Real-Time Hardware-in-the-Loop Validation for WAMPAC: Power System Protection and Communication

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Outline

• Motivation for RT-HIL Approach
• SmarTS Lab: An RT-HIL Lab for WAMPAC Apps Dev.
• Model-To-Data Workflow for SIL and RT-HIL Validation

• Recent Projects at SmarTS LAB for Power System Protection and Communication
  • Power System Modeling of Protective Relays
  • Power System Communication (GOOSE and Sampled Values) Validation using RT-HIL
    • Interfacing RTS for Station Bus and Process Bus Implementation
    • Comparison of Conventional and RT-HIL approaches for Power Protection Relay Testing

• A software development toolkit for developing and testing PMU based applications for Wide Area Monitoring, Protection and Control

Presented at 2012 3rd IEEE PES ISGT Europe, Berlin, Germany, October 14 -17, 2012
Timeline for M. Shoaib Almas

- Almas joined KTH, The Royal Institute of Technology, in 2009 to pursue his Masters in Electric Power Engineering majoring in Power Systems. Previously he has obtained a Bachelors in Electrical Engineering from National University of Sciences and Technology (NUST), Pakistan.
- He has two years of experience working as a Design Engineer for designing protection schemes for substations (132kV, 220 kV and 500kV) through microprocessor-based relays.
- His professional experience includes substation automation and coordination of protective relays to minimize the effect of faults in power transmission networks.
- He performed his master thesis “PMU-Assisted Local Optimization of the Coordination between Protective Systems and VSC-HVDCs” at the Electric Power System (EPS) division of KTH.
- Currently PhD. Candidate, Project Title “Real-Time Wide-Area Control of Hybrid AC and DC Grids”

Motivation

- Each substation has in average 50 IEDs performing protection (differential, bus-bar, overcurrent, over/under voltage, over/under frequency etc.) and communicating with various protocols/standards (C37.118, GOOSE, SV, MODBUS, DNP 3.0)
- In order to accurately model a power system, these IEDs along with their respective communication techniques need to be modeled precisely with the same settings as the real hardware relay. 
- With substations adopting IEC-61850 standards, RT HIL approach proves beneficial to exploit interoperability, the use of Station/Process Bus effectiveness, etc. 
- Digital Real-Time Simulators are compatible with long-established modeling software like MATLAB/SIMULINK (Opal-RT) and are IEC 61850 compliant (GOOSE & Sampled Values)
- RT-HIL approach provides freedom to carry on research related with Smart Transmission Grids:
  - Wide Area Monitoring Protection and Control (WAMPAC)
Smart Grid require **Smart Operation, Smart Control and Smart Protection**:

- The ultimate goal should be to attain an automatic-feedback self-healing control system
- Measure – Communicate – Analyze (System Assessment and real limits) – Determine Preventive/Corrective Actions – Communicate – Control and protect
- To achieve this vision, new applications need to be developed in a controlled environment, allowing testing and considering the ICT chain

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**The SmarTS Lab Architecture**

- **Opal-RT** Real-Time Simulator
- **PMUs** Synchrophasor Data

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**Communication Network (WAN /Network Emulator)**

- **PDC(s)**
- **WAMS Applications**
- **WAPS Applications**
- **WACS Applications**
- **WAMPAC Application Host Platform**
Recent Projects at SmarTS LAB
1. Model Validation of an Over-Current Relay

Block Diagram

Part 1: Three Phase Current → Analog Input of relay (Current from CT)
Part 2: Analog to Digital Converter → Digital Filtering
Part 3: Protection Algorithm (Instantaneous, Definite or IDMT) → Trip Signal

Input Current → Comparator → Trip Signal
Pickup Value

- Instantaneous
- Definite Time
- Inverse Definite Minimum Time (IDMT)
1. Model Validation of an Over-Current Relay (contd.)
Modeling and Implementation for RT Simulation

Current input from the secondary side of the CT. This is an analog signal.

Converts an input signal with continuous sample time to an output signal with discrete sample time.

Down-sampling to avoid anti-aliasing effects.

Fourier analysis of the input signal to extract fundamental out of it.

Comparing the input current level is greater than the pickup value or not.

S-function running an algorithm. It monitors the input and checks if the input is 1 or not, (i.e., input current greater than pickup). The S-function gives out the time at which this input current goes above the pickup value.

Output of this block is the time which has elapsed since the input current has exceeded the pickup value.

This block compares the operation time computed with the time elapsed by the timer.

This block implements the mathematical equation to compute the operation time corresponding to the type of characteristic curve chosen by the user.

The operation time corresponding to the type of characteristic curve chosen by the user.

Different Types of Inverse Characteristics

<table>
<thead>
<tr>
<th>Relay Characteristic Type</th>
<th>α</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Inverse</td>
<td>0.02</td>
<td>0.14</td>
</tr>
<tr>
<td>Very Inverse</td>
<td>1</td>
<td>13.5</td>
</tr>
<tr>
<td>Extremely Inverse</td>
<td>2</td>
<td>80</td>
</tr>
<tr>
<td>Long Inverse</td>
<td>1</td>
<td>120</td>
</tr>
</tbody>
</table>

T = \left(\frac{C}{I}\right)^{\alpha} \times TMS

1. Model Validation of an Over-Current Relay (contd.)
Protection Algorithm Implemented in the Overcurrent Relay Model
1. Model Validation of an Over-Current Relay (contd.)

Test Case Model Developed in SimPowerSystems (MATLAB/Simulink)

Digital I/O of relay are hardwired

SEL_487E (Set for OverCurrent Protection)

Fault Recorder
Event Recorder
Oscillography

Load

Dedicated block by Opal-RT which assigns a particular FPGA whose Analog and/or Digital I/Os will be accessed

Dedicated block by Opal-RT which assigns a particular FPGA whose Analog and/or Digital I/Os will be accessed

Conceptual Understanding

Phase Voltage = 1kV
Frequency = 50Hz
Length of Line = 100km
Three Phase to Ground Fault
Applied at t = 2sec
Active Power for Load = 1 MW
Frequency = 50Hz
Phase Voltage = 1kV

Alarm
Fault Pickup
Operation Time
Ratio Input/Pickup
OverCurrent Relay
OP5142 EX1 Ctrl
Board index: 1
Mode: Master

Error IDs

OP5142EX1 DigitalIn
OP5142EX1 Ctrl
Slot 3 Module A Subsection 2

Status
OP5142EX1 DigitalIn
Current Transformer
400 CT

ARTEMiS Guide
Ts = 50 us
SSN: ON

1. Model Validation of an Over-Current Relay (contd.)

Test Case Model Developed in SimPowerSystems (MATLAB/Simulink)

HIL Implementation

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1. Model Validation of an Over-Current Relay (contd.)

Validation Results

Comparison of SIL and HIL Simulation for Different Characteristic Curves

- Standard Inverse
- Very Inverse
- Long Inverse
- Ideal Calculations
- SIL
- HIL

2. Power System Communication (Station & Process Bus Implementation)

Comparison of the Real-Time Results with Stand Alone Testing Using Freja-300 (Relay Test Set)

The only way to validate the RT-HIL results for protection IEDs is to compare results with existing technology (stand-alone tests)
2. Power System Communication (Station & Process Bus Implementation (contd.))

Real-Time HIL (Process Bus IEC 61850-9-2 Implementation) [Opal-RT + ABB-RED 670]

Synchrononous Generator 500MVA, 20kV

Thevenin Equivalent

Transmission Line L1-3

Transmission Line L1-3a

Transmission Line L3-5

Step Up Transformer 20kV / 380kV

Step Down Transformer 380kV / 6.3kV

Transmission Line L1-3

Bus 1

Bus 2

Bus 3

Bus 4

Bus 5

OLTC Controlled Load

Induction Motor 4.3 MVA, 6.3kV

Softwares:
- MATLAB / SimPowerSystems
- ABB PCM 600: Relat Settings
- RT-LAB: Real-Time Execution
- WireShark: Network Analyzer
- ABB IET 600: Substation Automation Architecture

No Hardwires for CT and VT connections
No need of Amplifiers for RT-HIL execution

3. Comparison of Standalone and RT-HIL Testing Approach

Comparison of Results from Standalone and RT-HIL Testing Fault Applied at t=2 sec, protection tested= instantaneous overcurrent

<table>
<thead>
<tr>
<th>Testing Methodology</th>
<th>Feature</th>
<th>Tripping Time (sec)</th>
<th>Delay (msec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standalone</td>
<td>Hardwired</td>
<td>2.0083</td>
<td>8.30</td>
</tr>
<tr>
<td></td>
<td>GOOSE</td>
<td>2.0060</td>
<td>6.00</td>
</tr>
<tr>
<td>RT-HIL</td>
<td>Hardwired</td>
<td>2.0085</td>
<td>8.50</td>
</tr>
<tr>
<td></td>
<td>GOOSE</td>
<td>2.0062</td>
<td>6.20</td>
</tr>
</tbody>
</table>

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PMU App. SDK
A LabView-Based PMU Application SDK

PMU Recorder Light (PRL)

PMU Recorder Light (PRL)
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PMU App. SDK
A LabView-Based PMU Application SDK

a. Model

b. Implementation

Statnett

Prototype Implementation (PMU App. SDK Beta)

Connection with PDC
Configuration
PC Loading Monitor

Data Channel Selection
Real-Time Data Access

Straightforward Development of Monitoring Application

Comparison with a commercial monitoring tool

a. Results from developed synchrophasor based monitoring application (with Statnett)

b. Results from vendor specific (SEL-5073 PDC monitoring) tool
PMU Based Application Example

Real-Time Mode Meter

Estimates frequency of the electromechanical modes of the power system

Three different spectral estimators are used ensuring accurate signal spectrum estimation:
- Welch’s method,
- Auto-Regressive (AR) method
- Auto-Regressive Moving Average (ARMA) method

Conclusions and Further Work

- Smart Transmission Grids will benefit from RT HIL simulation for developing new technologies.
- Modeling for real time simulation is necessary:
  - Developing more models for protection functions like Distance protection, differential protection, over/under voltage, over/under frequency protection etc. to have available a library for protection functions.
- Consideration of actual measurement and automation streams is necessary:
  - Exploiting IEEE C37.118 (Synchrophasors from PMU) and IEC 61850 (Substation Automation) can be useful to develop applications which can serve as online oscillation detection, mode estimation, power oscillation damping, etc.
- PMU-Based applications can enable flexibility:
  - Developing a Real-Time controller which can read data from power system / substation components irrespective of the vendor protocol and can translate it to take either distributed or global control actions.
- RT HIL simulation can help us to achieve broader goals:
  - Power system which is more reliable and more flexible
Thank you!

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