APPLICATION NOTE

Solving Complex Test Challenges for Satellite Electrical Power Systems: Storage

Table of Contents

Satellite electrical power systems (EPS) play a crucial role in the success of satellite missions. They are responsible for ensuring a reliable and consistent supply of power to the satellite's subsystems in the harsh conditions of outer space. The storage aspect of EPS acts as a buffer between power generation and consumption. While there are various options for storing electrical energy, fuel cells and radioisotope power systems typically are reserved for specialized missions, whereas rechargeable battery systems commonly are used for most Earth-orbiting satellites. Although space applications have utilized multiple battery chemistries, contemporary spacecraft and satellites heavily rely on various lithium chemistries. Battery cell, module, and overall power-system design depend on numerous mission parameters, including satellite size, power requirements, orbital path, shading, and more. Despite utilizing lithium battery chemistries, their design differs significantly from those found in everyday electronics due to the harsh environment of space, the challenging journey into orbit, and the associated obstacles of space travel. Space conditions subject batteries to extreme temperatures, pressures, and physical stresses, requiring them to maintain optimal performance throughout long mission durations. In space, battery failure is unacceptable, as there is no cost-effective method to replace a deployed battery. Consequently, it's imperative that they undergo meticulous design, validation, and testing before launch.

Battery pack arrangement is based on a mission's specific needs. Smaller packs may consist of a single module, while larger packs may incorporate multiple modules to fulfill the voltage and power requirements outlined in the mission profile. In larger systems, the battery management systems (BMS) and cell management often are integrated per module, reducing weight and complexity by minimizing the amount of required electrical wiring. This configuration helps isolate BMS components from high-voltage buses, easing associated design and testing challenges. Mission requirements—ranging from small cube satellites to the International Space Station, which requires 90 kW of power—determine the satellite's bus voltage and its associated battery pack. Missions with greater power demands use higher bus voltages to reduce the current handling requirements, resulting in a lighter spacecraft. However, there are practical limits to bus voltage, as it's difficult to ensure isolation as system voltages exceed 150 VDC.

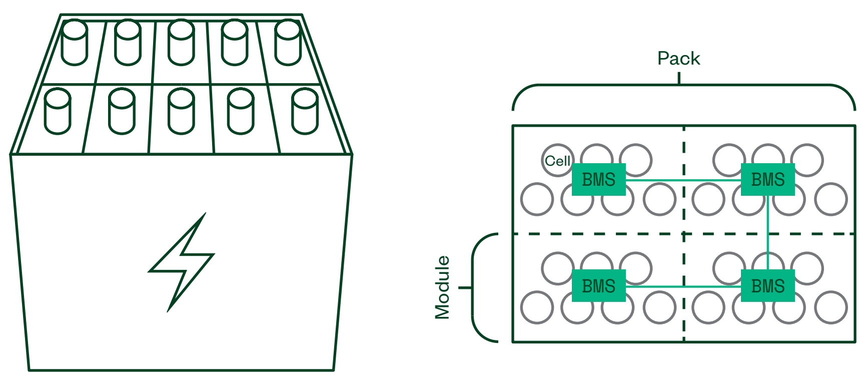


FIGURE 01

Battery Components

Batteries include:

- **Cells**—Cells serve as fundamental battery pack building blocks and are individually tested to assess performance and capacity.
- **Modules**—Modules are groups of cells connected in series and/or parallel configurations. They are tested to evaluate overall performance and capacity.
- **Packs**—Packs are collections of modules interconnected to form a complete battery system. They undergo testing to assess performance, capacity, and safety. In some designs, modules and packs are synonymous.

In addition to battery pack electrical characteristics, the physical design is equally crucial and must undergo validation. Module and pack layout needs to be optimized to fit within the spacecraft and satellite, minimizing assembly weight and maximizing physical robustness. Module assemblies undergo design verification tests (DVTs) to ensure that they meet operational requirements. These tests may include shaker table testing to validate the structural integrity of cell tabs, welds, separators, and holders; this ensures that they can withstand the journey into orbit, among other stress-inducing conditions. Modules are subject to these harsh conditions, inspected for damage, and retested to ensure their functionality.

Battery Test Challenges

The battery pack plays a vital role in the mission's success, and achieving an optimal design is crucial for avoiding potential issues and ensuring program success. The wide temperature variations and extensive range of pressures experienced during ground operations, launch, and orbit, combined with the loads and vibrations encountered on the journey to orbit, can significantly impact component operational life and performance. Ensuring the continued functionality of electrical storage systems during their deployment requires comprehensive ground testing to assess various performance parameters while simulating the harsh conditions of space and launch. This typically involves thermal vacuum test chambers, shock/vibration tables, and radiation testing. While these tests are standard for all space-bound components, batteries face additional concerns regarding performance degradation during cycling and usage, compared to solid-state components found in other parts of the electrical systems. Battery design and testing teams must strive to minimize cost, weight, and size while maximizing performance. With strict timelines and vehicle lifespan requirements, test teams ensure battery packs operate reliably and fail safely every time. These teams must validate their designs against the following requirements:

- **Safety**—The battery must maintain safety under all specified operating conditions. In the event of failure, it should gracefully handle all failure modes, whether caused by manufacturing defects, such as faulty cells or weak welds, or due to battery damage.
- **Performance**—The battery must meet performance design objectives, including charge time, peak energy transfer rates, and thermal stability over its operational lifespan.
- **Longevity**—The battery should retain a specific capacity over cycles defined by expected usage patterns and mission duration (e.g., retaining at least 80 percent of the original capacity after 2,500 charge cycles).

Battery characteristics necessitate numerous duplicate test cells for conducting long-term tests, which can be challenging to accelerate. This poses difficulties in managing the systems, test laboratories, and the resulting data. The evolving nature of test requirements increases the risk associated with closed, vendor-dependent test systems in terms of time to market and cost.

Most batteries employ a liquid electrolyte to facilitate electrochemical reactions and store electrical energy. The physical structure of these batteries is intricate, housing the anode and cathode while containing the liquid electrolyte. This design maximizes surface area and prevents electrode shorting, while enduring the effects of calendar aging, cycle aging, and the constantly changing operating environment of space. These factors necessitate extensive testing throughout the cell's lifespan until it reaches the point of failure. In battery labs, it is common to find cells that have been tested for more than a decade. Given that geostationary (GEO) satellites can remain operational for several decades, thorough battery cell testing comes as no surprise.

While GEO satellites can remain in orbit indefinitely, low Earth orbit (LEO) satellites have a significantly shorter lifespan before falling out of orbit (typically 7-10 years). Since LEO satellites have a shorter mission duration and often are deployed in large numbers within constellations, test coverage must be reduced to meet production volumes. However, the shorter lifecycle of LEO satellites introduces new challenges due to the sheer number of satellites and the need for accelerated development cycles. Given these challenges, smarter testing strategies leverage test data insights to focus on critical and statistical failure modes.

Battery Component Testing Methods

Using software-defined instruments can reduce overall test equipment costs by reusing equipment and measurement IP across validation and production testing lifecycles. Software-defined instruments provide flexibility in testing in that, a single piece of equipment performs multiple functions or standardizes hardware across an organization. In addition, software-defined instruments make it easy to automate tests to minimize manual measurements and support growing production volumes. With this flexibility, teams can choose hardware based on voltage, current, power, and timing requirements, while the remaining instrument behavior can be defined through software. For instance, source measure units (SMUs) can function as voltage or current sources controlled through software for a wide range of measurements. The timing and synchronization capabilities of PXI modules facilitate advanced functionalities such as waveform generation and acquisition for making complex measurements such as electrochemical impedance spectroscopy (EIS), cycle testing (Coulomb counting), and alternating current internal resistance (AC-IR). By changing the software, the same instrument can switch between different test methodologies. In addition to its parametric measurement capabilities, these instruments can run simulations using hardware-in-the-loop (HIL) software like VeriStand and perform test automation using tools such as LabVIEW and TestStand.

Cell Test/Measurements

The initial step in evaluating EPS storage capabilities involves qualifying individual cells. In qualification tests, specific cells and chemistry undergo system design or screening qualifications before assembling them into modules or packs. These tests encompass various parameters, including:

- **Open-Circuit Voltage (OCV)**—OCV represents the most fundamental testing method and can be conducted using various instruments based on specific measurement requirements. A commonly used instrument is a digital multimeter (DMM) due to its superior accuracy and isolation capabilities, especially when measuring large battery stacks. Although a DMM can support high-density configurations, it is often combined with a switch to enhance instrumentation density. Alternative instruments such as signal-conditioned DAQ (SC Express) may be more suitable where accuracy is not the primary concern, as they allow for simultaneous measurements while maintaining isolation. OCV serves multiple purposes including determining the state of charge (SoC) of a battery cell, identifying potential cell issues, and monitoring long-term cell performance. OCV measurement is a nondestructive approach that involves measuring the voltage of a battery cell without a load connected. Deriving SoC from OCV can be challenging due to their relatively flat discharge/charge curve in lithium chemistries. Charge counting often proves to be more reliable for cells, modules, or packs for accurate SoC determination.
- **Capacity**—Performing capacity testing on cells, modules, or packs requires utilizing current sources/sinks for charging and discharging the device under test (DUT). Modern lithium chemistries typically undergo capacity testing using constant current charge and discharge profiles for most of their capacity, transitioning to voltage control only during the final few percent of the charge/discharge process. The capacity is quantified as the integral of the current or voltage over the charge/discharge time, which can be calculated by the application software executing the test. The overall capacity is usually expressed in watt-hours (Wh) or ampere-hours (Ah), and discharge rates typically are indicated as a ratio relative to the cell/pack capacity. For example, a 1 Ah cell tested at 1A is referred to as a 1C rate test. Since the charge and discharge rates depend on the overall capacity of the DUT, the power requirements can vary significantly. For instance, single cells may require around 5 watts, while large packs may necessitate multiple kilowatts of test capability. Depending on the power requirements of the DUT, testing can utilize PXI SMUs, RMX source/loads, or large regenerative supplies from NH Research (NHR) for cell, module, or pack testing, respectively.

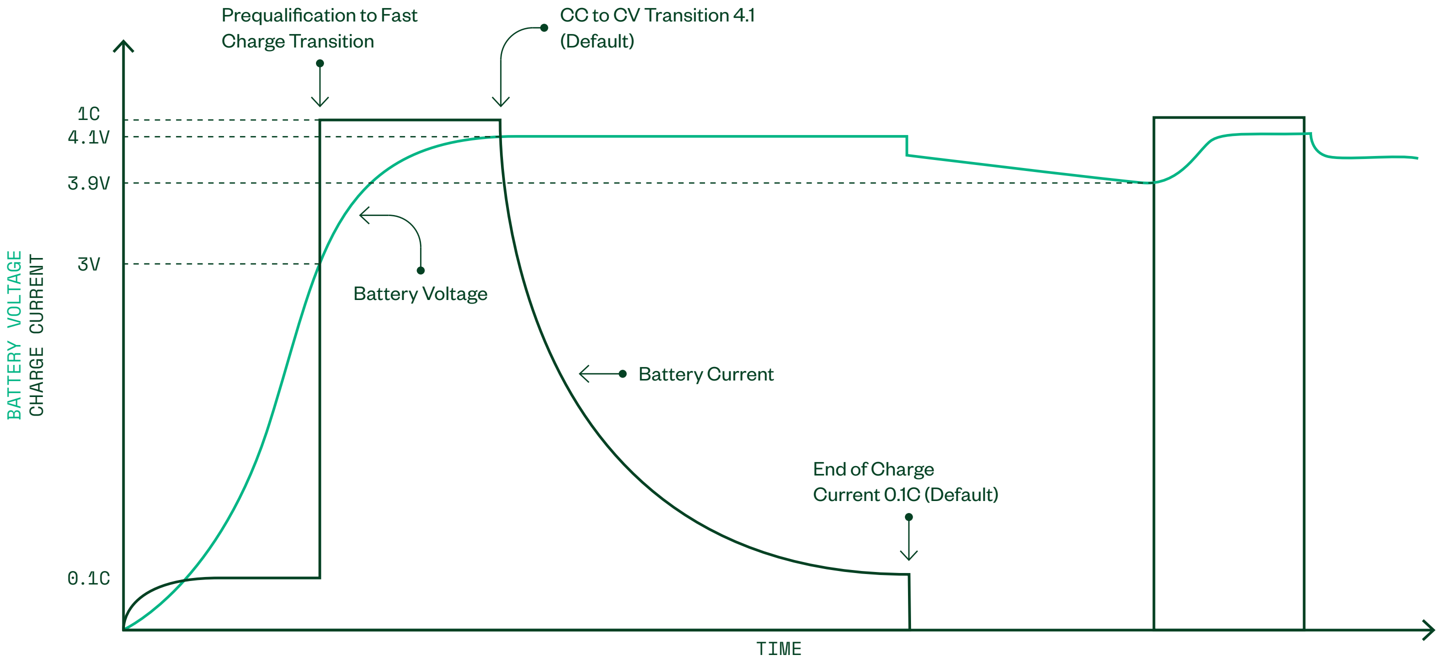


FIGURE 02

Example Charge Profile

- **Cycle Life**—Cycle life is the number of charge and discharge cycles a cell can undergo before its performance deteriorates below acceptable limits or it fails. Cycle-life testing involves analyzing the cell capacity as it undergoes repeated cycles under different conditions. Often, cycle life is characterized by the number of cycles required to reach 80 percent of the original capacity at a specific depth of discharge (DoD) and rate.
- **Voltage Drop Analysis**—Voltage drop analysis examines the magnitude of voltage drop that occurs when a cell is discharged at a specific rate. Teams can use various loads, such as PXI SMUs, RMX electronic loads, or NHR regenerative supplies based on the power requirements of the test setup. For precise and reliable measurements, it is crucial to configure the loads with remote sense capability. **Remote sense** helps ensure accurate voltage measurements by compensating for any voltage drops that may occur along the measurement leads.
- **AC-IR**—AC-IR analysis provides a nondestructive method for evaluating the health of a battery cell. This test involves applying a small AC current to the cell and measuring the resulting voltage drop. AC-IR is particularly important when assembling a module or pack by matching cells, as cells with similar parameters can distribute the load evenly, resulting in improved cycle life and overall performance. Typically, this test is conducted at the cell level and requires relatively low power levels. SMUs are well-suited for performing these measurements, as they can generate various voltage/current waveforms while accurately measuring the corresponding response. The internal resistance is then determined using Ohm's law based on the analysis of these waveforms.
- **Electrochemical Impedance Spectroscopy (EIS)**—EIS involves analyzing the frequency response of a sinusoidal voltage stimulus applied to a battery cell. Examining the phase of the resulting current response reveals valuable insights into the electrochemical properties of the cell. EIS finds applications in research, development, and quality control for electrode degradation, electrolyte changes, and phenomena detection at the electrolyte-electrode interface that can impact battery performance and longevity. While EIS commonly is used in cell research and development, it also can serve as an effective screening test in cell production. EIS measurements typically utilize specialized equipment, such as an impedance analyzer. However, NI's SMUs can provide equivalent measurements due to their ability to generate and acquire waveforms from the cell under test. NI's software-defined instrument approach extends the test capabilities of existing hardware, making EIS measurements possible without the need for additional dedicated equipment. EIS produces a Nyquist (Cole-Cole) plot, which is a graph that shows the impedance of a system at different frequencies. Impedance is a complex number that includes resistance and reactance. With the Nyquist plot, teams can analyze the different physical phenomena that occur within a battery, such as electrolyte resistance, charge transfer resistance, and diffusion resistance. The degradation level of a battery also can be evaluated by analyzing the charge transfer resistance on the Nyquist plot. For example, Figure 3A shows a Cole-Cole plot from an EIS test performed on a Lithium-ion battery with a frequency sweep from .1 Hz to 1 kHz; Figure 3B shows a high-frequency EIS test sweep from 1.1 kHz to 500 kHz.

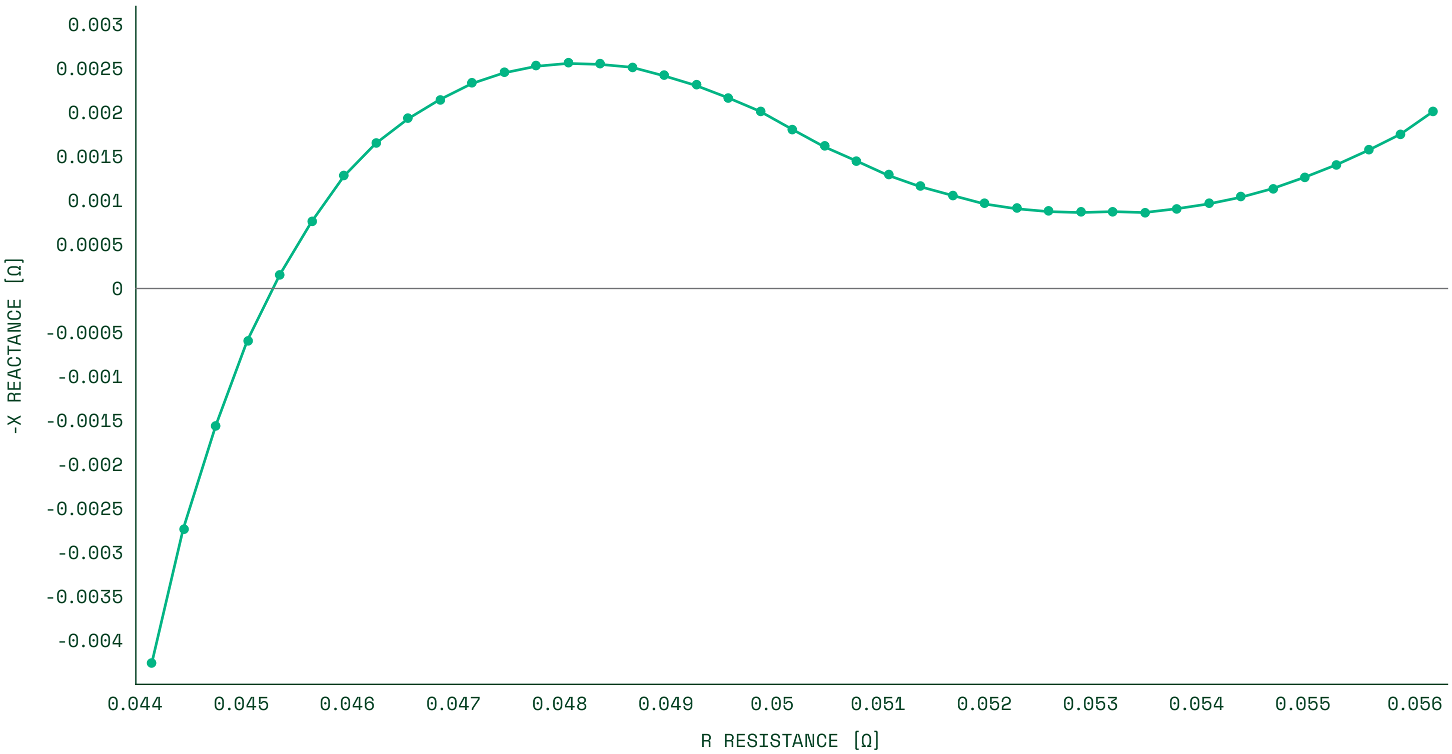


FIGURE 3A

An actual Cole-Cole plot produced by low-frequency EIS test of a lithium-ion battery using an NI PXI instrument.

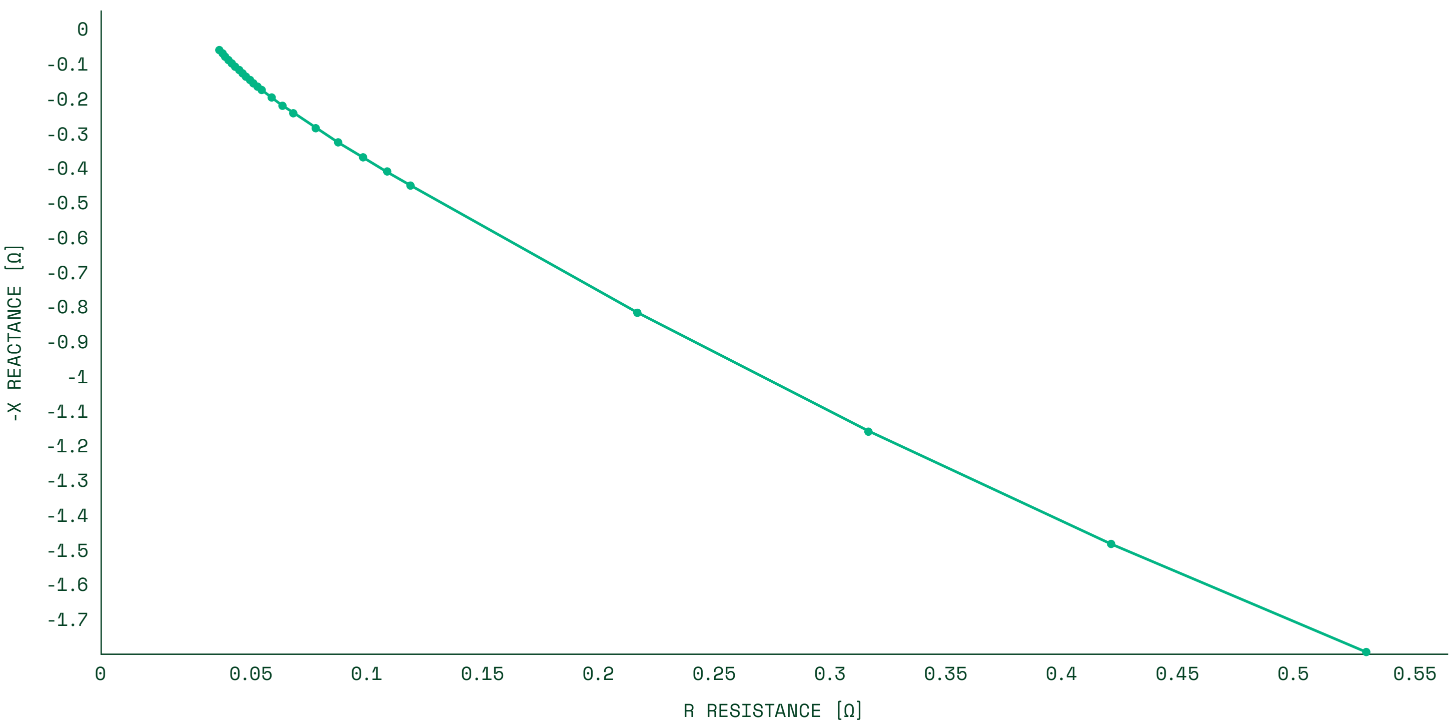


FIGURE 3B

An actual Cole-Cole plot produced by a high-frequency EIS test of a lithium-ion battery using an NI PXI instrument.

- **Failure Mode Tests**—Failure mode tests involve assessing and evaluating different potential failure modes that can occur in batteries. Understanding component failure modes is crucial for space assets as they are generally not serviceable once they have been deployed. While some satellites, such as the ISS, are more easily serviceable than other Earth satellites, failures pose a much larger risk—so failure modes must be well-understood. These tests are crucial for identifying and mitigating risks associated with battery operation. Several key battery failure modes for testing include:

  - **Overcharging/Overdischarging**—Although the BMS is designed to prevent these failure modes, instances of overcharging or overdischarging can occur due to the failure of another system or when the battery reaches the end of its cycle life, and its remaining capacity becomes insufficient for the intended mission profile. It is crucial to test the battery's response to excessive charging or discharging conditions, as they can lead to various adverse effects such as reduced performance, capacity loss, damage (e.g., shorts caused by dendrite formation), failure, or safety hazards. Controlled simulations of overcharge and overdischarge scenarios help analyze the battery's behavior and evaluate the effectiveness of its protective mechanisms.
  - **Thermal Runaway**—In the context of space applications, thermal management becomes more complex due to the absence of natural convection in a vacuum environment. To address this challenge, teams must simulate and analyze how batteries respond to elevated temperatures and heat accumulation. Thermal runaway tests subject the battery to high-temperature conditions to observe thermal stability, venting characteristics, and potential risks of ignition or explosion.
  - **Internal Short Circuits**—Evaluating the battery's ability to withstand and mitigate internal short circuits involves intentionally inducing short circuits within the battery to assess its safety features, such as thermal cutoff mechanisms and internal protection circuits.
  - **Mechanical Abuse**—Testing the battery's resilience against mechanical stresses and impacts includes evaluating its resistance to vibration, shock, and physical damage to ensure its robustness in real-world applications.
  - **Environmental Testing**—Assessing the battery's performance and safety under extreme environmental conditions such as high or low temperatures, humidity, or exposure to corrosive substances helps determine the battery's suitability for specific operating environments.

Assembly Testing

Once the individual cells have completed the qualification process, they are assembled into a pack. The pack then undergoes rigorous testing to ensure its compliance with the satellite's mission requirements. While some of the tests conducted at the cell level can be repeated on the assembled pack, additional tests are necessary to address the increased complexity and potential failure points introduced during the assembly process. The extent of testing can vary significantly depending on the specific mission profile. In some cases, limited testing may be conducted to preserve cycle life or due to high-volume production constraints. However, common testing procedures include:

- **Thermal Management and Testing**—Ensuring the pack's effective operation across the wide temperature range encountered in space is crucial. Thermal analysis typically is conducted using modeling techniques, which are then validated through physical testing in thermal or thermal vacuum chambers. Throughout charge and discharge cycles, the pack must maintain its temperature within acceptable limits. Satellites employ various thermal management strategies, including heaters and heat shields, to preserve operational temperature ranges. As integration levels increase, the EPS will require testing, even though charge/discharge profiles may differ at each stage. Whether passive or active, the pack's thermal management system, utilizing heating or cooling, must be capable of maintaining the pack temperature within the designated operational range. Operating outside of this temperature range can lead to degraded performance, reduced cell or pack capacity, or irreversible failure.
- **Pack Mechanical Construction**—The pack must withstand the mechanical stresses experienced during launch and the demanding conditions of space. Construction validation ensures that the pack meets design requirements and prevents assembly-related failures (e.g., cell tab weld failure) that could jeopardize the mission.
- **Battery Cell Weld**—Welding is a common way to join battery cells, aiming to establish a robust, low-impedance connection that maximizes current capacity and strength while keeping the weight minimal. While destructive testing evaluates weld parameters, nondestructive testing is crucial for pack assemblies. Thus, impedance measurements across the welds serve as an effective nondestructive evaluation technique. Accurate measurements can be challenging due to the typical milliohm or microohm range of battery welds. To enhance measurement accuracy, applying higher currents can assist in evaluating the weld impedance. Using a PXI SMU (Figure 5) offers higher current capabilities than a standard DMM for resistance measurements. Alternatively, a DMM, along with an external current source such as an RMX supply (Figure 4), provides a greater excitation current to improve the accuracy of impedance measurements. In either approach, a 4-wire measurement configuration ensures that lead resistance does not introduce any adverse effects that could affect result accuracy or reliability.

FIGURE 04

Using a DMM combined with external current excitation enables accurate low-impedance battery weld measurements, essentially providing a high-current four-wire measurement using two pieces of test equipment.

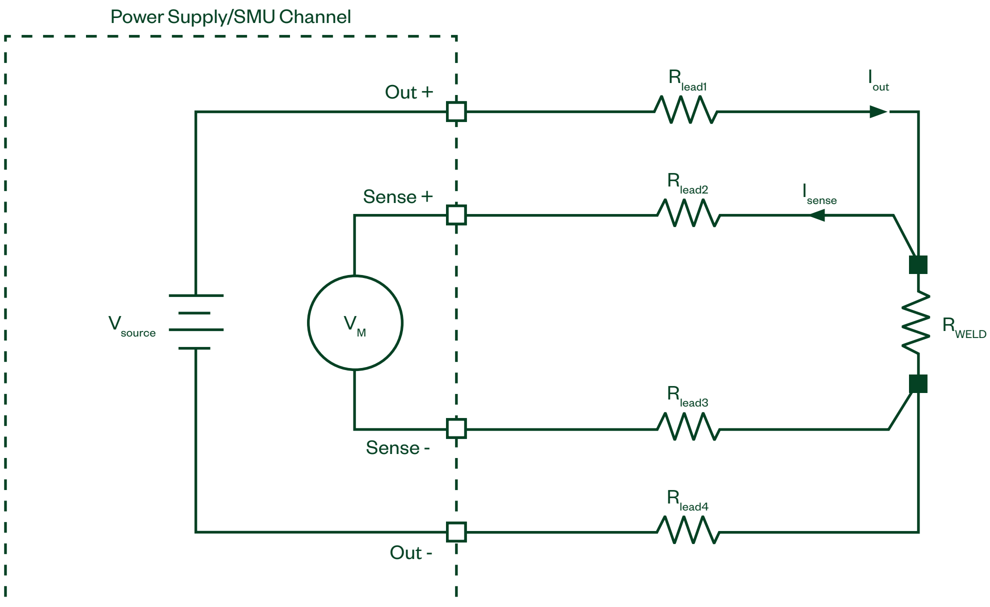


FIGURE 05

An SMU configured with remote sense allows a single instrument to perform a high-current four-wire resistance measurement with a single instrument. Higher excitation currents are required to accurately measure low-impedance welds.

- **Pack-Level Failure Testing**—Comprehensive testing identifies potential failure modes and mitigates risks to the mission. Depending on the fault tolerance of the pack, tests should ensure its ability to continue operating following a failure (e.g., shorted cell, high cell impedance, or weld failure).
  - **Shock and Vibration**—Pack integrity is crucial to withstand the vibrations experienced during launch and potential impacts from space debris. Typically, components undergo functionality tests both before and after subjecting them to rigorous shock and vibration tests conducted on shaker tables. These tests simulate the levels of stress that the components are anticipated to endure. While it is uncommon to perform functional tests while devices are undergoing testing on the shaker table, it is standard practice to monitor the test process to ensure the accuracy of the test profile. NI offers several PC- and PXI-based systems with plug-and-play DAQ devices with fixed functionality or configurable systems that let you mix and match hardware. Combine that with FlexLogger™ software, NI's no-code data acquisition software for validation and verification test applications, to monitor the test process to ensure the accuracy of the test profile.
- **Cell Matching for Pack Assembly**—Before assembling cells into a pack, it is crucial to characterize each cell individually to achieve optimal performance and longevity of the pack. Matching the capacity and impedance of cells within a pack is vital to ensure uniform energy utilization and balanced loads. This approach prevents excessive strain on individual cells, avoids capacity degradation, and extends the cycle life, thereby preserving the overall performance of the pack. Capacity and internal resistance tests are conducted

at the cell level to gather relevant data, which is then utilized to strategically position cells within the pack, optimizing their arrangement for improved performance.

- **Initial Pack Balancing**—Achieving balance within the pack is crucial to ensure that all cells contribute equally to the overall power output. While it is possible for an unbalanced pack to self-balance over multiple charge cycles, depending on the capabilities of the BMS, the pack will not reach its full capacity until proper balancing is accomplished. To prevent an unbalanced state after assembly, individual cells can undergo top balancing. This process ensures that cells are fully charged and brought to the same state of charge before pack assembly, thereby promoting balance and optimal performance of the pack.
- **BMS Communication Test**—Battery modules often incorporate components for the BMS, which, at a minimum, provide crucial cell voltage information. Once the modules are assembled, direct access to test points for measuring individual cell voltages is commonly lost. As a result, it becomes necessary to query the cell voltages from the BMS. It is worth noting that the BMS may utilize a variety of standard communication protocol such as SPI, I2C, or UART. Alternatively, it may employ a custom digital protocol, which is common for components designed for space applications. Establishing communication with the BMS often involves leveraging an **FPGA-based interface** due to its flexibility—especially for devices with custom interfaces. However, maintaining custom FPGA implementations can be burdensome. Therefore, it is recommended to utilize a platform such as an NI Reconfigurable I/O Module or NI FlexRIO, which efficiently handles digital communication. These devices offer a long lifecycle managed by NI and provide existing software support in multiple programming languages, minimizing the need for extensive new development efforts.

BMS Testing

The BMS plays a crucial role in monitoring and maintaining the health of the battery pack, as well as controlling its operation. One of the primary functions of the BMS is to ensure pack balance during cycling, so that all cells continue to contribute to system energy capacity and power performance. BMS capabilities can be categorized as either active or passive balance systems. Passive BMSs, commonly used in smaller satellite power systems, bleed energy from cell groups with higher charge to maintain balance and optimal capacity across the pack, dissipating the excess energy as heat through a resistor. Active balance BMSs, on the other hand, employ additional circuitry to actively redistribute charge between cell groups, ensuring pack balance and capacity. Active systems are more efficient and provide enhanced capability in maintaining the battery pack. While balance maintenance is a primary role of the BMS, it also performs tasks such as status monitoring (e.g., SoC, charge/discharge rate and coulomb counting). The BMS must undergo testing to ensure its ability to fulfill its mission responsibilities, which include:

- Balancing the battery pack to maintain usable storage capacity during operation.
- Protecting the battery pack from overvoltage, overcurrent, and undervoltage.
- Maintaining status information, such as state of charge, to enable proper utilization of stored electrical energy by mission systems.
    - Preventing overcharge/discharge to preserve battery performance and capacity over the mission lifespan.
    - Limiting pack cycling to 80% of capacity to maximize cycle life and allow headroom for emergency energy supply.
- Detecting and diagnosing cell issues to facilitate pack maintenance, including the potential bypassing of failed cells for continued operation.

Testing the BMS functionality can be challenging depending on its complexity. At a minimum, the test system must establish communication with the BMS and provide simulated cell voltages. For passive systems, simulated cell voltages can be supplied by a 1 quadrant DC power supply, while active systems require a 2/4 quadrant supply such as an SMU. Alternatively, specific Switch, Load, and Signal Conditioning (SLSC) modules in an SLSC chassis, coupled with a PXI test system, also can supply simulated cell voltages for a BMS. Using an NI DC-power-based SMU offers precise control and monitoring of cell voltages for comprehensive BMS testing in a manner impractical with an actual battery pack. High-voltage isolation is not as big of a concern for space applications compared to automotive applications, as the most high-power satellite systems typically operate with bus voltages under 150 V (e.g., 120 VDC on the ISS).

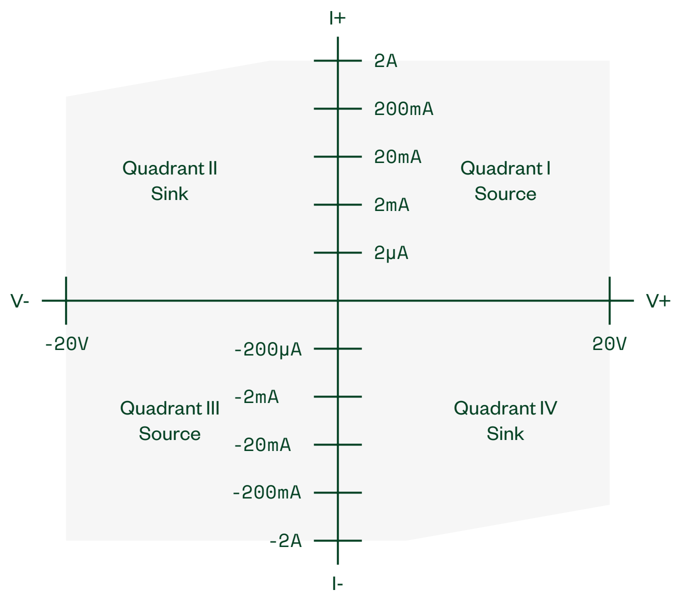


FIGURE 06

Simplified SMU IV Operating Boundary

When designing a BMS testing system, there are four criteria that aid in selecting the appropriate hardware. These criteria include:

1. **Passive or active balance BMS architecture**—This determines whether the system requires a single quadrant DC supply or two or four quadrant SMUs to simulate cell voltages, depending on the balance method employed.
2. **Cell voltage range**—The ideal voltage range of the supply is determined based on the nominal voltage range of the cells, typically around 2-4 V for most lithium chemistries.
3. **Cell stack in series within a pack**—Understanding the isolation requirements of the supplies used for cell simulation is crucial, considering the arrangement of cells in series.
4. **Max balance current**—Defining the source/sink capabilities of the supplies is necessary to handle the expected balance current during testing.

It is worth noting that supplies used for BMS test are software-defined and can play additional roles besides cell simulation for BMS test (e.g, solar simulation). These additional requirements would add to the selection criteria of the supplies chosen.

As an example, let's consider a passive balance BMS with four cells in series and a balance current of 200 mA. To meet these requirements, we can design a system accordingly. Assuming a nominal voltage of 3.6V with an operating range of 2.8 V to 4.5 V for the cells, an appropriate supply can be selected. In this case, the **PXIe-4113** DC power supply is suitable. It provides the necessary voltage and current range for the BMS, and its 150 VDC ground isolation is sufficient for the 18 VDC stack voltage in this BMS design. It's important to note that PXI supplies are floating supplies to facilitate stacking them, as shown in Figure 8B. However, avoid connecting the DC supplies in parallel, as shown in Figure 8C, to prevent single quadrant supplies from operating outside their range by forcing them to sink current. For an active balance system with the same parameters, hardware selection follows the same criteria, but a supply capable of operating in quadrants 1 and 2 is required. The **PXIe-4139** is a suitable supply given the cell voltage (2.5 V – 4.5 V) and balance current (200 mA) requirements.

Since the PXIe-4139 has multiple voltage and current ranges, the 6 V 1A range (Figure 7) of this device is most suitable to maximize the SMU accuracy for this BMS example. In the case of stacking for higher pack voltages, both supplies have a 150 VDC isolation, allowing stacking up to 33 cells. For higher density in an active balance BMS test, utilize multichannel SMUs such as the PXIe-4147 or PXIe-4162. However, consider that these SMUs share a common current return path for all channels. When using a PXIe-4147 or PXIe-4162, the stack voltage of the cells connected to the SMU needs to be below 2X the maximum voltage of the SMU such that the positive and negative range of the SMU can cover the battery stack voltage. The SMU would be configured as shown in Figure 8D when the number of cells is equal to the number of channels on the SMU, with the shared current return path centered in the cell stack to maximize the voltage range of the SMU. If the positive range of the SMU can cover the battery stack voltage, the shared Lo current return path can be placed anywhere in the simulated battery stack. Additionally, if the number of cells in the battery stack is less than the number of channels available on the SMU, the common Lo path can be left disconnected and act as a node with zero net current.

RANGE	RESOLUTION (NOISE LIMITED)	NOISE (0.1 HZ TO 10 HZ, PEAK TO PEAK), TYPICAL	ACCURACY (23°C ± 5°C) ± (% VOLTAGE + OFFSET)		TEMPCO ±(% OF VOLTAGE + OFFSET)/°CTO 55°C
			T_{CAL} ± 5°C	T_{CAL} ± 1°C	
600 mV	100 nV	2 µV	0.02% + 50 µV	0.016% + 30 µV	0.0005% + 1 µV
6 V	1 µV	6 µV	0.02% + 300 µV	0.016% + 90 µV	
60V	10 µV	60 µV	0.02% + 3 mV	0.016% + 900 µV	

FIGURE 07

PXIe-4139 Voltage Accuracy (Four-Quadrant Supply)

While simpler BMSs with basic balancing and maintenance algorithms easily can be automated using test sequencers such as **TestStand**, more advanced algorithms may require HIL systems running models in tools such as VeriStand for testing. Parametric tests ensure the accuracy of BMS measurements, especially as the battery system is integrated and direct measurements on individual cells and current paths become challenging. In later stages of integration, measurements are commonly queried directly from the BMS rather than relying on standard test equipment. BMS measurement calibration is crucial, and while high-level behavior and functional tests can be conducted using lower-cost equipment such as DAQ, BMS measurement calibrations should be performed using high-precision/accuracy instruments such as an SMU.

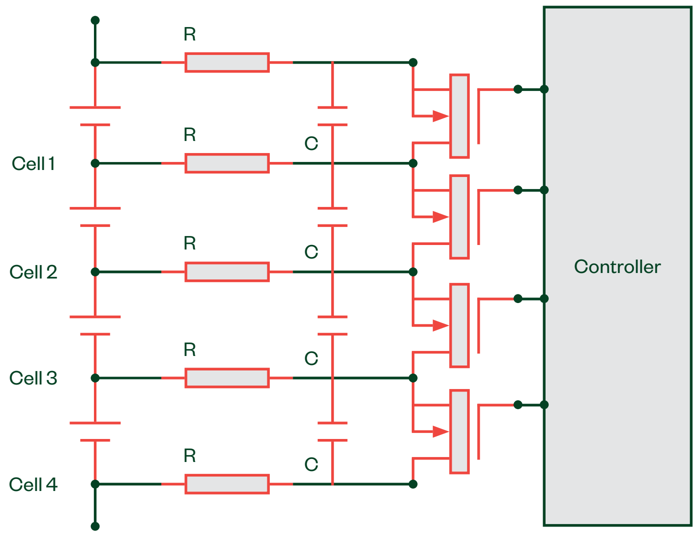


FIGURE 8A

Typical Passive Balance BMS Circuit.

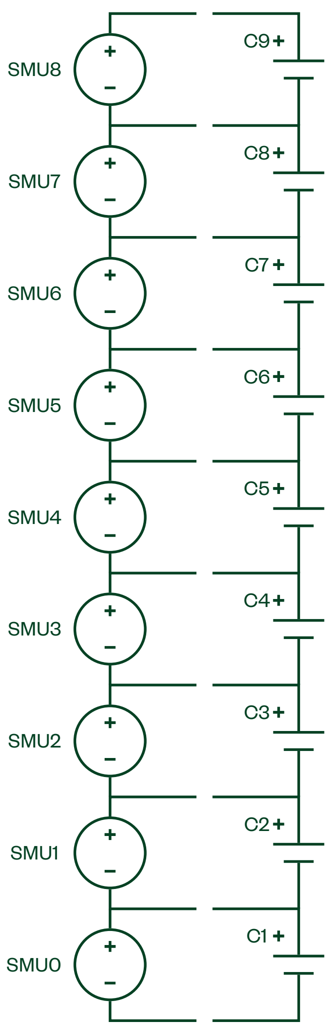


FIGURE 8B

Ideal battery cell simulation for active and passive balance BMS using isolated (floating) supplies

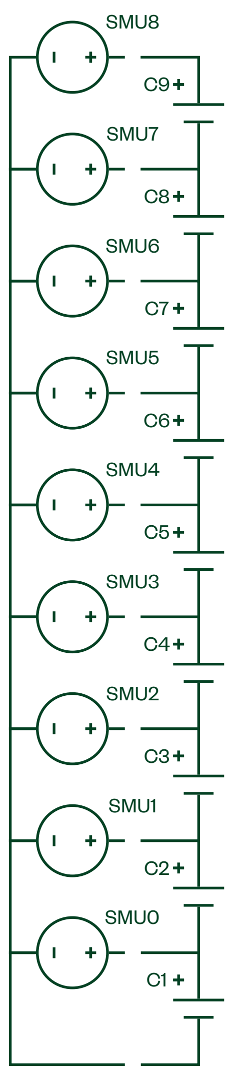


FIGURE 8C

Nonideal configuration; risk of pushing supplies outside quadrant 1

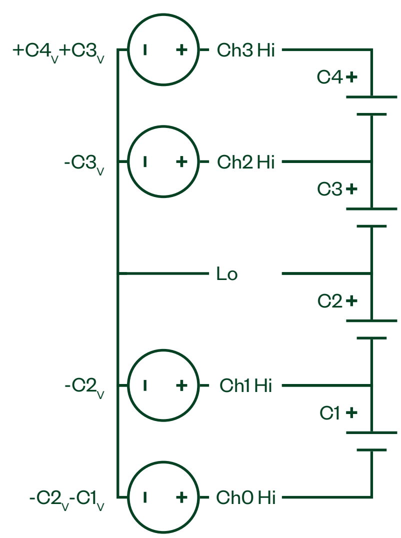


FIGURE 8D

Configuring and connecting a multichannel SMU as a battery cell simulator

NI's Approach to Battery Testing

The NI approach to satellite battery testing aims to optimize organizational efficiency and improve the quality and reliability of satellites by using integrated hardware and software tools and test automation so that engineers can make data a key part of their test strategy. Using data acquisition, signal conditioning, control systems, and automated test software across the product lifecycle are integral parts of this approach. The goal is to help engineers automate battery component test, accelerate assembly, integration, and test (AIT), and shift testing activities earlier in the development process. By incorporating data management and analytics into the test of satellite components and subsystems, it becomes easier and more cost-effective to identify and resolve issues earlier in the development cycle. NI provides a comprehensive solution that streamlines the testing process, helps ensure quality and reliability, and ultimately saves time and cost for satellite manufacturers.

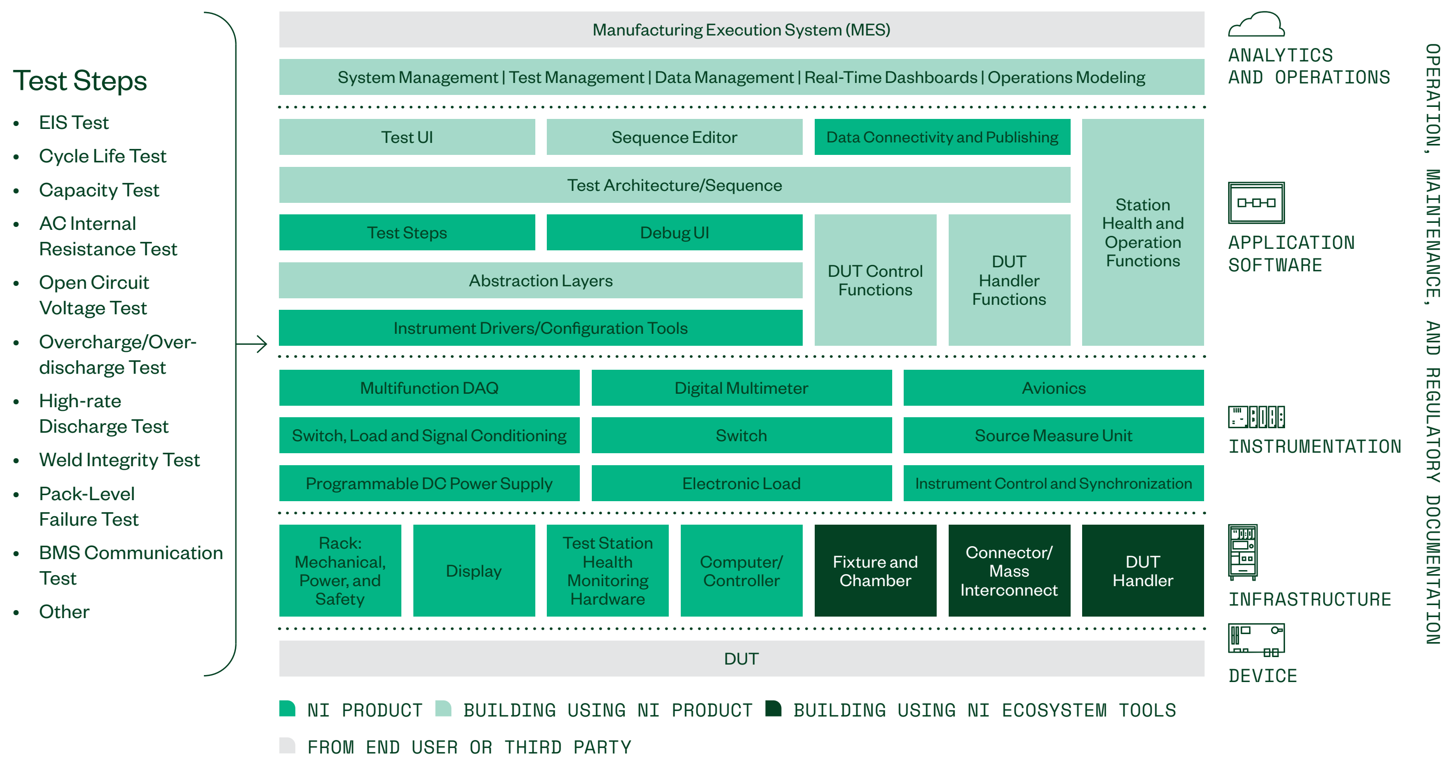


FIGURE 09

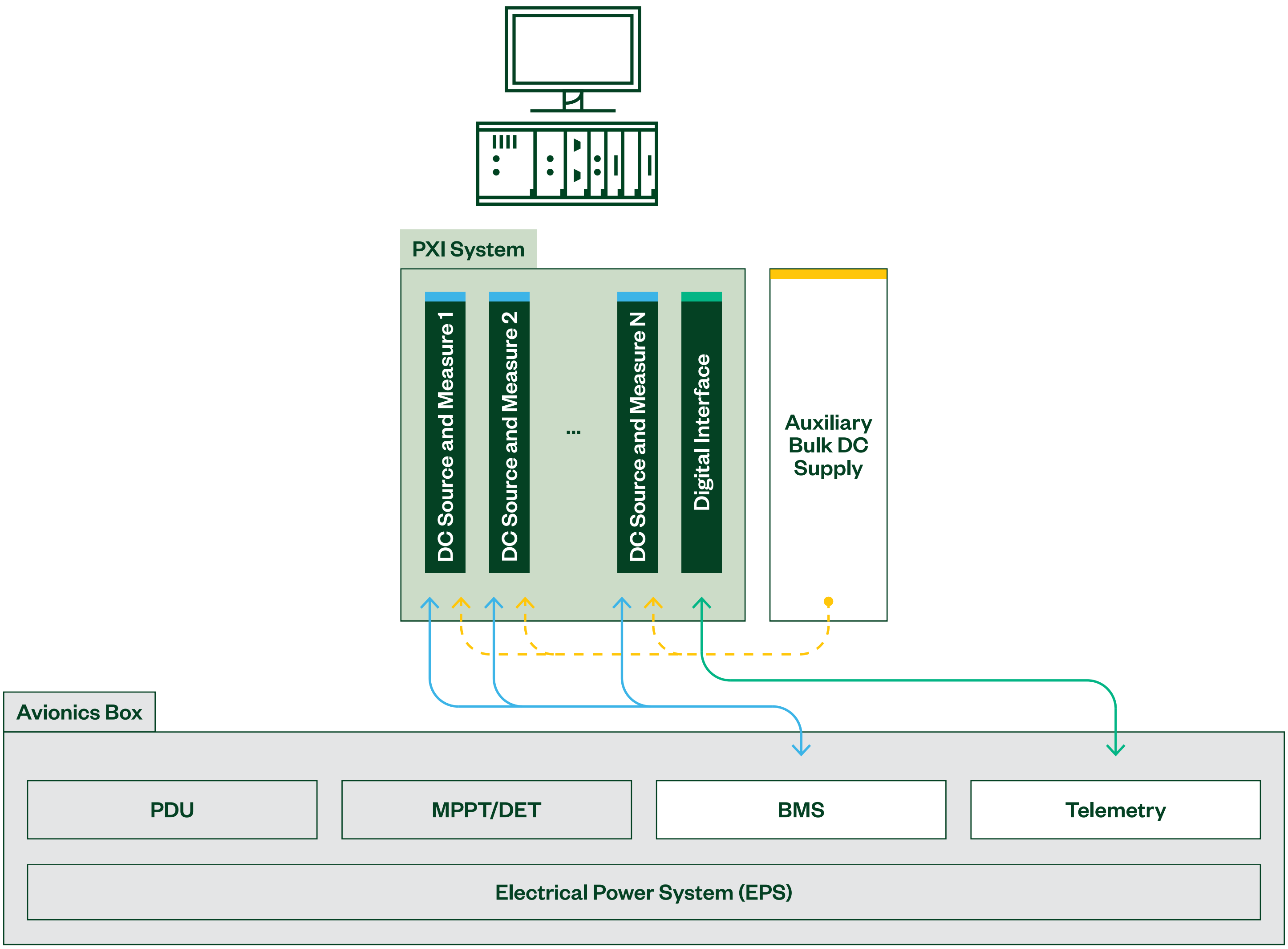
NI's Satellite Battery Test Approach

NI offers a comprehensive suite of battery testing solutions to test satellite batteries. Based on NI's expertise in data acquisition, automation, and visualization, leverage NI's solutions to test batteries at all stages of development, from early prototyping to final qualification.

NI's battery and BMS testing solutions include:

- **Modular and expandable I/O**—Add measurement channels to expand with minimum incremental cost per channel and quickly add mixed measurements.
- **Scalable power options**—Access a variety of power envelope coverage for range of satellite bus voltages.
- **In-chamber measurements**—Use rugged, synchronized, IP-rated measurement modules and thermal chamber control for temperature and humidity profile test execution, as well as other DUT measurements like strain, voltage, current, or vibration.
- **Digital interface communications**—Integrate digital DUT control communications standards and custom protocols to interface with application-specific requirements.
- **Enterprise management**—Create customized data dashboards with the right information for the right people, to take the right actions to maximize utilization and uptime, monitor test systems, and manage the test facility assets.
- **System simulation**—Decouple software development from hardware availability to validate test scripts without equipment present, to speed up development and derisk system deployments.

An example BMS test configuration would include battery cell simulation and a digital interface to communicate with the BMS under test. Cell simulation and digital interface instruments depend on the BMS. A representative configuration of a BMS test is shown in Figure 10.



TELEMETRY, COMMAND/CONTROL, BATTERY MODULE INTEGRATED BMS
RS422/485, TTL/LV CMOS, I2C, SPI, Ethernet, etc.

BATTERY CELL SIMULATION
Cell Voltage and Active/Passive Balance Current

DIGITAL CONTROL AND DATA | DC POWER | 48 V AUXILARY POWER | REQUIRED FOR SELECT HIGHER-POWER PXI MODULES

FIGURE 10

In this PXI-based BMS test configuration with a digital interface for DUT communication, the left bank provides four-channel active balance with SMUs, or the right bank provides 12-channel passive balance configurations.

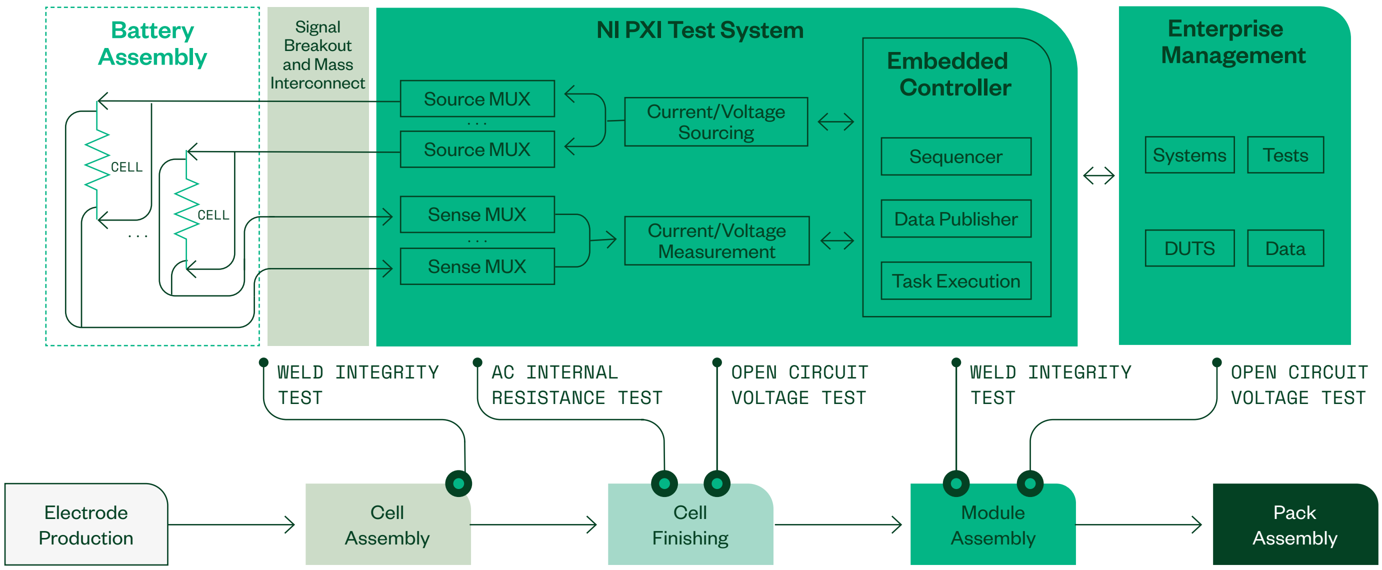


FIGURE 11

Battery Cell and Module Solutions

Choose from multiple solutions based on your testing needs:

- PXI provides the most compact and high-performance form factor to pack more test and scale up production volumes.
- The **SMU** provides repeatable and precise measurement and current sourcing for AC-IR and weld integrity test.
- The **programmable power supply and electronic load devices** provide the DC power and power-sinking capabilities to simulate and characterize the satellite bus.
- The **DMM** performs fast and precise voltage measurements for OCV and weld integrity test.
- NI's **multiplexers** effectively scale the system to 32 or 64 channels, depending on the type of test, for maximum coverage in a smaller footprint.
- **SLSC** modules coupled with a PXI test system simulates cell voltages for the BMS and offers a variety of sensor simulation options.
- The **digital avionics interfaces** support generic and high-speed interfaces as well as custom application-specific interfaces commonly found in satellites.
- **CompactDAQ** hardware offers synchronized mixed sensor measurement monitoring.
- Direct integrate with test software such as **TestStand**, **Switch Executive**, and **SystemLink™** software for enterprise data and systems management.

NI's Battery Test Solutions Advantages

- There are several benefits to using NI's battery testing solutions, including:
- Test speed to meet production volume with maximum precision and control for long test runs
- Cost-effective, precise, and high-throughput PXI configurations using SMU, DMM, and high-speed multiplexers
- Scalability from 32 to 64 channels depending on the test type per system in a small footprint
- Test execution and insight gathering improves uptime, monitors test assets, and performs preemptive test station maintenance
- Service programs ensure maximum equipment availability and uptime

Conclusion

The increasing complexity of satellite electrical power systems pushes engineering teams to deliver more intricate test systems while meeting increasingly constrained schedule expectations. These pressures are compounded by a more competitive manufacturing market, where cost savings from operational excellence can mean the difference between leading the market and struggling to compete. To combat these pressures, best-in-class engineering groups are standardizing their approaches to test with reusable frameworks of COTS components. This is helping them accelerate development while ensuring future scalability.

Serving manufacturers directly and through integration partners, NI has been a leader in test for more than 40 years. NI's battery testing solutions offer a comprehensive and flexible approach to testing satellite electrical power systems. These solutions ensure that satellite components and systems are tested properly and that the results are reliable. NI's platform approach to test combines high-performance instrumentation with test development, sequencing, and management software tools to meet specifications, time-to-market schedules, and budgets. Let NI help you standardize your processes, systems, software, and data infrastructure to build a strong foundation for digitalization technology, such as analytics, that make best use of your data to improve product and operational performance.