Cell Simulation Hardware for Safe and Efficient BMS Testing

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Abstract

Many battery and original equipment manufacturers (OEMs) of battery-electric products utilize actual Li-ion battery cells for testing electronic systems, including the battery management system (BMS). There are significant limitations with this approach in the various stages of product design, development and production. This paper presents BMS test techniques using commercially available cell simulation hardware for improved safety, efficiency, coverage and cost.

Introduction

The BMS is comprised of one or more printed circuit board assemblies (PCBA) with embedded software that monitors and controls the cells of an advanced-chemistry battery. Specifically, for a Li-ion battery, the BMS typically performs the following functions:

- Monitoring cell voltages, currents, and temperatures
- Balancing the cell voltage levels
- Estimating the state of charge (SOC) and state of health (SOH)
- Controlling the rate of charging and discharging
- Monitoring alarm levels and pack voltage
- Controlling the high voltage interlock (HVIL) contactors
- Communicating with the master controller, charging system, and other associated systems

The BMS may be designed by the OEM, battery manufacturer, or an electronic design house; and there are commercial BMSs as well. Regardless of its source, the BMS is typically highly customized for the end-use application, particularly the embedded software.

The BMS is CRITICAL to the safety, performance and longevity of the battery. Therefore, it must be thoroughly tested throughout the development lifecycle.

Types of BMS Testing

BMS Engineering Verification Test

During breadboard and proof-of-concept development, benchtop instruments—such as variable power supplies, electronic loads, and multimeters—are commonly employed to excite circuits and perform manual diagnostics. Bench testing can be effective for limited, static testing with one or a couple of cell channels, but quickly becomes unwieldy for larger modules and packs.

BMS Software Validation

Once a prototype is available, the BMS software should be validated using an automated test system. A validation system simulates battery cell behavior to assess proper operation of the BMS software in a test lab environment. Test scripts can trigger alarms, exercise cell balancing functions, and apply load profiles while monitoring the BMS control actions.

Each time the BMS software is revised, the validation system performs regression testing by executing a comprehensive set of automated scripts. This process ensures that new features operate correctly, and that previously validated functions continue to behave consistently across iterations.

A BMS Hardware-In-the-Loop (HIL) Test System is a validation system that runs a mathematical model in real time, which controls the test system's simulated electronic battery signals. The model typically simulates the battery pack, environmental conditions, load, and any number of external subsystems to replicate real-world conditions to the BMS. The models are developed using mathematical modeling software such as The MathWorks Simulink® and are executed on a computer with a real-time operating system.

The various model parameters are mapped to the test system's input and output electronic signals, enabling the model to control the instrumentation that simulates the battery cell voltages, currents, temperatures, as well as digital communications. These simulated battery hardware signals are applied to the BMS in a similar manner as real battery signals.

The BMS is then tested under many different simulated load profiles, environmental conditions, and fault scenarios. The real-time computing environment accurately preserves the timing relationships of the various signals and events. The result is a highly accurate characterization and validation of the BMS's behavior to a wide variety of real-world conditions and edge cases.

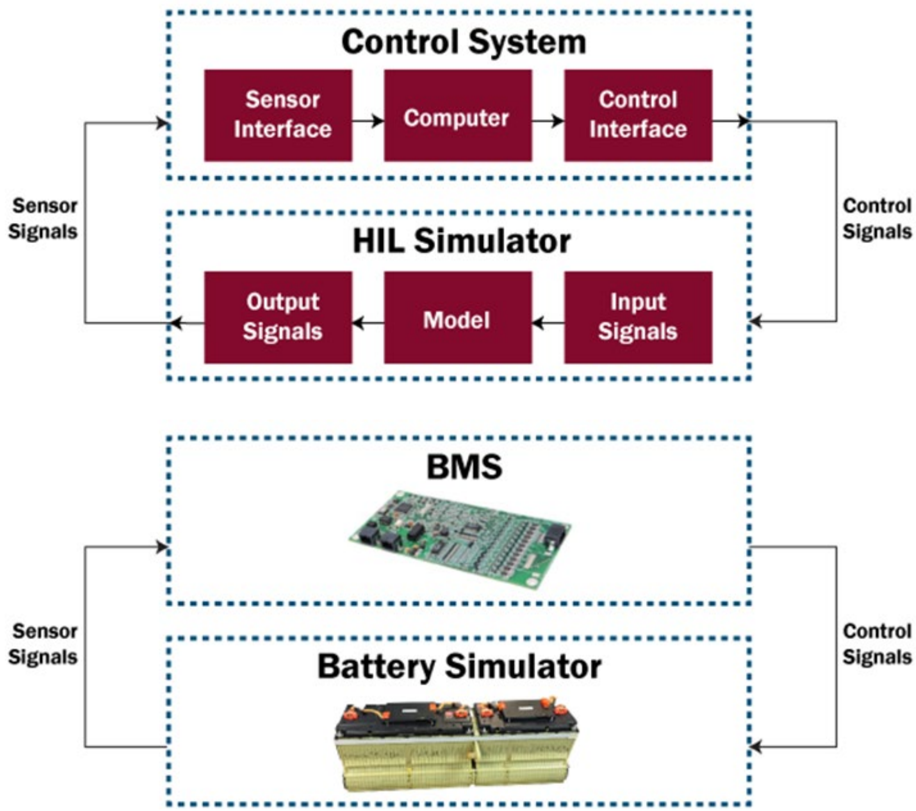

Figure 1. An HIL Simulator runs a model of the battery in real time that generates simulated battery and other signals that connect to the BMS.

BMS Design Verification Test

Design verification test is used to verify the environmental as well as functional performance specifications of the BMS. A batch of 6-8 BMSs are simultaneously tested in an environmental chamber. The system is programmed to run functional test scripts at different temperature, humidity and/or vibration set points across the BMS's specified operating range. The chamber is often controlled according to a ramp/soak profile, where the environmental chamber ramps up to a temperature setpoint, remains at this setpoint for a specified period of time, then decreases to a soak/dwell temperature setpoint. This method allows the BMS responses during both temperature ramp-up and ramp-down to be observed. Programmable cell, power , and signal I/O simulation hardware is required to exercise the BMS circuitry across all environmental and performance criteria.

In addition, Highly Accelerated Life Testing (HALT) and Highly Accelerated Stress Screening (HASS) repetitively run a subset of the design verification test scripts on batches of units inside an environmental chamber. The subset of tests, often referred to as a Short Form Operating Test (SFOT), is designed to exercise the limits of the BMS—including current, voltage, and cycle rates—under varying temperature, humidity, and vibration setpoints.

BMS Manufacturing Functional Test

Once the design is released to production, each manufactured unit should be tested prior to installation into a battery. During production, in-circuit testing (ICT) is commonly performed by PCBA contract manufacturers (CMs). ICT is invaluable for detecting missing components and for ensuring the individual components are functioning properly. However, ICT often misses defects in the functional interactions between multiple components and software at a system level.

A functional manufacturing test system (FCT) may be used to test the BMS PCBAs during production, just prior to assembly in the pack. The functional test system typically consists of a bed-of-nails fixture connected to an automated test system that runs a test script. The test script verifies voltage rails, ensures proper communication, and exercises each system at a functional level. Test coverage and limit values should be tuned appropriately to identify defects. The test script may also be used for calibrating cell monitors and temperature sensors, and for loading and programming software onto the processor or memory storage units (CPU, ASIC, FPGA, and EEPROM).

Some BMS manufacturers omit functional manufacturing test. The result is lower yields and higher rates of defects. Defective boards become progressively more expensive to fix once assembled into a battery pack or released out in the field. The ideal scenario for preventing defects and continuously improving the product is to deploy two identical BMS functional test systems, one for the CM to prevent defects, and one for the OEM to support the CM, retest any failed units, and perform sustaining development.

Many manufacturing functional test systems are dedicated to a specific product. In contrast, a universal BMS manufacturing functional test system equipped with a mass interconnect fixture is commonly used to test multiple BMS PCBAs and board types—including cell monitoring units and BMS masters—using a single system. Separate bed-of-nails fixtures and corresponding test scripts enable scalable and adaptable testing across all PCBA types.

Issues Using Li-ion Cells

Many battery manufacturers and OEMs of battery-electric products utilize Li-ion battery cells for testing the electronic systems, including the BMS, cell monitors, safety and high-voltage interlocks, charging systems, and master controller. This can be problematic for the following reasons:

- Safety – many cell chemistries are hazardous, and if they are stressed during testing they may leak, overheat or ignite. Furthermore, full packs carry immense energy that can damage equipment and jeopardize human safety.
- Efficiency – it is both energy and time intensive to charge and discharge cells in order to change the battery’s state of charge many times as required for testing.
- Repeatability – cell characteristics change slightly with every charge and discharge cycle. Therefore, real cells are not a repeatable test stimulus.

- Coverage – test scenarios are limited by the capabilities of the cells. Edge conditions, especially dangerous ones, are difficult or impossible to test using real cells.
- Cost – during product development, prototype batteries are both scarce and expensive. Furthermore, specialized facilities equipped with chemical fire suppression must be used.

Alternatives to Li-Ion Cells

There are two alternatives to automated testing using Li-ion cells: power supplies and loads, and battery cell simulators.

Power Supplies and Loads

Many BMS automated test equipment (ATE) systems utilize large equipment racks stacked with commercial programmable power supplies and loads. However, most commercial power supplies do not accurately represent a battery for two main reasons. First, they use noisy switching circuitry with high peak-peak ripple. This can cause major inaccuracies in the cell monitoring circuitry which are designed for monitoring very stable battery cells. Second, most power supplies are unidirectional sources that cannot simulate the true sink and source characteristics of real cells. This limits the veracity of testing the cell balancing and other algorithms of the BMS in real time. Achieving a more accurate simulation of the battery using commercial power supplies and loads requires many instruments, filtering, and switching which dramatically increases the hardware and software complexity of the ATE system. This equipment becomes large, cumbersome and complicated above a few channels.

Battery Cell Simulators

Fortunately, commercial battery cell simulators (aka emulators) exist that provide a safe and flexible alternative to Li-ion cells. While real Li-ion cells operate as two-quadrant sources, some cell simulators can be configured up to four-quadrant, allowing both sourcing and sinking of current in either polarity. This enables not only realistic multi-cell balancing, but also the safe simulation of faults that would be impractical or hazardous with real cells, including reversed cell polarity, over- and under-voltage, over-current, temperature extremes, and shorted or open cells. This comprehensive fault coverage ensures that every BMS alarm is exercised safely at low power.

For example, the Battery Simulator 1201 is a programmable 12-cell simulator in a 1U rack-mountable enclosure (Figure 2). Each channel is isolated up to 1000 V, allowing hundreds of simulated cells to be connected in series for large pack simulation3. The Advanced Battery Simulator 800 is an 8-cell 1U simulator capable of running a cell model and performing short, open and reverse-polarity faults onboard.

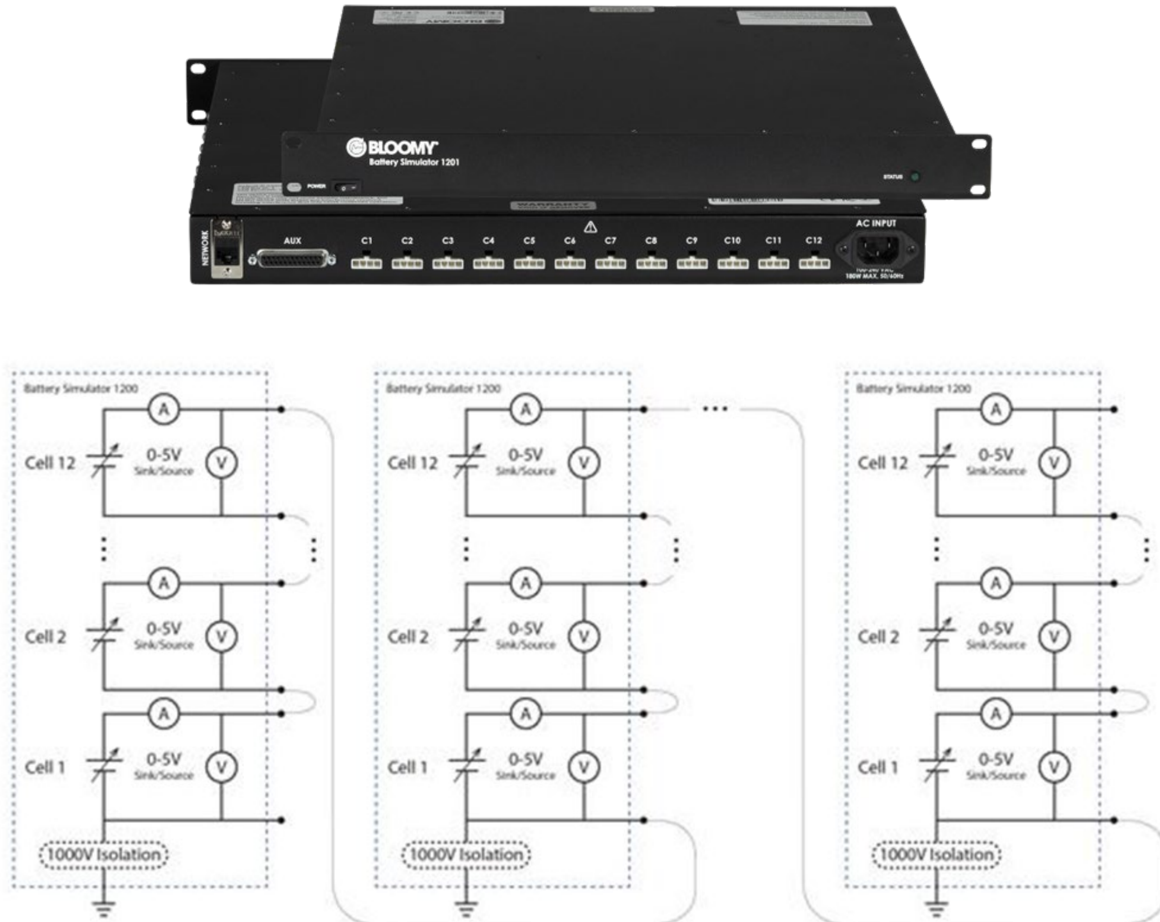

Figure 2. Top: Battery Simulator 1201   is a 12-Cell battery simulator in a 1U rackmount enclosure (front and back views). Bottom: Multiple 12-cell simulators are connected in series to simulate a larger pack.

Figure 3. The Advanced Battery Simulator 800 is an 8-Cell battery simulator in a 1U rackmount enclosure that can also run a cell model and perform short, open and reverse-polarity faults onboard.

Table I. Comparison

	Battery Simulator 1201	Advanced Battery Simulator 800
Number of cells per 1U	12	8
Cell voltage and current simulation accuracy	±1mV ±1mA	±0.75mV ±0.6mA @ 1A, 2.4mA @ 5A
Max current sink/source	500mA per cell	5A per cell
Temperature sensor simulation	-	8 thermistors (+/- 10V auxiliary analog outputs)
Faulting	[Requires FIU accessory $5,995 for 24 cells Open, short-to-rail]	Built-in open-, short-, reverse-polarity faulting on all cells
Cell model execution	[Host PC only]	Onboard 2nd order equivalent circuits cell model execution
Interface	Ethernet, HS CAN	Ethernet, HS CAN, RS485
Software drivers	CAN dbc, LabVIEW, Python with 1200 compatibility	CAN dbc, C/C++, Python, LabVIEW with SCPI
Certifications and compliances	CE, FCC, RoHS, IEC 61010-1, -2	CE, FCC, RoHS, REACH IEC 61010-1, -2 CB Ref. No US/10671/ITS
Price per 1 unit	$15,995, ($1,333/cell), no faulting $21,990 ($1,832/cell) with faulting	$15,995 ($1,999/cell)

Cell Qualification Testing

In order for any ATE system such as the BMS HIL Test System to run a real-time simulation of the characteristics of a specific cell, a mathematical model must be utilized. Cell qualification testing is the process by which the actual cells are characterized through comprehensive physical testing in all kinds of conditions and failure modes. Physical test data is then used to derive the parameters of a model. Numerous battery models and parameter estimation techniques exist that are beyond the scope of this paper. BLOOMY offers a second-order equivalent circuit cell model for use with its battery cell simulators. In the case of the Advanced Battery Simulator 800, the model runs onboard the simulator itself. In the case of the Battery Simulator 1201, the model runs on an external host computer.

Systems Integration Lab Testing

Commercial battery cell simulators are beneficial in many test applications that extend well beyond the BMS. Electric vehicle (EV) OEMs use systems integration labs (SIL) to verify the interoperability and performance of multiple electronic components and systems as they are integrated together on the vehicle. When the battery is the primary power source, it is necessary to rigorously test the battery sensitivities of ALL electronic components and systems, both individually as well as integrated together. A battery surrogate comprised of commercial battery cell simulators is the ideal means of safely and efficiently stimulating these electronic systems. For example, an 800V Battery Cell Simulation Tower may be used as the primary test stimulus for an automotive breadboard testing lab, as well as the iron bird of an electric vertical takeoff and landing (eVTOL) air taxi.

Conclusion

Comprehensive testing of advanced chemistry battery electronics is essential to ensuring safety, performance, and longevity of the battery and battery-electric products. Recommended testing methods include engineering verification, software validation, design verification, systems integration and manufacturing functional test. Commercially available battery cell simulation hardware is a safe, efficient, comprehensive and cost-effective approach to simulating battery cells for a wide range of automated testing applications.

End Notes

1. Blume, Peter, "Cell Simulation Hardware for Safe and Efficient BMS Testing", Rev. 101316J Copyright@2014, 2019 Battcon Vertiv, Westerville, OH 43082.
2. Blume, Peter, "BMS Testing Throughout the BMS Development Lifecycle," © 2017, www.bloomy.com.
3. Application Note AN 8700-00038, "Using the Battery Simulator 1200 in High-Voltage Applications", © 2022 Bloomy Controls, Inc., https://www.bloomy.com/support/resources/white-paper/using-battery-simulator-1200-high-voltage-applications
4. Gothing, Grant, "Testing Battery Sensitivities Using a Battery Surrogate", © 2025, Vertical Flight Society Transformative Vertical Flight.
5. Related products:
    a. Battery Simulator 1201
    b. Advanced Battery Simulator 800
    c. Desktop BMS HIL Test System
    d. BMS HIL Test System
    e. FLEX BMSTM Validation System
    f. BMS Environmental Test System
    g. BMS Manufacturing Test System
    h. 800V Battery Cell Simulation Tower