Leveraging Real-Time EMT Simulation Technology To Accelerate Large-Scale IBR Integration

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Electromagnetic Transient Simulation Workshop

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Introduction/Context

About OPAL-RT Technologies

- Founded in 1997 in Montreal, QC, Canada
- 350+ employees, growing sustainably
- 1000+ customers in all industries around the world
- 20% of annual revenue re-invested in R&D
- 40% academic, 60% industries
- 90% revenue from electrical and power electronics sectors
- Markets
  - HIL, RCP, real-time laboratories
  - ...and fast off-line and on-line close-to-real-time (cloud) simulation
  - for education, R&D and all industries: energy, power electronic, automobile, off-highway vehicle, aerospace, ships, trains ...

Strong International Footprint

International subsidiaries, offices and Excellence Centers:

- USA (Michigan, Colorado), Germany, France (Paris and Lyon), India, China, Brazil, Australia

Distributors:

- China, Australia, Japan, Korea, Singapore, Israel, Ukraine, Kazakhstan, Oman, Pakistan, Qatar, Turkey, United Arab Emirates , Kingdom of Saudi Arabia

Evolution of Real-Time EMT Simulators

2009
1 cabinet, 3 PC with 24 cores.
For 350 3-ph buses
950 nodes !

1975
30000 square feet Hybrid Simulator

OPAL-RT TECHNOLOGIES **1997**

eMEGAsim
eDRIVEsim,
eFPGAsim
HQ: **HYPERsim**

FPGA Simulator

PC-Based Digital Simulators

Supercomputer based simulators

2023
In-house 500-core HPC Cluster

- 22 * OP5033XG (18 cores)
- 1 * HITACHI 128-core server (2 sockets)
- **4000 bus 3 phase with 300+ real-code DLLs**
- **1s of sim in 3s of real-time in HYPERSIM**

Digital Custom Simulators

Hybrid (Analog/Digital) Simulators

Analog Simulators

1960 1970 1980 1990 2000 2010 2020

Challenges – Historically for EMT simulations

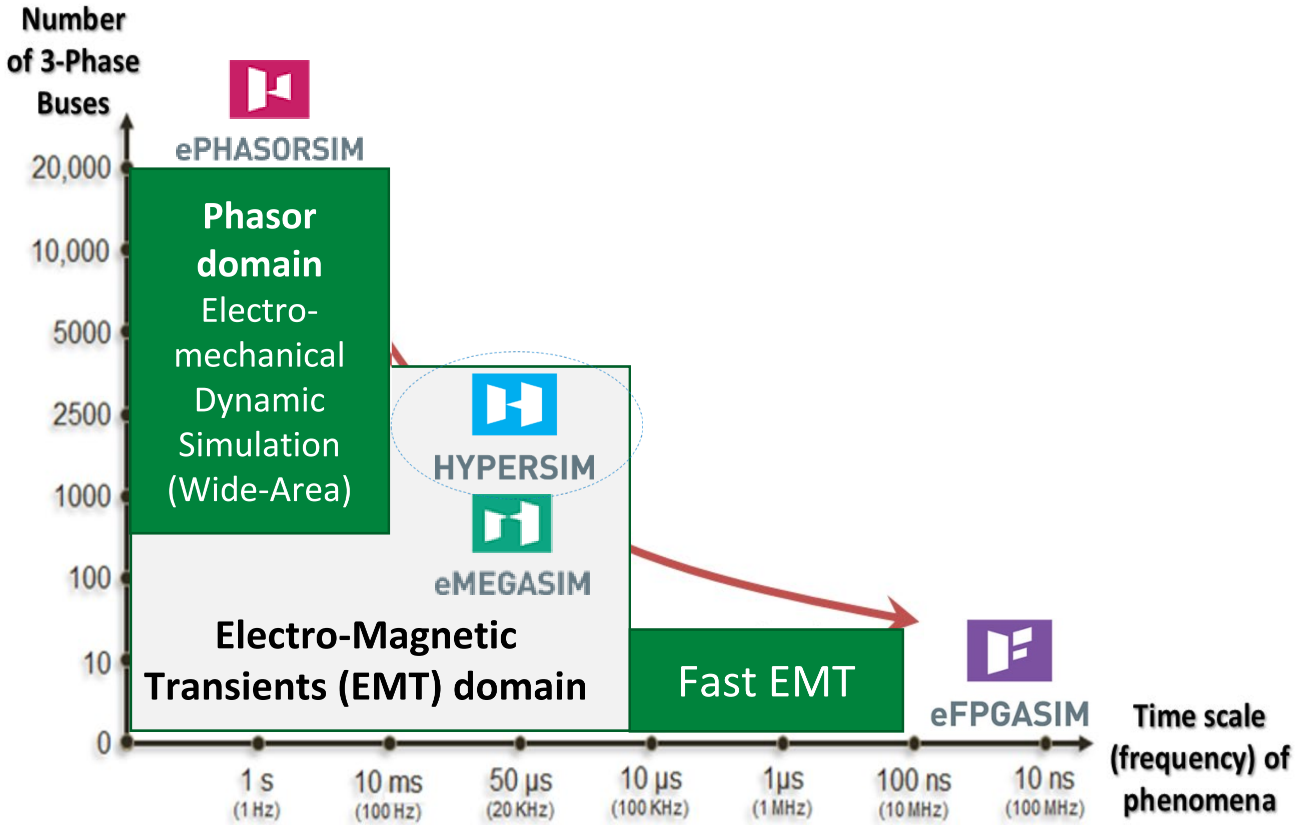
Real-Time EMT Simulation – A Spectrum of Use Cases

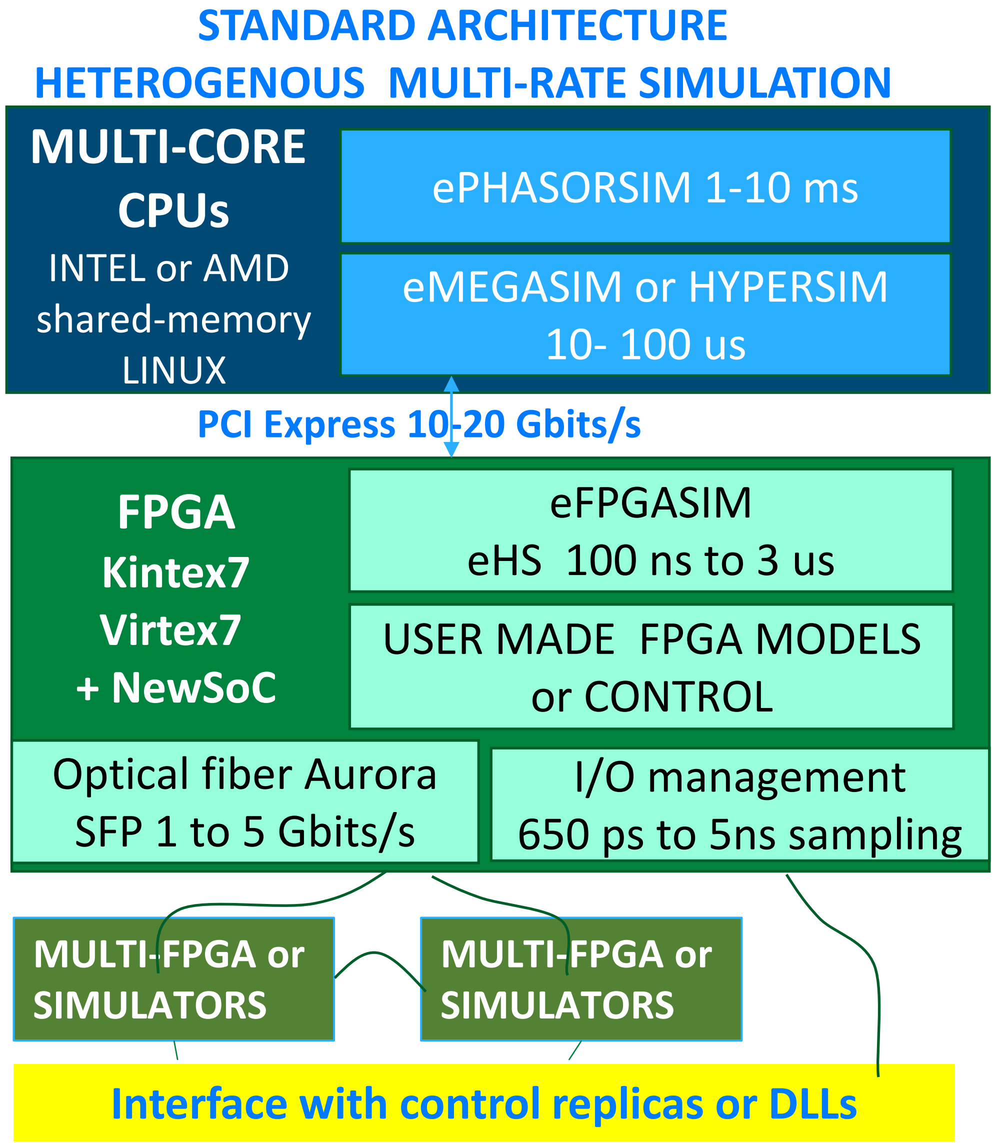
Offline EMT Simulation	Accelerated / Parallel EMT Simulation	Real-Time Simulation	Quasi Real-Time or Faster-Than-Real-Rime Simulation
with **Generic control** models	**SIL** with **real-code** controller emulation	**CHIL** with **control system replicas, PHIL** with **actual DERs**	**Digital Twins** for use in System Operations
• Typical EMT studies • Plant-level equipment stress evaluation	• DER integration studies • Interaction studies • Planning studies	• Protection and control design and testing/validation • Pre-commissioning tests	• Transient Security Assessment / Contingency Analysis • State Estimation to estimate system states every 5-10 min

• OEM controller model validation

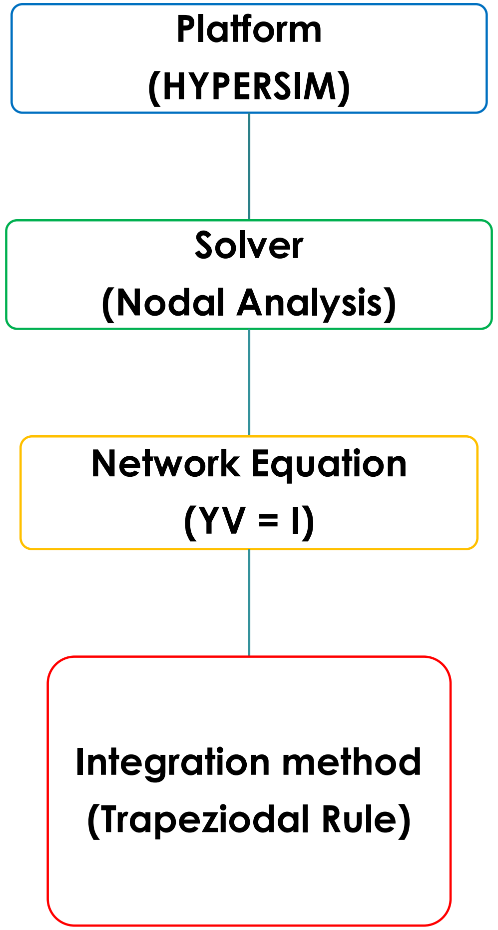
SIL – Software in the loop; CHIL – Controller Hardware in the loop

OPAL-RT's Simulation Tools and System Architecture



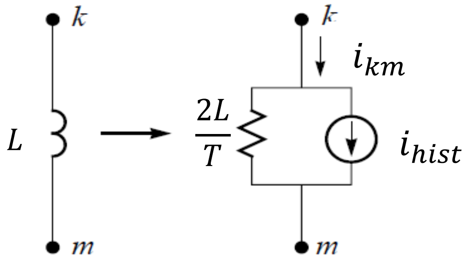


HYPERSIM - Capabilities for EMT Simulation



Network model split automatically into different CPU cores using a Constant Parameter Line that has a propagation delay greater than the simulation timestep

$$v_{km}(t) = L\frac{di_{km}(t)}{dt}$$

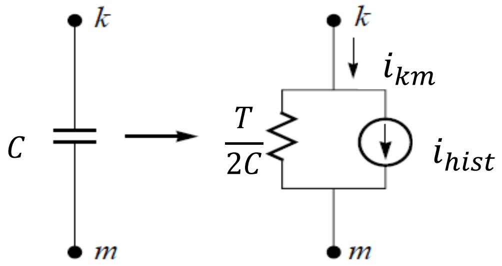


$$i_{hist}(t-T) = i_{km}(t-T) + \frac{v_k(t-T) - v_m(t-T)}{R_{eq}}$$

$$R_{eq} = \frac{2L}{T}$$

$$\mathbf{Y}\,\mathbf{V} = \mathbf{I}$$

$$i_{km}(t) = C\frac{dv_{km}(t)}{dt}$$



$$R_{eq} = \frac{T}{2C}$$

$$i_{hist}(t-T) = -i_{km}(t-T) - \frac{v_k(t-T) - v_m(t-T)}{R_{eq}}$$

Y : admittance matrix,
V : vector of node voltages
I : vector of injected currents

Interpolation for accurate simulation of power electronic converters
Iterative Solver for non-linearities (transformer saturation, surge arrester, etc.,)

Supported Hardware Platforms and HPC Compatibility

INTEL and AMD MULTICORE CPUs integrated with XILINX FPGAs and I/O systems

Compatible Simulator Platform from NI

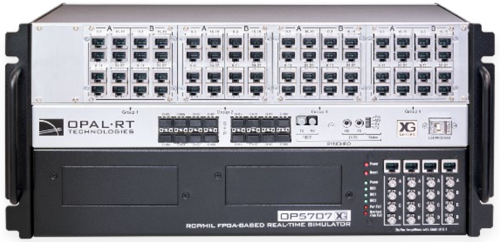
NI PXI FPGA

Compatible with OPAL-RT's FPGA-baser Power Electronics Toolbox (eHS)

Standard Simulator Platforms

OP4510

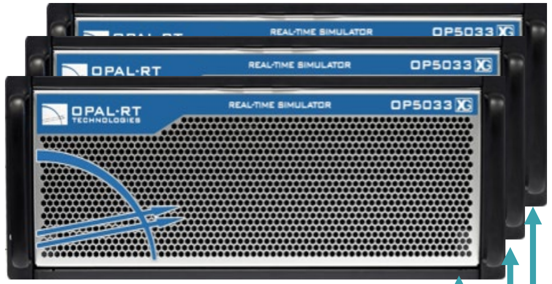
4 Cores | KINTEX7 FPGA



OP5707XG

8 to 16 Cores | INTEL Scalable Gold CPU | VITEX 7 FPGA

In-House High-Performance Computer Cluster



OP5033XG

8 to 64 Cores

5-Gbits/s

HITACHI Server

2-socket 128-Cores

SGI (HP) Supercomputer

100 to 2,000+ Cores

HYPERSIM On Demand

Microsoft Azure

Cloud

ORCHESTRA

Co-simulation

Scalability of hardware based on system size being simulated

Setting up Large-Scale EMT Simulation in HYPERSIM

Network Model Conversion/Import
(Automation through Unified Database and API)

OEM Controller Code Integration
(3 different approaches)

Model Quality Validation
(Different types of tests)

Simulation Studies & Post-Processing
(Scripted execution through API, Scope View for results)

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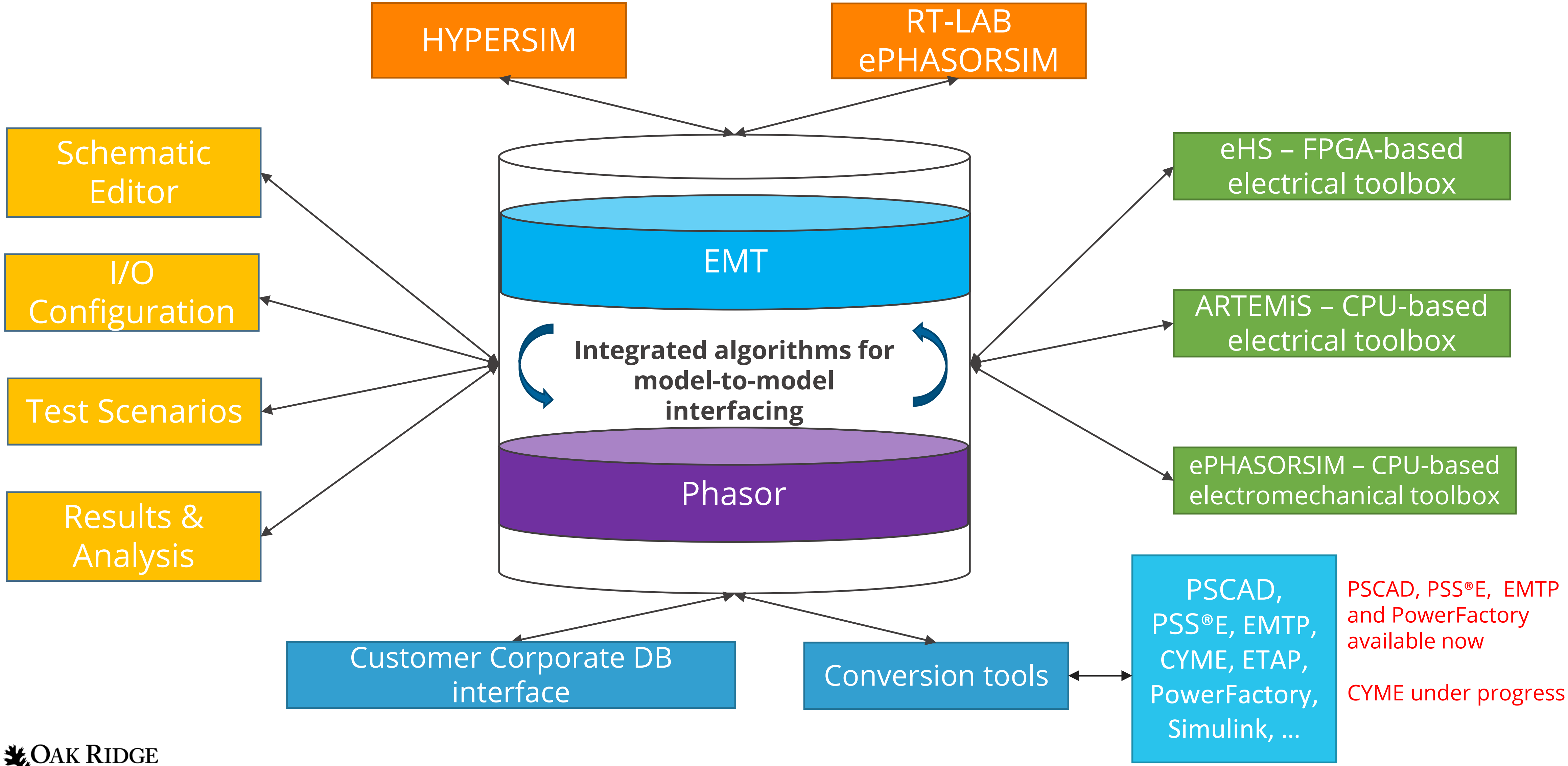
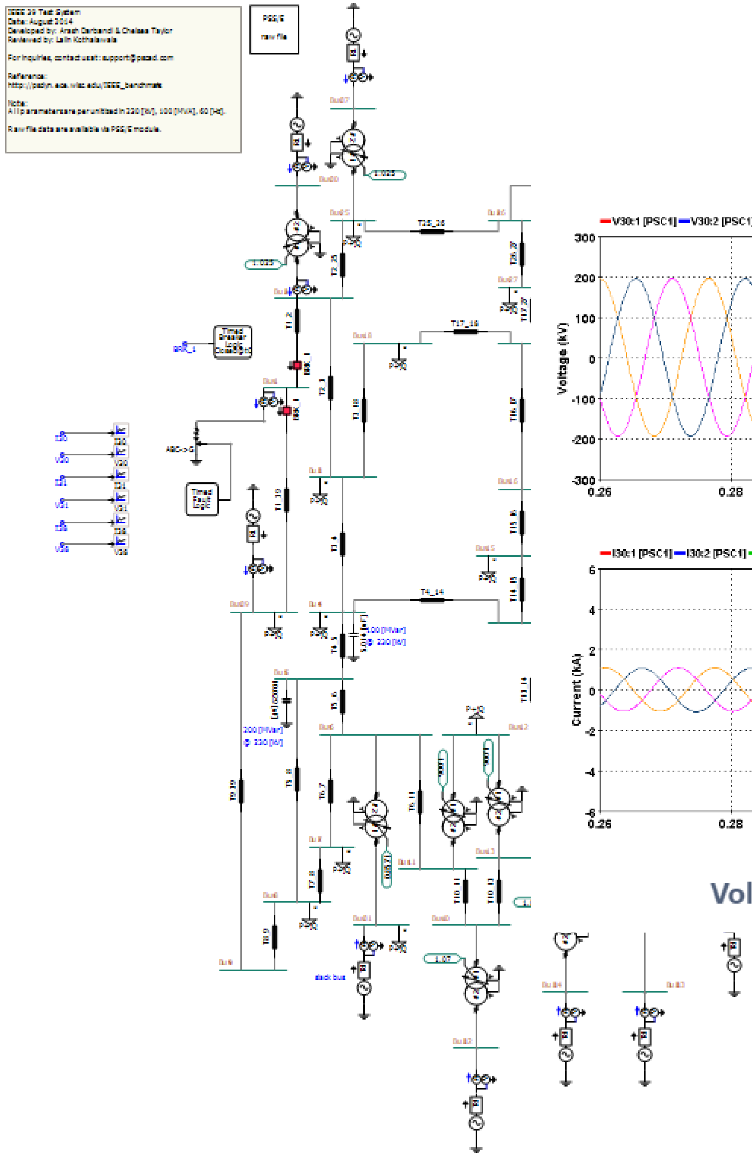
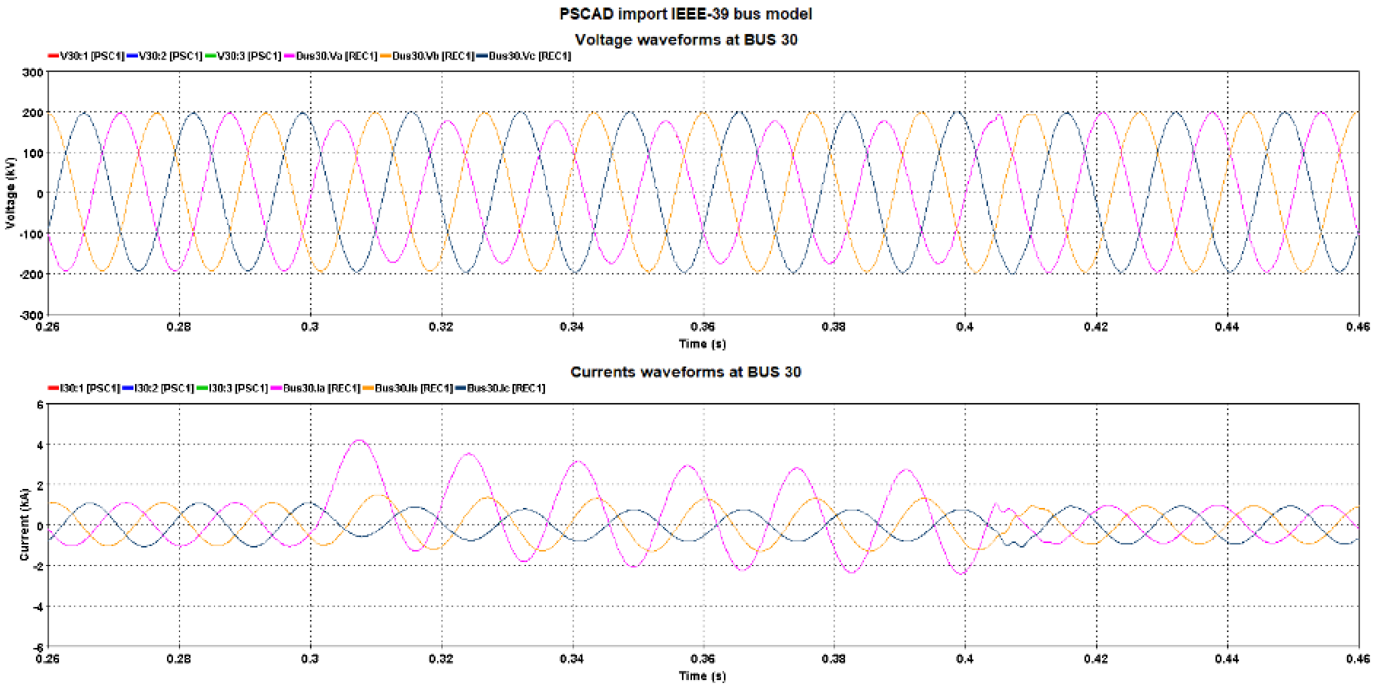
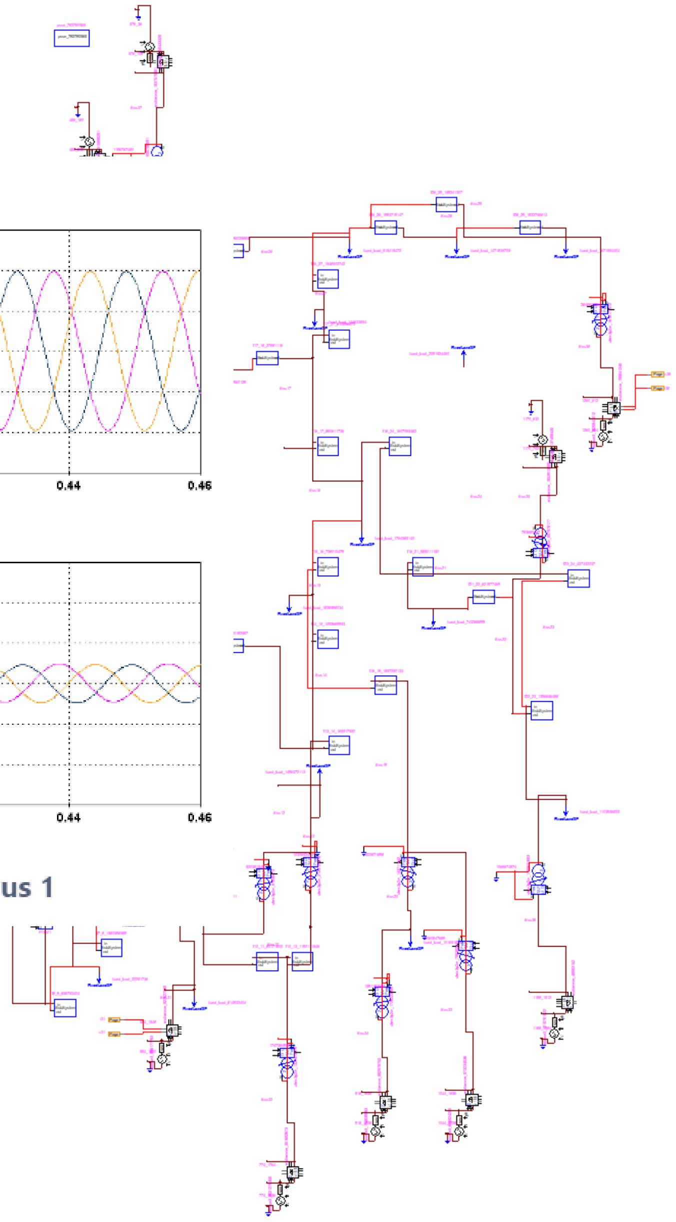
Unified Database for Automated Model Conversion



PSCAD Import into HYPERSIM





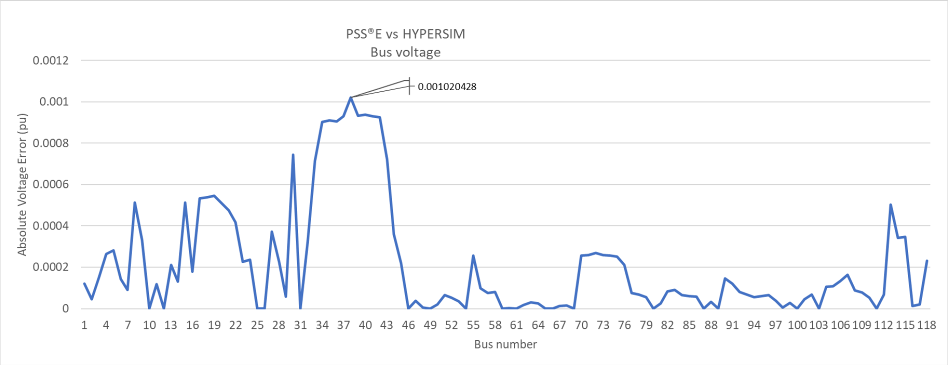


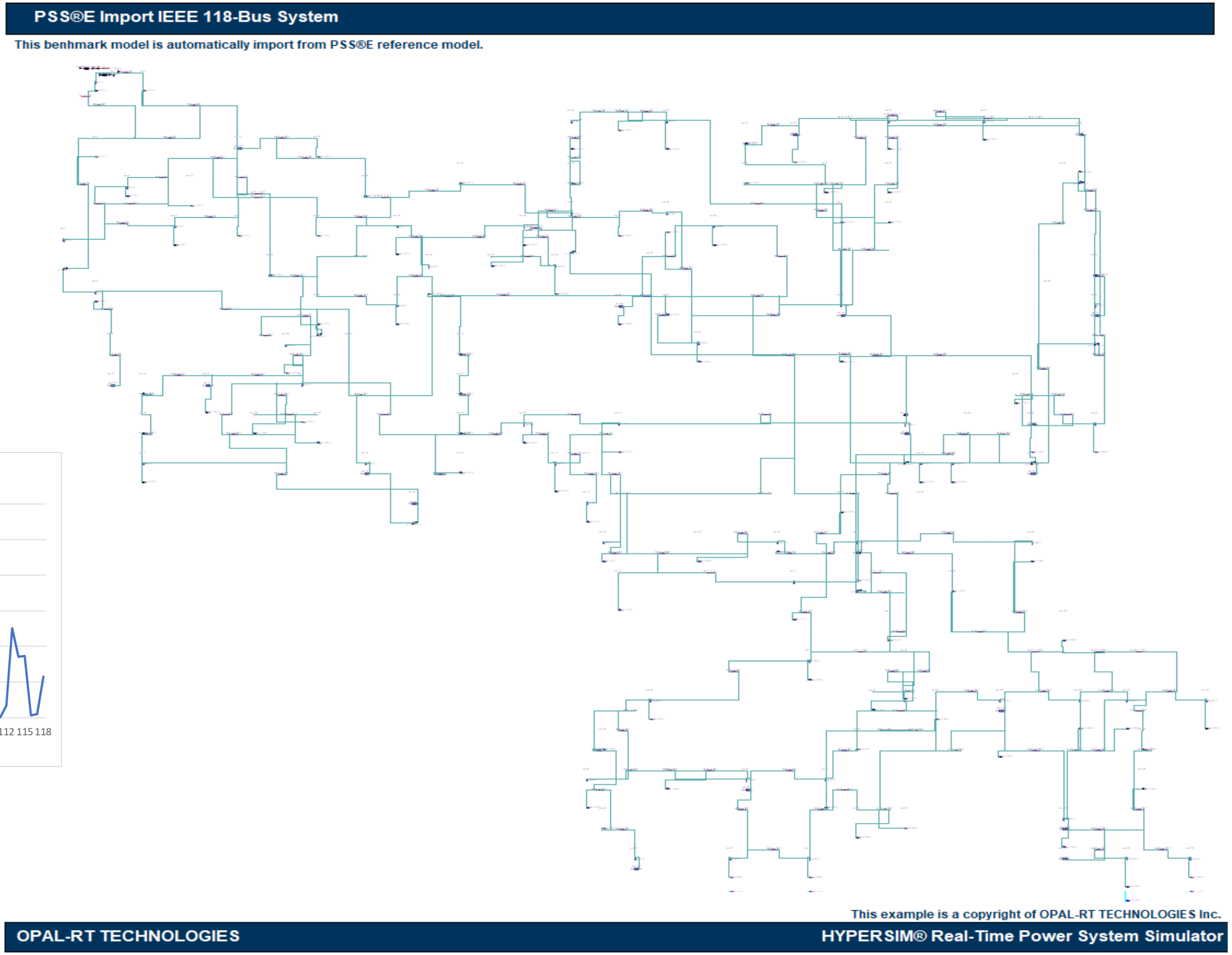
Voltage and currents of Buses 30 with a single-phase to ground fault at Bus 1

PSSE Import into HYPERSIM

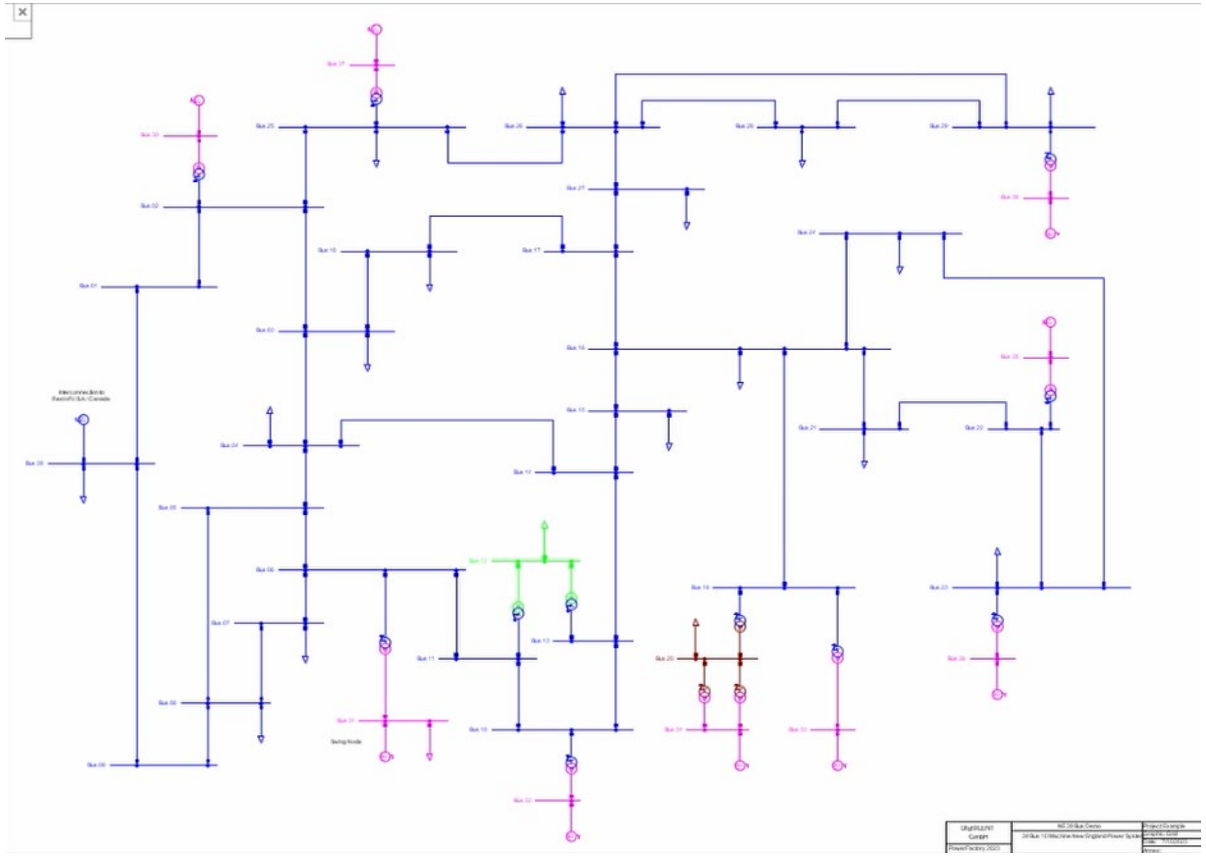
- Machines and controllers are grouped into subsystems
- GPS coordinates can be used to place the components

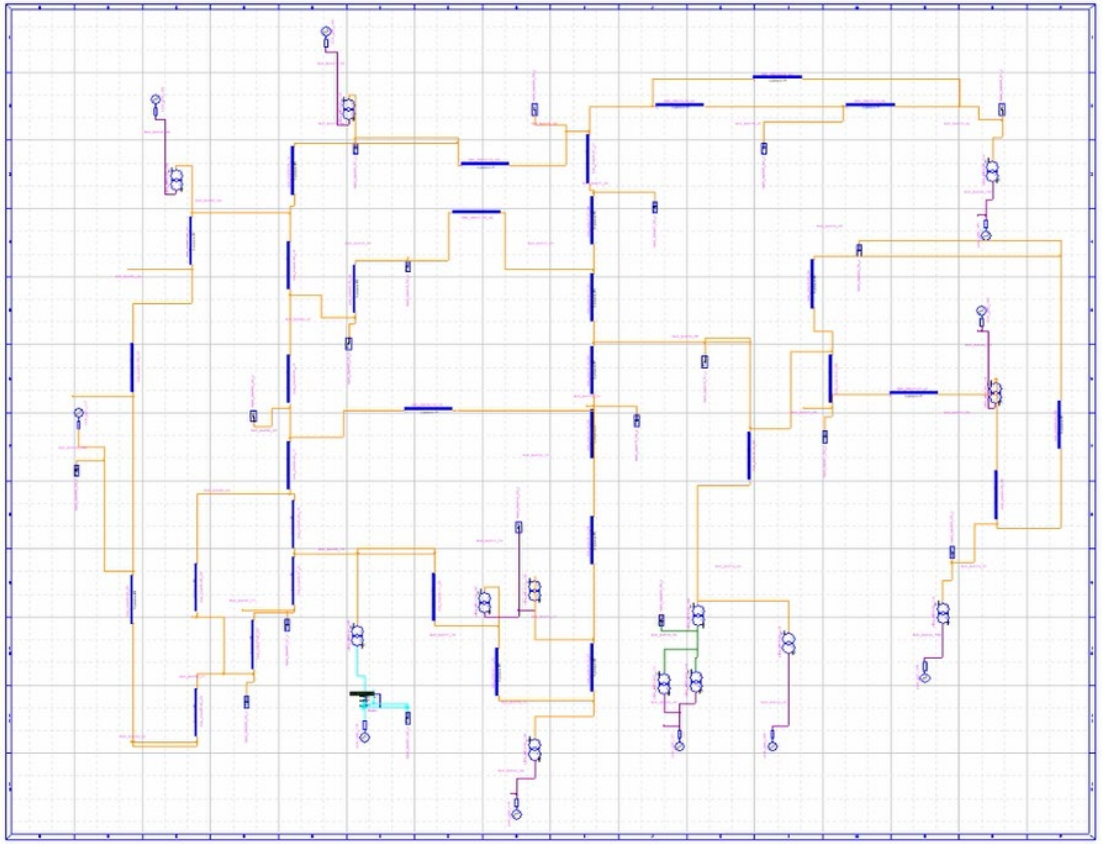
Comparison of Load Flow Errors





PowerFactory Import into HYPERSIM





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Setting up Large-Scale EMT Simulation in HYPERSIM

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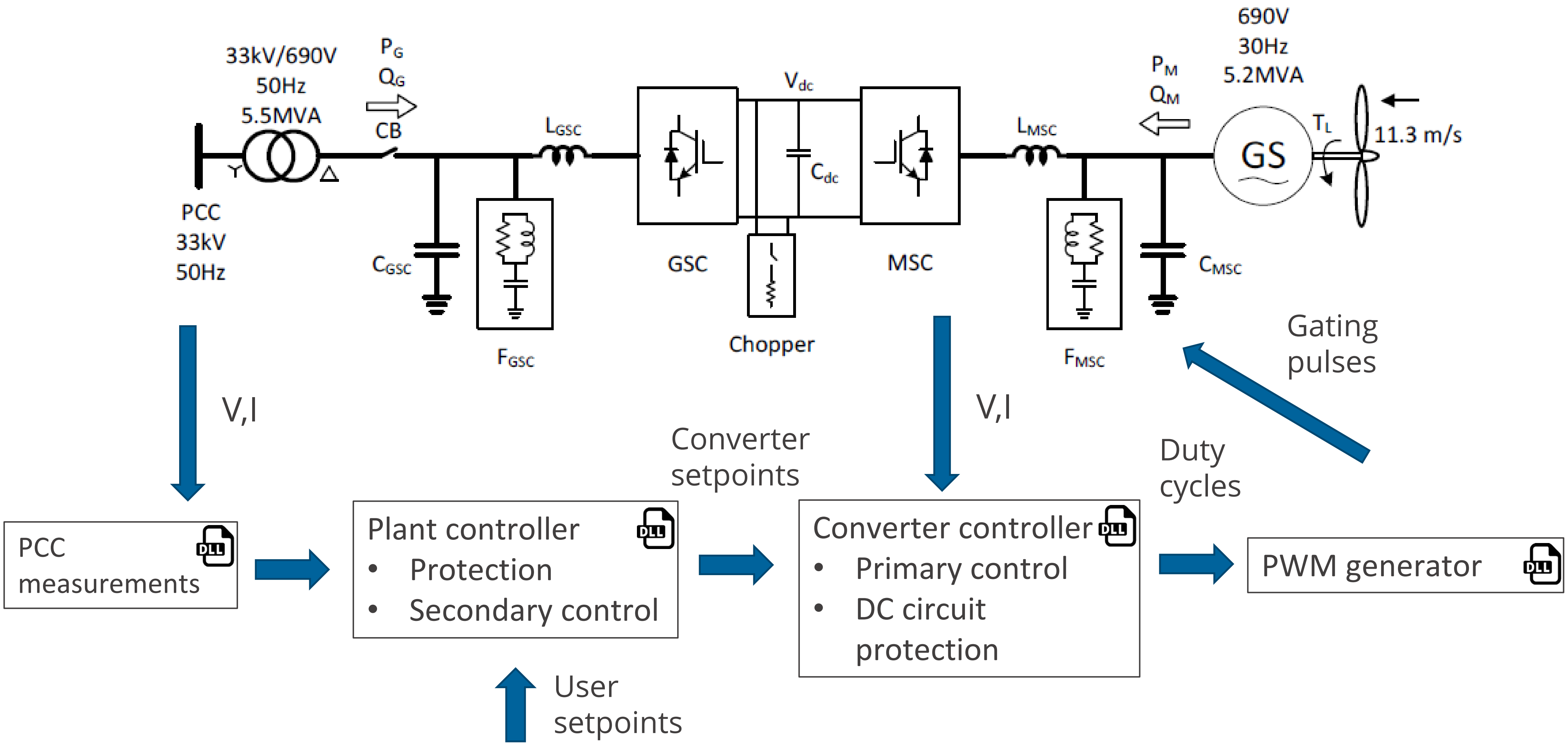
OEM Controller Code Integration with EMT Model

Generalized Conceptual View of Plant-level Model with different functional blocks



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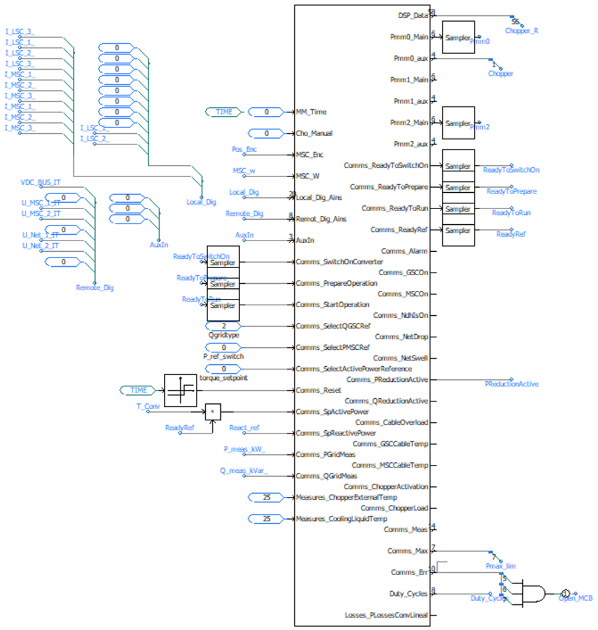
OEM Controller Code Integration in HYPERSIM

Approach 1: Automatic import of controller block (manufacturer code) from PSCAD to HYPERSIM

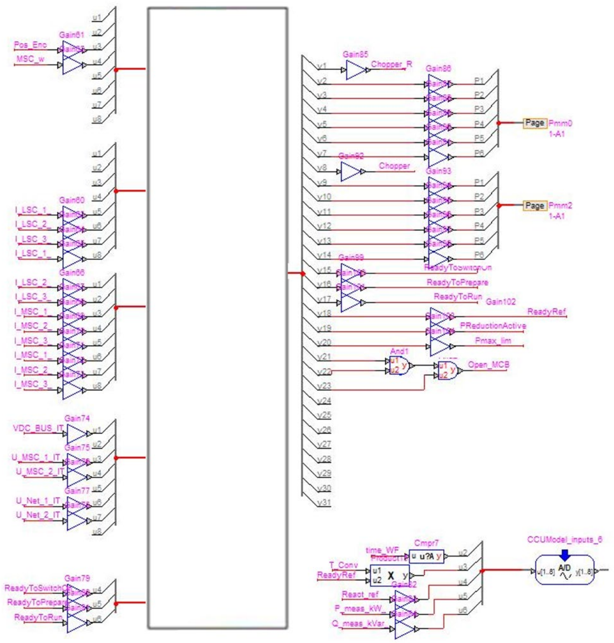
- The generated HYPERSIM block has the same I/Os and parameters as in PSCAD.
- Automated open-loop validation

PSCAD Controller Block



Automatic Import

HYPERSIM Controller Block



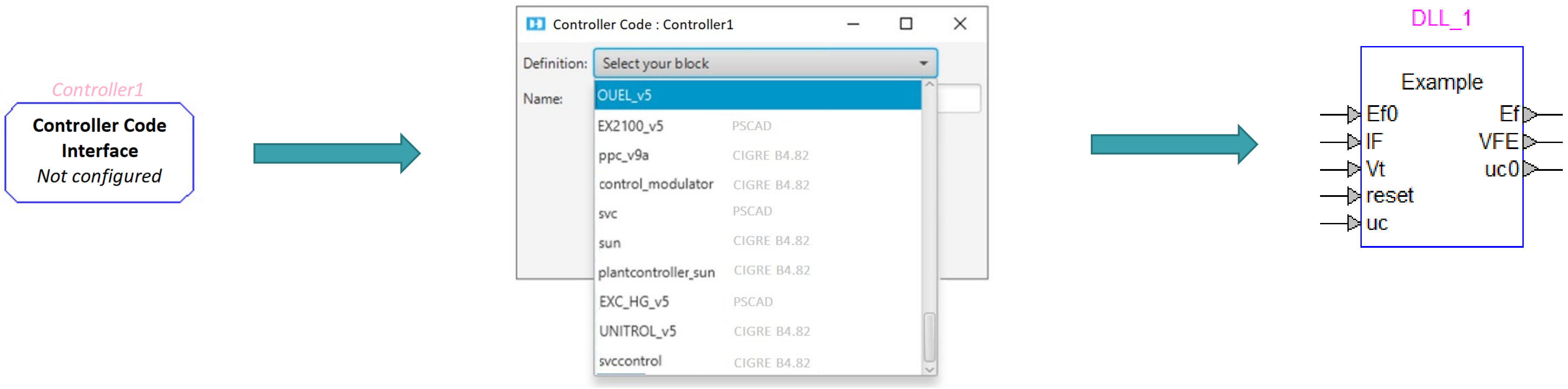
Status of OPAL-RT's product development

- Automation has been tested with success with controller codes from 6 different manufacturers
- Open for collaboration on projects
- Beta version available upon request

OEM Controller Code Integration in HYPERSIM

Approach 2: Automatic import of controller code developed according to standards/industry guidelines*

- Seamless integration
- The controller codes can be executed in real-time, and distributed on parallel processors or on a separate simulator

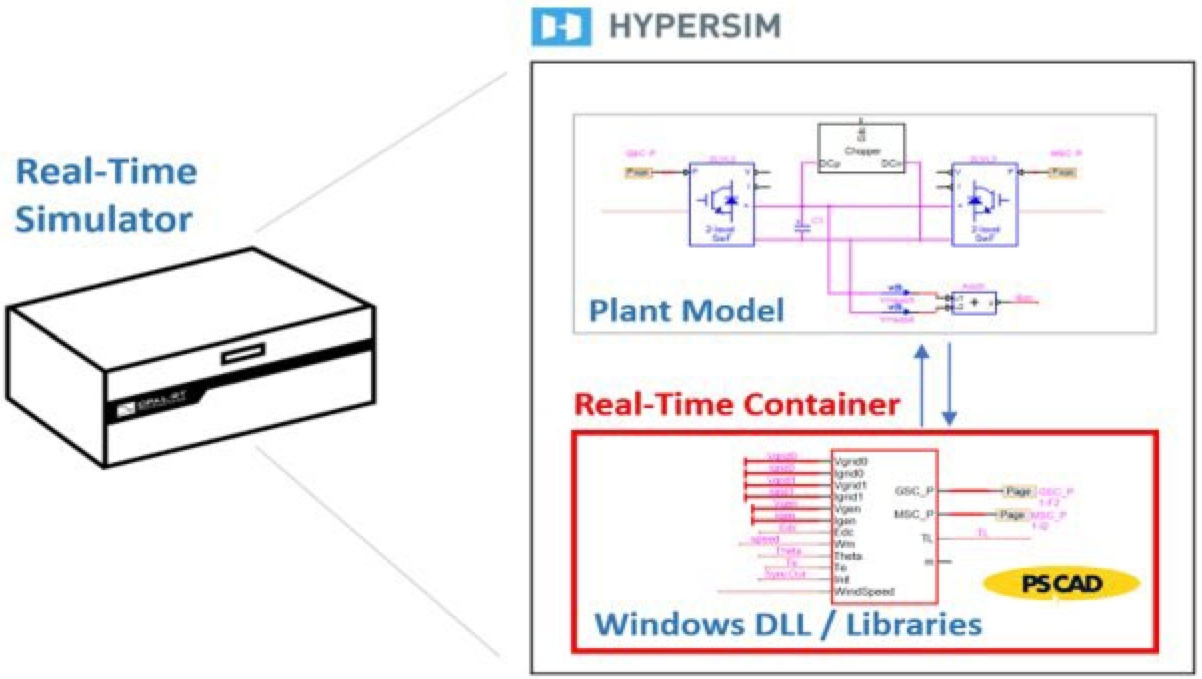


Source: *Joint IEEE TASS-TF and CIGRE WG B4.82 (Use of real code in EMT models for power system analysis)*
IEC 61400-27-1 Wind Energy Generation Systems - Part 27-1: Electrical Simulation Models - Generic Models

OEM Controller Code Integration in HYPERSIM

Approach 3: With HYPERSIM Linux Real-Time Container for HIL simulation of Windows-based controller code DLLs

- Can reuse the same Windows 64/32-bit DLLs
- No need to recompile the controller code in Linux



Setting up Large-Scale EMT Simulation in HYPERSIM

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(3 different approaches)

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(Different types of tests)

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(Scripted execution through API, Scope View for results)

Model Quality Validation for Detailed Plant Models

- Validation tests (based on applicable grid codes or standards such as IEEE 2800) are essential before integration plant models with the rest of the network
  - Flat run
  - Three phase-Ground, Line-Ground, Line-Line-Ground faults
  - Over-voltage, Under-voltage tests
  - Over-frequency, Under-frequency tests
  - Fault ride through tests with different dip size (fault impedance)
  - Change power setpoints, energy input level
  - Tests repeated for different Short Circuit Ratios

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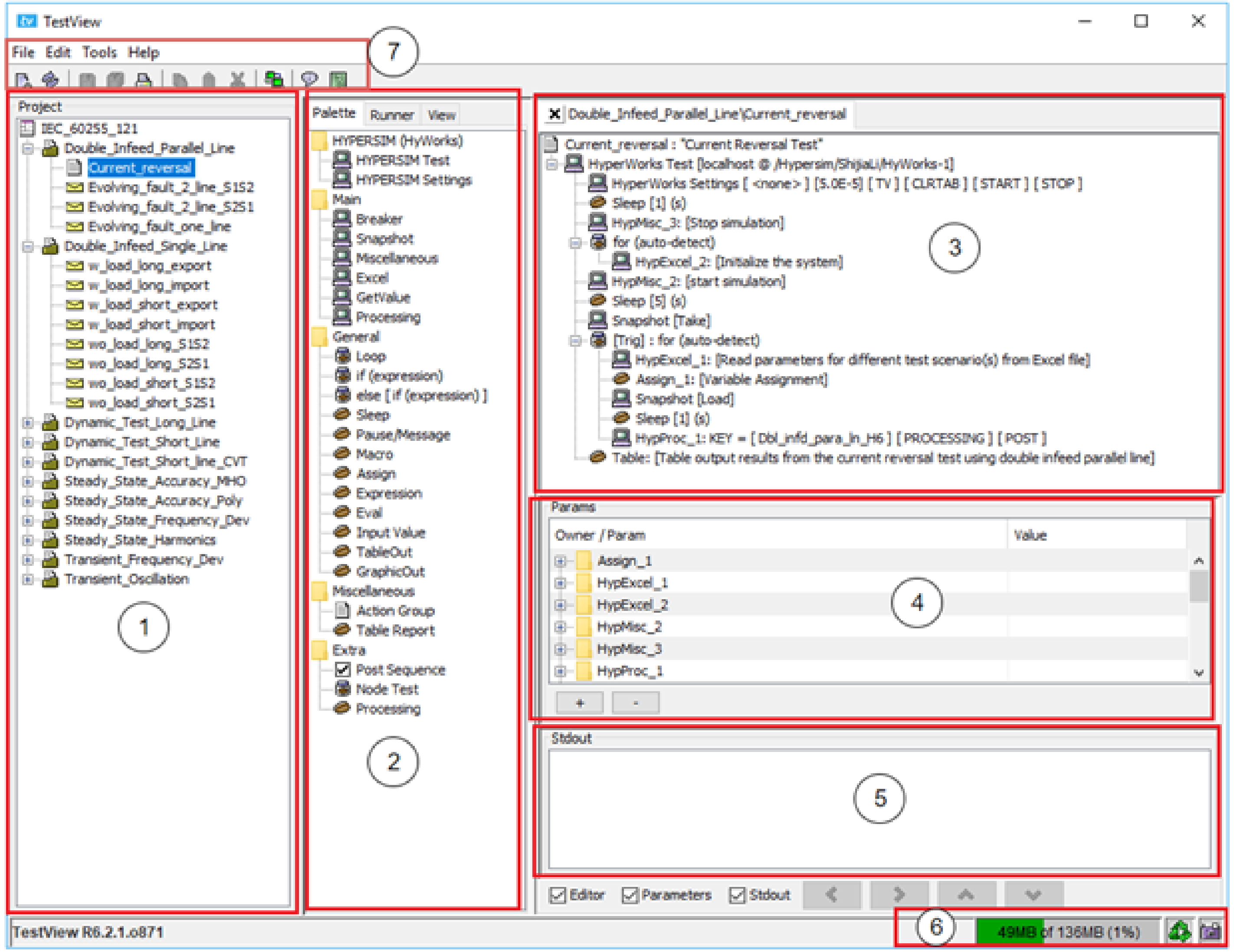
Simulation Studies & Post-Processing

Python API

```python
import os
import sys
sys.path.append(r'C:\OPAL-RT\HYPERSIM\hypersim-version\Windows\HyApi\python')
# Replace hypersim-version by the version you want to test

import HyWorksApiGRPC as HyWorksApi
import time

HyWorksApi.startAndConnectHypersim()
# This script finds the model next to it, when we launch python from the same directory
designPath = os.path.join(os.getcwd(), 'HVAC_735kV_38Bus.ecf')
HyWorksApi.openDesign(designPath)

HyWorksApi.setPreference('simulation.calculationStep', '50e-6')
calcStep = HyWorksApi.getPreference('simulation.calculationStep')

print('calcStep = ' + calcStep)

print('code directory : ' + HyWorksApi.getPreference('simulation.codeDirectory'))

print('mode : ' + HyWorksApi.getPreference('simulation.architecture'))

HyWorksApi.mapTask()
HyWorksApi.genCode()
HyWorksApi.startLoadFlow()
HyWorksApi.startSim()
print('startSim done')

volt = HyWorksApi.getComponentParameter('Ge7', 'baseVolt')
print(('baseVolt = ' + volt[0] + volt[1]))

HyWorksApi.setComponentParameter('Ge7', 'baseVolt', str(float(volt[0]) + 2.75))

volt2 = HyWorksApi.getComponentParameter('Ge7', 'baseVolt')

print(('baseVolt = ' + volt2[0] + volt2[1]))

if( abs( float(volt2[0]) - float(volt[0]) - 2.75) > 0.0001 ):
    print('SET_COMP ERROR')
else:
    print('SET_COMP SUCCESS')

time.sleep(5)

HyWorksApi.stopSim()
HyWorksApi.closeDesign(designPath)
HyWorksApi.closeHyperWorks()
```

Test View for Automation



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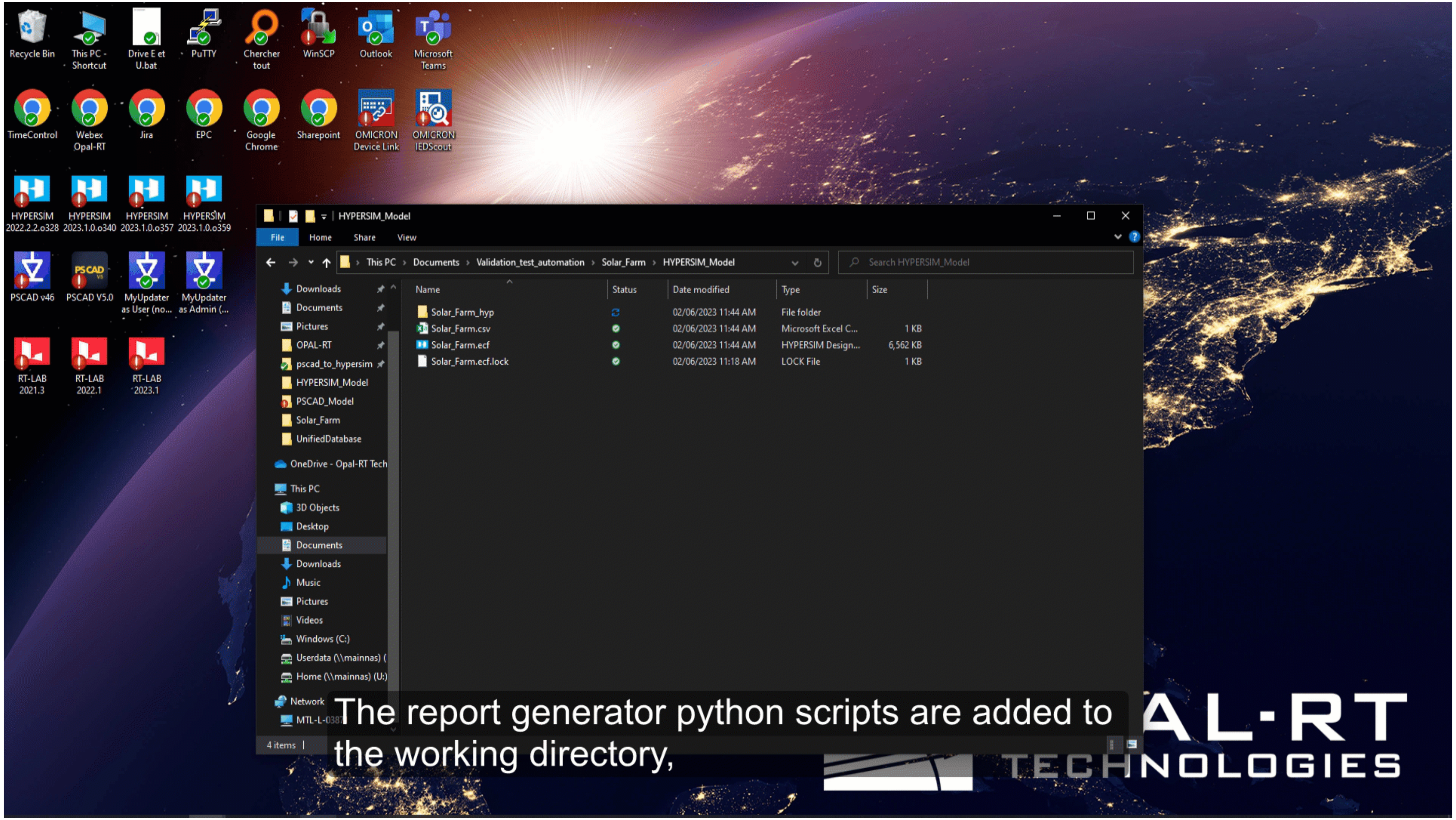
Simulation Studies & Post-Processing



4000-bus and 300+ Blackbox Controller EMT Benchmark

- 30s simulation in 90s wall clock time, 500-core Windows server
  - 50 us time step for the main grid
  - 10us or 16.67us for manufacturer controller codes

1x High Performance 128-core Windows Computer

22 x High-Performance 4-GHz 18-core Computers

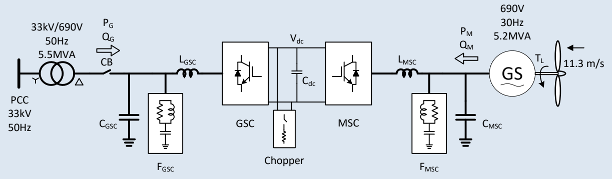
High-speed links between computer

MODEL BENCHMARK Approximate number of components (3-phase)	
Buses (3-phase)	4,000
Lines, loads, switched shunts reactors …	6,700
Transformers and synchronous machines	2,000
Inverter-based generation plants	150
Controllers using real-code (precompiled DLLs)	300+
FACTS and HVDC converters	70
Protection relay models	100

- **About 100 cores for the 4000-bus system**
- **300 cores for the controller codes**

4000-bus EMT benchmark – System Architecture

Main Grid Model EMT Simulation



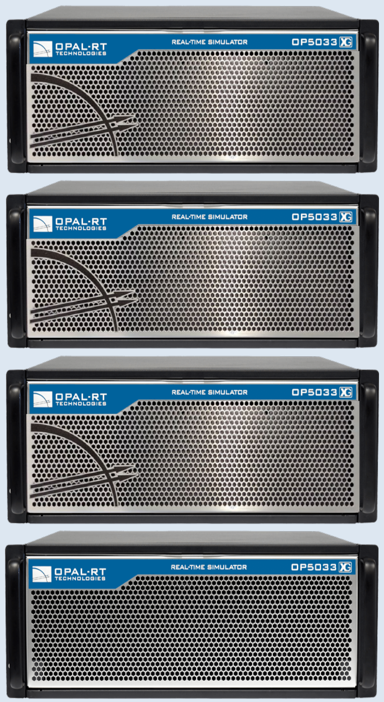
HYPERSIM

128-core Windows Computer

ORCHESTRA CO-SIMULATION
Fast 5-Gbits/s communication links

Controls/ Protection Simulation

DLL



20 x 18-core Standard 4.5 GHz AMD PCs

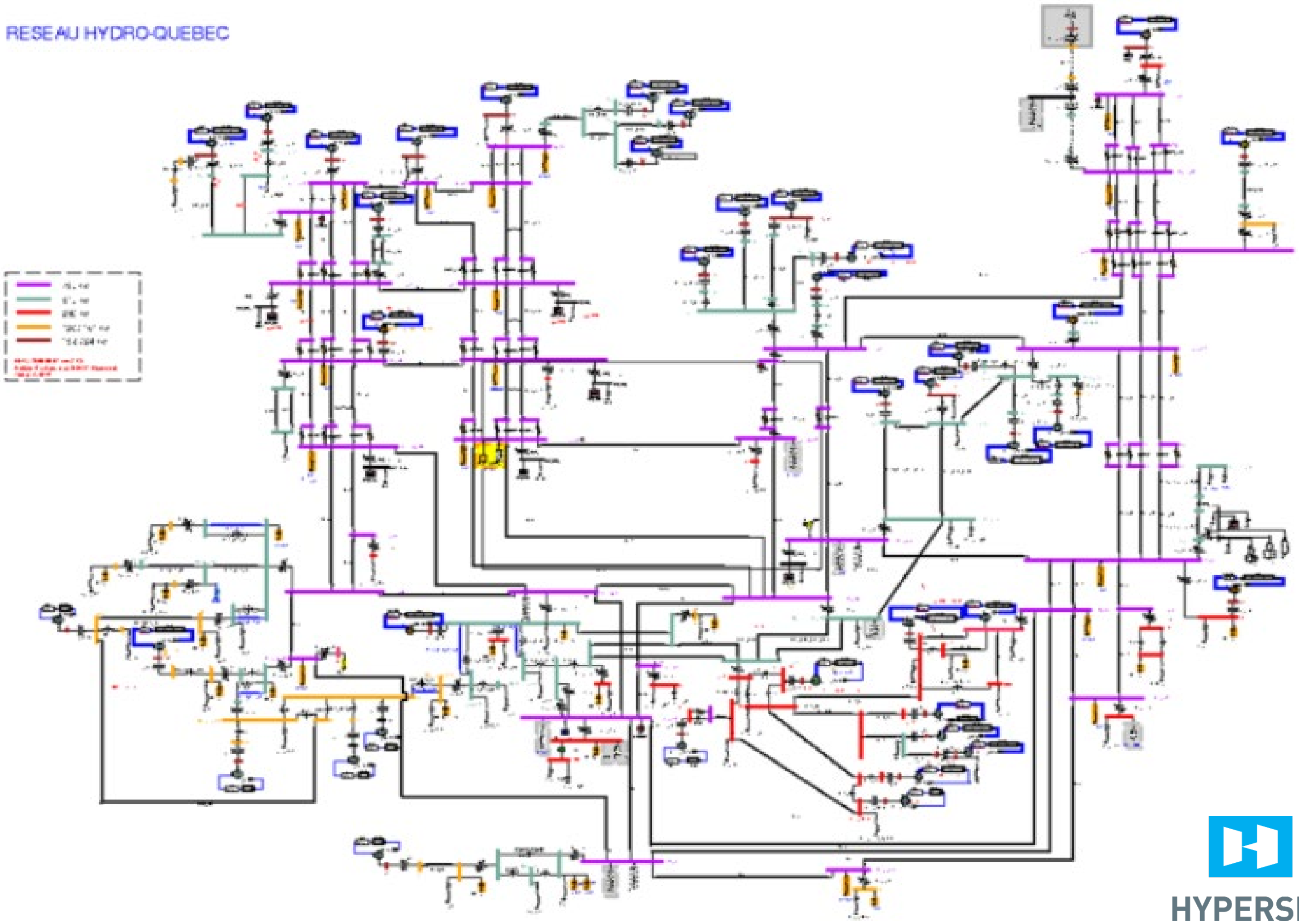
- PSCAD DLL for Measurement with PMU
- DLL for High-level P & Q control
- DLL for WT local measurement
- DLL for WT local control
- DLL for Converter control

GENERIC MODELS
(HYPERSIM and/or SIMULINK native models)

BLACK-BOX REAL-CODE PLANT/CONTROL/PROTECTION CODE EMULATION
(PSCAD 32-bit FORTRAN-based WINDOWS DLL)

Hydro-Quebec 735 kV Transmission System Model

- Hydro-Quebec 2023 grid: 56 cores, 40us in real-time
- 8 x 8 cores modules Xeon Scalable Gold 6144 @ 3.5GHz, 24.75 MB L3 Cache) in an HPE SuperDome Flex



Complex components	Quantity
Three-phase buses	1 666
Electrical machines	111
Lines and cables	432
Three-phase transformers	338
Governors	86
Excitation systems	81
Stabilizers	54
Static compensators	10
Wind power plants	6
HVDC converters	6
Dynamic loads	165

SIMULATION TIME FOR A 15 Second EVENT

Nbre of CPU	Measured Tstep (s)	Theoretical Tstep with 100% efficiency (s)	Actual efficiency
1	2565		
4	786	641	82%
56	15	46	305%

HYPERSIM

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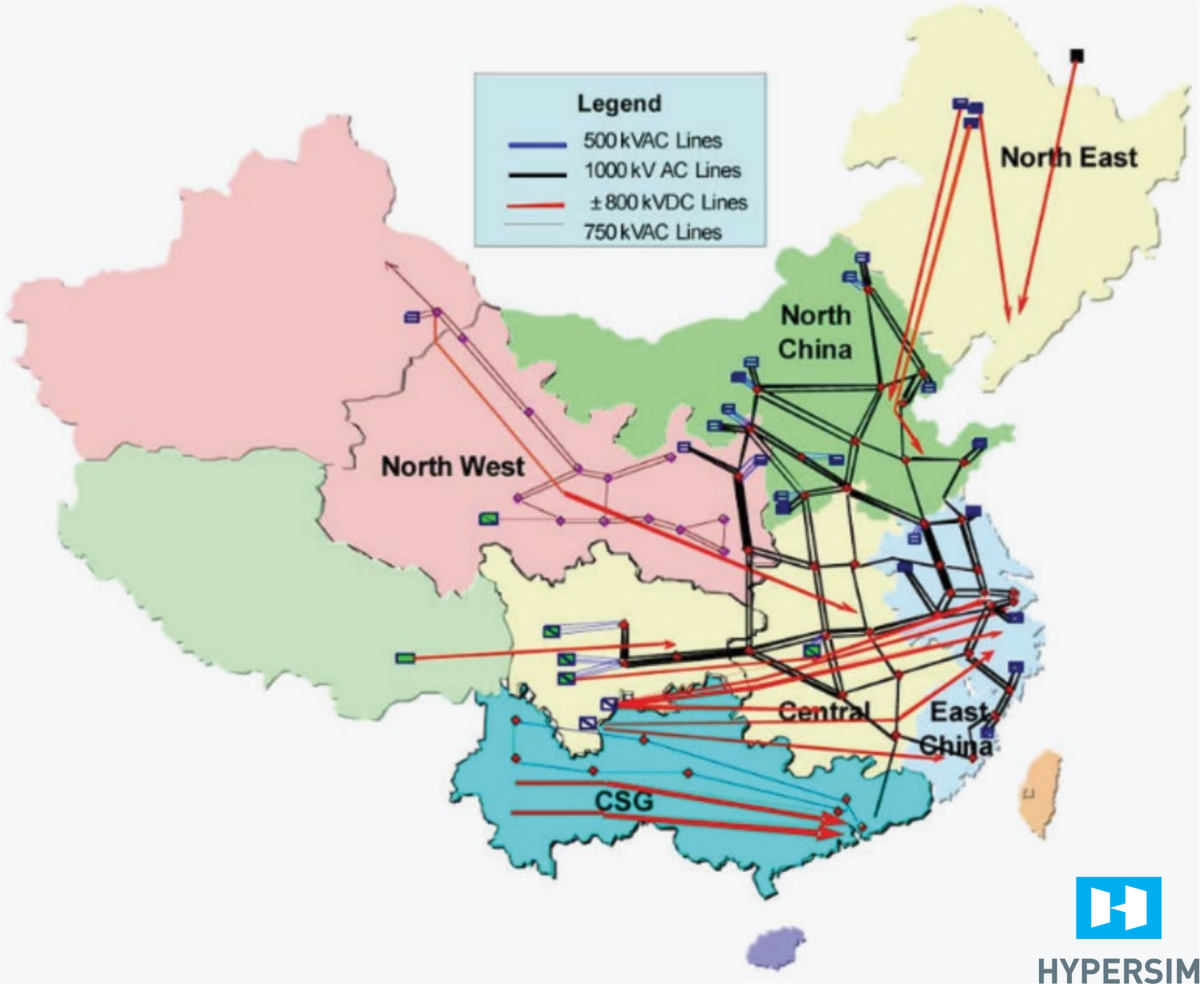
CEPRI – China Large Transmission System Model 500kV+

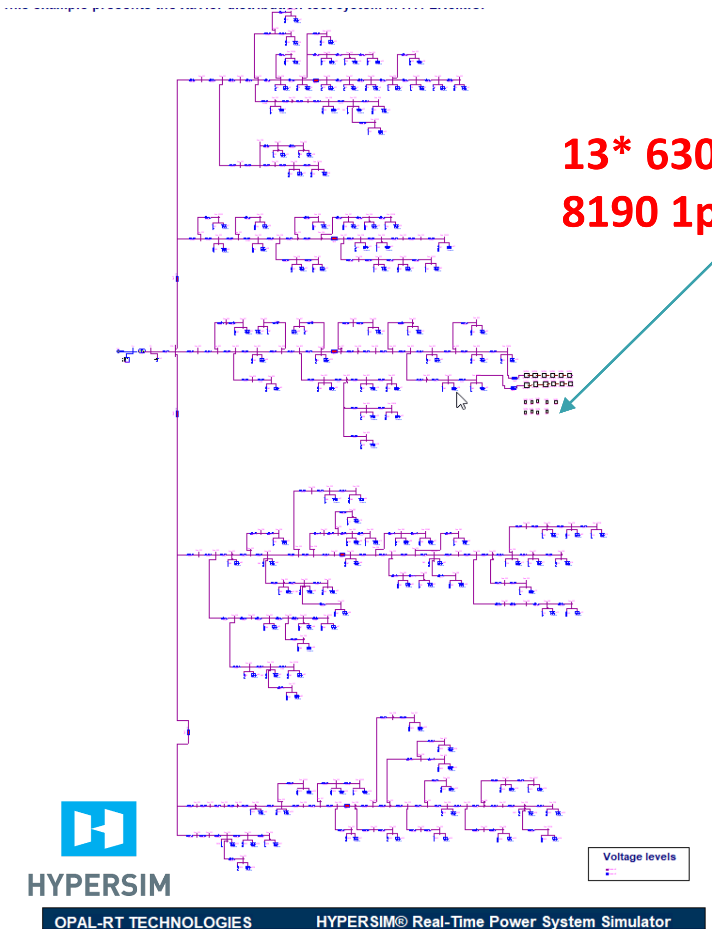


8500 3-phase nodes
350 generators
1300 sources
4500 transmission lines
10 HVDC links connected to replicas
1200 3-ph breakers
800 switches
1500 dynamic loads
5700 RLC
200 filters
900 transformers
37000 control components

- **300+ cores, 50 us**
- **2 SUPERDOM FLEX (HP) OF 300 cores each (600 cores in total) are now used interfaced with more than 70 OP5607 FPGA-based IO systems and simulators**

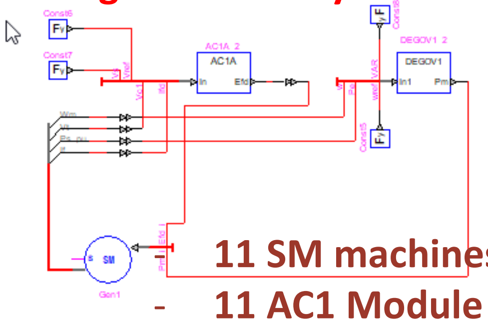
Distribution Grid Benchmark with 8190 1-ph nodes

- 22 CPU Cores, 100 us time-step
- **Compilation time: 98s only,** standard INTEL 32-core computer



13* 630 nodes system =
8190 1ph nodes

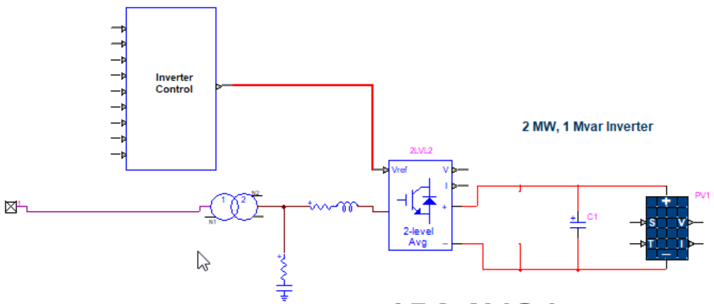
DG generation System



- **11 SM machines**
- **11 AC1 Module**
- **11 Machine Governors**

PV System

198 PV CTRL



198 PV Panels

- **154 AVG Inverters**
- **48 detailed Inverters**

Parts of the distribution grids and DER could be simulated with time steps between 100ns and 3 us on FPGA depending on study objective.

Demonstration

- Working on a combination of hands-on (laptop) + demo video
  - Show an example of PSCAD plant model + PowerFactory import to HYPERSIM
  - Show results from a video of simulation from 4000-bus benchmark.

Gaps & Challenges Observed

- **Automated Model Development/Import using Unified Database**
  - Extending support for more components in existing formats
  - Moving towards CIM-based model import

- **Model quality verification**
  - Availability of field test data
  - Automating various types of model quality tests
  - Validation Criteria
    - Aggregate vs. Detailed Plant-level IBR models

- **Numerical algorithm innovation for solvers on FPGAs**
  - Detailed Plant-level IBR models at very low time-steps

Gaps & Challenges Observed

- **OEM controller code Integration**
  - Standardizing OEM controller code IO for creating wrappers
  - Interoperability across tools and platforms
  - Model validation for OEM controllers like synchronous machine
  - Code optimization to work efficiently with EMT simulations
  - Initialization of OEM controller code

- **EMT-Phasor co-simulation**
  - Developing screening criteria for when EMT-Phasor simulation can be used
  - Interfacing approaches between EMT and Phasor
  - Identifying the right location for partitioning between EMT and Phasor

Questions?

OPAL-RT TECHNOLOGIES

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Thank You!