

FOUR-WIRE CONNECTION FOR PERFORMANCE MEASUREMENTS

Achieving Accurate Testing of Advanced Energy Storage Devices

Summary

This paper demonstrates the critical importance of proper electrical connections when measuring the performance of low-impedance, high-current devices. As energy storage technology advances, devices exhibit increasingly lower internal impedances and higher current capabilities, making connection methodology a determining factor in measurement accuracy. While two-wire and pseudo four-wire connections may suffice for preliminary assessments of older, high-impedance devices, only true four-wire (Kelvin) connections deliver the accuracy and reproducibility required for modern energy storage devices. Through theoretical analysis and experimental validation, we demonstrate that pseudo four-wire connections—despite appearing adequate—introduce significant measurement errors primarily due to unpredictable contact resistance. The data presented shows capacity measurement errors exceeding 1.35% and substantial impedance measurement discrepancies when improper connection methods are employed. For laboratories investing in precision test equipment, implementing true four-wire connections represents the most cost-effective method to ensure measurement reliability and data integrity.

1. Introduction

The rapid advancement of Energy Storage Device (ESD) technology has fundamentally changed the requirements for accurate performance testing. Modern devices possess significantly lower internal impedances and substantially higher current capabilities compared to their predecessors from just a few years ago. This technological evolution has exposed a critical weakness in conventional testing methodologies: connection techniques that were once adequate now introduce unacceptable measurement errors.

Historically, the testing industry has tolerated imprecise connection methods because the high internal impedances and limited current capabilities of earlier devices rendered connection-related errors negligible. The measurement inaccuracies introduced by suboptimal connections were simply too small to matter in practical applications. However, this tolerance is no longer justified in today's technological landscape.

The marketplace now features numerous manufacturers making aggressive performance claims for their energy storage products. During Maccor's development of the frequency response analyzer, the profound significance of proper four-wire connections became unmistakably apparent. Rigorous testing revealed that many of these performance claims fall short when devices are evaluated using correct measurement techniques. Critically, this measurement error affects not only impedance analyzers but also extends to precision laboratory equipment across the testing spectrum.

Organizations invest substantial capital in sophisticated test equipment, rightfully expecting reliable performance. While modern test equipment is indeed highly reliable when properly utilized, even the most advanced instruments yield unreliable data when connected improperly to the device under test. The connection interface—often overlooked as a mere detail—can completely undermine the accuracy of otherwise excellent measurement systems.

This paper systematically examines three connection methodologies: two-wire, pseudo four-wire, and true four-wire connections. Through theoretical analysis and experimental validation, we demonstrate why true four-wire connections are essential for accurate characterization of modern energy storage devices.

2. Two-Wire Measurements

2.1 Configuration and Limitations

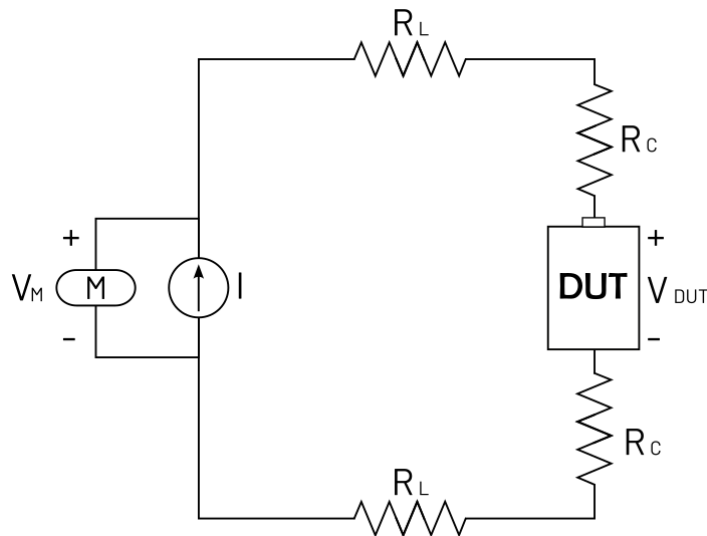
The two-wire measurement represents the simplest connection methodology, utilizing a single pair of conductors that simultaneously carry test current and serve as the voltage measurement path. This configuration provides no separation between the current-carrying circuit and the potential measurement circuit, fundamentally limiting measurement accuracy.

Various IR (current × resistance) compensation techniques have been developed to mathematically correct for the resistance introduced by this measurement method. However, these compensation approaches require assumptions about lead and contact resistance that may not remain valid throughout a test, particularly as connections experience thermal cycling or mechanical stress.

The two-wire connection introduces the highest measurement error of all connection types discussed in this paper. For devices with high internal resistance (typically greater than 10 Ω) or applications involving minimal current flow, this technique may provide acceptable results. However, for modern, low-impedance energy storage devices operating at high currents, two-wire connections are fundamentally inadequate.

2.2 Mathematical Analysis

The two-wire connection is illustrated below:



The measured voltage in a two-wire configuration can be expressed as:

$$V_M = I \cdot R_L + I \cdot R_C + V_{DUT} + I \cdot R_L + I \cdot R_C \text{ (Equation 1)}$$

Where:

- V_M = measured voltage at the test equipment terminals
- I = test current flowing through the circuit
- R_L = resistance of each lead wire
- R_C = contact resistance at each connection point
- V_{DUT} = actual potential across the device under test

Assuming symmetric connections where lead resistance and contact resistance are approximately equal for both the working and counter electrodes, Equation 1 simplifies to:

$$V_M = 2I \cdot (R_L + R_C) + V_{DUT} \text{ (Equation 2)}$$

Since the combined lead and contact resistance ($R_L + R_C \neq 0$), we arrive at the fundamental problem:

$$V_M \neq V_{DUT}$$

2.3 Practical Implications

The consequences of this inequality are significant and directionally dependent on current flow:

During charging (positive current): The measured voltage V_M is considerably higher than the actual device voltage V_{DUT} . The test equipment "sees" a higher voltage than actually exists across the device terminals. Consequently, the equipment terminates charging prematurely, believing the target voltage has been reached when, in reality, the device remains undercharged. This results in incomplete charging cycles and artificially reduced capacity measurements.

During discharging (negative current): The measured voltage V_M is lower than the actual device voltage V_{DUT} . The test equipment perceives the device as more depleted than it actually is, potentially terminating the discharge cycle before the true endpoint is reached, or conversely, allowing over-discharge if the equipment compensates incorrectly.

In practical applications, the combined lead and contact resistance can be substantial. Lead resistance, while predictable and calculable based on wire gauge and length, typically contributes 5-20 milliohms per connection. Contact resistance, however, is highly variable and can range from a few milliohms to over 100 milliohms depending on connection quality, surface oxidation, mechanical pressure, and thermal conditions. This variability makes two-wire measurements not only inaccurate but also irreproducible.

3. Pseudo Four-Wire Connections

3.1 Configuration and Common Misconceptions

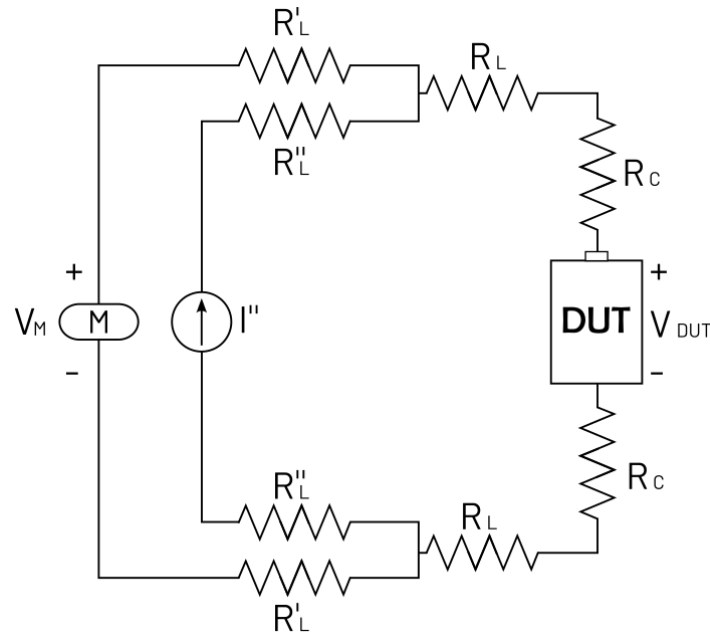
The pseudo four-wire connection represents an attempt to improve upon two-wire methodology by employing four separate conductors. However, despite using four wires, this configuration fails to achieve true four-wire performance because all four conductors ultimately connect to only two contact points on the device under test. This subtle but critical distinction means that pseudo four-wire connections retain many of the fundamental limitations of two-wire systems.

This connection method can produce acceptable results for high-resistance devices (typically those with internal resistance exceeding 10 Ω). However, as previously discussed, technological advancement has driven device impedances progressively lower while simultaneously increasing current capabilities. This evolution renders pseudo four-wire techniques increasingly inadequate for modern applications.

The pseudo four-wire configuration is particularly insidious because it appears to implement proper measurement technique while actually introducing significant errors. Many testing laboratories believe they are using "four-wire" connections when they are, in fact, using pseudo four-wire configurations that compromise measurement accuracy.

3.2 Mathematical Analysis

The illustration below shows a typical pseudo four-wire connection, where four leads are employed but converge to two contact points before reaching the device under test:



From this configuration, we derive the following voltage relationship:

$$V_M = 2(I' \cdot R_L' + (I' + I'') \cdot R_L + (I' + I'') \cdot R_C) + V_{DUT} \text{ (Equation 3)}$$

Where:

- V_M = measured voltage at the test equipment
- I' = current in the voltage sense circuit
- I'' = test current through the device
- R_L' = lead resistance of the potential measurement circuit before connection to current-carrying wires
- R_L = lead resistance of the shared conductor section
- R_C = contact resistance at the device interface
- V_{DUT} = actual potential of the device under test

In precision measurement equipment, the voltage sense circuit is designed with extremely high input impedance, causing the sense current I' to approach zero (typically in the

picoampere range). Under this condition, the term $2(I \cdot R_L)$ becomes negligible and approaches zero.

This leaves us with:

$$V_M \approx 2(I \cdot R_L + I \cdot R_C) + V_{DUT} \text{ (Equation 4)}$$

Simplifying further:

$$V_M \approx 2I(R_L + R_C) + V_{DUT} \text{ (Equation 5)}$$

3.3 Critical Analysis of Error Sources

While the lead resistance R_L in the shared conductor section can be measured and potentially compensated for, the contact resistance R_C remains fundamentally problematic. Contact resistance is:

- **Unpredictable:** Varies with surface conditions, oxidation, contamination, and mechanical stress
- **Unstable:** Changes with temperature, vibration, and connection aging
- **Unmeasurable in situ:** Cannot be accurately determined during actual device testing
- **Highly variable:** Can range from milliohms to hundreds of milliohms

The directional effects mirror those observed in two-wire connections:

During charging (positive current I): The measured voltage V_M exceeds the actual device voltage V_{DUT} , causing premature charge termination and incomplete charging.

During discharging (negative current I): The measured voltage V_M is lower than the actual device voltage V_{DUT} , creating uncertainty about the true state of charge and potentially allowing over-discharge.

3.4 Distinguishing Pseudo Four-Wire from Two-Wire

The key distinction between two-wire and pseudo four-wire connections lies in the magnitude of R_L —specifically, which portion of the lead resistance contributes to measurement error. In a two-wire system, the entire lead length from equipment to device contributes to error. In a pseudo four-wire system, only the shared conductor section (from the point where sense and current wires join to the device contact) contributes lead resistance error.

However, this distinction provides minimal practical benefit because, as experimental data will demonstrate, contact resistance R_C typically contributes far more error than lead resistance R_L . Since both connection types suffer equally from contact resistance errors, the pseudo four-wire configuration offers only marginal improvement over two-wire connections for low-impedance devices.

4. True Four-Wire (Kelvin) Connections

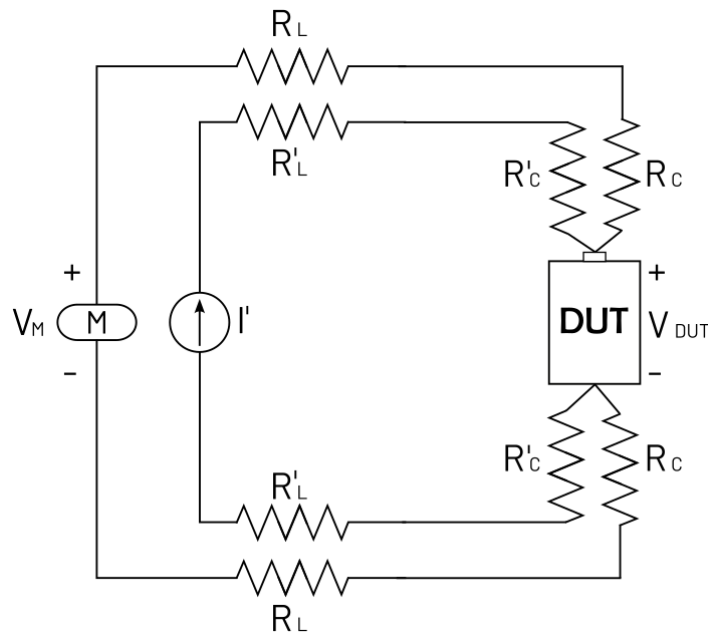
4.1 Configuration and Fundamental Principle

The true four-wire connection, also known as a Kelvin connection, represents the gold standard for precision electrical measurements. This configuration employs four completely separate conductors: two leads supply test current to the device, while two entirely independent leads sense the voltage drop directly across the device terminals. Critically, the voltage sense leads make separate, dedicated contact with the device under test, completely independent of the current-carrying conductors.

This separation is the key to eliminating measurement errors. In an ideal voltage measurement circuit—such as those found in precision laboratory equipment—the sense current exists in the picoampere range and can be effectively ignored in calculations. Modern digital voltmeters and precision measurement systems typically exhibit input impedances exceeding 10 GΩ, ensuring that sense current remains negligible.

4.2 Mathematical Analysis

The true four-wire connection is illustrated below:



From this configuration, we obtain:

$$V_M = 2 \cdot I \cdot (R_L + R_C) + V_{DUT} \text{ (Equation 6)}$$

Where:

- V_M = measured voltage

- I = voltage sense current (in the picoampere range)
- R_L = lead resistance of the potential measurement circuit
- R_C = contact resistance of the voltage sense connections
- V_{DUT} = actual potential of the device under test

Since precision measurement equipment maintains sense current at negligible levels, $I \rightarrow 0$, the equation simplifies dramatically:

$$V_M = V_{DUT} \text{ (Equation 7)}$$

This elegant result demonstrates that the measured voltage equals the actual device voltage, independent of:

- Test current magnitude
- Lead wire resistance
- Contact resistance at current-carrying connections
- Device impedance
- Temperature variations affecting resistance

4.3 Why True Four-Wire Connections Eliminate Error

The true four-wire configuration achieves measurement accuracy through several key mechanisms:

1. Current Path Isolation: Test current flows exclusively through the current-carrying leads and their associated contacts. Any voltage drop across these leads and contacts (which can be substantial at high currents) does not affect the voltage measurement.

2. Negligible Sense Current: The voltage sense leads carry virtually no current (typically < 1 nanoampere). Even if these leads have significant resistance or poor contact, the voltage drop ($V = I \times R$) remains negligible because current I is essentially zero.

3. Direct Device Measurement: The voltage sense leads connect directly to the device terminals, measuring the actual potential difference across the device without any intervening voltage drops from current flow.

4. Independence from Test Conditions: Because sense current is negligible, the measurement remains accurate regardless of:

- How much test current flows through the device
- How low the device impedance becomes
- How high the current-path contact resistance may be
- Temperature changes affecting conductor resistance

4.4 Practical Implementation Considerations

Implementing true four-wire connections requires attention to several practical details:

Contact Point Separation: Voltage sense contacts must be physically separate from current-carrying contacts. They should connect as close as possible to the actual device terminals, ideally on the device side of any current-carrying connection hardware.

Connection Hardware: Specialized test fixtures with dedicated current and voltage contacts ensure proper four-wire implementation. Simple alligator clips or single-point connections cannot achieve true four-wire performance.

Verification: The effectiveness of a four-wire connection can be verified by measuring the voltage drop across the current-carrying leads separately. In a proper four-wire setup, this voltage drop should have no effect on the device voltage measurement.

5. Experimental Results

To validate the theoretical analysis and quantify the practical impact of connection methodology, we conducted systematic experiments comparing pseudo four-wire and true four-wire connections under controlled conditions. These experiments utilized identical test equipment, identical devices, and identical test protocols—with connection methodology as the sole variable.

5.1 Capacity Measurement Experiment

Experimental Design:

Twenty identical cells were subjected to discharge testing using the same precision test equipment. The cells were randomly divided into two groups of ten. Group A was tested using pseudo four-wire connections, while Group B was tested using true four-wire connections. All other test parameters remained constant:

- Initial voltage: 1.61 V (nominal)
- Discharge current: 1.0 A (DC)
- Cutoff voltage: 0.5 V
- Temperature: 25°C ± 1°C
- Test equipment: Identical units from the same calibration batch

Connection Characterization:

Prior to testing, we measured the electrical characteristics of both connection types:

- Lead resistance (R_L): < 10 mΩ per lead
- Contact resistance (R_C): approximately 50 mΩ per contact (pseudo four-wire)
- Contact resistance (R_C): < 5 mΩ per contact (true four-wire voltage sense)

Results:

The experimental data revealed a systematic and significant difference between the two connection methodologies:

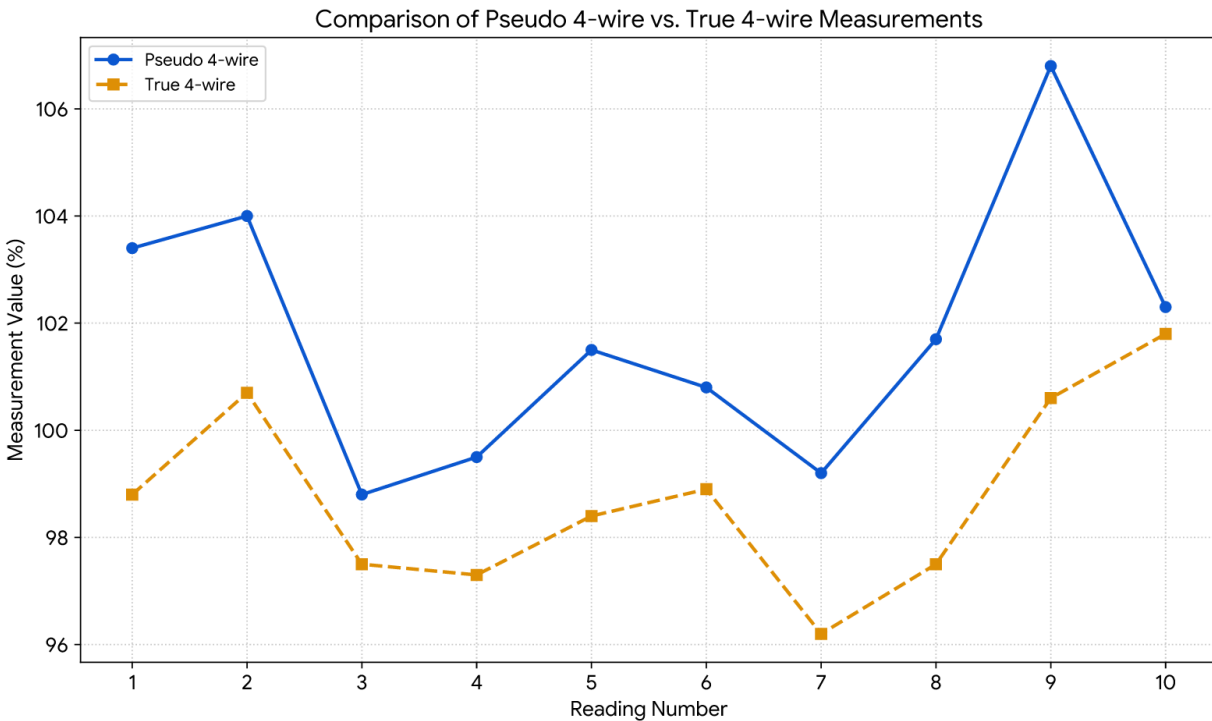


Figure 1: Capacity measurements for 20 identical cells discharged from 1.61 V to 0.5 V at 1 A DC current. Blue bars represent pseudo four-wire connections; red bars represent true four-wire connections.

Key Findings:

1. **Systematic Capacity Shift:** Cells tested with pseudo four-wire connections exhibited measured capacities averaging 1.35% higher than those tested with true four-wire connections.
2. **Error Mechanism:** This capacity increase is not real—it represents measurement error. The pseudo four-wire configuration caused the test equipment to measure a voltage 50 mV higher than the actual device voltage (due to $I \times R_c = 1 \text{ A} \times 50 \text{ m}\Omega = 50 \text{ mV}$). Consequently, when the equipment believed it had reached the 0.5 V cutoff, the actual device voltage was only 0.45 V. The cells were over-discharged by 50 mV, yielding artificially inflated capacity measurements.
3. **Contact Resistance Dominance:** The lead resistance ($< 10 \text{ m}\Omega$) contributed less than 10 mV of error, while contact resistance (50 m Ω) contributed 50 mV—five times more. This confirms that contact resistance, not lead resistance, is the primary error source in pseudo four-wire connections.
4. **Reproducibility:** The true four-wire measurements showed tighter clustering (lower standard deviation), indicating superior reproducibility in addition to improved accuracy.

5.2 Impedance Spectroscopy Experiment

Experimental Design:

To evaluate the impact of connection methodology on AC impedance measurements, we performed electrochemical impedance spectroscopy (EIS) using a frequency response analyzer. Two representative cells were each tested twice: once with a pseudo four-wire connection and once with a true four-wire connection.

Test Parameters:

- Frequency range: 100 kHz to 0.1 Hz
- AC amplitude: 10 mV RMS
- DC bias: Open circuit voltage
- Data points: 10 points per decade (logarithmic spacing)

Results:

The impedance spectra revealed dramatic differences between connection methodologies:

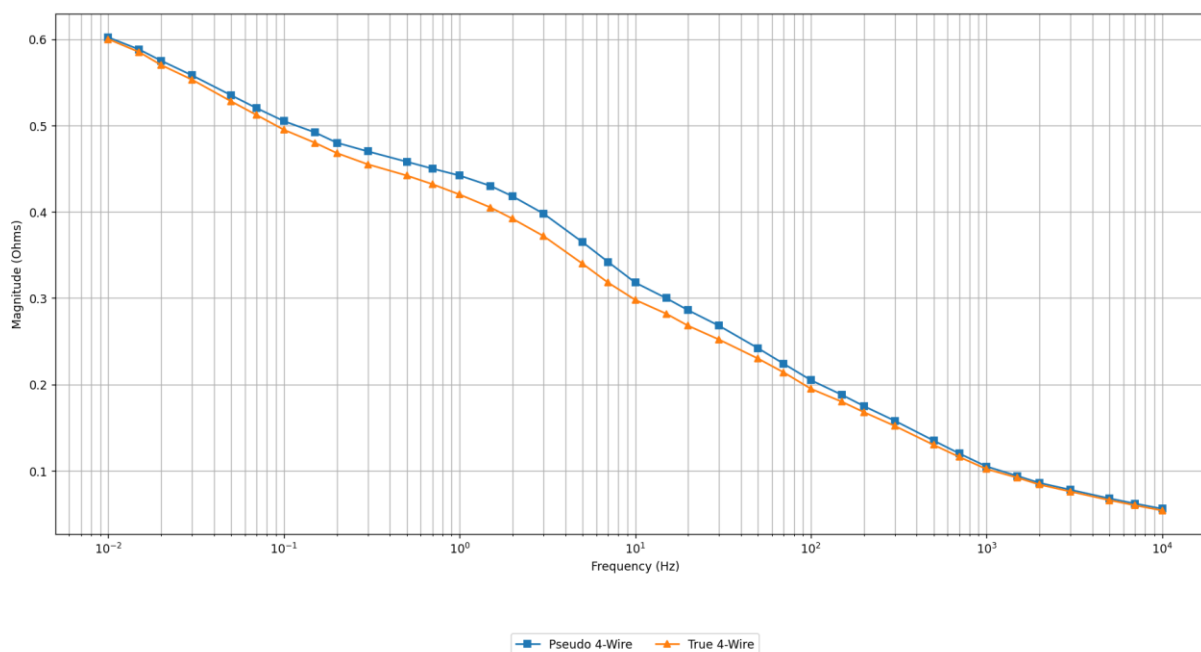


Figure 2: Electrochemical impedance spectroscopy results for two cells. Each cell was tested with both pseudo four-wire (dashed lines) and true four-wire (solid lines) connections. Frequency range: 100 kHz to 0.1 Hz.

Key Findings:

1. **High-Frequency Offset:** At high frequencies (100 kHz), where the measurement is dominated by resistive components, pseudo four-wire connections showed a

systematic offset of approximately 50-60 m Ω —consistent with the contact resistance measured in the DC experiment.

2. **Impedance Magnitude Error:** Throughout the frequency spectrum, pseudo four-wire connections yielded higher impedance values. This error is particularly problematic because it suggests the device has higher internal resistance than it actually possesses, leading to incorrect conclusions about device performance and health.
3. **Spectral Distortion:** The shape of the impedance spectrum was subtly altered by pseudo four-wire connections, potentially affecting the interpretation of electrochemical processes occurring within the device. Features such as charge transfer resistance and diffusion-limited behavior appeared exaggerated.
4. **Consistency Across Devices:** Both cells showed similar error patterns, confirming that the measurement artifact is systematic and reproducible, not a random anomaly.

5.3 Implications for Device Characterization

These experimental results have profound implications for energy storage device testing:

Performance Specifications: Manufacturers using pseudo four-wire connections may inadvertently report inflated capacity values and higher impedance than their devices actually exhibit. This creates discrepancies between manufacturer specifications and independent test results.

Quality Control: Production testing using improper connections may pass defective devices or reject acceptable ones due to measurement errors comparable to actual device variation.

Research and Development: Impedance spectroscopy is widely used to understand electrochemical mechanisms. Connection-induced errors can lead to incorrect mechanistic interpretations and flawed model development.

Comparative Testing: When comparing devices from different manufacturers or different production batches, connection methodology must be consistent. Mixed methodologies introduce systematic errors that can completely obscure real performance differences.

Lifetime Studies: Capacity fade and impedance growth are key indicators of device aging. Connection-related measurement errors of 1-2% can mask or exaggerate actual degradation, leading to incorrect lifetime predictions.

6. Conclusion and Recommendations

6.1 Summary of Key Findings

This investigation has demonstrated through both theoretical analysis and experimental validation that connection methodology profoundly impacts the accuracy of energy storage device measurements. The key conclusions are:

1. **Two-wire connections** introduce unacceptable errors for modern, low-impedance devices and should be avoided in precision applications.
2. **Pseudo four-wire connections**, despite appearing to implement proper measurement technique, introduce significant systematic errors primarily due to unpredictable contact resistance. Our experiments documented capacity measurement errors exceeding 1.35% and substantial impedance measurement discrepancies.
3. **True four-wire (Kelvin) connections** eliminate measurement errors by separating current-carrying and voltage-sensing paths, providing accuracy independent of test current, device impedance, lead resistance, and contact resistance.
4. **Contact resistance**, not lead resistance, is the dominant error source in pseudo four-wire connections. Measured at approximately 50 mΩ in our experiments, contact resistance contributed five times more error than lead resistance.

6.2 The Industry Misconception

The testing industry has been operating under a critical misconception: that pseudo four-wire connections provide adequate accuracy for modern device testing. This belief likely originated when energy storage devices had sufficiently high internal impedance that connection-related errors remained negligible. However, technological advancement has invalidated this assumption.

Many laboratories believe they are implementing "four-wire" connections when they are actually using pseudo four-wire configurations. This misunderstanding is perpetuated by:

- Ambiguous terminology in equipment manuals
- Test fixtures that appear to provide four-wire connections but actually implement pseudo four-wire configurations
- Lack of awareness about the critical distinction between pseudo and true four-wire methodologies

6.3 Cost-Benefit Analysis

Organizations invest substantial capital in precision test equipment—often hundreds of thousands of dollars for advanced battery testing systems and impedance analyzers. However, this investment is undermined if improper connections compromise measurement accuracy.

Implementing true four-wire connections represents the most cost-effective method to ensure measurement reliability. The incremental cost of proper connection hardware (specialized test fixtures, appropriate cabling, and connection verification tools) is negligible compared to:

- The cost of the test equipment itself
- The value of accurate data for product development and quality control
- The potential liability from releasing products with incorrectly characterized performance
- The competitive disadvantage of making decisions based on flawed data

6.4 Practical Recommendations

Based on this analysis, we recommend the following best practices for energy storage device testing:

For Testing Laboratories:

1. **Audit existing test setups** to determine whether true four-wire or pseudo four-wire connections are currently implemented. Many laboratories will discover they are using pseudo four-wire configurations.
2. **Upgrade test fixtures** to provide separate, dedicated contact points for current delivery and voltage sensing. This may require custom fixture design for specific device form factors.
3. **Implement connection verification procedures** as part of routine test setup. Measure the voltage drop across current-carrying leads separately to confirm it does not affect device voltage measurements.
4. **Document connection methodology** in test reports and data sheets. Specify whether true four-wire connections were used, as this information is essential for data interpretation and comparison.
5. **Train personnel** on the distinction between pseudo and true four-wire connections. Ensure that technicians understand the importance of proper connection implementation.

For Equipment Manufacturers:

1. **Design test equipment** with true four-wire capability as standard, not optional. Provide clear guidance on proper connection implementation.
2. **Supply appropriate test fixtures** that ensure true four-wire connections for common device form factors.
3. **Clarify terminology** in documentation. Explicitly distinguish between pseudo four-wire and true four-wire connections, and provide diagrams showing proper implementation.

For Device Manufacturers:

1. **Specify connection requirements** in test procedures and quality control protocols. Require true four-wire connections for all precision measurements.
2. **Design device terminals** to facilitate true four-wire connections. Consider providing separate current and voltage contact points on the device itself.
3. **Verify third-party test data** by confirming that proper connection methodology was used. Be skeptical of performance claims that cannot be reproduced with true four-wire connections.

For Researchers:

1. **Report connection methodology** in publications. Include sufficient detail for others to reproduce measurements accurately.
2. **Use true four-wire connections** for all impedance spectroscopy and precision voltage measurements. The small additional effort is justified by the substantial improvement in data quality.
3. **Re-evaluate historical data** that may have been collected using pseudo four-wire connections. Consider whether connection-related errors could affect conclusions.

6.5 Future Considerations

As energy storage technology continues to advance, the importance of proper connection methodology will only increase. Future devices with even lower impedances and higher current capabilities will be even more sensitive to connection-related errors. Additionally, emerging applications such as:

- Ultra-fast charging systems (requiring currents exceeding 100 A)
- High-power applications (electric vehicles, grid storage)
- Micro-devices with extremely low impedance ($< 1 \text{ m}\Omega$)

will demand rigorous attention to measurement technique.

The testing community must recognize that connection methodology is not a minor technical detail but rather a fundamental determinant of measurement accuracy. True four-wire connections should be considered mandatory, not optional, for precision characterization of modern energy storage devices.

6.6 Final Perspective

The transition from pseudo four-wire to true four-wire connections represents a paradigm shift in testing methodology—one that is essential for keeping pace with technological advancement. While this transition requires investment in new test fixtures and procedures, the alternative—continuing to generate inaccurate data with expensive precision equipment—is far more costly.



Organizations that implement true four-wire connections will gain competitive advantage through:

- More accurate product characterization
- Better quality control and reduced warranty costs
- Enhanced credibility of published performance specifications
- Improved research outcomes based on reliable data

The evidence presented in this paper demonstrates conclusively that true four-wire connections are not merely preferable but essential for accurate testing of modern energy storage devices. The question is not whether to implement true four-wire connections, but how quickly organizations can complete this critical transition.

About the Authors

Mike Sandoval, Vice President Business Development

Acknowledgments

The authors thank the Maccor engineering team for their contributions to the experimental work and for valuable discussions regarding measurement methodology.