Webinar:
Introduction to Real-Time Simulation and HIL Testing for Power System Innovators

RTDS Technologies

RTDS.COM

Agenda

Motivation and Background
Why?

HIL Testing Equipment
Hardware and software components

Applications
Flavours of real-time simulation

Case Studies
Real-world utility examples

Motivation and Background

Why?

How do we validate that controls and protection will operate as expected (and to grid code / standards) before they are installed?

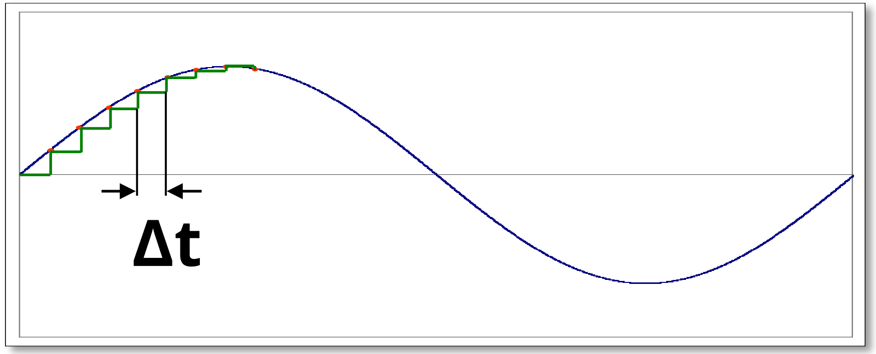
How confident are we that multiple devices in the grid are interoperable through a variety of operating scenarios?

How wide a range of system conditions are we modelling and testing for?

How detailed is our system representation when we model and test?

Types of Power System Simulation

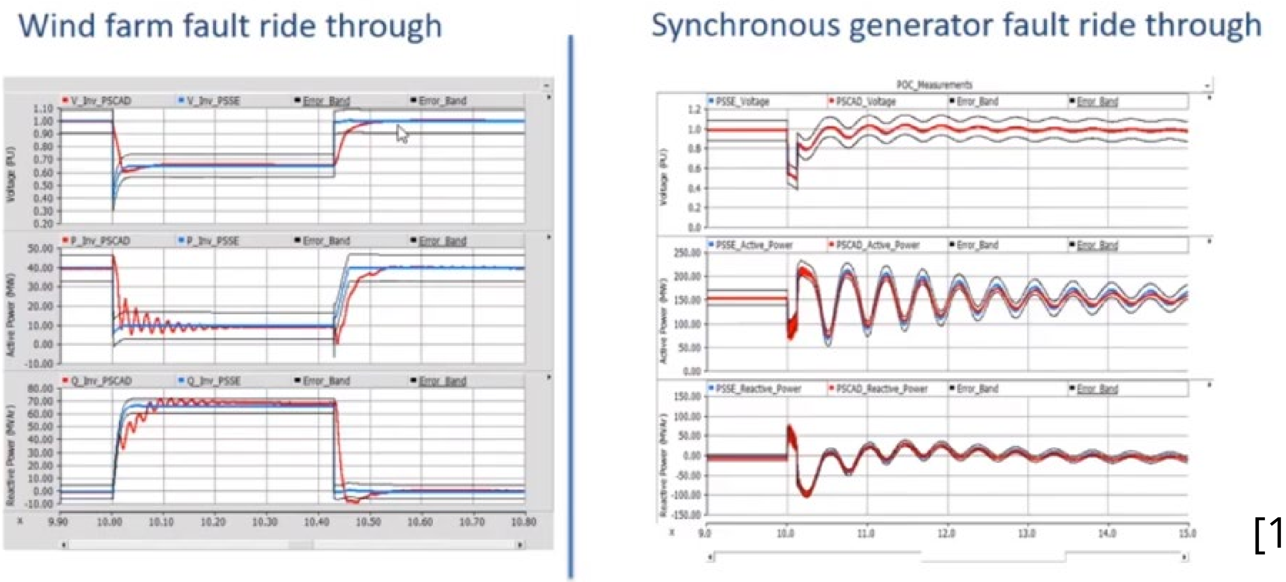
Type of Simulation	Load Flow	Transient Stability Analysis (TSA)	Electromagnetic Transient (EMT)
Typical timestep	Single solution	~ 8 ms	~ 2 - 50 μs
Output	Magnitude and angle	Magnitude and angle	Instantaneous values
Frequency range	Nominal frequency	Nominal and off-nominal frequency	0 – 3 kHz (<15 kHz)



Dommel algorithm of nodal analysis used in RTDS, PSCAD, EMTP, etc.

Benefits of EMT Simulation

- Allows for a greater depth of analysis than phasor domain (RMS) representations
- RMS models lack the ability to capture fast network dynamics during transient conditions and may provide optimistic results
- Important for modern systems with many power electronic converters (more likely to predict control instability



[1]

Benefits of EMT Simulation

Table 2.1: Solar PV Tripping and Modeling Capabilities and Practices		
Cause of Tripping	Can Be Accurately Modeled in Positive Sequence Simulations?	Can Be Accurately Modeled in EMT Simulations?
Erroneous frequency calculation	No	Yes
Instantaneous* ac overvoltage	No	Yes
PLL loss of synchronism	No	Yes
Phase jump tripping	Yes	Yes
DC reverse current	No	Yes
DC low voltage	No	Yes
AC overcurrent	No	Yes
Instantaneous* ac overvoltage—feeder protection	No	Yes
Measured underfrequency—feeder protection	No	No**

* Sub-cycle ** Due to very limited protective relay models in EMT today

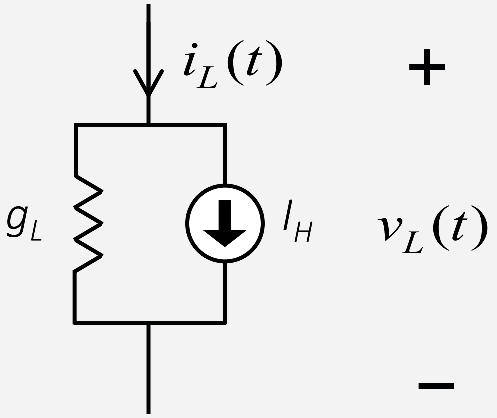
[2]

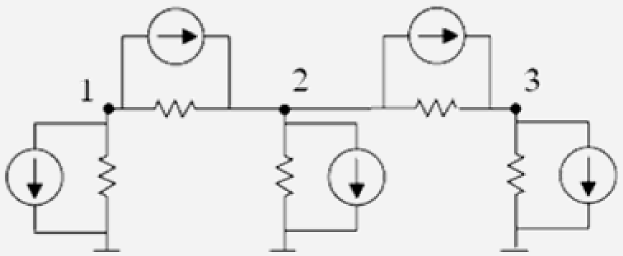
- NERC study – “strong need” for EMT modelling in support of renewable energy integration
- Majority of tripping events analyzed could not be accurately simulated using positive sequence only studies

EMT Simulation Algorithm

Dommel Algorithm

- Uses trapezoidal integration to interpret power system components as equivalent current source and resistor.
- Conductance matrix is formed for the network, which must be decomposed each timestep to solve for node voltages throughout the circuit.





$$\begin{bmatrix} V1 \\ V2 \\ V3 \end{bmatrix} = \begin{bmatrix} G11 & G12 & G13 \\ G21 & G22 & G23 \\ G31 & G32 & G33 \end{bmatrix}^{-1} \begin{bmatrix} I1 \\ I2 \\ I3 \end{bmatrix}$$

What is “real time”?

- **Real time it takes for an event to occur = Simulation time of an event.**
  - E.g. 3 cycle fault for 60Hz system = 0.05 seconds. RTDS simulates this fault in real time i.e. 0.05 seconds.
  - Non-real-time simulations will simulate events faster or slower than real time depending on case complexity.

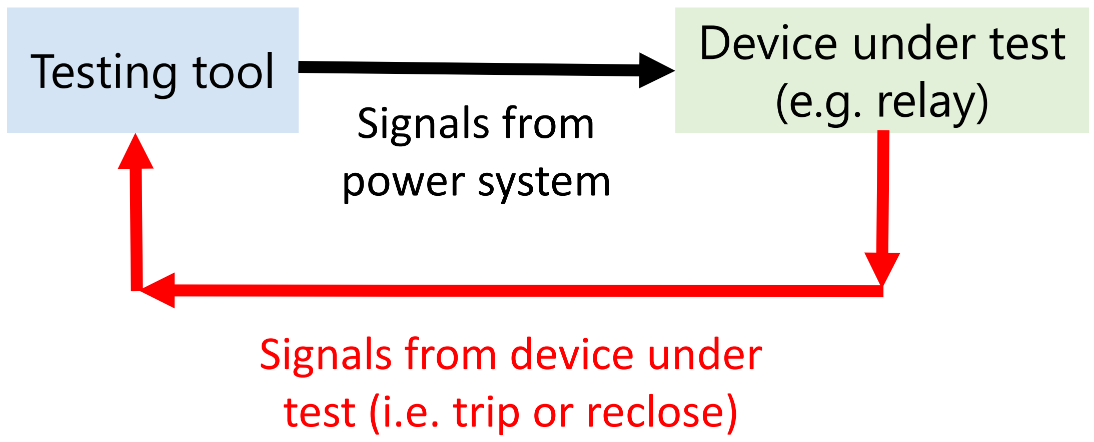
- **Values updated each timestep.**
  - All calculations and servicing IO completed within a timestep (~1-50 microseconds).
  - Every timestep has same duration and is completed in real time.

Real-time operation enables closed-loop testing.

Device testing: open vs. closed loop

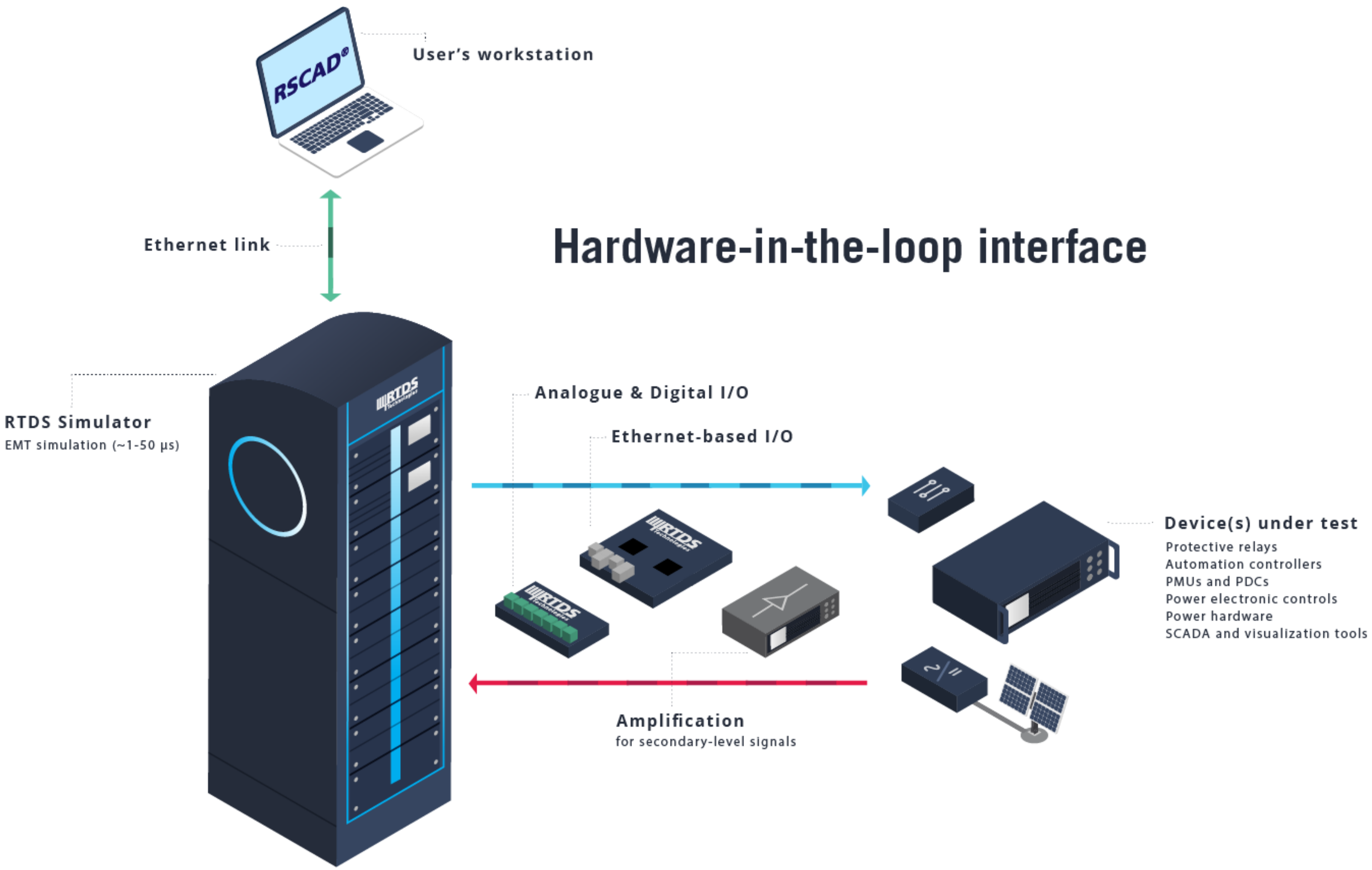
- **Open-loop testing**
  - Playback testing
  - Relay test sets – limited insight on dynamic response of the network to the protection device; typically can't test multiple devices simultaneously

- **Closed-loop testing**
  - Analogue simulation
  - Real-time digital simulation – flexible, accessible solution to closed-loop testing

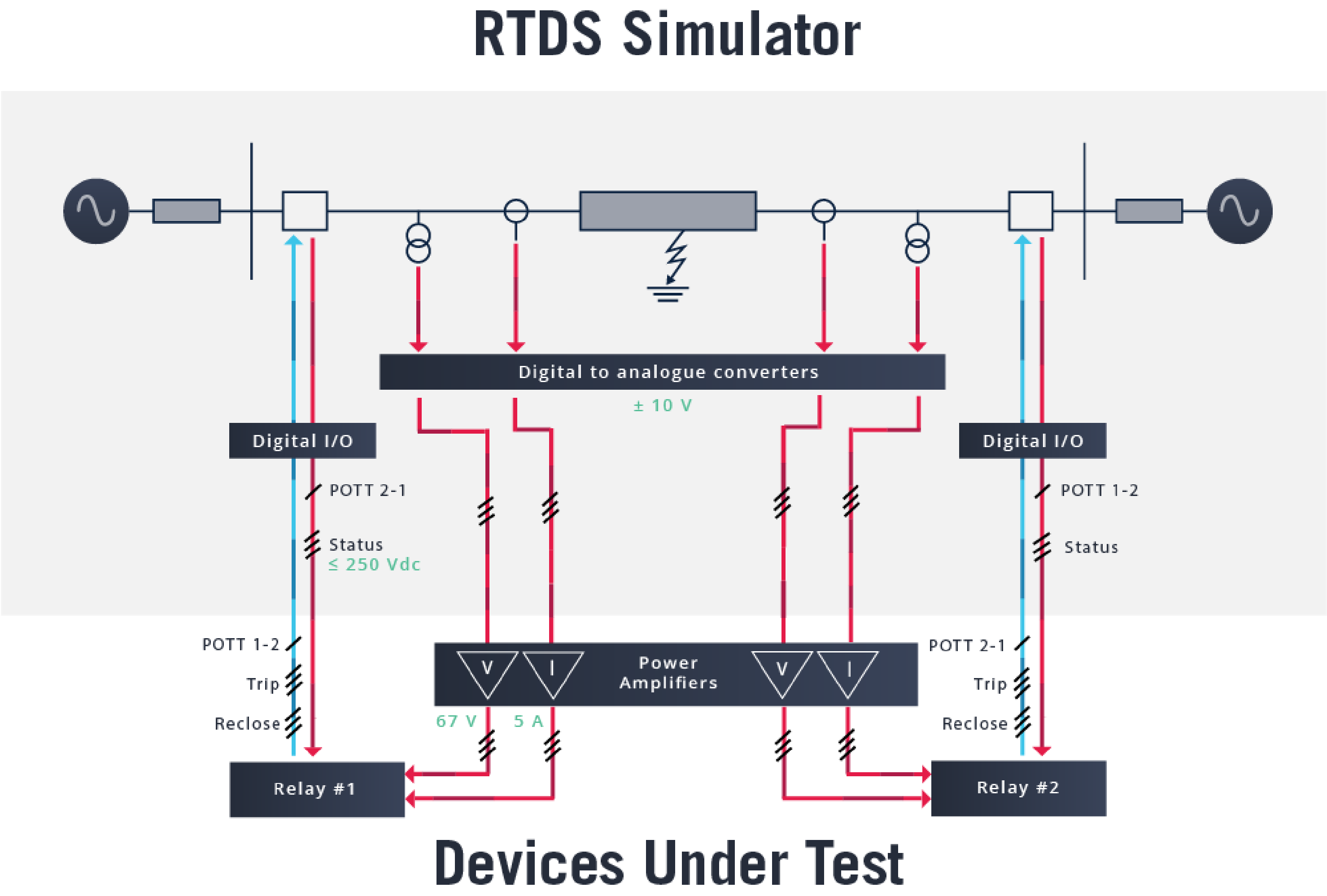


HIL testing with a real-time simulator

- **True closed-loop testing** is only possible with a real time simulator
  - Test continues after the action of the protection/control device
  - Test multiple devices (and entire schemes) at once
  - More detailed system representation than open-loop test systems provide (e.g. modelling power electronics)



Typical HIL test setup



About RTDS Technologies

- Headquarters in Winnipeg, Canada
- Pioneered real-time power system simulation in the 1980s
- The RTDS Simulator is the industry standard for real-time simulation and closed-loop testing, used by utilities, manufacturers, research and educational institutions, and consultants worldwide
- Learn more at www.rtds.com or the large library of videos on the RTDS Technologies YouTube channel

HIL Testing Equipment

Hardware and software

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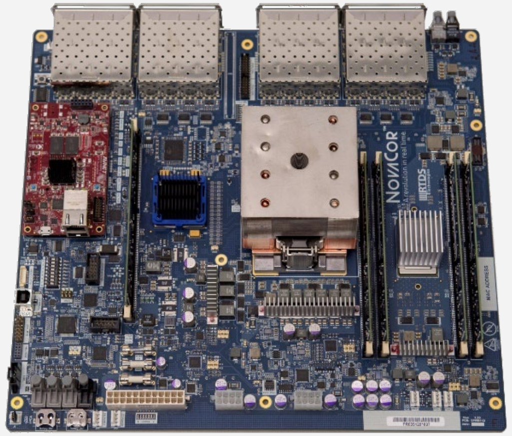
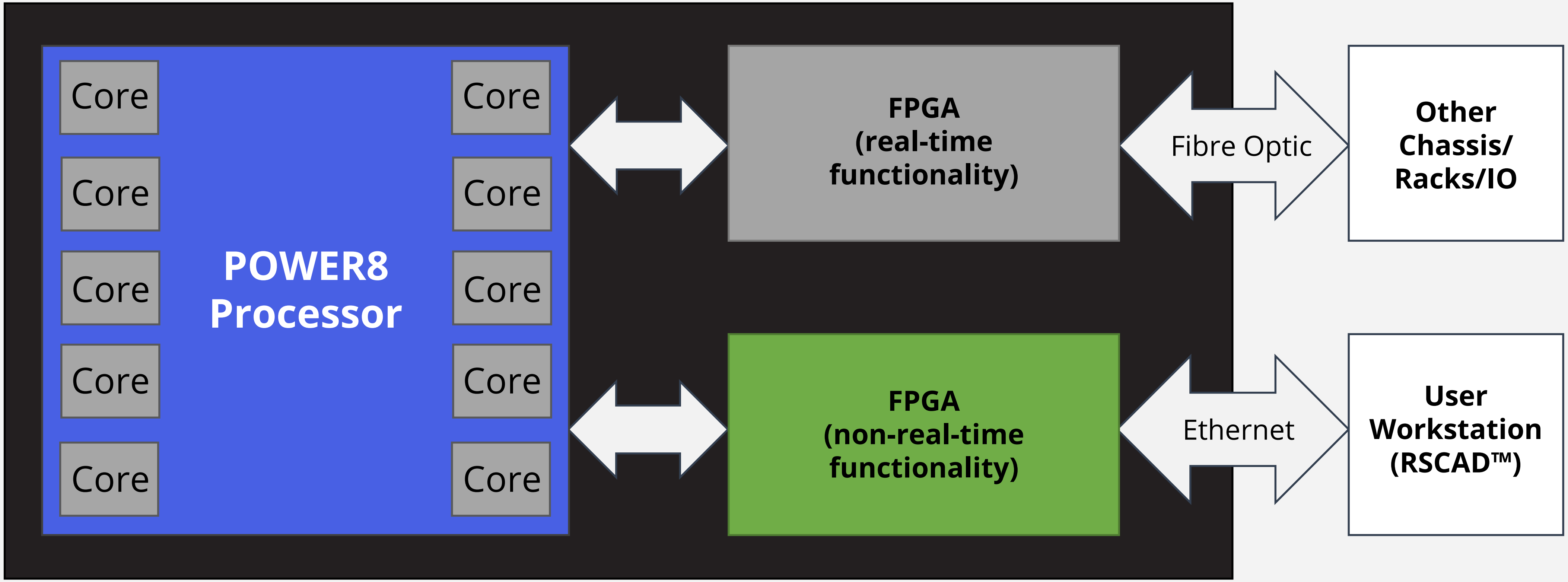
Parallel processing hardware



- Multi-core processor allows for simulation to be scaled via core licensing
- Platform optimized for hard real-time simulation
- No operating system used by the processor while simulation running — bare metal operation

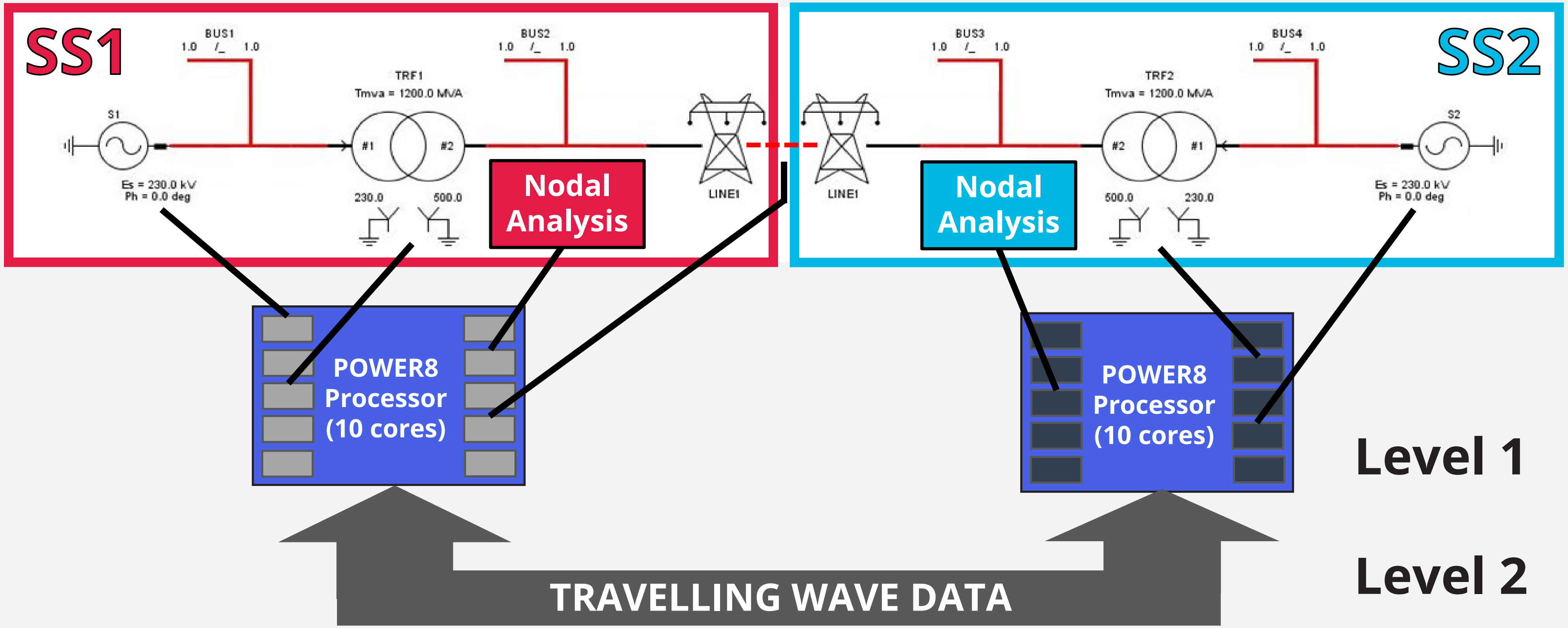
Inside the NovaCor chassis



A scalable system

- Modular and scalable hardware on two levels:
  - Number of cores licensed per chassis
  - Number of chassis
- Maximum configuration: 144 chassis with 1,440 cores licensed
- Units can be connected together for larger-scale simulation, or multiple users can conduct smaller simultaneous simulations

Parallel processing on two levels



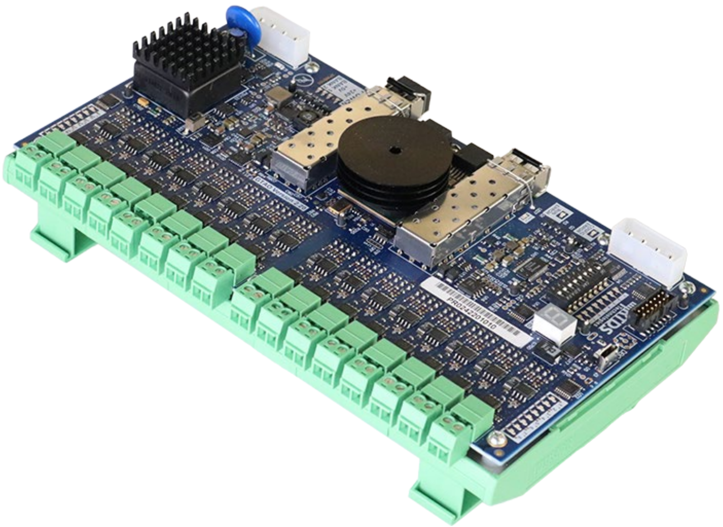
Level 1

Level 2

I/O devices for HIL testing

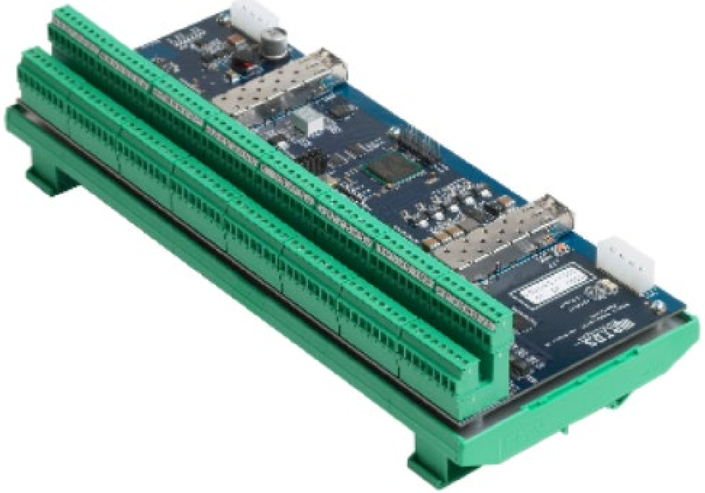
- Analogue and digital input and output

Analogue output card



- 16-bit analogue I/O with a range of +/- 10 Volts

Digital input card



- 64 channels with an input resolution of up to 10 ns

I/O devices for HIL testing

Interfacing via communication protocols

- Communication with external devices over Ethernet
- Card has two “modules” and can have two network protocols operating simultaneously

IEC 61850

- GOOSE Messaging
- IEC 61850-9-2LE, IEC 61869-9 Sampled Values

SCADA

DNP3 and IEC 60870-5-104

Large data playback

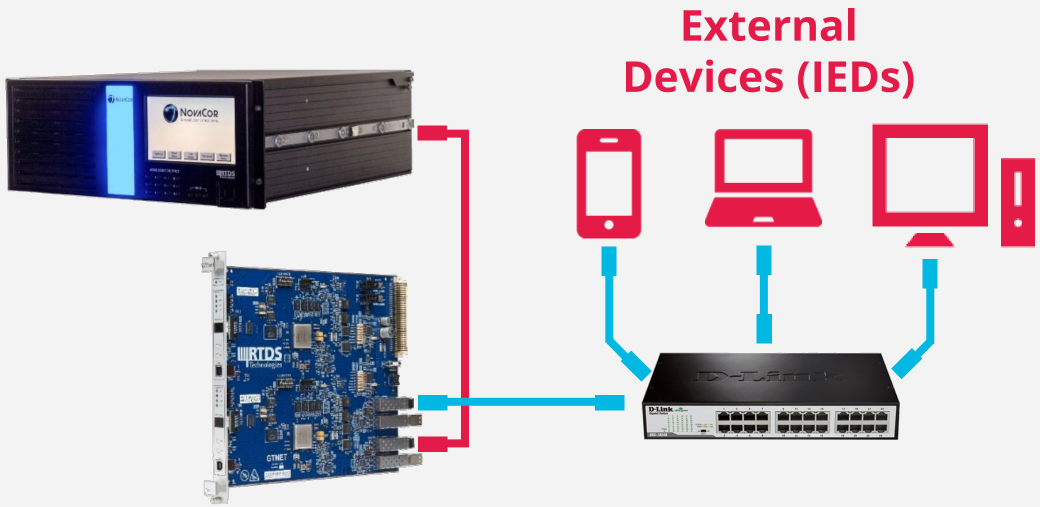
PMU

IEC/IEEE 60255-118-1

MODBUS

TCP, RTU over TCP, ASCII over TCP

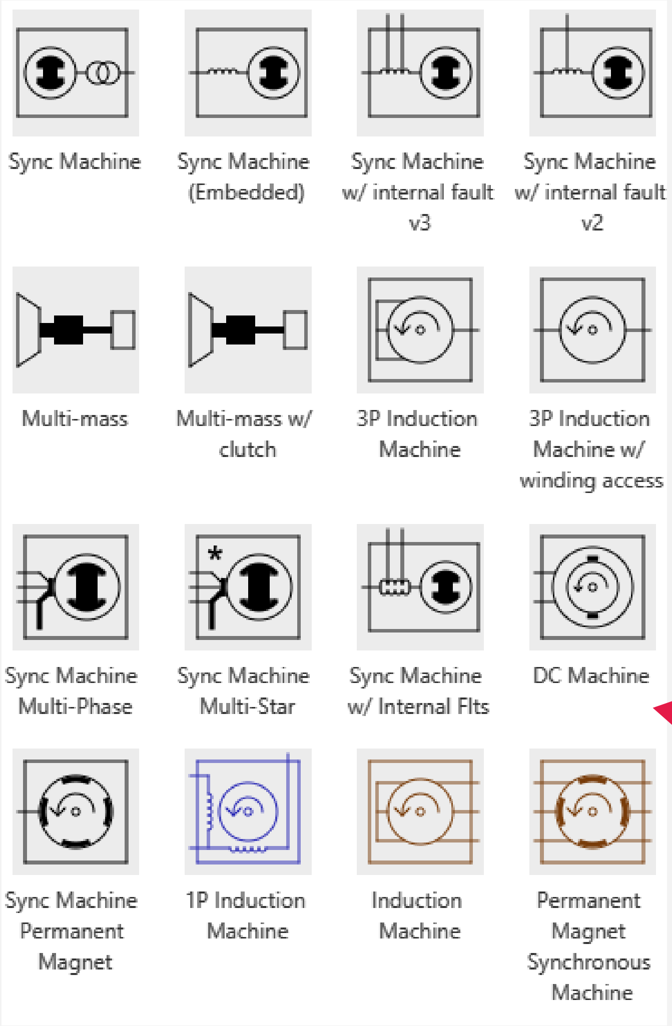
Generic TCP/UDP Sockets

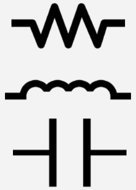


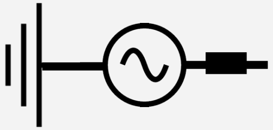
Real-time simulation software

- User-friendly GUI that allows user to develop their simulation case, dynamically interact with the simulation, and collect data
- Tests can be automated – thousands of scenarios run without user interaction
- Software is highly flexible – same all-in-one package can be used for wide variety of applications, i.e. power electronics, microgrids, protection, HVDC, etc.

Modelling library




RLC Components

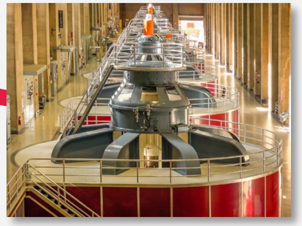

Source Models


Fault and Breaker Models


Transformer Models


Instrument Transformers


Series Compensation Models


Machine Models


Valve Group and SVC Models


Transmission Line and Cable Models

Applications

Flavours of real-time simulation

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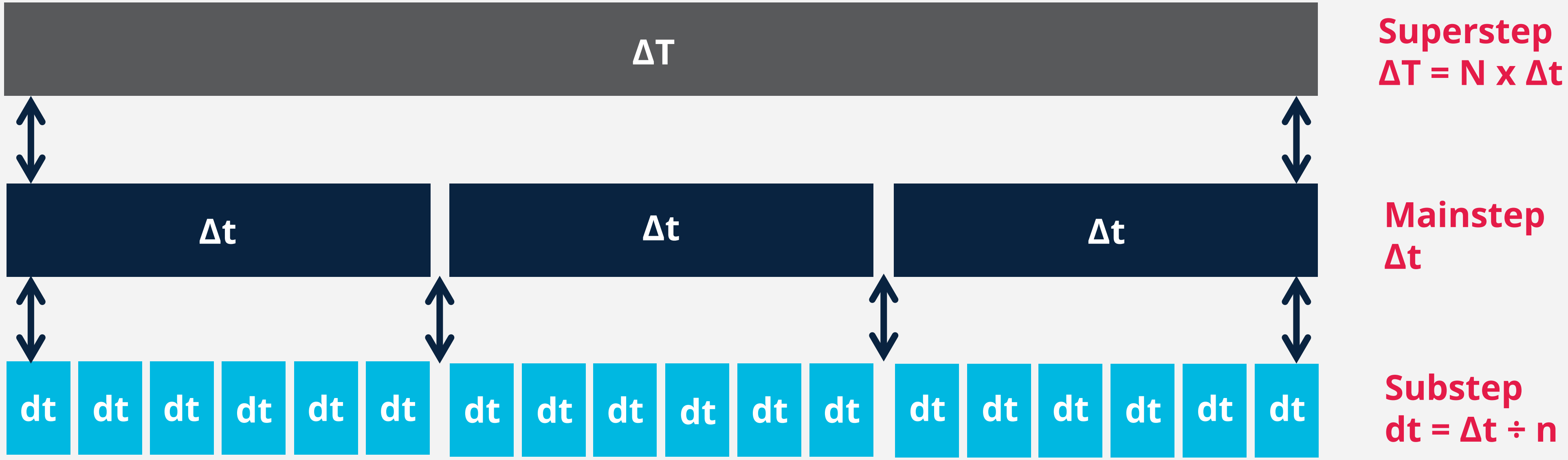
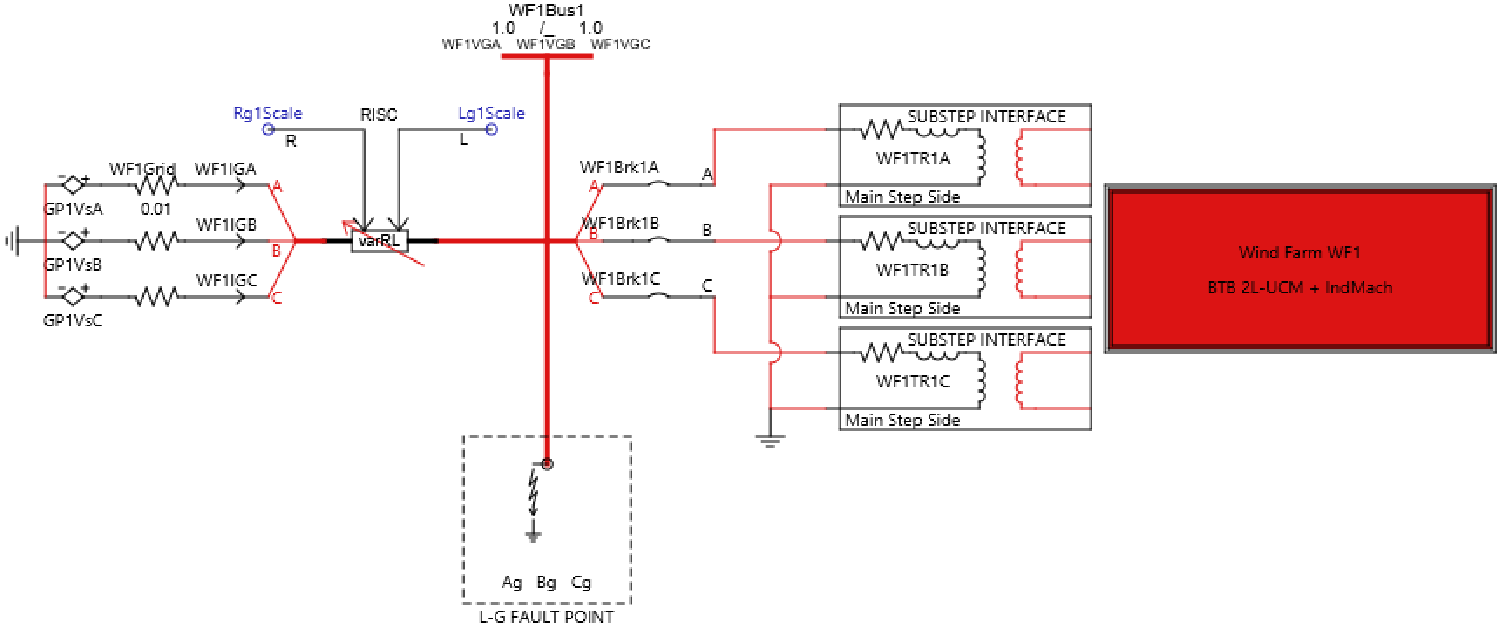
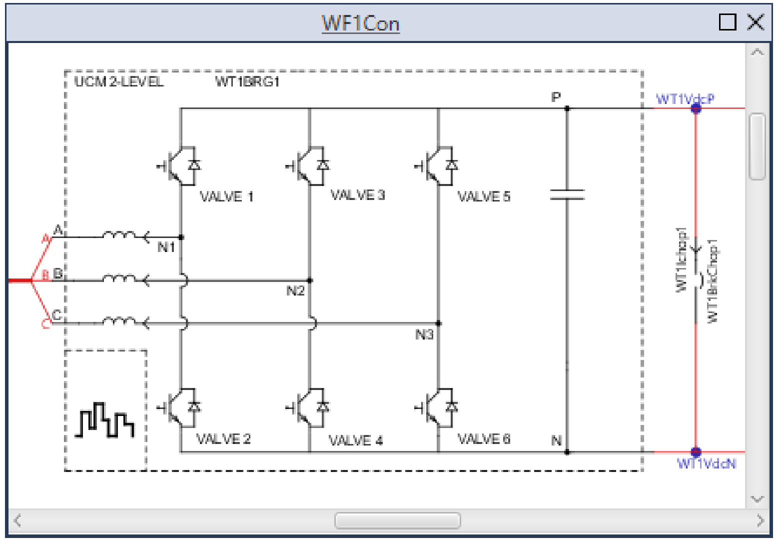
Multi-rate simulation



Universal converter model for power electronics

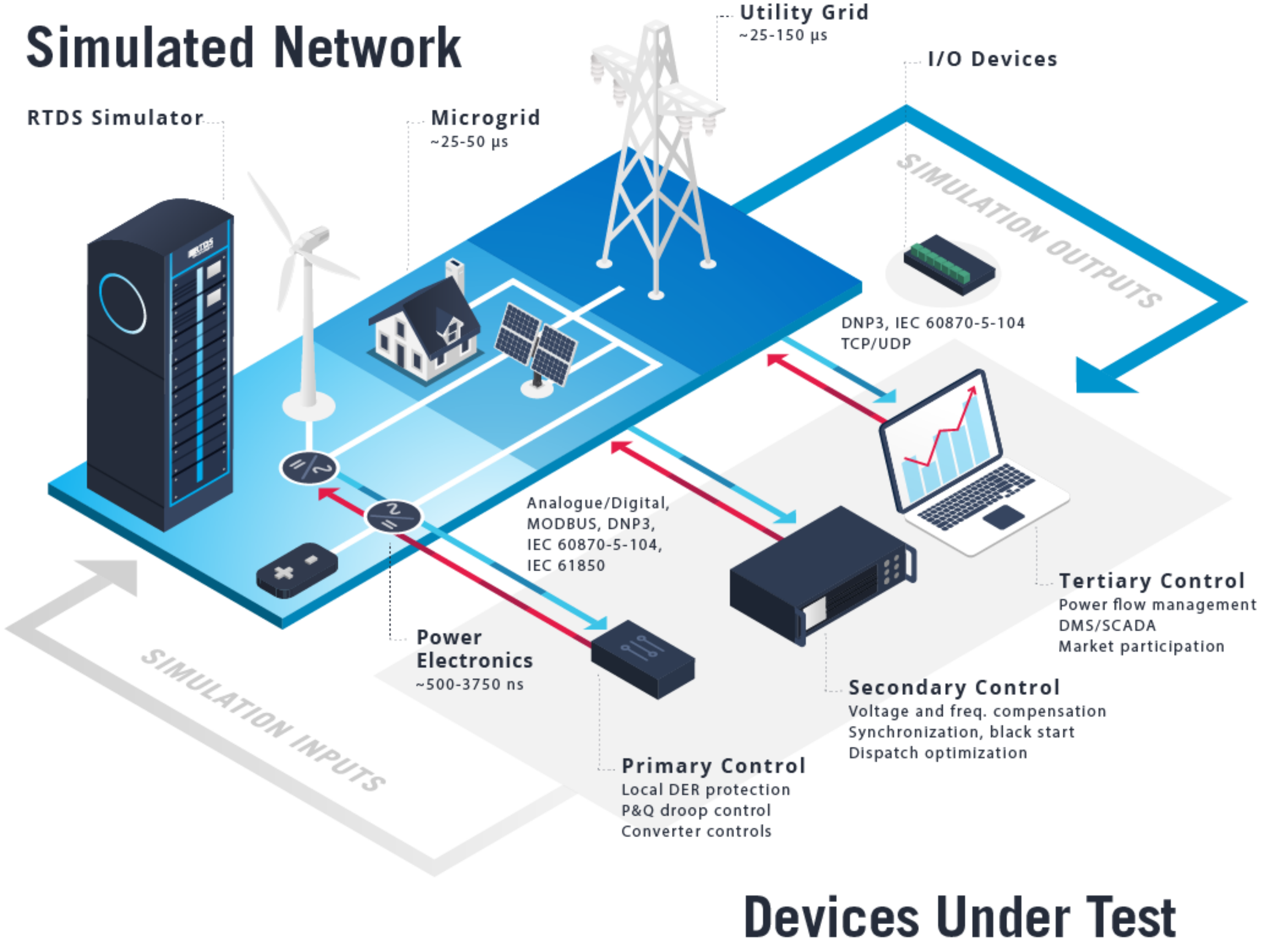
- Can run in parallel subnetwork in 1-10 us range (**switching at up to ~150 kHz**), or as part of main timestep environment (**switching at ~2-3 kHz**)
- Substep and main timestep environments exchange data every main timestep
- Can also perform as average value model (no detailed switching)
- Resistively switched, non-decoupled model





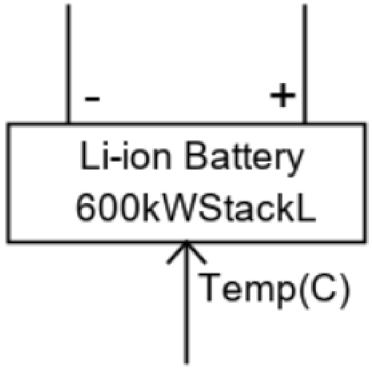
Microgrids

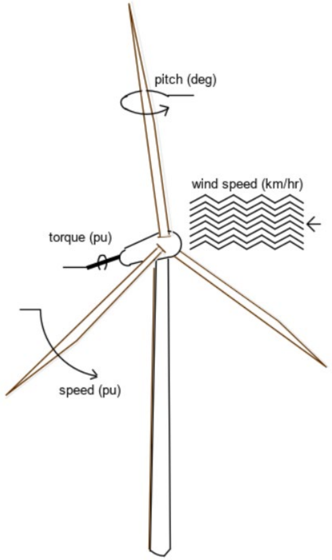
- Test multi-level microgrid control
- Connect local DER protection/control, secondary-level voltage and frequency control, and higher-level power flow control to the simulated environment
- Test functional requirements and dynamic performance of microgrid controllers

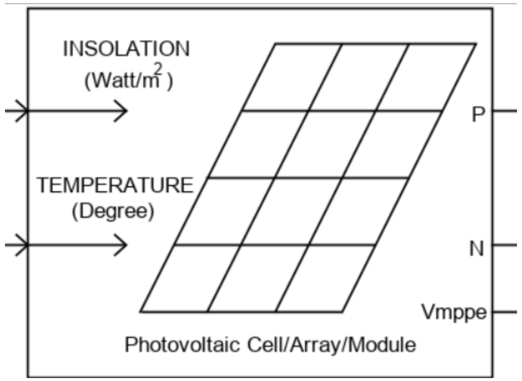


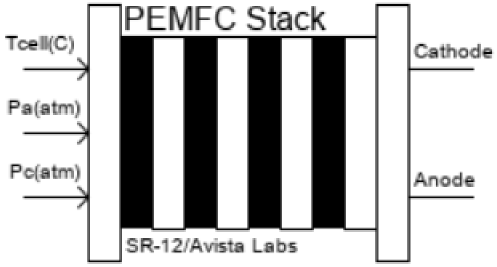
Renewable energy

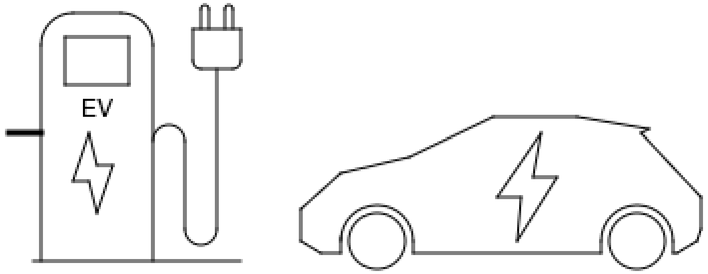
- Test protection, control, and small or large-scale integration of battery energy storage systems, solar PV, wind, hydrogen, electric vehicles, etc.





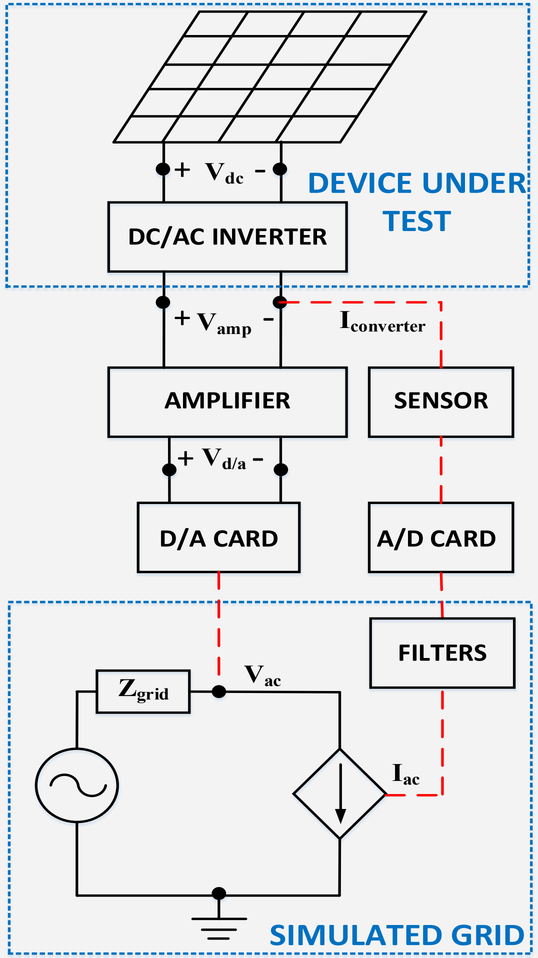






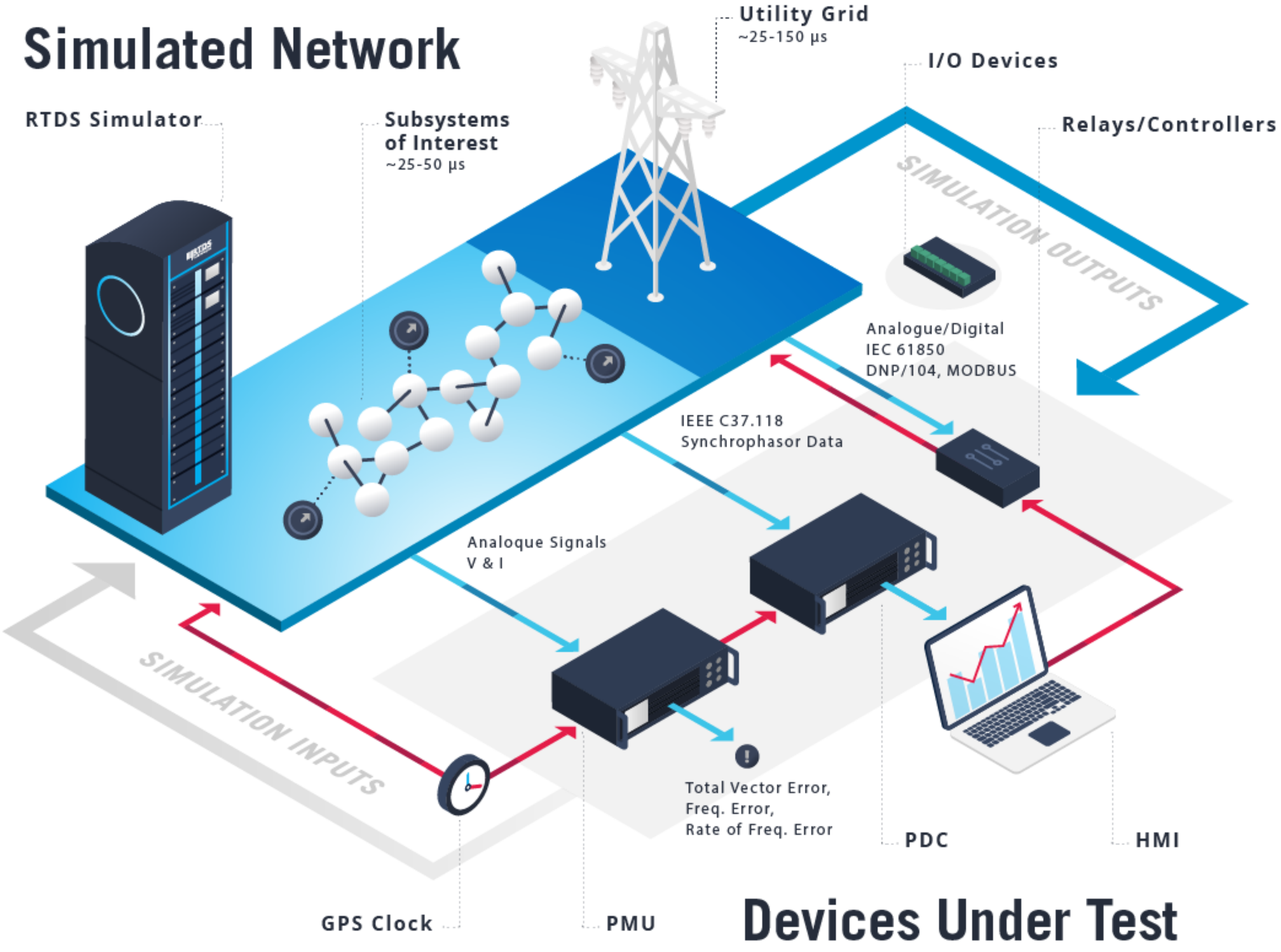
Inverter testing via power-hardware-in-the-loop

- Simulated environment exchanges power with renewable energy hardware, motors, batteries, loads, etc.
- Interface via four-quadrant amplifier and traditional I/O or Aurora communication.

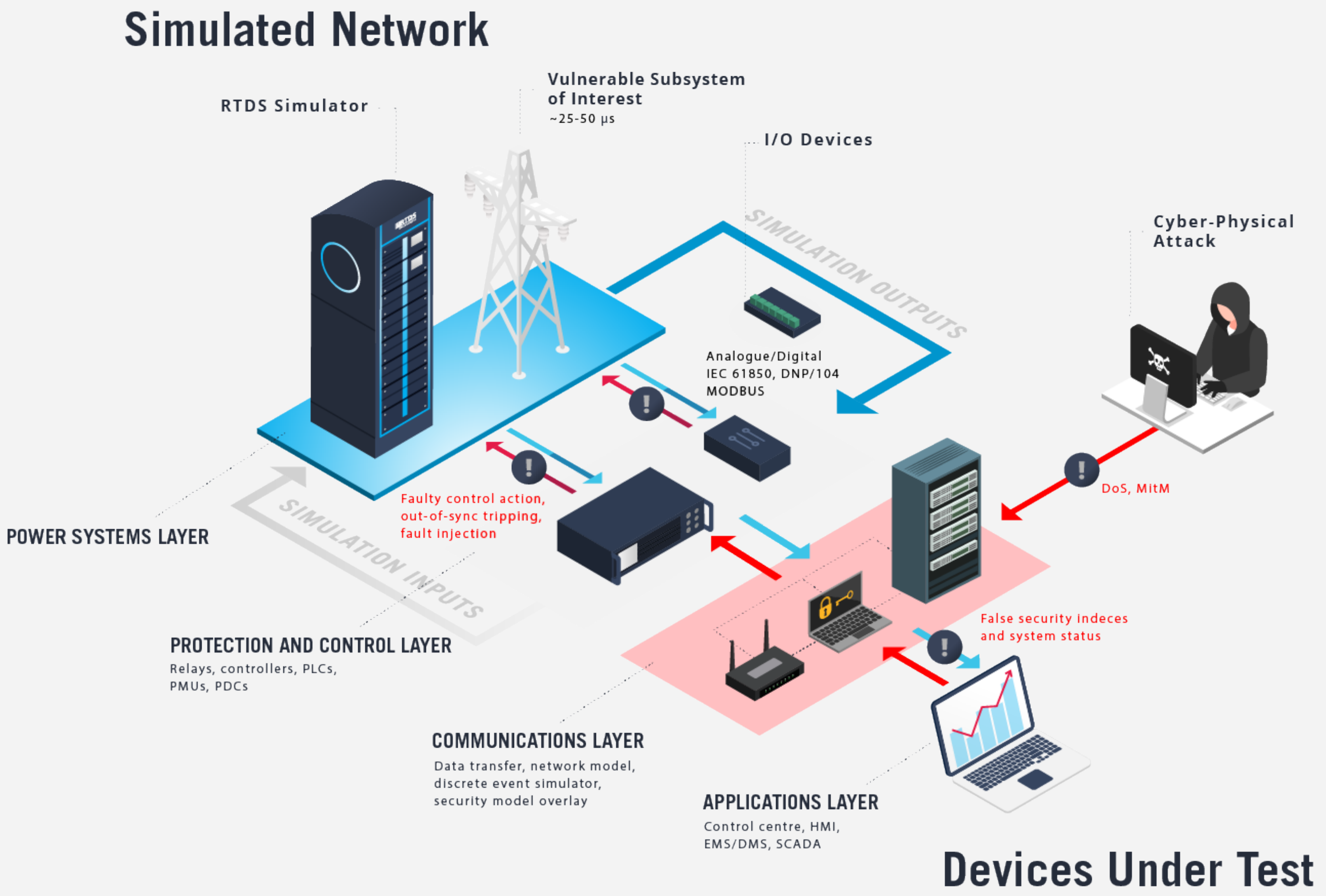


Wide area protection and control

- Synchronize the simulation timestep to external time reference
- PMU performance testing as per IEEE ICAP TSS specifications
- PDC testing for entire wide area schemes

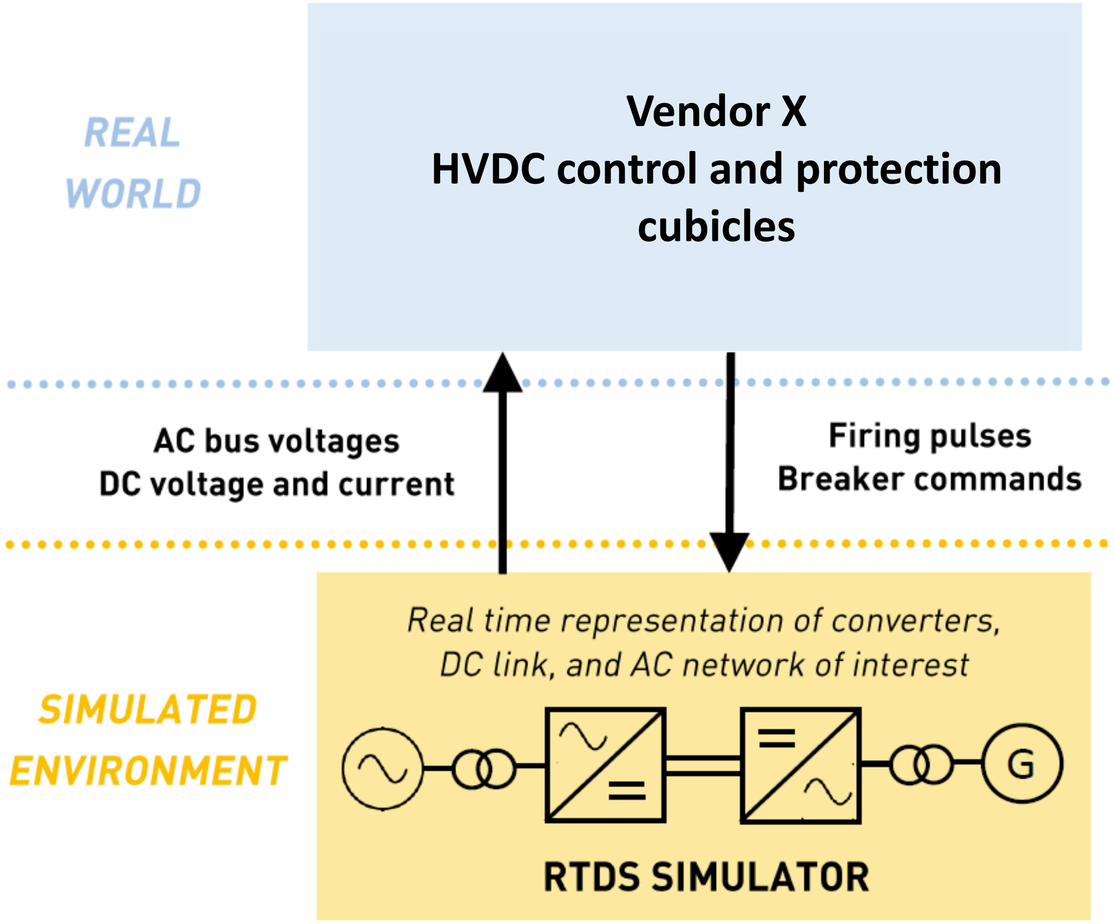


Cybersecurity



HVDC - Factory Acceptance Testing

- Vendor builds up a model of their HVDC/FACTS scheme and equivalent of the network where the scheme will be installed
- Tests include standard operating scenarios (start up, shut down, etc.) and performance tests for various contingency scenarios
- Simulations run for hours or days for comprehensive testing



HVDC - Replica Simulators for Utilities

- Assist during commissioning
- Investigate proposed network changes, control modifications
- Train personnel on theory and operation
- Accelerate project schedule and de-risk installation (prevent misoperation / negative interaction)

Furnas (Brazil)
TNB (Malaysia)
CSG (China)
SEPC (China)
ESKOM (South Africa)
SEC (Saudi Arabia)
Power Grid (India)
Powerlink (Australia)
REE (Spain)
Equinor (Norway)

DEWA (UAE)
ONS (Brazil)
NamPower (Namibia)
RTE (France)
BPA (USA)
Manitoba Hydro (Canada)
Transpower (New Zealand)
SSE (UK)
Zhejiang EPRI (China)
Amprion (Germany)

Case Studies

Real-world utility examples

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Travelling Wave Protection Testing

Public Service Company of New Mexico

- Divided 345 kV series compensated line into 2 segments at a new switching station to accommodate an interconnector
- Would result in ~150% overcompensation of first section of line
- Involved SEL Engineering Services to assist in developing adequate protection and coordination

Travelling Wave Protection Testing

- Original plan to use current differential for main protection and T400L for monitoring
- Factory Acceptance Testing at SEL with the RTDS Simulator

[4]

SEL-T400L and SEL-411L relays ⟷ RTDS Simulator

Travelling Wave Protection Testing

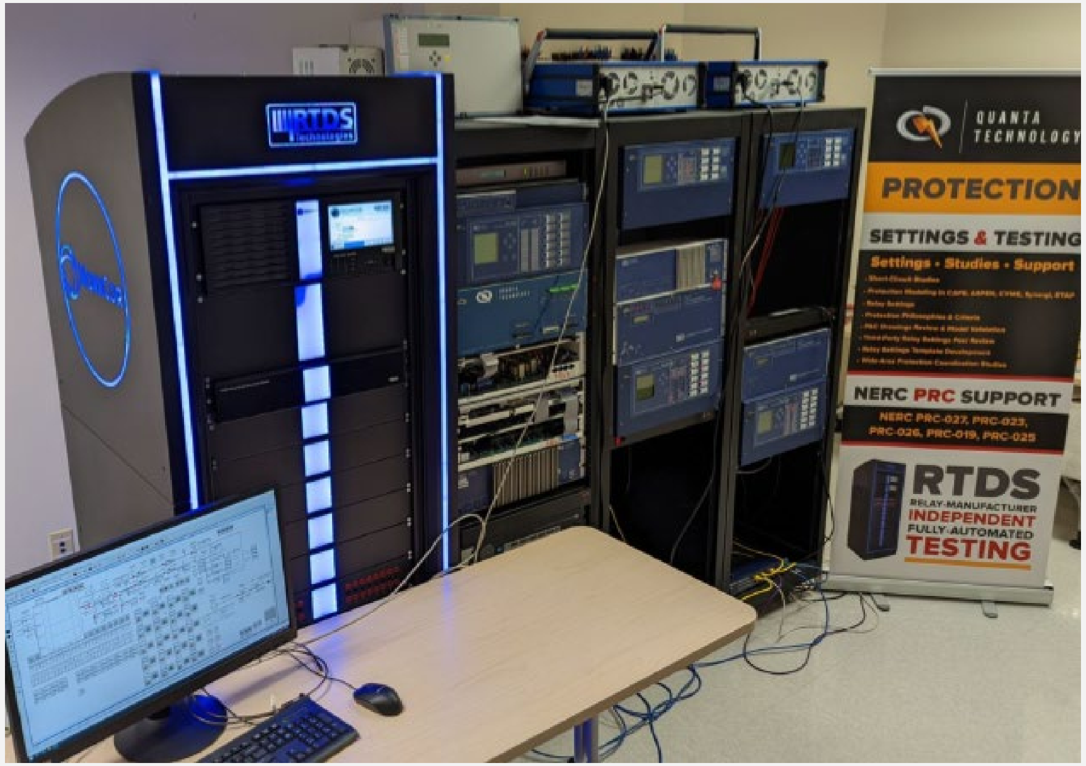
- HIL testing revealed 600 microsecond operation time for a midline single-phase fault
- Traveling wave fault locator reported the fault location to within 0.02 miles on a 33.1 mile line
- Gave PNM the confidence to deploy T400Ls with direct tripping – ***first utility in the world to use traveling-wave based protection with live tripping to CBs***

T400L relays installed in the substation [4]

Impacts of Renewable Energy on Protection

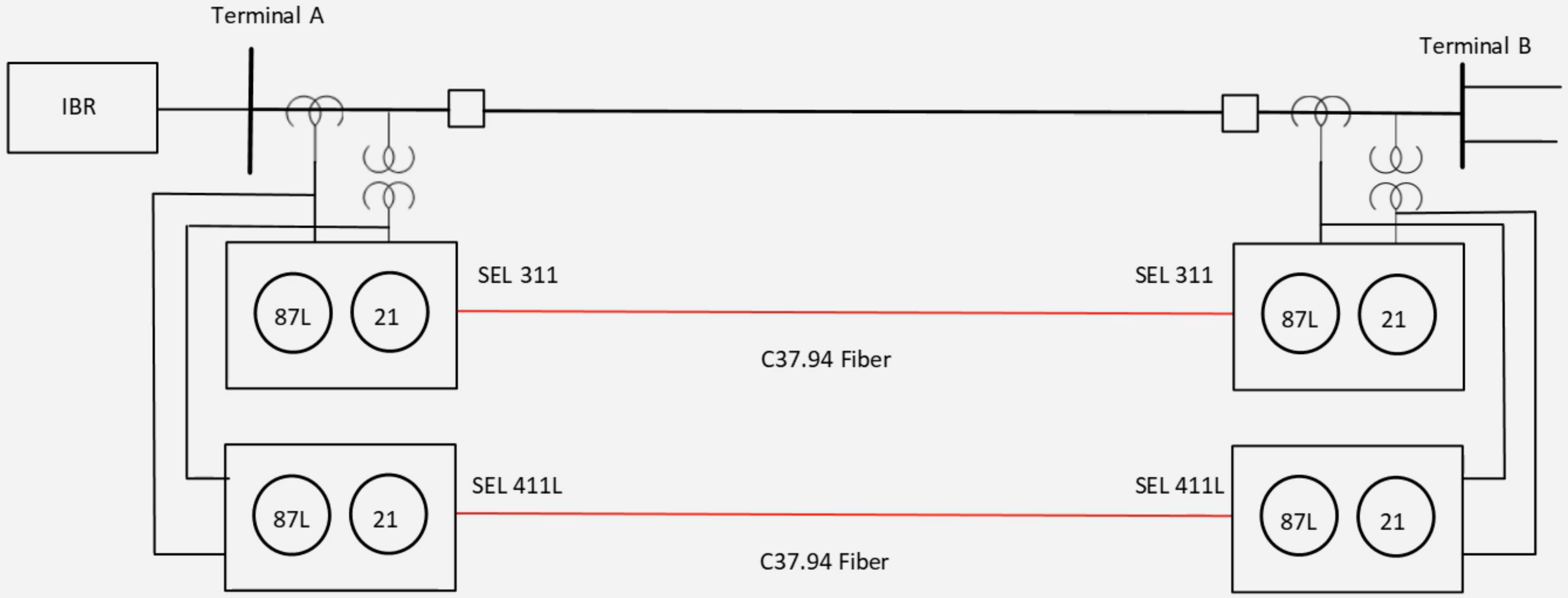
Quanta Technology

- Testing protection on a 345 kV series-compensated line tied to a Type IV wind farm facility
- Impacts of inverter-based resources on line protection:
  - Overcurrent – Not enough current; difficult to provide sensitivity and selectivity
  - Directional – Suppressed negative sequence current; difficult to detect asymmetrical faults
  - Distance coordination – Trip time and zone coordination is impacted



[5]

Impacts of Renewable Energy on Protection



[5]

- Modelled line, wind farm, and converter controller in RSCAD
- Tested SEL 411L and 311L relays – elements 87L (differential) as primary protection, 21 (distance) as back-up

Impacts of Renewable Energy on Protection

COMTRADE recording of A-G fault

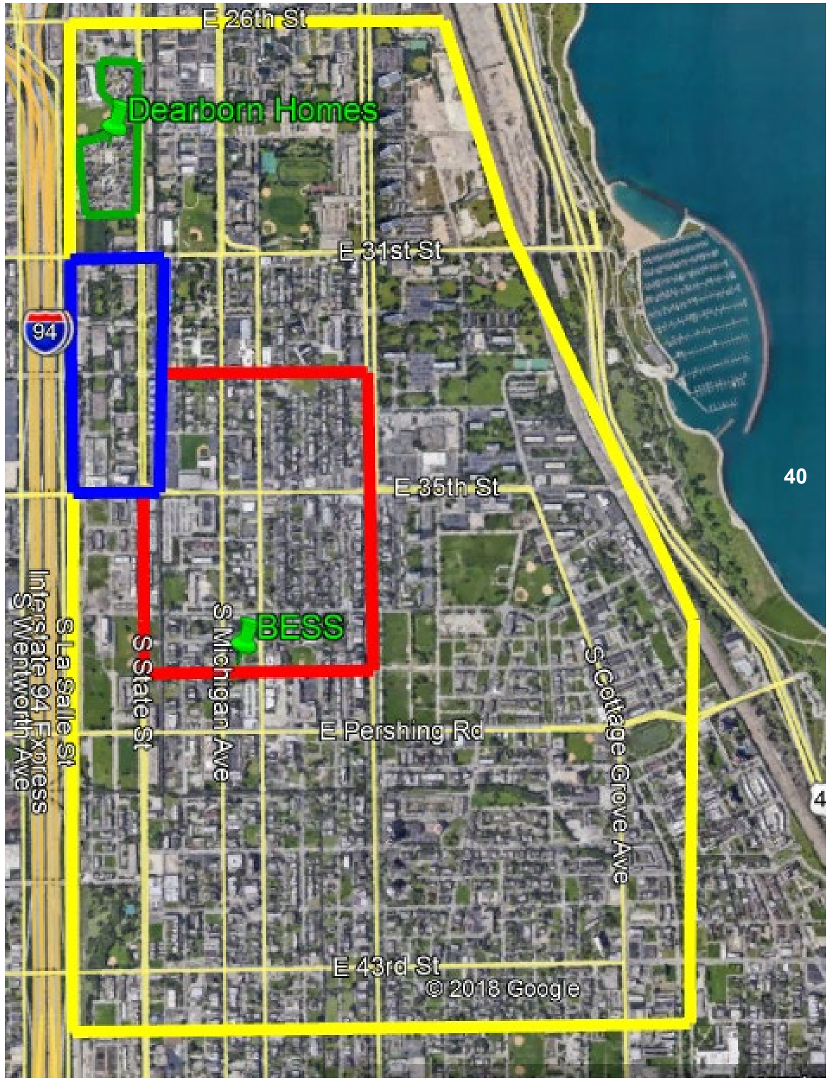
- Varied fault type, location on line, inception angle, and resistance
- 87L element passed all test cases
- 21 element did not pass the tests
  - No negative sequence current injection from IBR
  - Low fault current magnitude
  - Loop selection error in relay
- Worked with manufacturer to improve relay performance – further work required to achieve secure operation through all test cases

[5]

ComEd's landmark microgrid project: Bronzeville

- ComEd, an Exelon company, serves over 4 million customers in northern Illinois (incl. Chicago)

- Bronzeville Community Microgrid (BCM) enables a green, resilient, sustainable neighborhood for consumers



Green- Dearborn Homes

Blue - IIT

Red- BCM Footprint

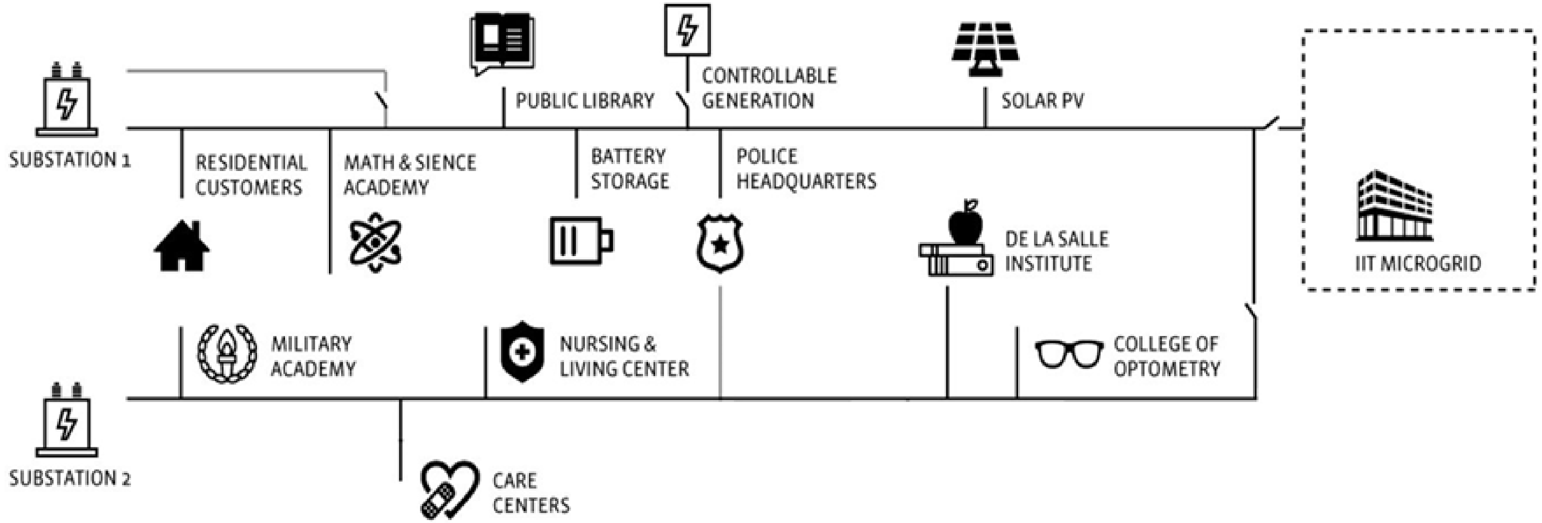
Yellow – Phase I Solar Boundary

Source: ComEd [6]

Bronzeville Community Microgrid

- 7 MW aggregate load, serving approximately 1,000 residences, businesses and public institutions
- Powered by DERs –

  750 Kw solar PV (owned by Chicago Housing Authority)
  500 kW/2MWh battery energy storage (owned by ComEd),
  4.8 MW controllable generation (owned by Enchanted Rock)
- Microgrid master controller is being tested in the ComEd Grid Integration and Technology Lab
- Can cluster with IIT Campus Microgrid – one of the most advanced urban microgrid clusters in the USA



Source: ComEd [6]

ComEd Grid Integration and Technology (GrIT) Lab RT-HIL Facility

Commissioned in 2018 | Located at Maywood, Illinois

Major project areas:

- HIL testing and validation of emerging technologies such as microgrid controller, DER management system, distribution state estimation
- Protection and relay testing
- Cybersecurity projects

Several Microgrid projects in Collaboration with Department of Energy (DOE), National Science Foundation (NSF), Universities, and National Laboratories

RTDS is the heart of RT-HIL test setup

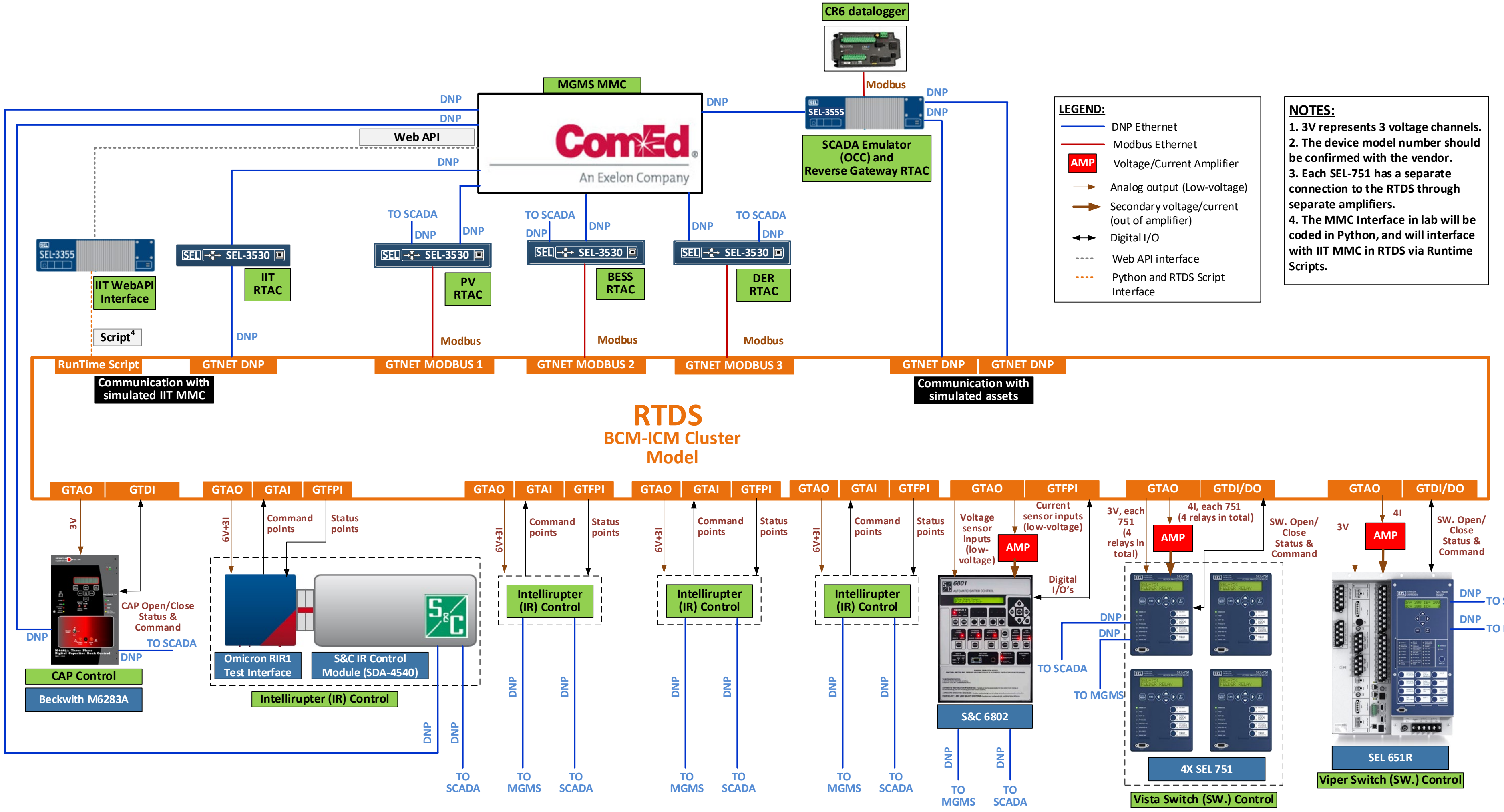
Source: ComEd [6]

Microgrid Management System (MGMS) Testing

- MGMS is a microgrid master controller (MMC) that monitors, manages, and operates the microgrid assets.
- **Key functionalities**
  - ❑ **Microgrid Optimization Module:** Decides the optimal operating plan of all microgrid resource for next 24 hours.
  - ❑ **Peak Shaving:** Use dispatchable resources in the microgrid to limit power import from the main grid.
  - ❑ **Solar Battery Coordination (SBC):** Utilize battery energy storage system (BESS) to compensate intermittent PV generation. PV and BESS together act as a dispatchable resource.
  - ❑ **Planned Islanding:** Disconnect the microgrid from the utility supply.
  - ❑ **Grid Reconnection:** Synchronization and connection of an islanded microgrid to the main grid.
  - ❑ **Black-start and Load Restoration:** After a system outage, MGMS detects the loss of good voltage at point of interconnection and initiates a black-start and restoration of the microgrid by utilizing the local DERs.

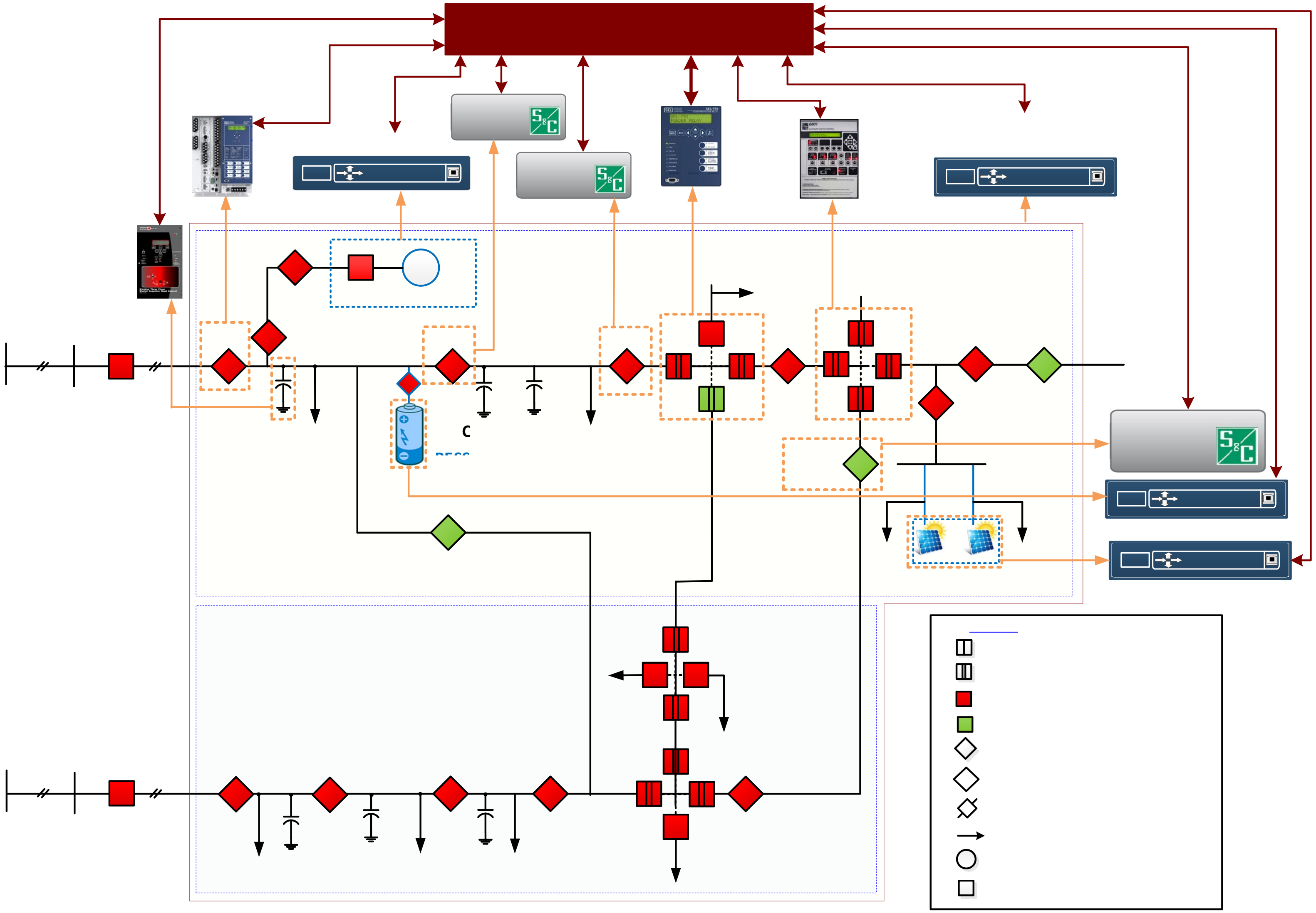
Source: ComEd [6]

MGMS HIL Test Setup: Components and Connections



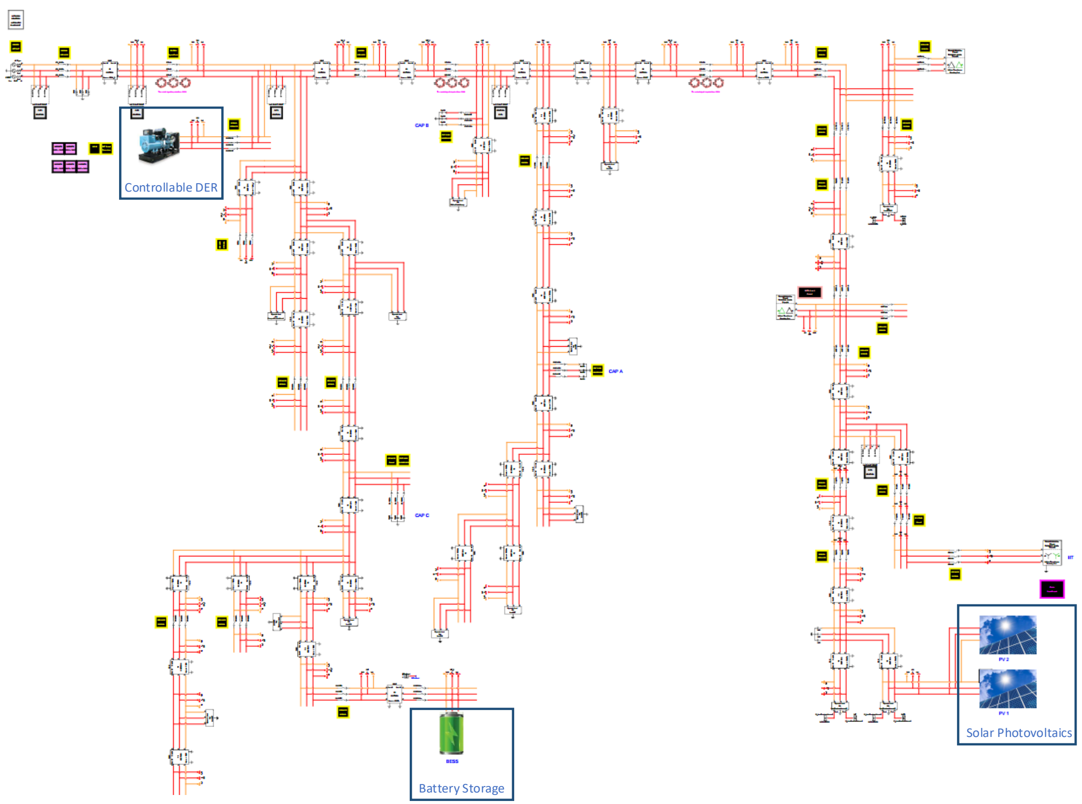
Source: ComEd [6]

MGMS HIL Test Setup: Detailed Diagram

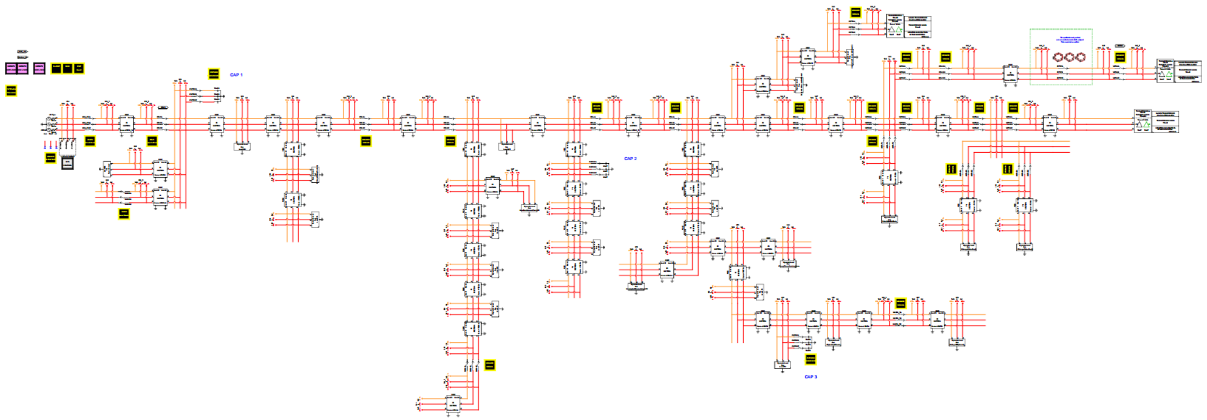


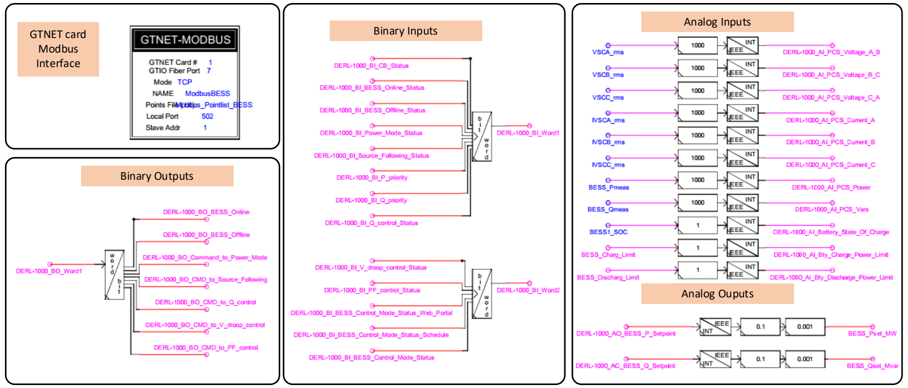
Source: ComEd [6]

Snapshot of BCM Model in RTDS



SS1 of BCM model in RTDS

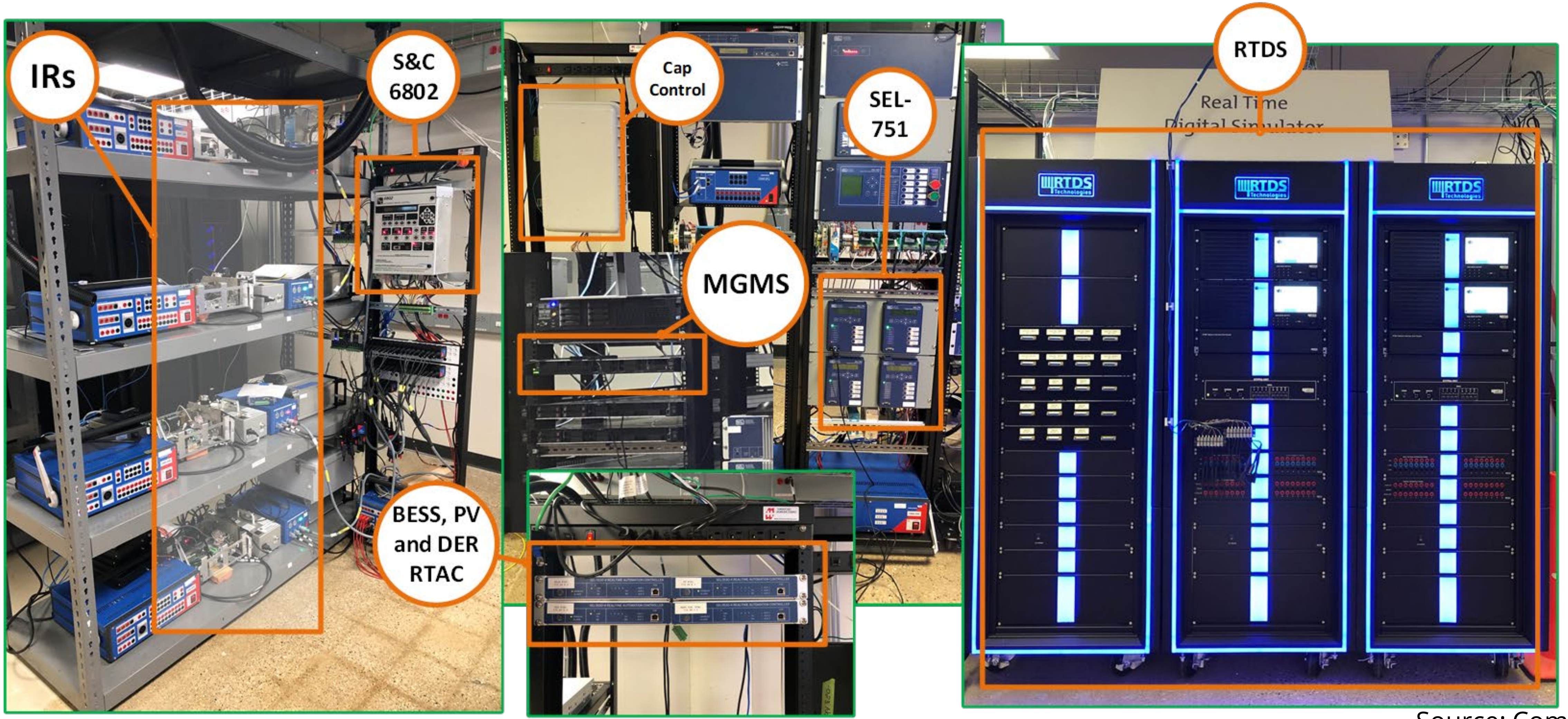

SS2 of BCM model in RTDS



Modbus TCP interface in RTDS for RTAC

Source: ComEd [6]

CHIL Testbed in ComEd's GrIT lab



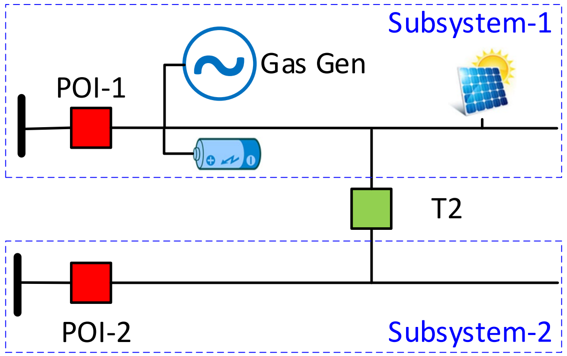
Source: ComEd [6]

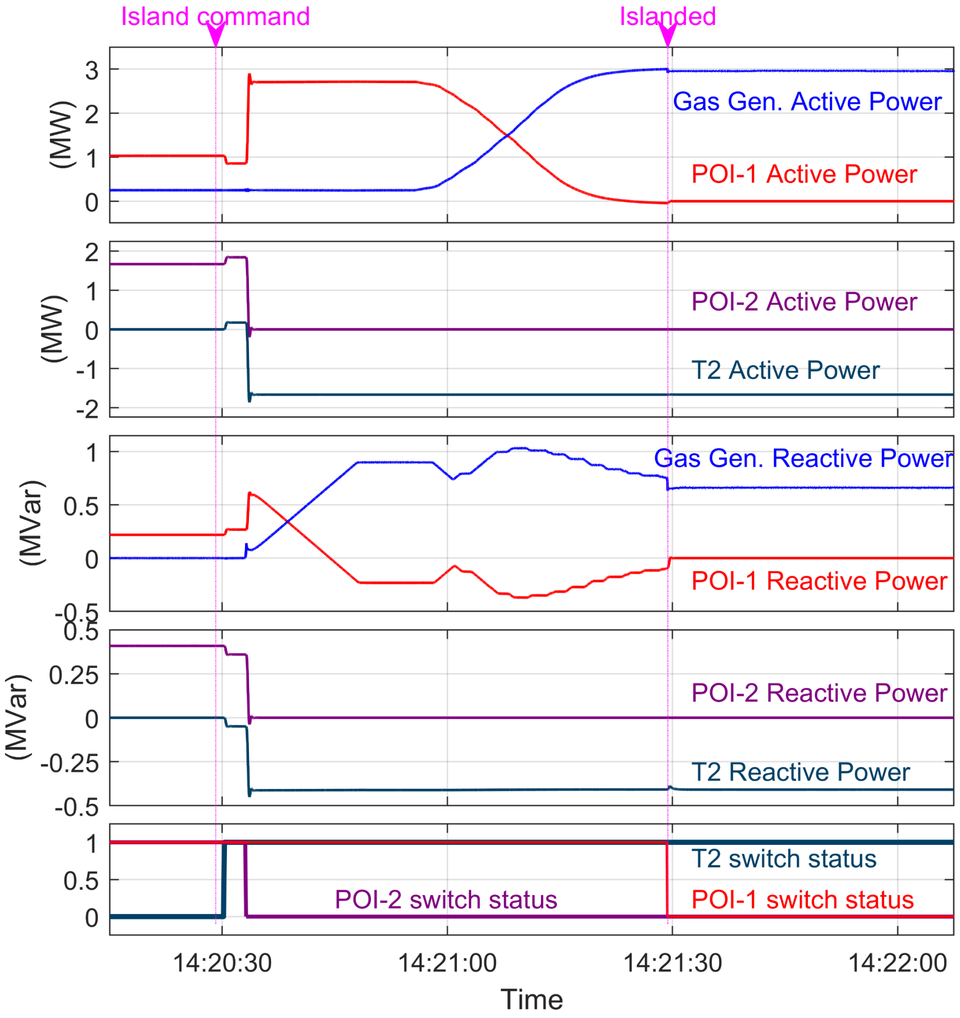
MGMS Functionality Testing Result

Planned Full Islanding

Island the entire BCM from the main grid.

- **Step 1:** Load transfer from lower feeder to upper feeder (Close Tie switch T2 and Open POI switch POI-2)
- **Step 2:** MGMS takes control over the Gas Generator. Turn it ON, if it was offline.
- **Step 3:** Ramp active and reactive powers of gas generator, to pick of load of BCM.
- **Step 4:** Open POI-1 when power exchange at VPL6 is close to zero to island BCM.
- **Step 5:** Change mode of operation of 'Gas generator' to 'grid-forming mode'.

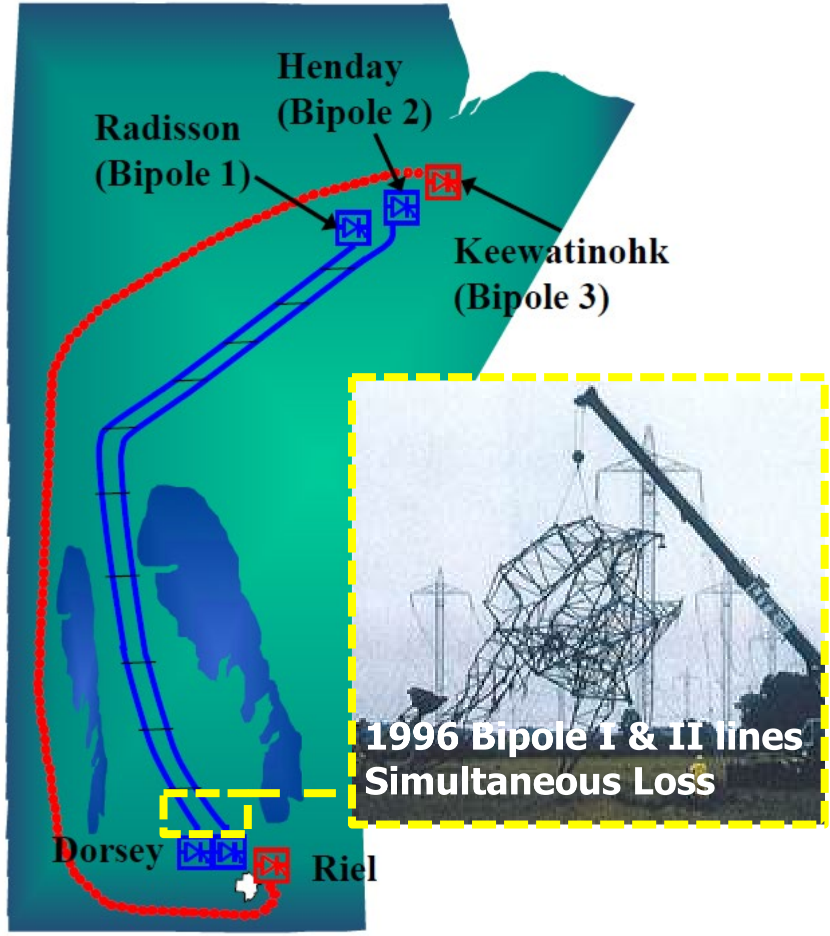




Source: ComEd [6]

Manitoba Hydro: An innovative utility facing operational challenges

Manitoba Hydro



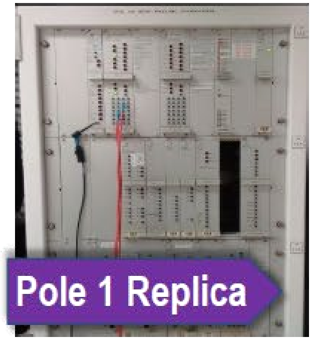
- Three LCC-based HVDC bipoles ranging from ~900-1300 km
- Multi-egress and multi-infeed – three rectifiers in electrical vicinity, three inverters feeding into tightly-coupled AC system with low short circuit capacity and system inertia
- High Multi-Infeed Interaction Faction (MIIF)
- Judicious coordination of HVDC recovery strategy vital – potential adverse interactions among bipoles
- **Transient stability & EMT study tools valuable but testing of physical controls irreplaceable & imperative**

Source: Manitoba Hydro [7]

Manitoba Hydro Real-time Simulation Centre

RTDS Fleet (2 Fully Licensed NovaCor & 14 PB5 Racks)

HVDC Control & Protection (C&P) & Auxiliary Equipment Replicas



Source: Manitoba Hydro [7]

HVDC Testing and Commissioning Process

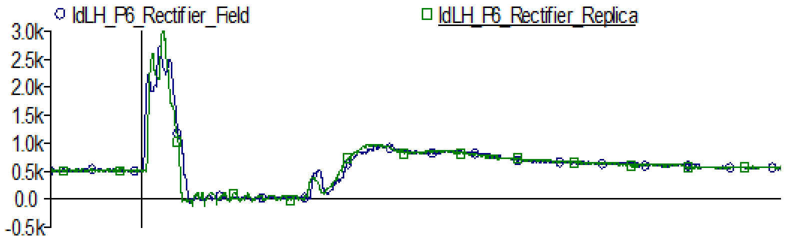
Operation Readiness

Off-Site Activities (Germany)

- Functional / Dynamic Performance Test (FPT/DPT)

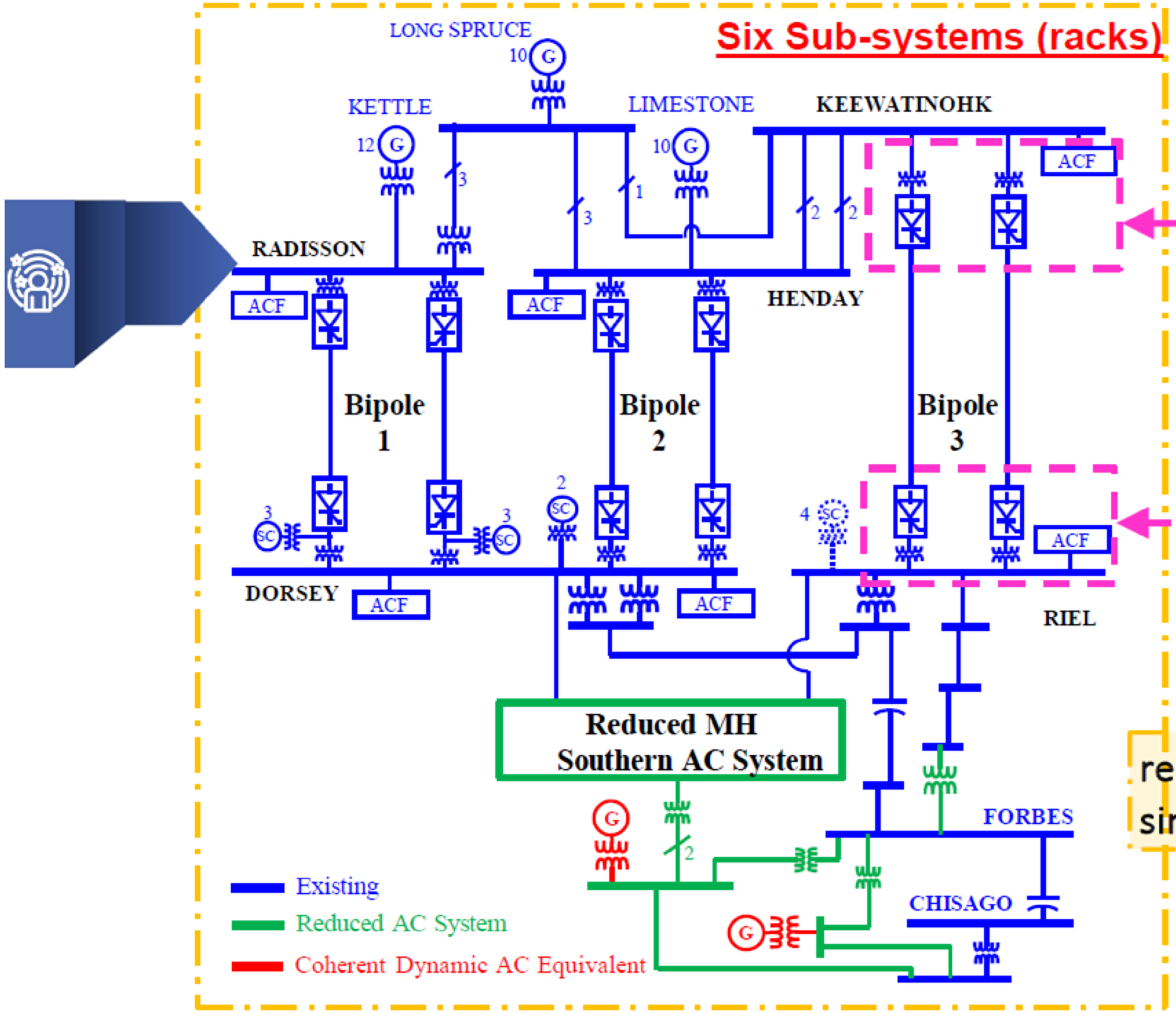
On-Site Activities (MB, Canada)

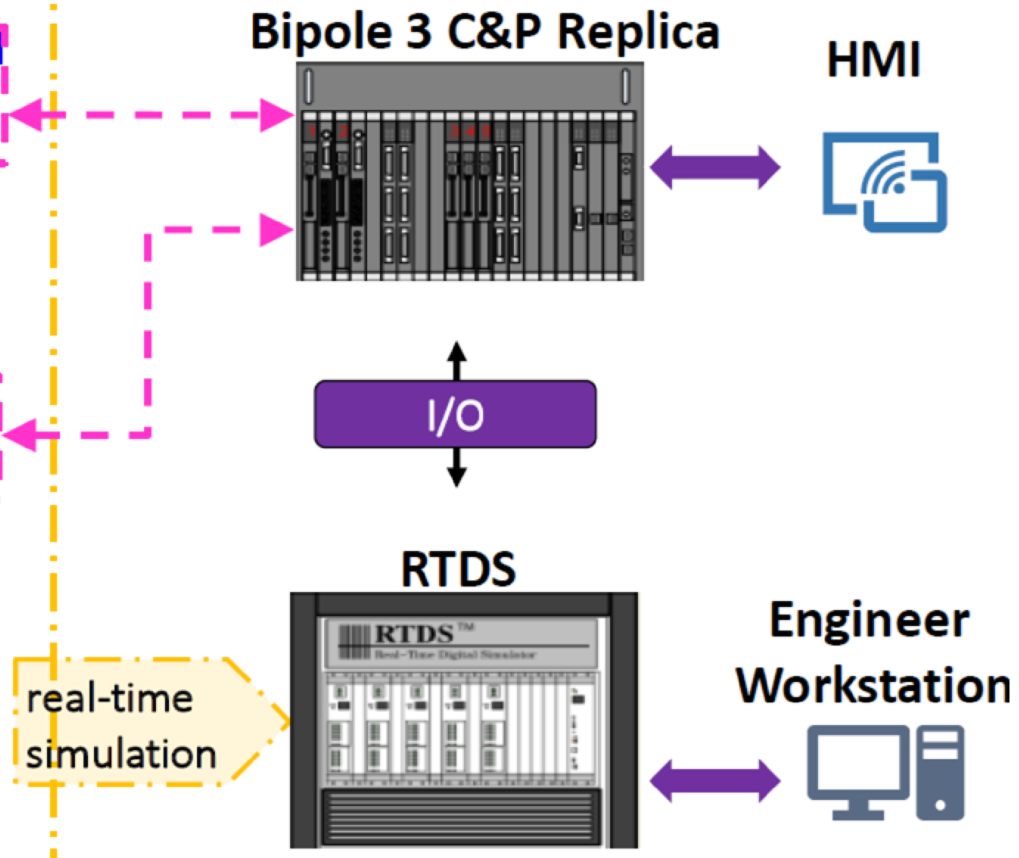
- Control & Protection (C&P) Replica Test (CTS)
- Pre-Commissioning (Pre-EF3) Test using System Forecast Condition
- Staged Faults Risk Assessments
- Test Review / Acceptance / Model Validation
- Trial Operation



Source: Manitoba Hydro [7]

Large-Scale Multi-Infeed HVDC HIL Simulation





Source: Manitoba Hydro [7]

The value of HIL testing for a wide range of projects

- **Bipole 3 in Multi-Infeed HVDC**
  - De-risked onsite commissioning of bipole 3
  - Significant schedule reduction (~3 months) and outage cost savings
  - Fast and secure integration

- **World's 1st HVDC controlled switching**
  - De-risked HVDC converter transformer – emerging technology
  - Substantial life-cycle cost reduction
  - Over $5 million saved
  - CEA Centre of Excellence Award for Innovation

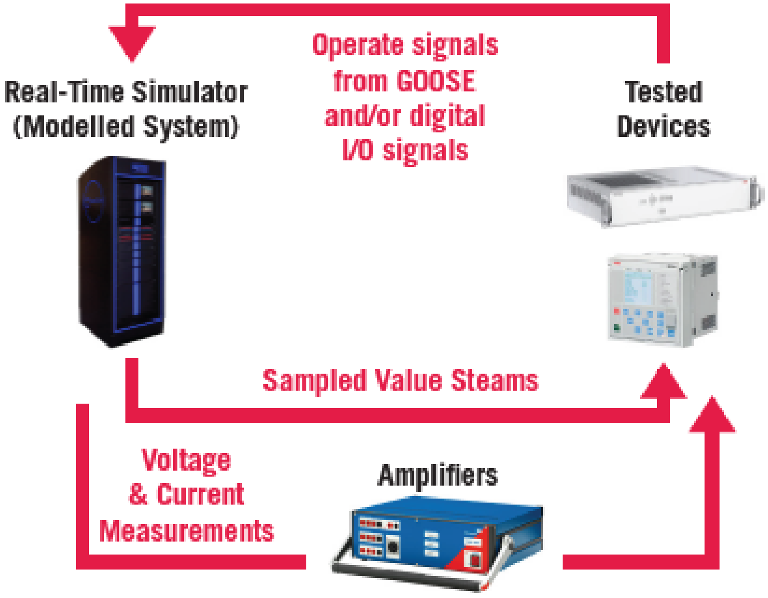
- **500 kV Fixed Series Compensation Inter-Tie**
  - De-risked crucial SPTR
  - Fast, reliable, secure, safe restoration of market access

- **Manitoba-Minnesota 500 kV Inter-Tie Protection**
  - De-risked complex protection schemes
  - Secured "buy-ins" and strengthened reputation

Source: Manitoba Hydro [7]

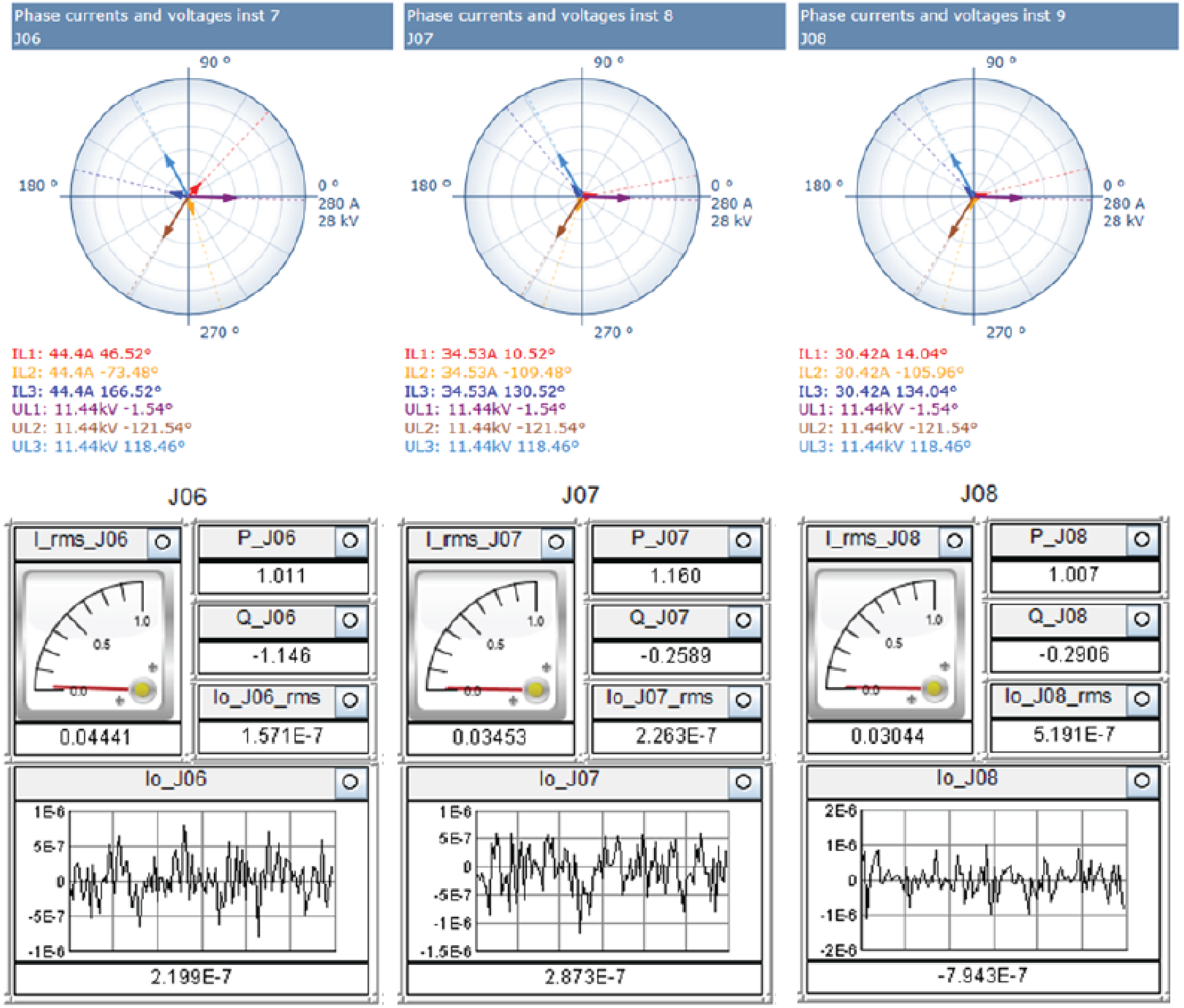
Testing distribution automation at ABB

- SSC600 – centralized substation protection and control – IEC 61850 and IEC 60870-5-104 compliant
- Developed simplified model of utility substation and surrounding network for HIL testing
- Verified interoperability of centralized substation control and REF615 feeder protection relay



Testing distribution automation at ABB

- Compared SV and GOOSE messages measured/issued by device to theoretical system values
- Verified earth fault protection operation for various fault positions, types, serverities
- Verified transformer differential protection operation with HV and MV-side faults
- Verified busbar differential protection and load shedding operation after frequency decay



Large-scale simulation: how big can we go?

NARI/SGEPRI (China)

- Can simulate >3600 three-phase buses and 20 HVDC links
- Validate wide area protection and control schemes, AC and multiple HVDC coordination, system stability control

Thank you!

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