October 17, 2024

END OF LIFE

This installation consists of a ceiling projection in a dark room from a cardboard projector made using a convex lens and a smartphone. The video is played in a continuous loop with sound. Audience members are invited to lie down on the floor to view the projection.

Depicted in the video are the impedance 'Nyquist' curves of three lithium-ion batteries, obtained at regular intervals during their lifetimes and colored by their power fade, where blue represents a fresh cell and red represents a severely degraded cell. In the video, each curve is accompanied with a sound wave generated using its frequency components. The pitch is made to shift lower as the power fade becomes more severe. Full technical details of the process can be found in the appendix.

Battery degradation is usually an invisible and silent process which is made explicitly visual and audible here. Viewing the end of a battery's useful life on the ceiling of a dark room encourages the audience to reflect on the death and afterlife of a battery cell.

APPENDIX

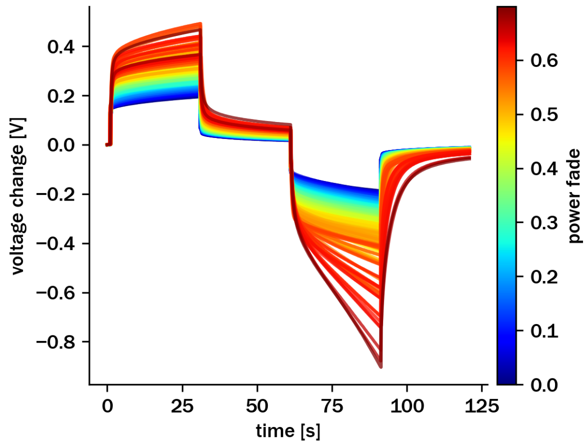


Figure 1: Voltage responses color-coded by power fade

In Fig. 1 are plotted the change in voltage of three Panasonic NCR18650PF lithium-ion battery cells, obtained in response to a bipolar charge-discharge current pulse applied at various states of charge at varying degradation levels, from 100% state of health to end-of-life (approximately 80%), sampled at 10 Hz. In total, there are 373 unique curves.

We have colored the curves by the cell's power fade, calculated using the equation

$$\text{power fade} = \frac{\int v_n(t)dt}{\int v_0(t)dt} \tag{1}$$

where $v_n(t)$ is the voltage response over time t of the n^{th} curve. This is not strictly a measure of power, but remains valid because the amount of charge passed during the current pulse is constant. The voltage-time product is therefore proportional to the cell's impedance.

To obtain the cell's frequency-varying complex impedance we:

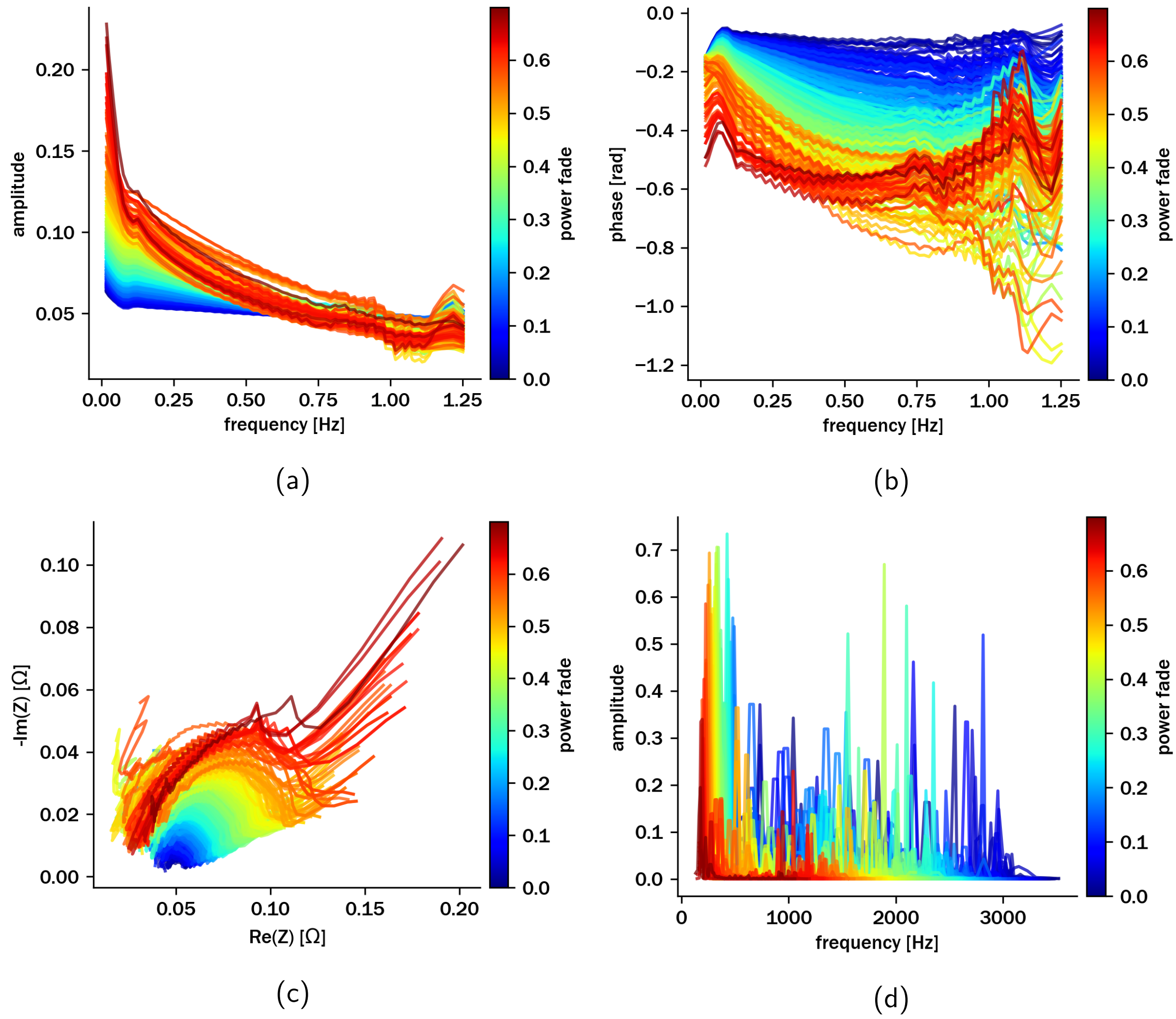
1. Obtain harmonic components of the current voltage by removing the average value
2. Apply Hamming window to reduce spectral leakage
3. Apply 1st-order low-pass Butterworth filter of width 1 Hz to avoid aliasing and attenuate high frequencies.
4. Take the Fast Fourier transform to obtain the complex impedance
5. Smooth the real and imaginary parts of the impedance to remove additional fluctuations

We can express the complex impedance as the ratio of the voltage and current phasors,

$$Z(s) = \frac{V(s)}{I(s)} \tag{2}$$

where we define the complex frequency as

$$s = j2\pi f \tag{3}$$



(a) (b) (c) (d)

Figure 2: Frequency-varying impedance components, showing (a) magnitude, (b) phase, (c) Nyquist plot, and (d) magnitude spectra of the output sound waves

and f is the frequency [Hz]. In Fig. 2a-b are plotted the amplitude $|Z|$ and phase $\angle Z$ of the impedance against frequency, with the Nyquist plot in Fig. 2c (imaginary vs real). The harmonic spectra of the final sound wave is shown in Fig. 2d.

As can be seen, the maximum observable frequency of the voltage responses is 1.25 Hz, which is far outside the audible range for humans. We therefore rescale the frequency from 440 to 3520 Hz, corresponding to 3 octaves of the note 'A', and shift it by a factor of $(1-\text{power fade})$ to produce distinct fundamentals. To create a coherent tone, it is desirable for the harmonic spectra to have discrete spikes and a strong single peak. Thus we take the gradient of the amplitude with respect to the phase and shape its envelope using the squared phase,

$$\text{sound amplitude spectra} \propto (\angle Z)^2 \frac{d|Z|}{d\angle Z} \tag{4}$$

This then normalized such that the spectral energy of each sound wave is identical.