

# Impedance Noise Identification for State-of- Health Prognostics

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# Impedance Noise Identification for State-of-Health Prognostics

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**Abstract:** *Impedance Noise Identification is an in-situ method of measuring battery impedance as a function of frequency using a random small signal noise excitation source. Through a series of auto- and cross-correlations and Fast Fourier Transforms, the battery complex impedance as a function of frequency can be determined. The results are similar to those measured under a lab-scale electrochemical impedance spectroscopy measurement. The lab-scale measurements have been shown to correlate well with resistance and power data that are typically used to ascertain the remaining life of a battery. To this end, the Impedance Noise Identification system is designed to acquire the same type of data as an on-board tool.*

*A prototype system is now under development, and results are being compared to standardized electrochemical impedance spectroscopy measurements. A brief description of the Impedance Noise Identification hardware system and representative test results are presented.*

**Keywords:** impedance monitoring; noise signal; state of health.

## Introduction

Battery systems are becoming more important in various technologies including military and commercial applications. Consequently, accurate state-of-health estimation techniques are also critical for prognosticating remaining useful life. The Idaho National Laboratory (INL), in collaboration with Montana Tech and Qualtech Systems Inc., has been working towards the development of a robust, in-situ smart battery status monitoring (SBSM) system that will provide this essential life estimation function. A key component to the SBSM is accurate in-situ impedance monitoring of the battery during its lifetime.

## Background

Electrochemical impedance spectroscopy (EIS) is a useful measurement technique that provides cell impedance data over a broad range of frequencies. Figure 1 shows a standard Nyquist curve for a representative lithium-ion cell cycle-life aged at 45°C for 68 weeks under the Department of Energy's Advanced Technology Development Program [1,2]. These data can be divided into three basic regions, as shown in Figure 2. The first region (between the origin and the high frequency tail) represents the electrolyte resistance ( $R_E$ ). The mid-frequency semicircle region represents the charge transfer resistance ( $R_{CT}$ ), which is primarily influenced by the positive and negative electrodes. The third, low frequency, region is the Warburg impedance, which is generally caused by the diffusion of ions [3]. EIS measurements take approximately ten minutes to complete (depending on settings and frequency range, typically 10 kHz to 10 mHz) using a small signal, constant AC voltage input signal (e.g., 20 mV) and measuring the current output response. These data have been shown to correlate very well with the resistance and power data measured from the standardized hybrid pulse power characterization test which requires about twelve hours to complete [2,4].

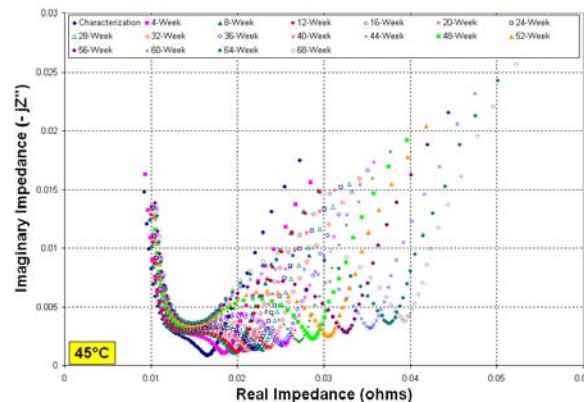
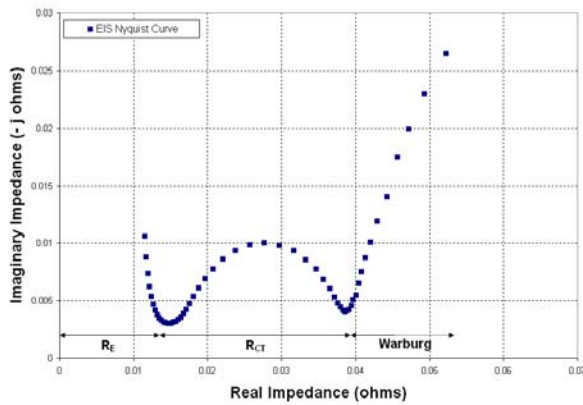


Figure 1. EIS for a Representative Lithium-Ion Cell.



**Figure 2.** Impedance Regions for a Representative Lithium-Ion Cell.

### Impedance Noise Identification

Although the EIS measurements significantly reduce the time required to determine battery degradation rates, it is not practical for an in-situ SBSM device since it is delicate and cumbersome. The Impedance Noise Identification (INI) system [5] is an in-situ method of using a random signal excitation to a battery for the purpose of measuring the spectrum of the battery impedance with high fidelity. The INI system begins with a charge neutral white-noise source that is filtered to the desired frequency range. The resulting charge neutral pink noise signal is then used to excite the battery. Through a series of averaged cross-correlations and Fast Fourier Transforms between the input signal and response, the battery complex impedance spectrum can be determined. These data, combined with life models, can be used to estimate remaining useful life of the battery.

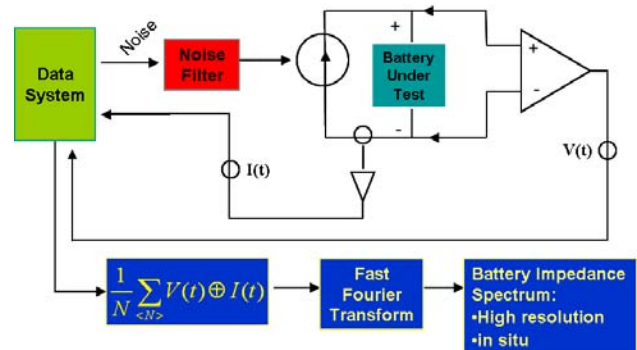
### Measurement Theory

Noise is typically something that a measurement system avoids. However, it has very interesting properties. A long time record of pure random noise as a voltage with zero mean and unity variance if applied to a one ohm resistor would dissipate exactly one watt of average power during the time record. Additionally, if the time record were auto correlated, normalized to the record overlap, and if the record was very long, then the result would be an impulse function. The longer the time record, the more perfect the impulse. The frequency spectrum of an impulse function is flat with all frequencies being equally present. Additionally, the frequency spectrum of a system function is the Fourier transform of the impulse response of that system. Thus the system response to random noise of zero mean and unity variance should carry the same information as the system response to a unit impulse. The essence of the noise identification process is a Cross Correlation of the System Response (CCSR) with the input noise. This is repeated for many time records and all of the various cross correlations are averaged. A Fast Fourier Transform (FFT) is performed on that average and the result is the frequency

spectrum, magnitude, and phase of the system response. The time record length will be limited by the lowest frequency in the spectrum and the time step will set the bandwidth of the spectrum. The quality of the result is set by the number of averages of the CCSR. Thus the performance trade-off, the more averages of the CCSR, the higher the fidelity but this causes the process to retreat further from real time. Nevertheless, this process lends itself very well for in-situ applications as the background noise is very low level and quite non-intrusive. For the INI system the excitation signal is bandwidth limited noise current and the response is the battery voltage. The averaged CCSR becomes the battery impedance in time and the FFT of that average is the desired impedance spectrum [6,7].

### Prototype INI Description

The INI system block diagram is given by Figure 3. The noise signal is computer generated and output via a D/A (digital to analog) output channel. The noise signal is bandwidth limited by the 5th order filter and then becomes a control signal driving a controlled current source. The charge neutral current excites the battery under test. A differential amplifier rejects the bias voltage from the battery and senses the battery response to the noise current. Additionally, the noise current is also sensed. These captured time records are processed by the INI data processing algorithm to obtain the impedance spectrum.



**Figure 3.** INI System Block Diagram.

The INI prototype system setup is shown in Figure 4. It consists of a host PC with a National Instruments 6120 DAQ card interfaced to an external custom designed preamp run by a dual analog power supply. The system software for control, data acquisition and data processing is run with LabVIEW, though it will eventually be upgraded to C code. Although the prototype setup is bulky, the system can be reduced to a size suited for on-board applications. As presently configured, it is limited to testing low-voltage battery systems not exceeding five volts, such as single lithium ion or nickel metal hydride cells. A 12-volt system is presently under development and higher voltage systems are readily achievable.

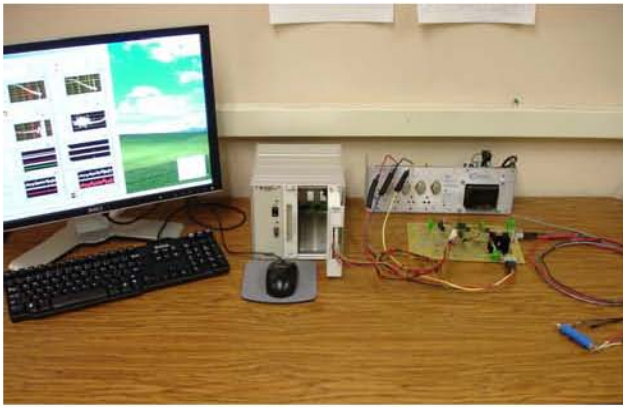


Figure 4. INI Prototype System Setup.

### INI System Test Results

The INI prototype system was applied to commercially available, 18650-size lithium-ion cells rated at 1800 mAh. Test results were compared with typical EIS measurements taken at the same open circuit voltage. A smaller frequency range was chosen for the INI (i.e., 2 kHz to 100 mHz), which reduced the test time to approximately five or six minutes per measurement.

Figures 5 and 6 show the comparisons between INI and EIS for two 1800 mAh cells (Cells A and B, respectively). The data are reasonably well matched for Cell A, especially at the lower frequencies. However, Cell B shows a larger impedance from the INI measurement compared to EIS. This is primarily due to a random phase error that is still under investigation. Figure 7 shows the comparison of the phase angle measured from the EIS and INI systems. Both show the same patterns, but the INI system is offset by about two degrees. The shifted INI phase angle data are also shown in Figure 7, and those data compare very well with the EIS results. Figure 8 shows the resulting shifted Nyquist curve, with very good agreement between the INI and EIS measurements.

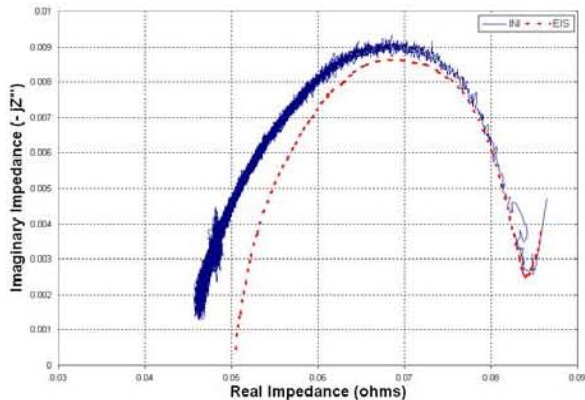


Figure 5. EIS and INI Nyquist Curves for Cell A.

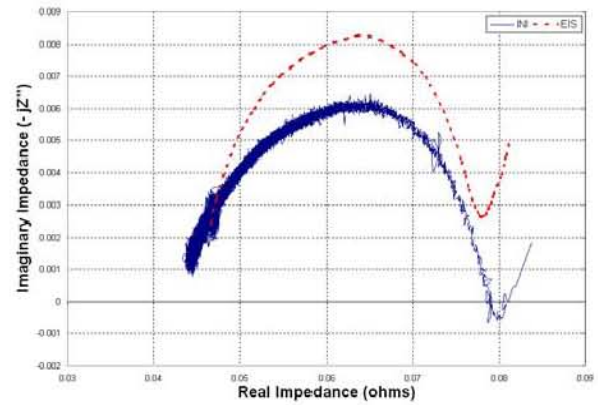


Figure 6. EIS and INI Nyquist Curves for Cell B.

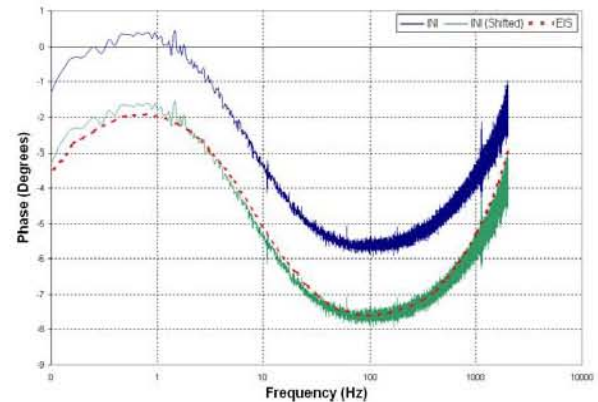


Figure 7. EIS and INI Phase Angles.

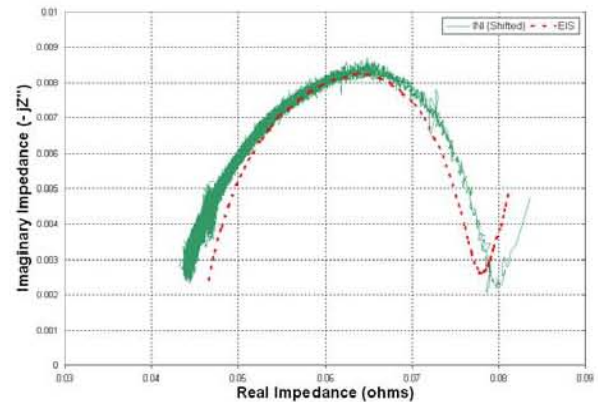
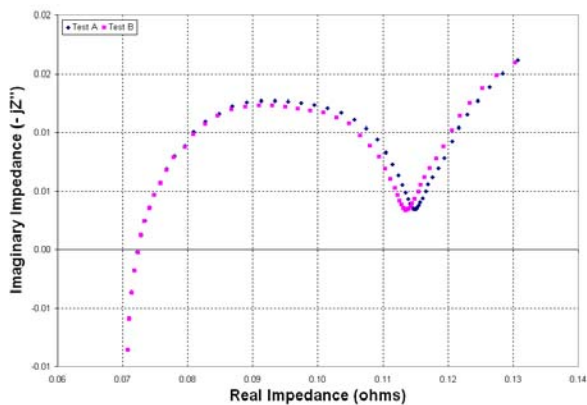


Figure 8. EIS and Shifted INI Nyquist Curves for Cell B.

### Discussion

Batteries are electrochemical devices that are not steady-state. Consequently, even when test conditions are closely controlled, back-to-back EIS measurements will likely yield slightly different responses from the battery due to small difference in state-of-charge, temperature, and system equilibrium. Figure 9 shows two consecutive EIS measurements on a representative lithium-ion cell, and that the semicircle widths for the charge transfer resistances are slightly different.



**Figure 9.** Back-to Back EIS Measurements for a Lithium-Ion Cell.

Likewise, an EIS measurement followed by an INI measurement should not be expected to provide an exact duplicate response. Additionally, the EIS system used a constant AC voltage signal and measured current response whereas the INI system applied a random current signal and measured the voltage response. Given these differences, the comparison between INI and EIS in Figures 5 and 8 is reasonable, and demonstrates that the INI is a good in-situ alternative to the lab-scale EIS system.

### Future Work

Of great importance is the comparison of impedance growth as a function of test time for a single set of batteries aged for a prolonged period of time. The INI system is still in the development phase, and comparisons between INI and EIS measurements thus far have been based on a limited number of small lithium-ion cells. Consequently, one significant task that remains is to periodically collect INI data during life aging of cells (similar to Figure 1), and compare results with EIS data. Application of the INI system to other battery chemistries such as lead-acid and nickel metal hydride is under investigation as well. Other improvements to the INI system include identifying and mitigating the random phase error, and reducing the amount of time required to complete the measurements.

Additionally, a second-generation measurement technique using the same hardware platform is also being developed [8,9]. This technique (known as compensated synchronous detection) will significantly reduce the measurement time to around 30 seconds or less, but at the expense of high resolution. Preliminary results from this system also look very promising compared to INI and EIS measurements.

### Conclusion

The INI system is a first generation device that will provide robust, in-situ impedance monitoring of a battery. It uses a truncated white noise source with a low amplitude current signal to perturb the battery. The resulting noise data are processed using auto-correlation, cross-correlation and Fast Fourier Transform techniques to determine the impedance

of the test device as a function of frequency. The prototype system has been successfully tested with small-size batteries (i.e., low voltage systems), though it can be readily configured to measure impedance on higher voltage systems as well. Results compare reasonably well with standard electrochemical impedance spectroscopy measurements which have been shown to correlate with power and resistance data from which remaining useful battery life can be estimated. The robust hardware platform lends itself to in-situ applications and is a key component to the overall smart battery status monitoring device for accurate battery state-of-health predictions.

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