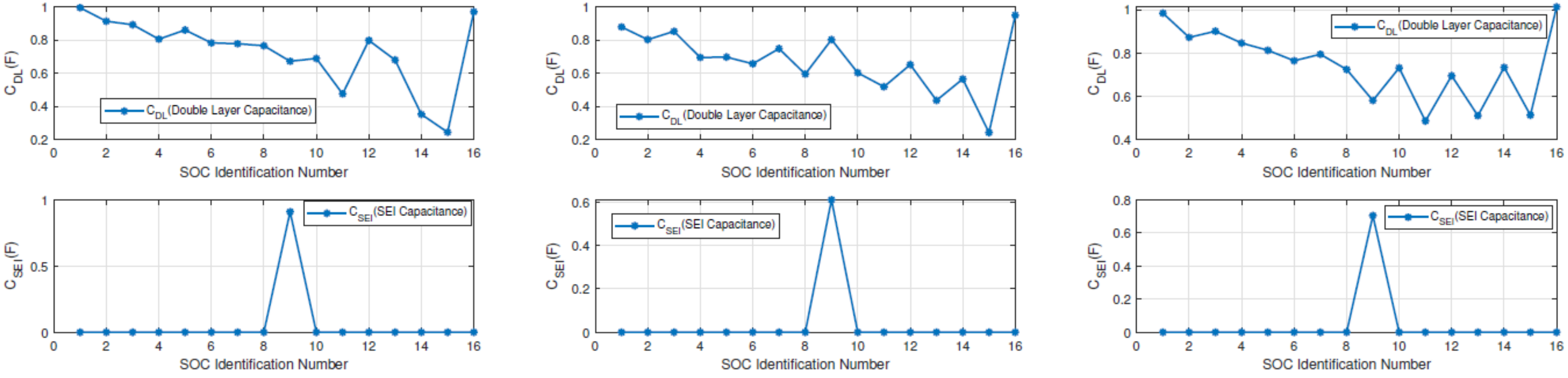
SOC values at different SOC identification number



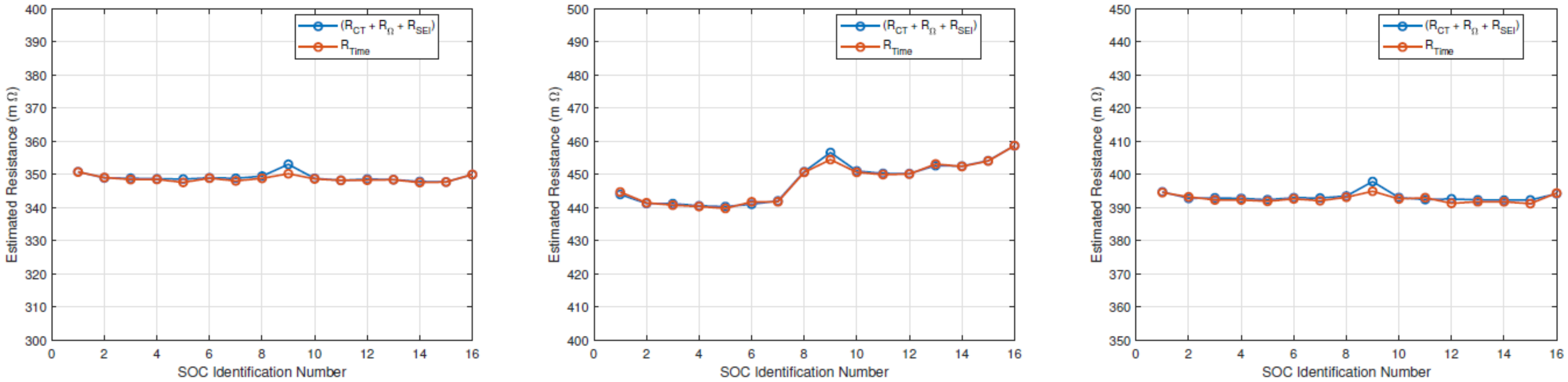

- $R_{SEI}$ is 0 in all cases except at 0 SOC.
- $R_\Omega$ can be seen higher at full and 0 SOC.

# Estimated Parameters

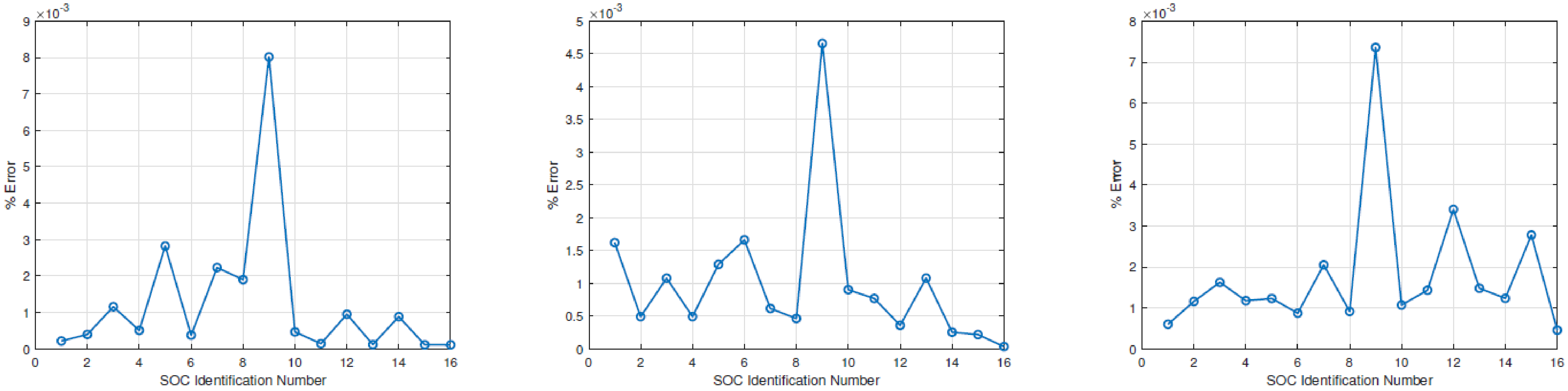
- Estimated resistance in time domain and frequency domain are compared.
- In frequency domain all the resistances are added together to be compared with internal resistance estimated in time domain.
- A significant difference can be seen at SOC identification number 9 (0 SOC).




(g) (h) (i)



# Error plots

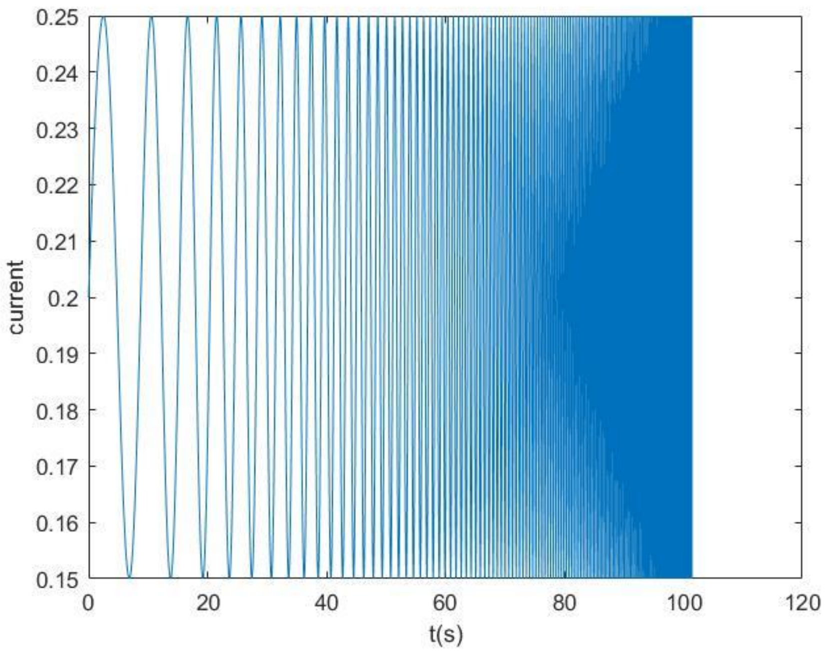


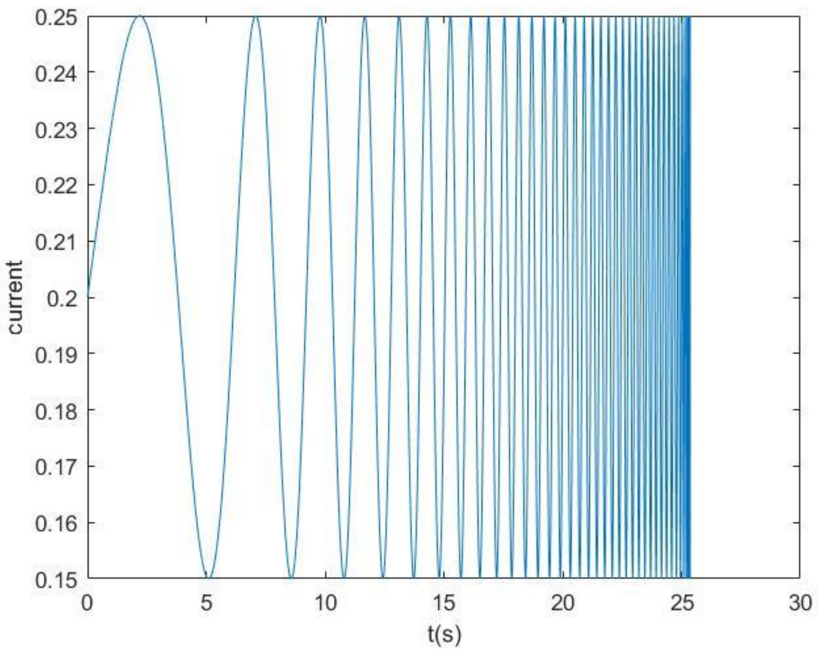

(a) B3201 (b) B3202 (c) B3203

- The % error between internal resistance estimated in time domain and frequency domain is shown.

# Remaining work






- Signal with frequency sweep is made.
- Reduce time to obtain Nyquist plot in as less time as possible (by varying signal time and signal to noise ratio).

# Timeline

| Semester/Tasks | Winter 2021 | | | | Summer 2021 | | | | Fall 2021 | | | | Winter 2022 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Coursework | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | | |
| Literature review of battery and its problems | | | | | | | ■ | ■ | | | | | | | | |
| Literature review of algorithms developed | | | | | | | ■ | ■ | | | | | | | | |
| Data collection and validation of algorithms with real data | | | | | | | | | ■ | ■ | | | | | | |
| Planning and execution of the experiment | | | | | | | | | | | ■ | ■ | | | | |
| Research paper writing | | | | | | | | | | | | | ■ | ■ | | |
| Research paper submission | | | | | | | | | | | | | | ■ | | |
| MASc thesis proposal formulation | | | | | | | | | | | | | | | ■ | |
| MASc thesis proposal - First seminar | | | | | | | | | | | | | | | ■ | |
| Simulation of reduced time for EIS | | | | | | | | | | | | | | | ■ | |
| MASc thesis documentation | | | | | | | | | | | | | | | ■ | |
| MASc thesis - Defence | | | | | | | | | | | | | | | | ■ |
| MASc thesis submission | | | | | | | | | | | | | | | | ■ |

# Publication



| Publication title | Publication status | Journal |
| --- | --- | --- |
| R. Sengar, M. Abaspour and B. Balasingam, “Battery Parameter Analysis Through Electrochemical Impedance Spectroscopy at Different State of Charge Levels" | Submitted | IEEE - TIE |

# References


1. M. A. Ghadi, *Performance Analysis and Improvement of Electrochemical Impedance Spectroscopy for Online Estimation of Battery Parameters.* PhD thesis, University of Windsor (Canada), 2021.
2. B. Balasingam and K. R. Pattipati, "*On the identification of electrical equivalent circuit models based on noisy measurements*," IEEE Transactions on Instrumentation and Measurement, vol. 70, pp. 1–16, 2021.
3. What is difference between frequency domain analysis and time domain analysis? – Quora

# Thanks