UNIVERSITY OF CALIFORNIA
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Winston Chung
Global Energy Center

2019 Energy Storage Technologies and Applications Conference

Real-Time Simulation for Energy Storage Applications

including Battery Management System Testing

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OPAL-RT TECHNOLOGIES

TUTORIAL OUTLINE

- About OPAL-RT
- Real-Time Simulation (RTS) Applications Overview
- RTS Approach and Fundamentals
- User Examples
- Battery Management System Overview
- In-Depth BMS HIL Testing Overview

ABOUT OPAL-RT

- Founded in 1997 in Montreal, QC, Canada
- 185 employees (20% growth in 2 years)
- US Offices: Michigan, Colorado
- Int’l: China, Germany, France, India, Australia, Chili, South Africa
- Giving back: over $50,000 raised in last 5 years towards local charities
- Winner of multiple SMB awards in 2016-2017

OPAL-RT systems have been mentioned in

CORPORATE OVERVIEW

Helping you build the best grid

OPAL-RT believes in empowering power engineers and researchers with accessible, cutting-edge, real-time simulation technology in order to accelerate the introduction of new technology to improve grid performance, reliability and resilience.

OPAL-RT TECHNOLOGIES

OPAL-RT'S CLIENTS

OPAL-RT has gained the trust from over 800 customers, including many Fortune 500 companies, academic institutions and institution labs. More than 2000 people are currently using OPAl-RT in 40 countries around the world.

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OPAL-RT'S ACADEMIC USERS

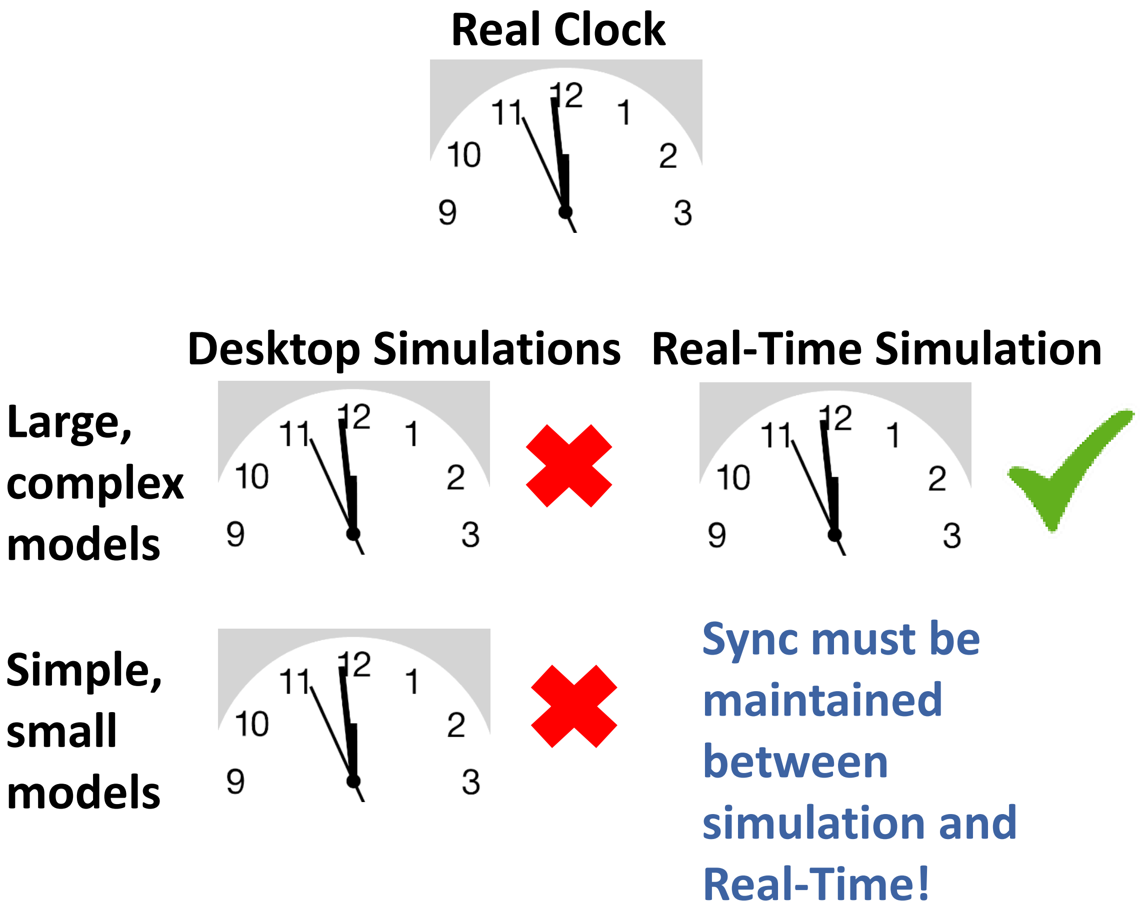
OPAL-RT has gained the trust from over 800 customers, including many Fortune 500 companies, academic institutions and institution labs. More than 2000 people are currently using OPAL-RT in 40 countries around the world.

The University of Auckland New Zealand
Massachusetts Institute of Technology
Michigan
Texas A&M University
Texas – The University of Texas at Austin
McGill University
Monash University
UNSW Sydney
Curtin University
Georgia Tech
AIT Austrian Institute of Technology
EPFL École Polytechnique Fédérale de Lausanne
Imperial College London
KTH Vetenskap och Konst
University of California Irvine
University of Toronto
QUT
RMIT University
UTS University of Technology Sydney
Fraunhofer IWES
Cal Poly San Luis Obispo

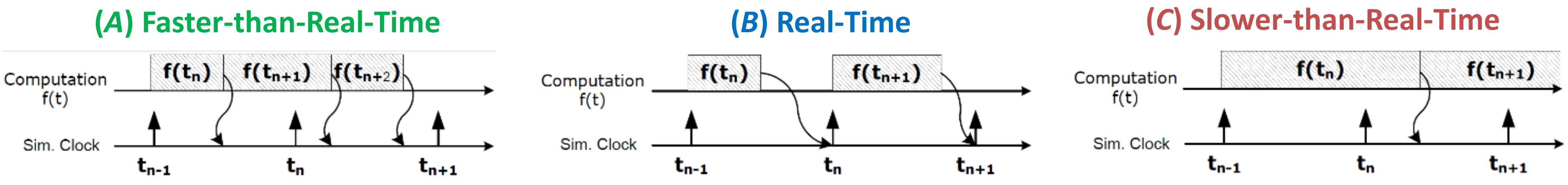
Real-Time Simulation (RTS) Applications Overview

WHAT IS REAL-TIME SIMULATION?

- Desktop (OFFLINE) Simulation
  - Tools typically run as fast as possible, which in the case of electromagnetic simulation can be very, very slow
  - Examples: EMTP-RV, PSCAD, ETAP, PSS/e, Digsilent, CYME, MATLAB/SIMULINK, PLECS, PSIM
- Real-Time Simulation
  - Objective: to connect and test real devices and systems (Devices-Under-Test = DUT)
  - Requirement: Ability to synchronize simulation clock to a real-time a well implemented combination of hardware and software
  - Challenge: Simulating higher-frequency and/or complex phenomena (small timestep)



COMPUTATION VELOCITY AND RTS TECHNOLOGIES



- A real-time process is defined by a mix of hardware and software systems subject to a "**real-time constraint**“
- **The Real-Time Constraint** (***B***)
  - Operations ***f(t)*** done within a **fixed time-step** T_s **(where** $T_s = t_n - t_{n-1}$**)**
  - Operations include (among other things):
    - **Reading Simulator/device input signals**
    - **Model/algorithm calculations**
    - » **Reading Simulator/device output signals**
- Operations could be achieved in faster (A) or slower (C) time steps, which are referred as offline simulator.

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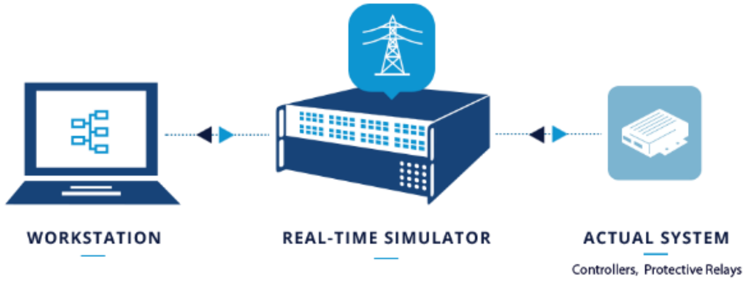
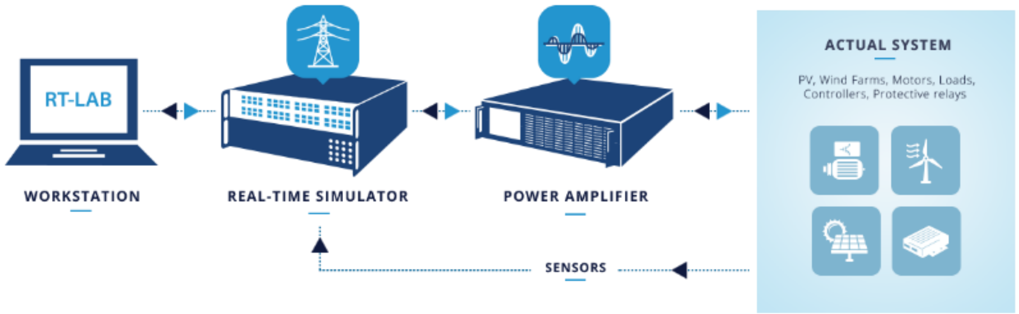
RTS APPLICATIONS

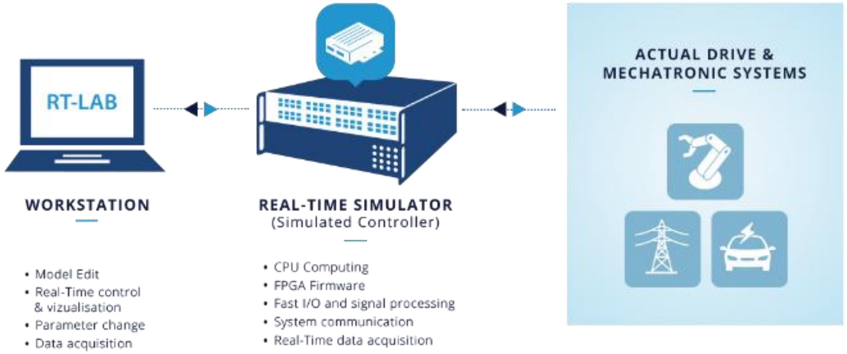
Hardware-in-the-Loop (HIL)



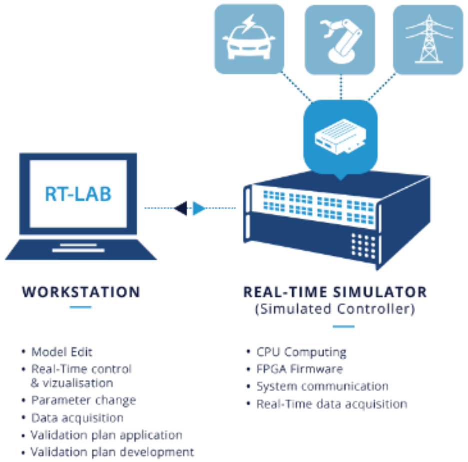
Power Hardware-in-the-Loop (PHIL)



Rapid Control Prototyping (RCP)



Software / Model in the Loop (SIL / MIL)



OPAL-RT TECHNOLOGIES

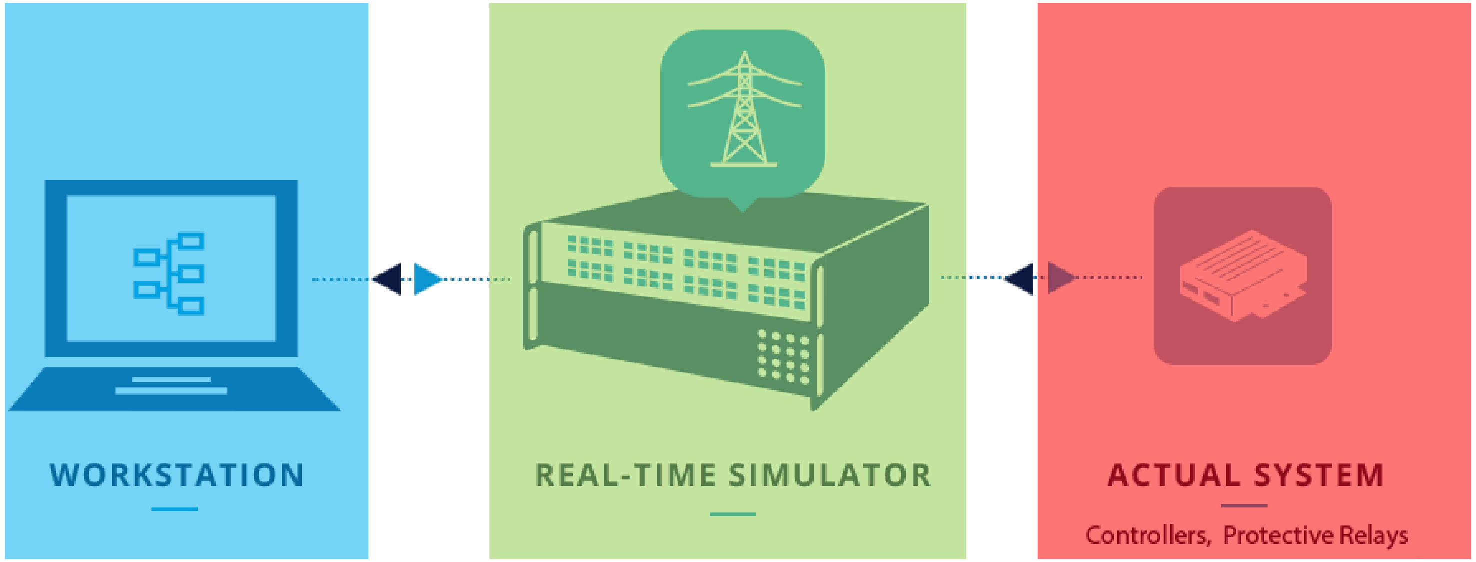
Hardware-in-the-Loop (HIL, HItL or cHIL)

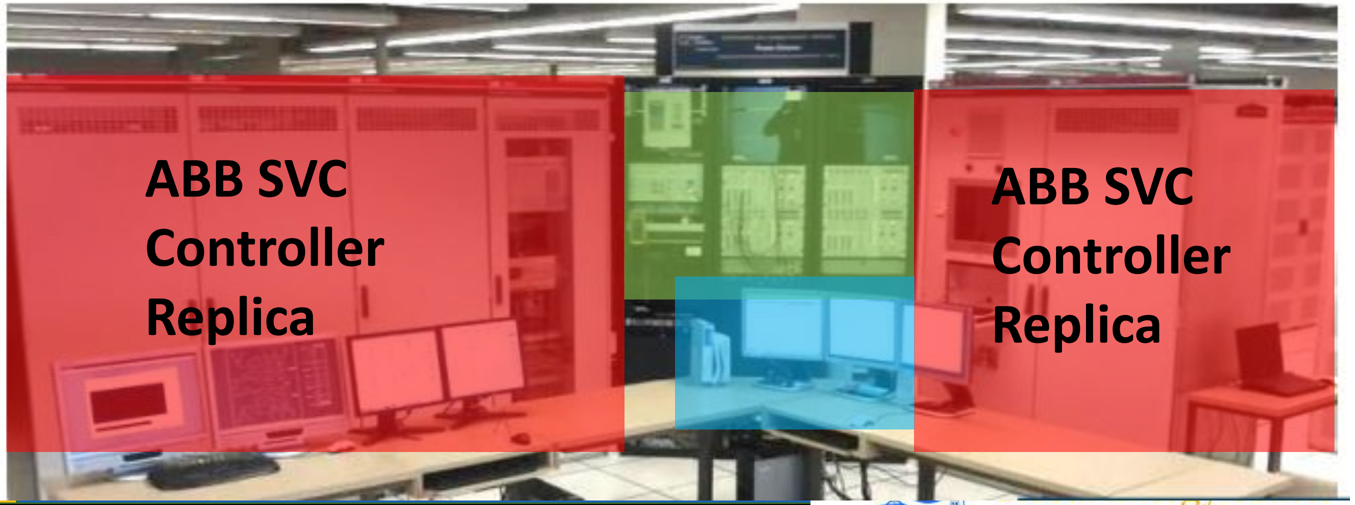
- Hardware-in-the-Loop (HIL) testing leverages Real-Time Simulation to connect real equipment and systems, through sensors and actuators, and “fool” them into thinking that they are connected to the real thing.
- This allows users to perform realistic closed-loop tests without the need for testing on a real system’
- While HIL typically refers to setups low-voltage level signal connections, Power Hardware-in-the-Loop (PHIL) can be employed for higher power testing (see later slide)

DUT examples

- Controllers
  - SCADA, EMS, DMS, Microgrid controllers
  - “Low-level” controllers
  - Vehicle ECU
- Sensors
- Intelligent Electronic Devices
  - Protection devices
  - “Smart” Sensors
- Software systems

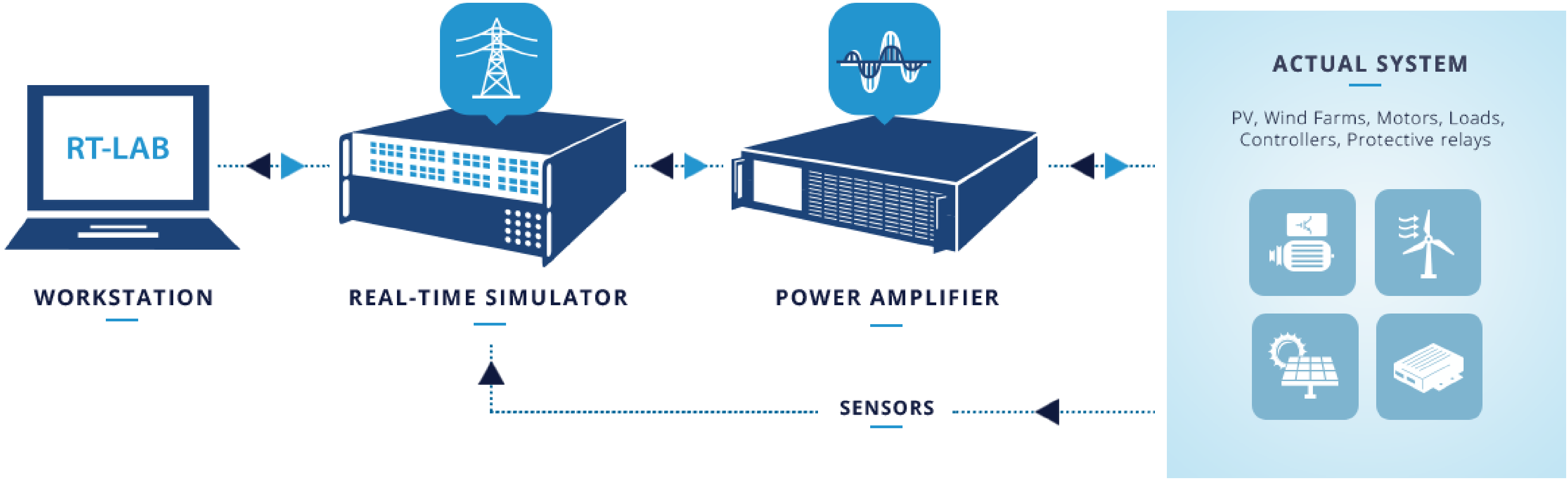
Hardware-in-the-Loop





Power Hardware-in-the-Loop (PHIL)

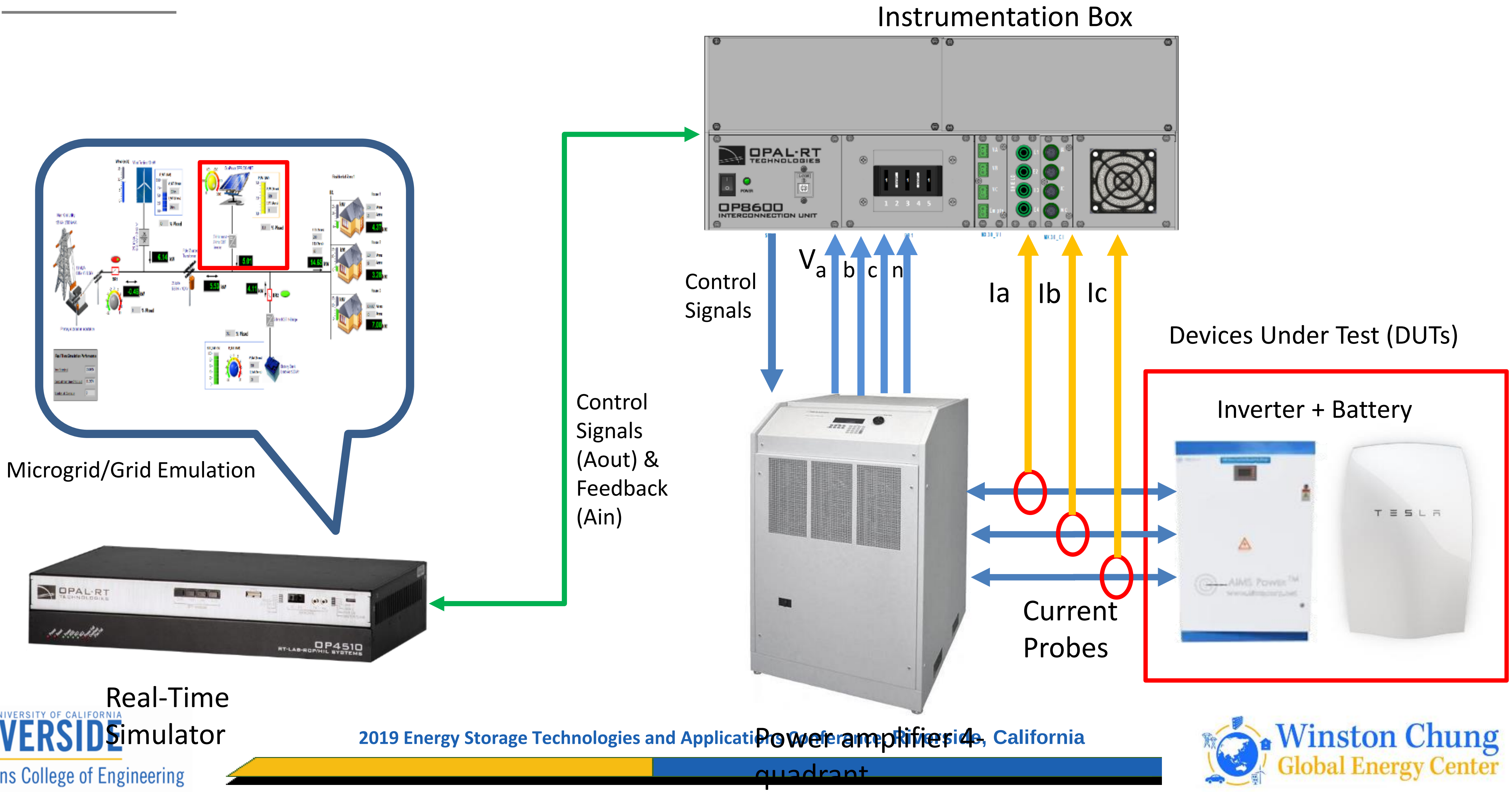
- An extension of Hardware-in-the-Loop (HIL), **Power Hardware-in-the-Loop (PHIL)** involves creating a virtual power interface between the digital simulation and devices under test
- Typically, the power interface involves power amplifiers (Voltage and/or current), which must be selected carefully depending on the application to act as a source or sink



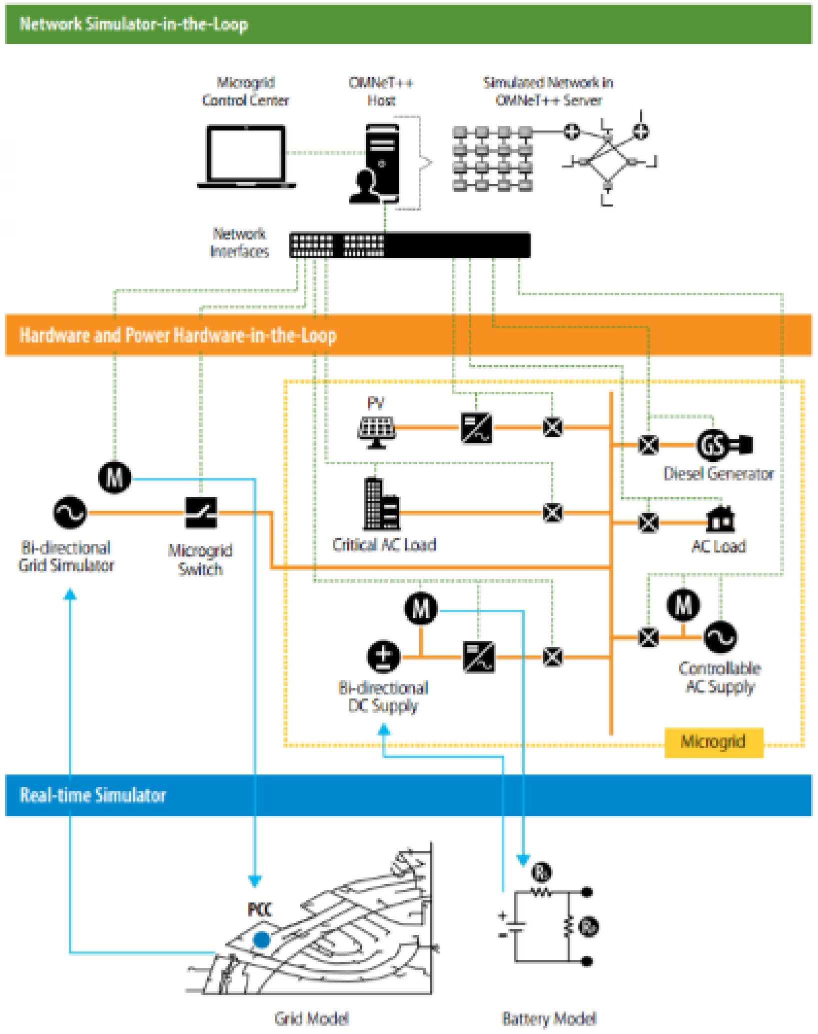
DUT examples

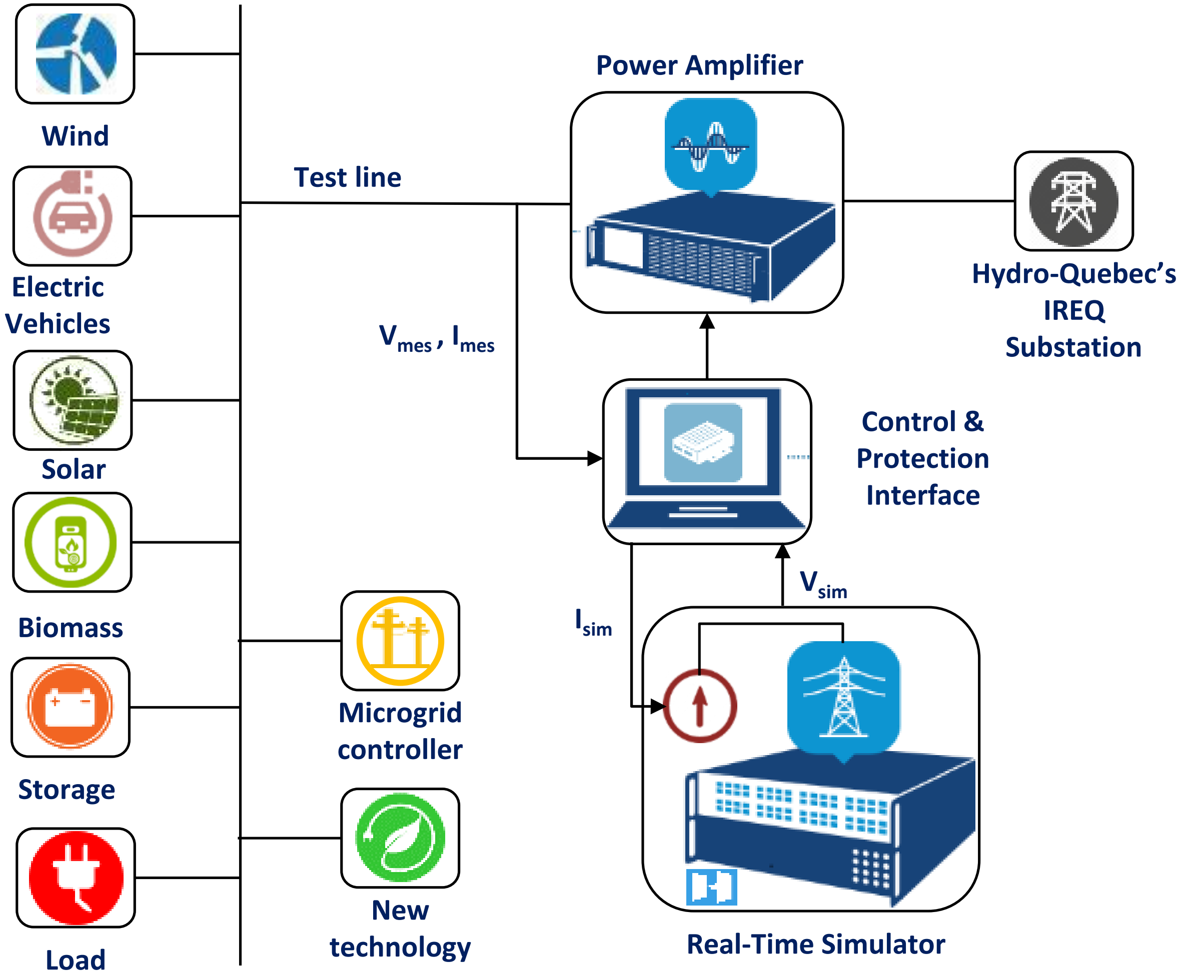
- Controllers that sense at power
- Power converters (Inverters, rectifiers, power supplies)
- Protection devices
- Electric machines
- Batteries, Battery management systems (BMS)

Power Hardware-in-the-Loop (PHIL)



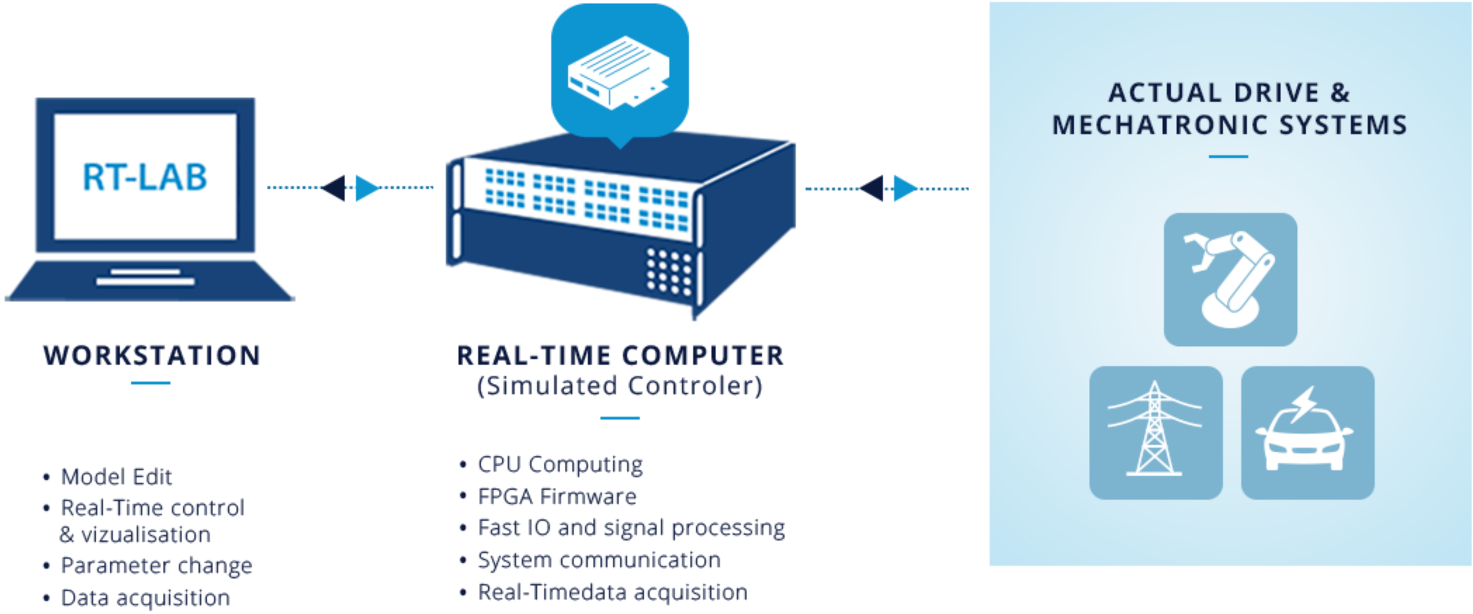
Power Hardware-in-the-Loop (PHIL)





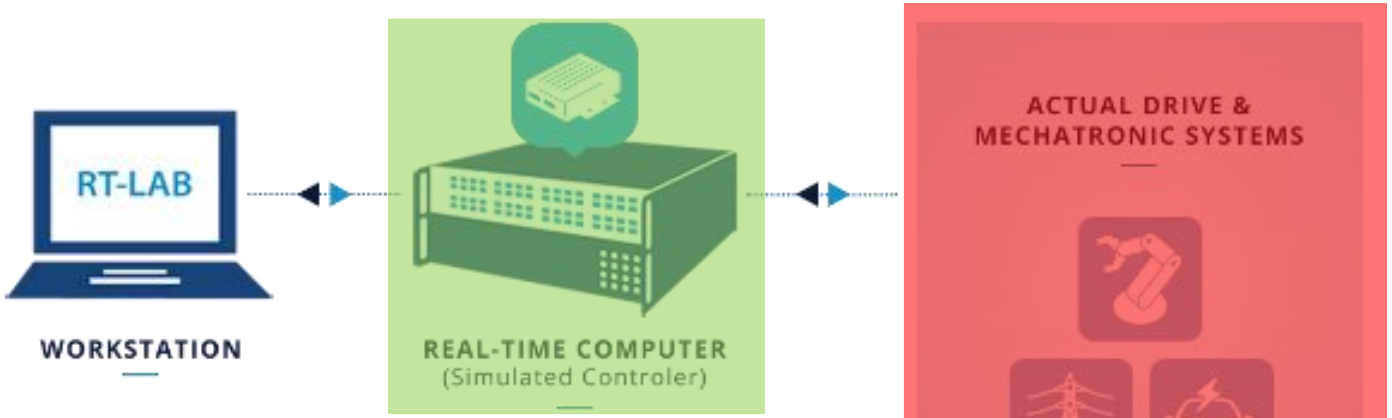
Rapid Control Prototyping (RCP)

- **RCP stands for Rapid Control Prototyping**
- **Definition:** RCP involves using the flexibility of a real-time simulator as a controller connected to real devices to facilitate controller development
- **Common application area:**
  - Robotics
  - Electric motor control
  - Inverter control



RAPID CONTROL PROTOTYPING CONCEPT

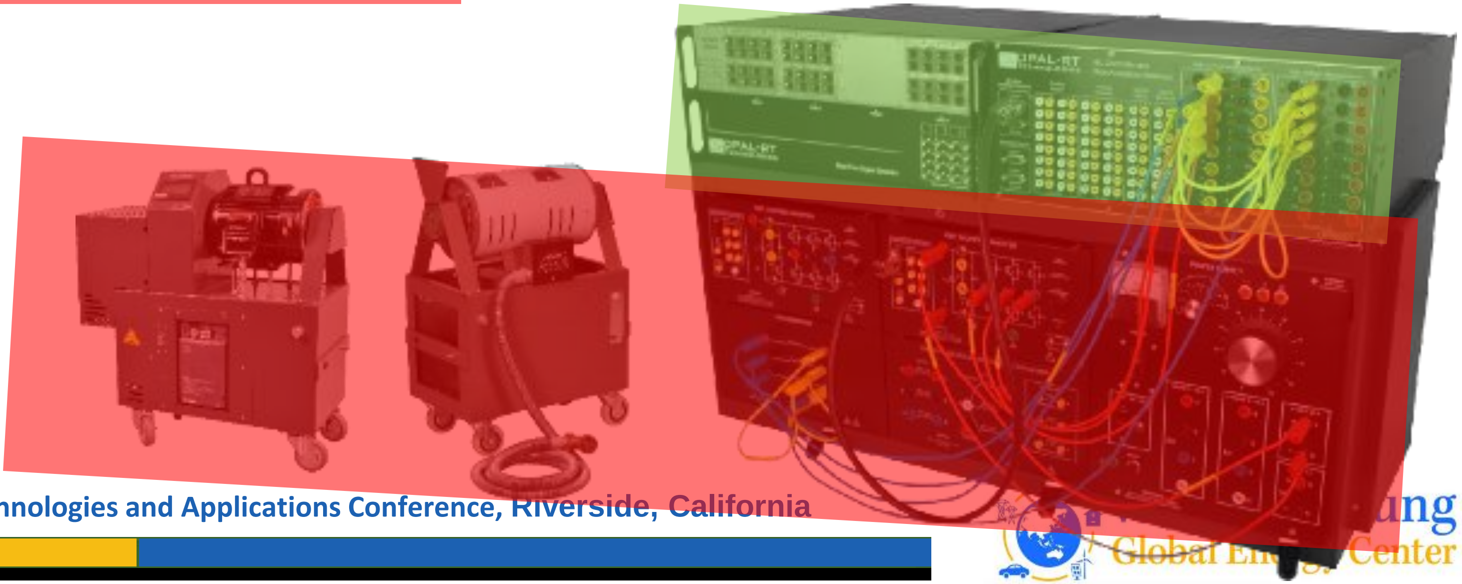
OPAL-RT TECHNOLOGIES



- Model Edit
- Real-Time control & vizualisation
- Parameter change
- Data acquisition

- CPU Computing
- FPGA Firmware
- Fast IO and signal processing
- System communication
- Real-Timedata acquisition

Lab-Volt®



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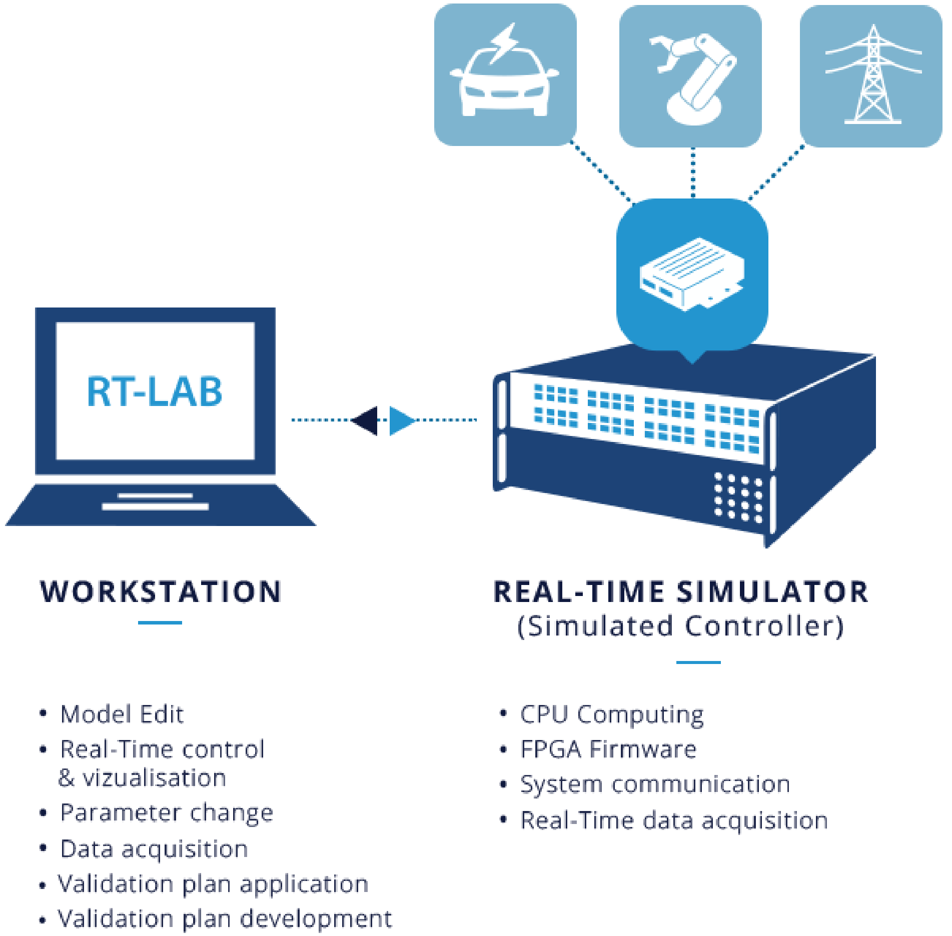
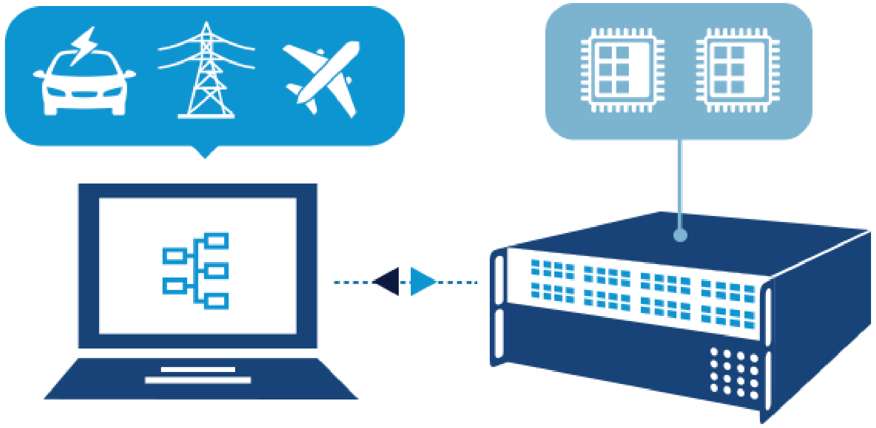
Software-in-the-Loop (SIL)

- **SIL stands for Software-in-the-Loop**
- **Definition:** The testing of production-grade software within the same system as the modeled plant.
- **Note:** SIL does not actually require a time-synchronized simulation and, in many cases, tests can actually be performed faster than real-time with OPAL-RT's capabilities



SIMULATION ACCELERATION

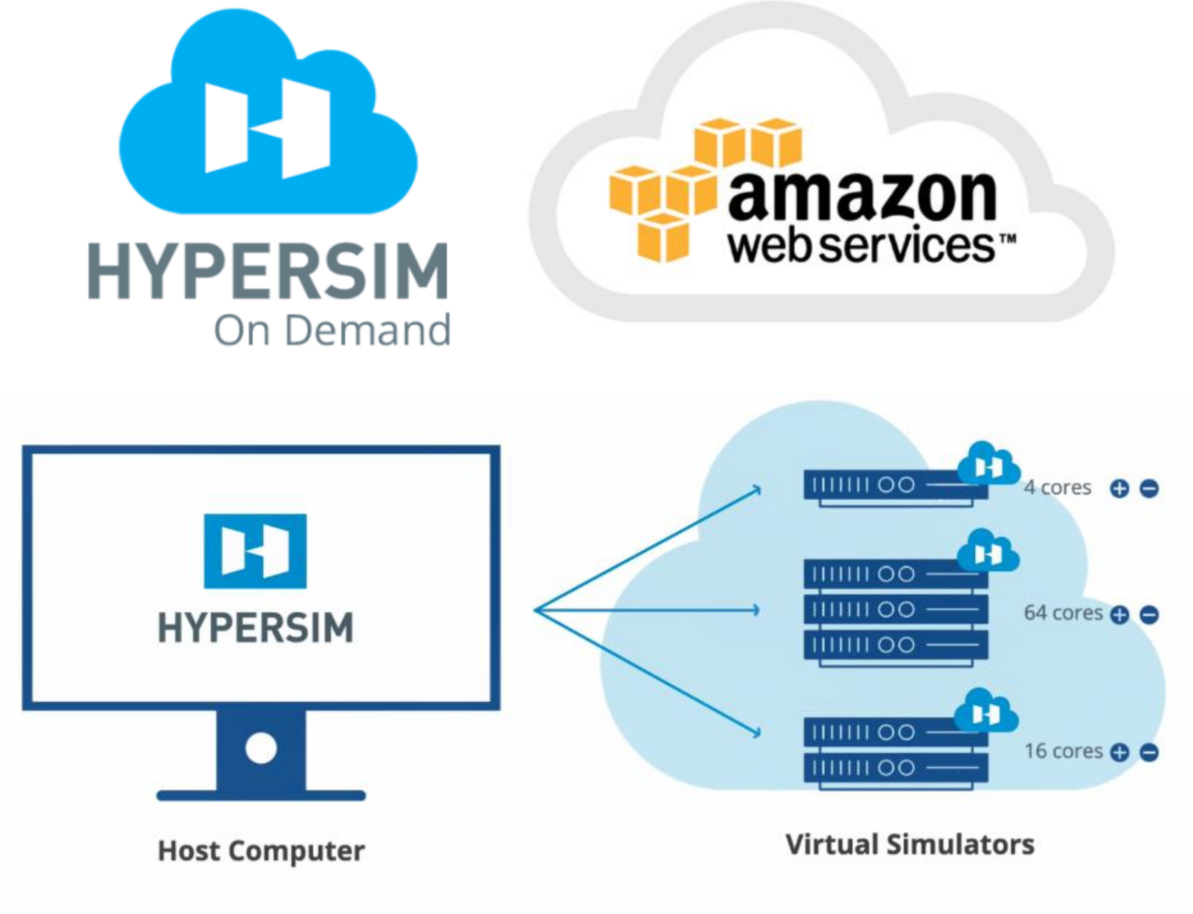


WORKSTATION

- Model editing
- generate & compile optimized code
- Simulation management & control
- Simulation visualization

SIMULATOR

- Optimized OS
- Multi-Core processor
- Dedicated FPGA
- Data acquisition



SIMULATION ACCELERATION

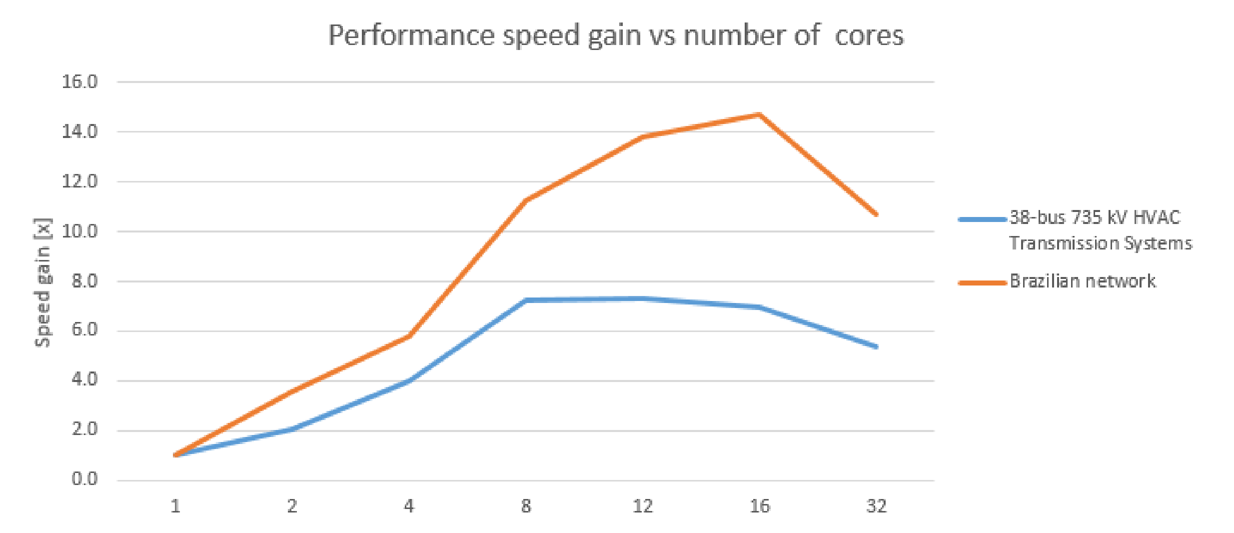
Brazil

- 950 3-phase buses
- 16 12-pulse converters
- 500 transmission lines

Run on 9 cores @ 50 µs with I/O!

HYPERSIM offline : 1 core vs N cores

	Number of cores						
	1	2	4	8	12	16	32
38-bus 735 kV HVAC Transmission Systems	1.0	2.0	4.0	7.2	7.3	7.0	5.4
Brazilian network	1.0	3.6	5.8	11.2	13.8	14.7	10.7



HYPERSIM vs PSCAD

RTS Approach and Fundamentals

OPAL-RT TECHNOLOGIES

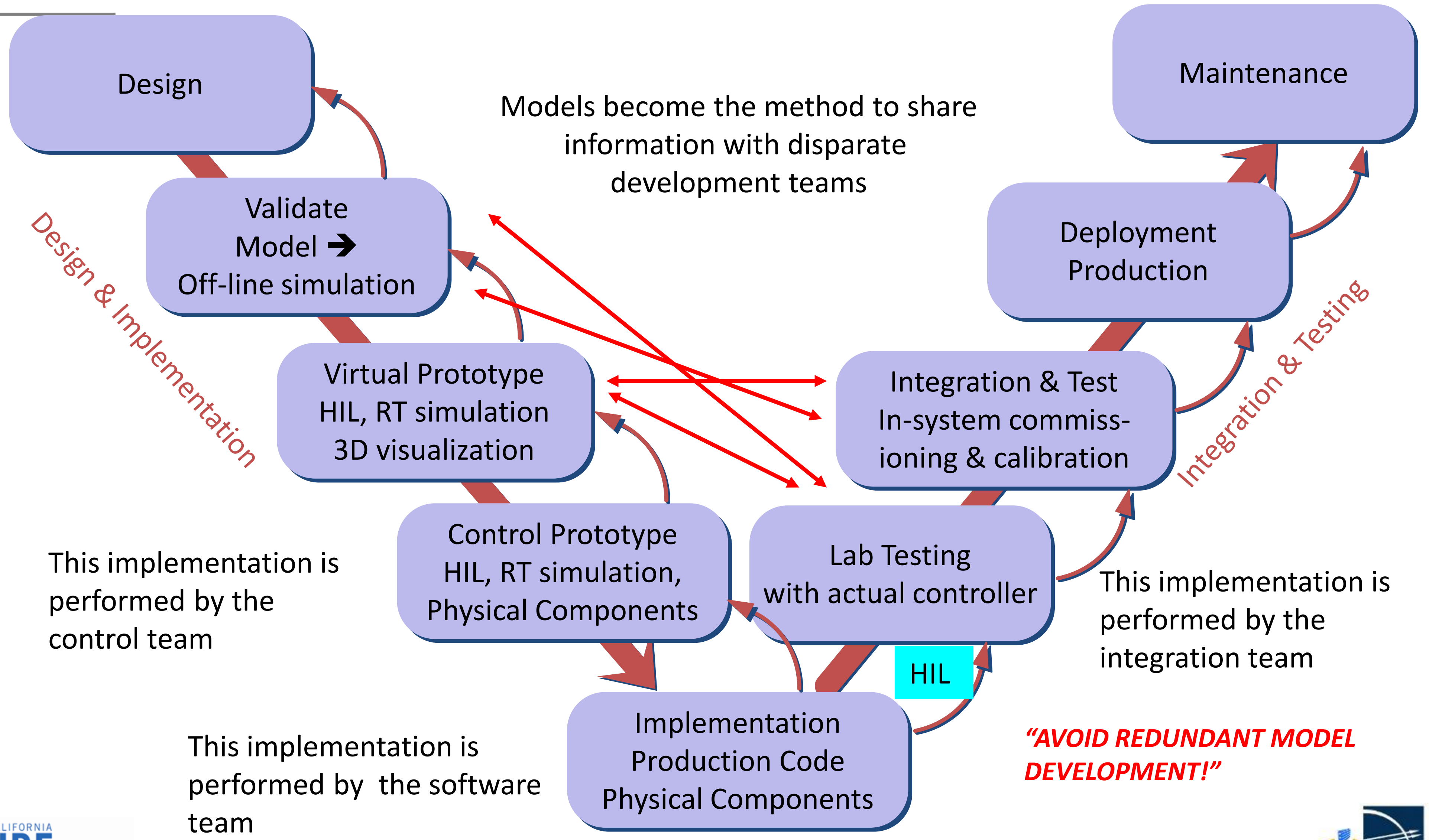
WHAT IS THE V-CYCLE?

- **Brief background**
  - Also known as the "V-Modell," this graphical process created in Germany in 1986 for planning and executing projects (Source: IABG)
  - Adopted and modified heavily for:
    - Product development
    - Software development
    - Systems engineering

- **V-Cy**
  - Ex

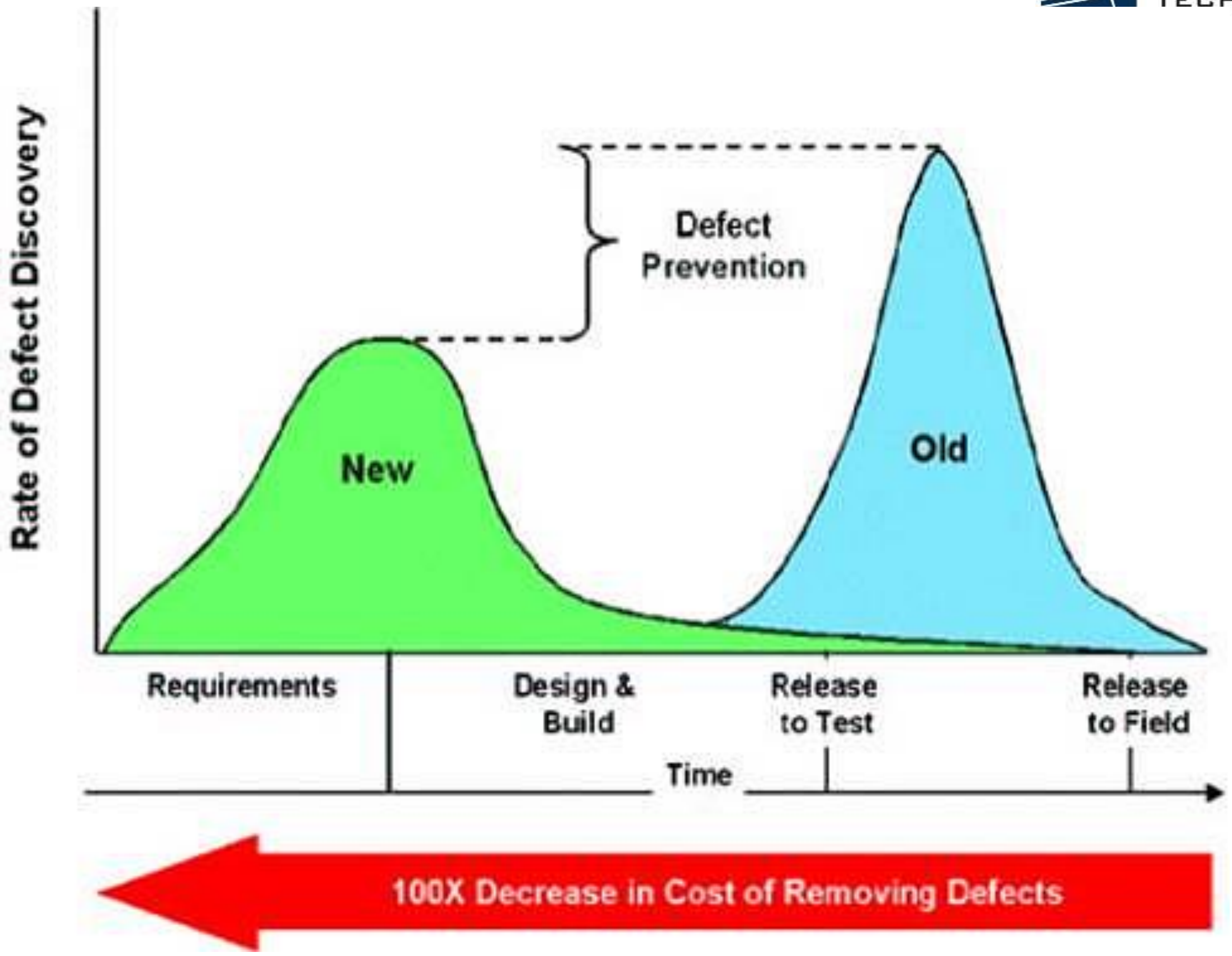
omen

WHAT IS THE V-CYCLE?



"AVOID REDUNDANT MODEL DEVELOPMENT!"

Model-Based Design



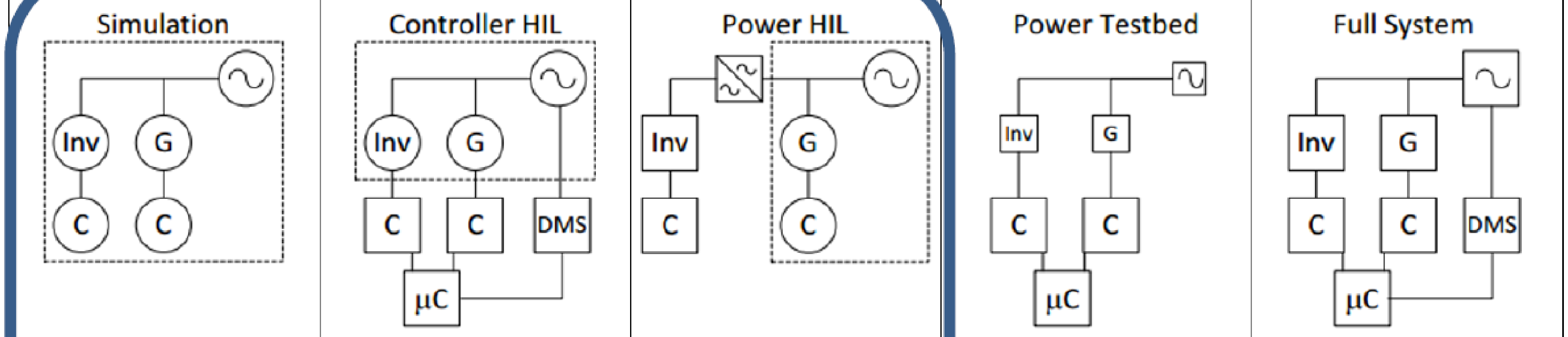
Boehm, Barry. Software Engineering Economics. Englewood Cliffs, NJ: Prentice-Hall, Inc. 1981.

OPAL-RT TECHNOLOGIES

Testbed tradeoffs

Applications of a Real-Time Simulator (RTS)

Figure modified from the concept originally proposed by MIT-LL

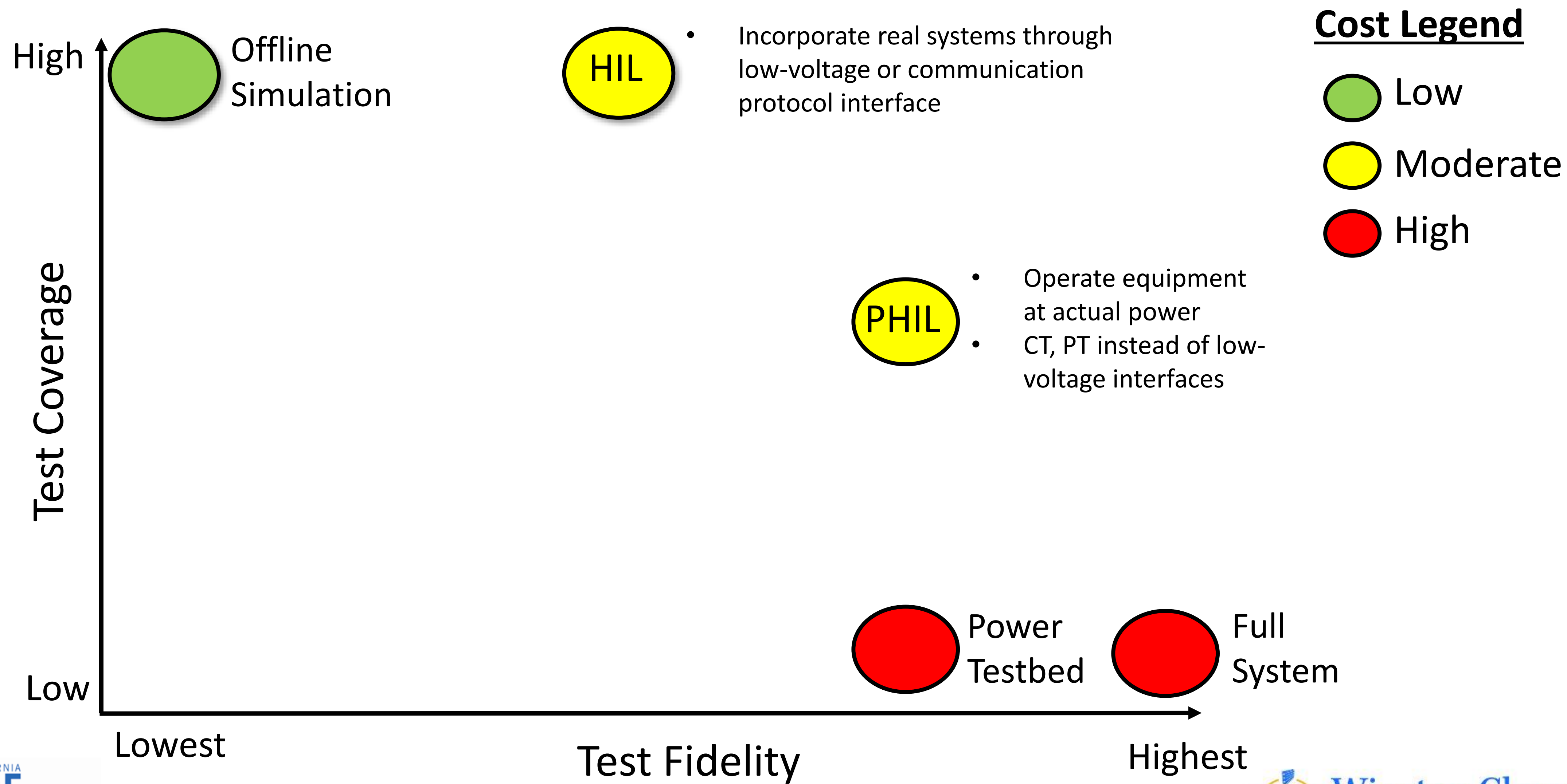


	Simulation	Controller HIL	Power HIL	Power Testbed	Full System
Testbed cost	-	+/-	+	++	+++
Test Fidelity	-	+	++	+/-	+++
Test Coverage	+	+++	++	+/-	-

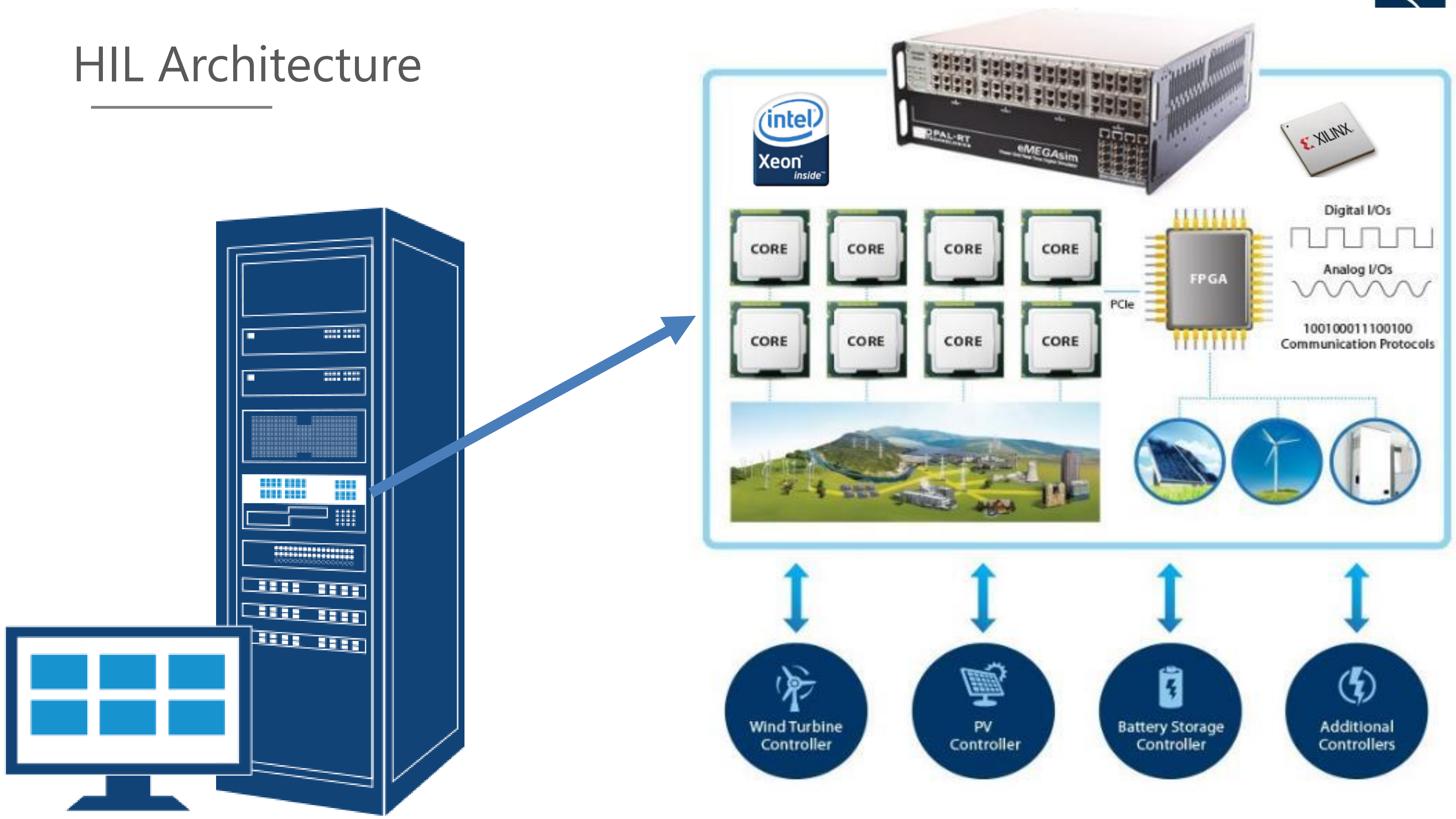
Source: R.O. Salcedo, J.K. Nowocin, C.L. Smith, R.P. Rekha, E.G. Corbett, E.R. Limpaecher, J.M. LaPenta, TR-1203: Development of a Real-Time Hardware-in-the-Loop Power Systems Simulation Platform to Evaluate Commercial Microgrid Controllers, MIT Lincoln Laboratory, Lexington, MA, Feb. 2016

- **Test fidelity** depends on **purpose** and model **validity**. For Power Testbeds, fidelity depends on equipment used and similarities between that and the real installation.
- **Test coverage** also depends on **purpose**. Simulation only does not allow testing of equipment per say, but with good models, it is a powerful tool for design studies. **CHIL provides the best coverage for testing Microgrid Control Systems**, allowing fault scenarios, transitions and dispatch scenario functional testing.

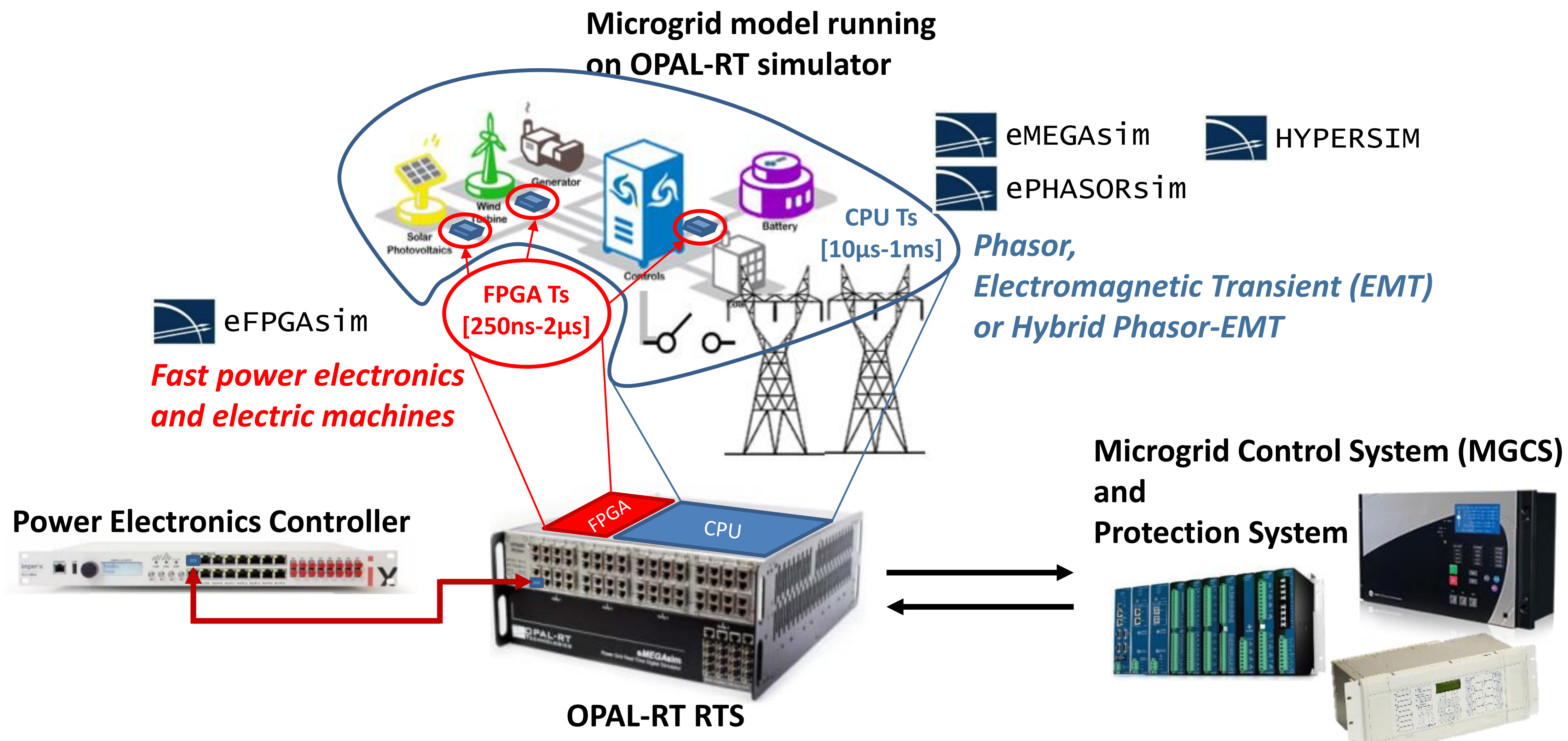
HIL VS PHIL


Cost Legend
Low
Moderate
High
High
Test Coverage
Low
Offline Simulation
HIL
Incorporate real systems through low-voltage or communication protocol interface
PHIL
Operate equipment at actual power
CT, PT instead of low-voltage interfaces
Power Testbed
Full System
Lowest
Test Fidelity
Highest

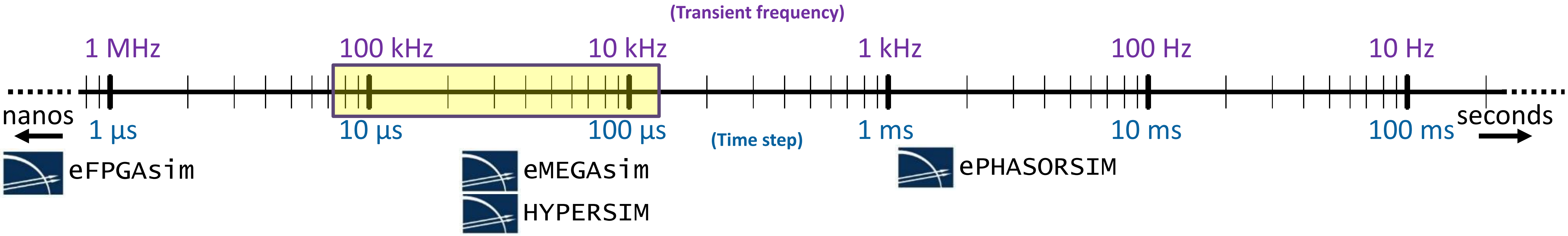
HIL Architecture

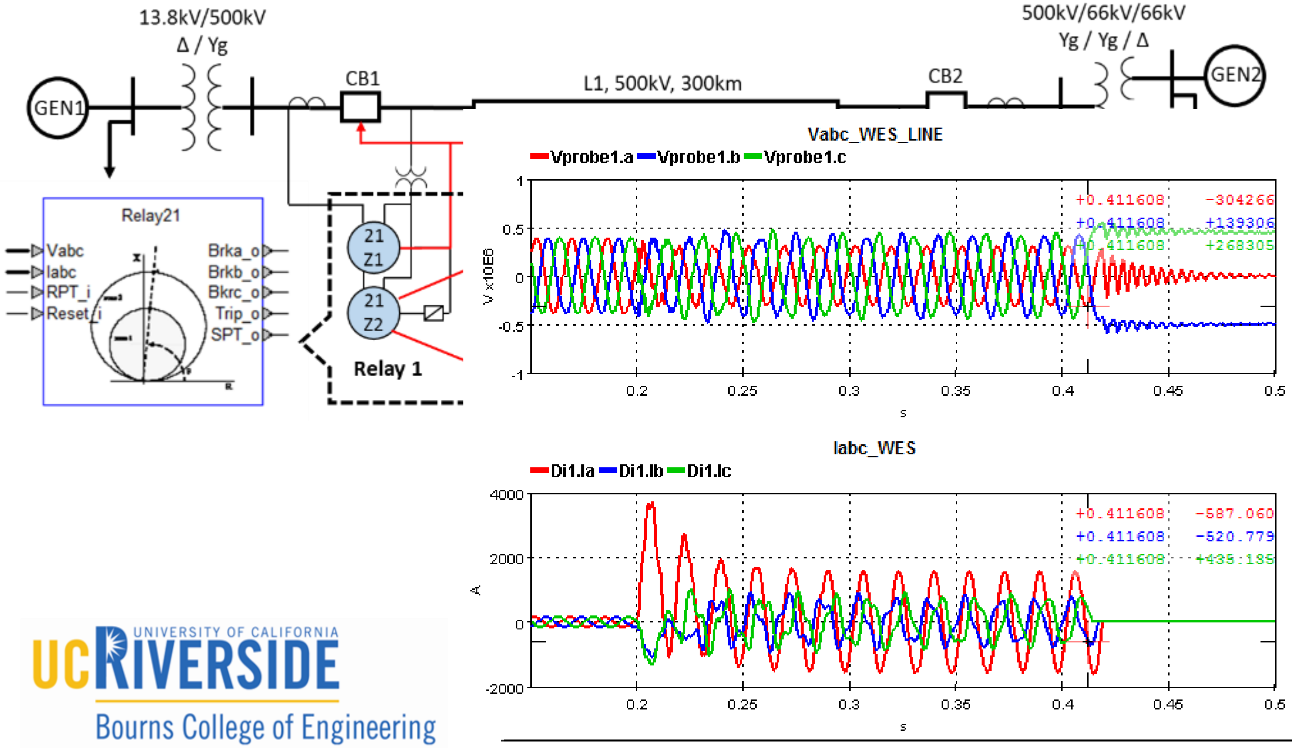


Real-time simulator architecture



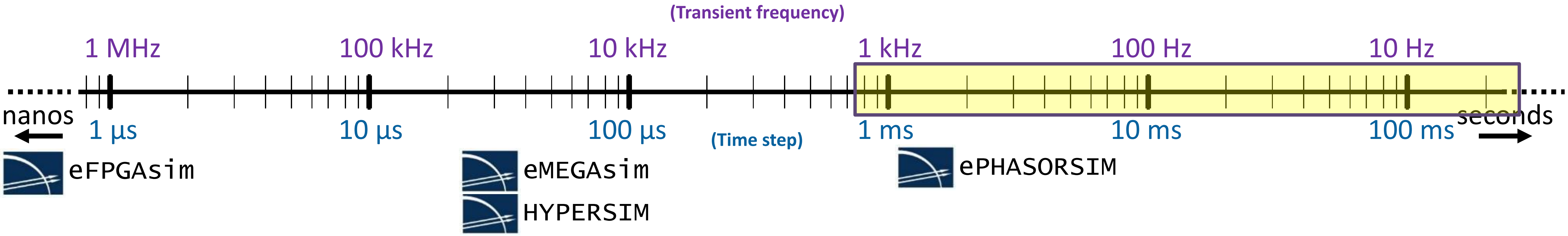
REAL-TIME SIMULATION TIME SCALE

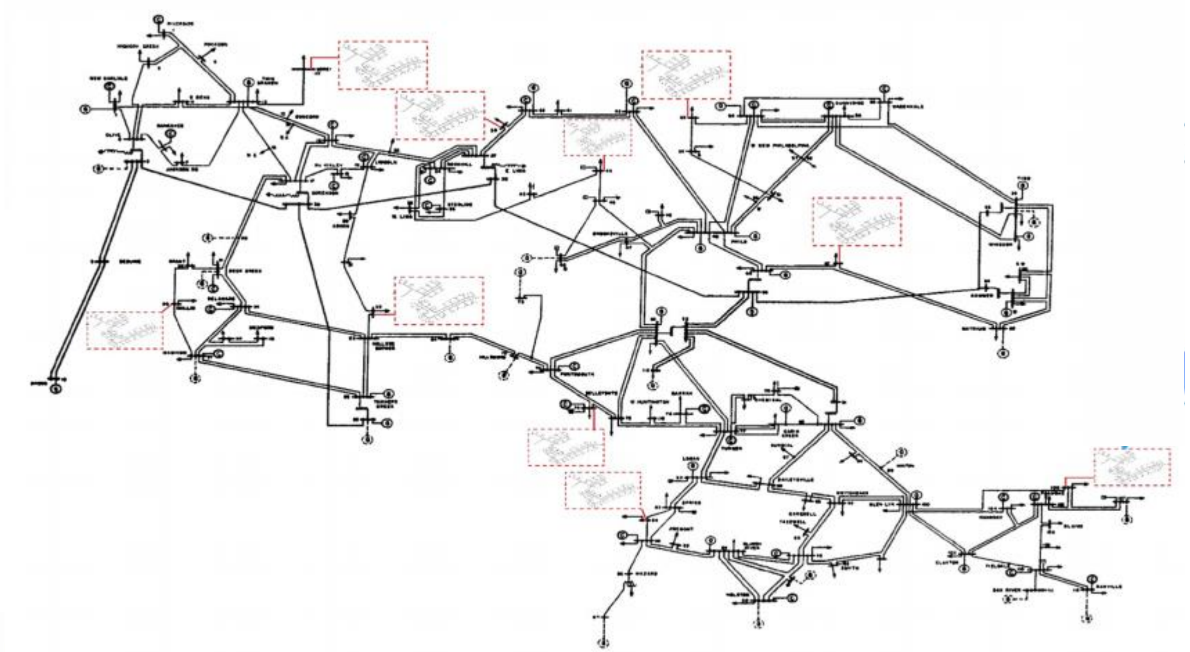




- Electromagnetic phenomena
- Most protection applications
- Device unit test
- Protection scheme test

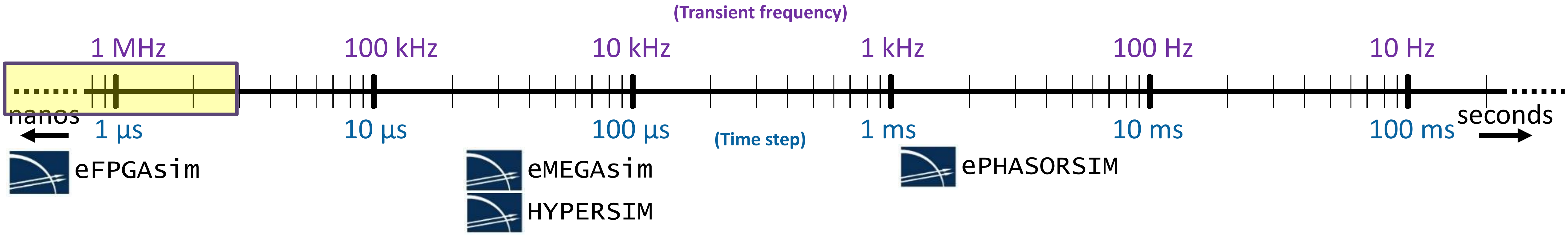
REAL-TIME SIMULATION TIME SCALE

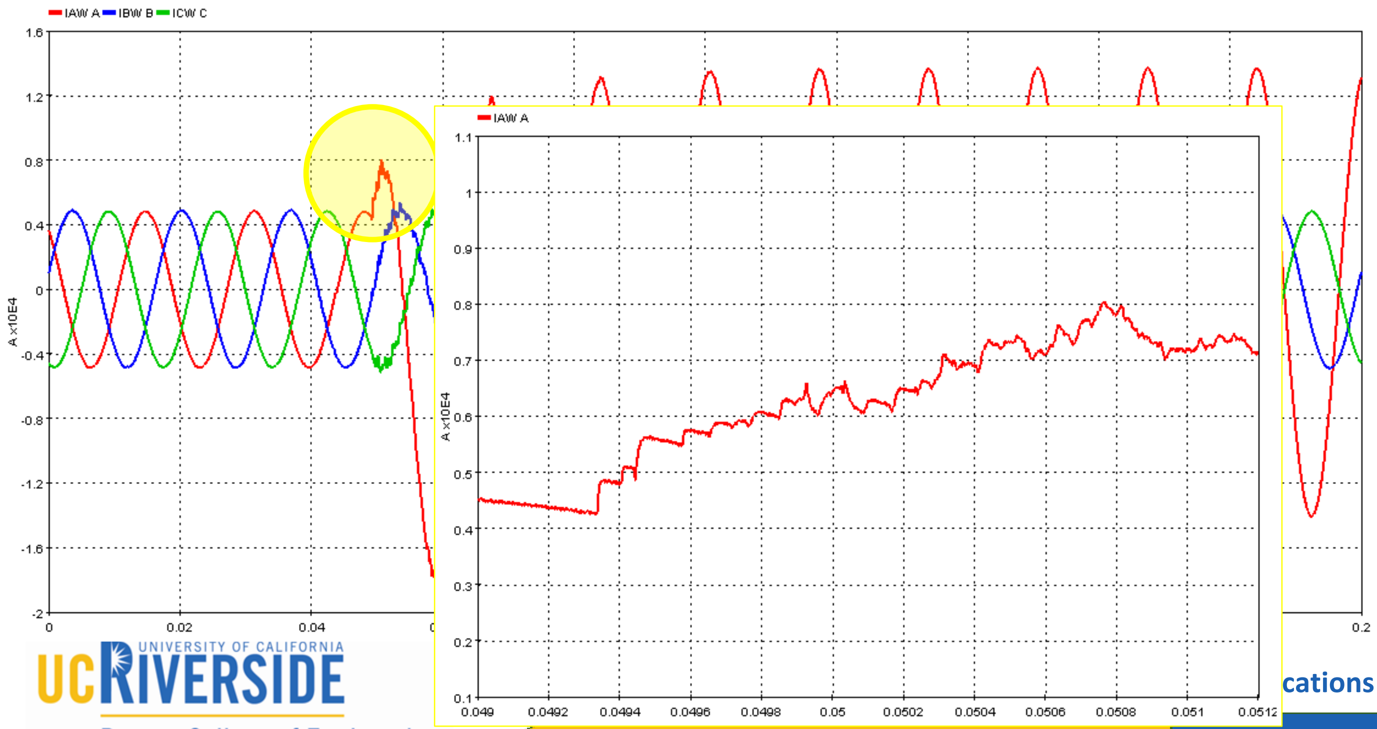




- Electromechanical phenomena
- Wide Area Protection And Control (WAMPAC)
- SCADA system

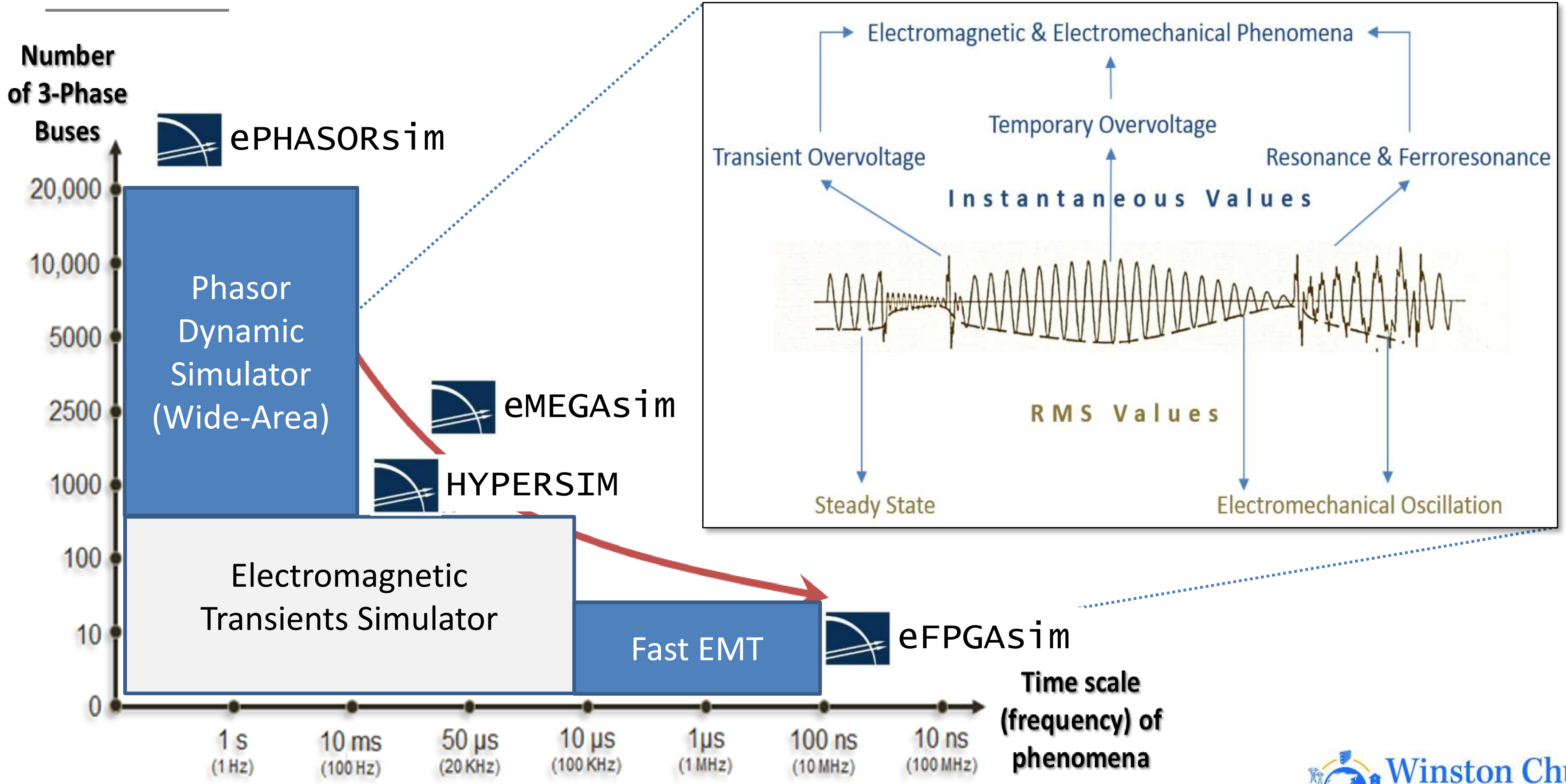
REAL-TIME SIMULATION TIME SCALE



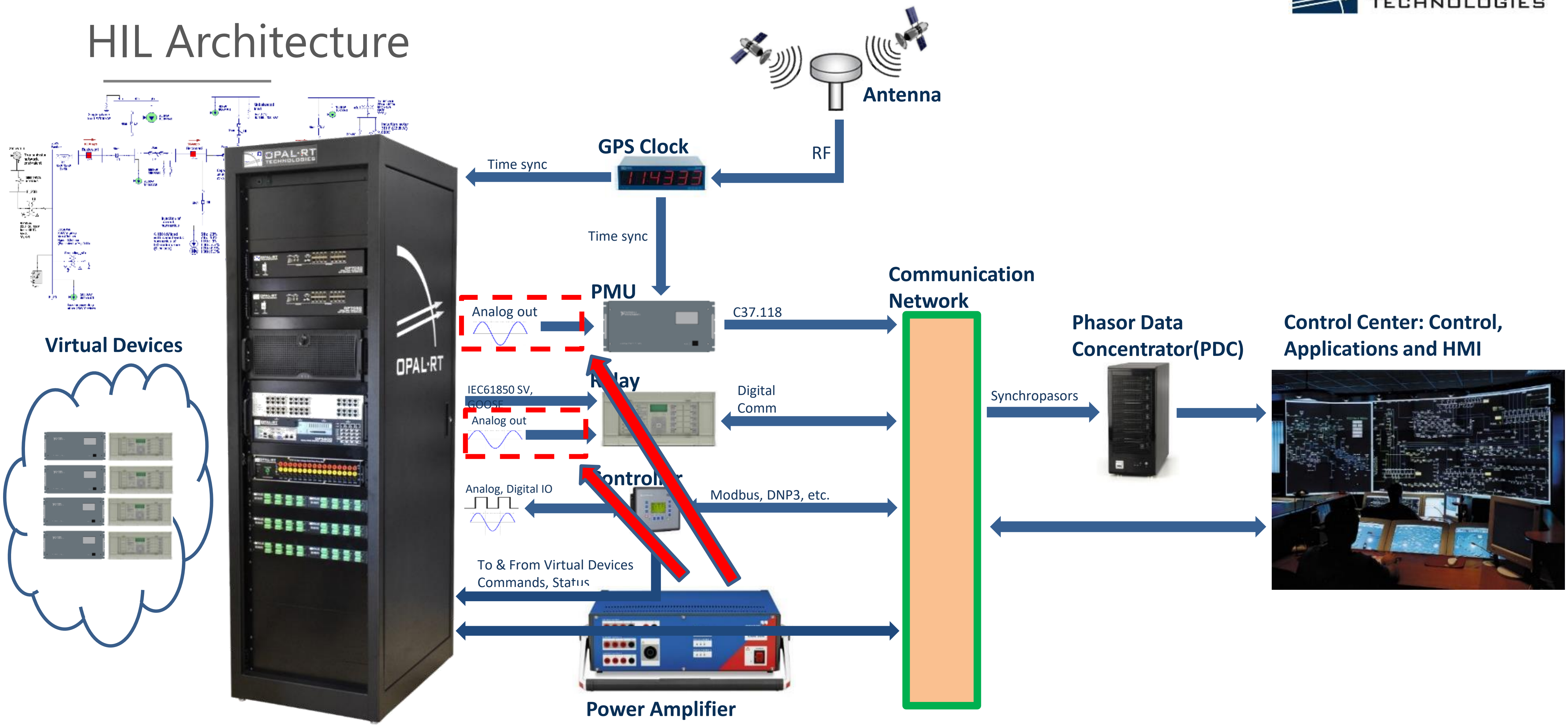


- Resonance & ferroresonance
- Traveling wave
- Fast switching power electronics

SIMULATION TOOL OVERVIEW

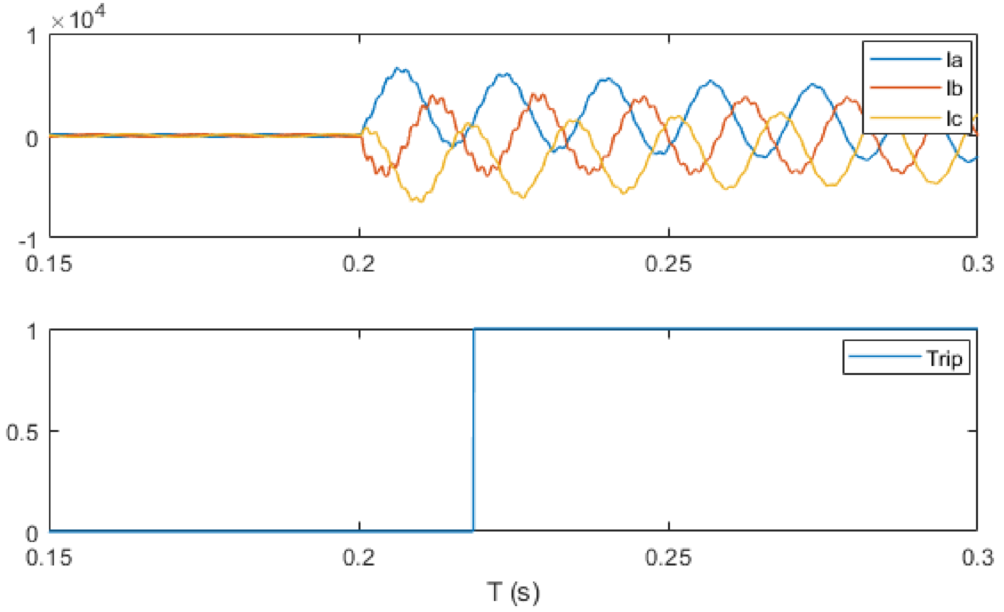


HIL Architecture

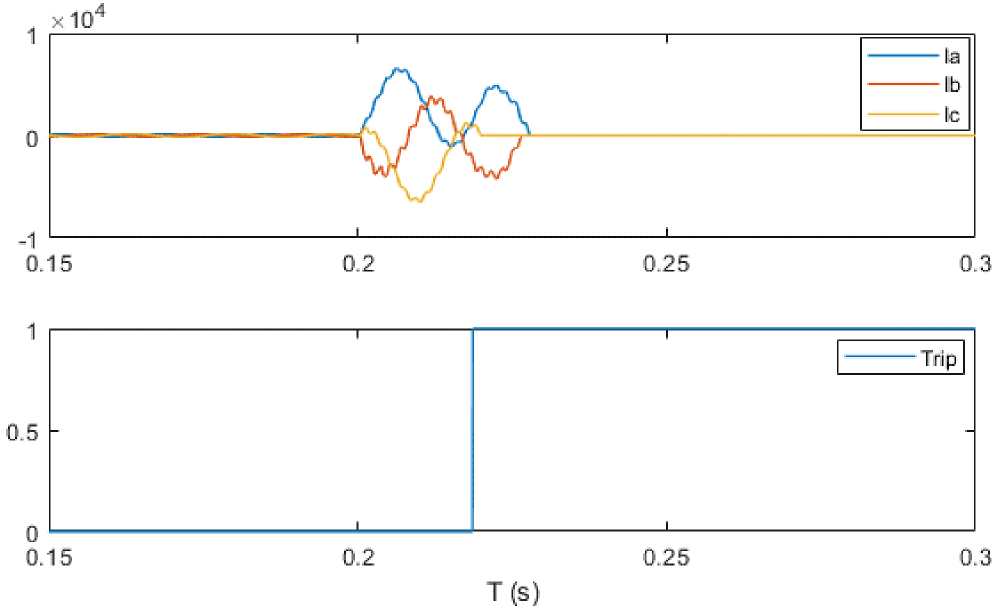


CLOSED-LOOP TESTING

- Open-loop testing



- Closed-loop testing



Relay operation time

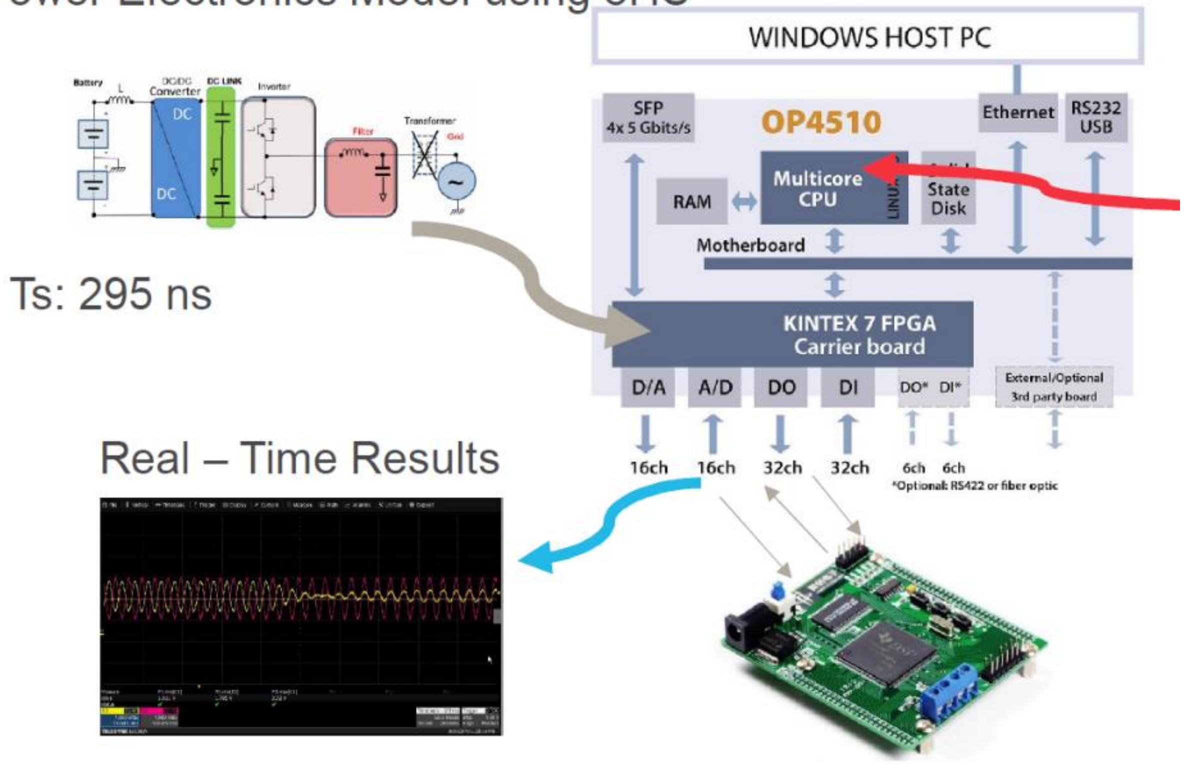
Circuit breaker open

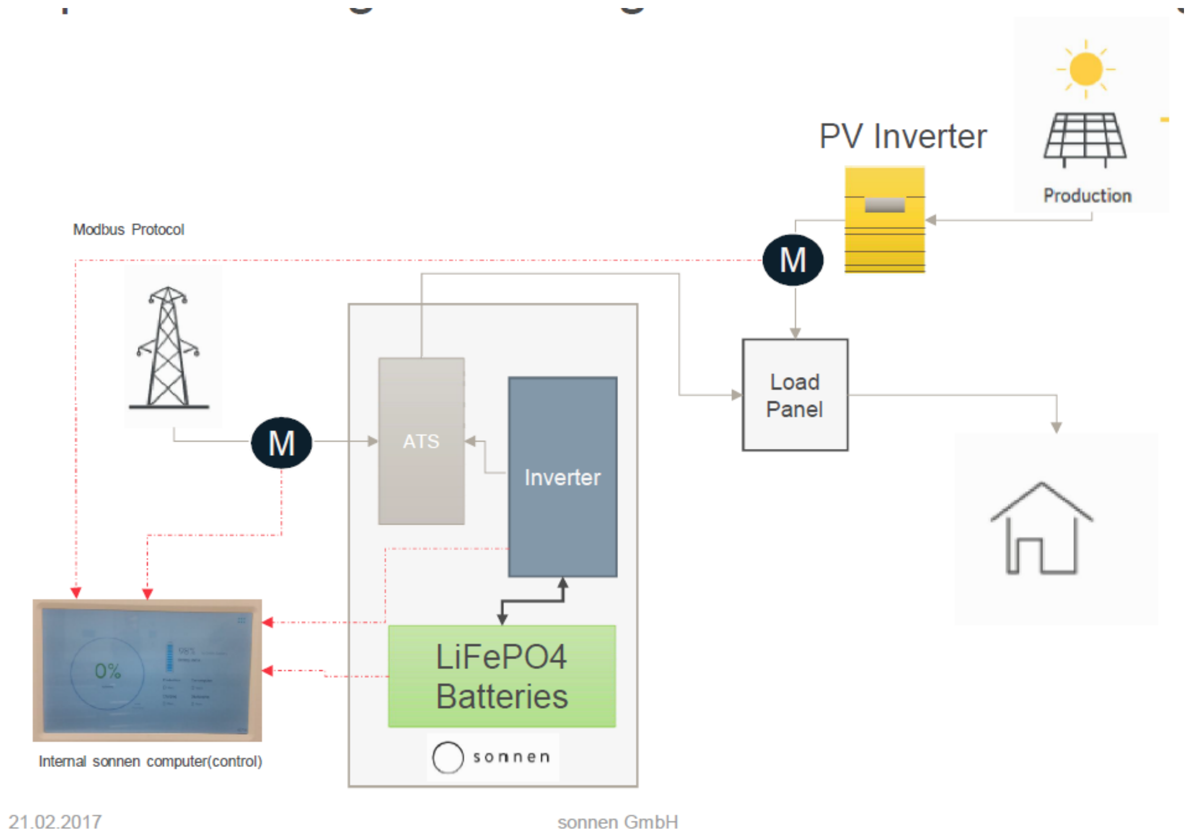
Reclose / evolving fault

EXAMPLES OF WORK ON ENERGY STORAGE USING HIL

nanoGrid: Sonnen

Power Electronics Model using eHS





Device-Under-Test (DUT)

https://www.opal-rt.com/wp-content/themes/enfold-opal/pdf/L00161_0492.pdf

V2G: Politecno Torino & RTWH Aachen

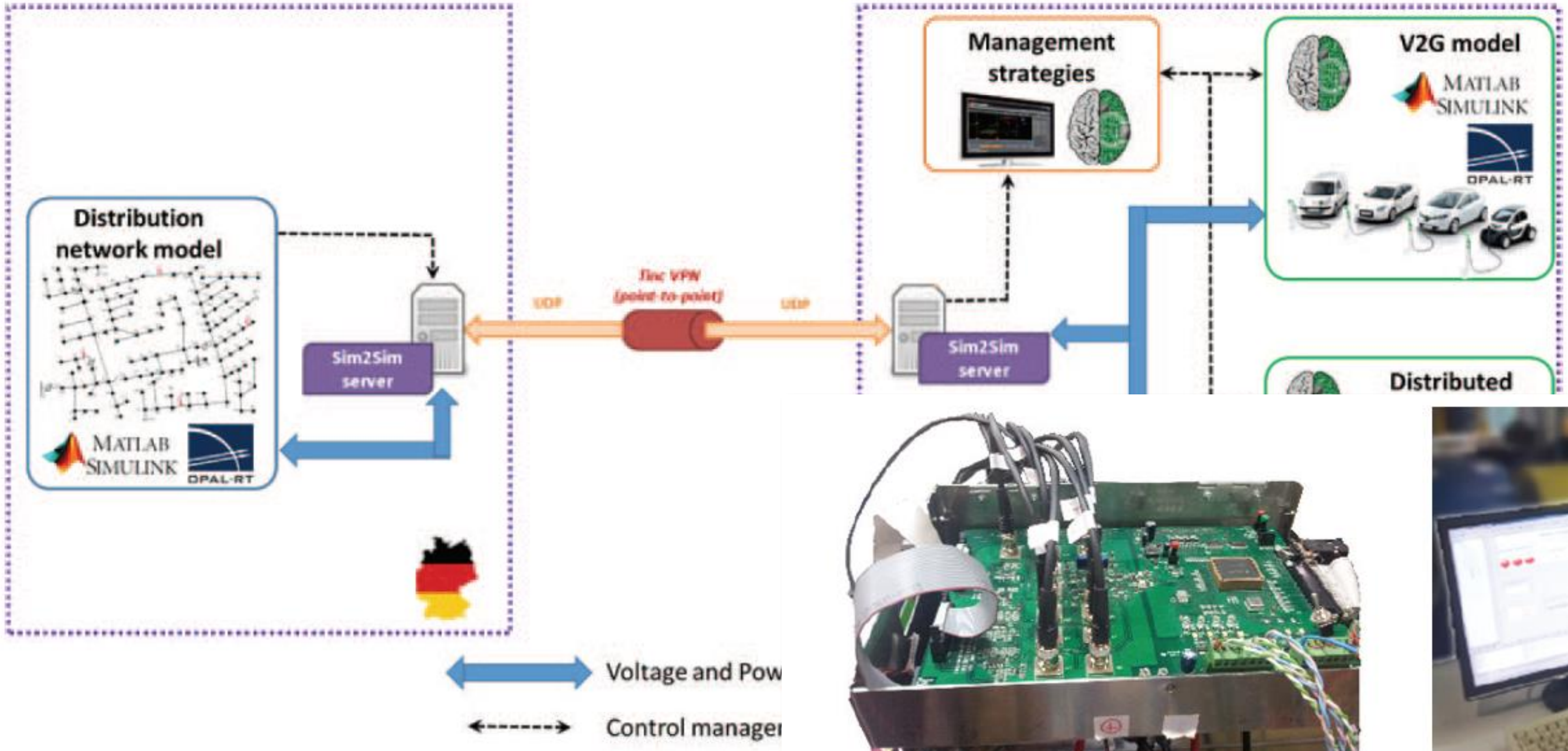
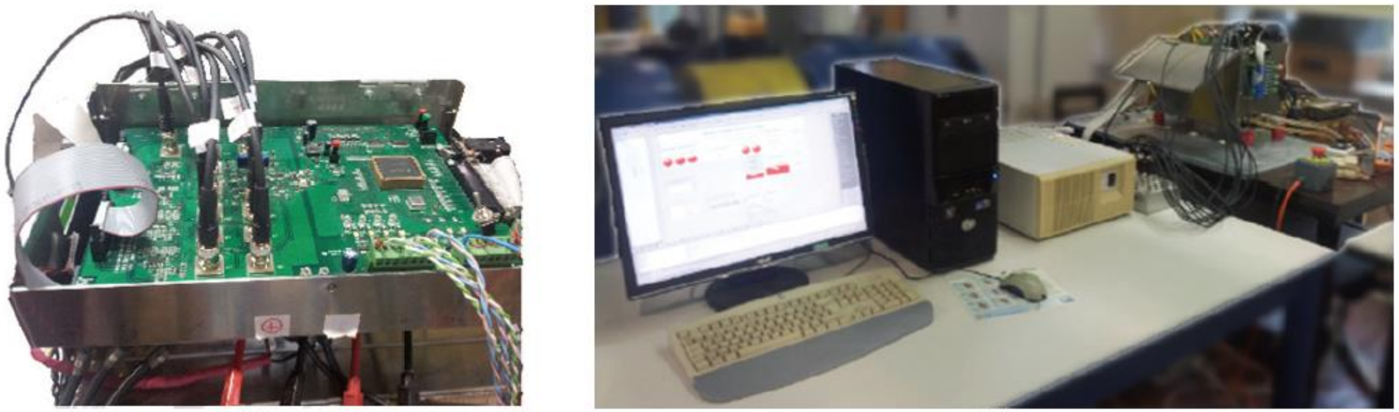


Fig.2. Structure of the proposed case study implem
platform.



(a) (b)

Fig.7. Prototypal bidirectional power converter: (a) detail of the power electronics control signals communication interface; (b) test bench setup.

Estebsari, Abouzar & Tenconi, Alberto & Bompard, Ettore & H ne co-simulation platform for the testing of control strategies of distributed storage and V2G in distribution networks. 10.1109/EPE.2016.7695666.

V2G: Politecno Torino & RTWH Aachen

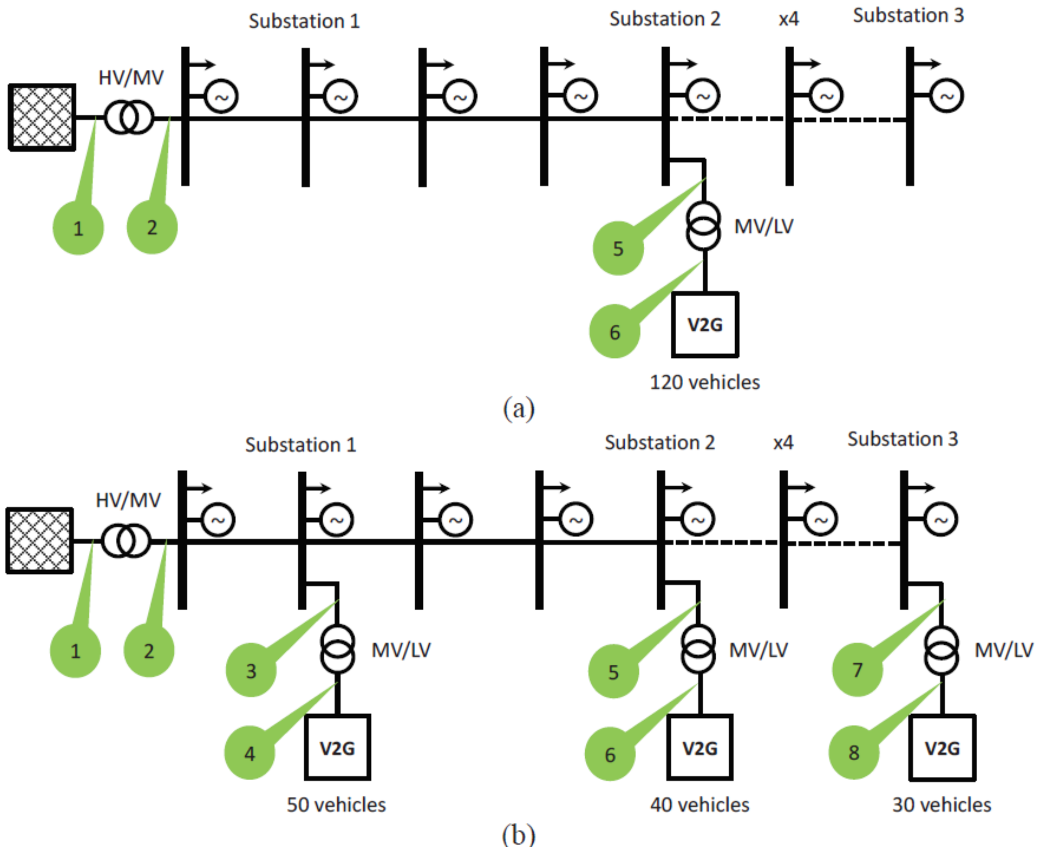


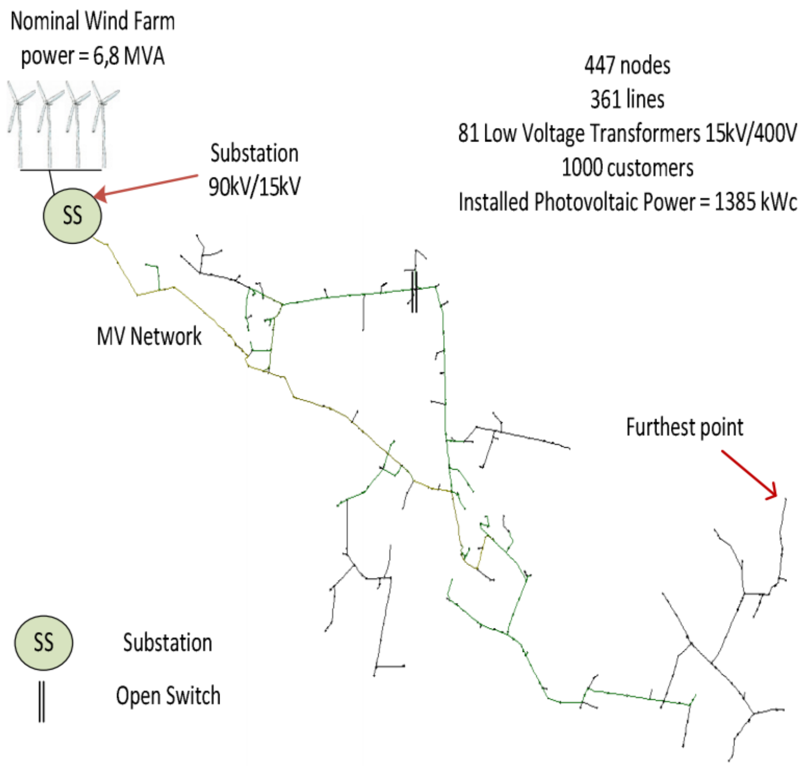
Table I: Simulation results

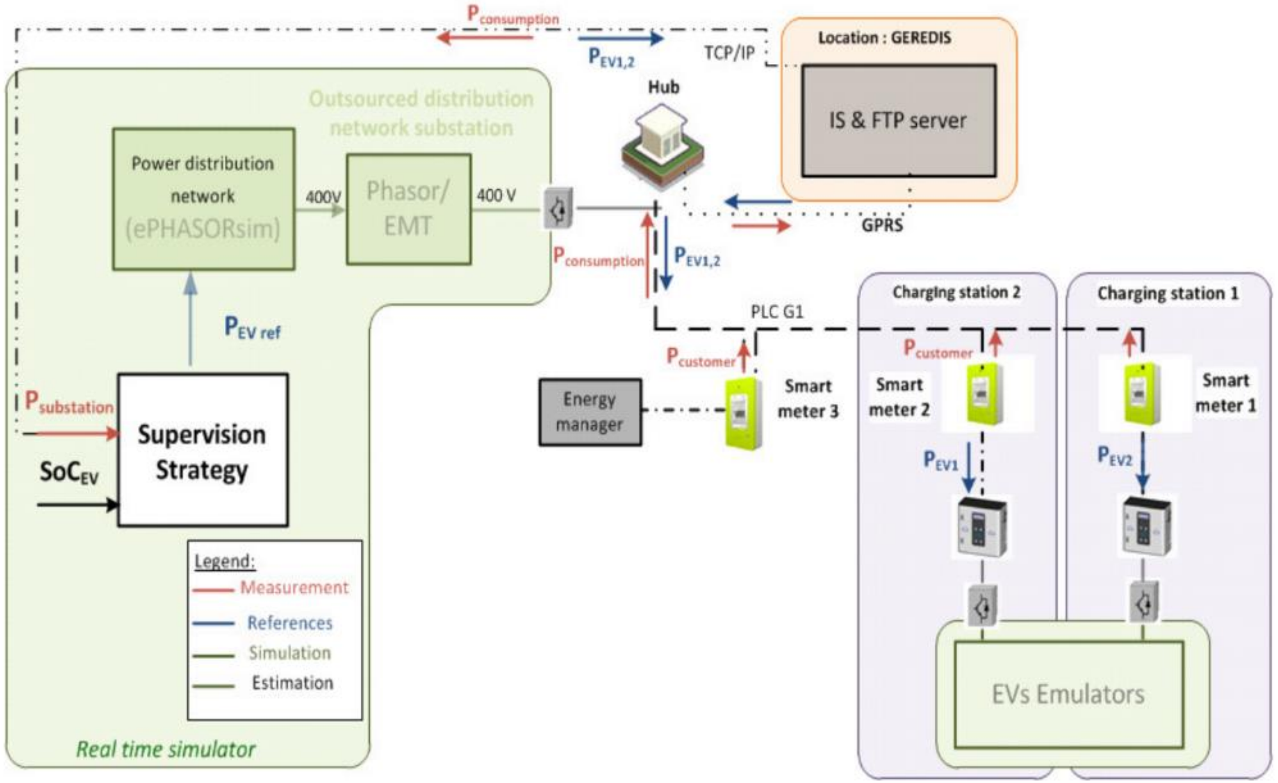
	V2G concentrated in substation 2, MWh	V2G distributed in 3 different substations, MWh	Percentage variation
Net energy absorbed from the HV network	55.58	55.64	+0.1%
MV lines losses	0.36	0.34	-6.5%
HV/MV transformer losses	1.02	1.02	0%
MV/LV transformers losses	0.12	0.22	+87%
Vehicles losses	0.32	0.28	-12%

Estebsari, Abouzar & Tenconi, Alberto & Bompard, Ettore & Huang, Tao & Pons, Enrico & Monti, A & Stevic, Marija & Vaschetto, Silvio & Vogel, Steffen. (2016). A multi-site real-time co-simulation platform for the testing of control strategies of distributed storage and V2G in distribution networks. 10.1109/EPE.2016.7695666.

V2G: L2EP, Lille, France

Laboratoire d'électrotechnique et d'électronique de puissance de Lille

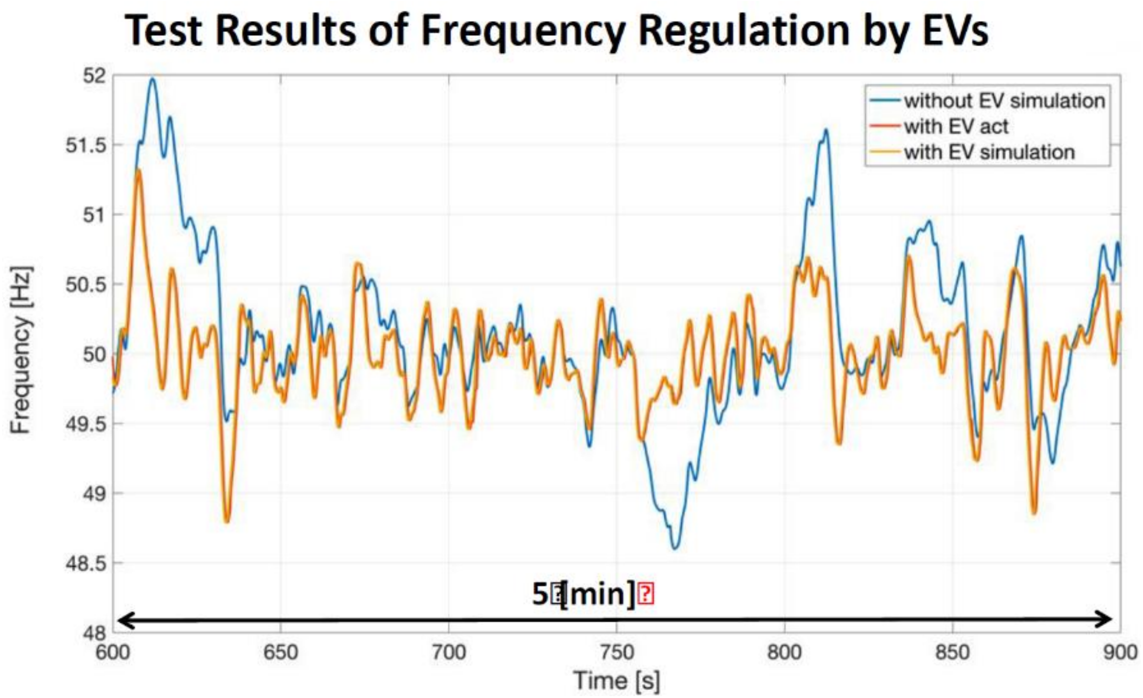




https://www.opal-rt.com/wp-content/themes/enfold-opal/pdf/L00161_0449.pdf

V2G: Tokyo City University

東京都市大学
TOKYO CITY UNIVERSITY



https://www.opal-rt.com/wp-content/themes/enfold-opal/pdf/L00161_0606.pdf

Application Overview:
Battery Management System Testing

What is a Battery Management System (BMS)?

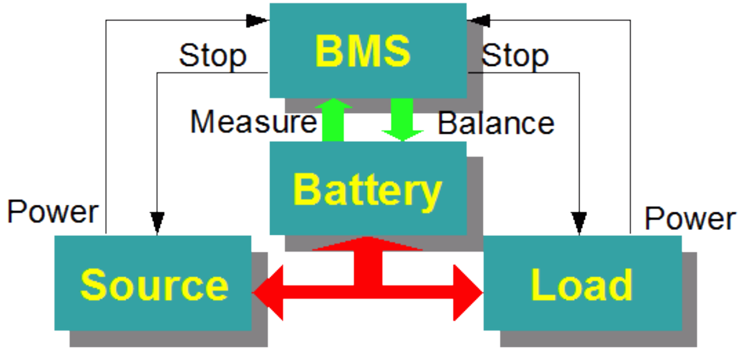
- A system comprising of various devices responsible for managing a rechargeable battery
  - At the cell level
  - At the cell module level
  - At the pack level
- Typically, a BMS has 2 control layers:

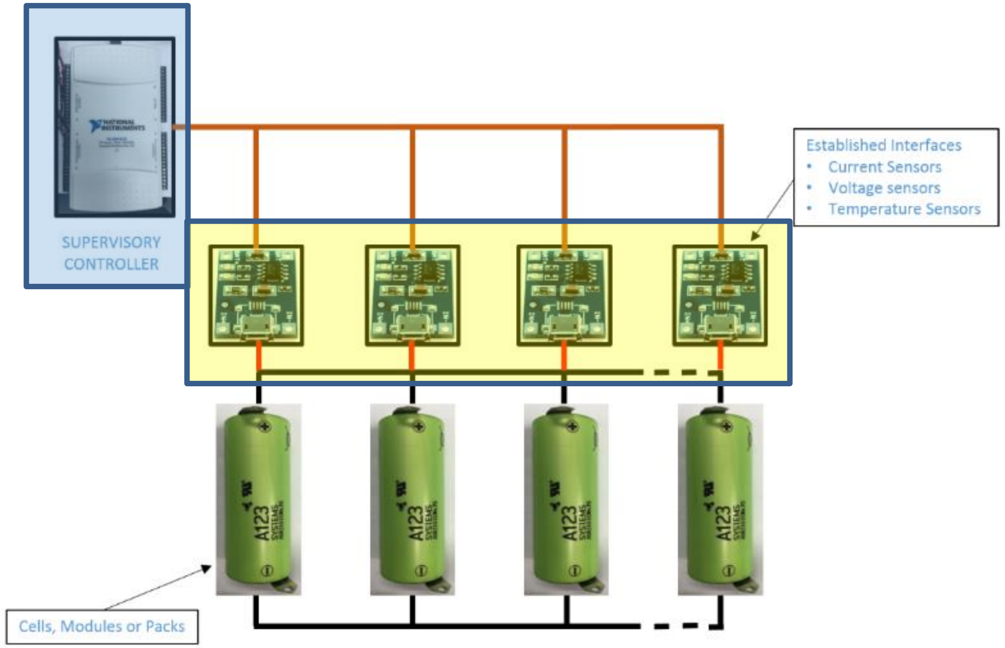
1. Battery Monitoring Unit(s) BMU

- Monitoring at the cell level
  - Voltage, current, temperature
- Performs cell balancing
- Acts as a slave to the BMS

2. Master/Supervisory BMS

- Top level controller
- Centre point of the complete battery status
- Perform battery control (decision maker)
- Communicate with other systems

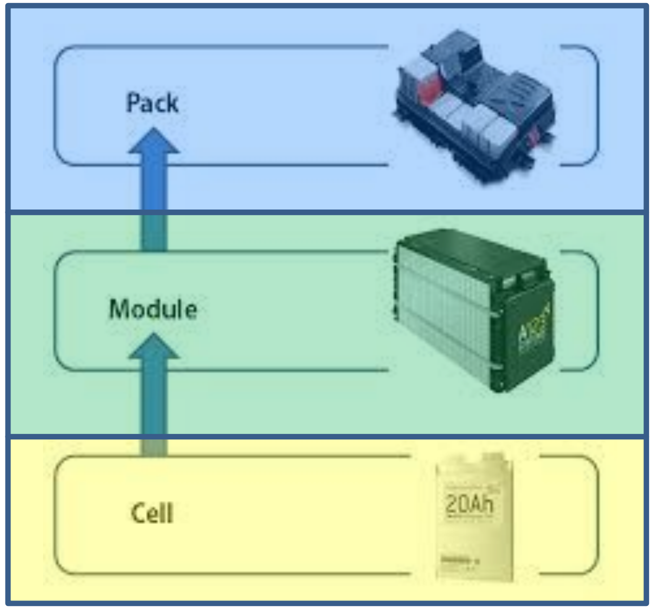


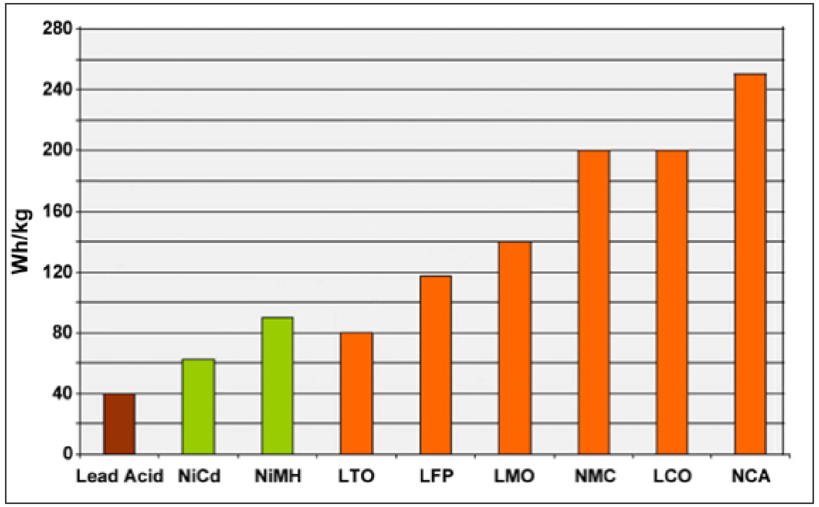


What is a Battery Management System (BMS)?

Battery Nomenclature and Components

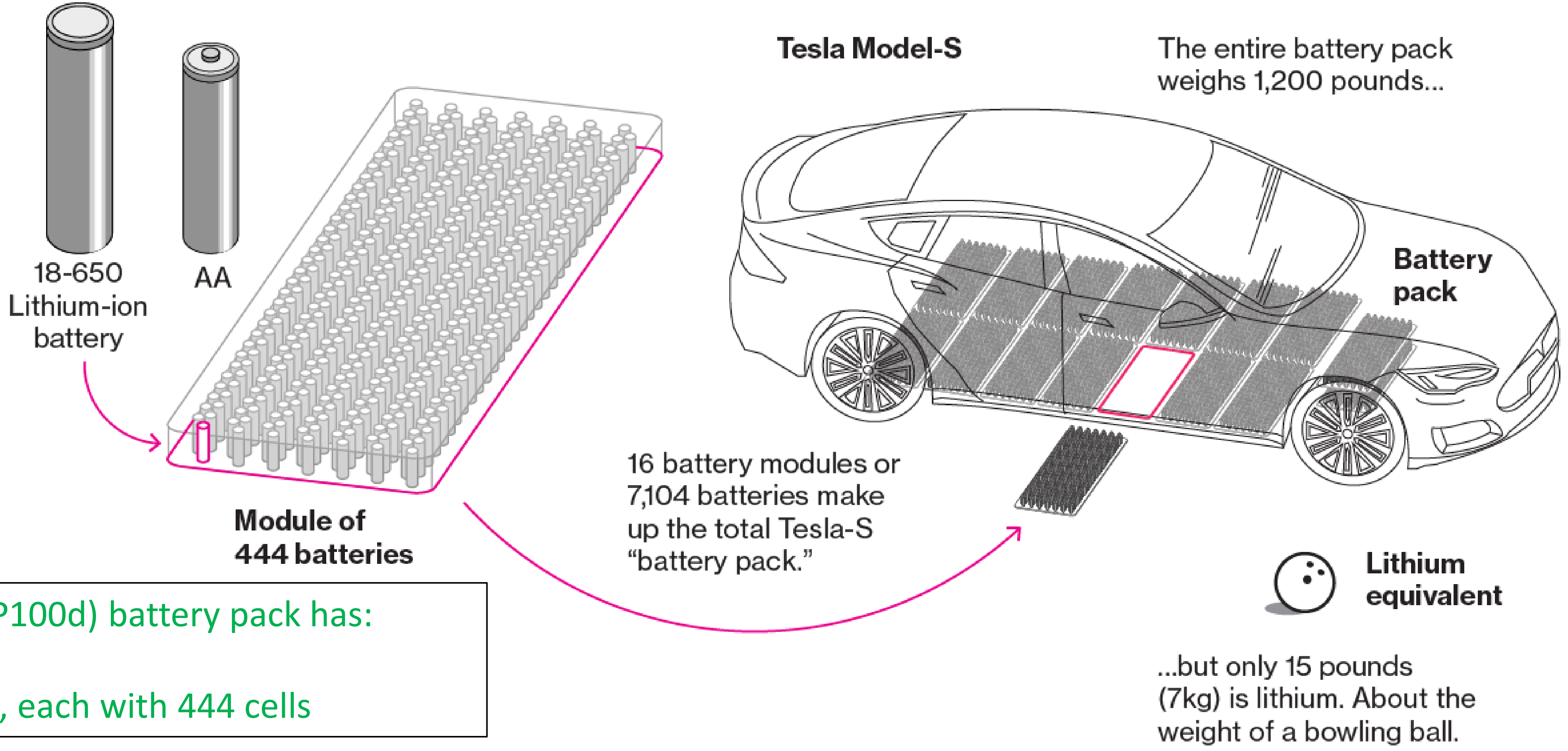
- Cell :
  - Individual elements of the battery assembly (chemistries)
  - Voltage range from 3.7V to 4.2V (Lithium-Ion)
  - Capacity in Amp-Hours
- Cell Module :
  - Grouping of individual cells (in series)
  - Increases the voltage output
  - Ranges typically from 4 to 16 cells per module
- Battery Pack
  - Consists of many cell modules (parallel and series)
  - Cell modules in parallel increase the maximum current/capacity





What is a Battery Management System (BMS)?

Here's what Tesla's battery pack looks like!



One Tesla Model S (P100d) battery pack has:

- 7104 cells
- 16 modules, each with 444 cells

What is a Battery Management System (BMS)?

A BMS can have many different functions:

Monitoring

- **Total and individual cell voltage monitoring**
- **Temperature monitoring**
- **State of Charge (SOC) of the battery**
- State of Health (SOH) of the battery
- State of Power (SOP) of the battery
- Current flow management
- **Cell balancing**
- Chassis isolation monitoring

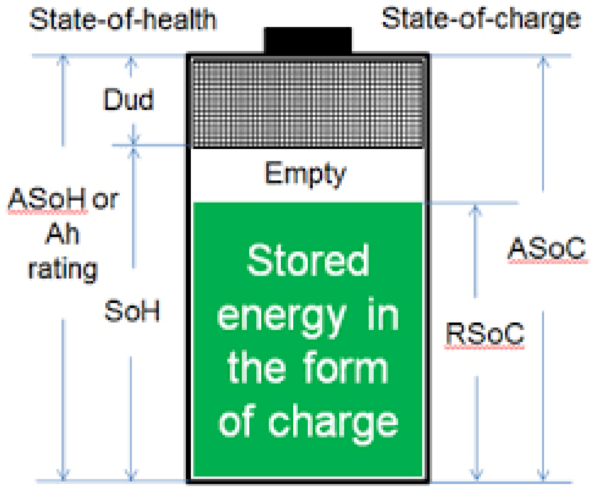
Computing

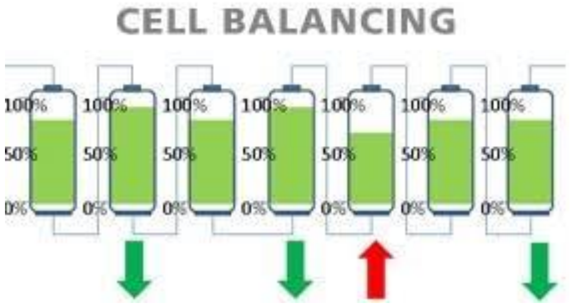
- Charge Current Limit (CCL) & Discharge Current Limit (DCL)
- Energy Delivered in kWh
- Number of cycles

Communication

Optimization

Etc.





What is a Battery Management System (BMS)?

A general control algorithm of a BMS will:

- Measure cell voltages
- Measure and control current discharge and charge
- Calculate State of Charge (SoC)
- Monitor temperatures
- Balance cells actively or passively during charging

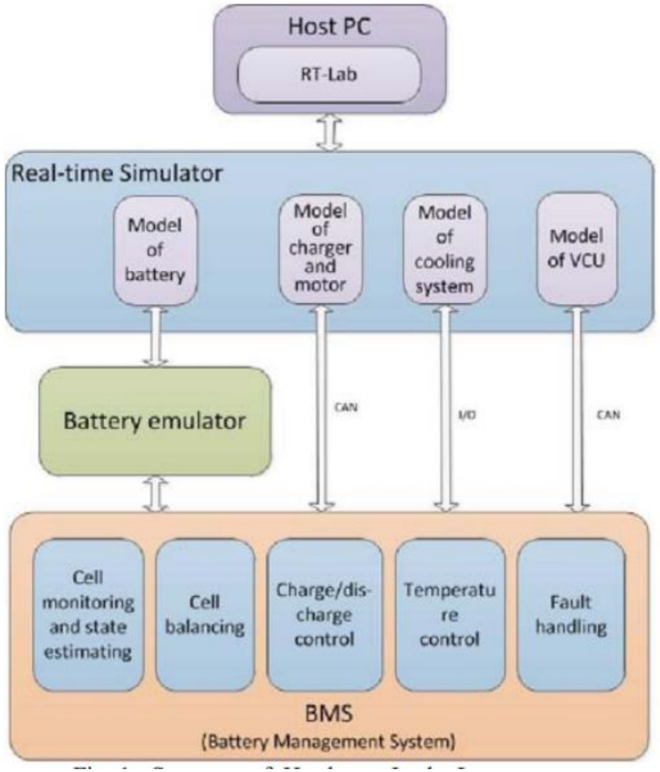
What is a Battery Management System (BMS)?

Typically, an OPAL user will want to test their BMS controller as HIL

In order to test a BMS, a battery (or battery emulator) is needed

Real batteries can be:

- Expensive
- A source of danger
- Limited (temperature, voltage, current, chemistry)
- Not ‘fault testing’ safe
- Required to have necessary chamber(s), chilling, chargers, etc



Industries where BMS is applicable

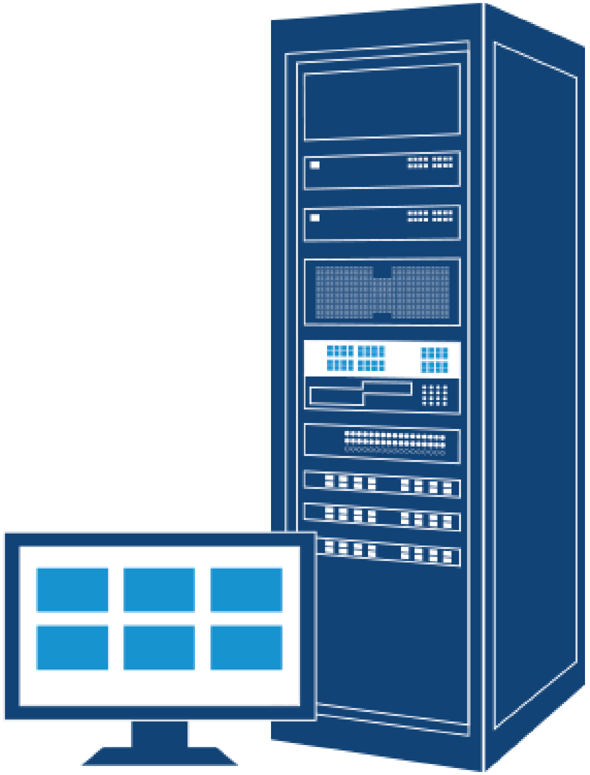
Any industry that uses high power batteries such as:

- Automotive (electric and hybrid vehicles)
- Aerospace (airplanes, satellites, rockets etc.)
- Energy storage (renewable energy, microgrids, building energy backup, etc.)
- Electrification of transport

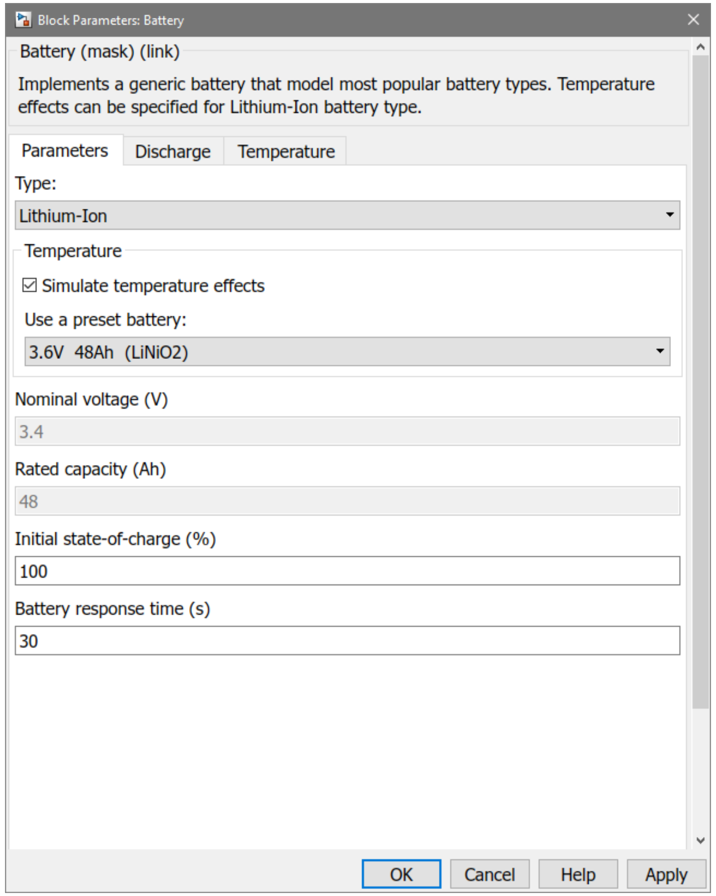
Model-Base Approach to Battery Emulation

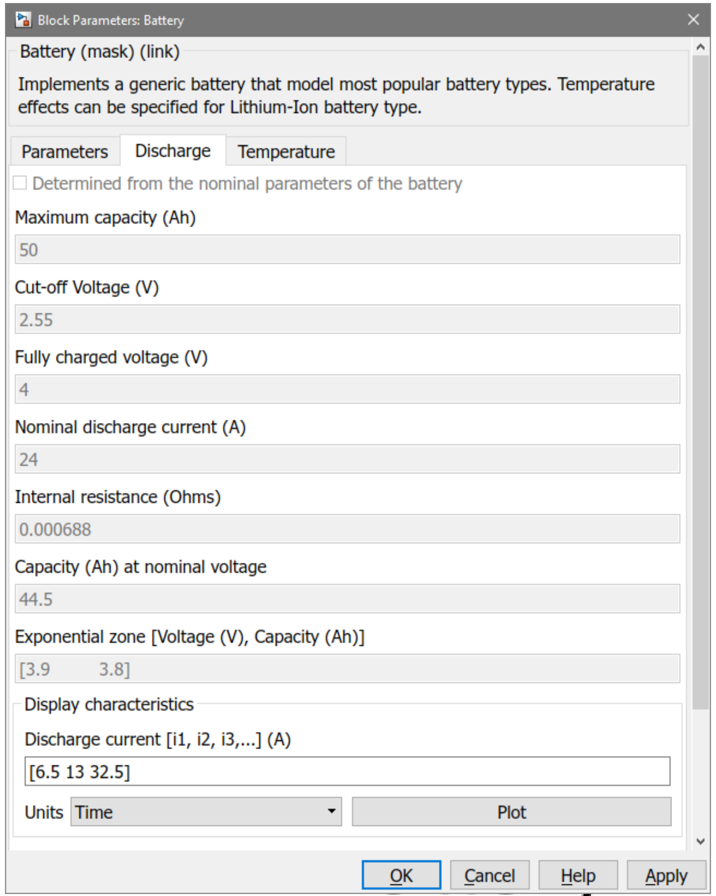
In one term → **OPAL-RT REAL TIME ENVIRONMENT**

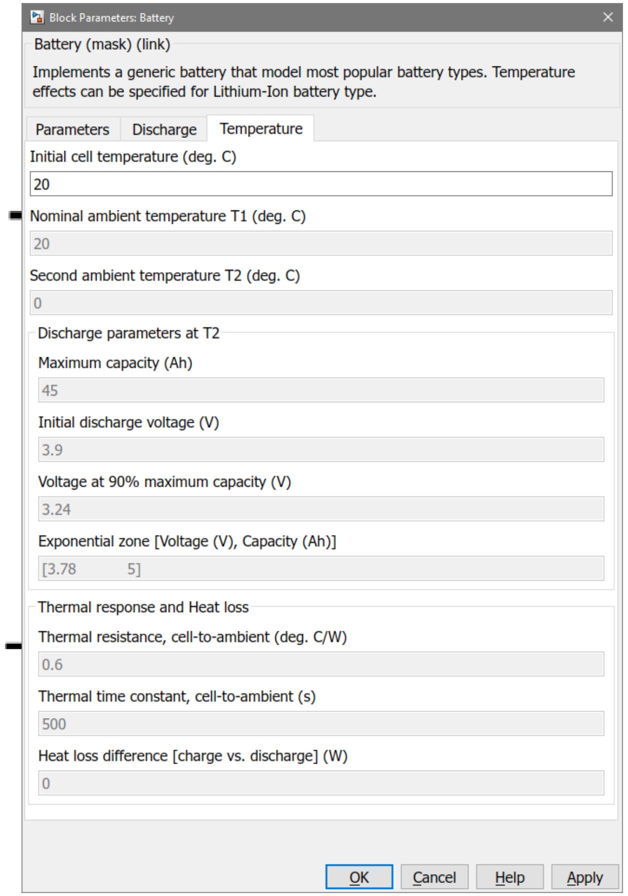
- A fully flexible, real-time BMS testing platform on CPU and FPGA
- Integrated with MATLAB/Simulink (SimScape Power Systems)
- Simulate the complete power line as well as mechanical model with our tools
  - PHIL
  - eHS
  - MOTOR-HIL
  - ARTEMiS
  - Full support of Simulink (control, communication, dynamic models, etc)



Advantages - SPS Battery Model

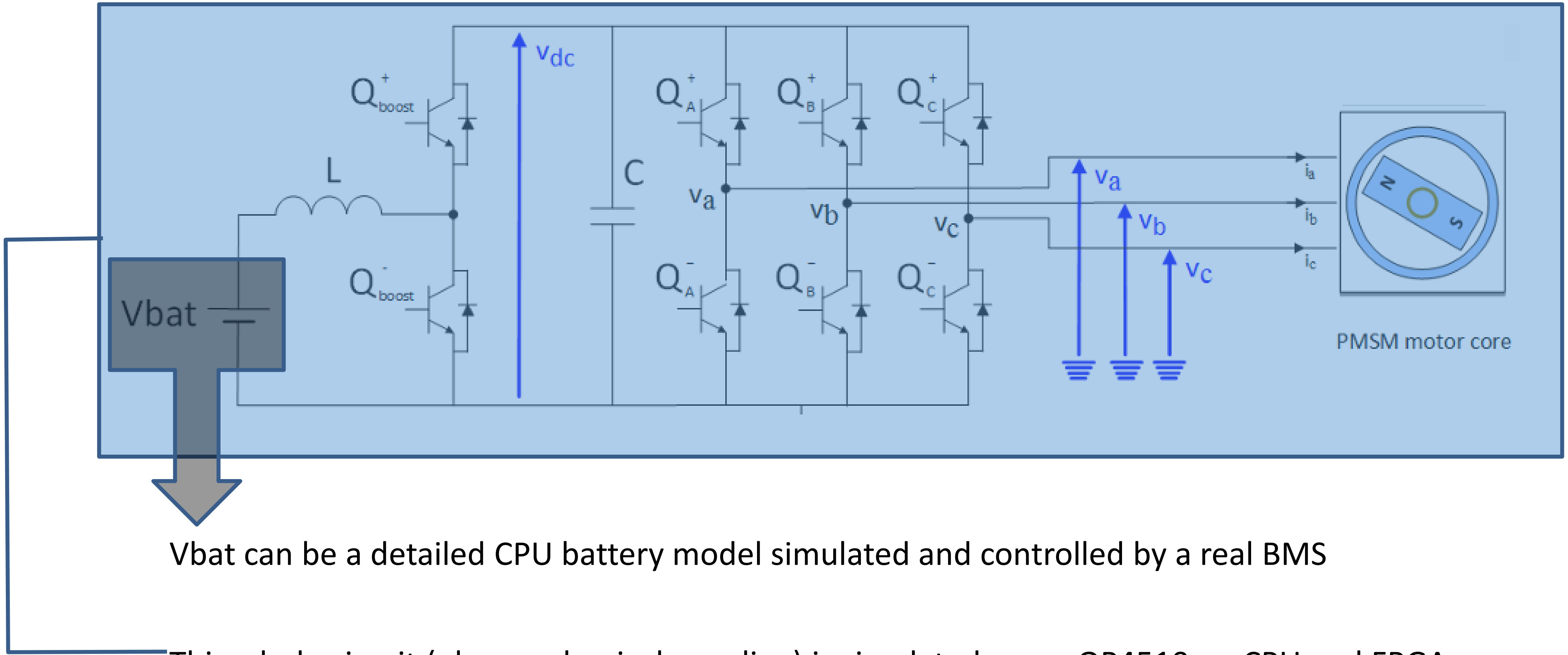






Advantages – eMOTORSIM capability

Coupling the BMS with an electric motor drive with eHS scenarios:



Vbat can be a detailed CPU battery model simulated and controlled by a real BMS

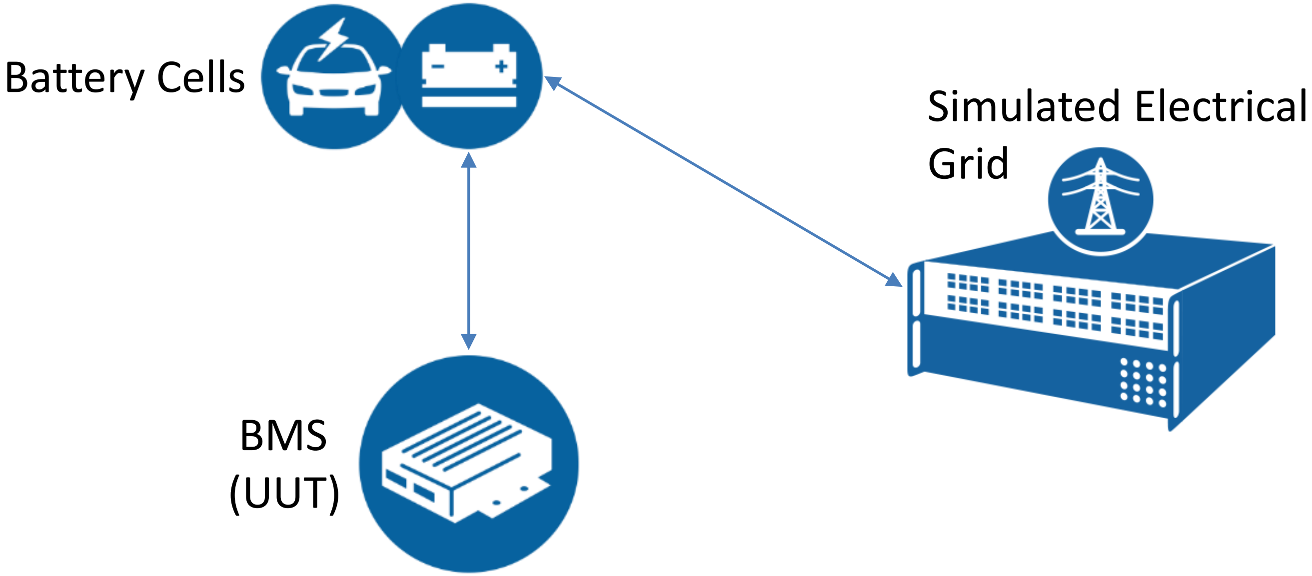
This whole circuit (plus mechanical coupling) is simulated on an OP4510 on CPU and FPGA

BEYOND BMS → VEHICLE-TO-GRID (V2G/G2V)

Study the effects/behaviour of having an EV/battery connected to an electrical grid

- i.e. distribution network, microgrid

OPAL-RT's industry-leading simulation tools are capable of simulating anything from detailed converters to large scale networks



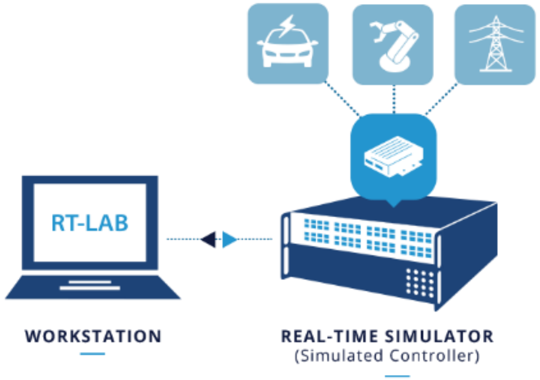
TODAY'S AGENDA

- What is a BMS?
- Industries that might use BMS
- Advantages of testing BMS with OPAL-RT
- BMS application architecture
- Technical specification of a BMS simulator
- Question to ask for BMS application
- Existing OPAL-RT projects and quotes

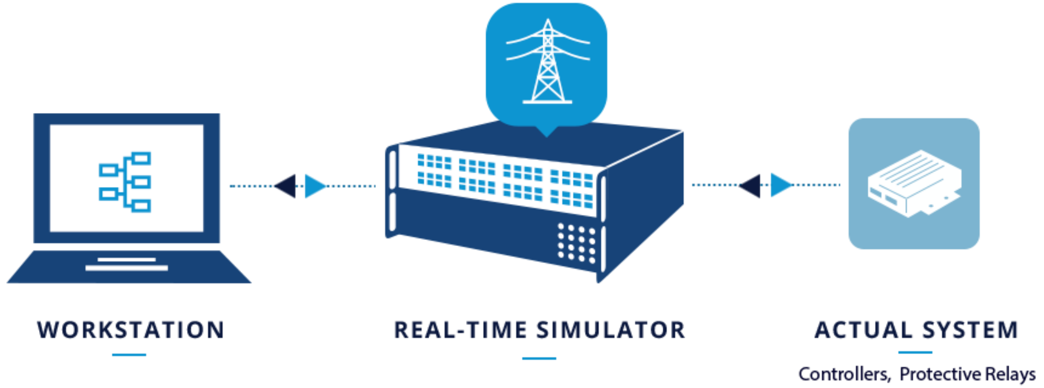
BMS Architecture for OPAL-RT

Testing a BMS can be done in several ways:

- SIL
- RCP
- HIL/PHIL



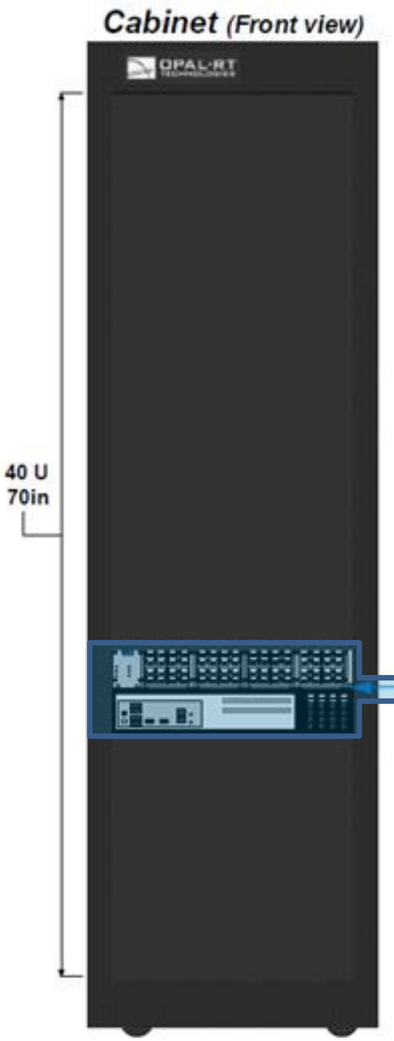
Generally, most BMS testing is done using a HIL/PHIL approach

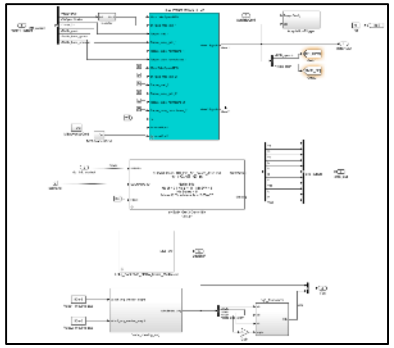


Other types of BMS testing - SIL

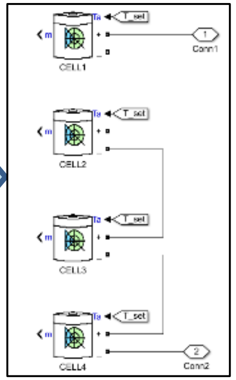
- Possibility to simulate a complete mechanical and/or electrical system
- Simulate controller and plant simultaneously

WORKSTATION

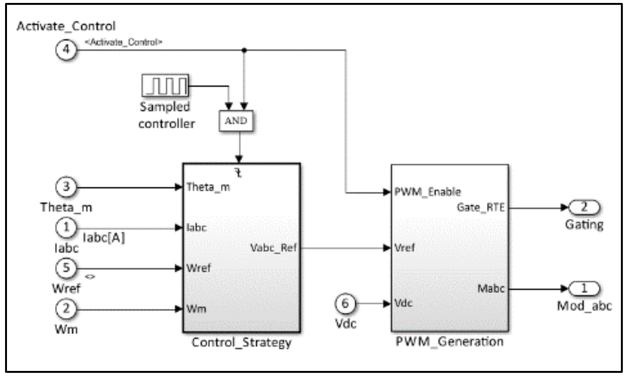




Complete system simulation (full EV power system)

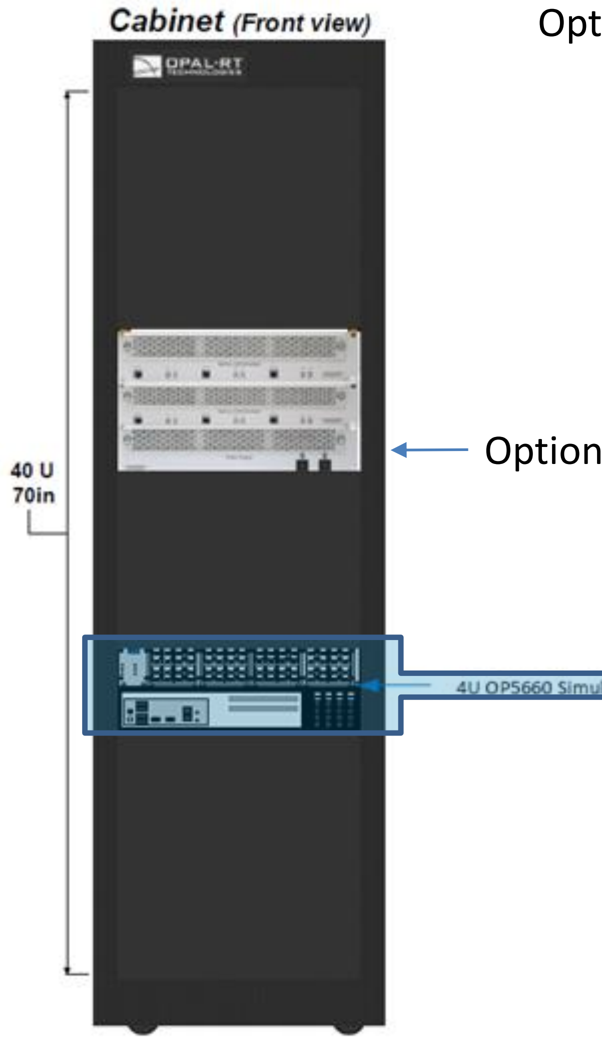


Simulated battery model (various chemistries)

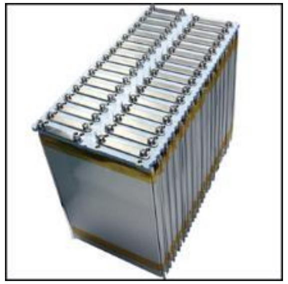


Control(s) for battery, motor, EV, etc

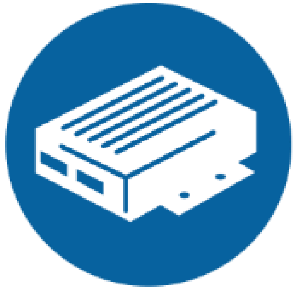
Other types of BMS testing - RCP



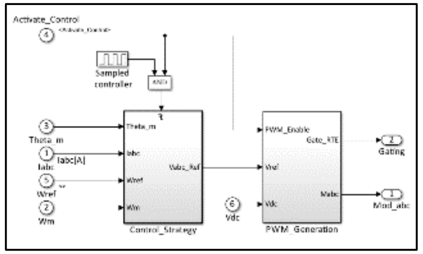
Optional Real Battery Cells



Optional Battery Cell Emulators



Simulated Controller(s)



- Quickly modify control algorithms
- Connect to real battery stack or battery cell emulator

BMS HIL Architecture

1) **Simulation →** OPAL-RT

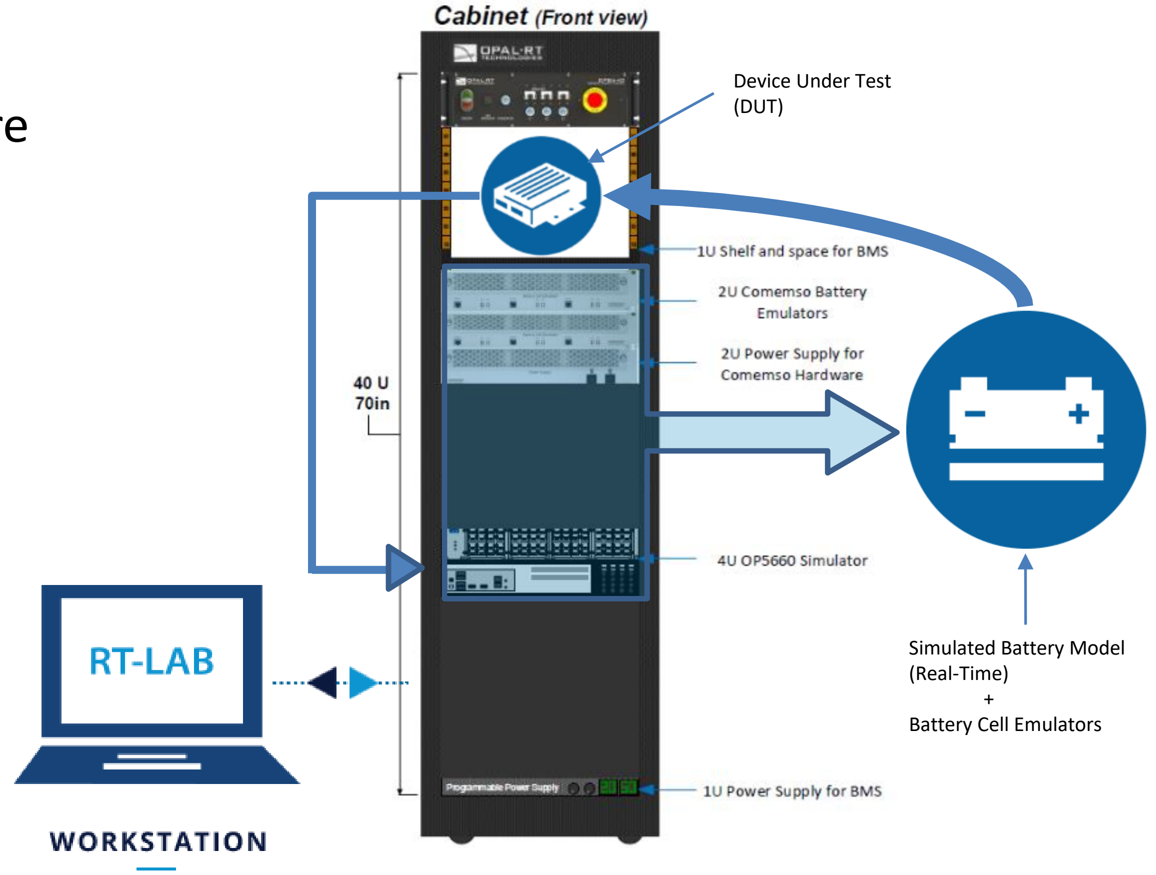
- Battery model simulating on OPAL-RT hardware
- Other electrical or mechanical components
- Control algorithms

2) **Battery Cell Emulation →** Third-Party

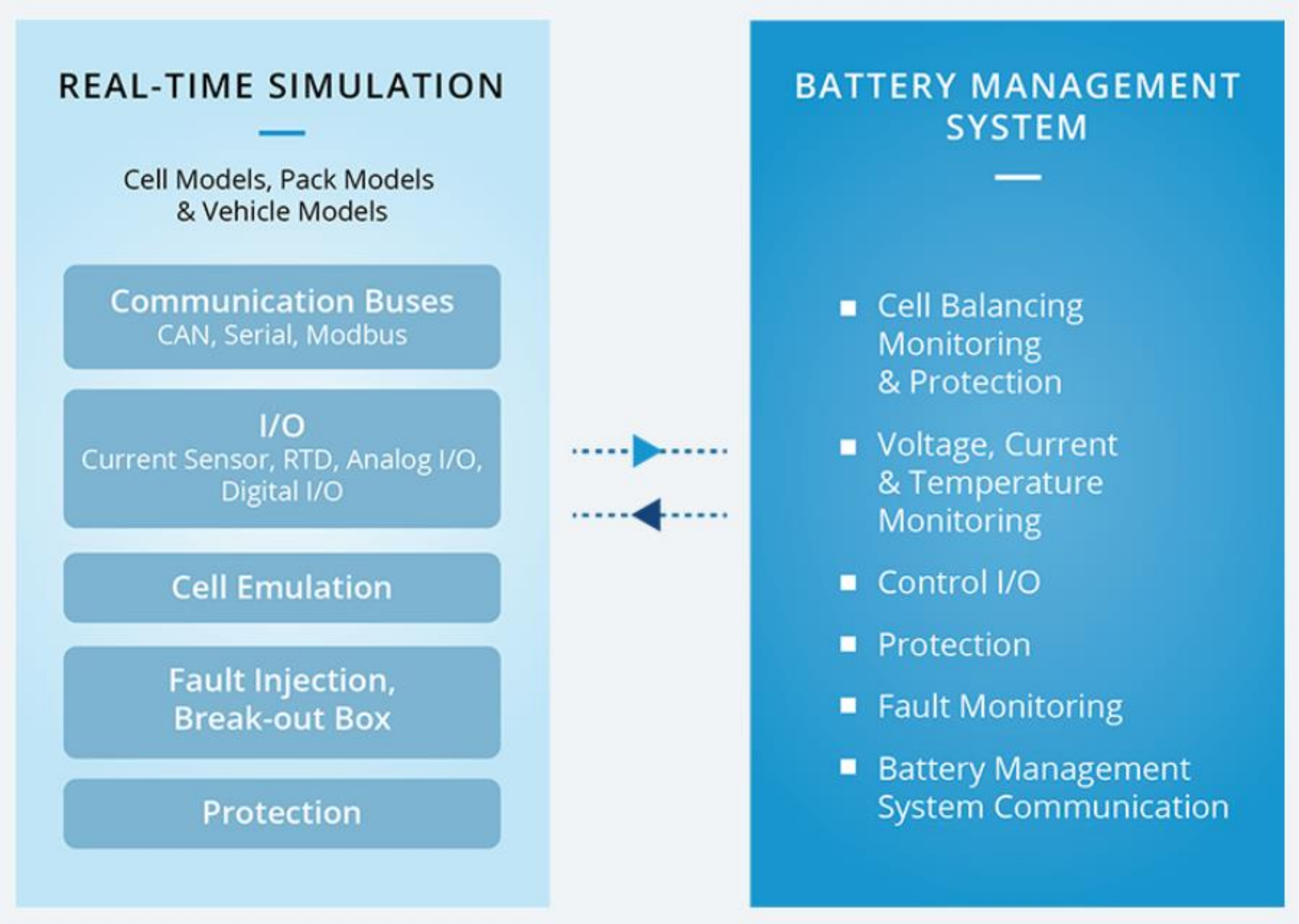
- Voltage
- Current
- Temperature
- Faults
- Isolation

3) **Device Under Test →** Customer

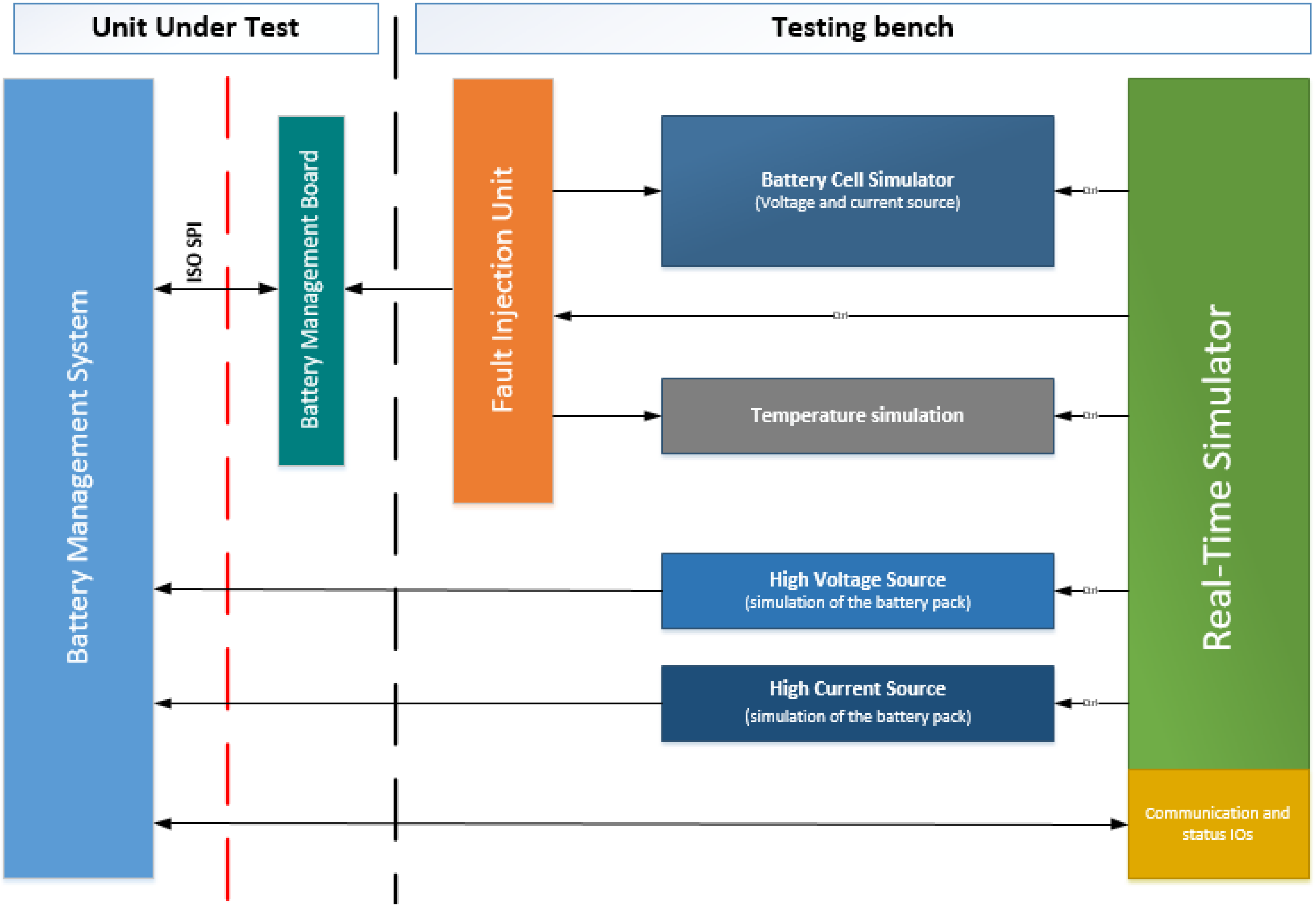
- Can be one device or several (1BMS + n other boards)



BMS Architecture - HIL



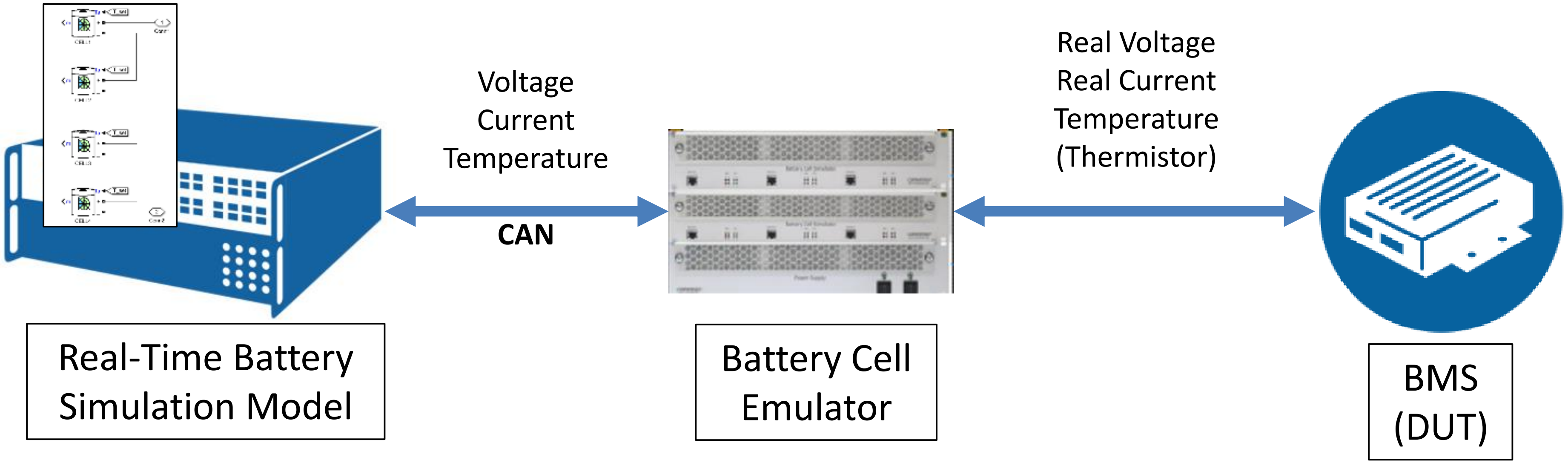
BMS Architecture - HIL



BMS Architecture - HIL

Typically, Battery Cell Emulators are required to test the BMS controller

- The battery emulator can supply voltage and current
- Can connect to a real-load/charger
- Other useful features that an OPAL simulator cannot provide



BMS Architecture – HIL Simulation Types

The two main configurations for BMS:

Complete simulation

- The complete battery is simulated with the battery emulator
  - Each and every cell is physically simulated
- Voltage and current is provided by the battery emulator
- Voltage and current are limited
- Costly

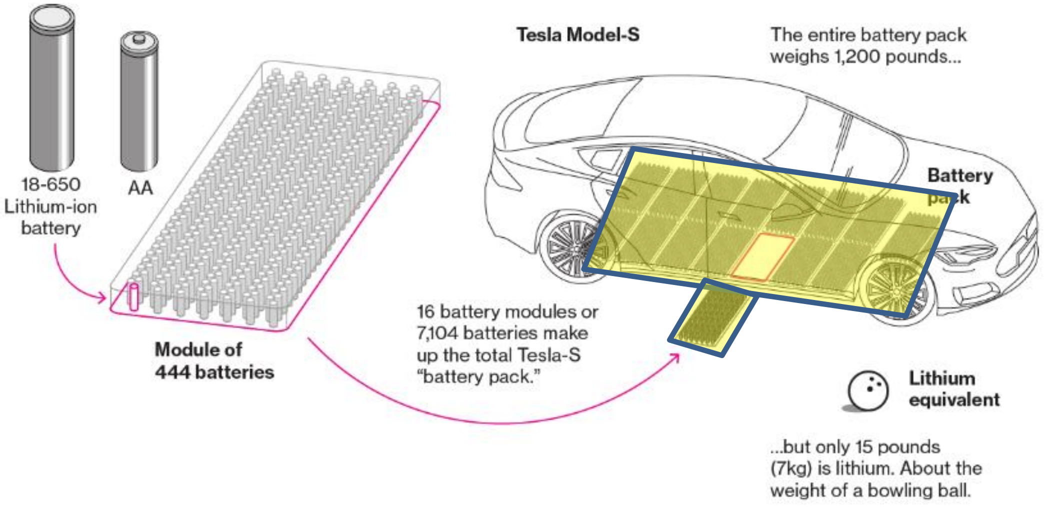
Hybrid simulation (preferred solution)

- Only a partial set of cell are physically simulated (one module, for example)
- The complete battery voltage and current are emulated with a controllable power source
- Full stack voltage and current possible
- Can be much less costly

BMS Architecture – HIL Simulation Types

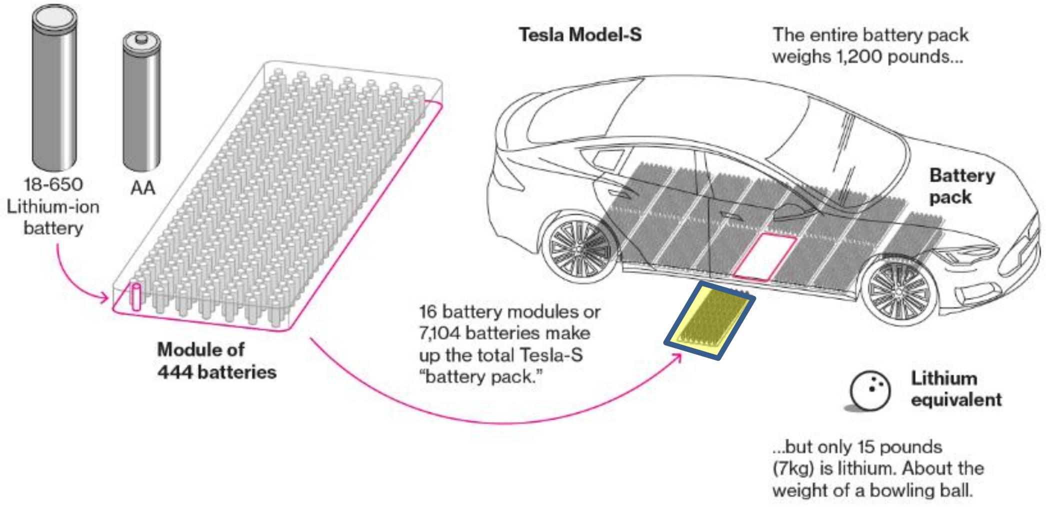
If we look back the Tesla example:

Complete Simulation



All of the battery cells are physically emulated

Hybrid Simulation

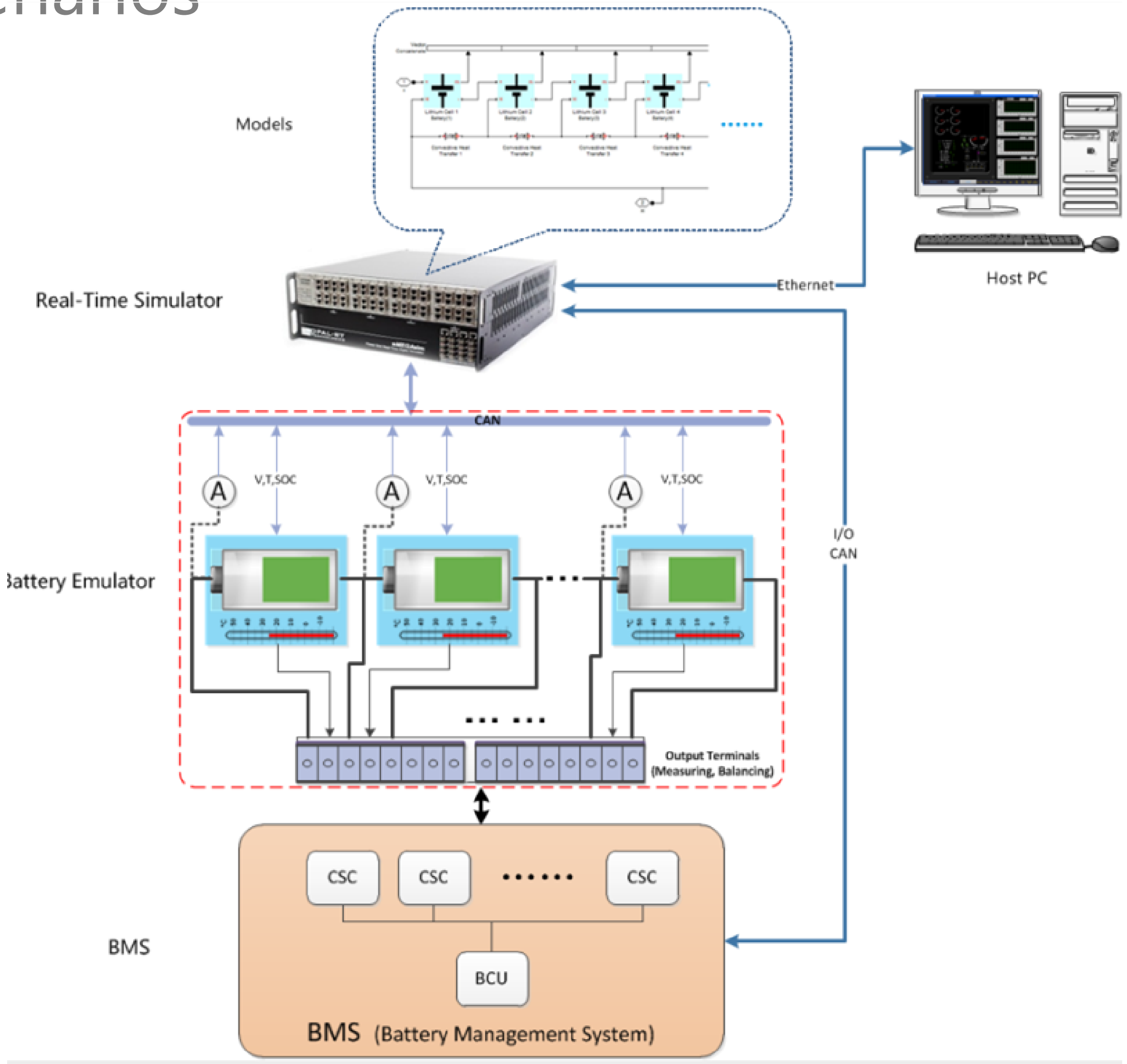


Some of the battery cells are physically emulated

BMS Architecture – HIL Testing Scenarios

Non-exhaustive list of tests required for BMS:

- FIU test
    - Open-Circuit Voltage
    - Shortcut of a cell
    - Polarity change of a cell
- Charge/Discharge (low and high rates possible)
- Single-cell balancing current
- Single-cell over-charge protection
- Single-cell over-discharge protection
- Over-temperature in charge protection
- Over-temperature in discharge protection
- Battery chassis isolation
- Activation delay measurement protection
- Release test protection
- CAN communication



BMS Requirements and Features

- Cell Simulation ✓
- Thermistor ✓
- CAN/SPI ✓
- Fault Injection ✓
- Unit testing ✓
- Real-Time ✓
- Safety ✓
- Isolation testing ✓
- Reliability ✓
- Full-Stack Rating ✓

BMS Architecture – HIL Features & Add-Ons

Battery Stack Emulation

High voltage

- Up to 1000VDC
- Max current : 60ma

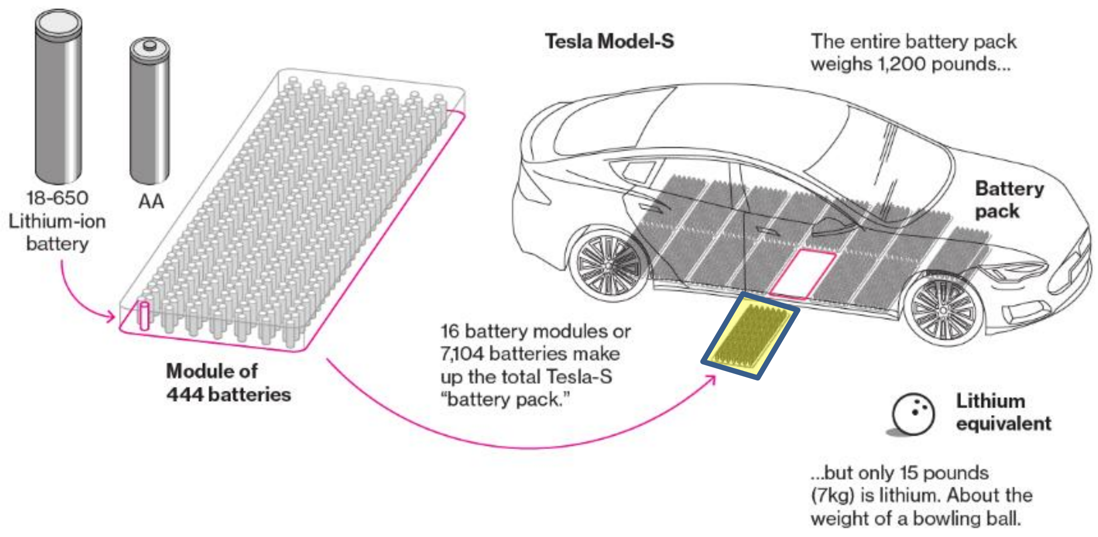
High Current

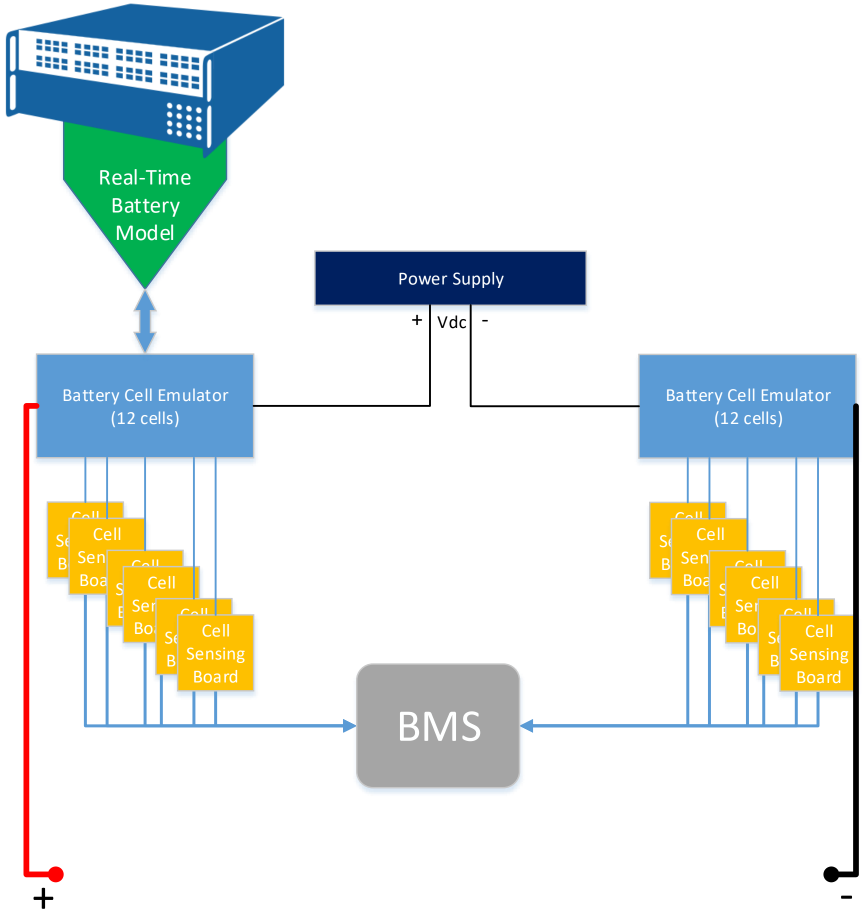
- Up to 250A
- Max voltage 5V

Used in Hybrid simulation where some cells will be simulated and the rest of the voltage/current will be provided by a power supply

BMS Architecture – HIL Features & Add-Ons

Example: Hybrid Simulation with power supplies in the loop



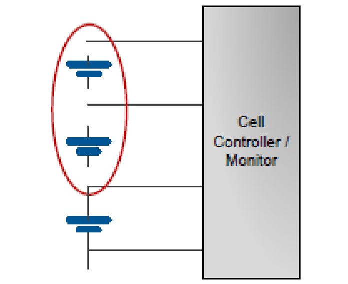
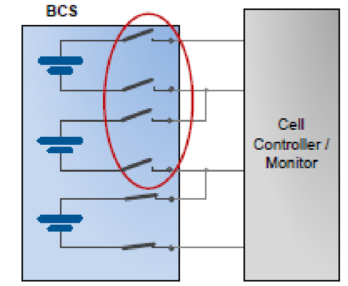
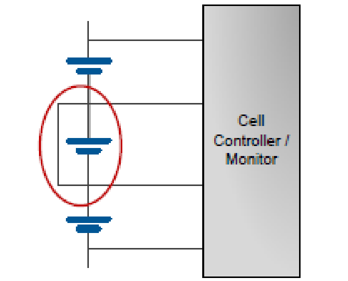
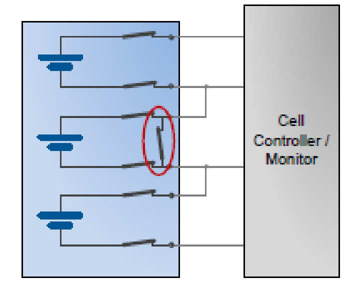
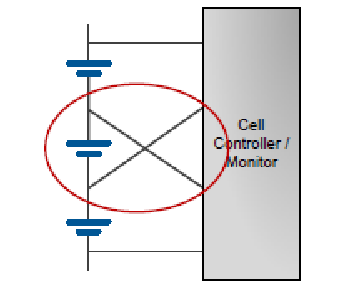
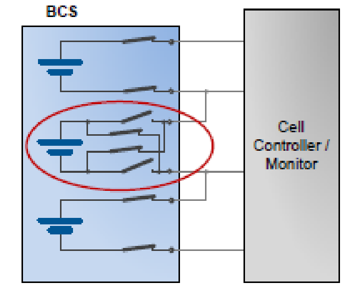


BMS Architecture – HIL Features & Add-Ons

Fault Injection Unit

Can be included in the battery cell emulator or as an add-on

This is a huge plus since performing these types of faults on real batteries can be destructive and dangerous

No.	Test Case fault Insertion	Sketch	Realization
1	Connecting of different cells to the BMS **Cause:** e.g. a sequenced connecting of the cells to the BMS by the ECU connector		
2	Shortcut of one cell **Cause:** Defect of cell or failure on cell controler, ...		
3	Polarity change of a cell **Cause:** Mistake in cabling, ...		

BMS Architecture – HIL Features & Add-Ons

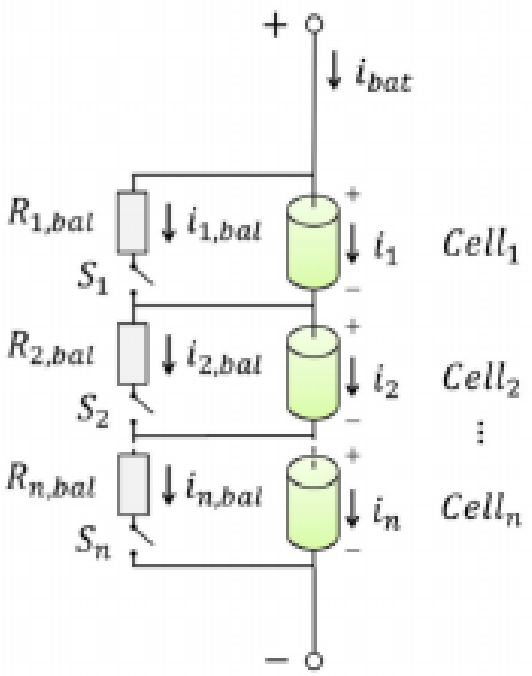
Cell Balancing (during charging)

Cell balancing is an algorithm that a BMS will run to ensure all cell voltages and SOCs are equal

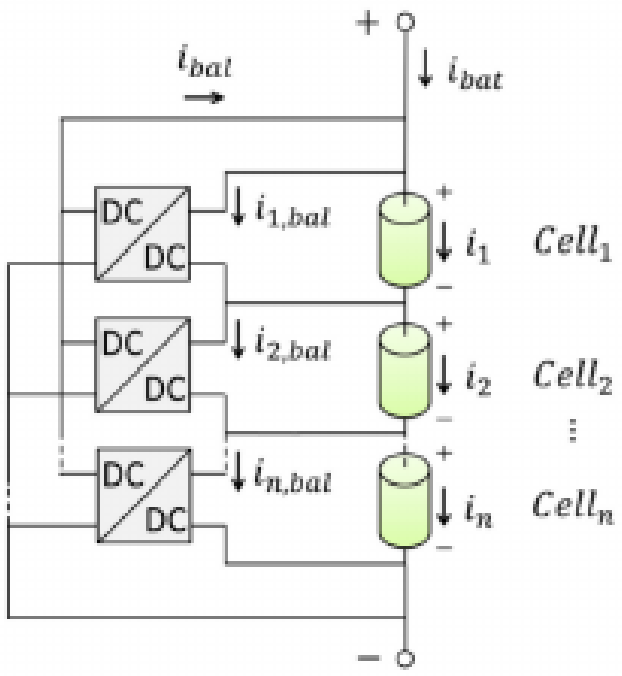
If one cell has less charge than another, the battery will only be used by the lowest amount of charge → think "weakest link"

During balancing, real current is pulled from the emulator which is one of the reasons why a standard OPAL IO cannot interface directly with a BMS under test

Passive



Active



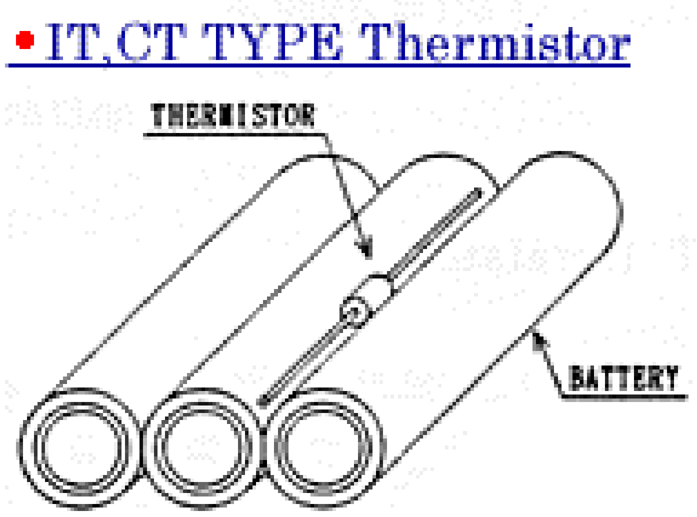
BMS Architecture – HIL Features & Add-Ons

Temperature Emulation (Thermistors)

Users testing a BMS will also be interested in the temperatures of each cell or module

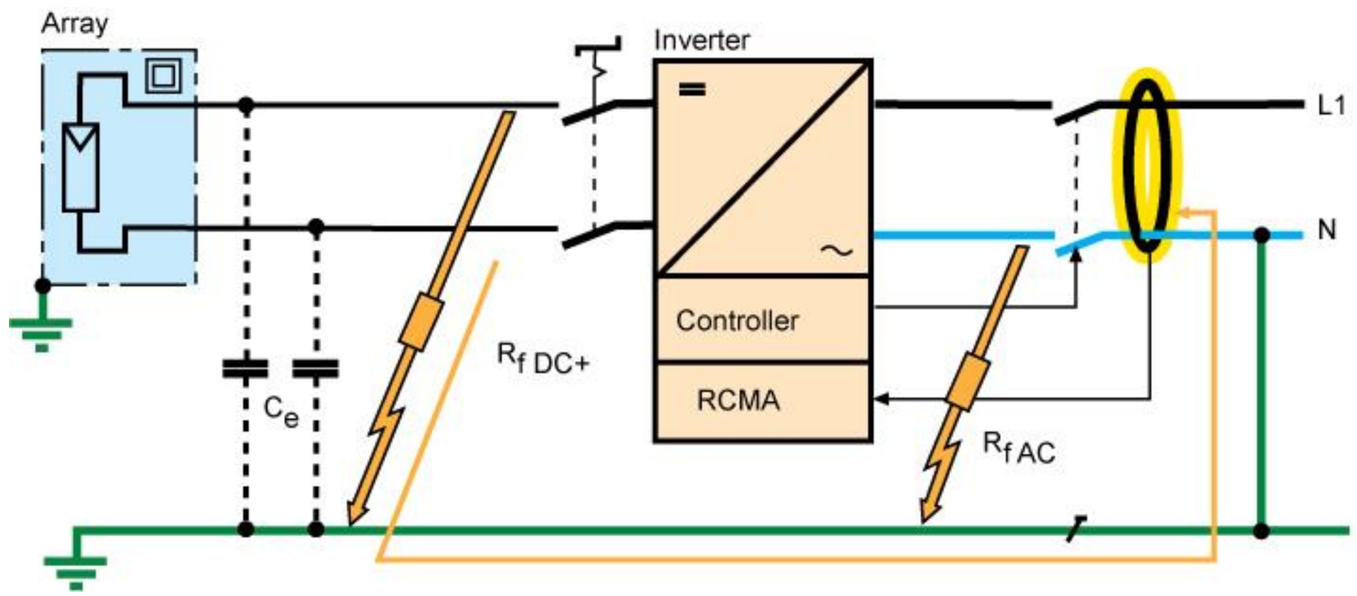
During faster charging and discharging cycles, batteries can heat up past their operating temperature

The use of thermistors can feed the BMS with emulated temperatures to validate the T control



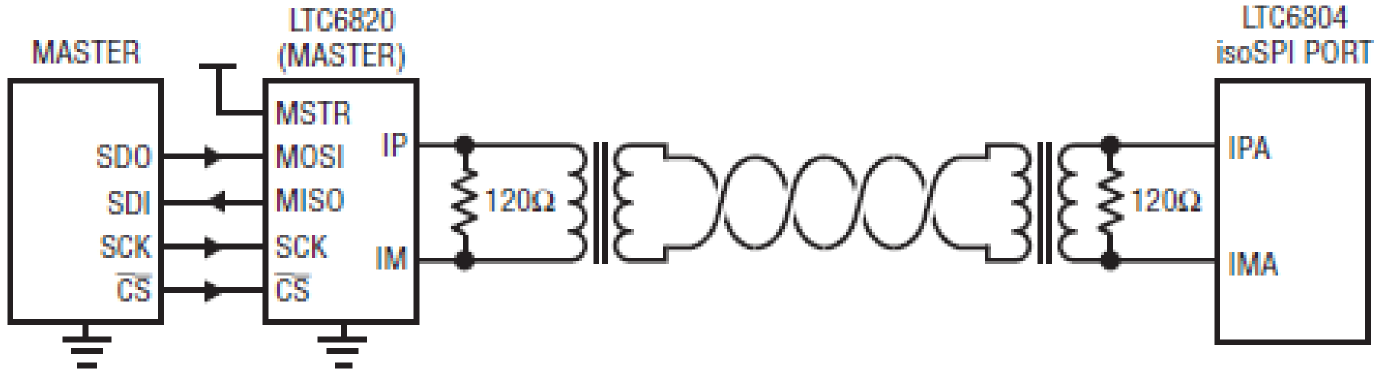
BMS Architecture – Battery Isolation Testing

When dealing with high voltages from the battery stack, users are typically also need to validate that the battery can stay isolated from other components (like the chassis, for example)



BMS Architecture – Communication

- ISO SPI : Dedicated communication between BMBs and BMS
- CAN: Dedicated communication between BMS and other supervisory control



BMS Specifications

Battery Cell Emulation Specifications Example

Battery Emulator (Based on Comemso)

Parameter	Piggy 7
Output voltage range:	0.01V ... 8V
Resolution:	125 µV
Voltage accuracy at up to 2A load: Temperature dependent variation: Ripple (AC noise): Short-circuit proof Max. input voltage at the cell output (for active balancing):	+/- 0.5mV +/- 1mV +/- 3mV at fg = 5kHz. Condition: 100mA int. Load and BCS-RippleFilterBox and 100nF at cable end (→ for filtering dipole / antenna behavior of open cable) Yes max. 20V for a short time
Step response Single Mode: 1V to 4V:	ca. 0.2ms
4V to 1V:	ca. 1-10ms (depending on load)
max. external load:	4.9 A
Accuracy of current measurement µA-Sensor: mA-Sensor:	+/- 10µA in range 0..10mA +/- 2mA in range +/-3A, +/- 3mA in range +/-5A

Battery Cell Emulation Specifications Example

Battery Emulator (Based on Comemso)

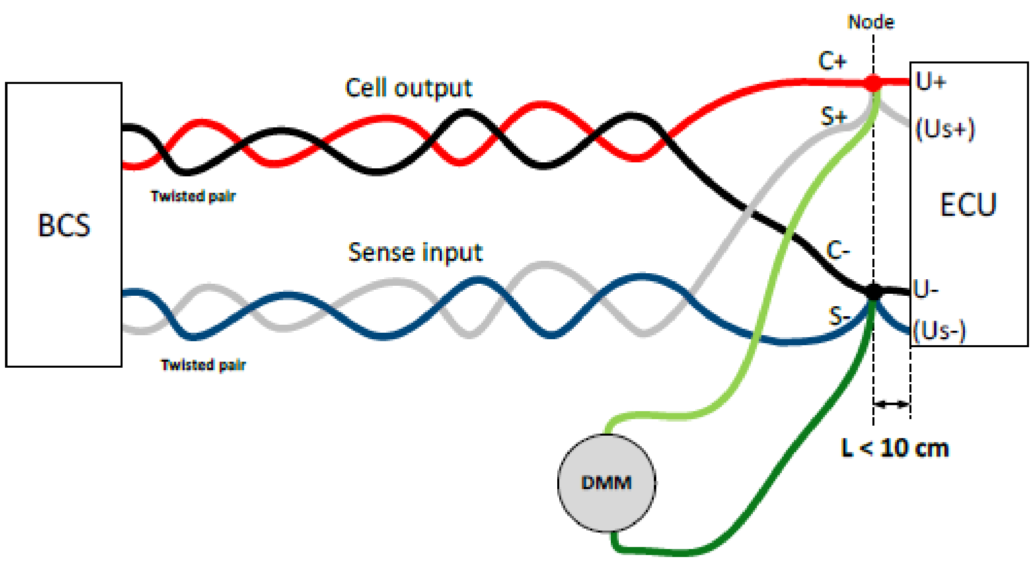


Figure 4-1: Cabling for high voltage precision

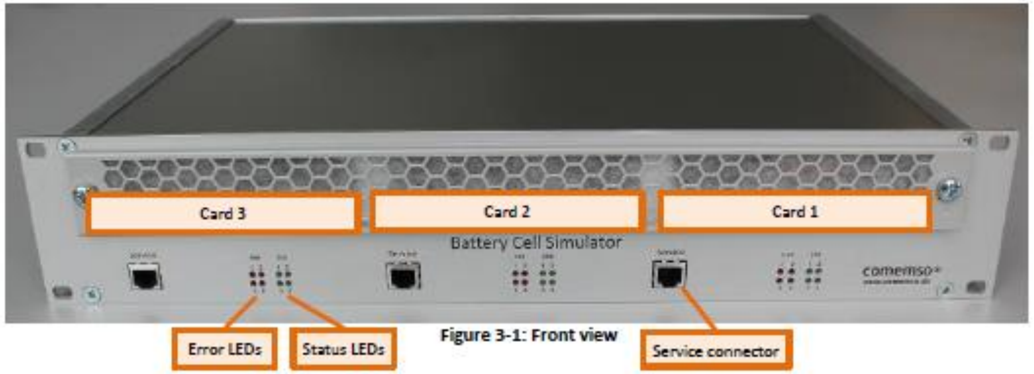
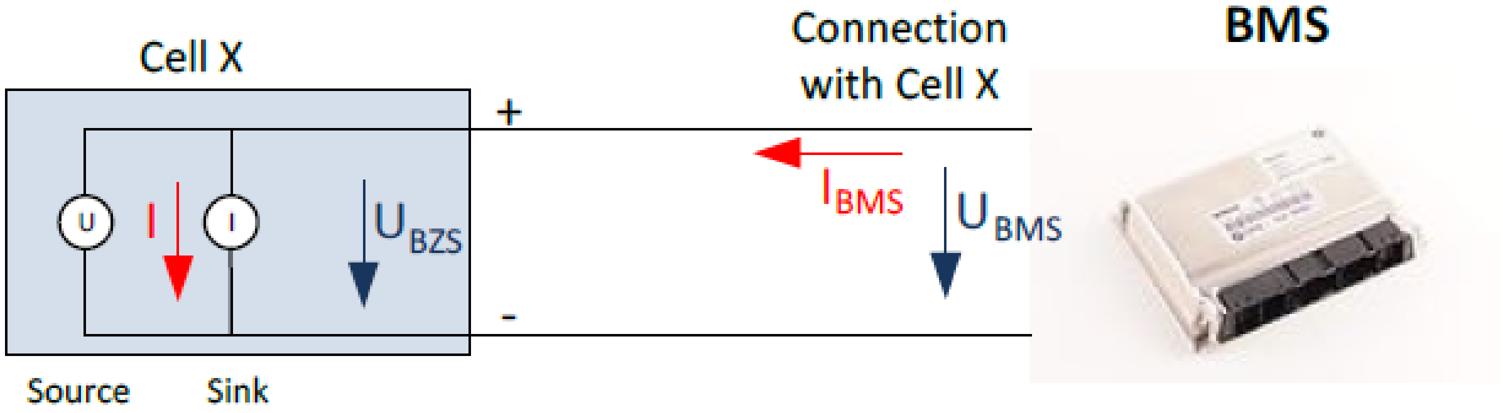


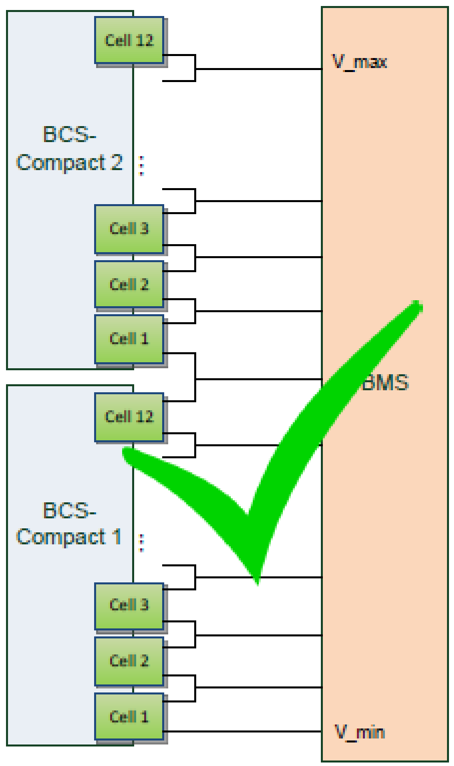
Figure 3-1: Front view

Figure 3-2: Rear view

Battery Cell Emulation Specifications Example

Battery Cell Simulator



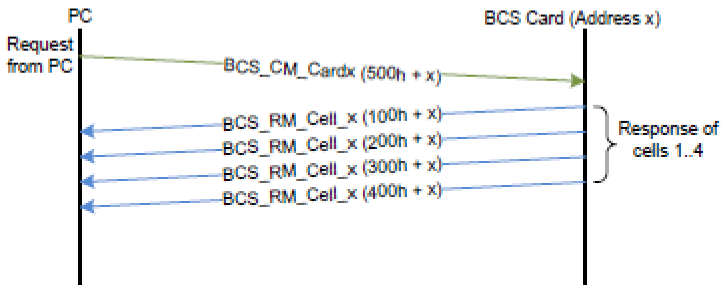


Battery Cell Emulation Specifications Example

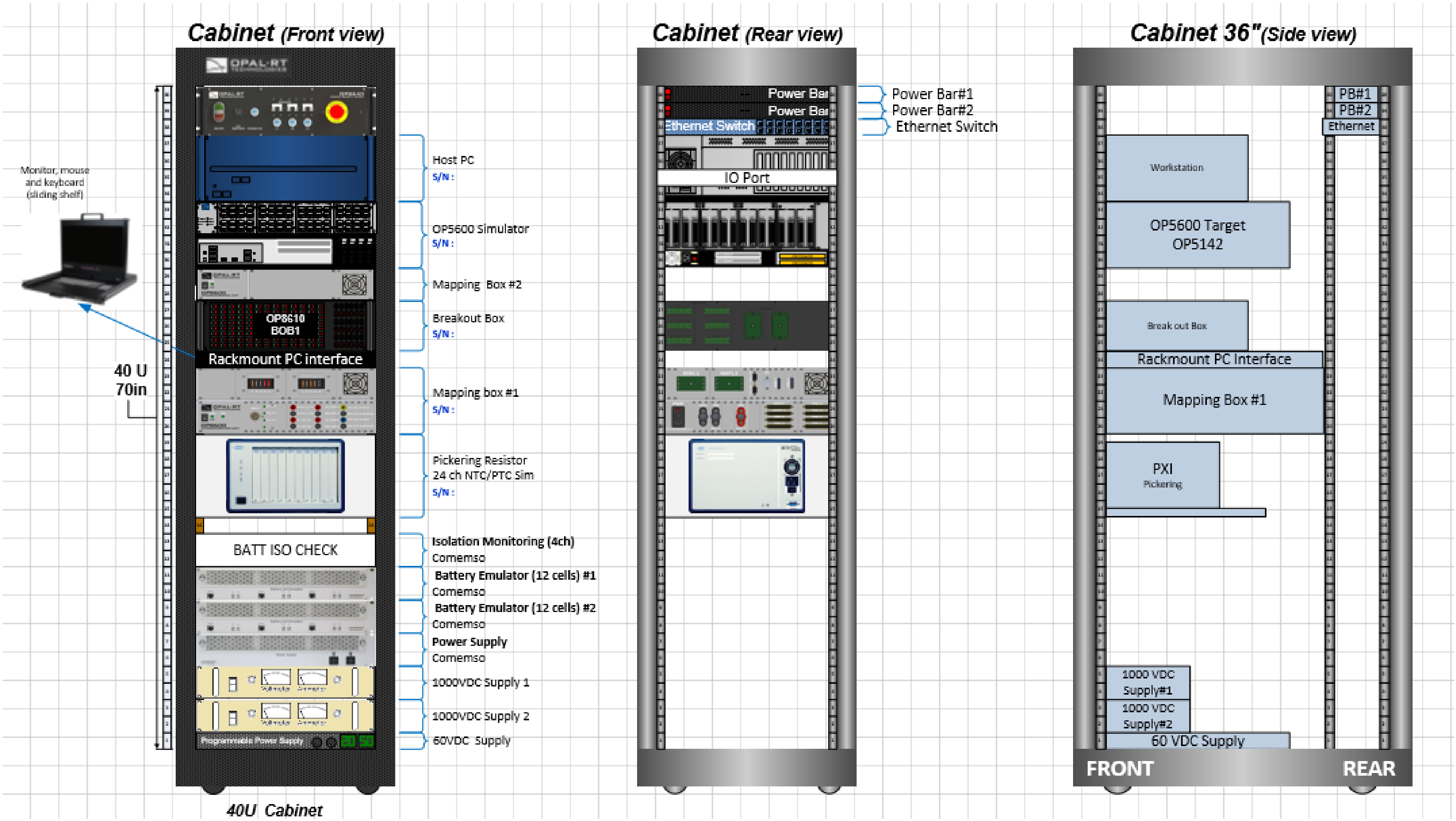
Battery Emulator (Based on Comemso)

CAN Communication

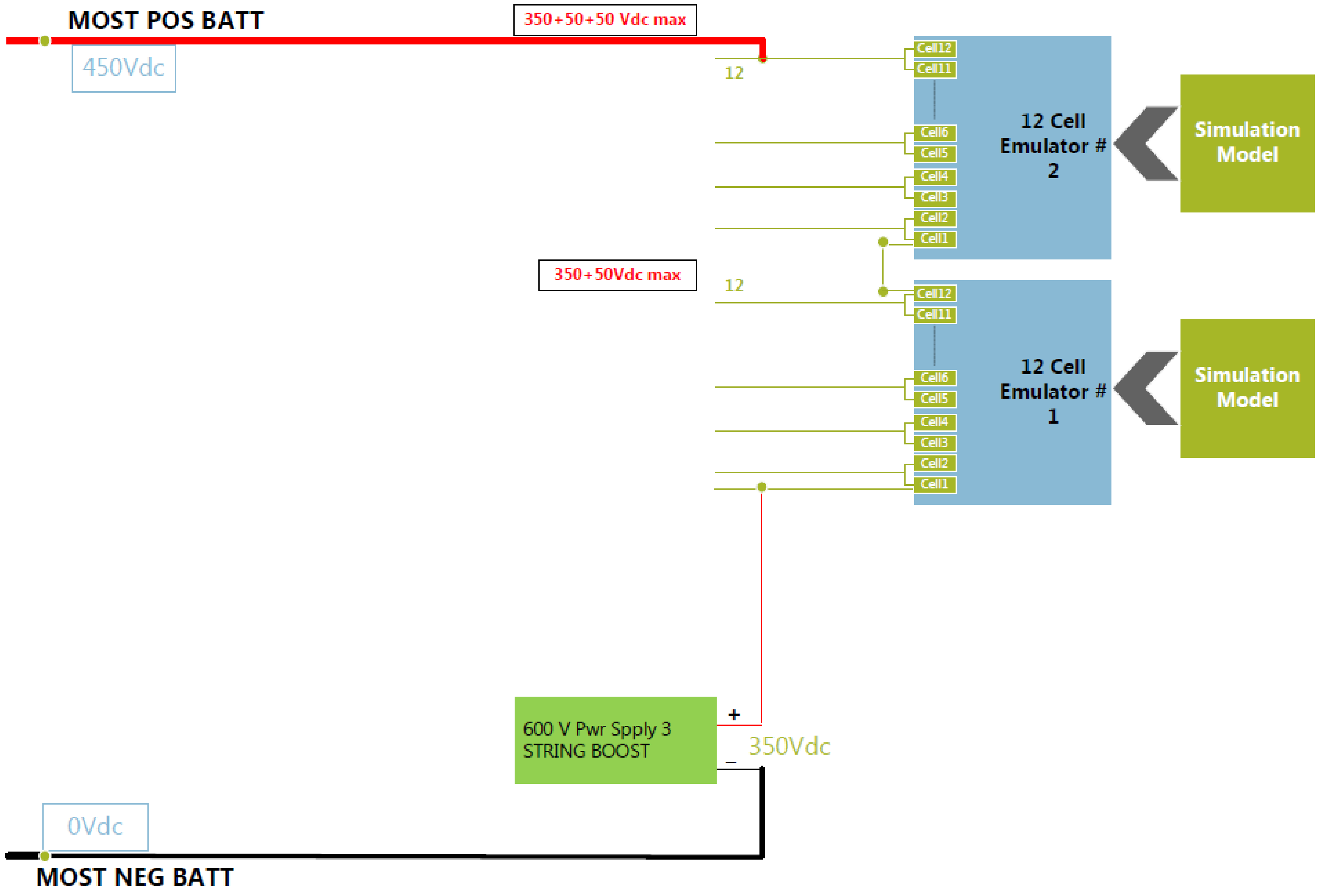
Message: RESPONSE		Direction: BCS→ PC
Signal	Value range	Meaning
VMeasure	0 – 8191.75mV	Measured cell voltage
CurrentType	00 = µA sensor 01 = mA sensor 10 = Coulomb sensor (old value) 11 = Coulomb sensor (new value)	Displays the value range of current value. The Coulomb value is separated in „old value" and „new value".
CurrentMeasure_mA	+/- 6500mA	Result of the mA sensor
CurrentMeasure_Coul	+/-0.838 C	Result of the Coulomb sensor
CurrentMeasure_uA	+/-32768 µA	Result of the µA sensor
ErrorFuse	0/1	Not used anymore
ErrorLoadReduction	0/1	Internal load reduced (due to overload/overtemperature)
ErrorSense	0/1	Sense error detected
TemperatureSensor	0/1	0.. Temperature sensor of Piggy



USER EXAMPLE: HYBRID APPROACH



USER EXAMPLE



THANK YOU!!!
HAVE A GREAT WEEKEND