

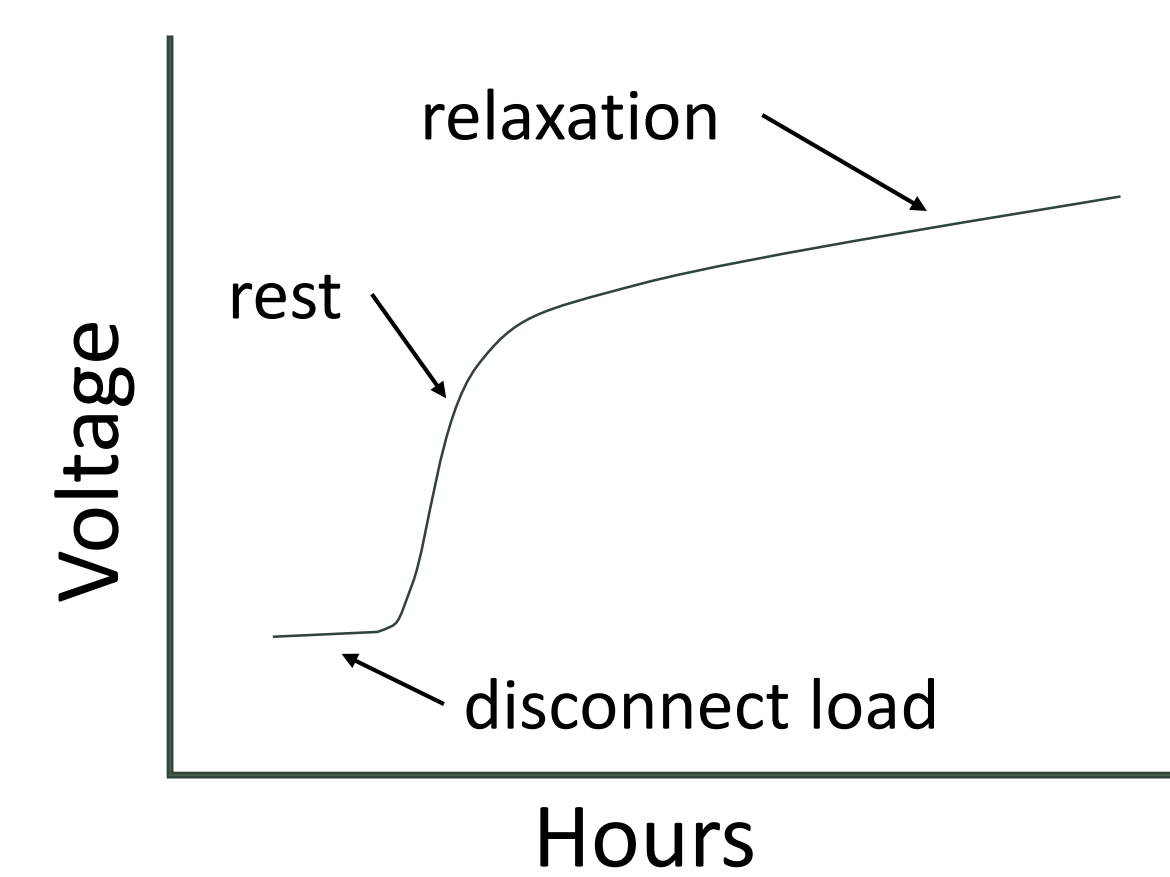
# Battery Relaxation Effects

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HEVPD&D CREATE

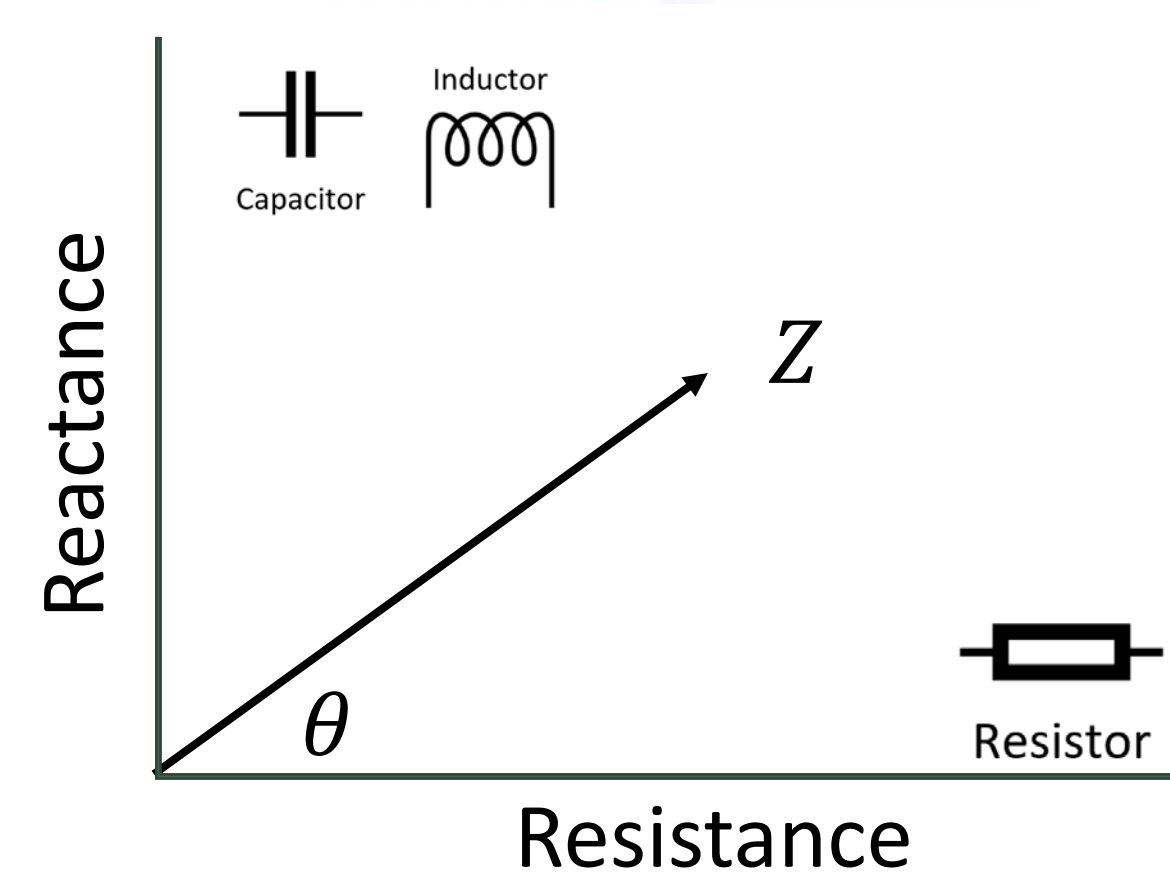
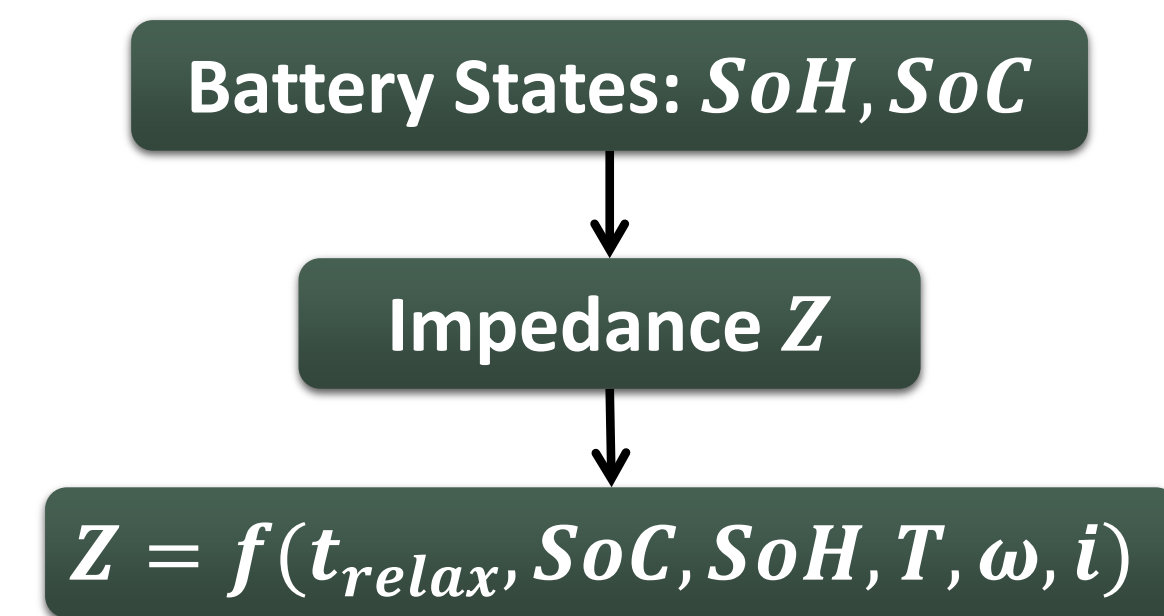
## WHAT IS BATTERY RELAXATION?

When discharge current is removed from a battery, the voltage jumps initially and continues to rise slowly over many hours. This slow voltage rise is known as the **relaxation effect**. In **lithium-ion** batteries, different lithium-ion concentration gradients exist throughout the battery after discharge or charge is stopped. These concentration gradients naturally tend to equalize themselves over time.



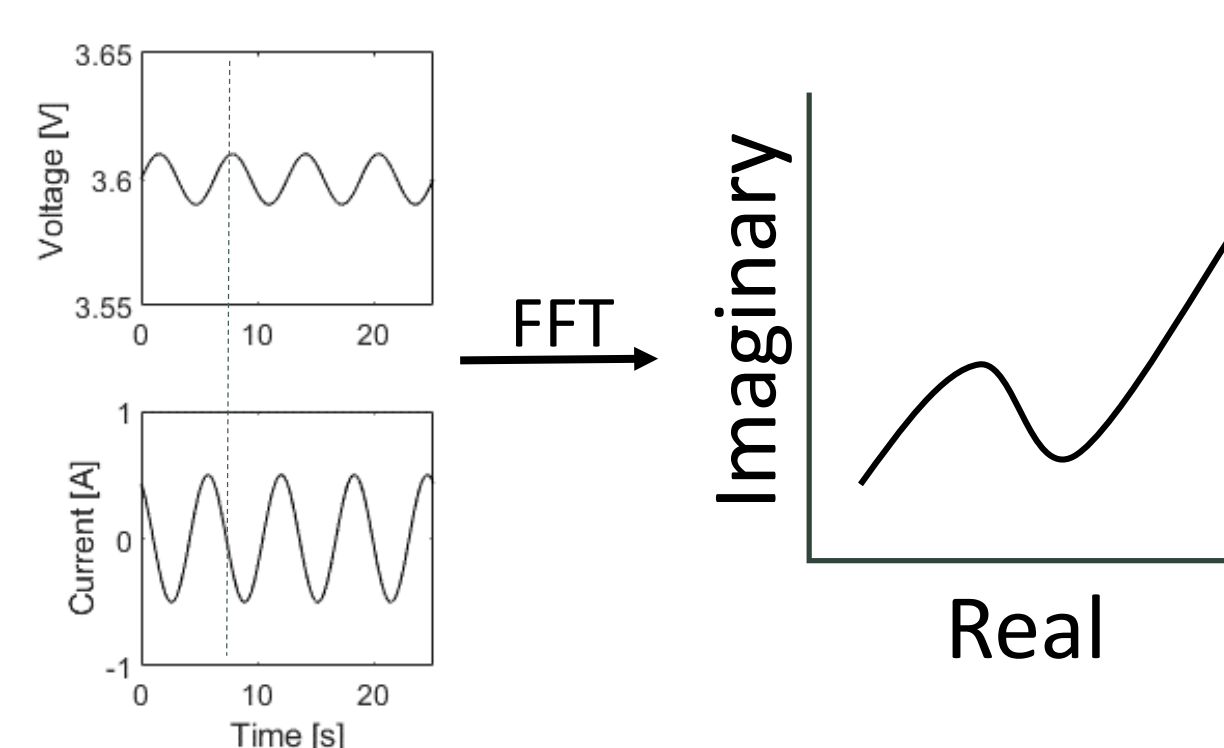
## WHY DOES RELAXATION MATTER?

The state of health (SoH) and state of charge (SoC) of a battery are related to its **impedance Z** at a temperature  $T$  and applied current  $i$  at frequency  $\omega$ .  $Z$  also changes with **relaxation time**  $t_{relax}$ . Therefore, consistent impedance measurements can only be obtained if the relaxation effect is known.



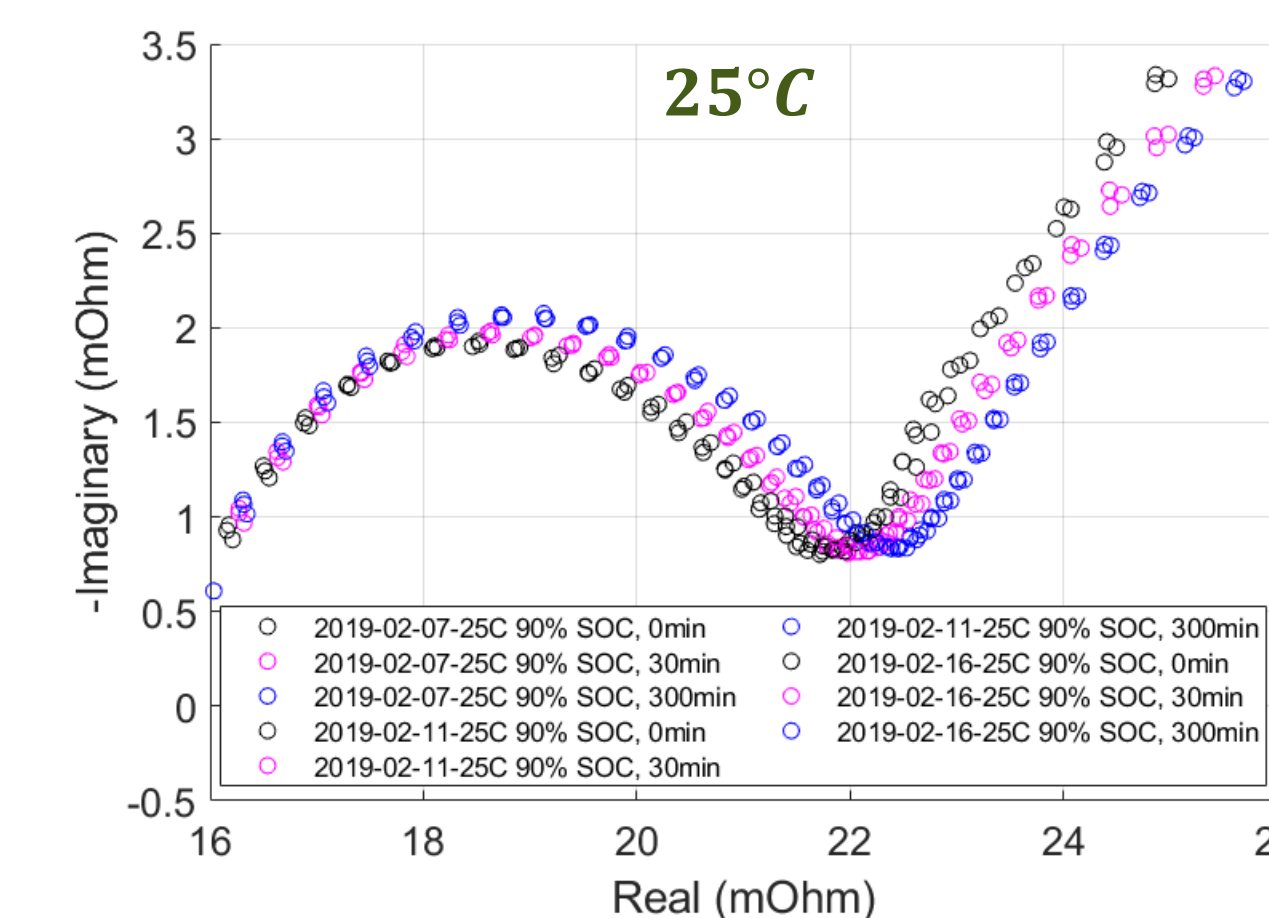
## EIS

A technique called **Electrochemical impedance spectroscopy (EIS)** is used to measure battery **impedance**. By applying sinusoidal current signals at different frequencies, a voltage response is measured. The magnitudes and phase shifts of the response are converted to complex impedance using the fast Fourier transform (FFT).



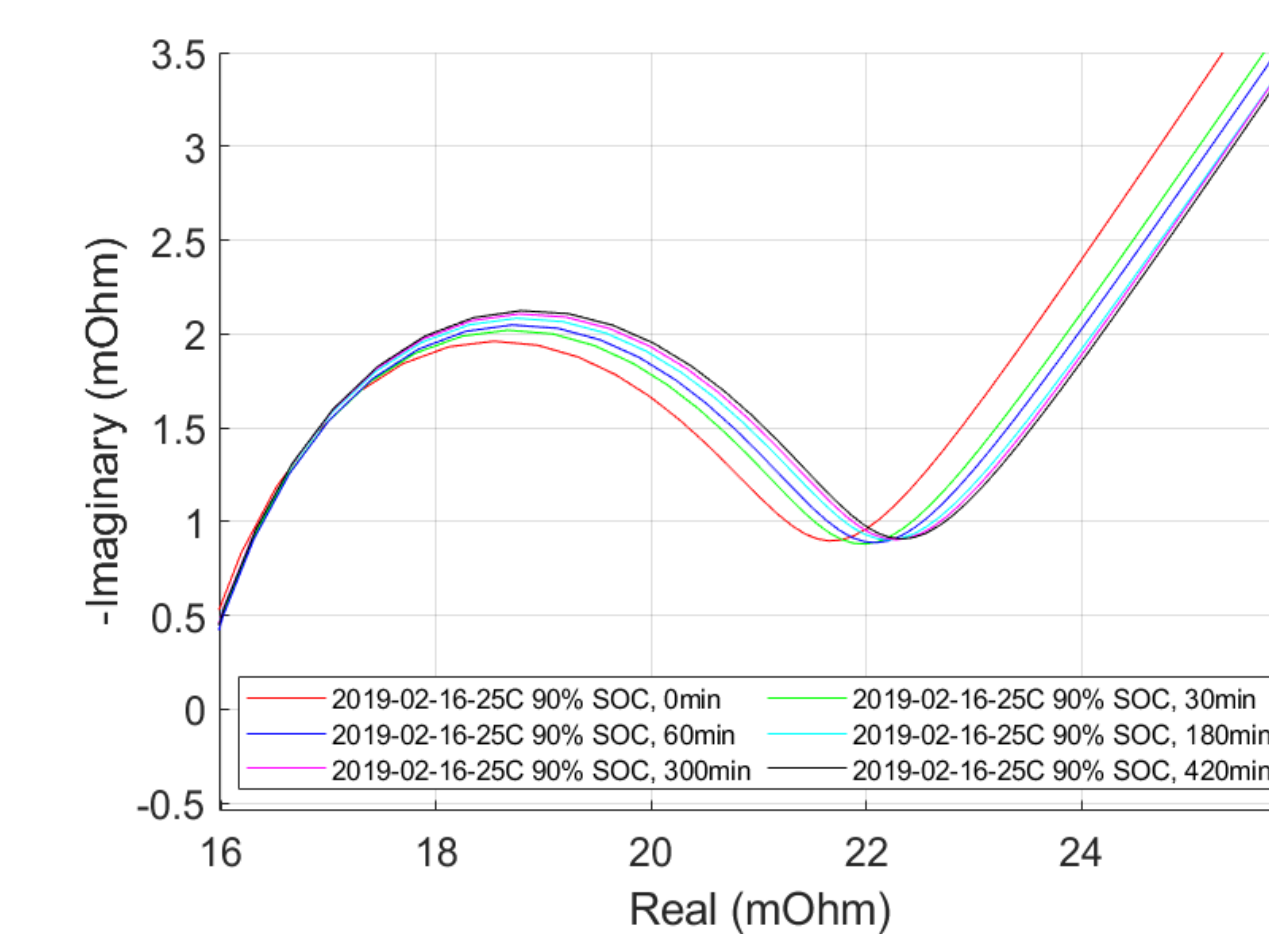
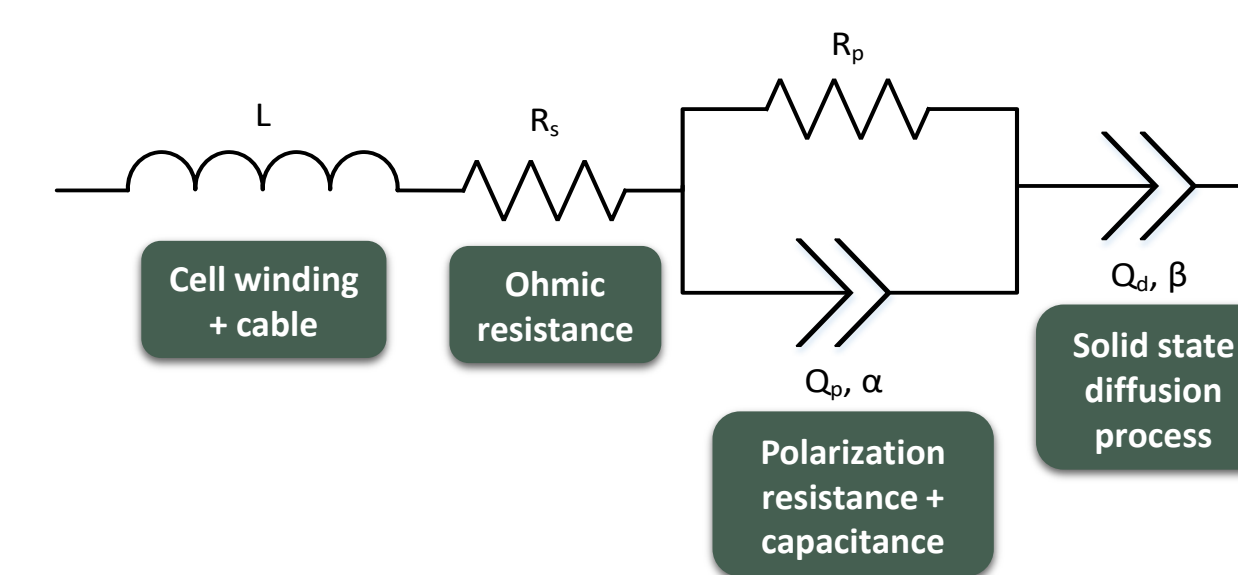
## EIS & REPEATABILITY

Relaxation tests were repeated on three different days (for the same battery). The results show that the relaxation effect is **repeatable** under constant conditions. The repeatability error is small enough to still distinguish relaxation effects.



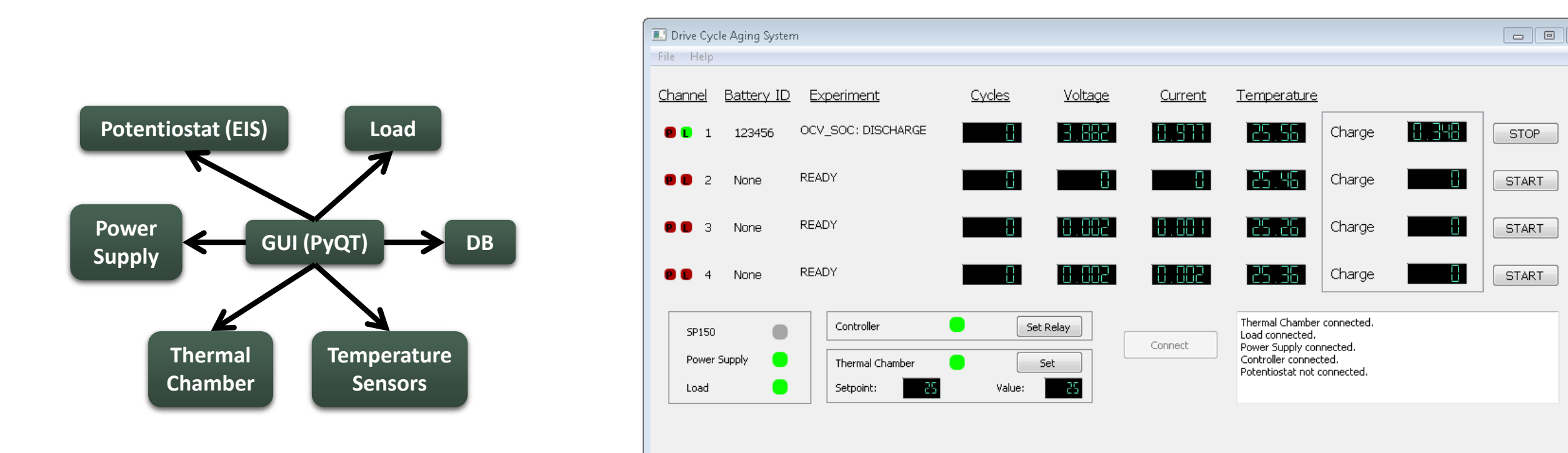
## IMPEDANCE MODELLING

To understand how different physical battery components are affected by the relaxation effect, an **impedance model** was fit to the EIS data [1].



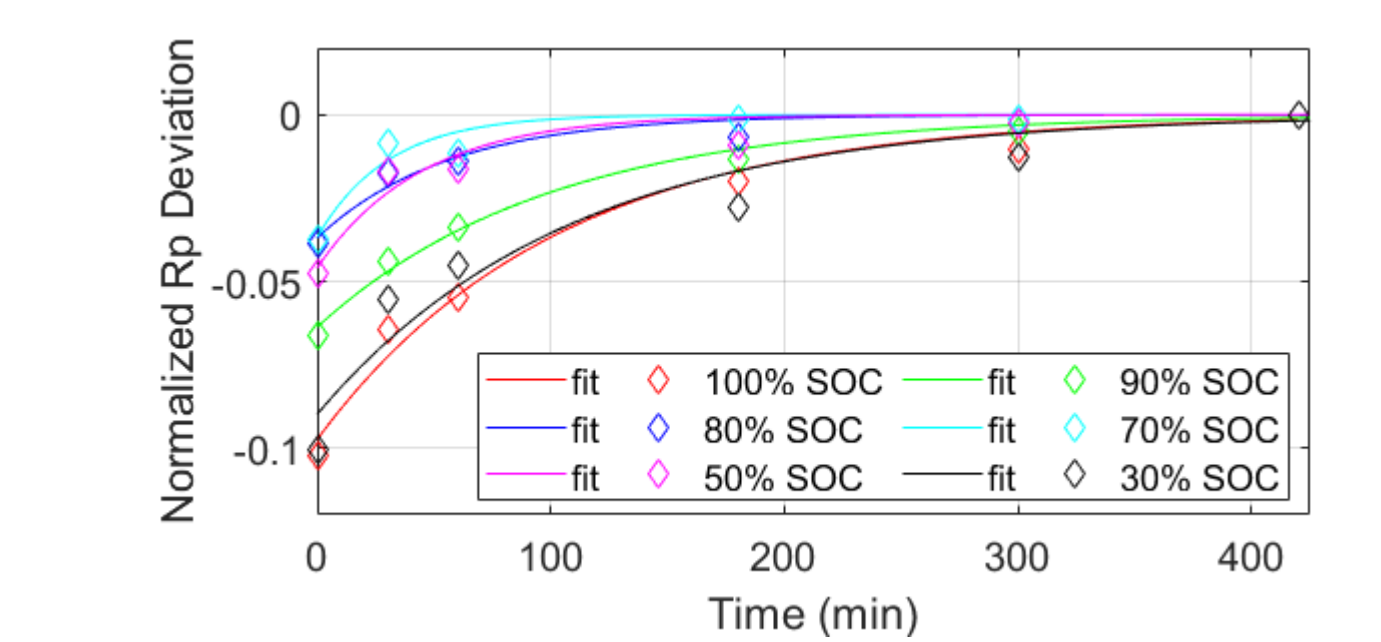
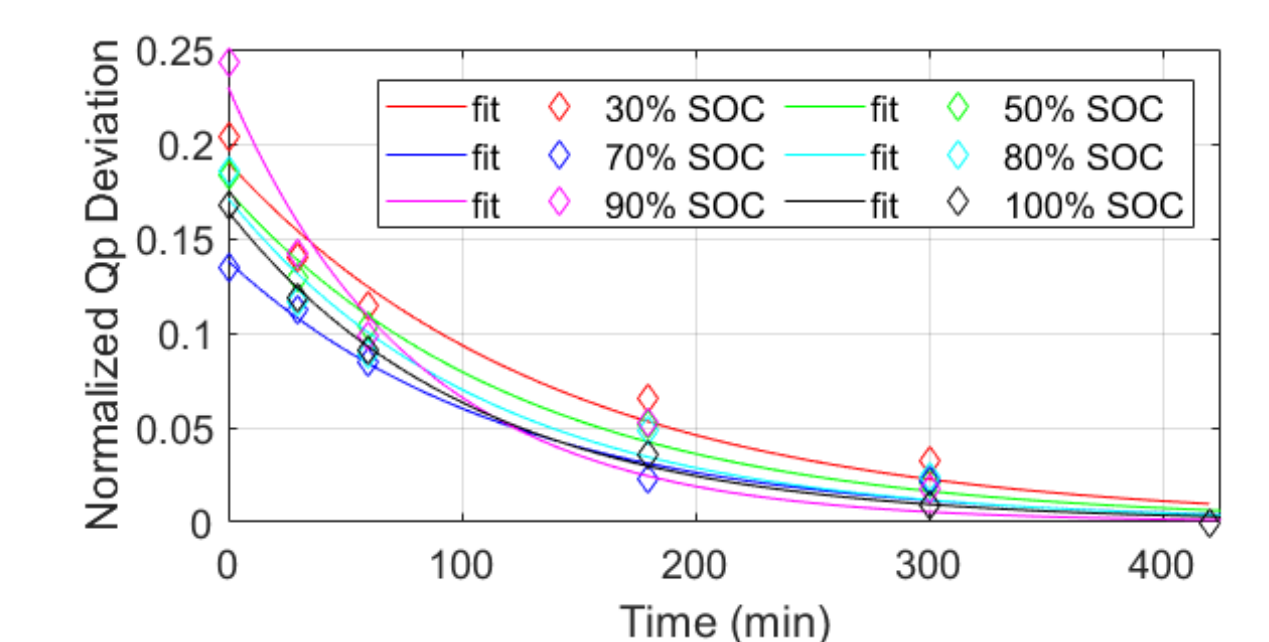
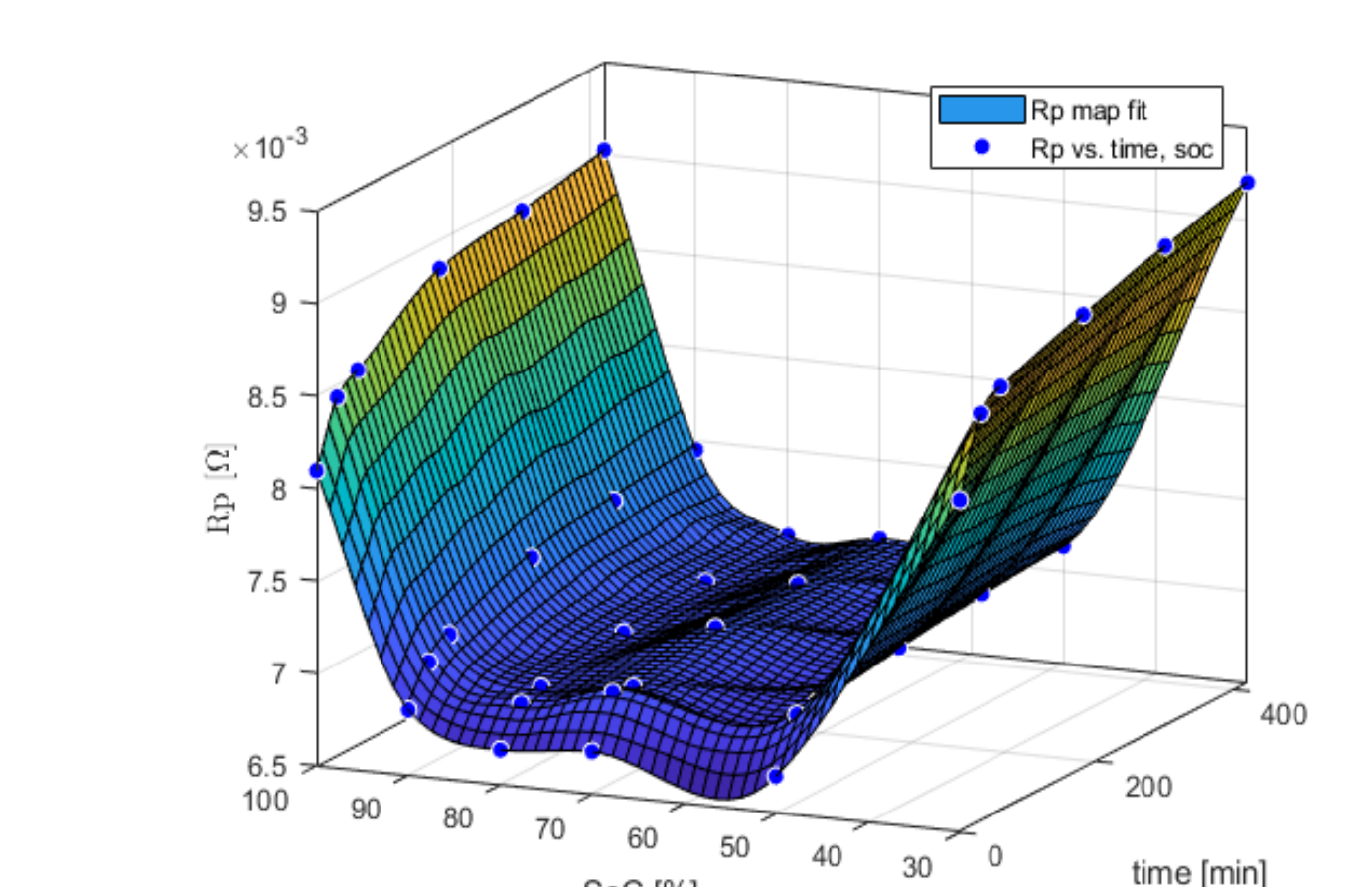
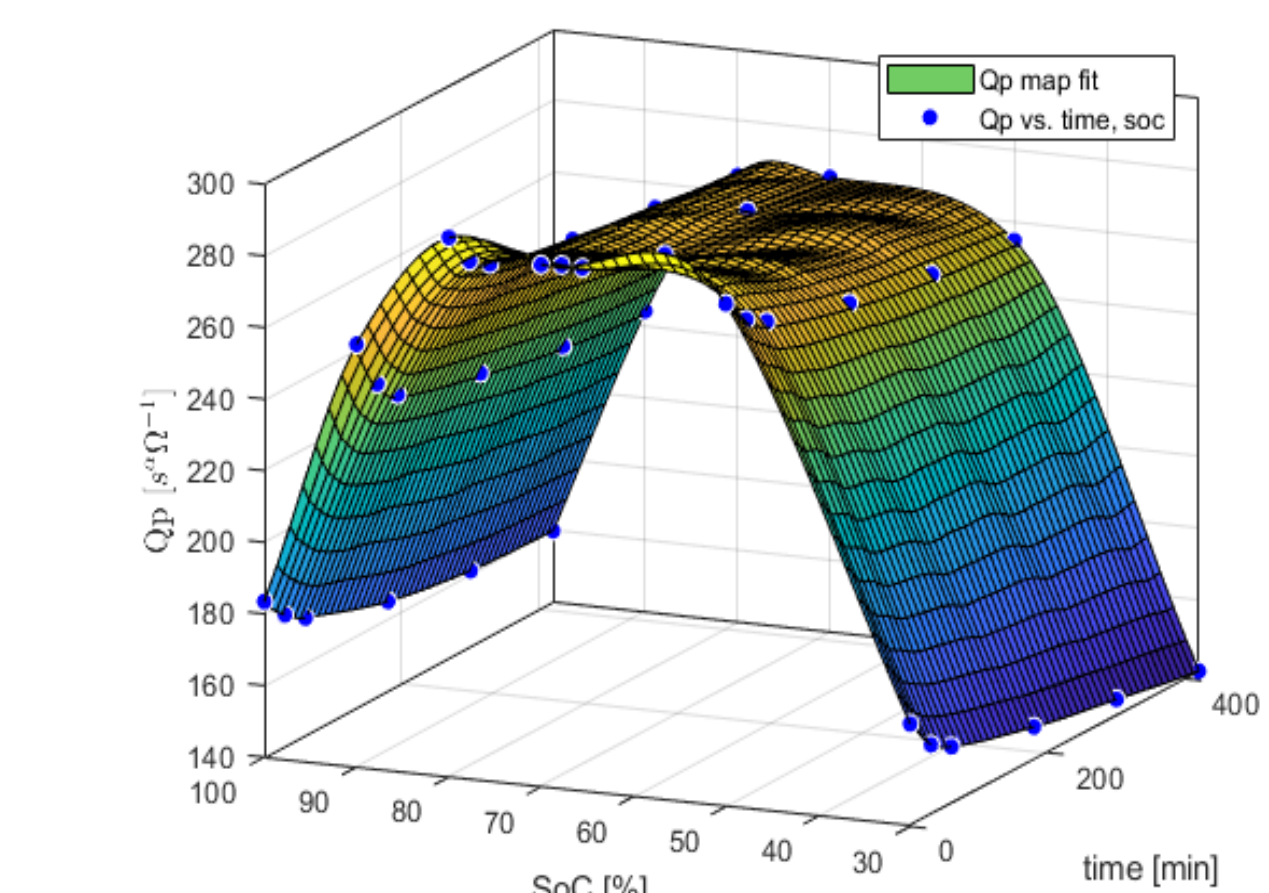
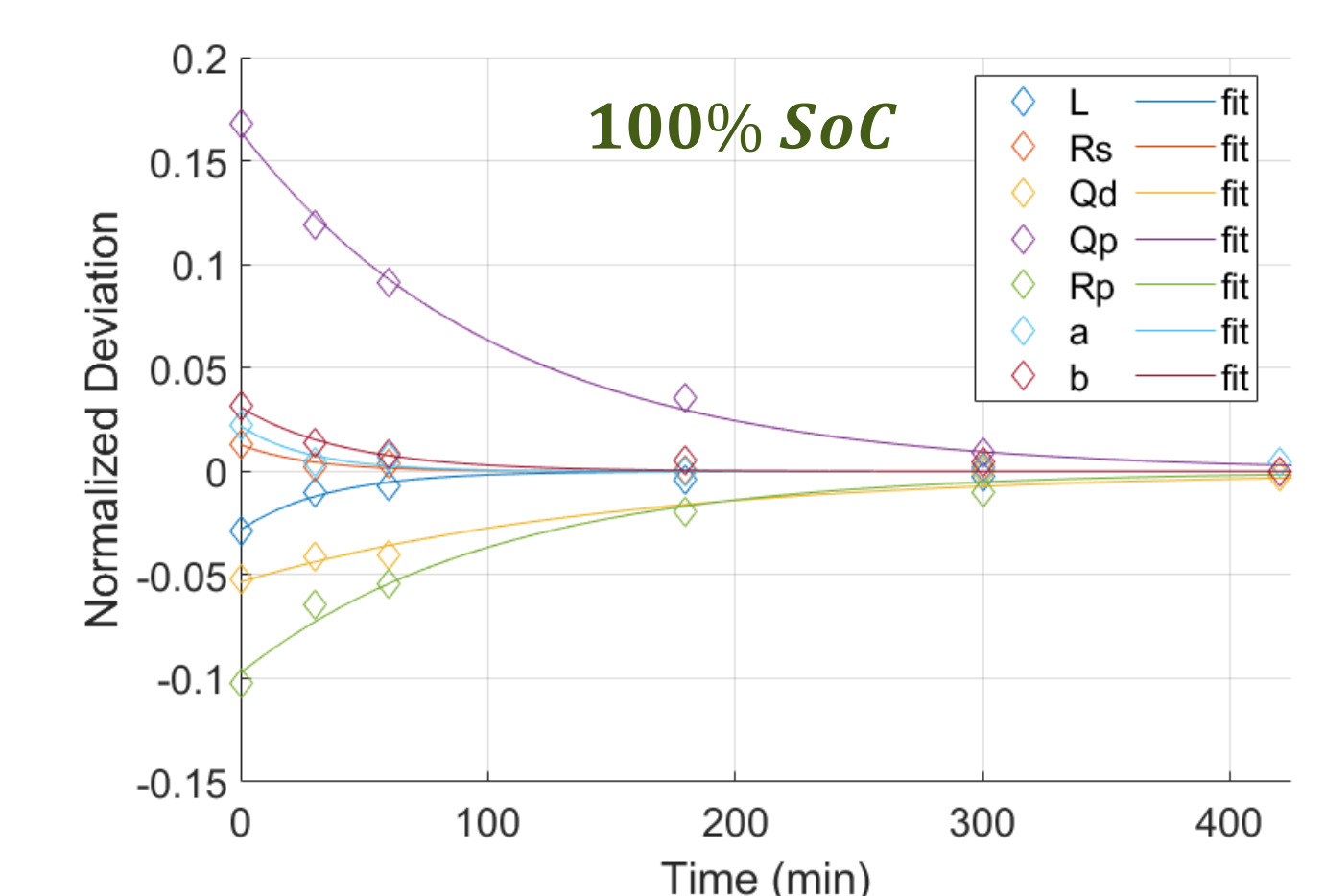
## EXPERIMENTAL

A **custom software** (Python) was developed to orchestrate the test procedures using different devices. A **Samsung INR21700-48G** (4.8 Ah) cylindrical cell was used as the test subject.



## RELAXATION & SoC

The changes in impedance model parameters were mapped over relaxation time and SoC. Deviation from the relaxed state was calculated for each model parameter [2]. The contribution of  $L$ ,  $a$ ,  $b$ , and  $R_s$  to the relaxation effect are small.  $Q_p$ ,  $Q_d$ , and  $R_p$  still change after 7 hours. The relaxation time is similar across different SoCs for  $Q_p$ , but changes for  $R_p$  with SoC.



## FUTURE WORK

- Reproduce results for a different cell of the same battery type.
- Expand temperature range.
- Explore how discharge rate affects relaxation.
- Compare relaxation effect after charge.
- Investigate impact of aging on relaxation effect.
- Compare relaxation effects of different types of batteries.
- Explore additional impedance models.

## REFERENCES

[1] J. Schmitt, A. Maheshwari, M. Heck, S. Lux, M. Vetter, Impedance change and capacity fade of lithium nickel manganese cobalt oxide-based batteries during calendar aging, *J. Power Sources*, 353 (2017) 183–194. doi:10.1016/j.jpowsour.2017.03.090.  
[2] F.M. Kindermann, A. Noel, S. V. Erhard, A. Jossen, Long-term equalization effects in Li-ion batteries due to local state of charge inhomogeneities and their impact on impedance measurements, *Electrochim. Acta*, 185 (2015) 107–116. doi:10.1016/j.electacta.2015.10.108.