Hardware In The Loop
REAL TIME DIGITAL SIMULATOR:
A Critical Grid Modernization Tool

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When Power Electronics and FACTS devices were introduced to the transmission grid, we called the grid – *The Modern Grid*

To that modern grid we have added digital communications, wide-area protection and controls, distributed and renewable energy resources both at transmission and distribution level

This has made the protection, operation and control of the network more complex than ever before and there is a great need to test these *system of devices* in ways that have never been necessary before

Design, development, commissioning, maintenance, failure analysis and operator training are just some of the areas that need new tools and approach

Testing new technologies on the live grid is out of the question yet realistic testing is essential and hence we need a *realistic laboratory testbed environment*

This is what the industry calls *Hardware In the Loop (HIL) Real Time Simulator* platform

A digital version of such a testbed is called the *Real Time Digital Simulator or RTDS®* in our case.
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• Analog Simulator were made out of miniature analog equivalent devices
• Interface to digital communication is difficult

• Fully Digital
• Uses the same advances in electronics and software technologies that has transformed the power systems
• Ideally suited to be the cyber physical system testbed
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What is **Real Time Simulator**?

- **IEEE Definition of a HIL Simulator** [1]
  
  “Digital Relay Performance Requirements for Relay Testing” states that a “simulator” may be defined as a system of software and hardware that generates output waveforms that are, **ideally identical to the secondary level waveforms** produced by the power system being modeled. These waveforms are used to drive the relay under test.”

- The relay is essentially a controller (it controls circuit breakers)
  - This definition applies to HVDC/FACTS controllers, Special Protection Schemes (SPS), Exciter/Governor/Stabilizer, Tap Changer, Reclosers, Micro-grid controller, SCADA, DMS, etc.

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# Types of Digital Simulation

<table>
<thead>
<tr>
<th>Type of Simulation</th>
<th>Load Flow</th>
<th>Transient Stability Analysis (TSA)</th>
<th>Electromagnetic Transient (EMT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical timestep</td>
<td>Power World ETAP (PSLF, PSS/E) Etc</td>
<td>PSLF PSS/E Etc</td>
<td>~ 2 - 50 µs</td>
</tr>
<tr>
<td>Output</td>
<td>Nominal frequency</td>
<td>Nominal and off-nominal frequency</td>
<td>Instantaneous values</td>
</tr>
<tr>
<td>Frequency range</td>
<td></td>
<td></td>
<td>0 – 3 kHz (&gt;15 kHz)</td>
</tr>
</tbody>
</table>

“ideally identical to the secondary level waveforms”

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EMT Simulation Algorithm

Dommel Algorithm

Convert DEs to algebraic equations using trapezoidal rule of integration

\[ X = R + j\omega L \]

\[ v(t) = L \frac{d}{dt} i(t) \]

\[ i(t) = \frac{1}{L} \int v(t) \, dt \]

\[ i(t) = C \frac{1}{C} \int \frac{d}{dt} v(t) \, dt \]

\[ v(t) = \frac{1}{C} \int i(t) \, dt \]

\[ i(t) = \frac{\Delta t}{2L} v(t) + I_h(t-\Delta t) \]

\[ i(t) = \frac{2C}{\Delta t} v(t) - I_h(t-\Delta t) \]

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EMT Simulation Algorithm

Dommel Algorithm: Discrete Integration

\[ i(t) = \frac{\Delta t}{2L} v(t) + I_h(t-\Delta t) \]

\[ i(t) = \frac{2C}{\Delta t} v(t) - I_h(t-\Delta t) \]
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EMT Simulation Algorithm

Can be applied to every power system device

All power system components are represented as equivalent current source and resistor

History term currents for complex components may require substantial computation
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1. Convert user-defined power system to equivalent network of only current sources and resistors

2. Formulate conductance matrix for equivalent network

\[
\begin{align*}
\begin{bmatrix}
V_1 \\
V_2 \\
V_3 \\
\end{bmatrix} &= 
\begin{bmatrix}
G_{11} & G_{12} & G_{13} \\
G_{21} & G_{22} & G_{23} \\
G_{31} & G_{32} & G_{33} \\
\end{bmatrix}^{-1}
\begin{bmatrix}
I_1 \\
I_2 \\
I_3 \\
\end{bmatrix}
\end{align*}
\]

3. Using data from previous timestep (or initial conditions for first timestep), compute new \([I]\) values

4. Solve for \([V]\) using new values of \([I]\)

5. Calculate branch currents with \([V]\) and \([I]\)

And repeat...
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Simulation Techniques:

- **Fundamental Frequency Analysis Tools**
  - PSS/E, TSAT

- **Electromagnetic Transient Tools**
  - EMTP, EMTDC, ATP

- **Real-Time Electromagnetic Transient Tools**
  - RTDS

Frequency ranges:
- 0 Hz
- 50/60 Hz
- 2000 – 3000 Hz (w/ time-step of 50 us)

- Requires longer duration simulations
- Special models and smaller time-steps
- Special models and smaller time-steps but w/ real-time constraints
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Parallel Processing Power

All-in-one chassis!
- Designed around IBM’s POWER8® RISC-based 10-core processor
- Clock speed: - 3.5 GHz!
- Fast, on-chip, core-to-core communication
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Flexible and Expandable I/O

Analog Input (GTAI)
  12 channel, isolated 16-bit analogue input

Analog Output (GTAO)
  12 channel, isolated 16-bit analogue output

Digital Input (GTDI)
  64 channel, isolated digital input

Digital Output (GTDO)
  64 channel, isolated digital output

The GT family of I/O cards can be daisy chain connected to a single NovaCor fiber port allowing for easy scaling of the simulators IO capabilities.
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Real-Time Protocols Based I/O

- **IEC 61850:**
  - GSE: binary messaging
  - SV: sampled values
- **PLAYBACK**
- **SCADA:** DNP3 and IEC 60870-5-104
- **PMU:** IEEE C37.118
- **MODBUS:** TCP, RTU over TCP, ASCII over TCP
- **SOCKET:** TCP/UDP (bidirectional, Asynchronous)
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GTSYNC: External time synchronization

- Synchronizes RTDS timestep to external time reference (e.g. GPS clock) and synchronizes devices under test or act as its own internal synchronization source
- 1 Pulse Per Second over BNC coax or ST fiber connectors
- IEEE 1588 over RJ45 or ST fiber connectors
- IRIG-B over BNC coax connection
- Necessary for PMU testing and advantageous for SV output
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GUI and Simulation Software

**FileManager**
The “home page” of RSCAD; organize simulation files and launch other modules.

**CBuilder**
Create user-defined components including graphical representation, data menus and real-time code.

**Draft**
Graphical assembly and data input for simulation circuit.

**RunTime**
Run, control and acquire results from simulations.

**MultiPlot**
Post analysis and annotation of results.

**Cable**
Calculation of cable characteristics based on physical data or sequence impedances.

**TLine**
Calculation of transmission line characteristics based on physical data or positive and zero sequence impedances.
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Automated Batch Mode Testing

- Efficient means of running many cases
- Script file
  - C-like programming language
  - Adaptive via if, for, while statements
  - User-defined subroutines
  - Customized results reporting
  - Automated plot printing

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Data Import

- PSCAD – Off-line emt simulator
- PSS/E – Transient Stability Simulator
- CYMDIST – Distribution System
- MATLAB/SIMULINK – Controls
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Applications

Hardware in the Loop for Grid Modernization

**DISTRIBUTION**
- Microgrid Testing
- Renewables/DERs
- Distribution Automation
- Inverter Testing

**POWER ELECTRONICS**
- HVDC & FACTS
- Energy Conversion Drives

**SMART GRID**
- WAMPAC Testing
- PMU Studies
- Cyber Security

**PROTECTION**
- Digital Substations
- Traveling Wave Testing
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Protection and Automation Suite

- Standalone facility within RSCAD
- Test and validate substation automation protocols
- Use the RTDS Simulator to emulate the following and communicate with external compatible devices:
  - 61850 MMS Server
  - DNP3 Master and Outstation
  - IEC 60870-5-104 Master
  - MODBUS Master
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The Advantage of Closed-Loop Testing

**Open-loop protective relay testing**
- Testing tool
- Signals from power system
- Device under test

**Closed-loop protective relay testing**
- Testing tool
- Signals from power system
- Signals from relay (i.e. trip or reclose)
- Device under test
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Protection: Electrical Interface
Protection: IEC 61850 Interface

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Accurately test traveling wave protection (such as the SEL-T400L) in a closed loop with the simulated power system

The industry’s only tool with robust Frequency Dependent Phase Domain transmission line models operating at the necessary small timestep for traveling wave testing

Multiple line segments represent physical transposition and allow fault modeling at multiple locations

More details and a video at: https://www.rtds.com/twrt/
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8 PMU models per component designed according to IEEE C37.118
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Power Hardware in the Loop - PHIL

- Real-time simulation environment exchanging power with real, physical power hardware, such as renewable energy resources, electric vehicles, batteries, motors and loads
- System (utility or microgrid) is simulated in Real Time Simulator and interfaced via power amplifier to the power device(s) under test

Analog I/O or Arora Protocol
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FEATURES:
• Two feeder sources (Left and Right)
• One Feeder Tie Breaker
• Two Reclosers
• One Voltage Regulator
• Three Cap Bank Controller
• Two switched loads
• Two DERs
• Two substation breakers and protection

All Controllers are modeled in RTDS in a single HIL simulation to test full control and protection interaction
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Wide Area Protection and Control

GPS time synchronization
  • Time reference for result comparison
  • Benchmark testing for steady state and dynamic response

GTSYNC
  • Input card for 1PPS, IRIG-B, and IEEE 1588

IEEE C37.118 Communication
  • PMU protocol for GTNET

Proof of Concept Facility – PG&E
Testing of Generator Controllers

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RTDS Simulator

- Main Generator
- Controlled Rectifier
- PPT
- Firing Pulses
- Digital Input
- Digital to Analogue Converters
- Power Amps
- Static Exciter
- Unit Transformer
- Field Flash Circuit

Synchronous Condenser Excitation Controls and DC Power Supply

DUT

<- PHIL
CHIL ->

RTDS

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Cyber-Physical Security Hardware-in-the-Loop Testbed
Florida State University – Center for Advanced Power Systems

- Capability to study cyber-physical system operation and security of physical power and controls hardware in a system relevant environment
- Substantial real-time power network and communication network simulation capacity provides large-scale rest of the system
- Physical devices such as embedded controllers and protective relays along with physical power hardware such as power electronic converters can be studied interacting with realistic simulated devices

Communications Network Simulator

Heterogeneous Large-Scale Distributed Control Platforms
- The RTDS Simulator was originally developed to model HVDC schemes
- Used by all manufacturers of HVDC for Factory Acceptance Testing (FAT) of LCC and VSC/MMC based schemes
- Many utilities have purchased replica controls and RTDS Simulators as part of their projects
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Controls Replica for Training

- Assist during commissioning
- Investigate proposed network changes
- Investigate proposed control modifications
- Test scheme upgrades and refurbishment
- Train personnel on scheme theory and operation
- Important to include in project specification
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**System Restoration and Black Start**

**Procedure and Equipment Testing**

**Full system representation**
- Grids with 3000 buses
- Detailed protection and control modes included
- Realistic behavior over entire operating range

**Real time operation**
- Allow testing of physical controllers
- Provide realistic feedback to operators
- Physical SCADA interface through DNP3 or IEC 60870-5-104

*RTDS POWER SYSTEM SIMULATORS*  
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- Why do I need a real-time simulator
- Which of my applications need HIL real-time simulation
- What is the difference between CHIL, PHIL, SHIL
- What is the difference between on-line and real-time simulation
- What is the difference between transient stability and electro-magnetic transient simulation
- What is the appropriate size of the network for a given application
- How do I determine the capability of real time simulator
  - Is number of buses an appropriate measure
- How to define and validate simulator capabilities and performance
- What are the advantages and disadvantages of network equivalents
- What is the application of HIL simulator for Synchrophasor / PMU
- What is involved in operating a real-time simulator at an utility –
  - Infrastructure
  - Labor, skillsets, resources
  - Maintenance, upgrades, ROI justification