Smart cell internal resistance measurement

Improving SoC, SoH, SoAP estimation using on cell DCIR measurement

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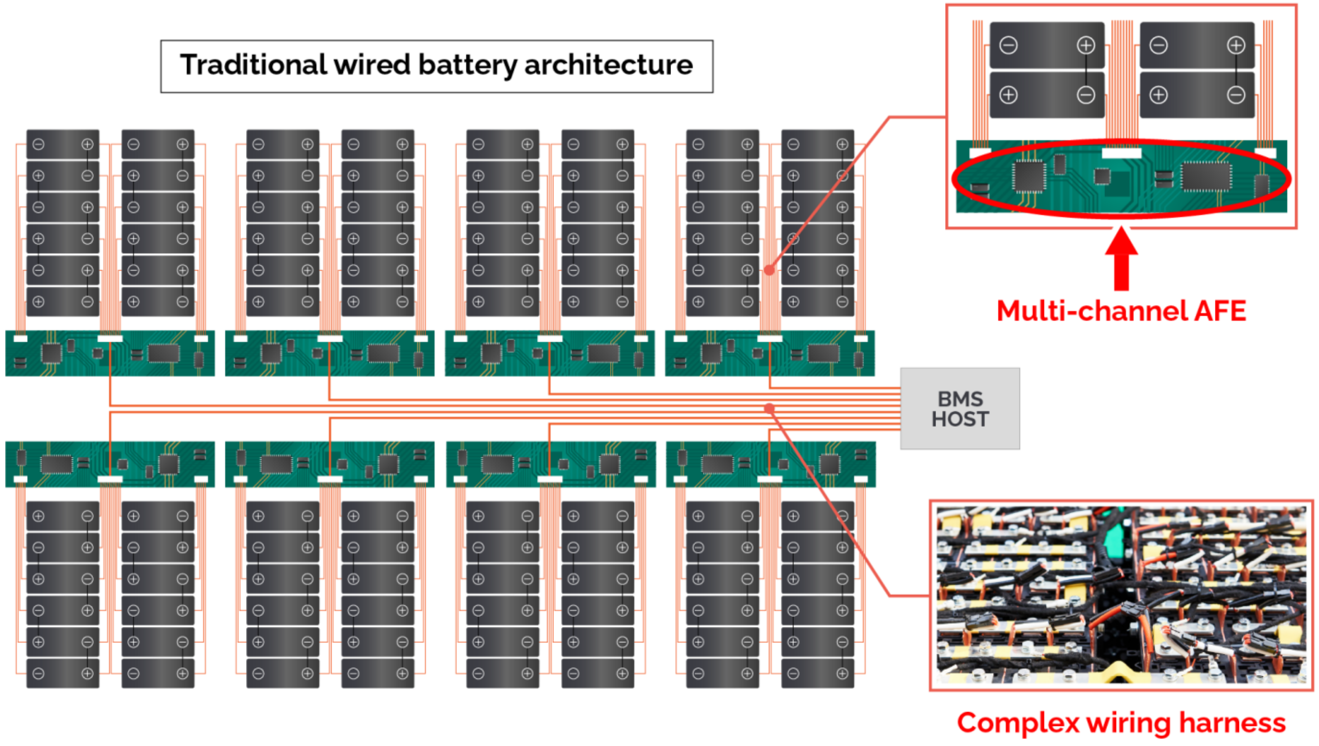
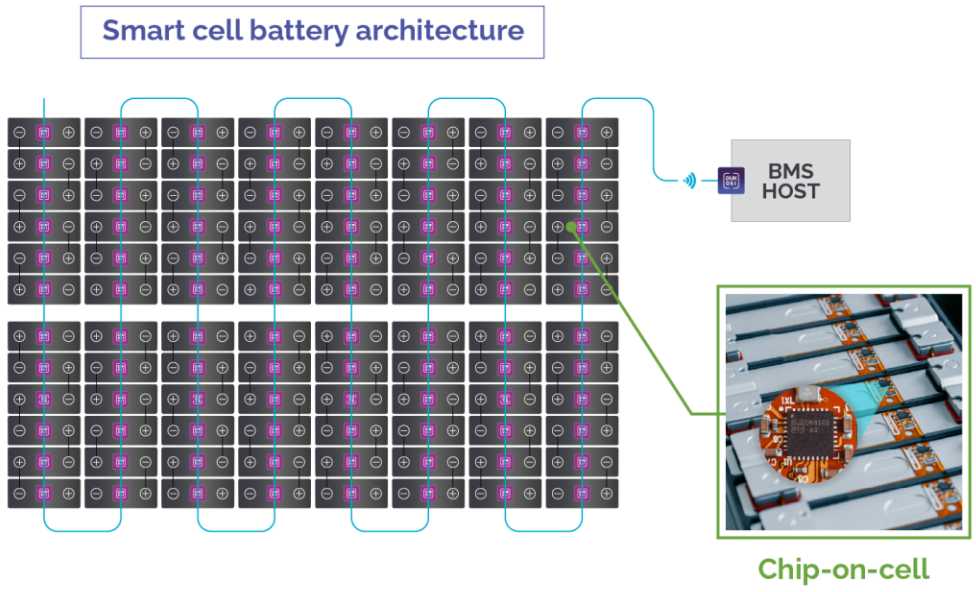
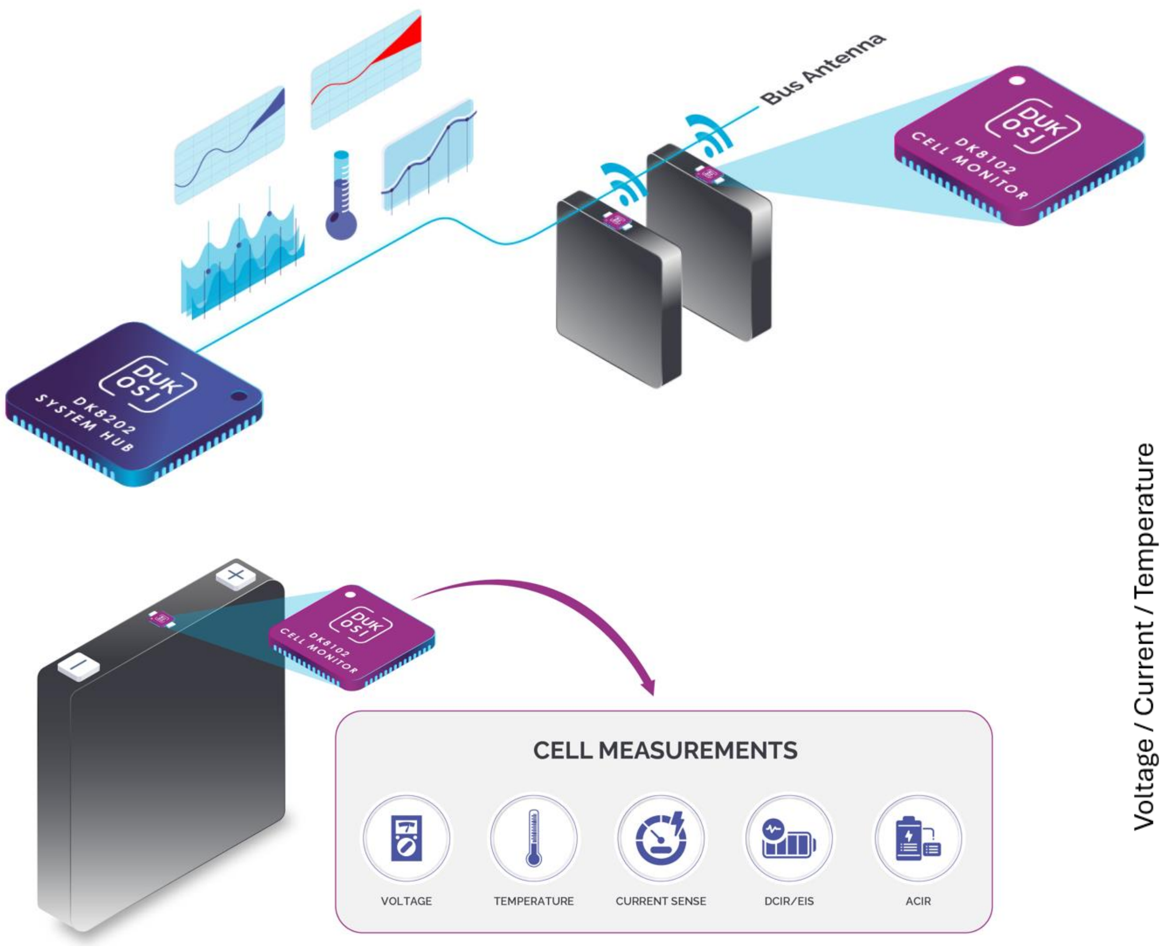
Intelligence on every cell

Making measurements on battery systems





Why do we make these measurements?



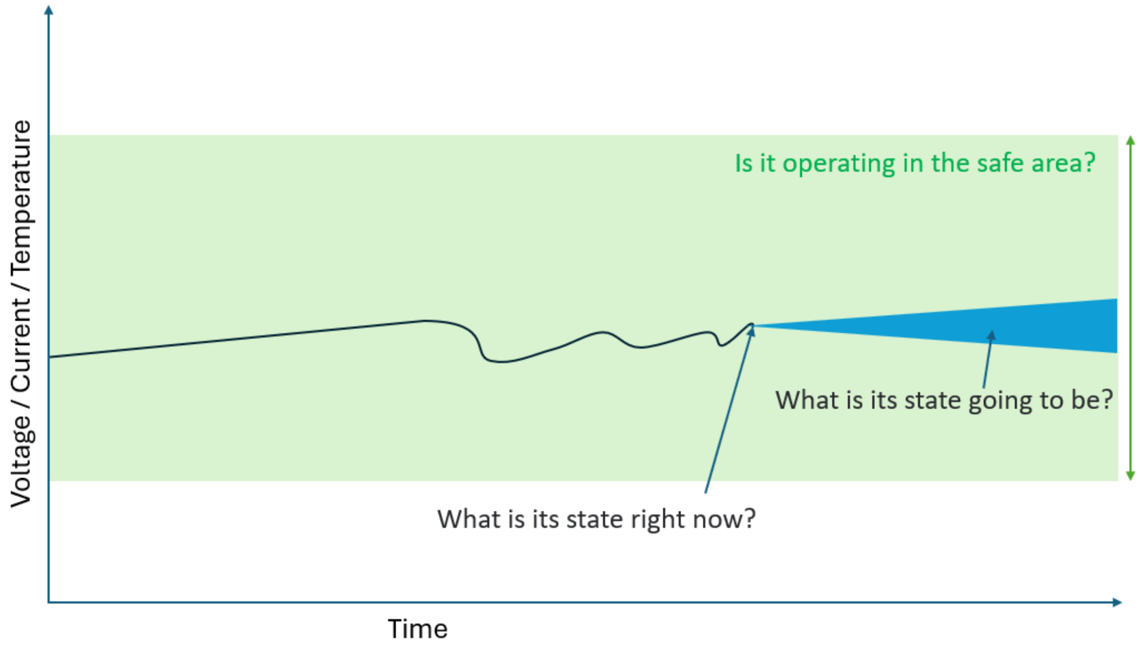


Image source: https://www.nacleanenergy.com/energy-storage/hidden-costs-of-inaccurate-state-of-charge

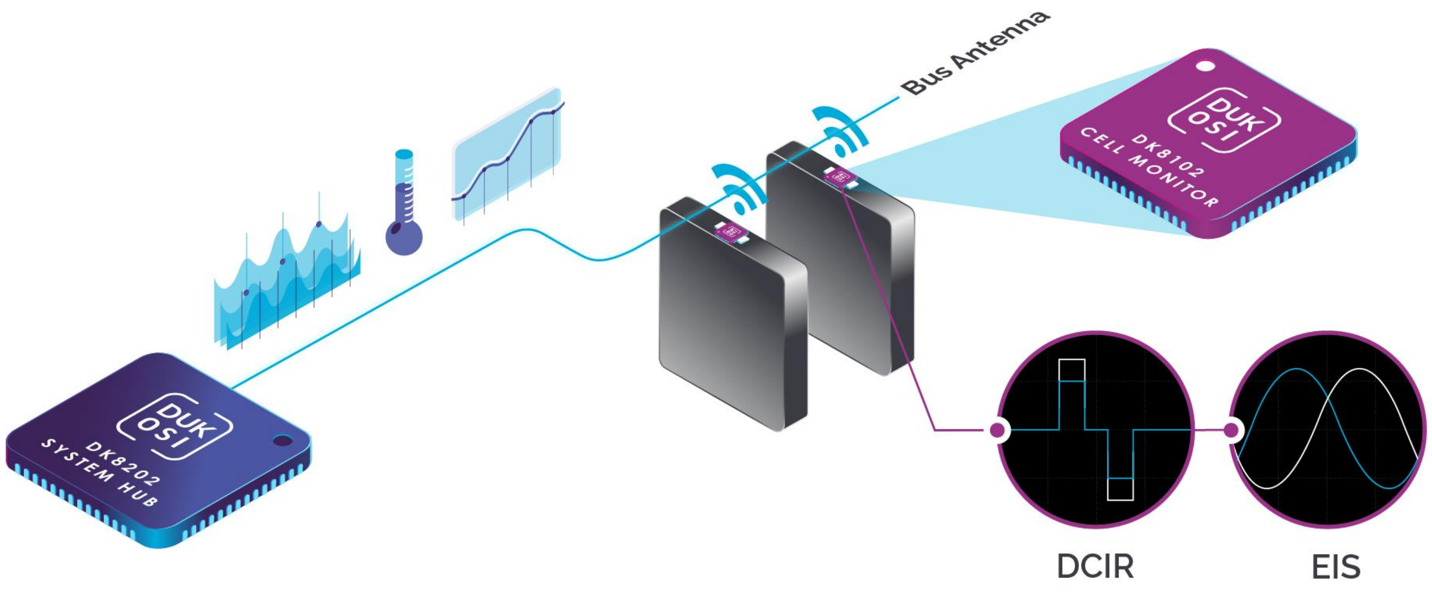
Advanced Cell Measurements

What can be determined about a cell's state beyond voltage or temperature?

- We can estimate SoC, SoH, SoAP….
- In-pack and on-cell technology can now measure resistance and impedance though **DCIR and EIS**.

What do these tell us?

- They are methods for assessing cell performance, efficiency, and degradation.
- They can improve SoC, SoH, and SoAP estimation accuracy.

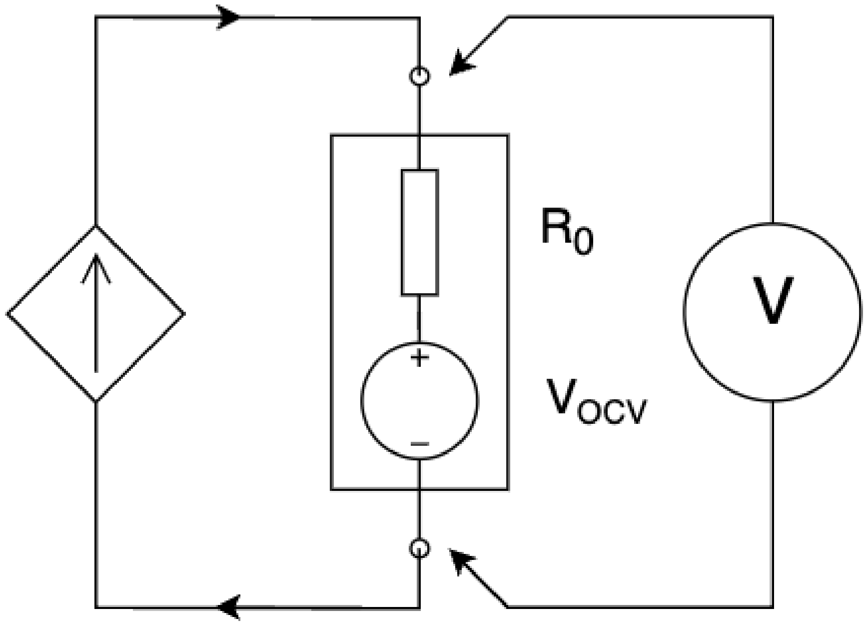


What are we measuring? A simple, useful model
- an ideal voltage source and a single resistance

- We can describe the behavior of the cell in terms of Ohms Law.
- Apply any current (I) to the cell, and this simple model will tell you what the terminal voltage V_{cell} will be

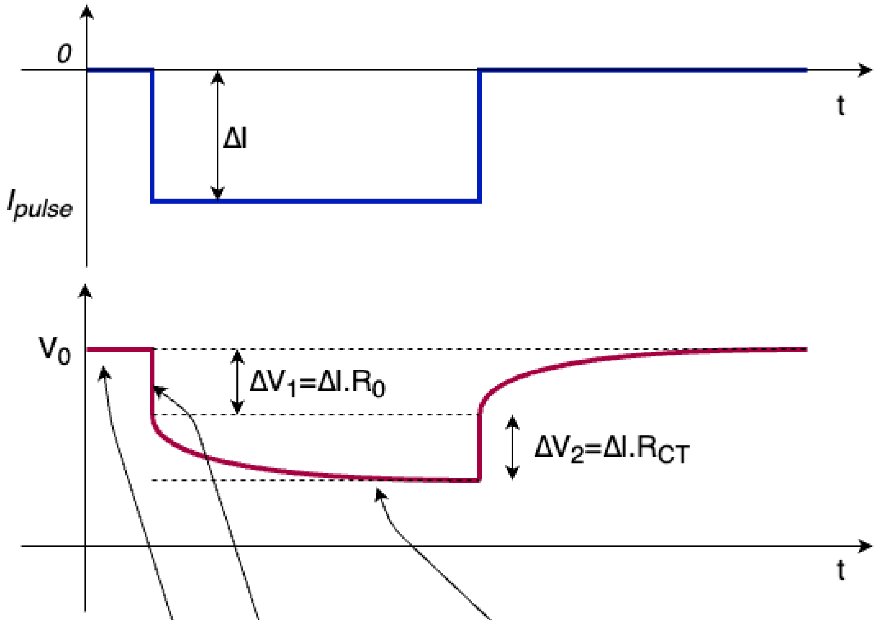
$$V_{cell} = V_{OCV} + I.R_0$$

- But there is no single value for R_0!
- R_0 varies with:
  - V_{OCV}, temperature, age, current
  - Variously non-linear

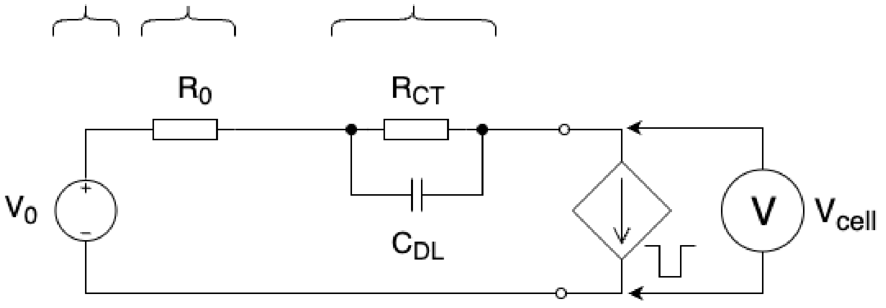


We either need to characterize the cell over a range of states – and assume it doesn't change, or measure the cell in-situ.

DC Internal Resistance – DCIR – performed on cell

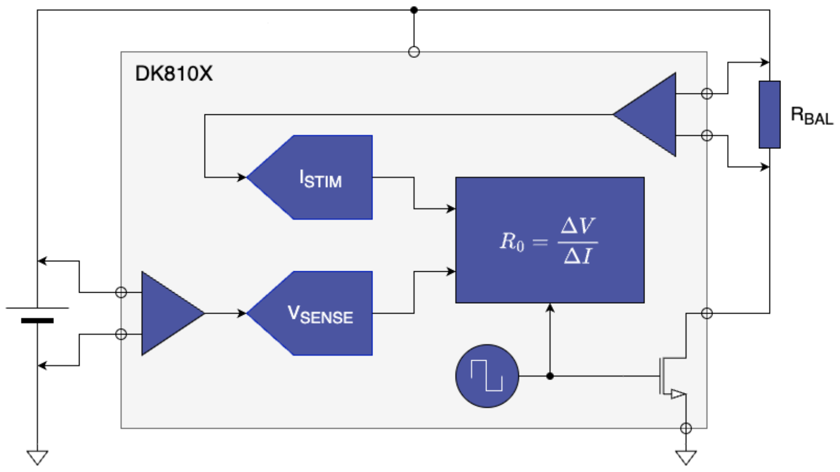


$$V_{cell}(t) = V_0 + I.R_0 + I.R_{CT}\left(1 - e^{\frac{-t}{R_{CT}.C_{DL}}}\right)$$



- Apply a current step ΔI
- Measure the immediate change in voltage ΔV_1
- Sample too late, and the charge transfer / capacitive double layer effects start to mount up

$$R_0 = \frac{\Delta V_1}{\Delta I} = \frac{R_{BAL}\,\Delta\,V_1}{\Delta V_{BAL}}$$



- Pack level stimulus – large current pulse, every cell sampled simultaneously

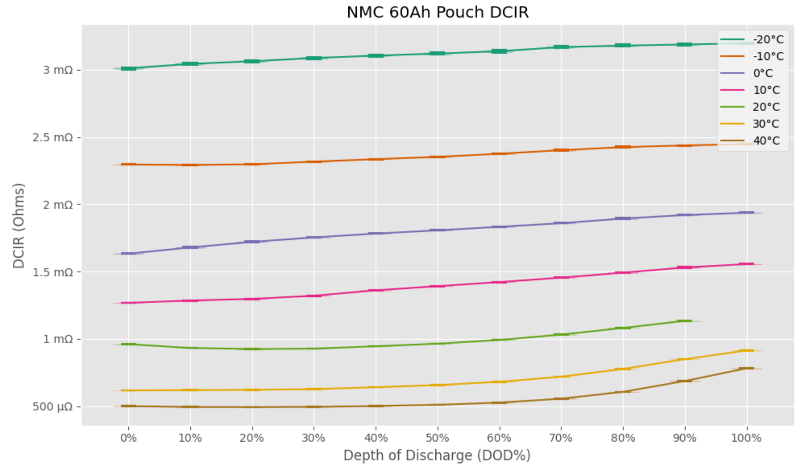
or

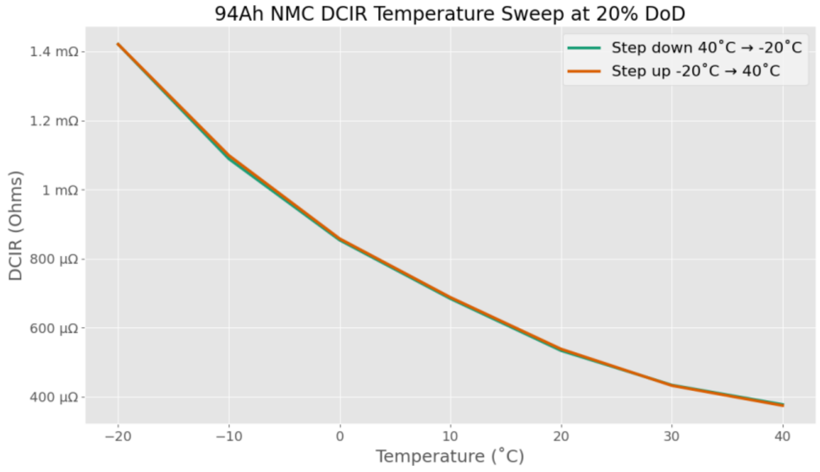
- Use a local stimulus on each cell and signal processing

What magnitude is a DCIR?

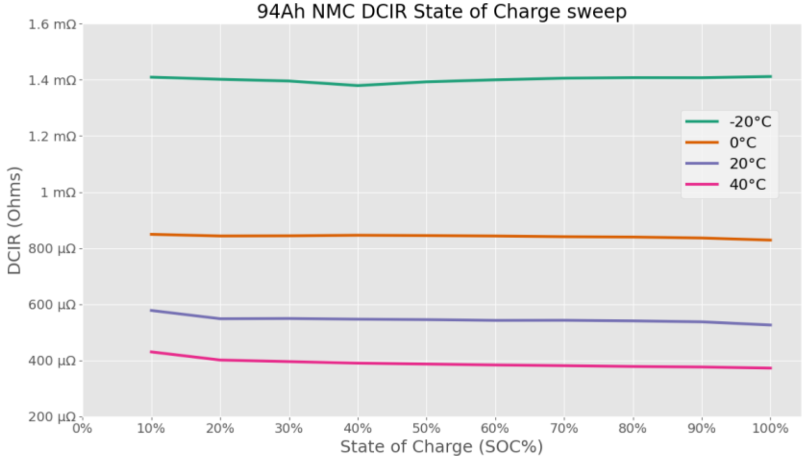
A typical DCIR for a large Li-ion cell is <1mΩ

For a 300Ah class cell, can be < 400μΩ

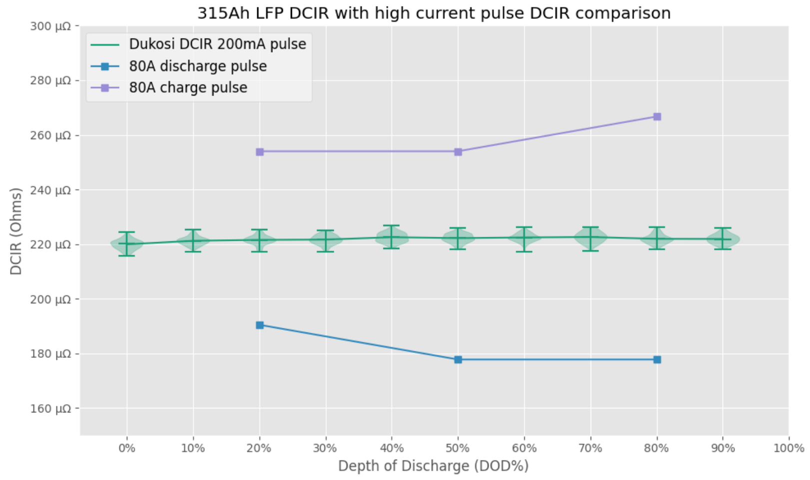




- DCIR will vary predictably with temperature
- DCIR can vary with State of Charge (SOC) – but chemistry dependant.



- DCIR typically increases with age/temp
- DCIR can vary with current – the value is dependent on the way it is measured!

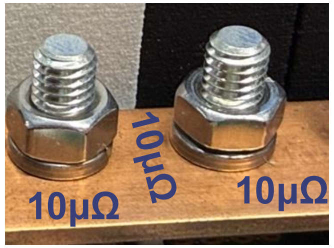


Measuring microOhms (µΩ)

- A 100mm long piece of 2mm diameter wire ≅ **500µΩ**
- A 50mm long, 20mm wide by 2mm thick copper bus bar ≅ **10µΩ**
- Bolted contact resistance **10µΩ** to **>>1mΩ**, depending on cleanliness

500µΩ means : A 10A stimulus (current step) → 5mV response

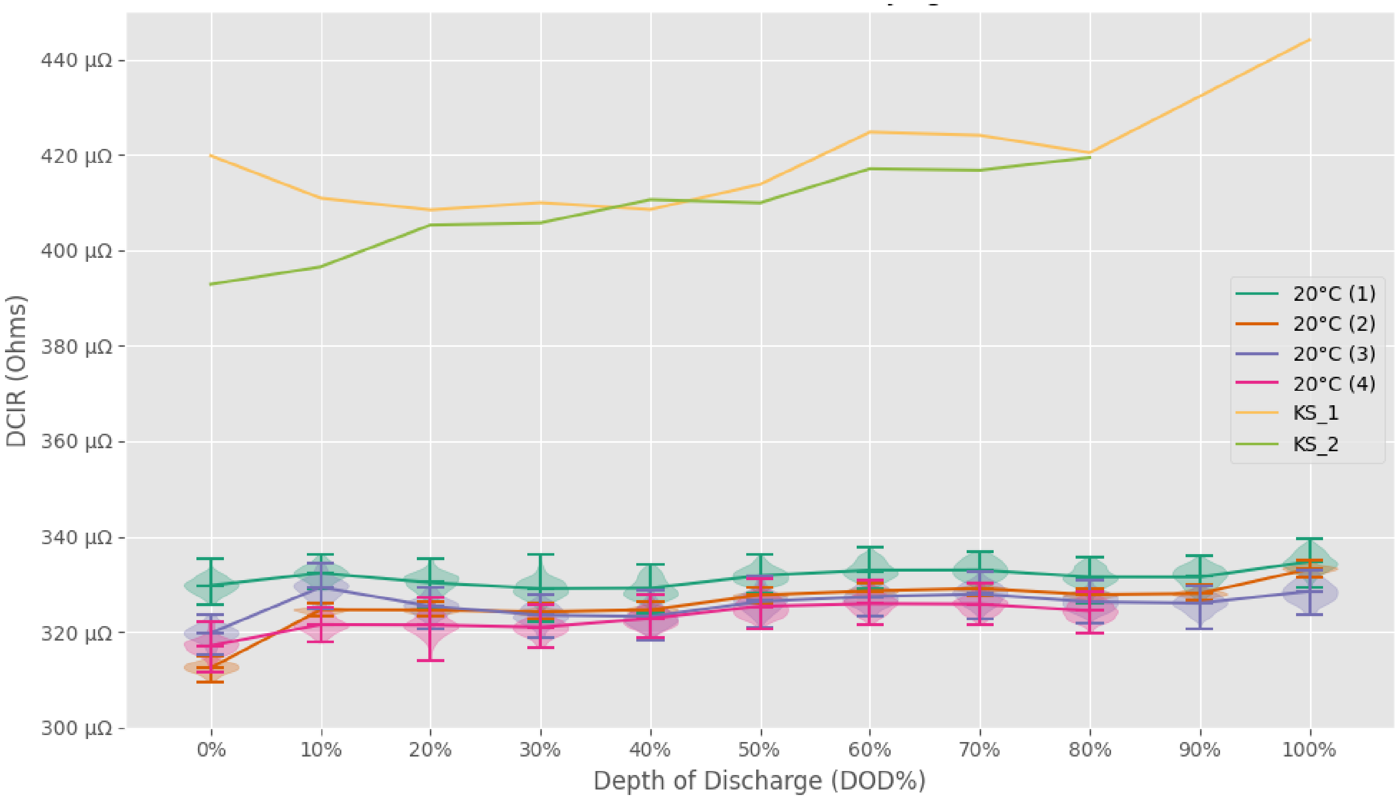
- A 100mA stimulus → 50µV response. On a 5V range this requires **>17bits resolution**
- They said it could not be done – but analogue electronics and digital signal processing shows otherwise.



Cell – all LFP	Datasheet DCIR/ACIR
LFP-100Ah	<350µΩ
LFP-271Ah	140µΩ ±50µΩ
LFP-86Ah	320µΩ ±50µΩ
LFP-280Ah	<250µΩ
LFP-80Ah	<700µΩ
LFP-184Ah	<450µΩ
LFP-340Ah	<500µΩ
LFP-165Ah	<400µΩ

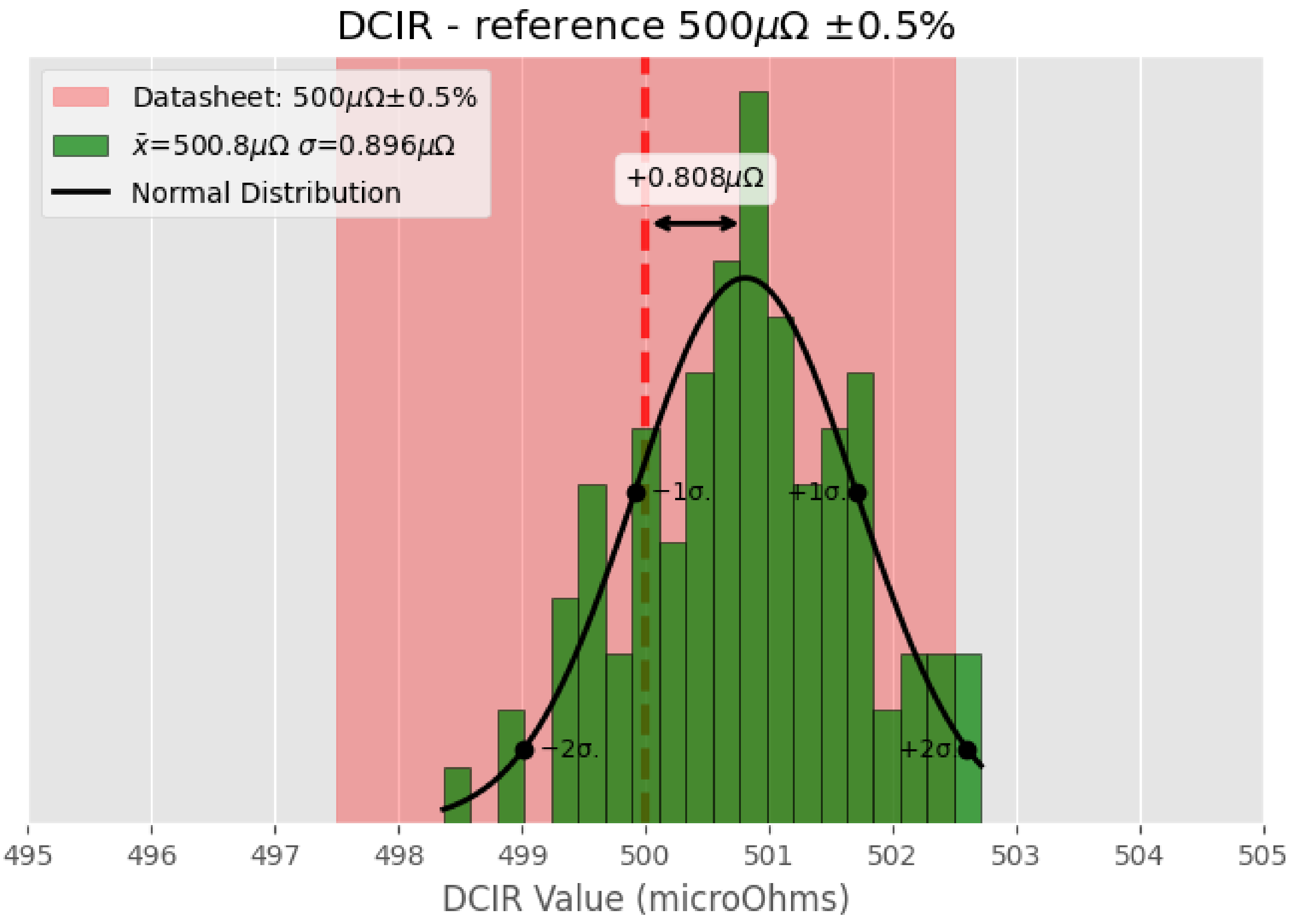
The impact of test configuration

- The violin plots show Dukosi's lab result of on-cell DCIR measurement for a large LFP cell
  - DCIR vs Depth of Discharge at 20˚C
  - Four sweeps, made on different days, show excellent repeatability and precision
- The 'KS' plots were made using our cell cycler – why the difference?
- The additional 70μΩ is fully accounted for by the cycler sense points being ~25mm away from the DK sense point
  - 2 x 25mm long, 20mm wide by 1mm thick aluminum plates



The test configuration is critical!

DCIR accuracy and precision



It's challenging measuring what the true DCIR of a cell is

- Cell charge transfer time constants of seconds can mean a fast measurement (ours) will give a smaller DCIR value than a slow measurement (lead acid legacy DCIR methods)
- A fast measurement is more linear

Measuring a known resistance is a useful test

- Plot shows the result of measuring a 500µΩ calibrated shunt resistor using 200mA stimulus for 1 second.
- After correction for the measured balance resistor value, the residual error and standard deviation are both less than 0.2%.
- In practice, the balance resistor tolerance determines the accuracy – not the AFE. Much of the (small) AFE error cancels out

State of Available Power

- SoAP or SOP estimation is an essential part of automotive BMS role
  - Necessary to find the ultimate limit on acceleration, regenerative braking and fast charging
  - The maximum continuous power that can be delivered or accepted over a predetermined time interval (pulse, 10s, until fully charged/discharged etc)
- There are a lot of methods for estimating SoAP – and it is dependent on many variables, including terminal voltage, SOC, cell temperature, ambient temperature, thermal management, whether charge or discharge, the immediate cell history, long term history and more
- But at the heart of all SoAP estimation methods, there is a **cell model**, and likely a **thermal model**. Both have the cell series resistance R_0 as a critical parameter.

SoAP goals:

Terminal voltage: keep between V_{min} and V_{max}

$$V_{terminal} = OCV \pm (I \cdot R_0 + \mathrm{V_{pol}})$$

Cell temperature: stay below T_{max}

$$\Delta T = \frac{(\mathrm{I}^2 \cdot \mathrm{R_0} \cdot \Delta \mathrm{t})}{(\mathrm{m} \cdot \mathrm{C_p})} - cooling\ effects$$

- R_0 increases at low temperatures, reducing SoAP
- R_0 increases with cell ageing, reducing SoAP
- R_0 can vary with SOC, typically at high SOC

And always – obey the cell manufacturers datasheet

Is DCIR needed for SoAP?

Some measure of the resistance R_0 is needed…

Measuring DCIR is nothing new – BMS may use current waveform 'structure' to estimate it.

- Large amplitude switch on/off transitions
- Powertrain noise
- Other (random or applied) stimuli

A simple method – demands tight synchronization of *i* and *v samples*

$$\underbrace{v_k - v_{k-1}}_{y} = R_0 \underbrace{i_{k-1} - i_k}_{x},$$

$$\underbrace{-\left(\hat{v}_k - \mathrm{OCV}(\hat{z}_k) - M\hat{h}_k + \sum_i \hat{v}_{c_i,k}\right)}_{y} = R_0 \underbrace{i_k^{\text{meas}}}_{x},$$

A more complex Kalman Filter (SPKF) method [#1]

These 'online' methods work well when there is plenty of structure in the current waveform

But - this assumption breaks down on occasion

- When DC charging,
- When the vehicle is parked
- When the system is **quiet and settled**, i.e. the best time to make a good measurement

#1 G. L. Plett and G. McVeigh, "Sensitivity of Lithium-Ion Battery SOH Estimates to Sensor Measurement Error and Latency," 2024 International Conference on Electrical, Computer and Energy Technologies (ICECET, Sydney, Australia, 2024

Other uses of DCIR in the field – State of Health

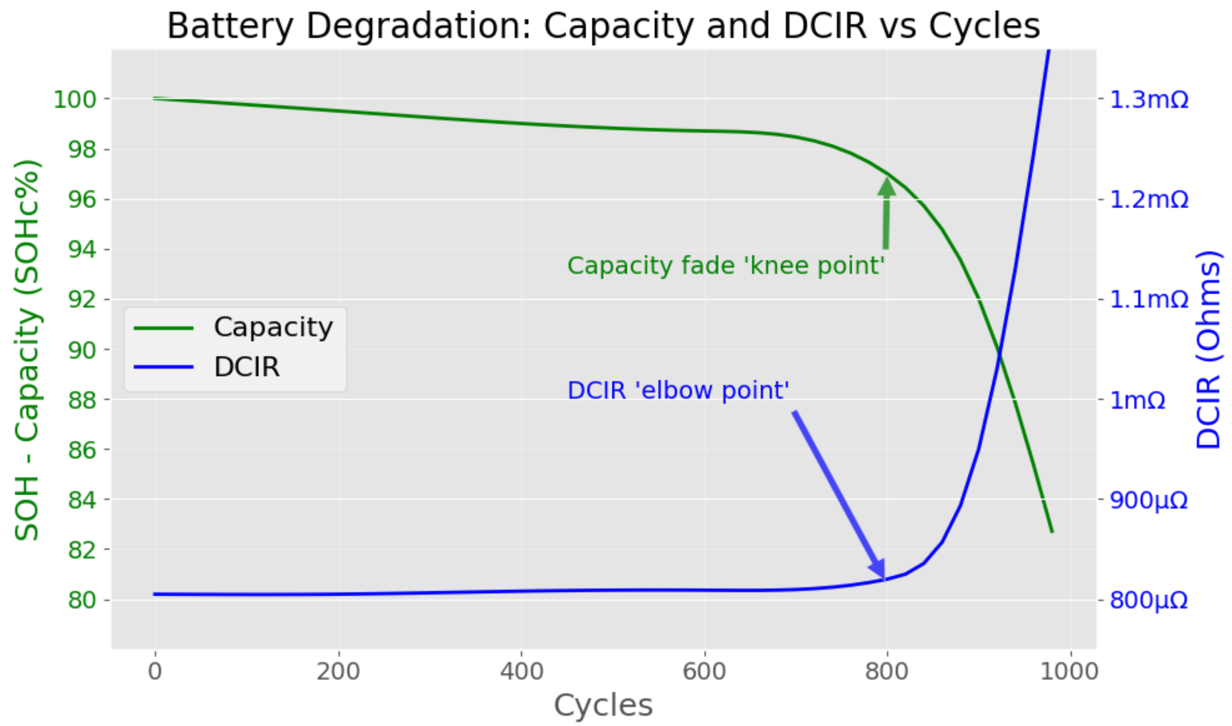
If measuring internal resistance to microOhm accuracy is not that critical for SoAP, what else is is useful for?

- It's a good proxy for State of Health

Maybe you don't want to use it to estimate the SOH directly, but it will indicate when you've hit the 'knee'. Or just call it SoHR.

Our DCIR takes <1s to measure

– Add SOH-resistance tracking to your BMS



$$SOH_R(t) = \frac{R_{EOL} - R(t)}{R_{EOL} - R_{init}} \times 100\%$$

DCIR for temperature indication

There's a great relationship with temperature – so can we use it for temperature indication?

- Indication – NOT measurement

We know that R0 also increases with age, so not a stable measurement.

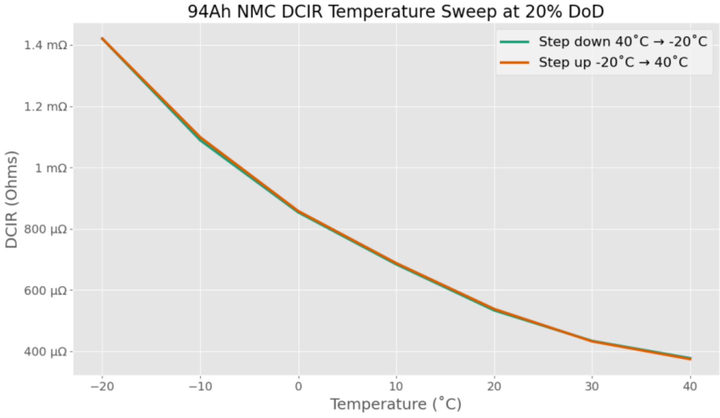
Worse, it will under-estimate the temperature as the cell ages!

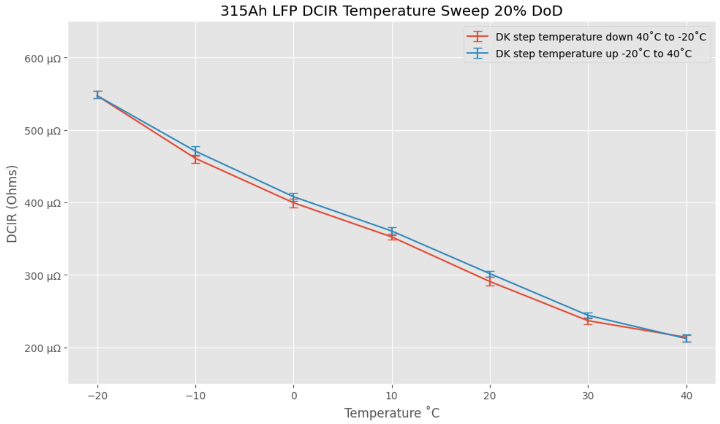
Solution - calibrate when you know the temperature is uniform and stable

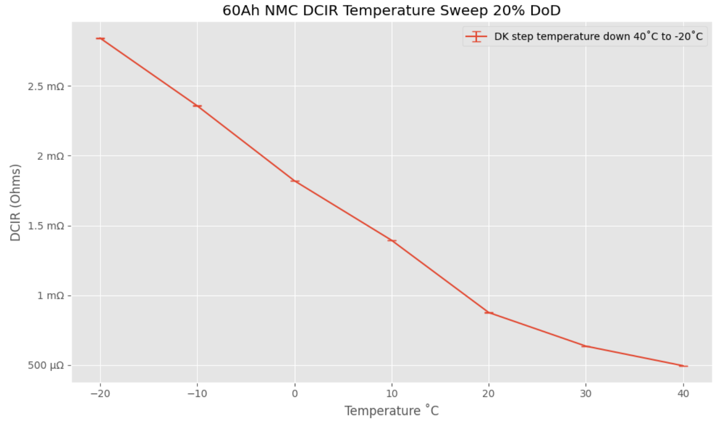
Better still, use Dukosi total pack per-cell temperature measurement, and DCIR as a cell core temperature indication

Our DCIR takes <1s to measure, with no additional BoM

– so add cell core temperature indication to your BMS

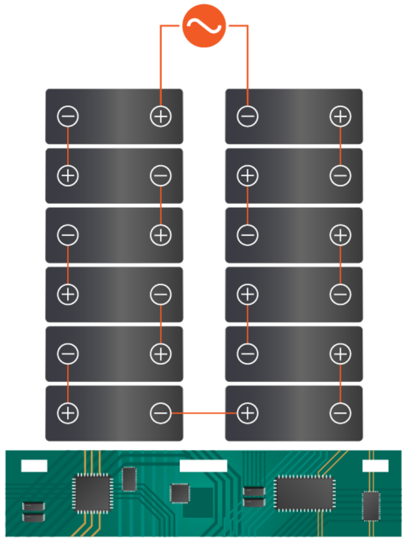


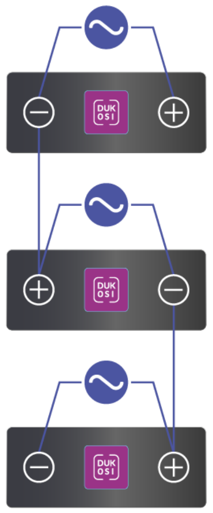




Electrochemical Impedance Spectroscopy - EIS

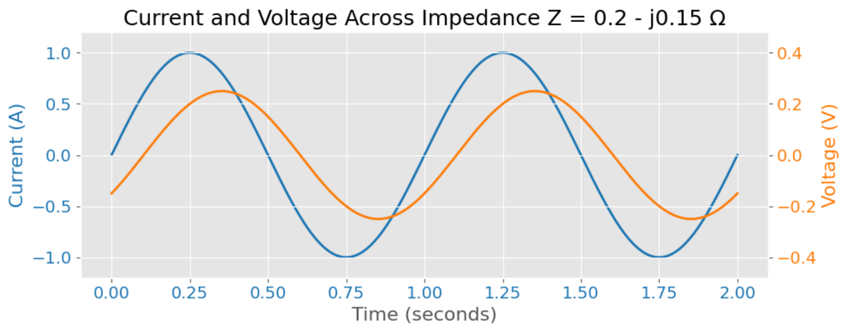
- Measuring Impedance swept across frequency
  - Real resistance
  - Imaginary reactance
  - Magnitude, phase, frequency
- There is useful information in frequency range 10mHz to 10kHz
- Standard lab measurement equipment costs $10k+!



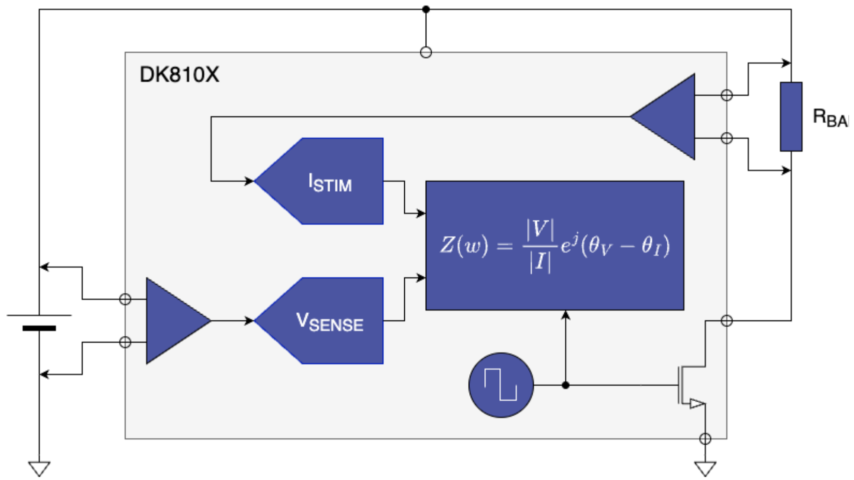


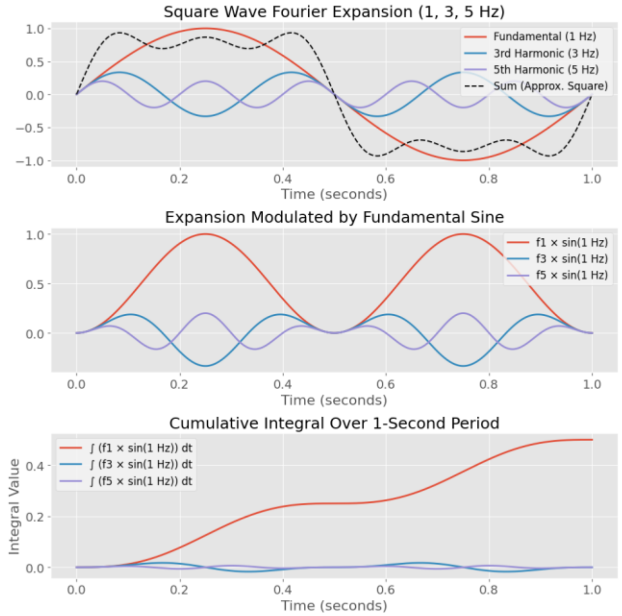
There is a lot of talk about EIS in the industry, but no killer use case. Possible uses include :-

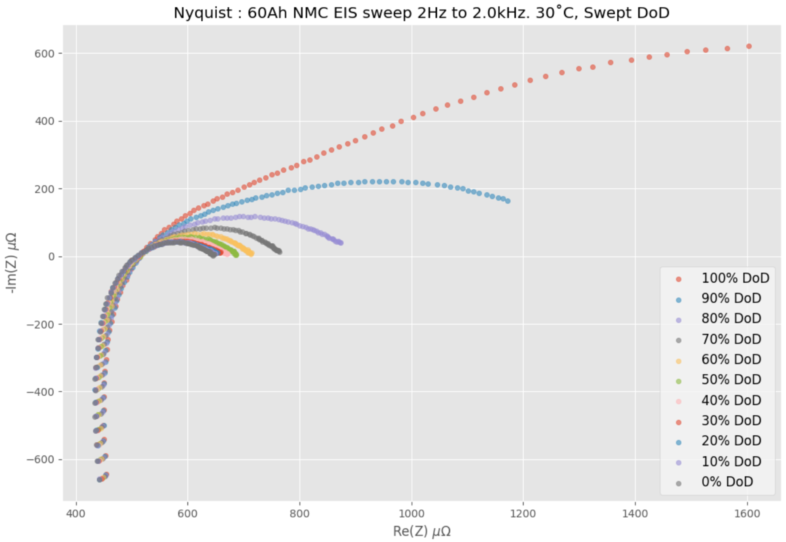
- Temperature indication (fast charging) – same issues as DCIR
- Diagnostics and prognostics
- More data is good!

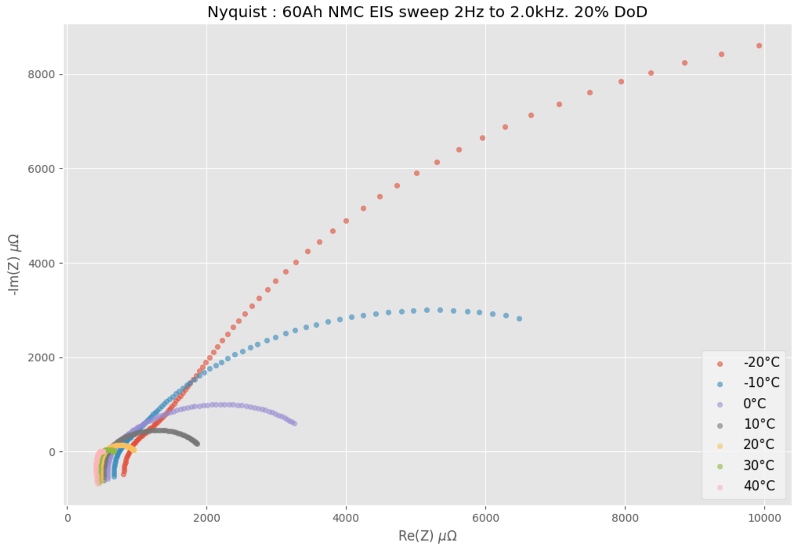


EIS – performed on cell

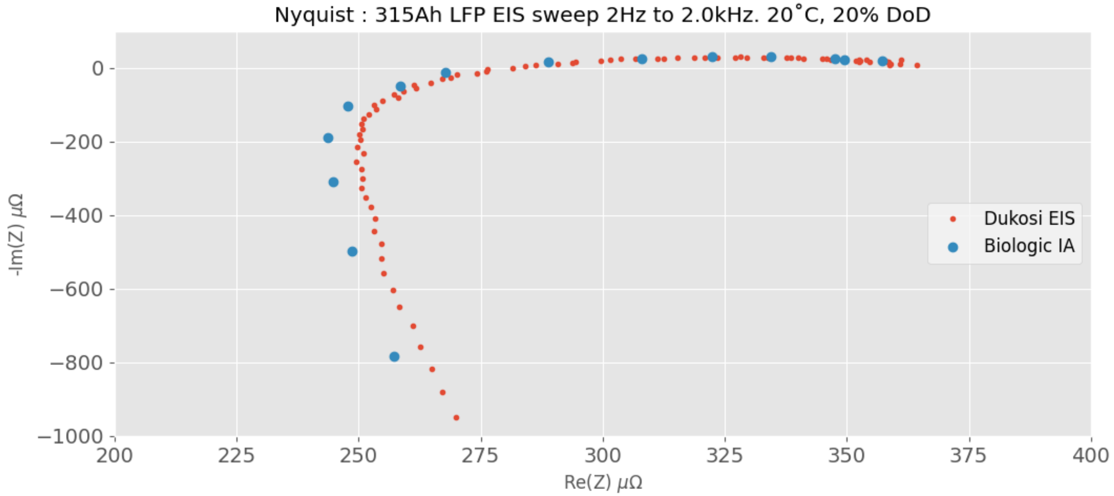








- Signal processing recovers the very small response to the small stimulus
- Integration over integer periods rejects response to square wave harmonics
- Response dominated by cell inductance at high frequency
- Useful information at low frequency?



Our EIS takes ~20sec to measure, with a small additional BoM – so add EIS to your BMS

How will they be used?

Use cases are still being worked out

- Challenges with interpretation, repeatability
- A solution in search of a problem?
- Lab → Field trials

Measure when?

- During operation (fast charging/optimal performance)
- During downtime (repeatable State of Health indication)

The best use case may simply be to just generate and bank the data now, for trend analysis later (AI / ML /Data Mining)

- Anomalies
- In-field use case insights
- Design improvement opportunities
- Mass recall avoidance
- New market opportunities

Conclusions

- By applying certain stimuli, and measuring the response, we can determine resistance and impedance values
- These values are only indicators of cell behavior and state. They are not direct measurement of cell properties.
- More informative of lifetime cell/pack state changes.
- We can do DCIR and EIS in the field, in operation – you don't need expensive lab kit to do this (but it has its place).
- Carefully consider how the measurement is being conducted: parasitics can make the best measurement meaningless
- Until a killer use case becomes apparent, perhaps just storing the data for future interpretation will be enough?

We'd love to connect and hear your thoughts on how to leverage DCIR/EIS in a production application.

Thank you!