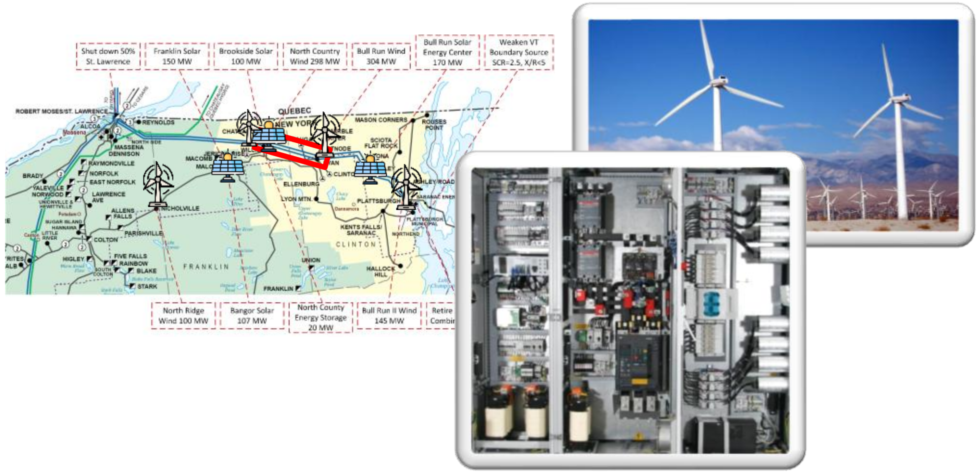
Importance of In-The-Loop Testing for Model Validation

ESIG
ENERGY SYSTEMS INTEGRATION GROUP

2025 Fall Technical Workshop
Session 6B

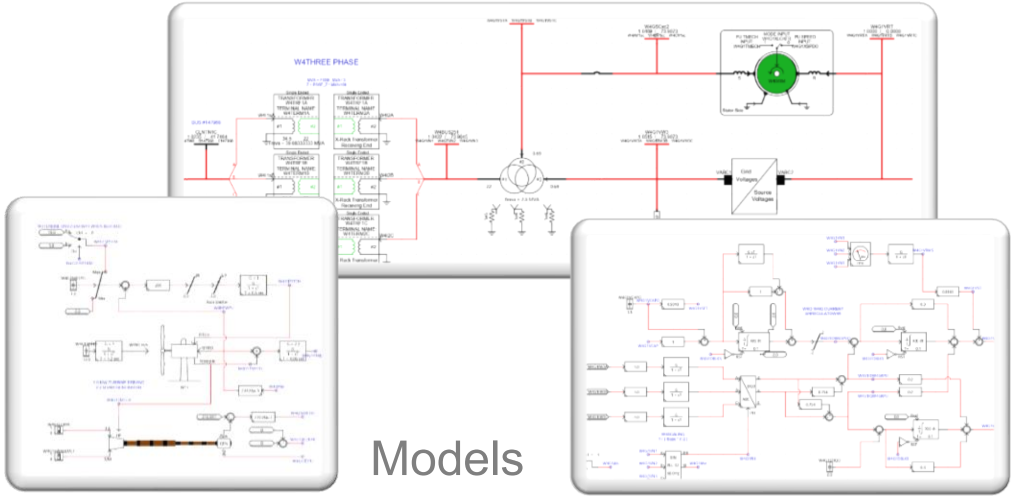
October 29, 2025

Why Do We Model and Study Power Systems?

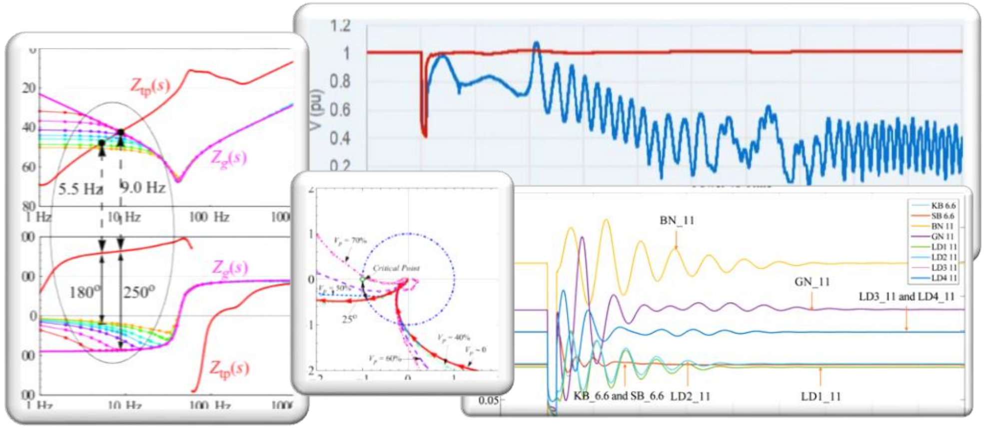


Systems

Experimentation to understand how systems behave



Models



Simulation to avoid experimentation

Why Modeling Helps & Where it Falls Short?

Why We Use Models

- ✅ Safe and controlled environment for testing
- ✅ Allows testing scenarios that are impractical or unsafe in the field
- ✅ Facilitates rapid iteration and comparison of different system designs
- ✅ Cost-effective and fast to run
- ✅ Enables early-stage concept and design studies
- ✅ Easy to repeat and scale for multiple cases

Modeling Limitations

Simplifications & Assumptions

⚠ Models are **simplified** compared to real hardware with many functionality limitations.

⚠ Require **assumptions** that reduce physical realism

⚠ May fail to reproduce true **nonlinear** or **dynamic** responses

⚠ Lack real-time behavior – analog, digital or communication-based

Validation & Data Scarcity

⚠ Model **quality** depends on accurate field data (often limited)

⚠ Scarcity of **validated**, high-fidelity models across technologies

⚠ Difficult to validate models without extensive **measurement data**

Longevity & Maintenance

⚠ Models become **outdated** as **firmware** or **controls** change

⚠ Maintaining **version alignment** between hardware and model is difficult

⚠ **Limited flexibility** when OEMs update or replace components

Cross-Platform Compatibility

⚠ Different OEM tools and formats reduce **interoperability**

⚠ Aggregating multi-vendor models is challenging in large projects

⚠ Model runs on a CPU with perfect determinism—not on actual hardware with limited cycle, interrupts, and execution jitter

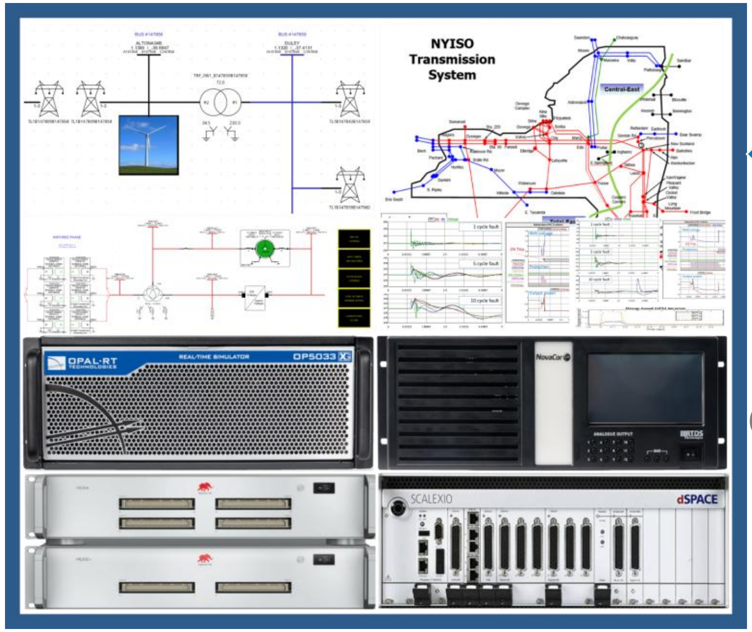
Practical Use Boundaries

⚠ Best suited for **early-stage studies** and **planning**

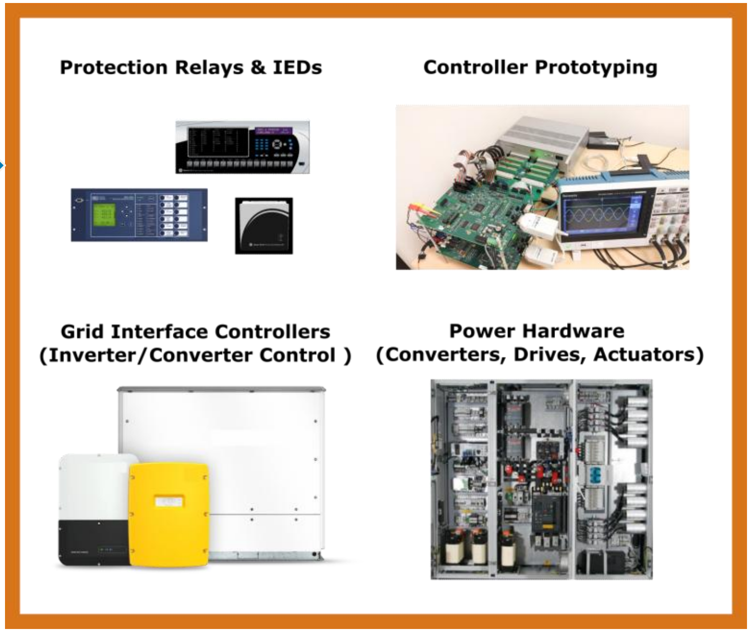
⚠ Less reliable for **final validation** or **commissioning** without hardware testing

Hardware-in-the-Loop: Bridging the Gap Between Models and Reality

Real-Time Simulator (RTS)



Device under Test (DUT)



Hardware-in-the-Loop
=
Closed real-time feedback

⚠ Simplifications & Assumptions	⚠ Validation & Data Scarcity	⚠ Longevity & Maintenance	⚠ Cross-Platform Compatibility	⚠ Practical Use Boundaries
✅ Real hardware replaces approximations; tests real nonlinear and dynamic behavior.	✅ Provides measured data and direct comparison with simulation for validation.	✅ Uses the actual firmware and control hardware; always current with OEM updates.	✅ Interfaces real devices from vendors; tests interoperability physically.	✅ Enables safe, repeatable tests of late-stage systems before field commissioning.

Panelists

Aditya Ashok
Director Energy Systems Research
OPAL-RT Technologies

Leveraging Hardware-in-the-Loop (HIL) Testing to Improve Model Fidelity and Accuracy

Bryan Buterbaugh
Application Engineer
Hitachi Energy

Software-in-the-Loop simulation – a must for today's MMC grid forming converters

Lukas Unruh
Engineering Manager
Electranix

Addressing Challenging System Stability and Model Validation while Retaining OEM Confidentiality

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Hardware-in-the-Loop (HIL) Testing:
Advancing Power System Innovation and Reliability

Reza Pourramezan

Advanced Grid Innovation Laboratory for Energy

A Digital Service of the New York Power Authority

Main Requirements for HIL Setup

Real-Time Synchronization

Determinism & Timing Alignment

- Simulator must operate in **real time** (every **time step** executes/outputs within its clock period).
- Maintain tight **synchronization** between the RTS and DUT (Definition of “**real-time simulation**”).
- Synchronize **clocks** using IRIG-B, PPS, or IEEE 1588 PTP.
- Ensure **deterministic latency** in feedback loops (especially in PHIL).
- **Example**: Time-aligned voltage waveform sent from RTS matches DUT’s response in microseconds.

Accurate Model & Computational Fidelity

Simulation Core & Stability

- Simulator must have a validated, **numerically stable** model of the system.
- Include all relevant **nonlinearities** and **switching behavior**.
- Use appropriate **time-step resolution** and **solver type** (fixed-step).
- Confirm **closed-loop stability** when connecting to real hardware.
- **Example**: EMT model validated against field measurements or other offline simulation tools.

Proper Interface

Hardware & Signal Connectivity

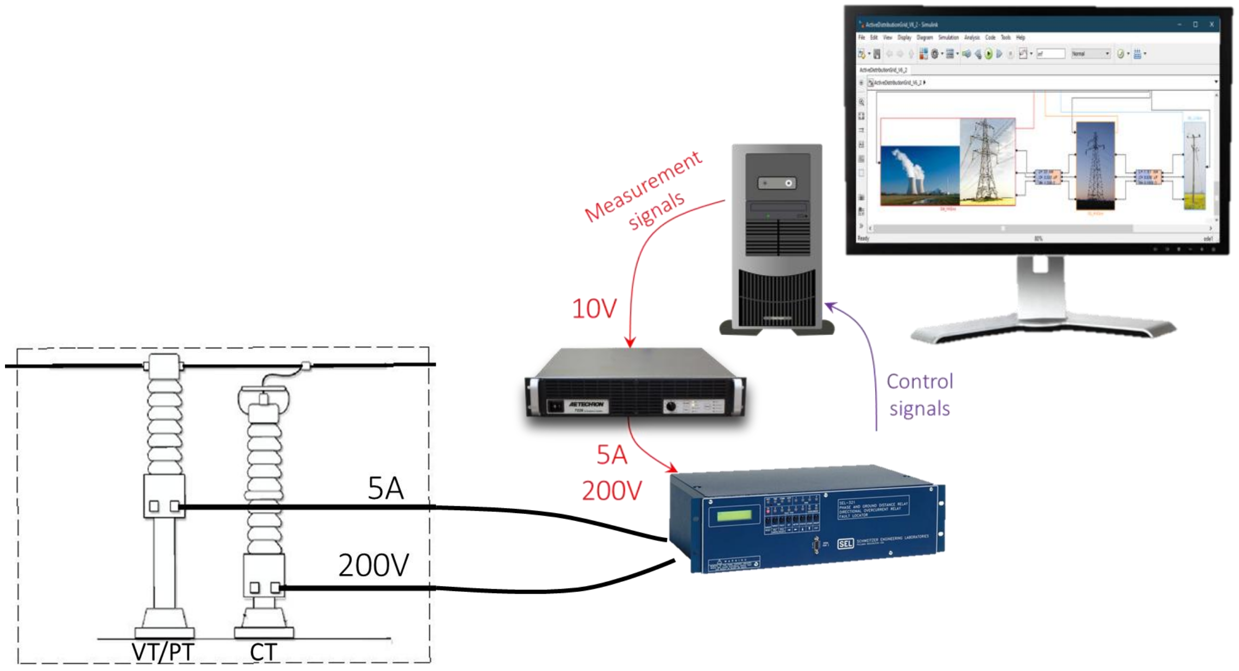
- **Reliable** and noise-immune electrical or optical **connection** between RTS and DUT.
- Includes correct **signal type mapping**: analog, digital, communication, or power.
- Ensure proper **signal scaling**, grounding, and isolation.
- Use compatible **I/O boards**, **amplifiers**, and **transceivers**.
- **Example**: Analog ±10 V control signals, 24 V digital I/O, IEC 61850 GOOSE, Aurora fiber link.

Real-Time Simulation— Concept

- **Real-time** simulation runs at the **same pace** as the **real world**!
- Without it, proper **communication** between simulation and a **hardware** is not possible!

Types of HIL Interfaces

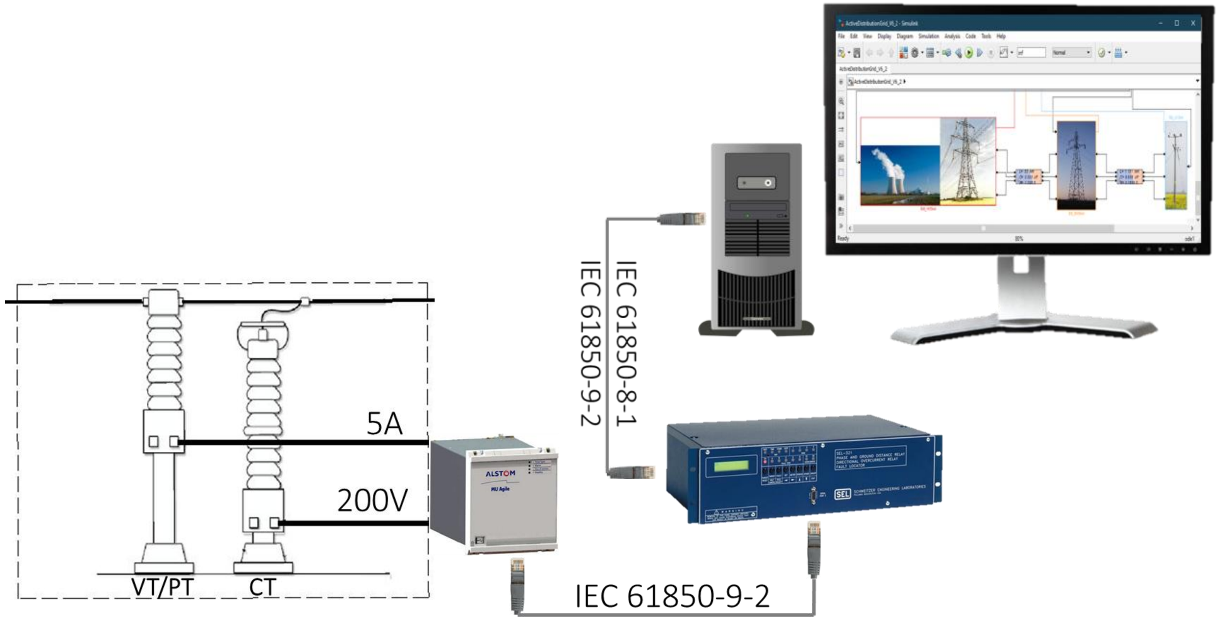
Electrical Waveform-based



- **Exchange** of **continuous** or **discrete** electrical waveforms representing physical quantities:
  - **Measurement** → Real-time feedback.
    -Voltages, currents, frequency, etc., that the simulator receives from the DUT.
  - **Control** → Actuation
    - Low-level analog or digital values like reference signals or switching commands
  - **Power** → PHIL
    - High-power analog signals, typically going through specialized power amplifiers.
- **Interface Media:**
  - **Copper** for all: shielded twisted pairs (analog), multi-core cables (digital),
  - **Power cables** (PHIL)
- **Typical examples:**
  - Analog: ±10 V, 0–5 V, 4–20 mA
  - Digital: 5 V TTL, 24 V logic, relay dry contacts
  - Power: amplified AC/DC via power amplifiers

Types of HIL Interfaces

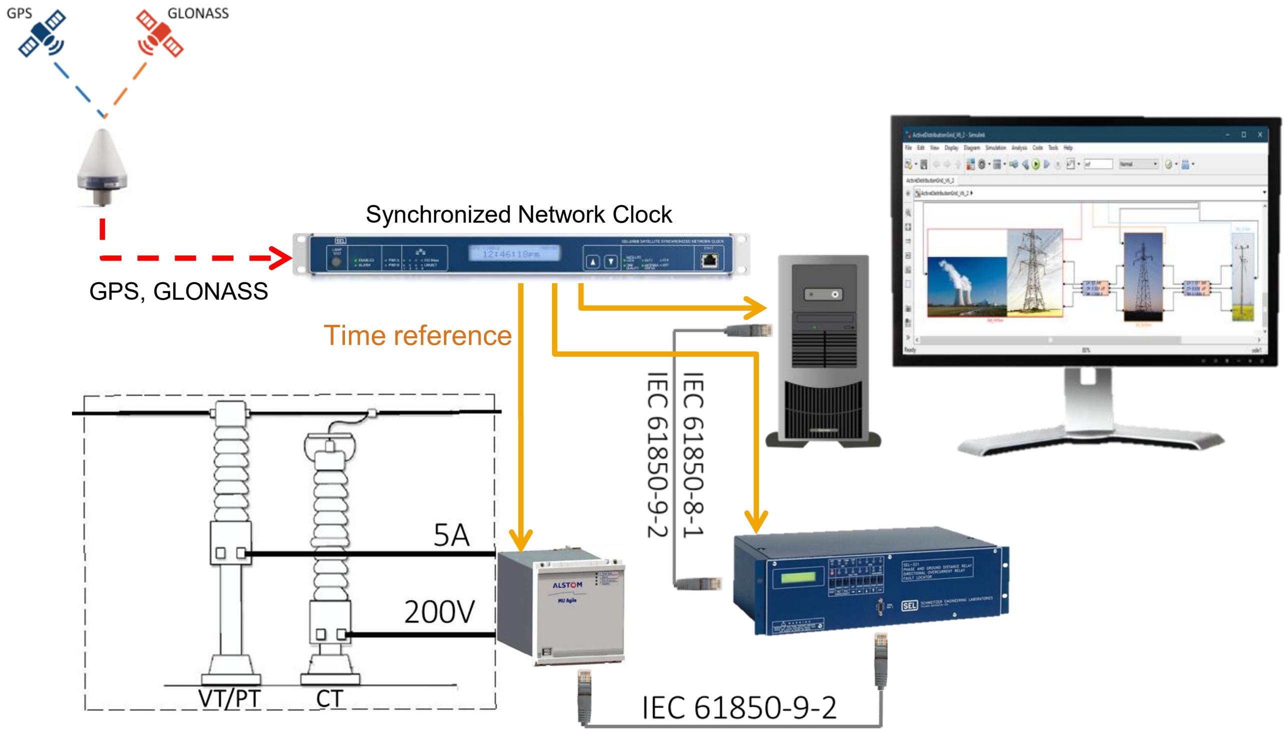
Network Communication-based



- **Exchange** of **digitally encoded**, **protocol-based data** between **simulator**, **controllers**, and **DUT**;
- **Includes** measurement, control, configuration, diagnostic, or synchronization data.
- **Interface Media:**
  - **Copper**: Ethernet, RS-485, CAN
  - **Fiber**: SFP-based optical Ethernet, IEC 61850 SV, Aurora/PCIe over fiber
- **Typical Examples:**
  - IEC 61850 GOOSE & Sampled Values;
  - DNP3; Modbus TCP
  - CAN; RS-485; UART, SPI
  - Ethernet (TCP/UDP);
  - Aurora; PCIe over fiber

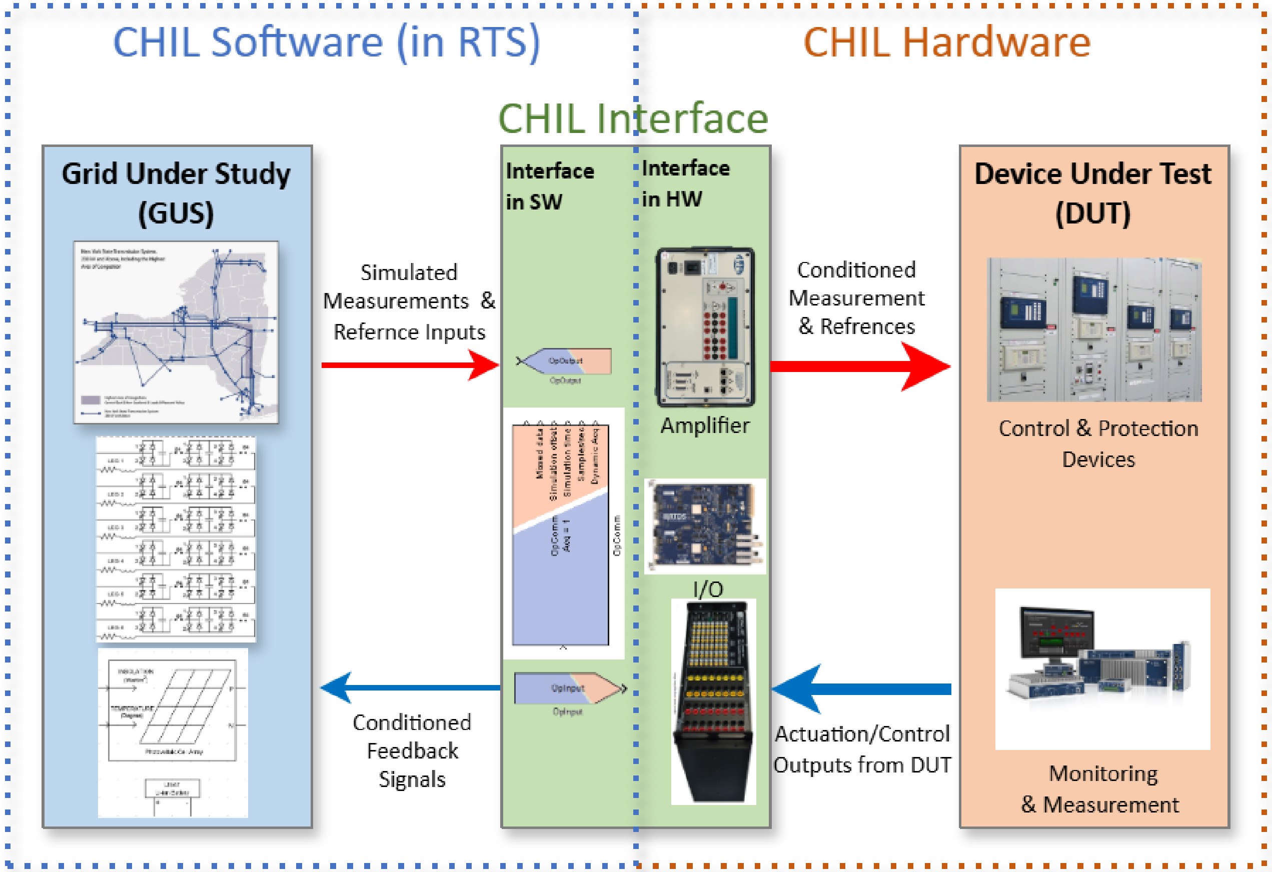
Types of HIL Interfaces

Time Synchronization-based



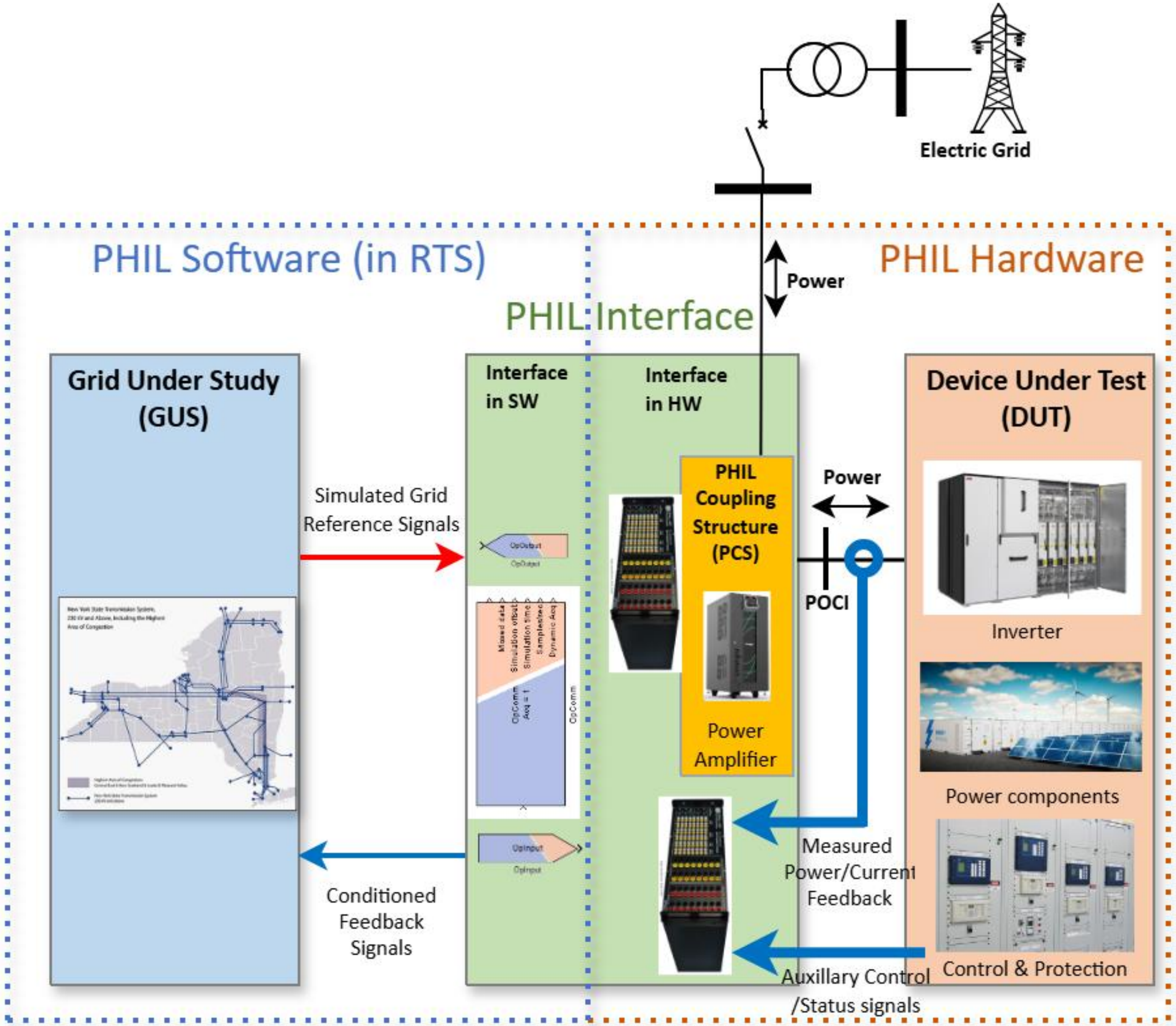
- Provides a **common time** and phase reference between simulator, controllers, and DUTs.
- Enables **accurate temporal alignment** of measured, control, and network data streams.
- Essential for **time-stamped data exchange**, event replay, or power hardware-in-the-loop tests requiring phase coherence.
- **Interface Media:**
  - **Electrical**: coaxial cable (IRIG-B, TTL PPS)
  - **Network**: IEEE 1588 PTP over Ethernet
  - **Optical**: fiber-based time transfer
- **Typical Examples:**
  - **IRIG-B** (DC/AC): Analog or digital coded time signals
  - **PPS** (1 Pulse Per Second): Hardware pulse for phase alignment
  - **IEEE 1588 PTP**: Network-based high-precision synchronization
  - **NTP**: software-based synchronization (lower accuracy, used for log or SCADA time alignment)

Types of HIL Testing: Control-HIL (CHIL)



- **Focus**: Tests control & protection (C&P) equipment and low-voltage interfaces; No real power flow.
- Supports deterministic real-time testing of embedded control logic without risk to physical power equipment.
- **Interface**: RTS exchanges analog, digital, or network-based signals **directly** with the DUT through I/O and conditioning circuits.
- **Signal conditioning**: May include amplifiers, transceivers, or attenuators to match voltage/current levels between simulator and device.
- **Loop closure**: Simulator sends simulated measurements; DUT responds with control, reference, or trip signals completing a closed real-time loop.
- **Applications**: Validation of inverter controllers and protection relays before field deployment.

Types of HIL Testing: Power-HIL (PHIL)



- **Focus**: Extends CHIL by enabling real power exchange between the RTS and power equipment.
- **Interface**: Includes high-power amplifiers to replicate simulated voltages/currents at the DUT's terminals.
- **Power loop**: DUT injects/absorbs power through amplifier, which enforces grid conditions of simulation.
- **Measurement feedback:** Amplifier or sensors measure current and voltage, feeding scaled signals back to the simulator to close the loop.
- **Applications**: Testing of converters, inverters, BESS, renewable systems, and grid-interfacing devices under realistic dynamic grid conditions.
- **Limitation**: DUT testing is constrained by amplifier capacity and grid interface.
- Requires careful stability tuning of amplifier–simulation coupling (impedance matching, delay compensation).

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Concept of HIL Testing for Inverter-based resources

Potentials Beneficiaries of HIL Testing

OEMs

- Hardware & Firmware verification
- FAT

Plant Developers

- IBR plant C&P FAT
- C&P parameter design & tuning

Utilities/System Operators

- Interconnection studies
- Maintenance & Training

Regulatory Bodies

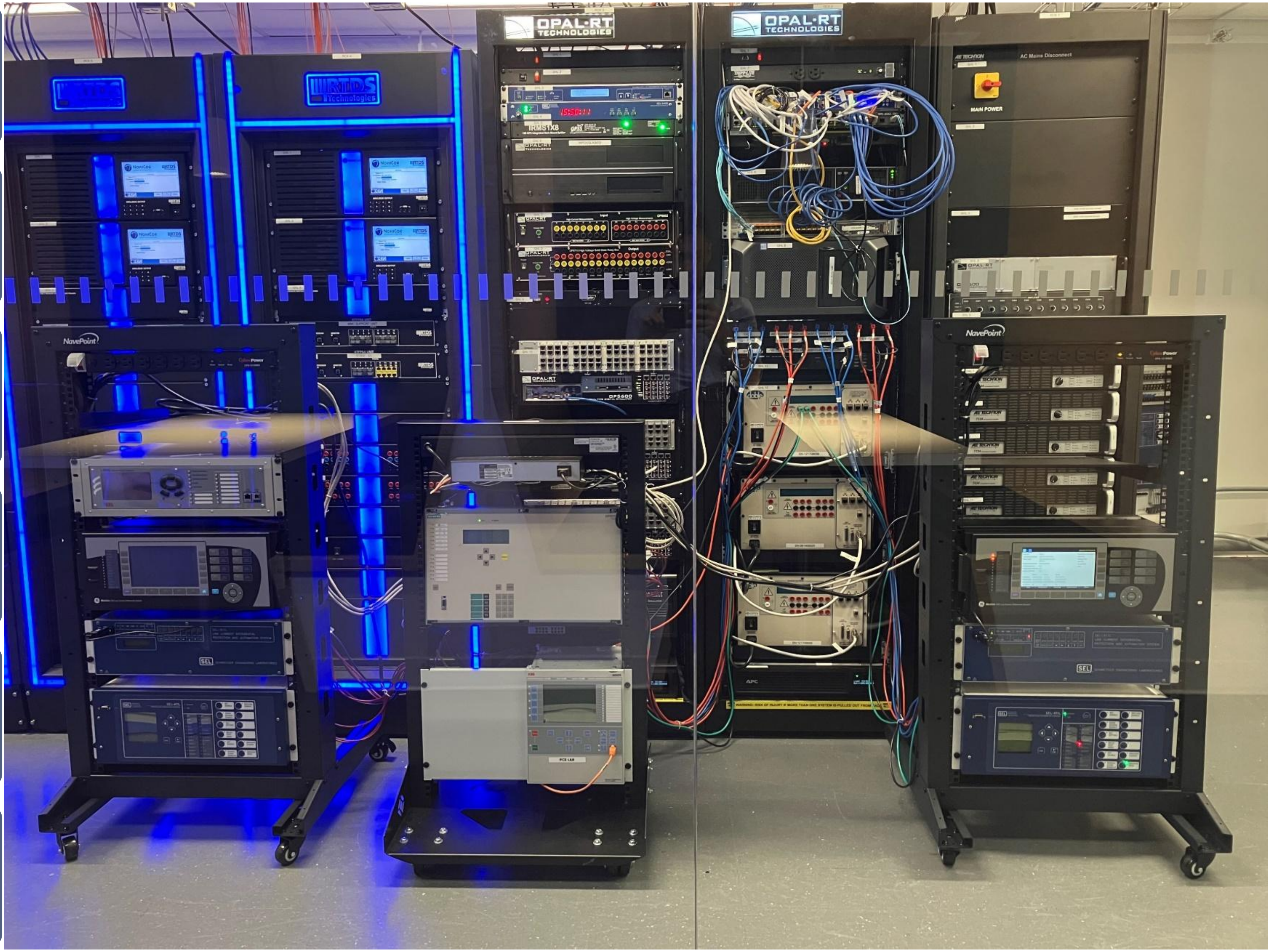
- Safety standards
- Grid compliance

Solution Providers

- Prototyping & Experimental analysis
- Solution optimization

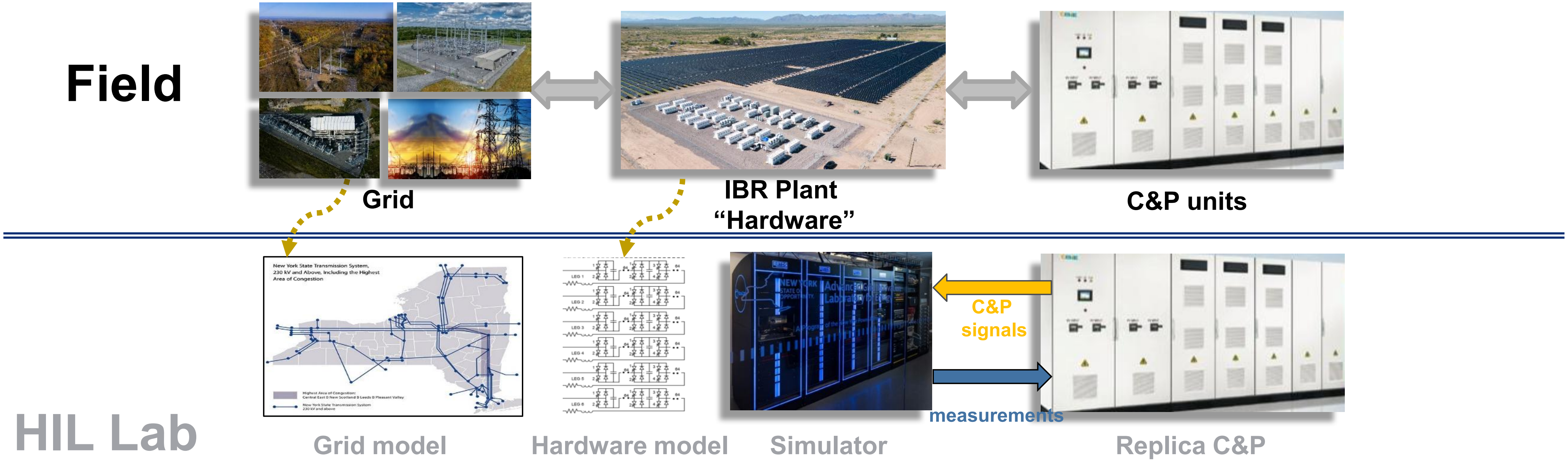
Researchers

- Novel control strategies & algorithm optimization
- Experimental evaluation



IBR Replicas for HIL Testing

- **C&P Units Replica:** A replica is an exact hardware copy of the actual control, protection and communication units of the IBR, provided by OEM/developer.



- **Who should run Replica-based HIL?**

Utility-space Practices with HIL Testing

Entity	HIL Facility Type	HIL Applications	IBR Types Tested
Hydro-Québec, IREQ Simulation Lab	Digital real-time simulator lab with HIL testing. PHIL capability	Grid integration, HVDC commissioning, control validation	HVDC, FACTS, wind/PV, BESS, DER
RTE International, HVDC Innovation Lab	Control HIL – HVDC Innovation Laboratory	HVDC interoperability, control validation, system upgrades	HVDC, FACTS, wind, PV, BESS
KEPCO / KEPRI	Large-scale RTDS & 350 kW PHIL inverter test bench	HVDC–FACTS studies, control algorithm testing, PV validation	HVDC, FACTS, PV, DER
National HVDC Centre	Real-time HVDC simulation and training facility	HVDC de-risking, interoperability, operator training	HVDC (LCC/VSC) and offshore wind
New York Power Authority, AGILe	Real-time simulation lab with CHIL and PHIL testing capabilities.	Grid integration, grid large-scale modeling, model validation, commissioning tests	Planned for upcoming renewables and BESS.
NREL ESIF/ARIES Labs	Megawatt-scale PHIL (1–7 MVA) and controller-HIL labs. PHIL capability	Grid integration, advanced inverter testing, standards validation	PV, BESS, EV, wind, hybrid systems
Oak Ridge National Lab	Microgrid HIL and cyber-physical testbeds	Microgrid control, cyber-resilience validation	PV, BESS, genset, DER controllers
Fraunhofer IEE – SysTec Lab	Smart grid PHIL test center (up to 6 MVA)	Grid code testing, DER model validation, EV integration	PV, wind, storage, EVs, DERs
Quanta Technology	Consulting RTDS-based HIL labs	Protection & control verification, anti-islanding studies	Solar, wind, BESS, protection & controls
State Grid Electric Power Research Institute (CEPRI)	Hybrid real-time simulation lab with HVDC control replicas	HVDC control & protection validation, grid studies	HVDC, FACTS, UHV systems
Hitachi Energy HVDC Simulation Center	Real-time HVDC grid simulator with C&P hardware-in-loop	Multi-terminal HVDC grid validation, technology R&D	HVDC and DC grid components
PG&E Applied Technology Services Lab	Power HIL microgrid testbed with real-time digital simulator	Microgrid operation & protection validation before field use	Microgrid PV, BESS, protection relays
Electric Power Research Institute	Distributed Energy Resource (DER) Labs.	Performance characterization, development of standardized test procedures, and model improvement for DER integration.	PV inverters, battery inverters, plant controllers, and aggregated DER systems.
Southern California Edison (SCE)	DER Integration HIL Testbed (USA),	Utility grid integration and compliance testing; PHIL validation of inverter behavior	Distributed PV and battery inverters, utility control systems (DERMS, protection).
Florida Power & Light (FPL)	Solar Inverter Lab & Daytona Deployment (USA)	Comparative inverter performance and compliance evaluation under controlled grid disturbances using PHIL experiments.	Utility-scale PV inverters (36 inverters, 8 manufacturers, total 1.1 MW AC).

Comparison between Software Simulations & Replica-based HIL

Challenge	Software Simulations with EMT models	C&P Replica-based HIL
Representation of IBR C&P	Less accurate due to the black box nature of OEM models	Highly accurate
Representation of IBR power components	Adequately accurate	Adequate accuracy but needs a lot more computation power
Representation of the large-scale grid	Adequately accurate	Adequate accuracy but needs a lot more computation power
Runtime for slow varying phenomena	Very long offline simulation times	As fast as the real-world phenomena
Modeling and simulation flexibility	1- Less flexible for black-box models 2- More flexible if Monte-Carlo simulations are needed 3- Different OEM-preferred software (type & version) in multi-vendor projects 4- Operator-specific functions & interventions NOT feasible	1- More access to C&P structure for owner/operator via replica 2- Less flexible with automated scenario runs 3- Different OEM-preferred software is NOT an issue. 4- Operator-specific functions & interventions ARE feasible through real-world HMIs.
Software & Parameter updates	Multi-platform coordination, uncertainty, and delays	Single platform, direct transfer of updates, accuracy, and faster studies
Costs	Low-cost	High capital investment and human resource

IBR Interconnection Challenges & Potential Applications of Replica HIL Testing

Pre-commissioning

Interconnection compliance
- Identify potential adverse C&P interactions.
- Proof of Concept of solutions.
- Reduce risk of non-compliance w/ emerging codes.
- De-risk damaging grid/equipment

Confidence in new IBR P&C technologies
- Greater insight and confidence in technology for operators

Commissioning delays
- Prepare and rehearse commissioning tests
- Reduce delays to commissioning stage

Cybersecurity development
- Use actual communication systems & HMIs for development and testing

Post-commissioning

Events & interaction studies
- Diagnose faults & interactions, prove the solution
- Speed up restoration and reduce downtime & cost
- Predict potential interactions, faults, and solutions
- Study interaction between replica C&P and new projects

In-house Training
- Train and develop skill for Planners, Operators, and Maintenance personnel
- Reduce reliance on suppliers

Maintenance Downtime
- Prepare & rehearse planned maintenance
- Reduce downtime and maintenance costs

SW/HW updates & upgrades
- Verify the impact of software and hardware updates or replacement
- De-risk the process of update/upgrade

Long-term model maintenance
- Reliable & accurate representation w/ HIL testing
- Less reliance on supplier
- Validate, update and maintain offline models using HIL measurements

Potential usage of HIL within IBR interconnection Process

Periodic Tests & Verifications

Process Name	Feasibility Study	System Impact Study	Facility Study	IBR Plant Construction	Conformity Assessment	IBR Commissioning	Post Commissioning Monitoring
What is done	Power flow Short-circuit	Peak & light load power flow Short-circuit Cost estimates	System impact Stability analysis Conceptual design	Build equipment Installation As-built models C&P settings	Final plant design evaluation & as-built validation	Plant-specific commissioning & model validation and verification	Re-validation, event analysis, upgrades, maintenance
Participants	ISO/RTO TO/Developer	ISO/RTO TO/Developer Affected systems	ISO/RTO TO/Developer Affected systems	TO/TP Developer OEM	TO/TP Developer OEM	TO/TP Developer OEM	TO/TP
Offline tools	Required	Required	Required	PS, EMT	PS, EMT	PS, EMT	PS, EMT
Recommended HIL	Not required	Not required	Not required	FAT w/ HIL Build replicas Setup HIL facility	Pre-commissioning Performance Model validation	Pre-commissioning Pre-SAT w/ HIL Validate SW	SW & models update Interaction studies Parameter tuning Training Maintenance

Existing Process

Recommended Addition

Source:
- IEEE P2800.2 Recommended Practice for Test and Verification Procedures for IBRs Interconnecting with Bulk Power Systems
- Interconnection Innovation e-Xchange (i2X), DoE

Forward Looking….

- HIL use cases are evolving in many areas — from specialized R&D setups to validation tools for IBRs.
- Replica-based testing helps close the gap between models and the real-world behavior.
- System operators, utilities , and OEMs share a common challenge: ensuring reliable behavior under real conditions.
- Collaboration and knowledge exchange will be key to making HIL more accessible across the industry.
- Next talks will show how this is already being achieved through real-world examples in IBR model validation.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