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To cite this article: Burak Ulgut 2022 *J. Electrochem. Soc.* **169** 110510

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Methods-Employing Multisine Electrochemical Impedance Spectroscopy for Batteries In Galvanostatic Mode

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Electrochemical Impedance Spectroscopy(EIS) is a standard technique for analyzing batteries in detail. It is immensely powerful as it can yield separate information about various components and interfaces inside while the battery is intact and operational. One drawback of the EIS measurement is the relatively large time it requires. One potential way to improve this issue is the use of the multisine, a technique akin to Fourier Transform techniques in various spectroscopies. In this manuscript, it will be shown that through judicious preparation of excitation signal, proper parameter choice and tweaking, the measurement can be sped up. Under the best conditions, the measurement can be completed within the shortest possible time that transforms to the lowest desired frequency.

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Manuscript submitted August 8, 2022; revised manuscript received September 13, 2022. Published November 7, 2022.

Following batteries in real-time for various changes is an issue that is and will continue to be at the forefront of academic and industrial research. As more and more devices are getting electrified, performance and safety concerns demands that various properties of batteries are reported in real time to the battery management systems particularly in the automotive sector.¹ Important data such as the battery voltage and the temperature are already reported through standard sensors that are employed.² This data is used in various algorithms mostly for state-of-charge(SoC) and state-of-health(SoH) estimations and as input for adaptive charging algorithms.³ For ultimate safety and performance, information beyond simple temperature and potential would be necessary. Detailed information regarding the electrodes, electrolyte and the separator are all important for various aspects especially if they can be obtained separately from each other. As the quality and the accuracy of the information increases, so would the performance and the safety of the battery pack.

Electrochemical Impedance Spectroscopy(EIS) has turned into a standard battery analysis technique that not only can provide parameters for the above mentioned components independently, but also the data that leads to accurate calculations of battery behavior under various conditions,^{4,5} even when used as asymmetric unmanaged hybrids.⁶ Shortly, EIS is a measurement that investigates the system at a wide range of frequencies(typically between MHz to mHz levels).⁷ The wide range in frequencies effectively resolve the properties of the various components in the battery that respond in different time-scales. This separation in timescale allows isolating the properties of the components in a non-destructive, operando fashion.⁸ Typical EIS measurements are made using specialized equipment and the best measurement can only be obtained with properly designed test conditions and parameters. This requires some prior knowledge of the system under test, trained operators and some trial-and-error. In this manuscript, it will be shown that, for a given system, with optimized signals, parameters and conditions, reproducible measurements can be performed with a prescribed signal without much tweaking.

The time required for EIS measurements is highly dependent on the desired frequencies and quality of data that is desired. Any desired frequency x will require a time of at least $1/x$ (e.g. 100 mHz will require at least 10 s). In practice, for every frequency, most measurements require more than a single period for desired signal to noise levels and initial transients have to be waited out⁹ for each frequency. The proper period required for the initial transient to settle to the required level has to be determined for the specific system in question. Without monitoring the response in the frequency domain, one cannot determine whether the initial transient has decayed below

noise level. For any sensor-type implementation, any improvement in the time required is a step in the right direction.

One way to improve the time necessary for the EIS measurement is the so-called "Fourier Transform(FT)" approach that is common in other chemical analysis methods. In FT-IR, broadband infrared light is sent through the sample at once with an interferometer analyzing the transmittance. Given the alternative is going through each wavelength one-by-one in dispersive instrument, this method is a much faster approach. In FT-NMR, the excitation again is broadband, with emission measured afterwards. In EIS, this corresponds to exciting with all the desired frequencies at the same time as lightly illustrated in Fig. 1. The major difference between the light based measurements and the impedance measurement is the way the excitation signal gets summed. Sending a broadband infrared light, or RF excitation does not adversely effect any samples. However, a large amplitude excitation(current or voltage) in EIS would lead to issues such as non-linearity.¹⁰

In principle, the multisine measurement only requires the time of a measurement of the lowest frequency signal only where the rest of the desired frequencies are added as multiples of the lowest frequency, on top of the lowest frequency signal. A small example of this is shown on Fig. 1 with three signals. By applying the signal shown in Fig. 1b, all three frequencies shown in Fig. 1a are applied at the same time. By transforming the applied and measured signals to the frequency domain, the impedance at all three frequencies can be measured at the same time. Within a single period of the lowest frequency, the rest of the frequencies can also be measured.

To the best of the author's knowledge, earliest attempts at using a multisine approach was from Smith and coworkers.¹¹⁻¹³ Various different signals were investigated in great detail for potentiostatic measurements of redox systems. The measurements were performed in the diffusive region of electrochemistry of various transition metal complexes. Results of these measurements were confirmed via comparisons with single-sine measurements. The work has been reviewed as part of a book as well.¹⁴ All the frequencies measured were excited with the same amplitudes throughout these studies.

Among the electrochemical instrument manufacturers, a number of implementations have been made over the years since the prospect of decreased measurement time is very appealing. To the best of the author's knowledge, the first commercial implementation was done in the 1990s by Princeton Applied Research and was employed in an attempt to speed up to measurement. This implementation was employed in a number of academic publications mostly in the fields of corrosion and coatings (e.g. Refs. 15 and 16). More recent implementations have all focused on optimizing different aspects¹⁷⁻²¹ with varying degrees of skepticism as to the utility of using a multisine approach.²² Almost all manufacturers of

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^aFor full disclosure, the author of the current paper worked on the implementation for Gamry Instruments Inc.. while employed there.

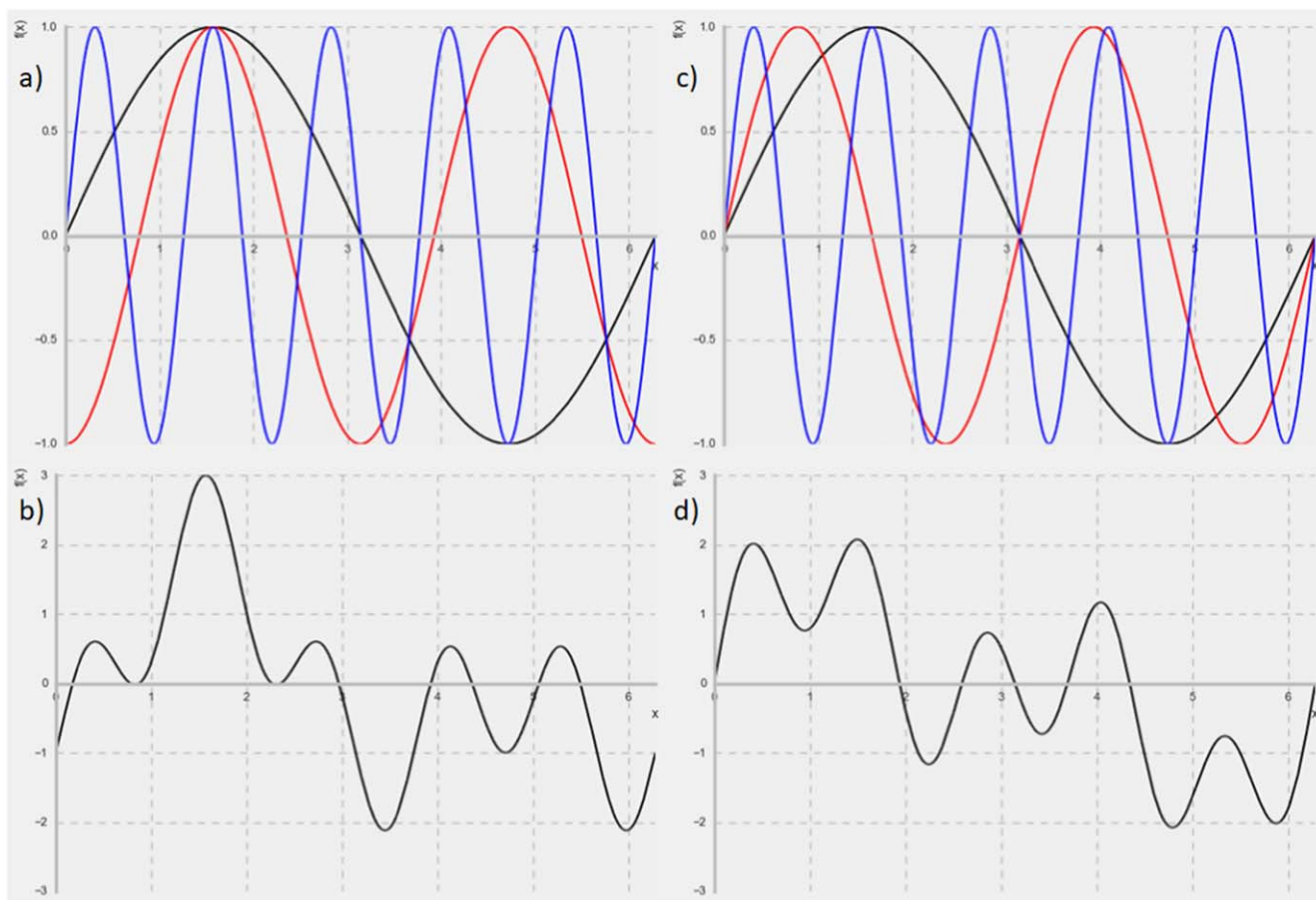


Figure 1. An illustration using three different frequencies, a fundamental (black), twice the fundamental (red) and five times the fundamental (blue), (a) Signals with all peaks aligned at $\pi/2$, (b) Sum of the signals in panel a), (c) Signals with phases shifted for lower peak value, (d) Sum of the signals in panel (c).

electrochemical instrumentation provide some form of a multisine measurement.

The first implementation to suggest using non-uniform amplitudes for the signal was published by Popkirov in 1993.²³ Frequencies that were harder to measure were excited with higher levels of excitation. This could be either due to the level of signal available and/or the noise level around that frequency. This implementation was shown to be more efficient, in that the signal-to-noise ratio measurements at the end of the measurement period were roughly similar for all frequencies.

Notable academic implementations of multisine measurements were made by the coatings group at NDSU,^{24,25} and later by the Hubin group in VUB²⁶ and Ref. 27. In the case of the Hubin group implementation, the measurement is admittedly not any faster than the single-sine version. However, since the measurements are made with multiple full periods at the lowest frequency, the data available in the frequency domain is rich with plenty of details including time progression of the sample, the noise levels and the non-linearities.

In some other implementations, a step function is applied as the excitation signal. This step function is then differentiated in order to achieve effectively a delta function which is broadband in the frequency domain.²⁸ In these cases, because the applied signal is divided into all the frequencies available, the signal is spread out to the entire frequency range. This effectively decreases the amplitude at each initial frequency. Ultimately, this method has been successfully used in certain cases (e.g. aniline oxidation,²⁹ however, for batteries and the required low amplitudes for linearity, this option is not available and therefore will not be investigated any further.

With all the required attention to detail, this measurement does not lend itself directly to real-time on-board sensing. However, there

are academic³⁰ and industrial³¹ implementations along with startup companies that implement some of these approaches.³²

In this manuscript, we will talk about a method of measuring the impedance spectrum of a battery that has the highest possible quality in the shortest time possible using a multisine signal. Certainly, there are trade-offs regarding speed and data quality, but there are ways to improve the data quality that do not involve measuring longer. These will be the main topics of discussion of the current manuscript. These methods will be presented through simulations and measurements.

Signal Design

Frequency selection.—Frequencies in a typical EIS experiment are selected in a log-spaced fashion for uniformity across the timescales that the electrochemical phenomena occur. On the flip side, all the frequencies used in a multisine signal have to be an integer multiple of a fundamental frequency. Assuming the measurement will be done as fast as possible (i.e. 1 period of the lowest frequency desired), there are only 10 linearly-spaced frequencies available in the lowest decade (i.e. between the fundamental and the 10th harmonic). Therefore the log-spacing has to be relaxed for the lowest decade for anything above 5 frequencies for decade^b. This is sub-optimal, however, in order to achieve the quickest measurement, this is the only option.

In the frequency selection process, avoiding multiples of other frequencies is a method that is sometimes followed. This is an

^bIt is possible to achieve properly log spaced frequencies if the measurement time is some multiple of the period of the lowest frequency as done in Ref. 27. Since the main focus of the current manuscript is the quickest measurement, this option will not be investigated further.

attempt to make sure that any given frequency is not complicated by the higher harmonics of other lower frequencies as shown in Figure 2.²⁷ However, in the case of batteries and using the excitation levels that we use, higher harmonics are not observed. Therefore, this concern was not treated in this manuscript.

Phase selection.—In order to make sure that the battery response stays in the linear region, the overall amplitude of the excitation must be kept as low as possible. In order to pack as much signal as possible with the lowest overall amplitude, one has to select the phases carefully. This is partly illustrated in Fig. 1 where simply shifting the signals around the overall amplitude can be reduced by roughly 1/3 while summing up three sine waves. This issue has been investigated in great detail by Schröder³³ within the framework of communications. The so-called *Schröder signal* is a very effective way of keeping the amplitude small while adding up sine waves. While the Schröder Signal cannot be beaten when all the harmonics of a given signal are excited, in the sparsely populated frequency domain signal necessary for EIS, the gradient descent algorithm developed by Green et al. have been shown to work better for uniform amplitudes in signals that are sparsely populated in the frequency domain.^{21,24,25}

In the current manuscript, the Schröder phases will be employed for consistency and reproducibility, following Equation 1

$$\phi_n = \phi_1 - 2\pi \sum_{l=1}^{n-1} (n-l) \cdot P_l \quad [1]$$

In this equation ϕ_n is the phase for the n^{th} component, n is the total number of frequencies that will be used, and P_l are the amplitudes for the l^{th} frequency component. Following Schröder, ϕ_1 will be selected as $\pi/2$.

Signal length and sampling.—The number and range of frequencies desired will determine the length and sampling-time of the signal to be used. The frequencies selected will be between two frequencies, f_{min} and f_{max} . The length of the shortest signal to be measured will be $1/f_{\text{min}}$ long (i.e. if $f_{\text{min}} = 0.1$ Hz the shortest signal to be measured will be 10 sec). The sampling frequency for the signal measured has to be at least twice the f_{max} (i.e. if $f_{\text{max}} = 1$ kHz, sampling has to be at least 2 kHz). The frequency of sampling and the data length define the number of points that will be required to be stored. The wider the range of frequencies to be investigated, the larger the amount of data to be stored.

One issue that also has to be mentioned is the fact that a clean sine cannot be generated with twice the highest frequency. The best approach would be to generate the signal with as high a frequency as possible. On the recording side however, as mentioned above, the

sampling frequency only has to be twice the highest frequency of interest. Therefore, where possible, the signal generation frequency and the sampling frequency should be decoupled from each other for the best performance. This way, the recorded number of points can be kept at a minimum while still applying a clean sine wave.

In the current work, since equipment available does not allow the separation of signal generation and the sampling timescales, 4 times the highest frequency measured will be employed.

Amplitude selection.—The amplitudes for the frequencies desired will be designed based on the signal to background ratio in the various regions of the frequency domain. Inspired by the work of Refs. 21 and, 23 the amplitudes for frequencies are adjusted for a better overall signal to noise. In the process, the lower frequency amplitudes are increased while the higher frequency amplitudes are decreased. The rationale behind this approach is that the higher frequency signals are averaged for many more cycles than the lower frequency ones, ultimately going down to a single cycle at the lowest frequency. We will be showing that this approach increases the signal-to-noise ratio for the lower frequency measurements at the expense of an acceptable decrease for the higher frequency ones.

In this work, two separate approaches will be employed and compared. The first approach (i.e. Uniform Amplitude) is where the signal amplitude is constant across all the frequencies of interest. In the second approach (i.e. variable Amplitude), the lower frequencies of interest are excited with a higher amplitude compared to the higher frequencies. For the battery that is used, an amplitude that depends on the 0.4th power of the frequency is employed based on trial-and-error. In either case, the final adjustment of the signal is done in the time domain to an absolute maximum amplitude to ensure linearity. The code that performs this operation can be found in the Appendix A.1. The time domain and the frequency domain representations of the signal can be found in Fig. 3

Evaluation of data quality.—In order to evaluate the quality of the EIS data collected for this manuscript, compatibility with the Kramers-Kronig relations is employed. In short, compatibility with the Kramers-Kronig relations confirm that the measured EIS data is linear, stationary and causal.⁷ Even though directly implementing a Kramers-Kronig transform is not practical, various ways of checking compatibility have been developed. The approach this manuscript will be using is implemented through fitting the data to multiple Voigt elements and looking for residuals. Specifically for the multisine measurements, compatibility with the Kramers-Kronig relations is not a confirmation of stationarity.¹⁰ Even when the system is provably non-stationary, Kramers-Kronig compatibility check via the fitting method shows no residuals. Therefore, any residuals to the fitting algorithm that checks the compatibility show the errors in the measurement either due to noise or other distortions.

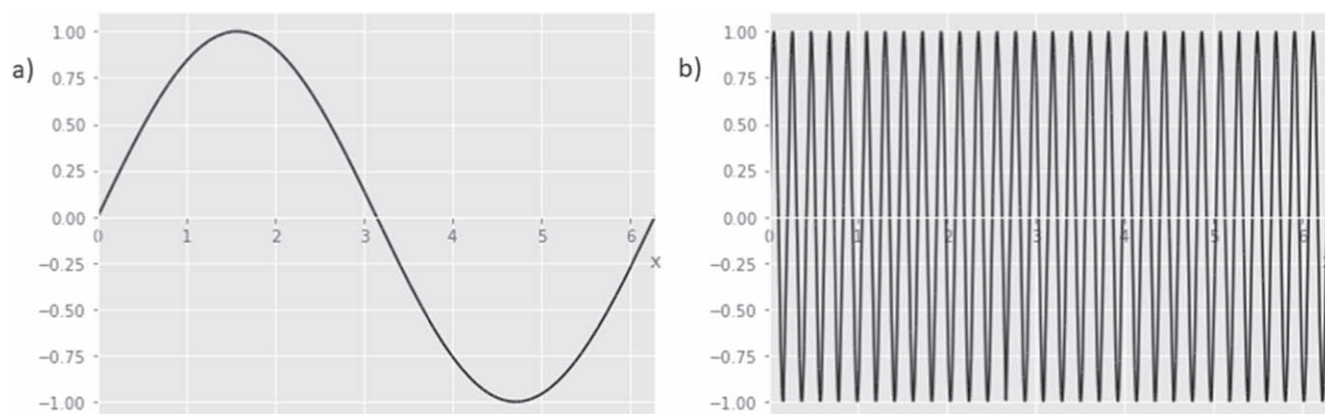


Figure 2. An illustration of the fundamental frequency shown in a) with an example of a much higher harmonic shown in b). The fundamental signal defines the length of the recording where the highest harmonic desired controls the number of points.

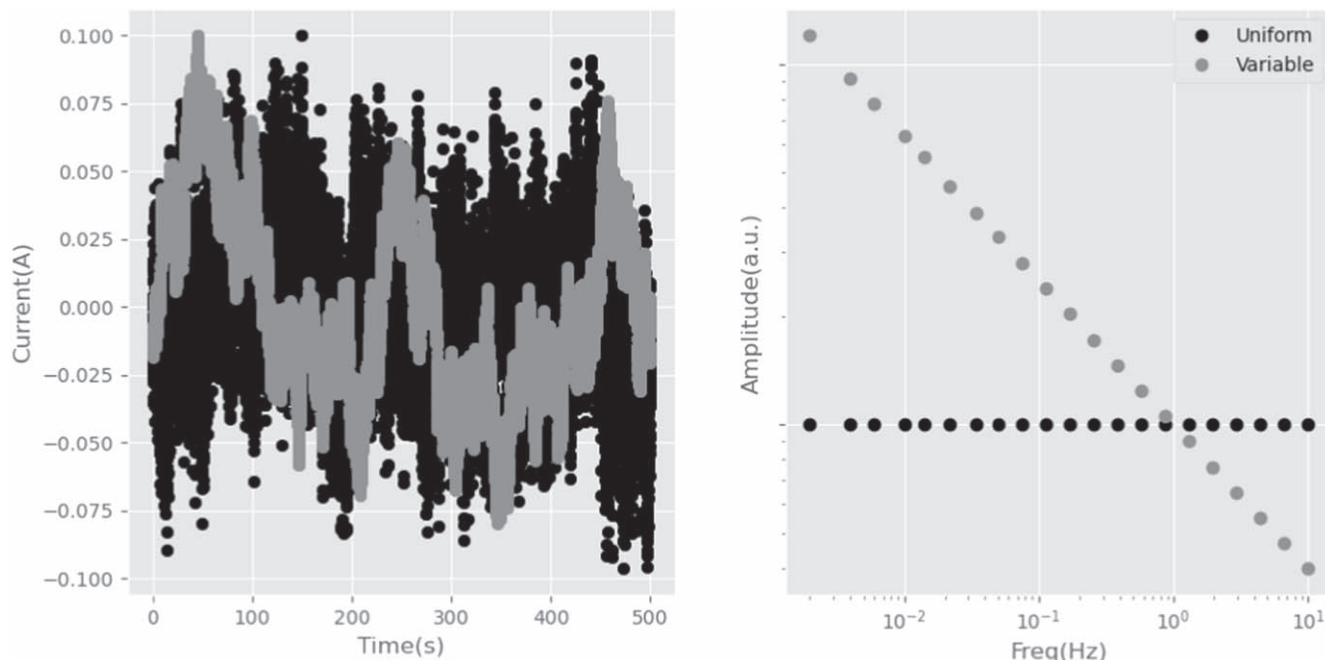


Figure 3. The uniform amplitude and the variable amplitude signal shown in time domain(left) and the frequency domain(right). The f-domain amplitudes are given in arbitrary units since the final adjustment is done to the correct amplitude in the time domain.

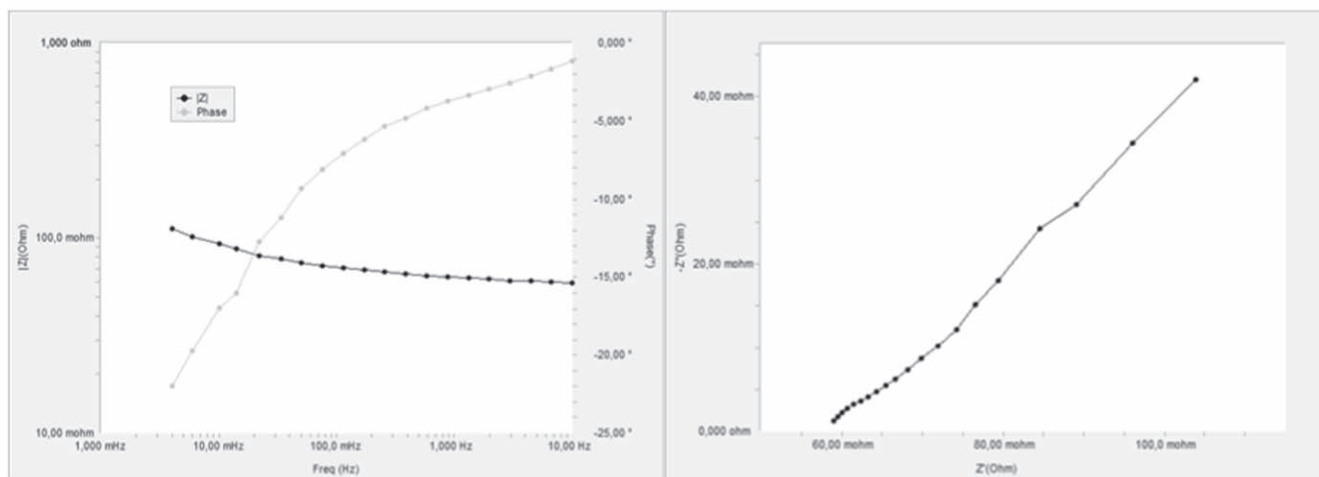
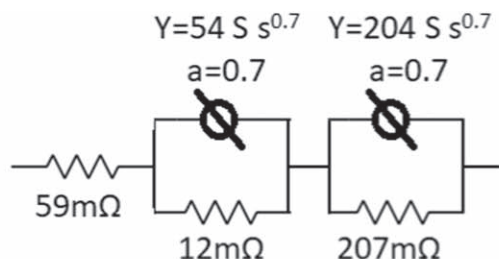


Figure 4. The impedance result of the battery shown as a Bode and a Nyquist plot along with the equivalent circuit model that is fit to the data.

Experimental

The sample used was an 18 650 battery with a capacity of 2 Ah with the LiFePO₄ chemistry with impedance shown on Figure 4. The instrument used to measure was a Gamry Reference 3000 along with the Virtual Front Panel(VFP600) software in order to apply arbitrary signals from an external file.

The signal was prepared by the code given in the Appendix A.1. The frequency limits were from 10 Hz to 2 mHz with 6 frequencies per decade. In summary, the preparation of the frequency list goes as follows. First, the standard logspace function from NumPy³⁴ is used as a starting point. Then the array gets adjusted to make sure that all frequencies are integer multiples of the lowest frequency desired and

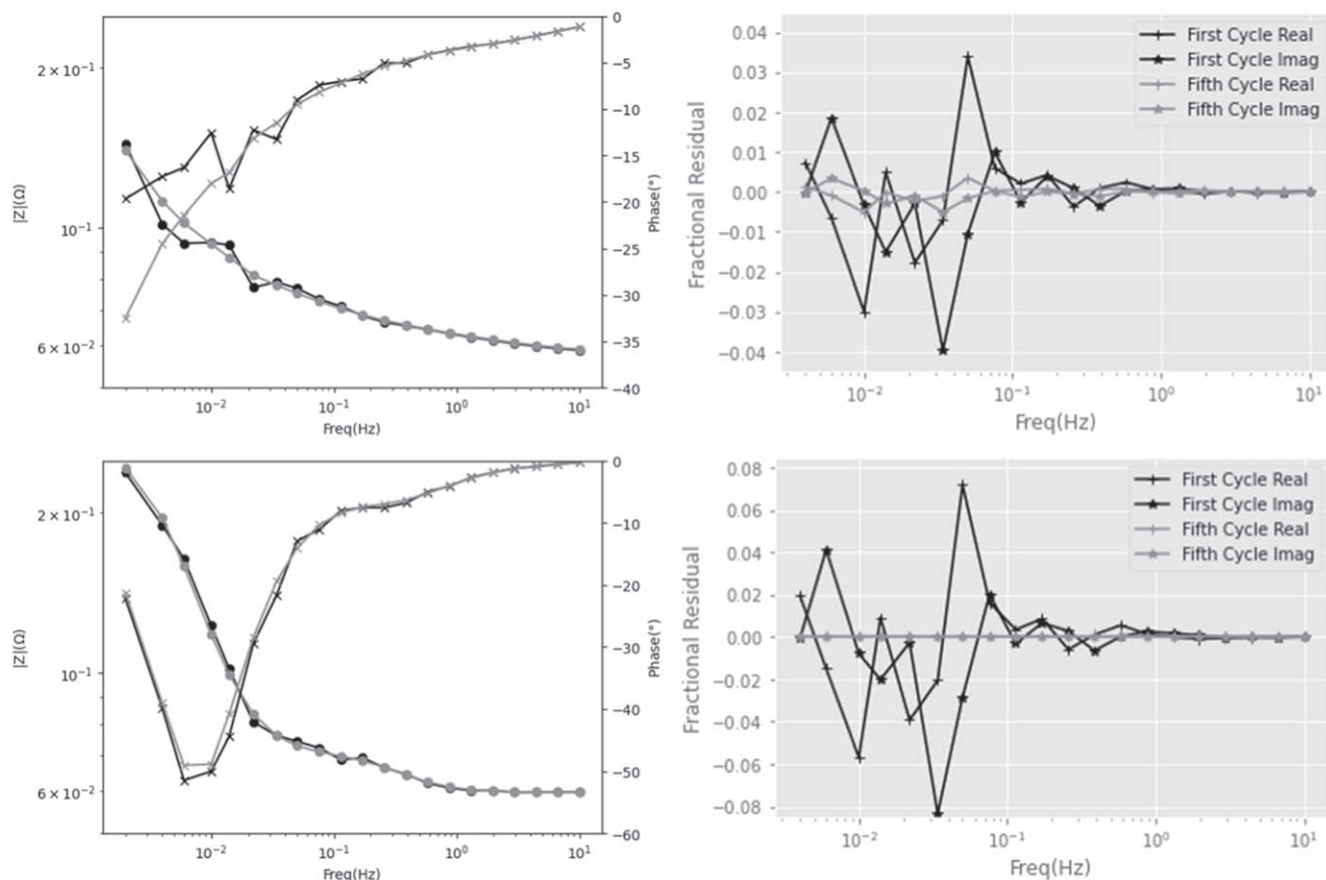


Figure 5. The impedances measured and the errors calculated using a uniform amplitude signal in simulation (bottom) and in measurement (top). The plots on the left show the Bode plots of the dummy cell in simulation and the battery in measurement. The plots on the right show the fractional residuals of the Kramers-Kronig compatibility tests.

finally the duplicates are removed. This leads to a list of frequencies shown in Table I.

The signal is then calculated via two nested loops (one over the list of frequencies and one over time). The sampling frequency for the signal generation and the sampling was chosen as 40 Hz since the highest frequency of interest is 10 Hz. For each frequency, the signal is calculated along with a phase shift following Eq. 1. This signal is repeated 5 times in order to follow the progression. Finally, the maximum amplitude of the signal is adjusted to 100 mA.

The simulation was done with a numerical simulation based on our earlier publication⁹ extended to a two time constant dummy cell given in the Appendix A.2. The dummy cell parameters and the fact that it has two time-constants were chosen based on the EIS result of the battery measured in the frequency range of interest.^c The spectra and the equivalent circuit model used is provided in Fig. 3.

The same signal was also used on the Reference 3000 to measure the voltage as a response of the signal to the cell. Throughout the measurement, 1 kHz low-pass analog filters were turned on both on the current and the voltage channels.

The analysis was performed with the code provided in the Appendix A.3. This code not only generates the spectra for every period length individually, but also provides the frequency domain plots for the current and the voltage for each cycle, helping with developing the necessary understanding.

Ultimately, the quality of the measured impedance will be estimated based on residuals to the Kramers-Kronig compatibility check generated by EChem Analyst.

^cSince the simulations are based on true capacitors, the exponents on the constant phase elements were simply ignored. This creates differences in the phase, but the magnitudes are roughly similar as functions of the frequency.

Results and Discussion

Uniform amplitude.—The results obtained for the battery in measurement and the dummy cell in simulation are shown in Fig. 5. The EIS data are shown in modulus and phase on the left hand side as a Bode plot from the first and the fifth cycle along with the fractional Kramers-Kronig errors shown on the right hand side. The data with the dummy cell is a great way of judging how much of the errors in the measurement are inherent to the method and what part is due to the method developed and signal used.

In all cases, the signal that is transformed to the frequency domain is only 500 s long, which is one cycle of the lowest frequency measured (i.e. 2 mHz). In both the measurement and the simulation, it is clear that by the time that the 5th cycle is measured, the effect of the aforementioned initial transient is diminished for this particular cell.^d Once the initial transient decays below the noise level, the error in the measurement, including all the external and instrumental noise sources are less than 1% with a measurement that is only a single cycle at the lowest frequency.^e In the case of the simulation, the error is almost perfectly zero once the effect of the startup transient has decayed.

This is exactly where a time gain can be obtained. The rest of the frequencies measured are simply running alongside the lowest frequency with consecutively higher number of cycles and the measurement only takes the minimum amount of time that can mathematically be transformed to obtain the impedance at the lowest

^dThe time-constant for the decay of the initial transient is estimated to be $R_p \times C$. Therefore, there is no way to estimate this a priori without the knowledge of the spectrum

^e1% is typically regarded as the accepted limits of EIS systems as published in many specification sheets.

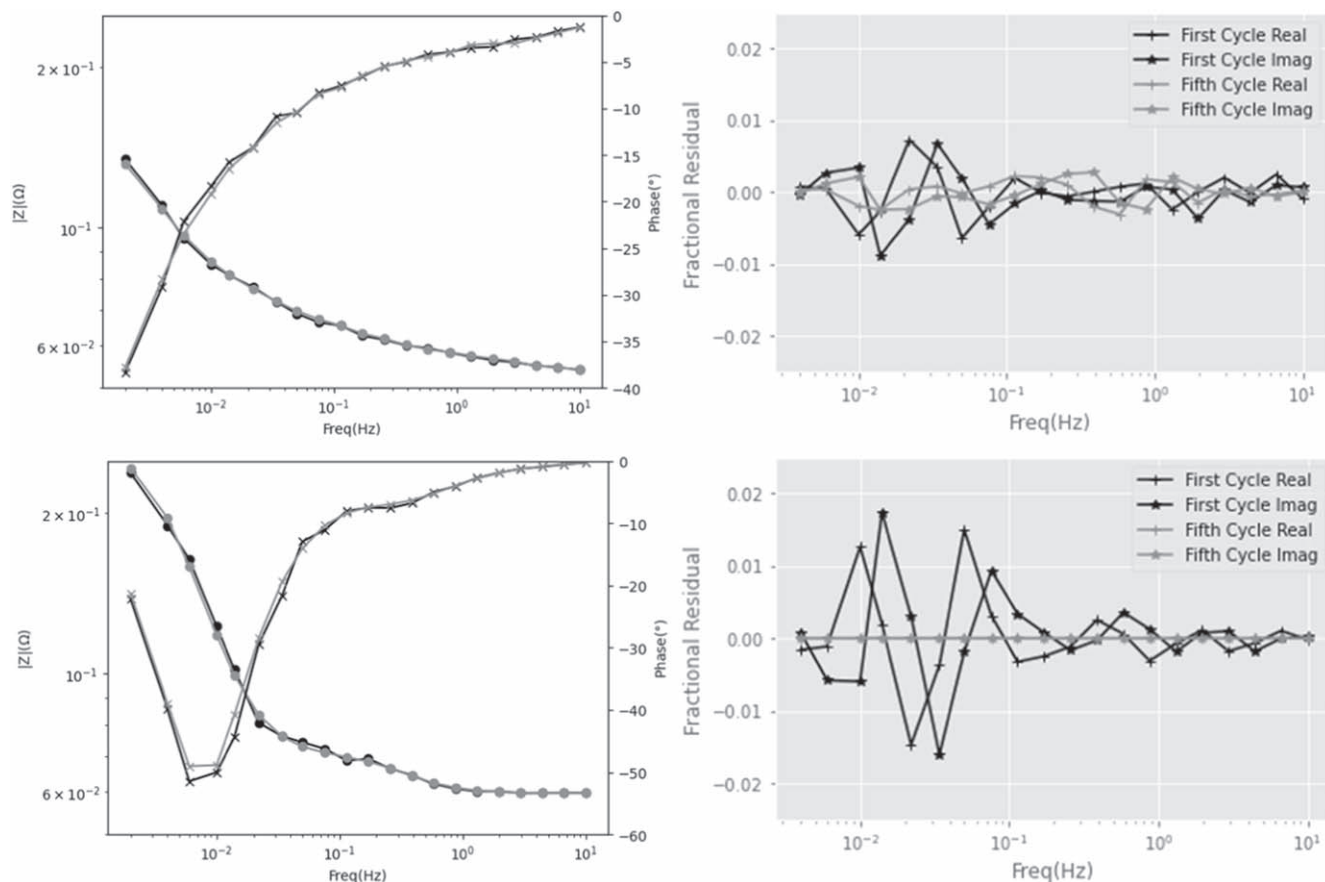


Figure 6. The impedances measured and the errors calculated using the variable amplitude signal in simulation(bottom) and in measurement(top). The plots on the left show the Bode plots of the dummy cell in simulation and the battery in measurement. The plots on the right show the fractional residuals of the Kramers-Kronig compatibility tests.

frequency desired. More on the actual time gain and the comparisons will be mentioned later.

The errors in the measurement are significantly lower at the higher frequencies compared to their lower counterparts. This can simply be explained by the larger number of cycles measured at higher frequencies. It is worth noting that the highest frequency in this measurement is 10 Hz, which goes through 5000 cycles within the measurement. Therefore, it is only natural to attempt to increase the amplitude at the lower frequencies for better signal-to-noise ratio overall. This will be investigated in the next section.

Since the impedance modulus of batteries do not change heavily within the frequencies of interest, even without adjusting any amplitudes, the measurement yields acceptable results. It is important to mention that this would not be the case for systems that have highly variable impedance moduli like capacitive coatings. In such systems, uniform amplitudes would be practically impossible to be used and amplitudes have to be adjusted in order to make sure that all the measurements can be done within a single gain and range settings.

Variable amplitude.—The results of the variable amplitude signal is shown in Fig. 6. In this case, the measurement already has an error below 1% after the first cycle. The higher amplitude at the lower frequencies overpower the effects of the initial transient. By the time the fifth cycle is measured, all the frequencies of interest show an error that is below 0.5%. Again, in the simulation, only the first cycle shows some error due to the initial transient with the fifth cycle showing no errors. Even then, the error in the entire spectrum is less than 2% which is roughly 4 times better than the uniform amplitude case.

Table I. The list of frequencies(in Hz) that are the result of the described procedure and parameters.

2 m	50 m	876 m
4 m	76 m	1.316
5 m	114 m	1.974
10 m	172 m	2.960
14 m	258 m	4.442
22 m	388 m	6.664
34 m	584 m	10.0

Time gain and data quality.—The issue of how much faster data can be obtained is not one that can be estimated directly. The currently described multisine is only a single cycle at the lowest frequency, which is 500 s since the lowest frequency is 2mHz. For the single sine measurement, different manufacturers employ different criteria for how many cycles are measured. Some employ fixed number of cycles where others follow the signal-to-noise ratio for a completion criterion. Therefore a one-to-one comparison is not be directly performed. However, a couple of cases will be investigated with rough time gain estimations in parantheses for each case:

- Assuming one cycle is measured per frequency, the single sine measurement would take 1222 s based on the list of frequencies shown in Table I. This can simply be calculated by summing over the inverse of the frequencies. (roughly 2.4).
- In the current multisine measurement, every frequency is measured for 500 s by themselves. Though a single sine

measurement would never integrate over every frequency for that long, assuming two cycles per frequency for every frequency above the lowest, the total measurement would take 1944 s. (roughly 5).

- In order to measure EIS in 1s or less,^f the main requirement is that the lowest frequency of interest has to be 1 Hz or higher. There is no way that a measurement down to 0.1Hz can be completed before 10s, i.e. one cycle at the lowest frequency.

- The data quality can be improved by using a variable amplitude excitation signal, however, the details of the said signal typically has to be tailored via meticulous trial and error. A number of processes(e.g. drift, start-up transient, external noise) effect the quality of the EIS data.

The issue of time required vs data quality was investigated by Milocco.³⁵ It was shown that for a “prespecified error” level, the quickest measurement is performed by sine wave excitation. This would indicate that for any measurement, the best way to achieve a low error measurement is the single sine. However, the multisine does achieve a time gain, albeit with acceptable degradation of data quality.

The number of sine waves measured clearly is one of the defining factors for data quality. For the same amplitude and noise level, the higher the number of cycles integrated, the lower the signal-to-noise level.

Conclusions and outlook

Through judicious design of the excitation signal, the impedance spectrum of a battery can be measured within a single cycle of the lowest frequency desired. The rest of the frequencies desired can be adjusted to be a harmonic of the lowest frequency with small modifications and can cycle consecutively more times than the fundamental frequency(which is selected to be the lowest frequency desired). Depending on how the timing is estimated, this represents a time gain of a factor of 2.4 to 5 with the selected parameters. It should be noted that this time gain is achieved at the expense of some data quality. It is possible to obtain a spectrum that has less than 0.5% error after the initial transient is allowed to decay.

Acknowledgments

The author gratefully acknowledges the initial encouragement and various discussions on the multisine measurement with Mr. Max Yaffe of Gamry Instruments during his employment.

Appendix

Python codes used throughout the manuscript will be provided in the appendix.

^fAs famously claimed by a number of companies

A.1. Signal design.—

```

import numpy as np
from math import pi,cos
import matplotlib.pyplot as mpl

fmax=10
fmin=0.002
ndec=6
nfund=5
maxcurrent=0.1
fsoverfmax=4

farray=np.logspace(np.log10(fmax),np.log10(fmin),\
                   int(np.log10(fmax/fmin)*ndec))

for i in range(len(farray)):
    farray[i]=fmin*int(farray[i]/fmin)
farray=np.unique(farray)

#phasearray=np.random.rand(len(farray))*pi
phasearray=np.ones(len(farray))
amparray=np.ones(len(farray))

variableAmplitude=False
if(variableAmplitude):
    for i in range(int(len(farray))):
        amparray[i]=1.0/farray[i]**0.4

ampsum=0
for i in range(len(farray)):
    ampsum=ampsum+(len(farray)-i)*amparray[i]
    phasearray[i]=(pi/2-2*pi*ampsum)/(2*pi)

fs=fsoverfmax*fmax
ts=1/fs
signallengthtime=nfund/fmin
signallengthcount=int(signallengthtime*fs)

signal = np.zeros(signallengthcount)
time=np.arange(0,signallengthtime,ts)

for i in range(len(farray)):

```

```

print(farray[i])
for j in range(len(time)):
    signal[j]=signal[j]+amparray[i]*cos(2*pi*farray[i]*time[j]\
                                         +phasearray[i])

signal = maxcurrent * signal/max(abs(signal))

mpl.plot(time,signal)
mpl.show()

np.savetxt("data.txt",np.column_stack((time,signal)))
np.savetxt("dataforVFP.txt",signal)
np.savetxt("freq.txt",farray)

```

A.2. Measurement simulation.—

```

import numpy as np

data = np.genfromtxt("data.txt").T
time=data[0]
current=data[1]

charge=0
charge2=0
R=0.06
Rp=0.01
C=50#1e15#
Rp2=0.2
C2=204

samplingfrequency=1.0/(time[2]-time[1])
capcurrent=np.zeros(len(time))
capcurrent2=np.zeros(len(time))
voltage=np.zeros(len(time))

for i in range (len(time)):
    charge = charge + capcurrent[i-1]/samplingfrequency
    capcurrent[i] = current[i] - charge/(Rp*C)
    voltage[i]= R*current[i]+Rp*(current[i]-capcurrent[i])

    charge2=charge2+capcurrent2[i-1]/samplingfrequency
    capcurrent2[i] = current[i] - charge2/(Rp2*C2)
    voltage[i]= voltage[i]+ Rp2*(current[i]-capcurrent2[i])
print("CalcDone")
np.savetxt("Measured.txt",np.column_stack((time,voltage,current)))

```

A.3. Data analysis.—

```

def freqfind(number, array):
    i=0
    epsilon=1e-6
    while (abs(number-array[i])>epsilon):
        i=i+1
        if i>=len(array):
            return i
    return i

import numpy as np
import matplotlib.pyplot as plt
from scipy import fftpack
from scipy.fft import fft
import math

design = np.genfromtxt("data.txt").T
time=design[0]
data=np.genfromtxt("Measured.txt").T
datafromVFP=np.genfromtxt("multisinemeas.dta",skip_header=7).T
#data=np.column_stack((data[0],datafromVFP[0],datafromVFP[1])).T

excitedfreqs=np.genfromtxt("freq.txt")
sampletime=time[0]-time[1]
freq=fftpack.fftfreq(len(data[2]),sampletime)

period=1.0/min(excitedfreqs)
periodinpoints=abs(int(period/sampletime))

for i in range(int(len(data[0])/periodinpoints)):

    fdomi=fft(data[2][i*periodinpoints:(i+1)*periodinpoints])
    fdomv=fft(data[1][i*periodinpoints:(i+1)*periodinpoints])
    sfreq=fftpack.fftfreq(periodinpoints,sampletime)
    plt.subplot(211)
    plt.loglog(sfreq[int(len(sfreq)/2):],abs(fdomi[int(len(fdomi)/2):]))
    plt.subplot(212)
    plt.loglog(sfreq[int(len(sfreq)/2):],abs(fdomv[int(len(fdomv)/2):]))
    plt.show()

Imp=np.zeros(shape=(len(excitedfreqs)),dtype=np.complex64)
for j in range(len(excitedfreqs)):
    freqindex=int(len(sfreq)/2)+freqfind(excitedfreqs[j],\
                                         freq[int(len(sfreq)/2):])
    Imp[j]= fdomv[freqindex]/fdomi[freqindex]

```

```

Zre=np.zeros(len(Imp))
Zimag=np.zeros(len(Imp))
Zmod=np.zeros(len(Imp))
Zphz=np.zeros(len(Imp))

for k in range(len(Imp)):
    Zre[k]=Imp[k].real
    Zimag[k]=Imp[k].imag
    Zmod[k]=math.sqrt(Imp[k].real*Imp[k].real+Imp[k].imag*Imp[k].imag)
    Zphz[k]=180*math.atan2(Imp[k].imag, Imp[k].real)/math.pi

mpl.subplot(211)
mpl.loglog(excitedfreqs,Zmod,marker='o',linewidth=1)
mpl.subplot(212)
mpl.semilogx(excitedfreqs,Zphz,marker='+',linewidth=0)
mpl.show()

mpl.scatter(Zre,Zimag)
mpl.axis('scaled')
mpl.show()
np.savetxt('Imp'+str(i),np.column_stack((excitedfreqs,Zre,-1*Zimag)))
mpl.show()

```

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