MathWorks
AUTOMOTIVE
CONFERENCE 2024
Korea

Hardware-in-the-Loop Testing for Battery Management Systems using Speedgoat Test System

Jihun Gong, Inno-X

MathWorks

About speedgoat

- **An associated company of**

MathWorks®

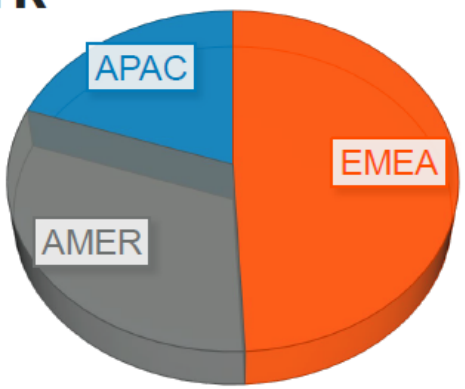
Main offices

- **Speedgoat GmbH Switzerland**
- **Speedgoat GmbH Germany**
- **Speedgoat Inc USA**

swiss safety center ISO 9001 ISO 14001 certified system

swiss safety center ISO/IEC 27001 certified system

Worldwide Sales and Distributor network



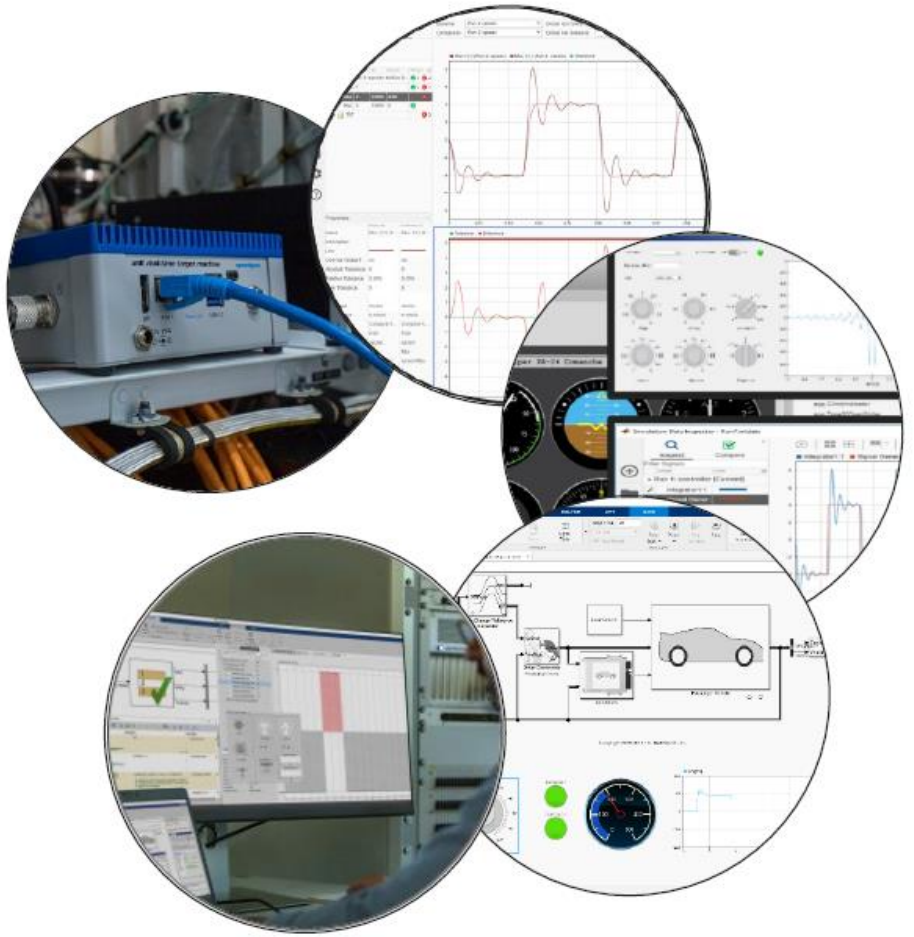
Official Speedgoat distributor in Korea

InnoX
(주)이노엑스

What Do We Offer?

speedgoat | MathWorks

- Testing of Control Designs and Embedded Controllers
- Virtual & Integrated Testing Solution
  - Deterministic emulation of plants, sensors & actuators
  - Plug & play I/O interfacing
  - Automate testing
  - Comply with certification requirements
- Frontload Verification & Validation
  - Test before plant hardware is available
  - Gradually integrate and test plant components
  - Detect design flaws and fix bugs earlier
  - Test corner cases and exceedances



What Do We Offer?

Real-Time-Enabled Model-Based Design

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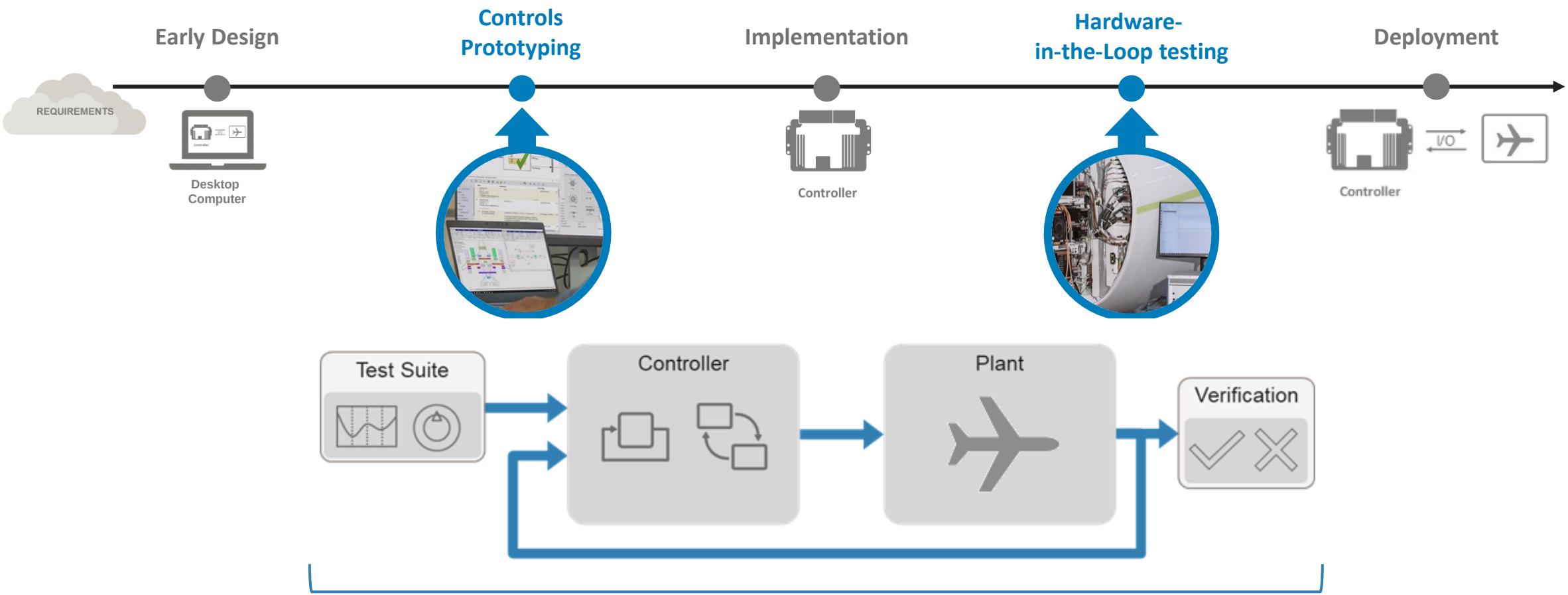


What Do We Offer?

Key Value Adds - Unified Desktop and Real-Time Simulation and Testing

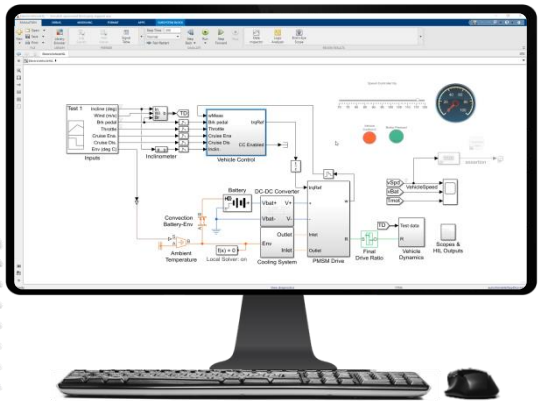
Work Better with Tools you Already Know and Trust

- Stay in MATLAB® and Simulink®
- Deploy and connect to hardware with a few clicks
- Rapidly switch between desktop and real-time simulation
- No extra knowledge required

Partner with an Experienced, Yet Agile, Organization

- Two organizations collaborating at all levels
- Synchronized engineering
  - Software/Hardware designed for one another
  - No release version lags
- Unified customer services

Simulink® Real-Time™



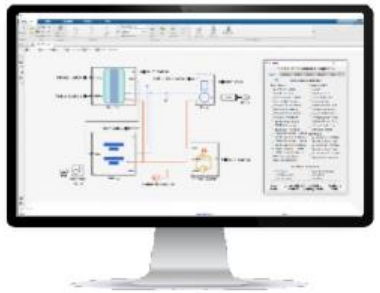
Speedgoat Test System

speedgoat Expressly designed for Simulink Real-Time™

Work Better with Tools You Know and Trust

Real-time testing, simplified

- Stay in MATLAB or Simulink
- Connect to hardware with a few clicks
- Rapidly switch between desktop and real-time simulation
- Deploy apps for desktop or web use



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Simulink Real-Time (SLRT)

- Real-time instrumentation
- Digital Twins
- Automated testing
- Code generation (C/VHDL)

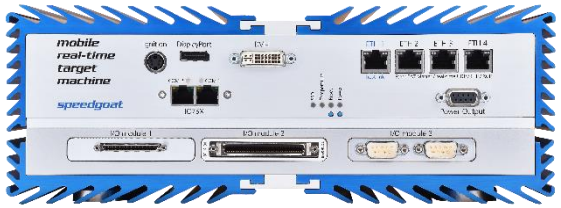
Real-Time OS

Speedgoat
Real-Time Test Systems

- I/O & protocol support
- FPGA-based solutions
- Speedgoat I/O blockset
- Complete racks

High-Performance, Scalable, and Modular HIL Test Systems

Performance



Mobile

Baseline

Unit

Multicore Processors

Latest generation Intel CPUs made for hard real–time execution

Choose from 2- to 8-core

Parallel execution and co-execution with FPGAs enabled from Simulink

BlackBerry | QNX

On-board connectivity

Gigabit Ethernet ports (UDP, TCP/IP, EtherCAT Master, XCP, PTP 1588)

Serial ports (RS232/422/485)

USB ports

Video ports (HDMI, DVI, VGA or DP)

Low latency / High throughput

PCIe gen 3

Direct Memory Access (DMA)

FPGA based I/O

Flexible I/O & chassis expansion

Add/replace I/O at any time

Expand with I/O expansion units or multi-chassis, distributed simulation

Connectivity and Protocol Support: 200+ I/O Modules

Automotive Protocols

- CAN, CAN FD
- LIN
- FlexRay
- SENT
- PSI5

General Purpose Protocols

- Serial (RS232/RS422/RS485)
- SPI
- I2C
- Ethernet
  - UDP
  - TCP/IP
  - XCP
  - EtherCAT

Motion and Motor Controls

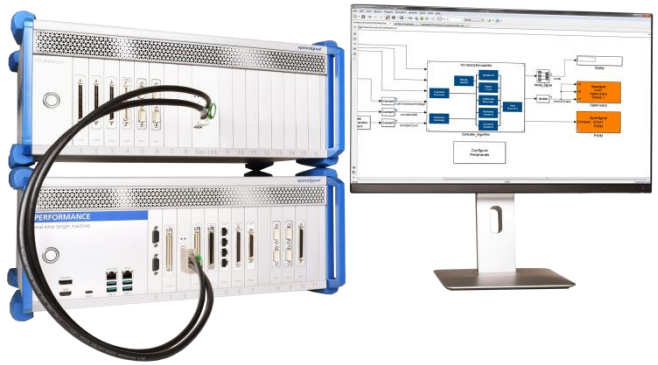
- Low latency analog and digital
- PWM generation and capture
- Encoders (quadrature, SSI, EnDat, BiSS)
- Resolvers
- Cam, Crank

ADAS/AD

- Vision
- Radar
- Lidar

Battery Management Systems

- Cell emulation
- Temperature emulation
- Fault insertion



And more...

- Installed in Speedgoat test system
- Always delivered with Speedgoat I/O blockset, cables, terminal boards, and test models

About Battery Management Systems

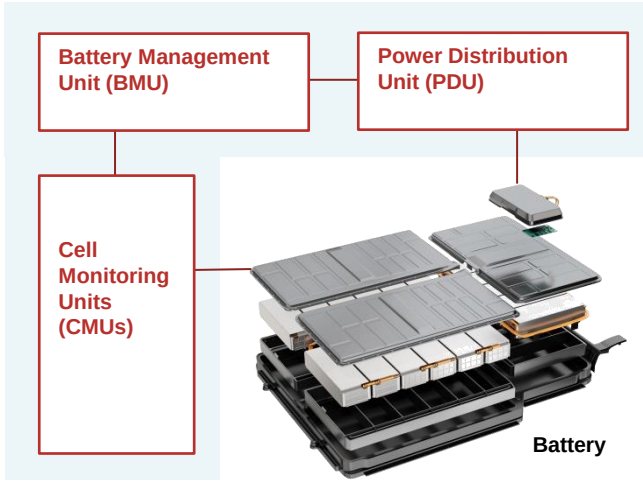
Batteries are crucial for electrification

- Electric Vehicles
- Aircrafts
- Energy storage systems
- Portable devices

Battery Management Systems (BMS) ensure

- Safe operation
- Best performance
- Optimized battery life

Battery Management System



BMS Testing: Challenges with Real Batteries

Batteries age, making it hard to reproduce reliable test conditions to test core algorithms such as:

- Cell balancing
- State of Charge (SoC)
- State of Health (SoH)

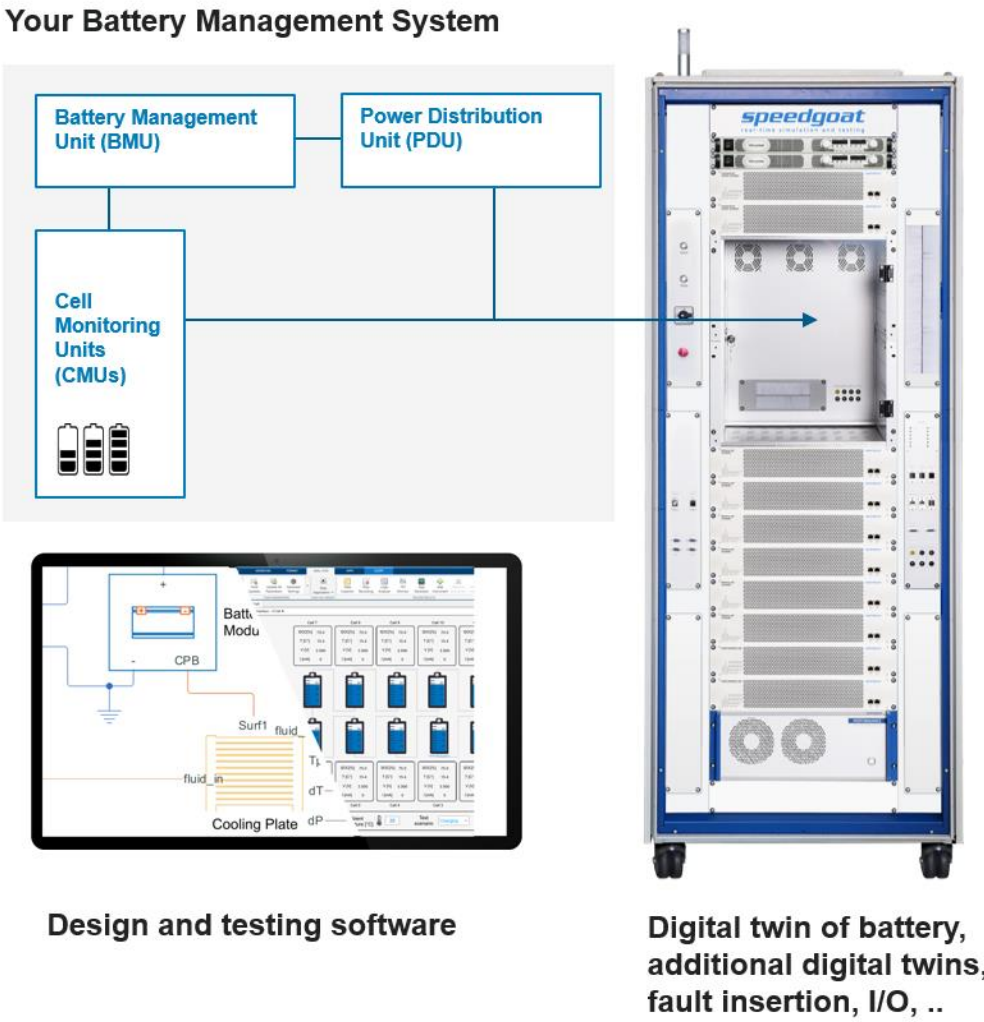
Testing over-voltage, extreme temperature, and fault conditions is dangerous

Batteries, BMS systems, connected products and infrastructures evolve. As a result, there is a need to test a large amount of configurations that can be hardly achieved using real hardware

BMS Testing with Digital Twins

Overcome BMS testing challenges with a digital twin of your battery and BMS components

- Flexibly configure different battery pack architectures
- Emulate real voltages and currents
- Adapt as battery technology evolves
- Integrate digital twins for connected components such as motor drives, chargers, and complete powertrains
- Perform requirements-based testing
- Continuously evolve your product and automate testing 24/7



Key Benefits using Speedgoat and Simulink for BMS Testing

Automated BMS Testing

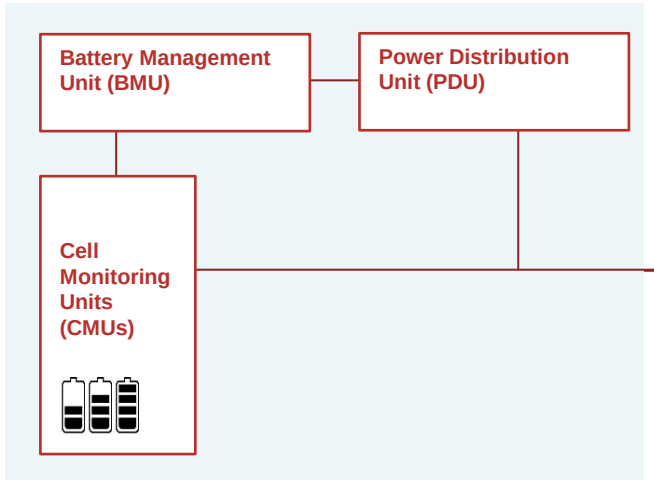
1. Define battery pack architectures, leverage industry norm specific testing frameworks, and design BMU or CMU algorithms as needed

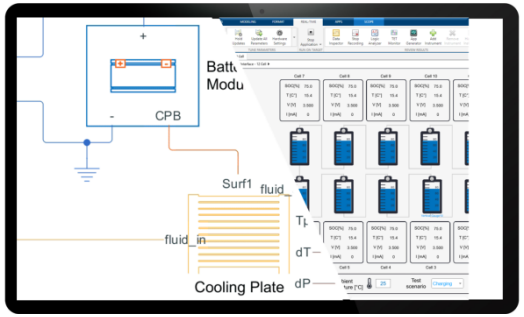
2. Define varying battery behavior depending on the battery technology and chemistry, age, surrounding temperatures, and required energies

3. Emulate battery packs and power distributions at real power levels, and connect the Speedgoat test system to the BMS I/O, protocols and power lines

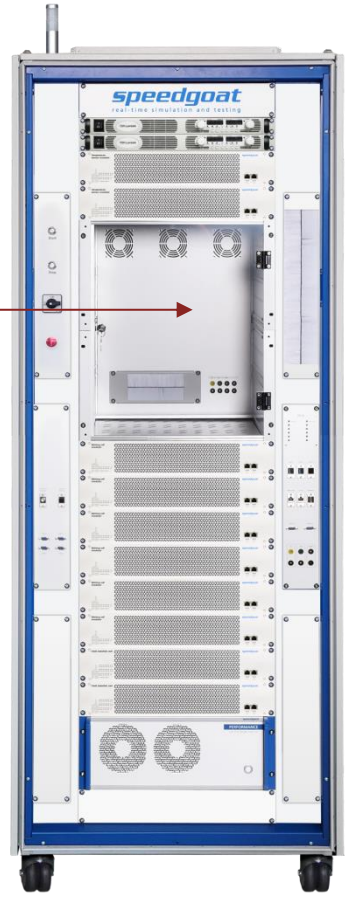
4. Perform automated 24/7 testing of your BMS under regular operation and with fault conditions

Your Battery Management System





Design and testing software



Digital twin of battery, additional digital twins, fault insertion, I/O, ..

Key Components of the Speedgoat and MathWorks® Solution

Ready to Use Battery Pack Architectures, CMU and BMU algorithmic designs

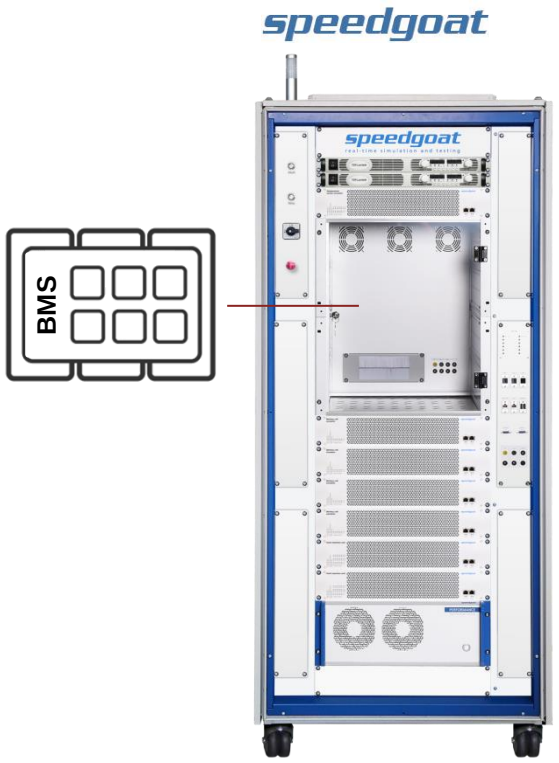
- Leverage and adopt ready to use Simulink reference designs to your needs

Complete Battery Pack Emulation

- Cell emulation at real voltage and power levels
- Power distribution emulation
- Temperature emulation
- Fault insertion support
- Communication protocols

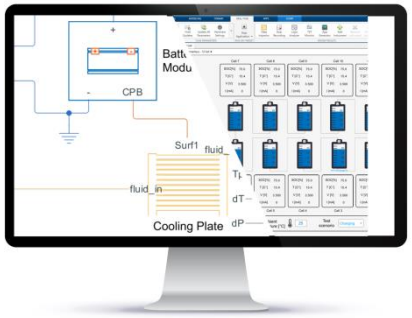
Requirements-based Test Automation

- Define requirements, and run tests 24/7
- Expand testing by also emulating motor drives, fuel cells or charging components



BMS test system
Emulate up to 252 cells

MathWorks



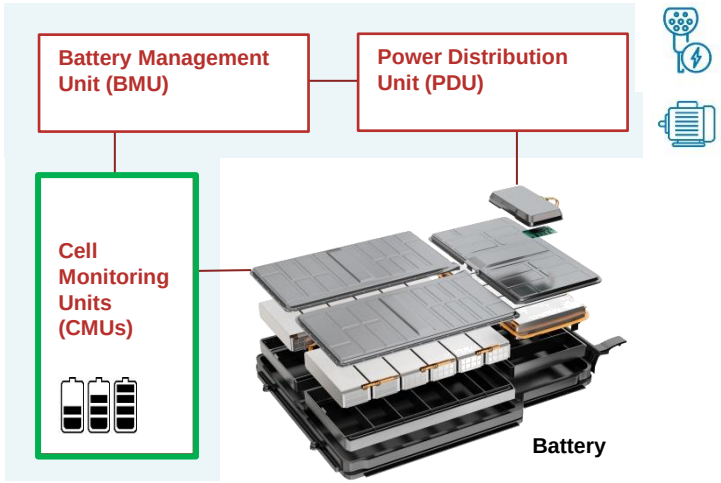
MATLAB® & Simulink®

- Design CMU and BMU algorithms
- Define battery pack architecture
- Interface with the Speedgoat BMS test system
- Perform automated, requirements based testing

Key Benefits using Speedgoat and Simulink for BMS Testing

Test Cell Monitoring Units

- Cell balancing, charging, and discharging algorithms
- Test against actual voltage, power, and temperature levels
- Test safely up to 1.3 kV
- Test behavior with faulty cells or overvoltage without risk
- Test with partially emulated CMUs connected through isolated protocols
- Test communication to and from BMU through isolated protocols



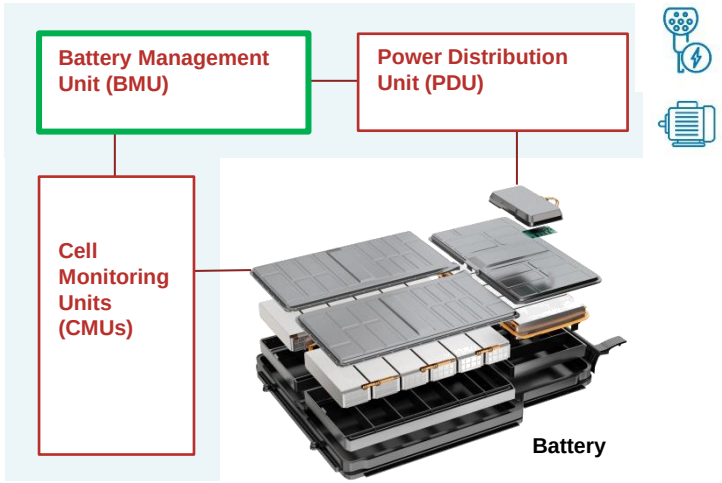
- Cell voltage measurement
- Cell current balancing
- Battery pack temperature monitoring

Key Benefits using Speedgoat and Simulink for BMS Testing

Test the Battery Management Unit

- Test algorithms such as protection, state of charge (SoC) and state of health (SoH)
- Test with real connectivity to and from Power Distribution with emulated sensors (e.g. shunt sensor, pyro fuse), high voltage measurements, or contactors
- Test communication to CMU, Power Distribution, or Vehicle Control Unit (VCU) through isolated protocols
- Test BMU behavior in case of a collision or other extreme events

- Data exchange between CMU and PDU
- Algorithms: State of charge (SoC), state of health (SoC), ..



Key Benefits using Speedgoat and Simulink for BMS Testing

Test the Power Distribution Unit

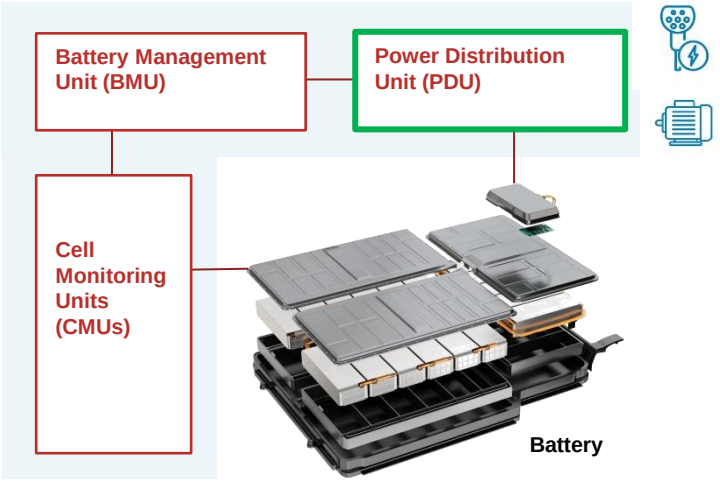
Test power distribution and protocols interfaces from the battery pack to:

- charging components
- motor drives
- fuel cells
- other components leveraging battery power

Test electrical systems and safety components like:

- high voltage and shunt sensors
- current sensors
- contactors
- pyro fuses

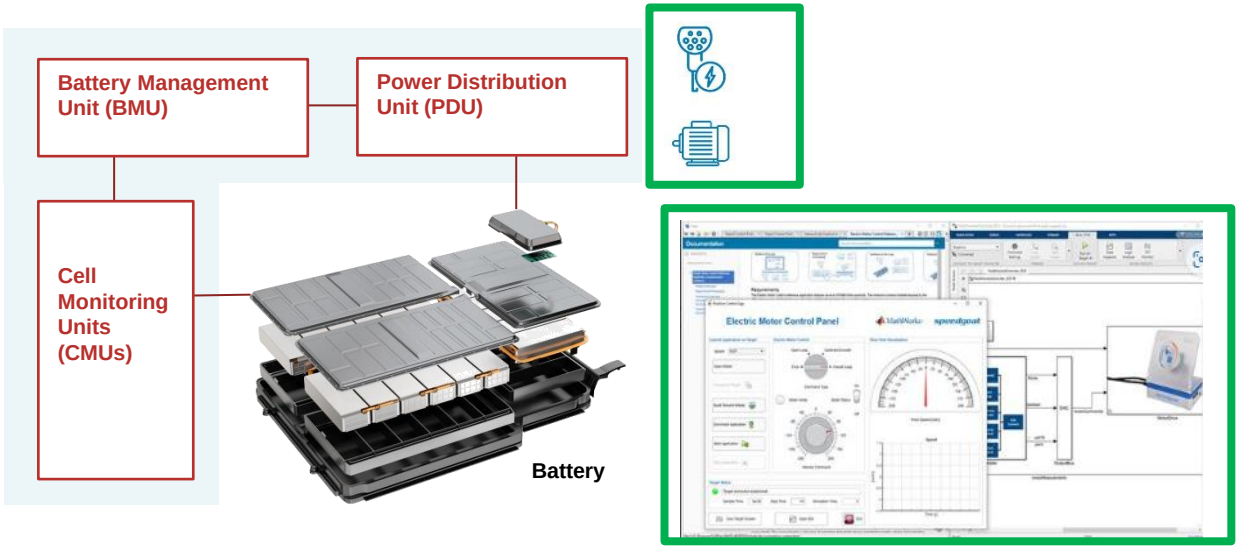
- PDU also known as junction, fuse or switch box
- Test power and communication lines
- Test safety conditions



Key Benefits using Speedgoat and Simulink for BMS Testing

Simulate and Test Interfaced Components

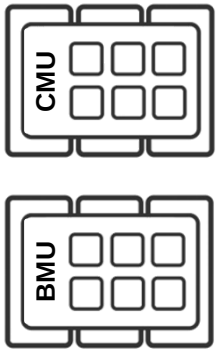
- Motors and drives
- Fuel cells
- Onboard charger or charging station
- Power electronics like DC/DC converters
- Complete powertrains
- Complete vehicles or aircrafts
- Other batteries
- and more!



A Scalable BMS Test System

1. Real-time target machine with I/O and protocols
2. Battery cell and temperature sensor emulators, and fault insertion units
3. Scalable rack design
4. Power distribution emulation
5. Software: Define battery pack topology, design algorithms, configure power and I/O lines, and perform requirements-based testing

Devices under Test:



1. Real-time target machine with I/O and Protocols

Select from a range of over 200 I/O modules, and benefit from a seamless Simulink integration

Built for High-Performance

- Performance real-time target machine with multicore CPU and programmable FPGAs
- Made for use with Simulink and Simulink Real-Time™

I/O and Protocols Interfaces

- Bus and isolated protocols (SPI, CAN, UART,…)
- Shunt emulation
- Cell controller emulation
- Fault insertion

2. Battery Cell Emulator

Battery Cell Emulators (BCE)

Cell-level emulation and measurement

- Replicate dynamic behavior of various battery types
- 12 independent and isolated battery cells
- Different voltage options: 5V, 6V or 8V
- Sink and source current up to 5A

Power input and interlock

- 48 VDC voltage input, rated 10 A
- Global enable for all cells

Test small BMS components and large battery packs

- Rack integration for large HIL testing or as standalone for testing individual BMS components

Test and validate your BMS

- Source and Sink capabilities
- Precise voltage and current measurements
- Test and validate BMS such as SoC, SoH or cell balancing

Reproduce battery packs

- Stackable design – Stack up to 252 cells @5V
- Series connections
- High cell-to-ground isolation: 1.3kV

2. Temperature Sensor Emulator

Temperature Sensor Emulator (TSE)

High-Precision and Isolated Temperature Emulation

- Emulate temperature sensors, such as PTC and NTC, for BMS thermal management

Compact and scalable

- 4 up to 36 channels on one 2U unit
- Multiple units per rack

Precise Temperature Profiles

- Resistance Range: 10Ω to 4MΩ
- Resolution: 1Ω
- Accuracy ±0.1% ± 500mΩ
- Fault Insertion: open and short circuit (typically 50mΩ)

Power input and interlock

- 48 VDC voltage input, rated 3 A
- Global enable for all cells

2. Fault Insertion Unit

Fault Insertion Units (FIU)

Extend battery cell emulation with failure insertion capabilities

Compact and scalable

- 12 up to 36 channels on one 2U unit
- Multiple units per rack

Test and validate BMS in normal and fault conditions

Fault scenarios:

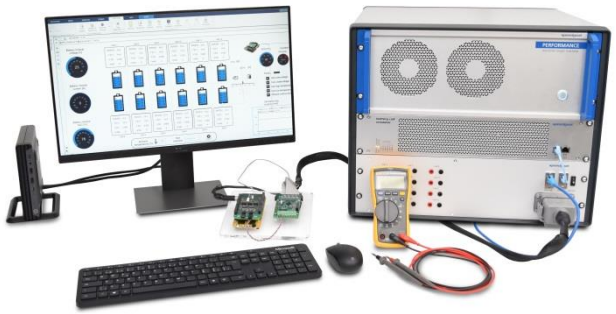
- Short-circuit
- Battery-cell broken-wire
- Reverse polarity
- BMS sense line broken-wire

Power input and interlock

- 48 VDC voltage input, rated 3 A
- Global enable for all cells

3. BMS Test System Scalability

- 22U, 38U or 42U rack or desktop solution
- Emulate up to 252 battery cells with 1.3kV cell-to-ground isolation
- Include temperature and power emulation
- Add I/O and protocol interfaces



Desktop

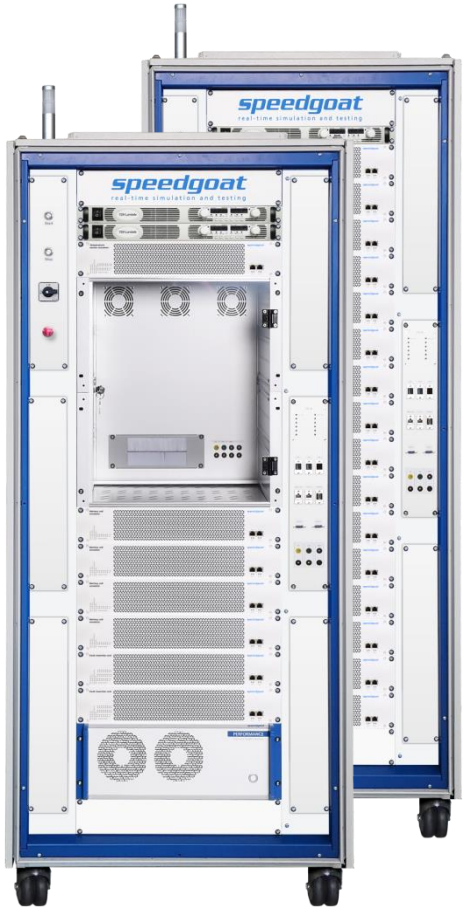
12 cells

For 48V battery modules testing designs

22U

24-36 cells

For 96V battery modules testing designs



38U

48 - 252 cells

For 400V battery packs testing designs

42U

< 252 cells

For 800 V battery packs testing designs

3. BMS Test System: Basic Rack Components

LED Tower

HV terminal board

Safety switch and safety relay

Insulation monitoring device

DIN rail in the back

DUT supply 12/24V

Battery emulation supply 48V

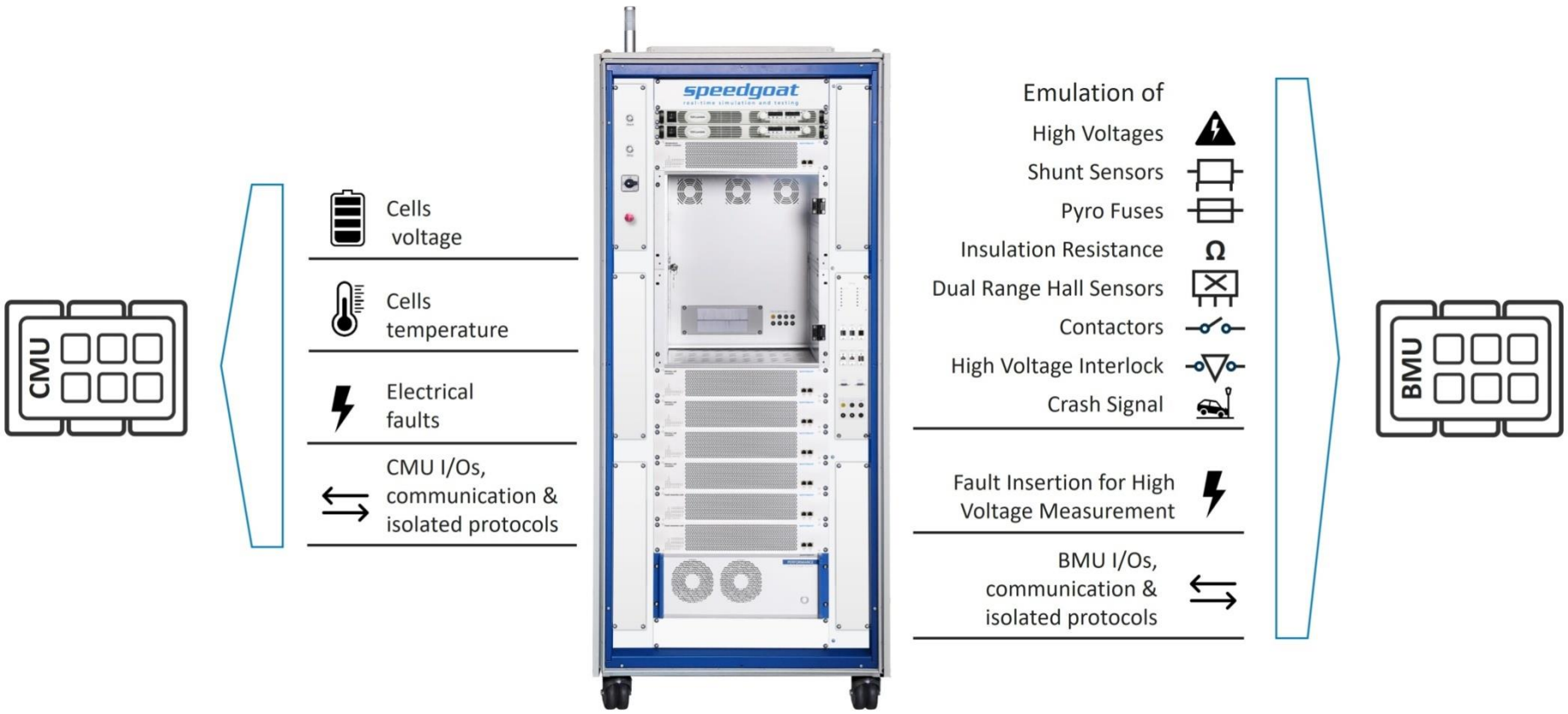
Safety compartment

Optional: High Voltage (HV) supply 1-1.5kV

4. Emulation of Power Distribution Components

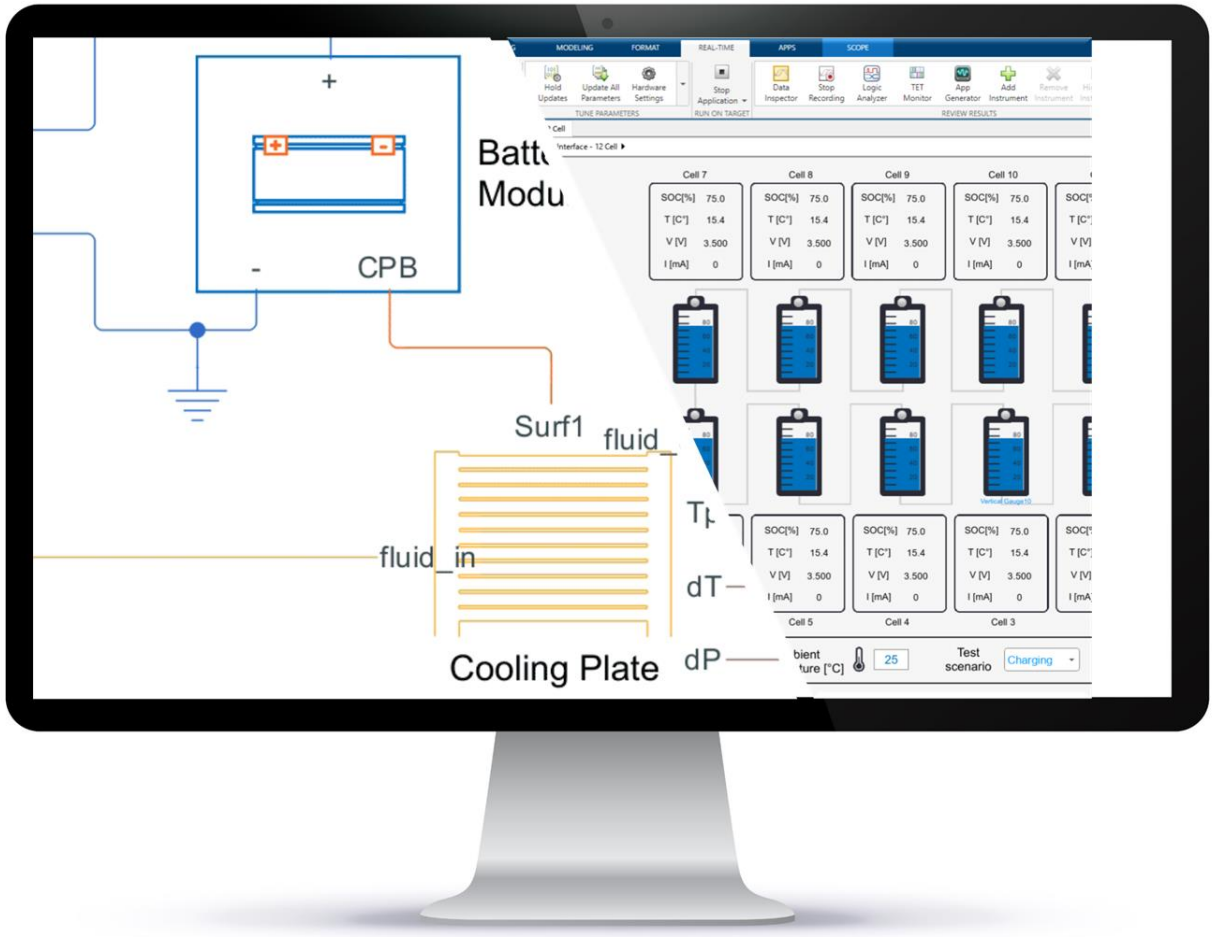
Battery emulation for CMU testing

Power Distribution component emulation for BMU testing



5. Battery Pack Architecture Definition

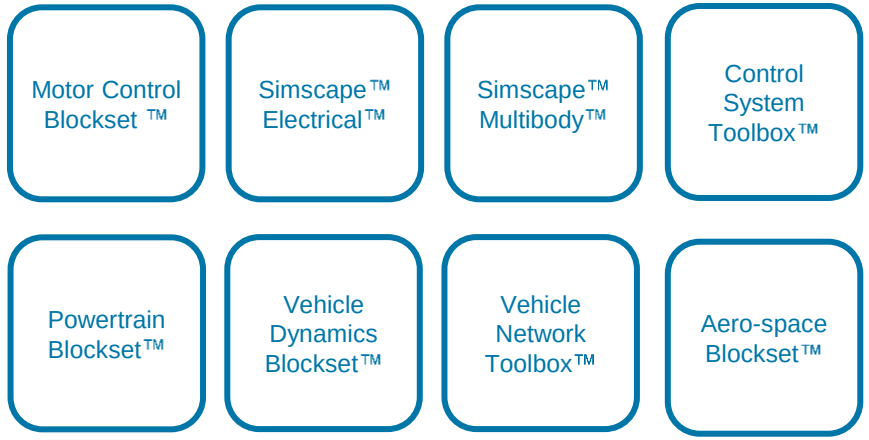
- Leverage reference example, and adjust to your needs with Simulink and Simscape™ Battery™
- Monitor and instrument from a Simulink dashboard, or using AppDesigner
  - Inspect SoC, temperature and voltage of cells
  - Monitor balancing currents



5. Expand Testing to Additional Components

Leverage Speedgoat Test Systems
to test control designs and controllers for:

- Motors drives
- Fuel cells
- Charging
- Power electronics
- Complete powertrains
- Complete vehicles or aircrafts
- and more!



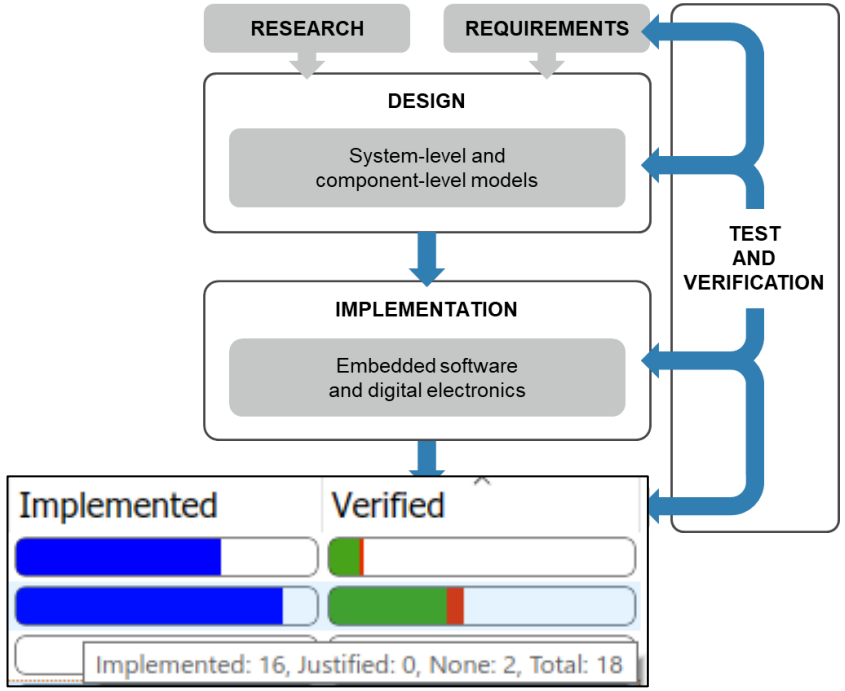
Examples of a few Simulink Blockset libraries

5. Perform Requirements-based Testing

Leverage the Requirements Toolbox to:

- Author or import, link and validate requirements
- Trace and document verified results with requirements
- Identify gaps in design or test
- Respond flexibly to requirements changes

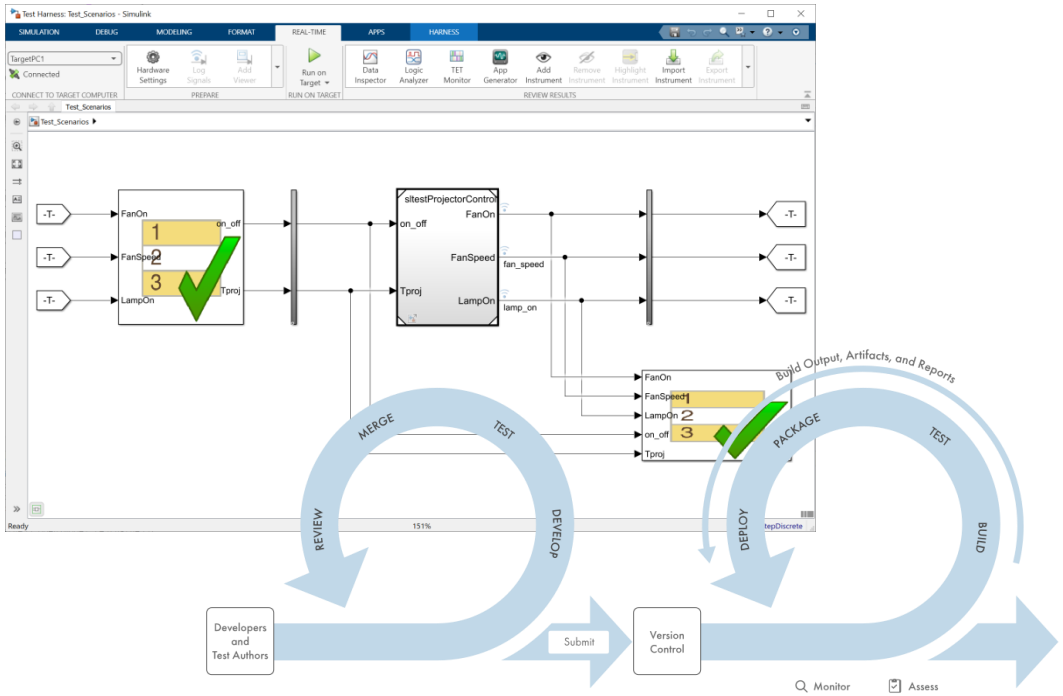
Learn more:
[Requirements Toolbox - MATLAB]



5. Automate Requirements-based Testing

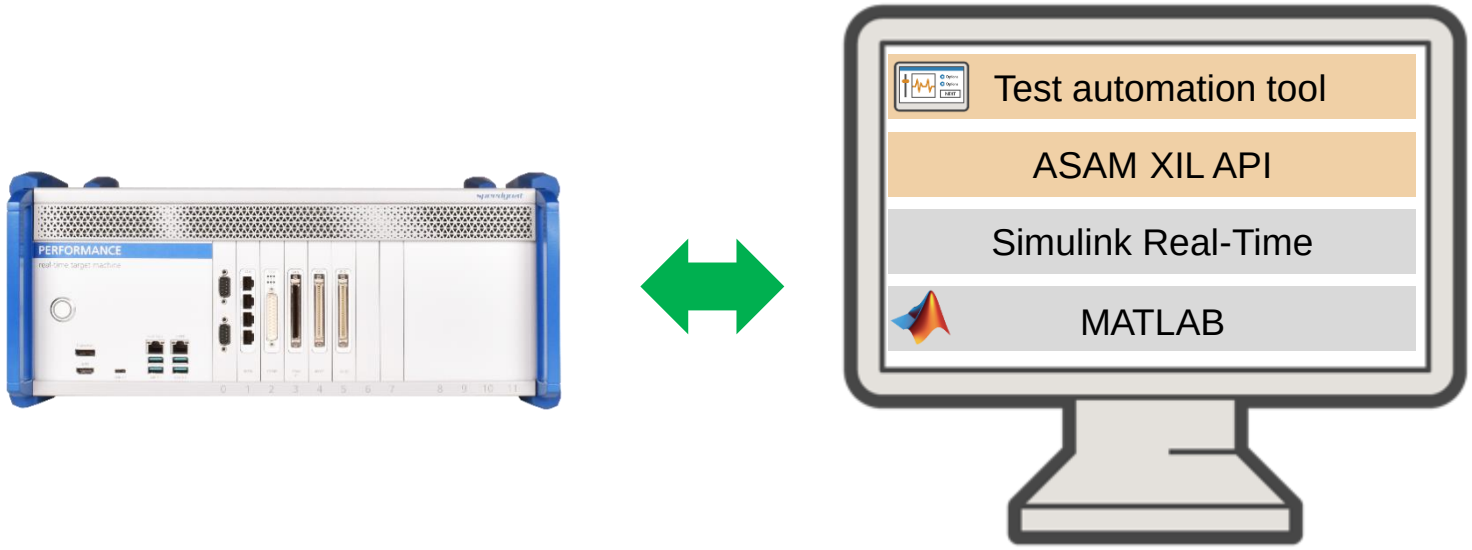
Enable continuous integration and testing through test automation

- Create test suites
- Automate and reuse
- Use Simulink Test™, Test Manager, or MATLAB scripts



Learn more:
[Test Real-Time Application in Simulink Test]
[Projector Controller Testing Using verify and Real-Time Tests]

5. Connect with third-party test platforms through ASAM XIL



BMS HIL Testing Demo – Components

HIL Simulator Performance real-time Target Machine

Battery Cell Emulator

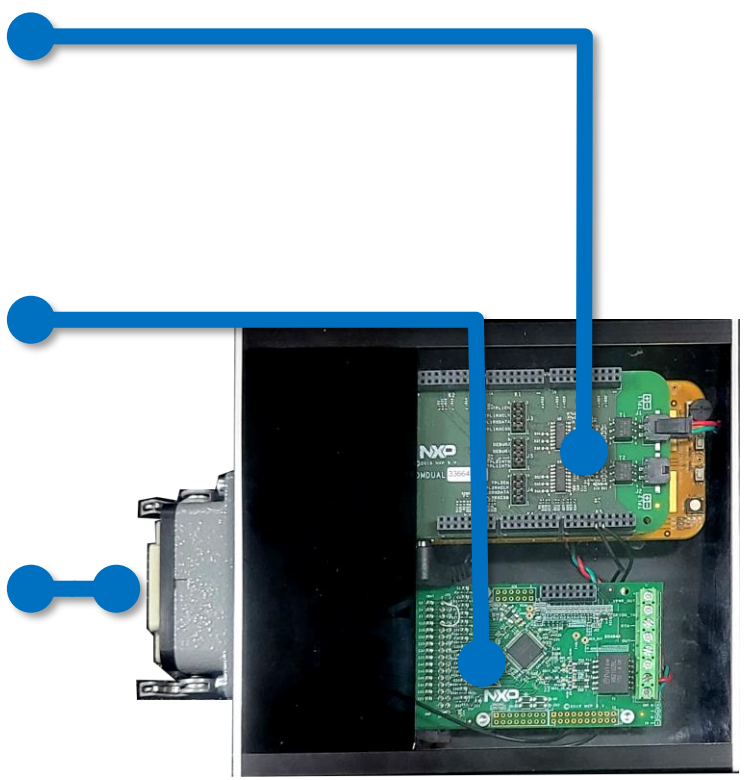
Measurement and Controller Interface

BMS HIL Testing Demo – Components

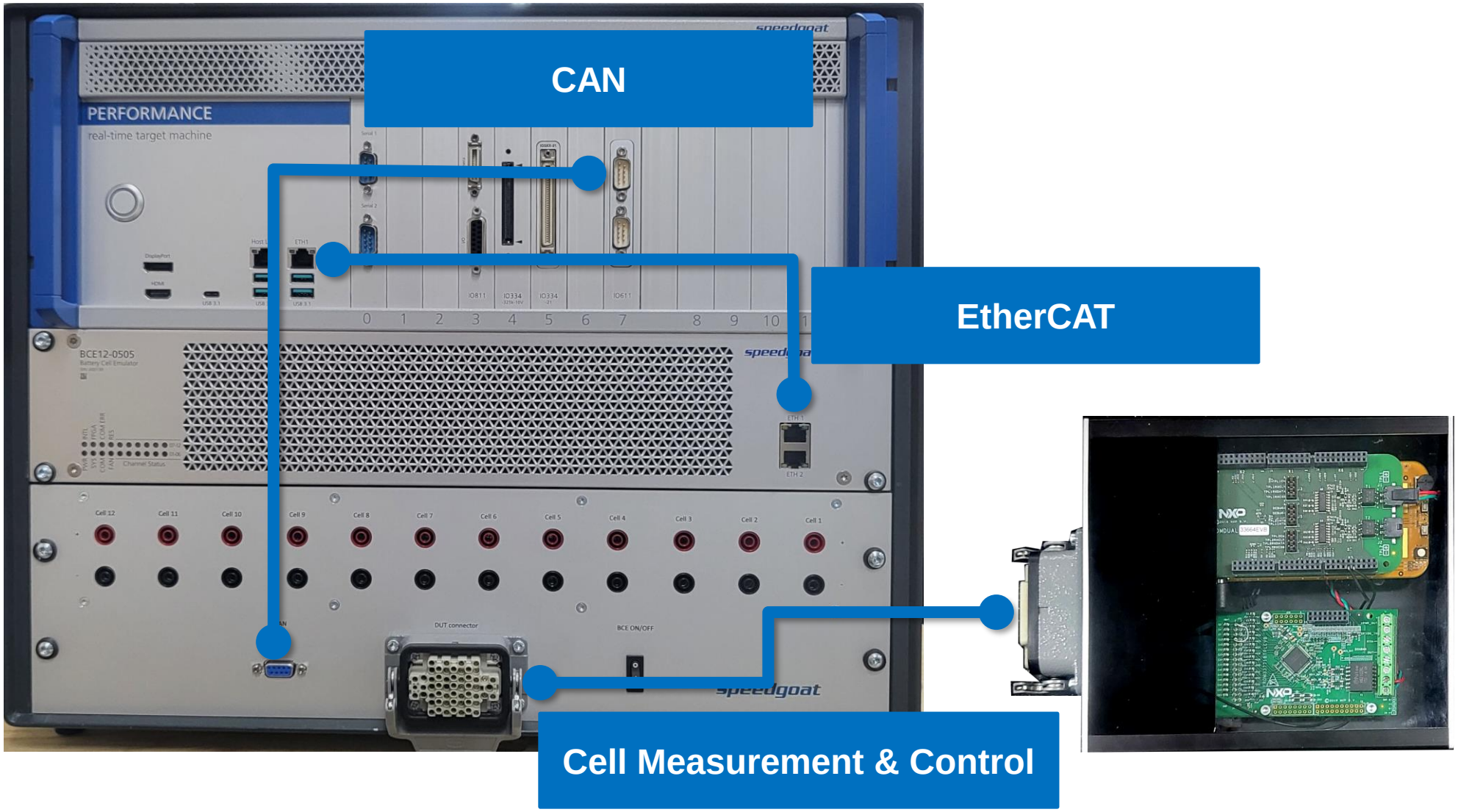
Battery Management Unit

Cell Monitoring Unit

DUT Connector

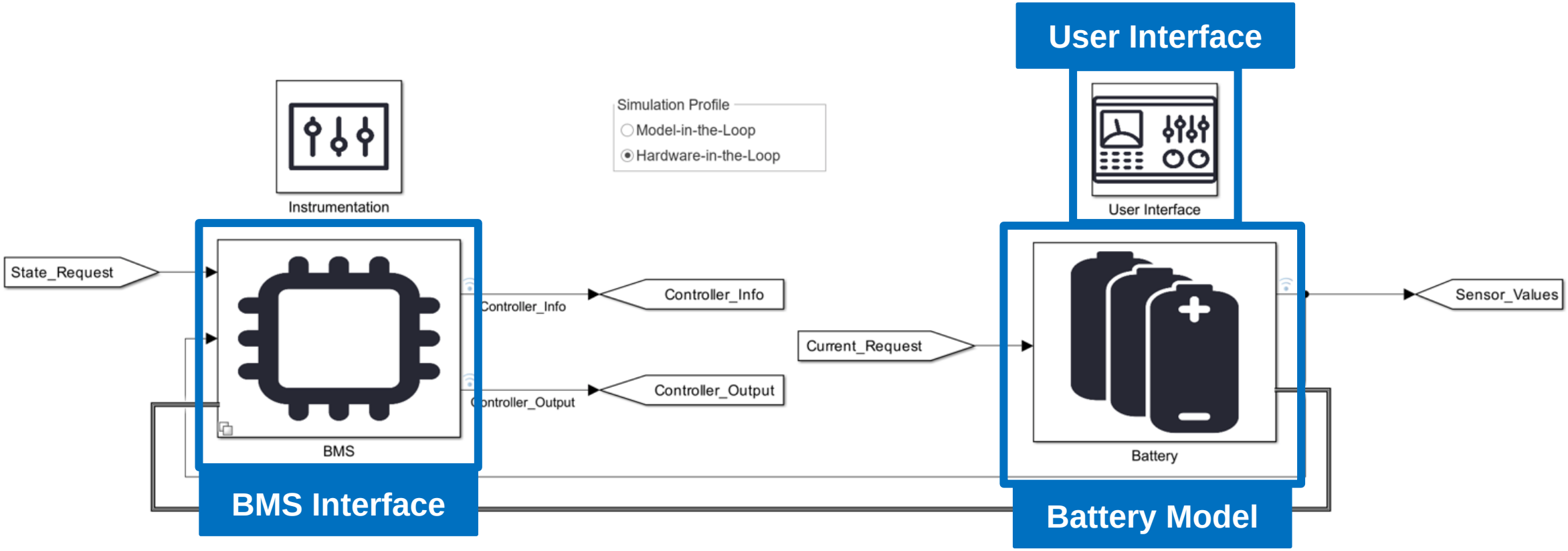


BMS HIL Testing Demo – Interface



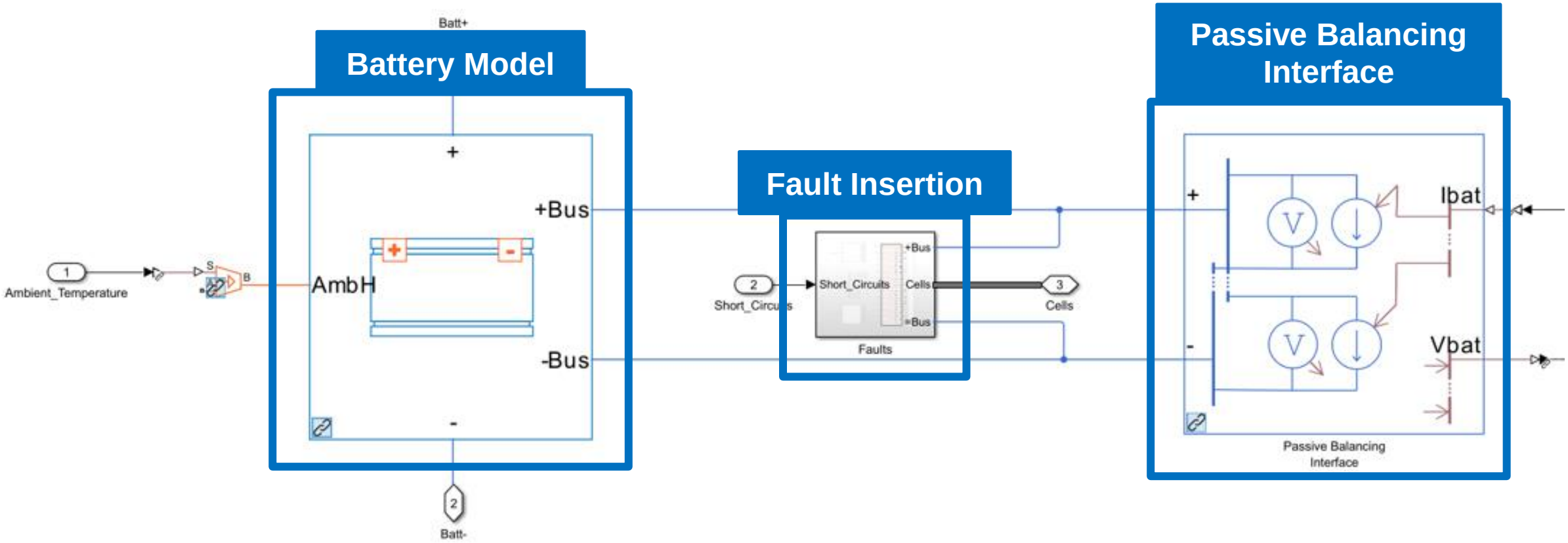
BMS HIL Testing Demo – Model

- Battery Model
- Interface to DUT
- User Interface



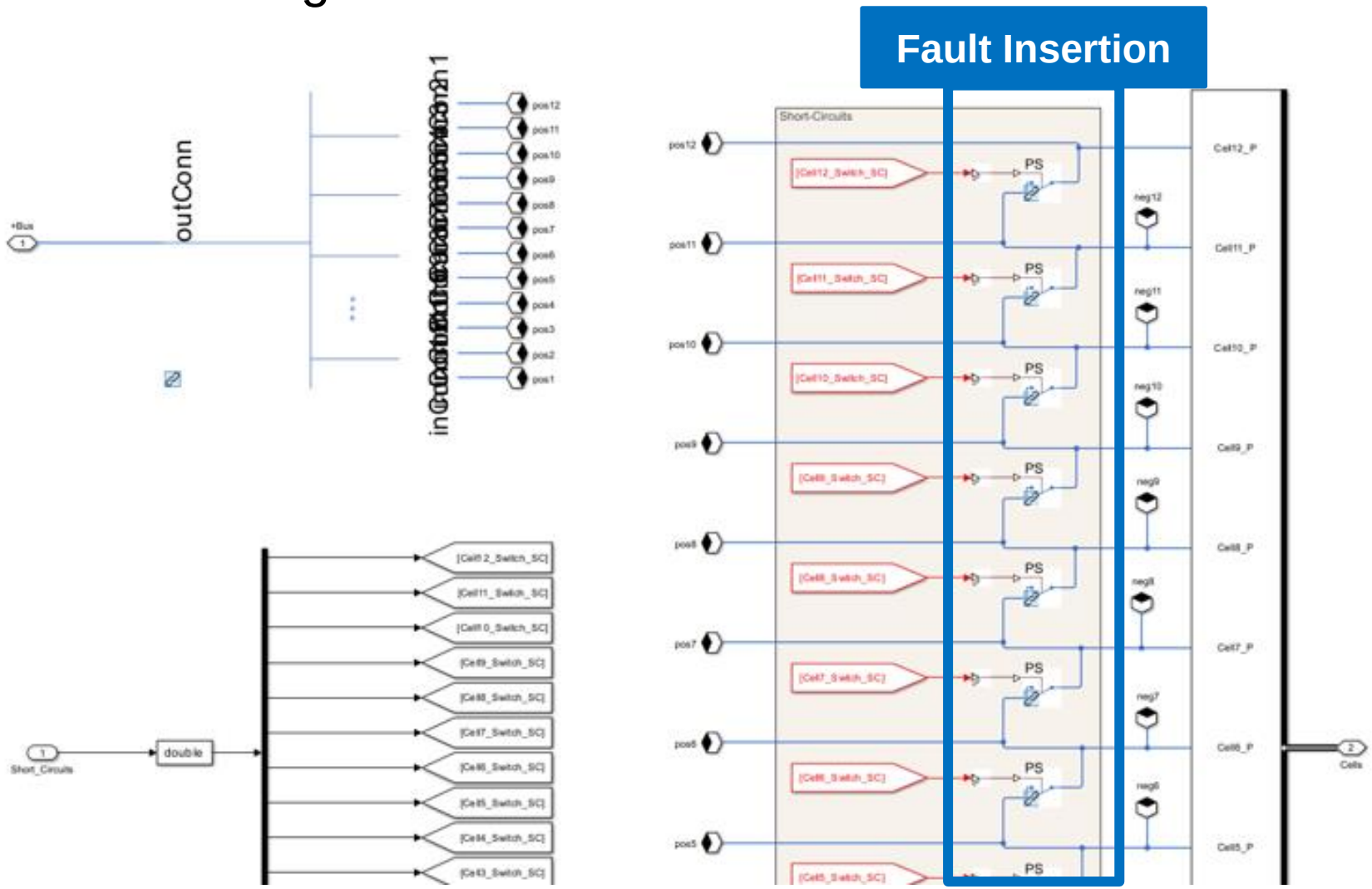
BMS HIL Testing Demo – Model

- Battery Model using Simscape



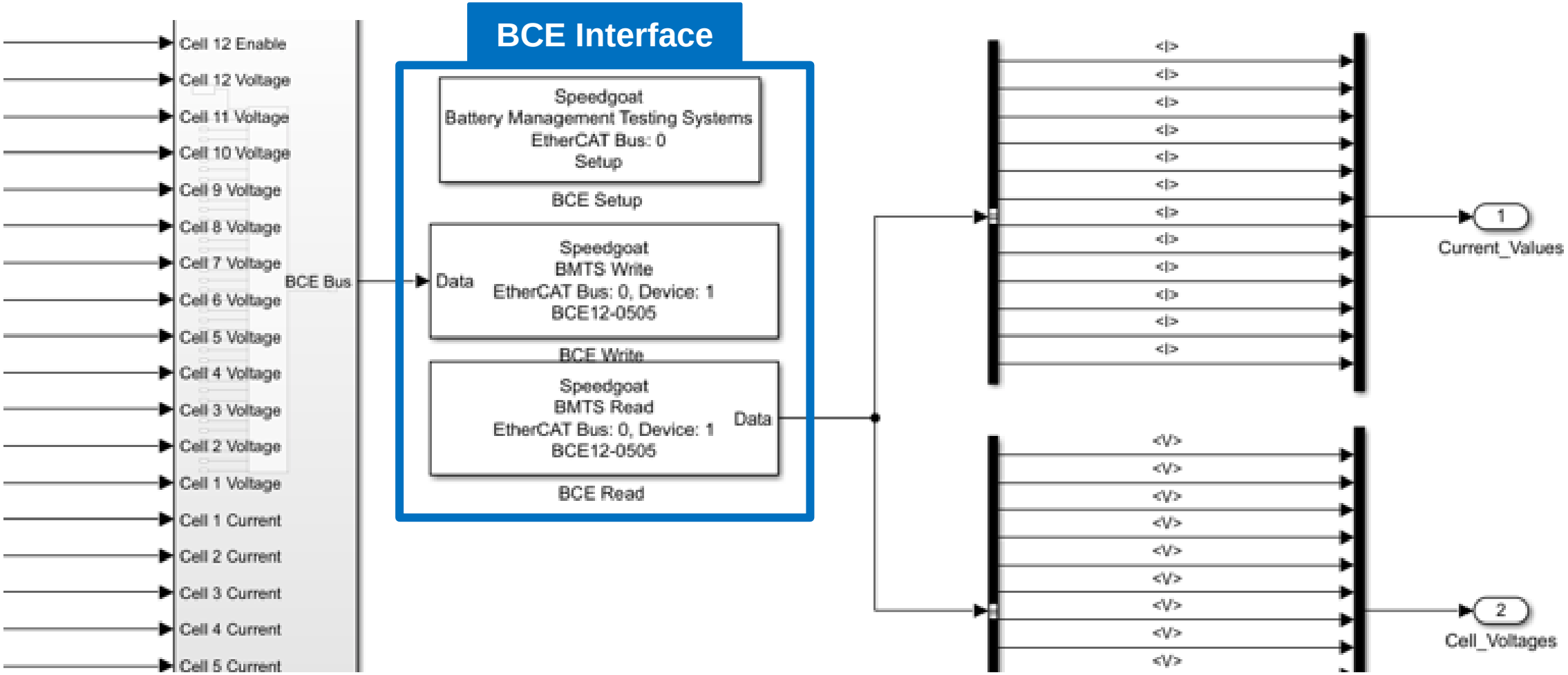
BMS HIL Testing Demo – Model

- Fault Insertion using Switch



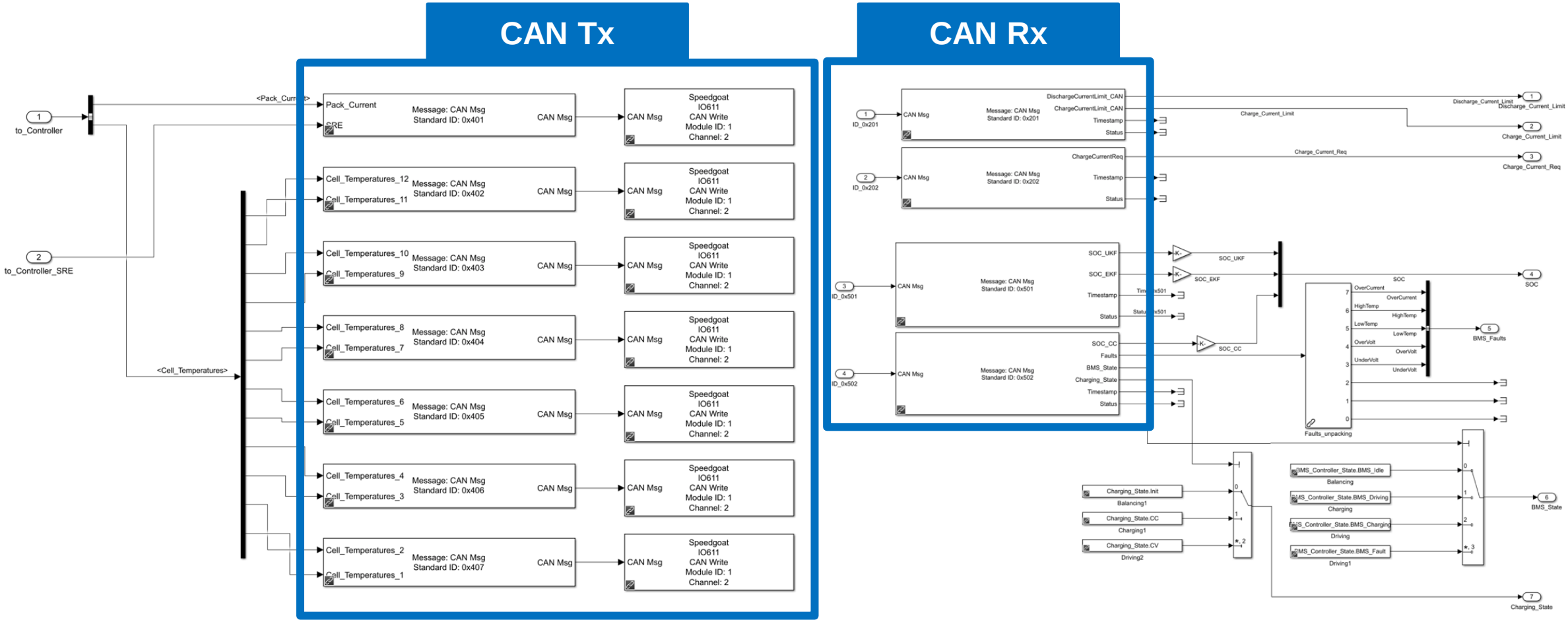
BMS HIL Testing Demo – Model

- Interface to Battery Cell Emulator using Speedgoat Library



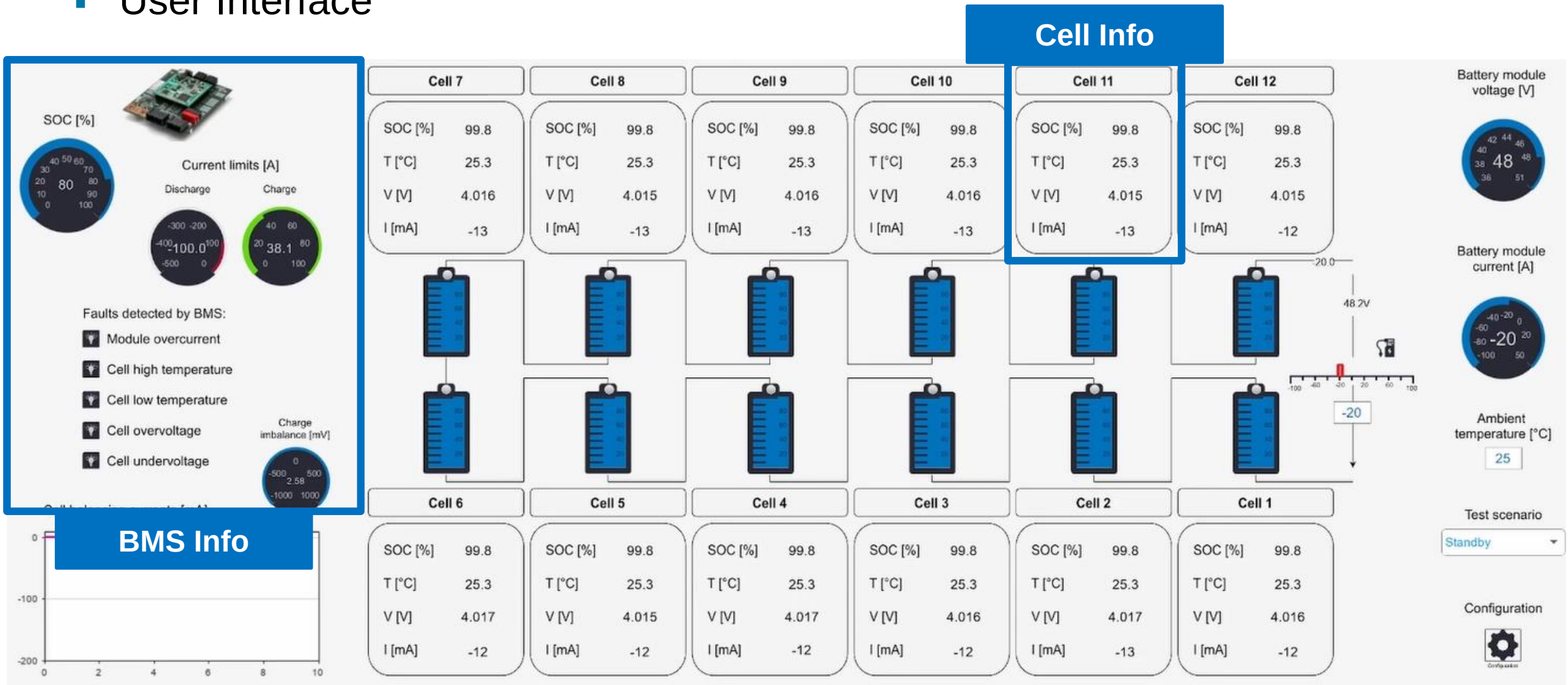
BMS HIL Testing Demo – Model

- CAN Interface to BMS



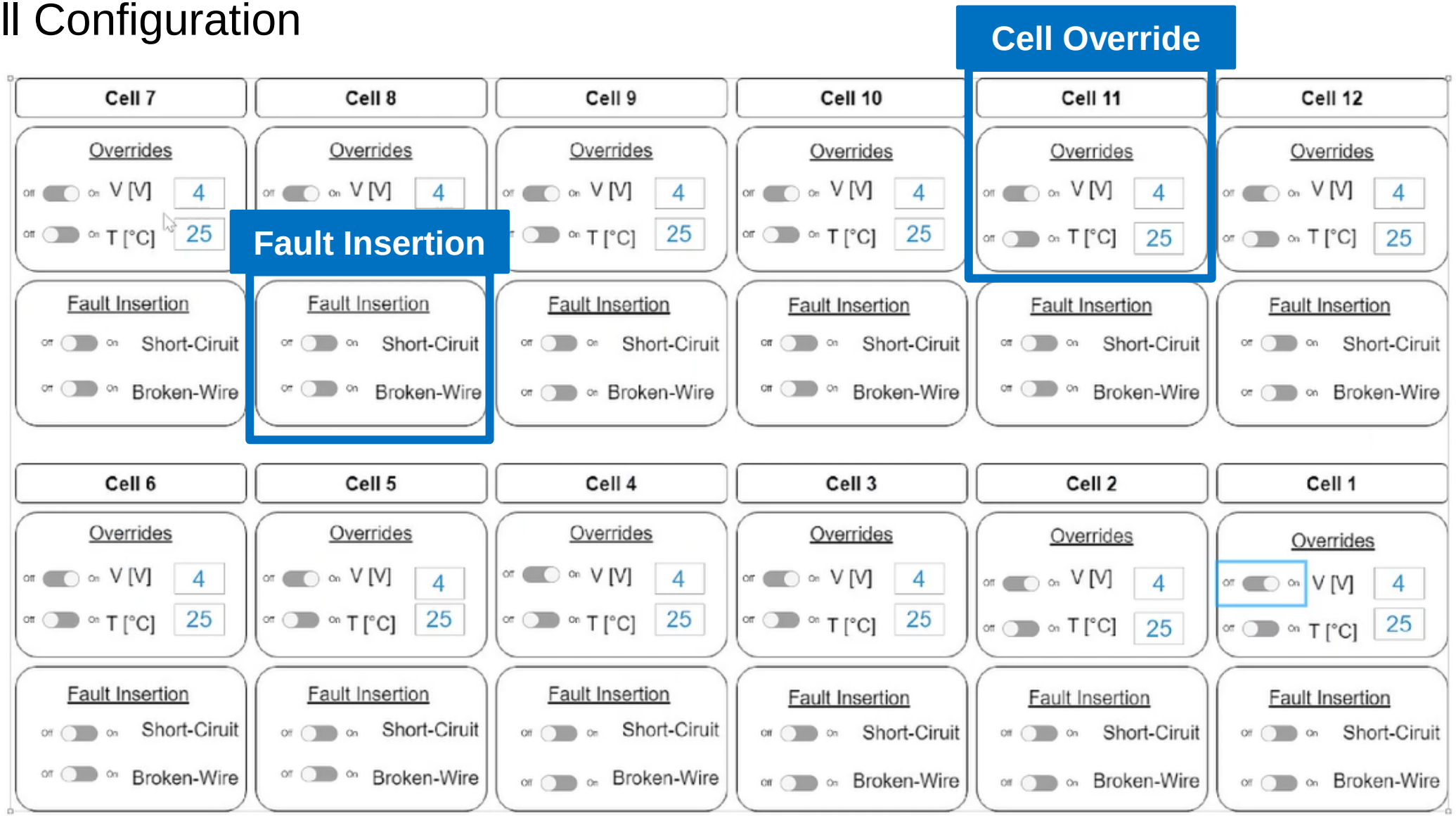
BMS HIL Testing Demo – Model

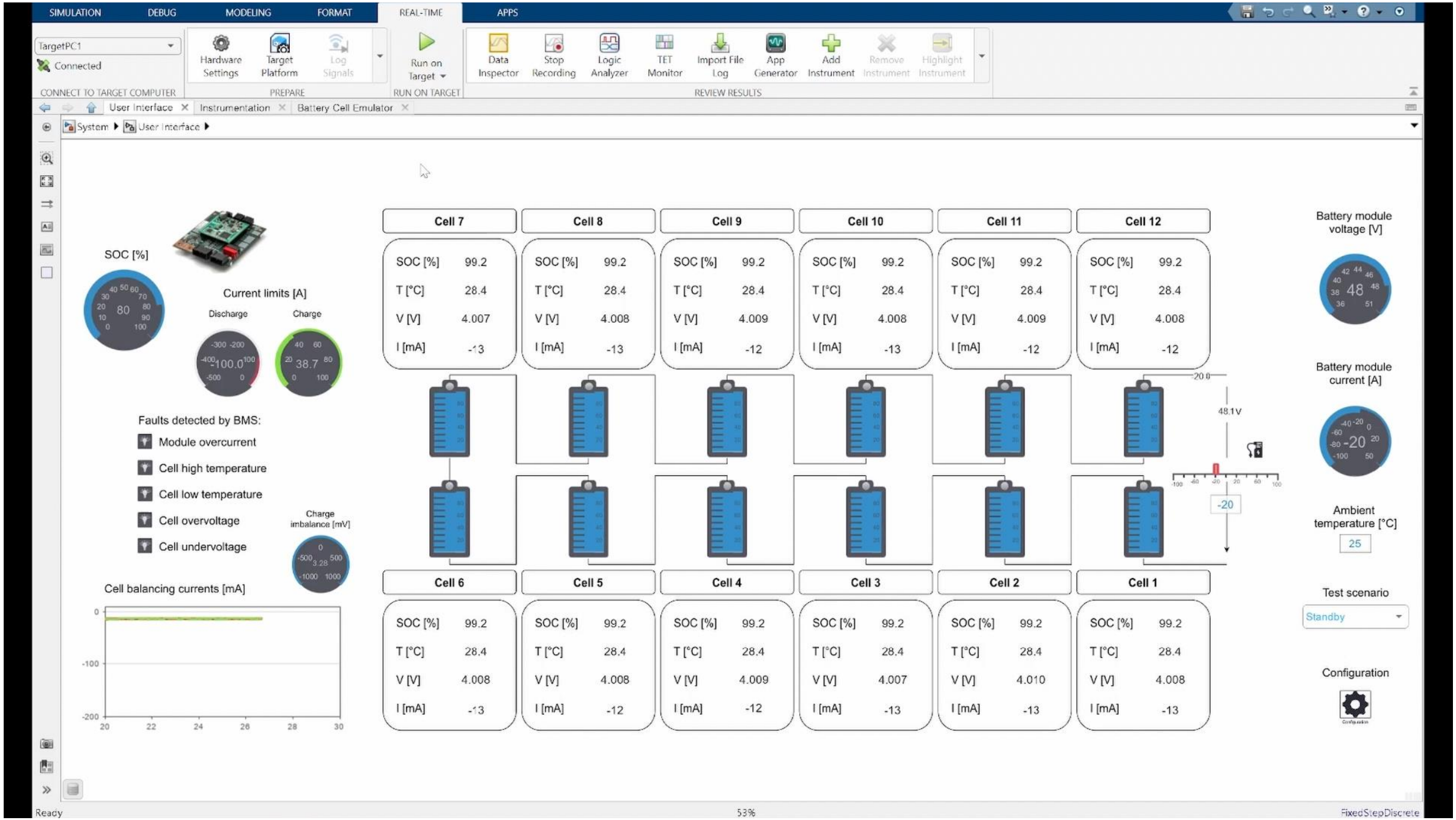
- User Interface



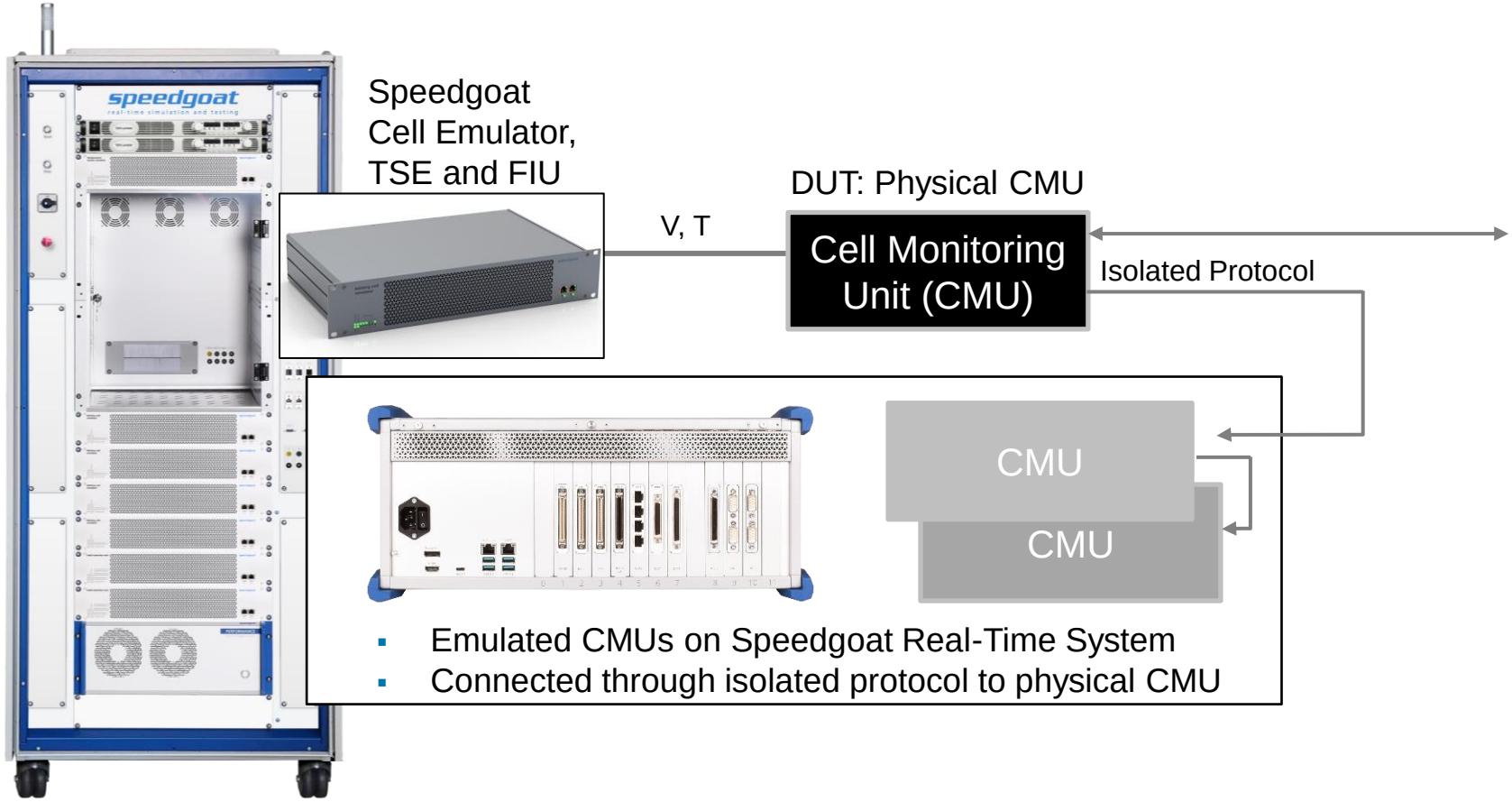
BMS HIL Testing Demo – Model

- Cell Configuration




SIMULATION
DEBUG
MODELING
FORMAT
REAL-TIME
APPS
TargetPC1
Connected
CONNECT TO TARGET COMPUTER
Hardware Settings
Target Platform
Log Signals
PREPARE
Run on Target
RUN ON TARGET
Data Inspector
Stop Recording
Logic Analyzer
TET Monitor
Import File Log
App Generator
Add Instrument
Remove Instrument
Highlight Instrument
REVIEW RESULTS
User Interface
Instrumentation
Battery Cell Emulator
System
User Interface
SOC [%]
Current limits [A]
Discharge
Charge
Faults detected by BMS:
Module overcurrent
Cell high temperature
Cell low temperature
Cell overvoltage
Cell undervoltage
Charge imbalance [mV]
Cell balancing currents [mA]
Cell 7
Cell 8
Cell 9
Cell 10
Cell 11
Cell 12
SOC [%] 99.2
T [°C] 28.4
V [V] 4.007
I [mA] -13
SOC [%] 99.2
T [°C] 28.4
V [V] 4.008
I [mA] -13
SOC [%] 99.2
T [°C] 28.4
V [V] 4.009
I [mA] -12
SOC [%] 99.2
T [°C] 28.4
V [V] 4.008
I [mA] -13
SOC [%] 99.2
T [°C] 28.4
V [V] 4.009
I [mA] -12
SOC [%] 99.2
T [°C] 28.4
V [V] 4.008
I [mA] -12
48.1 V
-20
Cell 6
Cell 5
Cell 4
Cell 3
Cell 2
Cell 1
SOC [%] 99.2
T [°C] 28.4
V [V] 4.008
I [mA] -13
SOC [%] 99.2
T [°C] 28.4
V [V] 4.008
I [mA] -12
SOC [%] 99.2
T [°C] 28.4
V [V] 4.009
I [mA] -12
SOC [%] 99.2
T [°C] 28.4
V [V] 4.007
I [mA] -13
SOC [%] 99.2
T [°C] 28.4
V [V] 4.010
I [mA] -13
SOC [%] 99.2
T [°C] 28.4
V [V] 4.008
I [mA] -13
Battery module voltage [V]
Battery module current [A]
Ambient temperature [°C]
25
Test scenario
Standby
Configuration
Ready
53%
FixedStepDiscrete

BMS HIL Testing
CMU Testing with Partially Emulated CMUs



BMS HIL Testing Reference Application

[Demo: Hardware-in-the-Loop Testing of Battery Management Systems]

- Download ready-to-use Simulink models from the Speedgoat website
- Access with log-in

Learn How to

- Model a 48V battery system using Simscape Electrical
- Go from model-in-the-loop (MIL) to hardware-in-the-loop without leaving Simulink or changing your model
- Interface your Simulink/Simscape battery models with battery cell emulation hardware
- Validate BMS functions, such as fault detection, cell balancing, and state of charge estimation
- Implement bus and signal-level communication with the BMS controller
- Simulate temperature sensors and implement fault conditions

Use Case Example: Leclanché

Next-Gen Li-Ion Battery Packs for Autonomous Vehicles

Challenge

- Unable to test and verify Battery Management Systems in realistic operating conditions before connecting to actual battery packs
- Late bug discovery and no preliminary testing can damage batteries
- Poor development tool compatibility leading to manual testing

Solution

- Use Simulink and Speedgoat products for HIL testing of BMS
- Speedgoat test platform with cell emulators, fault insertion, and CAN communication
- Simulink Test™ to thoroughly validate BMS and battery state estimation algorithms (SoC, SoH, etc.)

Results

- Reduced testing time by 50%
- Increased test coverage for safety features by 40%
- Faster development with early bug detection

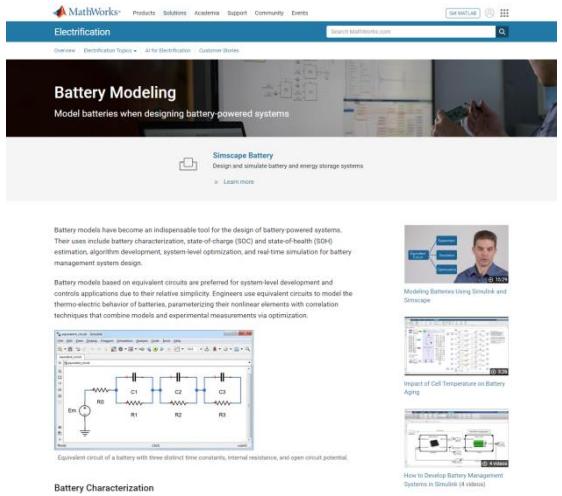
Leclanché Energy Storage Solutions

"Speedgoat and MathWorks products together offer a very efficient workflow to design, test and validate Battery Management Systems"

Marc Lucea, Senior Application SW Engineer

See more Success Stories
https://www.speedgoat.com/success-stories

Additional Resources

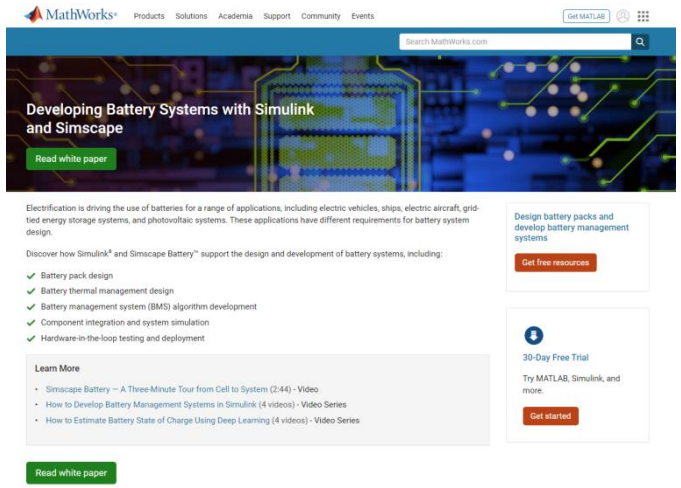


Websites

[Battery Management Systems Testing - Battery Cell Emulator]

[Battery Modeling - MATLAB & Simulink]

[Battery Systems - MATLAB & Simulink]



Whitepaper

[Developing Battery Systems with Simulink and Simscape - MATLAB & Simulink]

Webinars and Videos

[Hardware-in-the-Loop Testing of Battery Management Systems | Speedgoat]

[Real-Time Testing for VTOL and Conventional Aircraft Development | Speedgoat]

[Enabling Innovation for Automotive Hardware-in-the-Loop Testing and Control Design | Speedgoat]

[Optimize EV Battery Performance Using Simulation Video - MATLAB & Simulink]

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Thank you

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