

Extracting information from time series data from rechargeable batteries



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1. Introduction

While one can think of rechargeable batteries as storing charge or energy, they do not behave like capacitors.

Capacitor: $Q = CV$;

Battery: $Q \neq f(V)$; Charge Q is not even a function of voltage! Rather, $Q = f[V(t)]$, a *functional* of voltage against time t .

Knowing the energy stored in a battery depends on knowing the *time history* of voltage and current. Typically there are periods of rapid charge-discharge activity followed by long periods of inactivity:

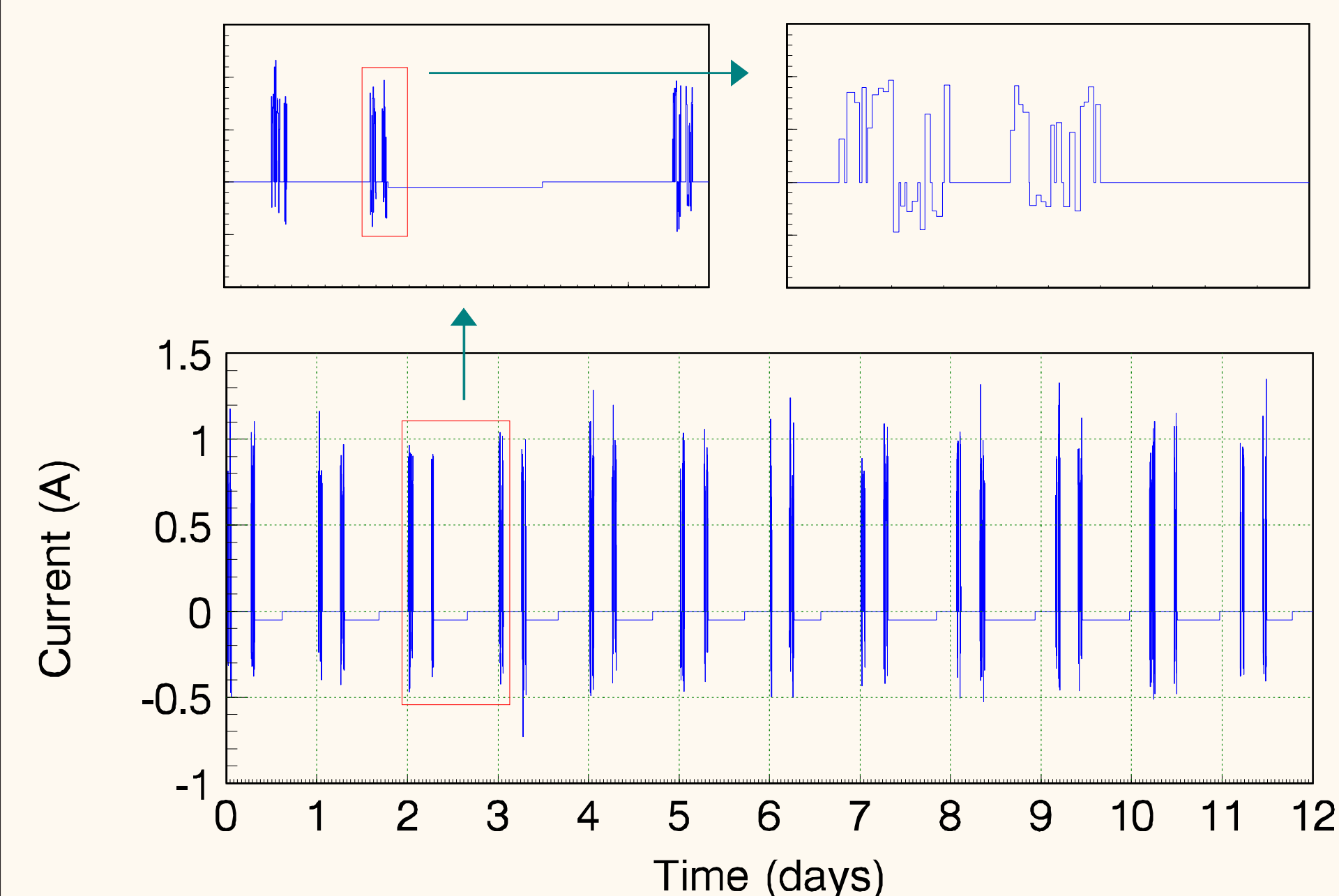


Figure 1: A stereotyped charge-discharge series for a battery cell in an electric vehicle.

Can we use time-series analysis to infer the state of a battery?

2. Theory

Rechargeable batteries are often modelled as *fractional capacitors* or *constant phase elements* (CPEs):

$$I = C_F \frac{d^\alpha V}{dt^\alpha}, \quad (1)$$

where α denotes the order of the fractional derivative, $0 < \alpha < 1$. When $\alpha \rightarrow 1$ the element is a capacitor; when $\alpha \rightarrow 0$ it is a resistor. For healthy modern batteries, $\alpha > 0.7$

For a sine-wave current input at angular frequency ω :

$$I(t) = I_0 \sin(\omega t); \quad (2)$$

$$V(t) = V_c + V_0 \sin(\omega t - \pi\alpha/2), \quad (3)$$

that is, the voltage trails the current by a constant phase dependent on order α .

The energy ‘in’ and ‘out’ of the battery can be evaluated during a cycle:

$$E_{\text{in}} = \int_+ I(t)V(t)dt; \quad (4)$$

$$E_{\text{out}} = - \int_- I(t)V(t)dt; \quad (5)$$

where the two integrals are performed over the part of a period where current is positive and negative respectively.

The cycle efficiency can then be derived as:

$$\epsilon = \frac{E_{\text{out}}}{E_{\text{in}}} \approx 1 - \left(\frac{\pi V_0}{2V_c} \right) \cos(\pi\alpha/2). \quad (6)$$

Measurement of the phase angle $\pi\alpha/2$ is thus likely to give us an indication of energy efficiency for the battery.

3. Methods

We have cycled a Lithium-Nickel-Cobalt (NCR) cell through 760 rapid charge-discharge cycles (~ 3000 s period). This took several weeks. The cycling includes six sets of 30 cycles performed in the same standard manner.

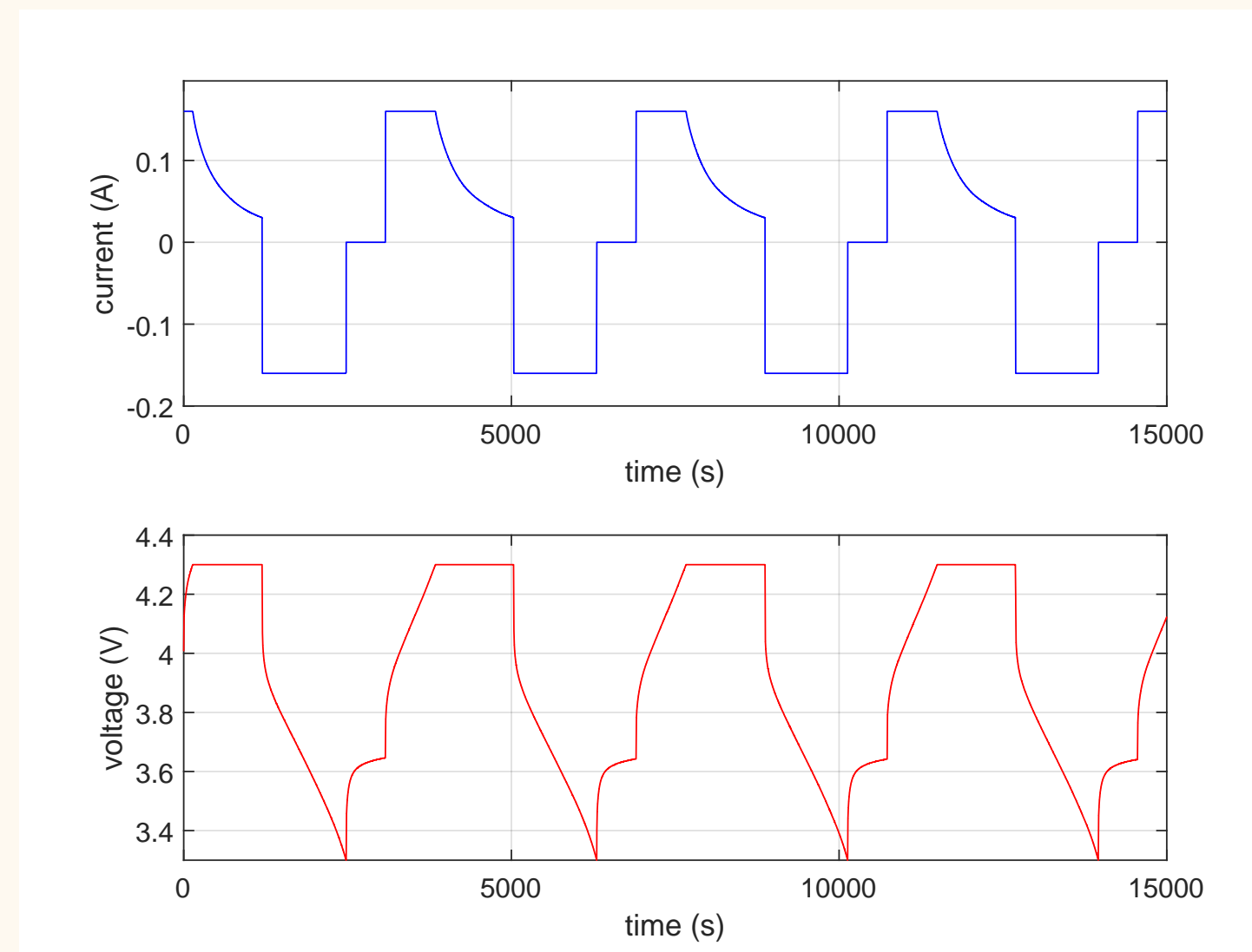


Figure 2: A plot of ‘standard’ cycles applied in the experiment; voltage is moved between defined limits.

For these sets, we have found E_{in} , E_{out} and ϵ to monitor degradation of capacity and efficiency. We also analyze the phase difference between $V(t)$ and $I(t)$ through Hilbert transforms using matlab. That is, instantaneous phase of $I(t)$ is found from

$$\text{phaseI} = \text{atan2}(\text{imag}(\text{hilbert}(I)), \text{real}(\text{hilbert}(I))) \quad (7)$$

and similarly for $V(t)$. The distribution of phase difference is then constructed and compared to energy efficiency to verify Eq. (6).

4. Results

Energy capacity and efficiency is shown in Fig. 3. Note $E_{\text{out}} < E_{\text{in}}$.

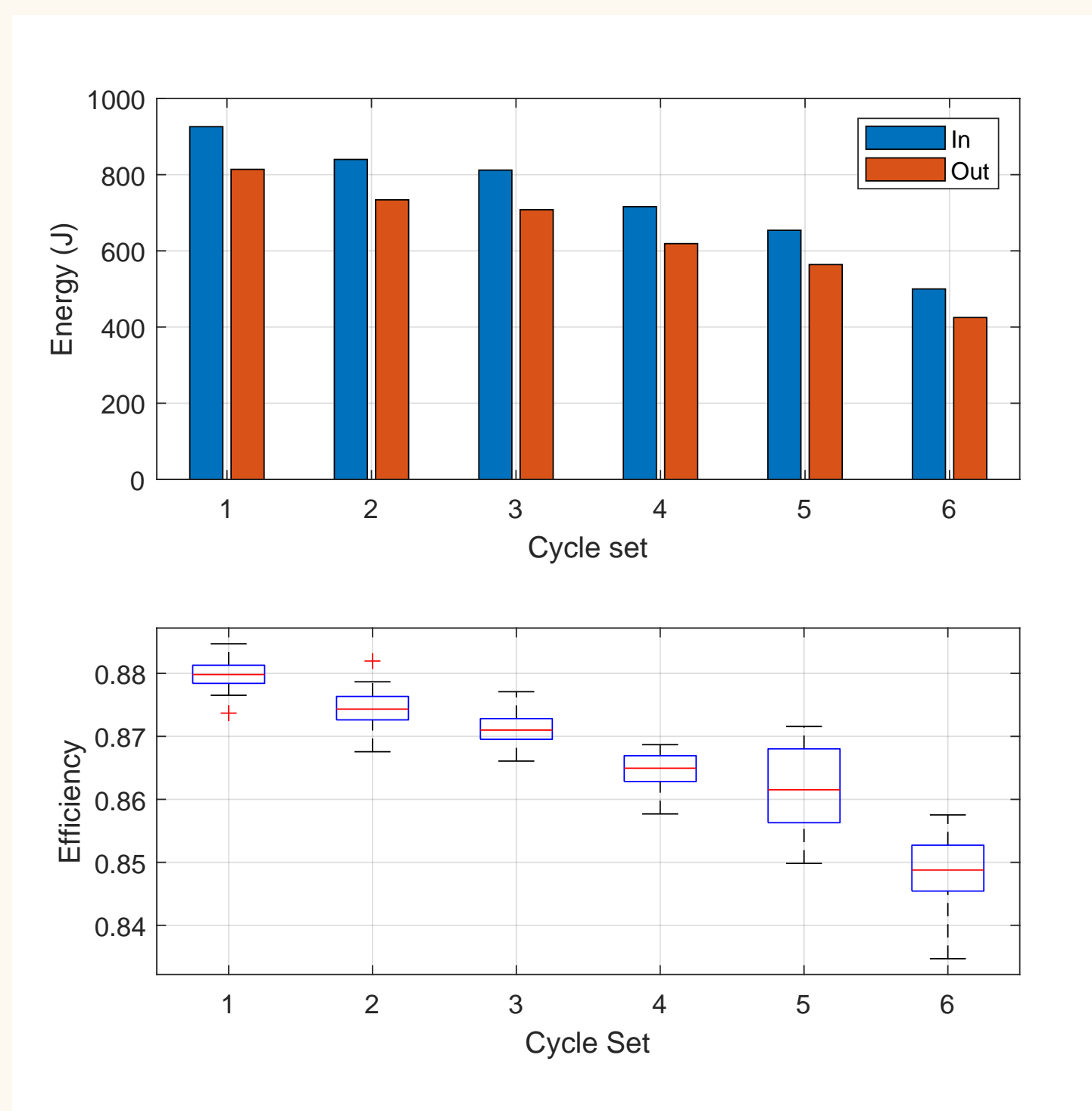


Figure 3: Top: The average energy in and out during a cycle, averaged over the final 27 cycles of each of six sets of 30 cycles as the battery ages. Bottom: The distribution of energy efficiency in each set.

As the battery ages, (i) the energy capacity on charge E_{in} and energy capacity on discharge E_{out} both reduce, and (ii) the efficiency also reduces.

Results (cont)

The distribution of phase difference between V and I is shown in Fig. 4.

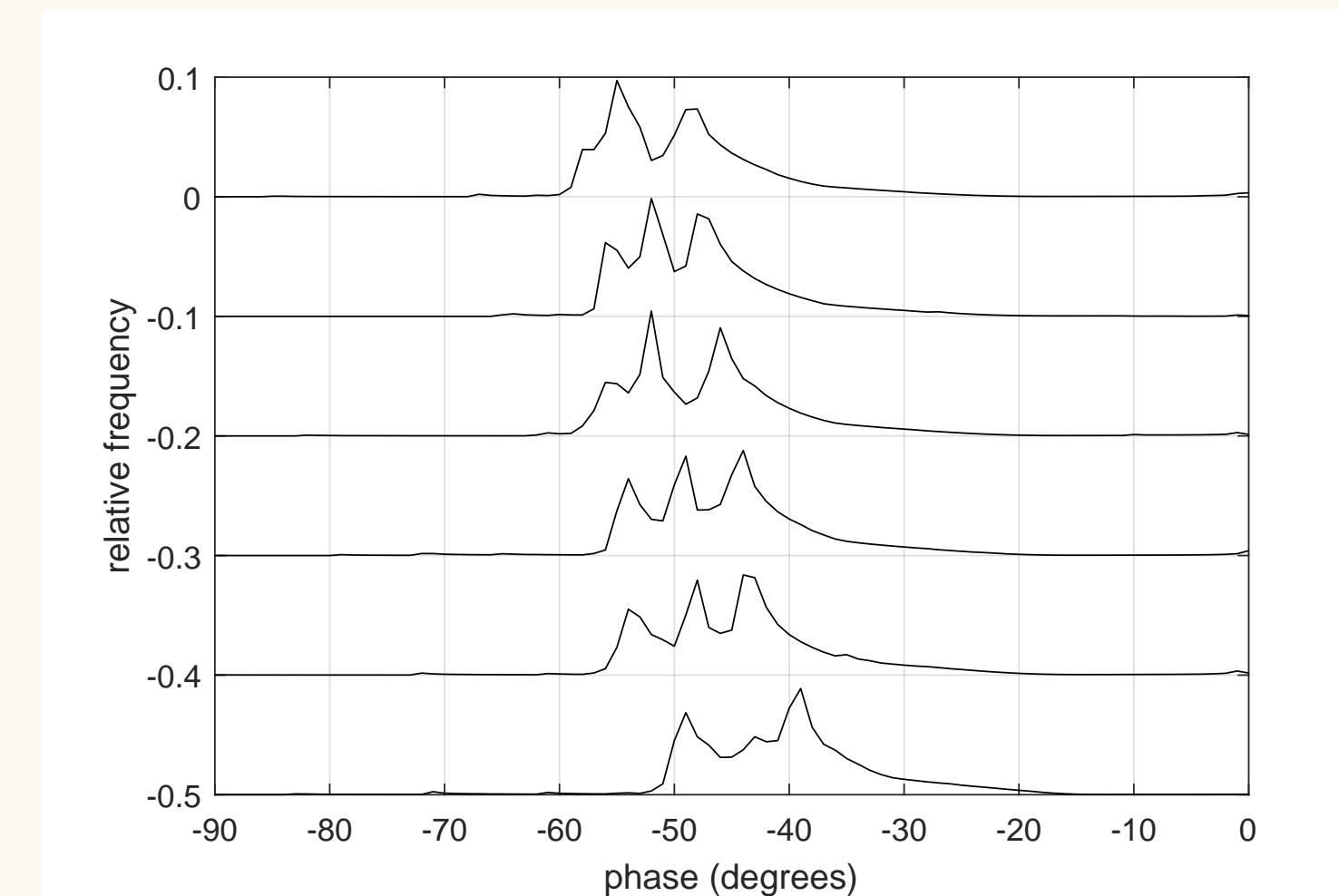


Figure 4: The distribution of phase difference between V and I as the battery ages. Each successive cycle set is displaced downwards.

The ageing battery gives a shift in phase difference towards zero (i.e. V and I become more in phase, more like a resistor than a capacitor). The mean phase angle moves closer to zero as the battery ages and ϵ decreases, in accordance with Eq. (6).

| Set | Cum. cycs | ϵ (%) | phase (rad) |
|-----|-----------|----------------|-------------|
| 1 | 310 | 87.9(5) | -0.837 |
| 2 | 400 | 87.5(6) | -0.816 |
| 3 | 430 | 87.2(5) | -0.794 |
| 4 | 520 | 86.5(6) | -0.771 |
| 5 | 580 | 86.2(13) | -0.754 |
| 6 | 760 | 84.8(13) | -0.681 |

Table 1: Mean phase difference and efficiency for each set of standard cycles

5. Conclusions

1. Time series analysis can be applied to voltage and current series for batteries
2. Phase differences extracted with Hilbert transforms and related to α
3. Changes in phase difference relate to degradation of energy efficiency

However, the relation between phase difference and aging is only clear-cut with the standard cycle shapes of Fig. 2. Using real battery cycling data, more like Fig. 1 is more challenging. **Perhaps MODA can help.**

6. References

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- [2] Vance Farrow. *Characterisation of rechargeable batteries: addressing fractional ultralow-frequency devices*. Master of Engineering, University of Waikato, Hamilton, New Zealand, September 2020.
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7. Acknowledgements

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