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Universal Auto-Calibration For A Rapid Battery Impedance Spectrum Measurement Device

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John L. Morrison
Jon P. Christophersen
William H. Morrison

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John L. Morrison
Montana Tech of the University of Montana
Butte, MT 59701
406-496-4515
jmorrison@mtech.edu

Jon P. Christophersen
Idaho National Laboratory
P.O. Box 1625
Idaho Falls, ID 83415
208-526-4280
jon.christophersen@inl.gov

William H. Morrison
Montana Tech of the University of Montana
Butte, MT 59701
406-496-4515
whmorrison@mtech.edu

Abstract—**Electrochemical impedance spectroscopy has been shown to be a valuable tool for diagnostics and prognostics of energy storage devices such as batteries and ultra-capacitors. Although measurements have been typically confined to laboratory environments, rapid impedance spectrum measurement techniques have been developed for on-line, embedded applications as well. The prototype hardware for the rapid technique has been validated using lithium-ion batteries, but issues with calibration had also been identified. A new, universal automatic calibration technique was developed to address the identified issues while also enabling a more simplified approach. A single, broad-frequency range is used to calibrate the system and then scaled to the actual range and conditions used when measuring a device under test. The range used for calibration must be broad relative to the expected measurement conditions for the scaling to be successful. Validation studies were performed by comparing the universal calibration approach with data acquired from targeted calibration ranges based on the expected range of performance for the device under test. First, a mid-level shunt range was used for calibration and used to measure devices with lower and higher impedance. Next, a high excitation current level was used for calibration, followed by measurements using lower currents. Finally, calibration was performed over a wide frequency range and used to measure test articles with a lower set of frequencies. In all cases, the universal calibration approach compared very well with results acquired following a targeted calibration. Additionally, the shunts used for the automated calibration technique were successfully characterized such that the rapid impedance measurements compare very well with laboratory-scale measurements. These data indicate that the universal approach can be successfully used for onboard rapid impedance spectra measurements for a broad set of test devices and range of measurement conditions.**

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1. INTRODUCTION

The impedance Measurement Box (IMB) was designed to acquire, very rapidly, impedance spectra using a hardware platform that could be embedded in a management system for energy storage devices (e.g. batteries). The prototype IMB system generates an excitation signal, captures the response from a battery, and then resolves that time response signal into a Nyquist or Bode representation of the spectra One method that can be used for rapid impedance measurement (RIM) is Harmonic Compensated Synchronous Detection (HCSD), which generates a sum-of-sines (SOS) excitation signal using frequencies separated by octave harmonics [1]. Previous testing with the HCSD technique has shown that it yields measurement results comparable with laboratory-scale electrochemical impedance spectroscopy (EIS) measurements, is benign to the test article, and the resulting RIM can be used for advanced diagnostic and prognostics [2]. For accurate results appropriate calibration of the IMB system is required. The typical system calibration determines scale factors that will convert the system response, typically some voltage, into the desired reference measurement units [3]. A calibration is typically performed by making controlled measurements on a known standard. This calibration process allows the systems measurement uncertainty to be quantified [4]. Previous methodologies relied on a manual approach that was time consuming prone to human-error. However, a new, universal auto-calibration system has been recently developed for the IMB such that a single calibration can be performed on the system to cover a wide range of measurement capabilities.

The original manual calibration required three, 1% non-inductive shunts (the reference standard) with monotonically-increasing resistance values; the actual impedance of each shunt was first characterized with standardized EIS measurements. The IMB system operating with HCSD was set for a designated frequency range and an SOS excitation current for the calibration. A RIM was performed on the middle shunt and the results used to pre-emphasize the SOS signal, similar to the method of Lathi [5], so as to negate the IMB system frequency

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response. Then another RIM was performed on each of the three shunts (using the pre-emphasis excitation signal). A linear regression was then performed to obtain the set of calibration coefficients to correct magnitude at each frequency. The middle shunt was again selected and multiple RIMs were performed each with each frequency in the SOS having a preset phase shift. This yielded multiple middle shunt RIM data sets, each with a different phase (all the frequencies in a given RIM have the same preset phase). The monotonically increasing phase shifts, over those multiple RIM data sets, were then processed with linear regression to yield phase calibration constants for each of the calibration frequencies. Although this approach yielded a good RIM response from the IMB [6], it was very specific to the requirements of the device to be measured (i.e., frequency range, amplitude, excitation current, etc.). Thus, a wide variety of calibrations was needed for the expected range measurement scenarios. Additionally, each manual calibration required an operator to attach and detach all the shunts being measured. It was labor intensive and subject to human error (e.g., hooking up a wrong shunt for a measurement). An auto-calibration technique was then subsequently developed, using relay contacts, to automatically switch between shunts [6]. The auto-calibration required only a single connect-disconnect operation. However, this technique still required calibration of 3 shunts that covered the expected range of measurement conditions and would require a different calibration if the measurement conditions changed.

New research has led to the development of a technique whereby a single universal calibration can be scaled to apply to a very wide range of the expected measurement scenarios. That universal calibration is used to synthesize a wide variety of specific calibrations needed for specific measurement conditions.

2. Universal Calibration Theory

Given a broad range of frequencies within a SOS excitation signal for an impedance spectrum measurement, a single standard calibration can be performed on the system using the worst-case scenario (i.e., the largest expected frequency sweep and highest expected excitation current) such that all other anticipated measurement scenarios within the standard calibration boundary can use a calibration that was synthesized from the standard. For example, a typical frequency range for a lithium-ion cell is 0.1 to 1638.4 Hz assuming an octave harmonic separation [6]. However, it may be beneficial to occasionally go to even lower frequencies for a better definition of the Warburg tail. Alternatively, when faster measurements are required for a quick assessment of health, the initial frequency should be higher. If starting frequencies for these two requirements were selected such that they are harmonically-related to the typical range (i.e., 0.0125 Hz for the long measurement and 0.8 Hz for the short measurement), then the universal auto-calibration system can be run with the longest duration (0.0125 Hz to 1638.4 Hz) and still be useful for the other measurement requirements. The shorter frequency measurements can use the calibrations of the long universal calibration where the frequencies overlap. Since the calibration is both magnitude and phase with overlapping frequencies, the phase is inherently universal and scaling of the calibration constants is only necessary for magnitude. Additionally, impedance spectrum measurements can be run at various current ranges depending on the requirements and signal-to-noise ratios. The universal calibration system would also assume the worst case (e.g., 500 mA RMS for a lithium-ion cell) and then scale for the actual excitation current used to measure a device.

As described in the introduction, IMB calibration is performed at each frequency; it consists of a pre-emphasis filter correction and response calibration [6]. The pre-emphasis filter correction is normalized and thus independent of the RMS excitation current so filter corrections of the relevant frequencies can be selected from a universal calibration and input directly into the synthesized measurement calibration. As previously mentioned, the phase calibration is inherently normalized so the phase calibration at the relevant frequencies are also selected from the universal calibration and input directly into the synthesized measurement calibration. The magnitude calibration is also selected from the relevant frequencies however, it must first be scaled for RMS current and number of frequencies before it can be used in the synthesized measurement calibration. The theory defining this scaling is as follows.

For magnitude calibration, after the IMB has been filter corrected for the desired frequency range, measurements are performed on three known monotonically-increasing shunts. The magnitude response at each frequency for each shunt is obtained using the HCSD technique. The response data are processed with a linear regression straight line fit to obtain calibration constants at each frequency [6]. Thus, impedance magnitude at the *ith* frequency $|Z_i|$ for a measurement using this calibration is given by Equation 1.

$$|Z_i| = (G_i V_i + OS_i) = \frac{\tilde{V}_{Pi}}{I_{Pi}} \tag{1}$$

Where: G_i is magnitude linear regression gain at the *ith* frequency
OS_i is the magnitude linear regression offset at the *ith* frequency
V_i is the magnitude of the voltage response at the *ith* frequency
I_{Pi} is magnitude of the excitation current at the *ith* frequency
$\tilde{V}_{Pi}$ is the corrected magnitude voltage response due to I_{Pi} at the *ith* frequency

The relationship between the RMS of the SOS current I_{RMS} and the peak of the individual SOS current sine waves I_{Pi} is given by Equation 2.

$$I^2_{RMS} = \sum_{i=1}^{M} \frac{I^2_{Pi}}{2} \qquad (2)$$

Where: M is the number of frequencies in the SOS

Because of the filter correction, all of the individual I_{Pi} will be equal and thus Equation 2 becomes Equation 3.

$$I_{RMS} = I_{Pi}\sqrt{\frac{M}{2}} \qquad (3)$$

The magnitude of the excitation current I_{Pi} in terms of the SOS RMS current I_{RMS} and the number of frequencies, M in the SOS is given in Equation 4.

$$I_{Pi} = I_{RMS}\sqrt{\frac{2}{M}} \qquad (4)$$

From Equation 4 and Equation 1 the basis of the normalized calibration magnitude constants can be obtained as shown in Equation 5.

$$G_{Ni} = G_{Ci} I_{RMSC}\sqrt{\frac{2}{M_C}}, \quad OS_{Ni} = OS_{Ci} I_{RMSC}\sqrt{\frac{2}{M_C}} \qquad (5)$$

Where: G_{Ni} is the normalized gain at the *ith* frequency
OS_{Ni} is the normalized offset at the *ith* frequency
G_{Ci} is the calibration gain at the *ith* frequency
OS_{Ci} is the calibration offset at the *ith* frequency
M_C is the number of calibration frequencies
I_{RMSC} is the SOS RMS current used in calibration

If the $\sqrt{2}$ is considered part of the constants G_{Ci} and OS_{Ci}, then the normalized gain and offset at the *ith* frequency can be described by Equation 6.

$$G_{Ni} = G_{Ci}\frac{I_{RMSC}}{\sqrt{M_C}}, \quad OS_{Ni} = OS_{Ci}\frac{I_{RMSC}}{\sqrt{M_C}} \qquad (6)$$

Then the magnitude calibration constants for the synthesized measurement calibration are obtained from Equation 7.

$$G_{Mi} = \frac{G_{Ni}}{I_{RMSM}}\sqrt{M_M}, \quad OS_{Mi} = \frac{OS_{Ni}}{I_{RMSM}}\sqrt{M_M} \qquad (7)$$

Where: G_{Mi} is the measurement gain at the *ith* frequency
OS_{Mi} is the measurement offset at the *ith* frequency
M_M is the number of measurement frequencies
I_{RMSM} is the measurement SOS RMS current

Equations 6 and 7 form the basis for a universal calibration approach.

3. Experimental Validation Of Universal Calibration

Three different test sequences were performed to validate the Universal Calibration (UC) technique. The first test sequence verified that one calibration shunt range will work for all expected measurements. All testing except the frequency-scaling test was done at the long frequency range (e.g. 0.0125 Hz to 1638.4 Hz). The second test sequence verified that a UC performed at a standard RMS current can be scaled to apply to a measurement performed at a different (lower) current. Finally, the third test sequence verified that a UC performed at a standard number of frequencies can be scaled to apply to a measurement using a smaller subset of the UC frequencies. Verification testing was done on Test Cells (TCs), which consists of non-inductive shunts and an ultra-capacitor assembled into circuits that have an impedance spectrum similar to a battery [6], a small 3.8V Li ion battery and four small 12V lead acid motorcycle batteries. These test articles were selected because they provide a range of impedance from 15$m\Omega$ to 1000$m\Omega$. The TCs cover the low impedance portion of the range (<100$m\Omega$) and the batteries cover the higher impedance range. The TCs are desirable as test devices, they are assembled with non-inductive shunts and an ultra-capacitor, and thus their impedance spectra are time invariant and have been measured by the Idaho National Laboratory (INL) Electro-Chemical Impedance Spectroscopy (EIS) system. For IMB development they have provided a constant measurement standard. Thus, the only difference between measurements performed on the same TC with the same calibration would be the IMB repeatability. The Li battery and the lead acid batteries impedance spectra will change over time. Thus, spectra comparison tests using batteries must be done in close time proximity or data processing applied to the same raw data set. The time variant battery issue for these test sequences was mitigated by applying the comparison calibrations to the same raw battery data set. Table 1 gives the magnitude of impedance provided by each test article.

Table 1. Test Article Impedance

TC No. 8:	15$m\Omega$	TC No.5:	60$m\Omega$
TC No. 3:	30$m\Omega$	Li:	50$m\Omega$
12V:	300$m\Omega$	48V:	1000$m\Omega$

4. Validate Mid-Shunt Range for Universal Calibration

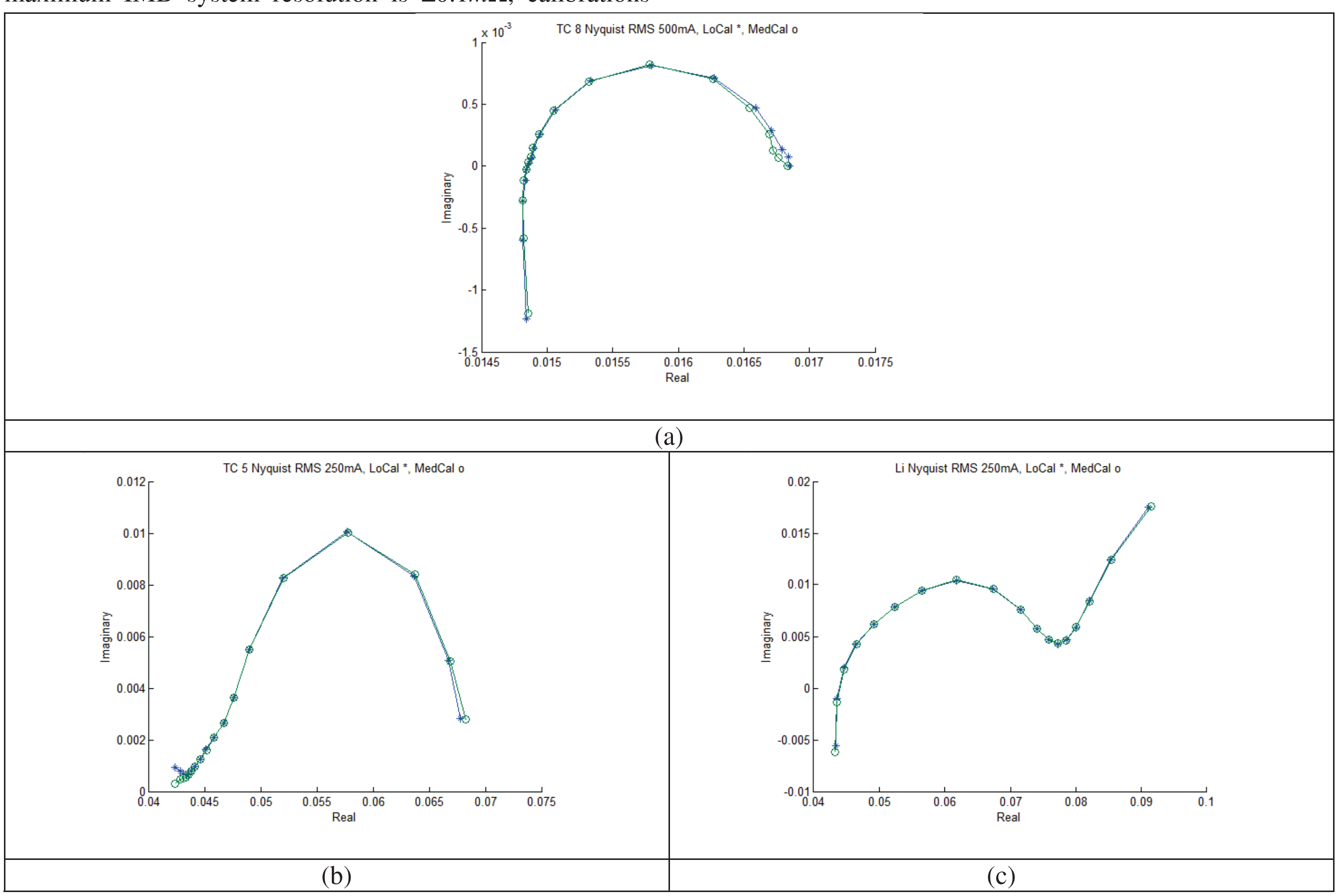
Previous development work for the IMB has led to three basic calibration shunt ranges to cover a low, medium or high impedance energy storage system. Table 2 shows the three shunt ranges used for calibrations.

Table 2. Calibration Shunt Range

Low	16.6$m\Omega$, 25$m\Omega$, 50$m\Omega$
Medium	25$m\Omega$, 50$m\Omega$, 100$m\Omega$
High	50$m\Omega$, 100$m\Omega$, 200$m\Omega$

Calibrations at shunt ranges other than these are possible but undesirable for the existing prototype system. Since the maximum IMB system resolution is ±0.1$m\Omega$, calibrations with shunts lower than the low range are degraded by the resolution limit. Calibrations done at shunt ranges above the high range become limited by the RMS current. High impedance with a large RMS current will exceed the input range of the digitizer.

The first objective was to show that a calibration conducted at a designated RMS current level for a medium-shunt range calibration and then subsequently applied to a lower and higher impedance device will match the corresponding results from a low-shunt range calibration and high-shunt range calibration respectively. First, a medium shunt range calibration and a low shunt range calibration were conducted at 500mA and used to perform measurements on TC No. 8, a very low impedance test article (see Table 1) and the results compared. Second, a medium shunt range calibration and a low shunt range calibration were conducted at 250mA and used to perform measurements on TC No. 5 (see Table 1) and a lithium-ion battery. Both the TC and battery are slightly higher impedance devices. The medium and low shunt range calibrations for 250mA were applied to the same measurement performed on a lithium-ion battery. Figure 1 shows the resulting impedance spectra displayed as Nyquist curves where the medium shunt ranges are the "o" symbols and the low shunt ranges are the "*"symbol. As shown the plots very closely match and thus it appears that medium shunt calibration range can successfully be used for lower impedance devices.

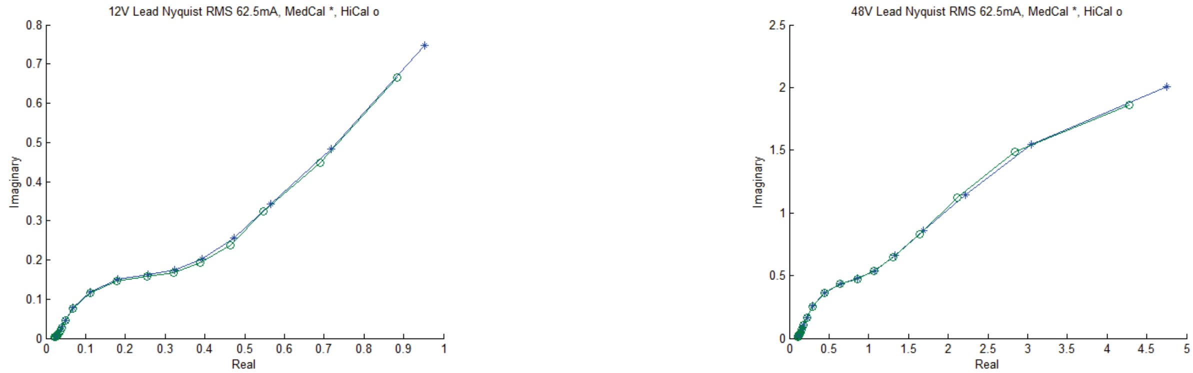


(a)

(b) (c)

Figure 1 – (a, b, c) Test Cell results for low shunt range vs. medium shunt range

The next comparison included medium and high shunt calibrations conducted at 62.5mA and then applied to a common measurement for a 12V lead acid battery and another common measurement for 48V lead acid battery, which are both high impedance batteries. Four 12V lead acid batteries were connected in series to form the 48V system. The results are plotted Figure 2 and show a very good match. Thus it also appears that the medium shunt range can be useful for higher impedance devices as well.

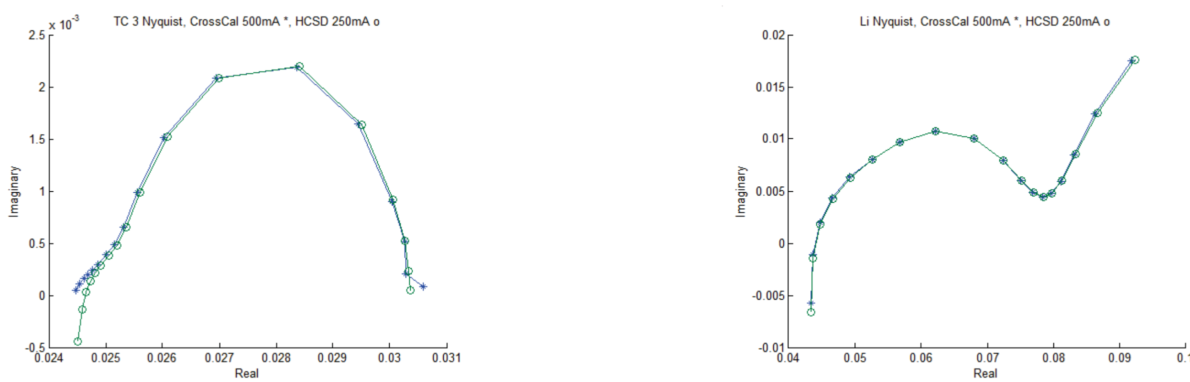


(a) (b)

Figure 2 – (a and b) Lead Acid cell response for High Shunt range vs. medium shunt range

5. VALIDATE SCALING THE RMS CURRENT FOR UNIVERSAL CALIBRATION

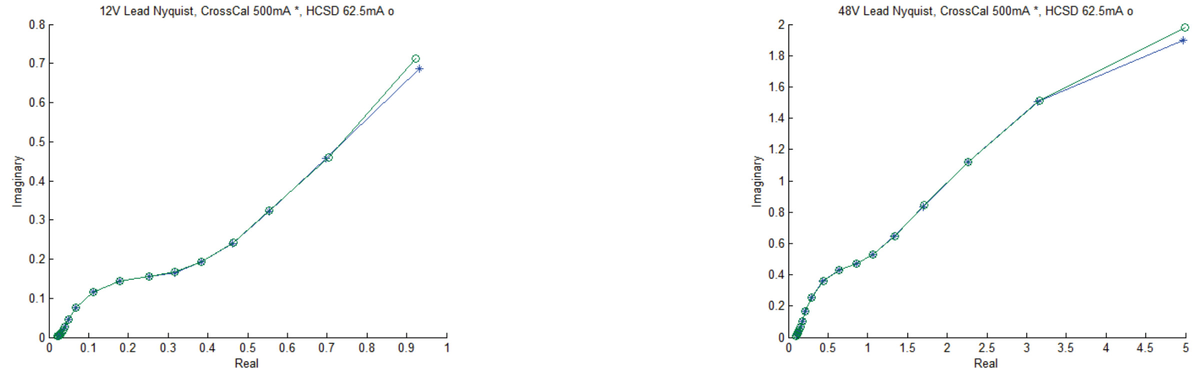
The next aspect of validating the concept of UC is to demonstrate that the RMS current used for calibration can scale to the value used for a measurement. As per Equations 6 and 7, the calibration scaling only applies to the magnitude constants and not the phase constants. All calibrations for this comparison were in the medium shunt range. The first used a 500mA calibration current that was scaled to 250mA and then compared to a measurement performed using a 250mA calibration. The calibrations were applied the same measurement time record. Tests will scale the current for calibrations done at 500mA to measurements at 250mA and compare with calibrations done at 250mA. The calibrations will be applied to the same time record. The 2 results are plotted together in Nyquist format. The test articles for this study were TC No. 3 (Table 1) and the lithium-ion battery. The results are shown in Figure 3.



(a) (b)

Figure 3 – RMS current scaling for 500mA to 250mA for TC No. 3 and a Li battery

With TC No. 3, there is a little error at the very high frequencies (left side) and the low frequency measurement (right side). However, the results show very good agreement for the critical mid-frequency region. For the lithium-ion battery, the match is very good over the entire frequency range. The second test was to scale a 500mA calibration down to 62.5mA for high impedance lead acid modules at both 12V and 48V. Figure 4 shows the resulting spectra. As with the lower impedance results the measurements using the current scaled calibration technique match the low current measurements very well over the mid-frequency region. There is some deviation at the Warburg tail but the effect seems mostly localized to just the lowest frequency measurement. Consequently, it also appears that the UC technique can be used to scale the excitation current for rapid impedance measurements.



(a) (b)

Figure – 4. RMS current scaling for Lead Acid 500mA to 62.5mA

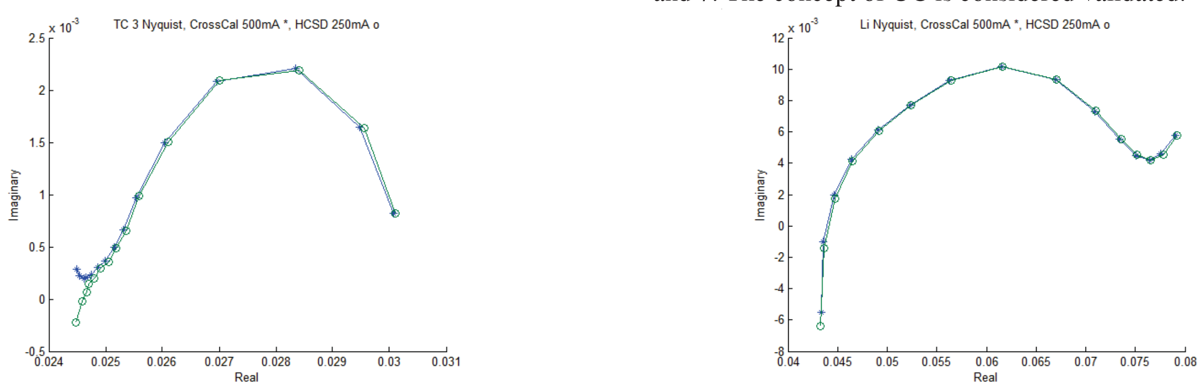
6. Validate Scaling the Number of Measurement Frequencies for Universal Calibration

The next validation test sequence was to demonstrate that the UC technique, per Equations 6 and 7, can scale long calibration (e.g., with 18 frequencies), for a measurement with a smaller frequency range. This will only work if the reduced set of measurement frequencies is a sub-set of the larger UC frequency set.

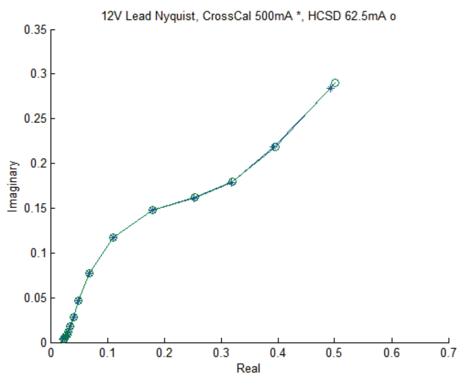
The UC used a 500mA excitation current with 18 frequencies covering a range from 0.0125 Hz to 1638.4 Hz. Measurements were then conducted on TC No. 3 (see Table 1), the lithium-ion battery, and both the 12V and 48V lead acid battery configuration using a 15 frequency measurement (i.e., 0.1 Hz. to 1638.4 Hz.). Note that both the number of frequencies and the RMS current were scaled (TC No. 3 and lithium-ion battery at 250mA; the 12V and 48V lead acid batteries at 62.5mA). Also the 2 calibrations were applied the same time record. Figure 5 shows the resulting impedance spectra for each test article.

The match is good at all frequencies except for some minor high frequency error for TC No. 3 in Figure 5a. Thus it appears that the UC technique can also successfully scale frequency range for rapid impedance spectra measurement.

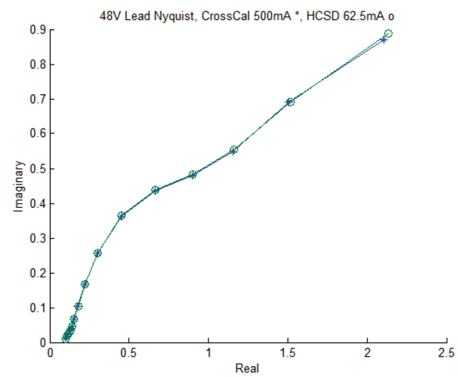
We have shown that the medium shunt range for calibration is adequate for a wide range of expected test article impedance magnitudes. We have demonstrated that a Universal Calibration (UC) carried out with 18 frequencies, 500mA RMS and the medium-shunt range will scale with current to a lower current level and with frequency to a lower number of frequencies as long as the lower frequency range overlaps with the 18 frequency range per Equations 6 and 7. The concept of UC is considered validated.



(a) (b)



(c)



(d)

Figure 5 – Frequency scaling for TC No. 3, Li battery and lead acid batteries 18 to 15 frequencies

7. Enhanced Auto Calibration

The final validation test sequence was to compare results from the rapid impedance technique with laboratory-scale EIS measurements. The universal auto-calibration system is realized in a small box that contains computer-controlled, printed circuit board-mounted, dual in line package relays that switch in and out the various calibration shunts. Since the shunts placed in the box are not readily accessible, it was not practical to characterize each shunt with an EIS measurement. However, this is a critical step for successful field (i.e., in-situ) rapid impedance measurements to be comparable to laboratory-scale results.

Consequently, a methodology was developed to characterize the shunts inside the auto-calibration box using an external shunt. First, the external shunt was subjected to an EIS measurement to determine its true value and then measured with an IMB to obtain a reference time response record that was saved. Using the same IMB calibration, rapid impedance measurements were performed on each shunt internal to the auto-calibration box while saving each of those time response time records. From these data, a correction factor was identified using Equation 8. The process was repeated at several different calibration currents and the results averaged. Figure 6 shows the resulting comparison between EIS and a rapid impedance measurement from the IMB for TC No. 3 using the low- and medium-shunt calibration ranges at an excitation current level of 250 mA. As shown, the HCSD and EIS measurements compare very well at all frequencies although there is a minor deviation at high frequencies for the low-shunt calibration range (Figure 6a).

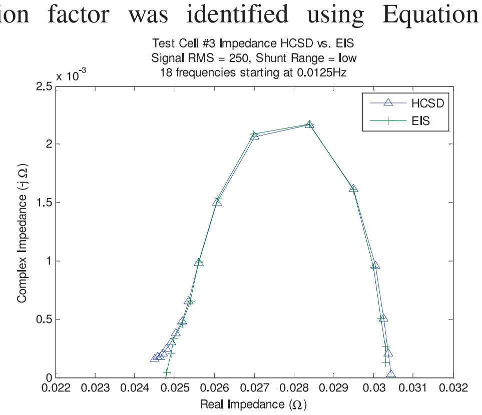
$$\frac{shunt_{EIS}}{STD_{EIS}} = \frac{shunt_{UK}}{STD_{UK}},\ shunt_{UK} = shunt_{EIS}\frac{STD_{UK}}{STD_{EIS}} \qquad (8)$$

Where: $shunt_{EIS}$ is the shunt value from EIS

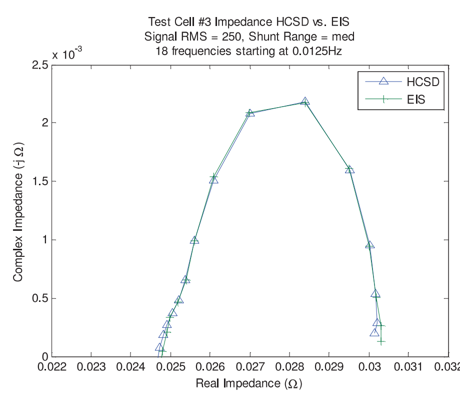
$shunt_{UK}$ is the unknown shunt value

STD_{EIS} Is the standard deviation from the EIS shunt time record.

STD_{UK} Is the standard deviation from the time record of the unknown shunt.



Auto-cal shunts (16m, 25m, 50m) I_{RMS} 250mA



Auto-cal shunts (25m, 50m, 100m) I_{RMS} 250mA

Figure 7 – Test Cell validation of auto-cal concept with IMB vs. EIS

8. Conclusions

Rapid impedance spectra measurements are a useful tool for onboard battery diagnostics, management, and control. Acquired data, however, require accurate calibration to ensure that onboard measurements are comparable to laboratory-scale results. A universal auto-calibration system was developed such that a single calibration could be performed for a wide variety of measurement conditions. Calibration is performed on the worst-case scenario and then scaled to the actual measurement window used for the device under test. Verification testing of the universal calibration technique shows that the calibrated results successfully scale for shunt ranges (medium-shunt levels applied to low-shunt and high-shunt measurements), excitation currents levels (500 mA applied to 250 mA and 62.5 mA), and frequency range (18 frequencies applied to measurements having only 15 frequencies). Additionally, a methodology was developed to calibrate shunts placed in a portable auto-calibration box such that rapid impedance measurements are comparable with laboratory-scale data. Results from these verification tests indicate that the universal calibration technique is a valid approach for rapid impedance measurements. The system can be automated with a single, wide-range, high-RMS current calibration from which several standard (but lower) calibration ranges can be obtained to support a suite of measurement conditions.

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Biography

John L. Morrison *has been teaching Electrical Engineering courses and advising graduate students for Montana Tech since 2001. He had taken early retirement from the Idaho National Environmental and Engineering Laboratory (INEEL) in the early summer of 2001. He holds a Ph. D. in Electrical Engineering from the University of Idaho (U of I) (1992) and an M.S. and B.S., also in Electrical Engineering, from the University of Connecticut (1967, 1968). He has taught Electrical Engineering courses for the U of I branch in Idaho Falls since 1980. He served as a Visiting Professor at Idaho State University for a 3-year appointment, 1997 to 2000.*

Jon P. Christophersen *received a B.S. and M.S. in electrical engineering from the University of Idaho (Moscow, ID) in 1999 and 2005, respectively, and a Ph.D. from Montana State University (Bozeman, MT) in electrical engineering in May 2011. He is the technical program manager for the Idaho National Laboratory's Battery Testing Center in Idaho Falls, ID. His research interests include developing accelerated aging protocols, battery life modeling, as well as battery life prognostics and state-of-health estimation. He received an R&D 100 Award in 2011 for the Impedance Measurement Box, which offers innovative breakthroughs on rapid impedance measurement techniques for onboard monitoring of energy storage devices. He has authored or co-authored over 15 peer-reviewed journal publications. He also has three patents, several patents pending, and numerous conference proceedings papers and presentations related to energy storage testing, modeling, and prognostics.*

William H. Morrison *is a Visiting Research Scientist with Montana Tech. Mr. Morrison's interests are development of control software for real time measurement and control systems, intelligent prognostic and diagnostic solutions and algorithms, and finding new and innovative ways to apply them. Mr. Morrison received his Bachelors of Science in Electrical Engineering (2003) and his Master of Science in Electrical Engineering (2012) from the University of Connecticut.*