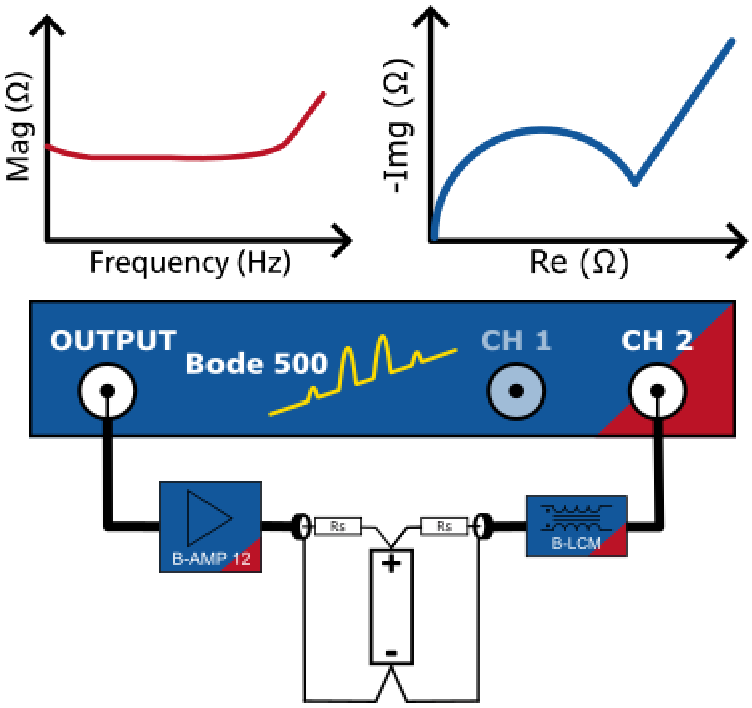
Bode 500 - Application Note

LI-ion Battery Impedance Measurement

Using the Shunt-Thru with Rs Method



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Note: Basic procedures such as setting up, adjusting, and calibrating the Bode 500 are described in the Bode 500 user manual available at:
https://www.omicron-lab.com/downloads/bode-analyzer-suite

Note: All measurements in this application note have been performed using the Bode Analyzer Suite V3.51. Use this version or a newer version to perform the measurements shown in this document. You can download the latest version at:
https://www.omicron-lab.com/downloads/vector-network-analysis

1 Executive Summary

A battery impedance measurement can provide information about the internal state of the battery. The impedance measurement can be used to determine information about the State of Health (SOH) and identify early signs of degradation of the battery [1]. The primary benefit of an impedance measurement is that it provides a non-invasive battery diagnostic. The measurement provides insight into the battery without any physical alteration. This type of impedance measurement is also referred to as Electrochemical Impedance Spectroscopy (EIS) since the Device Under Test (DUT) is of an electrochemical nature. The common methods to display the results are through Bode and Nyquist plots, depending on the goal of the measurement [2].

The measurement itself is sensitive to a multitude of factors, including the chemical and mechanical properties of the battery, test setup, State of Charge (SOC), State of Health (SOH), and temperature. While there have been extensive studies on each factor affecting the measurement and correlation between impedance and battery SOH, the scope of this application note is to provide a reliable setup for the impedance measurement using the Bode 100 or Bode 500.

This application note shows the connection setup and the device settings of the Bode 500 necessary to perform an impedance measurement on a battery.

2 Measurement Task & Device Under Test

The measurement goal of this application note is to perform an impedance measurement of a battery using the Bode 500 and provide details and recommendations on the physical setup, calibration, and Bode Analyzer Suite (BAS). The DUT is described in the following.

A cylindrical 18650 Lithium-Ion battery (see Figure 1) was used as DUT for the measurement. The battery has one contact point on each side. The battery was measured at a voltage of 4.2 V, as mentioned in the datasheet [1].

Table 1: DUT Lithium-Ion battery Specifications [1].

Lithium-Ion Battery	
Nominal Voltage	3.7 V
Maximum Voltage	4.2 V
Discharging Voltage	2.5 V
Internal Impedance	< 70 mΩ at 1 kHz AC frequency

Figure 1: Lithium-Ion battery used for the measurement.

3 Measurement Setup

3.1 Measurement Setup Selection

The DUT for the measurement is a Lithium-ion battery (Figure 1), the datasheet (Table 1) mentions an impedance < 70 mΩ at 1 kHz. For such a low impedance, a two-port Shunt-Thru setup will be preferred due to its suitability to measure low impedance values. However, the recommended limitation for the Shunt-Thru is a voltage of 3.3 V_{RMS} at the ports of the Bode analyzer. The battery's nominal voltage at full charge is 4.2 V, which is higher than the recommended voltage at Bode 500 input and output port. To be able to perform the measurement, a voltage divider will be used to lower the voltage at the Bode 500 ports. This can be accomplished using the “Shunt-Thru with Rs” respectively “Shunt-Thru with Series Resistor” setup. The series resistors, in combination with the internal 50 Ω of the ports (Figure 2) will act as a voltage divider, reducing the voltage at the ports of the Bode 500.

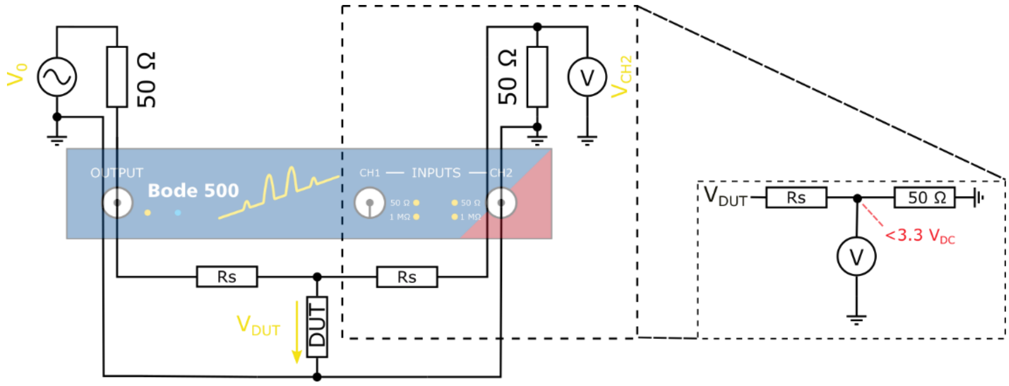


Figure 2: Bode 500 Shunt-Thru with Series Resistance schematics.

The series resistor selected for the measurement is 500 Ω. The selection was based on the attenuation of the voltage necessary for the measurement, simplicity, and availability of the resistors. The criteria for the input voltage of the Bode 500 from equation (3.1) must be satisfied by the series resistor. The voltage divider must also not attenuate the signal too low, since then the Bode 500 will not be able to measure it.

$$V_{DUT} \cdot \left(\frac{50\ \Omega}{50\ \Omega + R_s}\right) < 3.3\ V_{RMS} \tag{3.1}$$

$$R_s > \frac{50\ \Omega \cdot V_{DUT}}{3.3\ V_{RMS}} - 50\Omega \tag{3.2}$$

The Bode 500 measures the S_{21} parameter and calculates the impedance via an equation (3.3). The equation is modified to account for the series resistor; an accurate reading of the series resistor can improve the impedance calculation.

$$Z = \frac{50\ \Omega + R_s}{2} \cdot \frac{S_{21}}{1 - S_{21}} \tag{3.3}$$

The frequency range for the measurement is selected from 1 Hz to 1 MHz; the selection may vary depending on the battery; some may require going to lower frequencies to be able to identify the diffusion region in measurement, which will be discussed later in the result section. The upper limit of the frequency sweep is to display the inductive region of the battery; in many applications, the high-frequency response is neglected. In theory, the magnitude of the impedance of the battery should remain constant, but as the result will show, it varies depending on the frequency.

3.2 Accessories Required

The setup consists of two 500 Ω series resistors and the additional accessories B-LCM and B-AMP 12. The B-LCM is a common mode choke used to suppress the ground loop error in the Shunt-Thru setup; the effects of the error are seen during the measurement of low impedances at low frequencies; for more information, please check out the document “Impedance Measurements using the Bode 100” on our website. The B-AMP 12 is a power amplifier used to boost the Bode 500 signal and improve the Signal to Noise Ratio (SNR). Depending on the impedance range and frequencies of interest, these additional accessories may not be required. They are highly recommended for impedance measurement in mΩ range or below.

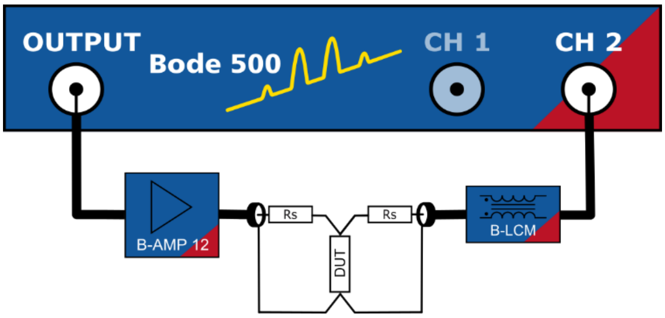


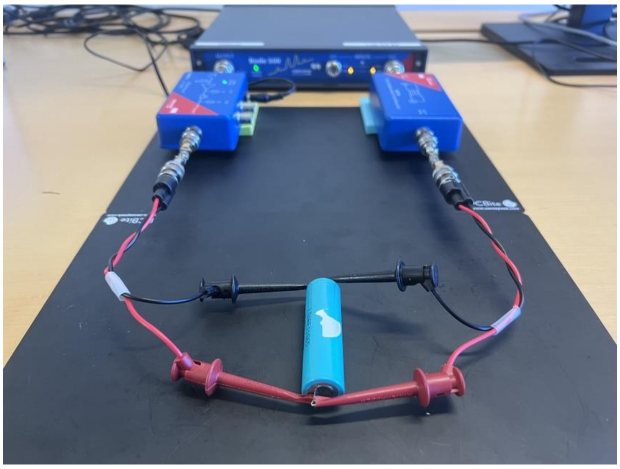
Figure 3: Battery measurement setup with Bode 500, B-AMP 12 and B-LCM.

3.3 Physical Setup and Recommendations

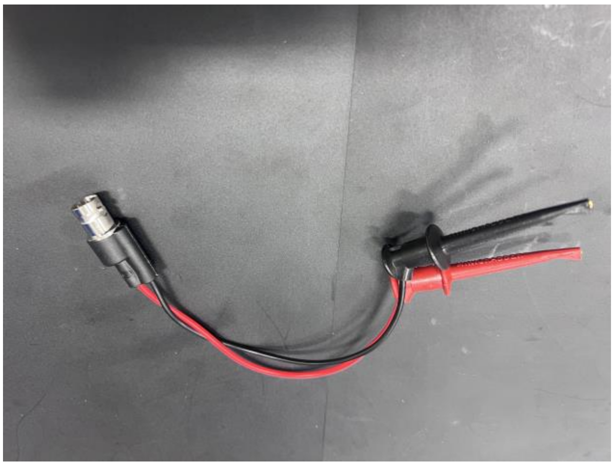
The measurement setup consisted of Bode 500, B-LCM, B-AMP 12, and two 500 Ω resistors soldered on a PCB with SMA connectors (see Figure 4c). The influence of the setup can be significant and needs to be considered when measuring very low impedances. Each connection component carries its own impedance that adds to the actual measurement. Below are a few recommendations that need to be considered for the setup.

- Minimize the distance the signal travels between the Bode 500 and DUT.
- Use coaxial connectors and cables like SMA or BNC connectors if possible.
- Avoid loops in cables and keep non-coaxial cabling as short as possible.
- If the signal and return cables are separate, then twist the two cables together to minimize electromagnetic coupling.

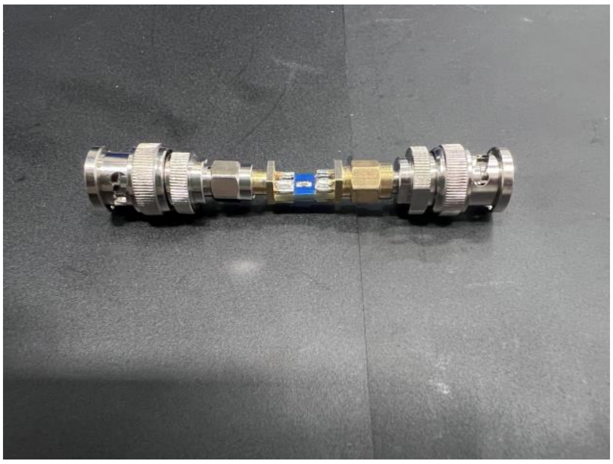
All the components in the setup were directly connected with various adaptors (Figure 4). The grabber hook test leads were the only wire components in the setup.



(a)



(b)



(c)

Figure 4: (a) The complete measurement setup, (b) grabbers to BNC connectors, (c) 500 Ω resistors.

3.4 Bode Analyzer Suite Configuration

The BAS was set up to measure the frequency range from 1 Hz to 1 MHz. This frequency range will sufficiently cover the low and high-frequency characteristics of the battery. If the application requires it to go lower or higher in the frequency range, the Bode 500 has the capability to measure from 10 mHz[1] to 450 MHz. There are three settings that require adjusting depending on the measurement needs: source level, number of points per measurement, and receiver bandwidth. These settings vary according to the measurement requirements. Below are the criteria to consider when setting up these variables.

- **Source level:** The source level is the power of the Bode 500 output. To have the correct source level, perform multiple measurements with the same setup (Figure 4a) to determine if the measurement results differ with the change in source level. Reduce the source level until the measurement does not change with the source level.
- **Number of Points:** The number of points in the BAS are the points measured at each measurement sweep. The higher the number of points the better the frequency-resolution of the graph but also increase in measurement time. Longer time can lead to changes in the DUT while under test and could lead to changes in the measurement.
- **Receiver Bandwidth:** The receiver bandwidth is the range of frequencies the Bode 500 will measure around the frequency of interest. Lowering the bandwidth will reduce noise but increase measurement time.

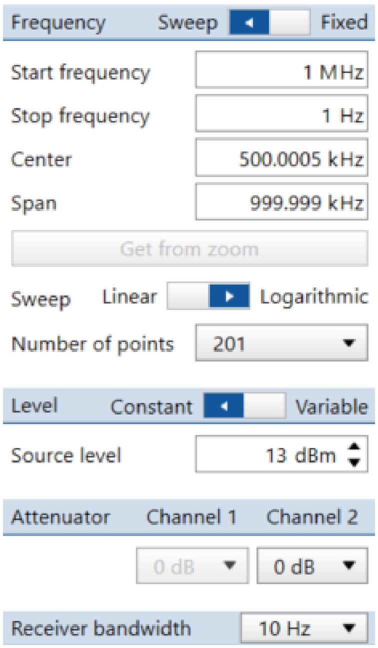


Figure 5: BAS settings for Lithium-Ion battery measurement.

[1] Up to BAS 3.51, the lowest frequency of Bode 500 is 1 Hz.

3.5 Calibration

The calibration can be performed in two ways: Thru calibration and Open/Short/Load (OSL) calibration. The Thru calibration is used to remove the gain and phase error from the setup, which is the attenuation of the signal due to the setup. OSL calibration eliminates parasitic errors, including setup inductance and capacitance. The OSL calibration must be highly accurate to minimize errors in the measurements. Due to its simplicity and since the measurement is expected to be in lower mΩ range, the Thru calibration was performed with the following setup in Figure 6. For more information on calibration methods, please refer to the application note "Impedance Measurements using the Bode 100" on our website or contact us at support@omicron-lab.com.

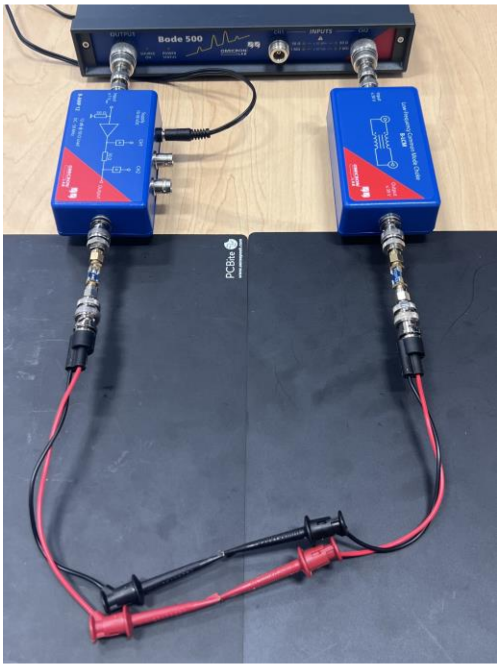


Figure 6: Thru calibration setup for Bode 500.

4 Results

The Bode plot in Figure 7 below shows the measurement result of the Lithium-Ion battery with impedance magnitude on the y-axis and frequency on the x-axis.

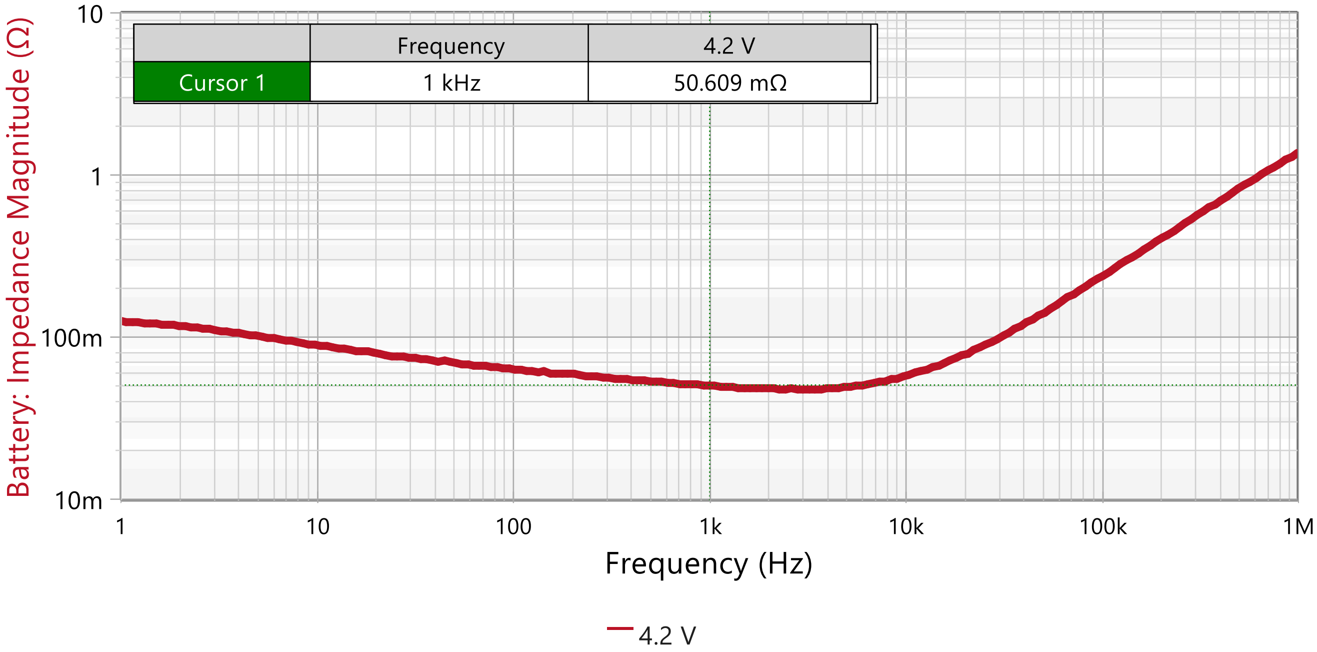


Figure 7: Bode plot of Lithium-Ion battery at 4.2 V.

The impedance of the battery is changing as the frequency increases. At the lower frequencies, the impedance decreases as the frequency increases, indicating capacitive behavior. At 1 kHz, the impedance is ~50 mΩ. Therefore, lower than 70 mΩ, as mentioned in Table 1. Around 6 kHz, the impedance begins to rise, showing inductive behavior.

The Lithium-Ion battery was also measured at various voltage levels. The Bode plot in Figure 8 shows a decrease in impedance below 100 kHz as the voltage increases. The impedance of the battery was given as less than 70 mΩ at 1 kHz in the data sheet and the measurement showcases it at three different voltage levels. This also highlights the difficulty of having an exact impedance of the battery since it will change according to its charging state.

Table 2: Impedance value at 1 kHz at various voltages.

Impedance Value at 1 kHz Frequency	
Voltage (V)	**Impedance (mΩ)**
2.5	55.08
3.7	53.06
4.2	50.61

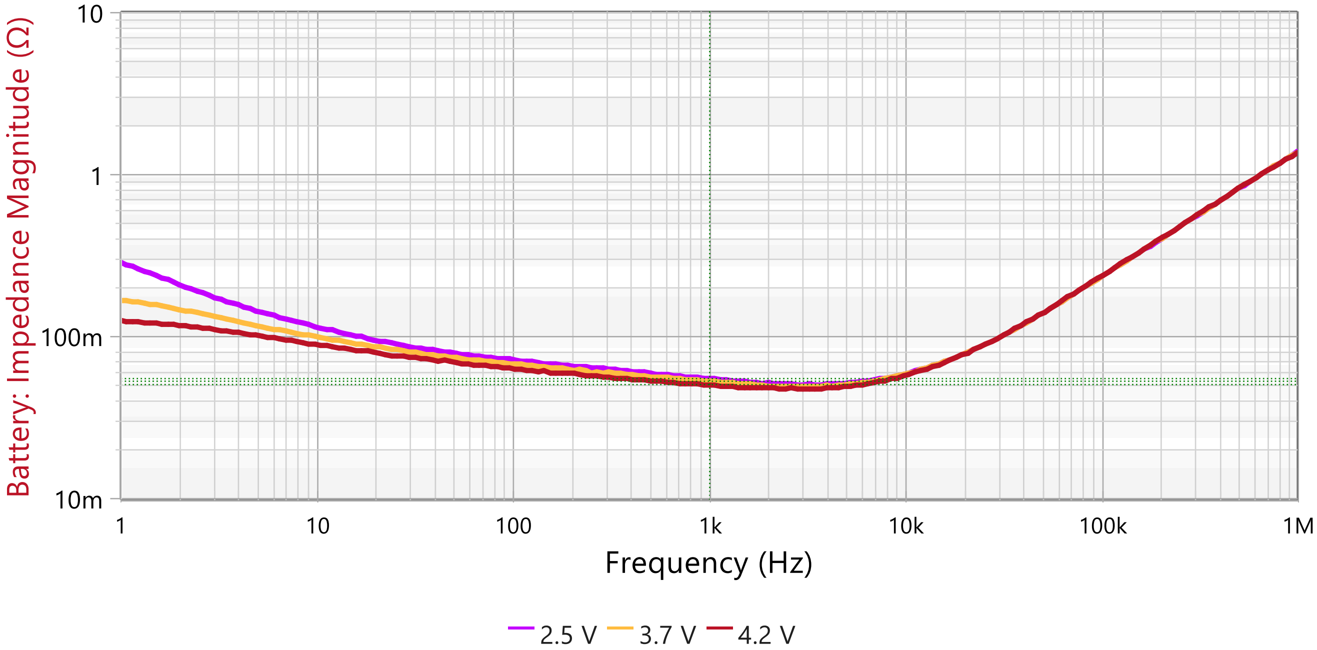


Figure 8: Lithium-Ion battery impedance at various voltages.

5 Summary

In this application note, we successfully conducted an EIS measurement of a Lithium-Ion battery using the Shunt-Thru with Series Resistance setup. The Bode 500 was able to perform a reliable measurement in the mΩ range and produce results with excellent resolution. The DUT was tested under three different voltages, and the results showed a difference in the measurement and matched the datasheet values.

6 References

[1] "LG ICR18650E1 Datasheet," Datasheet4U. Accessed: Feb. 26, 2025. [Online]. Available: https://datasheet4u.com/datasheet-pdf/LG/ICR18650E1/pdf.php?id=1097178

[2] W. Luo, A. U. Syed, J. R. Nicholls, and S. Gray, "An SVM-Based Health Classifier for Offline Li-Ion Batteries by Using EIS Technology," *J. Electrochem. Soc.*, vol. 170, no. 3, p. 030532, Mar. 2023, doi: 10.1149/1945-7111/acc09f.

[3] "Measuring Battery Impedance: Methods & Best Practices | Signal Integrity Journal." Accessed: Jan. 14, 2025. [Online]. Available: https://www.signalintegrityjournal.com/articles/3754-measuring-battery-impedance

[4] E. Barsoukov and J. R. Macdonald, Eds., "Impedance Spectroscopy," in *Impedance Spectroscopy*, 1st ed., Wiley, 2005. doi: 10.1002/0471716243.fmatter.

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