
KTH

Developing Real-Time PMU Applications for Smart Transmission Grids

In a Real-Time Hardware-in-the-Loop Laboratory

Dr.-Ing. Luigi Vanfretti

Docent and Assistant Professor

ROYAL INSTITUTE OF TECHNOLOGY

SmarTS Lab
Smart Transmission Systems Laboratory

Statnett

KTH Royal Institute of Technology
Stockholm, Sweden
E-mail: luigiv@kth.se
Web: http://www.vanfretti.com

Scientific Advisor
Smart Operation R&D Program
R&D Department
Statnett SF, Oslo Norway

International Workshop:
The use of Synchrophasors in Power Systems
Dec. 12th, 2012 – Rio de Janeiro, Brazil

COPPE UFRJ

CAPES

STINT The Swedish Foundation for International Cooperation in Research and Higher Education

Outline

- *Motivation:*
  - The paradigm shift – or ***why*** are “Smart Grids” needed (… also at the Power Transmission Level)
  - STRONgrid project
    - Goals, partners and LV PMU Network
- *Development of Smart Grid Apps:*
  - SmarTS Lab: A real-time Hardware-in-the-Loop Laboratory
  - Flexible Tools for Detecting and Monitoring Power System Oscillations
- Q&A

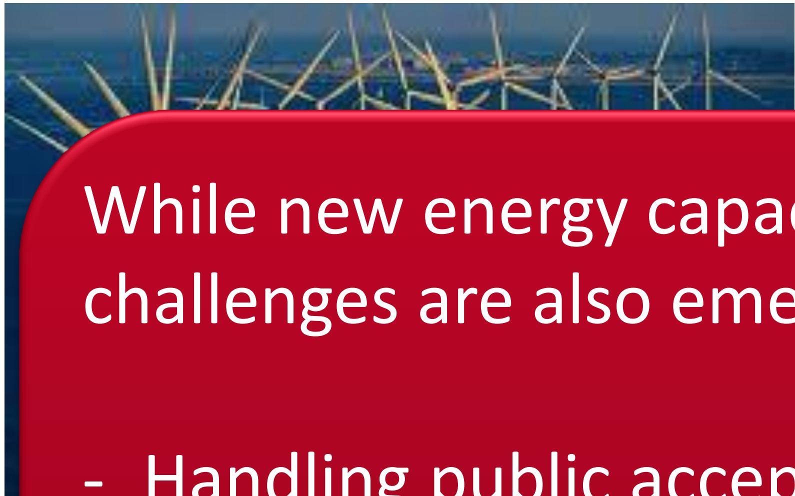
SmarTS Lab
Smart Transmission Systems Laboratory

ROYAL INSTITUTE OF TECHNOLOGY

Intermitted generation – brings renewable energy capacity

- New production of electricity:
  - Wind: *variable - uncertain*
  - Solar: *variable - uncertain*
- *Location:*
  - Most "new" wind is located at distant locations (Long-distance transmission required)
  - Most "new" solar sources sited "closer" to the customer – on all voltage levels (becoming bigger)
- **And more to come!**
  - **In Norway** – great potential for micro hydro plants at remote locations.

Intermitted generation – brings renewable energy capacity



While new energy capacity is coming in, new challenges are also emerging for *security of supply*:

- Handling public acceptance for the installation of transmission capacity! (Norway/Sweden)
- Meeting the challenges from the push for decommissioning of nuclear plants (Germany)
- Meeting EU 202020 goals (CO2 goals make it difficult to attain – dependency on fossil).

- New production of

rtain

rtain

cated

ong-

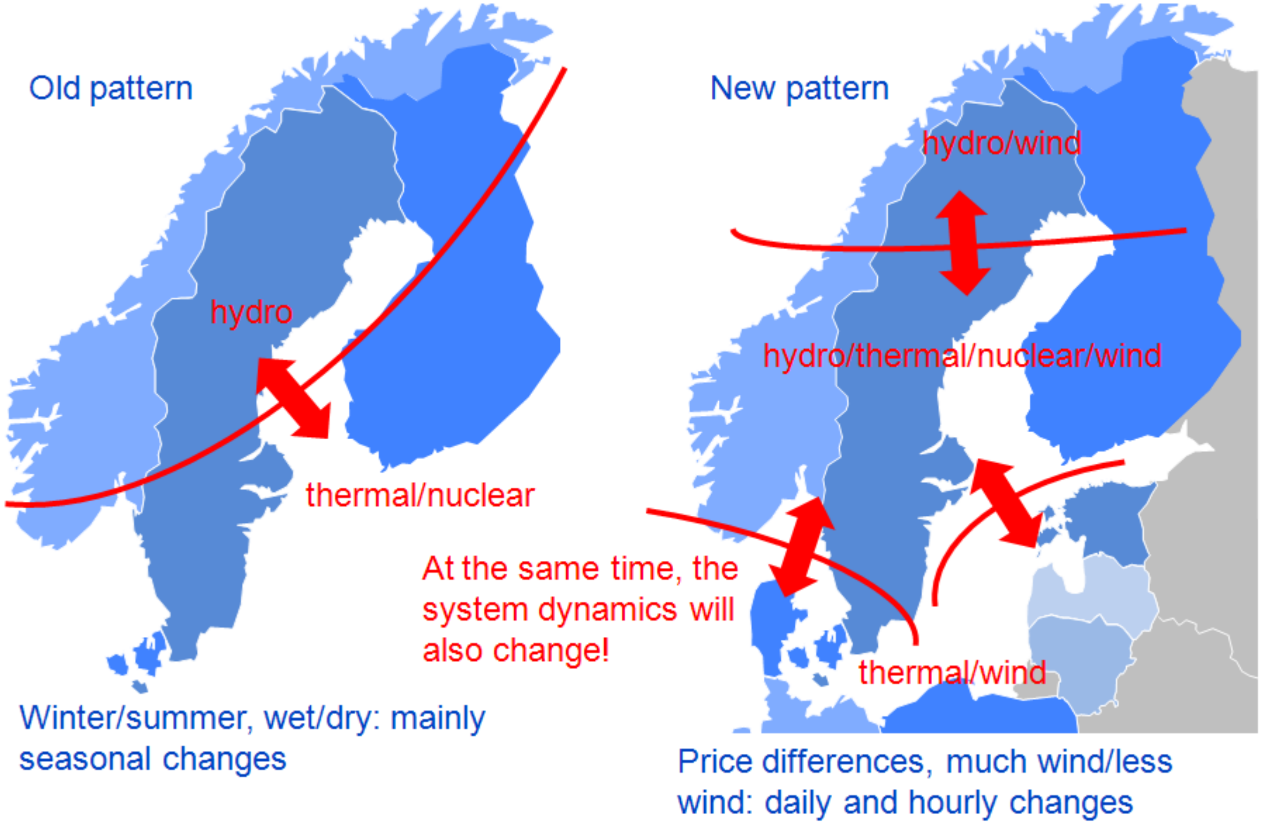
rces

age

er)

- **In Norway** – great potential for micro hydro plants at remote locations.

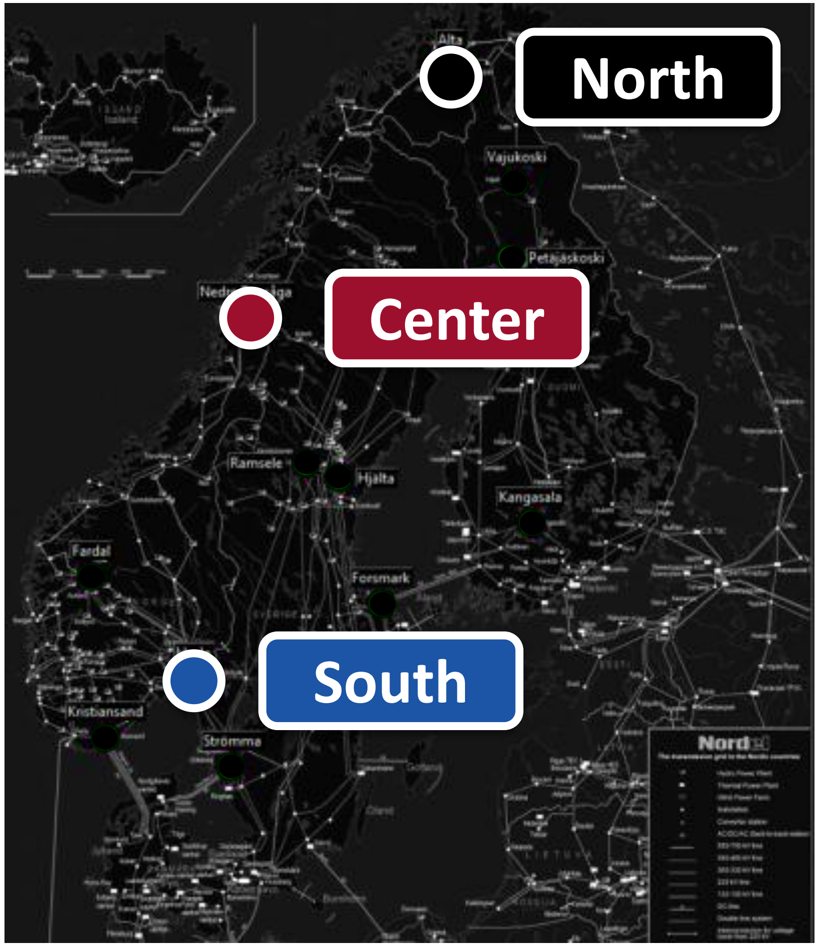
To deal with new generation sources ***requires a paradigm shift*** … also at the transmission level

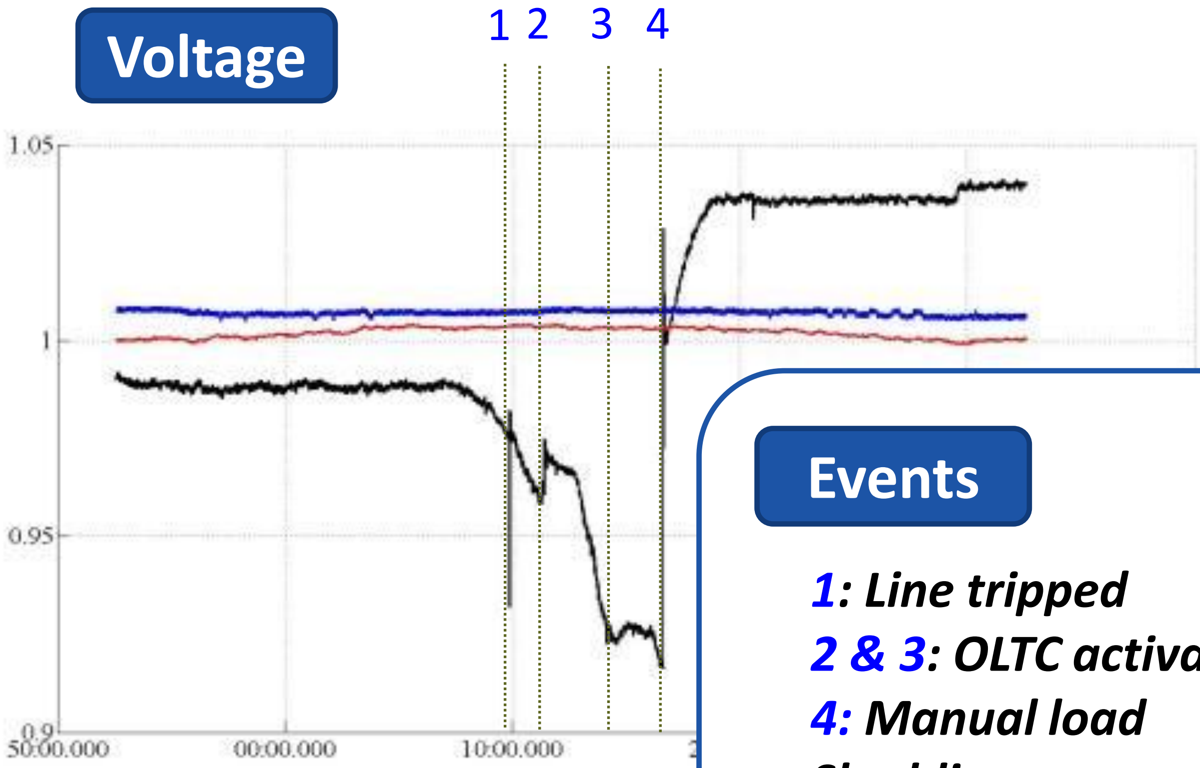


- Future generation patterns bring *faster power transfer interactions*
- It will become necessary to quickly attain a ***system wide*** visibility and ***awareness*** of the system's condition
- ***Real-time monitoring*** can provide real-time visibility of HV networks across traditional operational boundaries
- ***Real-time control*** can help handling operation under stringent conditions

Need for Flexibility: Near-voltage-collapse example

- System dynamics become increasingly important for system operation





Events

***1**: Line tripped*
***2 & 3**: OLTC activation*
***4**: Manual load Shedding*

- ***Flexibility becomes available*** with advancements in
  - Wide-area monitoring, protection, and control systems

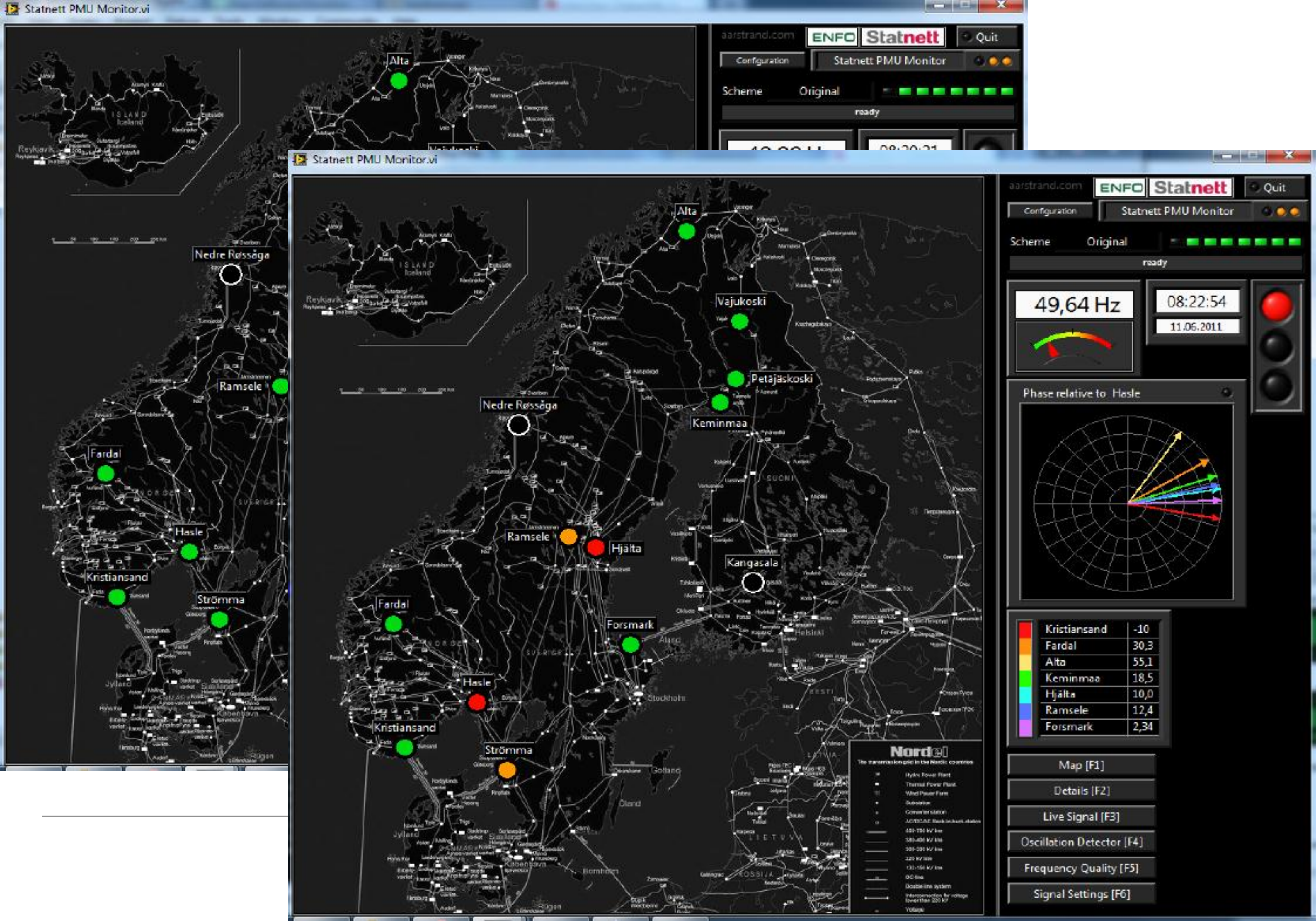
Smart Grids – Also at the Transmission Level

Monitoring, Operation, Control and Protection in Real-Time

A challenge also in Scandinavia:

Picture of the Regional Control Center at Alta, Norway.

Operators have the challenge of running a power system under severe weather conditions and guaranteeing supply to critical heavy industries


Statnett PMU Monitor.vi
aarstrand.com
ENFO
Statnett
Quit
Configuration
Statnett PMU Monitor
Scheme
Original
ready
49,64 Hz
08:22:54
11.06.2011
Phase relative to Hasle
Alta
Vajukoski
Petäjäskoski
Keminmaa
Nedre Røssåga
Ramsele
Hjälta
Kangasala
Fardal
Forsmark
Hasle
Kristiansand
Strömma
Reykjavik
Stockholm
Helsinki
Nordel
Kristiansand -10
Fardal 30,3
Alta 55,1
Keminmaa 18,5
Hjälta 10,0
Ramsele 12,4
Forsmark 2,34
Map [F1]
Details [F2]
Live Signal [F3]
Oscillation Detector [F4]
Frequency Quality [F5]
Signal Settings [F6]

Project Goals and Partners

STRON²grid
Smart Transmission Grids Operation and Control
KTH - NTNU - AALTO - DTU - UI

- Develop innovative applications that will enable operation and control of the Nordic power grid more reliably and with better information about security margins.
- Develop a research platform comprised by a power systems emulator (software and hardware labs), PMUs, PDCs and specialized software.
- Develop a set of software interfaces allowing PMU- data application development, and implementation
- *Partners:*

Academia

NTNU, KTH, Lund University, Aalto University School of Science and Technology, DTU, University of Iceland, Institute of Physical Energetics, TTÜ 1918

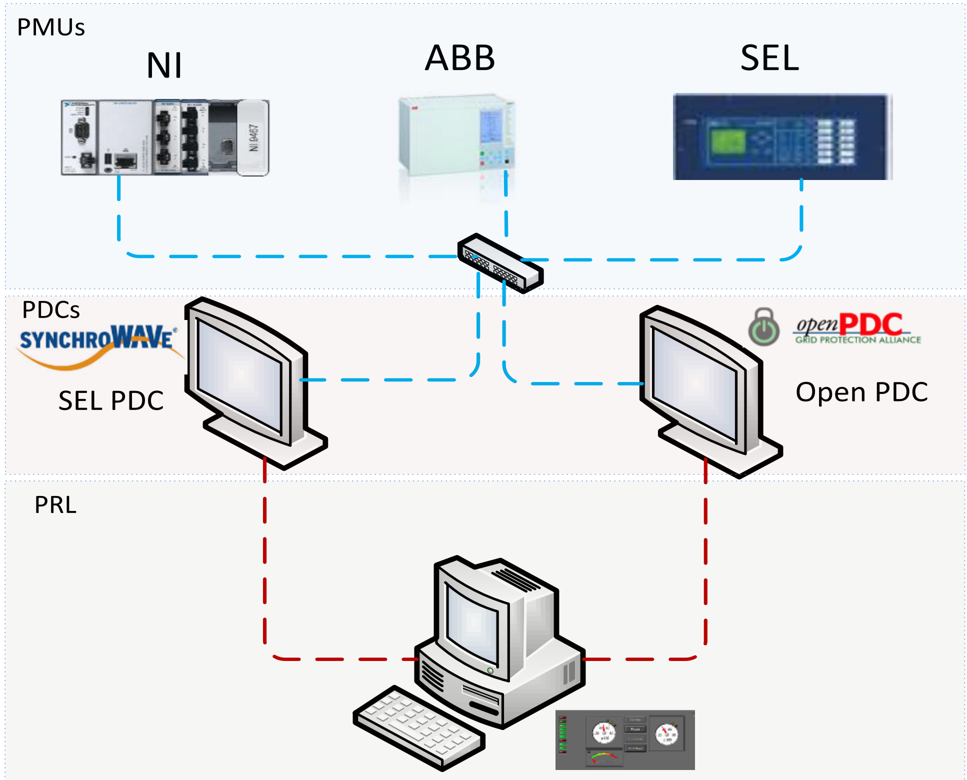
Industry

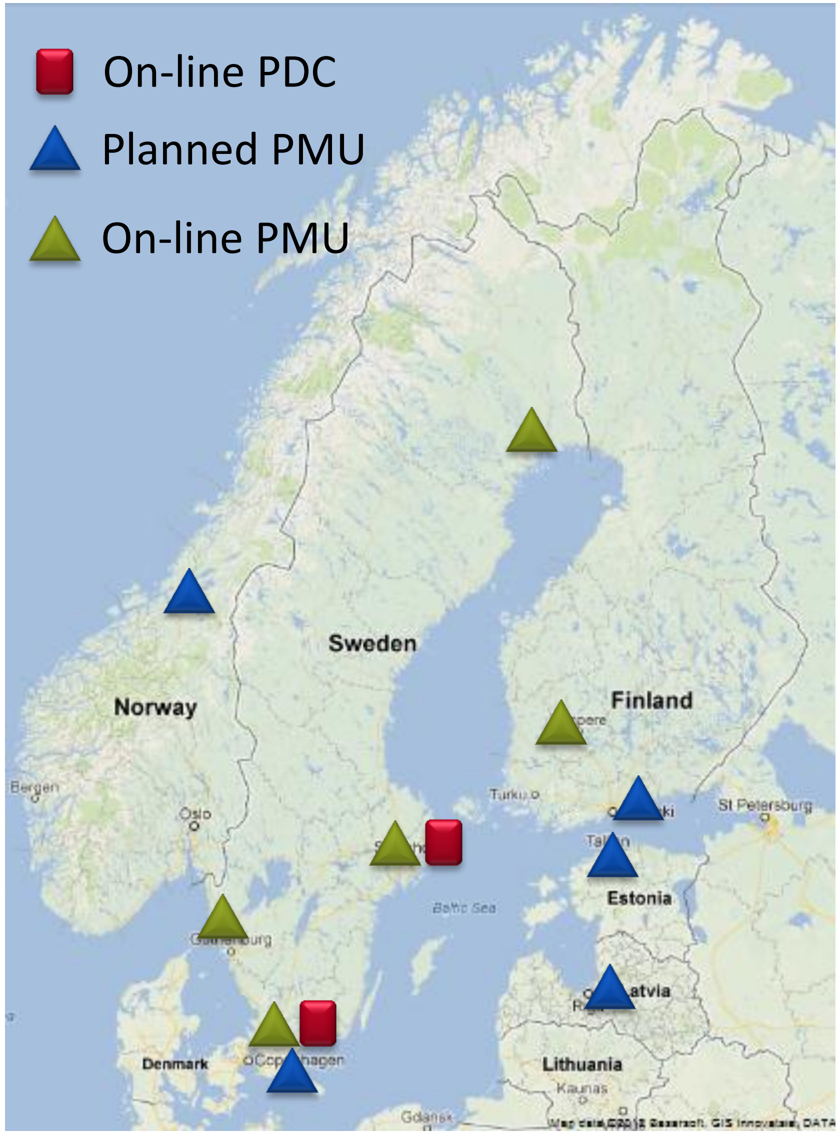
Statnett, Troms Kraft, Svenska Kraftnät, Gothia Power, Fingrid, Landsnet

LV PMU Network Extension in STRONg²rid

Smart Transmission Grids Operation and Control
KTH - NTNU - AALTO - DTU - UI

- Build up from initiative by Lund University.
- PMUs are connected at the LV network
  - Inputs: 3 phase voltage
  - Outputs: Voltage magnitude, angle, frequency and df/dt



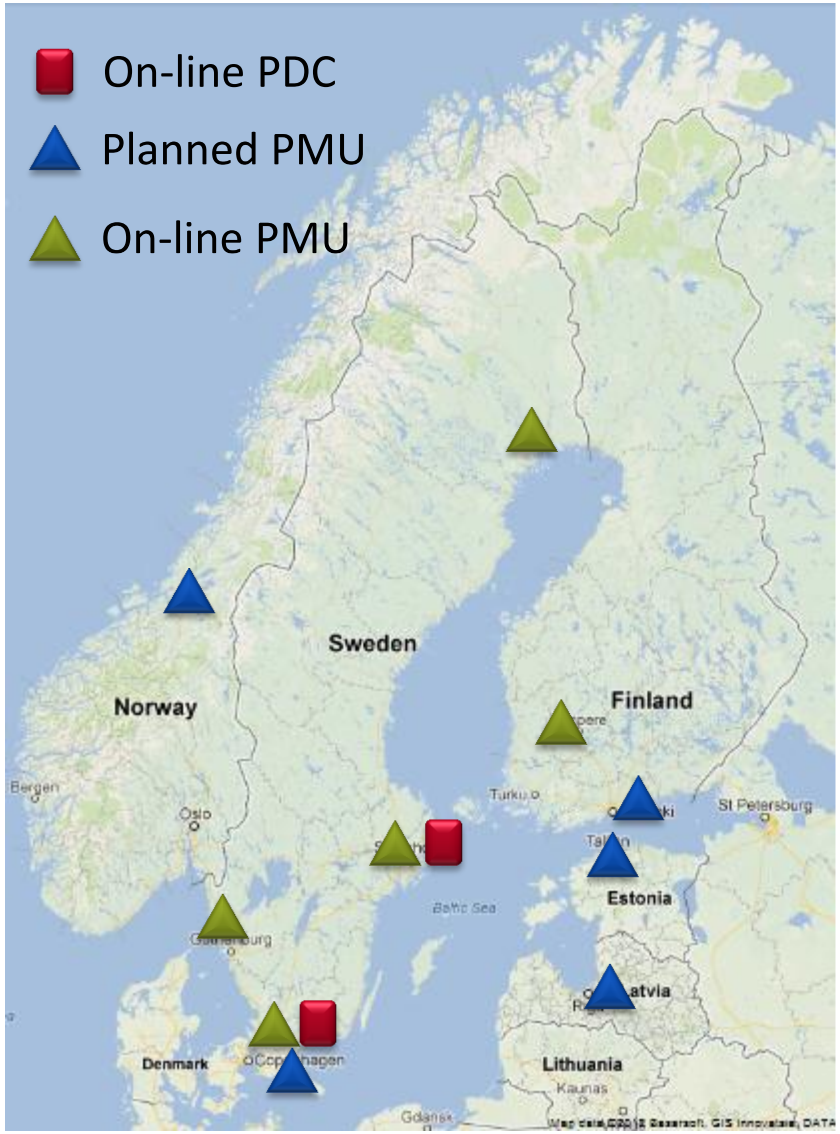


ROYAL INSTITUTE OF TECHNOLOGY

LV PMU Network Extension in STRONg²rid

STRONg²rid
Smart Transmission Grids Operation and Control
KTH - NTNU - AALTO - DTU - UI

- Build up from initiative by Lund University.
- PMUs are connected at the LV network
  - Inputs: 3 phase voltage
  - Outputs: Voltage magnitude, angle, frequency and df/dt
- 5 On-line PMUs:
  - KTH (Stockholm), CTH (Gothemburg), LTH (Lund), LTH (Luleå), Tampere
- 2 On-line PDCs:
  - Lund (homebrew PDC)
  - KTH (openPDC)
- 4 New PMUs will be installed on 2012:
  - NTNU (Trondheim), DTU (Bingby), TUT (Estonia), IPE (Latvia)



ROYAL INSTITUTE OF TECHNOLOGY

Sample Event: Totalstopp för SL

Outage affecting the whole railway system in Stockholm

- The incident happened on Nov 6th 2012 at 2pm
- All newspapers wrote about it: http://www.dn.se/sthlm/totalstopp-for-sl
  - Fault due to bad reconnection during planned maintenance work in Älsjö (Stockholm area). This triggered protection on one line
  - All railway systems affected (T-bana, Pendeltåg and local trains)
  - Some households (84000) without power during one hour
- More stories available under #strömavbrott on Twitter
- How we noticed:
  - The lights blinked in KTH, some electric protection triggered in our Lab

Strömlöst betyder match i dagsljus på Kopparvallen

Uppdaterad 2012-10-31 22:33. Publicerad 2012-10-31 20:33

Strömavbrott på Kopparvallen. Foto: Stefan Jerrevång/Scanpix

ÅTVIDABERG

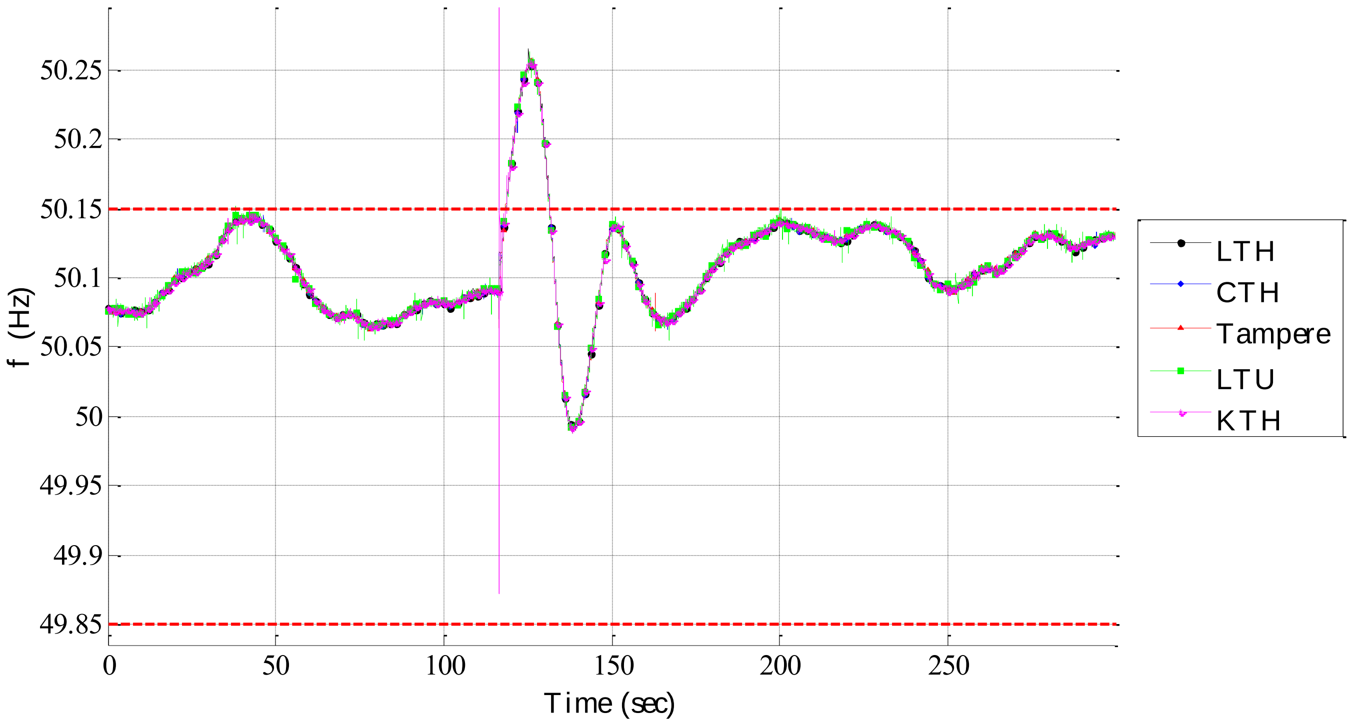
Oavgjort Åtvid - Sundsvall

Publicerat: måndag 01 oktober kl 09:00 , Nyheter P4 Östergötland

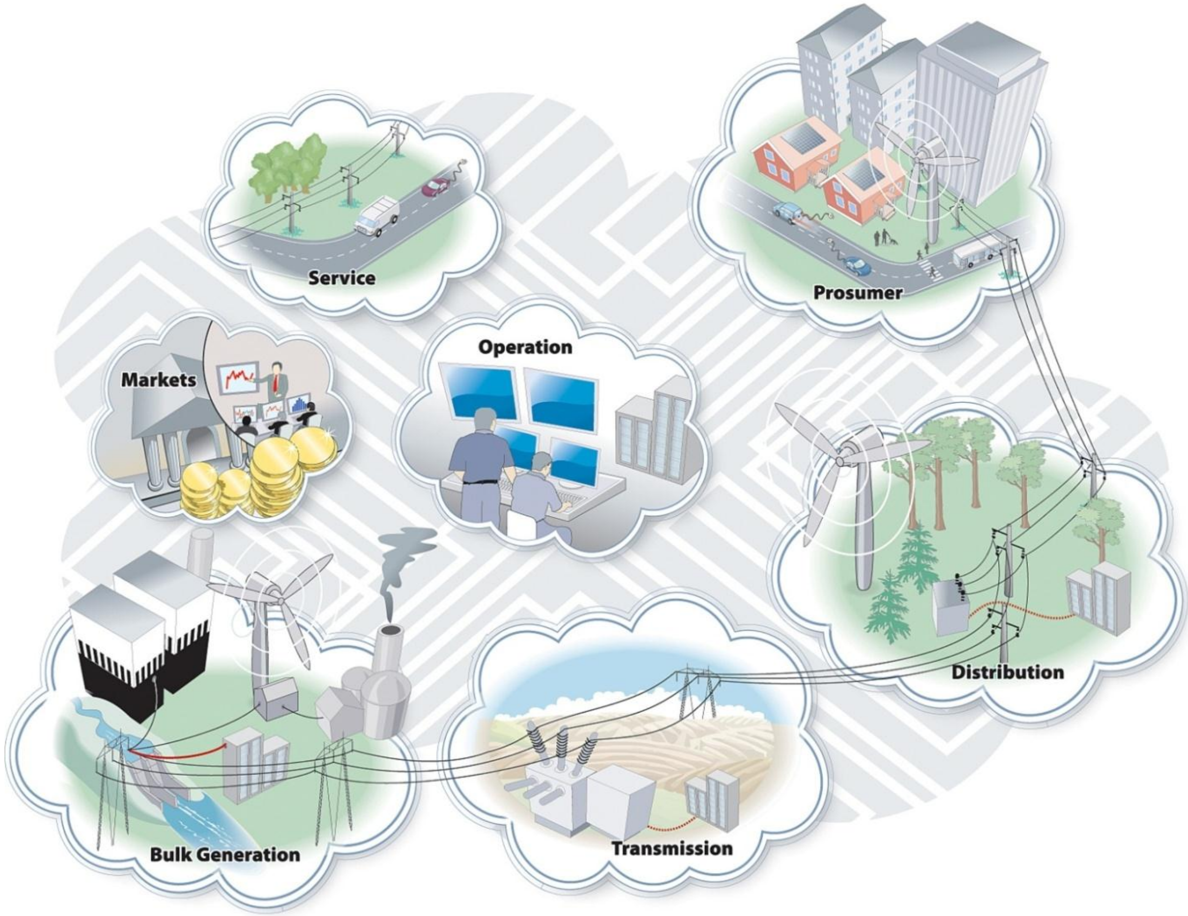
Dagens återstående 26 minuter att spela mellan Sundsvall och Åtvidaberg innebar upphämtning för Sundsvall. Gårdagens 1-0 till Åtvid vändes till 2-2 som matchresultat.

Measurements and preliminary analysis: *The Nordic Grid is quite sensitive!*

- The fault had an impact across the whole Nordic network.
  - Approx. 0.15 Hz deviation!
- The grid mode frequency measured on the graph is approx 0,04 Hz
  - Frequency/load governing mode of the network



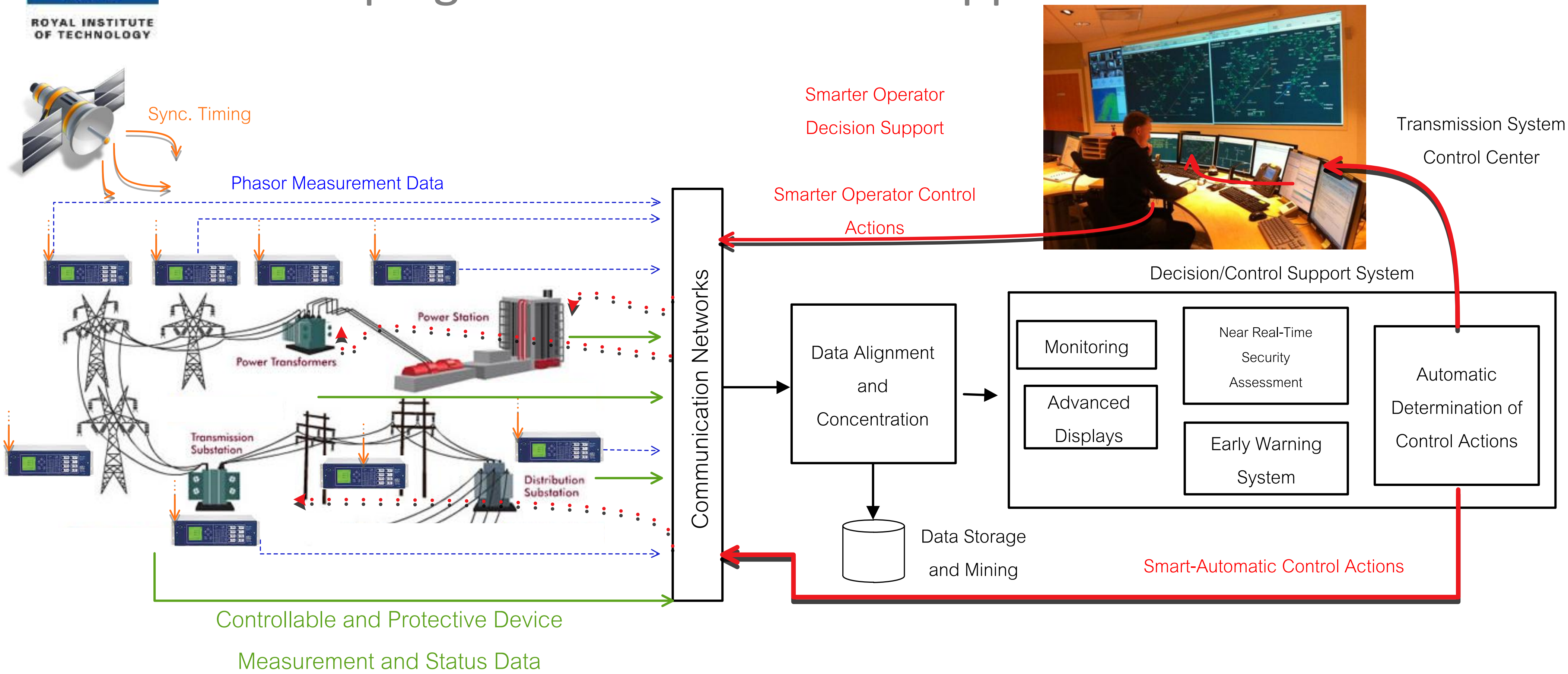
- The total generated capacity for the Nordic grid is roughly 50 GW.
  - The lost load during the fault was 300 MW. This is less than 1% of the generation capacity in the grid.
- **Such a small fraction of disconnected load should not have such far reaching impact in the entire grid.**
- With a larger availability of detailed and time-syncrhonized measurements (from PMUs) spread over the grid there is a possibility of using them as inputs to controls.



SmarTS Lab

A real-time hardware-in-the-loop laboratory for WAMPAC / PMU Application Development

How to develop a controlled environment for developing Smart Transmission Apps?

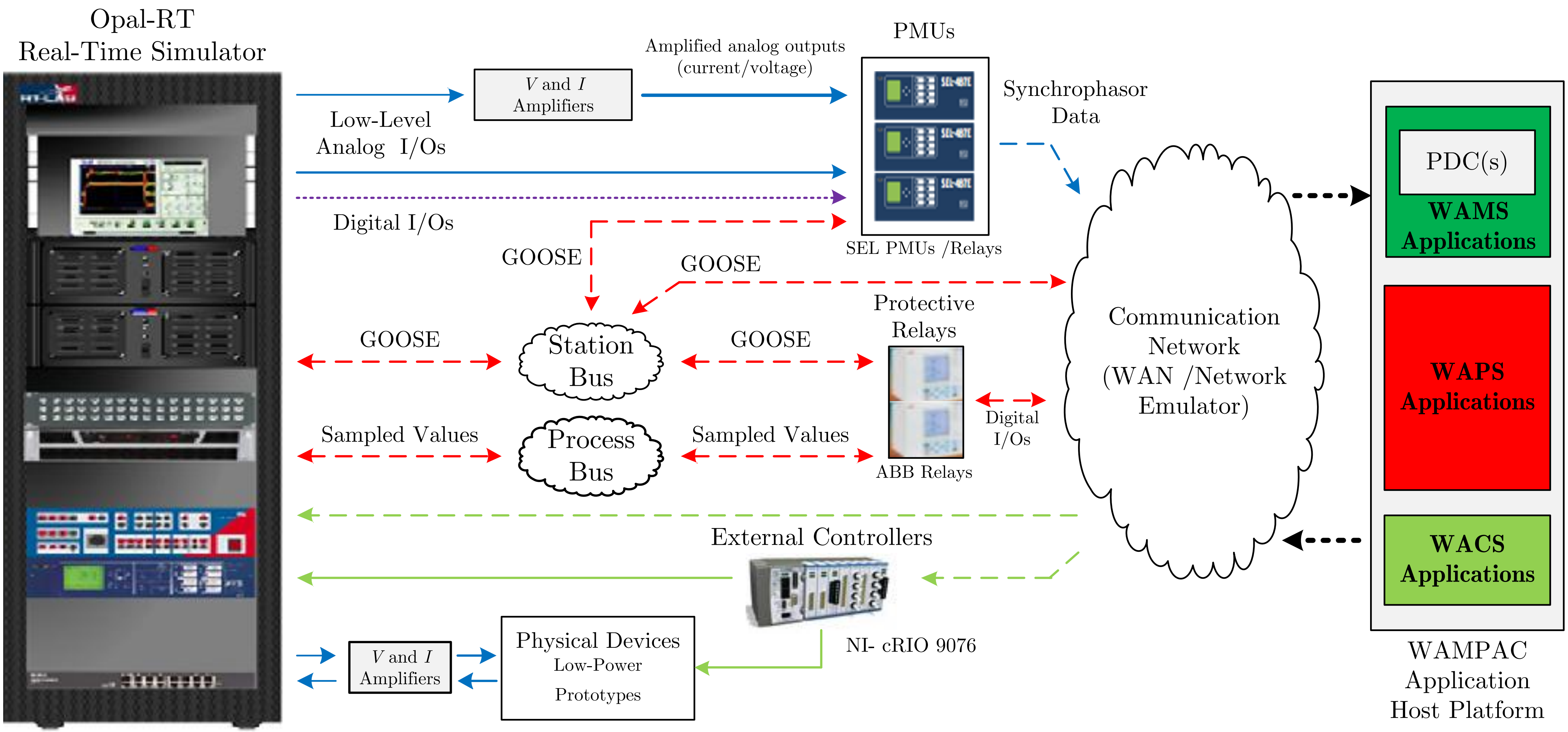


- Smart Grid require **Smart Operation, Smart Control and Smart Protection**:
  - The ultimate goal should be to attain an automatic-feedback self-healing control system
- Measure – Communicate – Analyze (System Assessment and *real* limits) – Determine Preventive/Corrective Actions – Communicate – Control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

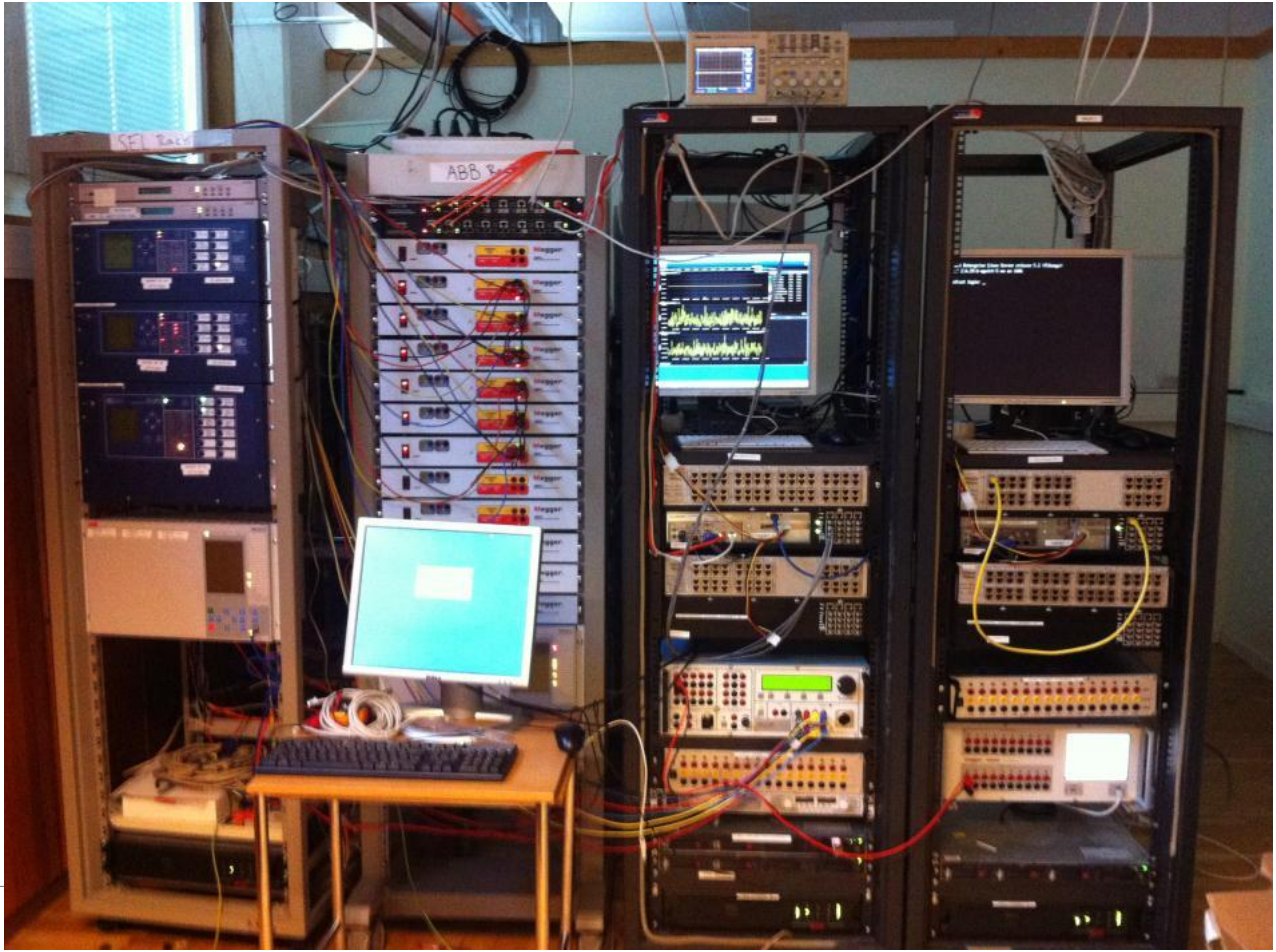
KTH VETENSKAP OCH KONST
ROYAL INSTITUTE OF TECHNOLOGY

SmarTS Lab
Smart Transmission Systems Laboratory

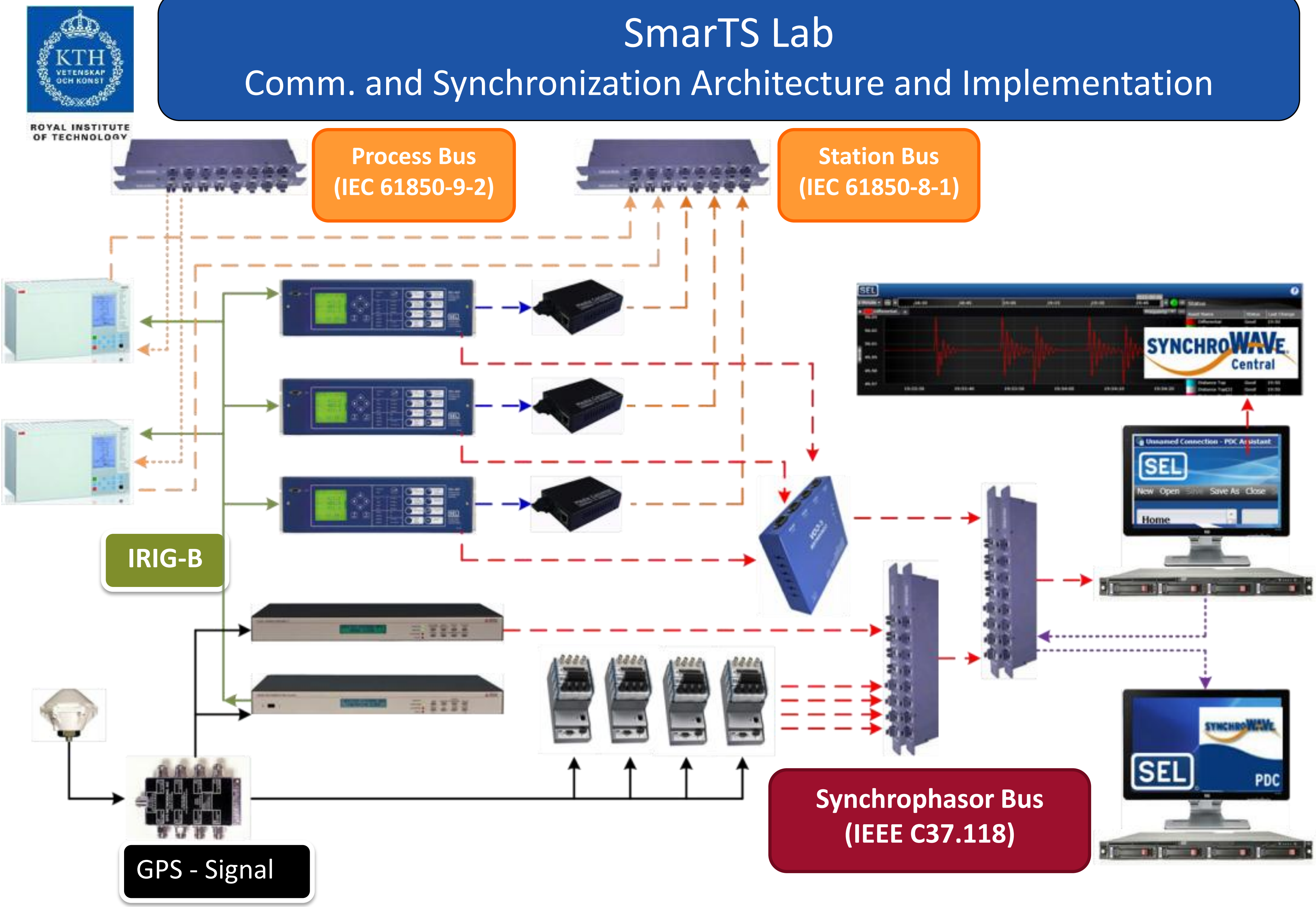
The SmarTS Lab Architecture

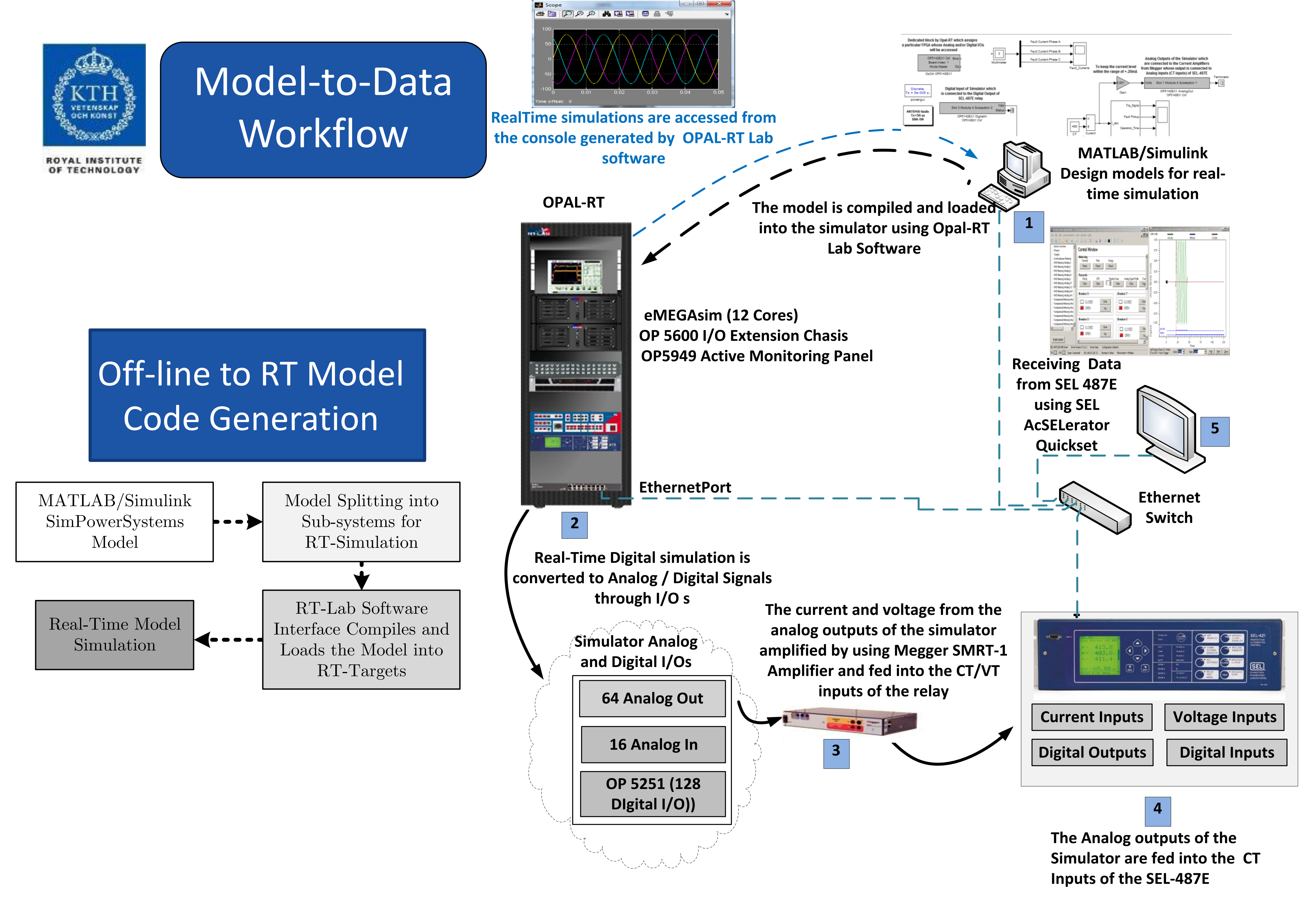


SmarTS Lab
Hardware Implementation



SmarTS Lab
Comm. and Synchronization Architecture and Implementation

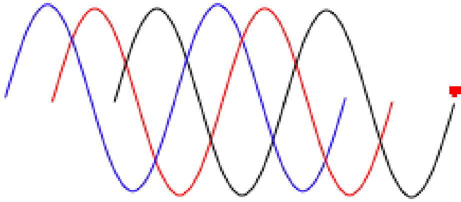




ROYAL INSTITUTE OF TECHNOLOGY
Model-to-Data Workflow
Off-line to RT Model Code Generation
MATLAB/Simulink SimPowerSystems Model
Model Splitting into Sub-systems for RT-Simulation
RT-Lab Software Interface Compiles and Loads the Model into RT-Targets
Real-Time Model Simulation
RealTime simulations are accessed from the console generated by OPAL-RT Lab software
MATLAB/Simulink Design models for real-time simulation
The model is compiled and loaded into the simulator using Opal-RT Lab Software
1
OPAL-RT
eMEGAsim (12 Cores)
OP 5600 I/O Extension Chasis
OP5949 Active Monitoring Panel
EthernetPort
2
Receiving Data from SEL 487E using SEL AcSELerator Quickset
5
Ethernet Switch
Real-Time Digital simulation is converted to Analog / Digital Signals through I/O s
Simulator Analog and Digital I/Os
64 Analog Out
16 Analog In
OP 5251 (128 DIgital I/O))
The current and voltage from the analog outputs of the simulator amplified by using Megger SMRT-1 Amplifier and fed into the CT/VT inputs of the relay
3
Current Inputs
Voltage Inputs
Digital Outputs
Digital Inputs
4
The Analog outputs of the Simulator are fed into the CT Inputs of the SEL-487E

Model-to-Data Proof of Concept Experiment (Hardware-in-Open-Loop)

Real-Time Simulator



Generate 3-Phase RT Signals (Voltages and Currents)

Output signals, low level through simulator I/Os (+/- 16 V., +/- 20 mA)

Amplifier

Amplifying from low-level to standard rating (1-60 Amp, 60-300 V)

PMU/Relay

PMU Transmits Computed Phasors through Serial Port

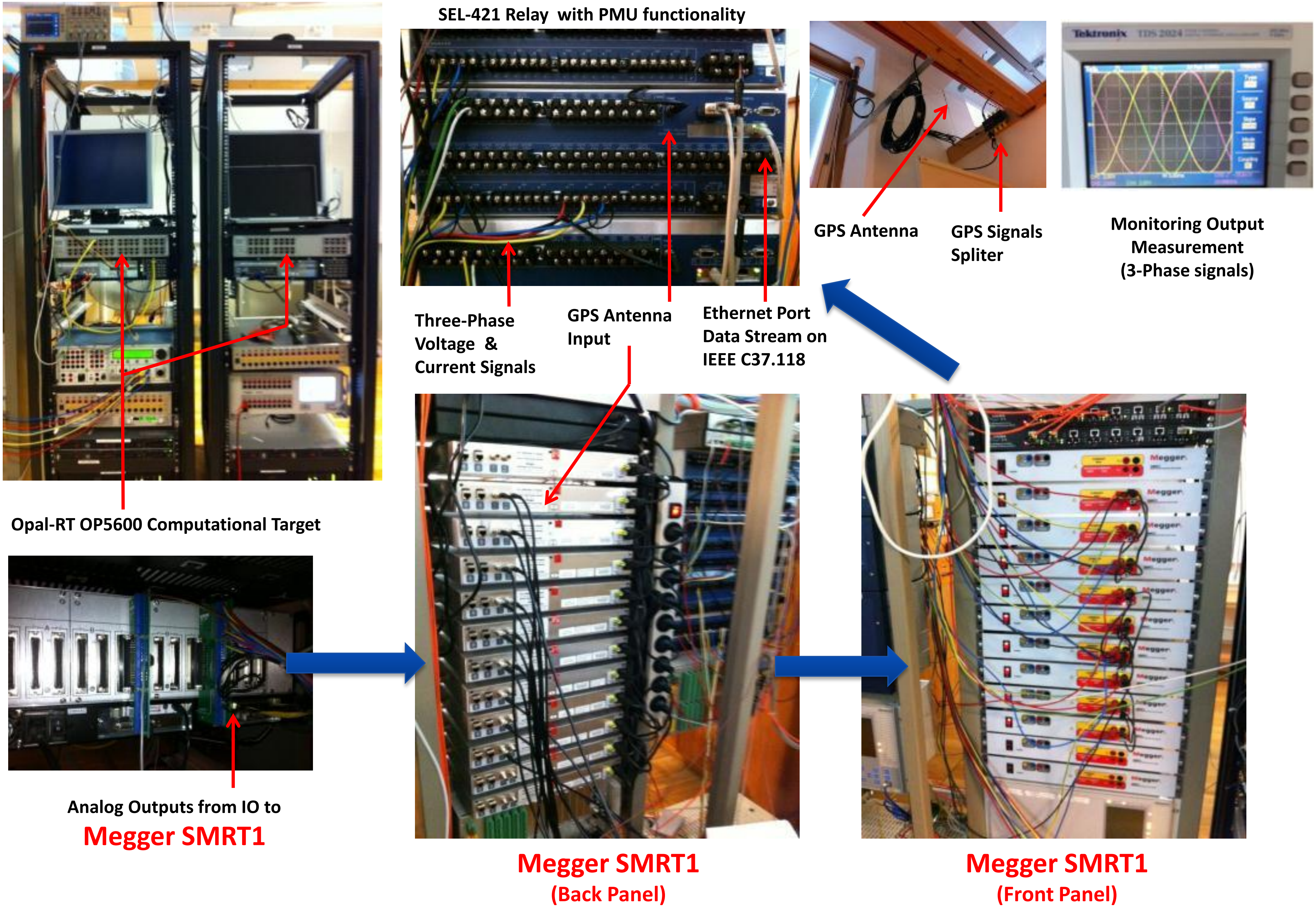
Media Converter

RS232 to TCP/IP over Ethernet

SEL Synchrowave PDC

Hardwired

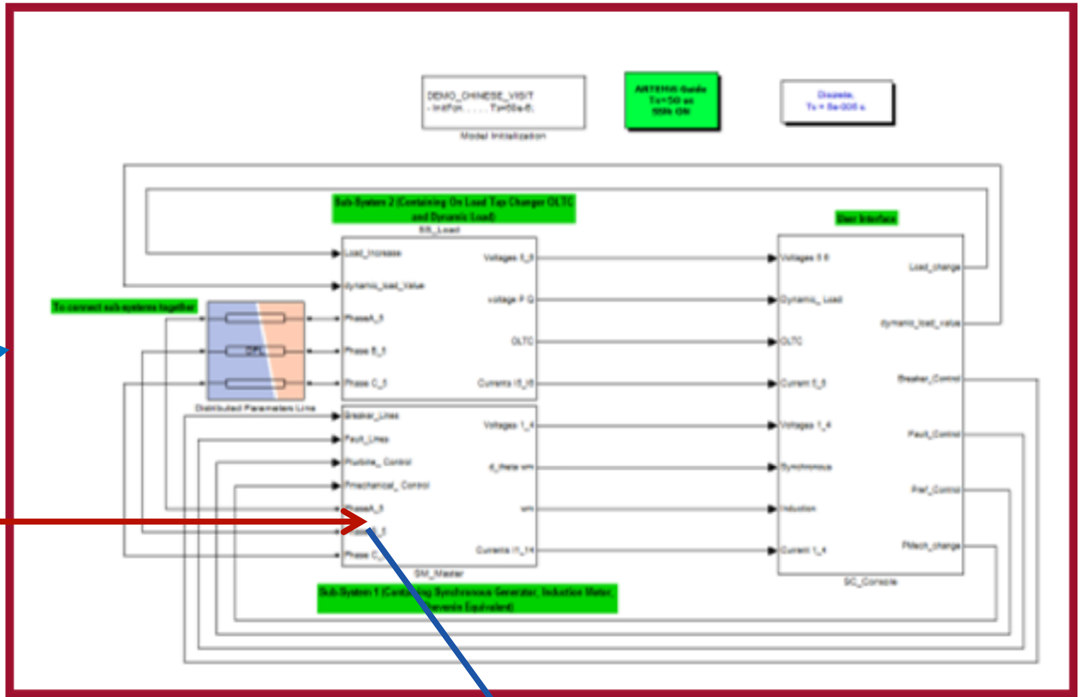
Ethernet

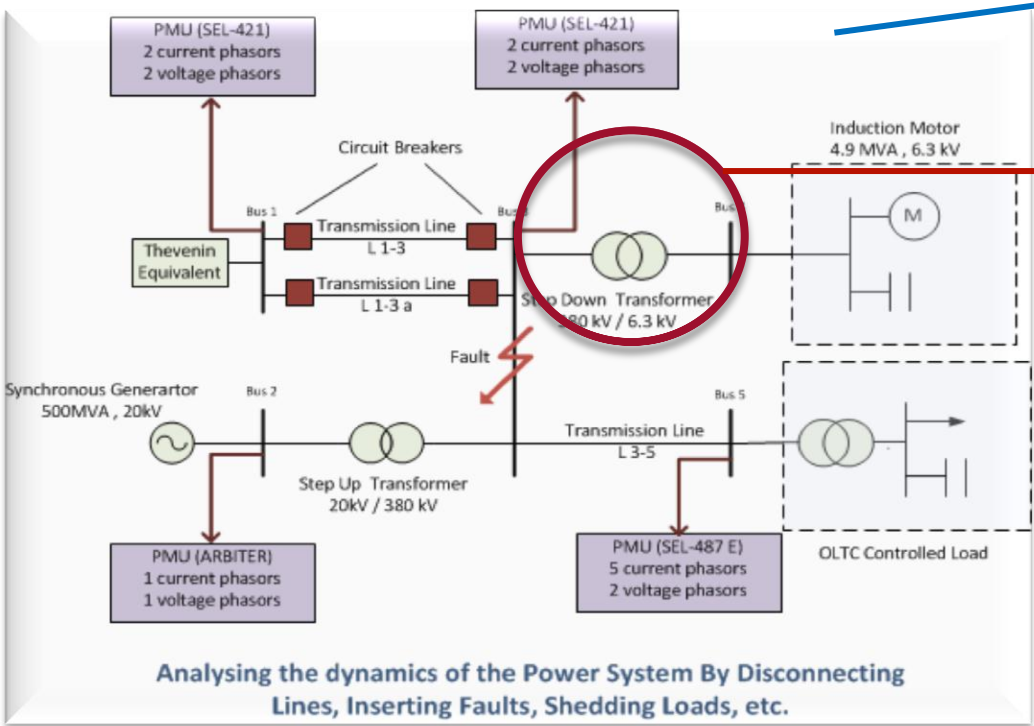


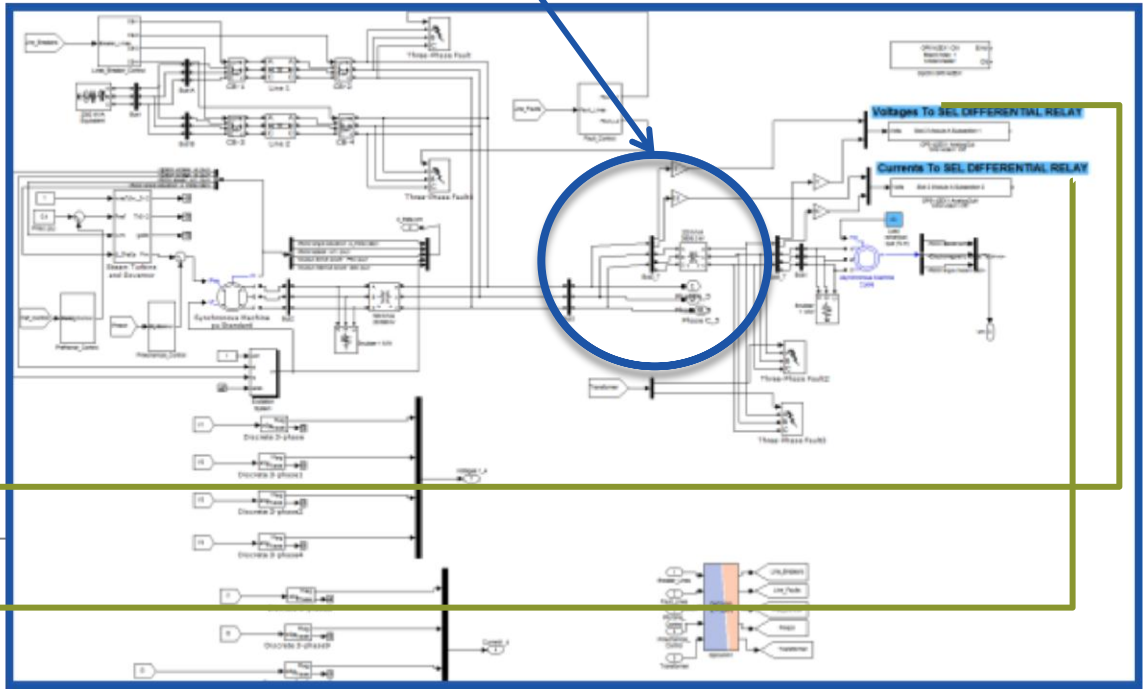
SEL-421 Relay with PMU functionality
GPS Antenna
GPS Signals Spliter
Tektronix TDS 2024
Monitoring Output Measurement (3-Phase signals)
Three-Phase Voltage & Current Signals
GPS Antenna Input
Ethernet Port Data Stream on IEEE C37.118
Opal-RT OP5600 Computational Target
Analog Outputs from IO to
Megger SMRT1
Megger SMRT1
(Back Panel)
Megger SMRT1
(Front Panel)

Modeling for Real-Time Hardware-in-the-Loop Simulation

ROYAL INSTITUTE OF TECHNOLOGY



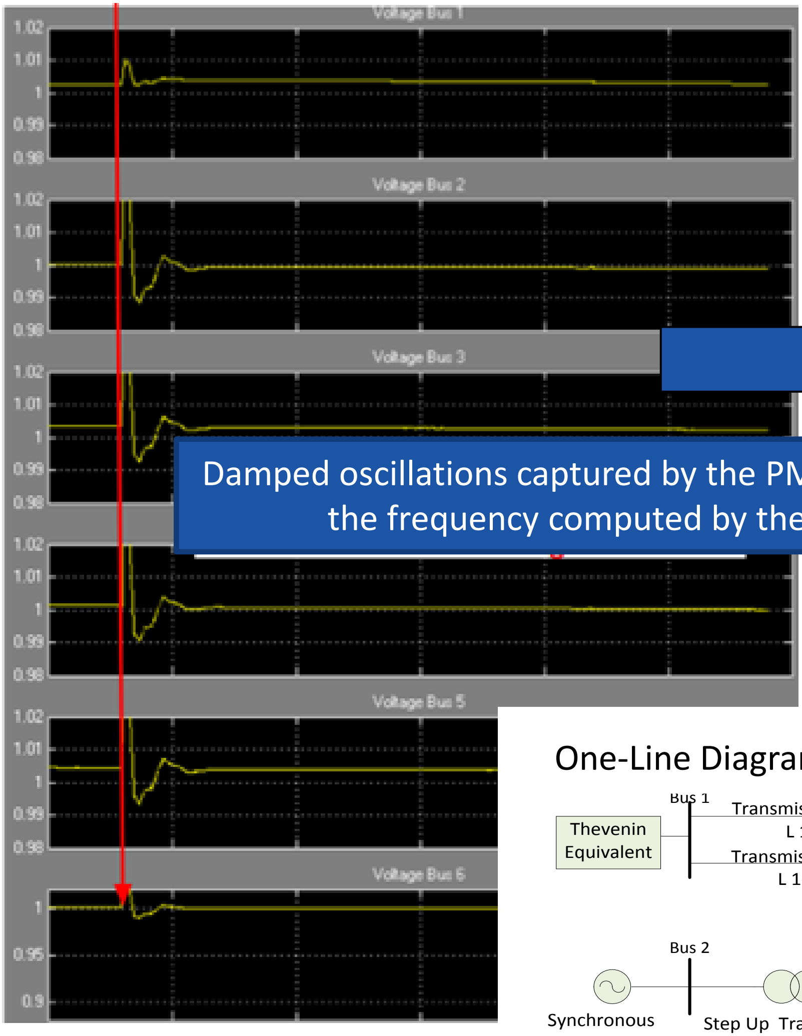




Video!

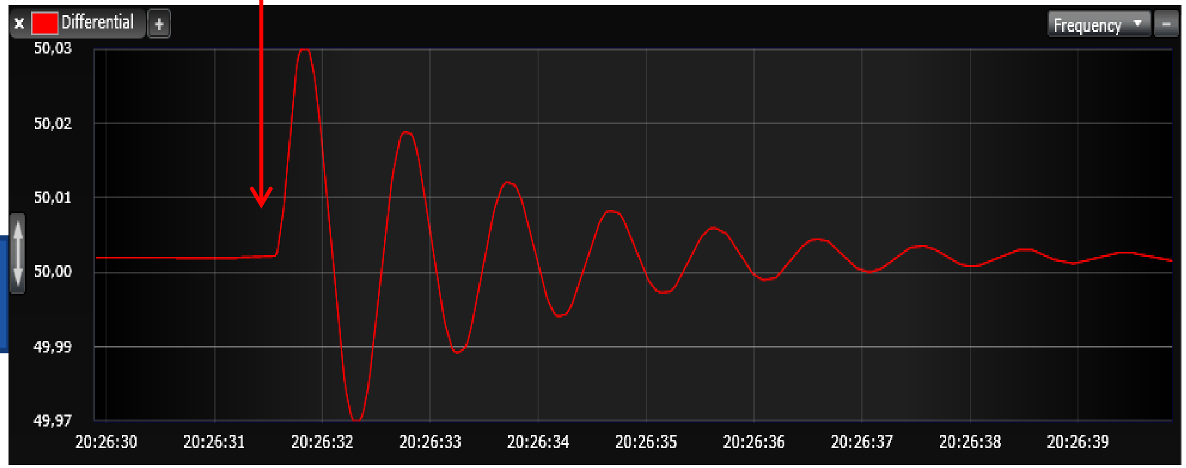
The whole process in real-time:
Interaction with the model in real-time (Hardware-in-open-loop)

Generator mechanical power perturbation

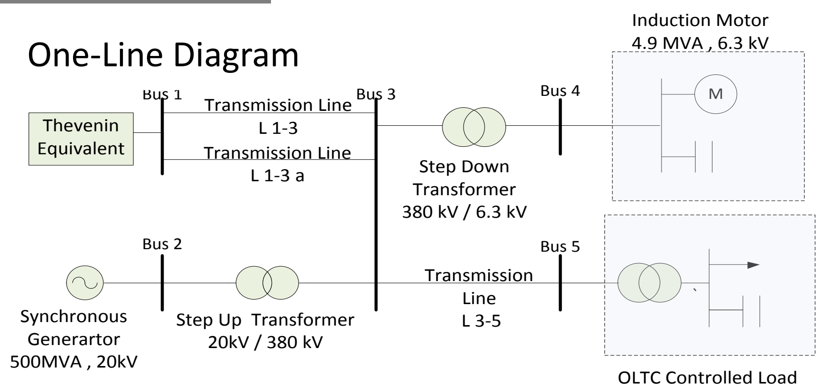


What is observed at the PMU at 50 fps reporting rate?

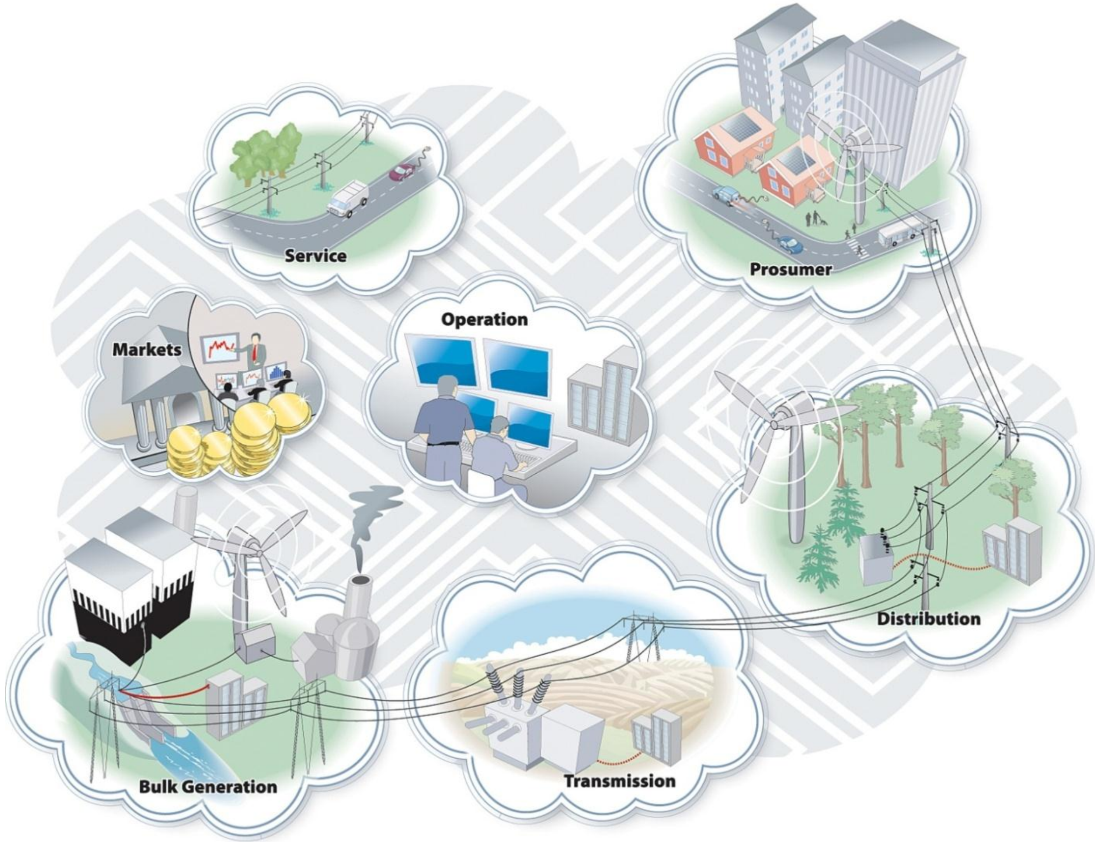
Generator mechanical power perturbation



Damped oscillations captured by the PMU at 50 fps in the frequency computed by the PMU



ROYAL INSTITUTE
OF TECHNOLOGY

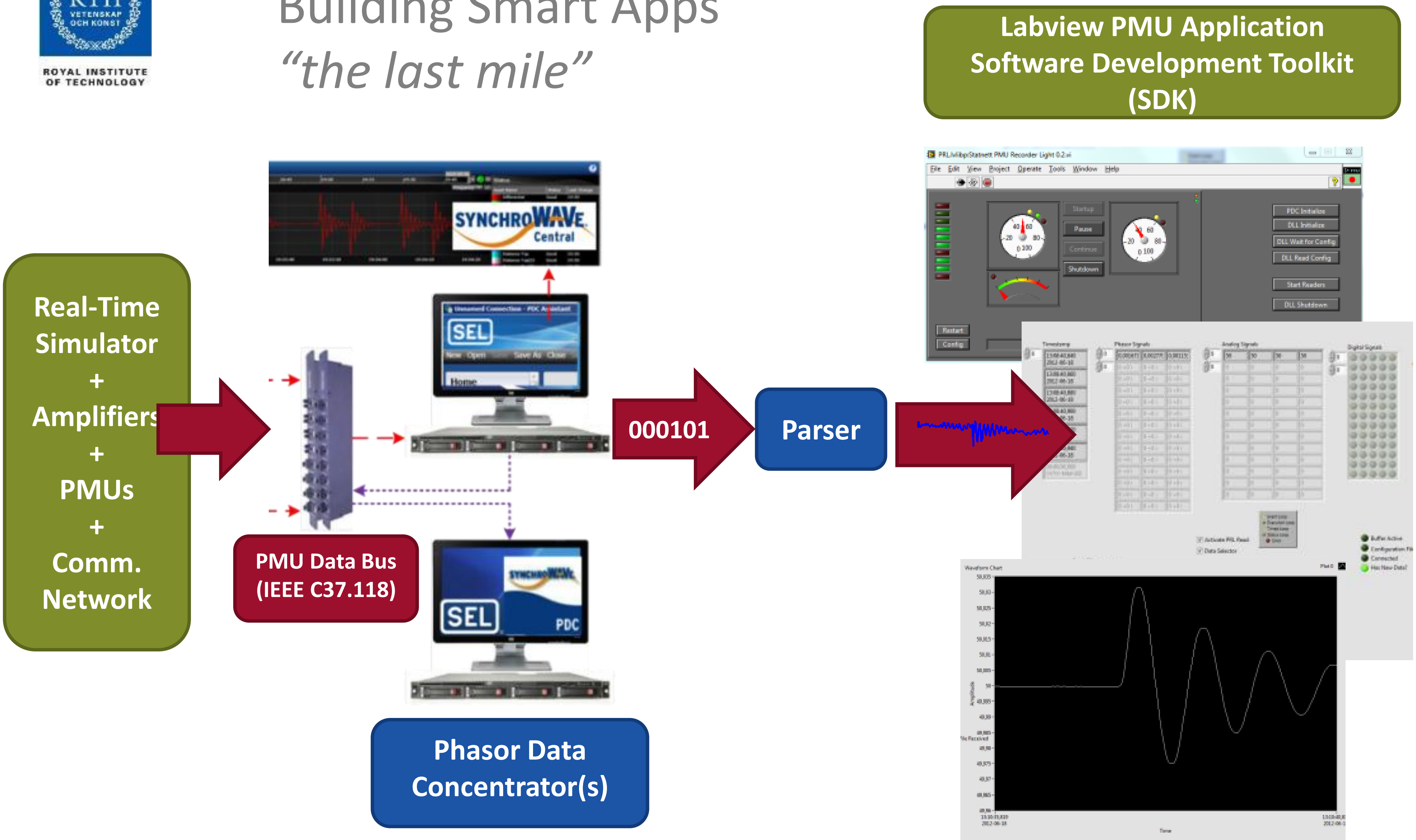


A LabView PMU Application Software Development Toolkit (SDK)

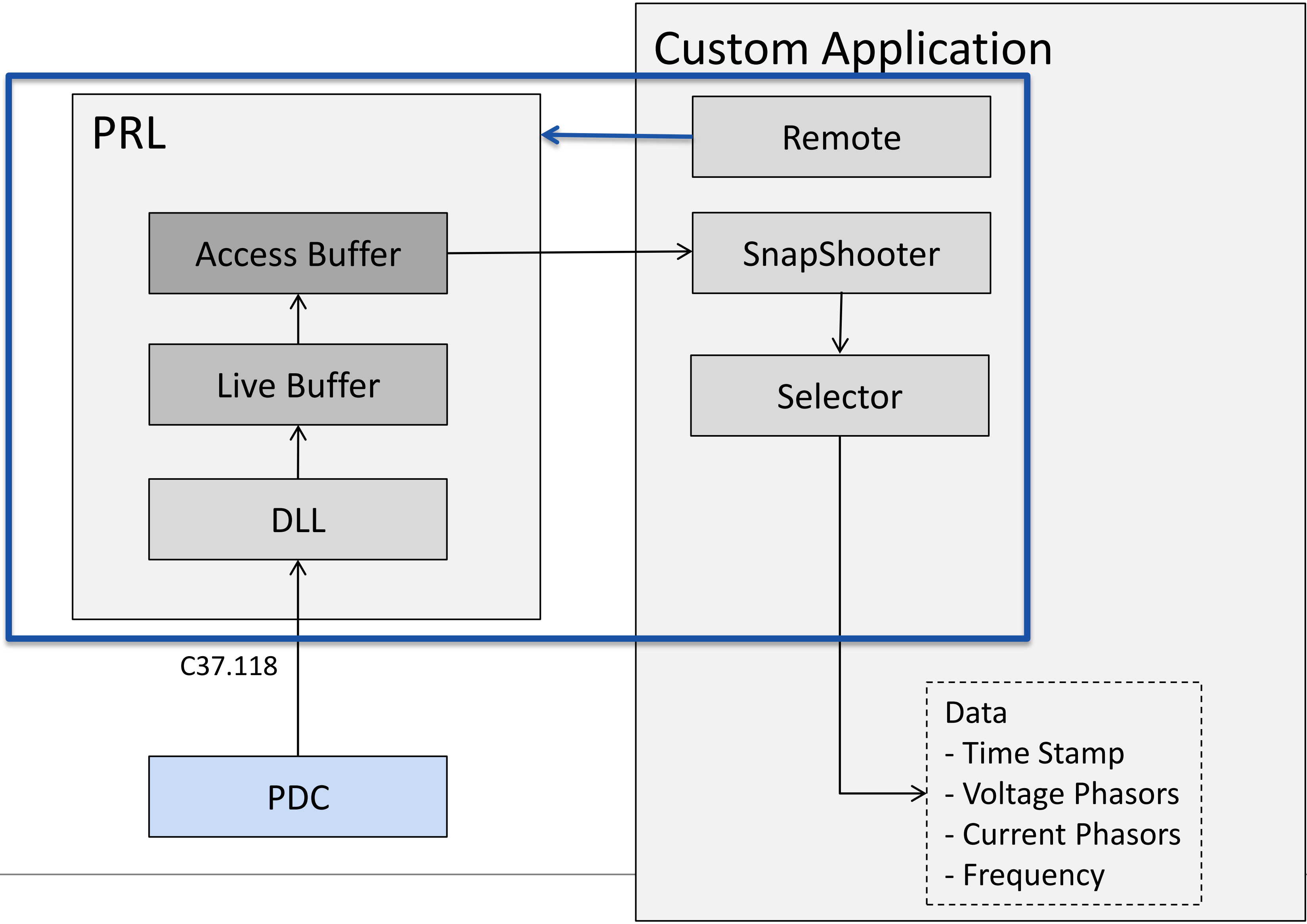
PMU App. SDK
A LabView-Based PMU Application SDK

- Connection mechanims for the IEEE C37.118 protocol and IEC 61850-9-5
- Make PMU-data available in a buffer
- Allow data access from the buffer with adjustable update rate
- Allow selection of channels
- Allow receiving data on a queue

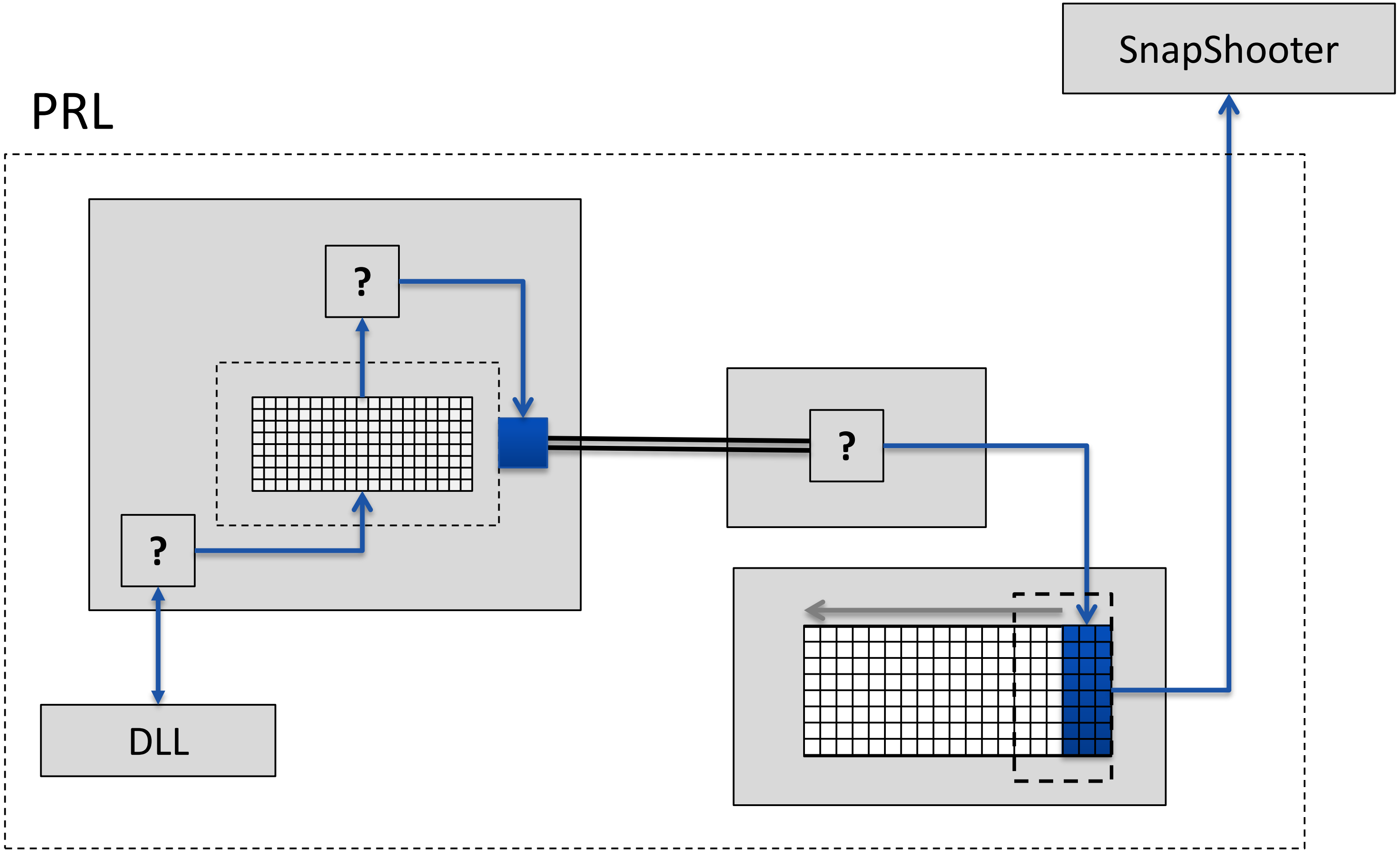
Building Smart Apps
"the last mile"



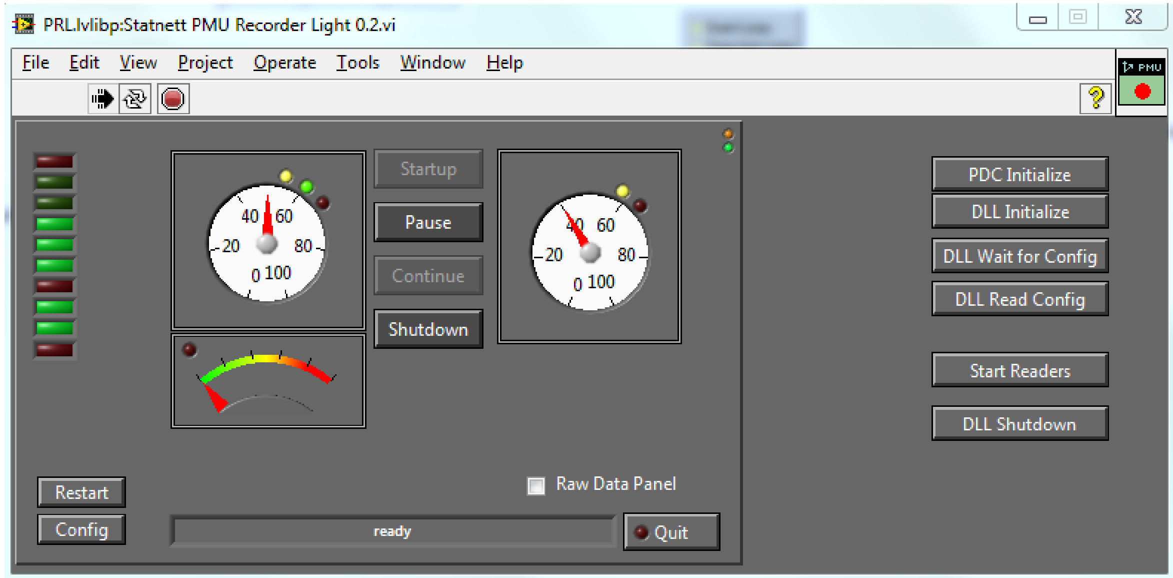
SDK Platform

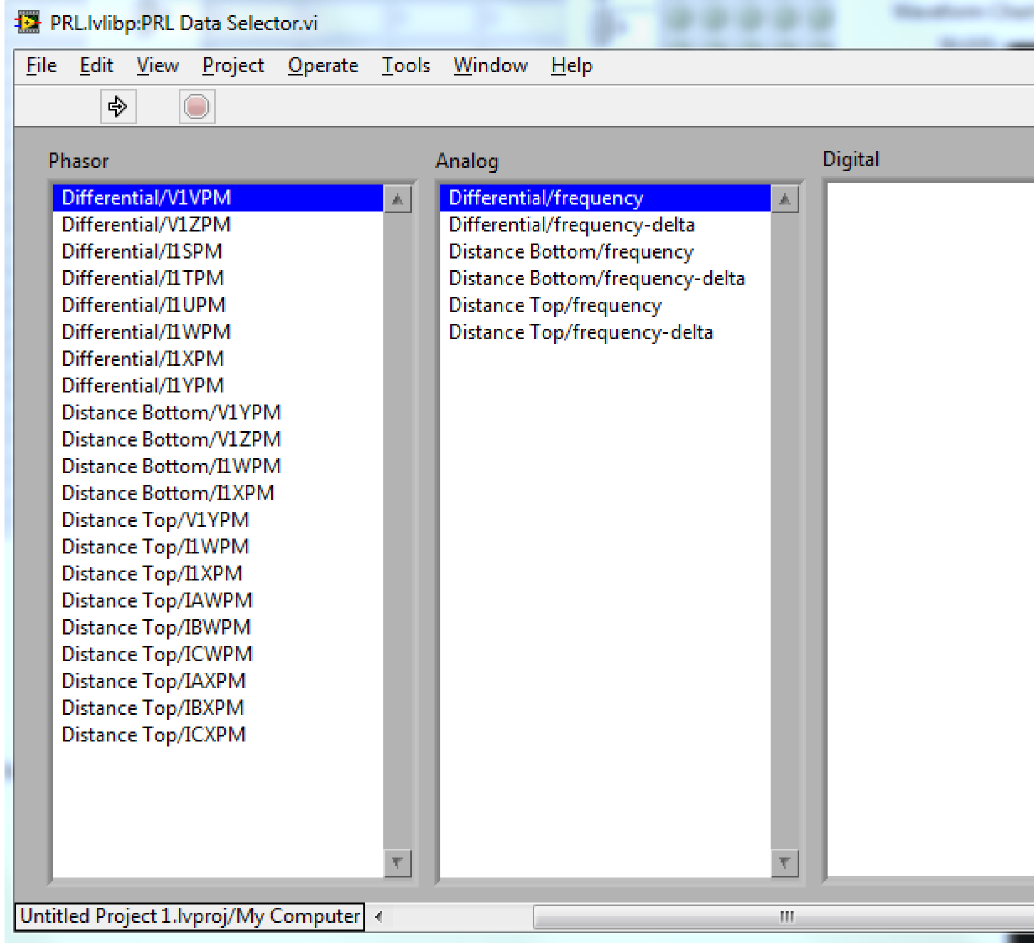


PMU Recorder Light (PRL)



Prototype Implementation (PMU App. SDK Beta)

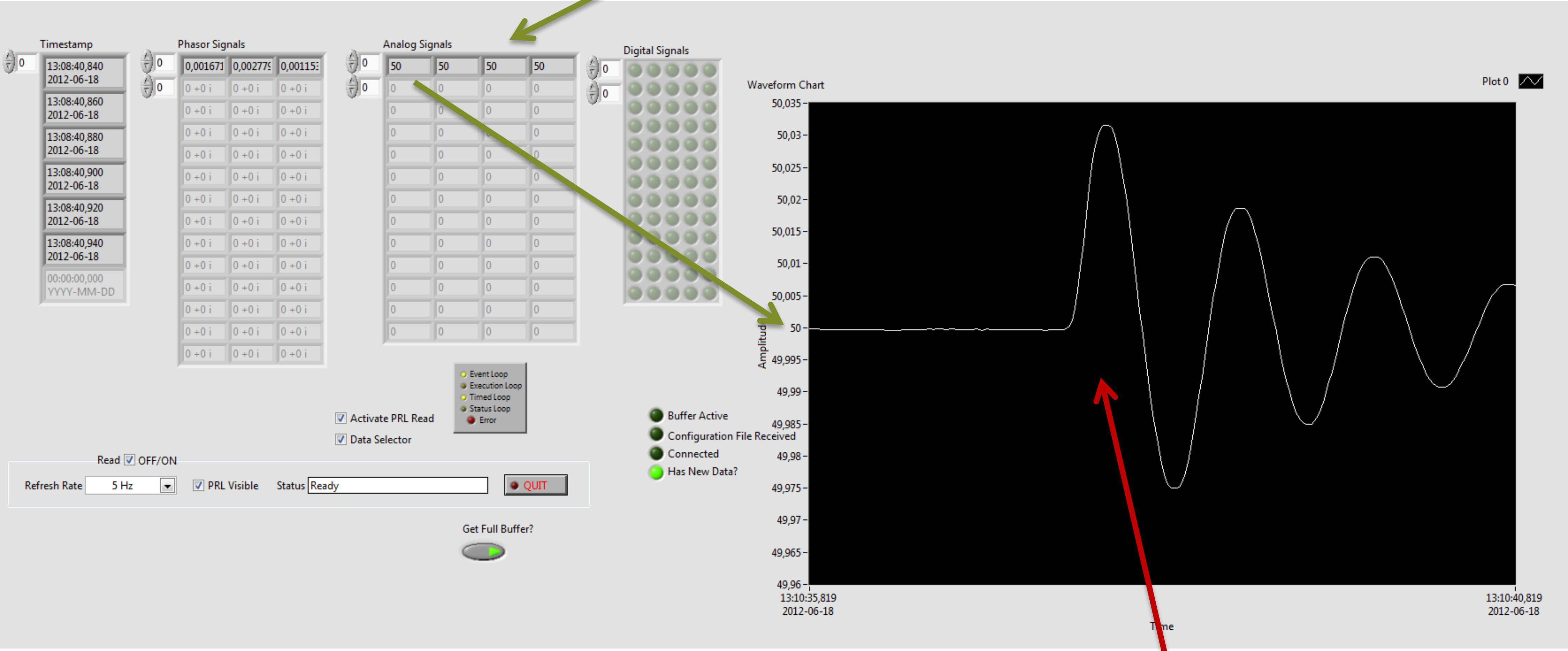




Connection with PDC
Configuration
PC Loading Monitor

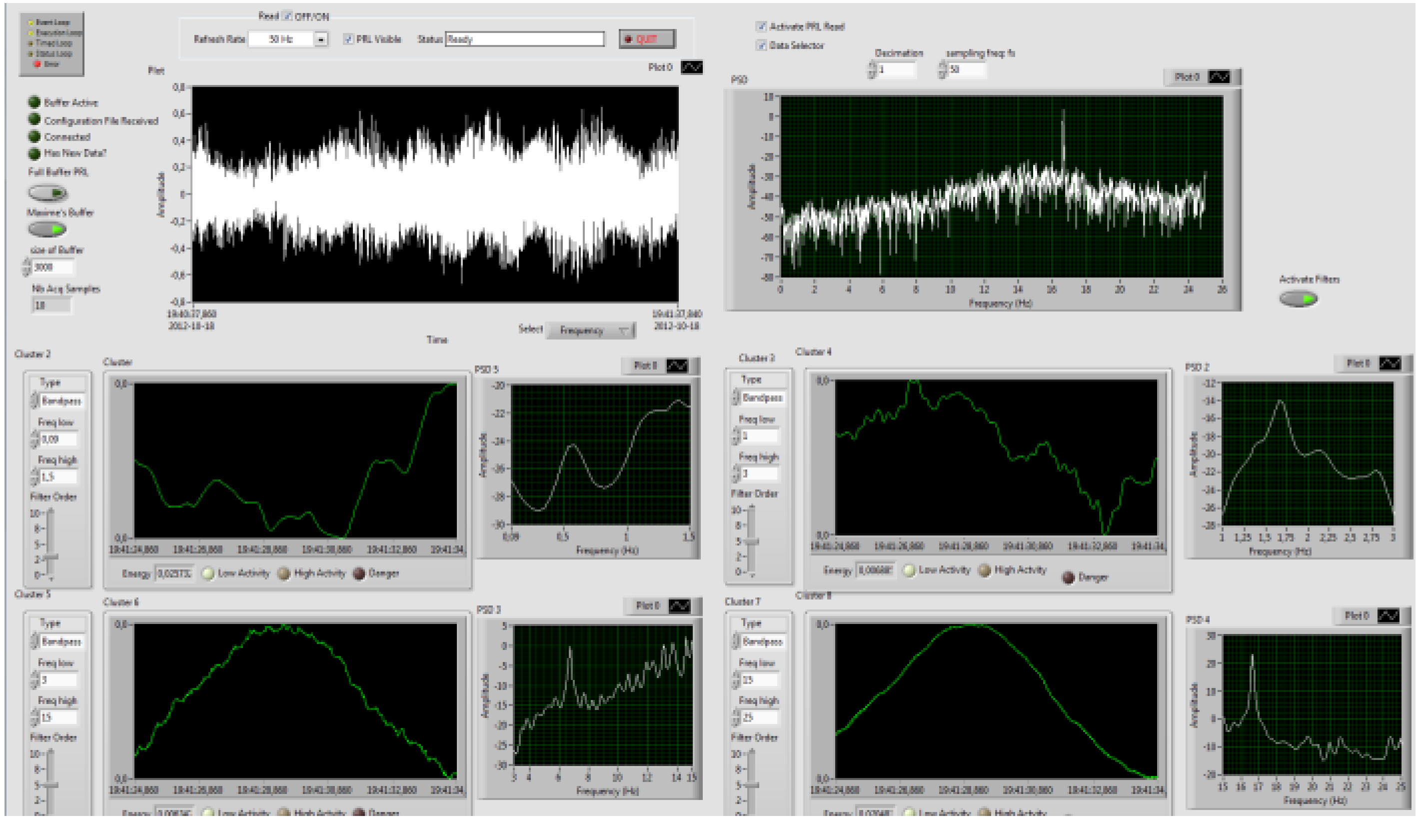
Data Channel Selection

Real-Time Data Access



Straightforward Development of Monitoring Application

KTH
VETENSKAP OCH KONST
ROYAL INSTITUTE OF TECHNOLOGY

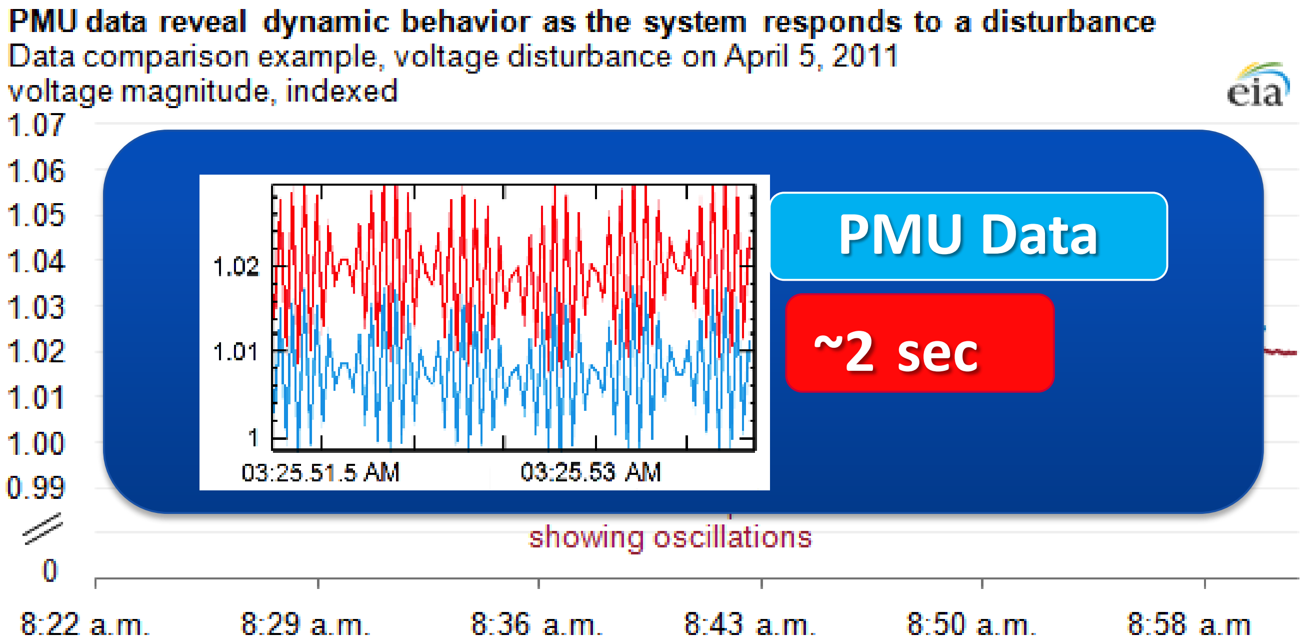


FAST REAL TIME OSCILLATION DETECTION AND MONITORING TOOL

Background

Problem that we are aiming to address

- Awareness of system dynamics is becoming increasingly important for system operation due to uncertainties of intermittent generation:

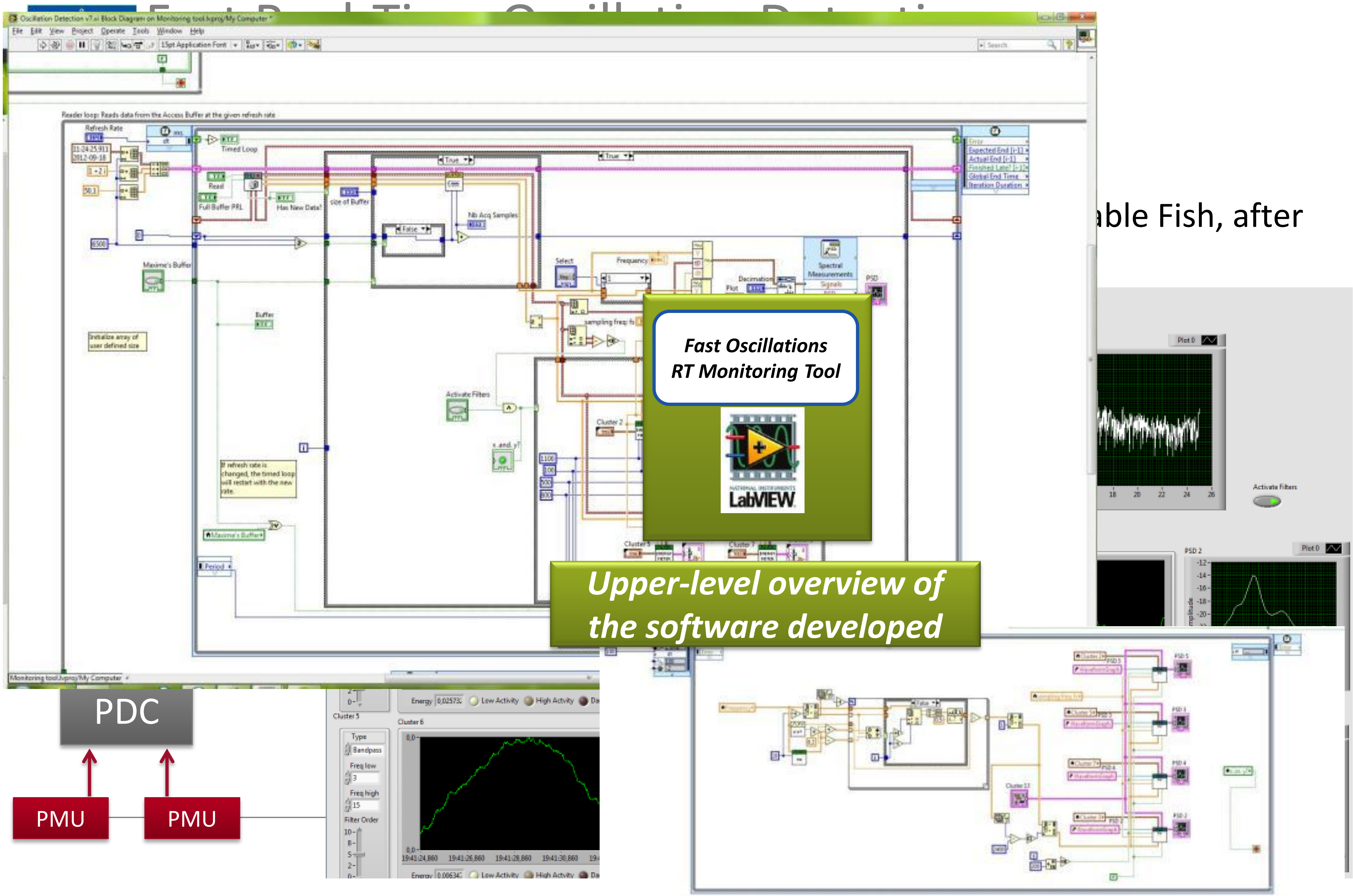


- In December 2010, OG&E monitored oscillations on the transmission system in northwestern Oklahoma.
- ***Occurring during periods of high wind generation.***
- ***5% fluctuation at a frequency of 13-15 Hz.***
- ***The oscillations were product of interactions between controllers in two different wind farms.***
- ***Countermeasures:***
  - ***Switching to electrically isolate the wind farms.***
  - ***Curtail the power output!***

- This is an example of the ***"dynamic operation challenges"*** that intermittent generation brings.
- **NEED for innovation:** SCADA is too slow, can never capture the phenomena.

- Operators can benefit from **"new real-time operation tools"**, that can allow them to monitor, track and control these oscillations without resorting to curtail power or isolated wind generation.

able Fish, after



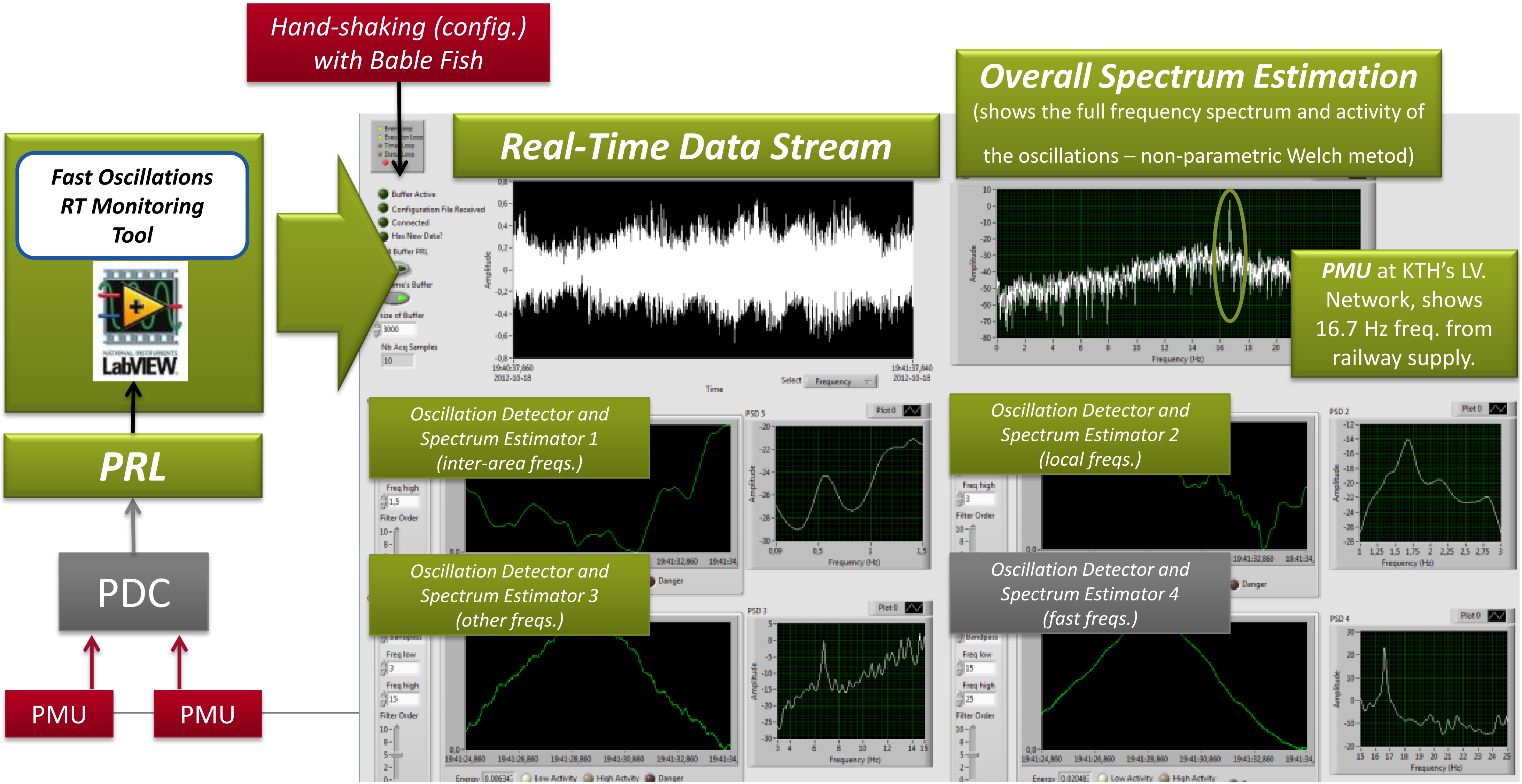
Fast Real-Time Oscillation Detection and Monitoring Tool

- Algorithms used: ***oscillation detectors*** and ***spectral estimators***.

- Oscillation Detector:
  - A tool used to detect oscillatory *activity.*
  - Provides fast generalized alarm of oscillation activity in real-time for **a given frequency range.**
  - Once initialized, it requires *only the latest data sample* to provide a new indication (recursive filtering)
- Spectral Estimator:
  - A tool used to estimate the spectrum of a signal
  - Uses digital signal processing methods – non-parametric Welch's method (fft averaging), FFT and others
  - It requires a larger parcel of data (few minutes, slower update) – ***speed up by recursive data parceling.***
- ***Fast RT Oscillation Detection and Monitoring Tool Components:***
  - Real-time data stream display (measured variable to display to be selected by the user)
    - Provides real-time monitoring of the selected measurement and its corresponding overall spetrum estimation (range [0 – fs/2])
  - Oscillation detectors at four different and configurable ranges (low frequency inter-area modes, local modes, and fast modes (up to Nyquist freq.))
  - Detection and Alarming:
    - Energy of the oscillation at the given frequency
    - Alarm levels at configurable thresholds (green = ok, orange = high activity, red = dangerous activity)

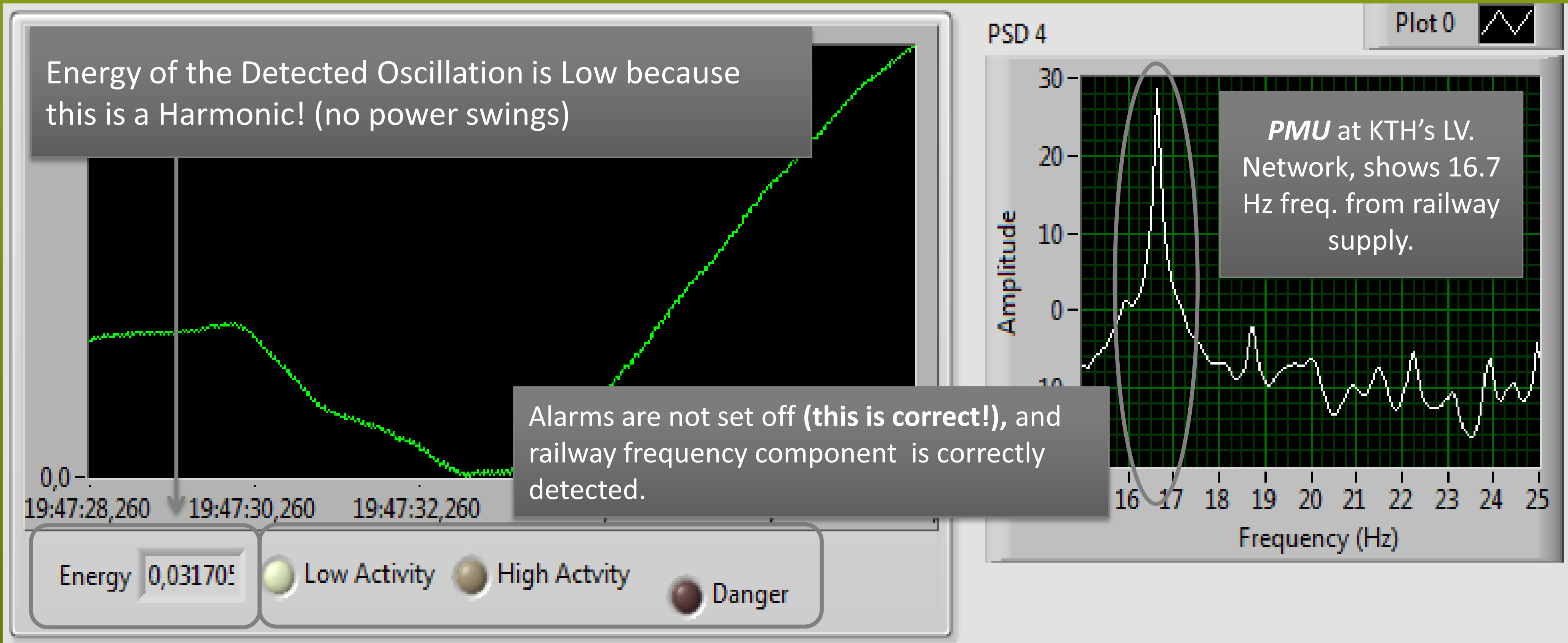
Fast Real-Time Oscillation Detection and Monitoring Tool

Illustration of where the algorithms are used



Fast Real-Time Oscillation Detection and Monitoring Tool

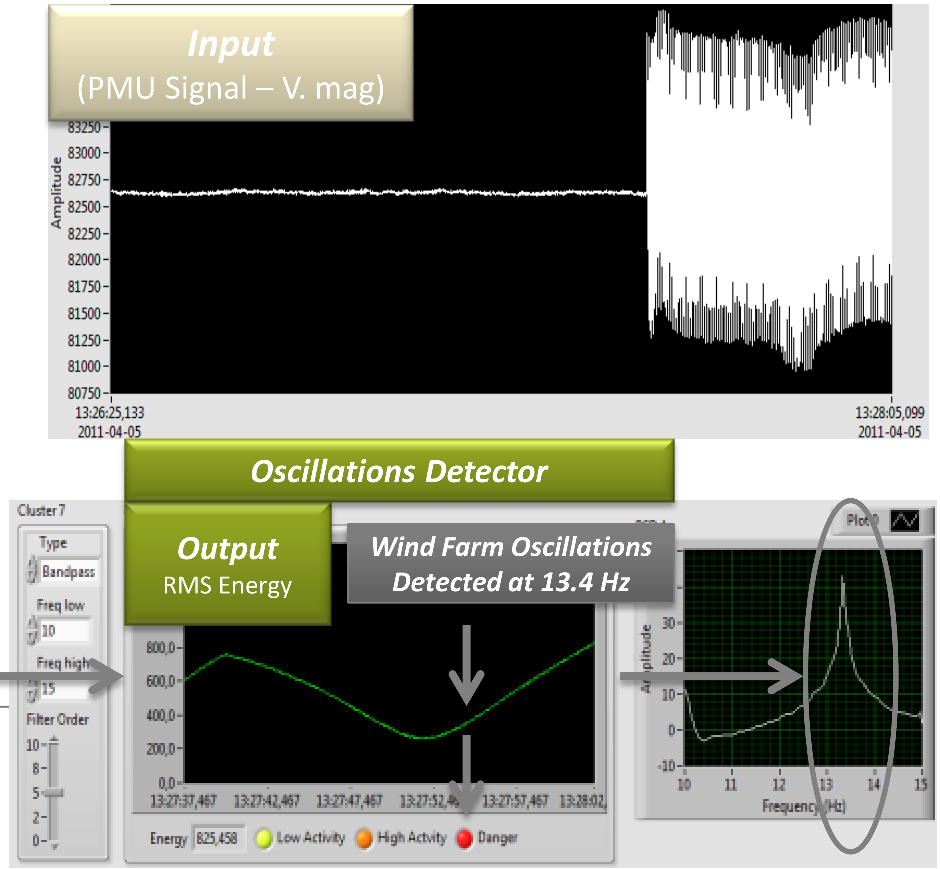
Real-Time Execution Example



Fast Real-Time Oscillation Detection and Monitoring Tool

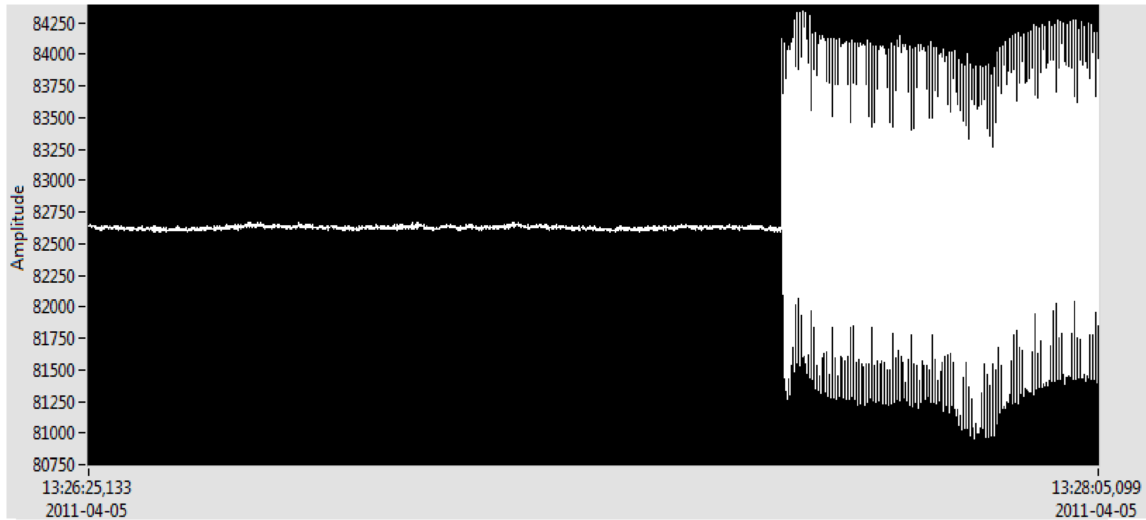
- ***Oscillation Detectors:***
  - ***RMS Energy Computation***

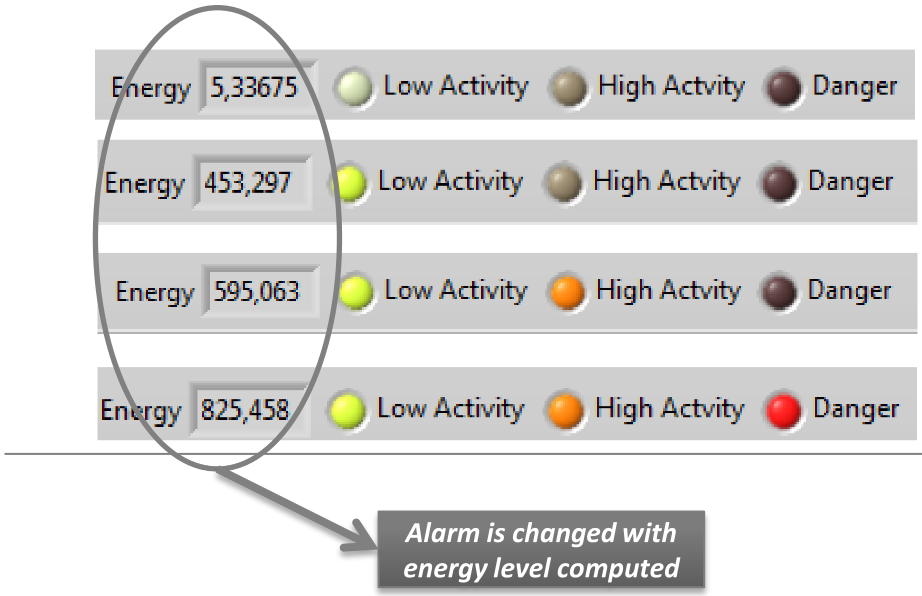
- ***Frequency bands:***
- Configurable frequency range for detecting oscillations for particular dynamic behaviour.
- Recommended frequency bands:
  - FB1: 0.01 Hz to 0.15 Hz, 200 sec. response time. (Slow governor-load dynamics, i.e. balancing)
  - FB2: 0.15 Hz to 1.00 Hz, 12 sec. response time. (Low frequency inter-area modes, i.e. power swings)
  - FB3: 1.00 Hz to 5.00 Hz, 6 sec. response time. (Low frequency intra-area and local area modes, i.e. internal plant swings)
  - ***FB4: 5 Hz to 15 Hz, 3 sec. response time. (High frequency oscillations, i.e. wind farm controller interactions)***
  - FB5: 15 Hz to 25 Hz, less than 3 sec. response time. (Sub-synchronous oscillations)

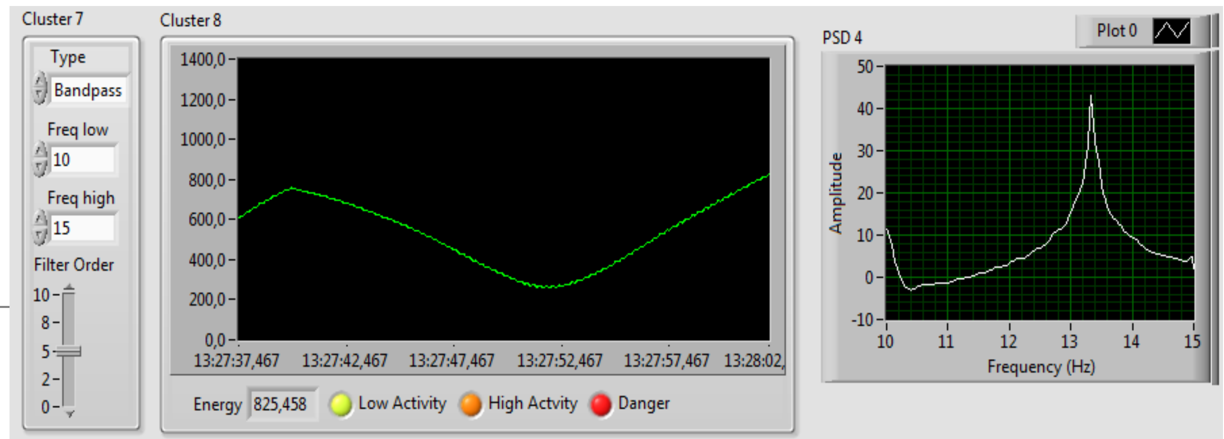


Fast Real-Time Oscillation Detection and Monitoring Tool

- ***Oscillation Detectors:***
  - ***Alarming (Threshold level comparison):***



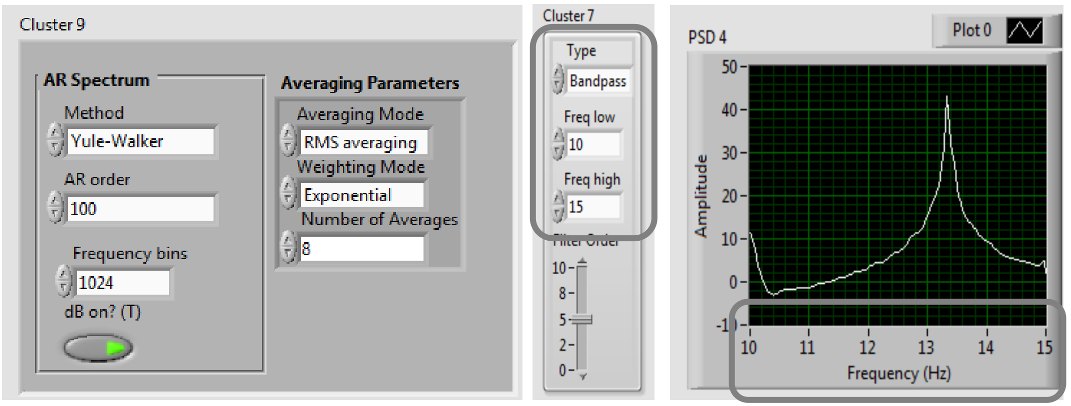


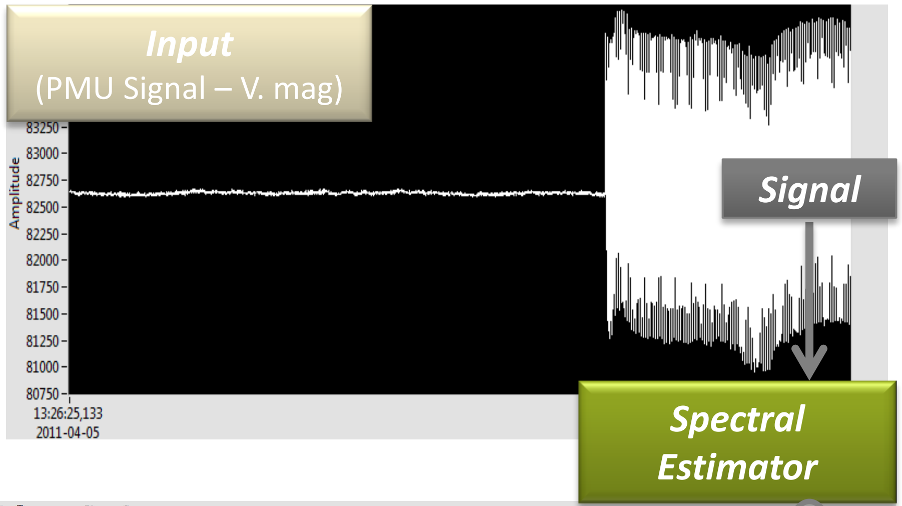


Fast Real-Time Oscillation Detection and Monitoring Tool

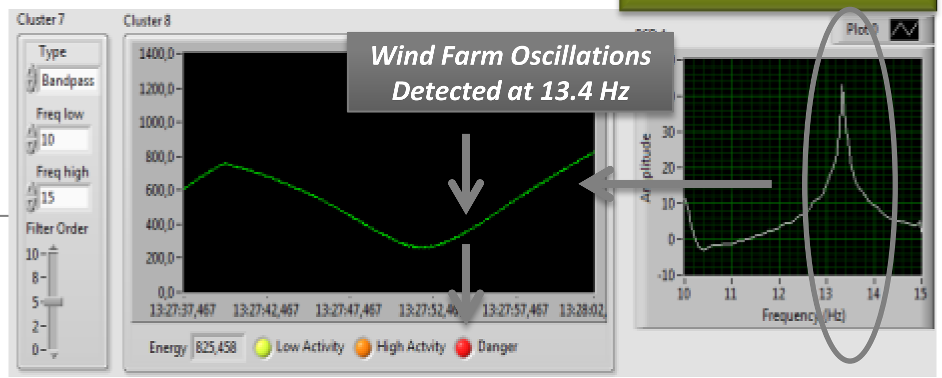
- ***Spectral Estimators:***
  - ***Estimation of the spectrum of the signal***

  - ***Uses a configurable parametric YW AR method to estimate the spectrum in each frequency band.***





  - *Frequency bands:*
  - Configurable frequency range for estimating the spectrum of the signal at the given frequency range.
  - Recommended frequency bands – same as with the oscillation detector



- ***Aim: allow correlation between the input signal, its spectrum and the oscillation frequency that is active (and detected)***

Going Forward:
Collaboration with COPPE/UFRJ and KTH

- KTH and COPPE/UFRJ have obtained a grant for collaboration from STINT and CAPES.
- We will work in implementing methods for voltage stability monitoring.
- KTH will try to aid COPPE in developing their own RT lab.
- The openPMU will be provided to COPPE next year for educational and research purposes.
- We hope this collaboration can continue into the future!

SmarTS Lab
Smart Transmission Systems Laboratory

KTH
VETENSKAP OCH KONST
ROYAL INSTITUTE OF TECHNOLOGY

luigiv@kth.se
http://www.vanfretti.com

Thank you!

Software and Hardware Demostration

Software and Hardware Demonstration

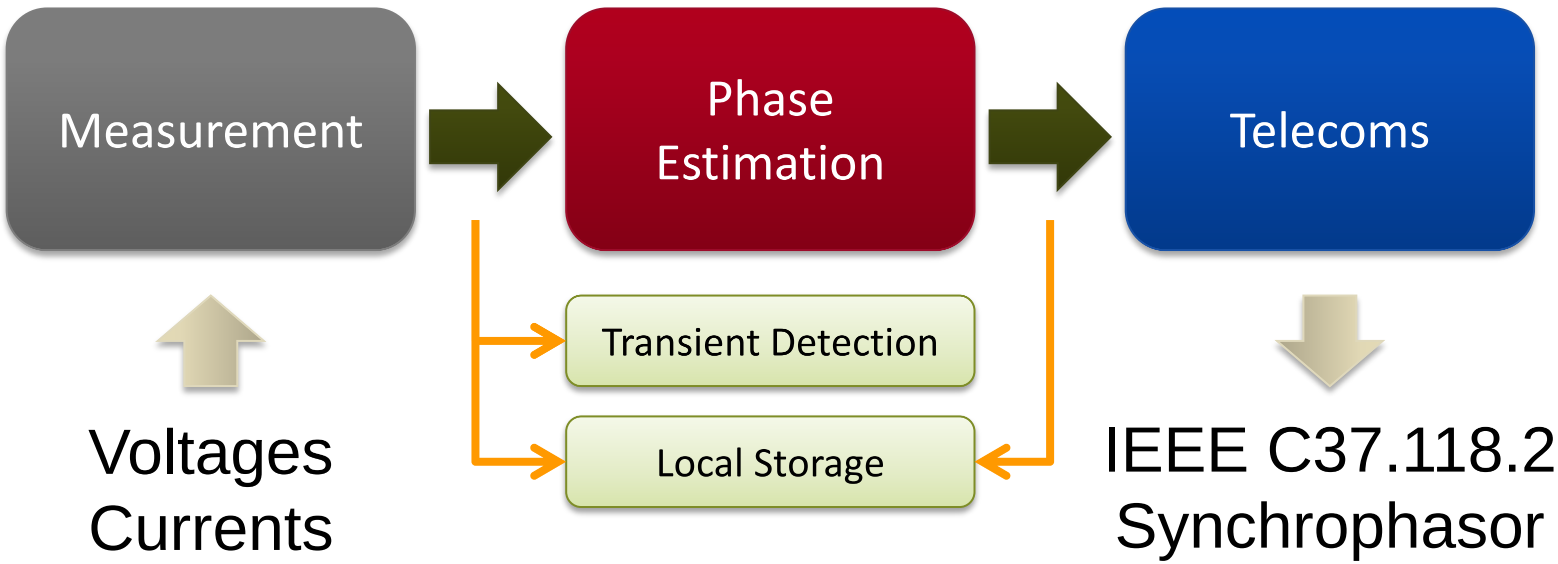
- Devices:
  - PMUs: openPMU, cRIO PMU (National Instruments)
  - PDCs: openPDC and SEL PDC

- Software:
  - PMU Connection Tester
  - PRL – PMU Recorder Light
  - Real-time and off-line fast oscillation detection tool

- Real-time
  - Wind farm models with Hardware-in-the-Loop Simulation
  - HVDC Models

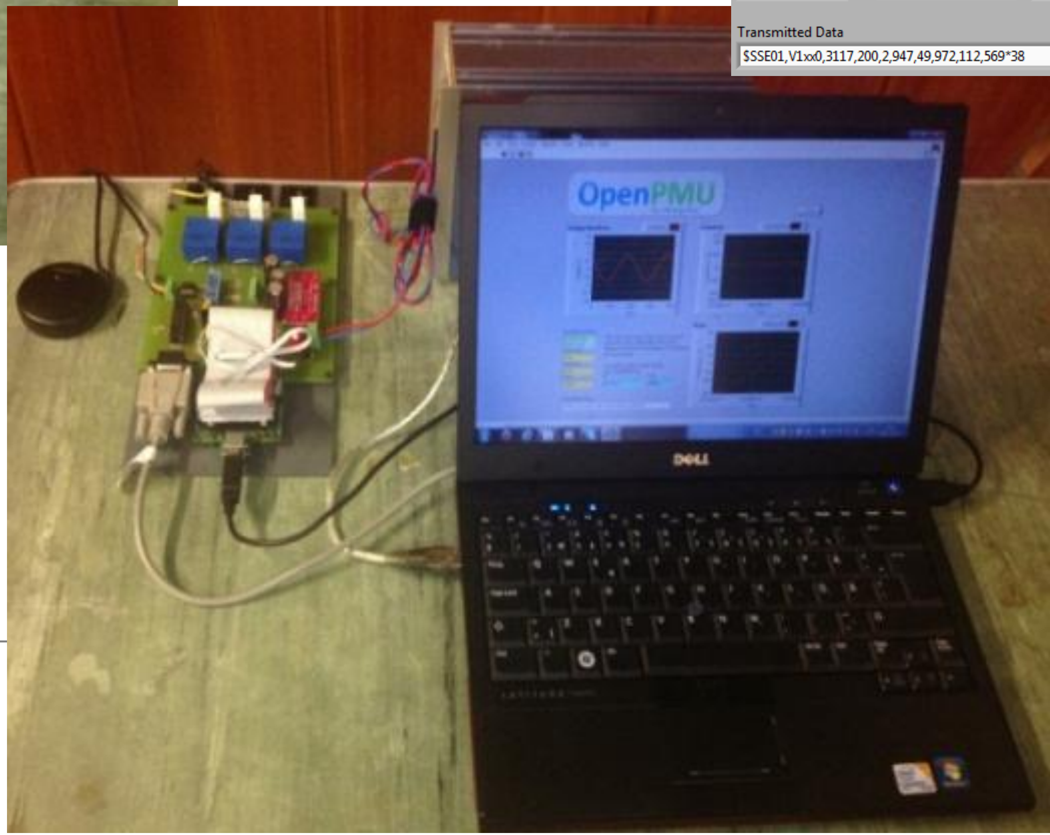
OpenPMU

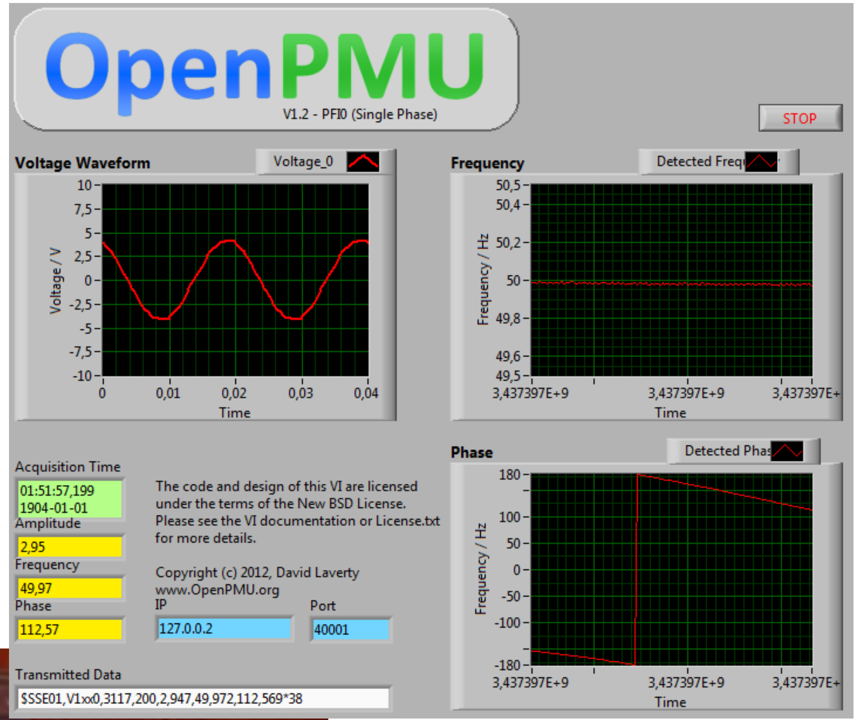
- Developed by Queen's University of Belfast



- Replicated at KTH in 2012.

OpenPMU KTH's Replica





OpenPMU

Queen's University Belfast

How *well* does it work?

ROYAL INSTITUTE OF TECHNOLOGY


```xml
<?xml version="1.0" encoding="UTF-8" ?>
<DATA>
    <TIME>12:03:14.120</TIME>
    <DATE>2011-06-13</DATE>
    <CHANNELS>1</CHANNELS>
    <SAMPLES>256</SAMPLES>
    <FREQ>12800</FREQ>
    <RATE>50</RATE>
    <CHANNEL_0>
        <TYPE>VOLTAGE</TYPE>
        <NAME>PHASE_A</NAME>
        <SCALE>400V</SCALE>
        <PAYLOAD>
        k1lvdSBrbm93IG1vcmUgdGhhbiB5b3UgdGhpbmsgeW91IGtub3csIGp1
        bGVzcyB0aGFuIHlvdSB3YW50IHRvIGtub3culCB+IE9zY2FyIFdpbGRl
        </PAYLOAD>
    </CHANNEL_0>
</DATA>
```