Synchrophasor Application Studies using Real-Time Simulators
Overview

• Company Backgrounds

• Collaboration between OPAL-RT and VIZIMAX
  o PMU Test Setup
  o Tests Applied to the VIZIMAX PMU

• Comparison of Test Results for Different PMU Algorithms

• Advanced Applications using Model-Based Design, Studies and Testing
  o The Mont-Rothery Wind Farm in Canada
  o Protection Applications using PMUs
  o Control Design and Prototyping using Virtualized PMUs

• Conclusions
Company Backgrounds
• Some Facts
  • Established in 1997 – Corporate office in Montreal
  • Over 140+ Employees worldwide
  • More than 500 customers worldwide
  • Real-time simulators available for power systems, power electronics, automotive and aerospace industries
  • Power grid simulators scalable from 10 to 10,000 electrical nodes or more

• Corporate Mission
  • To provide solutions and expert services for design research, studies and testing in the fields of electrical and power electronics systems
  • To provide Engineers with open simulators that use the latest COTS computer technology

• Long-Term Vision
  • A real-time simulator on each engineer’s or researcher’s desk
  • Simulators interconnected and working for designing and studying large and multi-disciplinary systems.
  • Imagination will be the only real limit to complex system design.
• The Company
  • Established in 2008 from a merger between Snemo (1977) and STR (1988)
  • Provides innovative solutions for energy applications – Power Grids, Power Generation, HV/MV Equipment, Heavy Industry
  • Customers in over 35 countries

• Products
  • Phasor Measurement Unit
  • Analog Merging Unit
  • SynchroTeq™: Controlled switching device (CSD)/Inrush current limiter
  • RightWON™: Substation automation controller

• Mission
  • To help optimize how Energy is Generated, Transported & Distributed
  • To protect as much as possible their customers’ assets by focusing on innovation, quality, and customer service
Collaborations with Hydro-Quebec Research Institute (IREQ)

- OPAL-RT and IREQ signed a strategic collaboration agreement for the shared commercialization and development of HYPERSIM (2012)

- Agreement for integration of estimation algorithms resulting from research at IREQ. Algorithms have been enhanced by VIZIMAX for accurate real-time estimation and standard compliance.

- Other collaborations for validation of automation and control equipment and certification for use on the Hydro-Quebec grid.
• Automated testing of PMUs based on C37.118.1
  • Study requirements of the IEEE std
  • Program test sequence using OPAL-RT Hardware and TestView software
  • Calibration of the test equipment
  • Help validating the VIZIMAX PMU using automated test-set – faster and larger test coverage

• Develop a PMU - foreseeing IEEE-ICAP certification
  • Develop their own test bench using an OMICRON CMC-256plus universal calibrator
  • Provide a low-voltage input version of their PMU to OPAL-RT
  • Help validating the performance of OPAL-RT test equipment on specific tests
PMU Test Setup
Typical PMU Test Setup

- **VIZIMAX PMU**
- **V & I Amplifier**
- **OPAL-RT Simulator**
- **HYPERSIM / TestView**

**Power Amplifier**
- 3 x V: ±16 V peak
- 3 x I: 150 V AC, 50 A AC

**Ethernet Switch**
-Slave
-Master

**IRIG-B**
-Master Clk
-Slave

**C37.118**
-Master
-Slave

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*OPAL-RT Technologies*
PMU Test Setup using Low-Voltage Interface

- **VIZIMAX PMU**
- **Ethernet Switch**
- **OPAL-RT Simulator**
- **HYPERSIM / TestView**

**Specifications:**
- **C37.118 Slave**
- **3 x V ± 10 V_peak**
- **3 x I**
Automating tests in HYPERSIM

- Define model parameters to be modified or applied using an EXCEL spreadsheet
  - Use model component name as defined in netlist
  - Use component parameter as defined in netlist
- Program test sequence directly in TestView...
- Or import EXCEL test sequence
Test Automation using TestView

Generate test reports

- View test waveforms in ScopeView and automate printing of .pdf report for each test
- Output post-processed values calculated during test in a pre-formatted EXCEL spreadsheet
- Analyze data in EXCEL or ScopeView
Calibration capability of the test setup

- VIZIMAX PMU
- V & I Amplifier
- OPAL-RT Simulator
- HYPERSIM / TestView
- IRIG-B
- Master CLK
- Ethernet Switch
- C37.118 Slave
- C37.118 Master
- OPAL-RT Technologies
Calibration capability of the test setup

\[ V_{\text{ref}} = \delta a \cdot \{A \sin(2\pi f \cdot [t + \Delta t] + \varphi)\} \]

Basic calibration variables
Tests Applied to the Vizimax PMU
<table>
<thead>
<tr>
<th>Test</th>
<th>Influence quantity</th>
<th>P Class Criteria</th>
<th>M Class Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Signal freq. Range</strong></td>
<td>Signal frequency:&lt;br&gt;±2Hz for P class&lt;br&gt;±5Hz for M class</td>
<td>TVE &lt;1%&lt;br&gt;FE &lt;0.005Hz&lt;br&gt;RFE &lt;0.4Hz/s</td>
<td>TVE &lt;1%&lt;br&gt;FE &lt;0.005Hz&lt;br&gt;RFE &lt;0.1Hz/s</td>
</tr>
<tr>
<td><strong>Signal Mag. (V/I)</strong></td>
<td>Voltage magnitude:&lt;br&gt;80% to 120% for P class&lt;br&gt;10% to 120% for M class&lt;br&gt;Current magnitude 10% to 200%</td>
<td>TVE &lt;1%&lt;br&gt;FE &lt;0.005Hz&lt;br&gt;RFE &lt;0.4Hz/s</td>
<td>TVE &lt;1%&lt;br&gt;FE &lt;0.005Hz&lt;br&gt;RFE &lt;0.1Hz/s</td>
</tr>
<tr>
<td><strong>Harmonic Dist.</strong></td>
<td>2\textsuperscript{nd} to 50\textsuperscript{th} harmonic:&lt;br&gt;1% for P class&lt;br&gt;10% for M class</td>
<td>TVE &lt;1%&lt;br&gt;FE &lt;0.005Hz&lt;br&gt;RFE &lt;0.4Hz/s</td>
<td>TVE &lt;1%&lt;br&gt;FE &lt;0.025Hz</td>
</tr>
<tr>
<td><strong>Out-of-Band Interf.</strong></td>
<td>10Hz - f0-Fs/2 and f0+Fs/2 – 120Hz:&lt;br&gt;10% for M class only</td>
<td>No requirement</td>
<td>TVE &lt;1.3%&lt;br&gt;FE &lt;0.01Hz</td>
</tr>
<tr>
<td><strong>Meas. BW Phase &amp; Amp. Modulation</strong></td>
<td>0.1Hz – min (Fs/10, 2) for P class&lt;br&gt;0.1Hz – min (Fs/5, 5) for M class</td>
<td>TVE &lt;3%&lt;br&gt;FE &lt;0.003<em>Max Mod Freq&lt;br&gt;RFE &lt;0.18</em>pi<em>Max Mod Freq</em>2</td>
<td>TVE &lt;3%&lt;br&gt;FE &lt;0.003<em>Max Mod Freq&lt;br&gt;RFE &lt;0.18</em>pi<em>Max Mod Freq</em>2</td>
</tr>
<tr>
<td><strong>Freq. ramp</strong></td>
<td>±2Hz for P class&lt;br&gt;±5Hz for M class</td>
<td>TVE &lt;1%&lt;br&gt;FE &lt;0.01Hz&lt;br&gt;RFE &lt;0.4Hz/s</td>
<td>TVE &lt;1%&lt;br&gt;FE &lt;0.01Hz&lt;br&gt;RFE &lt;0.2Hz/s</td>
</tr>
<tr>
<td><strong>Phase step change Mag. Step change</strong></td>
<td>±10°&lt;br&gt;±10% of nominal magnitude</td>
<td>Delay time 1/(4*Fs)&lt;br&gt;TVE response time 2/f0&lt;br&gt;Overshoot, undershoot 5% of step&lt;br&gt;FE response time 4.5/f0&lt;br&gt;RFE response time 6/f0</td>
<td>Delay time 1/(4*Fs)&lt;br&gt;TVE response time 7/Fs&lt;br&gt;Overshoot, undershoot 10% of step&lt;br&gt;FE response time max(14/f0, 14/Fs)&lt;br&gt;RFE response time max(14/f0, 14/Fs)</td>
</tr>
<tr>
<td><strong>Reporting latency</strong></td>
<td>1000 consecutive reports</td>
<td>2/Fs</td>
<td>7/Fs</td>
</tr>
</tbody>
</table>
Comparison with Certification Results—Step Change Test

**OPAL vs Certification Test Results (P60)**

- Delay time: 0.004167s
- TVE Response Time: 0.033s
- FE Response Time: 0.075s
- RFE Response Time: 0.1s
- Overshoot: 5%

**OPAL vs Certification Test Results (M10)**

- Delay time: 0.025s
- TVE Response Time: 0.7s
- FE Response Time: 1.4s
- RFE Response Time: 1.4s
- Overshoot: 10%

**Phase Step Test (10 degree)**
Comparison with Certification Results—Dynamic Modulation Test
Comparison with Certification Results—Steady-State Test

**OPAL vs Certification Test Results (P60)**

- **Frequency range**
  - TVE FE RFE

- **Magnitude range**
  - TVE FE RFE

- **Harmonic distortion**
  - TVE FE RFE

- **FE (Hz)**
  - 1% 0.005Hz 0.4Hz/s
  - 1% 0.005Hz 0.4Hz/s
  - 1% 0.005Hz 0.4Hz/s

**OPAL vs Certification Test Results (M10)**

- **Frequency range**
  - TVE FE RFE

- **Magnitude range**
  - TVE FE RFE

- **Harmonic distortion**
  - TVE FE RFE

- **Out-of-band interference**
  - TVE FE RFE

**PMU Steady-State Test**

**OPAL**

**Calibration Lab**
Out-of-Band Interference Test Signal

\[ X(t) = X_m \cdot \cos(2\pi f t + \varphi) + 0.1 \cdot X_m \cdot \cos(2\pi f_i t + \varphi) \]
P Class Out-of-Band Interference Test– 60Hz, 60 fps

• Interference range: 10-55Hz and 65-120Hz
• Injection level: 10%
Performance under step changes at 10 fps (P Class) VS C37.118.1 Requirements

- A series of tests \( (N \text{ tests, where } n=[1,N]) \) with the step applied at varying times relative to the reporting times can be used to ‘fill in’ the response curve.

IEEE Std C37.118.1-2011:
- In general, an accurate measurement of the PMU response time, the delay time, and the overshoot percentage can be made with \( n(\text{e.g. } N) = 10 \).

IEEE Std C37.118.1a-2014:
- The time when error limits (TVE = 1%) are crossed shall be determined to an accuracy of one-tenth of the reporting rate (ten times the reporting rate?) that is being tested.
- Here, \( N=10 \) is too small to measure TVE response time at lower \( F_s \).
Comparison of Test Results for Different PMU Algorithms
Comparison of Test Results for Different Algorithms

PMU Algorithms Under Test - TVE
Comparison of Test Results for Different Algorithms

PMU Algorithms Under Test (M Class) - FE

PMU Algorithms Under Test (P Class) - FE
Comparison of Test Results for Different Algorithms

PMU Algorithms Under Test (M Class) - RFE

PMU Algorithms Under Test (P Class) - RFE
Phase Angle Step Response Test for Different Algorithms

**Va Phase Angle**
- Algo 1, Delay Time -0.0017s, Overshoot 1%, Undershoot 0%
- Algo 2, Delay Time 0.0018s, Overshoot 8.7%, Undershoot 6.5%
- Algo 4, Delay Time -0.0014s, Overshoot 1%, Undershoot 0.2%
- Algo 7, Delay Time 0.0037s, Overshoot 7.4%, Undershoot 0%
- Algo 8, Delay Time -0.0002s, Overshoot 4.5%, Undershoot 5.8%

**TVE**
- Algo 1, TVE Response Time 0.031s
- Algo 2, TVE Response Time 0.305s
- Algo 4, TVE Response Time 0.029s
- Algo 7, TVE Response Time 0.073s
- Algo 8, TVE Response Time 0.055s
- Algo 9, TVE Response Time 0.364s

**FE**
- Algo 1 FE Response Time 0.052s
- Algo 2 FE Response Time 0.667s
- Algo 4 FE Response Time 0.060s
- Algo 7 FE Response Time 0.203s
- Algo 8 FE Response Time 0.094s
- Algo 9 FE Response Time 0.619s
Advanced Applications using Model-Based Design, Studies and Testing
Wind farms and other Independent Power Producers (IPP) have to comply with a number of network grid requirements. This usually means installing complex and costly Static VAR Compensators (SVC) and/or mechanically switched capacitor banks and shunt reactors.
Model-based design - Mont Rothery Wind Farm in Canada

• Uses a VIZIMAX PMU to measure voltages and currents at the PCC (120 fps)

• An industrial controller receives C37.118 streams, does the calculations, corrections using PID loops and makes decisions

• The controller sends setpoints to the Wind Power Control Unit.

• The controller also controls mechanically switched capacitor banks and shunt reactors that allow meeting the requirements.

• Time to commission the system with full test coverage?
Model-Based design in Power System Engineering

- Typically, a number of studies are required in Engineering design (power plants, T&D, P&C upgrade, etc.)
- Different studies usually require different analysis and simulation tools
- For equipment design, special control and protection prototyping and testing:
  - Goes from offline studies to real-time HIL testing...
  - ... Without increasing the modeling efforts is a huge advantage
eMEGAsim is already compatible with Matlab/Simulink/SimPowerSystems

HYPERSIM will have the same graphical engine than EMTP-RV released in April 2016

Working on full compatibility with EMTP-RV models
Phenomena Simulated Using OPAL-RT Simulators
Protection Applications using PMUs
Intelligent Relay Design and Testing For Distributed Generation

- Data-mining based relay setting methodology using automated simulations
- Short tripping time and high dependability and security
- Smaller Non-Detection-Zone
- BEST PAPER AWARD – IET DPSP 2016 Conference

**Supervised Training**
Define training events, perform simulation and obtain feature database.

**Data Mining**
Based on the training database, generate Decision-tree based protection logic using Data Mining techniques.

**Testing**
Perform testing with unknown events, analyze the acquired intelligent relay performance.

Intelligent Relay Design and Testing For Distributed Generation

Number of tested operating conditions: 256
Test Duration: 1h56m49s

Selected key variables used for the Intelligent Relay Decision-Tree:
- $V_{012}$, $V_{abc}$
- $I_{012}$, $I_{abc}$
- $\Delta f$, $df/dt$, $df/dP$, $df/dQ$
- $\Delta V$, $dV/dt$, $dV/dP$, $dV/dQ$
- $dP/dt$
- $dQ/dt$
- $pf$, $dpf/dt$
Control Design and Testing using Emulated or Virtualized PMUs
Virtualized PMU Dynamics with ePHASORsim

- How to simulate PMUs in Real-Time?
- How to design, study, and test a Wide-Area Control and Protection Schemes?
- How to ensure sufficient test coverage?

- Let’s look at the dynamic response of a PMU compared to ePHASORsim...
Virtualized PMU Dynamics with ePHASORsim

$V_1$ Magnitude - Bus22

$V_1$ Angle - Bus22
Virtualized PMU Dynamics with ePHASORsim

$\textbf{I}_1$ Magnitude - L22-23

$\textbf{I}_1$ Angle - Bus22
Conclusions

• PMUs are becoming a key part of ensuring grid reliability, but applications are numerous and need specialized studies and testing

• It was demonstrated that the use of a real-time simulator providing analysis capability is valuable for:
  
  o Pre-certification test of monitoring, control, protection devices such as PMU, with an accuracy comparable to that of calibration lab equipment and the capability to go beyond the standard requirements
  
  o Increasing test coverage by simulating (otherwise) « destructive tests » or contingencies with lower probability of occurrence by that have higher potential economical impact

  o Equipment and power grid design studies as well as real-time testing using the same models throughout the Engineering efforts

  o Development and study of various protection applications using IEDs with new algorithmic approaches as well as legacy functionalities

  o Design and real-time testing of Wide-Area Protection and Control schemes by emulating PMU dynamic response
Thanks!

Questions?

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