# Testing Battery Sensitivities of Electric Aircraft Systems Using a Battery Pack Surrogate

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## ABSTRACT

Many eVTOL and electric aircraft systems are highly sensitive to battery performance, states, algorithms and behavior, which necessitates thorough testing. However, lab testing with real battery packs is not practical or desirable in most cases due to potential issues with safety, availability, cost, energy, and test coverage. A battery pack surrogate hardware-in-the-loop (HIL) test system may be used in place of the battery in order to safely and efficiently test many battery-sensitive aircraft systems across an extended range of battery conditions. This paper describes an 800V battery pack surrogate comprised of commercially available components including battery cell simulators providing over 200 cells of simulation, as well as signal and power IO, communications, cell models, a real-time controller, and battery management system (BMS). Important design considerations including safety, isolation, topologies, and interconnections are addressed, and applications for systems integration lab (SIL) and iron bird testing are presented.

## INTRODUCTION

Electric and eVTOL aircraft are rapidly evolving, with many airframers pursuing certification within the next 1-3 years. For many of these aircraft, lithium-ion (Li-ion) battery packs are the primary energy source that provide power to the entire aircraft. Because Li-ion battery packs contain complex control electronics, they must be tested in a systems integration lab (SIL) to ensure seamless integration with other aircraft systems, including energy management, propulsion, flight controls, avionics, and charging. However, due to the volatile nature and high energy density of these packs, testing with real battery packs is difficult, time consuming, expensive, power intensive, and dangerous. An alternative test stimulus capable of exercising and/or "flying" electric aircraft systems in a manner that is equivalent to the real battery is strongly desired.

This paper introduces the battery pack surrogate as a means for safe and efficient validation testing of an aircraft's battery pack and control electronics as well as for testing how they interact with the rest of the aircraft's battery-sensitive systems. Because each aircraft, battery pack design, and test application is unique, each battery surrogate must be customized to meet the corresponding requirements.

Bloomy Controls, Inc. (BLOOMY®) provides hardware in-the-loop (HIL) and SIL test systems for Li-ion battery management system (BMS), line replaceable units (LRUs) and other units under test (UUTs). Based on our experience developing BMS HIL and battery pack surrogates for a wide range of industries, including electric vehicles as well as electric aircraft, we present the driving factors for requiring battery pack surrogates during SIL and iron bird test. Key considerations for battery pack signal simulation into the BMS from both hardware and software/modeling perspectives will be discussed as will the overall topology and design of a battery pack surrogate. Finally, several example test scenarios are presented as part of this paper.

## BATTERY INTERACTIONS WITH ELECTRIC AIRCRAFT SYSTEMS

The battery pack, including the cell modules, cell monitoring units (CMUs), and battery management unit (BMU), is the energy storage system that all of an electric aircraft's electrical and propulsion systems rely on. As such, the battery pack plays a critical role in the performance and safety of the aircraft. The battery pack delivers all required power to the propulsion system, environmental system, vehicle management system, and in-aircraft electronics. The BMS provides the necessary monitoring and control circuitry and logic to ensure that the battery pack is operating safely and at top performance, and communicates the battery's states to many other aircraft systems.

The BMS monitors and controls the operating conditions of the overall pack as well as those of the individual cells. It is comprised of the BMU, CMUs, and disconnect circuitry. The CMUs are connected to the individual battery modules, monitoring cell voltages and temperatures, and controlling balancing. The BMU monitors the overall pack voltage, current, and

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temperature, and communicates with the CMUs. It uses this information to estimate the pack's state of charge (SoC) and state of health (SoH), control safety contactors, charge and discharge enable relays, pack environmental factors such as heating or cooling, and output diagnostic trouble codes.

Because every electronic system relies upon the battery pack, its behavior is critical to the operation of the aircraft as a whole. Figure 1 shows the common aircraft systems which interact with the battery pack. Some systems, like the propulsion, charging, and DC/DC conversion are very tightly coupled with the battery pack, often receiving direct power, safety, and control signals from the BMS, as indicated by the red arrows. Other systems like avionics, flight controls, and navigation shown in blue may be less directly coupled, using the aircraft system power derived from the battery pack. However, these systems make decisions and manage aircraft controls based on battery pack information, including SoC, available capacity, or diagnostic trouble codes.

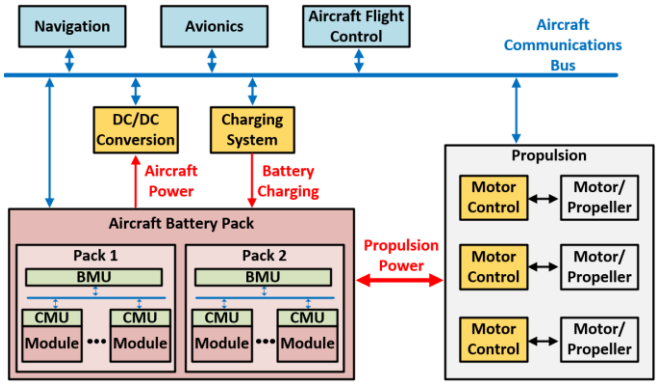


**Figure 1. Battery-sensitive electric aircraft systems**

## AIRCRAFT INTEGRATION TESTING

### Overview of Hardware in-the-Loop Test

Hardware-in-the-Loop (HIL) test is a method of validating the performance and functionality of complex control systems by simulating all of the conditions that the system is designed to monitor and control using real hardware. In HIL test, the control system is connected to a simulation system which simulates sensor signals under the control of a software-based model of the plant. The outputs of the control system, as well as other external systems, are measured by the HIL test system and fed back into the plant model, closing the loop of the stimulus and response cycle around the unit under test. HIL testing is often used to characterize and validate how the control system handles situations both within and outside of its normal operating envelope. Once an aircraft enters service, HIL test is further utilized to comprehensively test any revisions to the control systems' software in a process called regression testing.

For example, consider the BMS inside of a battery pack. HIL simulation is a particularly effective means of testing real BMSs and algorithms with simulated battery cells. Real cells can be hazardous, and because their characteristics change slightly with each charge/discharge cycle, they are not a repeatable test stimulus. Using HIL test for BMS development allows simulation of the behavior of multiple battery chemistries and simulates charge and discharge cycles based on the simulated or measured pack currents, balancing currents, and control signals from the BMS. As the mathematical model of the battery discharges and charges, the modeled SoC, cell voltages, and pack temperatures are calculated and simulated as analog signals back into the BMS, effectively making the BMS perform as if it were connected to a real battery pack. The inherent risk of real chemical cells is eliminated, and the test and the test environment is repeatable.

### Overview of SILs and Iron Birds

A system integration lab, or SIL, is a test lab where multiple systems are connected together to perform integration testing, validating the individual behaviors and complex interactions between the systems. In a SIL, each control system is typically connected to its own HIL simulator running plant models and simulating signals corresponding to that control system's functionality. These control systems, with their simulated IO interact with each other as if they were in a real aircraft, allowing engineers to validate the overall system as a whole, across a wide range of operating conditions in a repeatable and highly configurable environment. Whereas SILs usually only include the electronic controls connected to simulated sensors, actuators and effectors, an "iron bird" (so-called for their tendencies to be heavily mechanical structures made from steel and other structural metals thereby being completely incapable of flight) is a specialized type of SIL which includes the full complement of an aircraft's flight control systems combined with real sensors, actuators and effectors. The real hardware may include aircraft actuators, interface hardware, flight control computers, avionics, propulsion systems, etc., along with whichever sensors are required for successful operation of the systems. Additional simulated sensors and loads close the loop around the control systems in the iron bird.

Airframers use both SILs and iron birds to validate system integration in different phases of development. SIL testing enables iterative test and debug of the embedded system software starting early in the aircraft development. In addition, SIL testing is more often focused on validating individual control systems and their interactions. Iron bird testing incorporates electrical controls, mechanical systems, sensors and actuators to validate overall integration at a more mature state of the aircraft. Iron birds and SILs rely on test systems designed to test one or more of the control systems within the airframe. With proper design, SILs and iron birds are modular in nature such that the individual control systems may be tested independently, then connected together with other control systems in any appropriate combination. This affords the control development teams the ability to develop their control

systems independently of one another and at different paces. After suitable confidence is gained in the independent development environments, the systems are usually connected to each other, both between the simulations as well between the control systems themselves, for system integration testing. If designed in an appropriately modular fashion, the development stations for a single-channel of a multi-channel control may also be connected together to test the control system in its duplex or triplex configuration.

## CHALLENGES OF TESTING WITH REAL BATTERIES

Battery packs for electric aircraft contain hundreds of kilowatt-hours of energy, with the ability to instantaneously provide over 400 amperes at 800 volts. This immense power and capacity, while critical to aircraft performance, poses safety risks when testing aircraft systems with real battery cells. Packs are configured in complex topologies of series and parallel cells, making it difficult to set up very specific test scenarios. Furthermore, this energy is stored in a chemical form which does not return to its exact starting state after a discharge/charge cycle, thus adding repeatability of test to the list of challenges of testing with real battery cells.

### Dangers of real battery testing

Using real battery packs involves significant risks because of the high amount of chemical energy contained within them, most notably the risks of electrical hazards and thermal runaway. These risks are heightened in validation testing which involves exercising the pack outside of normal operating conditions and which is often experimental in nature. The high voltage and current of the packs present risk of serious electrical hazards, such as electrical shock, short circuits, and arc flash, which can arise from improper handling, incorrect connectivity, faulty equipment, or unvalidated safety hardware and algorithms. The thermal energy available in the pack presents the possibility of thermal runaway, another critical safety concern for test with real batteries. Thermal runaway occurs when a cell overheats and triggers a positive feedback reaction, releasing energy which in turn further heats the cell and may spread to adjacent cells. This results in a rapidly increasing temperature and cascading effects resulting in fire or explosions. Without proper safety controls, the edge conditions tested during validation, including imbalances, fast charging, over charging, high power, short circuit or environmental tests, can all contribute to the risk of thermal runaway. For these reasons, many test labs restrict the use of real chemical cells for any electrical or algorithmic testing. When allowed, test labs that utilize real battery cells must be properly equipped for chemical fire suppression.

### Configurability challenges of real-battery testing

Aircraft battery packs contain hundreds of cells in series, and dozens of cells in parallel, providing high voltage, high current, and high capacity. Preparing for a particular test case based on initial capacity and overall pack SoC can take hours to prepare on a real pack, requiring precise charging and discharging of the pack which takes significant time and energy. Setting parameters such as cell, module, or string imbalances can take hours or even days, if possible at all. Consider the imbalanced pack of 9 modules shown in Table 1 where Module 8 is stronger, and Module 9 is weaker than Modules 1-7.

**Table 1. Imbalanced pack configuration parameters.**

| Parameter | Module 1-7 | Module 8 | Module 9 |
|---|---|---|---|
| Initial Capacity | 25kWh | 28kWh | 20kWh |
| Initial SoC | 90% | 85% | 98% |
| Initial Temp. | 25°C | 22°C | 38°C |

Setting this exact configuration could entail days of setup, requiring specific capacity setup (including adding or removing cells), SoC setup (requiring charging each module individually and maintaining that state until the test is ready), and thermal setup (heating or cooling each module individually). Take this a step further to individual cell imbalances, or to dangerous edge conditions such as over-charged or over-temperature cells and modules, and the configuration is highly dangerous and virtually impossible to accurately create.

### Repeatability challenges of real-battery testing

In considering the challenges associated with configuring a particular test scenario, one can imagine the additional difficulty in precisely repeating the same scenario multiple times. The chemical properties of real batteries change slightly with every charge and discharge cycle, and these small perturbations in initial conditions could have a large impact on final test results. Creating the same test conditions multiple times would require replacement of older cells with newer cells and could add significant cost and days to weeks to overall test time. All the while, the chemical properties of real batteries change slightly with every charge and discharge cycle. Real batteries are simply not a repeatable, consistent test stimulus for aircraft systems testing.

## THE BATTERY PACK SURROGATE

Because of the hazards and inefficiencies of testing with the real battery pack, a battery pack surrogate should be used in its place. The battery pack surrogate is a type of HIL test system which mimics the complete functionality of the real battery pack by integrating the real BMS with simulated sensors and cells into a closed-loop simulation. It may also contain a high-power supply to provide substantial power needed to drive other aircraft systems, depending on the application of the battery pack surrogate. The battery pack surrogate allows design and validation engineers for aircraft systems to interface with a simulated battery pack that behaves just like the real battery pack, but without the aforementioned issues. This replacement for testing with a real battery pack can dramatically improve safety, accelerate testing time, and help reduce and optimize precious flight test hours. Engineers can test the effect of hardware, firmware, and algorithm changes on the state of charge, state of health, and hazard conditions of the battery. Conversely, engineers can test the effects of initial

conditions, such as cell, module, and pack capacity, SoC imbalances, thermal conditions, and states, on the BMS and other aircraft systems.

The battery pack surrogate provides the ability to instantaneously change states and initial conditions for complex tests that would otherwise be time consuming, dangerous, or difficult to test on a real battery pack. Fault conditions, such as a single weak cell, unbalanced cells or modules, broken wires, insulation resistance breakdowns, welded contactors, sensor faults, or extreme temperatures, can readily be implemented in a matter of seconds. Test scenarios, including actual pre-recorded flight data or engineered missions, can be played back into the battery pack surrogate to tune algorithms and system responses to BMS signals, including pack state of charge, diagnostic trouble codes, contactor states, and health alerts. Furthermore, while this simulation is taking place, all channel and communications data can be logged in real-time for post-processing and correlation of system events with battery behaviors.

In the next sections, an overview of a typical electric aircraft battery pack will be presented and then the major components of a battery pack surrogate will be discussed.

### Overview of an electric aircraft battery pack

To understand the battery pack surrogate, we must first summarize the details of a typical electric aircraft battery pack. The aircraft battery pack is comprised of thousands of cells, each providing a typical nominal voltage between 3.0V and 4.0V and a capacity between 10Wh to 100Wh. In the battery pack, these cells are organized into series and parallel configurations to achieve the desired voltage, current, and capacity. A typical aircraft battery pack connects between 192 and 250 macrocells in series to generate the 800V pack voltage, with each series-connected macrocell being comprised of dozens of individual battery cells connected in parallel to store hundreds of amp-hours of capacity. Furthermore, where electric traction vehicles will typically disconnect all battery outputs in a fault scenario, most electric aircraft batteries incorporate redundant strings or packs. In a traction EV, disconnecting the pack means that the vehicle loses propulsion and eventually stops. In an aircraft, however, the propulsion loss from disconnecting the entire pack could be catastrophic. Redundant packs are used to ensure that if one pack fails, the aircraft can safely land under reduced power.

Due to the high nominal pack voltage, typically 800VDC, electric aircraft battery management systems employ a distributed BMS topology. This topology is optimized for large, complex, high power applications. While many variations of overall pack topology are used throughout the industry, this discussion will be confined to a basic, high-level pack topology. Figure 2 shows one such topology. This distributed BMS topology groups the entire stack of battery cells into smaller modules. Generally, a module is a convenient subdivision of the overall battery pack which satisfies the distributed topology of the BMS. For instance, a pack of 216 cells in series may be comprised of eighteen 12-cell modules.

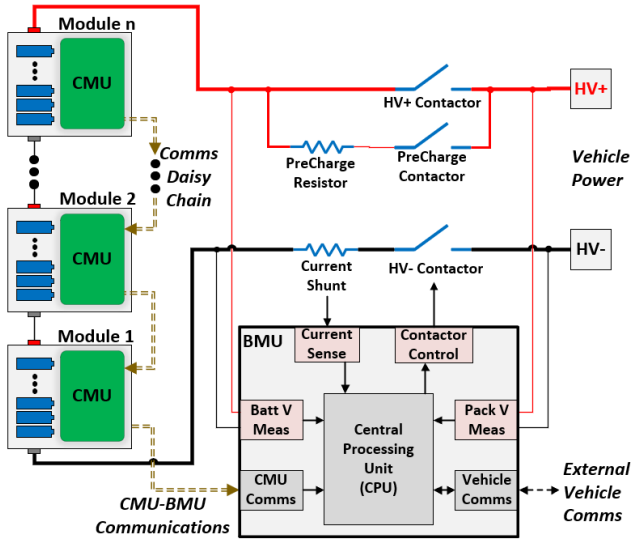


**Figure 2. Battery pack block diagram**

Because of the high-power density, high volatility, and relatively flat charge curves of lithium-based batteries, advanced monitoring and control electronics are critical to their performance and safety. Each module is equipped with a cell monitoring unit (CMU). The CMU is an electronic assembly which accurately measures cell voltages and temperatures, detects cell-level faults, and controls individual cell balancing, as shown in Figure 3. The CMU only monitors and balances the series-connected cells within the module, as parallel cells only add capacity and cannot be individually measured. Data from each module is reported back to the battery management unit (BMU), over an isolated digital communications interface such as isolated SPI, UART, or CAN. This communications interface is typically daisy-chained from one module to the next, and back to the BMU.

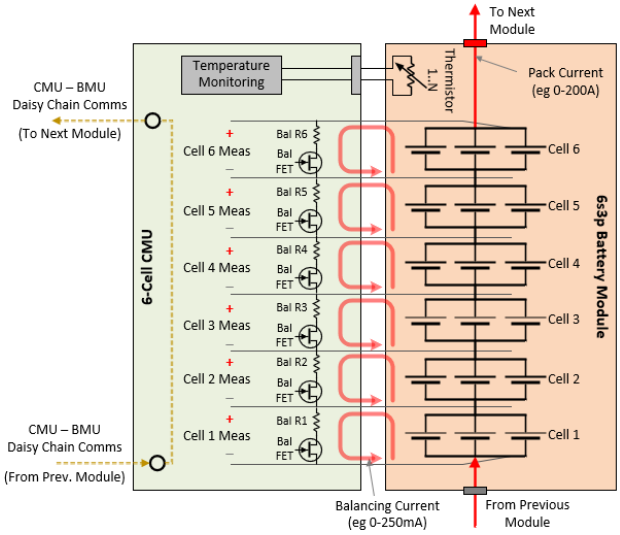


**Figure 3. Example module and CMU**

The BMU, shown in grey in Figure 2, is responsible for pack-level monitoring and control. The BMU aggregates all cell data reported by CMUs, measures battery and pack voltage (before and after the pack contactors, respectively), pack current, pack temperatures, discrete control and communications, and other pack signals. Because of the high-voltage, high-current nature of the BMU voltage and current input signals, the BMU often employs an analog front end (AFE), shown as red blocks in Figure 2, to perform signal conditioning before feeding measurements to the analog-to-digital converters (ADCs) on the board. The AFE scales the high-voltage signals on the *Batt V Meas* and *Pack V Meas* inputs from 0-1000V down to the signal level required by the ADC, such as 0-10VDC. If a shunt is used for current measurement, the output is typically in the range of ±150mV. The *Current Sense* AFE scales this up to the a higher voltage range for the ADC, such as ±150mV, improving measurement resolution. The BMU uses this information from the cell and pack voltages, currents, and temperatures to calculate overall SoC, SoH, and remaining capacity using mathematical models of the battery. It also executes safety algorithms to control disconnects (either solid-state transistors or mechanical contactors), controls heating and cooling, and reports all battery information back to the rest of the aircraft via digital communications. In redundant electric aircraft systems, the entire pack is often duplicated or triplicated and, with a separate DC power aggregator unit, provides the multi-pack connectivity to the aircraft.

### Anatomy of the Battery Pack Surrogate

A complete battery pack surrogate for integration testing employs the real LRUs and control electronics within the pack while using instrumentation to simulate the analog signals that are monitored and controlled by these components. An example battery pack surrogate test system is shown in Figure 4. In this system, the BMS components are located within the system's enclosure with commercial, off-the-shelf instrumentation providing the simulated signals into the BMS.

**Figure 4. Example 800V battery pack surrogate**

The following sections will walk through building up the battery pack surrogate physical hardware from the individual cell simulators to the external aircraft-accessible signals.

## CMU/MODULE SIGNAL SIMULATION

CMU signal simulation entails replacing the cell, thermistor, and other external sources monitored by the CMU with programmable simulated signals as shown in Figure 5. A typical CMU monitors and reports cell voltages and temperatures of a single module back to the BMU via a daisy-chained communications interface. All CMUs must be present and communicating to the BMU so that an alarm or fault is not triggered by the BMU safety algorithms. The CMU also controls the balancing of cells as shown in the 6-cell example in Figure 3. While a module will often have many cells in parallel to add capacity, the CMU only monitors the series-connected cell voltages. Furthermore, full module current does not typically pass through the CMU itself, only between the cells and load. Therefore, simulating the cells to a CMU requires only simulating the individual series-connected cell voltages with enough power to satisfy the passive- or active-balancing circuitry. Full pack power is also not required in the CMU cell simulation, as capacity will be simulated with modeling, as discussed later. Temperature monitoring is typically performed by the CMU via thermistors, which can be simulated using either analog voltages or programmable resistors.

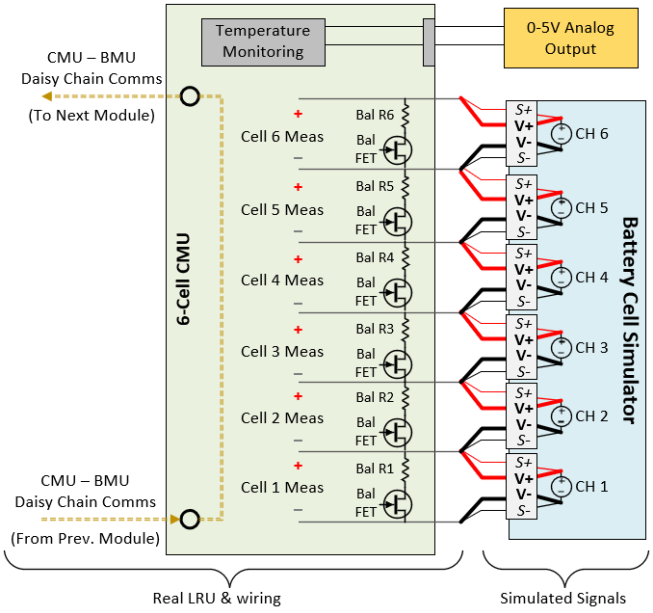


**Figure 5. Signal simulation into the CMU**

### CMU – Cell Voltage Simulation

Just as cells are the fundamental elements of the battery pack, cell simulators are the fundamental building blocks of the battery surrogate. Each series-connected cell that is monitored by the CMU must be simulated using an isolated, high-accuracy voltage source. For instance, comparing Figure 3 to Figure 5, the six series-connected cells would be replaced with individually programmable simulated cells. The three cells in parallel

for each series cell only add current capacity and do not need to be individually simulated. Most lithium-based battery chemistries provide an individual cell voltage between 2.5VDC and 4.25VDC, with under-voltage and over-voltage conditions extending to 0V and 5V, respectively. Therefore, the cell simulators should be able to programmatically control individual cell voltages from 0-5VDC.

Output current from each cell must be high enough to satisfy the monitoring and balancing circuitry of the CMU. Nominal CMU current draw is typically on the order of 5-20mA while individual balancing currents may range from 20mA-500mA for passive balancing applications, and higher for active balancing. Cell simulators must be able to source or sink enough current in each individual cell to satisfy CMU nominal current draw plus individual balancing currents.

Accuracy and resolution of the simulated voltage output and current readback are critical. The relatively flat SoC/voltage curves associated with lithium-based batteries means that small variances in voltage can result in large inaccuracies in the SoC estimation algorithms. Most commercially available cell monitoring integrated circuits have a total measurement error of around 2-3mV. Therefore, cell simulators should have a voltage output accuracy of ±1mV or better, with resolutions of 500μV or less. Furthermore, high accuracy current readback is critical when testing balancing algorithms or for feeding balancing current back to mathematical models for overall SoC simulation. Current readback accuracy of ±1mA is generally sufficient for most battery pack surrogate applications.

Finally, because the cells are series-connected at the module, and modules and their CMUs are further stacked in series to create a pack, simulated cells must be galvanically isolated to the highest pack voltage potential connected to a CMU, which could be the full pack voltage of over 800VDC to ground. When selecting a cell simulator, special attention must be given to the type of isolation specified by the instrument. Because the battery pack surrogate could be operating continuously at voltages of up to 1000VDC, the cell simulators should be rated for 1000VDC reinforced insulation per IEC61010 safety for laboratory instruments. Basic isolation, while offering protection of live voltages under normal operating conditions, requires additional safety precautions to ensure user and safety for continuous operation. Reinforced insulation offers a higher level of protection such that even if a single failure occurs, all non-isolated equipment and operators will be protected.

Figure 6 shows the Battery Simulator 1201, a commercial battery cell simulator which provides 12 channels of 0-5V, ±500mA individually programmable cells. Each cell channel of the simulator is individually programmable and has 1000VDC of reinforced isolation to ground. Cell channels across many cell simulators may be stacked in series to simulate all the cells in a module or pack.

**Figure 6. Commercial battery cell simulator**

**CMU – Thermistor Simulation**

The majority of CMUs monitor module temperatures using thermistors, either onboard or externally via connector interfaces. Most thermistor monitoring circuits are simple voltage dividers, with the variable resistance thermistor placed in series with a fixed resistor to pull-up to 3.3V or 5V or pull-down to board ground. The CMU will then monitor the voltage at the junction between the thermistor and fixed resistance. Therefore, a thermistor may be simulated by using a variable resistor in place of the thermistor or by providing an analog voltage corresponding to the voltage divider output associated with a particular temperature. Selecting the method of thermistor simulation depends on the type of test fidelity required. Generally, analog voltage-based simulation reduces cost and is sufficient for any algorithmic or behavioral testing associated with a battery pack surrogate. If full hardware testing, including validating the CMU pullups is required, then programmable resistance-based simulation should be selected. In either case, the battery pack surrogate software environment must have a scaling mechanism to match the nonlinearity of thermistors. In most cases, a simple interpolation table from temperature to voltage or temperature to resistance is sufficient and can be derived from the real thermistors' datasheets.

**Cell Stack Simulation Topologies**

The stack of cells of high-voltage battery packs may be simulated using one of three common methodologies, discussed in the following sections. For illustrative purposes, a 216-cell stack with eighteen 12-cell CMUs will be used, though the concepts can be adapted to other common high-voltage distributed BMS topologies.

The first methodology is *full stack simulation*. In this configuration, shown in Figure 7, all 216 cell voltages of the stack are simulated using eighteen cell simulator instruments, each containing 12 individually programmable cells connected to all 18 CMUs of the BMS. All simulated battery cells are connected in series on each CMU, and all CMUs are connected in series, as they would be in a real pack. In this configuration, full stack voltage may be provided directly into the BMU "Batt V+" measurement terminal. Because CMUs are raised to high voltage, any additional signal simulations or measurements, such as thermistor simulation, must be fully isolated from ground, since they are typically referenced to the bottom-most "Cell 0" signal on the CMU.

The advantage of full stack simulation is that it most closely resembles the actual battery pack configuration by providing the highest-fidelity environment for validation testing at full voltage. In addition, it allows individual cell voltage and balancing current control and monitoring. The main disadvantage is that it requires a large number of high-voltage connections over 100VDC and up to 1000VDC, which may be restricted or heavily regulated in some laboratory environments, as per the NFPA 70E standard (2024) (Ref 1), Table 130.4(D)(b). However, increased safety may be provided by implementing a number of safety precautions within the HIL simulator and supporting equipment, as outlined by NFPA 70E and BLOOMY's application note on using cell simulators in high-voltage applications (Ref 2). These precautions include setting the simulator cell current limits to the minimum required for powering the CMU and exercising its balancing circuitry, restricting access to all high-voltage connections when power is applied using safety enclosures, and implementing electrical hardware interlocks and lockout/tagout systems to ensure the control systems and instrumentation are de-energized when operators have access to them.

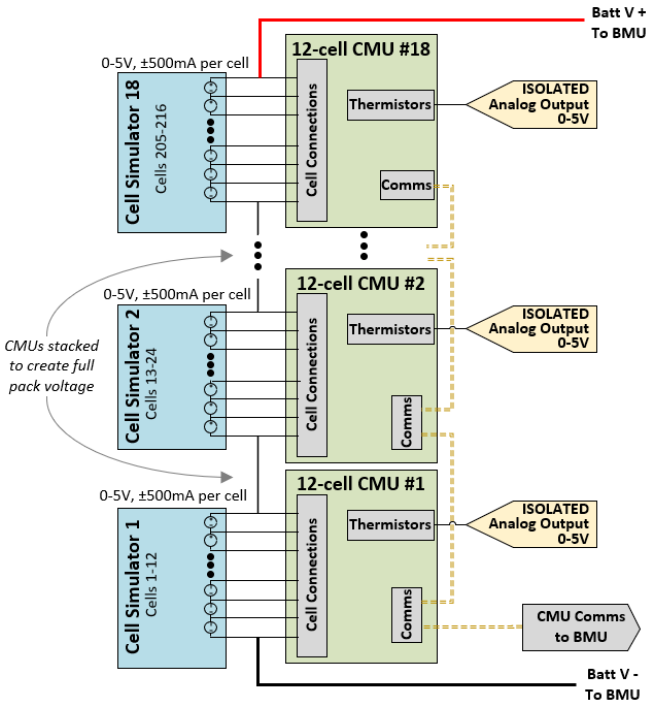


**Figure 7. Full stack cell simulation**

The second methodology, *low-voltage full cell simulation*, shown in Figure 8, also involves individually simulating all 216 cells into all 18 CMUs. However, rather than stacking all CMUs in series as in a real battery pack, each CMU's "Cell 0" (lowest voltage cell input) is referenced to system ground. In this configuration, the simulated voltages will never exceed a single CMU stack (5V/cell x *n* cells per CMU). Because the CMUs are not stacked to the full pack voltage, a separate high-voltage source must be used to provide the pack voltage to the BMU's "Batt V±" measurement terminals. Note that the high voltage source may be set to a very low current (i.e. milliamps) limit in order to minimize power. This configuration maximizes safety by reducing the number of high voltage connections while still maintaining independent control and monitoring of all cells in the pack. Furthermore, additional signal simulators, such as thermistors can remain non-isolated or single-ended which often saves equipment cost.

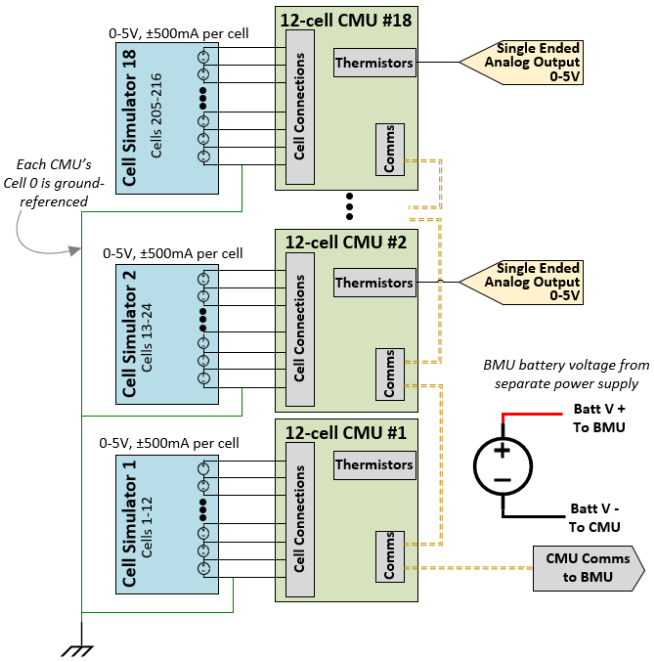


**Figure 8. Low-voltage full cell simulation**

Shown in Figure 9, *low-voltage shared cell simulation* minimizes the number of cell simulators by sharing simulated cells across multiple CMUs. Like the low-voltage full cell simulation, this configuration maintains a low voltage cell simulation system by ground-referencing the CMU's lowest-potential cells. However, in this configuration a single cell simulator may be shared across two or more CMUs connected in parallel. The primary limitation is that the shared cell currents must not exceed the cell simulator instrument's maximum current per cell. For example, if one CMU balances at 200mA per cell, then three CMUs in parallel may require up to 600mA, potentially exceeding the current limit of the cell simulator instrument. The advantage of this configuration is that it reduces overall system cost by minimizing the number of cell simulators, though at the expense of slightly more complex control software. The major disadvantage is that sharing simulated cells across multiple CMUs limits the individual voltage simulation and balancing measurements associated with full cell simulation.

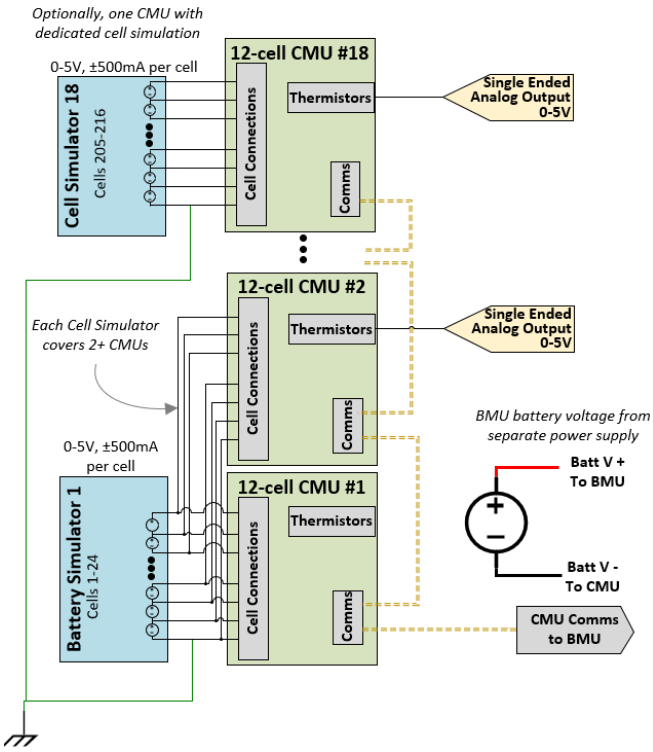


**Figure 9. Low-voltage shared cell simulation**

### CMU to BMU Communications

The CMU to BMU communications is critical to BMU functionality. Without continuous communications to the CMUs, the BMU will fault. When a battery pack surrogate application uses the full complement of real CMUs, no direct simulation of the CMU to BMU communications is required since the CMUs' communications can simply be connected to the BMU as it is in a real battery pack. This provides the only authentic implementation of the BMU to CMU communications interface, matching that of the real battery pack.

One other approach to simulating the CMUs involves removing physical CMUs entirely and using digital communications simulation to replicate the communications from the CMUs to the BMU, only. This approach has a benefit of reduced hardware associated with CMUs, including cell and thermistor simulators and connectivity. However, this is at the expense of highly customized CMU to BMU communications simulation software, as well as loss of authenticity. Communications between the CMUs and BMU is most often a proprietary version of isolated SPI, though isolated UART, ethernet, or CANbus may also be used. To simulate this communications interface in a battery pack surrogate requires custom FPGA-based software to emulate the state machines, clock signals, and tight query/response timings associated with the proprietary communications and cell monitoring integrated circuits on the CMU. While this method does reduce instrumentation costs and space, it is not an authentic representation of the control systems inside the BMS, and may inject unintended faults, or could result in masking real-world faults. For that reason, if simulated CMU to BMU communications is to be employed, it is recommended that this methodology be reserved only for a subset of the battery pack surrogate, in tandem with real CMU-based simulation methodologies. The preferred approach is to implement at least one of the redundant packs of the battery as real CMUs with simulated cells and thermistors, while the other pack's CMUs are simulated via communications.

## BMU/PACK SIGNAL SIMULATION

Where the CMU monitors module and cell-level signals, the BMU monitors pack-level signals. While the CMU is generally only monitoring and reporting cell and module data and controlling simple cell balancing, the BMU is aggregating cell- and pack-level sensor data and is running complex algorithms to make decisions about safety and performance. The total number of signals monitored and controlled by the BMU is fewer than the CMUs, but the variety is larger. A BMU will monitor multiple high-voltage measurement points, overall pack current (either via a current shunt or Hall effect sensor), environmental and control signals, as well as communications to the CMUs and to the aircraft. The BMU also has a larger variety of output signals than the CMU, including control of multiple contactors or disconnects, heating and/or cooling, and aircraft/charger interactions.

At a high level, BMU signal simulation entails replacing all pack-level interactions, such as those shown in Figure 2 with simulated signals. Many of these signals, such as thermistors, discrete input/output control, and environmental control can be simulated and monitored with simple digital and analog inputs and outputs. The most critical and complex simulations to the BMU are the overall pack voltage, current, and contactor/disconnect simulation and monitoring.

### BMU – Pack Voltage/Current/Contactor Dependencies

A typical BMU will monitor two to four pack voltage-level (i.e., 800VDC) touchpoints, depending on the contactor/disconnect arrangement. Figure 2 shows the most common arrangement, with pre- and post-contactor measurement points, often referred to as the "Batt" and "Pack" voltages, respectively, though many other topologies may be used. In a real battery pack, "Batt" is the internal battery stack voltage and should match the sum of CMU cell voltage measurements. "Pack" measures the external voltage out to the aircraft. "Batt" and "Pack" may differ as a function of contactor state, pack current, and the resistance associated with the current shunt, contactors, precharge resistors, and cabling. When contactors are open, the "Pack" will be close to 0V, whereas when the contactors are closed, "Pack" should be close to "Batt." As the aircraft discharges the battery, "Pack" will drop with respect to "Batt" based on the current flow and series resistance. Conversely, when charging, "Pack" will be higher than "Batt." The BMU monitors pack current and adjusts the expected voltages for "Batt" and "Pack" as a function of the expected system resistances. If there is a discrepancy between the expected values and measured values, the BMU should flag a fault, such as excessive contactor resistance. Due to the

tightly coupled nature of these variables, simulation of the voltages, current, and contactor conditions must be implemented as a unified and cohesive simulation.

Because of the high-voltage, high-current nature of the BMU input signals, the BMU employs the AFE to perform signal conditioning that scales the high-voltage and high-current measurements at the connectors to signal levels compatible with the analog-to-digital converters on the board. Therefore, test system engineers must make a critical decision at the outset of battery pack surrogate design: test at high voltage and high current using the complete AFE at full power; test using a mix of high-power and low-power simulations which also use the complete AFE; or create a low-voltage system that simulates high voltage and current signals by tapping into the BMU behind the AFE, bypassing the AFE entirely. The three most common implementations are discussed in the following sections.

### BMU Pack Simulation – Full Power, Pre-AFE

In this implementation, shown in Figure 10, a high-power bidirectional power supply is used to emulate the power associated with the real battery pack. The power supply can be specified for the full power (voltage and current) of the real pack, or for derated power based on the limits of the overall system integration test requirements.

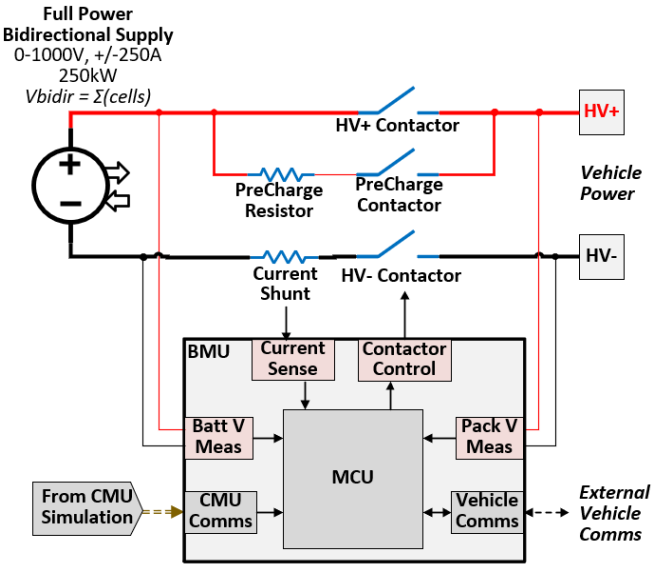


**Figure 10. Full power, pre-AFE simulation**

The BMU monitors the battery voltage as the output of the bidirectional supply. The full power from the bidirectional supply is routed through the real current shunt and contactors that would be included in the pack and which are controlled directly by the BMU. The post-contactor pack voltage is monitored by the BMU as in the real pack, then output to the outside world via the pack connections, denoted HV+ and HV- in Figure 10. In this way, the BMU monitors all high voltage and current through the onboard AFE signal conditioning, and manages the real contactors for control of the full power outputs. This power may be connected to the external aircraft systems to provide full battery power to propulsion and other high-power consumption systems.

To satisfy the BMU safety algorithms, the bidirectional power supply voltage must match the sum of the cell voltages simulated into the CMUs and reported back to the BMU. This implementation, paired with the full stack cell simulation methodology, most closely mimics a real-world battery pack. It includes all of the real CMUs, the BMU, and high-power control and monitoring electronics, such as the shunt and contactors.

### BMU Pack Simulation – Reduced Power, Pre-AFE

While the prior implementation is the most representative of a real battery pack, it has limitations in the types of faults that may be simulated into the BMU because of the inherently coupled nature of the single power supply's voltage and current. It requires hard-wired contactor and power connections, which limits the ability to change contactor configurations, or simulate stuck contactors, or resistance buildup faults on the fly. This limitation can be remedied using the low-power (but still high voltage) pre-AFE simulation implementation shown in Figure 11.

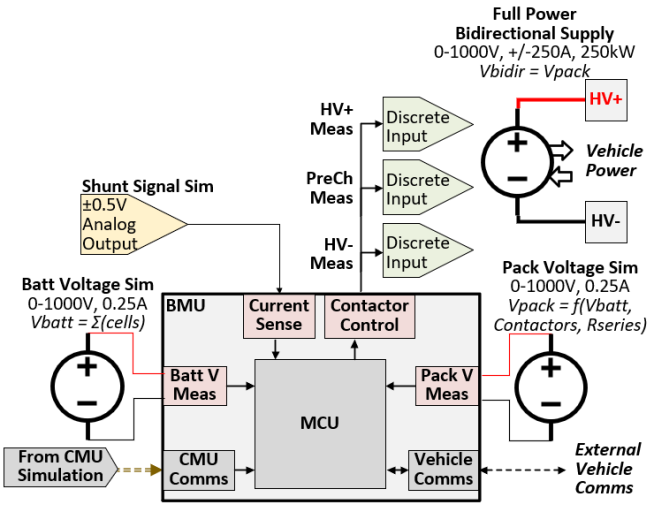


**Figure 11. Reduced power, pre-AFE simulation**

In this simulation methodology, the signals measured by the BMU are simulated using lower power instrumentation connected to the standard BMU connectors, thus using the BMU's AFE. Battery and pack voltages are provided to the BMU using high-voltage, low-current sources with only enough current to satisfy the measurement signal conditioning in the BMU's AFE. Pack current is simulated using an analog output voltage from the test equipment which is scaled to match the corresponding shunt or Hall effect sensor's output. Contactor control signals from the BMU are monitored using discrete input measurement circuits in the test instrumentation. By monitoring the contactor control signals from the BMU, the HIL test system can use software models to control

the “Pack” voltage simulation as a function of the simulated battery voltage, pack current, and simulated characteristics of the current shunt, wiring, and contactors.

Just as with the full power simulation, “Batt” voltage must match the sum of CMU cells to satisfy the BMU. However, this configuration has the advantage of enabling simulation of edge conditions, such as contactor short faults or contact resistance buildup, through individual control of the “Batt,” “Pack,” and current simulations as a function of the simulated pack voltage and current. For example, if multiple different contactor topologies are to be considered, this methodology also enables the various setups to be modeled in software. In this way, the software can monitor the contactor control signals from the BMU and use contactor topology software models to control the simulated high current and high voltage signals in a more granular fashion. Furthermore, this configuration has the advantage of simulating all BMU I/O at reduced power, though not necessarily at low voltage. If desired, a separate full power bidirectional supply may optionally be used to provide battery power to propulsion, charging, and other aircraft systems. If utilized, the voltage of the bidirectional supply must be commanded by the battery pack surrogate HIL system to match the pack voltage simulation signal, and the current supplied must be monitored and used to control the pack current simulation.

### BMU Pack Simulation – Low Voltage, Post-AFE

The pre-AFE simulation solves issues associated with simulated edge conditions pertaining to the contactor, shunts, or wiring. However, the pre-AFE simulation still requires the battery pack surrogate HIL system to make use of high-voltage signals, which may be restricted in some lab environments. Satisfying the requirement for a low-voltage system often requires modification of the BMU circuitry by connecting the simulated signals into the BMU “behind” the AFE signal conditioning as shown in Figure 12.

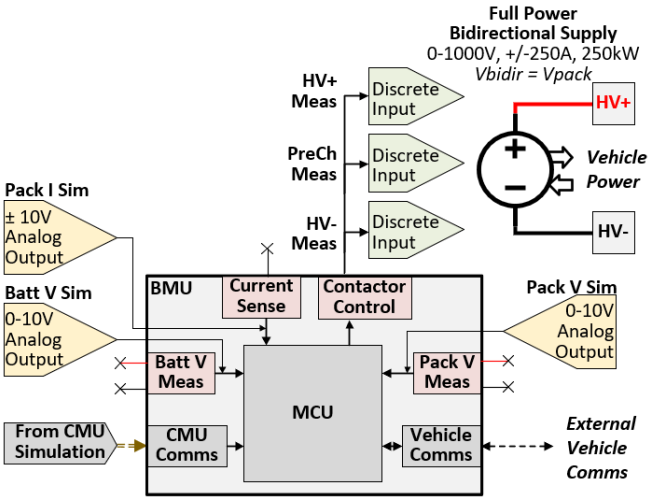


**Figure 12. Low Voltage, Post-AFE simulation**

Post-AFE simulation entails disconnecting portions of the analog front end signal conditioning on the BMU and replacing it with low-voltage signals as they would be fed into the BMU’s analog-to-digital converters. This is typically a case of removing several passive components or lifting pins on the signal conditioning ICs. Once the BMU is modified, “Batt” and “Pack” voltages and pack current can then be simulated by ±10V analog signals, with values scaled to match the BMU AFE gains and offsets. The benefit of this method is that all signals into and out of the BMU may be monitored using common low-cost instrumentation with no high voltages or power present. However, like the pre-AFE methods of simulation, a separate full power bidirectional supply may be optionally added for providing battery power to the rest of the aircraft.

### CMU and BMU Integration

Once the desired CMU and BMU simulation methods are selected, the overall battery pack surrogate hardware may be integrated. Figure 13 shows an integration of the CMU using full stack simulation with the BMU using full pack power, pre-AFE simulation. The battery pack surrogate HIL system represented by this block diagram corresponds to the actual system shown in Figure 4. As shown here, eighteen real CMUs are connected to 216 simulated cells and isolated thermistor simulations. All simulated cells are stacked in series to create the full 800V stack that would be seen in a real battery pack. The isolated communications from the CMUs are then routed to the real BMU. Because the simulated cells cannot provide full battery power, a full power bidirectional power supply is employed to deliver full battery power through the real current shunt and contactors. The BMU monitors communications from the CMUs, Batt and Pack voltage, and pack current, while controlling the real contactors. All BMS boards, high power control and monitoring, as well as simulation instrumentation are enclosed within the battery pack surrogate system. The output of the battery pack surrogate system includes the exact connections that would be provided by the real battery pack, including high power (HV+ and HV-), communications to the aircraft, and other I/O (such as interlocks, switches, and environmental feedback). This configuration provides the most accurate representation of the battery pack, and therefore, highest fidelity test capability. For this reason, most iron bird test setups use this configuration of battery pack surrogate.

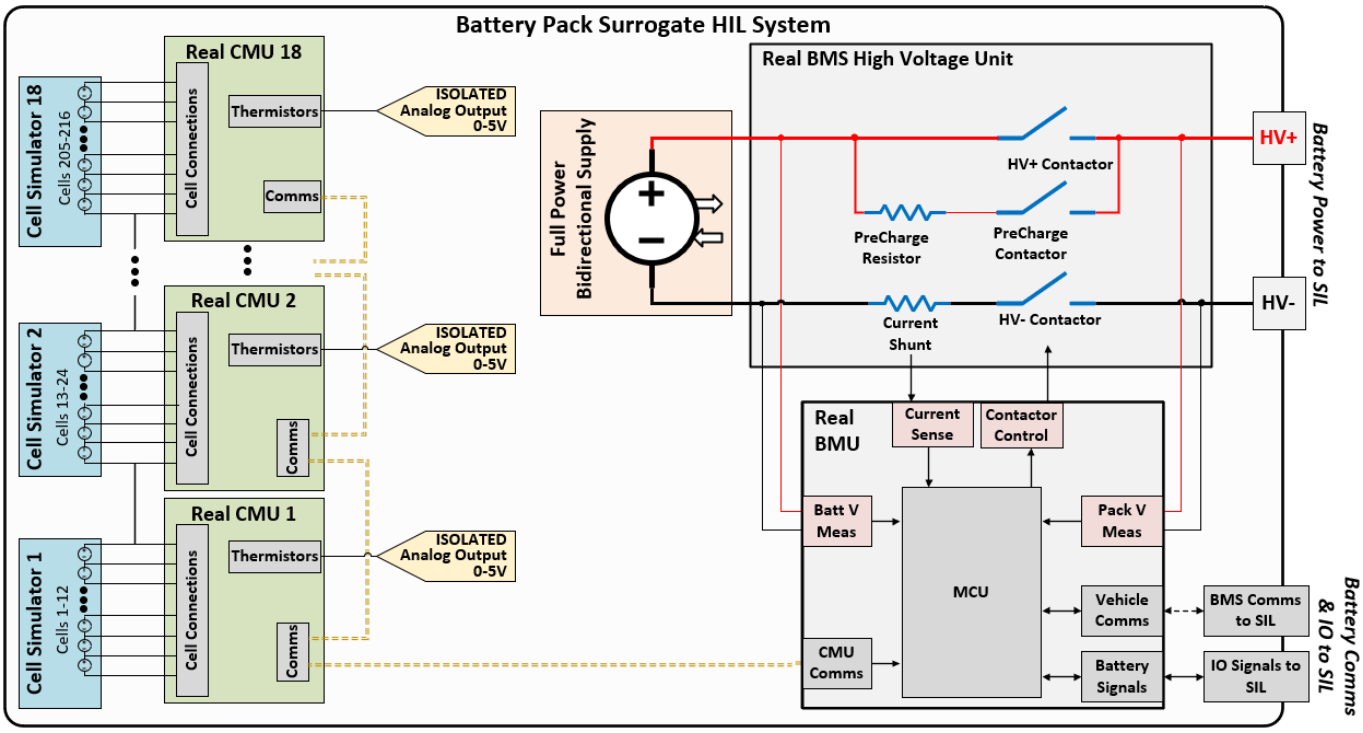


**Figure 13. Battery pack surrogate CMU & BMU integration**

## BATTERY PACK SIMULATION SOFTWARE AND MODELING

While simulated signals enable the battery pack surrogate to affect and monitor the internal measurement and control circuitry of the BMS, software is required to make these signals behave like a real battery to the electric aircraft systems. Central to the software is a HIL simulation environment. Commercial software toolchains including, but not limited to NI VeriStand, The MathWorks Speedgoat, and ADI ADEPT provide this environment. Furthermore, the battery pack surrogate may be integrated into airframers' proprietary software tools using direct control or via reflective memory. The HIL environment, shown in Figure 14, provides a real-time control, model execution, and mapping engine that drives the battery pack surrogate. This real-time HIL engine executes cell chemistry, pack control, and other plant models, then maps the inputs and outputs of the models to physical instrumentation signals and calculated channels. It controls the instrumentation and communicates with the BMS, all within a deterministic control loop which executes at a rate of between 200Hz and 2,000Hz, depending upon computing resources, model complexity, and number of IO. External to the HIL engine, applications for test automation, graphical user interfaces, data playback, and model development may be used to augment or interact with the real-time control systems.

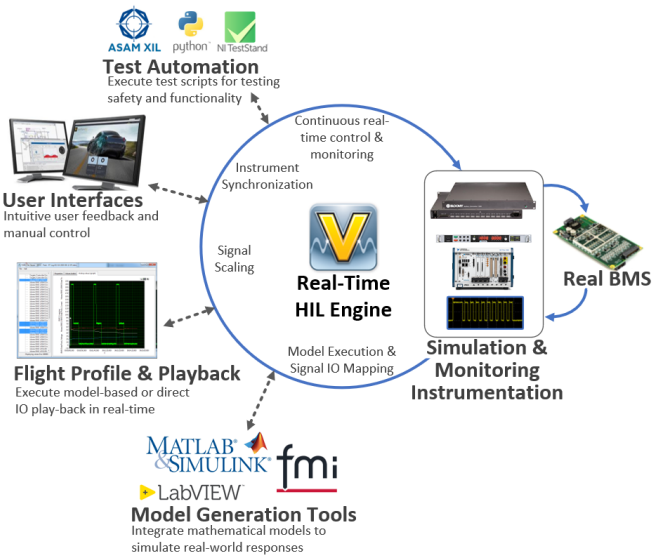


**Figure 14. HIL Engine block diagram**

The real-time HIL engine is the heart of the battery pack surrogate software. Once configured with modeling, scaling, mapping, and signal control, the real-time engine controls the previously-described simulation hardware to behave like a real battery. Python, NI TestStand, or some other test scripting environments are used to automate common setup and test scenarios, such as pack startup and shutdown, setting initial test conditions, or causing fault or edge conditions.

A graphical user interface is an important tool for providing engineers with easily-manipulated and viewed access to individual signals and model parameters for setup, monitoring, and control. Customizable user interfaces can provide different views of the battery pack surrogate for tasks like direct signal control, model preparation and execution, and monitoring BMS-communication parameters.

In addition to controlling the simulation with user controls, some test cases may require playback of pre-recorded data into the various aircraft systems under test. Using a HIL environment that supports data playback, with direct control of both all I/O as well as model inputs such as a pack power flight profiles, further enhances the capabilities of the battery pack surrogate. Typically, this capability allows basic comma-separated value tables to define millisecond-level control of any signals in the HIL environment.

Lastly, the key to making the battery pack surrogate behave like the real battery pack comes down to the battery cell and pack models that are executed in real-time. These may be provided by cell manufacturers, developed by in-house battery scientists, or generated by third party test system integrators. While MATLAB and Simulink are the most common model generation applications, open standards such as FMI are becoming increasingly popular, and can be executed by most commercial HIL environments.

### Cell and Pack Models

Just as the cell is the basic building block of the battery pack and the cell simulator is the foundation of the simulated hardware, the cell model is one of the most critical components of the battery pack surrogate software. The cell model enables the entire system of signals to behave like a battery of a particular chemistry, adjusting cell voltages, temperatures, pack voltage, and pack current as the simulated pack is charged and discharged.

A typical model for a battery pack surrogate HIL system will receive initial conditions, including number of series and parallel cells, initial per-cell SoC and capacity, thermal and chemical characteristics. It uses these initial conditions as the starting point for the simulation. The simulated pack's state is updated by the model as it receives pack current and air/coolant temperature information, either from a real or simulated propulsion system, through the system's bidirectional power supply, via a manual user interface, or from an engineered flight profile or playback. Additionally, the state is updated by inputs to the model from instrumentation monitoring the BMS and other external system components. The model's outputs are mapped to the physical instrumentation which provides inputs to the BMS as shown in Figure 15.

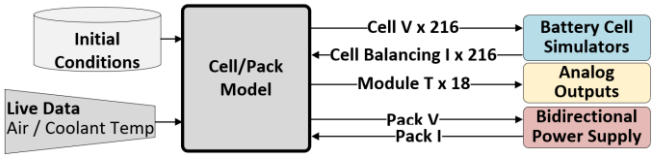


**Figure 15. Cell/Pack model overview**

The HIL real-time engine executes the model in discrete time steps. As shown in Figure 16, at each time step, the model calculates each cell's total current, state of charge, voltage, and temperature. The cell total current is calculated as a sum of the overall pack current plus the individual cell's balancing current. This is then used to calculate the cell's SoC as a function of the model's execution time step, cell current, and the total cell capacity (individual cell capacity times the number of cells in parallel). Cell voltage is then calculated using the current, SoC, and specific cell chemistry model parameters which are dependent on the cell chemistry model in use. Cell temperature is then calculated as a function of the time step, cell current, cell resistance, cell thermal parameters, and the air/coolant temperature. Finally, pack-level parameters, such as pack voltage, adjusted pack current, and pack temperature may be calculated based on the individual cell values. These calculated parameters are then output from the model to be mapped to physical channels, such as cell simulator instruments for cell voltage, analog output signals for temperatures, and power supplies for battery output voltages. The bidirectional supply reads output current to the aircraft and maps it back as a model input for the next iteration to drain or charge the cell models. Cell simulators read individual cell balancing and quiescent currents and feed these back into the model, allowing the model to drain or charge each cell individually. This repeats at the HIL real-time execution's control loop rate, typically on the order of every 0.5ms to 5ms.

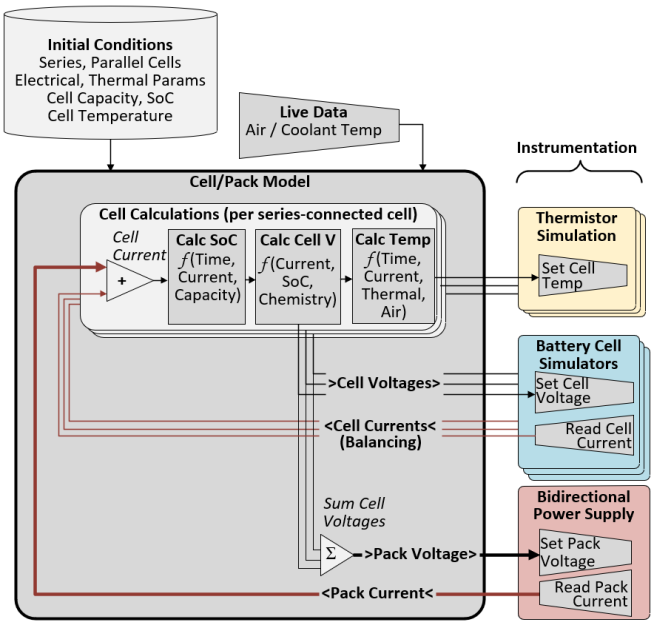


**Figure 16. Cell/Pack model block diagram**

Cell and pack models come in many different flavors, though there are two major categories of model: physics-based and equivalent circuit. Physics-based models simulate the internal electrochemical and physical properties of a lithium-ion cell. While an excellent model for predicting cell behavior, including voltage, thermals, degredation, aging, and mechanical stresses, they tend to require high levels of computational power and are typically not used in high channel count, real-time HIL test systems. An equivalent circuit model (ECM), like that shown in Figure 17, is a simplified mathematical model that uses basic electrical circuit components to represent the behavior of the cell.

In an ECM, the open circuit voltage (OCV) and circuit parameters are each a function of the cell's state of charge and temperature. This is usually represented by 2D interpolation tables for each parameter. The OCV dictates the resting voltage of the cell as if it were to sit with zero current for several hours. $R_0$ represents the effective series resistance (ESR) of the cell, while $R_1$, $C_1$, $R_2$, and $C_2$, represent R-C circuits that model the dynamic characteristics of the cell (Ref 3). The cell voltage, $V_{cell}$, can be calculated using standard circuit analysis methods. Many additional variants of the ECM exist that provide different features such as ageing, hysteresis, or additional R-C pairs.

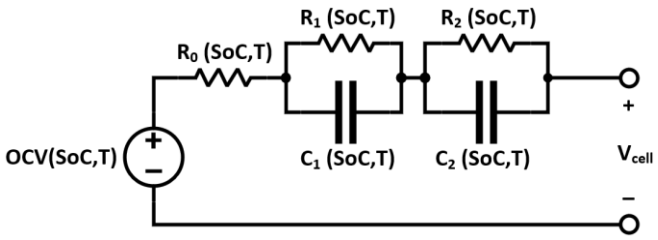


**Figure 17. Equivalent circuit model**

While the ECM is not a perfect representation of a cell, it provides a "good enough" approximation for most electric aircraft systems integration testing purposes. Where Figure 17 shows a single cell, the full pack model must replicate this once for each series-connected cell in the pack. Because the validation team will likely reconfigure the battery pack or cell initial conditions frequently, the model should be implemented such that the coefficients for each of the circuit parameters can easily be modified and reloaded for testing. Therefore, it is recommended that the model code utilize some external configuration file for storing of coefficients. A graphical user interface (GUI), like that shown in Figure 18, makes cell model configuration especially straightforward for test operators looking to develop specific test cases.

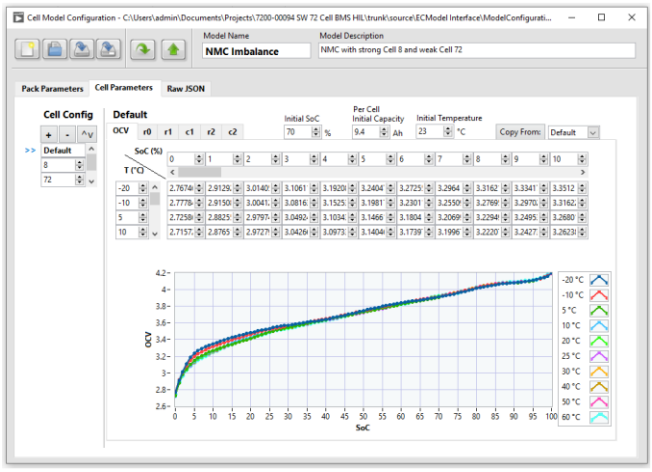


**Figure 18. Cell model configuration GUI**

## PUTTING IT ALL TOGETHER

Once the entire battery pack surrogate's connectivity to the BMS and software control with modeling have been integrated with simulated signals, the system may be used for testing with other aircraft systems. Referring back to Figure 13 and Figure 16, the physical outputs, including pack power and vehicle communications from the battery pack surrogate HIL system are controlled by the real BMS, while all signals into the BMS are simulated by instrumentation controlled by the cell and pack models. In this way, the entire battery pack surrogate HIL system acts as a real battery. Each battery pack surrogate must be configured to the requirements of the aircraft, battery, and validation team.

The example system shown in Figure 4 is a battery pack surrogate which includes the BMS components housed inside the rack alongside the simulation instrumentation. This system contains eighteen 12-cell simulators for a total of 216 cells. All cells are stacked in series to each CMU, and all CMUs are stacked in series to provide full pack voltage to the BMU, as shown in Figure 19. A bidirectional power supply provides full power out to the external aircraft systems.

**Figure 19: Full stack battery surrogate CMU connections**

Figure 20 shows a different battery pack surrogate configuration for a low-voltage lab. In this system, multiple BMS prototypes were to be tested. Therefore, all simulated signals are routed through commercial industry-standard connectors on the front of the system. The system contains 192 simulated cells, 96 simulated thermistors, and various analog and digital IO for CMU and BMU interfaces. Because the simulated cells are routed through front-panel D-subminiature connectors, with a maximum voltage of 250VDC to ground, and because all thermistor simulation signals are non-isolated, it is intended to be configured for the low-voltage full cell CMU simulation method. The system also contains 10x 0-1000VDC, 1mA outputs for simulating the high voltage measurement points into the BMU. This particular system uses contactor simulation models to control the 10 high voltage outputs as a function of the simulated pack current and BMU contactor control signals, allowing the validation team to simulate multiple different contactor arrangements, without rewiring the contactor interfaces.

**Figure 20. Example low-voltage battery pack surrogate**

An operator may configure the initial conditions of the cell and pack models, such as pack topology, per-cell capacity, initial cell states of charge, and initial temperatures, and then initiate the model execution. At this point, the HIL system is running independently as if it were a real battery. Any current drawn by the external systems will be read by the HIL instrumentation and fed back to the model. Meanwhile, the real BMU is managing communications and interactions with the external aircraft systems and is controlling disconnects, safety, and performance algorithms. For all intents and purposes, any aircraft system connected to the battery pack surrogate will perform as if it were interacting with a real battery. The model will drain and charge the pack based on the bidirectional power supply readback, and the corresponding signals to the BMS LRUs will be adjusted such that the BMS responds as if it were connected to and controlling real chemical cells.

The following sections outline several examples of applications of the battery pack surrogate HIL system and the resulting acceleration of electric aircraft integration and validation.

**Example 1. Iron bird systems integration lab**

An iron bird is used to ensure that all major systems within the aircraft are functioning in a fully-integrated environment. In an iron bird, many aircraft systems and LRUs will annunciate faults without receiving battery data. Systems such as mission planning, aircraft management, and propulsion require information such as available capacity, state of charge, fault states and pack voltages to be supplied by the BMS. Other systems such as environmental controls, actuators, DC/DC converters, and auxiliary electrical systems require power from the battery. Furthermore, the interactions of the various aircraft systems will have complex behaviors dependent on the battery pack's state, including fault and edge conditions. The battery pack surrogate allows these systems to operate normally during basic integration testing, as well as testing of error conditions caused by the battery pack.

Using a battery pack surrogate also ensures that validation teams have nearly infinite control over the battery pack state from the high-level initial pack state of charge down to individual cell chemistry, capacity, SoC, and temperature parameters. At any point during integration testing, the battery pack surrogate allows any pack and cell parameters to be reconfigured. This empowers the validation team to repeatedly run different full aircraft integration tests without waiting for a real battery pack to charge or to be reset to a particular set of initial conditions.

**Example 2. Propulsion system dynamometer testing**

A dynamometer test system for the electric aircraft propulsion system is shown in Figure 21. The validation team would use this system to understand how different initial states and edge conditions of the battery pack may affect the motor controller across various flight profiles. Their end goals include tuning the motor controller's parameters to optimize performance and flight time, as well as to configure the battery fault response of the motor controller. In this setup, the battery pack surrogate is providing real power to the motor controller by way of the bidirectional power supply. The BMS is communicating with the motor controller as if it were connected to a real battery, although all I/O of the BMS are simulated by the battery pack surrogate. In this scenario, the battery pack surrogate is configured with initial conditions for the desired cell chemistry and the initial pack state of charge, capacity, and temperatures. A flight profile is used with the real aircraft motor controller which powers the real motors that then provide feedback to the controller using real speed sensors. The flight profile also controls a dynamometer to load the motors for simulating takeoff, cruise, and landing.

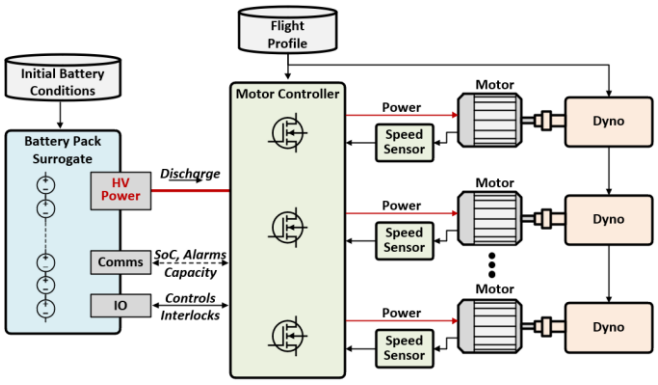


**Figure 21. Example propulsion dyno test**

Because the motor controller draws real power from the battery pack surrogate during the flight profile execution, the surrogate feeds the current readback from the bidirectional supply into the cell and pack models. The models then drain the pack SoC, causing cell and pack voltages to drop as if they were chemical cells of a real pack. These voltages are then fed to the cell simulators, bidirectional power supply, and other instrumentation. In addition, because the actual BMS is included in the surrogate, the validation engineers may easily test potentially dangerous edge conditions, such as a weak module or cell, over-temperature, or low initial SoC. In these edge cases, the validation engineers may even test scenarios where part of the redundant pack faults and disconnects – ensuring that the remaining pack provides sufficient power to safely land the aircraft. At the end of testing, the HIL simulator provides a data log of the pack current draw, calculated cell voltages, temperatures, pack voltage, and SoC, as well as BMS reported values like cell and pack voltage, current, SoC, and alarm information.

**Example 3. Charger and ground support integration**

Ground support equipment, such as chargers, are usually a separate system external to the aircraft and are often developed separately from the aircraft itself. However, the charger and ground support equipment are tightly coupled with the battery pack functionality. Safe and efficient charging is critical to the success of any electric aircraft program. Overcharging due to improper charge control algorithms poses a high risk of battery damage and thermal runaway. This is especially true for quick flight industries, such as electric air taxis, which may endure several fast-charge cycles per day. Validation of the interaction between the battery, the BMS's safety, control, and balancing systems, and the external charger is essential.

A block diagram of charger integration testing is shown in Figure 22. During charger integration testing, the battery pack surrogate is configured to an initial pack SoC, capacity, and temperature. Once model execution is started, the battery pack surrogate runs stand-alone, behaving like the real battery pack. Validation engineers can then validate and monitor the constant current/constant voltage charge profile, protection circuits, charge controller, and AC/DC conversion of the

charger. Charger to BMS communications can be monitored, interlocks and protection circuitry can be validated, and the overall charging algorithm can be tuned. Furthermore, individual cells may be set to varying SoCs, capacity, and temperatures to simulate cell, module, or pack imbalances. Because a real battery is not in use, validation engineers do not need to worry about inadvertently overcharging and causing damage to the pack while validating the control algorithms.

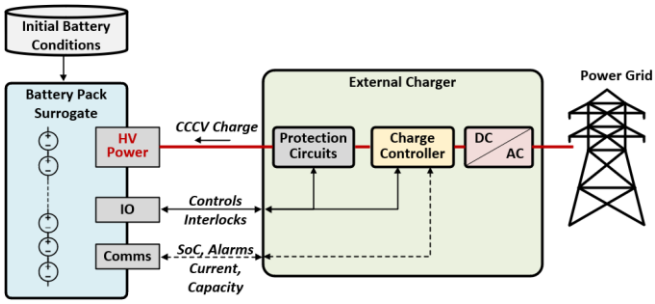


**Figure 22. Example charger integration test**

### Test Data Collection

One of the keys of successful validation testing is data collection. Because the battery pack surrogate is a HIL test system, the real-time HIL engine allows continuous and deterministic data collection on all physical I/O channels, model inputs and outputs, and intermediate data channels. This collection can be helpful for troubleshooting integration issues between systems, when the culprit of an unintended behavior is not obvious. Beyond troubleshooting, proper data collection, management, and validation is critical to certifying flight readiness. Figure 23 shows an example of data collected for the model-calculated SoC, the real BMU-reported SoC, and overall pack voltage as a function of a charge/discharge pack current profile.

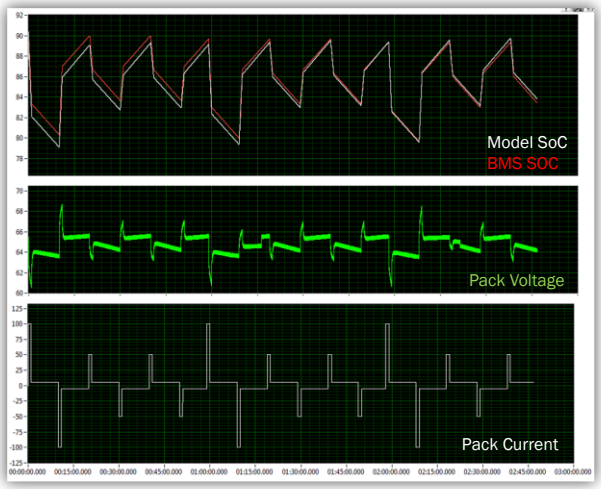


**Figure 23. Example charge/discharge profile data**

## CONCLUDING REMARKS

A battery pack surrogate is a hardware in-the-loop simulation system which includes real BMS components, such as the cell monitoring units (CMUs) and battery management unit (BMU), connected to instrumentation which simulates the physical signals of the battery pack. The simulated signals of the battery pack surrogate are controlled by mathematical models of the cell chemistry, disconnects, and thermal behaviors of the battery, effectively making the BMS perform as if it were connected to real physical cells, sensors, contactors and other pack infrastructure. Combining these components with quickly-reconfigurable models into a single HIL system provides marked improvements in validating electric aircraft systems' interaction with the battery pack.

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