1

Synchrophasor Fundamentals: from Computation to Implementation

Prof. Mario Paolone
Distributed Electrical Systems Laboratory - http://desl-pwrs.epfl.ch
École Polytechnique Fédérale de Lausanne - EPFL

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

IEEE PES General Meeting

Vancouver, July 21-25, 2013

Tutorial - Synchrophasor Fundamentals and Applications: Leveraging the Investment

Outline

- Introduction
- PMU requirements
- Synchrophasor Estimation Algorithms
- Example of DFT-based synchrophasor estimation
- Implementation
- Experimental validation
- Conclusions

Introduction

Drivers

Evolution of the whole power systems infrastructure

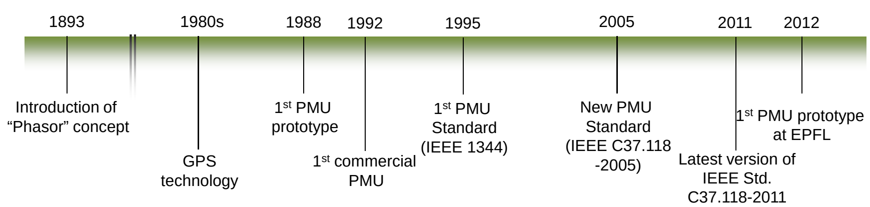
- major changes in their operational procedures;
- need of advanced and smarter tools to manage the increasing complexity of the grid;
- main involved aspect is the network monitoring by means of Phasor Measurement Units (PMUs);

> PMU definition (as stated in IEEE Std.C37.118-2011):
> *"A device that produces synchronized measurements of* phasor *(i.e. its amplitude and phase),* frequency, ROCOF *(Rate of Change Of Frequency) from voltage and/or current signals based on a common time source that typically is the one provided by the* Global Positioning System UTC-GPS*."*

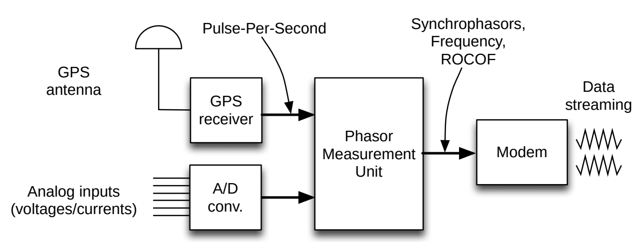
Introduction

What is a Phasor Measurement Unit (PMU)?

PMU timeline:



PMU typical configuration:

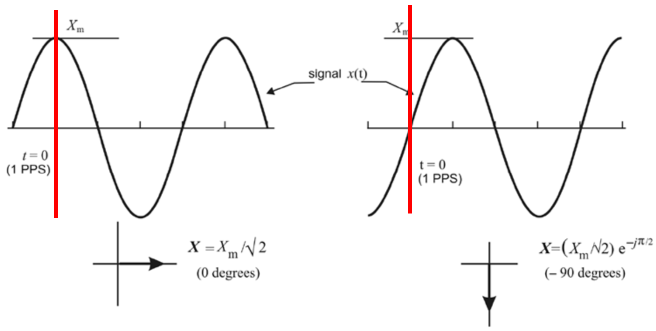


PMU requirements

IEEE Std. C37.118-2011 - Definitions

Synchrophasor definition:

$$x(t) = X_m \cos\left(2\pi f_0 t + \varphi\right) \Leftrightarrow X = \left(X_m / \sqrt{2}\right) e^{j\varphi}$$



PMU requirements

IEEE Std. C37.118-2011 – Measurement compliance

Reporting rates:

System frequency	50 Hz			60 Hz					
Reporting rates (F_s—frames per second)	10	25	50	10	12	15	20	30	60

Performance classes:

- P-class: faster response time but less accurate
- M-class: slower response time but greater precision

Measurement evaluation:

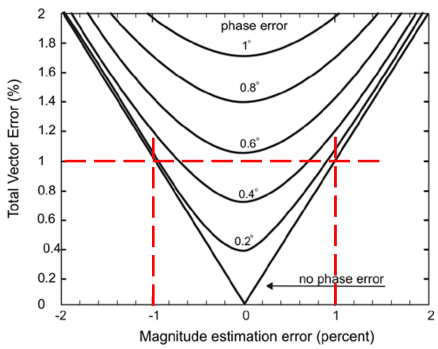
Frequency measurement Error: $FE = \left| f_{true} - f_{measured} \right|$

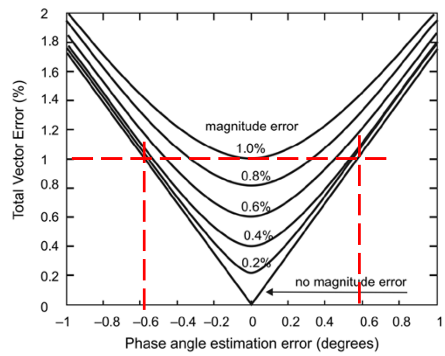
ROCOF measurement Error: $RFE = \left| (df/dt)_{true} - (df/dt)_{measured} \right|$

Total Vector Error $\mathrm{TVE}(n) = \sqrt{\frac{\left(\hat{X}_r(n) - X_r(n)\right)^2 + \left(\hat{X}_i(n) - X_i(n)\right)^2}{\left(X_r(n)\right)^2 + \left(X_i(n)\right)^2}}$

PMU requirements

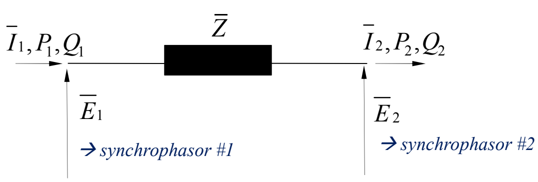
TVE and magnitude-phase accuracies

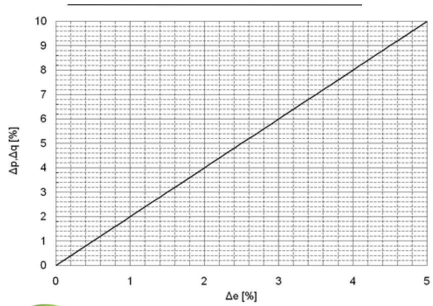




PMU requirements

Magnitude accuracy vs power flow estimation error





Estimated phasor errors:

RMS: ΔE

phase: $\Delta\vartheta$

phase angle difference between phasors $\bar{E}_1, \bar{E}_2$: δ

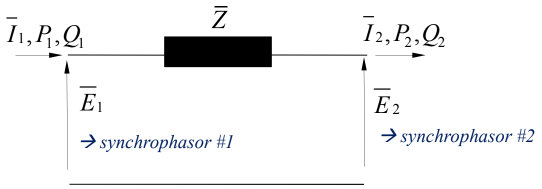
→ $\Delta\delta = 2 \cdot \Delta\theta$

$$\Delta p\big|_{\Delta E} = 2\Delta e$$

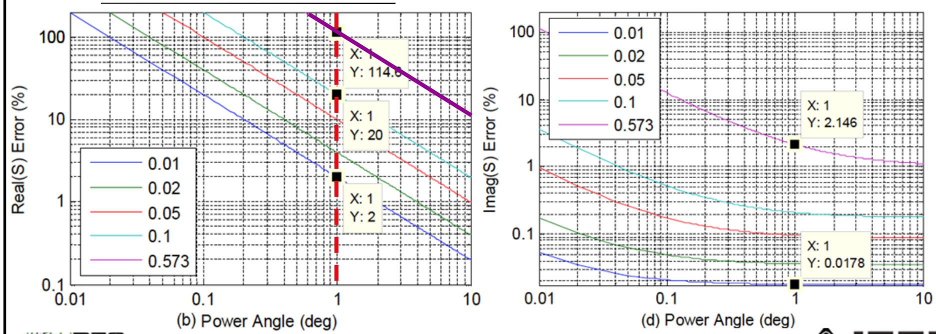
$$\Delta q_2\big|_{\Delta E} = 2\Delta e$$

PMU requirements

Phase accuracy vs power flow estimation error



$$\Delta \bar{s}_{12}\Big|_{\Delta\vartheta} = \frac{1 - e^{j(\delta + 2\Delta\vartheta)}}{1 - e^{j\delta}} - 1$$



Synchrophasor Estimation Algorithms

General notions and typical algorithm parameters

- A wide **variety** of algorithms is currently available in the literature but few of them are characterized by an affordable computational complexity needed by real-time applications.
- Generally speaking the main **issues** arises when $f(t) \neq f_0$ and in the specific during dynamic conditions of the power network since the "phasor" concept is by definition static.
- Most of the algorithms are **window-based**, i.e. the synchrophasor is estimated based on a previously acquired set of data point representing a portion of the acquired waveform (current or voltage)

- Synchrophasor estimation algorithm **typical parameters**:
  - Window length (**half-cycle**/**full-cycle**/**multi-cycle**)
  - Window type (**rectangular**, **flat-top**, **raised cosine**, etc.)
  - Sampling process (**coherent**/**incoherent**, **high**/**slow rate**)

Synchrophasor Estimation Algorithms

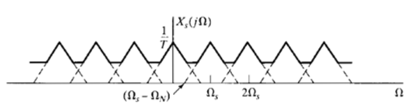
Window based Synchrophasor Estimation Algorithms

Class	Typical algorithms	Advantages	Drawbacks
DFT based	Fourier analysis (e.g., [18])	Low computational complexity, harmonic rejection	Spectral leakage, Harmonic interference, Off-nominal freq.
	Interpolated DFT (e.g., [19])		
Wavelet based	Recursive wavelet (e.g., [20])	Harmonic rejection	Computational complexity
Optimization based	WLS (e.g., [21])	They usually provide accurate estimates in combination with other methods	Non deterministic: driven by optimality criteria
	Kalman Filter (e.g., [22])		
Taylor series based	Dynamic Phasor (e.g., [23])	It intrinsically reflects the dynamic behaviors of power systems	Computational complexity

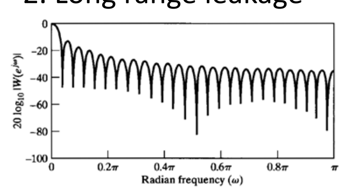
Ex. of DFT-based synchroph. estimation

Main sources of error

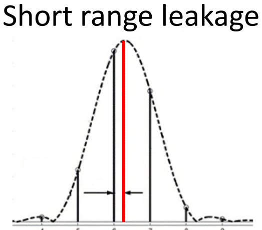
1. Aliasing



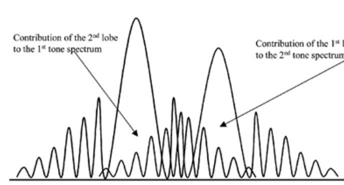
2. Long range leakage



3. Short range leakage



4 Harmonic interference



Ex. of DFT-based synchroph. estimation

Possible corrections

1. Aliasing

- Introduction of adequate anti-aliasing filters
- Increasing of the sampling frequency

2. Long range leakage

- Use of appropriate windowing functions

3. Short range leakage

- Interpolated DFT methods

4 Harmonic interference

- Iterative compensation of the self-interaction

IEEE PES Power & Energy Society IEEE

Ex. of DFT-based synchroph. estimation

Algorithm structure

I. Signal acquisition (voltage/current), within a GPS-PPS tagged window T (e.g. 80 ms, i.e. 4 cycles at 50 Hz) with a sampling frequency in the order of 50-100 kHz.

II. DFT analysis of the input signal, opportunely weighted with a proper window function.

III. First estimate of the synchrophasor by means of an interpolated-DFT approach.

IV. Iterative correction of the self-interaction between the positive and negative image of the DFT main tone.

IEEE PES Power & Energy Society IEEE

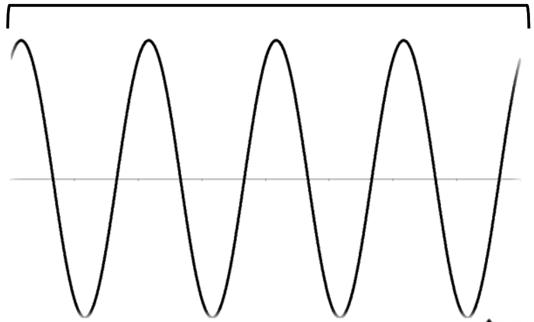
Ex. of DFT-based synchroph. estimation

Computation process

Input signal → Apply window function → Compute DFT → Calculate 1st estimate of tone parameters →

$$s(n) = \tilde{s} + \sum_{m=1}^{M} A_m \cos\left(2\pi m f_1 n \Delta t + \varphi_m\right),\ n \in [0, N-1]$$

3-4 periods of the fundamental frequency tone



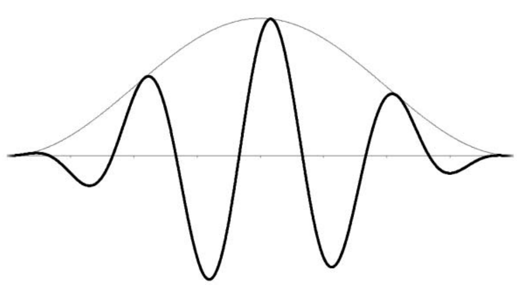
Ex. of DFT-based synchroph. estimation

Computation process

Input signal → Apply window function → Compute DFT → Calculate 1st estimate of tone parameters →

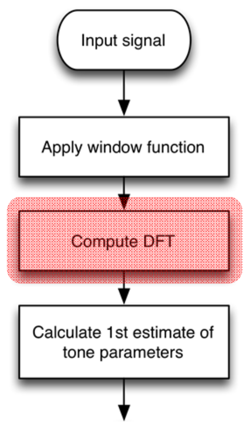
Hanning window:

$$w(n) = 0.5\left(1 - \cos\left(\frac{2\pi n}{N-1}\right)\right),\ n \in [0, N-1]$$

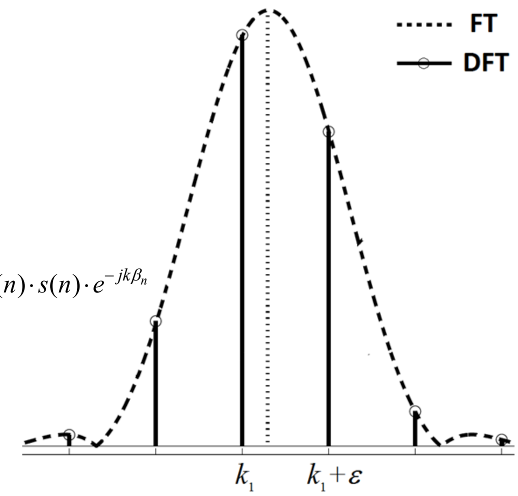


Ex. of DFT-based synchroph. estimation

Computation process

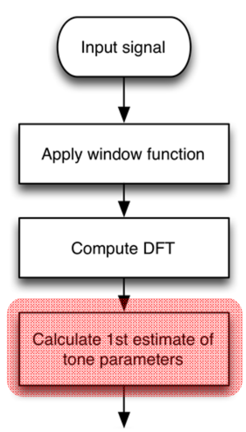


$$S(k)=\frac{1}{B}\sum_{n=0}^{N-1} w(n)\cdot s(n)\cdot e^{-jk\beta_n}$$



Ex. of DFT-based synchroph. estimation

Computation process

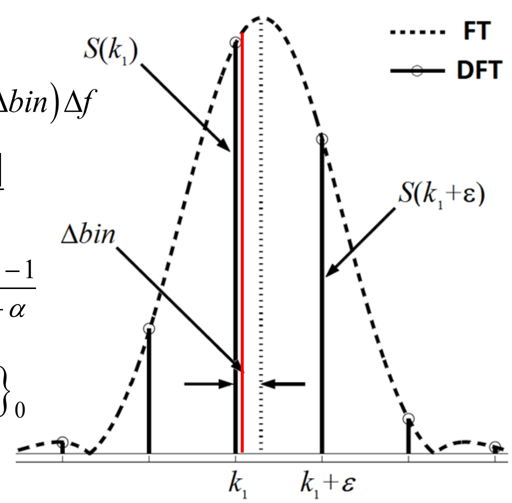


$$f_1=\left(k_1+\Delta bin\right)\Delta f$$

$$\alpha=\frac{\left|S\left(k_1+\varepsilon\right)\right|}{\left|S\left(k_1\right)\right|}$$

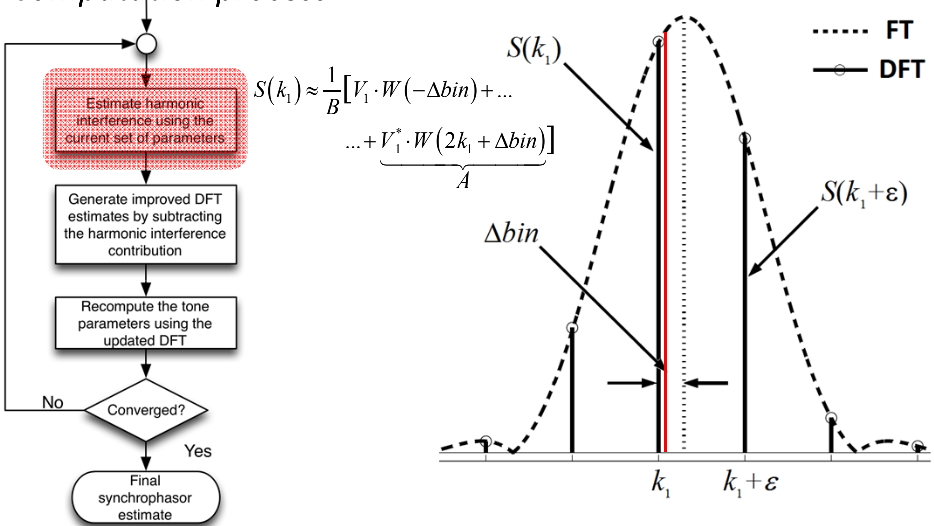
$$\Delta bin=\varepsilon\frac{2\alpha-1}{1+\alpha}$$

$$\left\{f_1, S_1, \varphi_1\right\}_0$$



Ex. of DFT-based synchroph. estimation

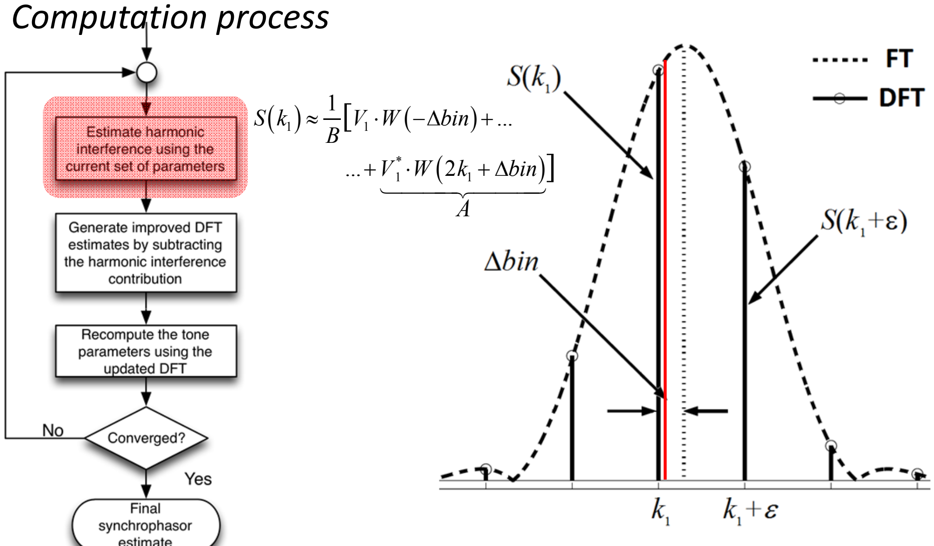
Computation process



PES Power & Energy Society® IEEE

Ex. of DFT-based synchroph. estimation

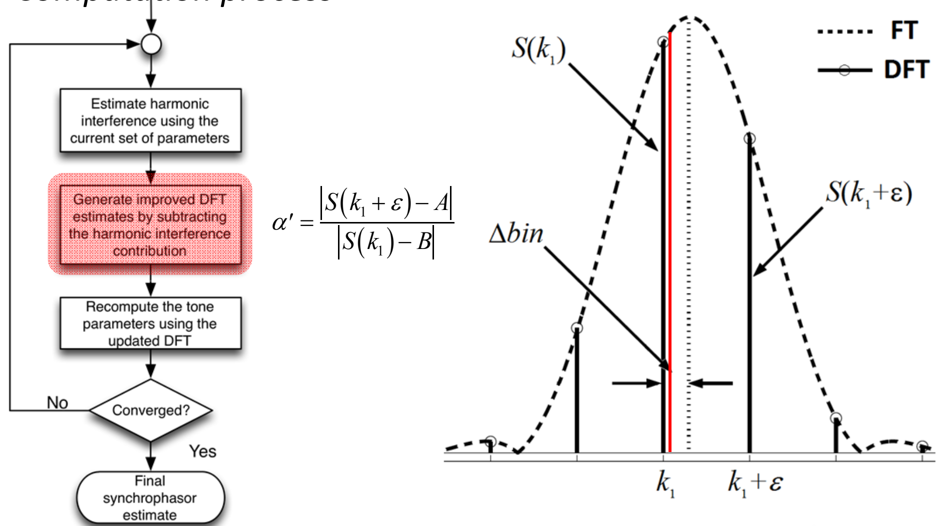
Computation process



PES Power & Energy Society® IEEE

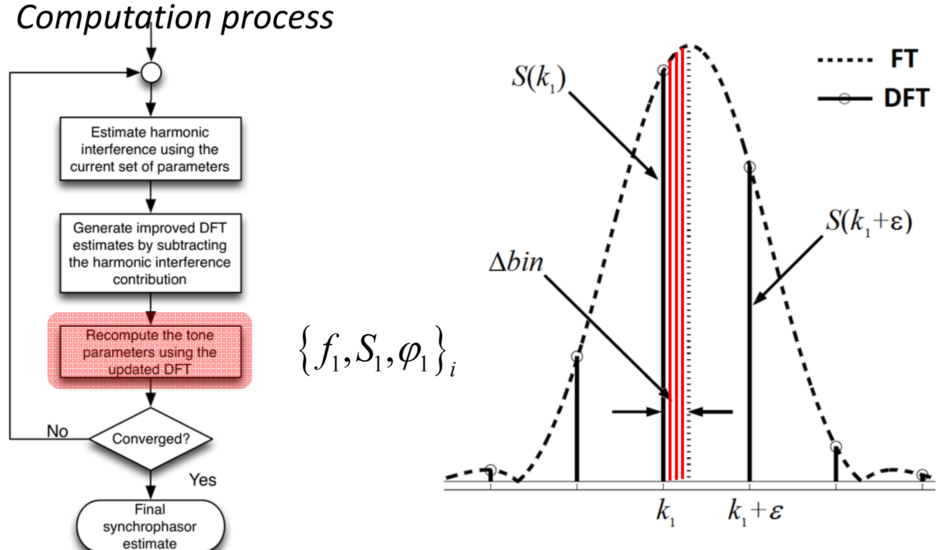
Ex. of DFT-based synchroph. estimation

Computation process



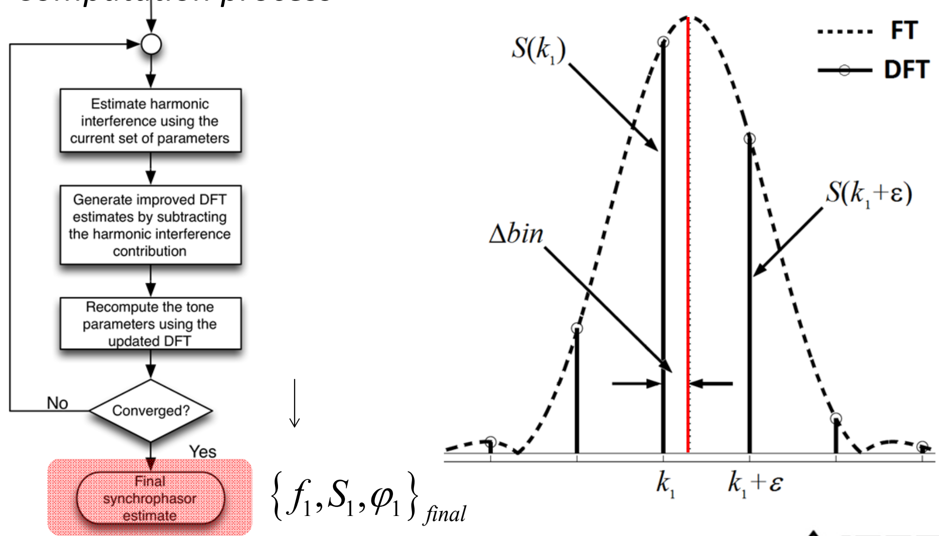
Ex. of DFT-based synchroph. estimation

Computation process



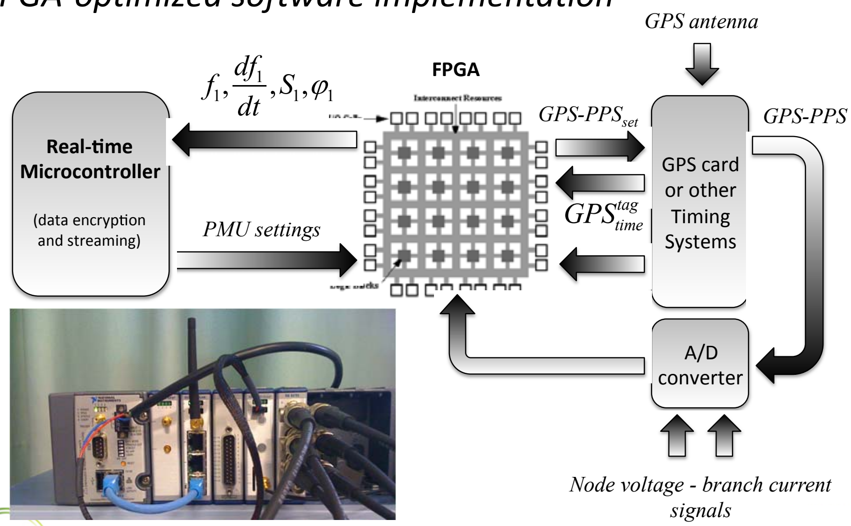
Ex. of DFT-based synchroph. estimation

Computation process



Algorithm implementation

FPGA-optimized software implementation



Algorithm implementation

FPGA-optimized software implementation

Process #1

GPS-synchronization process:

- Time uncertainty of ± 100 ns
- Compensation of the FPGA clock drift

Process #2

Pipelined signal acquisition:

- 6 parallel channels (3 voltages 3 currents)
- Phase correction

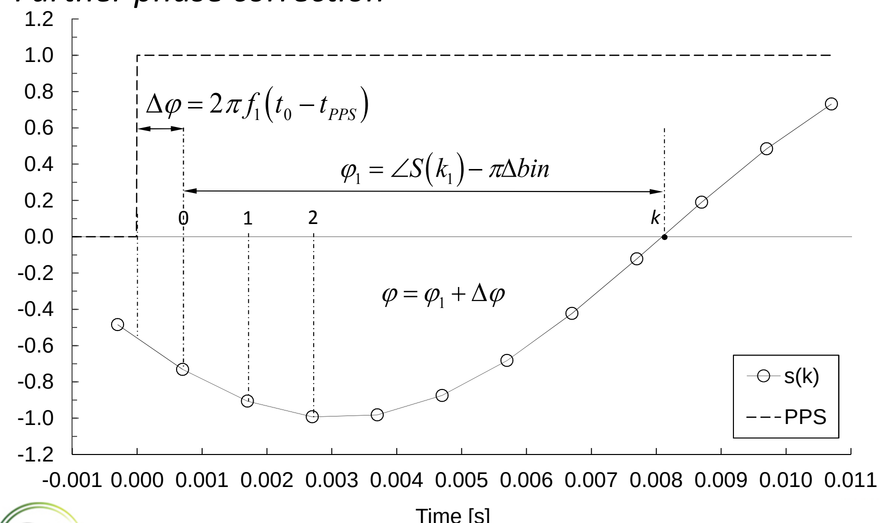
Process #3

Synchrophasor estimation algorithm:

- Optimized DFT computation for power systems typical frequencies
- 32-bits fixed-point implementation

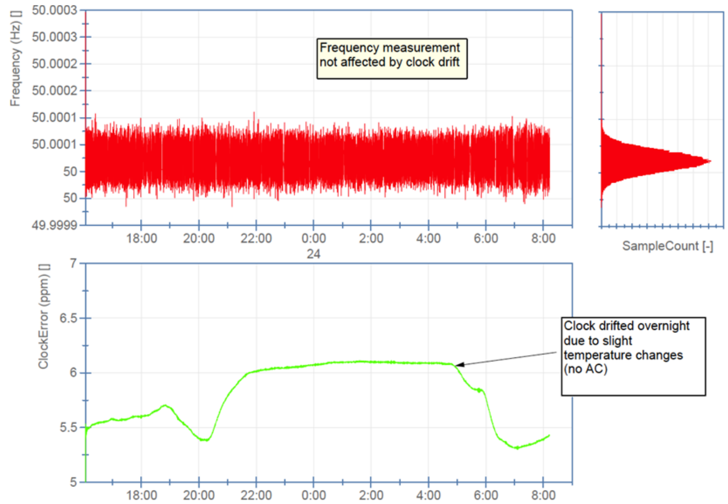
Algorithm implementation

Further phase correction



Algorithm implementation

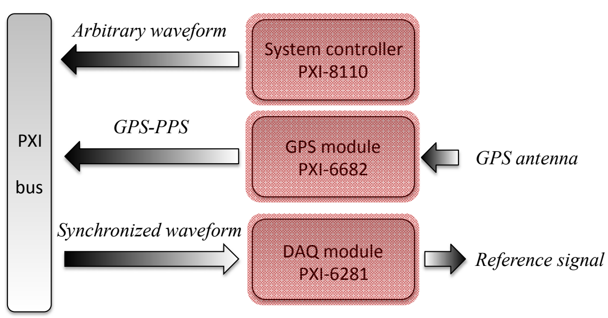
FPGA clock error compensation



Experimental validation

Compliance verification platforms

Hardware - PXI based platform:



Control and synchronization of the other PXI boards

Time-Sync accuracy ±100 ns with 13 ns standard deviation

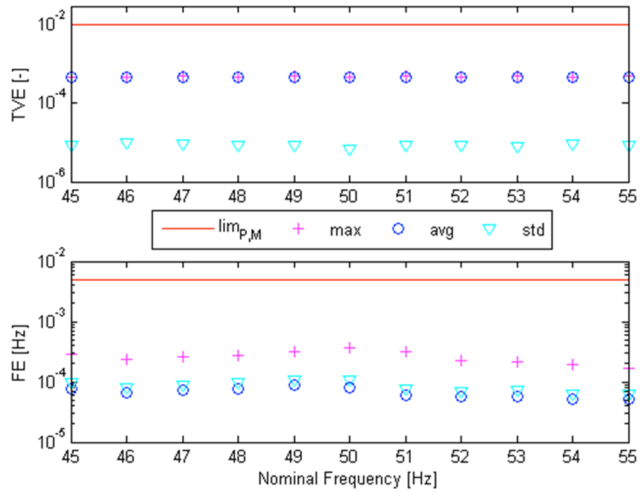
18-bit resolution inputs at 500 kS/s, analog input accuracy 980 μV over ±10 V input range (accuracy of 0.01%)

SW - Desktop based platform:

- Generate the test signal in host according to each test item in IEEE C37.118, 2011 then run the FPGA algorithm in desktop.

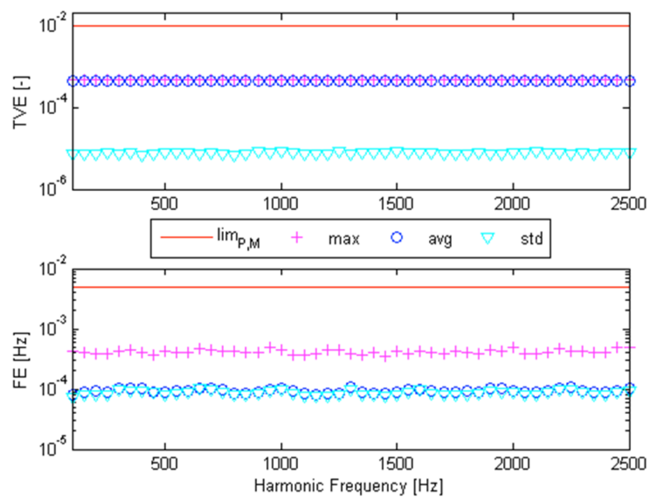
Experimental validation

Static tests – Signal frequency range



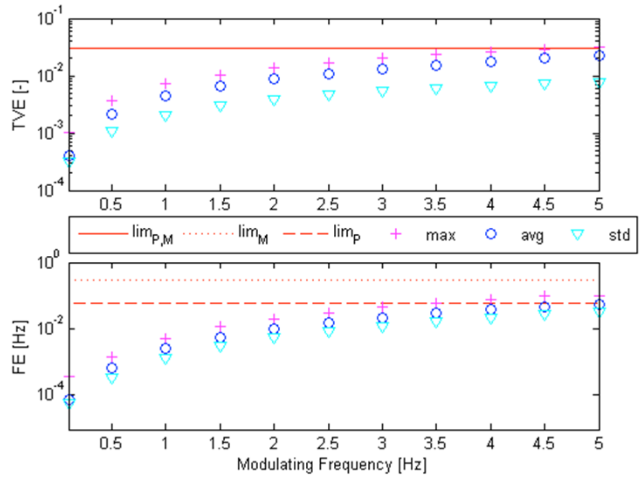
Experimental validation

Static tests – Harmonic distortion



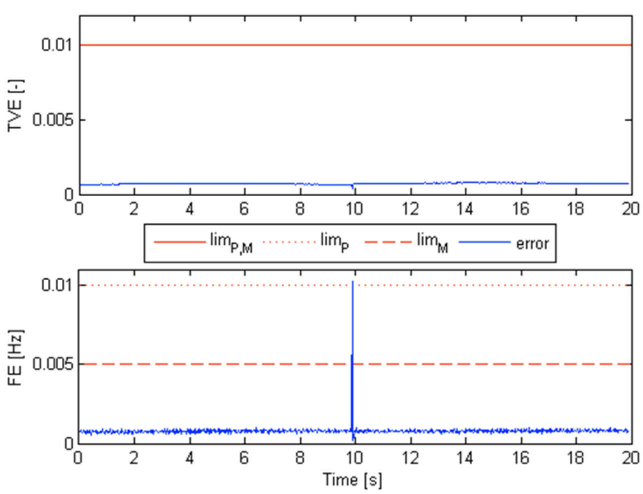
Experimental validation

Dynamic tests – Amplitude-phase modulation



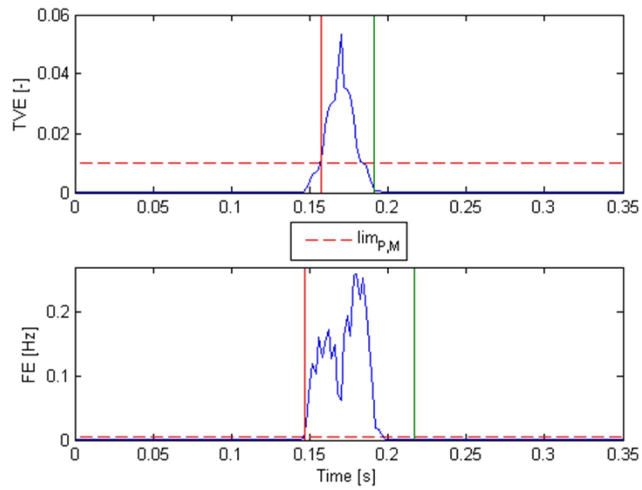
Experimental validation

Dynamic tests – Frequency sweep



Experimental validation

Dynamic tests – Amplitude step



Conclusions

The **design process** of a **synchrophasor estimation algorithms** is driven by the following factors:

- **Accuracy** vs **computation complexity**
- **Hardware platform**
- Possibility to **compensate error sources**

Concerning this last point, it is worth observing that:

- it is fundamental the **evaluation of the potential countermeasures** that **might compensate** the various **sources of error**;
- the PMU **validation** must be able to **metrologically characterise** these compensations and **drive the designer towards the PMU performance assessment**.

References

1. IEEE Std. C37.118.2011-1, IEEE Standard for Synchrophasor Measurements for Power Systems, revision of the IEEE Std. C37.118.2005, Dec. 2011.
2. IEEE Std. C37.118.2011-2, IEEE Standard for Synchrophasor Data Transfer for Power Systems, revision of the IEEE Std. C37.118.2005, Dec. 2011.
3. A. G. Phadke and J. S. Thorp, Synchronized Phasor Measurements and Their Applicationm New York: Springer, 2008.
4. A. Phadke, "The Wide World of Wide-Area Measurements", IEEE Power and Energy Magazine, vol. 2, no. 4, September/October 2008. pp. 52-65.
5. F. J. Harris, "On the Use of Windows for harmonic Analysis with the Discrete Fourier Transform", Proc. IEEE, vol. 66, no.1, pp.51-83, Jan. 1978.
6. K. Jain, Vijay, W. L. Collins, D. C. Davis, "High-Accuracy Analog Measurements via Interpolated FFT", IEEE Trans. on Instrumentation and Measurement, vol. 28, issue: 2, pp. 113-122, June, 1979.
7. T. Grandke, "Interpolation algorithms for discrete Fourier transforms of weighted signals", IEEE Trans. Instrumentation and Measurement, vol. 32, no. 2, pp. 350-355, June 1983.
8. G. Andria, M. Savino, A. Trotta, "Windows and Interpolation Algorithms to Improve Electrical Measurement Accuracy", IEEE Trans. Instrumentation and Measurement, vol. 38, no. 4, pp. 856-863, Aug. 1989.

IEEE PES Power & Energy Society® IEEE

References

9. V. Terzija, M. B. Djuric, B.D. Kovacevic, "Voltage phasor and local system frequency estimation using Newton type algorithm", IEEE Trans. on Power Delivery, vol. 9-3, July 1994, pp: 1368-1374.
10. C. Liguori, A.Paolillo, A. Pignotti, "An Intelligent FFT Analyzer With Harmonic Interference Correction and Uncertainty Evaluation", IEEE Trans. Instrumentation and Measurement, vol. 53, no. 4, pp. 562-568, Aug. 2004.
11. A. Moriat, "System and Method for Estimating Tones in an Input Signal", U.S. Patent 6 965 068 B2, Nov. 15, 2005.
12. J. Warichet, T. Sezi, J.-C. Maun, "Considerations about synchrophasors measurement in dynamic sys-tem conditions", Electrical Power and Energy Systems, vol. 31, 2009, pp. 452-464.
13. A. Carta, N. Locci, and C. Muscas, "GPS-Based System for the Measurement of Synchronized Harmonic Phasors", IEEE Trans. on Instrumentation and Measurement, vol. 58, no. 3, pp. 586-593, march 2009.
14. D. M. Laverty, D. J. Morrow, R. J. Best, and P. A. Crossley, "Differential ROCOF relay for loss-of-mains protection of renewable generation using phasor measurement over internet protocol," in Proc. CIGRE/IEEE Power Energy Soc. Joint Symp. Integr. Wide-Scale Renewable Resources Power Del. Syst., Calgary, AB, Canada, Jul. 29–31, 2009, pp. 1–7.
15. A. Borghetti, C. A. Nucci, M. Paolone, G. Ciappi, A. Solari, "Synchronized Phasors Monitoring During the Islanding Maneuver of an Active Distribution Network", IEEE Trans. on Smart Grids, vol. 2, issue: 1, march, 2011, pp: 82 – 91.

IEEE PES Power & Energy Society® IEEE

References

16. M. Paolone, A. Borghetti, and C. A. Nucci, "A synchrophasor estimation algorithm for the monitoring of active distribution networks in steady state and transient conditions," in Proc. of the 17th Power Systems Computation Conference (PSCC 2011), Aug. 22-26, 2011, Stockholm, Sweden, vol. 1, pp. 213–220.
17. D. Macii, D. Petri and A. Zorat Accuracy, "Analysis and Enhancement of DFT-Based Synchrophasor Estimators in Off-Nominal Conditions", IEEE Trans. Instrumentation and Measurement, vol. 61, no. 10, pp. 2653-2664, Oct. 2012.
18. A. G. Phadke et al., "A new measurement technique for tracking voltage phasors, local system frequency, and rate of change of frequency," IEEE Trans. Power App. Syst., vol. PAS-102, pp. 1025–1038, May 1983.
19. P. Romano, M. Paolone, J. Arnold and R. Piacentini, "An interpolated-DFT Synchrophasor Estimation Algorithm and its Implementation in an FPGA-based PMU Prototype", IEEE PES General Meeting, 2013.
20. C.-K. Wong et al., "A novel algorithm for phasor calculation based on wavelet analysis," in Proc. PES 2001 Summer Meeting, Vancouver, BC, Canada.
21. M. S. Sachdev and M. Nagpal, "A recursive least error squares algorithm for power system relaying and measurement applications," IEEE Trans. Power Del., vol. 6, no. 3, pp. 1008–1015, Jul. 1991.
22. A. Pradhan, A. Routray, and D. Sethi, "Voltage phasor estimation using complex linear kalman filter," in Eighth IEE International Conference on Developments in Power System Protection, 2004., 2004.
23. R. K. Mai, Z. Y. He, L. Fu, W. He and Z. Q. Bo: 'Dynamic phasor and frequency estimator for phasor measurement units', Generation, Transmission & Distribution, IET, 2010, 4, (1), pp. 73-83.

1

Synchrophasor Fundamentals:
From Computation to Implementation

The OpenPMU Project

Dr David Laverty
EPIC Research Cluster, Queen's University Belfast
david.laverty@qub.ac.uk

Queen's University Belfast

energy, power
& intelligent control

IEEE PES Power & Energy Society®

IEEE

2

Agenda

Part 1 - The OpenPMU Project

Part 2 - The OpenPMU Device

Part 3 - Experiences of PMU Networking

How I Learned to Stop Worrying and Develop a
Modern PMU Communication Standard

IEEE PES Power & Energy Society®

IEEE

Part 1
The OpenPMU Project

OpenPMU
Open Source Phasor Measurement Unit

The OpenPMU Project

The OpenPMU Project is a suite of tools for R&D in Synchrophasor Technology.

OpenPMU
Open Source Phasor Measurement Unit

There is also The OpenPMU Device, a low cost PMU suited to education and laboratory work.

It is not a commercial enterprise and is not a threat to equipment vendors. It relies on community support for survival.

The OpenPMU Project

Devices

Data Representation

Networking

Data Analysis, Storage & Compression

How Are OpenPMU?

Development Team: **Queen's University Belfast, UK**

KTH Royal Institute of Technology, Sweden

Letterkenny Institute of Technology, Ireland

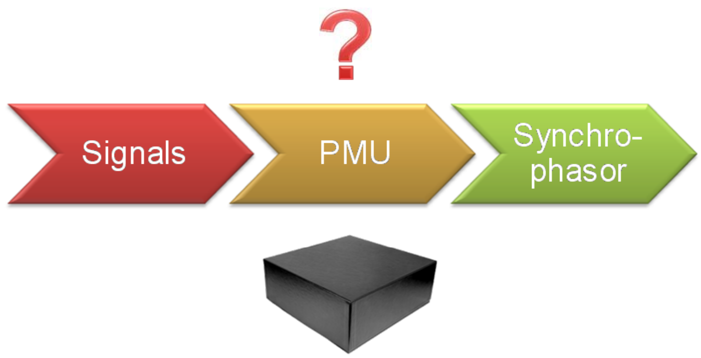
Feedback from: Colorado State University, USA

US Military Academy, USA

Kwangwoon University, South Korea

Why build an OpenPMU?

Commercial PMUs developed under 'black box' philosophy



Why Open Source?

The 'black box' philosophy makes research very difficult:

- Measurement process unknown
- Phase estimation algorithms unknown
- Transient performance different between vendors

Some commercial PMUs, don't meet the **IEEE C37.118** standard!

They can also be needlessly complex and difficult to work with.

Lack innovative thought!

Too many 'features' isn't always a good thing!

Why Open Source?

Universities working in isolation leads to:

- Duplication of work / costs
- Delays / mistakes

OpenPMU's philosophy is based on the GPL freedoms

- The freedom to **run the program**, for any purpose.
- The freedom to **study how the program works**, and change it so it does your computing as you wish.
- The freedom to **redistribute copies** so you can help your neighbour.
- The freedom to **distribute copies of your modified versions** to others.

IEEE PES Power & Energy Society IEEE

Why not use commercial product...

Not to single any particular vendor out, but…

- Bad hardware.
- Unstable software.
- Cryptic config / error messages. >>>
- Why 1 box when 3 does the same job?
- Terrible manuals.
- Obsolete technology.
- Ridiculously expensive.

IEEE PES Power & Energy Society IEEE

Why does this matter for Industry?

OpenPMU does not compete with commercial PMUs.

Rather, the project aims to:

- Drive progress for better PMU technology
- Deliver consistent performance
- Provide support over long time spans
- Compatibility
- Reliability
- Security

IEEE PES Power & Energy Society® — IEEE

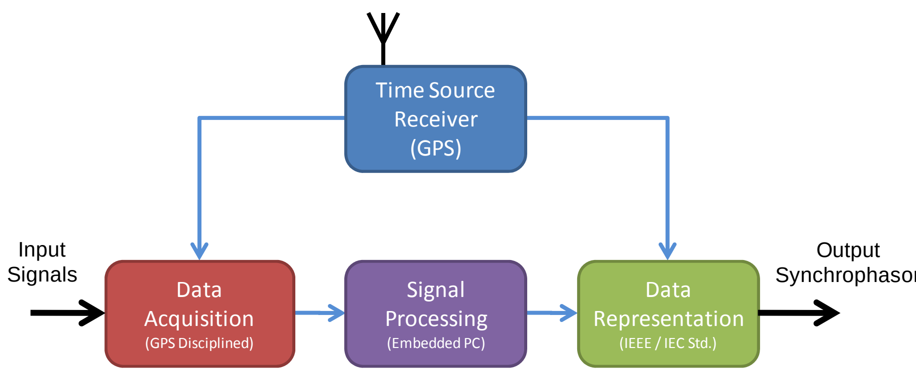
Part 2

The OpenPMU Device

IEEE PES Power & Energy Society® — IEEE

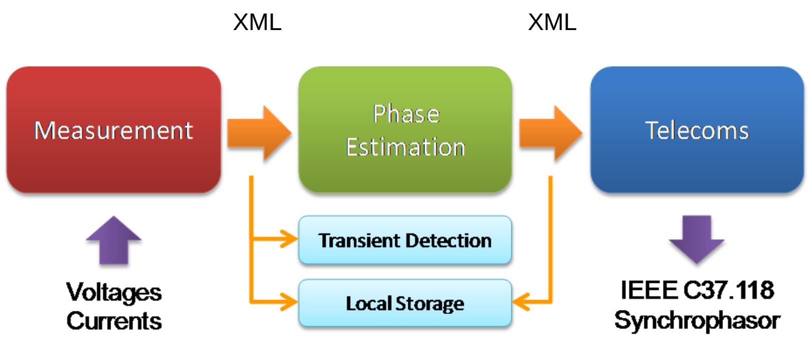
Open-OpenPMU

How OpenPMU Works



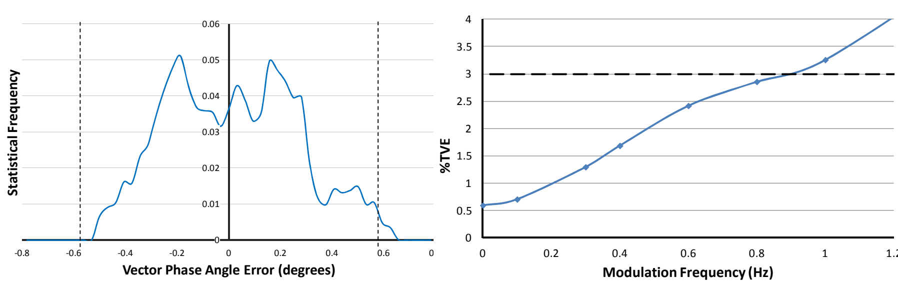
Common to all PMUs, described by Phadke et al.

How OpenPMU Works



XML data interfaces unique to OpenPMU

How **well** does it work?

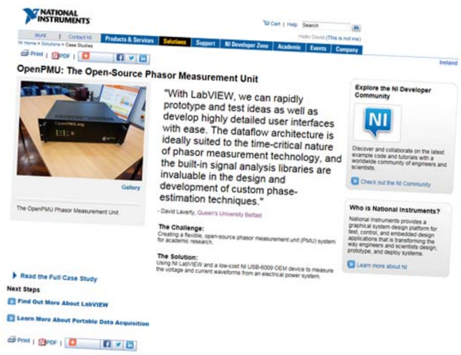


Phase estimation error during
IEEE C37.118.1-2011 test conditions

Publications


The OpenPMU Platform for Open Source Phasor Measurements

David M. Laverty, Member, IEEE, Robert J. Best, Paul Brogan, Iyad Al Khatib, Member, IEEE, Luigi Vanfretti, Member, IEEE, and D. John Morrow, Member, IEEE



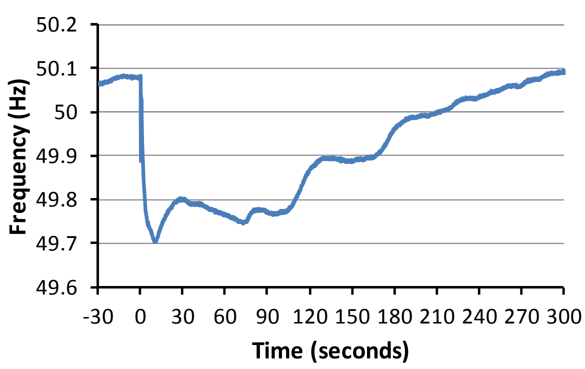
IEEE Trans. on Instrumentation & Measurements
(April 2013)

Several conference publications since 2010

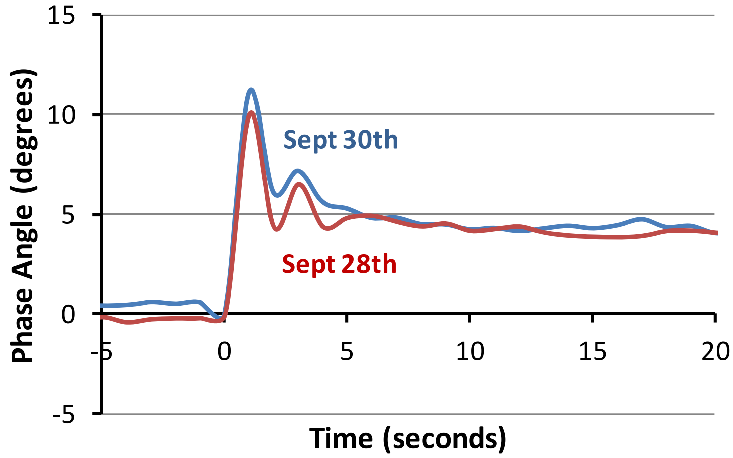
www.OpenPMU.org

Examples of Faults Detected by OpenPMU

DC Interconnector between France and Great Britain trips on 28th September 2012 causing 1 GW loss.

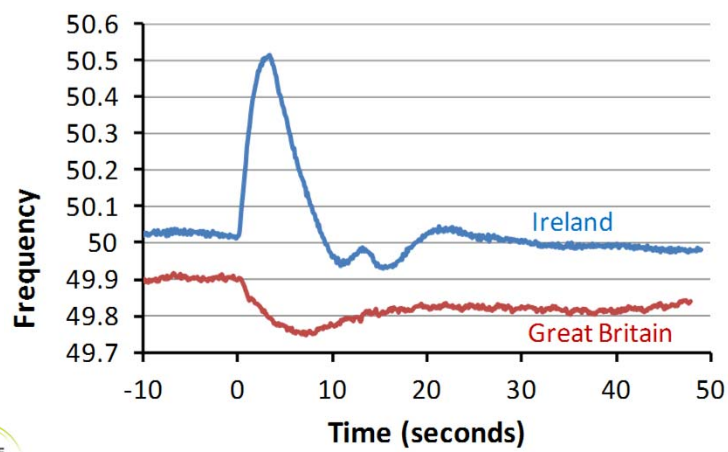


1 GW Losses on GB System



High Wind Penetrations

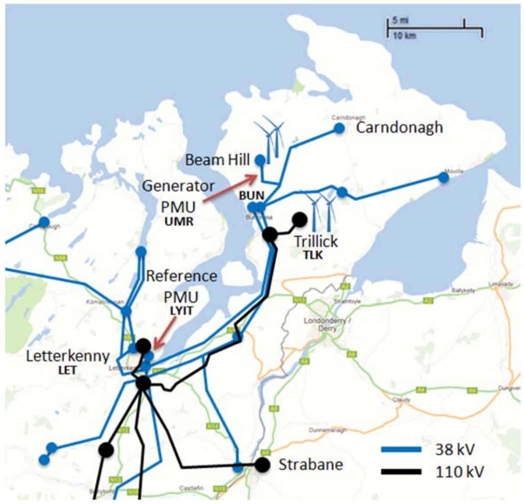
DC Interconnector between Ireland and Great Britain trips resulting in 500 MW imbalance.
Ireland operating with 35% wind generation.



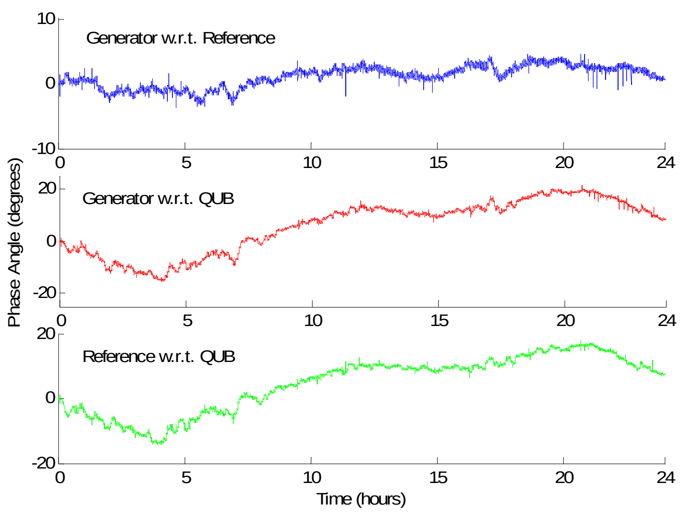
Phase variation on Wind Farm feeders

Inishowen,
Co. Donegal.

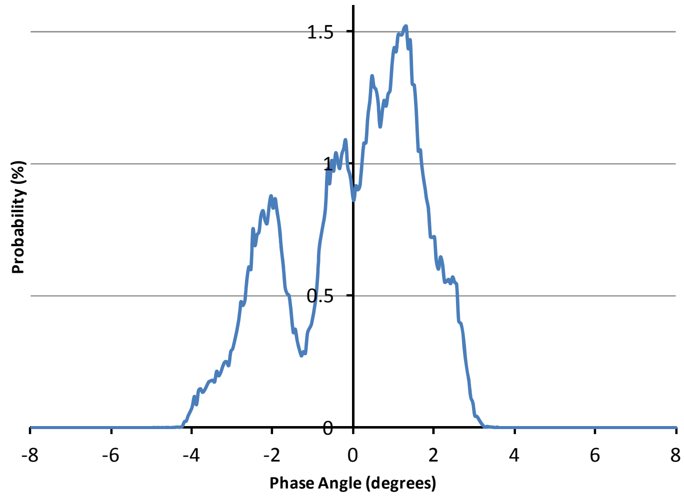
The world's **41st largest** producer of wind power!



Phase variation on Wind Farm feeders



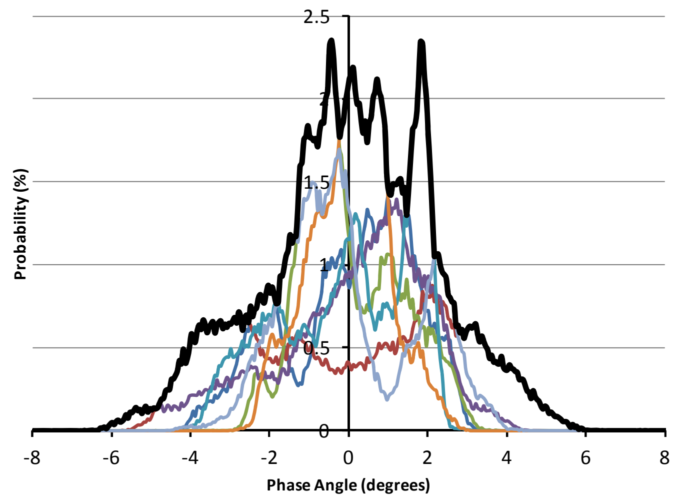
Phase variation on Wind Farm feeders



IEEE PES Power & Energy Society

IEEE

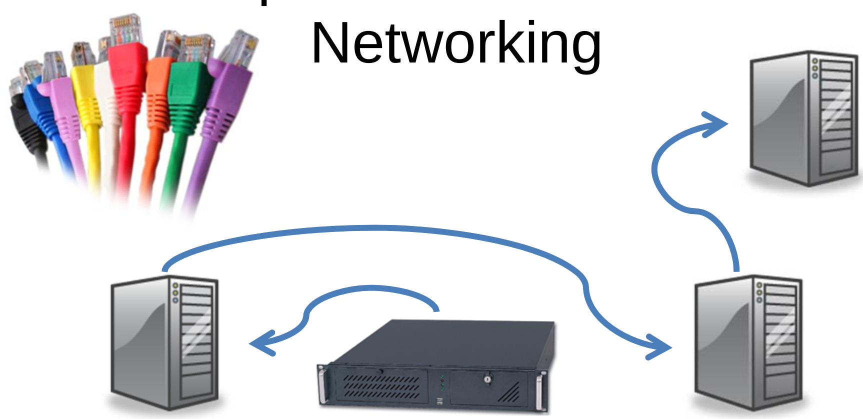
Phase variation on Wind Farm feeders



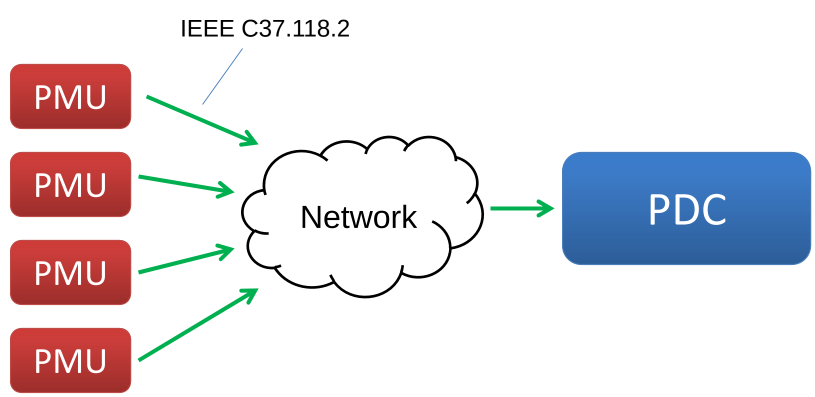
IEEE PES Power & Energy Society

IEEE

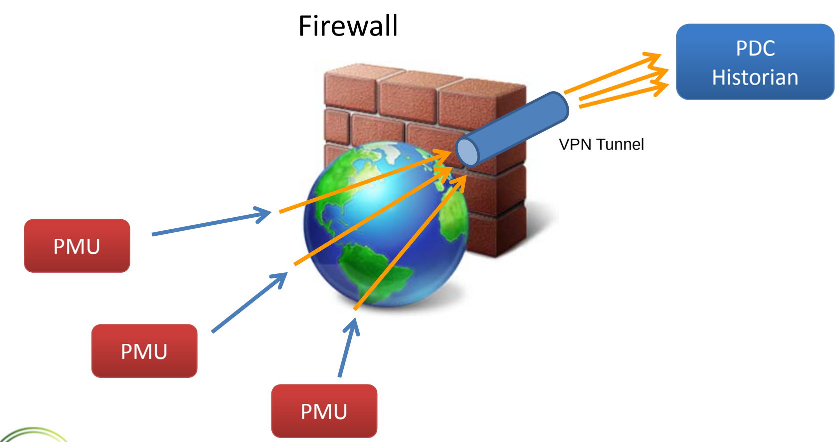
Part 3
Experiences of PMU Networking



The Theory…



The Theory... (WAN)



The practice...

The problem

IEEE C37.118.2	This is a **“data representation”** standard Concerned with **bit efficiency** It doesn’t have much to say about **WANs** It is agnostic regarding **security**
We require	Device discovery Handshaking Buffering Security
Less concerned with	Remote Configuration Compression

IEEE PES Power & Energy Society IEEE

The problem

The present IEEE PMU Standard has been focused on accuracy of phasor estimation.

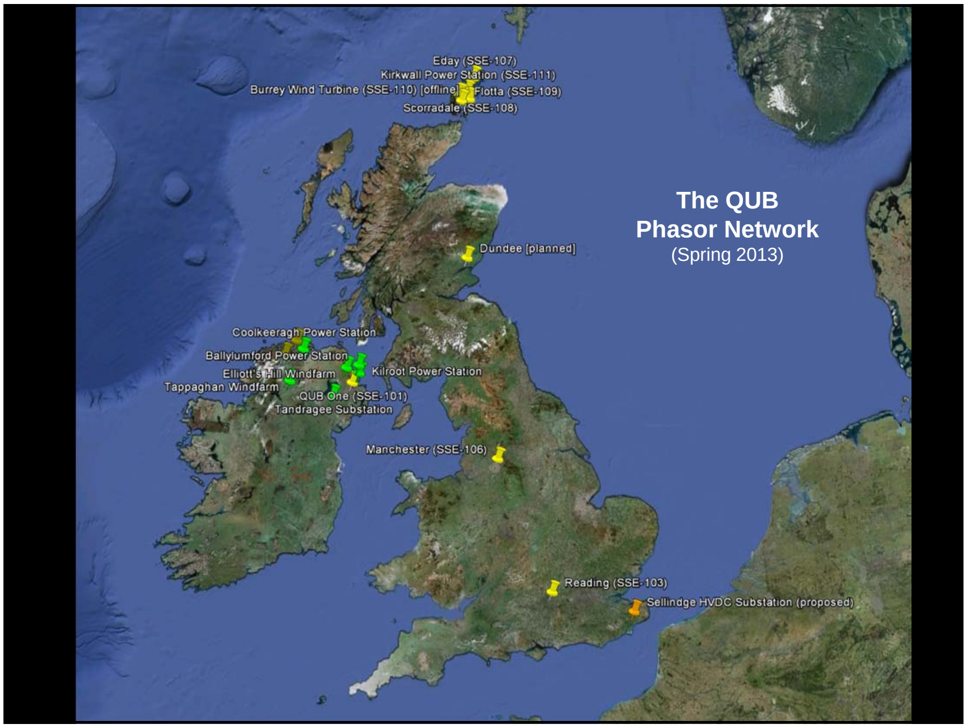
There is a need to gather data *reliably* over a **wide area**.

Present solutions are hampered by poor software / network design.

The OpenPMU Project is developing a solution that will be made available freely for vendors to adopt.

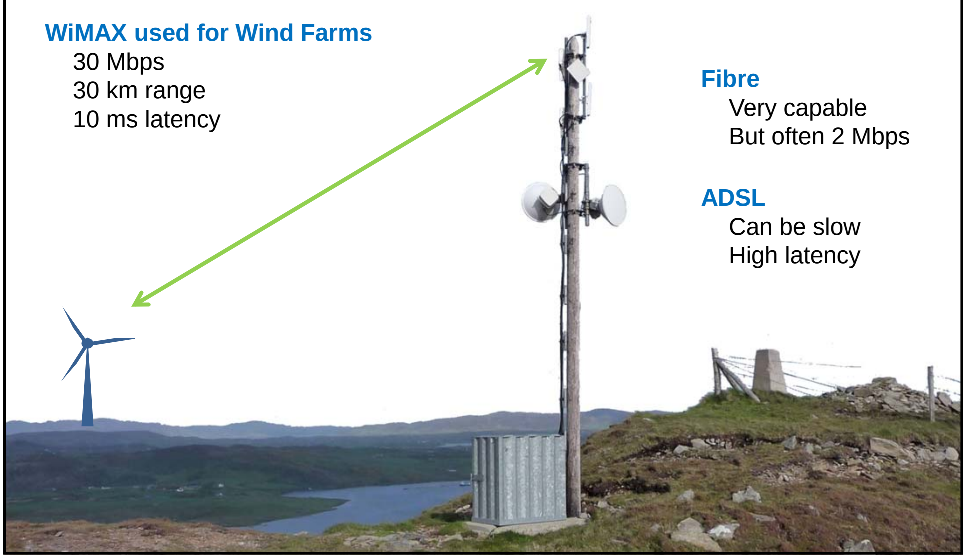
This is a *computer science* problem, not power engineering. There are commercial solutions at the moment, but they too have failings.

IEEE PES Power & Energy Society IEEE



Wide Area Networking

WiMAX used for Wind Farms
- 30 Mbps
- 30 km range
- 10 ms latency

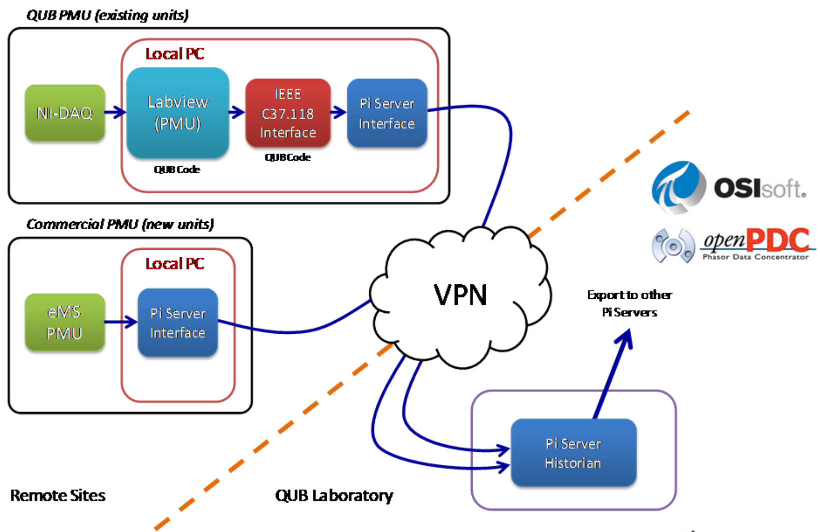


Fibre
- Very capable
- But often 2 Mbps

ADSL
- Can be slow
- High latency

33

Pi Server Historian



IEEE PES Power & Energy Society

IEEE

Review of Pi Server for PMU

The Good	Works great (ish) Does most of the things we want **Buffering** **Compression**
The Bad	Very expensive Proprietary Database built on very old technology
The Mediocre	Needs to run on a Windows PC Another point of failure Another security vulnerability Not that easy to configure

Why isn't this all part of the PMU functionality?

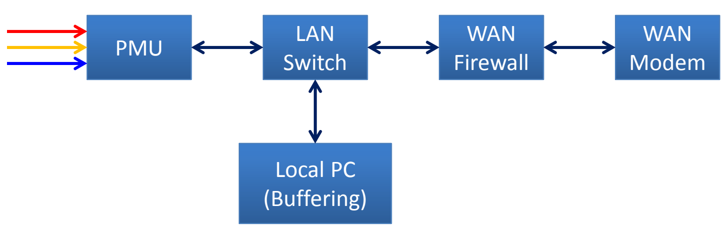
IEEE PES Power & Energy Society

IEEE

Towards a Modern PMU Comms Std.

Throughput	PMU needs circa **75 kbps** Most delivery technologies can achieve this **Compression** is desirable
Latency	Only matters for real-time applications Most technologies will achieve **< 100 ms**
Wide Area Network	Protocol needs to be **routable** Link might not be reliable ∴ **buffering** Might traverse Internet ∴ **security**
Remote Configuration	**Convenience** is the **enemy** of **security**
Scalability	Automatic device **discovery** Zero-configuration

Present Wide Area PMU Operation



- Local PC exists as interface to remote historian.
- PMU doesn't have means of buffering own data.

Future Wide Area PMU Operation

- Buffering is done on the PMU.
- Eliminates two points of failure.

IEEE PES Power & Energy Society IEEE

This is what happens when you leave the gate open…

IEEE PES Power & Energy Society IEEE

Synchrophasor Fundamentals:
From Computation to Implementation

The OpenPMU Project

Dr David Laverty
EPIC Research Cluster, Queen's University Belfast
david.laverty@qub.ac.uk

Queen's University Belfast

energy, power
& intelligent control

Phasor Measurement Unit Installation and Testing

IEEE Summer Power 2013

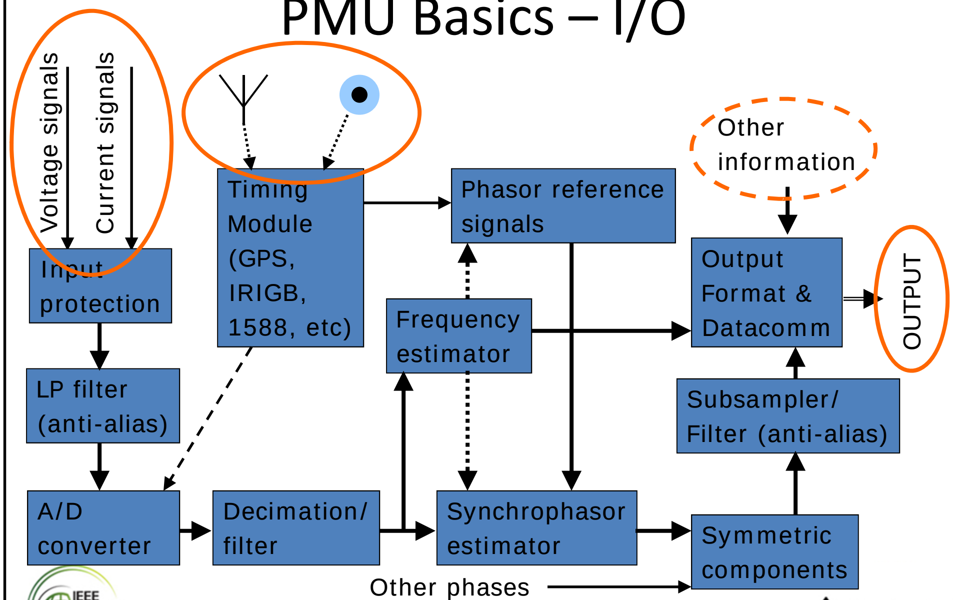
Ken Martin, Electric Power Group (EPG)

Electric Power Group

Outline

- PMU equipment selection
- Installation essentials
- PMU testing

PMU Basics – I/O



PMU selection – device options

- Stand-alone PMU
  - Specifically for PMU functions
  - Design optimized for PMU operation
- Integrated PMU
  - Part of another device – relay, DFR
  - Specs for or compromise to other function
- Considerations
  - Performance (does not seem to be an issue)
  - Device management
  - Installation and maintenance cost

PMU selection – measurements

- Meet standards & company requirements
- Measurement capability
  - Number/type of inputs
    - 3 channels/measurement (V or I)
  - Measurement characteristics
    - M or P class (filtering, latency, accuracy)
    - Measurement ranges (V & I inputs)
- Compatible with communications
- Other factors
  - Maintainability (designs, spares, training)
  - $$ Cost $$

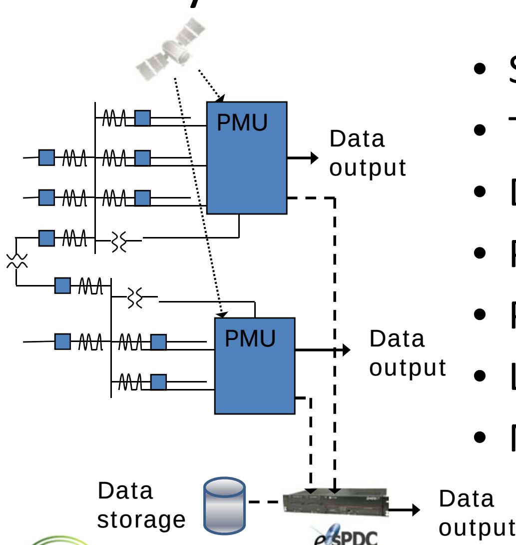
Determine application needs

- All applications need
  - Good coverage of major substations
  - Reliable data system
- Visualization & situational awareness
  - Slower data rates & longer latency OK
- System analysis
  - Accurate measurements
- State estimation
  - Good coverage, both V & I
- Controls
  - More specific measurements, low latency

Installation planning

- Based on application requirements
  - PMU locations
  - Selection of signals to measure
  - Communication requirements
- Select PMUs
  - Number & type of inputs
  - Meets measurement criteria
  - Good match for communications
  - Meets other criteria
- Scheduling
  - Deadlines, workforce, & outages

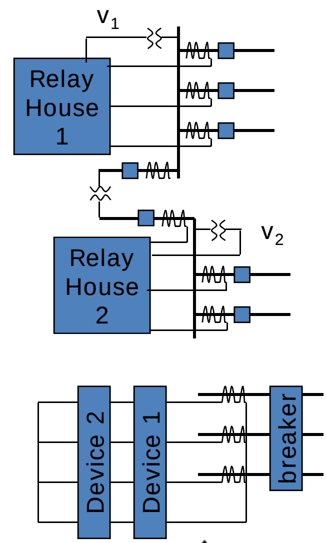
Physical installation overview



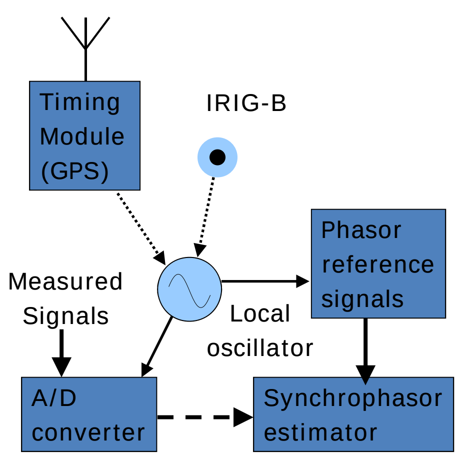
- Signal input
- Timing input
- Data output
- Physical layout
- Power input
- Local subsystem
- Maintenance & service

PMU signal inputs

- How many signals to measure?
  - 3 input channels/phasor
- Where are the signal sources?
  - Separate buildings – need several PMUs
  - Analog or digital (status) inputs
- Need aux current or voltage transformers? Usually plan for--
  - I < 4x (full load)
  - V < 2x (rated voltage)
  - PMUs are not usually used for fault conditions
- Need remote access to PMU?
  - Separate data-comm required & available?
- Power for PMU



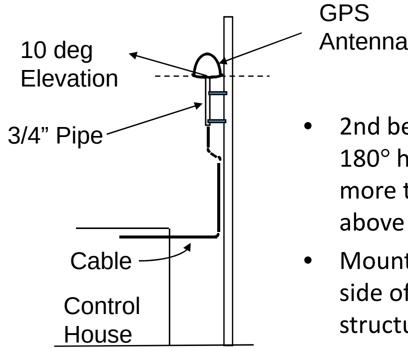
Measurement timing



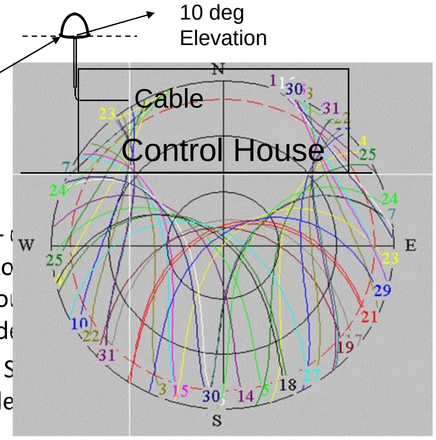
- GPS
  - Needs lock indication
- IRIG – B
  - Needs lock indication
  - Needs edge for sync
    - Level shift, Manchester coding, or 1 PPS
- IEEE 1588
  - Distributed by Ethernet
  - Needs time quality
  - Requires qualified network
- Internal LO for holdover

GPS input – Antenna mounting

- Best - clear 360° horizon above 10 deg. elev



- 2nd best – 180° horizo more to Sou above 10 de
- Mount on S side of pole structure



24 Hr. satellite trajectory plot

PMU communications

- Interface between PMU & communication system
  - Modem, router, SPDC
  - Match for interface on both sides
- PMU output is continuous in data frames
  - Size communication bandwidth to handle message size including overhead
  - Latency (delay) in transmission within application limits

PMU output – C37.118, all integer

Data rate - bytes/sec		
Smp/sec	5 Phasors	10 Phasors
12	480	720
30	1200	1800
60	2400	3600

PMU output – C37.118, all floating point

Data rate- bytes/sec @ 30 frames/sec			
Analog	Digital	5 Phasors	10 Phasors
0	0	1980	3180
2	0	2220	3420
2	2	2340	3540

Data rate in bits/sec (BPS) is approximately 10X(rate in bytes/sec)

Typical PMU rack installation

Front

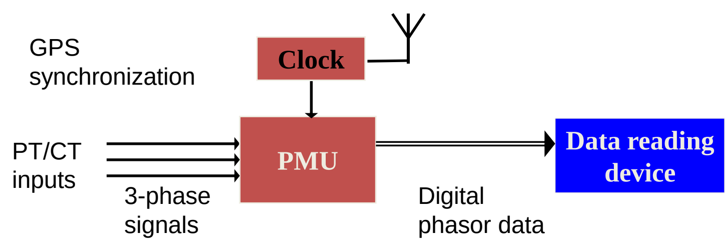
Rear

Installation checkout

- Purpose is to confirm operation
  - Assure timing, measurements, & communications
- Measurements
  - Confirm correct signal inputs, phasing, scaling
  - Assure values by comparing with other measurements
- Check PMU timing input & synchronization
- Communications
  - Establish communications
  - Check datacomm quality & latency

PMU installation

- 3-phase AC signals (V & I)
  - Check phase rotation, magnitude, relative phasing
- GPS or other timing input
  - Achieves sync and lock
  - Detects and indicates loss of signal and sync
    - (eg, disconnect antenna)



Measurement comparisons

- At substation
  - Portable or installed instruments
- At control center
  - SCADA or other reported data

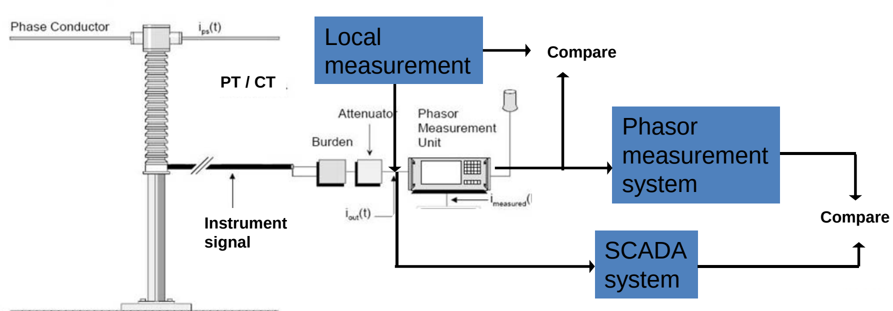


Diagram - EIPP measurement accuracy doc, S. Meliopoulis

Communication checkout

- Connect with destination device
  - Check that data received correctly
  - Observe over time (24 hr) - check reliability, latency
- Problems with connection or data?
  - Check addressing & routing setup
  - Use network analyzer for troubleshooting (Ethereal, etc)
- Communications usually works or doesn't (not half performance)

PMU Testing

- Basic goals
  - Measurement conformance
    - C37.118.1 measurement standard
  - Communication conformance
    - C37.118.2 or 61850-90-5 communication standards
  - Test conformance with other applicable standards (C37.90, etc)
  - Special user performance or operational requirements
- Additional goals
  - Reveal errors in measurement & operation
  - Test other functions – Eg., data archiving & added calculations
- This only covers Measurement Conformance

Synchrophasor Measurement Standard IEEE C37.118.1

- New C37.118.1 standard covers all measurements
  - Phasor, frequency, & ROCOF
  - (ROCOF: acronym for Rate of Change of Frequency)
- Retains 2005 steady-state requirements
- Adds measurement under dynamic conditions
  - Measurement bandwidth, tracking, and response time
- Tests keyed to apply to all measurements
  - Same tests for phasors, frequency, & ROCOF

New generalized definitions

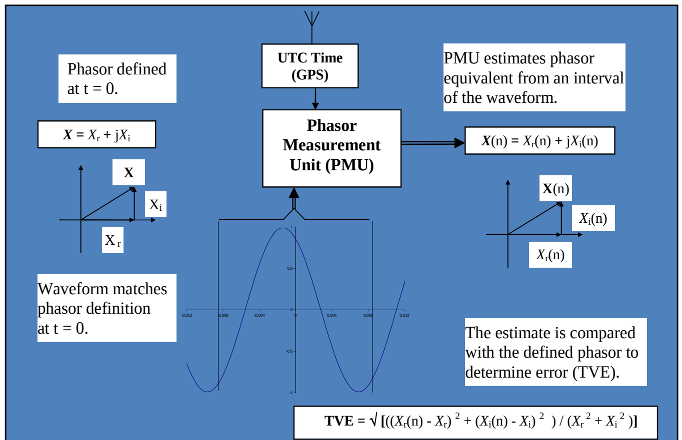
- Generalized definitions allow precise expression of dynamic measurements for phasors, frequency, and ROCOF as functions of time:
- $x(t) = X_m(t) \cos[\psi(t)]$
  $= X_m(t) \cos[2\pi f_0 t + (2\pi \int g dt + \varphi(t))]$
- The phasor value is:
- $\boldsymbol{X}(t) = (X_m(t)/\sqrt{2}) e^{j(2\pi \int g dt + \phi(t))}$
- Frequency: $f(t) = 1/(2\pi)\, d\psi(t)/dt$
- ROCOF: $ROCOF(t) = df(t)/dt$

Basic measurement criteria - TVE

- Synchrophasor estimate of AC signals
- Steady-state and dynamic conditions

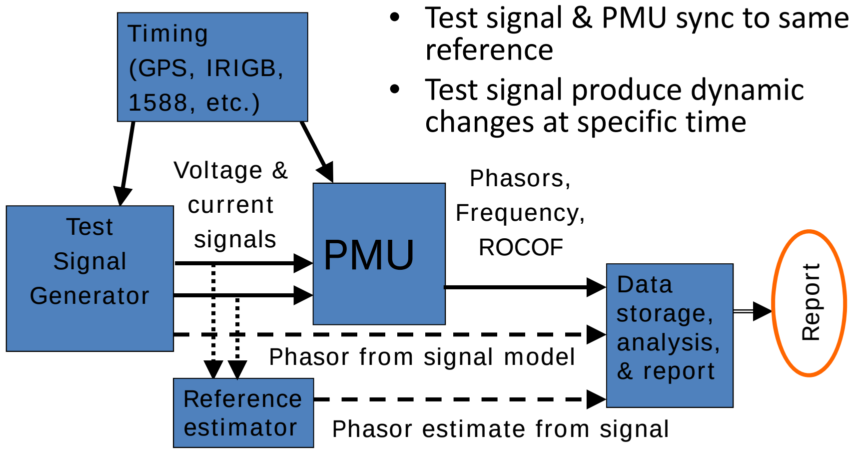
Total Vector Error (TVE):

the difference between the theoretical and estimated phasors, calculated as the RMS difference using the rectangular component representation.



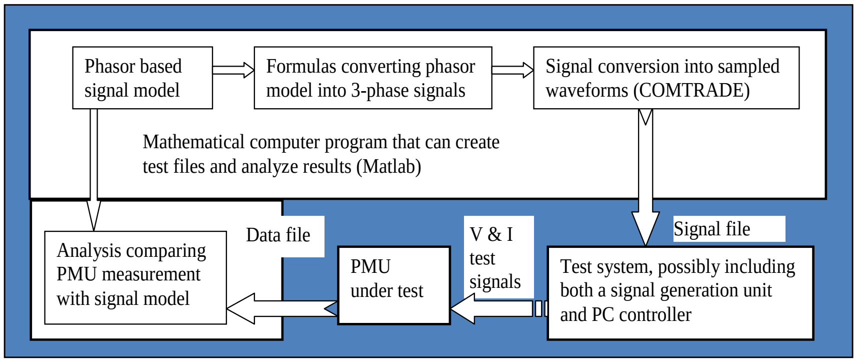
PMU Test methods

- Test signal & PMU sync to same reference
- Test signal produce dynamic changes at specific time



- Method 1 – Playback of test signal, requires precise generator
- Method 2 – Test signal generator monitored, reference provides corrections

Playback testing method



Start with the phasor model – generate test signals
Signals into PMU using precise timing
PMU measurement compared with the phasor model
Alignment by signal playback time and PMU timetags

Test types

- Steady-state
  - Parameters under test are not changing
  - Emphasize accuracy, conversions
- Dynamic performance
  - Measured values are changing
  - Measure accurately during operational state
  - Measurement recovery after transition (step)
- PMUs intended to measure performance values
  - Fault, non-linear change not measured

Reporting rates & measurement classes

- Reporting rates
  - Rate at which measurement data is transmitted
  - Required 10-60, others allowed
  - Reports evenly aligned to hour (=> min & sec)
  - Factored into many compliance requirements
- M class – includes 20 dB anti-alias filtering
  - Emphasize accuracy
- P class – no anti-alias filtering
  - Emphasize low latency

Steady-state accuracy tests

- Amplitude scan – relative to rated input
  - Voltage: 80 – 120% (P) or 10 – 120% (M)
  - Current: 10 – 200%
- Phase scan – absolute angle, -180° to +180°
- Frequency operating range
  - Nominal f_0 ± Fs/5 Hz, ± 5 Hz max
- Temperature – perform frequency range test
  - At T = 0° C; nominal (23° C); 50° C.
- Phase imbalance, amplitude & angle*

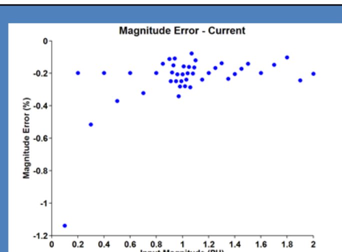
* Advisable for positive sequence, not part of standard

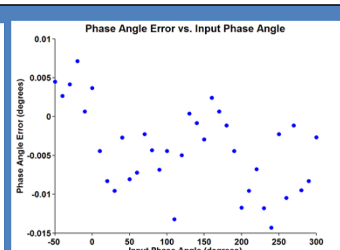
Steady-state interference rejection

- Harmonic scan – harmonics 2-50, at nominal f_0
  - Single harmonic at a time
  - Positive sequence to check rejection
  - 1% (P class) or 10% (M class) amplitude level
- Out-of-band rejection – 10 to $2xf_0$ Hz
  - Single frequency signal (tone) at a time
  - 10% signal level
  - Center frequency (f_0) varied ± 10% of Nyquist range
  - M class only

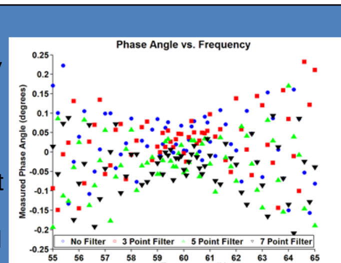
Accuracy test examples

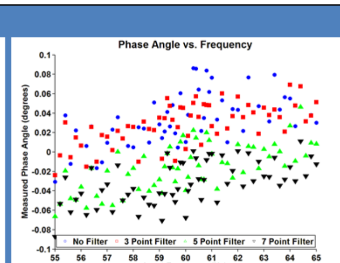
Magnitude & Phase angle errors – Very small except at extremes





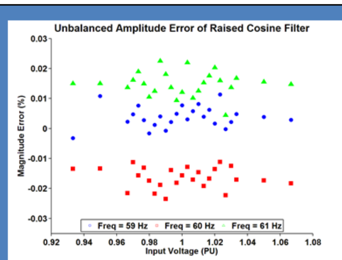
Phase-frequency Tests – 4 different PMU filter settings - with and without frequency tracking enabled

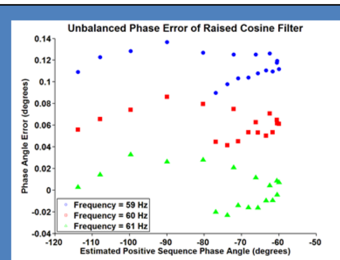




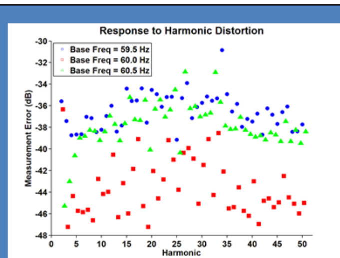
Imbalance & rejection examples

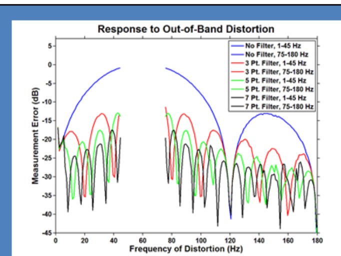
Phase Imbalance - magnitude & angle - small errors with typical patterns





Interference rejection – Harmonic & single frequency scan with 4 filters





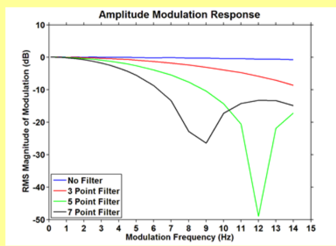
Dynamic tests

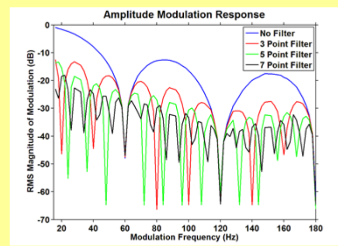
- Characterize PMU in dynamic operational conditions
  - Should provide comparability between PMUs
  - Restricted to emulate real operational situations
- Modulation of the system fundamental signal (f_0)
  - Determines bandwidth of measurement
  - Emulates what the PMU will see in a system swing
- Ramp of the system frequency
  - Determines measurement tracking the system and each other
  - Emulates sudden loss of generation or load
- Step tests
  - Shows the measurement during a step change and response time
  - Emulates changes due to switching events

Modulation tests

- Two modulation tests
  - Combined amplitude and phase modulation
  - Phase only modulation
  - Phase and amplitude indexes both 0.1
- Performance is flat within TVE = 3% (~ 3 dB)
  - M class: 0.1 to Fs/5 Hz with max 5 Hz (Fs reporting rate)
  - P class: 0.1 to Fs/10 Hz with max 2 Hz

Amplitude modulation – pass & reject bands. Note reject band is same as with single freq test

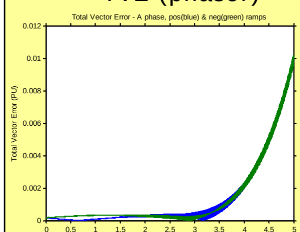




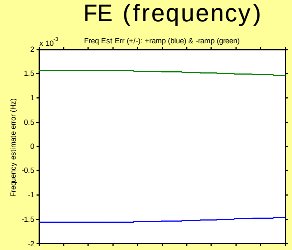
Ramp tests

- Frequency ramp ± 1 Hz/s
  - M class range: f_0 ± Fs/5 Hz up to f_0 ± 5 Hz
  - P class range: f_0 ± 2 Hz
  - Exclusions where filter includes frequency out of range
- Max errors: TVE = 1%, FE = .01 Hz(P) & .005 Hz(M), RFE = 0.1 Hz/s
- Example: M class, reporting rate Fs =30 fps, f_0 = 60 Hz

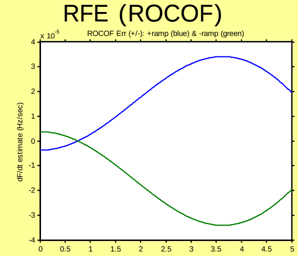
TVE (phasor)



FE (frequency)



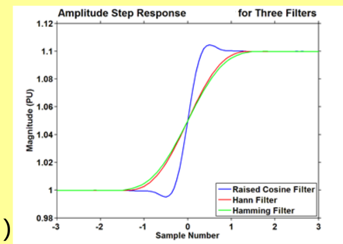
RFE (ROCOF)

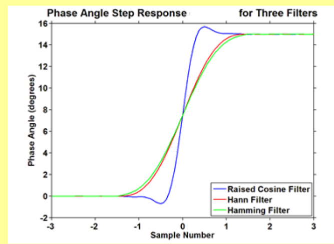


Step tests

- Balanced 3 phase step change in signal
  - Amplitude step – 10% of nominal amplitude
  - Phase step – 10°
- Response centered – delay < 1/(4Fs)
- Overshoot limited – 5% (P) or 10% (M) of step size
- Response time limits – 1.7, 3.5, 4 x f_0 (P), longer for (M)

Amplitude & phase steps – differences in response clearly shown with delayed sampling (slip-sampling)





Current activity – C37.118.1

- Amendment to correct errors
  - Typographical
  - Excessive noise in frequency
  - Filter exclusion on ramp
  - Consideration for actual PMUs
- IEC – IEEE joint standard development
  - Will be a revision
  - May make other changes to standard

Summary

- PMUs have many configurations and setting options to choose
  - Base on planned application requirements
- Reviewed installation considerations
- Plan for validating installation
- PMU performance testing
  - Overview and sample results

Designing IT and Communications for PMU Applications

Now that I have all this data what do I do with it?

IEEE PES Power & Energy Society® IEEE

BRIDGE ENERGY GROUP

BRIDGE Energy Group is a vendor-neutral, Smart Grid Systems Integration & Utility Solutions Company, focused on IT & OT convergence and business transformation, working exclusively within the energy industry.

CIO 100 Inc.5000

BRIDGE helps Utilities improve operational efficiency, customer services and outage resolution with standards-based solutions BRIDGE helped to develop.

NIST NASPI SGIP

Specialization:	**Utility / Power Industry** Power Transmission, Distribution Utilities, ISOs, Munis and Coops
Offices:	Marboro, MA (HQ), Albany, Austin, Rutland, Sacramento
Established:	2004
Financials:	Growing and Profitable Updata Partners portfolio company
Solutions:	Smart Grid strategy, solutions, expert services and analytics
Differentiation:	Authors of multiple standards, Vendor & standards agnostic

IEEE PES Power & Energy Society® IEEE

3

Acknowledgement and Disclaimer

- Acknowledgment: This material is based upon work supported by the Department of Energy under Award Number DE-OE0000364.

IEEE PES Power & Energy Society®

IEEE

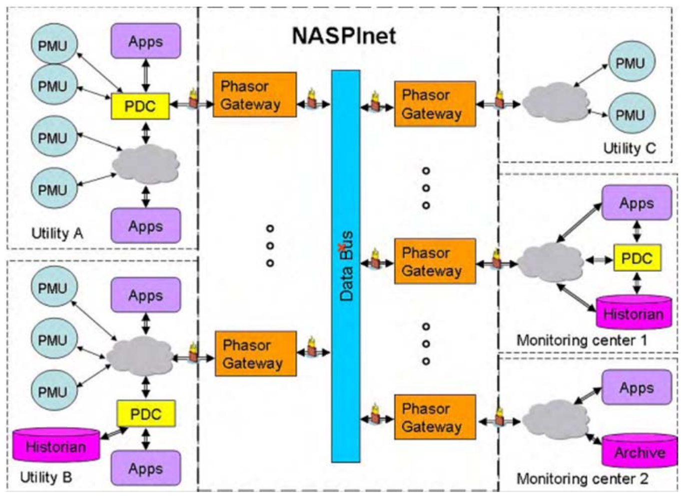
4

INFRASTRUCTURE

IEEE PES Power & Energy Society®

IEEE

The Original Vision



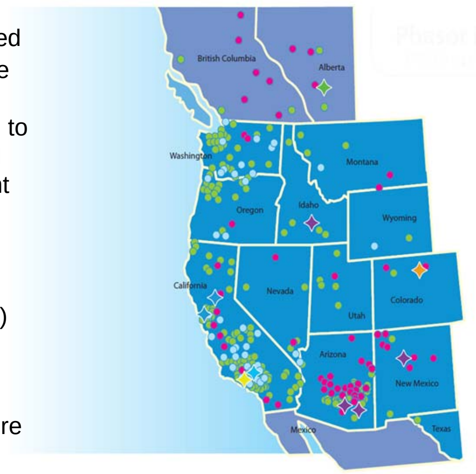
Design Requirements

- 400 PMUs strategically placed around the bulk electric system
- System must be capable of doubling capacity over the next 5 years
- High availability low latency communications network
- New analysis and visualization applications
- Support peer to peer sharing of synchrophasor data
- ***Increase Wide Area Situational Awareness***

WISP 18 participants have deployed synchrophasor devices throughout the U.S. portion of the Western Interconnection. The project goal was to improve electric-system reliability and restoration procedures, and to prevent the spread of local outages to neighboring regions.

The project has deployed:

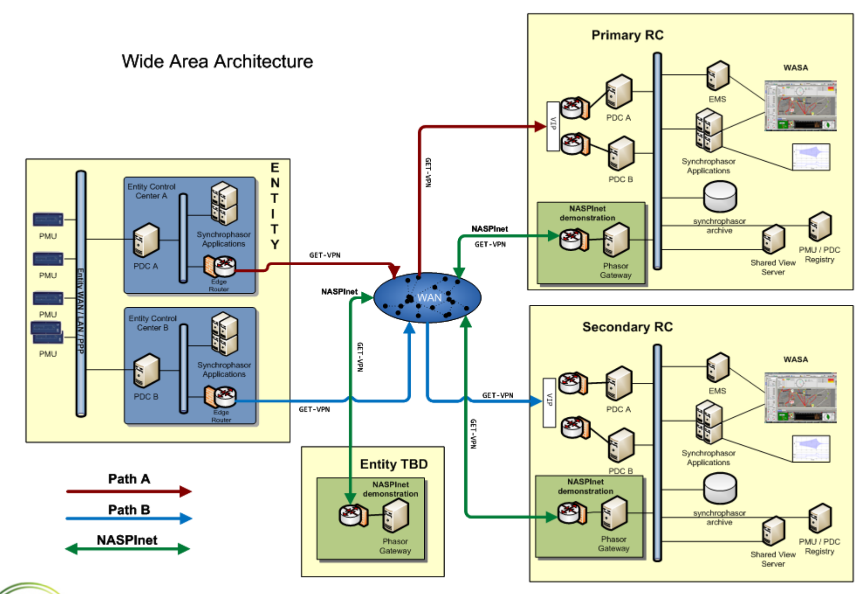
- Phasor measurement units (PMUs)
- Phasor data concentrators (PDCs)
- Communication infrastructure
- Information technology infrastructure
- Advanced transmission software applications



Wide Area Network requirements

- Edge router to edge router < 30ms latency
- Backbone network 99.9999% available
- Last mile (local loop) 99.98% availability
- Source PDCs: Dual redundant PDCs at two separate physical locations
- Destination PDCs: Dual redundant PDCs at two separate physical locations

- Data flows and speeds:
  - PMU to PDC communication controlled by each Participant — latency varies among Participants.
  - PDCs to RCs for centrally processed applications:
    - Edge router to edge router latency requirement is 30 ms average over 10 min, experiencing 19 ms; and
    - Jitter requirement is 2 ms average over 10 min, experiencing 1.4 ms.
    - WAN availability 99.99 percent (measurement beginning May 2012).
  - Expecting 2100 phasor measurements initially — WAN capable of 10X this volume limited only by 'last mile' connection.



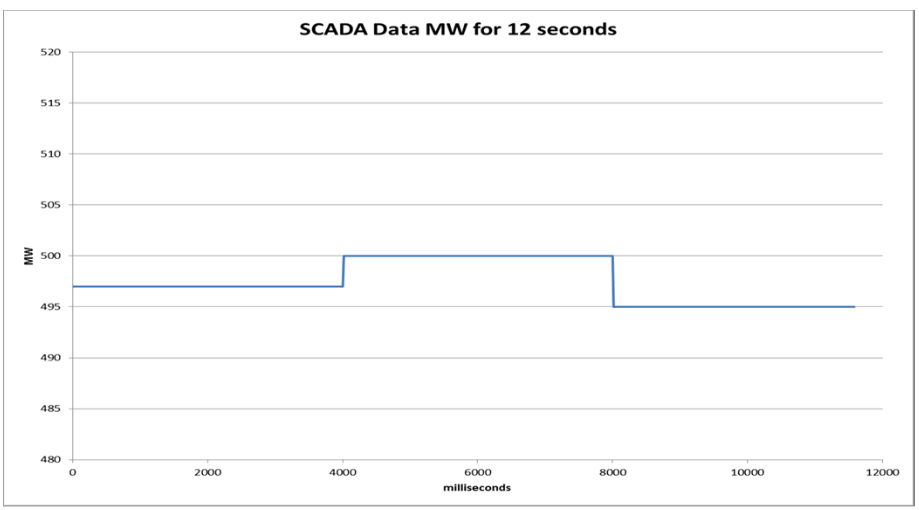
11

SYNCHROPHASOR DATA

IEEE PES Power & Energy Society®

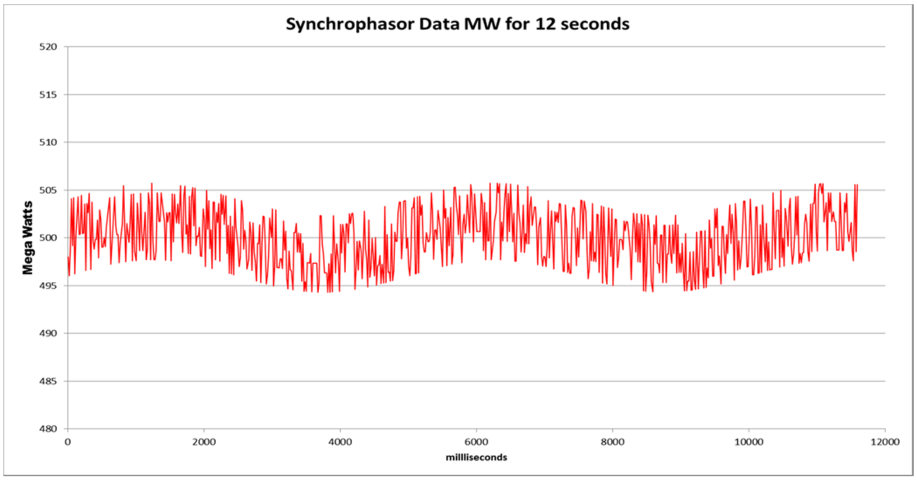
IEEE

12



IEEE PES Power & Energy Society®

IEEE



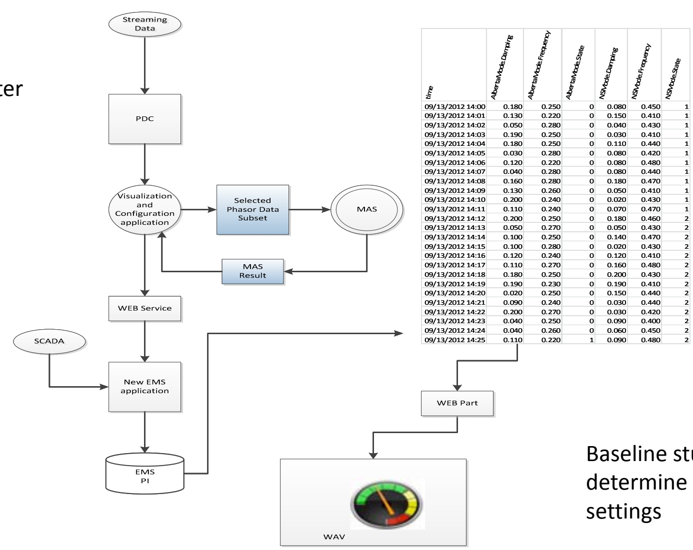
General Uses

- New high speed synchronous data aware applications
  - Wide Area Situational Awareness (WASA)
  - Dynamic Voltage stability
  - Mode meter
  - Oscillation detection
  - Islanding
- Archival Data
  - Post even analysis
  - Model Validation

Key location Phase Angle Delta measurements

Baseline studies to determine threshold settings

Mode Meter



time	AlbertaMode.Damping	AlbertaMode.Frequency	AlbertaMode.State	NSMode.Damping	NSMode.Frequency	NSMode.State
09/13/2012 14:00	0.180	0.250	0	0.080	0.450	1
09/13/2012 14:01	0.130	0.220	0	0.150	0.410	1
09/13/2012 14:02	0.050	0.280	0	0.040	0.430	1
09/13/2012 14:03	0.190	0.250	0	0.030	0.410	1
09/13/2012 14:04	0.180	0.250	0	0.110	0.440	1
09/13/2012 14:05	0.030	0.280	0	0.080	0.420	1
09/13/2012 14:06	0.120	0.220	0	0.080	0.480	1
09/13/2012 14:07	0.040	0.280	0	0.080	0.440	1
09/13/2012 14:08	0.160	0.280	0	0.180	0.470	1
09/13/2012 14:09	0.130	0.260	0	0.050	0.410	1
09/13/2012 14:10	0.200	0.240	0	0.020	0.430	1
09/13/2012 14:11	0.110	0.240	0	0.070	0.470	1
09/13/2012 14:12	0.200	0.250	0	0.180	0.460	2
09/13/2012 14:13	0.050	0.270	0	0.050	0.430	2
09/13/2012 14:14	0.100	0.250	0	0.140	0.470	2
09/13/2012 14:15	0.100	0.280	0	0.020	0.430	2
09/13/2012 14:16	0.120	0.240	0	0.120	0.410	2
09/13/2012 14:17	0.110	0.270	0	0.160	0.480	2
09/13/2012 14:18	0.180	0.250	0	0.200	0.430	2
09/13/2012 14:19	0.190	0.230	0	0.190	0.410	2
09/13/2012 14:20	0.020	0.250	0	0.150	0.440	2
09/13/2012 14:21	0.090	0.240	0	0.030	0.440	2
09/13/2012 14:22	0.200	0.270	0	0.030	0.420	2
09/13/2012 14:23	0.040	0.250	0	0.090	0.400	2
09/13/2012 14:24	0.040	0.260	0	0.060	0.450	2
09/13/2012 14:25	0.110	0.220	1	0.090	0.480	2

Baseline studies to determine threshold settings

17

18

Design Requirements

- 400 PMUs
- 400 frequency and frequency rate of change measurements
- 2400 positive sequence voltage and current synchrophasors
- ***Measurement Data streaming at 60 frames per second***

Archives

- Storage duration and capacity:
  - All Data On-Line – 15 months
  - Disturbances – 7 years
  - 100+ TB
- Redundant Archives at each archive location

Archives

- Any measurement with a rate of change greater than X% or that drops more than Y MW / MVAR / kV/Hz
- Any measurement with a MW oscillation magnitude greater than X% or Y MW, results ordered by magnitude of oscillation
- Any measurement with a kV oscillation magnitude greater than X% or Y kV, results ordered by magnitude of oscillation
- Any monitored phase angle pairs that exceed angle separation greater than X degrees
- System damping less than X% for a user selected mode or across all monitored modes
- Specified path MW, or all path MW at X% or greater capacity (path limits are also stored in the historian)
- Specified bus voltage, or all bus voltages less than X kV
- Specified frequency, or all frequency outside the bounds of X Hz (example "select all frequency points where frequency is less than 59.90 or greater than 60.10")
- Any point that is available in the historian can be selected and plotted
- Other combinations of the above data. For example, "select all phase angle differences greater than X where path MW flow is greater than Y% of limit and system damping is less than Z%"

PROTOCOLS

Requirements

- Must be interoperable
  - C37.118-2005
  - C37.118-2011
  - COMTRADE
  - 61850 -90-5
  - Existing PMUs (Macrodyne)
- Must be compatible
  - SCADA
  - EMS
  - State Estimator

Measurements

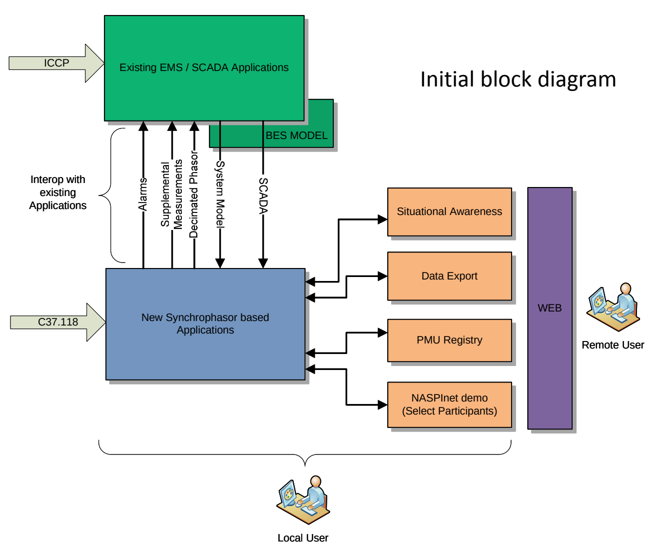
Synchrophasor

- High Frequency
  - 30 to 240 *per second*
- Time Stamp
  - GPS Sync to 1 microsecond accuracy
- System Wide
  - Synchronization and High Resolution allow improved situational awareness

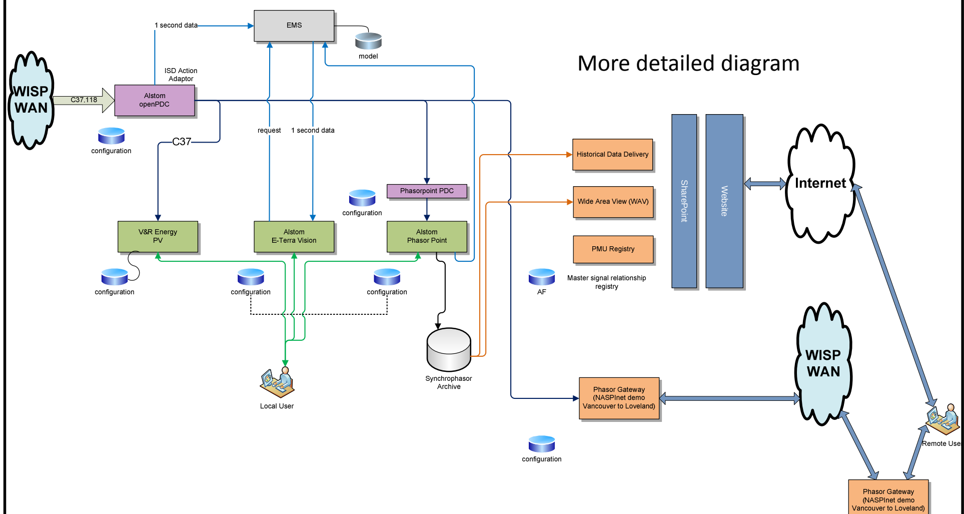
SCADA

- Low Frequency
  - 1 measurement every 1 to 10 seconds
- Time Stamp
  - When measurement arrives at EMS
- System Wide
  - ICCP

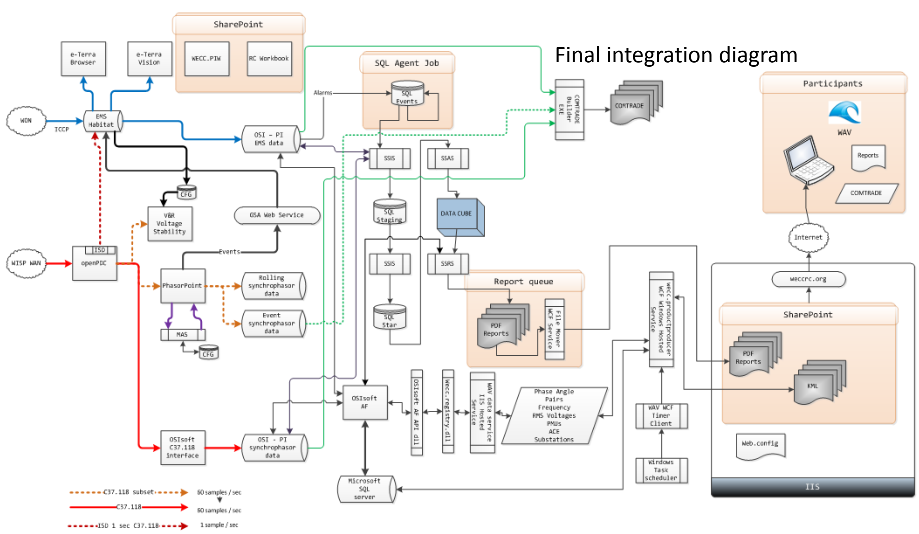
Initial block diagram



More detailed diagram



Final integration diagram

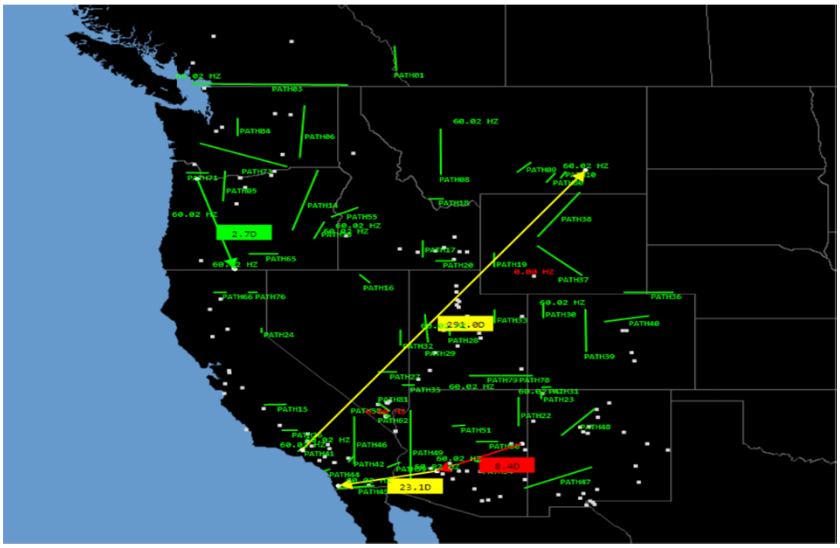


27

RESULTS

28

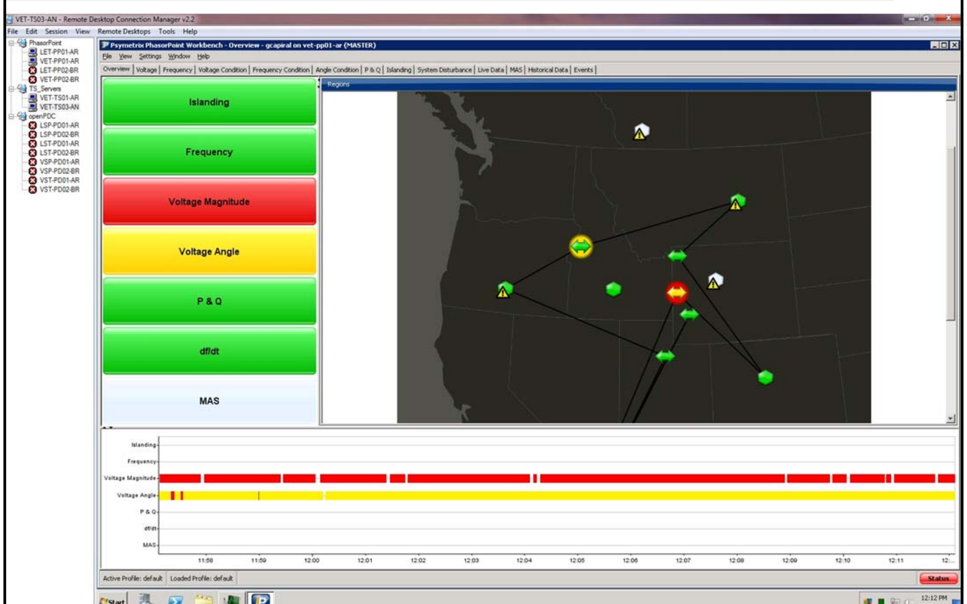
29



IEEE PES Power & Energy Society®

IEEE

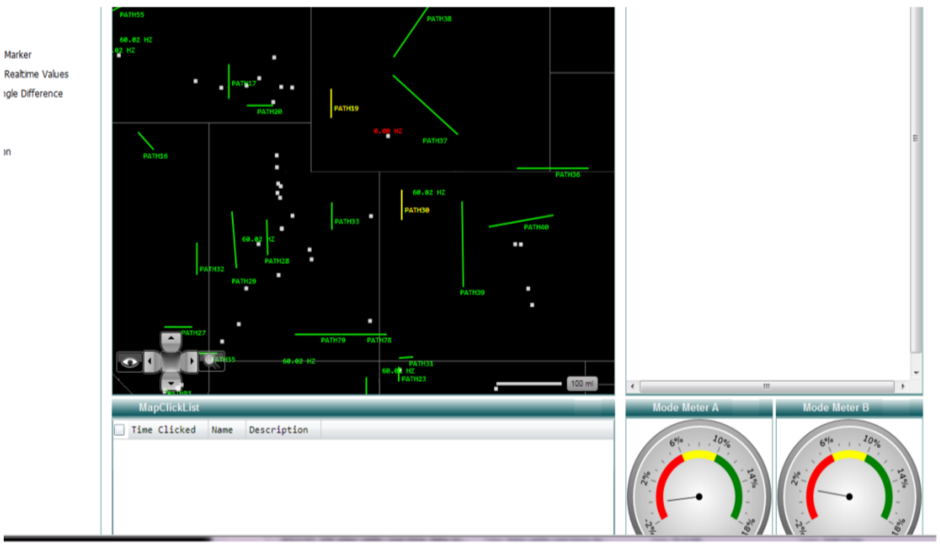
30



IEEE PES Power & Energy Society®

IEEE

31



IEEE PES Power & Energy Society

IEEE

32

COMTRADE

- Schema for Phasor Data Using the COMTRADE File Standard will be used to share all historical synchrophasor data
  - Post event analysis
  - Model Validation
  - IEEE C37.111-1999 (-2011 approved)

http://Schema_for_Phasor_Data_Using_the_COMTRADE_File_Standard.pdf

IEEE PES Power & Energy Society

IEEE

What have we accomplished

- State of the art WAN
  - Secure
  - Encrypted
  - High Availability
  - Low Latency
  - 19 separate contracts with WAN vendor
- Synchrophasor Data Archive
  - 60 Hz time aligned phasor measurements
  - Quad redundant storage 400+ TB
- Adopted Signal Naming Convention
- 19 separate participants working together toward a common goal
  - Data sharing agreement
- New synchrophasor applications RFI-RFP-Contracts-Purchase-Install-SAT-UAT
  - Visualization, Analysis, and Archive. ***All Integrated***

What value will synchrophasor measurements bring to the organization

- Common shared view of the BES
  - High frequency synchronized measurements
  - More effective group communication during events
- High speed field communications now available out to substation
- Single data archive
  - Post event analysis
  - Model validation
  - Planning

35

What are the largest obstacles to full operational implementation of synchrophasor technology

- User community acceptance
- Application performance and reliability
- Engineering Tools
- Data sharing road blocks
- Measurement accuracy
- C37.118 and 61850-95
  - Need true Publish / Subscribe architecture

IEEE PES Power & Energy Society

IEEE

36

BRIDGE ENERGY GROUP

Thank You

Dan Brancaccio
Principal Consultant
DBrancaccio@BridgeEnergyGroup.com
Toll Free: 1.888.351.8999
Main: 1.508.281.7133
info@BridgeEnergyGroup.com
www.BridgeEnergyGroup.com

IEEE PES Power & Energy Society

IEEE

Development of RT Synchrophasor Applications in the Lab.

SW Tools, Real-Time Hardware-in-the-Loop Testing and Validation Methods in Laboratories

Dr.-Ing. Luigi Vanfretti

E-mail: luigiv@kth.se

Web: http://www.vanfretti.com

ROYAL INSTITUTE OF TECHNOLOGY

SmarTS Lab
Smart Transmission Systems Laboratory

Associate Professor, Docent
Electric Power Systems Department
KTH Royal Institute of Technology
Stockholm, Sweden

Statnett

Special Advisor in Strategy and Public Affairs
R&D Division (FoU)
Statnett SF
Oslo, Norway

Tutorial:
Synchrophasor Fundamentals and Applications: Leveraging the Investment
Date: Tuesday July 23, 8:00 am-5:00 pm
Vancouver, BC, Canada

IEEE PES Power & Energy Society

IEEE

Acknowledgement

- The work presented here is a result of the collaboration between KTH SmarTS Lab (Sweden), Statnett SF (Norway), and the IREC research center (Spain).
- This work has been financed by:
  - The STandUP *for* Energy Collaboration, funded by the Swedish Energy Agency.
  - Statnett SF, the Norwegian transmission system operator, through its Smart Operation R&D program.
  - The European Institute of Technologies, EIT, through the Key Innovation Collocation Center InnoEnergy project "Smart Power"
  - The Nordic Energy Research through the STRONgrid project.
- The following people have contributed to this work:

Statnett

IREC Institut de Recerca en Energia de Catalunya
Catalonia Institute for Energy Research

  - KTH SmarTS Lab: Maxime Baudette, Dr. Iyad Al-Khatib, M. Shoaib Almas
  - Statnett SF: Vemund H. Aarstrand, Stig Løvlund, Jan O. Gjerde
  - IREC: Ignasi Cairó, Jose Luís Dominguez, Gerard del Rosario, Alberto Ruiz
- Austin White of OG&E is gratefully acknowledged for providing PMU measurements from the Oklahoma power network which was used to develop our off-line tools.

IEEE PES Power & Energy Society

IEEE

Outline

SmarTS Lab
Smart Transmission Systems Laboratory

- Motivation - system dynamics
- RT-HIL Laboratory:
  - SmarTS Lab: A real-time hardware-in-the-loop laboratory for developing PMU applications
- SW Development Kit for PMU App Development:
  - Statnett's PMU Recorder Light (PRL): Real-Time Synchrophasor Data Mediation for developing real-time applications:
- Developing a Fast RT Oscillation Detection Application
- Testing and validation methods

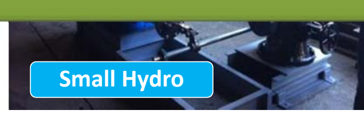
IEEE PES Power & Energy Society® IEEE

Intermitted generation – brings renewable energy capacity

New production of electricity:
ncertain
ertain
ocated
ong-
n
rces
tage
ger)
otential
nts at
remote locations.

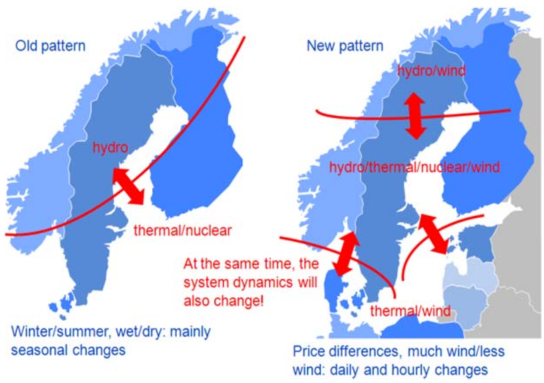
While new energy capacity is coming in, new challenges are also emerging for *security of supply*:

- 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).

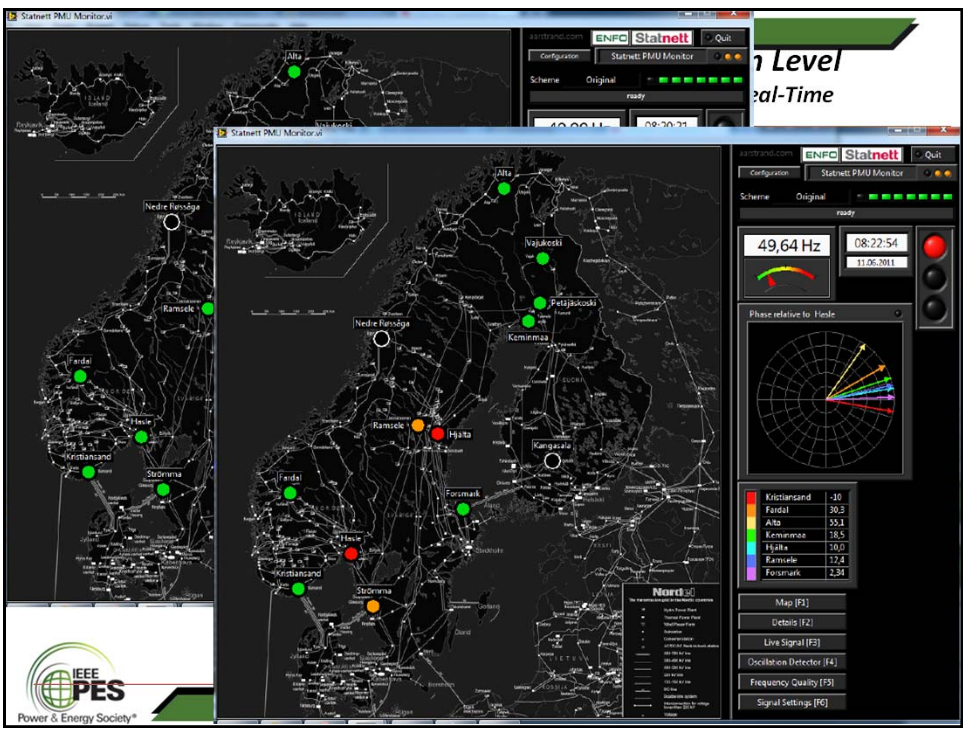


IEEE PES Power & Energy Society® IEEE

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



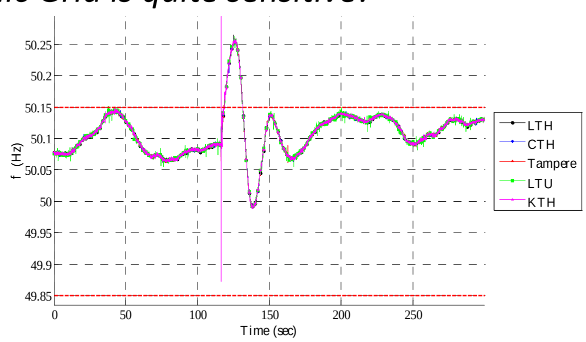
Totalstopp för SL

Outage affecting the whole railway system in Stockholm

- An 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

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!



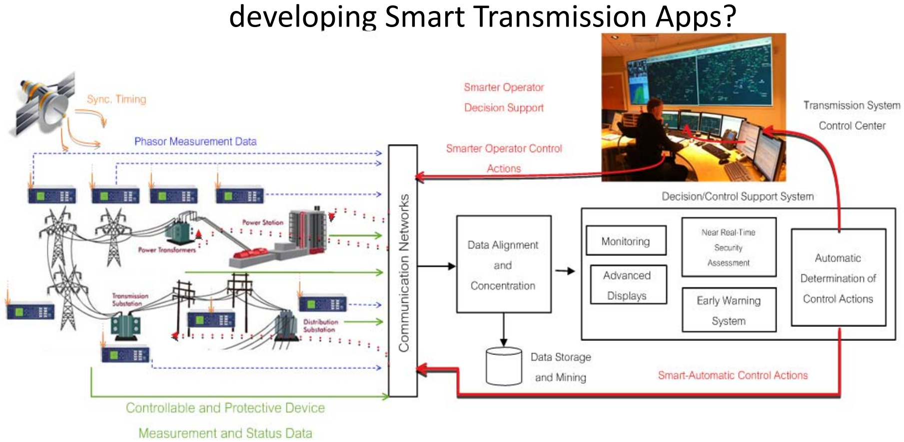
- The total generated capacity for the Nordic grid is roughly 50 GW.
  - The lost load during the fault was 300 MW. This is less than 1% of the generation capacity in the grid.
- **Such a small fraction of disconnected load should not have such far reaching impact in the entire grid.**
- With a larger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

SmarTS Lab

High-speed power system monitoring for the age of renewables

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

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



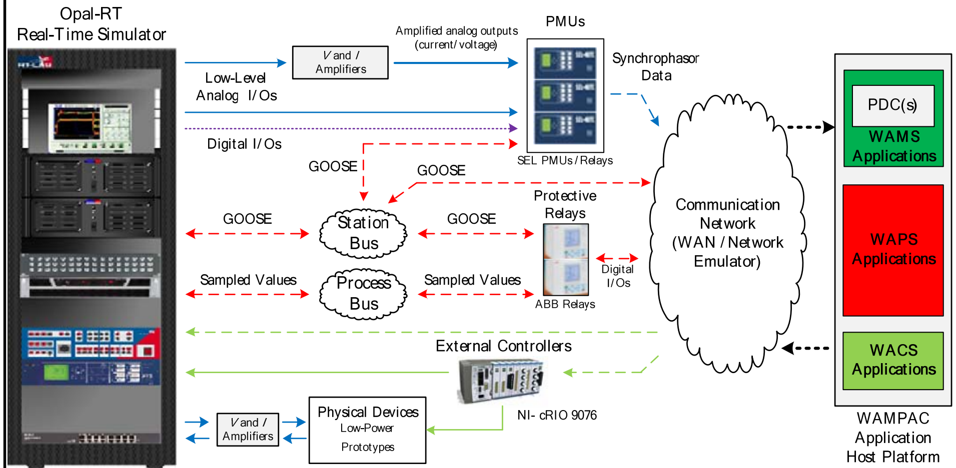
- Smart Grid require **Smart Operation, Smart Control and Smart Protection**:
  - The ultimate goal should be to attain an automatic-feedback self-healing control system
- Measure – Communicate – Analyze (System Assessment and *real* limits) – Determine Preventive/Corrective Actions – Communicate – Control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

Power & Energy Society®

SmarTS Lab

Smart Transmission Systems Laboratory

The SmarTS Lab Architecture

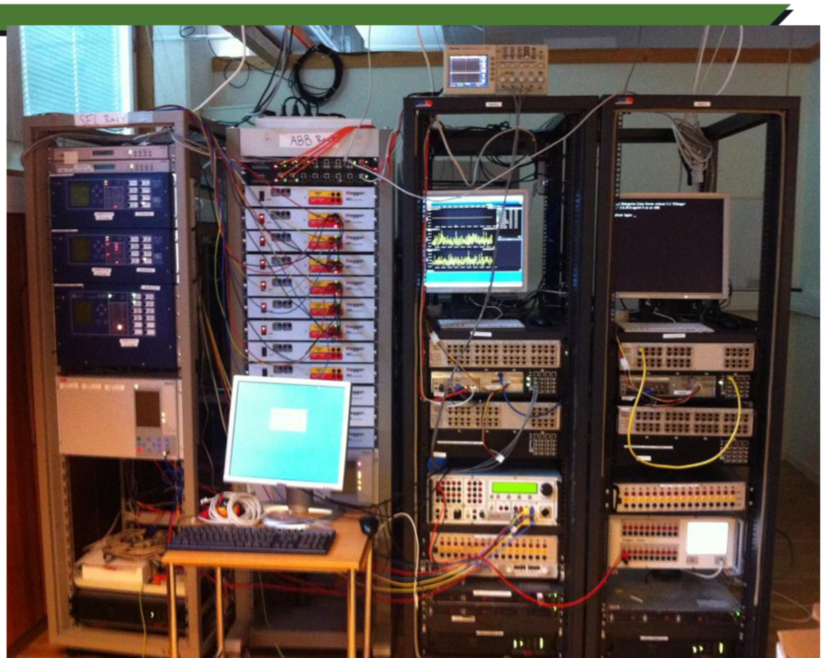


IEEE PES Power & Energy Society

IEEE

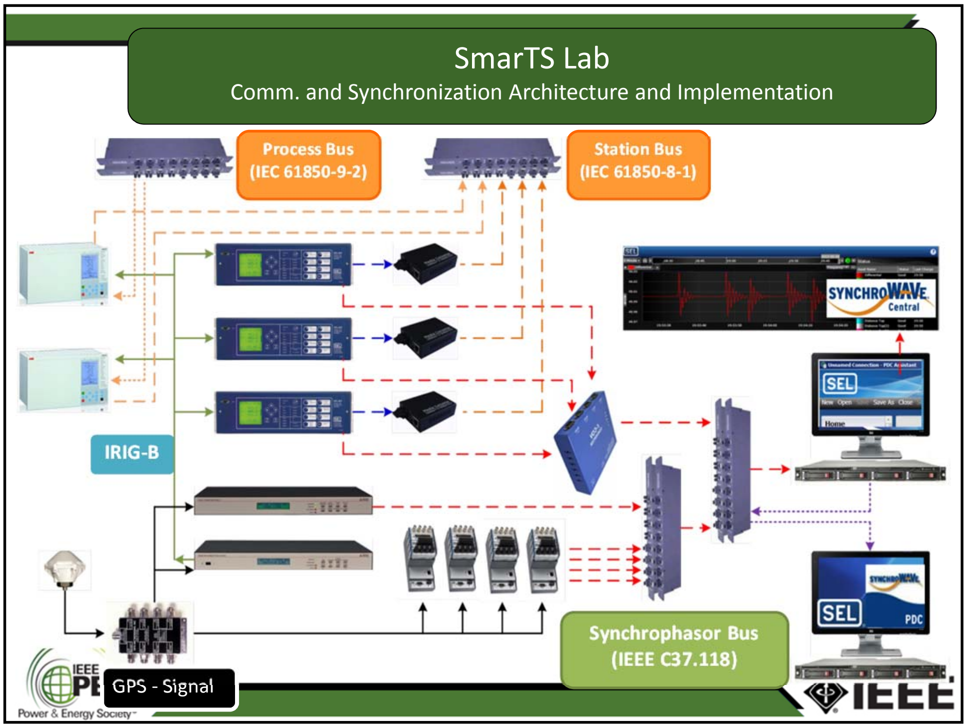
SmarTS Lab

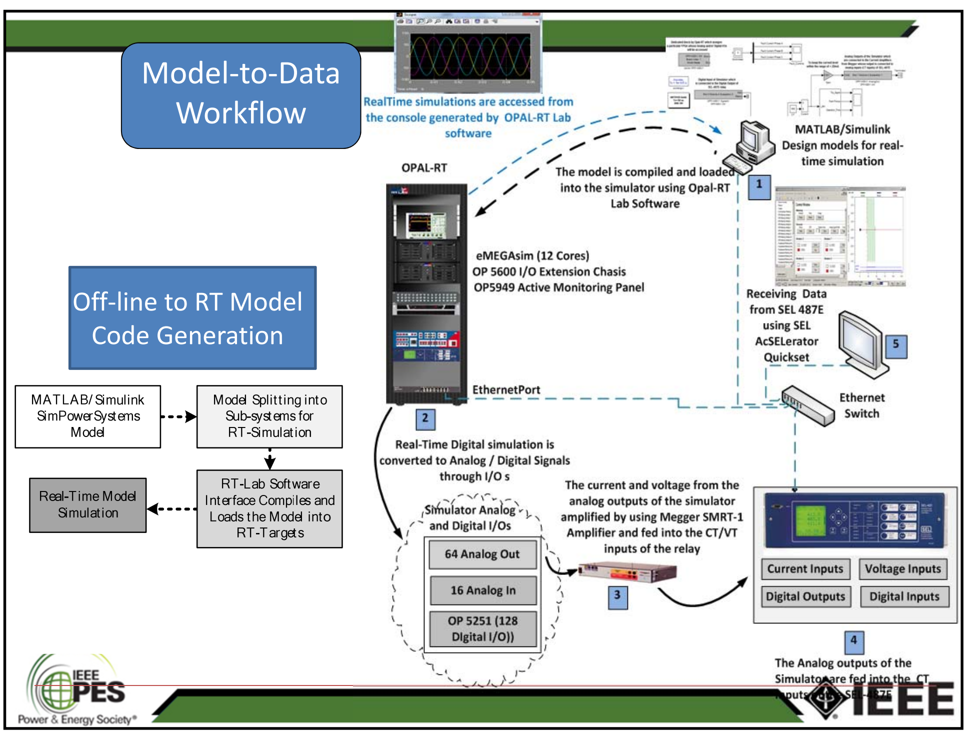
Hardware Implementation

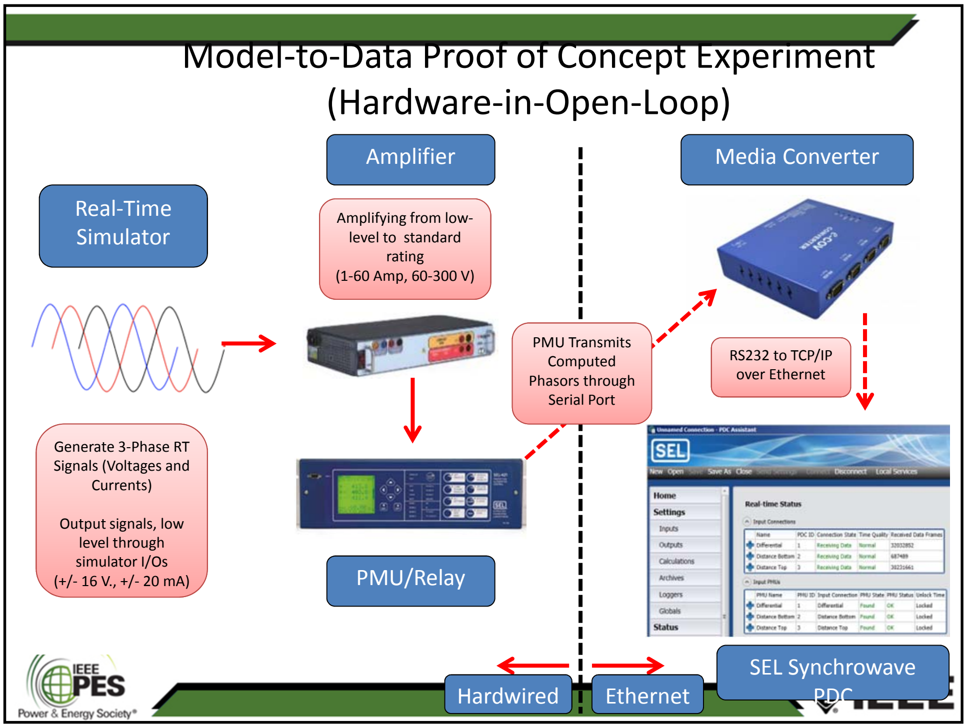


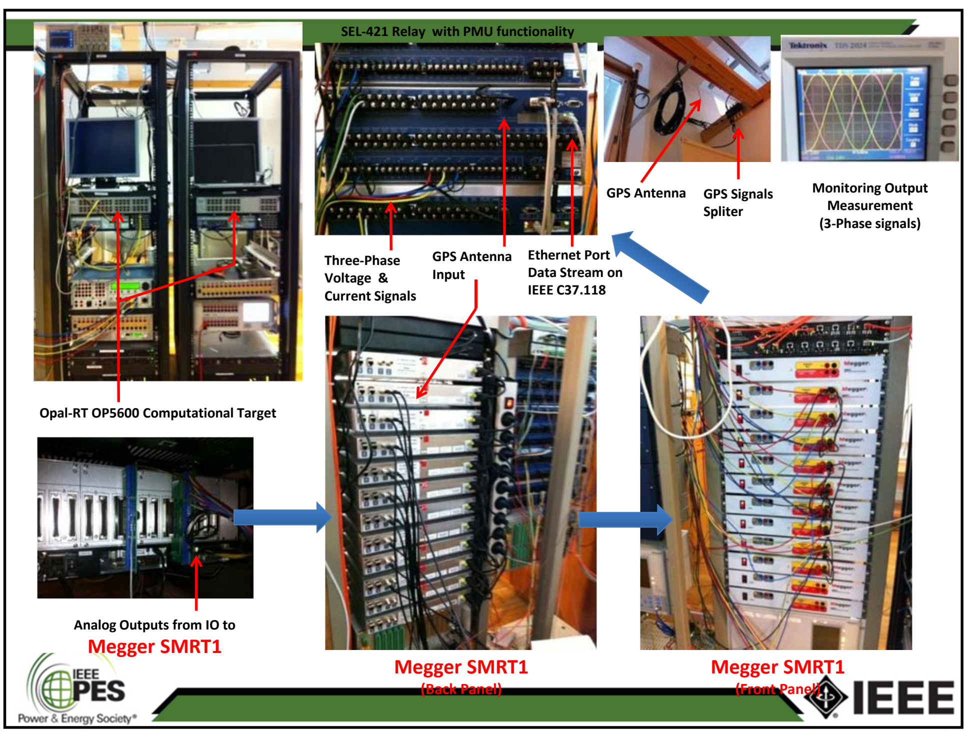
IEEE PES Power & Energy Society

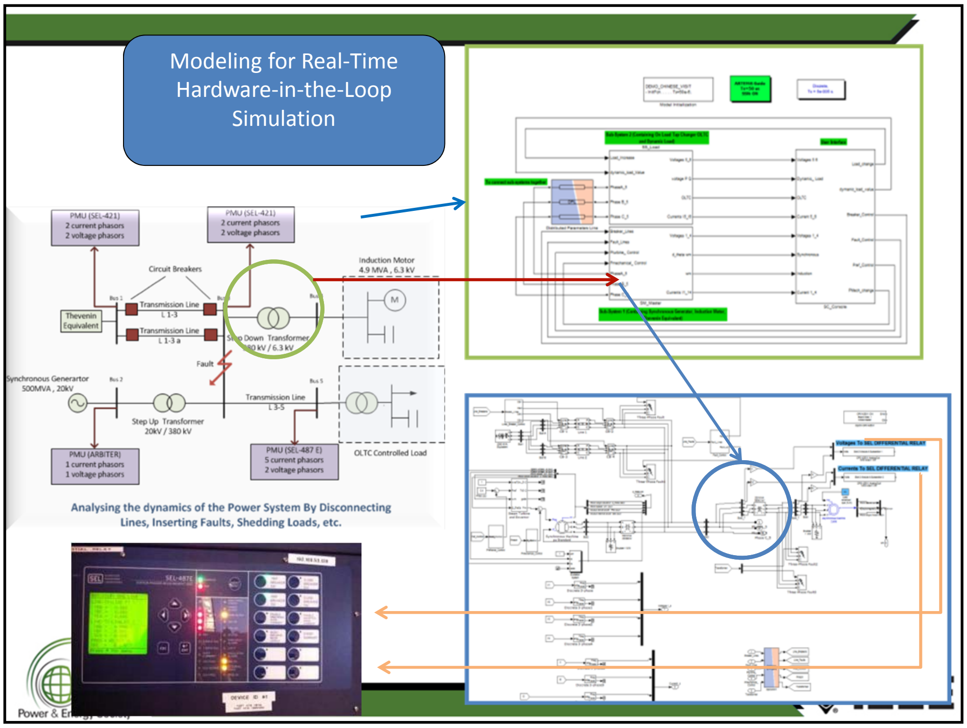
IEEE

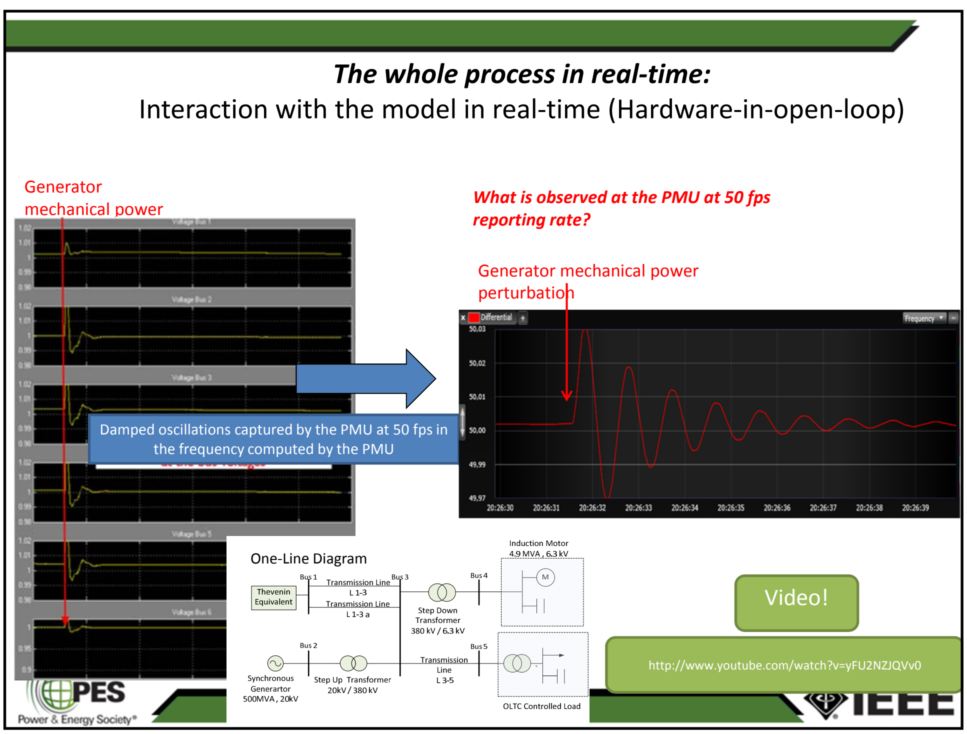

SmarTS Lab
Comm. and Synchronization Architecture and Implementation
Process Bus
(IEC 61850-9-2)
Station Bus
(IEC 61850-8-1)
IRIG-B
Synchrophasor Bus
(IEEE C37.118)
GPS - Signal
SYNCHROWAVE
Central
SEL
PDC
IEEE PES
Power & Energy Society
IEEE


Model-to-Data
Workflow
RealTime simulations are accessed from
the console generated by OPAL-RT Lab
software
MATLAB/Simulink
Design models for real-
time simulation
OPAL-RT
The model is compiled and loaded
into the simulator using Opal-RT
Lab Software
1
eMEGAsim (12 Cores)
OP 5600 I/O Extension Chasis
OP5949 Active Monitoring Panel
Receiving Data
from SEL 487E
using SEL
AcSELerator
Quickset
5
Off-line to RT Model
Code Generation
MATLAB/Simulink
SimPowerSystems
Model
Model Splitting into
Sub-systems for
RT-Simulation
Real-Time Model
Simulation
RT-Lab Software
Interface Compiles and
Loads the Model into
RT-Targets
EthernetPort
Ethernet
Switch
2
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
IEEE PES
Power & Energy Society
IEEE


Model-to-Data Proof of Concept Experiment
(Hardware-in-Open-Loop)
Amplifier
Media Converter
Real-Time Simulator
Amplifying from low-level to standard rating
(1-60 Amp, 60-300 V)
PMU Transmits Computed Phasors through Serial Port
RS232 to TCP/IP over Ethernet
Generate 3-Phase RT Signals (Voltages and Currents)
Output signals, low level through simulator I/Os
(+/- 16 V., +/- 20 mA)
PMU/Relay
Hardwired
Ethernet
SEL Synchrowave PDC
IEEE PES Power & Energy Society
IEEE

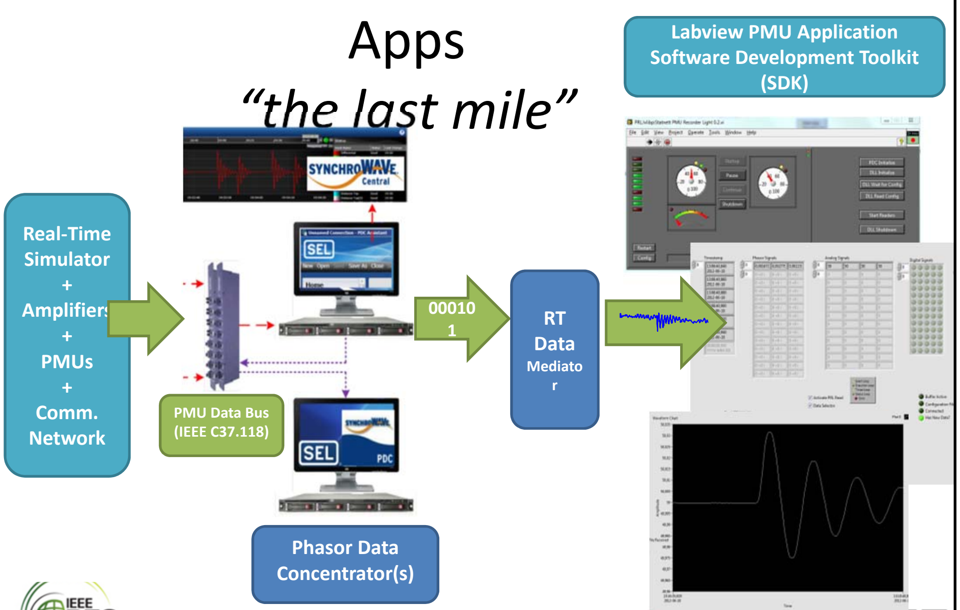

SEL-421 Relay with PMU functionality
GPS Antenna
GPS Signals Spliter
Monitoring Output Measurement
(3-Phase signals)
Three-Phase Voltage & Current Signals
GPS Antenna Input
Ethernet Port Data Stream on IEEE C37.118
Opal-RT OP5600 Computational Target
Analog Outputs from IO to
Megger SMRT1
Megger SMRT1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


Modeling for Real-Time Hardware-in-the-Loop Simulation
PMU (SEL-421) 2 current phasors 2 voltage phasors
PMU (SEL-421) 2 current phasors 2 voltage phasors
Circuit Breakers
Thevenin Equivalent
Transmission Line L 1-3
Transmission Line L 1-3 a
Induction Motor 4.9 MVA, 6.3 kV
Fault
Synchronous Generartor 500MVA, 20kV
Step Up Transformer 20kV / 380 kV
Transmission Line L 3-5
PMU (ARBITER) 1 current phasors 1 voltage phasors
PMU (SEL-487 E) 5 current phasors 2 voltage phasors
OLTC Controlled Load
Analysing the dynamics of the Power System By Disconnecting Lines, Inserting Faults, Shedding Loads, etc.
Power & Energy Society


The whole process in real-time:
Interaction with the model in real-time (Hardware-in-open-loop)
Generator mechanical power
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
One-Line Diagram
Thevenin Equivalent
Transmission Line L 1-3
Transmission Line L 1-3 a
Step Down Transformer 380 kV / 6.3 kV
Induction Motor 4.9 MVA, 6.3 kV
Synchronous Generartor 500MVA, 20kV
Step Up Transformer 20kV / 380 kV
Transmission Line L 3-5
OLTC Controlled Load
Video!
http://www.youtube.com/watch?v=yFU2NZJQVv0
PES
Power & Energy Society
IEEE

A LabView PMU Application
Software Development Toolkit (SDK)

Building Smart Apps
"the last mile"



PMU App. SDK

A LabView-Based PMU Application SDK

STRONgrid

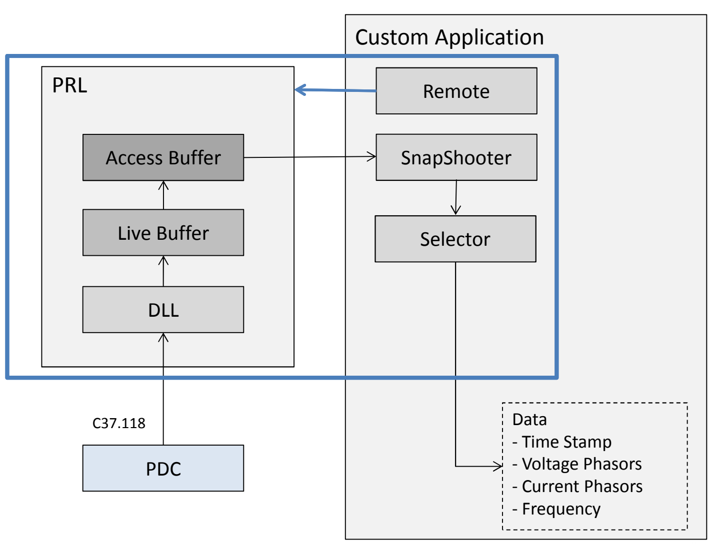
Smart Transmission Grids Operation and Control

KTH - NTNU - AALTO - DTU - UI

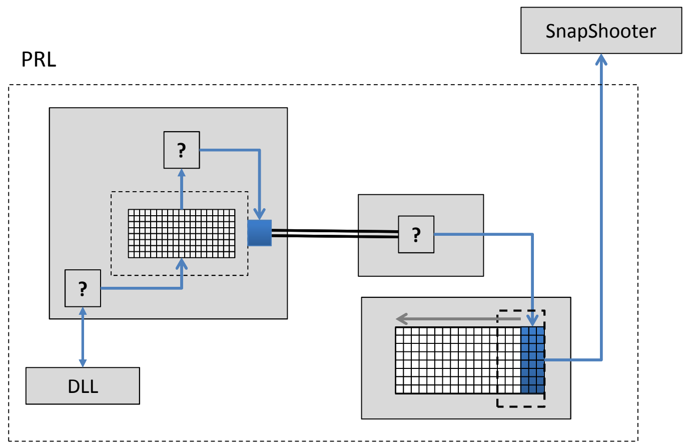
Statnett

- 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

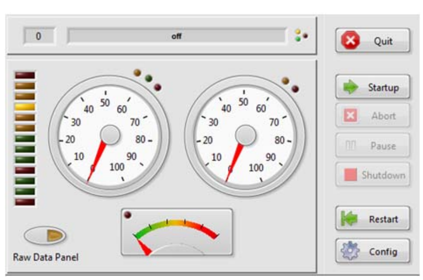
SDK Platform

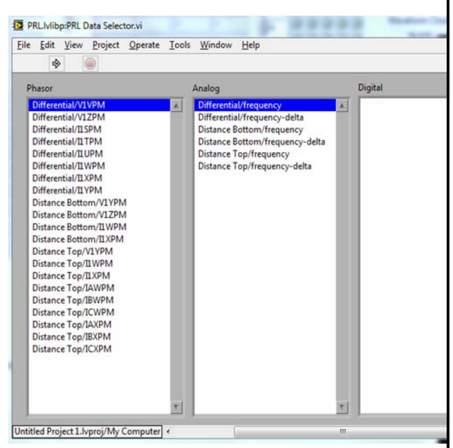


PMU Recorder Light (PRL)



Prototype Implementation (PMU App. SDK Beta)



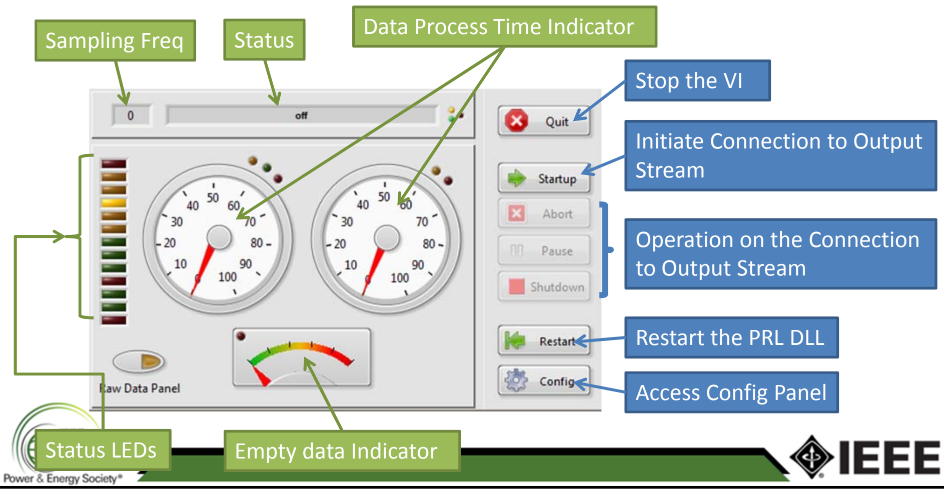


Connection with PDC
Configuration
PC Loading Monitor

Data Channel Selection

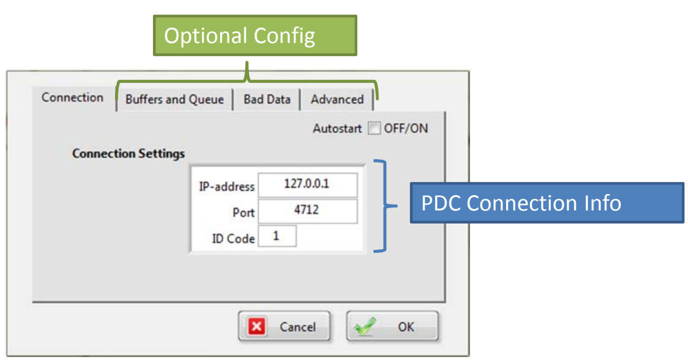
Main Window

- Accessible via LabView Project Explorer



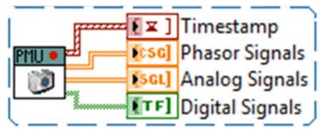
Configuration

- Connection settings of the Output Stream



Using in Labview VI's

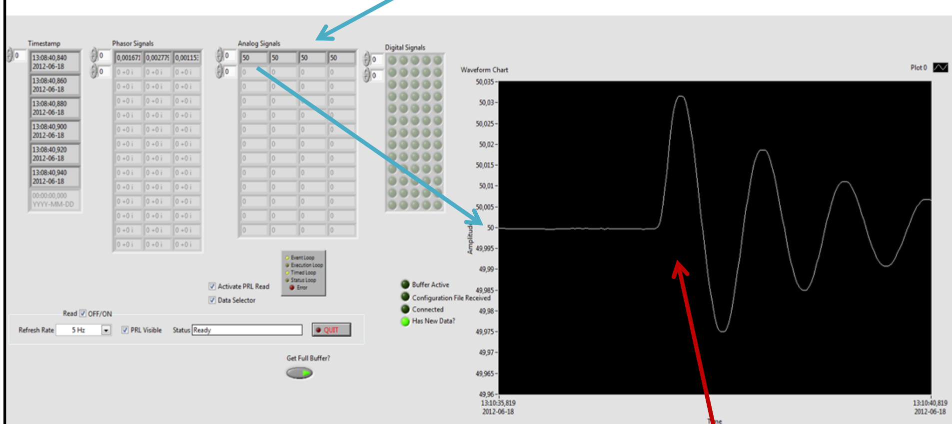
- Use PRL SubVI to get Measurements



- Make a new application!

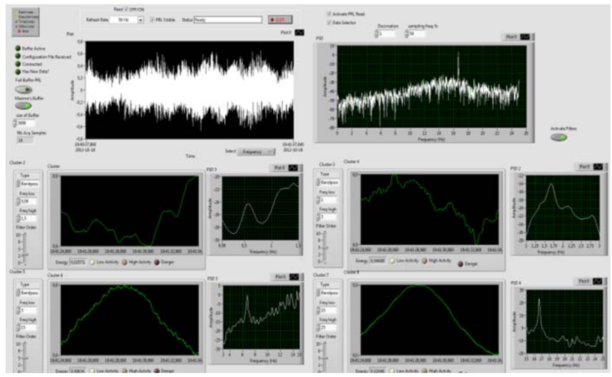
Power & Energy Society IEEE PES IEEE

Real-Time Data Access



Straightforward Development of Monitoring Application

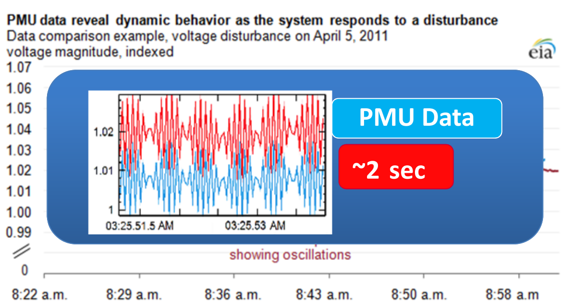
Power & Energy Society IEEE PES IEEE



FAST REAL TIME OSCILLATION DETECTION AND MONITORING TOOL

Use case: Wind-Farm Oscillations @ OG&E

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

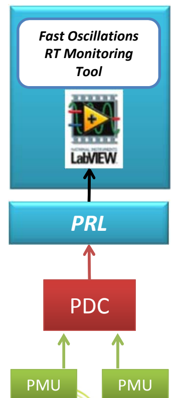


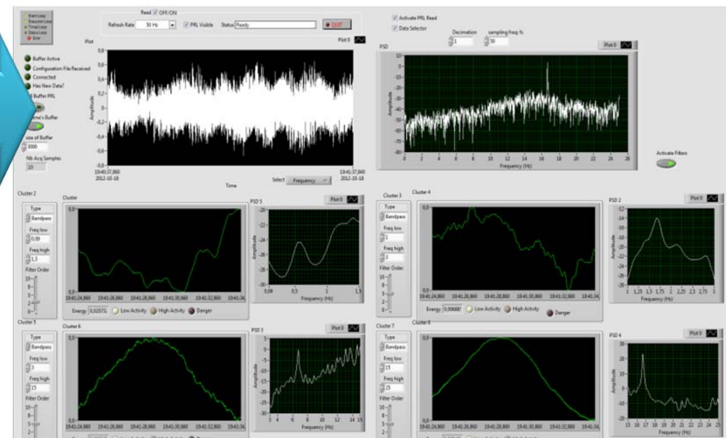
- In December 2010 @ OG&E
- ***Occurring during periods of high wind generation.***
- ***5% fluctuation at a frequency of 13-15 Hz.***
- ***The oscillations were product of interactions between controllers in two different wind farms.***
- ***Countermeasures:***
  - ***Switching to electrically isolate 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

Fast Real-Time Oscillation Detection and Monitoring Tool

- The PMUs stream data to the PDC. PDC concentrates and sends to PRL, after hand-shaking (config.), the application runs in real-time.



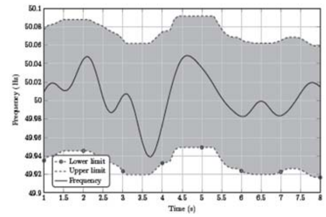


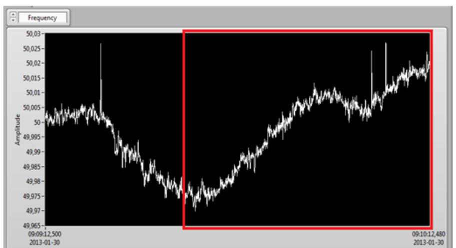
Fast Real-Time Oscillation Detection and Monitoring Tool

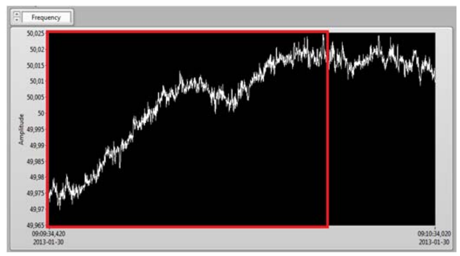
- Algorithms used: ***oscillation detectors*** and ***spectral estimators***.
- Oscillation Detector:
  - A tool used to detect oscillatory *activity.*
  - Provides fast generalized alarm of oscillation activity in real-time for **a given frequency range.**
  - Once initialized, it requires *only the 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)

Pre-processing on the fly

- Outlier removal for measurement errors.
- Interpolation for signals outside of a confidence interval (linear interpolation avoiding divergence)



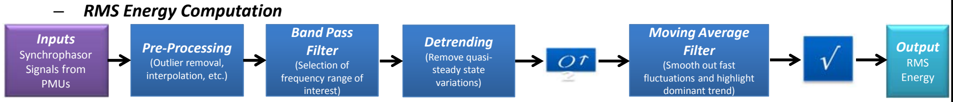




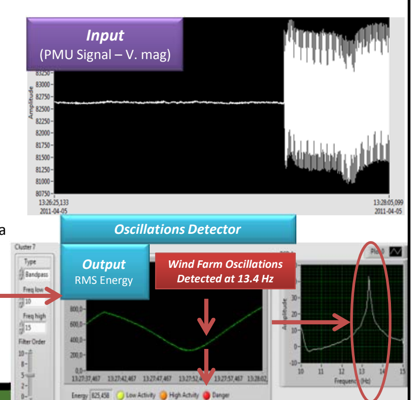
IEEE PES Power & Energy Society®
IEEE

Oscillation Detectors and Frequency Bands

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



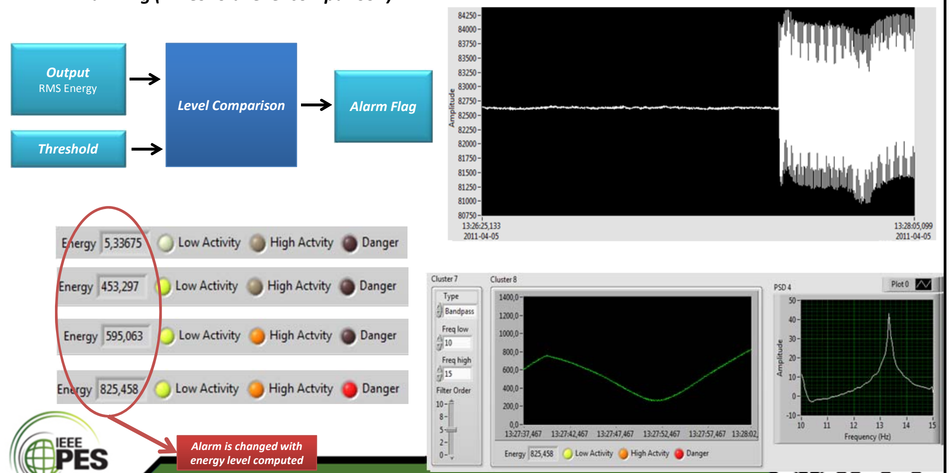
  - ***Frequency bands:***
  - Configurable frequency range for detecting oscillations for particular dynamic behaviour.
  - Recommended frequency bands:
    - FB1: 0.01 Hz to 0.15 Hz, 200 sec. response time. (Slow governor-load dynamics, i.e. balancing)
    - FB2: 0.15 Hz to 1.00 Hz, 12 sec. response 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)



IEEE PES Power & Energy Society®

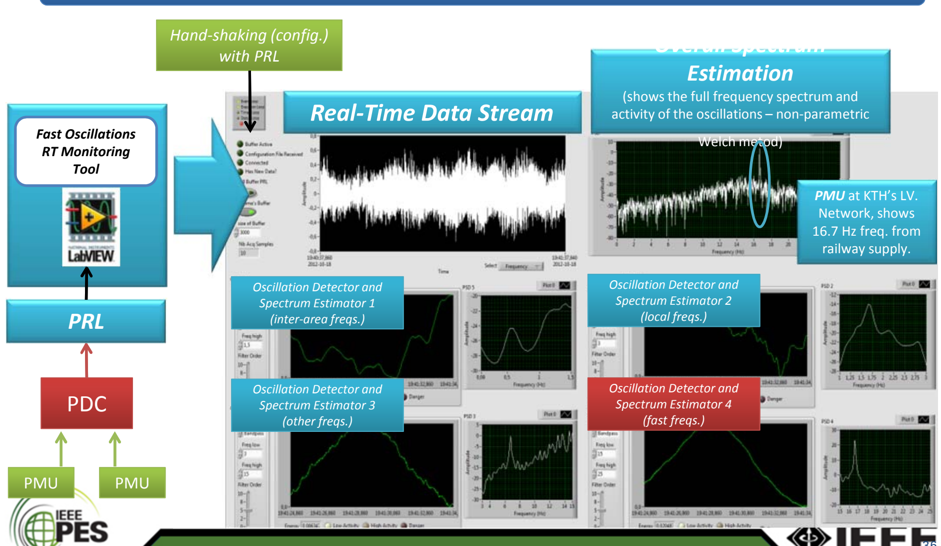
Oscillation Detector and Alarms

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



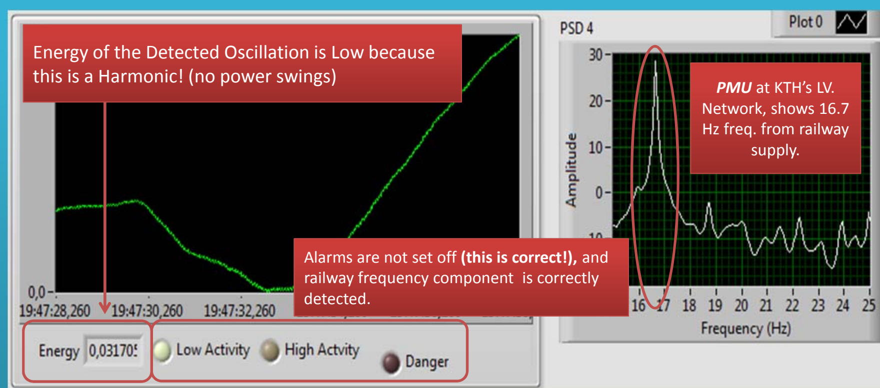
Fast Real-Time Oscillation Detection and Monitoring Tool

Illustration of where the algorithms are used



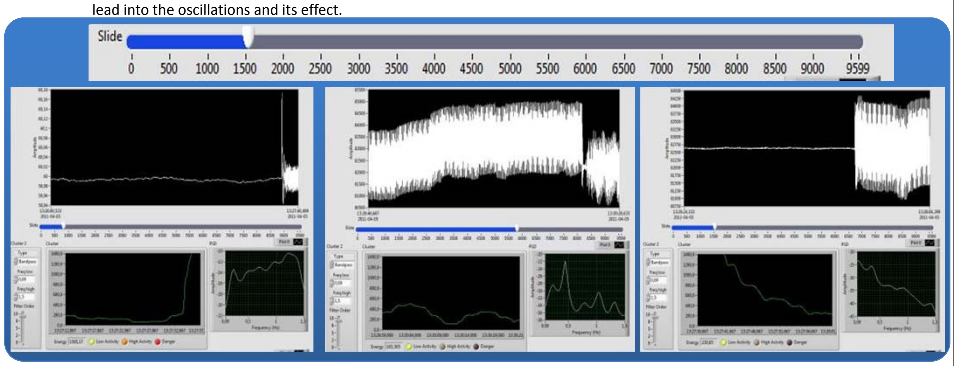
Fast Real-Time Oscillation Detection and Monitoring Tool

Real-Time Execution Example

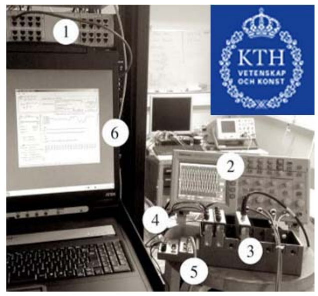


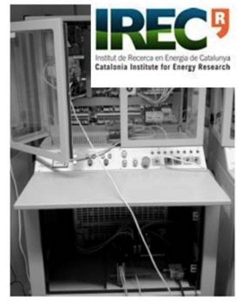
Off-line Oscillation Analysis Tool

- ***Off-line data replay:***
- Feeds into **the same algorithms** as used in the real-time application.
  - This is possible by recreating the "real-time" stream by parceling and buffering the archived data.
    - Consistent data analysis regardless of the runtine: "off-line" algorithms are the same as the "on-line algorithms".
  - Because the data comes from an archived data set, it is possible to **slide through** the archived file to ***analyze*** the process that lead into the oscillations and its effect.



- **Shared code development for both applications:**
  - Having the same underlying code regardless if the data stream comes from real-time PMUs or archived file makes the development of the two different applications heterogeneous.





TESTING AND VALIDATION OF PMU APPS

IEEE PES Power & Energy Society

IEEE

Testing and Validation

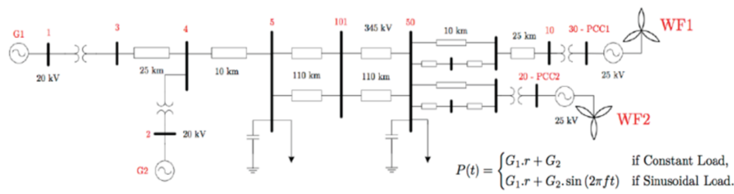
- ***Testing: using the RT HIL Approach***
  - Real-time simulation model
  - Chain of real-time data acquisition
  - Experiment design
  - Analysis of results and tuning of the application
- ***Validation: at a Microgrid Lab connected to the Distribution Grid***
  - Converter set-up for signal injection
  - Chain of real-time data acquisition (replica)
  - Experiment
  - Equipment limitations

IEEE PES Power & Energy Society

IEEE

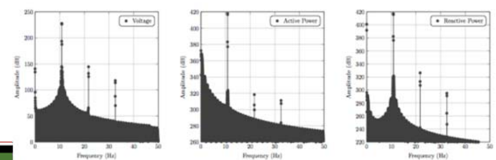
Real-Time Simulation Model

- Sensitivity study (not shown here) determined the main cause of the oscillations due to controller interactions (Grid side converter).
- Power System Model – Modified Klein-Rogers-Kundur system:
  - Loads vary with a Gaussian white noise input plus a configurable load portion



$$P(t) = \begin{cases} G_1.r + G_2 & \text{if Constant Load,} \\ G_1.r + G_2.\sin(2\pi f t) & \text{if Sinusoidal Load.} \end{cases}$$

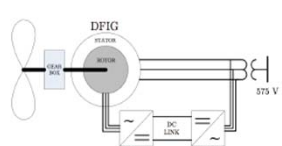
- Simulation spectrum – very similar to an actual power grid:

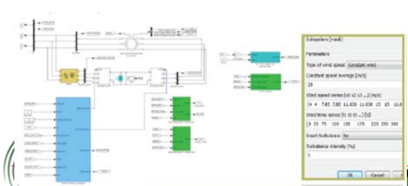


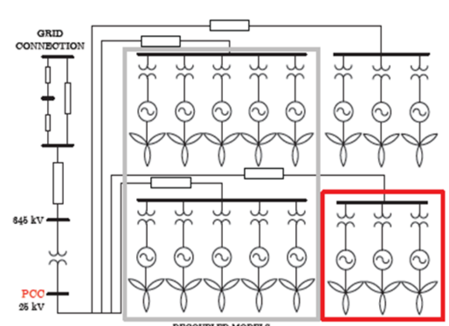
(a) Voltage (b) Active Power (c) Reactive Power

Wind Farm Models

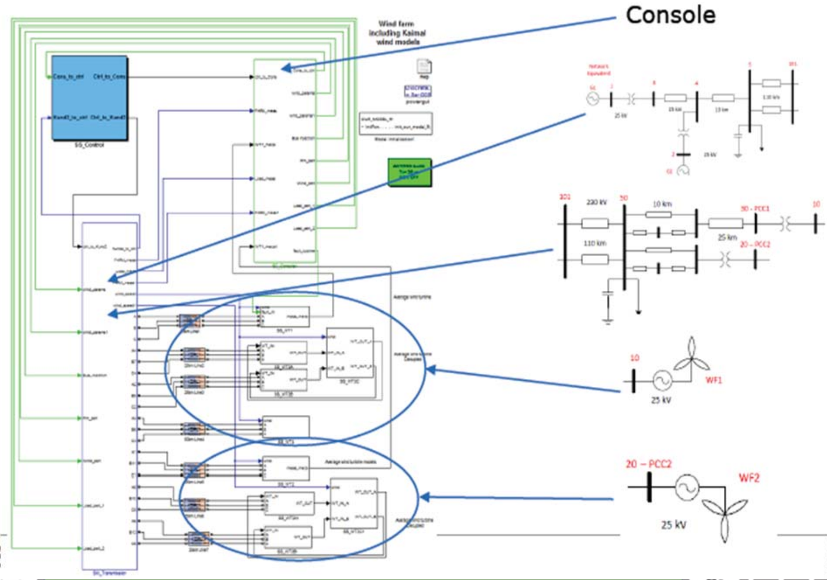
- Type 3 – DFIG turbines using average VSCs and representing 4 to 6 turbines each.
- Controls: Grid side, rotor side and pitch control.
- Farm 1: 16 Turbines, Farm 2: 13 Turbines





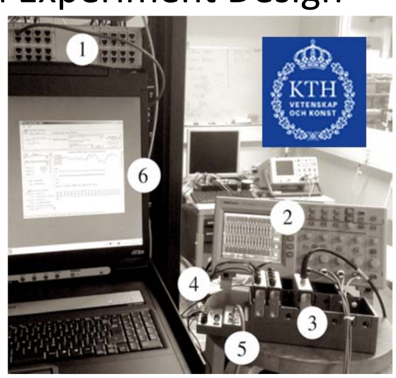


Real Time Simulation Model



Experiment:
RT Data Acquisition and Experiment Design

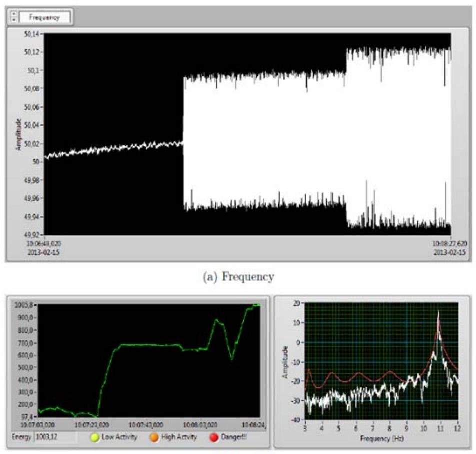
1. RT Simulator running the RT Model
2. Oscilloscope connected to analog outputs
3. National Instruments cRIO-based PMU
4. Voltage measurement module(s) connected to the analog output
5. Connection to network for comm with PDC
6. PDC server with output stream configured



Experiment Design:

Start	Oscillation Injection	Additional Perturbations	Major Fault	End
Random load variation	Set perturbation at 10.83 Hz	Generating minor faults	Three phase Fault and line opening	End of the oscillation injection

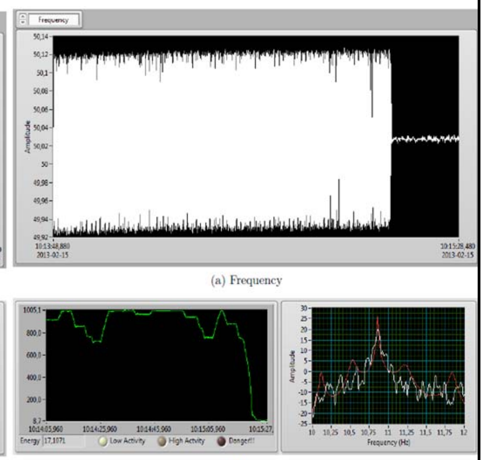
Testing Results



(a) Frequency

(b) Module

Figure 6.3: Screen shots of the *Monitoring Tool* during the increase of oscillation injection at 10.83 Hz



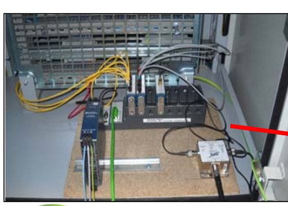
(a) Frequency

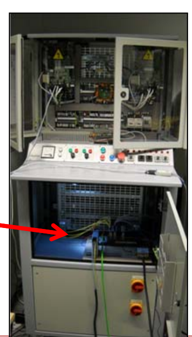
(b) Module

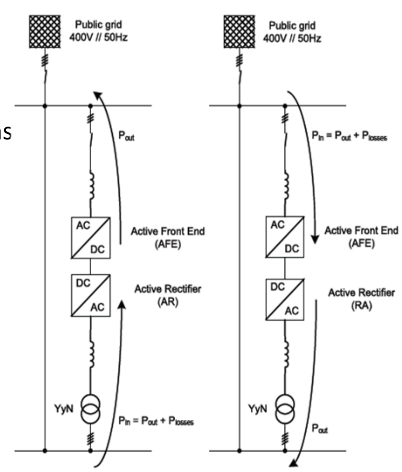
Figure 6.6: Screen shots of the *Monitoring Tool* at the end of the oscillation injection at 10.83 Hz

Validation Set-Up and Tests

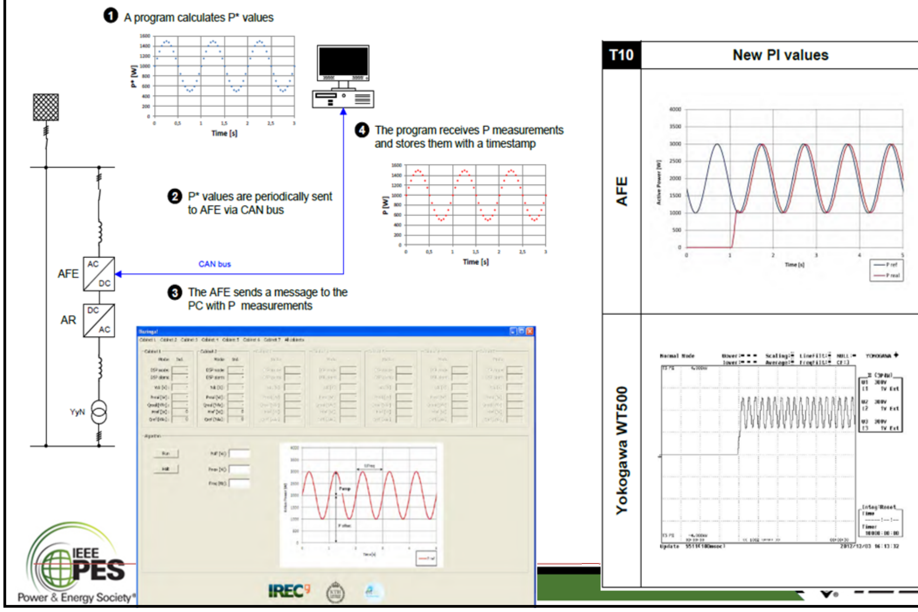
- Validation experiments were carried out on a grid emulator (Microgrid Lab.)
- Converters generate real power injections controlled by inverters



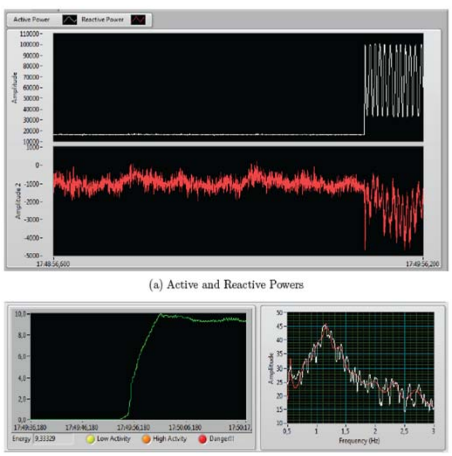




Validation Signal Generation and Injection



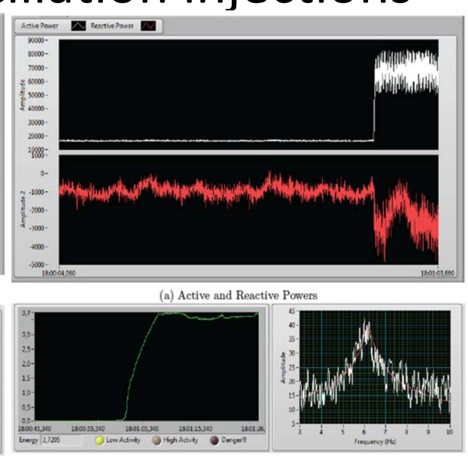
Validation Results
1Hz and 6 Hz oscillation injections



(a) Active and Reactive Powers

(b) Module

Figure 6.10: Screen shots of the *Monitoring Tool* at the beginning of the oscillations injection at 1 Hz



(a) Active and Reactive Powers

(b) Module

Figure 6.11: Screen shots of the *Monitoring Tool* at the beginning of the oscillations injection at 6 Hz

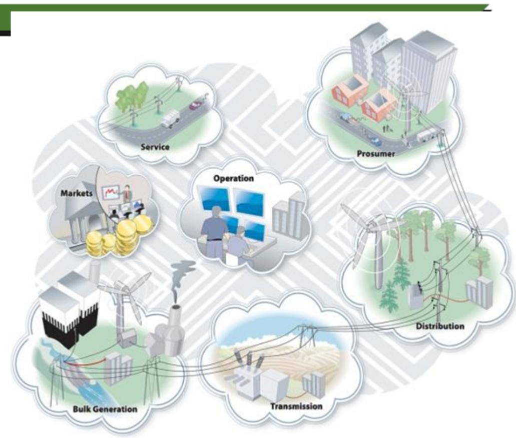
Lessons Learnt

- Working in a RT HIL Lab and designing new applications:
  - It's a lot of fun… but also a lot of hard work.
  - Not necessarily will lead to journal papers… but you will learn more than you imagine (or be willing too…)
- It takes the work to a different level: stuff has to work!
  - The most important side-product: more experts!

- References:
  - On SmarTS Lab:
    - L. Vanfretti, et al, "SmarTS Lab: A laboratory for developing applications for WAMPAC systems," IEEE PES General Meeting 2012, San Diego, CA, USA.
  - On the PRL:
    - L. Vanfretti, V. H. Aarstrand, M. Shoaib Almas, V. Peric and J. O. Gjerde, "A software development toolkit for real-time synchrophasor applications," IEEE PowerTech 2013, Grenoble, France.
  - On the Fast RT Tool:
    - M. Baudette, "Fast Real-Time Detection of Sub-Synchronous Oscillations in Power Systems using Synchrophasors". MSc Thesis, KTH Royal Institute of Technology, Feb. 2013.
  - On the Testing and Validation Methods:
    - M. Baudette, "Fast Real-Time Detection of Sub-Synchronous Oscillations in Power Systems using Synchrophasors". MSc Thesis, KTH Royal Institute of Technology, Feb. 2013.
    - L. Vanfretti (Editor), Chapter 5 and 6 in "Real-Time Synchrophasor Software Tools for Developing Software Applications Detecting Wind-Farm Induced Sub-Synchronous Oscillations". Technical report 2012 – 2013. KIC InnoEnergy Smart Power Action 2.6 PMU-Based Operation Tools.

Thank you!

Questions?



Real-Time Simulation:
Fundamentals and Applications

What is a real-time simulation?

- The term "real-time" is used by several industries to describe ***time-critical technology.***
  - *Ambiguity:*
    - For some sectors of the power industry real-time can range from seconds to 5-10 minutes, while for others is in the range of milliseconds and lower.
    - This is connected to the "physical process" which is being dealt with, e.g. real-time markets (~10 min), real-time balancing (~5 min.), real-time control (5-20 ms), and protection (~10-50 micro sec.).
- The most proper usage of "real-time", *and the one we will use*, is in the reference of **embedded systems**.
- **Embedded systems** are (intelligent) electronic devices which interface with the real world to provide control, interaction and convenience.
  - Controllers, protective relays, etc.
- So, when talking about "real-time" we will be talking of process taking place in fractions of a second (10-50 micro sec.)

Real-Time *Digital* Simulation of Power Systems (origins)

Hydro-Quebec's Network Simulation Center

-Focus:

Real-time electric power system networks simulation.

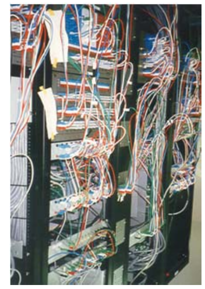
Needed to test controllers for an unstable network

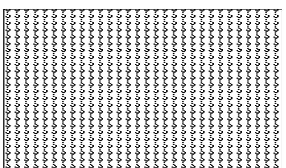
-Technical Challenges:

High bandwidth

Complex model requiring massively-parallel hybrid computing

- Large I/O count



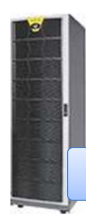


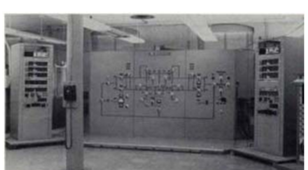
Power & Energy Society

IEEE

Power System Simulation - Evolution

* COTS: Commercial-Off-The-Shelf





FPGA-based Simulators

COTS Simulation-On-Chip

Digital COTS* Simulators

Digital Custom Simulators

Digital Supercomputer Simulators

Hybrid (Analog/Digital) Simulators

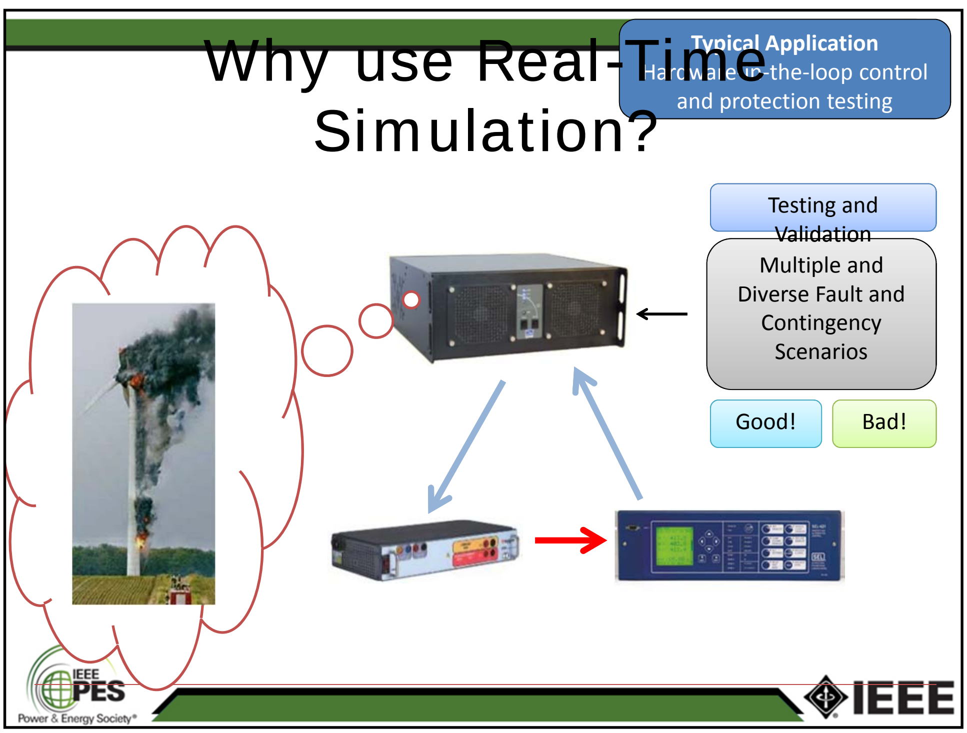
Analog Simulators

1960 1970 1980 1990 2000 Year

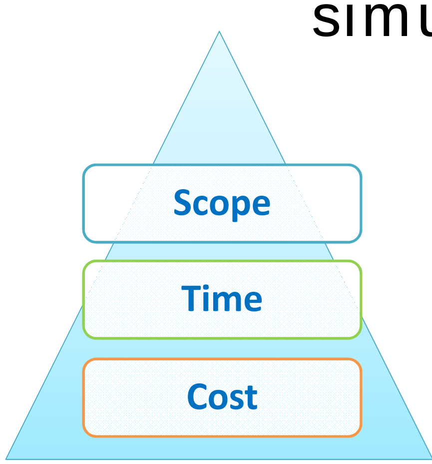
IEEE PES Power & Energy Society

IEEE


Real-Time System Configurations and Applications
Rapid control/protection prototyping
Hardware-in-the-loop
Pure Simulation
controller
I/O
Plant
controller
I/O
Plant
controller
I/O
Plant
IEEE PES Power & Energy Society
IEEE


Why use Real-Time Simulation?
Typical Application
Hardware-in-the-loop control and protection testing
Testing and Validation
Multiple and Diverse Fault and Contingency Scenarios
Good!
Bad!
IEEE PES Power & Energy Society
IEEE

“*Values*” of real-time simulation



- Faking all possible system faults.
- Easily adapting the system for different protection tests

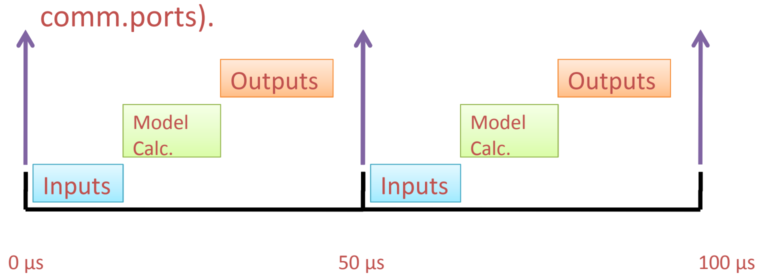
- More effective and efficient way to solve controller problems
- Validating protection settings with actual devices

- Less manipulations on the element under protection
- Less tests on the power system components/network.

What is a real-time simulation ?

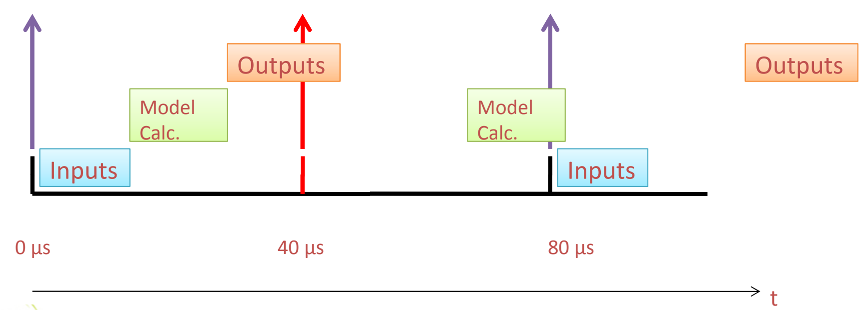
Definition : In a real-time system, we define the Time Step as a predetermined amount of time (ex: Ts = 10 µs, 1 ms, or 5 ms).

Inside this amount of time, the processor has to read input signals, such as sensors, to perform all necessary calculations, such as control algorithms, and to write all outputs, such as control signals (through analog, digital, or comm.ports).



What is a real-time simulation ?

Overruns : In a real-time system, when a predetermined time step is too short and could not have enough time to perform inputs, model calculation and outputs, there is an overrun.



What is a real-time simulation ?

Fixed-step solvers solve the model at regular time intervals from the beginning to the end of the simulation.

The size of the interval is known as the step size: ***Ts***.

Generally, decreasing ***Ts*** increases the accuracy of the results while increasing the time required to simulate the system.

Synchrophasor Applications

Austin D. White P.E.
Oklahoma Gas & Electric

2

Outline

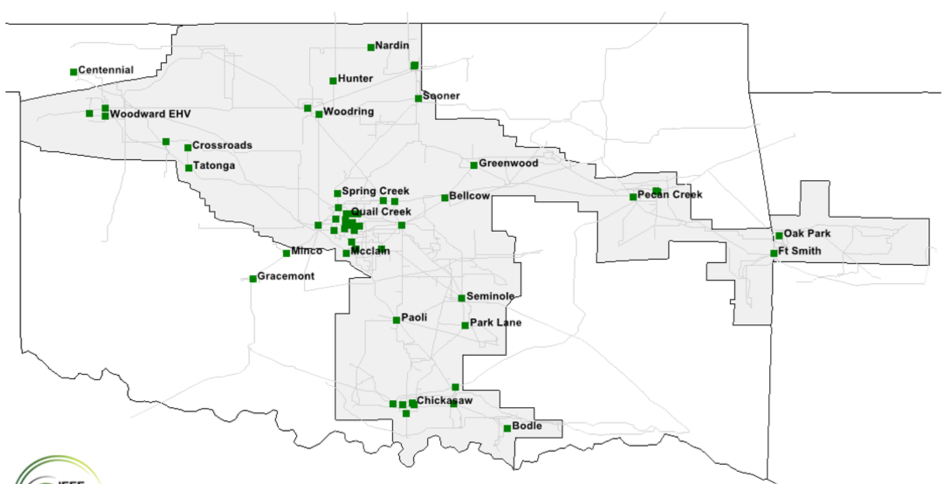
- Introduction
- Background of Architecture
  - Three iterations
- SynchroPhasor Applications
  - Five tools

2

Introduction

- Multifunction PMUs were already installed
- Project enabled by expanding IP communications to substations
- Purchased a data concentrator and started streaming data
- Began in 2008 with 8 PMUs

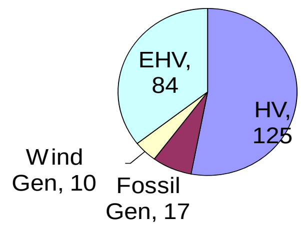
PMU Locations



5

PMU Coverage Stats

- 100% of EHV System
  - 63 Line Terminals, 21 Autotransformers
- 100% of Wind Farms
  - 1623MW, 10 Plants
- 90% of Fossil Generation
  - 6200MW, 17 Units
- 34% of HV System
  - 125 Line Terminals



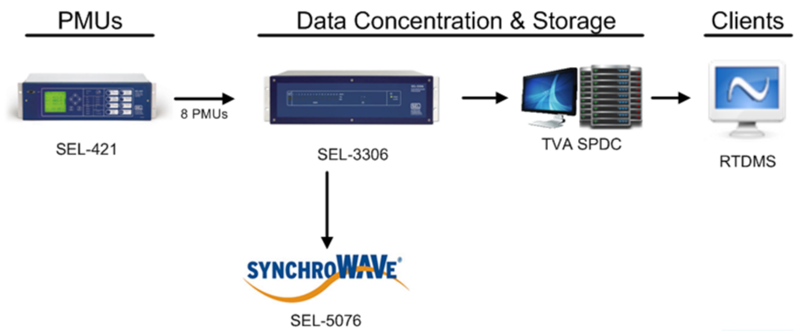
6

Development Methodology

1. Identification of a problem through observation
2. Develop a solution to the problem
3. Refine/improve the tools as needed to achieve the goal
4. Keep it simple and attack one problem at a time

7

First Iteration (2008)



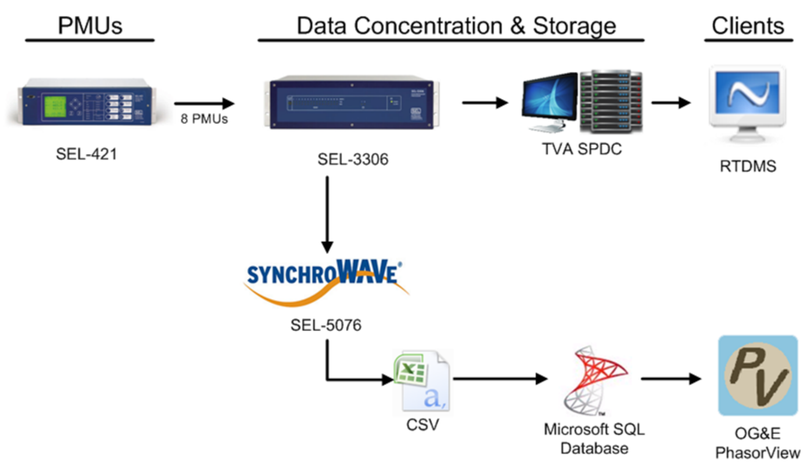
8

Problems Identified with Ver 1

- We needed a continuous archive
- Realtime and Historical Visualization
- Tie into existing disturbance databases

9

Second Iteration (2009)



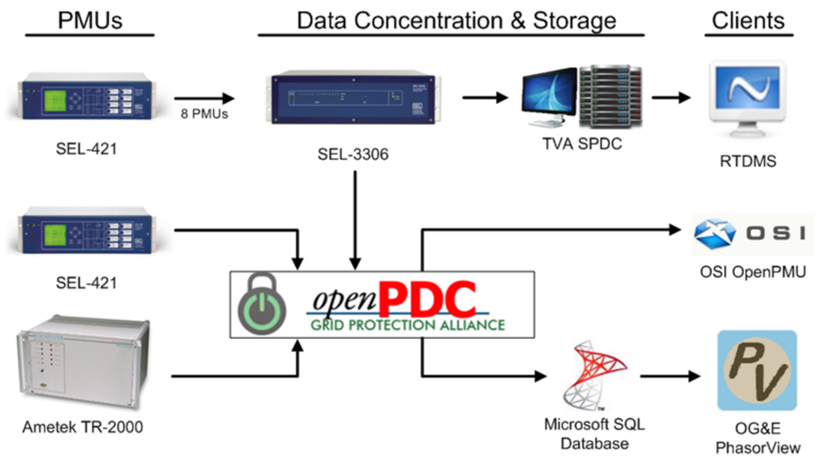
10

Problems Identified with Ver 2

- Scalability beyond 8 devices
  - Database limited to 8 PMUs
  - Hardware limitation of 40 devices
- A need for a GIS interface
- Need to correlate weather events and disturbances

11

Third Iteration (2010)



12

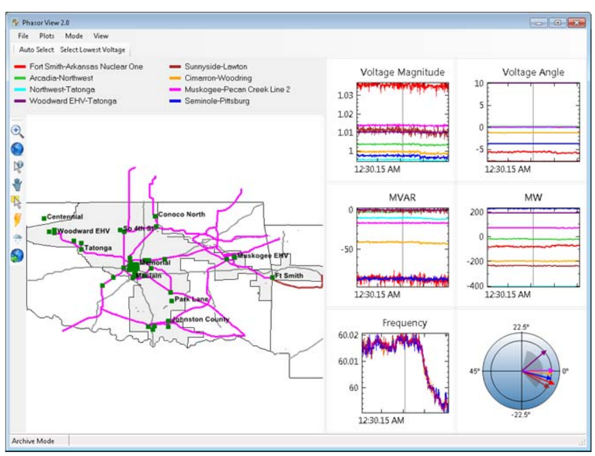
Application Tools

- After we had a good architecture, the observations led to new tools
- It took 3 iterations before we had a system that we could develop additional apps upon.
- With the matured architecture, we started building automated analysis tools to address observed problems.

Synchrophasor Applications

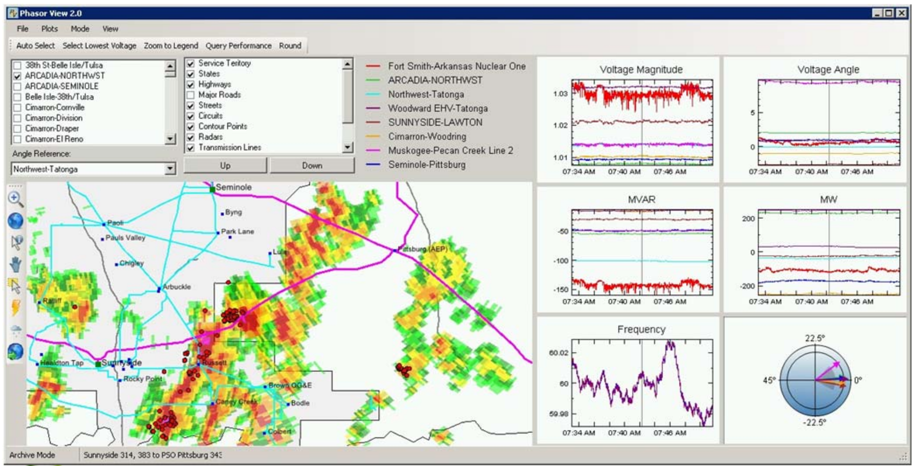
- PhasorView
  - Situational Awareness, Disturbance/Misoperation Analysis
- PMU Availability Report
  - Identify PMU and communications failures
- PT Problem Report
  - Proactively Find Equipment Problems
- Real Time FFT Monitor
  - Stability Assessment, oscillation monitoring, wind farm integration
- Tarigma Automated Fault Detection
  - Uses PMU data to log disturbances

Problem # 1 – Visualization



15

Situational Awareness



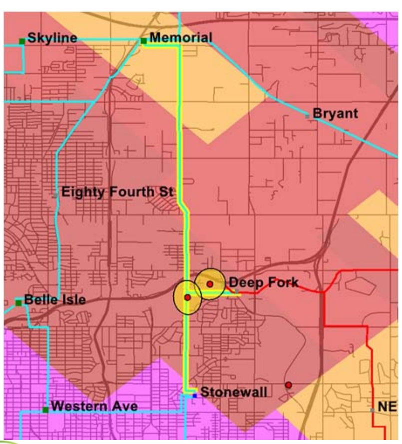
IEEE PES Power & Energy Society

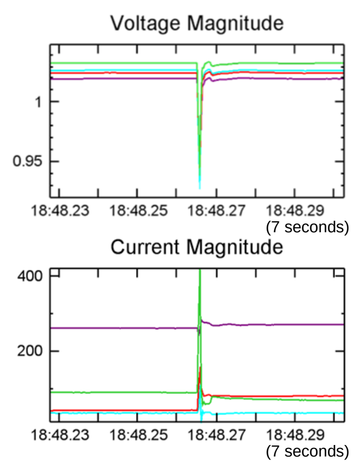
IEEE

15

16

Disturbance/Misoperation Analysis





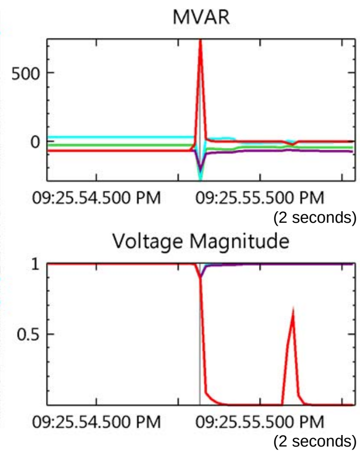
IEEE PES Power & Energy Society

IEEE

16

17

Fault Location Using VAR Flows



17

18

Problem #2 – Availability

- Need to assess the performance of the system
- Samples received divided by 2,592,000 equals availability
- Report identifies PMU and communications failures

PMU Availability Report - 2013/04/06

PhasorServer@oge.com

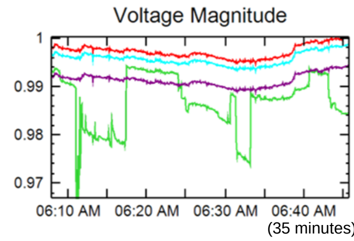
Sent: Sun 4/7/2013 7:08 AM

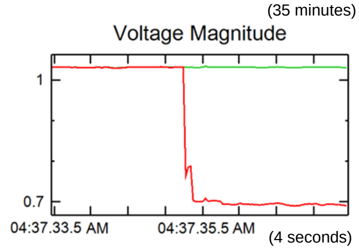
To:

00.0000% - Woodring-Cottonwood Creek
00.0000% - Woodring-Hunter
00.0000% - Woodring-South 4th St
00.1232% - Sooner-Woodring
73.3412% - Spring Creek-Sooner
92.8834% - Woodring-Sooner
97.2796% - Northwest-CWC/Ketch
98.3166% - Paoli-Pauls Valley
98.3397% - Paoli-Cedar Lane/Canadian
98.3429% - Paoli-Seminole
98.4709% - Horseshoe Lake Transformer 1 (138-69kV)
98.4709% - Horseshoe Lake-Jones Kamo
98.4709% - Horseshoe Lake-Lincoln County
98.4709% - Horseshoe Lake-Memorial
98.4709% - Horseshoe Lake-Unit 9,10
98.4941% - Horseshoe Lake-Forest Hill/Inglewood
98.4941% - Horseshoe Lake-Reno 1
98.4941% - Horseshoe Lake-Reno 2
98.4941% - Horseshoe Lake-SE 15th St
99.1739% - Arcadia-Northwest
99.2076% - Sunnyside Transformer 3

Problem #3 – Failing Equipment

- Discovered many loose connections in the potential circuits at fuses or terminal blocks
- This has caused misoperations in the past (relays get confused)
- Proactively finding these helps prevent future outages and misoperations



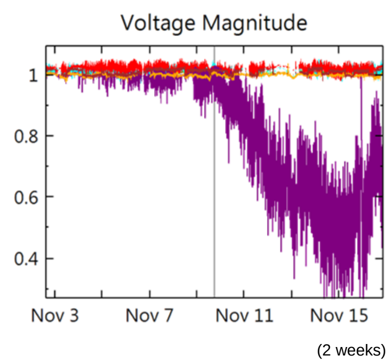


PT Problem Report

- Our daily PT Problem report performs a dV/dT to help identify abnormal voltage fluctuations

PT Problem Report
PhasorServer@oge.com
This message may contain extra line breaks.
Sent: Thu 11/17/2011 7:05 AM
To:

6 - Cimarron-Draper
5 - Cimarron-Minco
5 - Cimarron-Northwest
181093 - Cimarron-Woodring
1 - Cimarron-Cornville
1 - Cimarron-Division
1 - Cimarron-El Reno

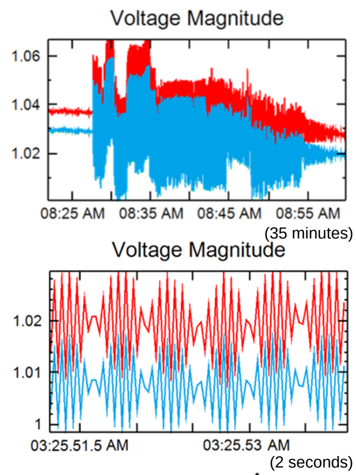


Failing analog input

21

Problem #4 – Stability

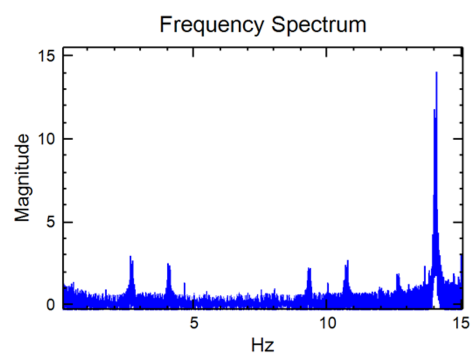
- Oscillations during high winds
- FFT analysis shows 13-14Hz
- Voltage fluctuations as high as 5%
- Interaction between wind farms?
- Switching performed to electrically isolate the wind farms
- Determined it was a problem at different wind farms with the same turbine model
- The only solution was to curtail output



22

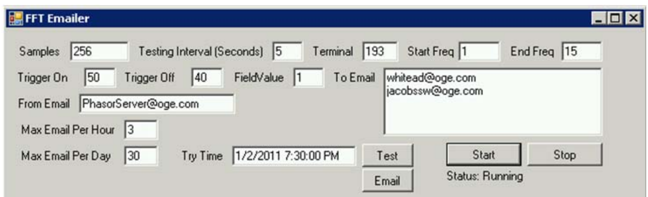
Stability Assessment - FFT

- FFT algorithm used to detect oscillations
- Sends email or text message when the oscillations reach an objectionable level
- This wind farm PMU shows many undesirable components, the worst at 14Hz



FFT Parameters

- Queries a number of samples at a specified interval
- Specify the PMU and frequency range
- Specify the trigger on/off amplitude range (dead band)
- Specify the email recipients with reasonability limits
- We can test the parameters against a historical sample to tune



Problem #5 – Disturbance Logs

- Disturbance logs inaccurate
- SCADA timestamps inaccurate
- Human error during events

Automatic Event Processing

- Automatically Collects Substation Data from Relays and DFRs
  - Event Reports
  - Sequence of Event Data (SOE, SER)
- Presents all data in a web interface
- Mapping capabilities for Distance to Fault
- Uses existing engineering access through the communications processors (DCP)

Automatic Event Processing

- Use synchrophasor data for real time event detection
- Digital data stores relay trip bits, breaker position, line dead, etc.
- Algorithm associates this digital data with specific events like a line trip
- A disturbance log is created with the timestamp and the line that operated.
- Software will then retrieve associated relay/DFR records, SER

27

Automatic Event Processing

1. PMU on both ends, Trip signal from both ends
2. One PMU, Trip signal, Dead Line and dV/dt
3. One PMU, Trip signal, dV/dt and Hot Line
4. No PMU, specified number of dV/dt's

PMU Fault Analysis ?
Live update of PMU faults and the Partial Faults from devices

Top PMU Faults

Area	Station	Device	Fault Type	Occurred
Ardmore	Park Lane	pmu_9	PMU-3PT-dvdt-deadLine	04/08/2013 11:02:58.073
Metro	Mustang	pmu_5	PMU-3PT-bothEnds	04/07/2013 00:01:05.693
Metro	Mustang	pmu_5	PMU-3PT-bothEnds	04/06/2013 23:58:11.760
Enid	Woodring	pmu_3	PMU-3PT-bothEnds	04/06/2013 23:54:01.300
Metro	Mustang	pmu_5	PMU-3PT-bothEnds	04/06/2013 23:51:42.923
Metro	Mustang	pmu_5	PMU-3PT-bothEnds	04/06/2013 23:49:59.353
Enid	Woodring	pmu_3	PMU-3PT-bothEnds	04/06/2013 23:47:55.807
Metro	Pennsylvania	pmu_6	PMU-multi-dvdt	04/06/2013 23:46:36.243
Enid	Woodring	pmu_3	PMU-multi-dvdt	04/06/2013 23:46:31.120
Enid	Woodring	pmu_8	PMU-multi-dvdt	04/06/2013 23:46:29.380

IEEE PES Power & Energy Society

27

IEEE

Conclusions

- Iterative approach can be very effective
- Identify problem, then tackle a solution
- Keep it simple
- Thanks! Feel free to contact me if you have any questions.
  - Austin White
    - whitead@oge.com (405-553-5996)

IEEE PES Power & Energy Society

IEEE

IEEE – Session 5

IT Frameworks for Using and
Managing Synchrophasor Data

IEEE – Session 5: Overview

GPA Background
GPA Product List
Open Source Quick Look
Phasor Data Management Basics

Utilicast Overview
The Problem
The 4 Steps
Examples

Contact Information

GPA Background

Formed in 2010

- –Stewards for code libraries initially developed at TVA
  - •To support the EIPP and NASPI synchrophasor activities
  - •Largely developed through public funds
  - •moved to open source when transitioned to GPA

FOSS development and support company

- –Synchrophasor data and real time systems
- –Enterprise wide disturbance analytic systems

Well established in the electric utility community

- –Projects involving all facets of the industry
- –Products in use around the world

Grid Protection Alliance

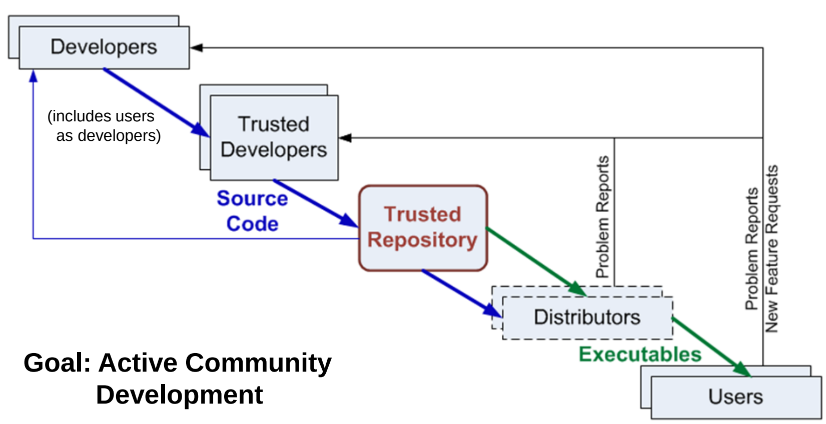
GPA is a not-for-profit corporation that builds collaborative efforts among government, regulators, vendors, grid owners and grid operators.

- **Mission** – to improve the reliability and resiliency of the electric grid
- **Purpose** – to advance the technology of the electric grid by providing high value, high tech software systems and support services

GPA Open Source Products

- **PMU Connection Tester** – Version 4.3.10 December 2012
- **openPDC** – Version 1.5 October 2012, SP1 July 2103
- **openHistorian** – Version 1.0 integrated with openPDC
  – Version 2.0 Beta planned for end of 2013
- **SIEGate** – Version 1.0 Beta demonstration at PJM Summer 2013
- **openFLE including openPQDIF** – Version 1.1 February 2013
- **EPRIopenFLE** – Version 1.0 February 2013
- **openXDA** – Version 1.0 Beta May 2013

OSS Development Model



Goal: Active Community Development

From David A. Wheeler Presentation, 11/4/2009

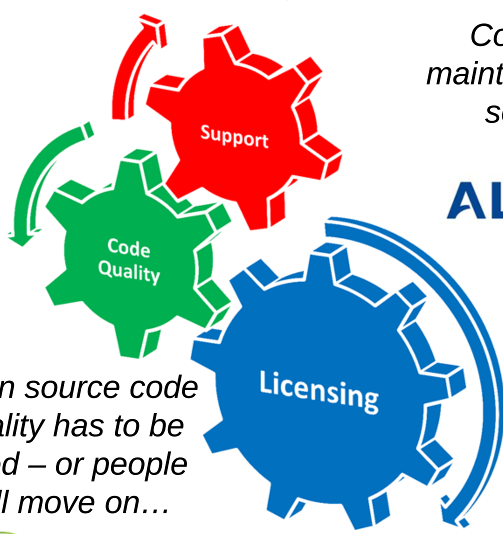
Open Source in Electric Power

- Driving Standards
- Research / Security
- Application Development
- Infrastructure
- *Platforms*

IEEE PES Power & Energy Society · IEEE

Challenges of Open Source

Commercial support and maintenance services for open source are available…



ALSTOM

GRID PROTECTION ALLIANCE

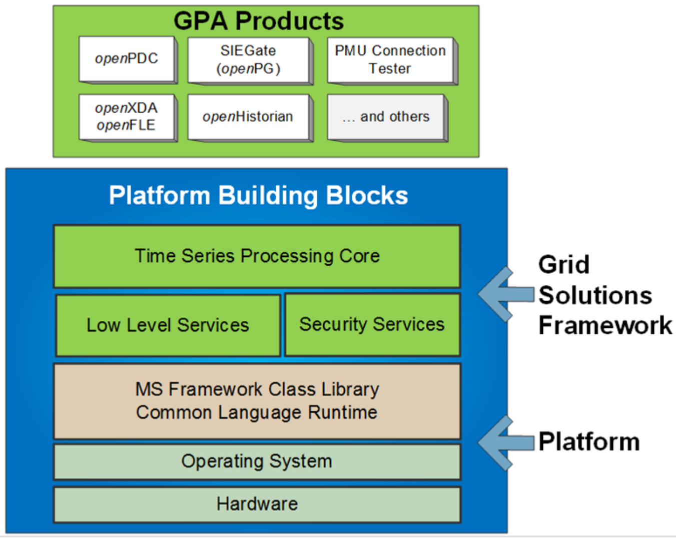
green energy corp

Phasor Data, Inc.

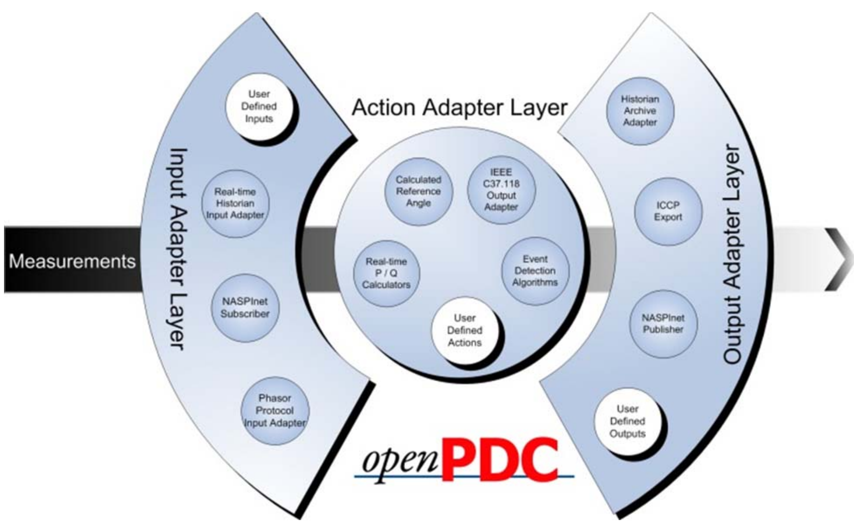
Open source code quality has to be good – or people will move on…

IEEE PES Power & Energy Society · IEEE

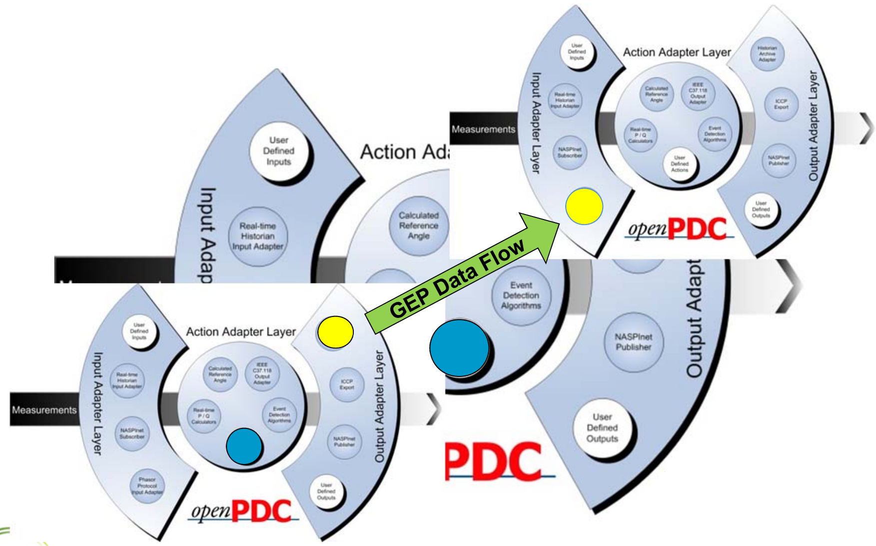
GPA Software Environment



Adapter Based Architecture



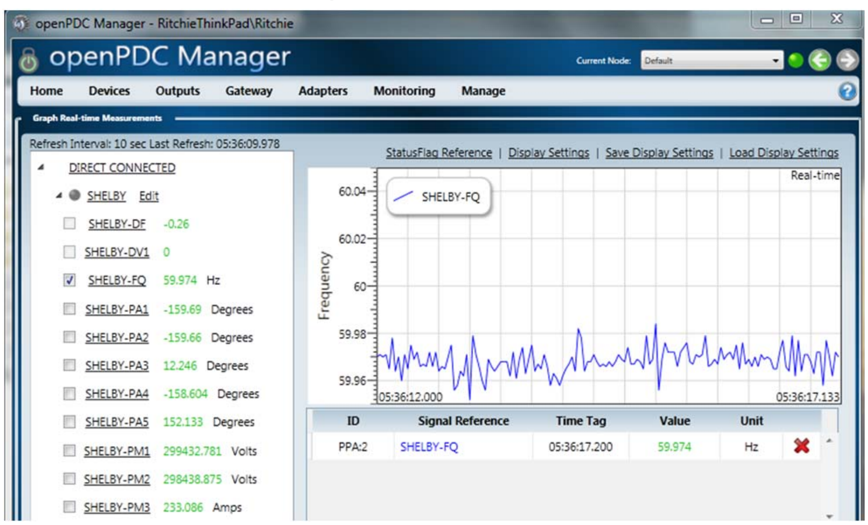
Scalable Adapter Distribution



IEEE PES Power & Energy Society

IEEE

Subscribing to Measurements



IEEE PES Power & Energy Society

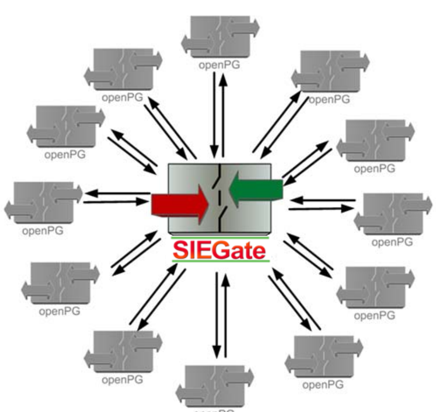
IEEE

Primary Data Flow

Publication APIs

Subscription APIs

Performance Requirements

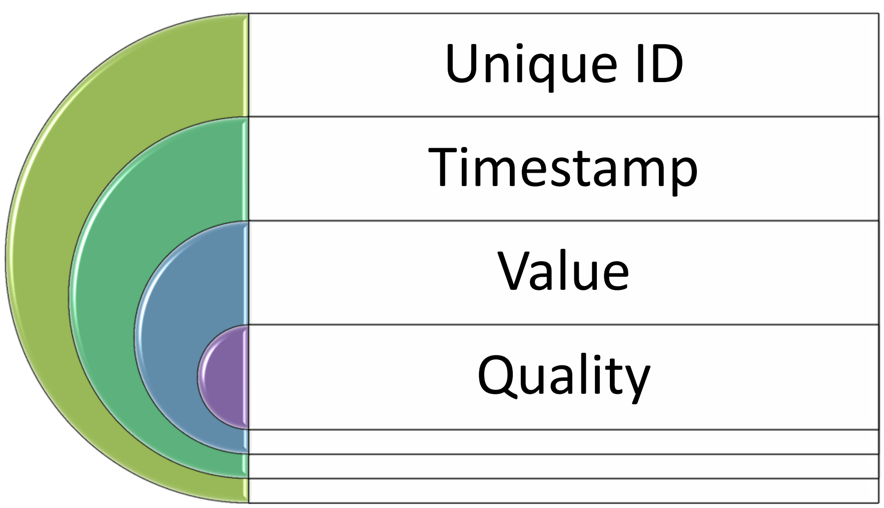


Publication and subscription APIs must move a *continually variable* set of points at low latency to be successful, around 1 million points per second.

Gateway Exchange Protocol (GEP)

- GEP is an extremely simple, small and fast wire format than can be used to exchange data points without a fixed predefined configuration – that is:
  - Points arriving in one data packet can be different than those arriving in another data packet. This can be due to each point having a different delivery schedule – or a dynamic schedule (e.g., alarms).
- GEP is a signal level publish/subscribe protocol with two available channels:
  - ***Command Channel (TCP)***
  - ***Data Channel (UDP or TCP)***

Moving Measurement Data



Simple Optimizable Structure

- Measurement data is well structured and can be safely condensed into a simple data structure (per signal):
  - ID
  - Time
  - Value (32-bit real number)
  - Flags
- There are many fast, highly effective lossless data compression opportunities for time-series data:
  - Simple 7-bit encoding can remove large volumes of “white space”
  - Due to the nature of the streaming measurement data, back-tracking compression methods can be highly effective

-18-

Utilicast Overview

- Founded: 2000
- Headquarters: Kirkland, Washington USA
- Organization: Over 50 U.S. and Canadian Consultants
- Corporate Mission Components:
  - Key Market: Electric Utility Organizations
  - Contribution: Specialized and General Consulting
  - Distinction: Lowest Cost-for-Experience, Exceptional Track Record and References

Utilicast Overview

For over 12 years, Utilicast has focused on providing professional services and industry expertise to the electric utilities. Throughout our history, we have kept focus on providing best people to support our clients by having:

- Focused - Network of senior consultants with a focus on the electric utility industry
- Relevant - Completed projects at the largest 7 U.S. Grid Operators in the last three years
- Independent -
  - No Software Products: Keeps focus on improving consulting model
  - No Software Alliances: Provides no conflict-of-interest in Procurement or Vendor Management assignments

Problem

- Problem: How do we store, correlate, and visualize the "Big Data" Synchrophasor with existing SCADA, State Estimator, Weather and other data sources

- Some of the system are surpassing 1 Billion data elements per hour
- Many of the RT needs of synchrophasors data are still being flushed out

What we found

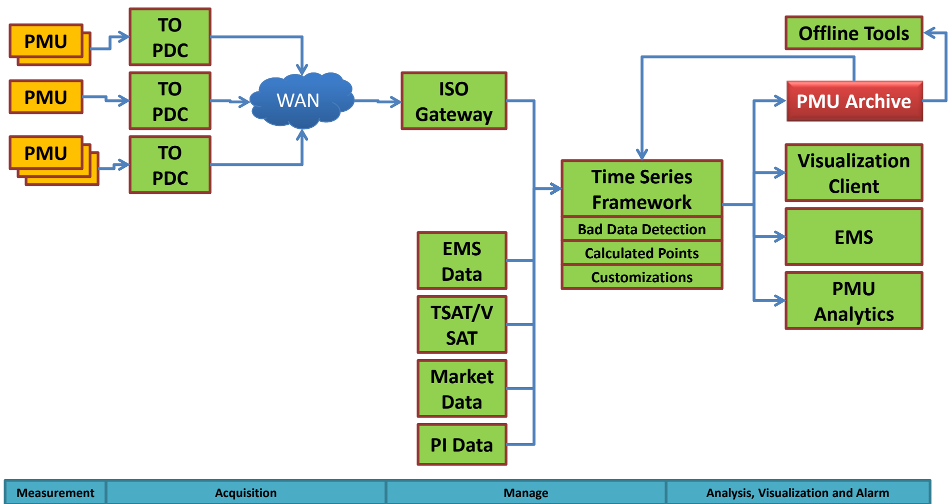
- All PMUs are not created equal
- There sure is a ***lot*** of data
- Operators were skeptical
- Software was immature
- Uncharted territory

4 Steps

- Measurement
- Data Acquisition
- Data Management
- Analysis, Alarm & Visualize

Same process as SCADA but orders of magnitude with 30-120 samples per second data

Architecture



IEEE PES Power & Energy Society IEEE

Data Management

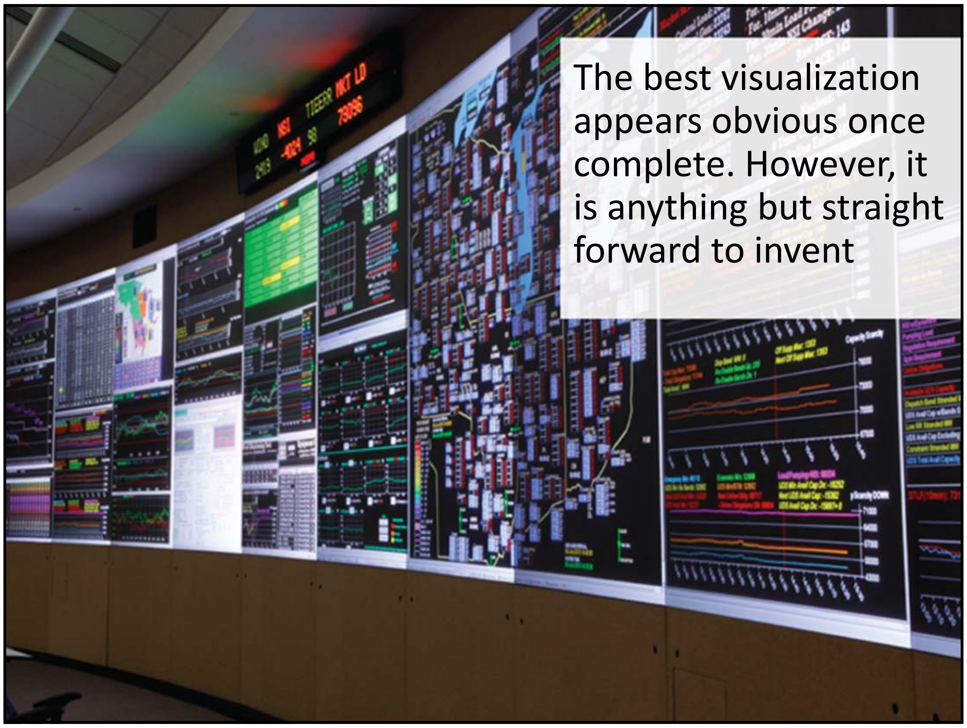
- OpenPDC / OpenPG has the ability to acquire and manage the data

IEEE PES Power & Energy Society IEEE

Data Analytics

- OpenHistorian can archive
- OpenPDC has the ability to serve data to analytic systems

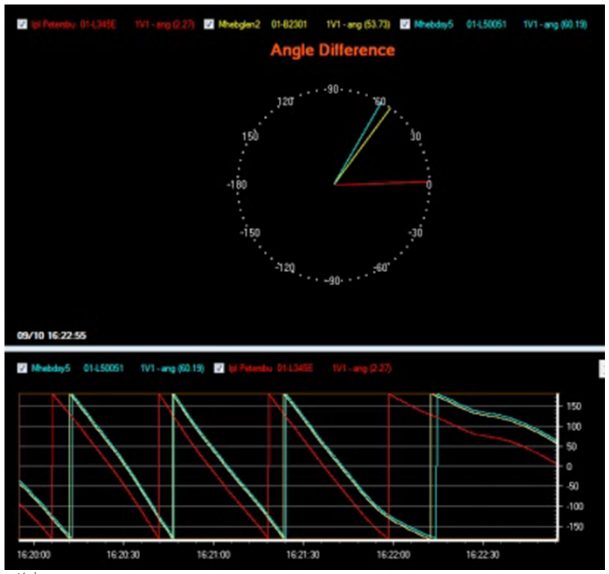
Visualization

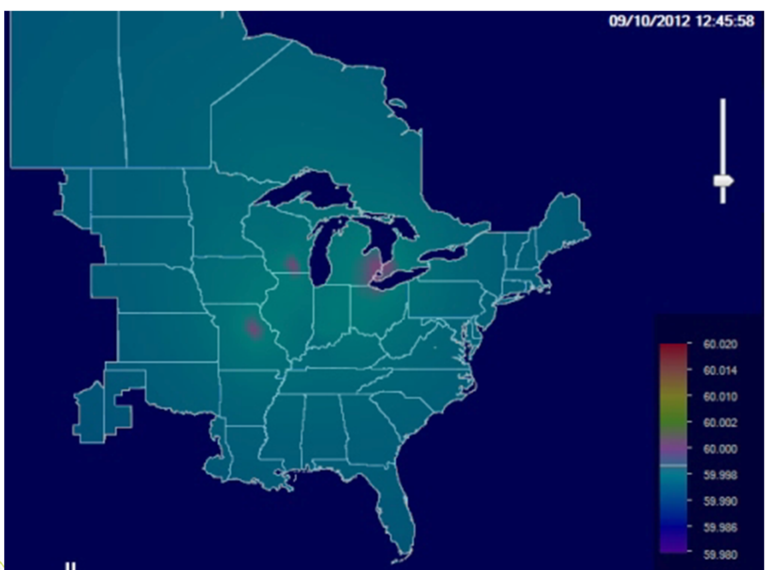


-28-

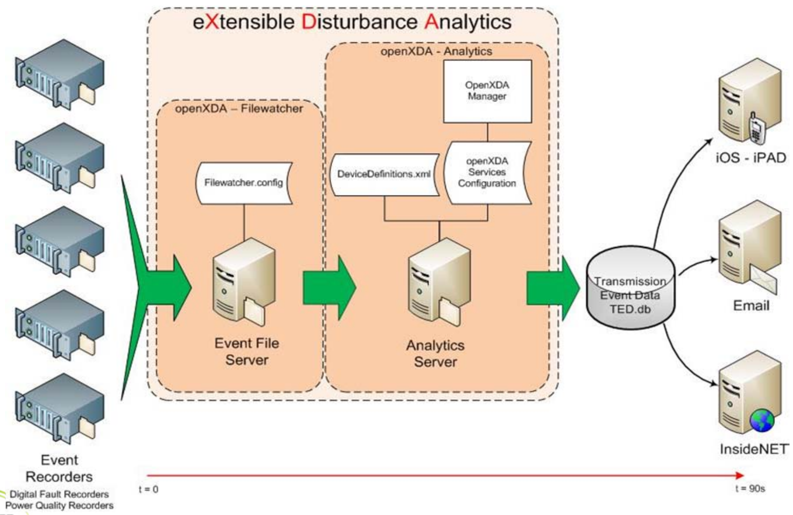
Confidential Document

www.utilicast.com

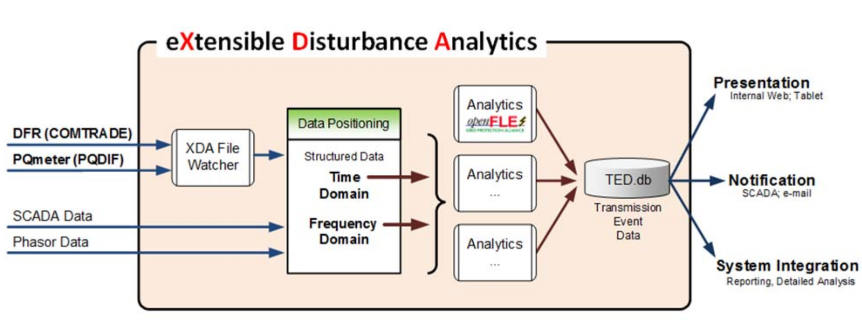

Angle Difference
-90
120
60
150
30
-180
0
-150
-30
-120
-60
-90
09/10 16:22:55
150
100
50
0
-50
-100
-150
16:20:00
16:20:30
16:21:00
16:21:30
16:22:00
16:22:30


09/10/2012 12:45:58
60.020
60.014
60.010
60.002
60.000
59.998
59.990
59.986
59.980

Disturbance Analytics Platform

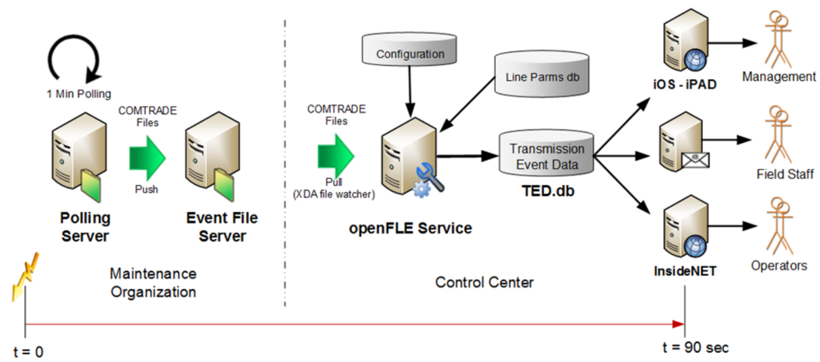


openXDA Overview



-33-

TVA Implementation



Contact Information

GRID PROTECTION ALLIANCE

Fred Elmendorf
Manager, Grid Solutions Services
1206 Broad St, Chattanooga, TN 37402
Office:423.702.8136 Desk:423.973.4729 Cell:423.280.2464
FElmendorf@GridProtectionAlliance.org
View my profile on LinkedIn
2013 GPA User's Forum August 13-14, NERC offices, Atlanta

Utilicast

Scott Stapels
P.O. Box 38
Kirkland, WA 98083
tel: 866.243.2650
fax: 866.424.6132
cell: 248.760.1058
sstapels@utilicast.com

Phasor State Estimator: Enhancing Data Quality and Wide-Area System Monitoring

Joe H. Chow
Scott G. Ghiocel
Rensselaer Polytechnic Institute

Phasor State Estimator Concept

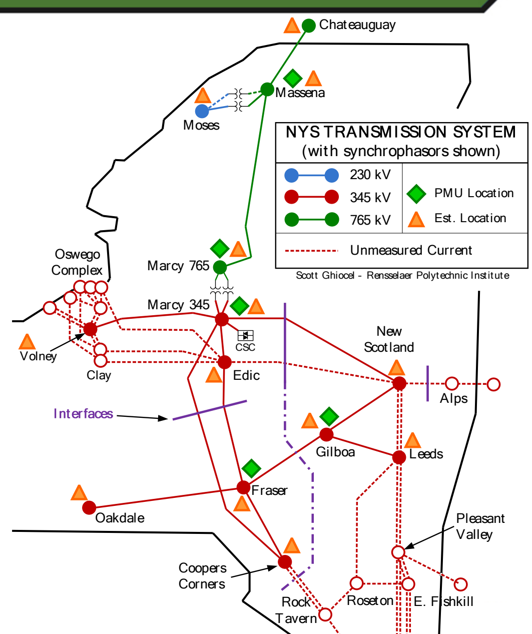
- What is a phasor state estimator (PSE)?
  - A state estimator performed at 30 samples per second, using only synchrophasor measurements of bus voltages and line currents
  - Intended for high-voltage buses: 765/345/230 kV
- Why use PSE?
  - Calculate "pseudo" PMU measurements at unmeasured buses and lines
  - Correlate PMU data across a network, allowing data quality enhancement and filling in missing data
  - Enable interface flow calculation even though not all flows are directly measured with PMUs
  - Monitor generator (fossil and wind turbine) active and reactive power outputs without having a PMU at the generator substation
  - High-sampling-rate allows visibility of disturbances (voltages and power flows), disturbance propagation, frequency response, and oscillations

Phasor State Estimator Concept

- What is needed for a PSE?
  - Good PMU coverage of the high-voltage buses
    - One-third coverage for observability
    - One-half coverage for cross validation (NY and NE)
  - Network data (same as SCADA SE) but no load values required
  - A least-squares algorithm with ability to correct for scaling errors and phase biases (formulation using voltage magnitude and phase)
  - No differential equations required
  - For real-time operation: launched from a PDC
- Other potentials with PSE:
  - Cross-regional SE for stability and vulnerability monitoring: a PSE across MISO-PJM-NY-NE
  - Within a control region, a hierarchical SE with PSE as anchored values for the higher voltage buses, and a non-iterative state calculator for the lower voltage buses

PSE for Central NY

- 6 PMUs in 6 substations
- 13-bus observable network (one-third of NY by area)
- Covers critical power transfer interfaces
- Some interface flows are unmeasured (dashed lines)
- PSE calculates missing flows and enables interface monitoring



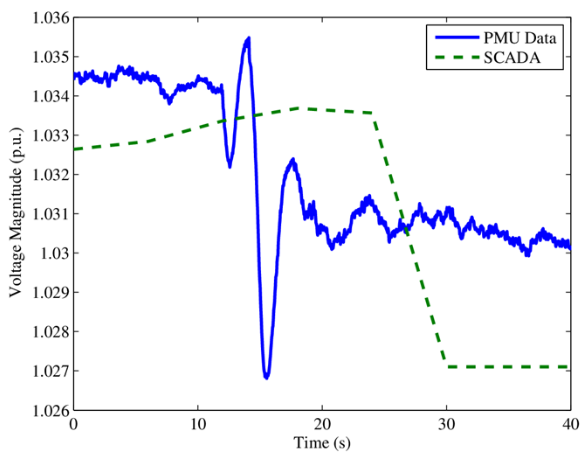
Phasor State Estimation

- Objective of PSE:
  - Find the best-fitting solution for the network model given a set of phasor measurements with error
- Why use synchrophasors only?
  - RTUs report data every few seconds
  - Conventional state estimator (SE) takes the latest value

	Conventional SCADA	Synchrophasors
Reporting Rate	Once every few seconds	30+ samples/sec
State Estimation	No time-alignment	Time-aligned
System Dynamics	Not visible	Visible to operators

Goal: Wide-area coverage of the high-voltage transmission system.

PMUs Enable Dynamic Visibility



Comparison of SCADA vs. PMU data for a loss-of-generation event

Maximum-Likelihood Estimator (MLE)

- Measurements (z): voltage and current phasors
- States (x): voltage phasors
- Weighted least-squares: $\min \sum W_i e_i^2$ subj. to $e_i = z_i - h_i(x) \quad \forall i \in M$
- Minimize the error (e) between the measurements and the network model, $h(x)$:

Voltage measurements: $\tilde{V}_i^{\text{meas}} = \tilde{V}_i + e_{\tilde{V}}$

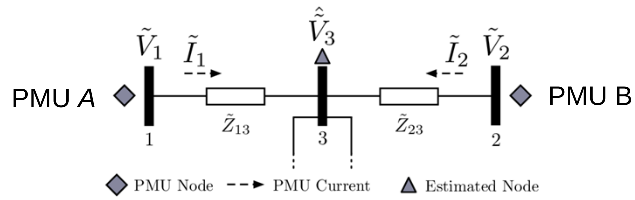
Current measurements: $\tilde{I}_{ik}^{\text{meas}} = \dfrac{1}{R_{ik} + jX_{ik}}\left(\tilde{V}_i - \tilde{V}_k\right) + \dfrac{1}{2} jB_{ik}\tilde{V}_i + e_{\tilde{I}}$

- Can be implemented in rectangular or polar coordinates

Phase Angle Bias

- Relative phase angle bias can be caused by:
  - Timing error
  - Phasor calculation (frequency estimator algorithm)
- All channels of a PMU share the same timing circuitry and phasor calculation algorithms
- **Approach:** Estimate the phase angle bias by introducing a new variable in the measurement equations

Phase Angle Bias – Equations



PMU *A* at Bus 1

Voltage Angle → $\theta_1 - \theta_1^{\text{meas}} + \phi_A = e_{\theta_1}$

Current Angles:

$\delta_{13} - \delta_{13}^{\text{meas}} + \phi_A = e_{\delta_{13}}$

$\vdots$

$\delta_{1n} - \delta_{1n}^{\text{meas}} + \phi_A = e_{\delta_{1n}}$

Same angle bias variable ϕ_A for all PMU channels

PMU *B* at Bus 2

$\theta_2 - \theta_2^{\text{meas}} + \phi_B = e_{\theta_2}$

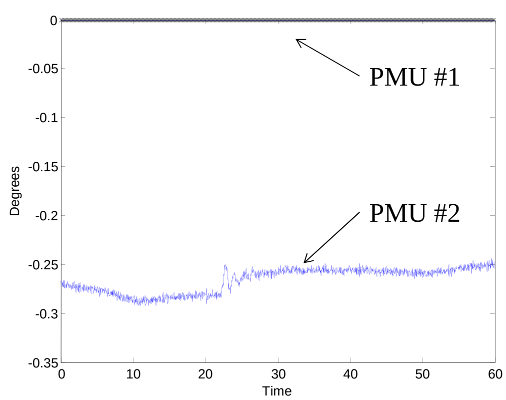
$\delta_{23} - \delta_{23}^{\text{meas}} + \phi_B = e_{\delta_{23}}$

$\vdots$

$\delta_{2k} - \delta_{2k}^{\text{meas}} + \phi_B = e_{\delta_{2k}}$

Phase Angle Bias – Example

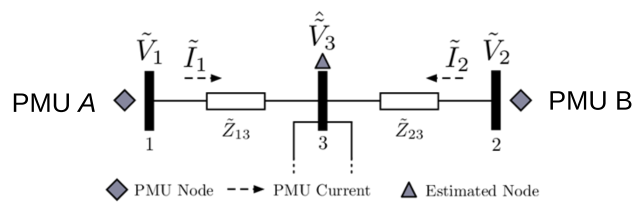
- Two multi-channel PMUs at one substation
- Measured voltage phase angles have a 0.25° difference



Current Scaling Factors

- Unlike voltage phasor measurements:
  - Current flows have a wide range of values
  - No simple "sanity check" (e.g., 0.95-1.05 p.u.)
- Bad scaling is harder to detect in current phasors than voltage phasors
  - More easily detected by correlating measurements from different substations
- **Approach:** Estimate the scaling error using a new variable in the current measurement equations

Current Scaling Factors – Equations



<u>PMU ***A*** at Bus 1</u>

$$(1+c_{13})I_{13} - I_{13}^{\text{meas}} = e_{I_{13}}$$

$$\vdots$$

$$(1+c_{1n})I_{1n} - I_{1n}^{\text{meas}} = e_{I_{1n}}$$

Independent scaling for each current channel

Current Magnitudes

<u>PMU ***B*** at Bus 2</u>

$$I_{23} - I_{23}^{\text{meas}} = e_{I_{23}}$$

$$\vdots$$

$$(1+c_{2k})I_{2k} - I_{2k}^{\text{meas}} = e_{I_{2k}}$$

Independent estimates of $\tilde{V}_3$ should agree.

Line Parameter Estimation

- Normally, line parameters $(R_{ik}, X_{ik}, B_{ik}, a_{ik})$ are constant
- We can estimate them by treating them as states
  - Augment the state vector
  - Include their derivatives in the measurement Jacobian
- Generally, for any line or transformer we have:

$$e_{\tilde{I}} = \frac{1}{R_{ik} + jX_{ik}}\left(\tilde{V}_i - \left(\tfrac{1}{a_{ik}}\right)\tilde{V}_k\right) + \frac{1}{2} jB_{ik}\tilde{V}_i - I_{ik}^{\text{meas}} e^{j\delta_{ik}^{\text{meas}}}$$

$$= f\,(\underbrace{V_i, \theta_i, V_k, \theta_k}_{\text{states}};\ \underbrace{R_{ik}, X_{ik}, B_{ik}, a_{ik}}_{\text{parameters}})$$

PSE Solution Method

- Gauss-Newton iteration: solve for $\begin{bmatrix}\Delta x \\ \Delta\alpha\end{bmatrix}$ ← states (voltage phasors); ← parameters (bias, scaling, line parameters)

$$WH\begin{bmatrix}\Delta x \\ \Delta\alpha\end{bmatrix} = We$$

- Weight matrix W is the inverse of the covariance matrix
- Measurement Jacobian H must be nonsingular:

$$2N_V + 2N_I \geq 2N_B + N_\alpha$$

  - In other words, the measurements must provide enough information to estimate states and parameters
  - High condition number can indicate insufficient information

Form of the Measurement Jacobian

$$H = \left[\frac{\partial e}{\partial x} \,\middle|\, \frac{\partial e}{\partial \alpha} \right]$$

$$= \left[\begin{array}{cc|ccccc} \frac{\partial e_V}{\partial V} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{\partial e_\theta}{\partial \theta} & \frac{\partial e_\theta}{\partial \phi} & 0 & 0 & 0 & 0 \\ \frac{\partial e_{I_{ik}}}{\partial V} & \frac{\partial e_{I_{ik}}}{\partial \theta} & 0 & \frac{\partial e_{I_{ik}}}{\partial c} & \frac{\partial e_{I_{ik}}}{\partial X} & \frac{\partial e_{I_{ik}}}{\partial B} & \frac{\partial e_{I_{ik}}}{\partial a} \\ \frac{\partial e_{\delta_{ik}}}{\partial V} & \frac{\partial e_{\delta_{ik}}}{\partial \theta} & \frac{\partial e_{\delta_{ik}}}{\partial \phi} & 0 & \frac{\partial e_{\delta_{ik}}}{\partial X} & \frac{\partial e_{\delta_{ik}}}{\partial B} & \frac{\partial e_{\delta_{ik}}}{\partial a} \end{array} \right]$$

Voltage phasor measurements $2N_V$

Current phasor measurements $2N_I$

States $2N_B$

Parameters N_α

Rank condition: $2N_V + 2N_I \geq 2N_B + N_\alpha$

Disturbance Events

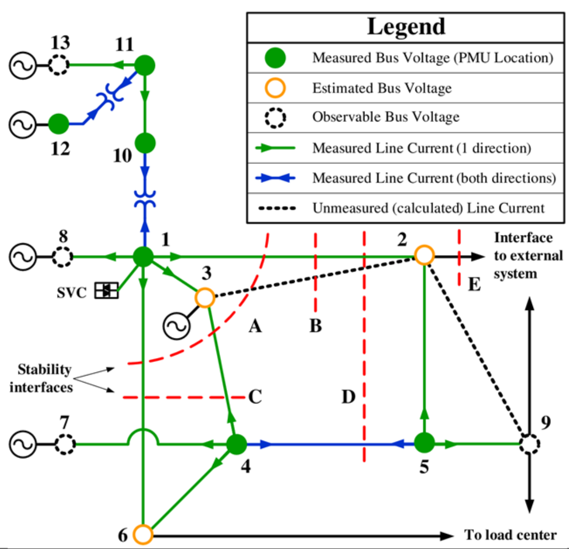
- Examine 20 sec window of data including disturbance
  - Disturbances occur around 2 sec
  - PSE solution calculated for each time sample (30/sec)
- Interface monitoring for real events:
  - Power flow
  - Angle separation

Name	Description
Event 1	Loss-of-generation to the East (500 MW)
Event 2	Loss-of-generation to the East (800 MW)
Event 3	Loss-of-generation to the East (700 MW)
Event 4	Loss-of-generation to the West (800 MW)
Event 5	Loss-of-generation to the East (No PMU data from Bus 5)
Event 6	Tap changing (to demonstrate tap ratio estimation)

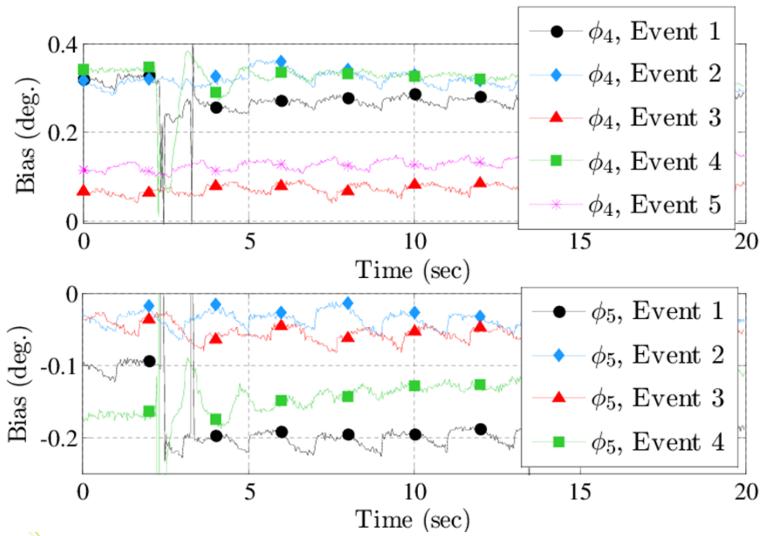
Estimated Parameters

Name	Description
$\phi_{\text{ref}} = 0$	PMU 1A (at Bus 1) is the reference for angle bias
ϕ_1	Angle bias for PMU 1B (at Bus 1)
ϕ_4	Angle bias for PMU 4 (at Bus 4)
ϕ_5	Angle bias for PMU 5 (at Bus 5)
ϕ_{10}	Angle bias for PMU 10 (at Bus 10)
ϕ_{11}	Angle bias for PMU 11 (covers Buses 11 and 12)
c_{46}	Scaling correction for current measurement I_{46}
c_{45}	Scaling correction for current measurement I_{45}
X_{45}	Series reactance for Line 4–5
B_{45}	Shunt susceptance for Line 4–5
$a_{1-10,1}$	Transformer tap ratio on Branch 1–10, Circuit 1
$a_{1-10,2}$	Transformer tap ratio on Branch 1–10, Circuit 2
a_{11-12}	Transformer tap ratio on Branch 11–12

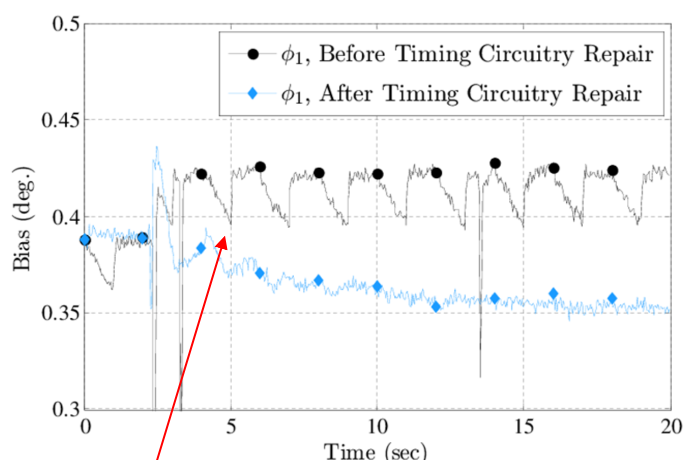
Central NY System



Angle Bias – PMUs 4 & 5

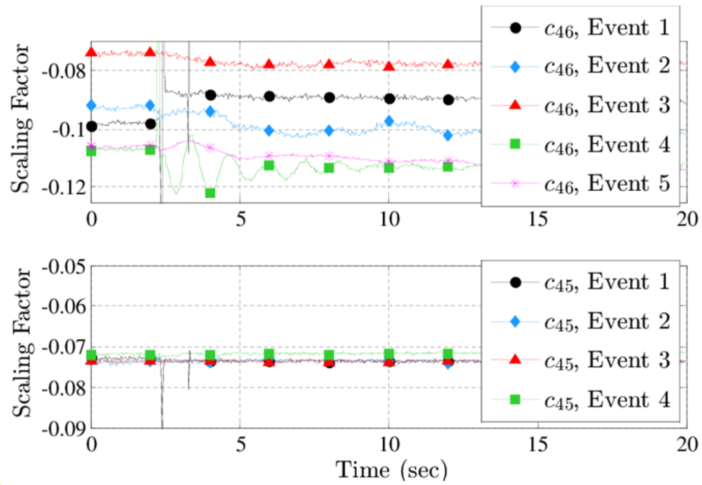


Angle Bias – Timing Signal Problem

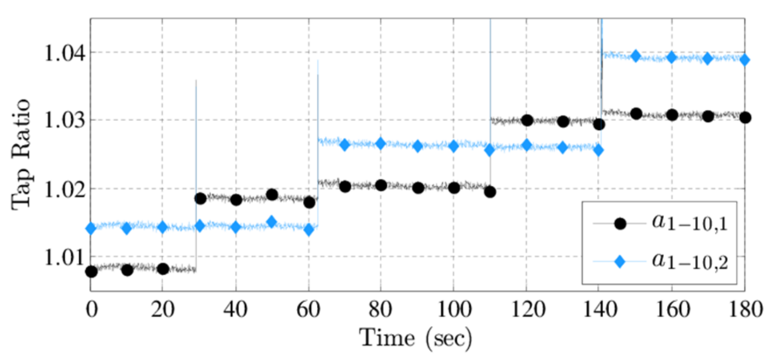


Transients occur at the top of each second (GPS signal)

Estimated Current Scaling Factors



Transformer Tap Ratio Estimation



Data Quality Enhancement

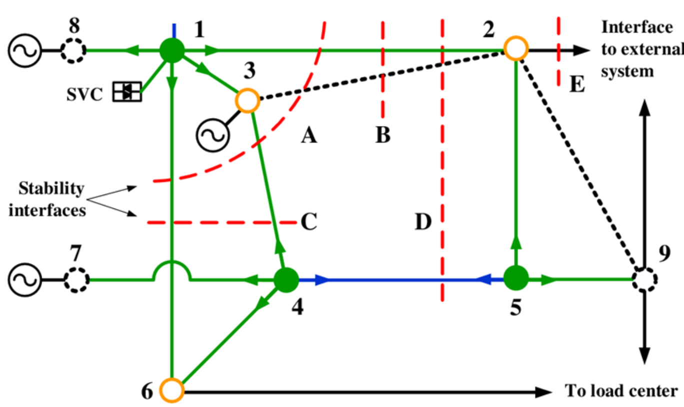
- Calculate system-wide total vector error (TVE)
  - With real data, actual state values are unknown
  - Include current scaling factors to correct large errors
  - Assume PSE solution is correct
- Reduction of TVE across all PMUs (< 1%):

Mean Total Vector Error (TVE)

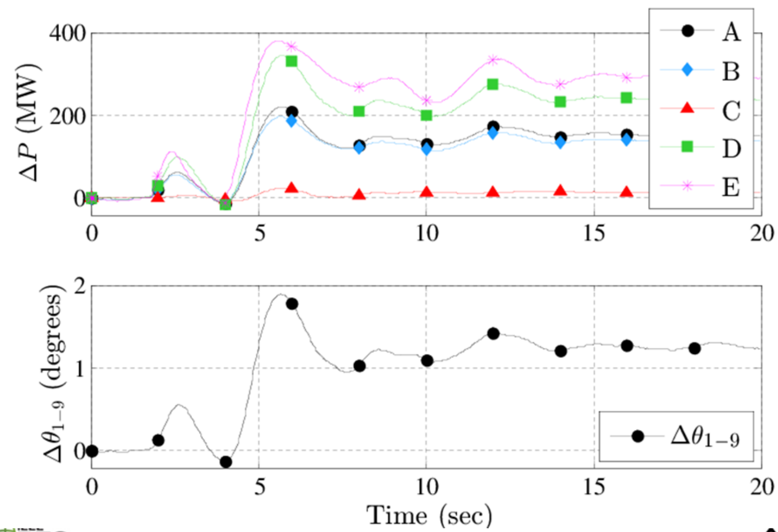
Event	**Current scaling correction only** Mean TVE	**Current scaling and angle bias** Mean TVE
Event 1	1.162%	0.890%
Event 2	1.106%	0.907%
Event 3	0.993%	0.701%
Event 4	1.051%	0.852%

Interface Monitoring for Central NY

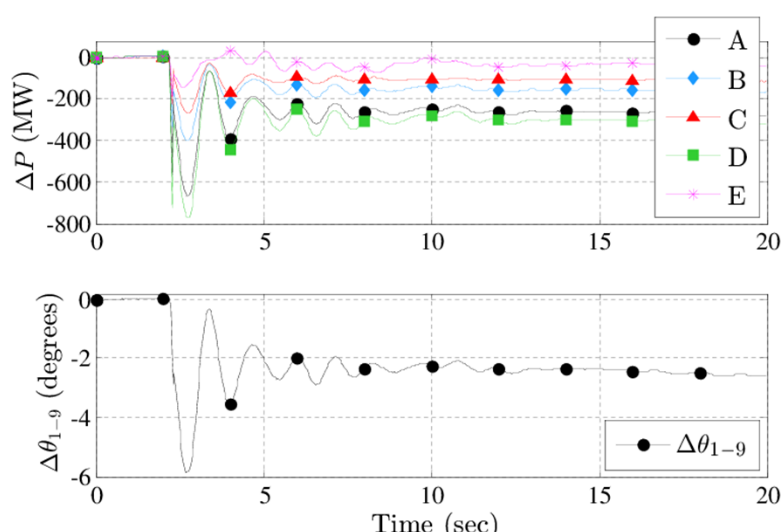
- Use PSE to estimate unmeasured buses and flows
- Monitor interfaces in real time for disturbance events



Monitoring Transfer Interfaces – Event 2



Monitoring Transfer Interfaces – Event 4



Conclusions

- Data quality improvement by using current synchrophasors to correlate PMUs across the system
- Unmeasured voltage and current phasors (and thus interface flows) can be estimated if observable
- Estimation of angle biases, current scaling factors, and line parameters with sufficient redundancy
- PSE enables system monitoring for dynamic propagation of disturbances across transfer interfaces

Synchrophasor-Only State Estimation and Synchrophasor Data Conditioning and Validation

James Thorp
Virginia Tech

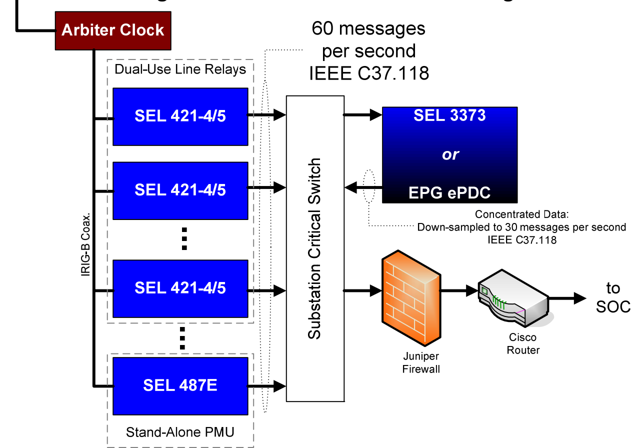
Kevin Jones
Dominion

Background

- A phasor only - three phase- state estimator has been installed on the Dominion Virginia Power 500kV system as part of a DOE demonstration project DE-0E0000118 led by Virginia Tech.
- By summer of 2013 a total of more than 600 measurements from twenty one 500kv stations, five 230kv stations, and one 115kv station will give an estimate at a rate of 30 times a second of the three phase complex voltages on the 500kV network. Both bus voltage and line currents are measured and communicated through a SONET network to the Control Center in Richmond. There is a PDC in each substation and a PDC in the control center.
- The linear estimator software and it's applications were implemented in C# for the openPDC platform in the Dominion Control Center

Substation PMU Deployment Strategy

PDC phasor data concentrator – take data with the same time-tag make one vector with one time tag



SEL Dual-Use Line Relay/PMU also give time tagged breaker status

Monitoring Requirements:

1. PMU shall provide *voltage* measurements for every 500kV bus element that can be isolated.
2. PMU shall provide *current* measurements for all lines and transformers connected at 500kV.
3. PMU shall stream synchrophasors to SEL-3373 at the rate of 60 messages per second.
4. For every current and voltage, the following synchrophasors shall be measured:
   - i. A-phase
   - ii. B-phase
   - iii. C-phase
   - iv. Positive Sequence (calculated)
5. Where dual primary line relays exist, both relays shall provide synchrophasors.
6. Synchrophasor data shall be archived locally within the SEL-3373 (substation phasor data concentrator)
7. Down-sampled synchrophasors shall be streamed to central data concentrator at rate of 30 messages per second.

- PMUs measures real and imaginary parts of bus voltage and line currents. Using both current and voltage measurements of the 29 buses, 8 are observed only once, 7 twice, 8 three times, 5 four times, and 1 five times
- Then the measurements are given by:

$$z = \begin{bmatrix} \text{II} \\ YA + Y_s \end{bmatrix} E + \varepsilon$$

- II is a unit matrix with rows missing where there are no PMUs. Repeated measurements of the same voltage also possible. II and A are real but Y and Ys are complex
- A lot of previous work on PMU placement for this problem, complete observability, degree of unobservability, sequential placement, redundancy, etc.

Topology Changes

In complex (or rectangular) form the measurements are linear functions of the complex bus voltages.

$$z = Hx, \quad \hat{x} = Mz$$

Where M is fixed and only changes as the network topology changes. The tripping of a line who's current is in the measurement set can be detected by the time tagged breaker status from the dual use line-relay/PMU or treated as missing data.

Symbolically

$$z = Hx + \varepsilon$$

$$\hat{x} = (H^T W^{-1} H)^{-1} H^T W^{-1} z = Mz$$

W is the covariance matrix of the measurement error

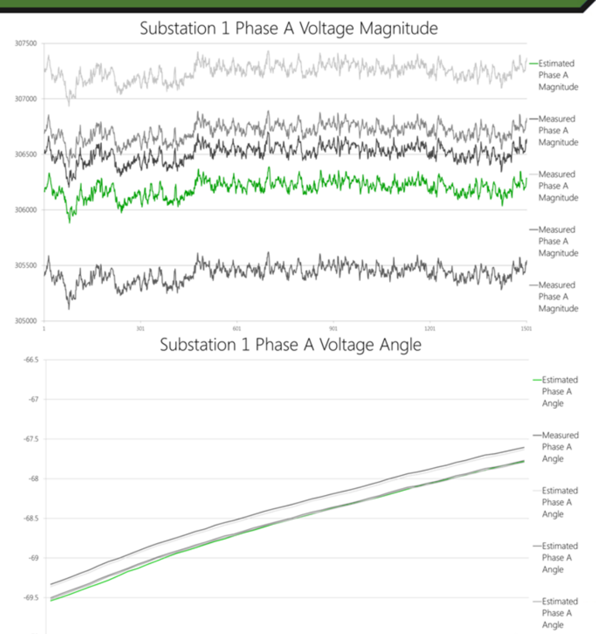
- Not recursive - M fixed except for topology changes

- Can treat breaker open as just missing data

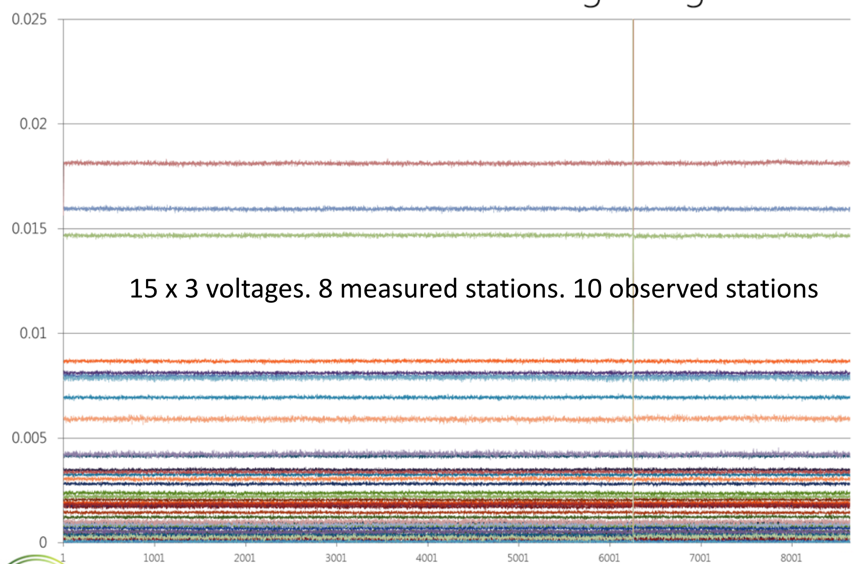
Every entry in the old positive sequence matrix replaced with a 3x3 matrix

-Effect of multiple measurements of the bus voltage with four 500kV lines with SEL 421 relays

-It is obvious that there are fixed multiplicative errors in CTs and VTs With three phase measurements these ratio errors can be determined if one good voltage measurement is available (a PT at the 115kV bus on slide 2 is used) and if the measured quantities form a tree.



Observation Residuals for Voltage Magnitudes

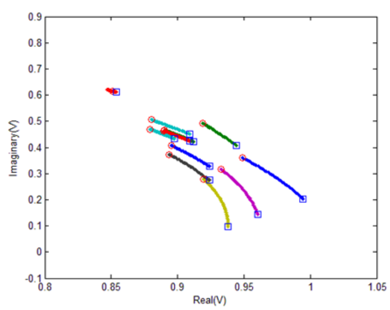


Auto-Regressive Modeling

- Try to predict next set of measurements based on prior measurements:

$$\hat{y}_t = \alpha_1 y_{t-1} + \alpha_2 y_{t-1} + \cdots \alpha_m y_{t-m} + \omega_t \quad t = m+1, \cdots n$$

- Morning load pickup: 60% increase in load in an hour



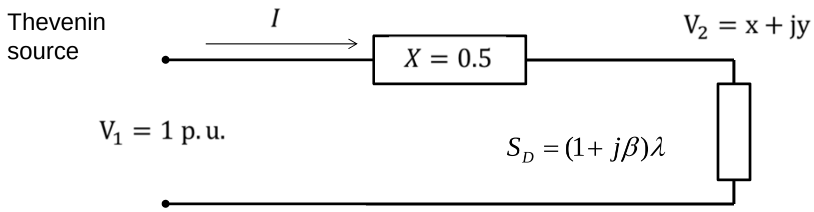
345 kV voltages for 60% load increase

These are load flow solutions every 90 seconds as load increases. (no approximation)
The trajectories are quadratic in the sense
a_k b_k and c_k are complex numbers
Quadratic fit is very close~10^{-5}

$$V_k(\lambda) = a_k + b_k\lambda + c_k\lambda^2 \text{ where } Load_{new} = Load_{old} + \lambda\Delta L$$

Reason for the curves being Quadratic

- Load is increased at Constant Power Factor



$$S_D = V_2 I^* = (x + jy)\left(\frac{1 - x + jy}{-jX}\right) = (1 + j\beta)\lambda$$

$$x^2 - x + X^2\lambda^2 + X\beta\lambda = 0 \quad y = -X\lambda$$

$$x = \frac{1 \pm \sqrt{1 - 4X^2\lambda^2 - 4\beta X\lambda}}{2}$$

x+jy is approximately quadratic in t.
By writing a Taylor series can get mote accuracy if needed

Coefficients used for Prediction Vandermonde matrix

- If $y(t)$ be an n^{th} order polynomial, sampled at time t,

$$y(t) = \alpha_n t^n + \alpha_{n-1} t^{n-1} + \alpha_{n-2} t^{n-2} + \ldots + \alpha_1 t + \alpha_0$$

- Then, for equally spaced samples

$$\begin{bmatrix} y(n) \\ y(n-1) \\ \vdots \\ y(1) \\ y(0) \end{bmatrix} = \begin{bmatrix} 1 & n & n^2 & \ldots & n^n \\ 1 & (n-1) & (n-1)^2 & \ldots & (n-1)^n \\ 1 & \vdots & \vdots & \ddots & \vdots \\ 1 & 2 & 2^2 & \ldots & 2^n \\ 1 & 1 & 1 & \ldots & 1 \end{bmatrix} \begin{bmatrix} \alpha_0 \\ \alpha_1 \\ \vdots \\ \alpha_{n-1} \\ \alpha_n \end{bmatrix} = V\alpha$$

- The first row of V^{-1} gives the desired coefficients [3]:

b's are the binomial coefficients

$$b_n y(n) = -b_{n-1} y(n-1) - b_{n-2} y(n-2) \ldots - b_1 y(1) + y(0)$$

Where, $b^T = [b_n \quad b_{n-1} \quad \ldots \quad b_2 \quad b_1]$ $is\ the\ first\ row\ of\ V^{-1}$

$$y = V\alpha \quad V^{-1} y = \alpha \quad b^T y = \alpha_0 = y(0)$$

Conditioning Bad Data

If x(n) is a complex 500kV voltage

$$\hat{x}(n) = 3x(n-1) - 3x(n-2) + x(n-3)$$

$$\begin{bmatrix} \hat{x}(n) \\ x(n-1) \\ x(n-2) \end{bmatrix} = \begin{bmatrix} 3 & -3 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} x(n-1) \\ x(n-2) \\ x(n-3) \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} w(n) \quad z(n+3) = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} x(n+3) \\ x(n+2) \\ x(n+1) \end{bmatrix} + r(n+3)$$

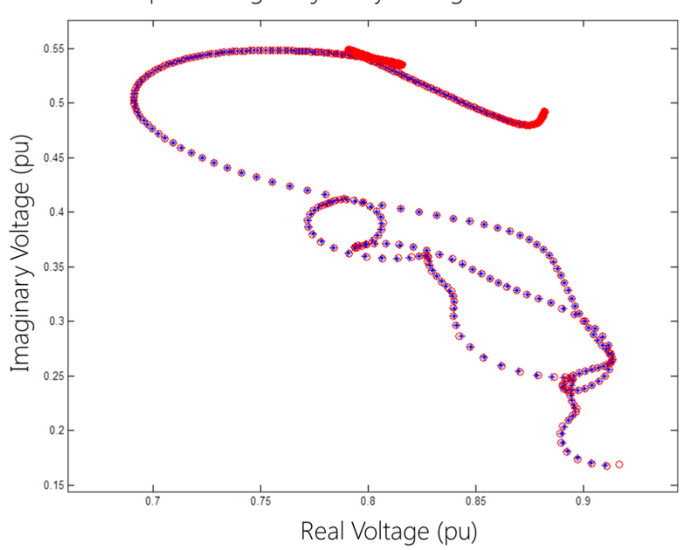
w ($s_w=10^{-5}$) and r ($s_r=10^{-3}$) random, white, and independent, can predict the state and the next measurement and form the observation residual. To make a state equation add and subtract

$$\begin{bmatrix} \hat{x}(n) \\ x(n-1) \\ x(n-2) \end{bmatrix} = \begin{bmatrix} 3 & -3 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \hat{x}(n-1) \\ x(n-2) \\ x(n-3) \end{bmatrix} + \begin{bmatrix} 3 \\ 1 \\ 0 \end{bmatrix} \left[x(n-1) - \hat{x}(n-1) \right]$$

Observation residual

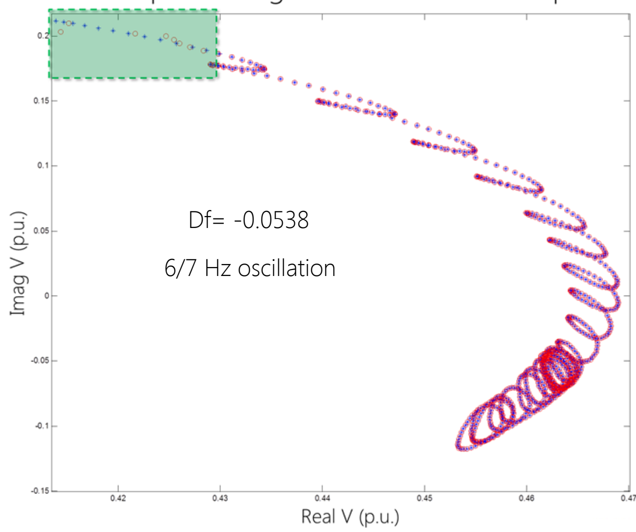
The added term is the "Kalman gain" multiplying the observation residual. This is the steady state Kalman gain for all covariance in w if the covariance of r is zero. For $s_w=10^{-1}$, $s_v=10^{-2}$ K=[2.8793 .9915 .0244]^{T}In general K depends on the ratio of the two covariances

Complex Voltage Trajectory During Loss of Excitation

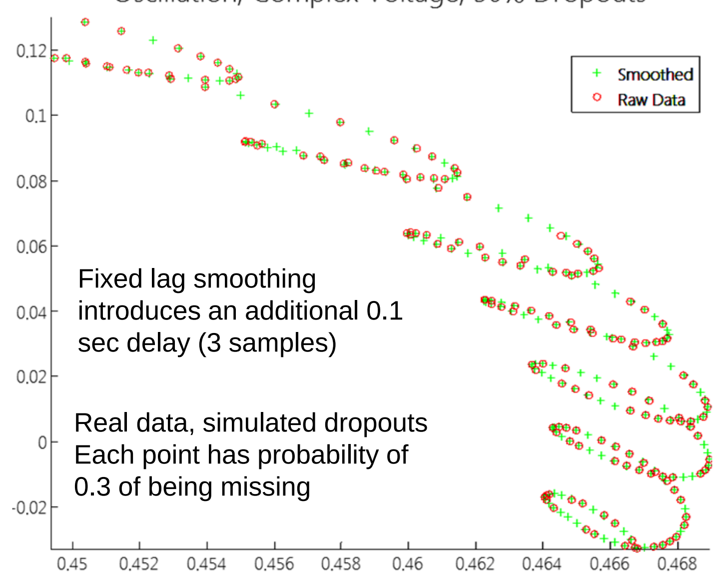


Complex Voltage for Oscillation Example

Next three slides –field data measurements + and estimate o formed by the last 3 values of this voltage using a Kalman Filter based on model on slide 5



Oscillation, Complex Voltage, 30% Dropouts



Fixed lag smoothing introduces an additional 0.1 sec delay (3 samples)

Real data, simulated dropouts
Each point has probability of 0.3 of being missing

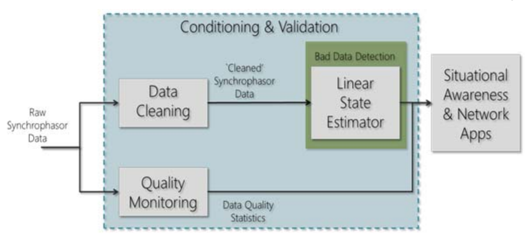
Need for a Commissioning Process: Data Validation

- Initially there were data drop out problems reported by others and that have been observed elsewhere.
- The problem was in the settings of PDCs. After correction observed no more data drop out have been observed. PJM has commented on the quality of our data. (PJM gets the positive sequence data)
- Dominion has developed data validation scripts that execute in both Matlab and Excel for pre-connection data validation. These scripts have been tested already on data from 17 substations and have been used to find issues that have been handled before the data is connected to the System Operation Center.
- They have algorithms for online determination of Signal to Noise Ratio (SNR) of the PMU data which can be used to monitor health of electrical components and detect potential problems in them. Dominion has had experience in this regard using synchrophasor data to find and mitigate problems with instrument transformers.

IEEE PES Power & Energy Society®

IEEE

- This preceding process can be used to detect bad data by using an observation residual or to smooth data by using subsequent measurements to obtain a better estimate (a technique for supplying missing data).
- Each measurement, whether used for state estimation, control, or alarms, can be subjected to the same preprocessing as the linear estimator.
- It should be recognized that the proposed solution is in general a low cost solution requiring only an open PDC and some C# code.
- Even if a state estimator is not desired, the linear estimator can be thought of as part of the data conditioning algorithm in that it detects bad data, finds the best estimate, and increases the observability of the network.



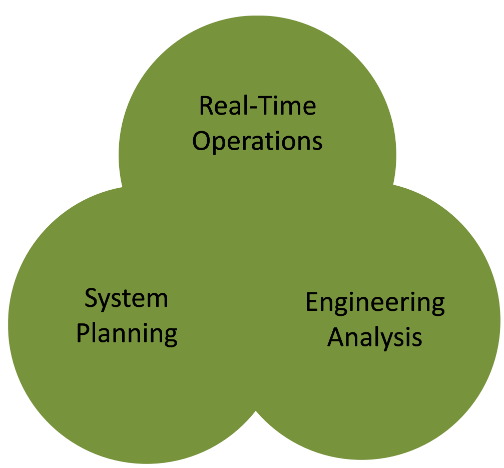
IEEE PES Power & Energy Society®

IEEE

Implementation

- Linear Estimator source code in C#
- Developed as Adapters for a host openPDC instance
- Easily Configurable as Positive Sequence/Three Phase based on needs
- Fully extensible as synchrophasor footprint grows to encompass entire transmission network.
- Breaker/Switch model fully emulates information available in EMS
- Basic Bad Data Detection & Identification and Plausibility Checks
- RCF/PACF correction with CT/PT calibration algorithms
- Handles computational and physical islands
- Built in Real/Reactive Power Flow and Sequence Component calculation as part of the real-time state information.

Where is the Business Value?



Complementing & Augmenting the Production EMS

- Applications leveraging PMU data can help improve performance of EMS State Estimator
  - ISD Adapter to bring in PMU Data to EMS
  - CT & PT calibrations improve raw SCADA measurements
  - Calculated P & Q from PMU Estimator to be used as pseudo-measurements in EMS
  - Empirically (and frequently) determined line impedance values
- Linear State Estimator as EMS Estimator Backup
  - Fully paralleled from substation
  - If EHV observability is lost through EMS, operations must dispatch resources to all EHV substations and monitor by phone.
  - EHV network fully observed by PMU-only estimator
  - Solves in real time, omnipresent, even for small EMS related issues

LSE as Platform for App Development

- We have already benefitted from the power and flexibility of our system architecture by developing several other applications in-house.
- Quick prototyping, testing, and deployment.
- Examples: Equipment monitoring with SNR, Status Flag Parser for not using measurements during relay testing.
- As non-linear SE is to traditional EMS functions, LSE should represent the data source for any network application that uses synchrophasor data.
- As a hedge against the future, all source code will be available on Codeplex – http://phasoranalytics.codeplex.com by our final demonstration on August 19, 2013. Anyone with synchrophasor data can use it, just need an openPDC instance to host the application.
- My future work includes a full GSF solution of the application as a stand alone piece of open source software.

Organic Growth Through Standardized Deployment

- Scalability of Dual-Use Relay PMUs & Substation PDCs
  - As digital relays continue to replace EM relays, take advantage of scheduled replacements by using relays with PMU capabilities
  - We have changed our substation protection and control standards for to reflect this. When new PMU-capable protection relays are installed for capital or O&M projects:
    - Satellite clock coaxial cables are connected to the PMU-capable relays
    - PMU-capable relays have PMU settings enabled/configured
    - A PDC is installed in the control house(s).
- Expectations for First Year 'Post-Stimulus'
  - More than 35 locations (transmission lines, transformers) will have PMUs installed
  - 3 Phase voltages, 3 phase currents, and breaker statuses for each relay/PMU deployed
  - All voltage levels: 500, 230, 115

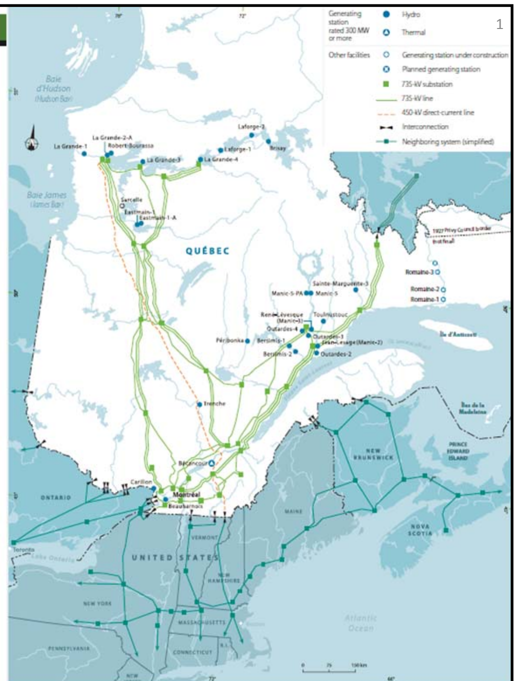
IEEE PES Power & Energy Society® IEEE

Helpful Hints & Lessons Learned

- PMUs/PDCs are not plug and play! Take the settings seriously!
- Managing memory/CPU resources on clusters/servers
- There is a critical mass for the ROI of synchrophasors to become sustainable.
- Synchrophasors make it possible to begin to question established assumptions (positive sequence, impedance values, etc)
- Make larger 'pie-in-the-sky' goals achievable by asking how can we extract value not just in the future but presently (today, tomorrow)

IEEE PES Power & Energy Society® IEEE

Wide-Area Control at Hydro-Québec



Innocent Kamwa
Chief Scientist for Smart Grid
Hydro-Québec/IREQ

IEEE PES Power & Energy Society

22-26 July, Vancouver, BC, Canada

IEEE

Background information on Hydro-Québec:

98.3% of Renewables and 735kV transmission backbone

- Historic domestic peak load of 39 120MW, 23 January 2013, 17:30 PM
- 43 870 MW of generation with 35 125 MW from 60 hydro-power plants owned by Hydro-Québec Production (2012)
- Private wind generation: 1716 MW in April 2013, 4000 MW in 2015

http://www.hydroquebec.com/publications/en/annual_report/pdf/annual-report-2012.pdf

735 kV substation near the 5 616 MW Robert-Bourassa generating station

- No synchronous tie with NPCC
- 512 substations and 33 000 km of transmission lines, including 11000km of 735-kV series compensated lines
- 18 Interconnections, including one +/- 450 kV multi-terminal HVDC line (2000 MW)

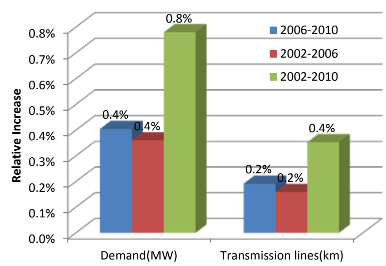
IEEE PES Power & Energy Society

Hydro-Québec

IEEE

Transfer Capacity Issues in Québec

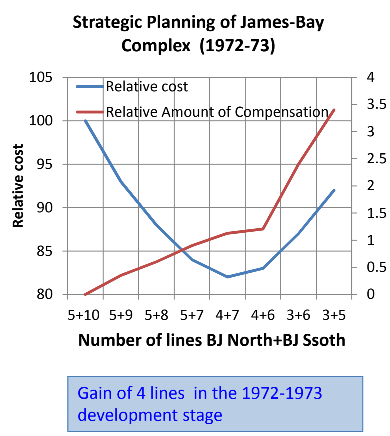
- **The grid is increasingly under pressure: rate of network expansion is 2 times less than than the rate of peak load increase** (3.5% vs 7.8% over the 2002-2010 decade)

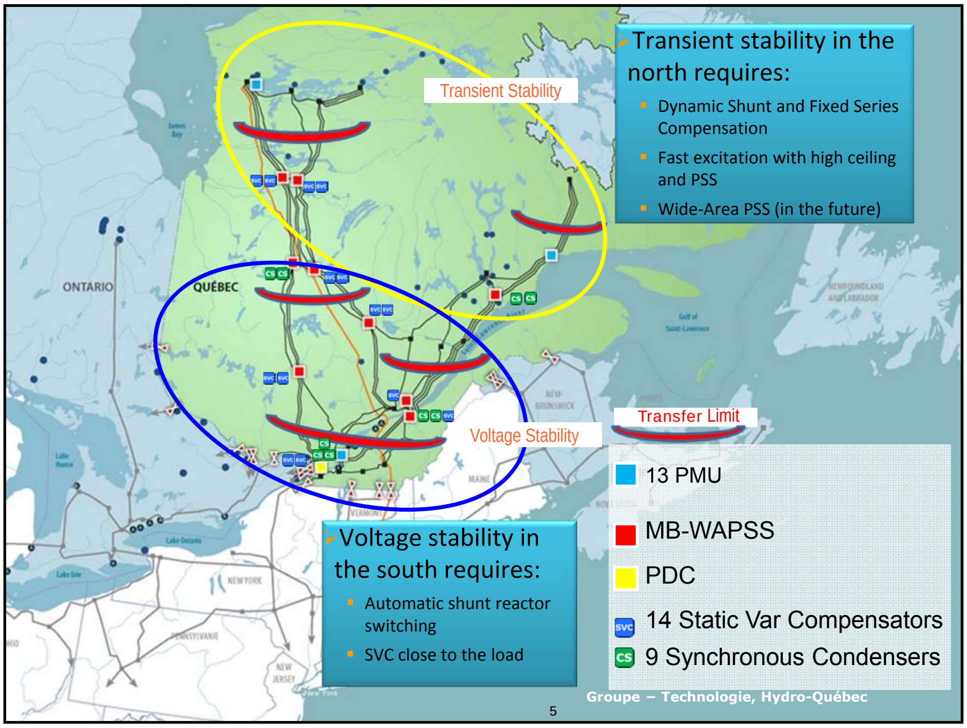


- **Increase of the transfer in the south: Doubling of net exports between 2007 and 2011**
  - Exports to rise from 15,2TWh in 2008 to 24,9TWh in 2013 (63%)
  - **From 1500MW/line in 1965-1970 to 2200-2700MW/line today: thermal limits issues are emerging**
  - Integration of remote Wind and Hydro resources (1716 MW of wind in April 2013, 26% of Canadian capacity)

Basic Measures for Transfer Capacity Improvement in Québec

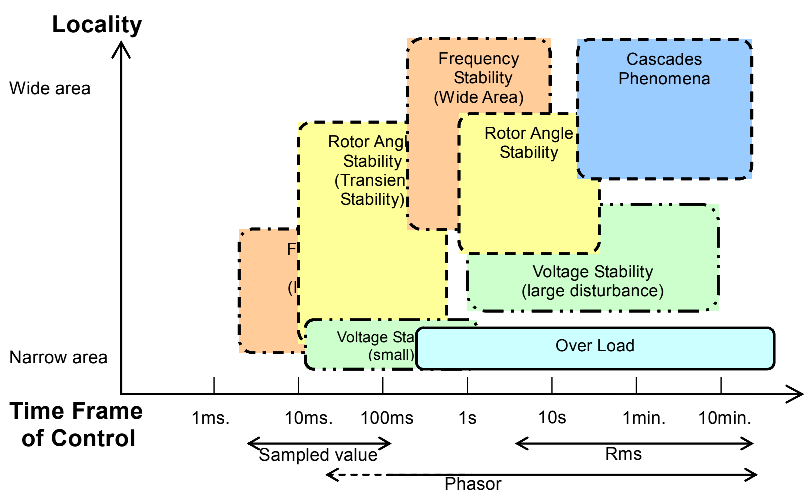
1. **Adding shunt compensation for reactive voltage support during fault and increased steady state loadability at peak hours**
2. Adding breakers to 735 kV shunt reactors to improve voltage security at increasing high power transfer durint peak hours
3. Reduction of fault clearing time at 735 kV (normal: 4-7 cy.; delayed: 11-13cy.)
4. Excitation systems with high field voltage ceiling (up to 15 p.u. during faults)
5. Widespread series compensation
6. Adding PSS with optimized settings to improve the damping of post-fault oscillation
7. **Development and widespread deployment of Multi-Band PSS (MBPSS): IEEE PSS4B**





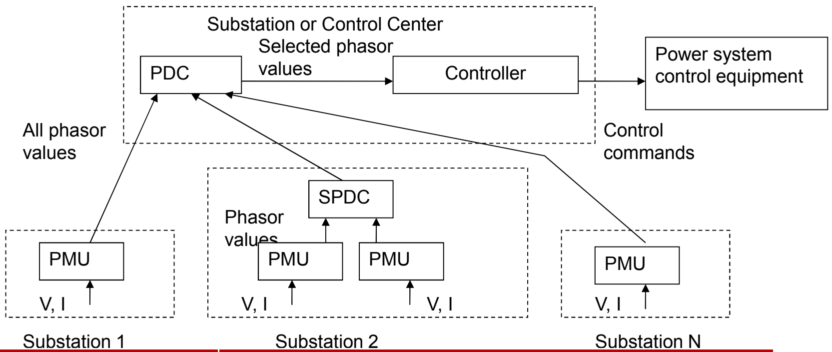
Application locality and time scale

"IEC/TR 61850-90-5 FDIS, Communication networks and systems for power utility automation - Part 90-5": Use of IEC 61850 to transmit synchrophasor information according to IEEE C37.118, June. 2011



Hydro-Québec

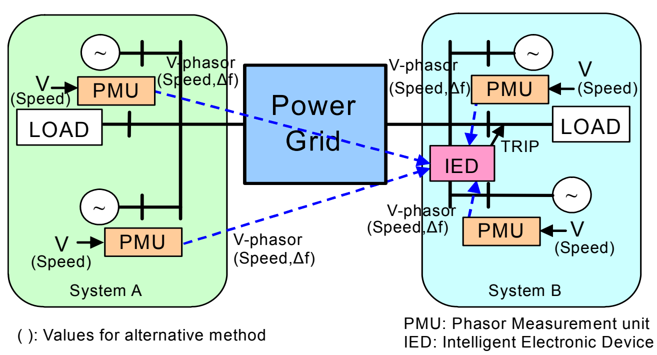
Wide Area Controls Use Case
IEC 61850-90-5



Actor Name	Role description
PMU	Computes synchrophasors & frequency
SPDC	Substation Phasor Data Concentrator – collects, aligns, selects, & possibly decimates data from several PMUs in the substation
PDC	Phasor Data Concentrator – collects, aligns, selects, & possibly decimates data from several PMUs or other PDCs
Controller	Receive data from the local PDC & execute algorithms that implement control functions
System control equipment	Power system control elements including breakers, switches, FACTS power controllers, DC controls, and similar equipment

Power & Energy Society® Hydro-Québec IEEE

Wide Area Predictive Stability Controls Use Case
IEC 61850-90-5



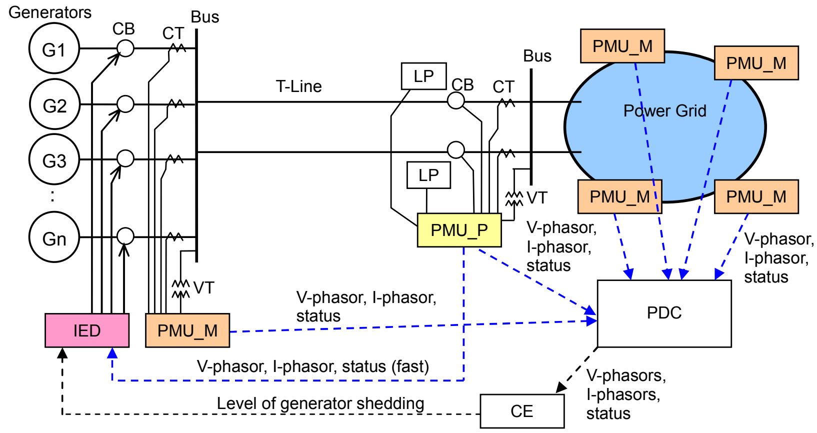
( ): Values for alternative method

PMU: Phasor Measurement unit
IED: Intelligent Electronic Device

Name	Role description
PMU	Computes synchrophasors
IED	Receives data from PMUs, predicts dynamic stability & power system control

PES Power & Energy Society® Hydro-Québec IEEE

Use case diagram for WAMPAC
IEC 61850-90-5



LP: Line Protection relay, PDC: Phasor Data Concentrator, CE: Center Equipment

PMU Delay Requirements
IEC 61850

Factor		Reporting rate range	End-to-end latency	Measurement timing error	Sensitivity to transmission jitter	Sensitivity to lost packets
Sync-check		≥ 4/s	100 ms	50 µs	Medium	High
Adaptive relaying		≥ 10/s	50 ms	50 µs	Low	Medium
Out-of-step protection		≥ 10/s	50 ms – 500 ms	50 µs	Medium	Medium
Situational awareness		1/s to 50/s	5 s	50 µs	Low to medium	Low to medium
State-estimation & security assessment		1/300s to 10/s	5 s	50 µs	Low	Medium
Data archiving		Any	N/A	50 µs	Low	Medium
Wide area controls		≥ 10/s	50 ms – 500 ms	50 µs	Medium	High
Predictive Dynamic Stability Maintaining System		≥25/s or 30/s	50ms	50µs	Medium	High
Under Voltage Load Shedding		≥25/s or 30/s	100ms	50µs	Low	High
Phenomenon assumption type WAMPAC	PMU to PDC	1/s to 10/s	5s	50µs	Low to medium	Low to Medium
	PMU to IED	50/s or 60/s	20ms	50µs	Medium	High

PMU for WAPSS : Hydro-Québec Requirements (1)

	D. Trudnowski and BPA	Hydro-Québec
Gain (interference)	<-40 dB beyond Nyquist frequency	<-40dB beyond Nyquist frequency
	<-60dB for harmonics at n×[fc-2, fc+2], n≥1 with fc the fundamental frequency	<-40dB at n×fc, n=2..11 with notch at changing harmonics. fc is fundamental frequency
Gain (modulation)	<-40 dB beyond Nyquist frequency	<-30dB beyond Nyquist frequency
	<0.5-dB ripple below 1.5Hz	<1dB peak resonance (10%) in pass band
	3-dB bandwidth >5Hz	3-dB bandwidth >6Hz
Phase (modulation)	Start 0° at DC	Start 0° at DC
	>-20° below 2Hz (i.e. phase lag is not larger than 20° below 2Hz)	Phase lag not larger than that of a 40-ms time constant from 0 to 3Hz
	Linear phase in the pass-band	Linear phase in the pass-band
Step (modulation)	Rise time to 90%≤50msec	Rise time to 95%≤70ms
	Overshoot≤10%	Overshoot≤10%
	2% settling time<3×peak time	0.5% settling time ≤ 3× rise time to 95%

Hydro-Québec

Hydro-Québec

PMU for WAPSS : Hydro-Québec Requirements (2)

- **Device configuration.** The number of inputs is application dependent.
  1. Most SPS are designed with a "corridor" concept in mind. Each corridor has three lines with shunt inductance. The minimum number of 3-phase currents is 6 (12 single phase currents).
  2. Measurement of four three-phase voltage required at most substations : three line voltage (CCVT) and one bus PT voltage (MAIS)
  3. Digital inputs for line outage detection and distance relay output signals (at least 6 inputs)
  4. C37.118.1 Class M and P accuracy with two to four simultaneous output streams

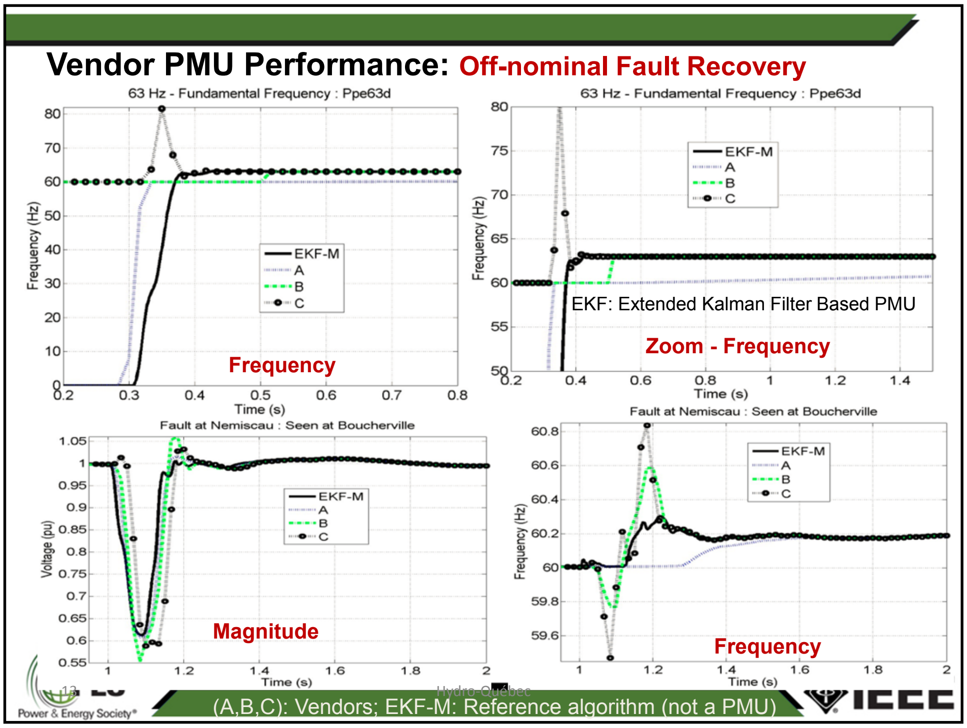
PMU requirements under faults

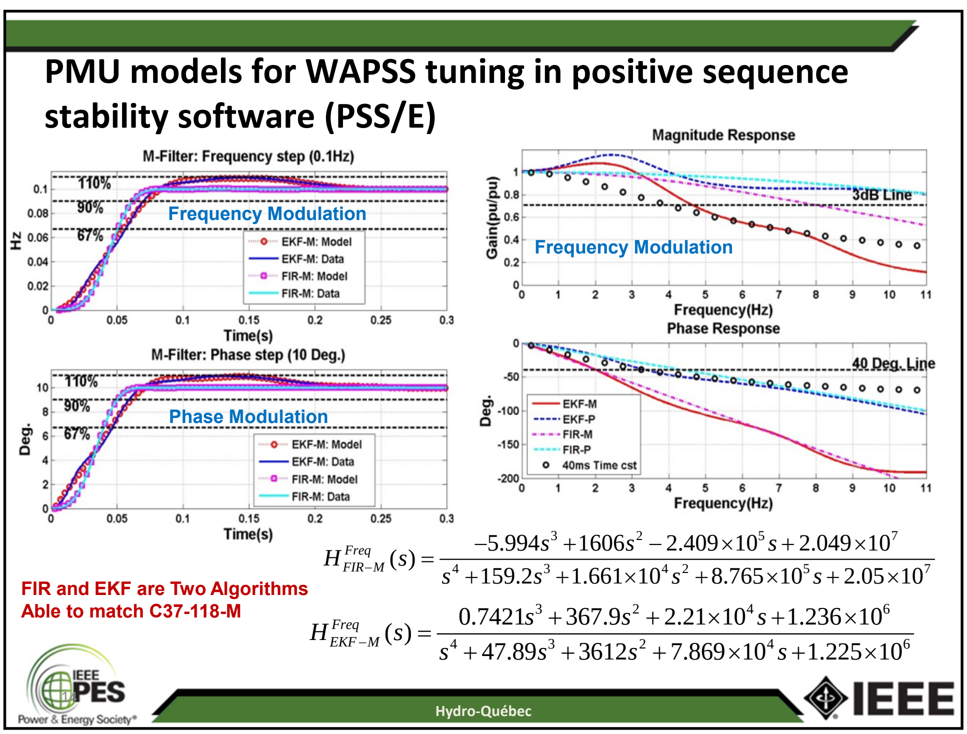
1. No specific requirement yet
2. An obligation to "minimize" fault induced glitches on angle, frequency and ROCOF measurements during and shortly after switching (best effort).

PDC requirement for WACS

1. PDC data transit time of 1ms and End-to-end latency of 50ms (in addition to PMU processing and filtering latency) from a PMU site to the control site through the PDC (including time-alignment and any data buffering overhead in the PDC).
2. Private dedicated Ethernet links with dual independent routing: round-trip transmission delay of 2 cycles (1000 km x 2)

Hydro-Québec

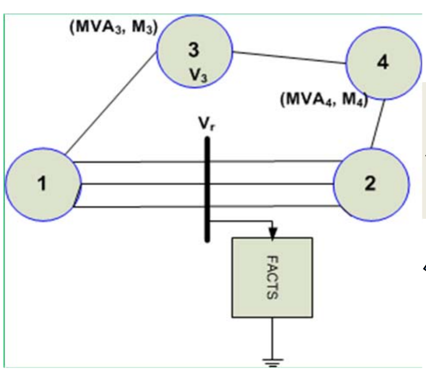

Vendor PMU Performance: Off-nominal Fault Recovery
63 Hz - Fundamental Frequency : Ppe63d
Frequency (Hz)
Time (s)
EKF-M
A
B
C
Frequency
63 Hz - Fundamental Frequency : Ppe63d
EKF: Extended Kalman Filter Based PMU
Zoom - Frequency
Fault at Nemiscau : Seen at Boucherville
Voltage (pu)
Magnitude
Fault at Nemiscau : Seen at Boucherville
Frequency
Power & Energy Society
(A,B,C): Vendors; EKF-M: Reference algorithm (not a PMU)
IEEE


PMU models for WAPSS tuning in positive sequence stability software (PSS/E)
M-Filter: Frequency step (0.1Hz)
110%
90%
67%
Frequency Modulation
EKF-M: Model
EKF-M: Data
FIR-M: Model
FIR-M: Data
Time(s)
M-Filter: Phase step (10 Deg.)
Phase Modulation
Magnitude Response
Gain(pu/pu)
3dB Line
Frequency(Hz)
Phase Response
40 Deg. Line
EKF-M
EKF-P
FIR-M
FIR-P
40ms Time cst
$H_{FIR-M}^{Freq}(s)=\frac{-5.994s^3+1606s^2-2.409\times10^5 s+2.049\times10^7}{s^4+159.2s^3+1.661\times10^4 s^2+8.765\times10^5 s+2.05\times10^7}$
FIR and EKF are Two Algorithms Able to match C37-118-M
$H_{EKF-M}^{Freq}(s)=\frac{0.7421s^3+367.9s^2+2.21\times10^4 s+1.236\times10^6}{s^4+47.89s^3+3612s^2+7.869\times10^4 s+1.225\times10^6}$
IEEE PES
Power & Energy Society
Hydro-Québec
IEEE

Wide-Area Control Assessment

- Proposed Small-Signal Analysis Methodology:
  - Angle-shifts between FACTS neighboring busses are local signals while Remote angle-shifts are wide-area signals
  - Control loop efficiency is compared in terms of the joint observability/controllability measure of the competing scenarios.
  - The higher this measure, the more effective the control will be.
- Statistical confirmation of global control dominance using large perturbations on a production scale network (PSS/E)

Technical Gain Definition



$$\Delta\theta_{Local} = \begin{bmatrix} \theta_r - \theta_1 \\ \theta_r - \theta_2 \end{bmatrix}$$

Local Variables

$$\Delta\theta_{Remote} = \begin{bmatrix} \theta_1 - \theta_{coi} \\ \theta_2 - \theta_{coi} \\ \theta_3 - \theta_{coi} \\ \theta_4 - \theta_{coi} \end{bmatrix} \qquad \theta_{coi} = \frac{\sum_i \theta_i M_i}{\sum_i M_i}$$

Global Variables

Linearized model (A,B,C,D)

$$\begin{cases} \dot{x}(t) = Ax + Bu(t) \\ y = Cx(t) \end{cases}$$

1 input x 6 outputs

- Local loop: (in, out)=(l, l) the SVC variables
- Global Loop: (in, out)=(l, j) with j the remote variable

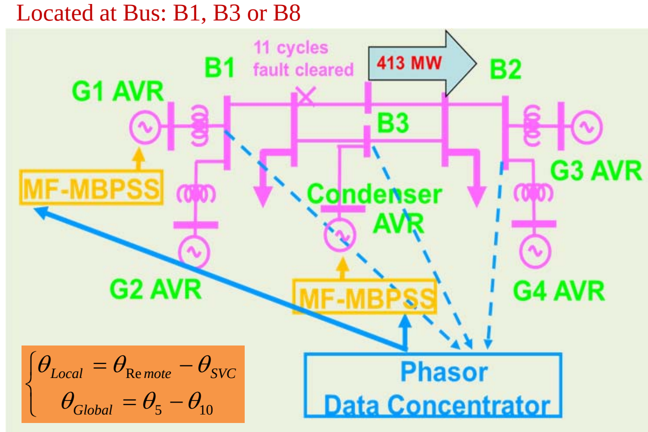
$$TechnicalGain(l, j) = \frac{\left\| R_k^{Global}(l, j) \right\|}{\left\| R_k^{Local}(l, l) \right\|}$$

$R_k(l, j)$= mode k residue, giving the j-th output signal

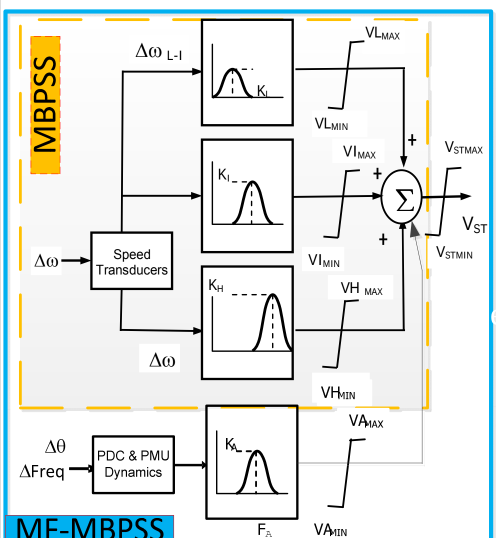
Test Networks with shunt compensators

- Two times more observability for the Wide-area signal
- Tow times more controllable at the sending & receiving end than at in midlle
- Controllability & Observability phase shape are reversed under reversed power transfer.

SVC or Synchronous Condenser
Located at Bus: B1, B3 or B8



WAPSS structure and Settings



WAPSS Structure

$$PSS = \underbrace{H^{Freq}_{EKF-M}}_{PMU\ \ Dynamics} \times \underbrace{\left(\frac{1}{1+sT_{PDC}}\right)}_{PDC\ \ Dynamics} \times K_l \times 66\left(\frac{sT_w}{1+sT_w}\right)\left(\frac{1+sT_{l1}}{1+sT_{l2}} - \frac{1+sT_{l7}}{1+sT_{l8}}\right)$$

$$\begin{cases} K_l = 12;\ T_w = 0.3s;\ T_{PMU} \approx Time\ Delay = 3cy; \\ T_{l1} = 0.0833s;\ T_{l2} = T_{l7} = 0.1s;\ T_{l8} = 0.12s \end{cases}$$

The Design Problem

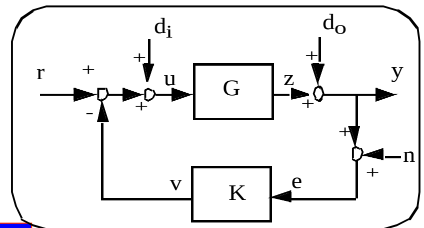
$$\min_{p} J(p) \quad \text{Subject to} \quad \{C_1, C_2, C_3, C_4\}$$

$$\max\{Re(\lambda_k)\} < 0 \qquad (C1)$$

$$\begin{cases} M_S \le 2 & M_T \le 1\cdot 5 \\ GM \ge 2 & PM \ge 30^o \end{cases} \qquad (C2)$$

$$M_U = \|K(j\omega)S(j\omega)\|_\infty \le u_{max} \qquad (C3)$$

$$N_L(F_{LF}) \le -20\,dB \qquad N_H(F_{HF}) \le -20\,dB \qquad (C4)$$

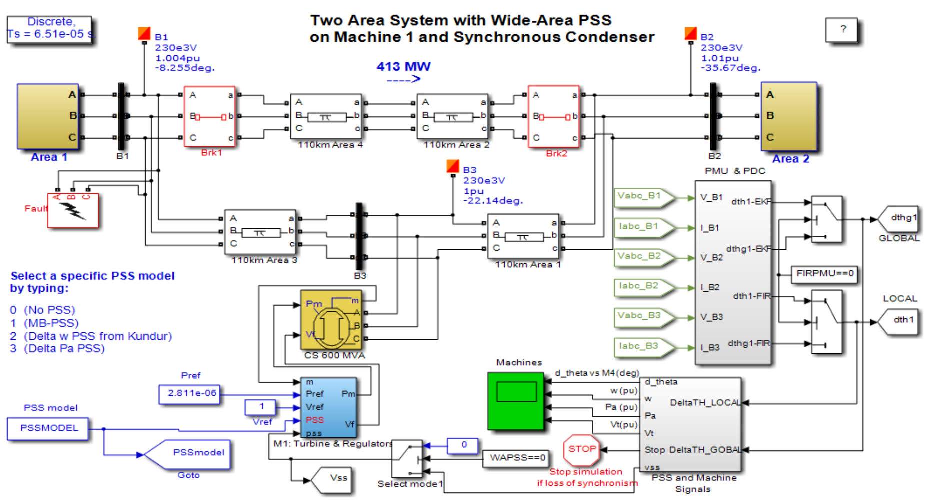


$$S = (I + GK)^{-1} \quad T = SKG \quad U = SG$$

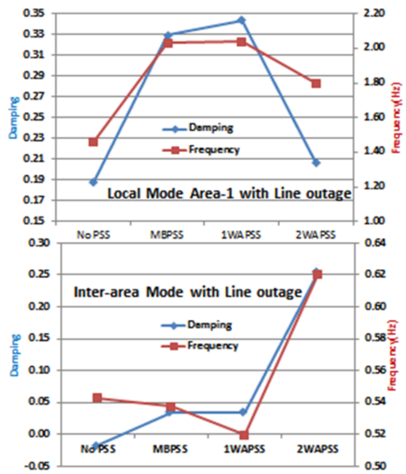
$$M_S = |S(j\omega)|_\infty \qquad M_T = |T(j\omega)|_\infty$$

- **J(p) is the Modal Performance Measure = Integral of the surface between upper-lower envelopes of exp($Re(\lambda_k)$t)**

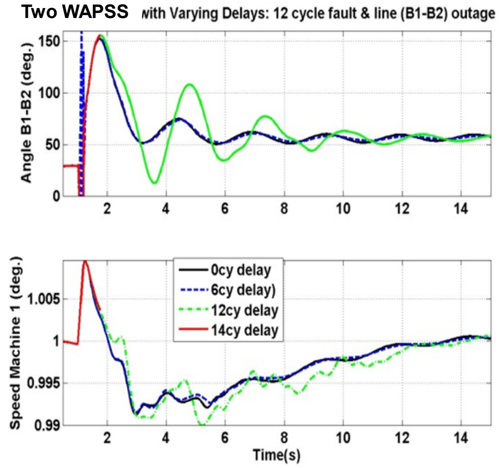
EMT simulation of WAPSS in SimPowerSystems with Software PMU: Test System



EMT based WAPSS Performance on Two-Area Four Machine Test System



Two WAPSS with Varying Delays: 12 cycle fault & line (B1-B2) outage

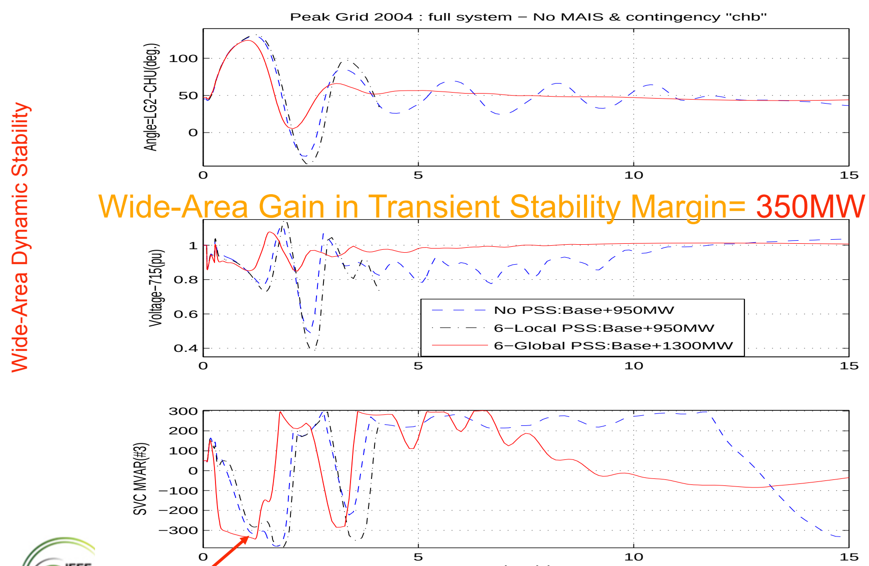


Small Signal performance

Electromagnetic Transient Simulation with Software PMU and Transmission delay

Hydro-Québec

Contingency "chb" : No Gain from Local PSS

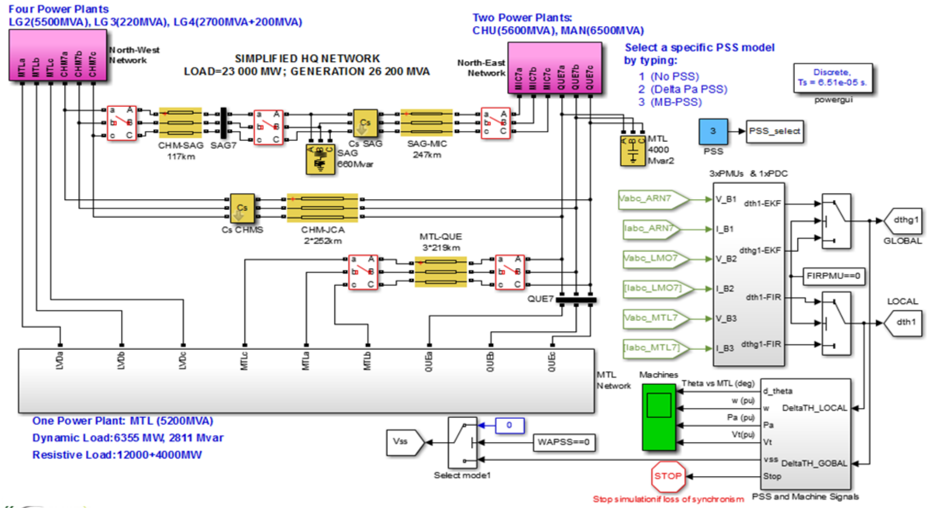


Wide-Area Dynamic Stability

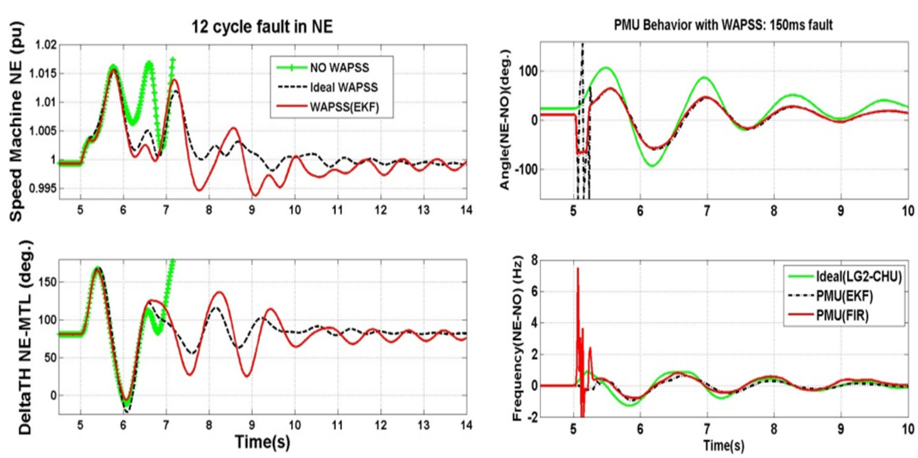
Fast/Massive VAR injection→ Carson Taylor WACS

Hydro-Québec

EMT simulation of WAPSS in SimPowerSystems with Software PMU: Reduced Hdro-Québec network



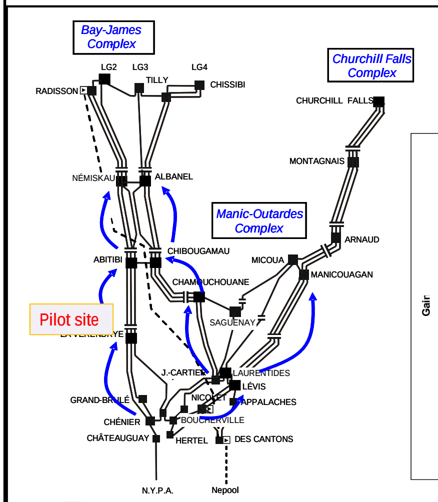
EMT based WAPSS Performance on Reduced HQ Network



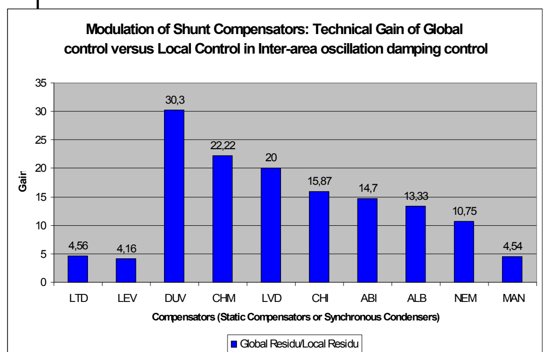
WAPSS performance when the Hydro-Québec EMT model is subjected to an 11-cycle duration contingency.

EKF vs FIR-PMU behavior on Hydro-Quebec EMT model

Distributed VAR support near voltage collapse can be quite effective



1. Controlability : Load bus voltage response to a shunt compensator set-point change
2. Observability: Shunt compensator bus voltage response to a load voltage change

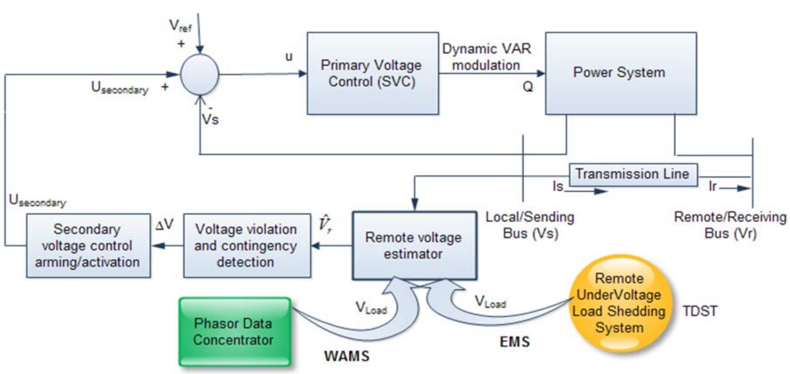


Shunt compensator bus

SVC set-point modulation using an estimate of the remote voltage error

Power & Energy Society — Hydro-Québec — IEEE

Mathematics of the secondary voltage control: Distributed *vs* Wide-Area Sensors



Distributed Soft-Sensor

$$\Delta V_{Distributed} = |\vec{V}_s| - |\vec{V}_r|$$

$\vec{V}_r$ **Estimated from** $\vec{V}_s, \vec{I}_s$ **and line model**

Wide-Area Soft-Sensor

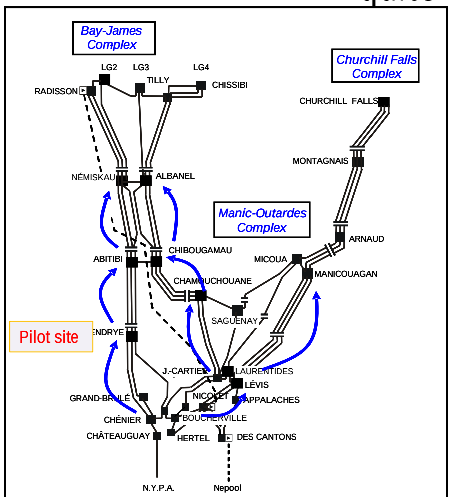
$$\Delta V_{Wide-Area} = |\vec{V}_s| - |\vec{V}_{Load}|$$

$\vec{V}_{Load}$ **is measured by WAMS or EMS**

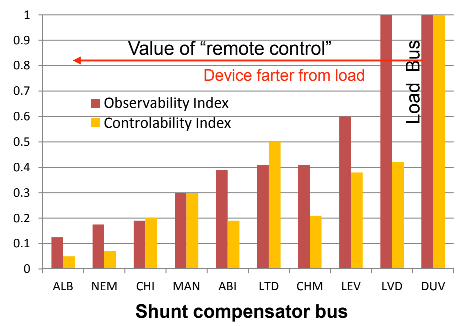
Remote voltage is estimated locally or obtained through a WAMS or EMS

Power & Energy Society — Hydro-Québec — IEEE

Distributed VAR support near voltage collapse can be quite effective



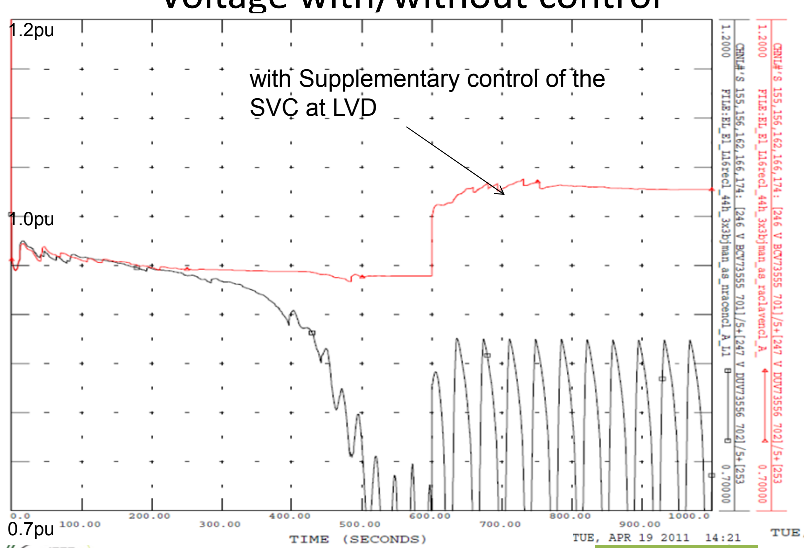
1. Controlability : Load bus voltage response to a shunt compensator set-point change
2. Observability: Shunt compensator bus voltage response to a load voltage change



SVC set-point modulation using an estimate of the remote voltage error

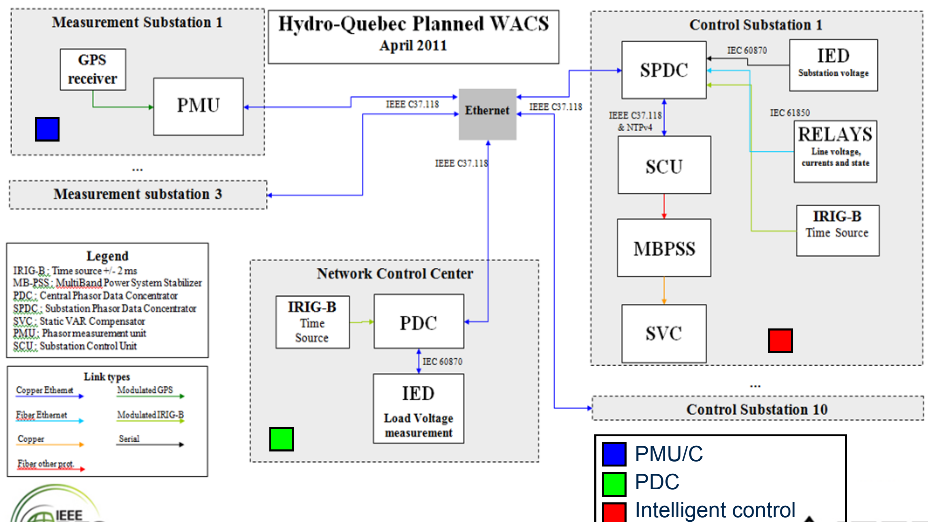
IEEE PES Power & Energy Society — Hydro-Québec — IEEE

Sample case for Simulator Playback: Load Voltage with/without control



IEEE PES Power & Energy Society — Hydro-Québec — IEEE

WACS Experiment Architecture : Voltage stability control

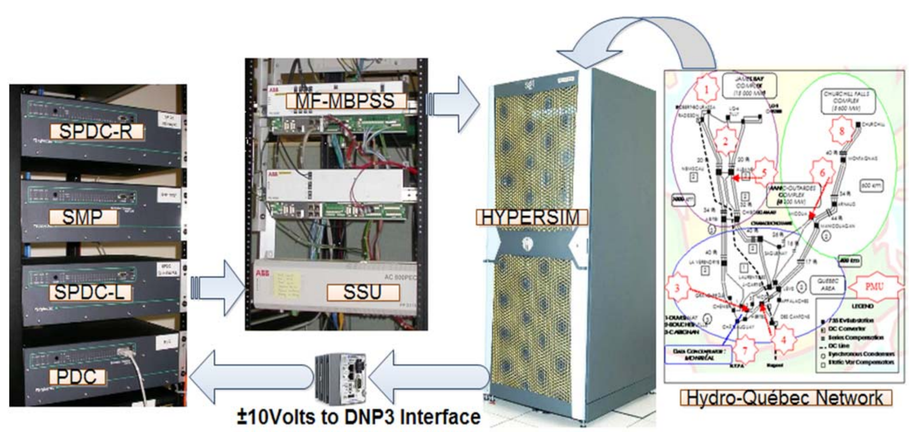


IEEE PES Power & Energy Society®

Hydro-Québec

IEEE

Real-time Simulator Configuration for Playback and Feeback-in-the-Loop Tests



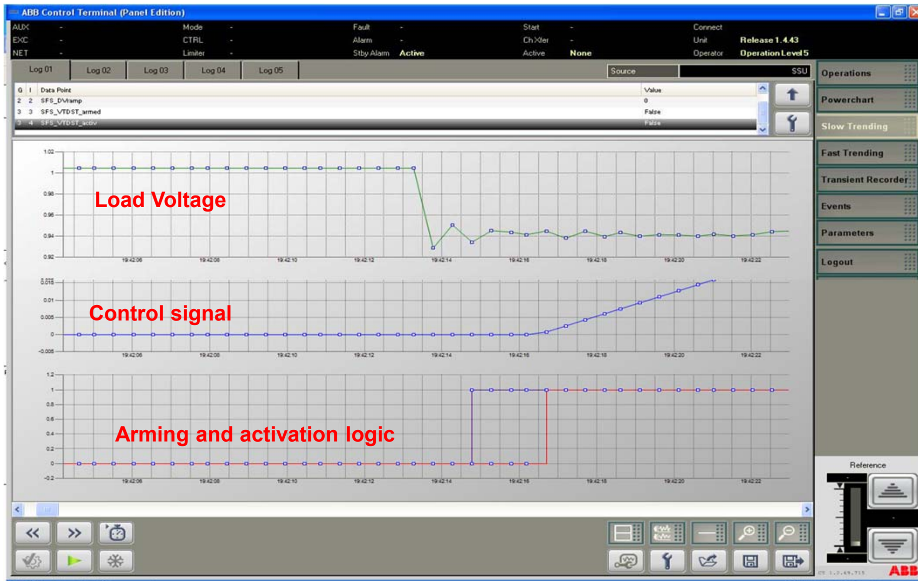
Proof-of-Concept

IEEE PES Power & Energy Society®

Hydro-Québec

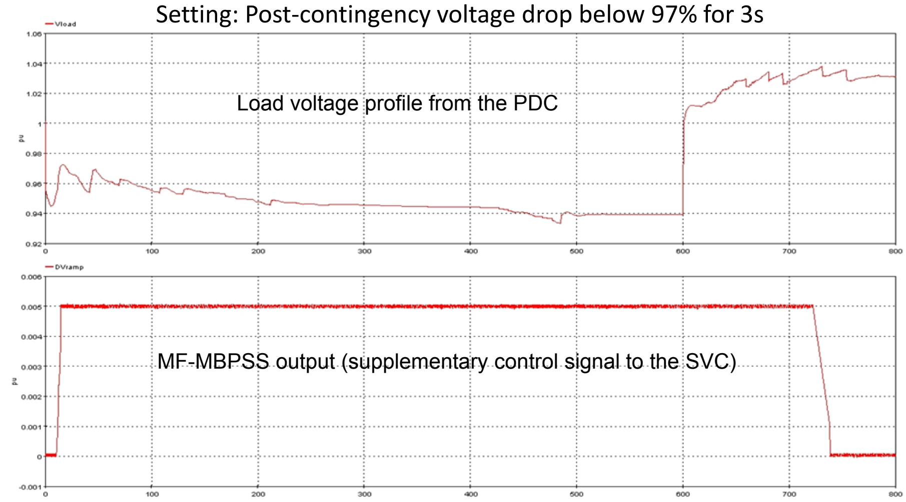
IEEE

Arming and Activation of the Voltage Set-Point Controller

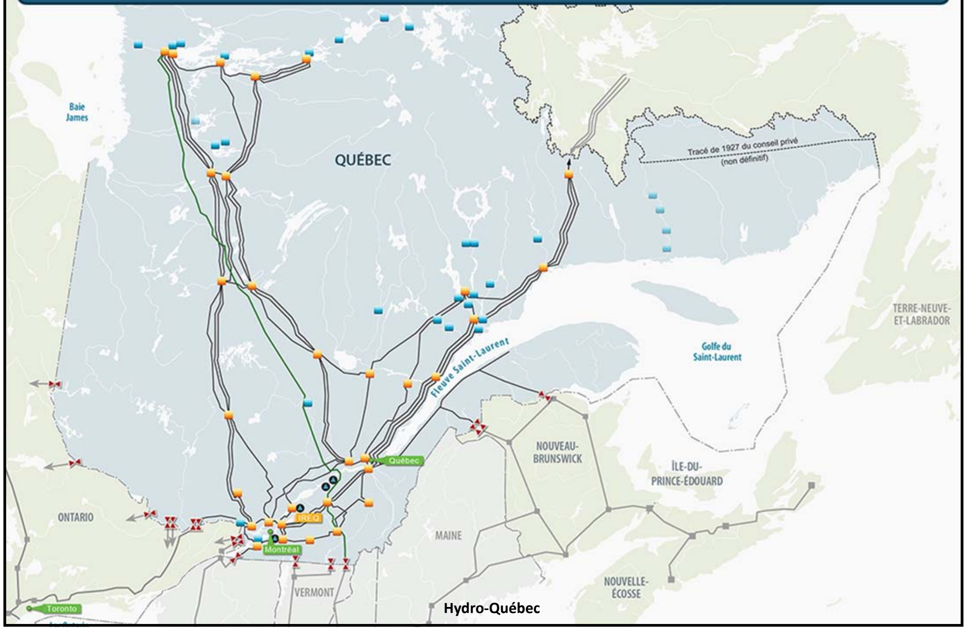


Hypersim records of the WACS order to the SVC during a load voltage collapse event

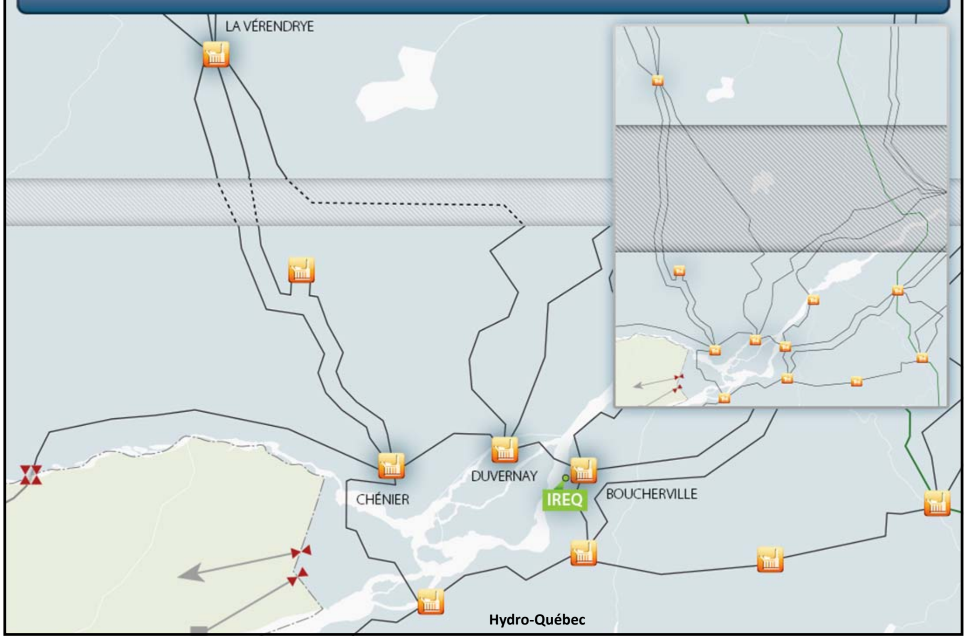
Setting: Post-contingency voltage drop below 97% for 3s



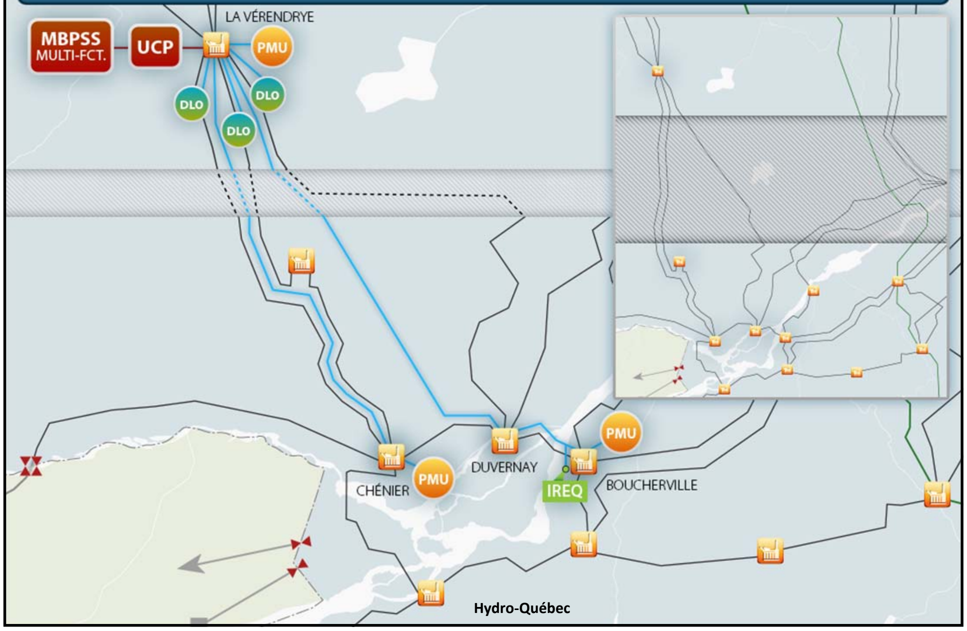
Context of transfer capacity Increase at Hydro-Québec



Field experiment



Field Experiment - Continued



Moving forward

Status

> **Done (May 2013)**
- PDC, SPDC, SCU, MF-MBPSS
- Telecom network design and delay assessment
- First playback tests on the Hypersim network simulator

> **Next (July 2013-Dec 2014)**
- Open-loop field test of the PDC-based wide-area secondary voltage control
- Closed-Loop field test of the local/distributed secondary voltage control

Bottom Line

> **Big immediate gains in voltage stability constrained transfer limits and power exchanges with the United States (400 to 2000MW)**

> **Deferral of capital investments in dynamic reactive power compensation infrastructure (50M$ per SVC)**

> **Deployment of a robust backbone for wide-area PSS (damping-control)**

IEEE PES Power & Energy Society

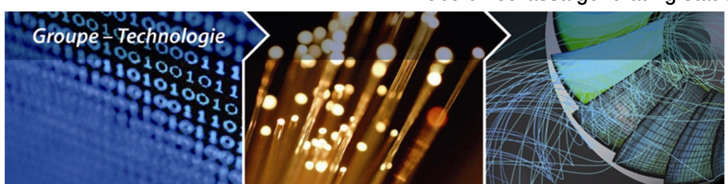
Hydro-Québec

IEEE

Thanks

735 kV lines near the 5 616MW
Robert-Bourassa generating station

Hydro Québec



IEEE PES Power & Energy Society®

Hydro-Québec

IEEE

IEEE PES GM, Vancouver, 23 July 2013
Tutorial on "Synchrophasor Fundamentals and Applications: Leveraging the Investment"

"Wide-Area Control"

Kjetil Uhlen,
NTNU
Norwegian University of Science and Technology
kjetil.uhlen@ntnu.no

1

Outline

- Possibilities and need for Wide Area control
- Design of "Wide Area" Power Oscillation Damping Controllers
- Prototype implementation of a WAPOD
- Concluding remarks

2

Outline

- **Possibilities and need for Wide Area control**
- Design of "Wide Area" Power Oscillation Damping Controllers
- Prototype implementation of a WAPOD
- Concluding remarks

Promising applications of phasor measurements

- Improved measurements (frequency, voltage angle)
- Improve state estimation
- Improve power system security assessments
  - Power quality monitoring (e.g. voltage flicker)
  - enables monitoring of dynamic (stability) properties
    - Voltage stability indices
    - Angle stability indices
- Improved control
    - Coordinated voltage control (e.g. optimal utilisation of SVCs)
    - Stability control (e.g. use of $\Delta\theta$ instead of *P*)
    - (Adaptive) system protection
- Improved protection (e.g. fault location in networks with coil compensated grounding of transformer neutrals)

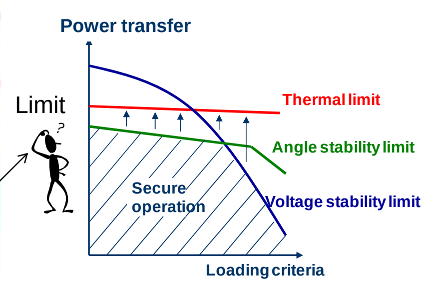
For on-line operation, disturbance analysis and model validation

When and how to utilize PMUs and WAMS for power system control?

- When there is a need for
  - system wide information (more than just local information) AND
  - high resolution dynamic information AND/OR
  - time synchronized measurements
- Power oscillation damping
- Frequency instability (out of step) protection
- Emergency control / System integrity protection schemes
- Voltage collapse protection (based on fast detection of voltage instability problems)
- How:
  - Power system stabilisers (coordinated design)
  - Control of SVC/FACTS and HVDC (active and reactive power control)
  - Controlled islanding / Network splitting (breaker control)
  - Generator tripping / Load shedding

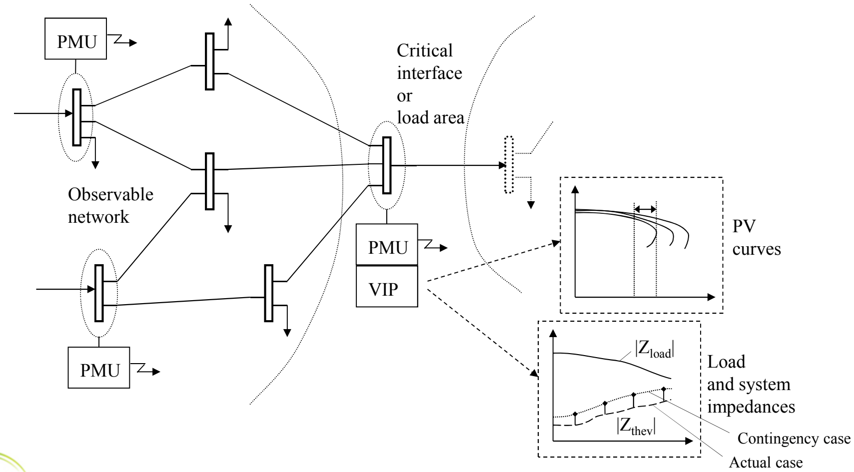
Motivation → Maintaining security by managing transmission limits..

- ***Capacity limits*** in transmission planning
- ***Available transmission capacity*** in operation planning (as given to market operator)
- ***Power transfer limits*** in on-line operation



6

Examples: State estimation and on-line voltage stability monitoring



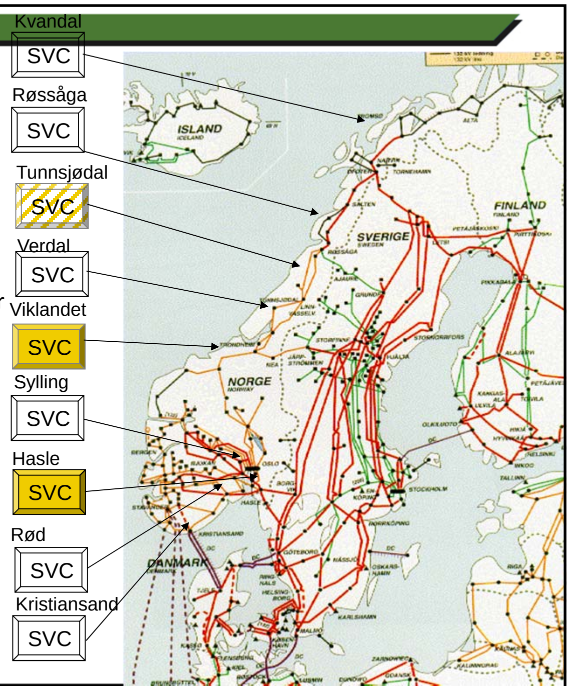
Outline

- Possibilities and need for Wide Area control
- **Design of "Wide Area" Power Oscillation Damping Controllers**
- Prototype implementation of a WAPOD
- Concluding remarks

"Wide-area POD"

Goals:

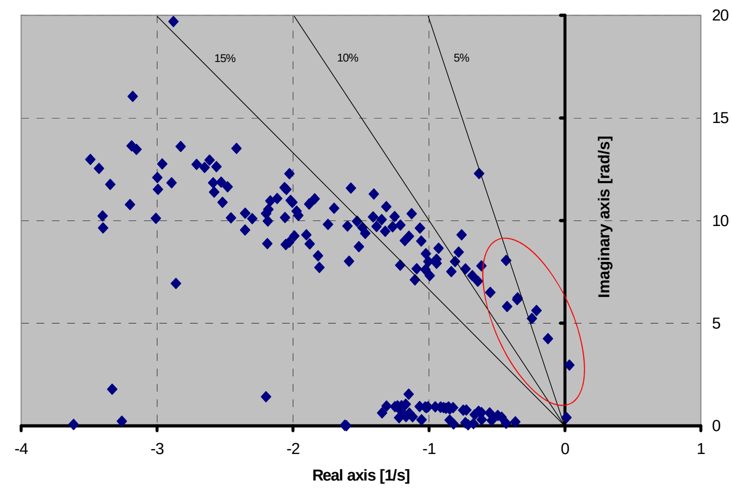
- Study the use of PMUs as measurement signals,
- Investigate coordinated stabilizer design, using SVCs
- Identify benefits and challenges with wide area measurements, compared to traditional local measurements



"Wide-area POD" design

- To improve **damping of low frequency inter-area modes**:
  - Targeting more than one mode: Two main inter-area modes of interest (approximately at 0.3 Hz and 0.5 Hz)
- **Observability**: New measurements available by utilizing the **PMUs**
- **Controllability**: Several **SVCs** available (see map)
- **Robust design**: Ability to improve damping in a largest possible range of operating conditions.
- **Coordinated design**: Avoid adverse interactions (between different SVCs)

Nordic system model
Electromechanical modes - eigenvalues



Modal Analysis

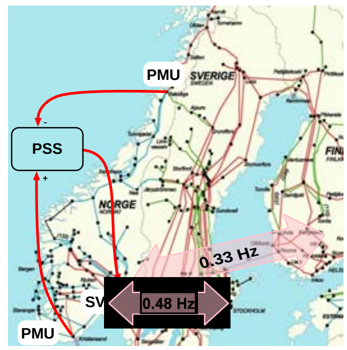
- Summary
  - Identified and classified oscillatory modes

Oscillatory Frequency	Relative Damping	Mode Classification	Main Observability Area
0.33 Hz	**5.40 %**	**Inter-area mode**	**Finland / Southern Norway**
0.48 Hz	**2.48 %**	**Inter-area mode**	**Sweden / Southern Norway**
0.55 Hz	3.39 %	Local area mode	Northern Norway
0.62 Hz	6.20 %	Inter-area mode	Sweden / Central Norway
0.76 Hz	1.48 %	Local area mode	Western Norway

Coordinated Stabilizer Design

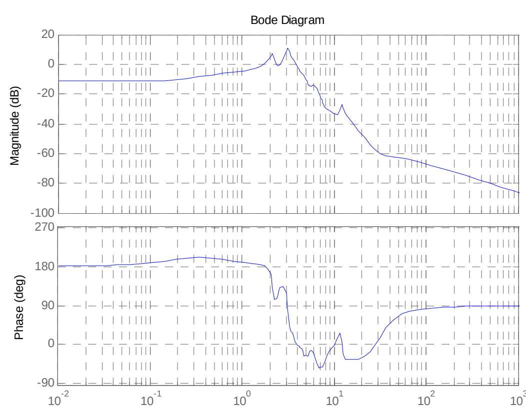
- Control-loop design
  - Wide-area controllers

SVC	Observation variable
Sylling	Voltage angle difference: Kristiansand – Nedre Røssåga
Rød	Voltage angle difference: Kristiansand – Nedre Røssåga

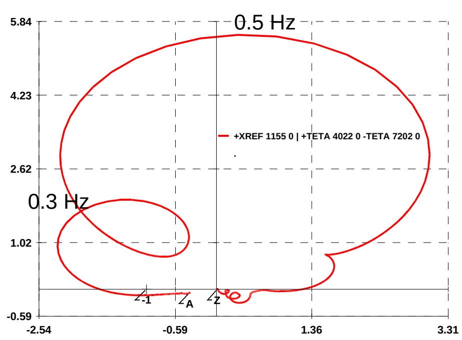


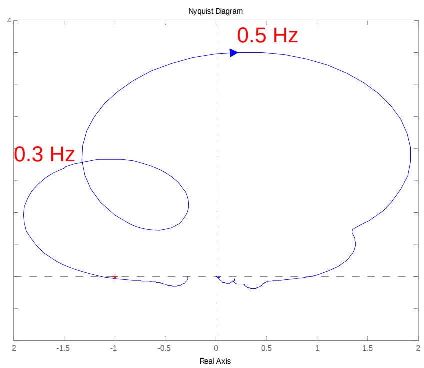
Transfer function

Frequency response of linearised model



Model identification (Nyquist plots)



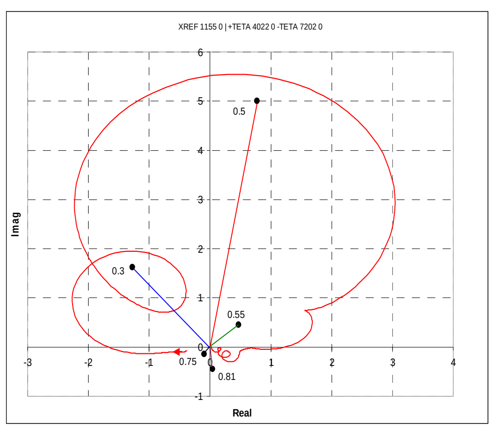


PacDyn (Large model)

Reduced model by Subspace identification

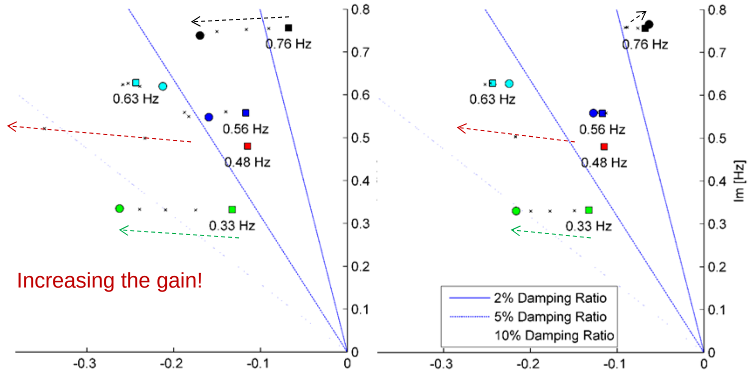
[Ref]: Korba, Uhlen: “Wide-area monitoring of electromechanical oscillations in the Nordic power system: practical experience”, IET Gener. Transm. Distrib., 2010, Vol 4, Iss. 10

Transfer function residues



Coordinated Stabilizer Design

- Controller design and tuning
  - Tuning of gain and analysis of adverse effects



Root-locus plots: Wide-area measurements **Local measurements**

Conclusions from simulations

- Stabilizers with local or wide area measurements considerably improves damping of inter-area power oscillations
- Wide-area solution can be more robust with better performance
  - for wider range of operating scenarios
  - and subject to larger disturbances
- Remote PMU measurements enhances observability
  - Simplifying stabilizer design
  - Improving damping on wider range of modes
- Potential PMU challenges: Availability and communication delays
  - Suggested solution: dual input solution
    - Possibility of fall-back to local signals
    - Provides increased robustness

Outline

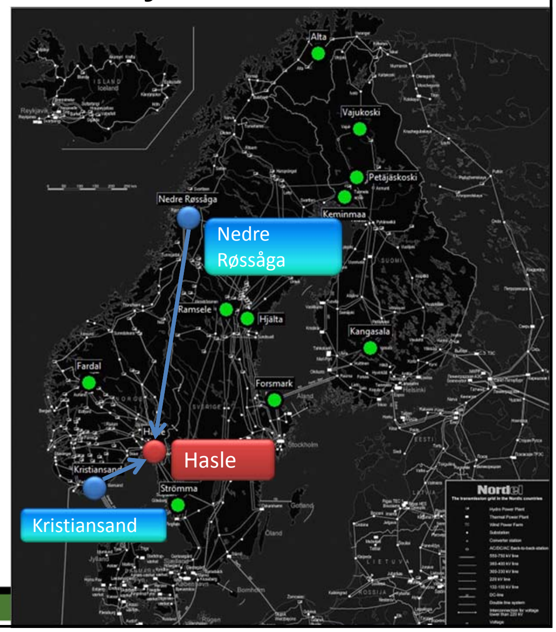
- Possibilities and need for Wide Area control
- Design of "Wide Area" Power Oscillation Damping Controllers
- **Prototype implementation of a WAPOD**
- Concluding remarks

Field test of WA-POD in Hasle

- Field test in Hasle substation 8 November 2011-11-15.
- Purpose: Test and verification of Wide Area Power Oscillation Damper (WA-POD) on a 180 Mvar TCR Static Var Compensation unit in Hasle.
- System damping measured and analysed during disconnection and re-connection of the 420 kV line Hasle-Tegneby.
- Performance of WA-POD was tested and compared against ABB's state of the art Phasor-POD and the case without any power oscillation damper.

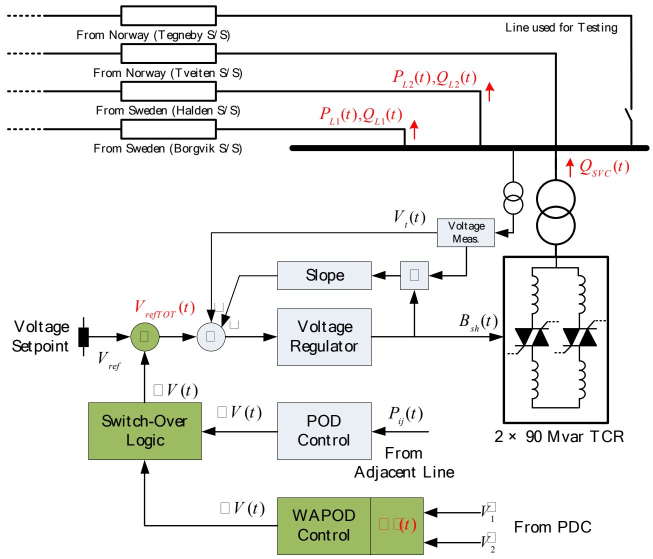
Wide area measurements *for POD Control*

- PMUs streaming phasors from:
  - Nedre Røssåga
  - Kristiansand
- SVC Located at Hasle
  - PDC receiving voltage phasors
    - Extracts voltage phasor angle
  - ABB Mach2 Controller
    - Local control
    - WAPOD Control
    - Switch-over logic

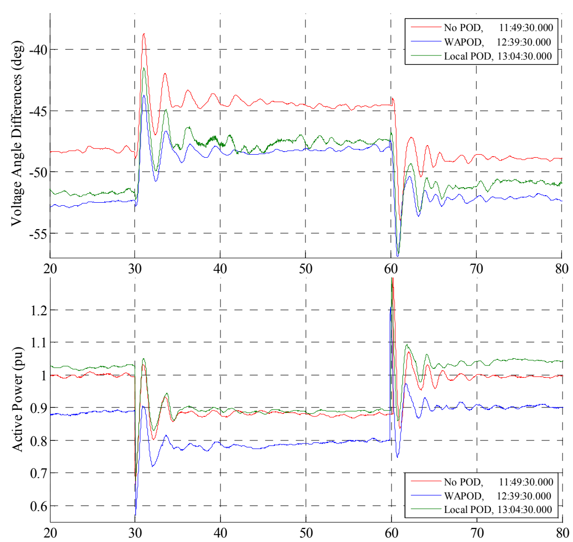


Hasle SVC (4x90 Mvar TCR)

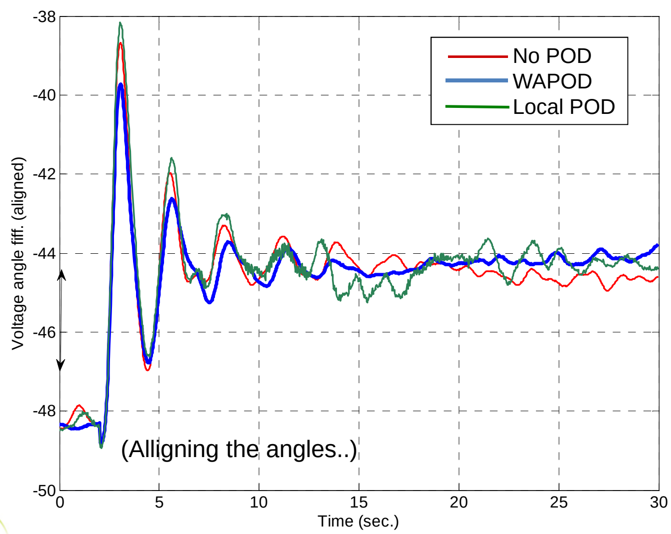
SVC and WA-POD implementation



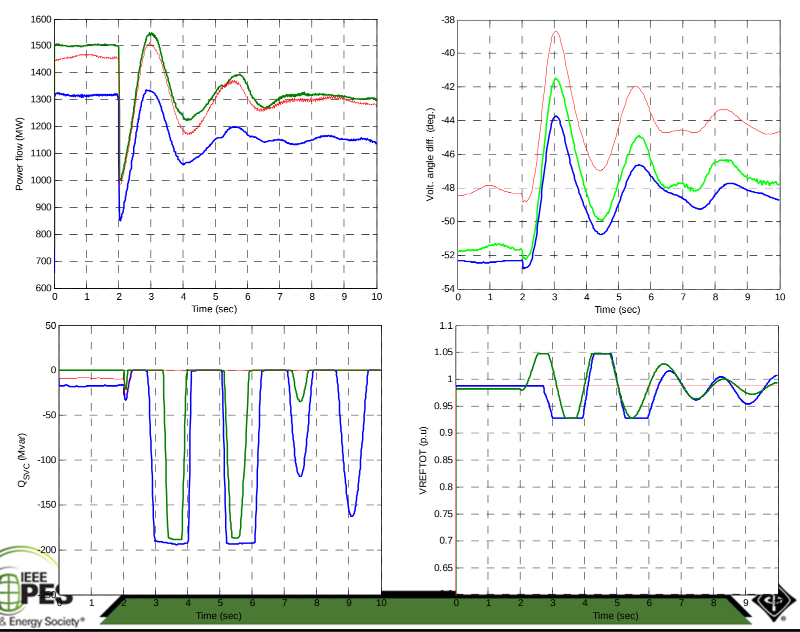
Test: Switching of 420kV Hasle-Tegneby



Disconnection of 420 kV Hasle-Tegneby



Disconnection of 420 kV Hasle-Tegneby

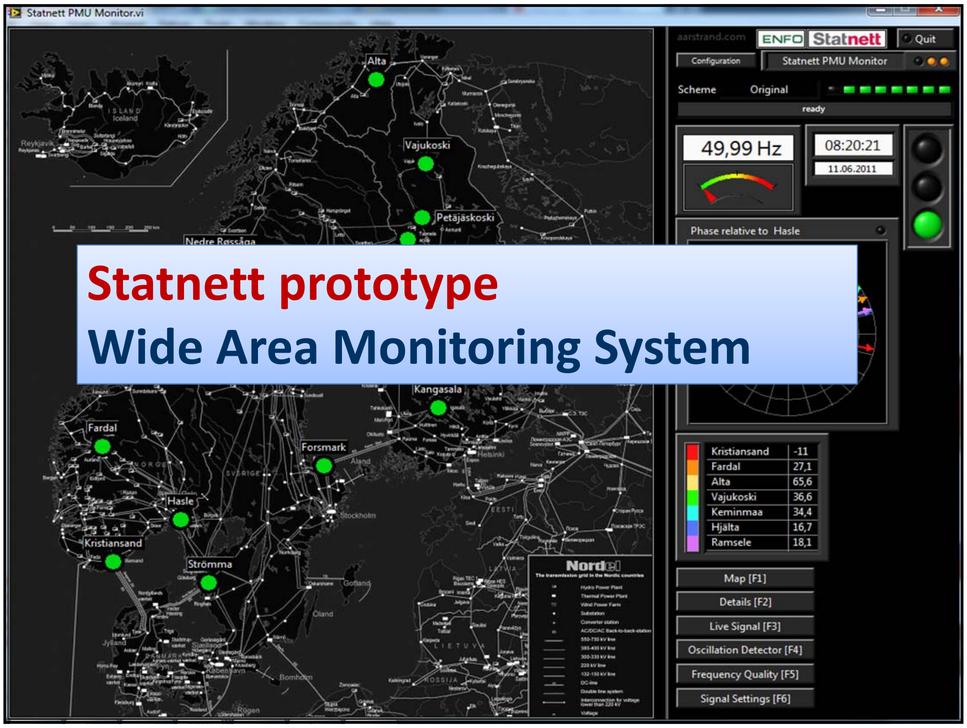


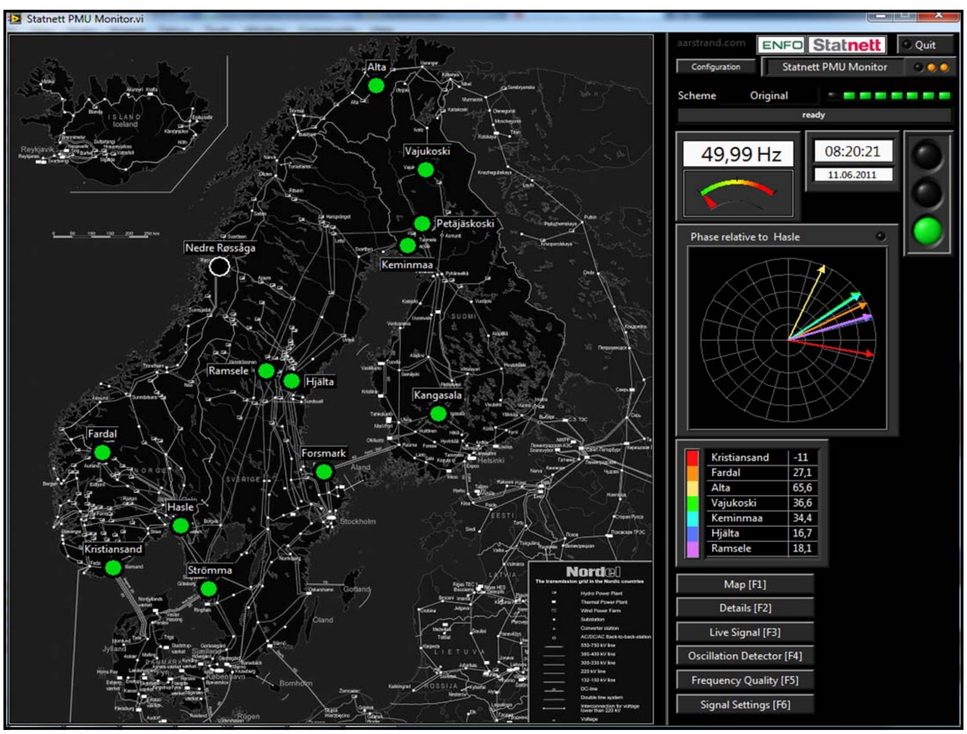
Outline

- Possibilities and need for Wide Area control
- Design of "Wide Area" Power Oscillation Damping Controllers
- Prototype implementation of a WAPOD
- **Concluding remarks**

Conclusions from tests

- ***The main conclusion is that the WA-POD performed as intended and fully according to expectations.***
- System damping was clearly improved compared to the case without POD.
- The performance depends on the actual tuning of the compensators and the availability of good local measurements.
- ***The flexibility provided by the WA-POD to select the best measurements from available PMUs as control inputs can be an advantage.***
- End-to-end latency due to communication was mainly insignificant (in the order of 30 milliseconds)


Statnett prototype
Wide Area Monitoring System
Statnett PMU Monitor.vi
aarstrand.com
ENFO
Statnett
Quit
Configuration
Statnett PMU Monitor
Scheme
Original
ready
49,99 Hz
08:20:21
11.06.2011
Phase relative to Hasle
Kristiansand -11
Fardal 27,1
Alta 65,6
Vajukoski 36,6
Keminmaa 34,4
Hjälta 16,7
Ramsele 18,1
Map [F1]
Details [F2]
Live Signal [F3]
Oscillation Detector [F4]
Frequency Quality [F5]
Signal Settings [F6]
Alta
Vajukoski
Petäjäskoski
Nedre Røssåga
Kangasala
Fardal
Forsmark
Hasle
Kristiansand
Strömma
Nordel


Statnett PMU Monitor.vi
aarstrand.com
ENFO
Statnett
Quit
Configuration
Statnett PMU Monitor
Scheme
Original
ready
49,99 Hz
08:20:21
11.06.2011
Phase relative to Hasle
Kristiansand -11
Fardal 27,1
Alta 65,6
Vajukoski 36,6
Keminmaa 34,4
Hjälta 16,7
Ramsele 18,1
Map [F1]
Details [F2]
Live Signal [F3]
Oscillation Detector [F4]
Frequency Quality [F5]
Signal Settings [F6]
Alta
Vajukoski
Petäjäskoski
Nedre Røssåga
Keminmaa
Ramsele
Hjälta
Kangasala
Fardal
Forsmark
Hasle
Kristiansand
Strömma
Nordel

Experiences and concluding remarks

- Several WAMS-applications have been assessed and tested by the Norwegian TSO (Statnett)
- Power oscillation monitoring (POM) is considered most useful by operators
- Measurements have been valuable for post-disturbance analysis
  - Cause of oscillations easily identified from PMU measurements
- Promising experiences with on-line POM
  - Amplitude, frequency and damping signals are robust when needed
- SVCs are shown to provide significant controllability on power oscillations:
  - A "Wide area POD" has been implemented and tested.

IEEE PES Power & Energy Society

IEEE