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ABB Protective Relay School Webinar Series
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ABB Protective Relay School Webinar Series

Wide area monitoring, control and protection using synchrophasor measurements

Galina Antonova

November 24, 2015

Presenter

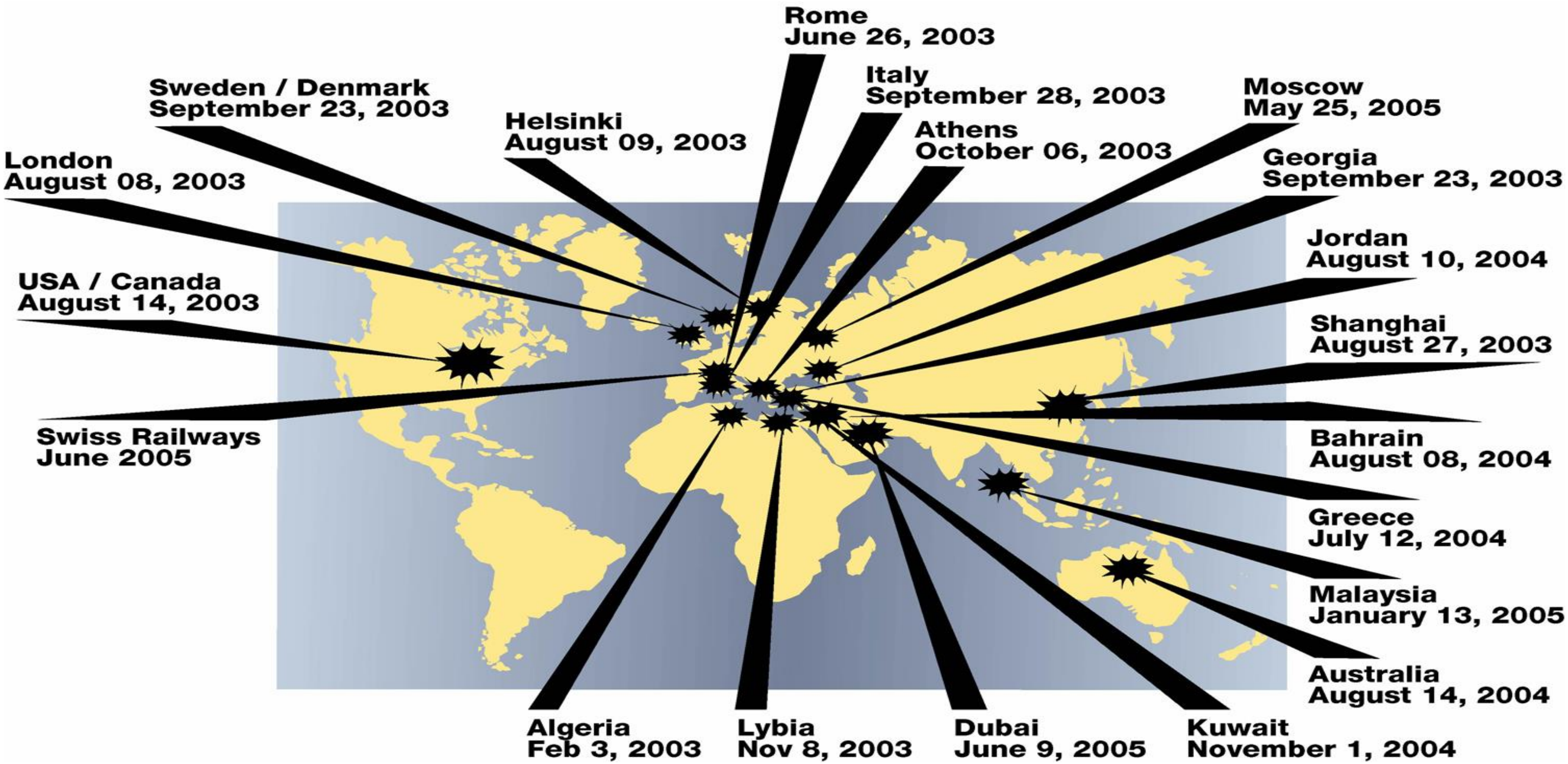
Galina Antonova

Galina Antonova is with ABB Substation Automation and Communication group, North America. She has over 15 years of experience in the area of electrical engineering, data communications and time synchronization, which she mainly applied to the power industry. In her current role with ABB, Galina is applying her expertise to substation automation and protective relaying applications. Galina received her M. Sc. degree (1993) and a Ph.D. (1997) in Electrical Engineering and Data Communications from the State University of Telecommunications, St. Petersburg, Russia, and spent one year at University of British Columbia (UBC) on a scholarship from the Russian President. She is actively involved with IEEE PSRC and is a Canadian member of the IEC TC57 WG10.

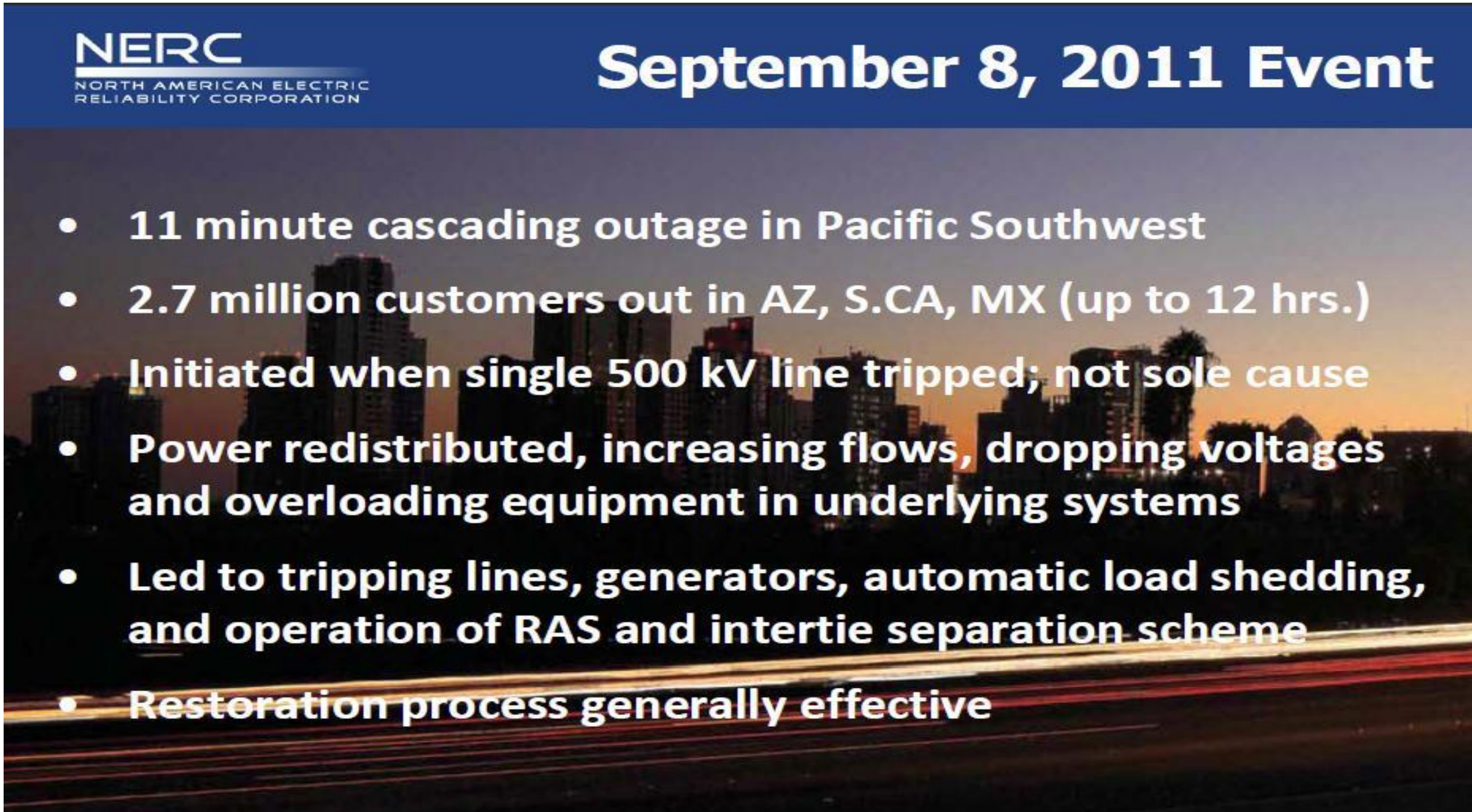
Learning objectives

- Understand the synchrophasor technology and its use in power systems
- Become aware of related industry standards and guides
- Learn about synchrophasor-based monitoring, control and protection applications
- Review examples of synchrophasor-based applications deployed in existing power systems world wide

Hot summer blackouts

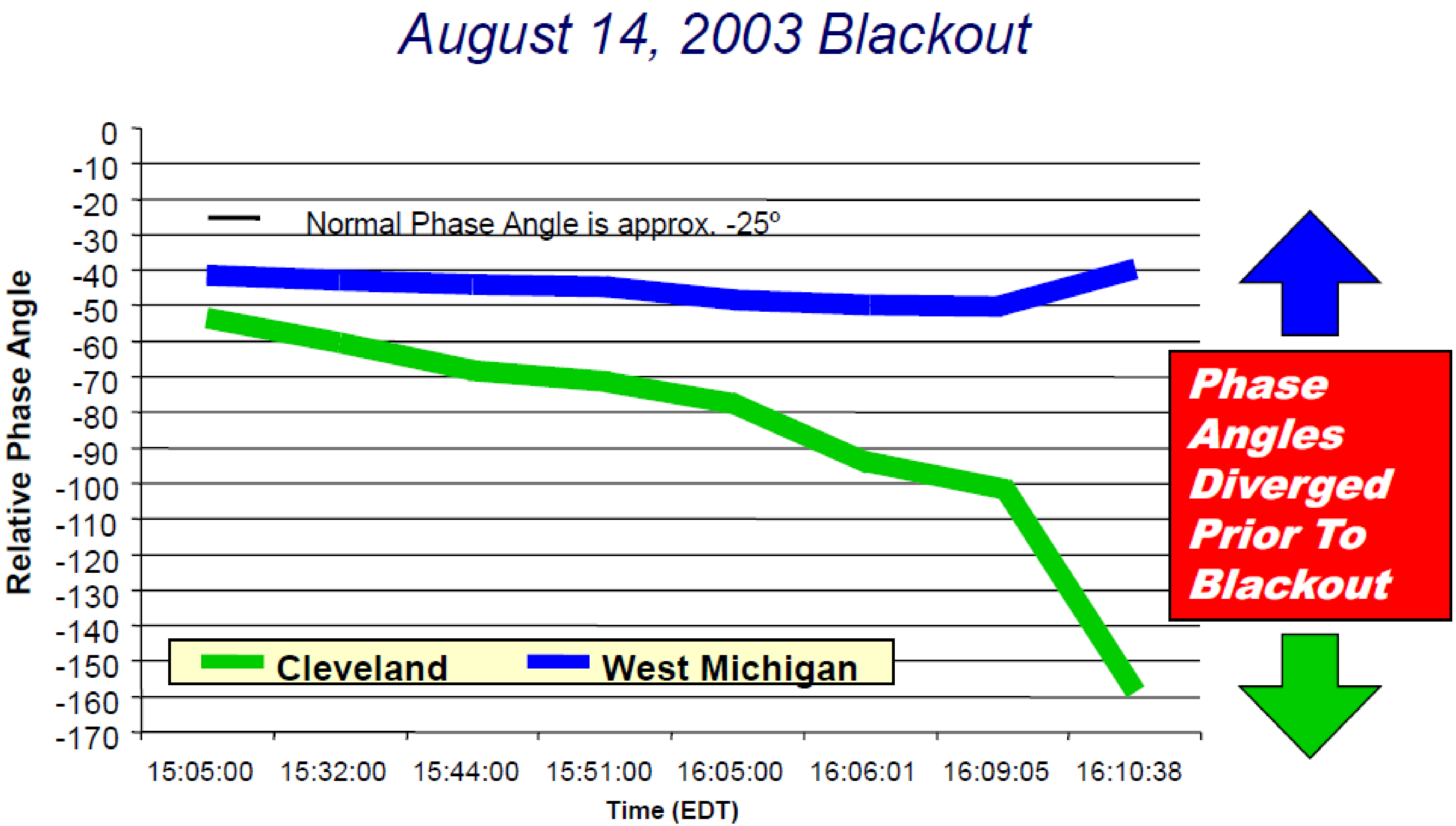


September 2011 Southwest US Outage



Source: NERC Recommendations from 2011 Southwest Outage May 8 2012

What can help ?



Power Systems Challenges and Solutions

Applications and technologies

Gateways with bi-directional communication for consumer interaction

Smart meters, Internet/mobile telecom, smart houses

Customer service systems including billing

Fault detection, isolation and restoration; voltage optimization

FACTS, HVDC,

WAMS → WAMPACS

1) Integration of renewables

Remote grid operation with distributed generation (wind/solar farms)

Increase grid capacity and stability

Balance load to supply

2) Integration of electric vehicles

Charging / billing

Energy storage

Load management

3) Demand response

Real time pricing / tariffs

Home automation / load management

Distributed generation / storage

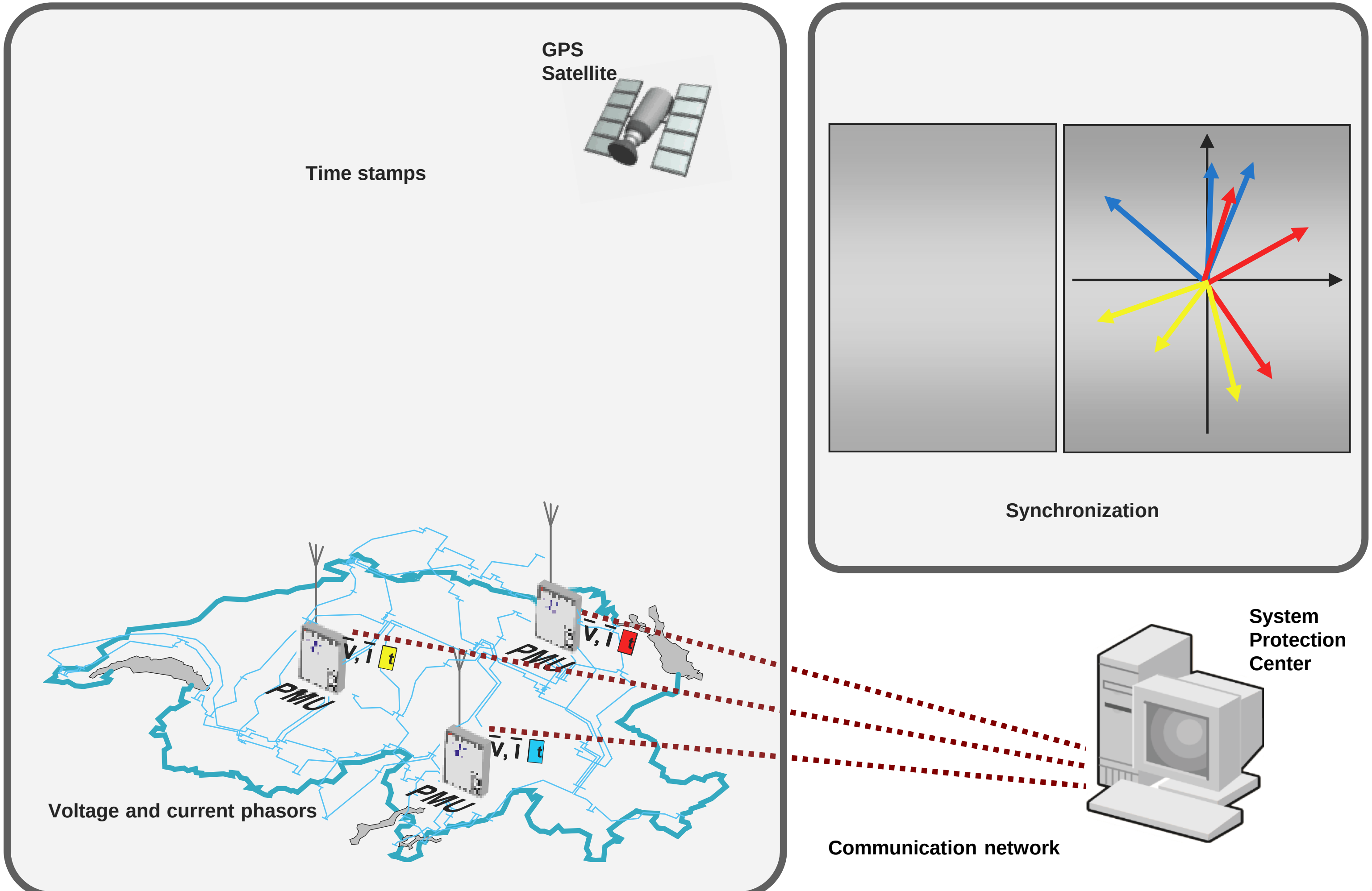
4) Reliability and efficiency

cyber security

customer outage information

emergency / peak power

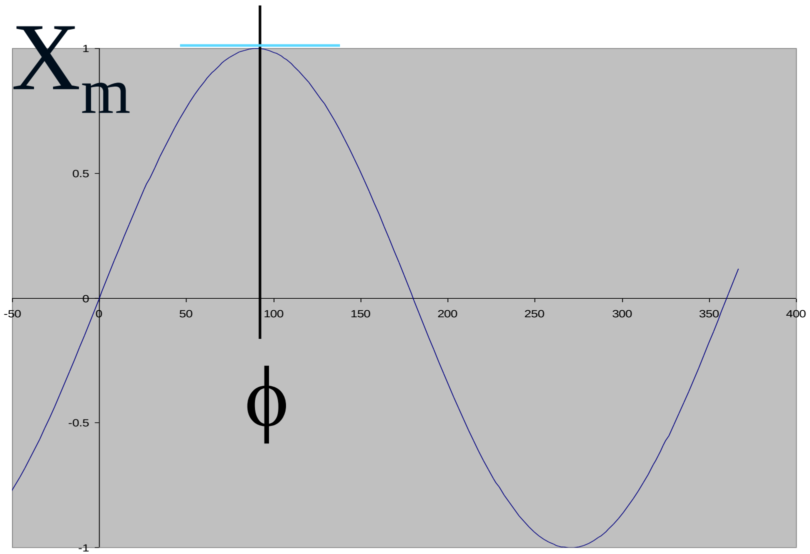
Wide-area Monitoring and Control

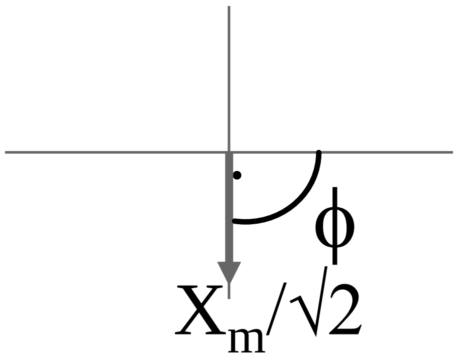


What is Phasor ?

A complex number that represents the phase and magnitude of an AC waveform

$$X_m \cos(2\pi 60 t + \phi) \qquad X_m/\sqrt{2}\, e^{j\phi}$$

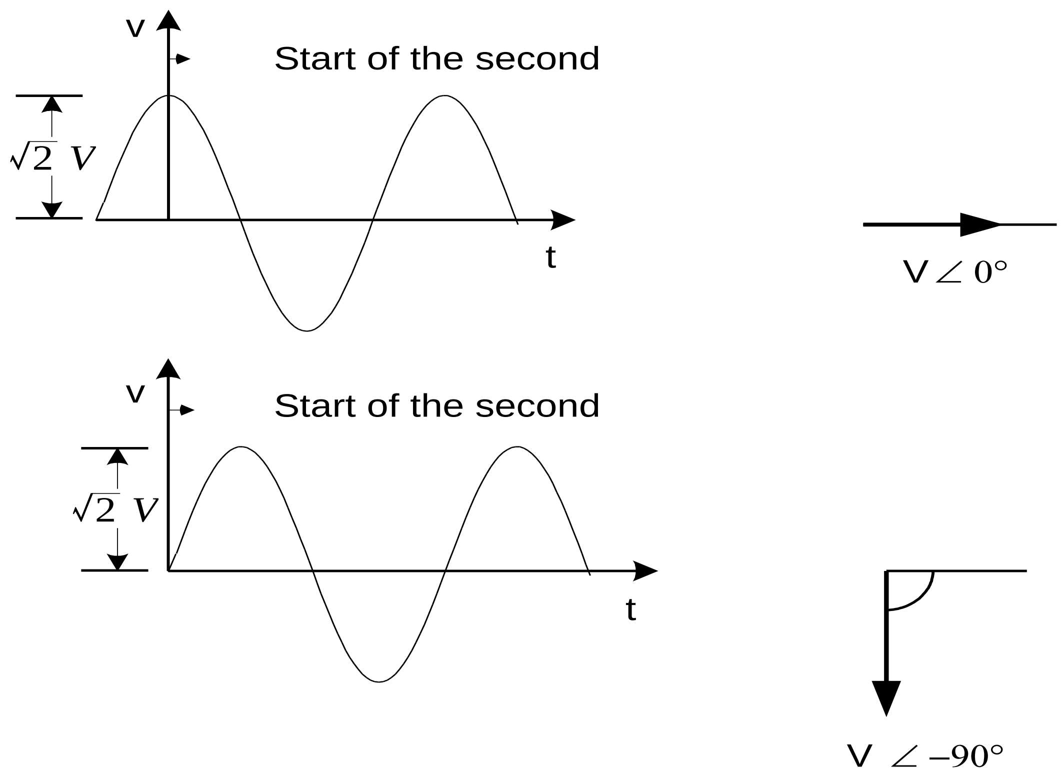




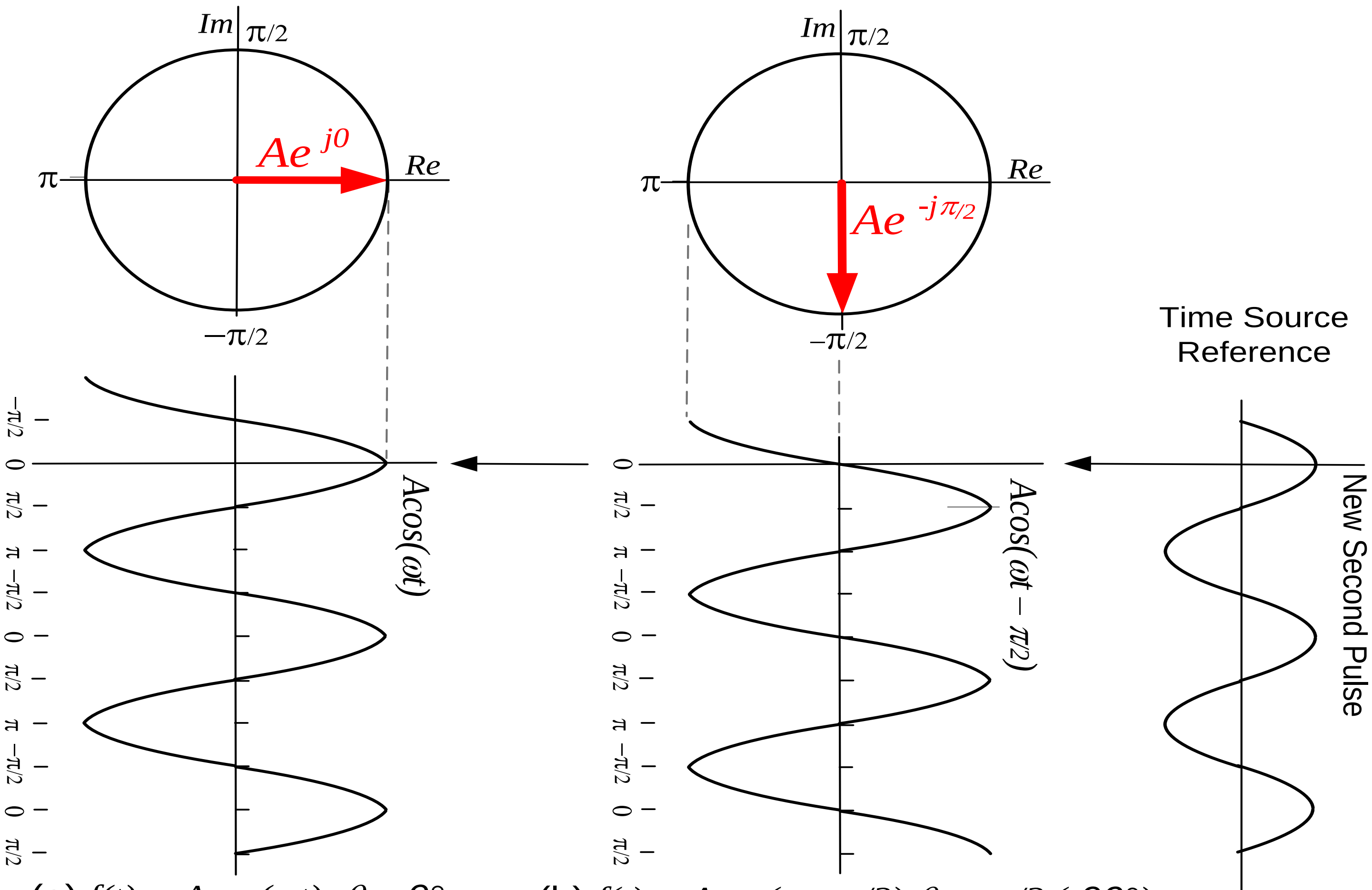
What is Synchrophasor ?

- Synchrophasor is a phasor with a **phase** determined by UTC time (start of the second)
- Reference waveform is cos(wt) at a nominal system frequency
  - Angle = 0° for positive maximum at the start of UTC second
  - Angle = -90° for positive zero crossing at the start of UTC second

$$v(t) = \sqrt{2}\, V \cos\left(\omega_0 t + \varphi\right)$$



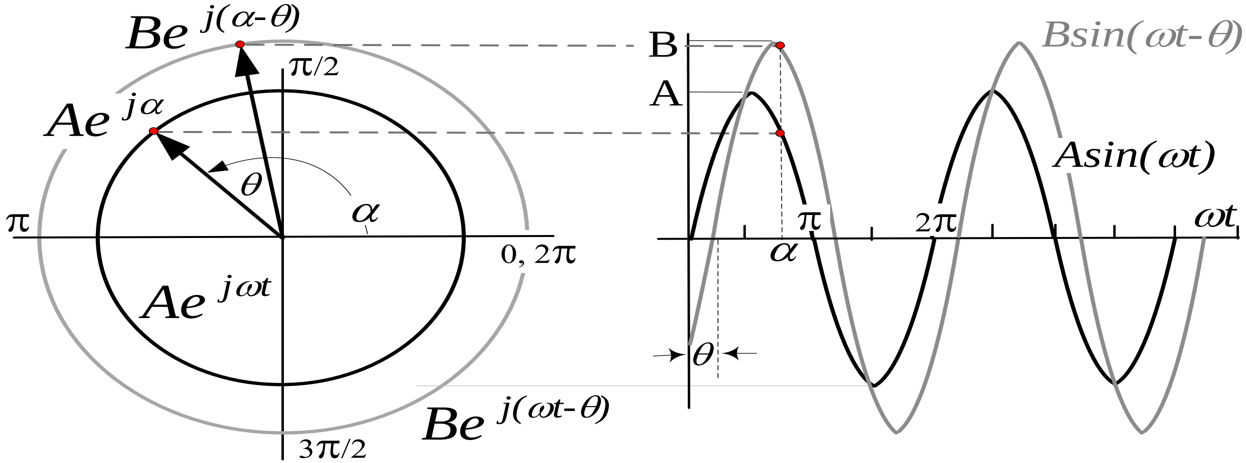
Synchrophasor definition



(a) $f(t) = A\cos(\omega t),\ \theta = 0°$

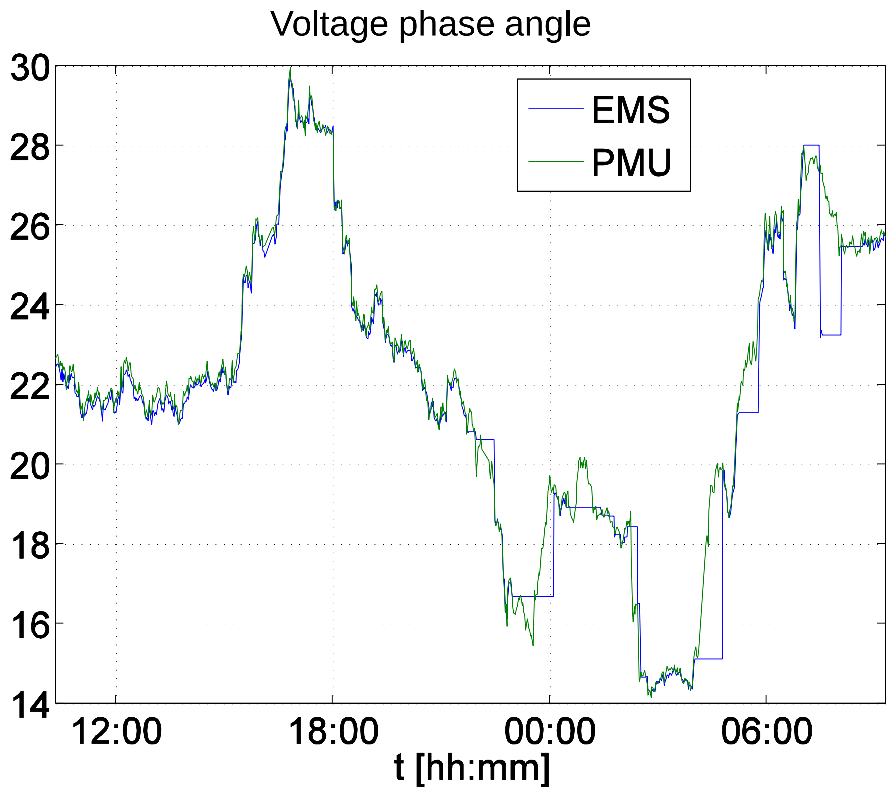
(b) $f(t) = A\cos(\omega t - \pi/2), \theta = -\pi/2\ (-90°)$

Why use Synchrophasors



- Consider the ability to measure the voltage magnitude and phase angle at every system bus and current magnitude and phase angle at every branch (lines, transformers and other series elements) in the power system network simultaneously and continuously and having them instantly available where we need them when we need them

PMU measurements vs SCADA/EMS



What is new ?

- Higher resolution
- Faster response
- Higher accuracy

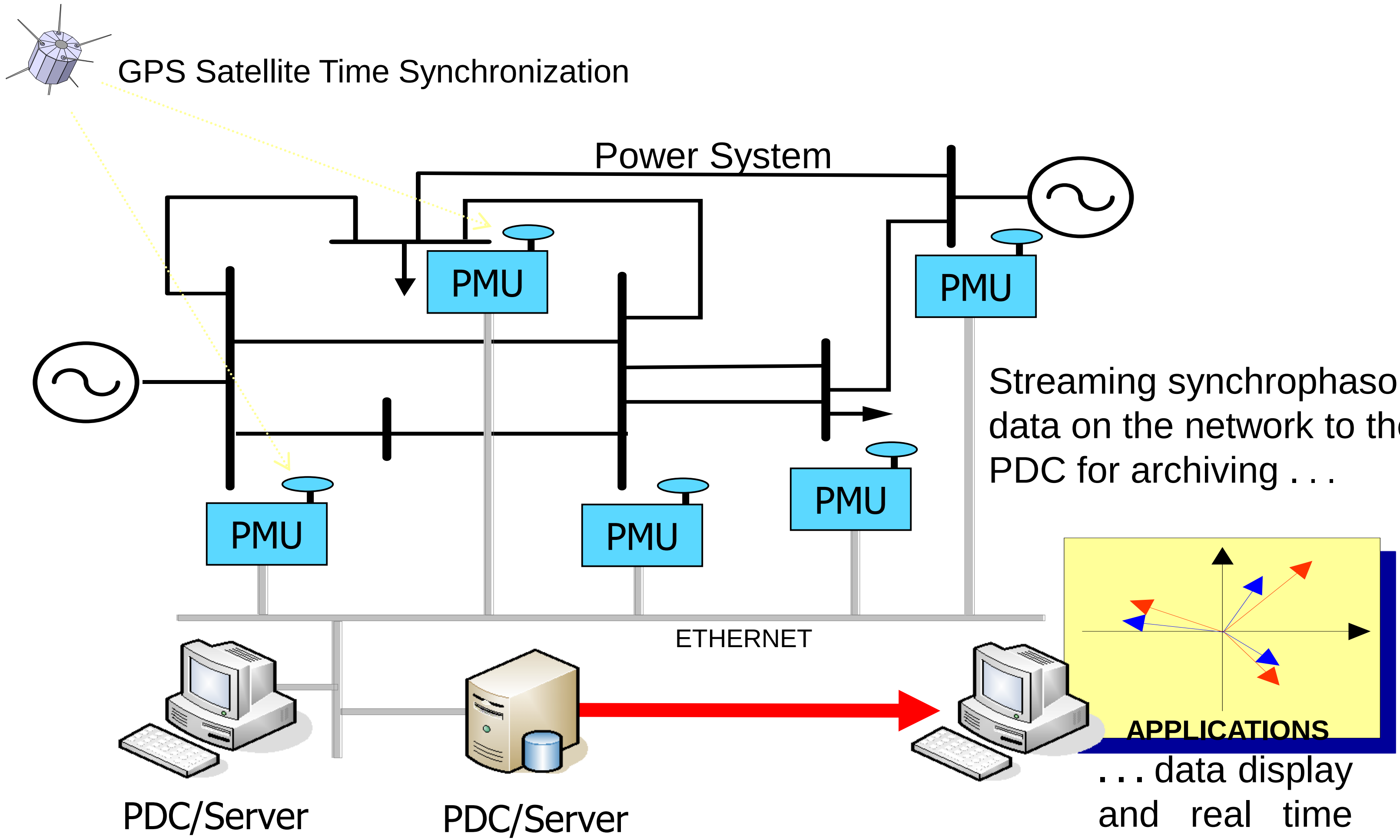
How to use:

- Supervision of dynamic phenomena
- Closed-loop control
- Model-calibration

Synchrophasors Terminology

- UTC - Universal Time Coordinated
- GPS – Global Positioning System with time traceable to UTC
- PMU – Phasor Measurement Unit
  - Measures bus voltages and line currents
  - Estimates phasors
  - Synchronizes each phasor with UTC time – 1.0 μs accuracy
  - Sends synchrophasor data at 240, 120, 60, 30 frames/s to clients, PDC, etc
- PDC – Phasor Data Concentrator
  - Merges, synchronizes and archives synchrophasor data

Synchrophasor Measurement System



Streaming synchrophasor data on the network to the PDC for archiving . . .

. . . data display and real time control actions

Synchrophasor Measurement Unit: RES670

- Up to 8 Analog Phasors
  - Positive / Negative / Zero sequence
  - Polar or Rectangular phasors
- Transmission rates
  - 8/10-200/240 frames/s at 50/60 Hz
- TVE < 1%
- Configurable time stamp position
- 8 fully configurable binary signals
- 8 independent users / data recipients
- 2 optical Ethernet ports
- Embedded GPS, electrical / optical IRIG-B
- Built on protective relay platform

Time synchronization options

GPS time synchronization
- 1us time accuracy to UTC
- Embedded GPS receiver, or external clock
- GPS cable (20m, 40m)

Electrical IRIG-B interface
- BNC cable
- 1 kHz Amplitude Modulated or DC shift

Optical IRIG-B interface
- Optical cable, with ST connector
- Immune to surrounding noises

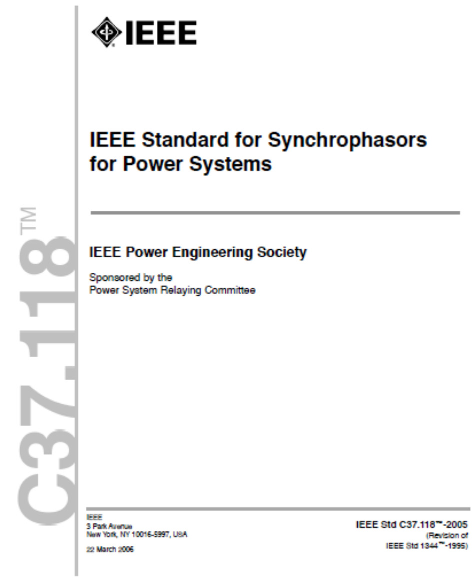
Emerging Precision Time Protocol
- IEEE 1588 / C37.238 standards
- Ethernet, with 1us time accuracy to source

Synchrophasor Standardization

- IEEE 1344-1995 Synchrophasor standard superseded by IEEE C37.118-2005
- IEEE C37.118-2005 Synchrophasor standard superseded by
  - IEEE C37.118.1-2011 Standard for Synchrophasor Measurements
  - IEEE C37.118.2-2011 Standard for Synchrophasor Data Transfer
  - Amendment IEEE C37.118.1a-2014
- IEC 61850-90-5 Technical Report for Synchrophasor Data Transfer over in IEC 61850
- Joint IEC / IEEE Standard on synchrophasor measurements (initiated)

IEEE C37.118-2005 Synchrophasor Standard

- IEEE Std C37.118-2005 - Replaced IEEE 1344
- Measurement requirements
  - Phasor estimation characteristics
  - 2 performance levels
- Data transmission formats
  - Similar to 1344
  - Many improvements
  - Includes single or multiple PMU data
  - Simple Communication protocol (serial, Ethernet, IP)


IEEE

IEEE Standard for Synchrophasors
for Power Systems

C37.118™

IEEE Power Engineering Society

Sponsored by the
Power System Relaying Committee

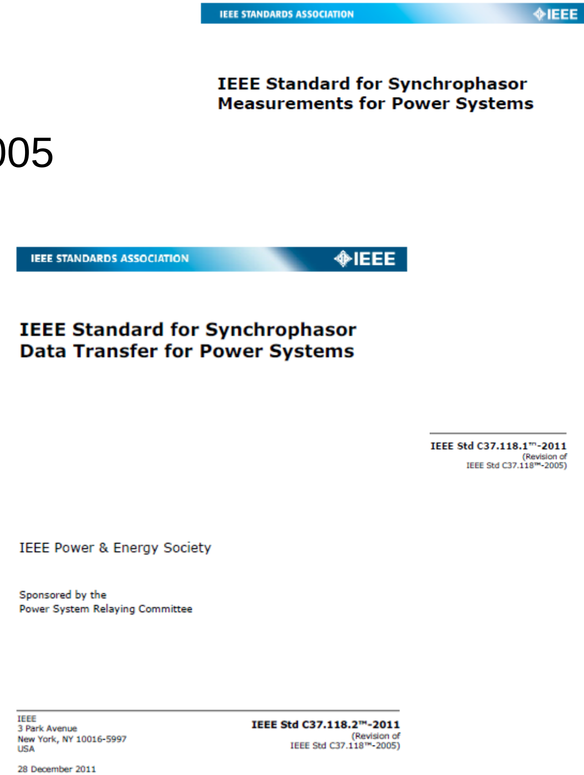
IEEE
3 Park Avenue
New York, NY 10016-5997, USA

22 March 2006

IEEE Std C37.118™-2005
(Revision of
IEEE Std 1344™-1995)

IEEE C37.118.1/2-2011 Standards

- IEEE Std C37.118.1/2 – 2011 Replaced IEEE C37.118-2005
  - C37.118.1 – Measurements
  - C37.118.2 – Communications (legacy)
  - Dynamic tests added
  - 2 classes – Measurement (M) and Protection (P)
  - Higher reporting rates recommended, new filtering
  - Dynamic tests, new configuration frame (CFG-3)
  - Continuous Time Quality
  - Locked definition


IEEE STANDARDS ASSOCIATION IEEE

IEEE Standard for Synchrophasor Measurements for Power Systems

IEEE Std C37.118.1™-2011 (Revision of IEEE Std C37.118™-2005)

IEEE STANDARDS ASSOCIATION IEEE

IEEE Standard for Synchrophasor Data Transfer for Power Systems

IEEE Power & Energy Society

Sponsored by the
Power System Relaying Committee

IEEE
3 Park Avenue
New York, NY 10016-5997
USA

IEEE Std C37.118.2™-2011 (Revision of IEEE Std C37.118™-2005)

28 December 2011

Amendment to IEEE C37.118.1a-2014 contains corrections to performance parameters

Other Synchrophasor Standards

- IEC TR 61850-90-5 Approved and published in May 2012
  - Transport of synchrophasor data
  - Integration with IEC 61850 systems
  - Routable transport (targeted to substation to substation)
  - UDP transport, unicast and multicast (preferred)
  - Security included
  - Multiple communications layers

Work on joint IEC / IEEE standard on synchrophasor measurements started

IEEE Guides and Reports on Synchrophasors

IEEE PES PSRC Working Groups generated the following documents

- IEEE Report Published in August 2013

  Use of Synchrophasor Measurements in Protective Relaying Applications

- IEEE C37.242-2013 Published in March 2013

  Guide for PMU Synchronization, Calibration, Testing and Installation

- IEEE C37.244-2013 Published in May 2013

  Guide for PDC Requirements for Power System Protection, Control and Monitoring

Report on use of Synchrophasors for Protection

- Present applications
  - Wide-area frequency monitoring
  - Power swing detection
  - Load shedding
  - Automatic generator shedding
  - Distributed generation anti-islanding
  - Line reclosing selectivity
  - Distance to fault
- Future applications
  - Bus differential relaying
  - Line differential relaying
  - Distance function
  - Line backup protection

USE OF SYNCHROPHASOR MEASUREMENTS IN PROTECTIVE RELAYING APPLICATIONS

Power System Relaying Committee
Report of Working Group C-14
of the
System Protection Subcommittee

Members of the Working Group

Jim O'Brien, Chair
Alla Deronja, Vice-Chair

Alex Apostolov
Andrew Arana
Miroslav Begovic
Sukumar Brahma
Gustavo Brunello
Fernando Calero
Herb Faulk
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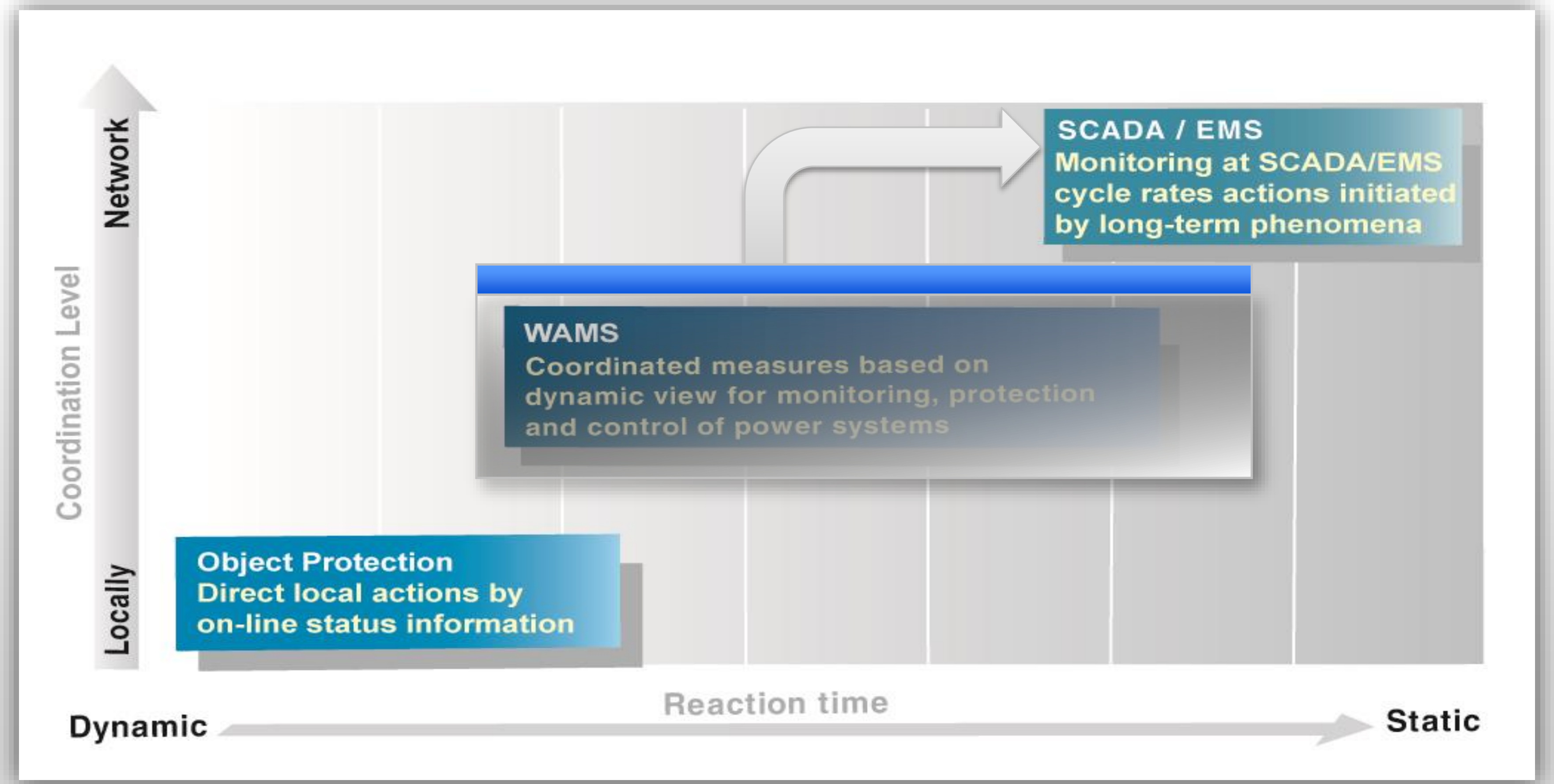
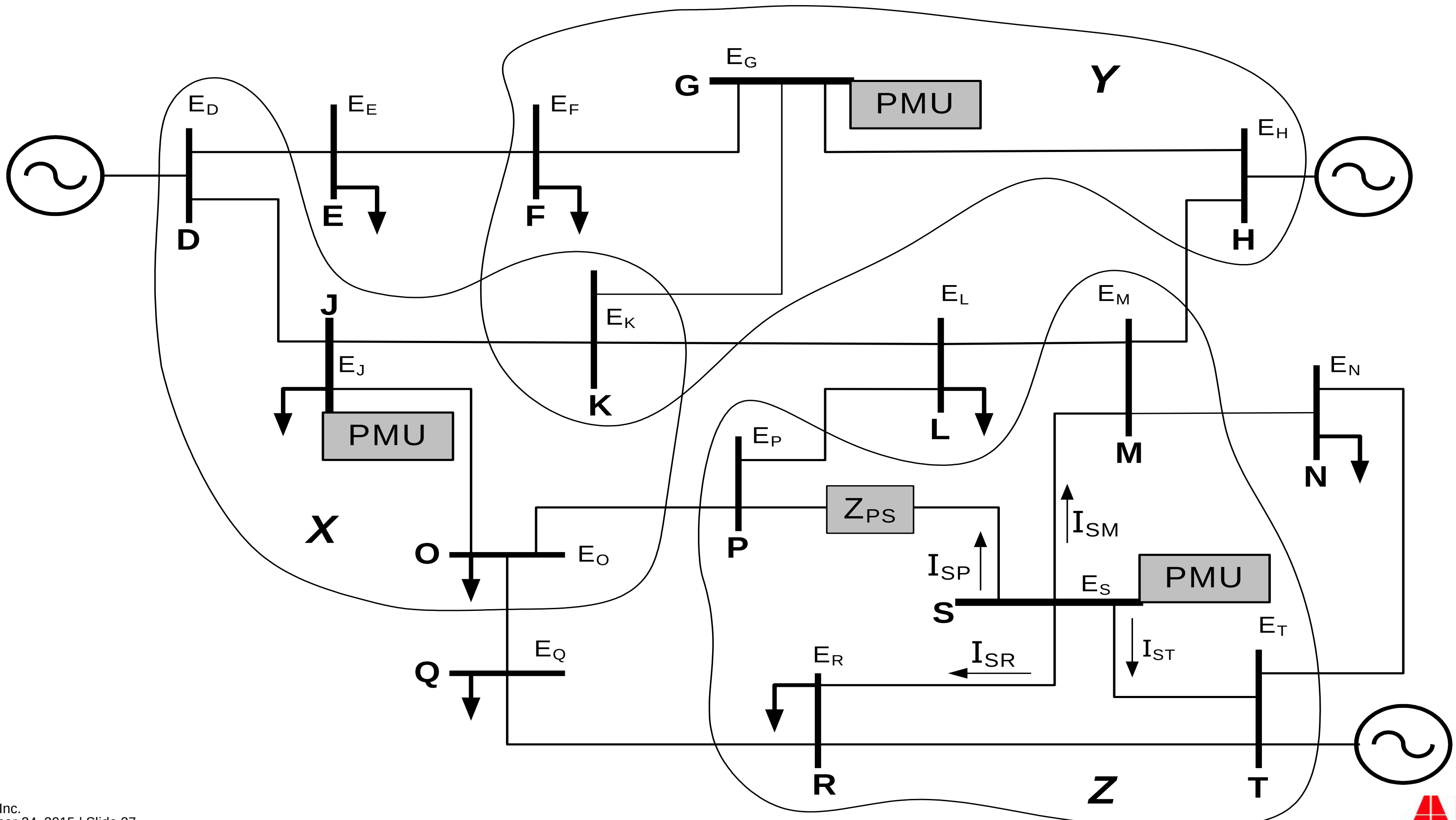
Don Lukach
Ken Martin
Joe Mooney
Jay Murphy
Krish Narendra
Damir Novosel
Mahendra Patel
Elmo Price
Sinan Saygin
Veselin Skendzic
Rick Taylor
Demetrios Tziouvaras
Solveig Ward

Synchrophasor-based applications



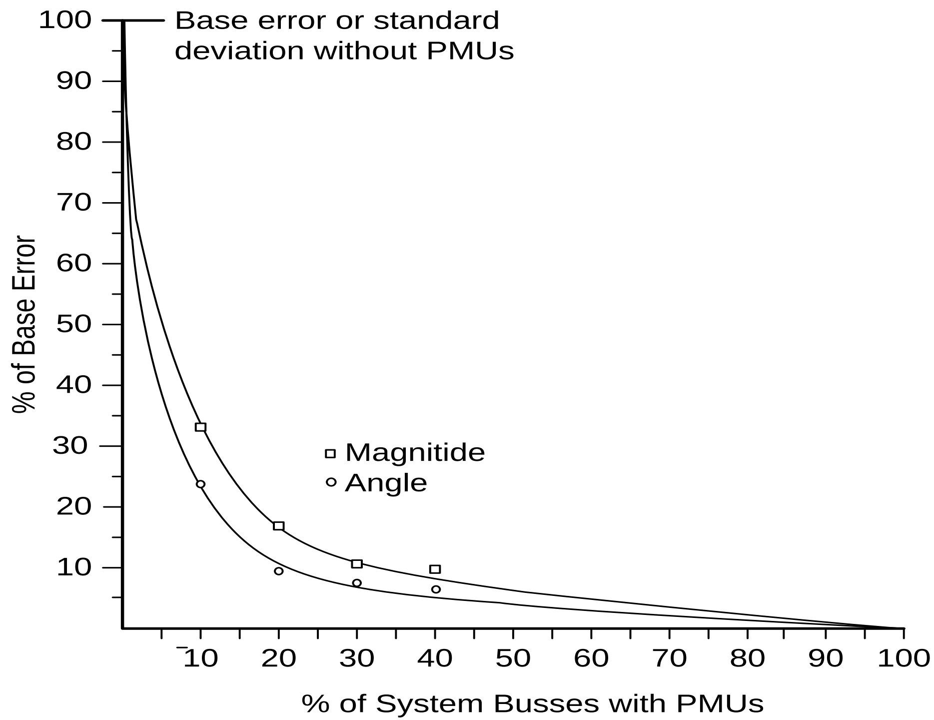
Phasor-Enhanced State Estimator



Phasor-Enhanced State Estimator

- Benefits are increased observability, redundancy, accuracy, and bad data detection capability

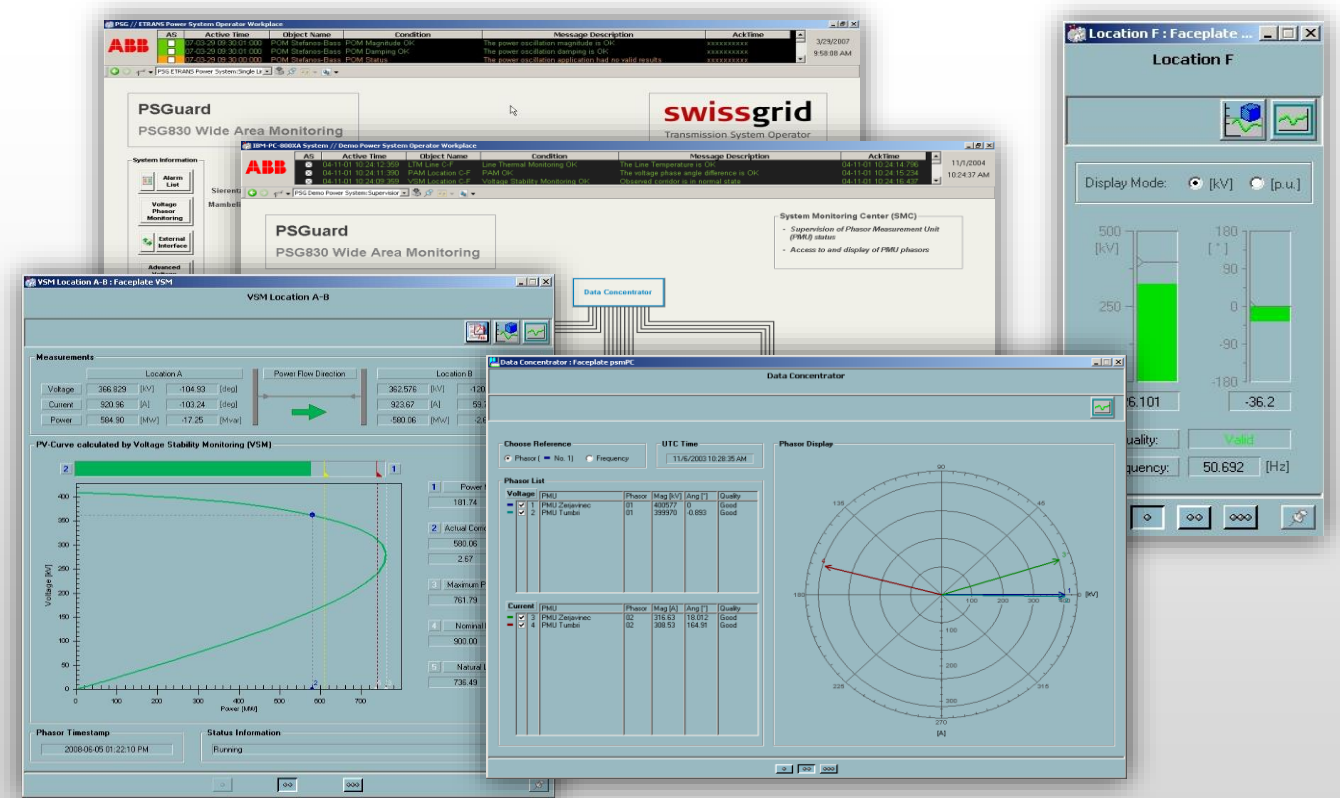
- The application of a sufficient number of PMUs across the system will improve the State Estimation solutions to the point they will be called state calculations.



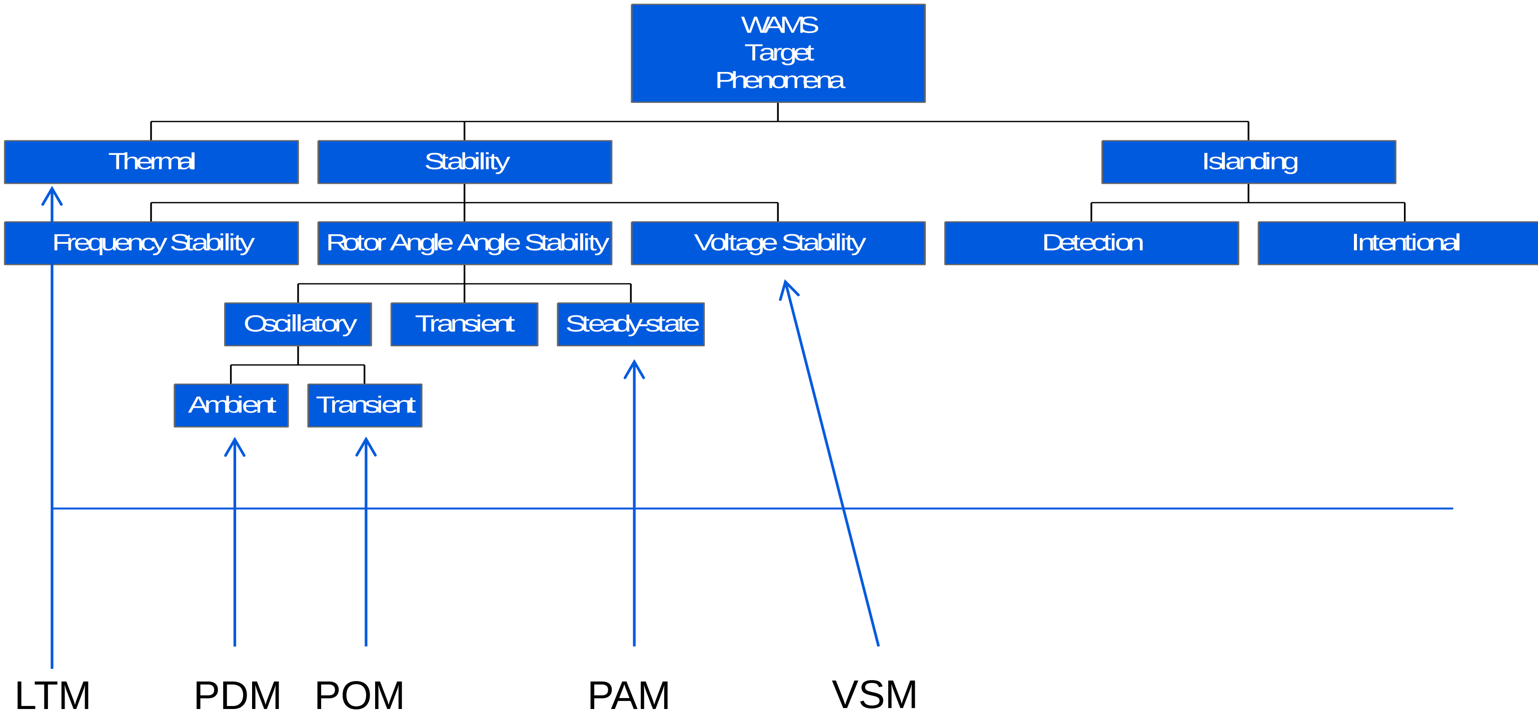
PSGuard: Wide-Area Monitoring System

PSGuard Applications

- Phase Angle Monitoring
- Voltage Stability Monitoring
- Line Thermal Monitoring
- Event Driven Data Archiving
- Power Oscillation Monitoring
- Power Damping Monitoring
- SCADA/EMS integration
- Communication gateway



Power System Stability Applications

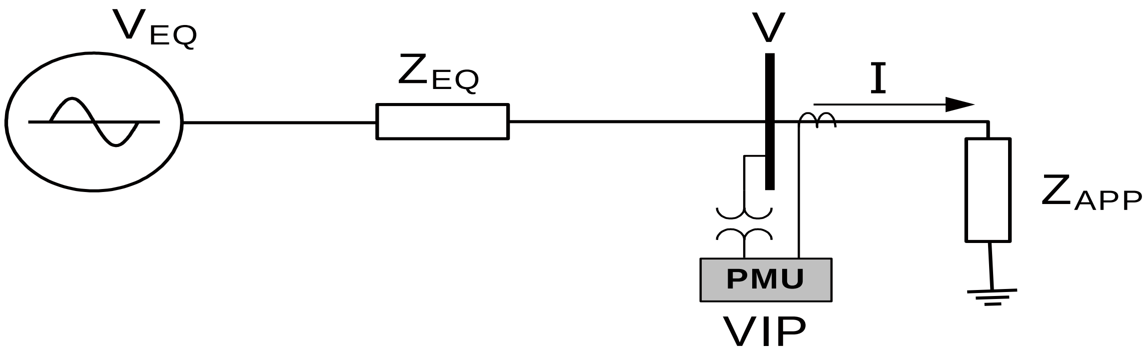


Power System Stability Constrains

- Loadability of (AC) transmission lines are limited by
  - Thermal constraints
  - Voltage contraints
  - Dynamic angle constraints
    - Oscillatory stability
    - Transient stability
  - Steady-state angle constraints

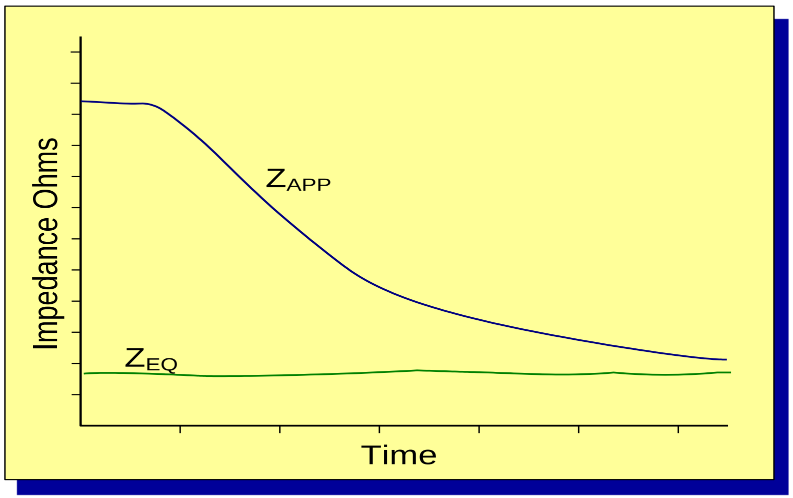
- WAMS Applications provide a way of monitoring the proximity to the stability limits and constraints

Voltage Instability Predictor

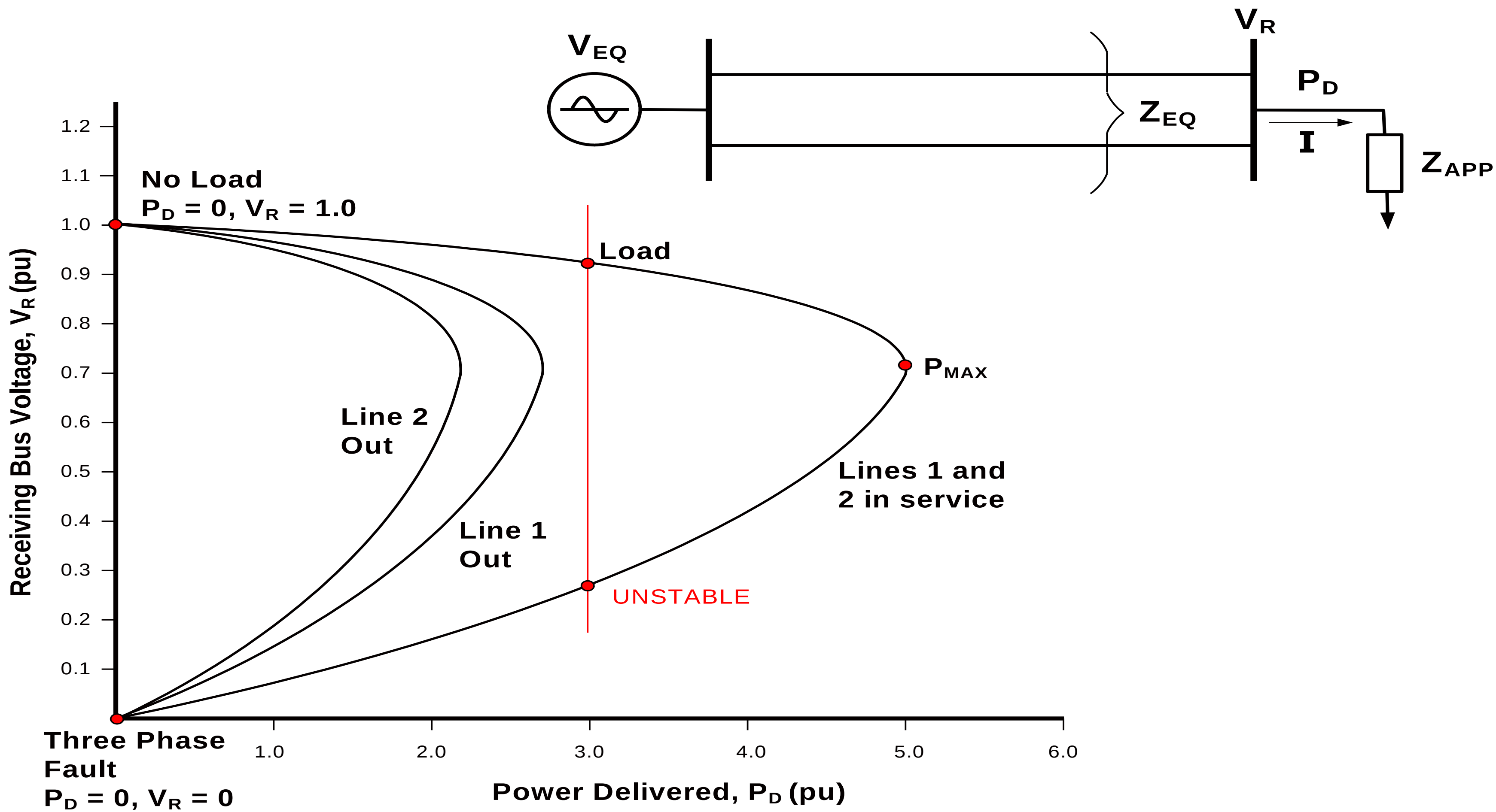


$$Z_{APP} = \frac{V}{I}$$

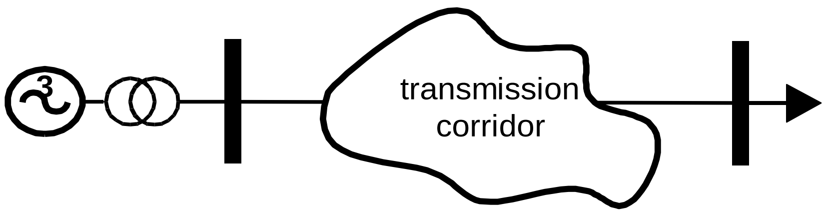
$$Z_{EQ} = \frac{V_{EQ} - V}{I}$$

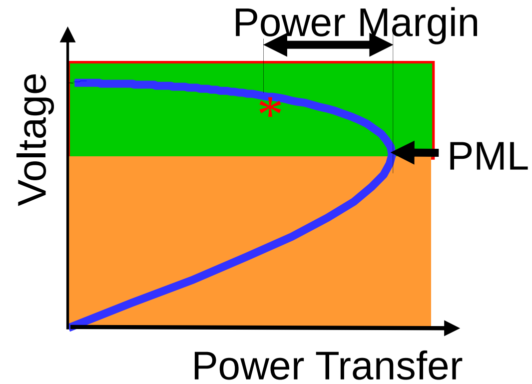


Voltage Instability



Voltage Stability Monitoring (VSM) Principle

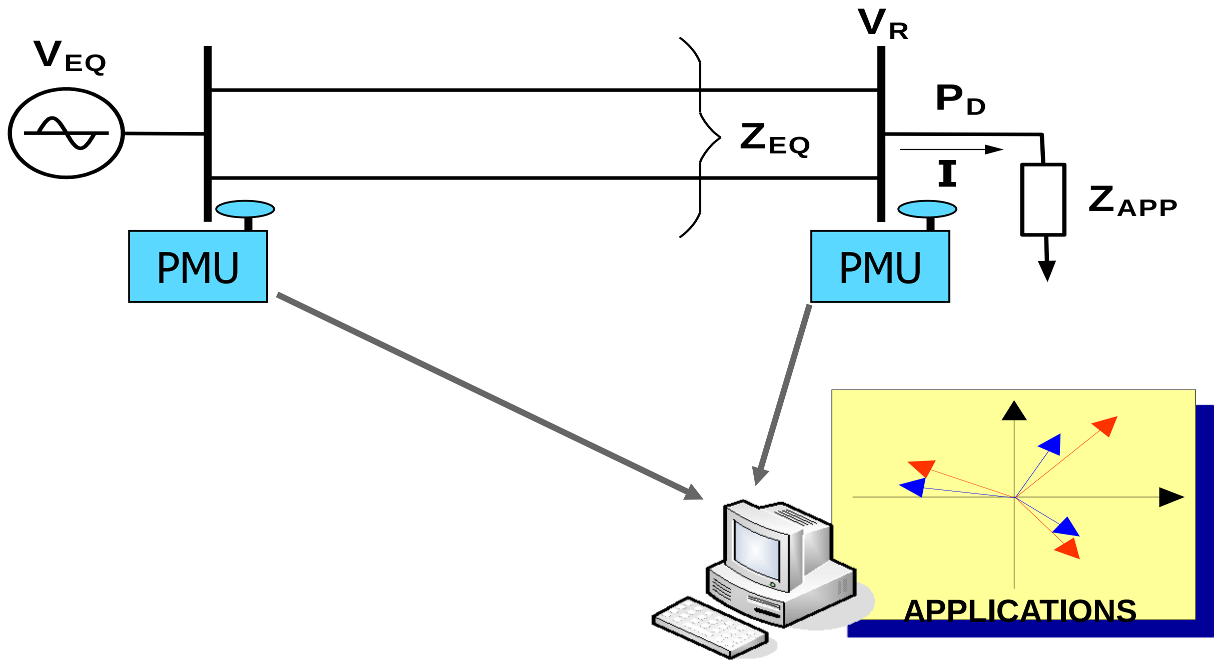




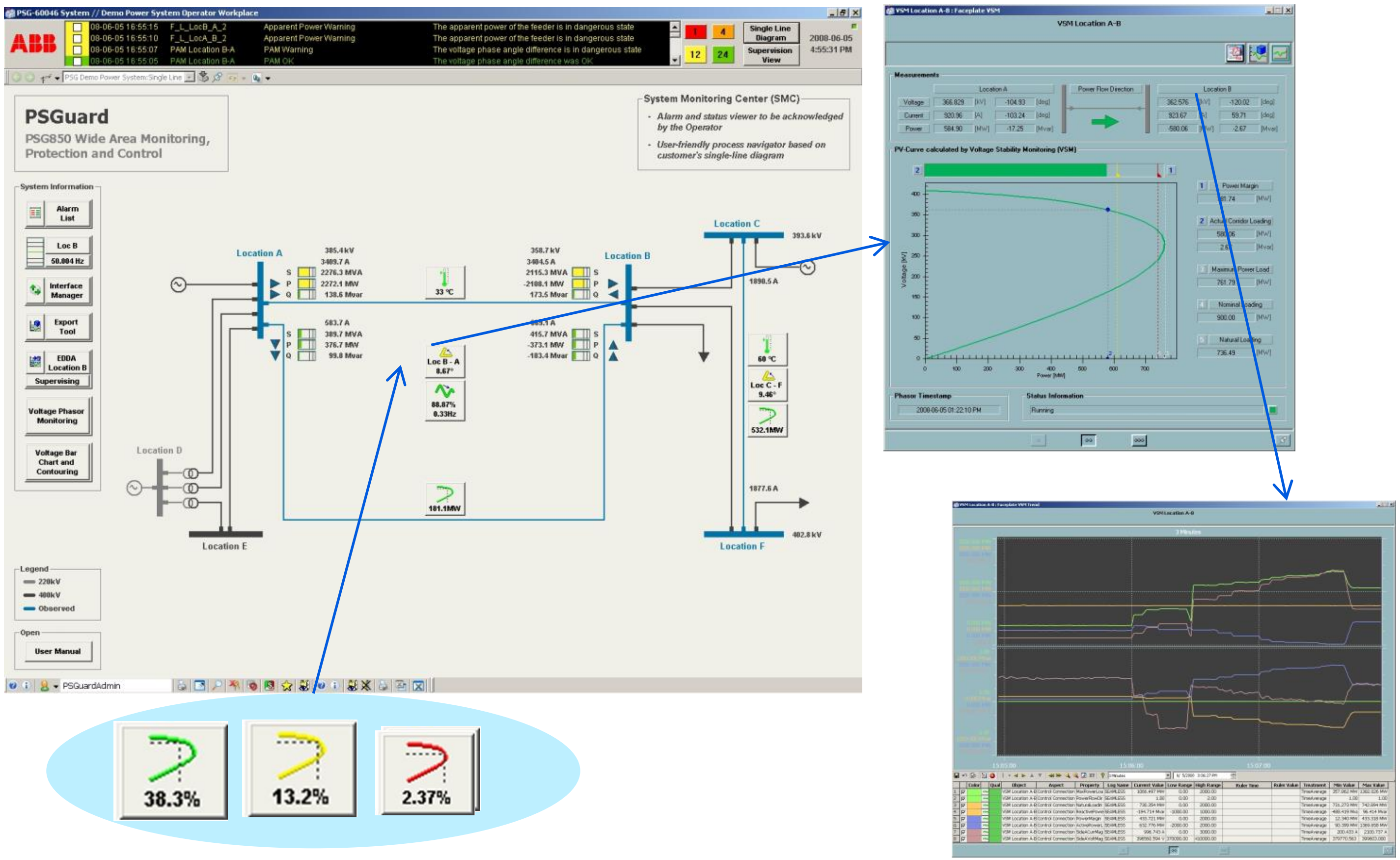
- Assessment of distance to Point of Maximum Loadability, PML
  - Identify network equivalent
  - Stay on top section of PV Curve !
  - Trigger emergency actions when Power Margin too small
  - Patented Method

Voltage Stability Monitoring (VSM) Application

PMU measurements from both ends of the line are used

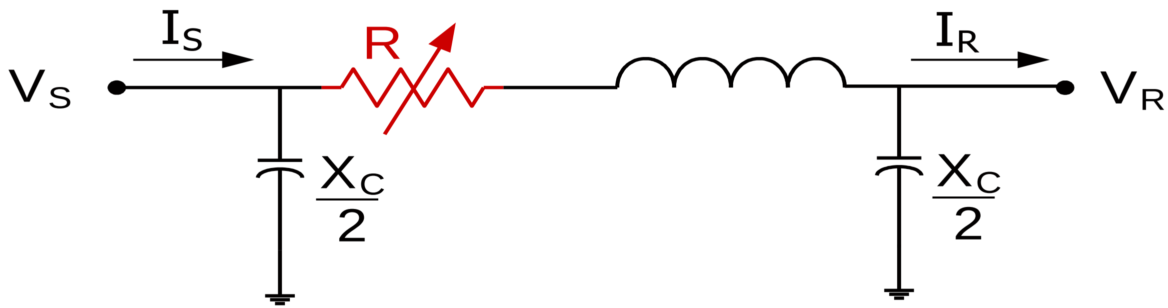


Voltage Stability Monitoring (VSM) User Interface



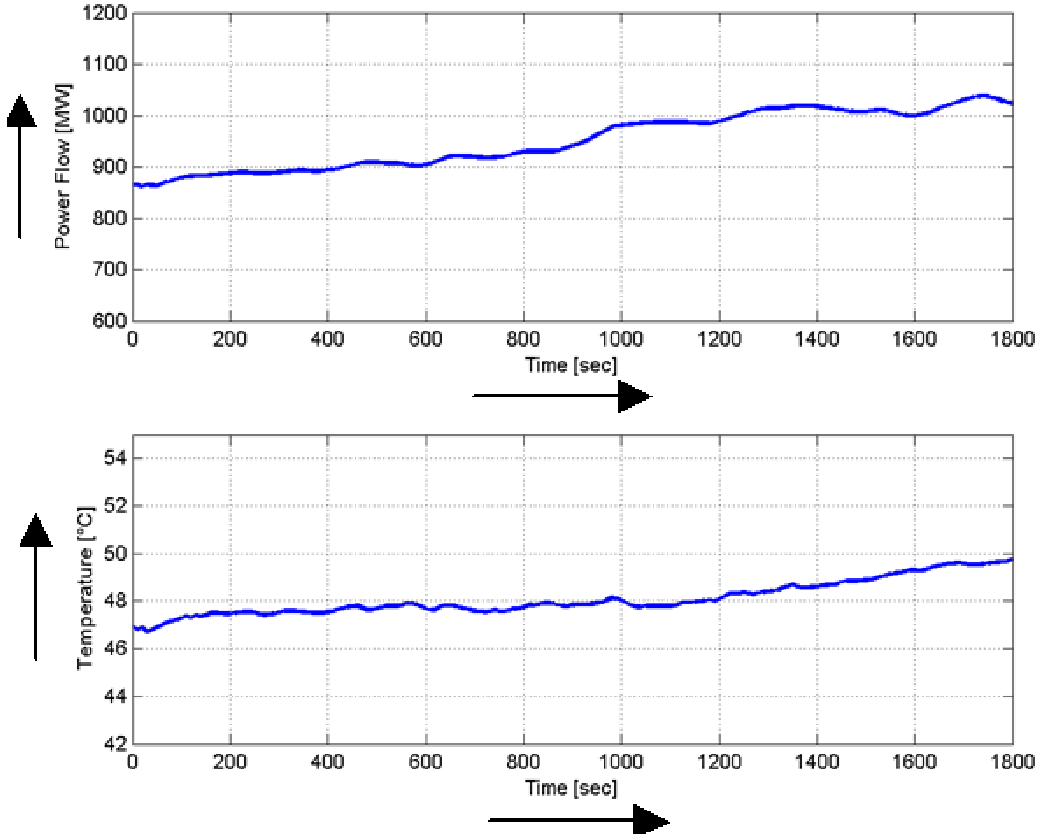
Line Thermal Monitoring (LTM) Application

- Transmission Line Thermal Monitoring



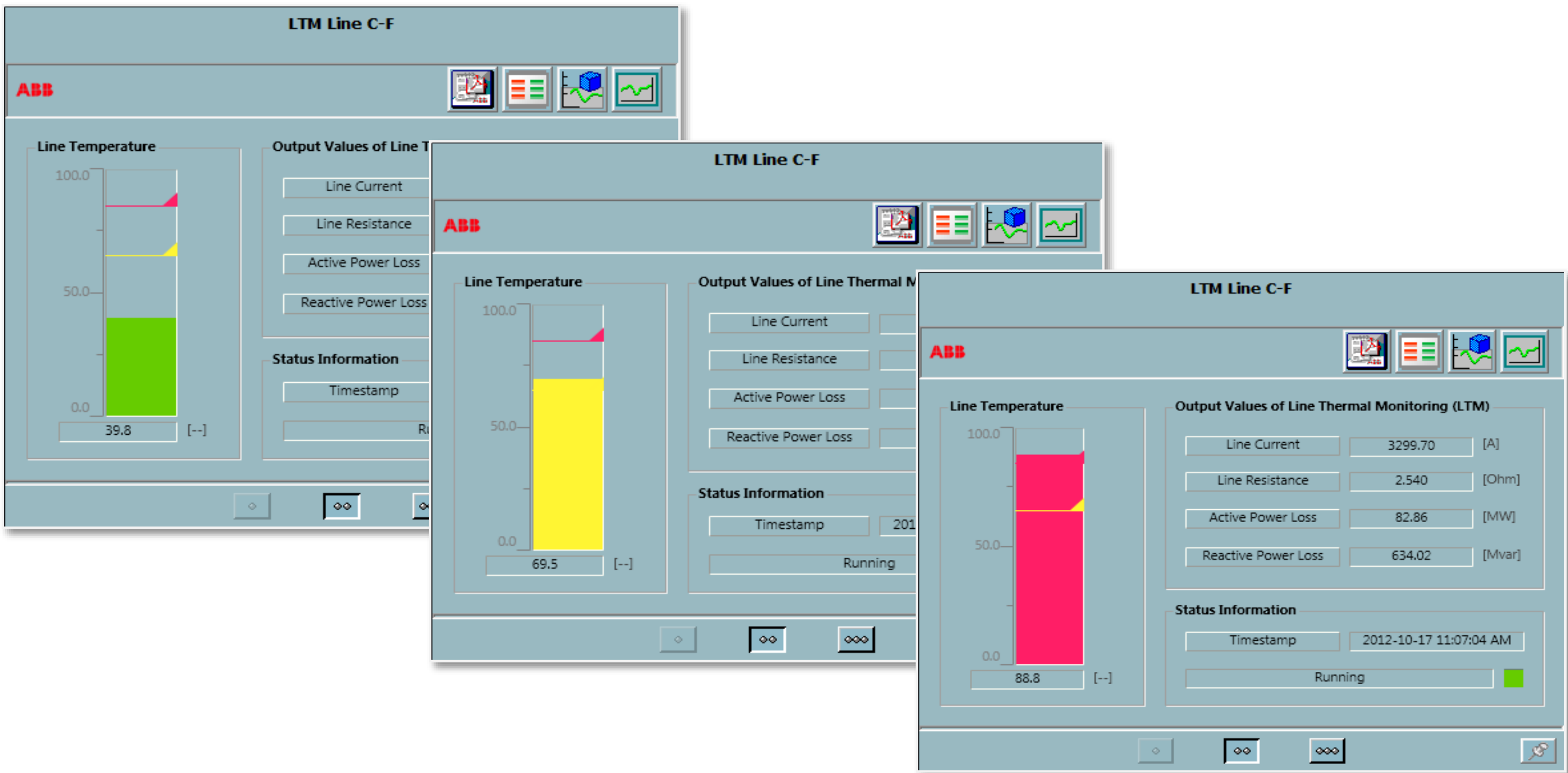
- Compute average conductor temperature to provide
  - Real-time assessment of loadability
  - Early warnings in case of overload
  - Available line capacity
  - Indirect estimation of line sagging

Line Thermal Monitoring (LTM) Example

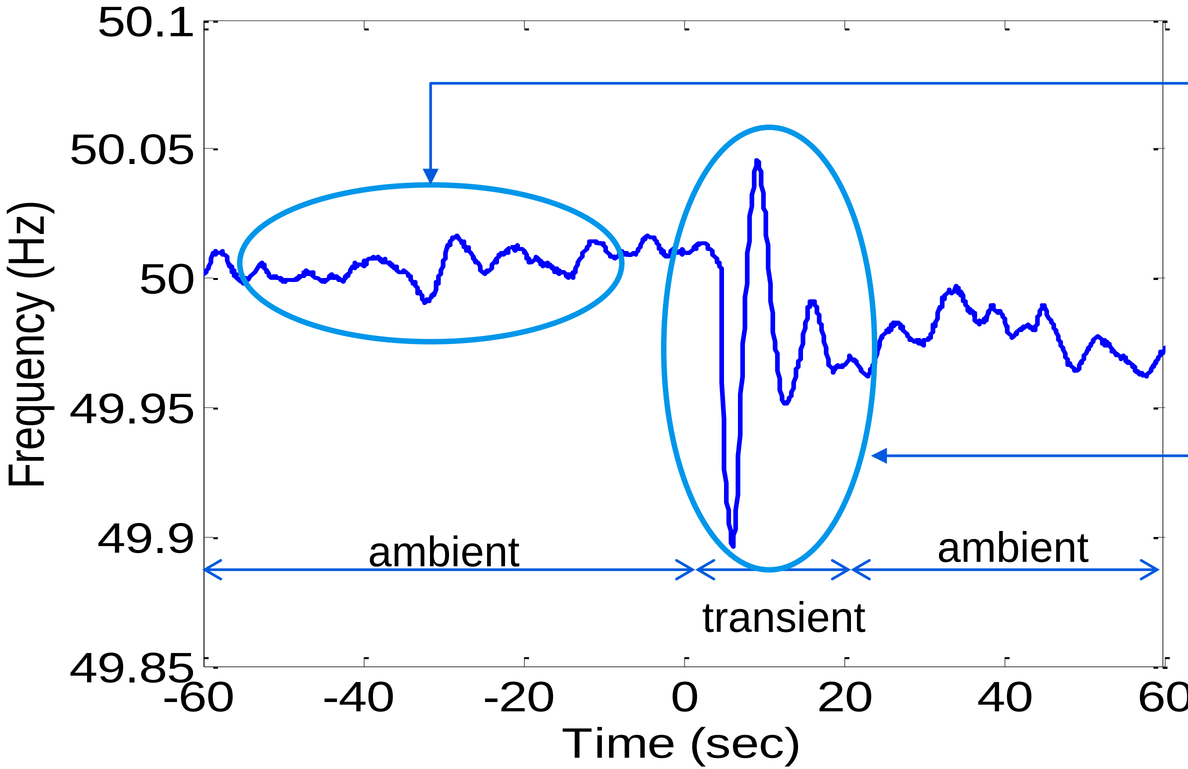


Field results correlate increased power transfer from 950 MW to 1150 MW leads to an average temperature increase from 46C to 49C over 30 min

Line Thermal Monitoring (LTM) User Interface



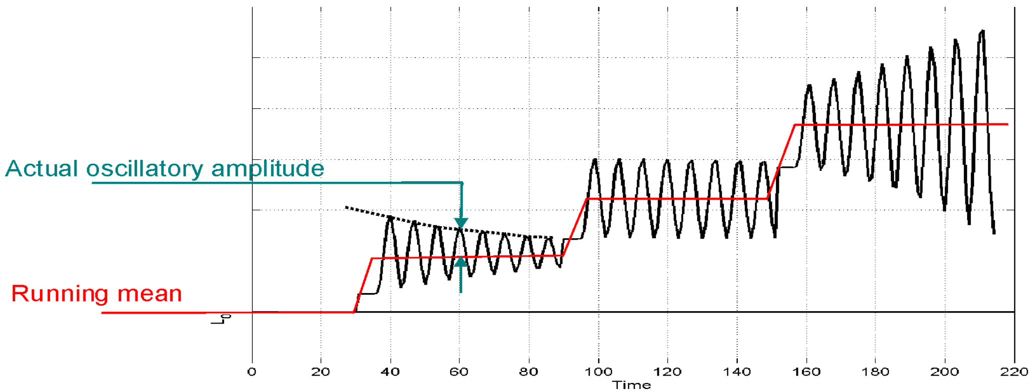
Ambient and Transient Power Oscillation Monitoring



PDM
determining modes and characteristics based on ambient variations

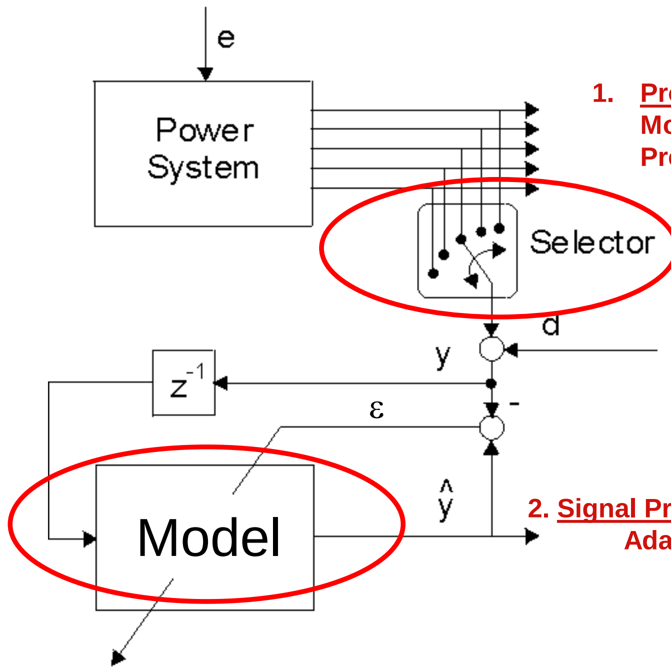
POM
detecting transient oscillations

Power Oscillation Monitoring (POM) Application



- Detection of power swings in a high voltage power system.
- Algorithm is fed with the selected voltage and current phasors.
- Detection of the various swing (power oscillation) modes.
- Quickly identifies the amplitude and frequency
- Negative damping identification

Power Oscillation Monitoring (POM) Principle



1. **Proper selection of measured signal**
   Modal Analysis
   Previous experience

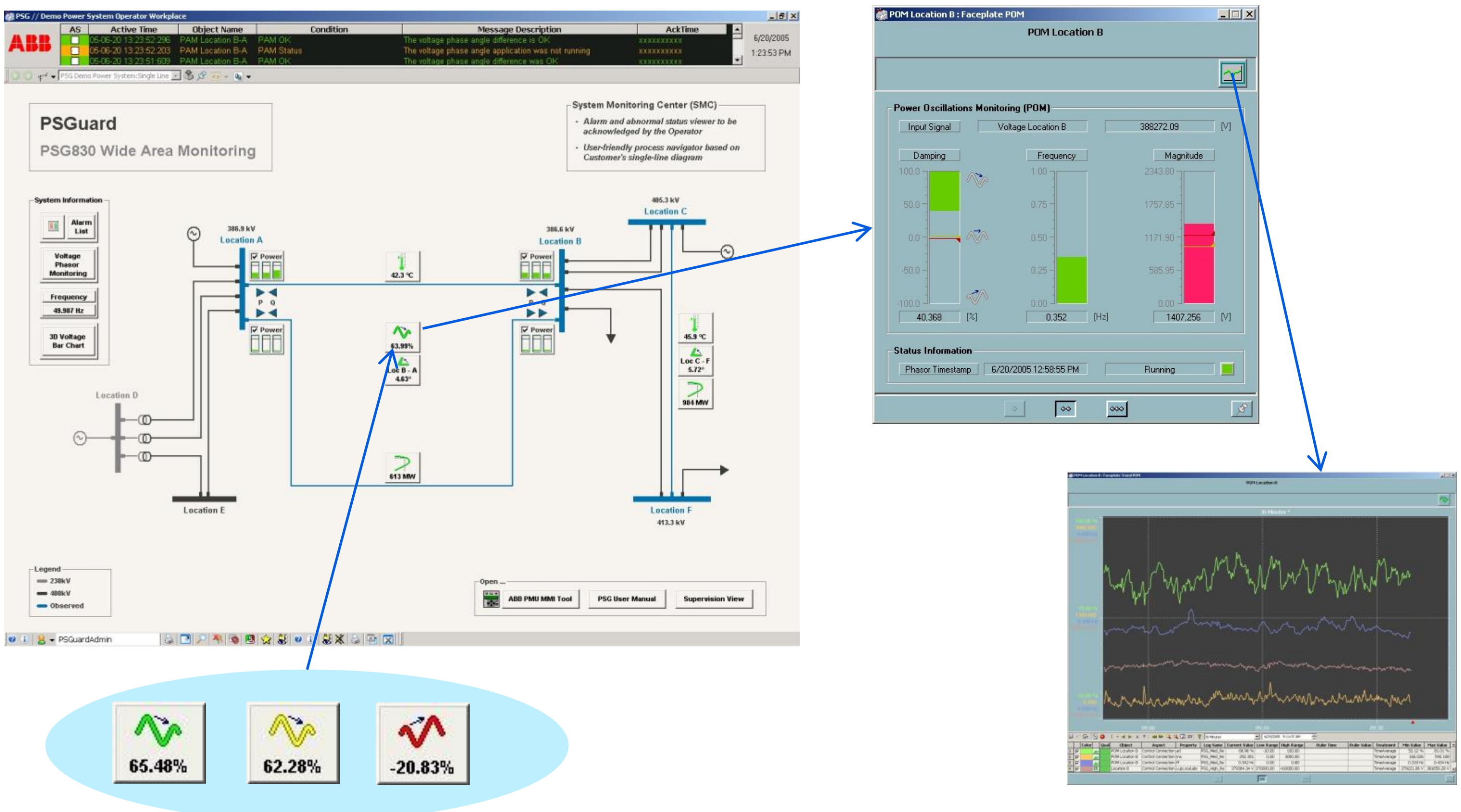
2. **Signal Processing**
   Adaptive Kalman-Filter

Model parameters

➔ Parameters of critical oscillations

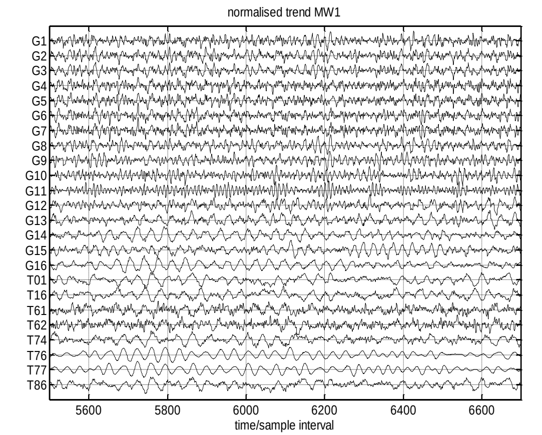
Modal Frequency [Hz] + Damping [%] ➔ Amplitude (time-domain)

Power Oscillation Monitoring (POM) Use Interface

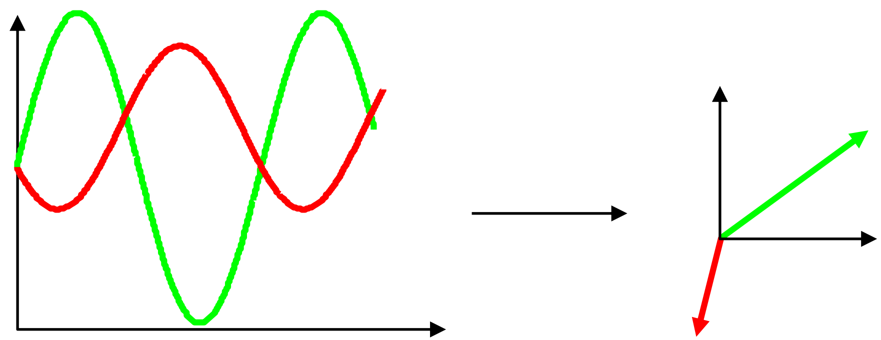


Power Damping Monitor (PDM) Application

- Determine in real-time from ambient oscillations
  - Modal frequencies and damping
  - Phase in each measurement signal
  - Modal activity



- Challenge
  - Ambient noise small



Power Damping Monitor (PDM) Principle

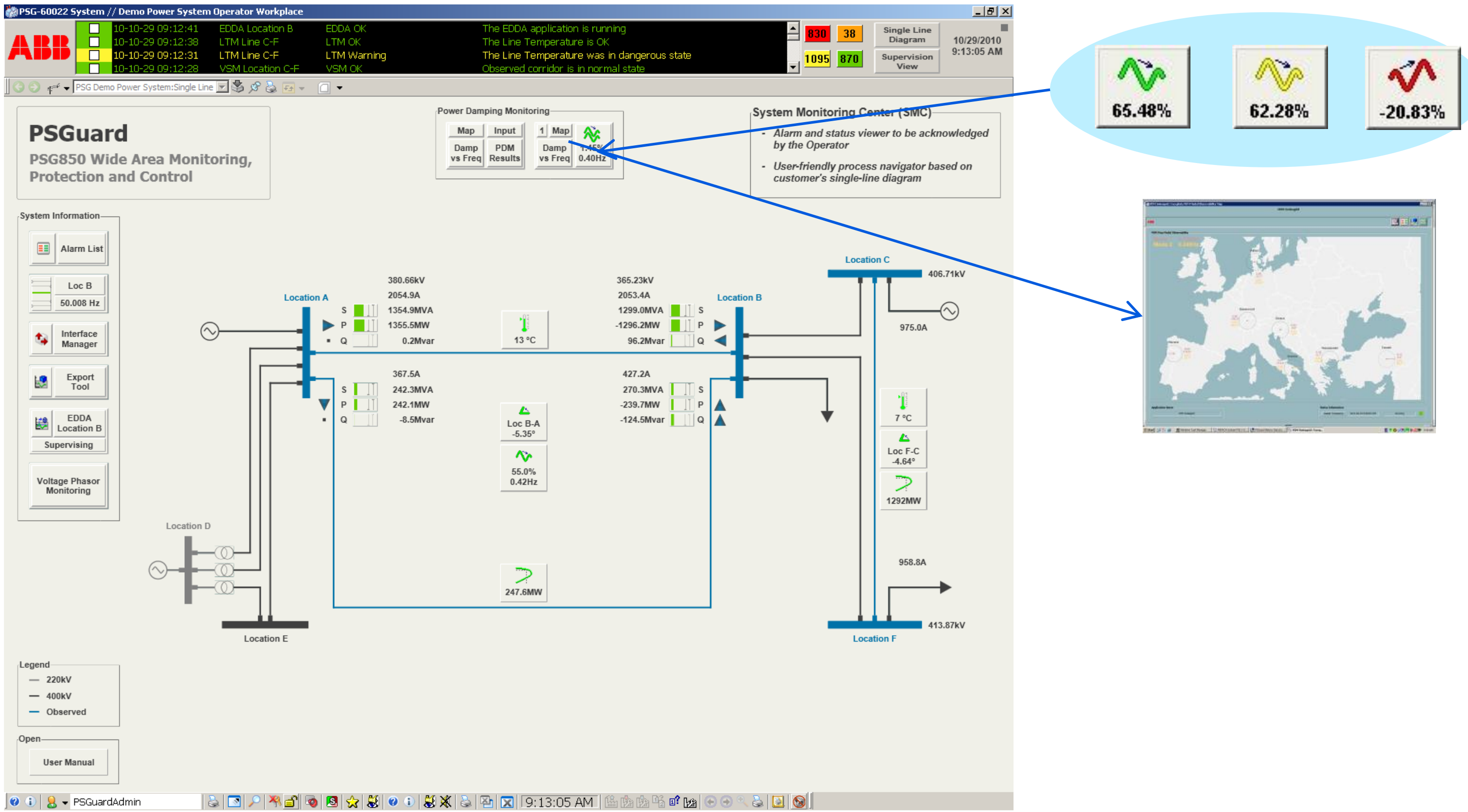
- Sliding window of 10-15 minutes length
- Estimate MIMO statespace model

$$x(k+1) = Ax(k) + Ke(k)$$
$$y(k) = Cx(k) + e(k)$$

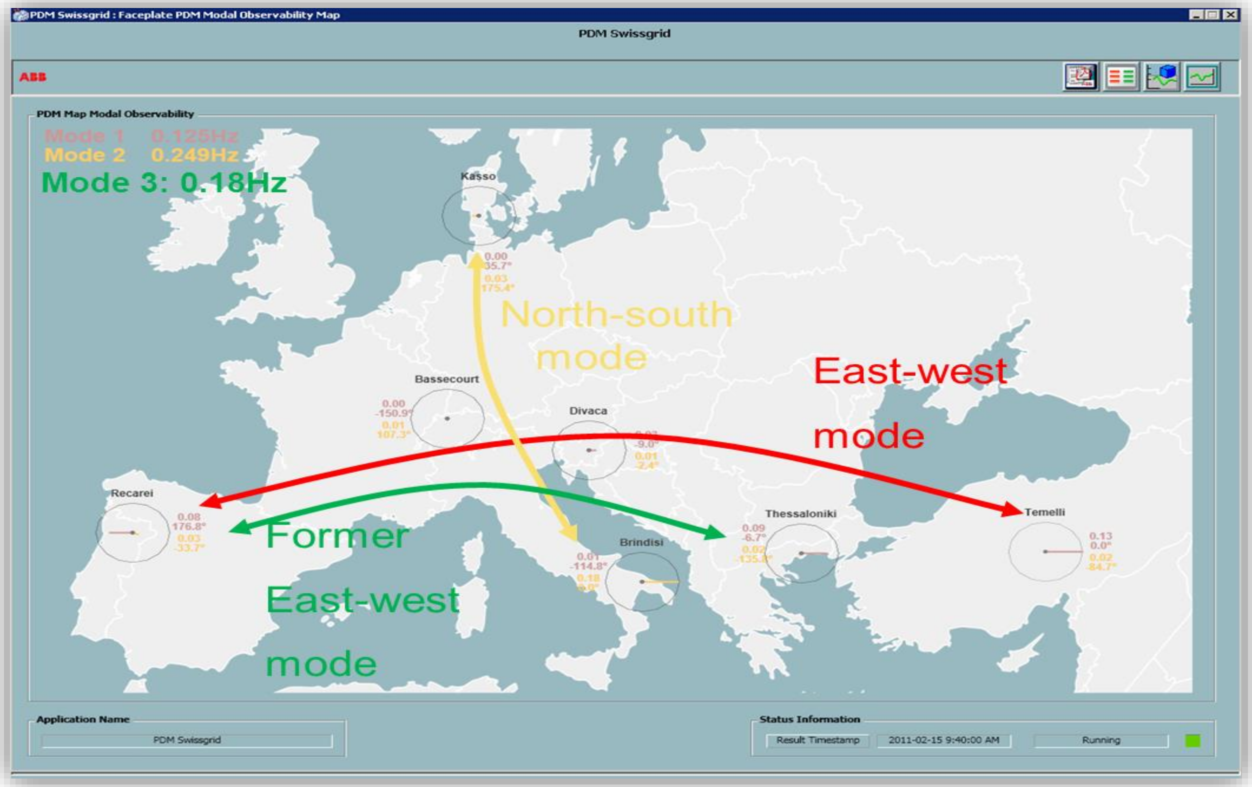
- $e(k)$ – background power system load variations
- $y(k)$ – frequency measurements

- Carry out modal analysis
  - Diagonalization of A
  - Damping & frequency of critical modes
  - Visibility in different measurements (mode shape)
  - Confidence intervals for damping and frequency

Power Damping Monitor (PDM) User Interace

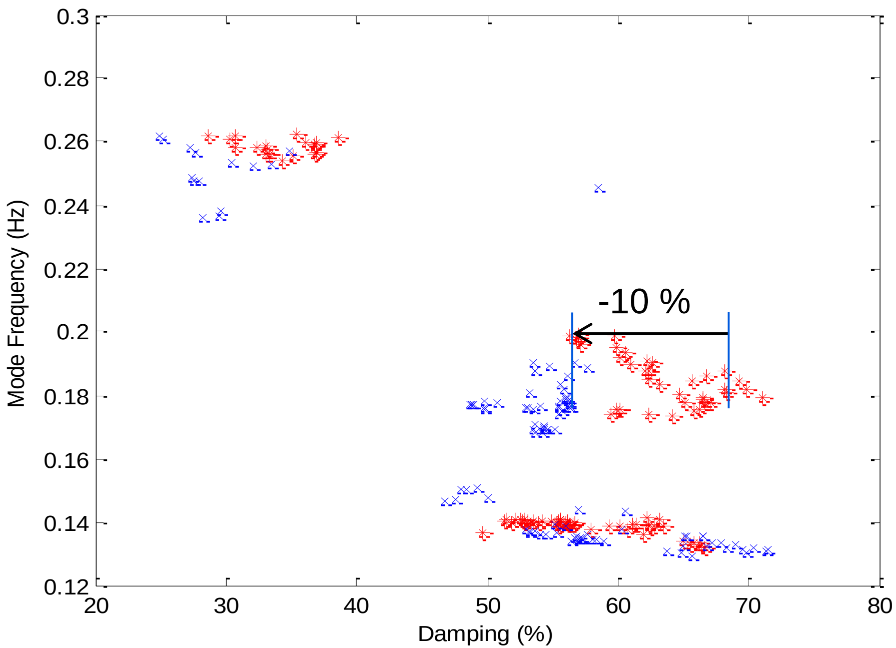


Power Damping Monitor (PDM) Example



- East-west mode - ~0.13 Hz
- North-south mode - ~0.25 Hz
- Former east-west mode - ~0.17 Hz

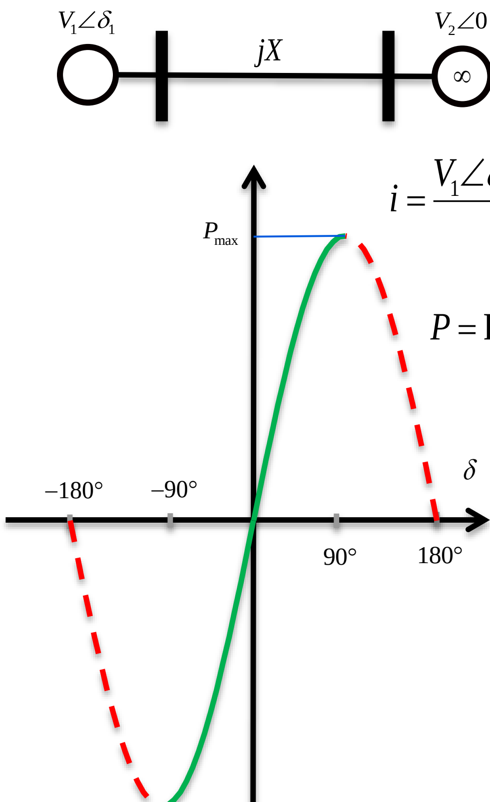
Power Damping Monitor (PDM) Output



- Results for October 25, 2011 event
  - 14:30 -14:59 CET during fault
  - 15:00 – 15:30 CET post fault
- Trip reduced damping of the former east-west mode by 10%
- PDM reported around 60% damping of the east-west mode before and disturbance (nearly unaffected)

- North-south mode - 0.25 Hz
- East-west mode - 0.13 Hz
- Former east-west mode - 0.17 Hz

Phase Angle Monitoring (PAM) Principle



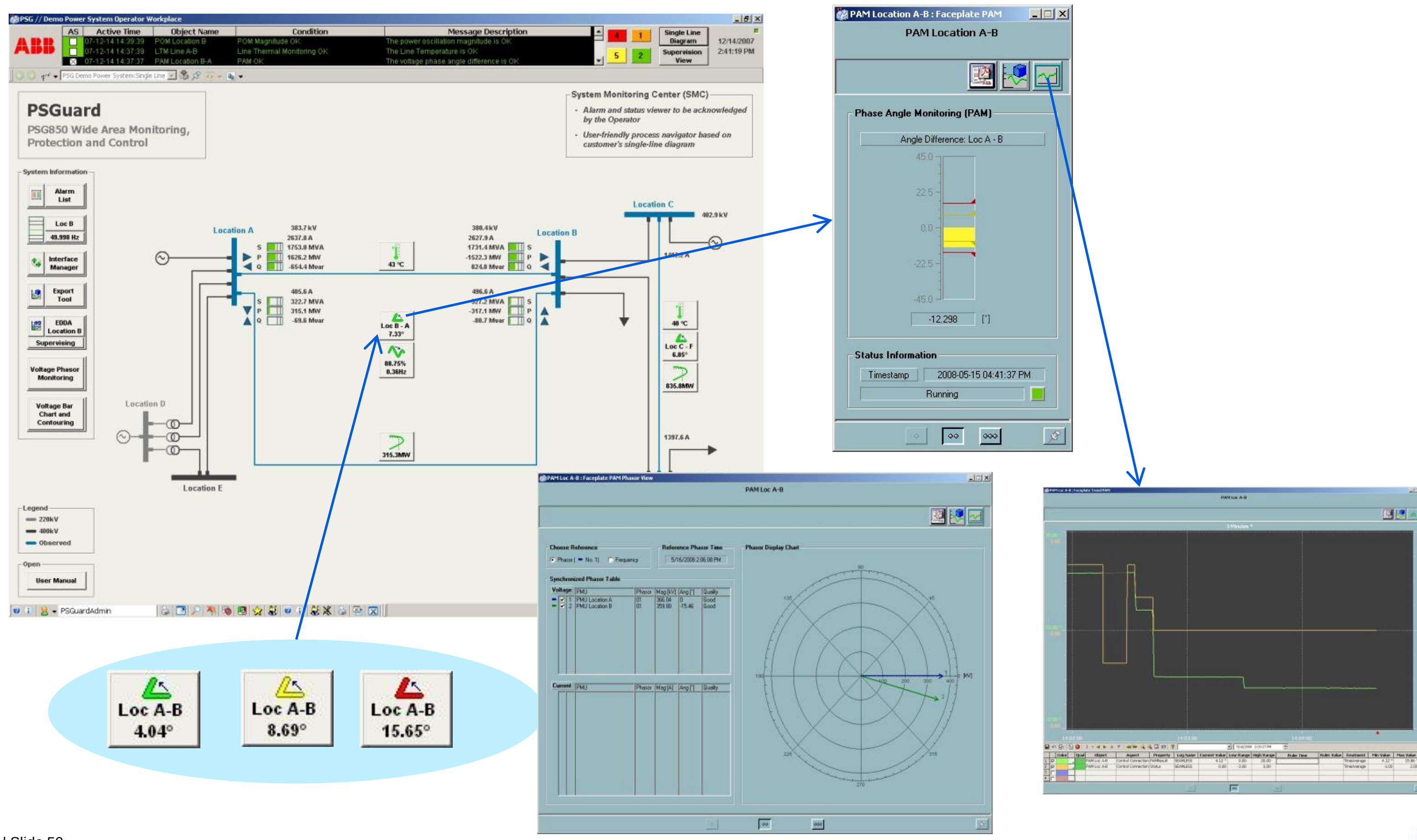
$$i = \frac{V_1\angle\delta - V_2\angle 0}{jX}$$

$$P = \mathrm{Re}\{v_1 i_1^*\} = \frac{V_1 V_2}{X}\sin\delta$$

Phase Angle Monitoring

- Phase angle difference (δ) is indicative of:
  - Relation between grid strength and power transfer
- Abnormal values of the phase angle difference is indicative of
  - Unusual power transfer
  - Line trips
  - Abnormal voltage levels

Phase Angle Monitoring (PAM) User Interace



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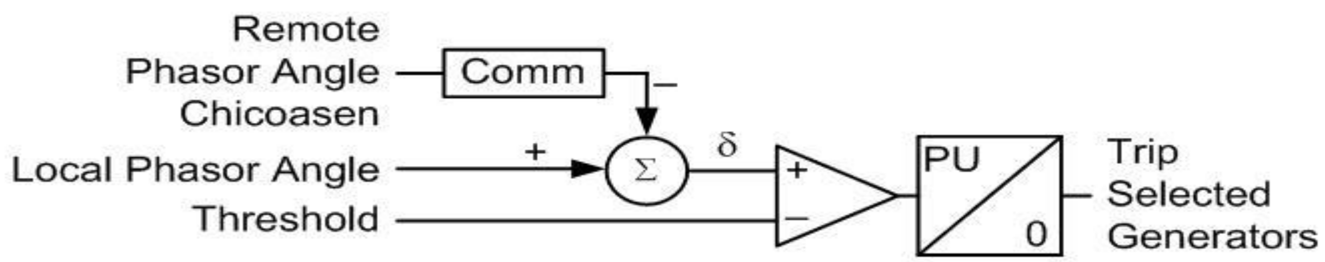
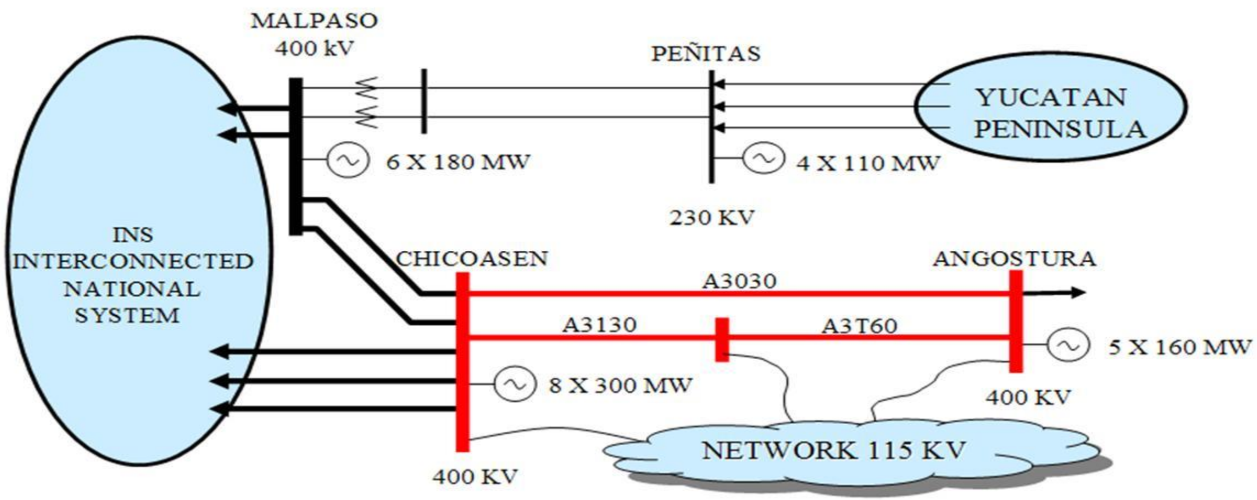
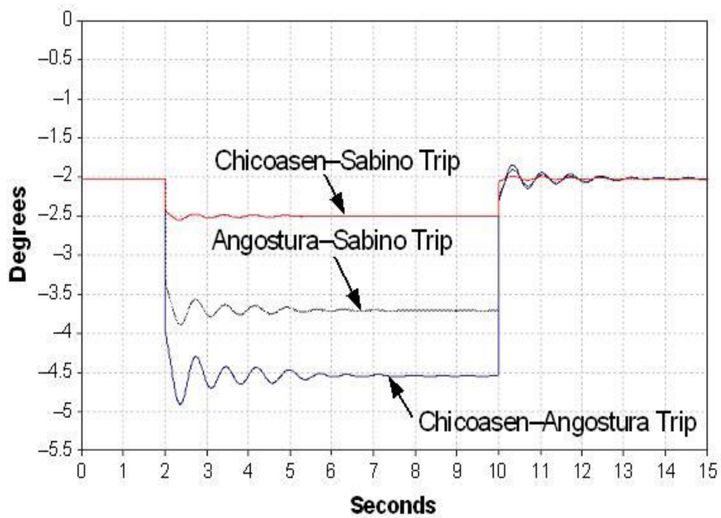
Angular Differential Protection Example

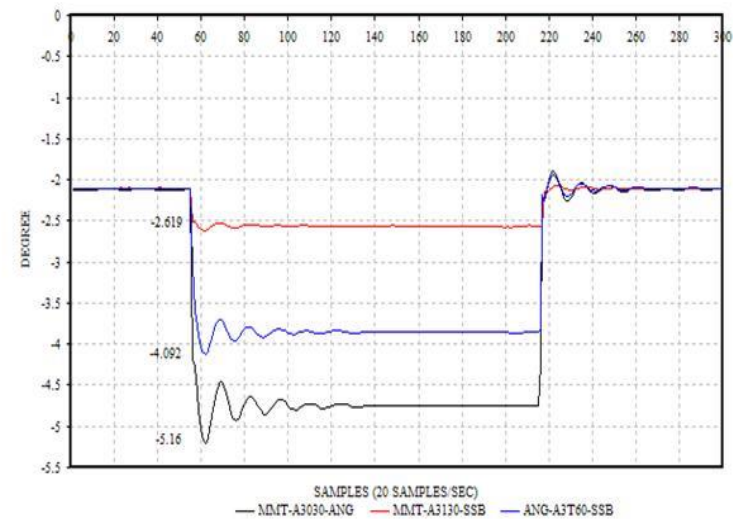




Source: E.Martinez Angular Difference Protection Scheme, Conference on Actual Trends in Development of Power System development and Automation, Sept 2009, Moscow, Russia

Angular Differential Protection Example

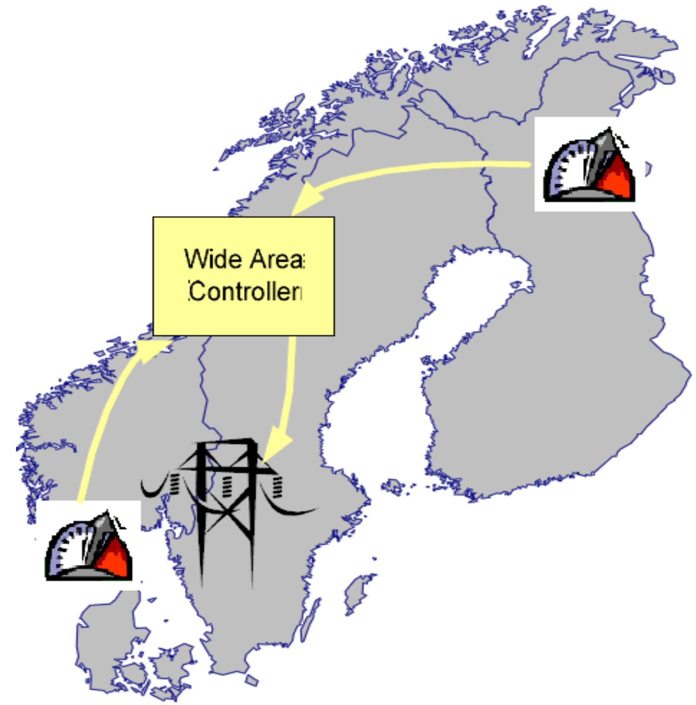




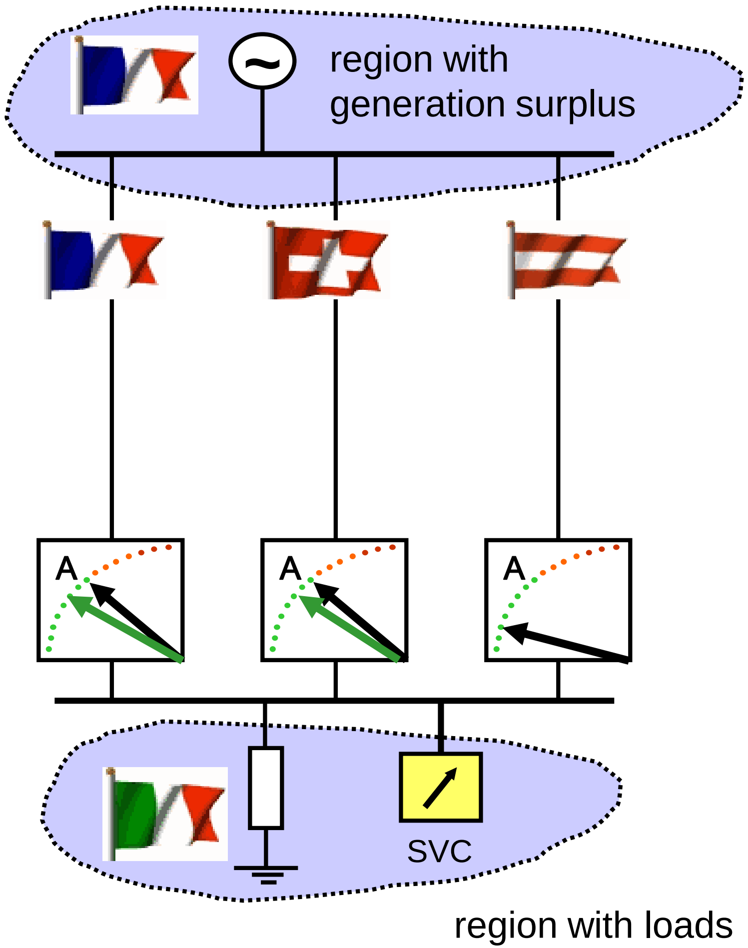
Source: E.Martinez Angular Difference Protection Scheme, Conference on Actual Trends in Development of Power System development and Automation, Sept 2009, Moscow, Russia

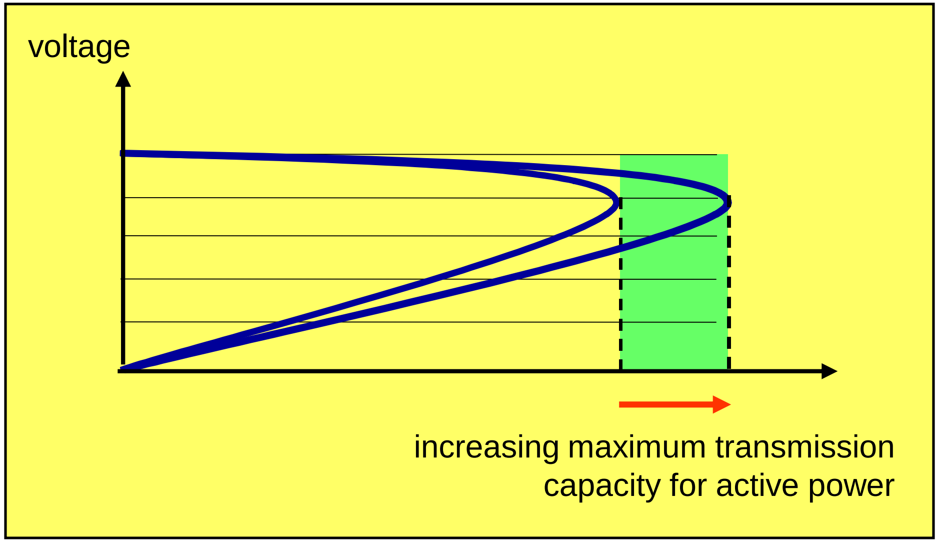
Wide-Area Control Applications

- Wide Area Power oscillation Damping control WA-POD
- Choose feedback signals from any PMU equipped substation
- Coordinated POD action from several actuators (SVC, FACTS, Generators)
- Prototype WACS implemented and tested
  - PMU-PCU400 PDC-MACH2 control system
  - Wide Area Power Oscillation Damper (POD) with local signal based POD as backup
- Deployed in 2010



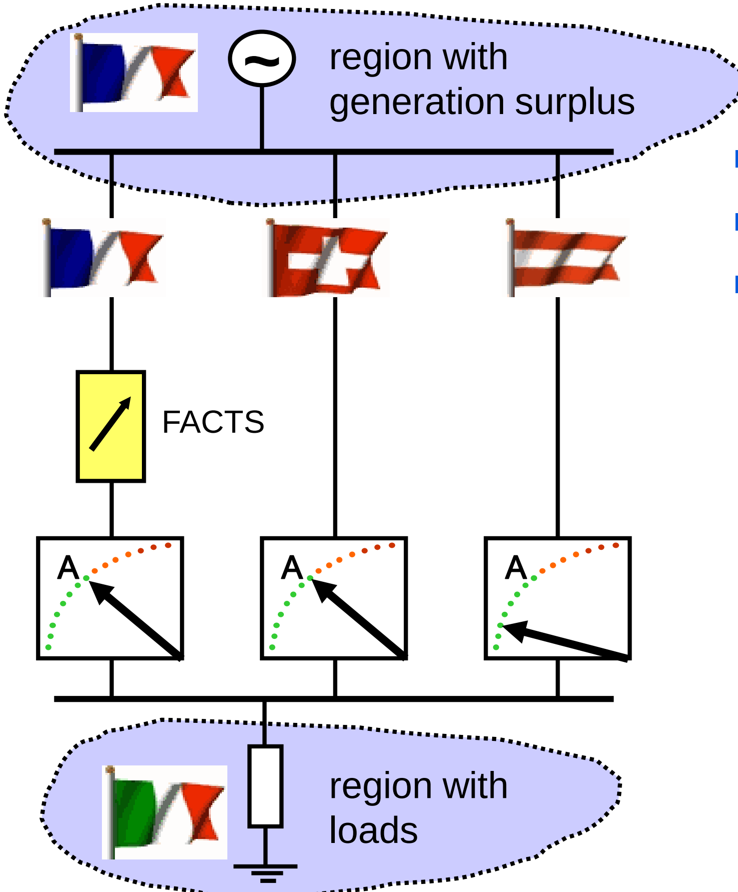
2004: Increasing capacity with SVC





SVC: static var compensation

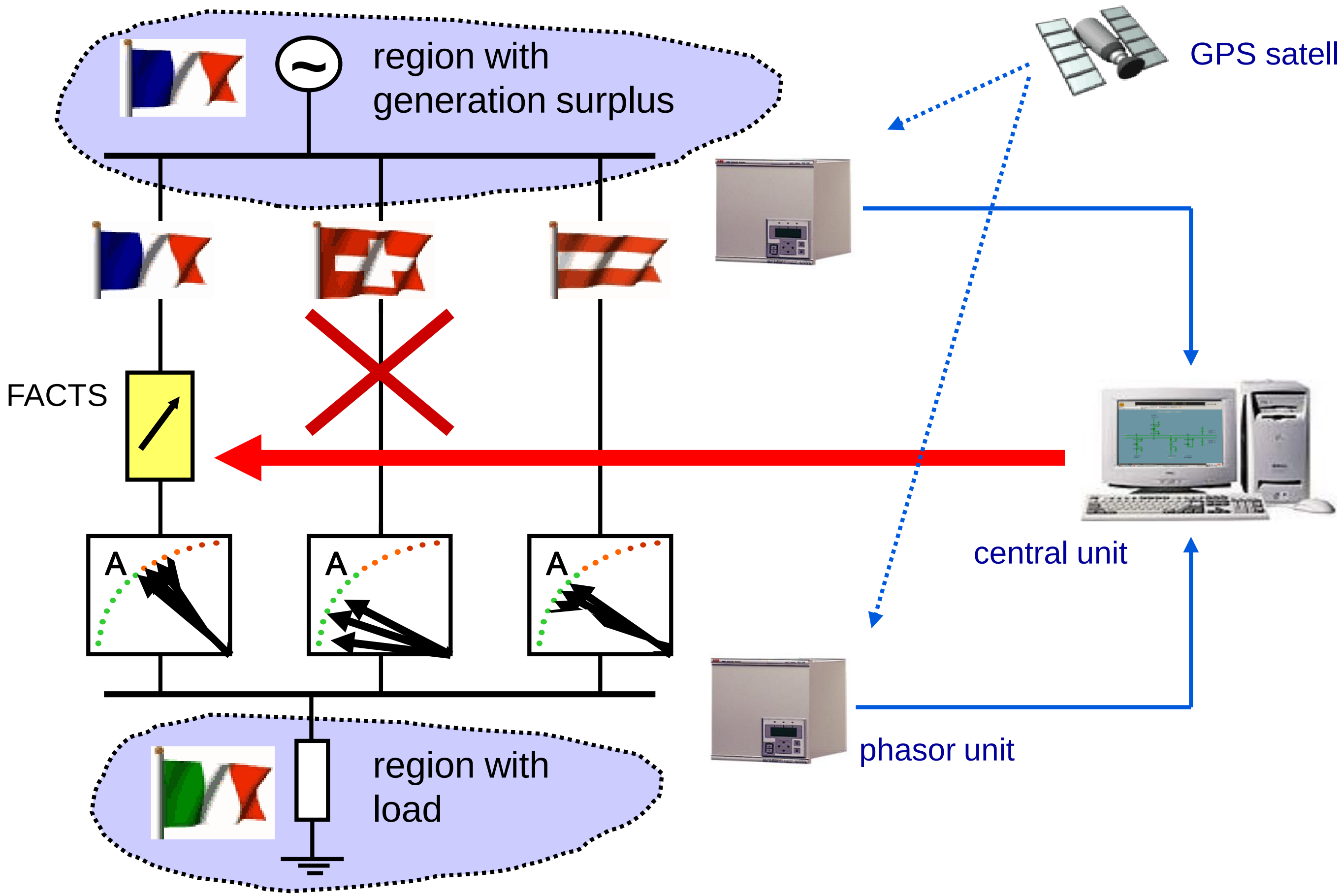
2004: FACTs for Power Flow Control



- switched series compensation (SC) *new 2004*
- thyristor controlled series compensation (TCSC)*
- dynamic flow control (DFC)* *vision*

* fast control

2004 vision: combining intelligent solutions



Step 1:

- system analysis
- free capacity available
- temporary overload acceptable

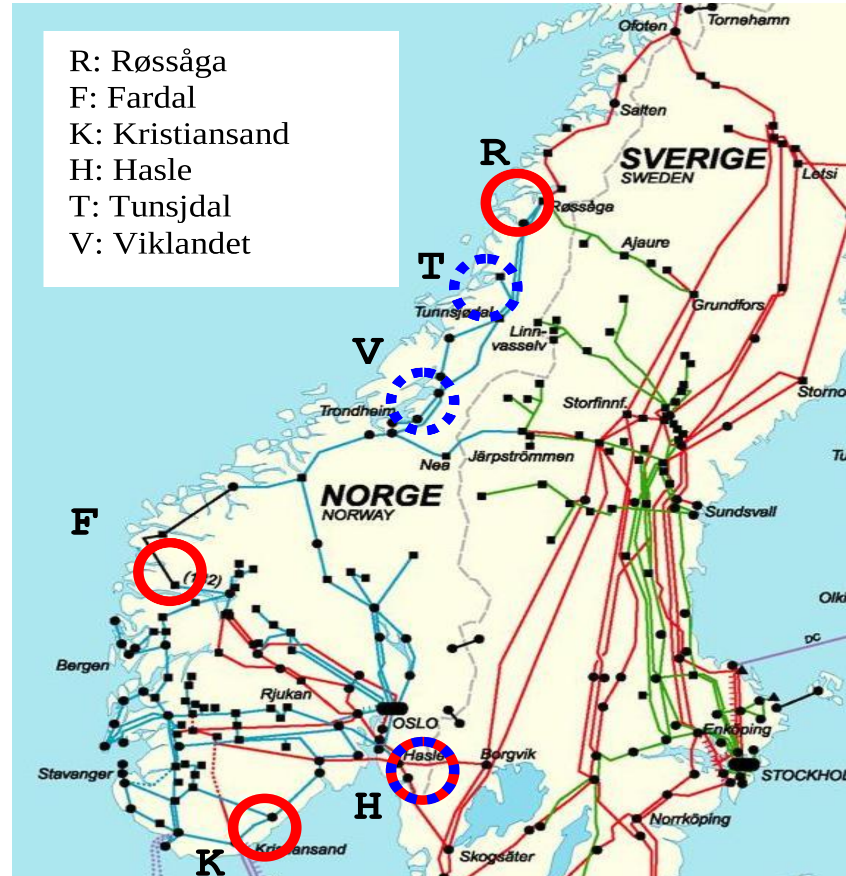
Step 2:

- increase reactance of overloaded line
- stable situation

Nordic Power System

- Interconnected power systems
  - Finland
  - Sweden,
  - Norway,
  - East Denmark
  - West Denmark
  - Iceland (isolated)

- Recently installed in Norway
  - PMUs (locations R, F, K, H)
  - SVCs (locations H, T, V)

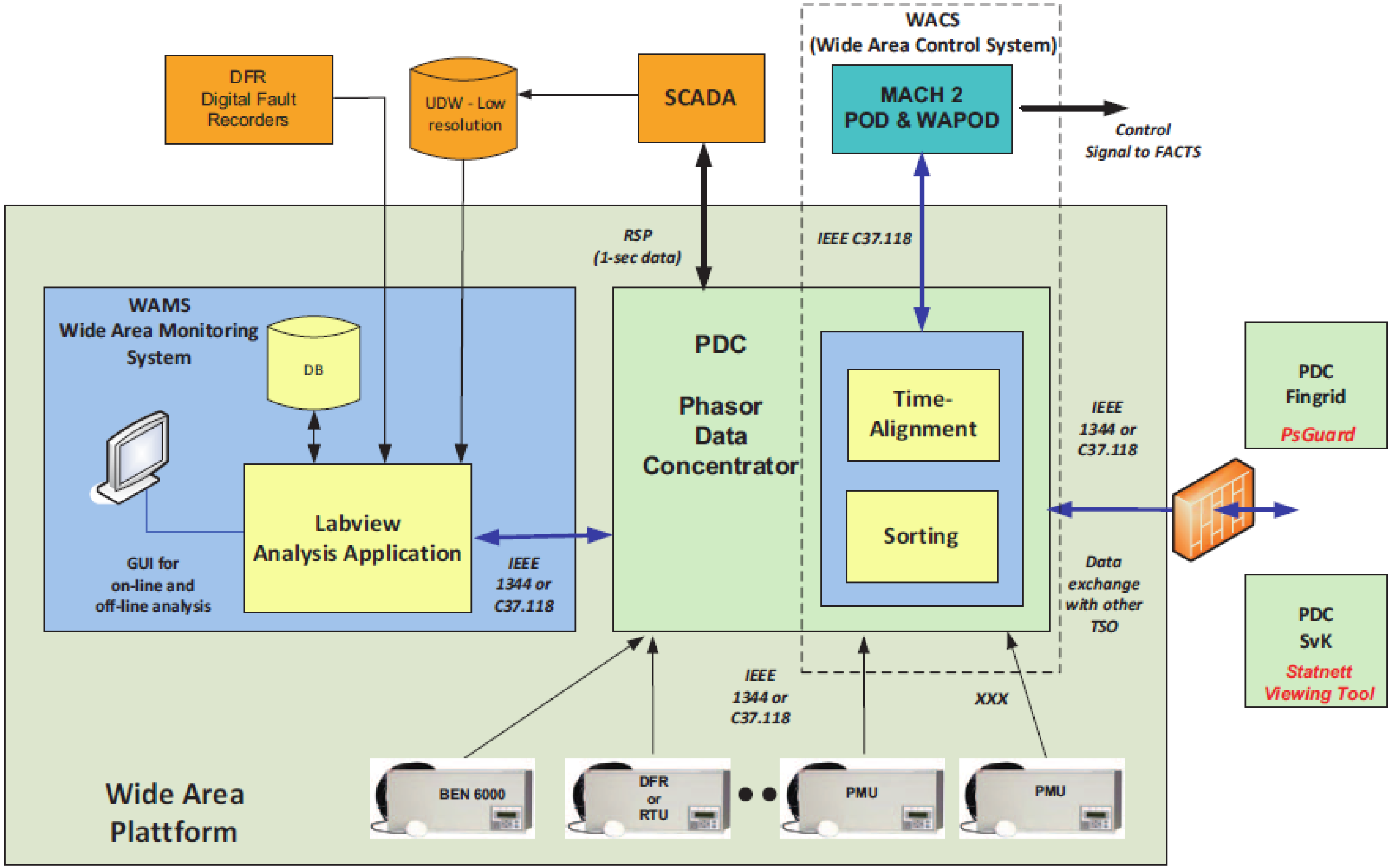


Wide-area Power Oscillation Damper Control

- PMUs streaming synchrophasors
  - Nedre Røssåga
  - Kristiansand
- SVC is located at Hasle
  - PDC
    - receives voltage phasors
    - extracts voltage phasor angle
  - ABB Mach2 Controller
    - Local control
    - WAPOD Control
    - Switch-over logic

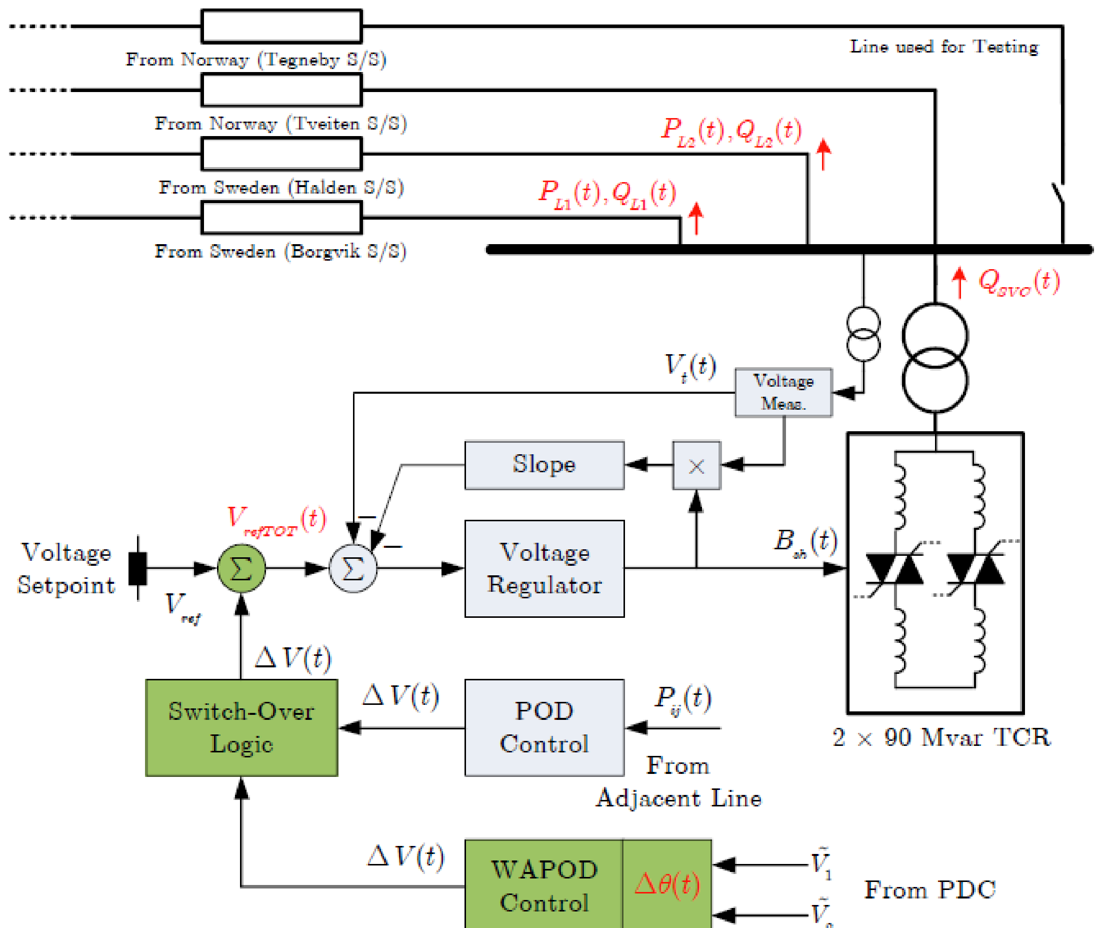
Source: K. Uhlen, etc Wide-Area Power Oscillation Damper Implementation and Testing in the Norwegian Transmission Network, IEEE PES 2012.

Wide-area Monitoring and Control System



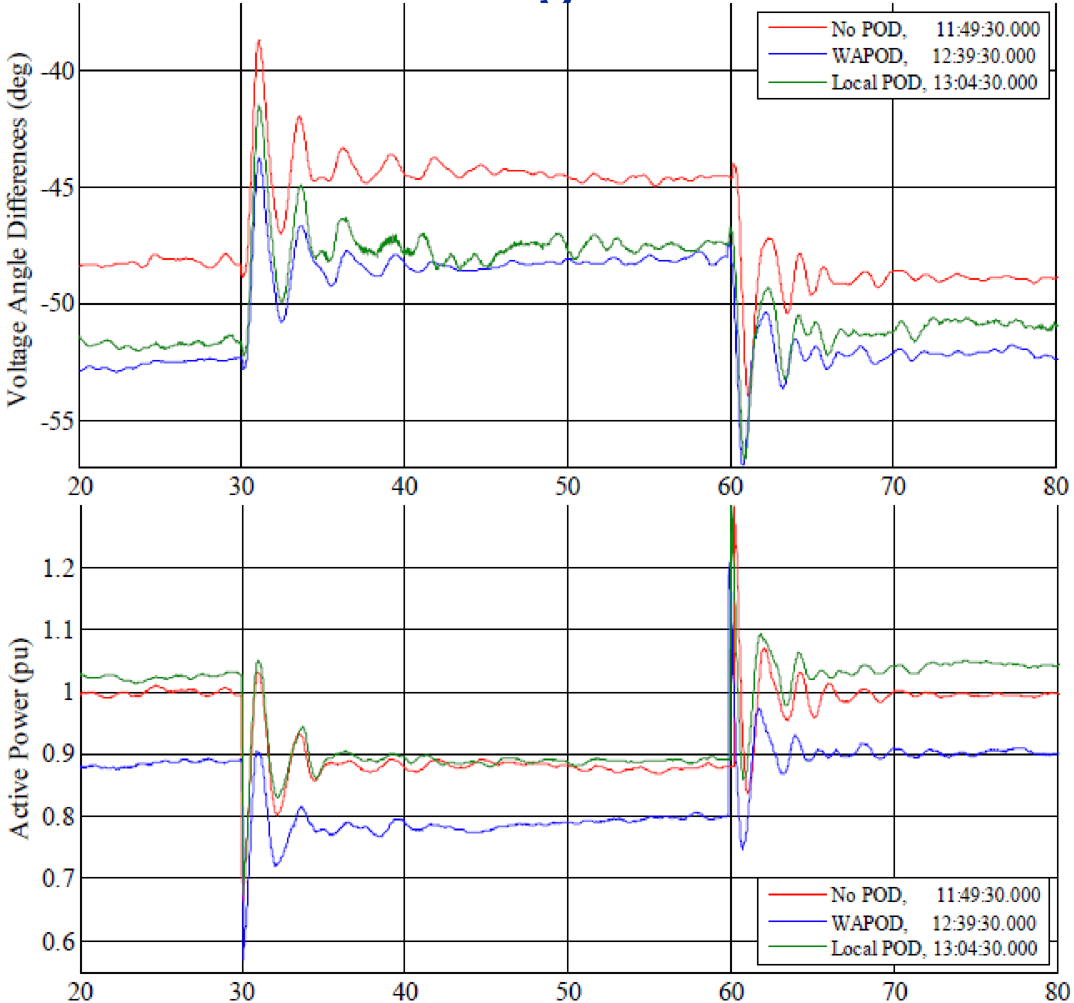
Source: K. Uhlen, etc Wide-Area Power Oscillation Damper Implementation and Testing in the Norwegian Transmission Network, IEEE PES 2012.

SVC Control Implementation



Source: K. Uhlen, etc Wide-Area Power Oscillation Damper Implementation and Testing in the Norwegian Transmission Network, IEEE PES 2012.

Field Test Results: Switching 420kV Hasle-Tegneby



Source: K. Uhlen, etc Wide-Area Power Oscillation Damper Implementation and Testing in the Norwegian Transmission Network, IEEE PES 2012.

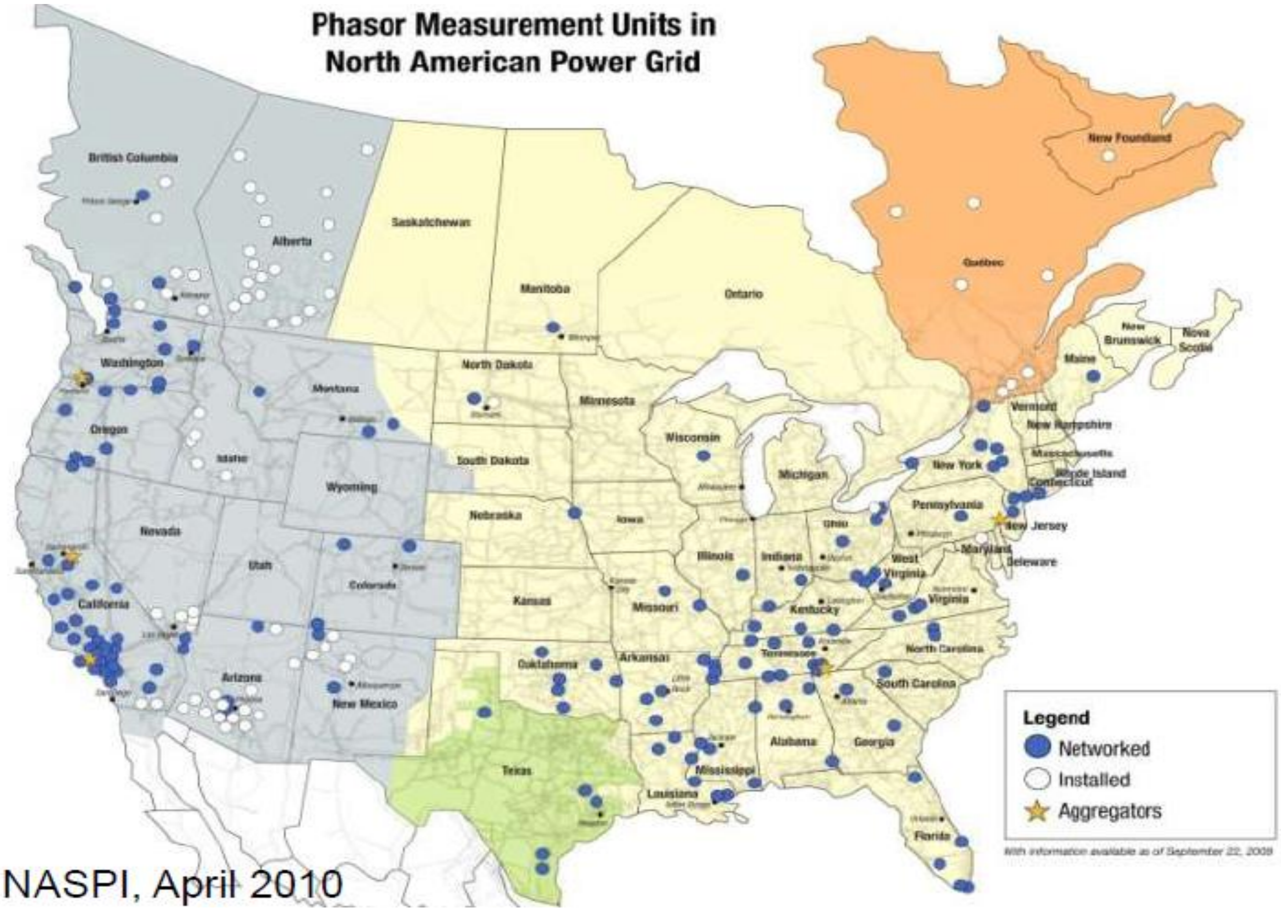
SVC at Hasle (4 x 90 Mvar TCR)

WAPOD Field Tests:

Completed on 2011-11-15

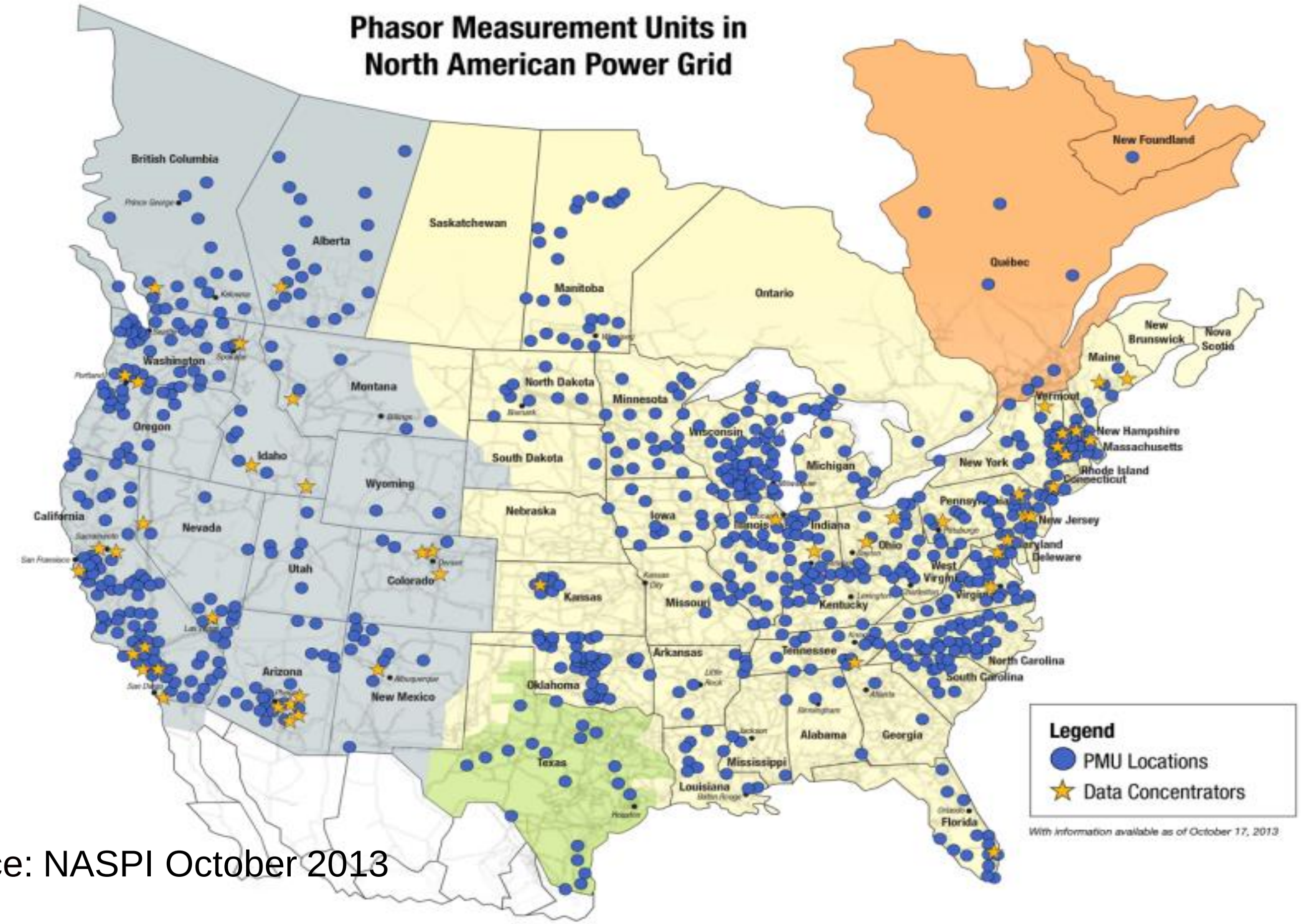
Source: K. Uhlen, etc Wide-Area Power Oscillation Damper Implementation and Testing in the Norwegian Transmission Network, IEEE PES 2012.

North American Synchrophasor Initiative



Source: NASPI, April 2010

North American Synchrophasor Initiative

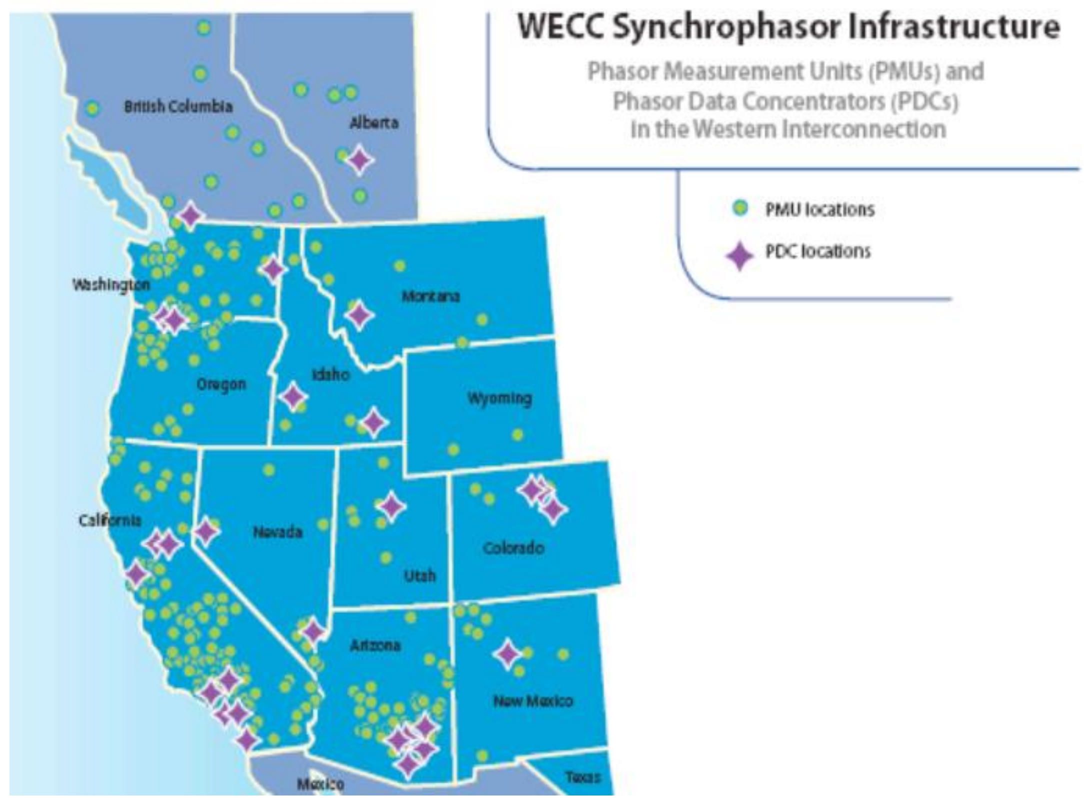


Source: NASPI October 2013

Western Interconnection Synchrophasor Program

Western Interconnection Synchrophasor Program

- 244 Substations with PMUs
- Sampling Rate 30-120 sps
- Installation Rate:
  - 2011 Q3 22
  - 2011 EOY 38
  - 2012 EOY 267
  - 2013 Q1 362



Source: WECC WISP Western Interconnection Synchrophasor, Vickie VanZandt NASPI Work Group Meeting October 12-13, 2011

WISP Communications

Harris Press Release

Printer Friendly Version

Harris Corporation Network to Provide the Communication Infrastructure for Enhancement of Reliability in the Western Interconnected Electric Grid for Western U.S., Canada, and Northern Mexico

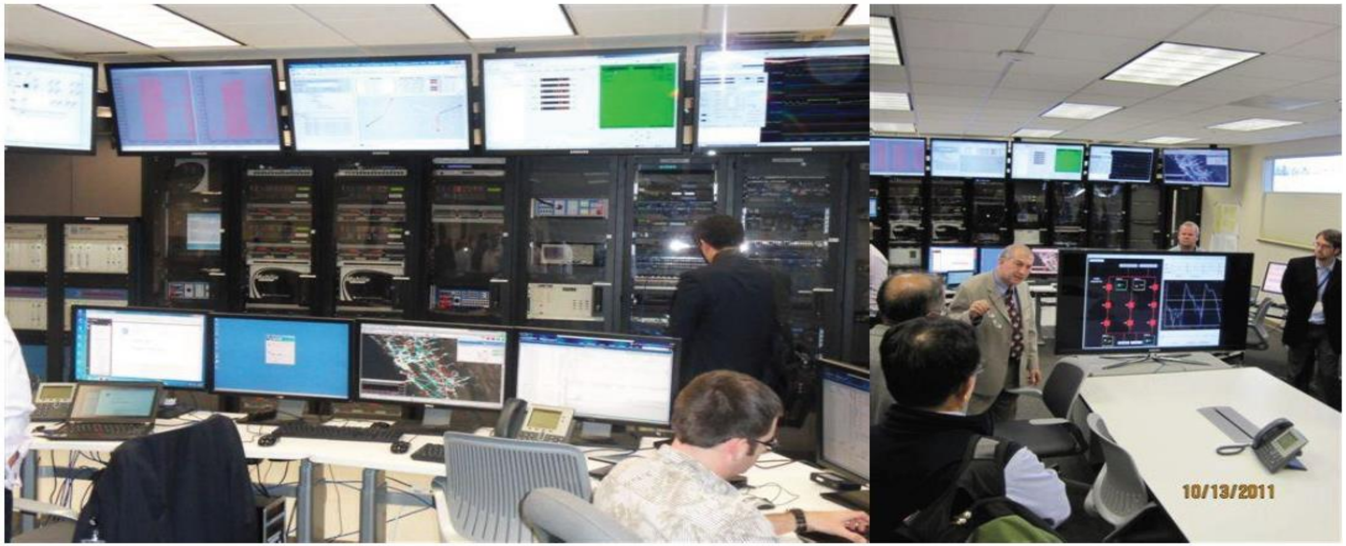
Highlights

- Wide area network to support the Western Electricity Coordinating Council and other participating electric utility organizations
- Key infrastructure component in implementing real-time vulnerability detection in western region's electric grid
- Enables utilities to have better visibility into the condition of the power system and take timely actions to mitigate widespread electrical outages

MELBOURNE, FL, July 14, 2011 — Harris Corporation (NYSE:HRS), an international communications and information technology company, has been awarded a five-year contract to provide a wide-area network that will help detect and assist in avoiding or mitigating regional electrical system disturbances in a service area that extends from Canada through 14 western U.S. states and northern Mexico.

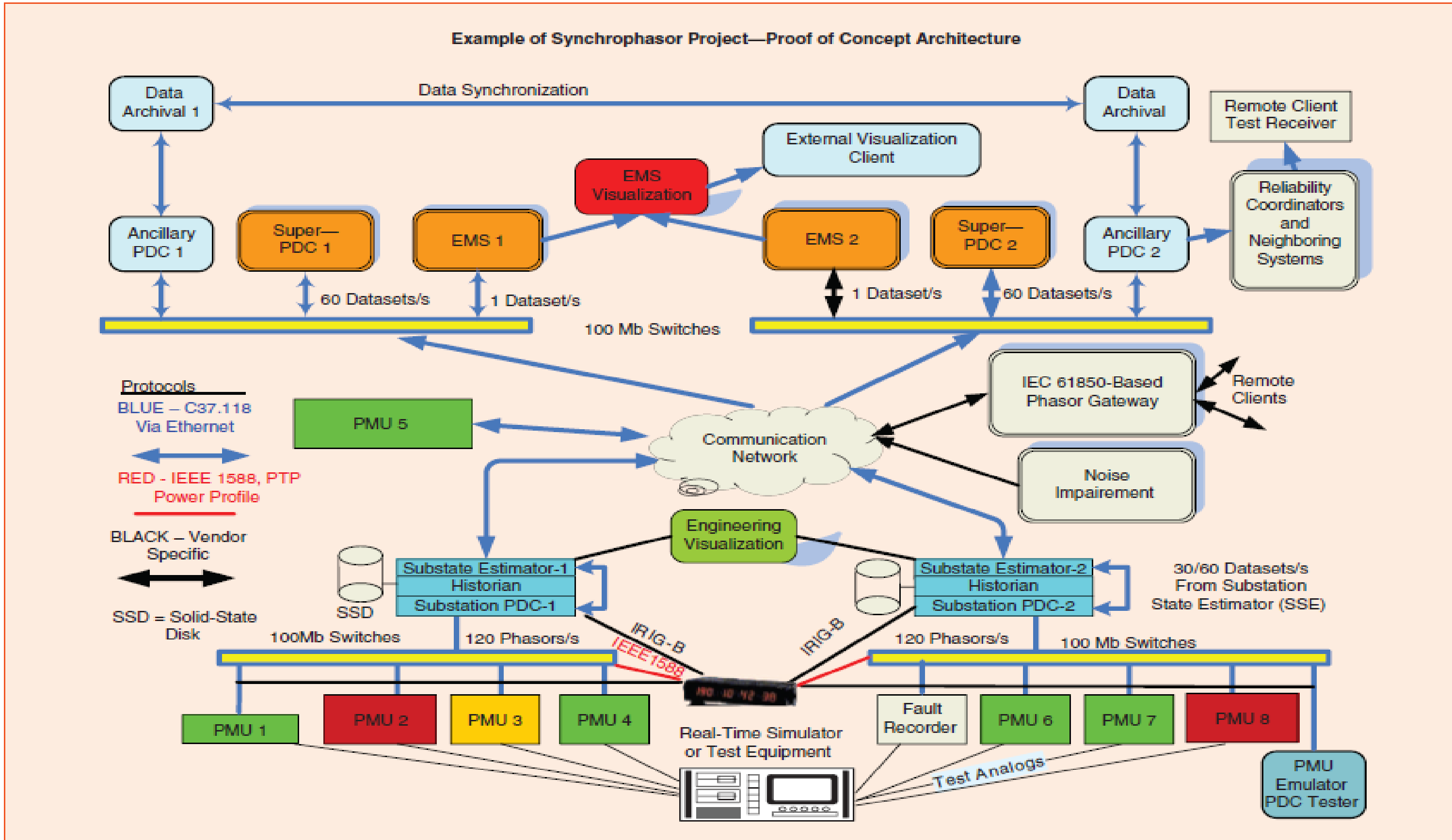
The private network will enable the Western Electricity Coordinating Council (WECC) Reliability Coordinator, and other participating entities, to detect and take timely actions to mitigate the risk of impacts such as oscillations, grid instability and ultimately, widespread system blackouts.

PG&E synchrophasor proof-of-concept facility



PG&E Synchrophasor Proof-of-Concept Facility (POC) is a smaller scale synchrophasor system used to **test**, **validate**, and **demonstrate** various functions and interoperability before field deployment

PG&E synchrophasor proof-of-concept architecture



Source: Grid monitoring and situational awareness: PG&E synchrophasor proof-of-concept project presentation at ABB APW 2013

Conclusion

- Use of synchrophasor measurements can assist greatly in meeting strenuous reliability and power delivery requirements placed on power systems evolving today
- Synchrophasor measurements could be used for local and wide-area monitoring, control and protective relaying applications
- Active standardization (supported by smart grid developments) enables interoperability and faster adoption of the synchrophasor technology by the power industry

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