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# Real-time Monitoring of Power Oscillations and Modal Damping in the European ENTSO-E System

# Recent Advances and Experience with Power System Oscillation Monitoring and Control using Wide-area Phasor Measurements

## Motivation

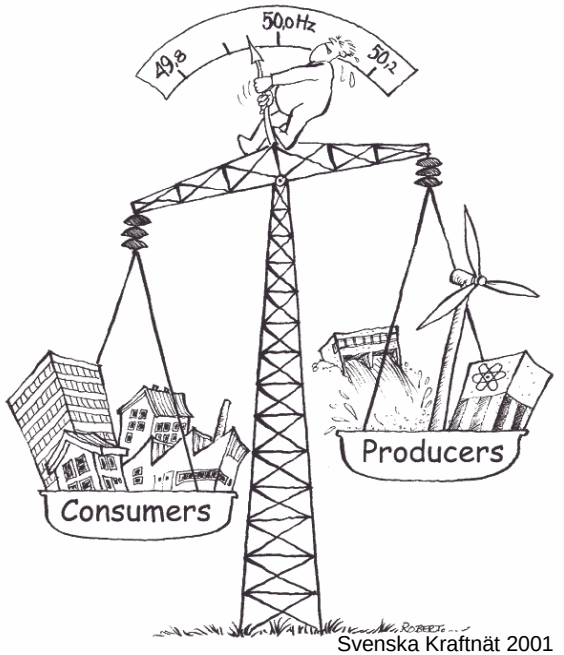
- Power oscillations are a growing concern among power system operators worldwide
  - Increased penetration of renewables
  - Increased transmission asset utilization
- Phasor measurement units (PMUs) are becoming commonplace in the grids worldwide
- Phasor measurements are ideal sensor to monitoring of local as well as inter-area oscillations

# Wide Area Monitoring Systems
## General challenges in transmission networks

- Increasing demand for power
- Transmission networks get bigger by aggregation (island ➔ interconnected)
- Distance between generation and load changes
  - Laws, regulations & politics often impede building power plants where they are needed
  - Introduction of distributed energy resources e.g. wind
  - ➔Load flow becomes volatile

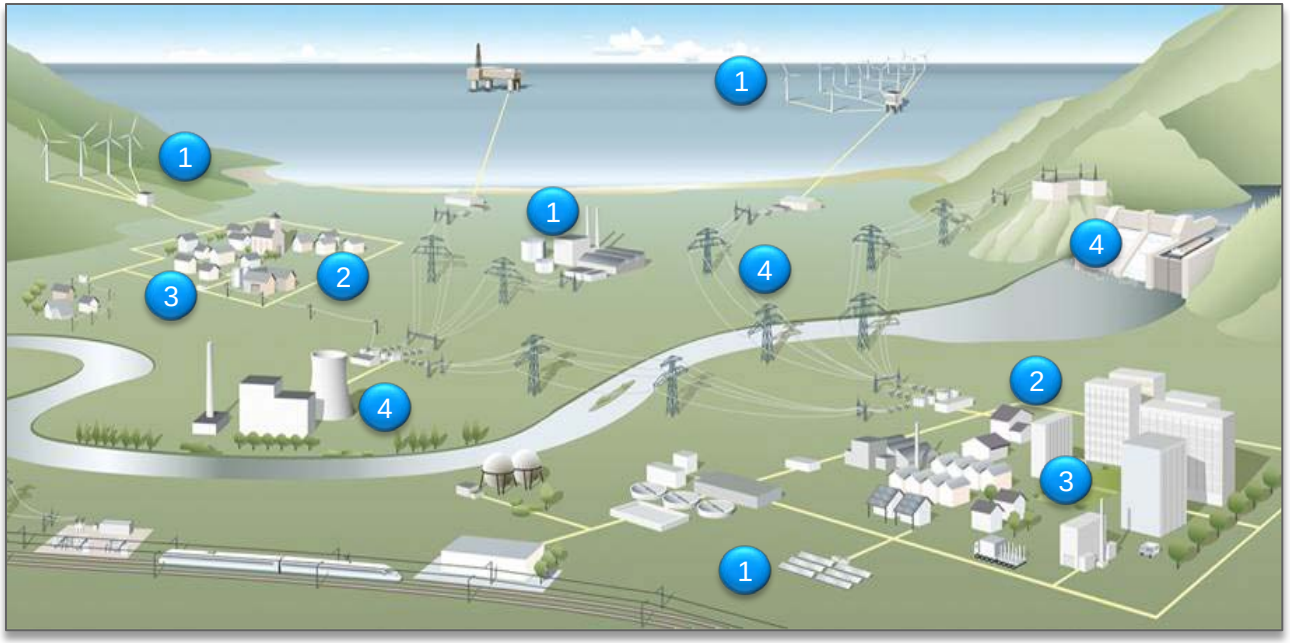
➔ Modern supervision and tools are needed

- ➔Increase the utilization of new technologies e.g. **WAMS** to allow the networks to operate closer to its capacity while maintaining system security



Svenska Kraftnät 2001

# Wide Area Monitoring 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**

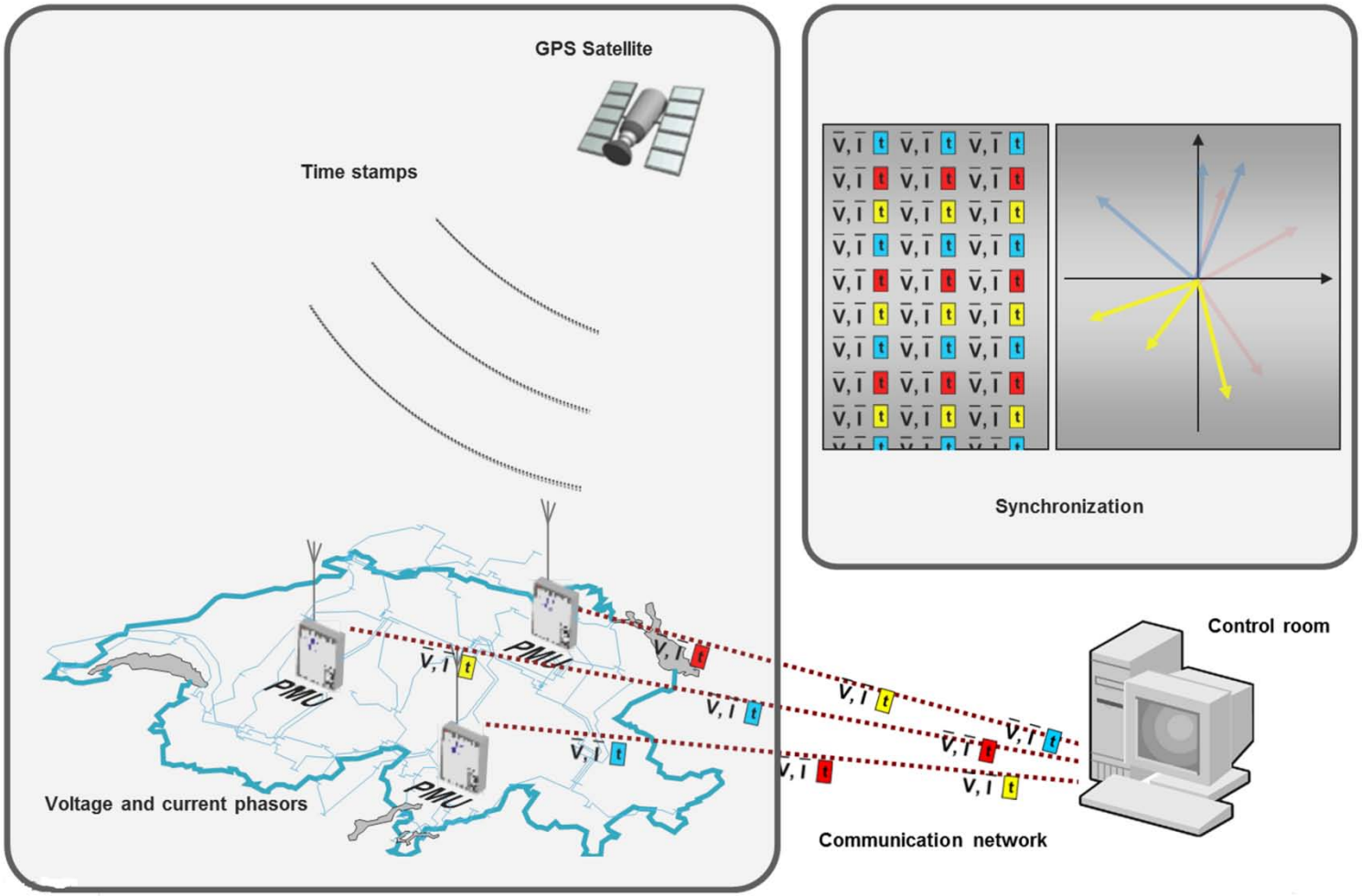
- Real time pricing / tariffs
- Home automation / load management
- Distributed generation / storage

**4) Reliability and efficiency**

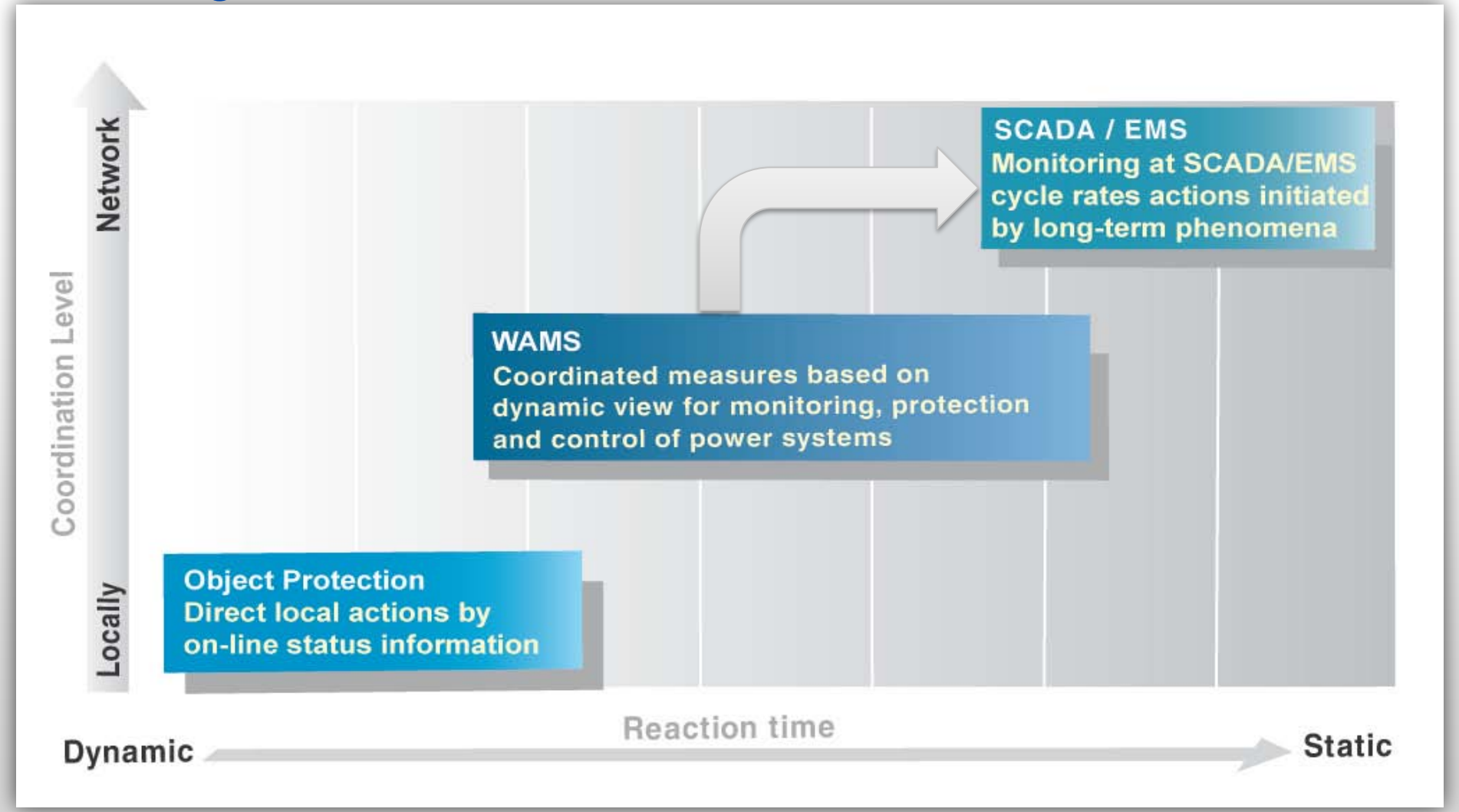
- cyber security
- customer outage information
- emergency / peak power

# Wide Area Monitoring Systems
## Basic idea

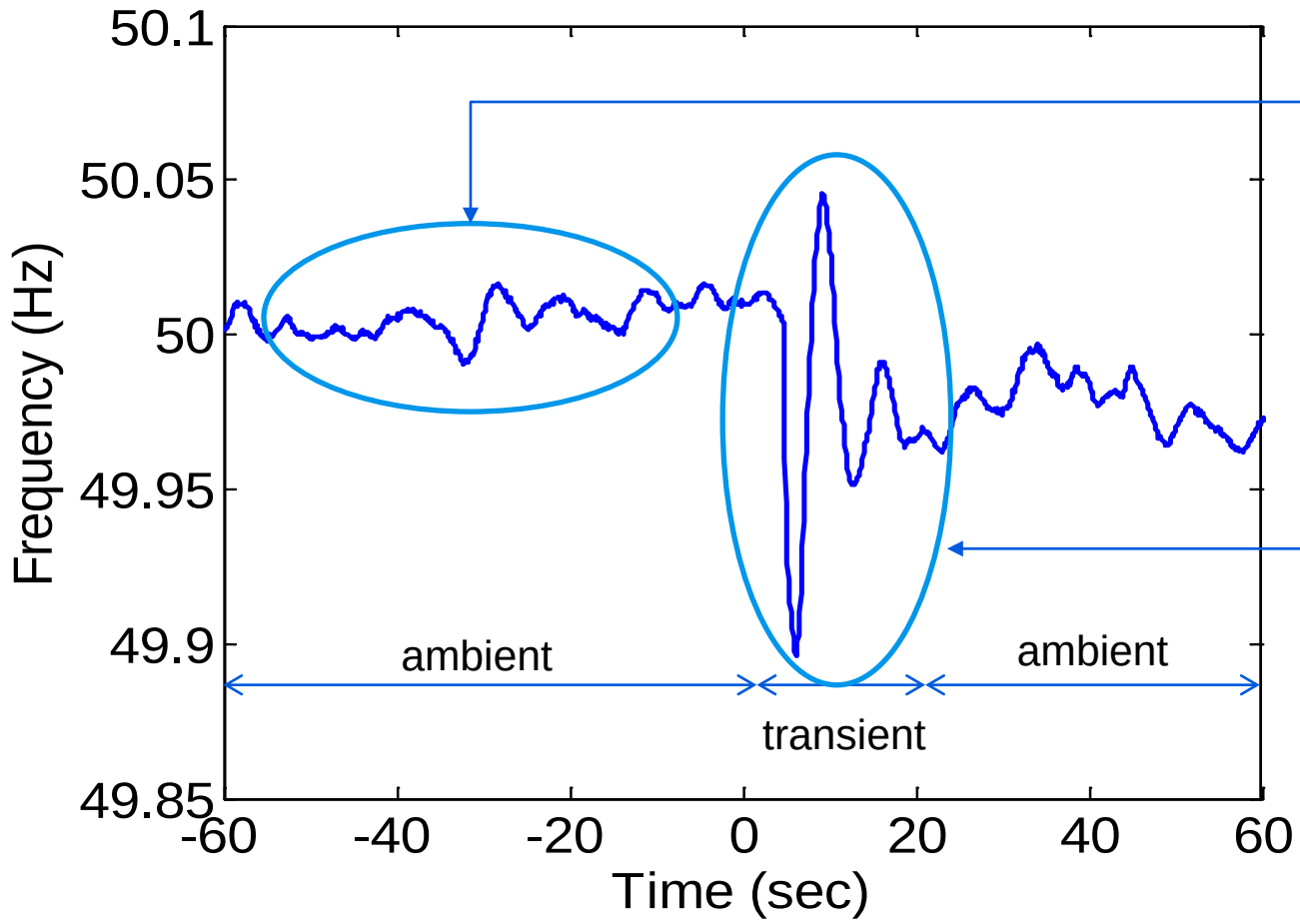
- Synchronous sampling by PMUs locally in substations
- Periodic (10-50Hz) transmission of measurements to central location
- Processing and monitoring/control applications at central location



# Wide Area Monitoring Systems
## Positioning



# Power Oscillation Monitoring
## Ambient vs. Transient Oscillations

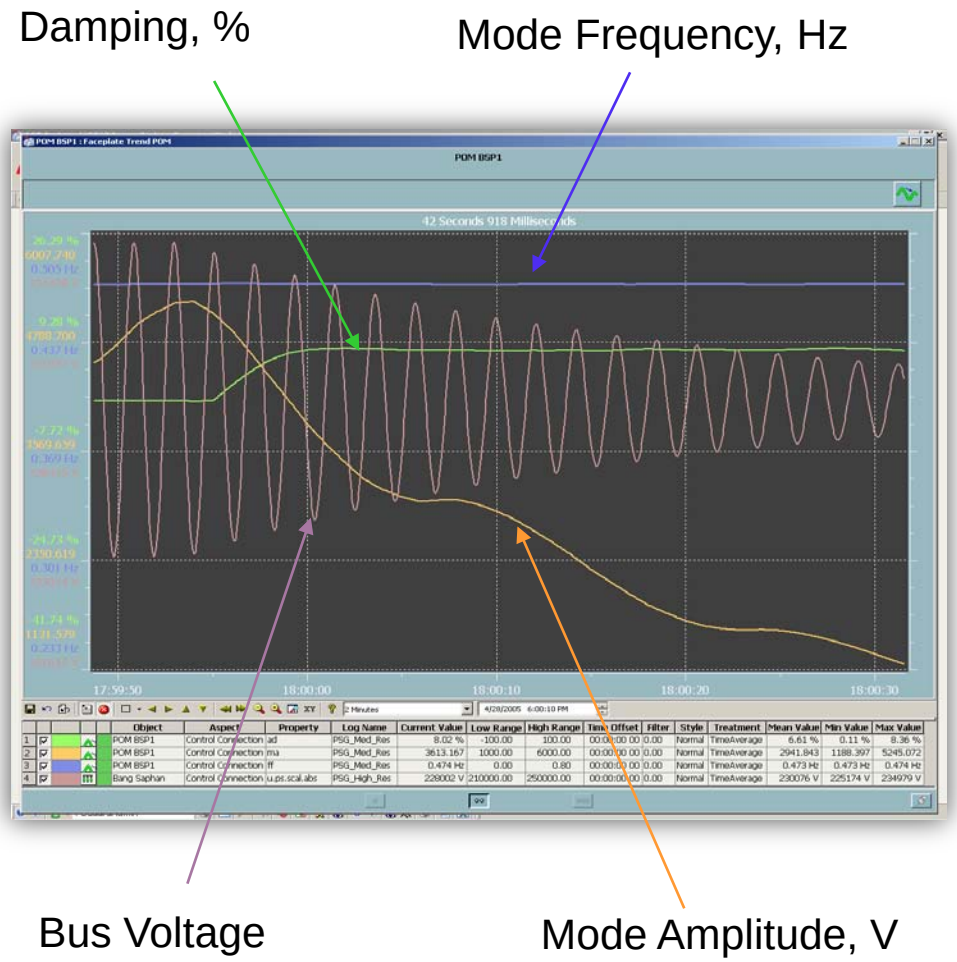



**PDM**
determining modes and characteristics based on ambient variations

**POM**
detecting transient oscillations

# Wide Area Monitoring Systems
## Power Oscillations Monitoring (POM)

- Real-time detection of power swings
- Algorithm is fed with selected voltage and current phasors
- Detection of various swing (power oscillation) modes
- Quickly identifies amplitude and frequency of oscillations (in order of seconds)
- First generation of oscillation damping monitoring: accurate estimate of **transient** oscillations
- In service since 2005
- Field experience in Switzerland, Croatia, Thailand, Finland, Norway, Austria



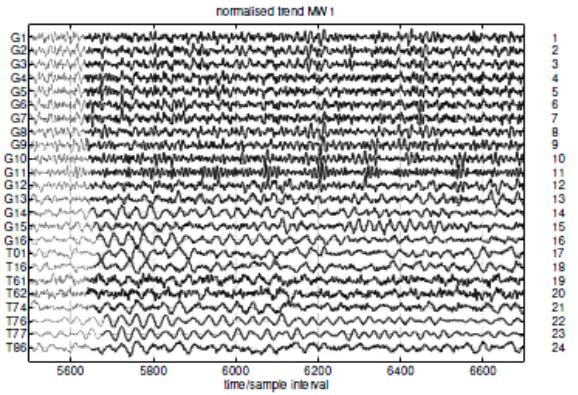
# Wide Area Monitoring Systems
## Power Oscillations Monitoring (POM)

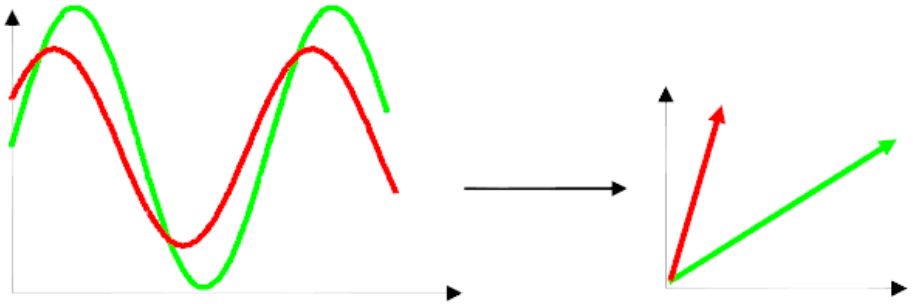
**Use Cases**

- From 2005 Swissgrid uses POM to continually track the both the north-south and the east-west modes
- POM is used as event detector to detect low-damping situations
- Statistical post-processing has revealed key factors:
  - low damping – low load conditions
  - certain generation dispatch patterns (different Power System Stabilizers, PSSs for different generation units)
- Action has been to retune PSSs in Greece and Spain
- Occurrence of low-damping situations now much less frequent
- Low damping condition implies that the damping estimate stays low for a certain amount of time, and that the oscillations were excited

# Wide Area Monitoring Systems
## Power Damping Monitoring (PDM)

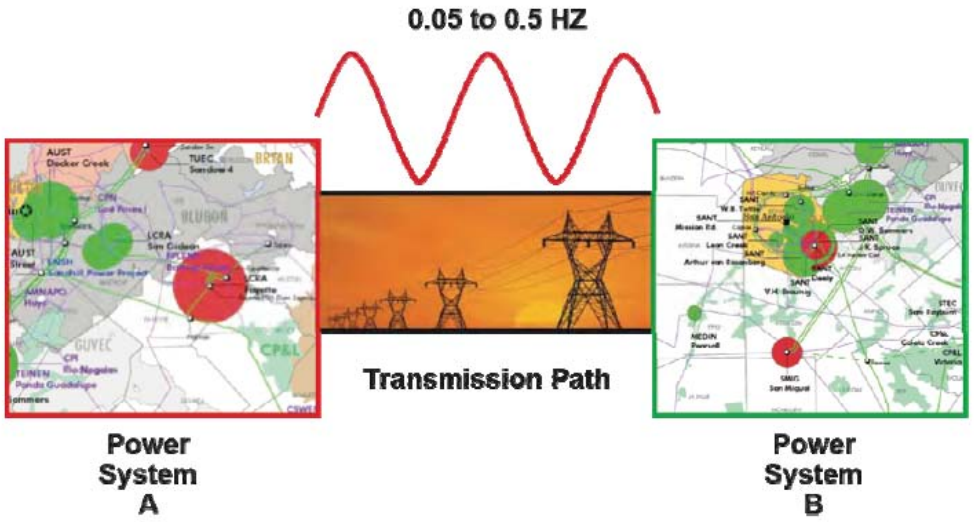
- In 2010 ABB Corporate Research developed second generation of oscillations monitoring and damping, called Power Damping Monitoring, PDM
  - Accurate determination of damping levels for **ambient** oscillations
  - Mode shape determination
  - Use of multiple input signals: frequency, angle and power differences can be used
  - Simultaneous detection of multiple modes
- Verified against other algorithms in collaboration with University
- Verified using data captured in the field from Fingrid WAMS (uses 4 frequency measurements)
- Implemented in Swissgrid WAMS in December 2010 (uses 7 frequency measurements)
- A system with PDM under is development for CORPOELEC in Venezuela



# Wide Area Monitoring Systems
## Power Damping Monitoring (PDM)

- Real-time detection and visualization of multiple oscillation modes to truly understand the system behavior
- Monitor damping and modal activity of most dangerous modes in the power system from ambient data (before large excitations happen)
- Quickly identify the participants and sources of inter-area oscillations using online visualization of modal shapes




Early warning of poorly damped lines allows operators to react before an event triggers an inter-area oscillation

# Power Damping Monitoring (PDM)
## Principle

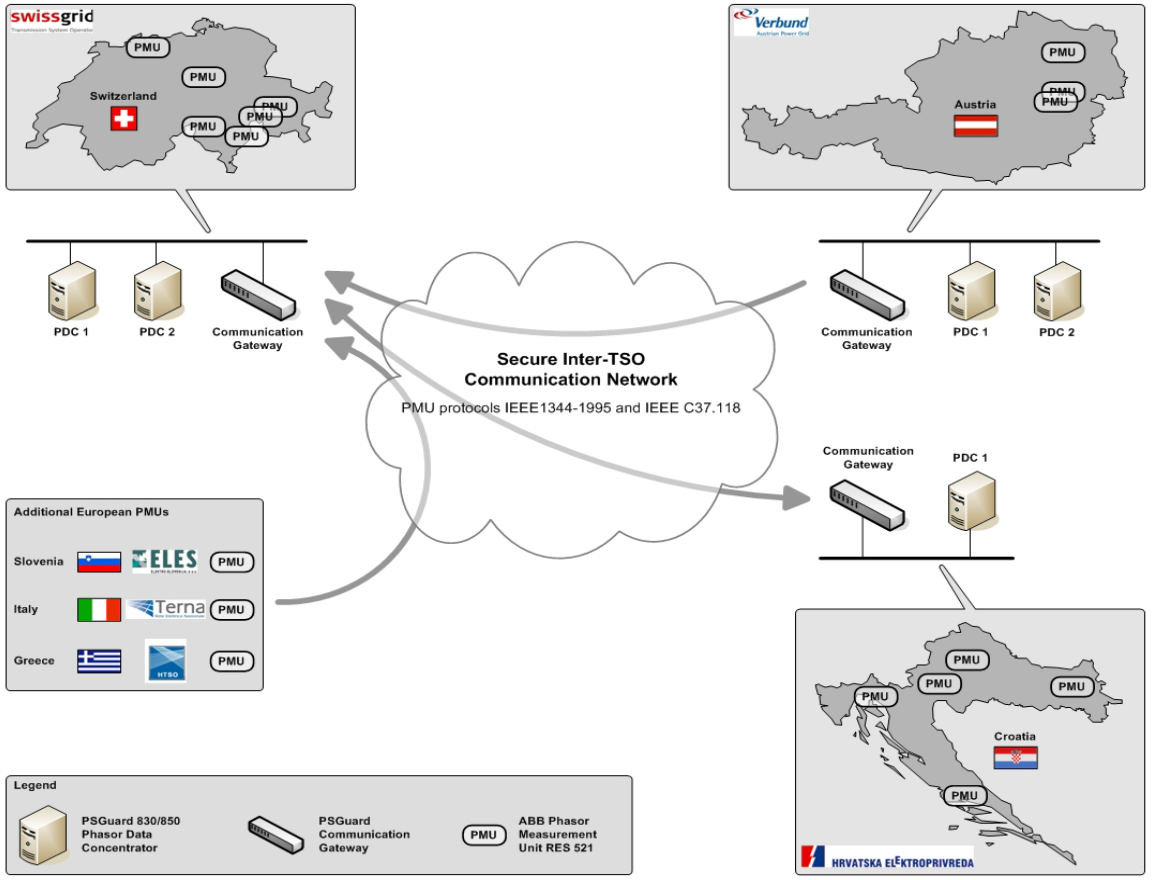
- Sliding window of 10-15 minutes in length
- Estimate Multiple Inputs Multiple Output (MIMO) state space model

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

- e(k) – background power system load variations
- u(k) – probing signals (optional)
- y(k) – angle difference measurements
- Carry out modal analysis
  - Damping & frequency of critical modes
  - Visibility in different measurements (mode shape)
  - Activity in each mode

# European ENTSO-E System

- Consists of Nordic, UK and Continental European Systems, coordinated from Brussels
- 22 PMUs in 9 countries in Continental European System
- Communication over secure Inter-TSO Network, multi-vendor interoperability through IEEE C37.118
- 3 ABB PSGuard Systems: Switzerland, Austria and Croatia, super PDC in Switzerland
- PMU data exchange between utilities in real-time, using IEEE1344-1995 and IEEE C37.118 protocols
- PDM functionality implemented in Swissgrid in 2010. It was added to POM functionality in operation from 2005.



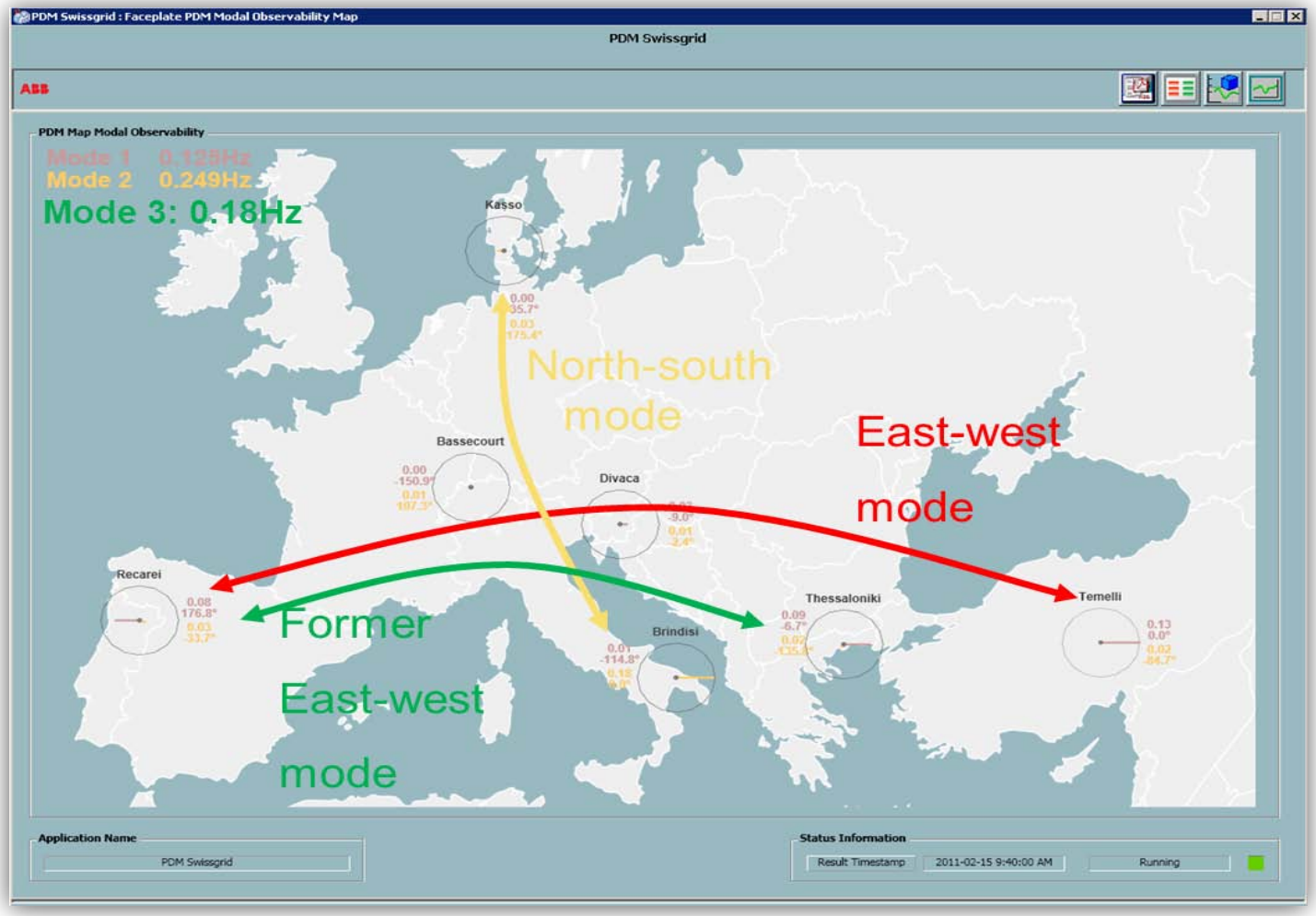
# PDM Modal Observability Map
## Identification of participants in inter-area oscillations

**Power Damping Monitoring**

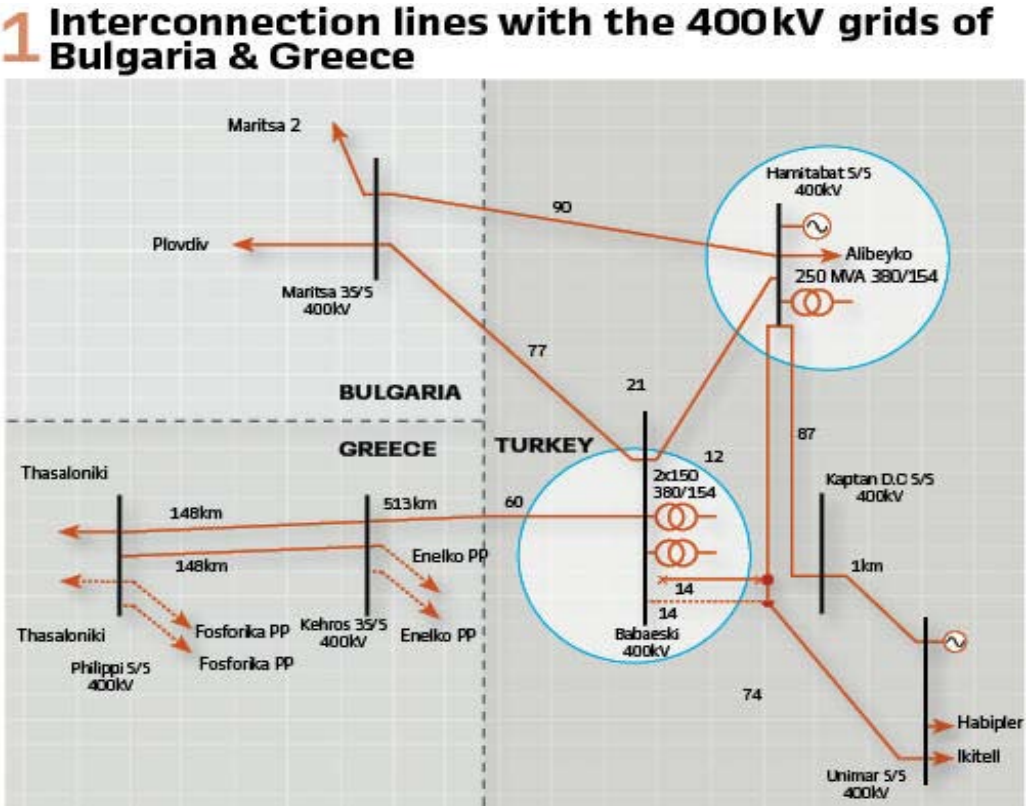
- Determines in real-time **ambient oscillations**
- Detects upto 2Hz oscillation, requires at least 10 measurements per second
- Modal frequencies and damping
- Simultaneous monitoring of multiple modes (2 modes tracked for Swissgrid, no theoretical limit)
- Phase in each measurement signal
- Modal activity
- In operation at Swissgrid since December 2010

**Oscillatory behavior dominated by 3 modes**

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



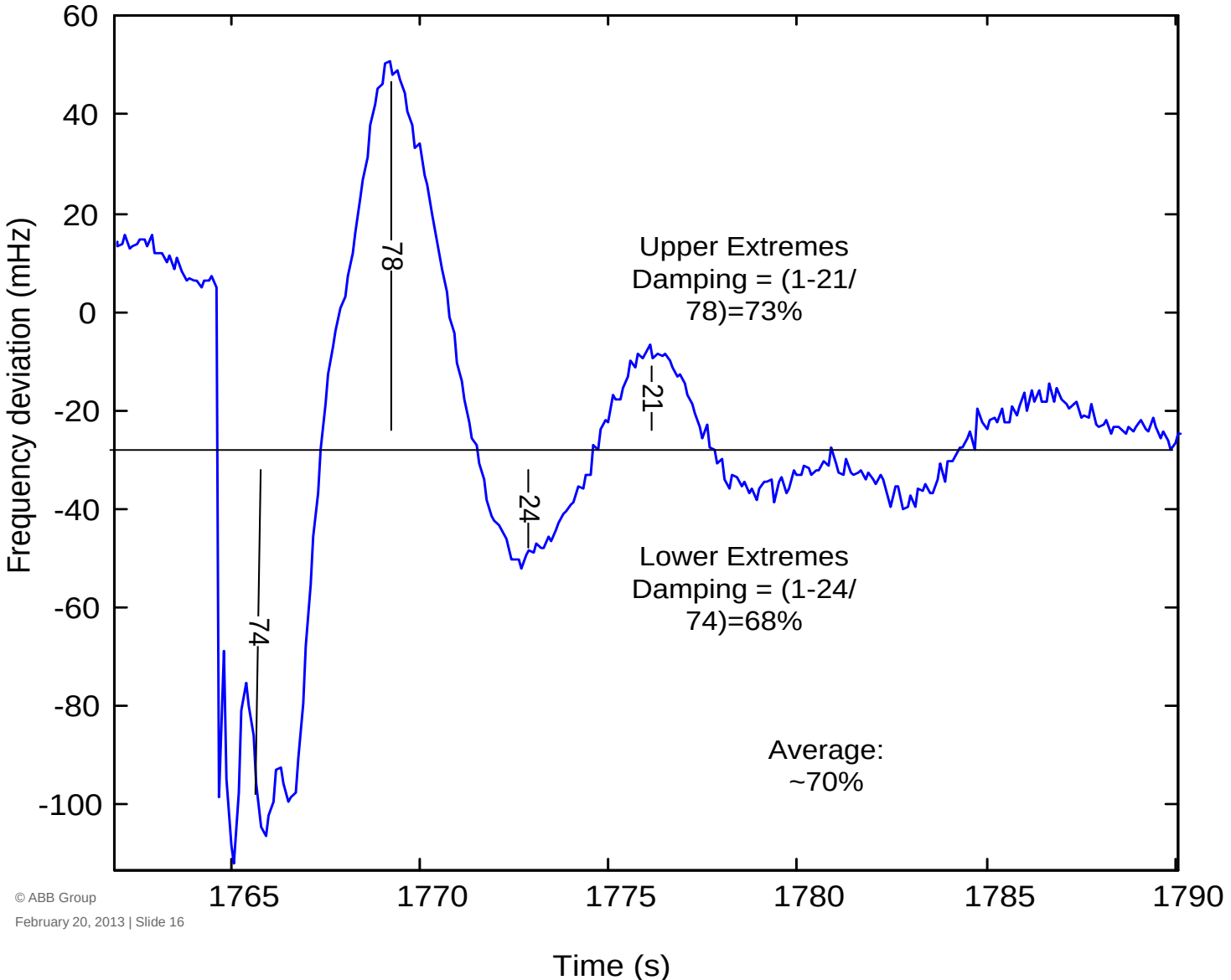
# Disturbance during Pilot Test
## Huge Generator Trip in Turkey




Reference: PACWorld Magazine

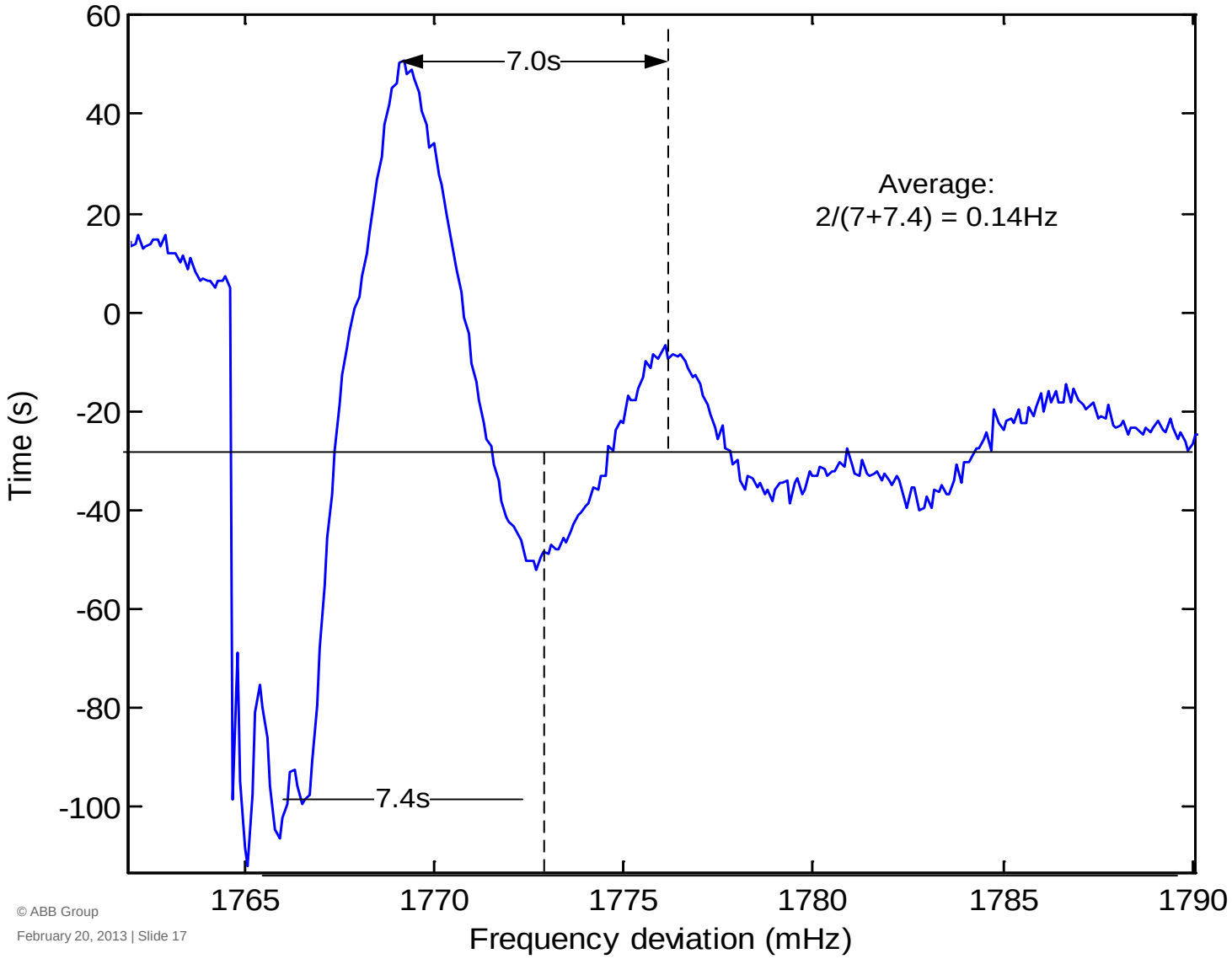
- At 14.59, a busbar fault causes a hydro power plant in Turkey to trip off the grid
- 1300 MW generation loss, registered by PDM
- 270 MW of load is tripped by system protection scheme (load shedding)
- A well-damped oscillation in the east-west direction follows
- Prior to the event PDM reported a damping of 60 % (magnitude ratio)

# Analysis of Raw Data
## Oscillation Damping



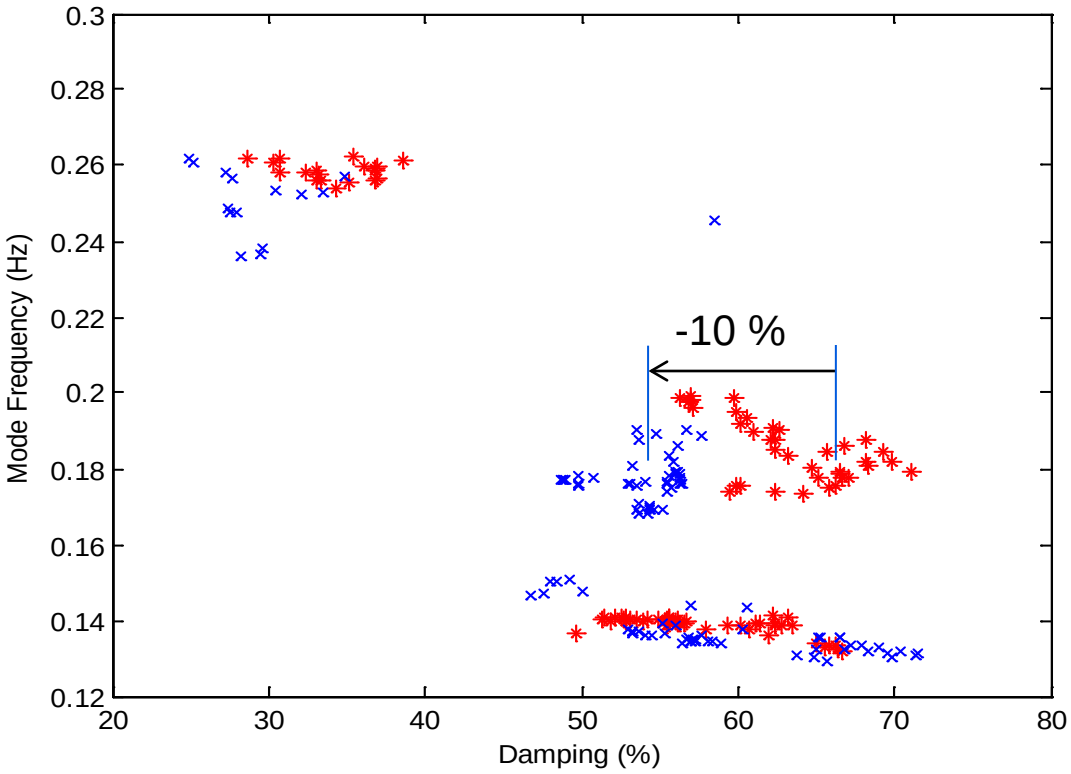

- ~Time-domain damping ~ 70 %

# Analysis of Raw Data
## Oscillation Frequency




- Frequency ~0.14 Hz

# PDM Output
## Before event (red) and After Event (blue)




- Trip of plant appears to have reduced damping of the old east-west mode with around 10%
- PDM reported around 60% damping of new east-west mode before disturbance

# Conclusions

- Recent developments are changing power utility networks from radial to distributed, with loads and generations being dispersed, making achieving system reliability requirements much more challenging
- Wide-area monitoring provides a handy toolbox for managing existing and emerging system challenges
- PDM extends the capability of POM with mode shape estimation and the ability to characterize the damping under ambient conditions
- The capability of newer PDM application, in Swissgrid registered oscillations damping at 60% prior to a disturbance event in Turkey, which happed shortly after and was also captured by PDM
- POM and PDM applications are continuously monitoring and analyzing **transient and ambient** oscillations in ENTSO-E system, particularly the dominant oscillations of East-West and North-South