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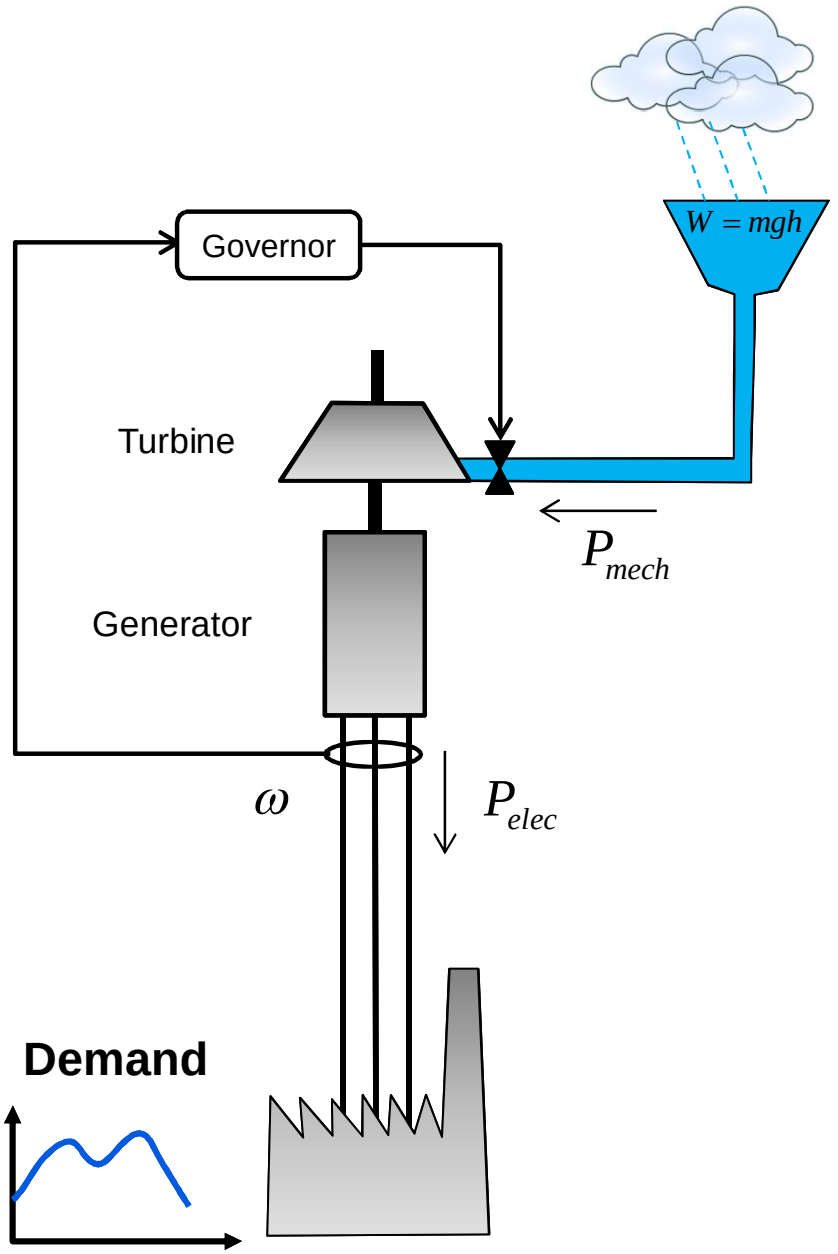
# Wide-area Monitoring and Control for Electric Power Systems

**HYCON2 Workshop on Energy, Bruxelles 2012-09-04**

# Outline

- Monitoring and Control of Power Networks
- Angle and Frequency Dynamics in Power Systems
- Wide-area Monitoring and Control
- Power Damping Monitoring (PDM)
- Pilot Experience from swissgrid
- Conclusion

# A Simple Power System



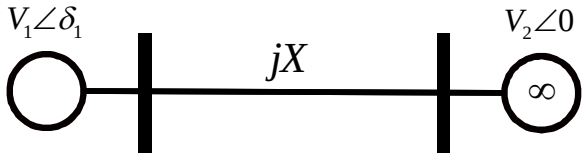

- Dam acts as long term energy storage
- Generator/turbine act as short term energy storage

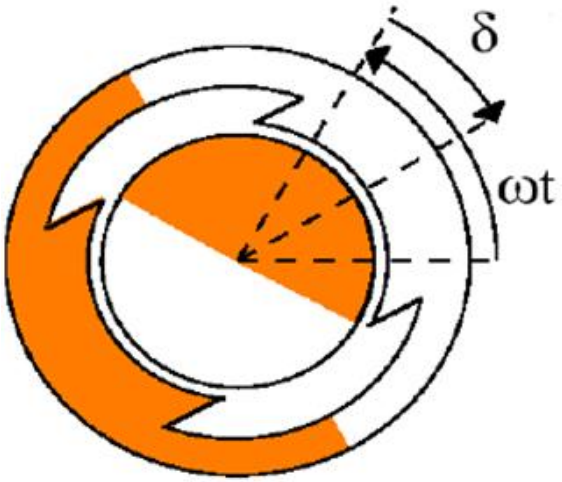
$$2H\frac{d\omega}{dt} = P_{mech} - P_{elec} - D\omega$$

$$\frac{d\delta}{dt} = \omega - \omega_s$$

- Governor control adjusts mechanical power to keep frequency constant

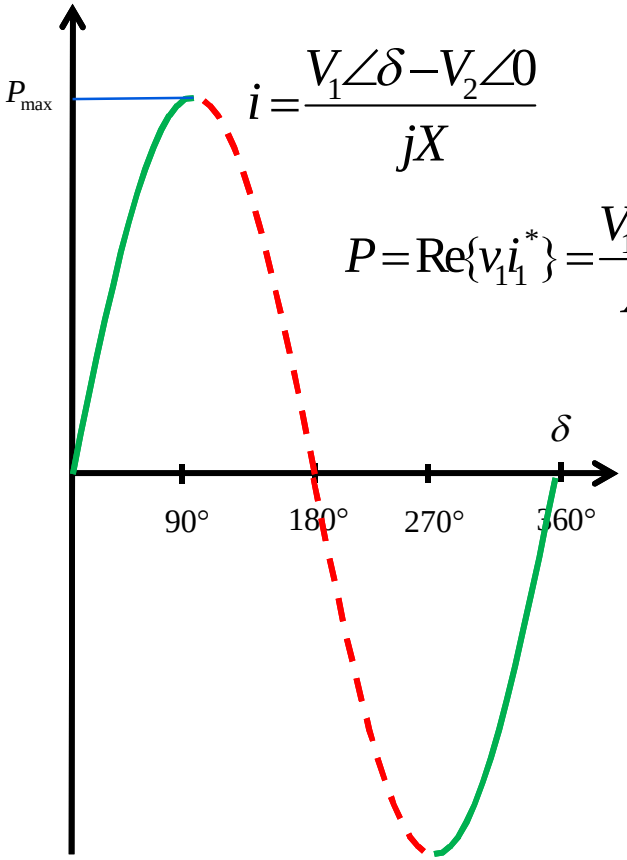
# Static Stability of a Generator
## How do generators stay synchronized ?



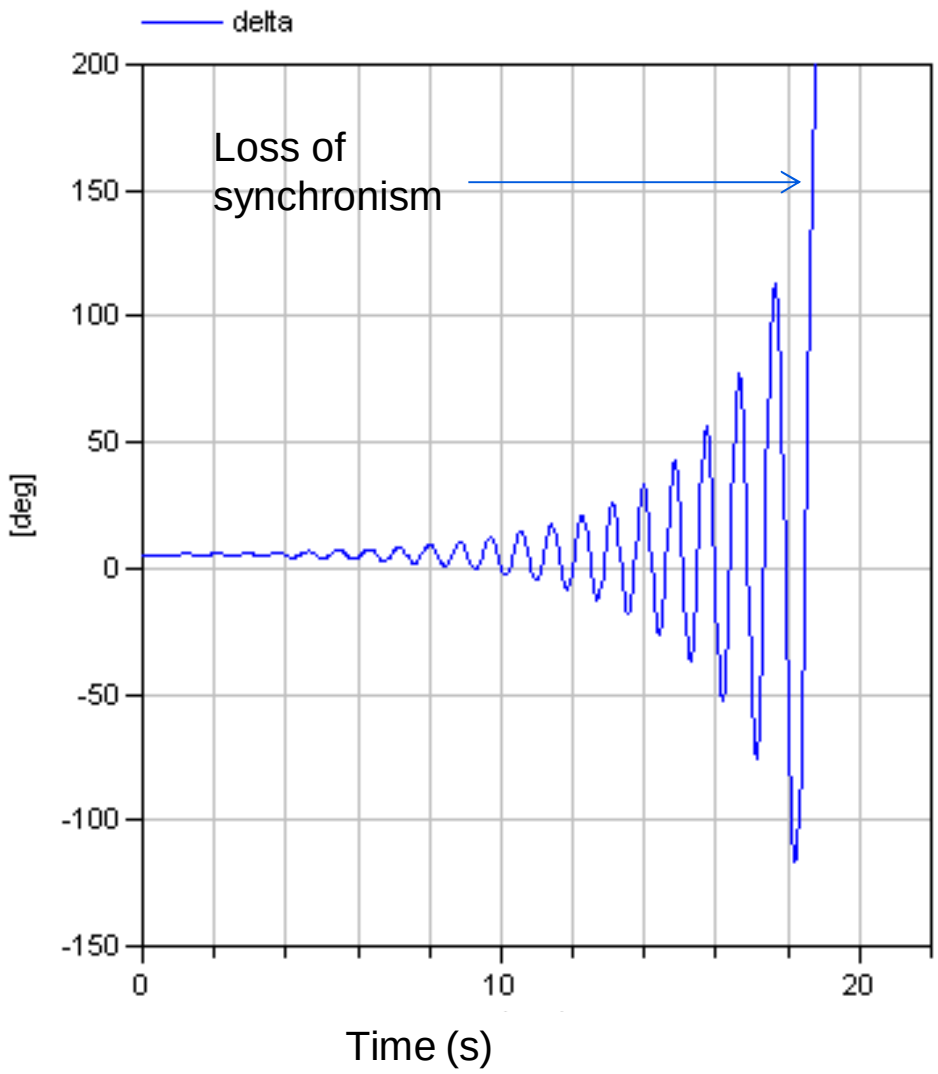

$$i = \frac{V_1\angle\delta - V_2\angle 0}{jX}$$

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




- Increased generation requires increase in load angle (δ)
- Stable only for δ<90°
- There is a maximum power transfer capacity Pmax

# Generator Connected to a Strong Grid
## Classical Generator Model




$$\frac{2H}{\omega_s}\frac{d^2\delta}{dt^2}+\frac{D}{\omega_s}\frac{d\delta}{dt}+\frac{V_1V_2}{X}\sin\delta=P_{mech}$$

linearise around $\delta=\delta_0$ and

set $K=\frac{V_1V_2}{X}\cos(\delta_0)$:

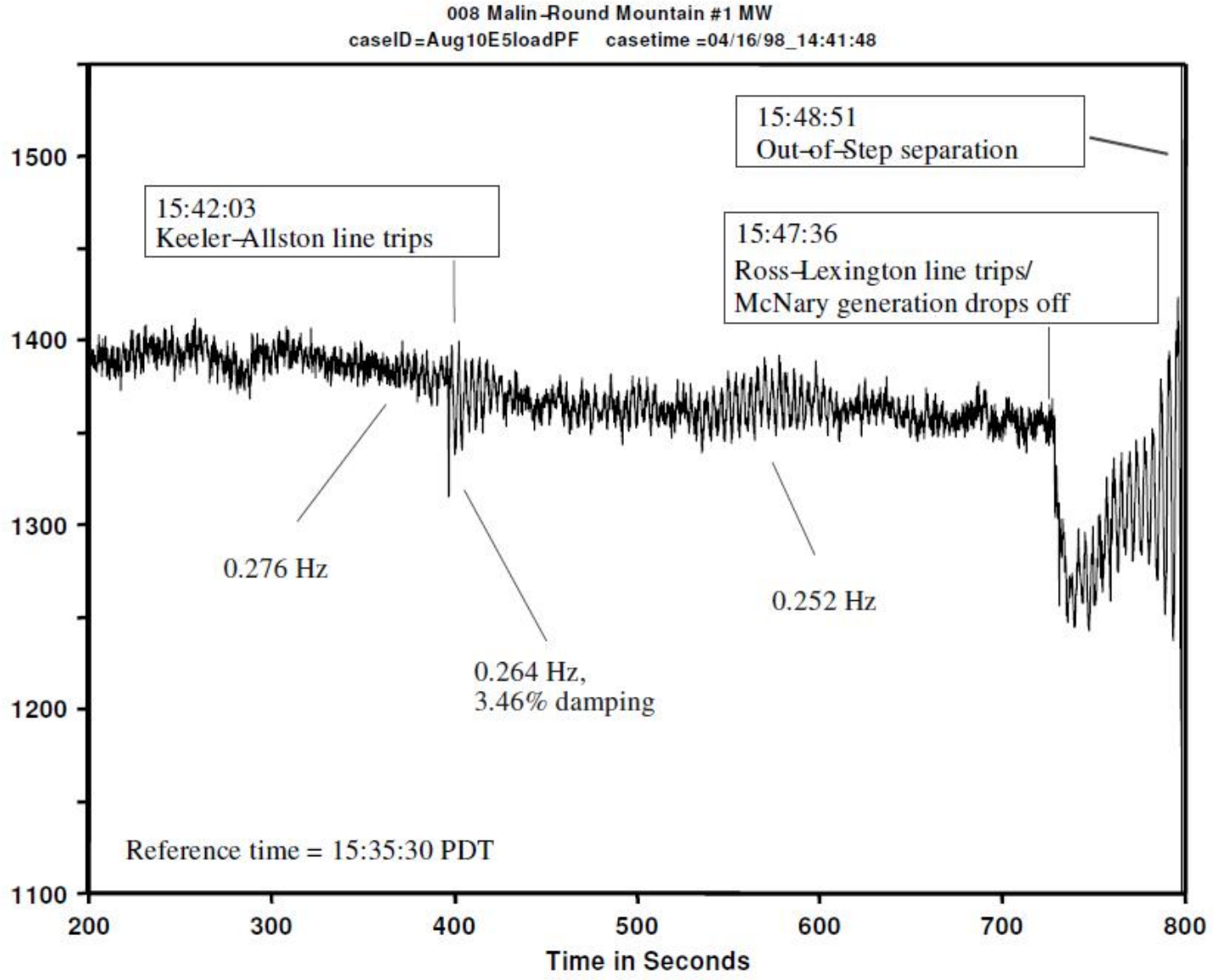
$$\frac{2H}{\omega_s}\frac{d^2\Delta\delta}{dt^2}+\frac{D}{\omega_s}\frac{d\Delta\delta}{dt}+K\Delta\delta=0$$

Change in stored energy

Damping power

Synchronizing Power

# WSCC Blackout , USA
## August 10, 1996



# Oscillations in an Interconnected Grid

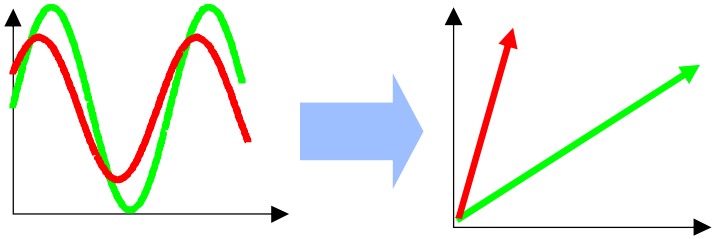
- Theoretically each pair of generation units can form an oscillatory mode
  - Local modes
  - Inter-area modes

- Video 1 (Macedonia, medium res)
- Video 2 (Macedonia, high res)
- Video 3 (Italy, high res)

# ABB – Phasor Measurement Unit RES 521
## Provides High Accuracy

- Phasor Measurement Units (PMU)
- Voltage and Current Phasors
- Synchronization by GPS clock
- Timestamp accuracy < 1 microsecond
- Angle accuracy < 0.1 degree
- Programmable action logic


- 4x3 Current inputs
- 2x3 Voltage inputs
- 8 binary inputs/outputs

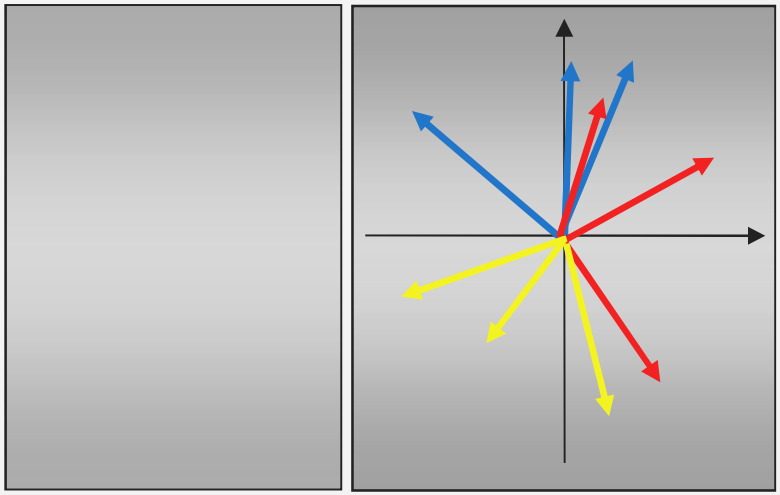


- Synchrophasor data format IEEE 1344 or C37.118 over TCP (IP & UDP)

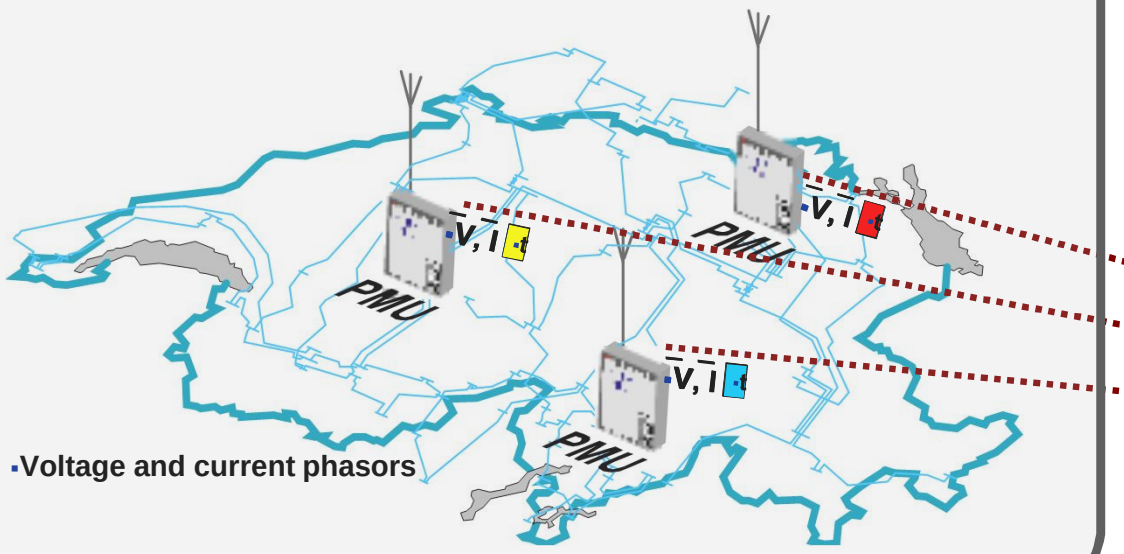
# Wide-area Monitoring and Control

- GPS Satellite

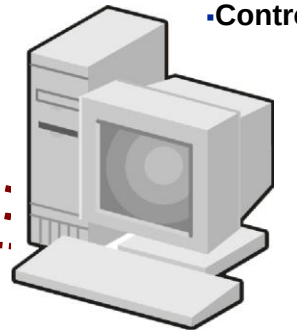
- Time stamps



- Synchronization




- Voltage and current phasors

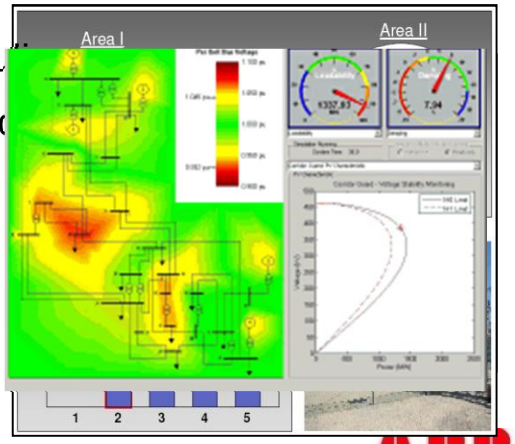


- Control room

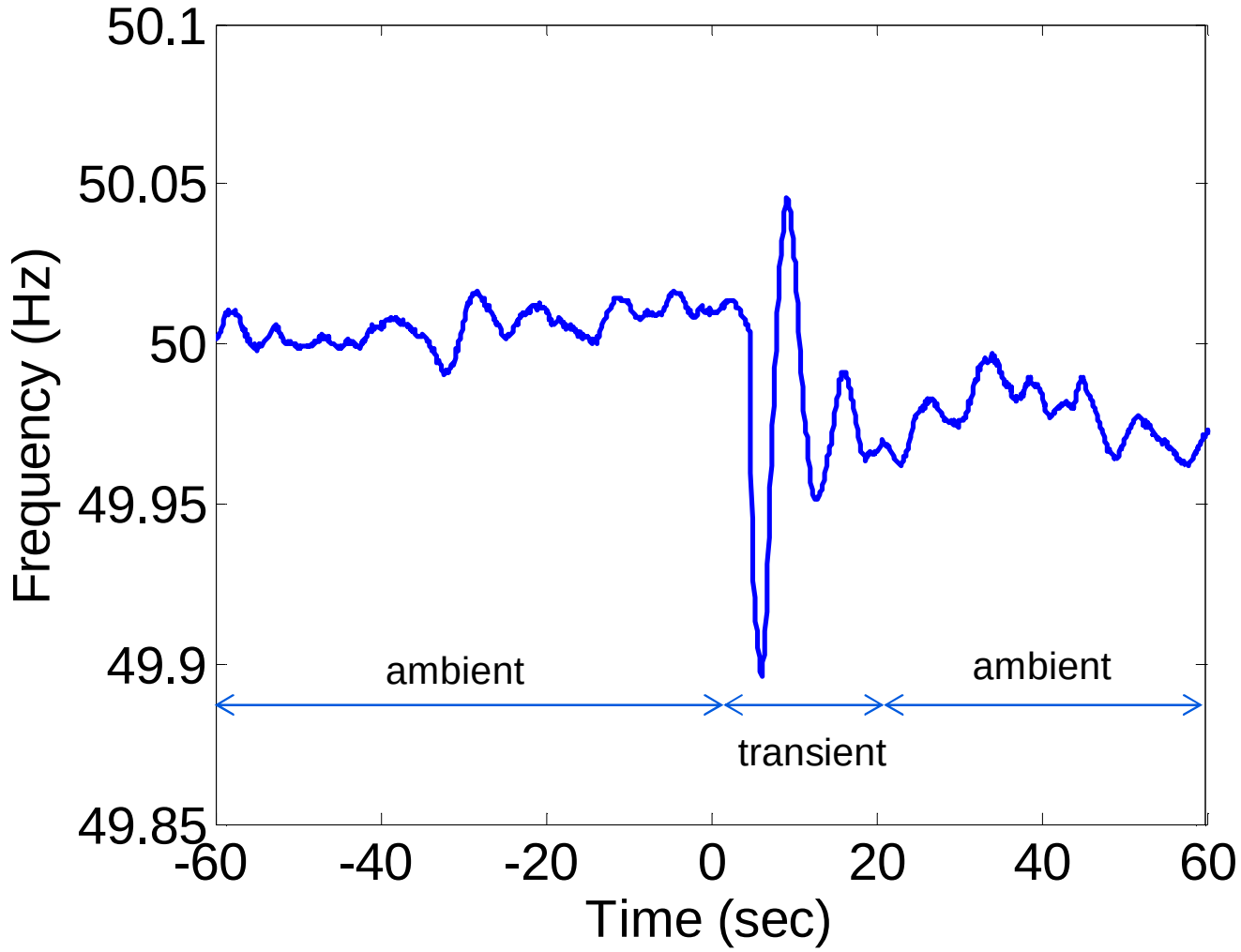
- Communication network

# WAMS Application Overview

- Advanced Visualization of Raw Measurements
  - Voltage and Phase Angle Profiles
  - Real-time Power Swing Display
  - Phasor-assisted or Linear State-estimation
  - Contour Mapping / Geographical Displays
- Monitoring & Prediction of Transmission Capacity (Wide Area Monitoring)
  - Corridor Voltage Stability Monitoring
  - Power Oscillation Monitoring
  - Line Thermal Monitoring
- Coordination of Actions in Emergency Situations (Wide Area Control and Protection)
  - Emergency FACTS/HVDC setpoint reschedu
  - Wide-area control for Damping of Power Osc

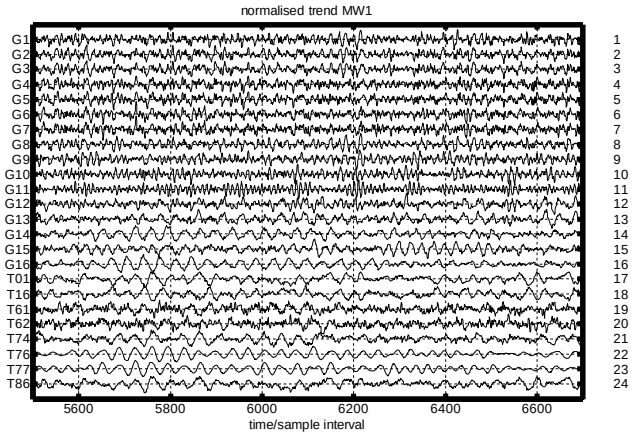


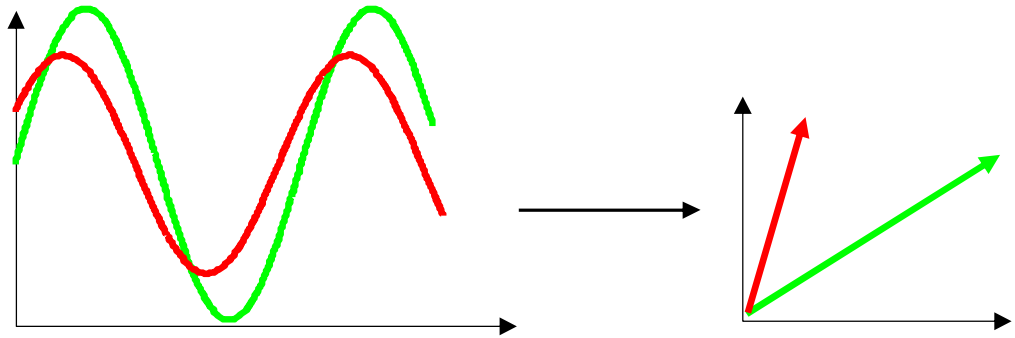
# Ambient vs Transient Oscillations



# Power Damping Monitoring
## PDM

- Capabilities
  - Accurate determination of damping level under ambient conditions
  - Mode shape determination
  - Possibility of incorporating probing signals
  - Use of multiple input signals
  - Simultaneous detection of multiple modes



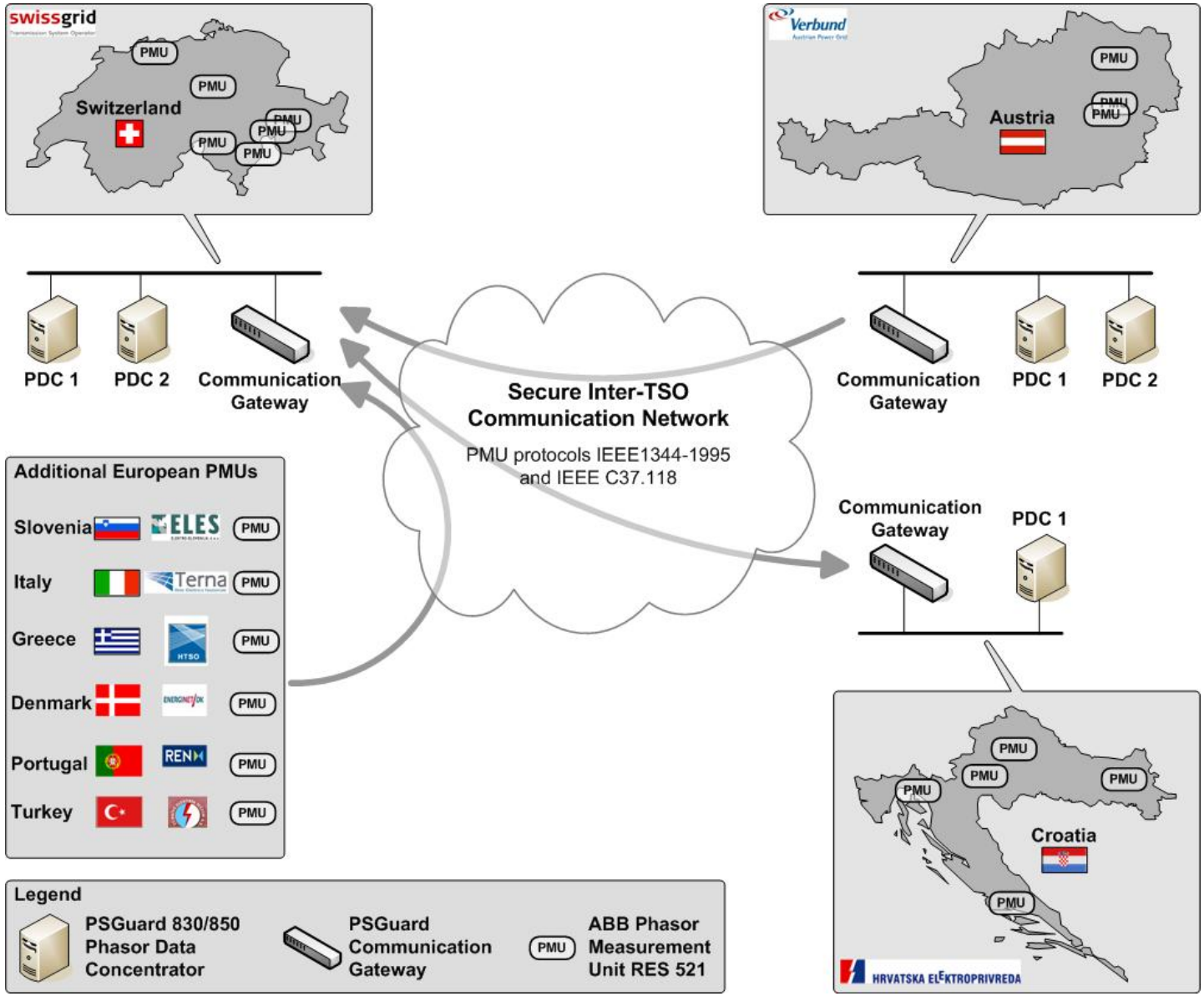
# Power Damping Monitoring (PDM)
## Principle

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

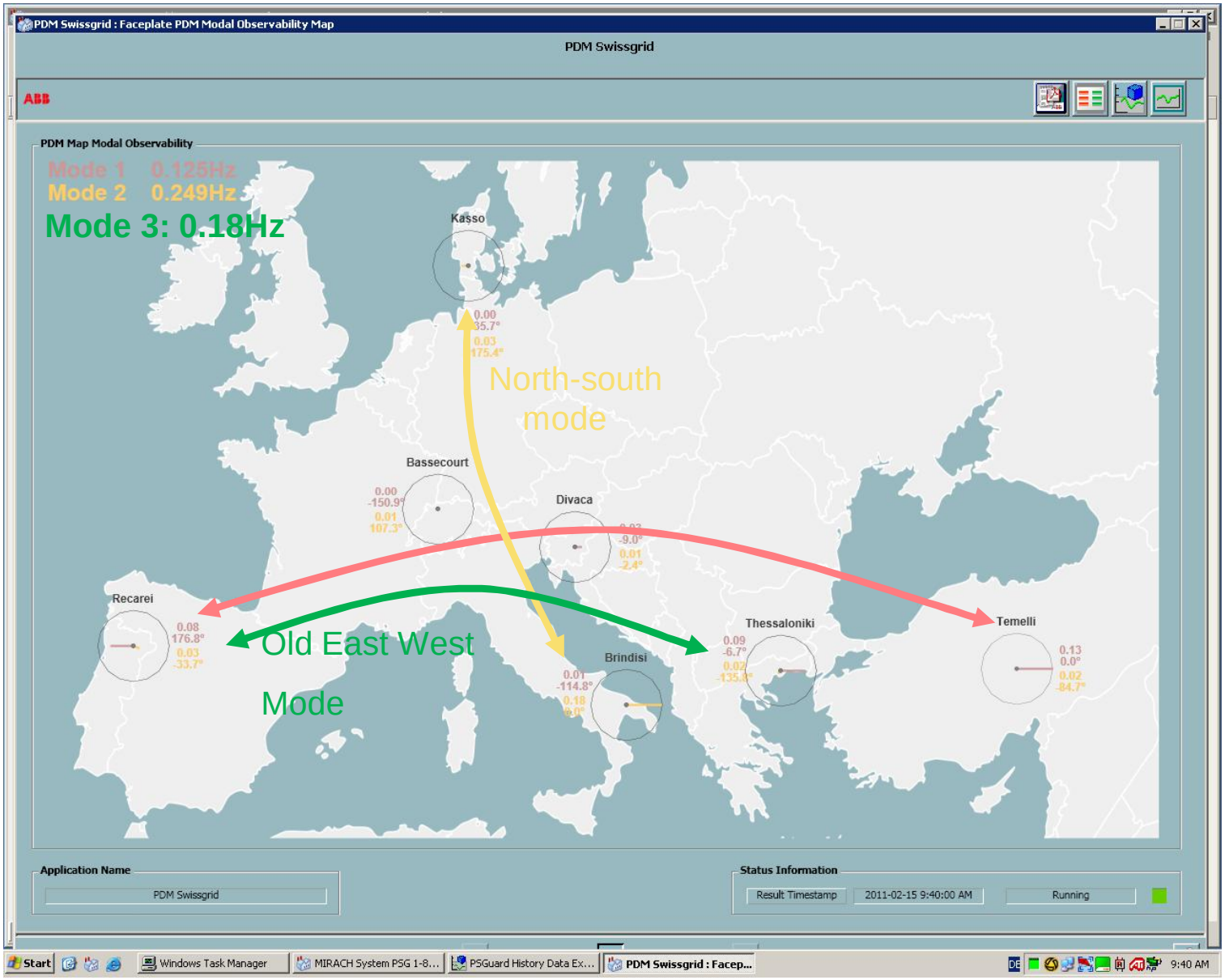
$$x(k+1) = Ax(k) + Bu(k) + Ke(k)$$
$$y(k) = Cx(k) + Du(k) + e(k)$$

- 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

# swissgrid PSGuard



# ENTSO-E
## Major Oscillation Modes found by PDM

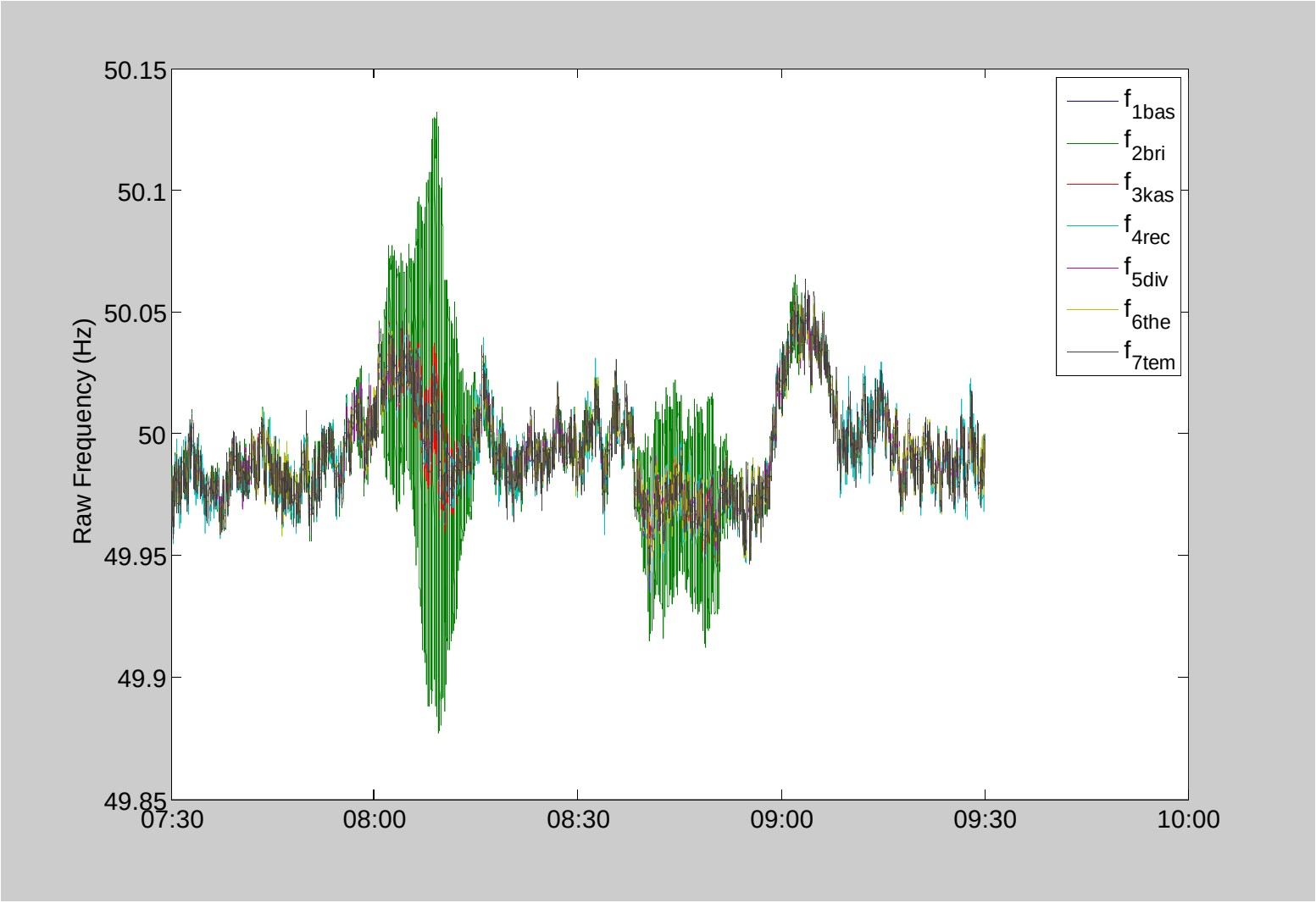


# ENTSO-E Disturbance 2011-02-19
## Summary of Events

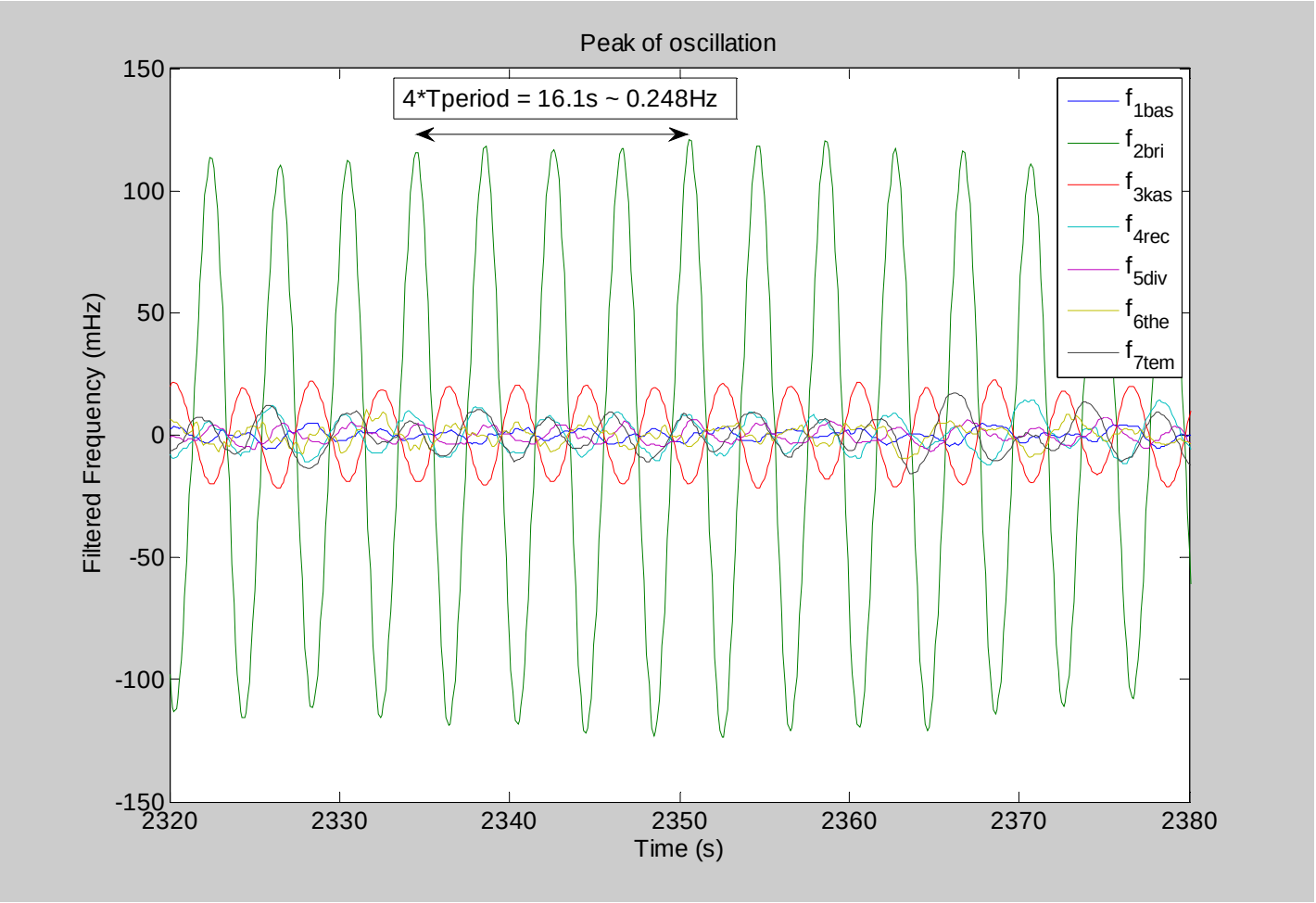
- At 08:00 on morning of 2011-02-19 a major oscillation starts growing in the north-south direction
- The north-south mode is significantly excited
- The oscillation grows to a peak amplitude at 08:09
  - of +/- 100 MW measured at Soazza on the connection to Italy
  - of +/- 120 mHz measuread in southern Italy
- The oscillation is damped out at around 08:16

- Two smaller oscillations are excited at 08:38 and 09:00, respectively

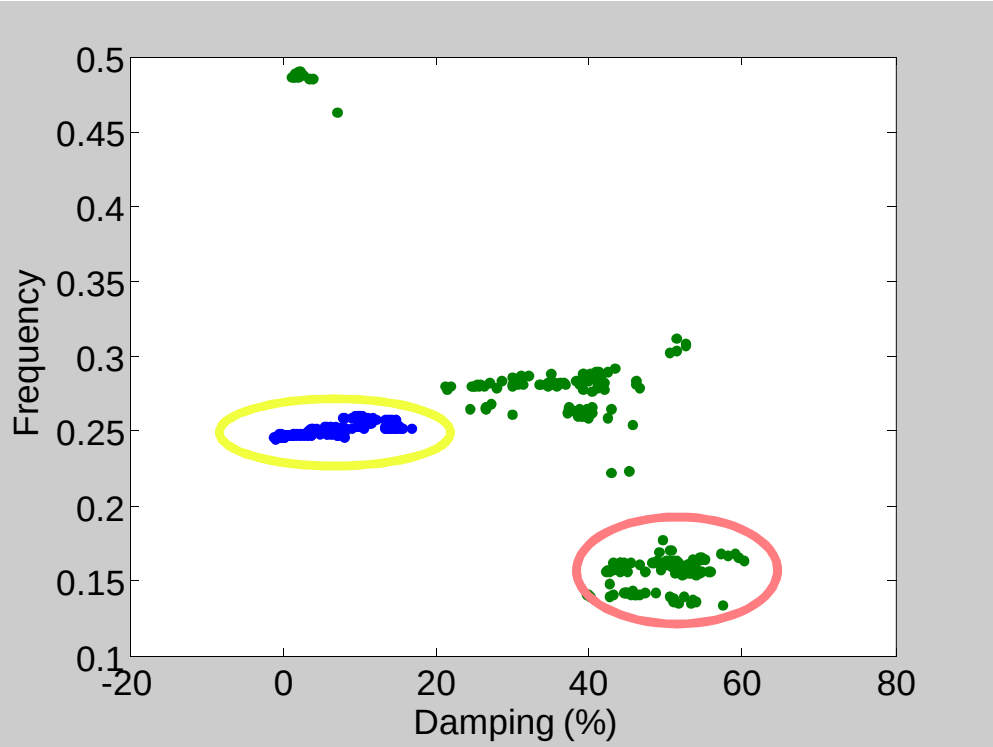
# PSGuard Frequency Recording
## Raw Data

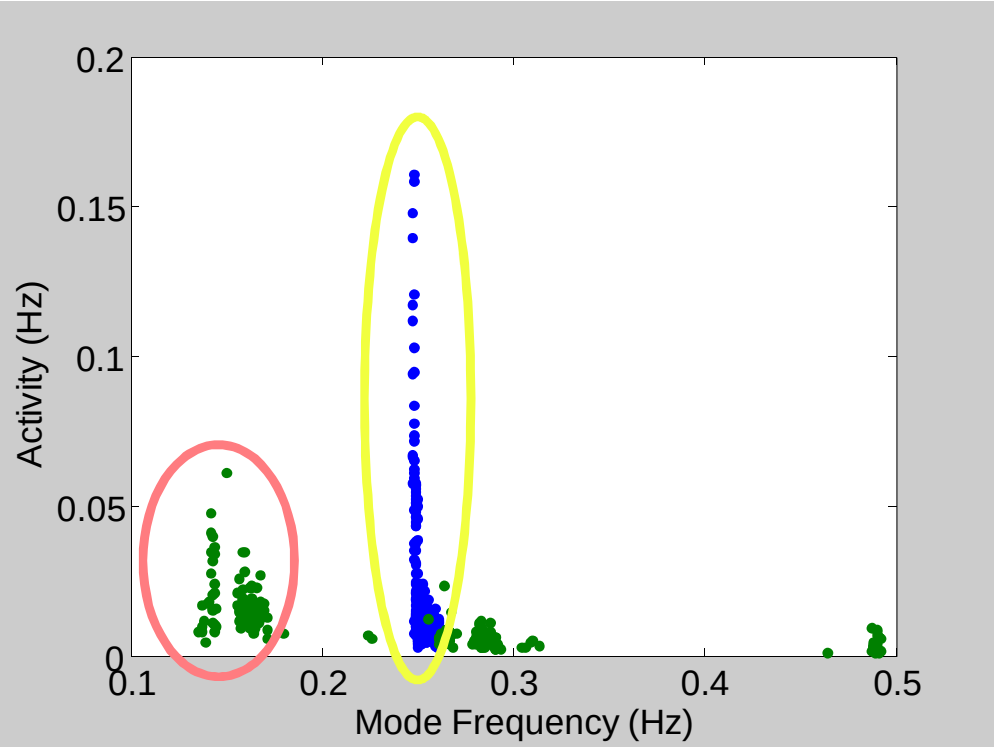


# Filtered PSGuard Frequency Recording
## Zoomed in at 8:09



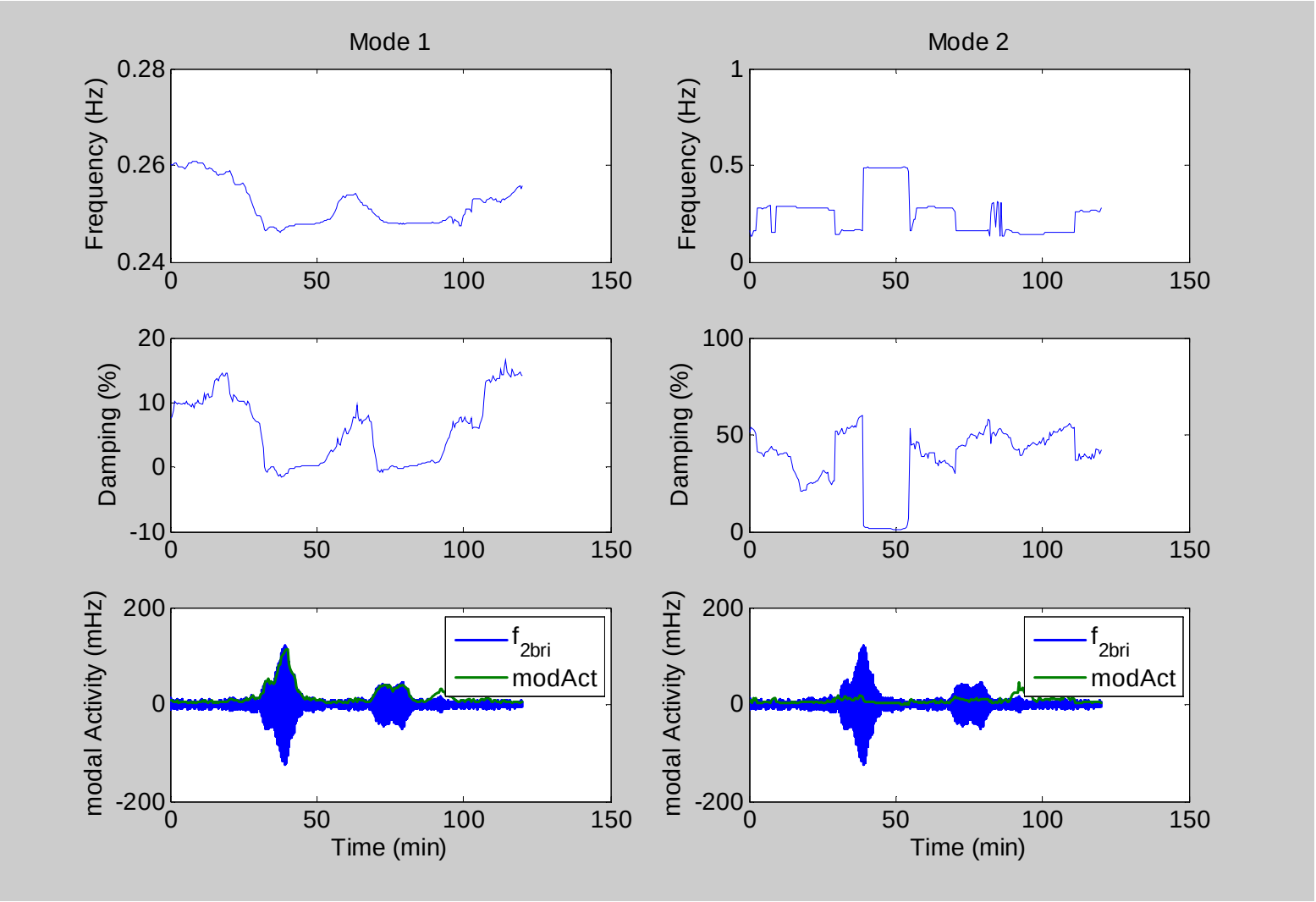
# PDM Results
## I – Oscillatory Activity (xy-plot)




- Very poorly damped oscillations at 0.25 Hz – main oscillation (worst -2%)
- East west-mode (0.13 Hz) still detected, but well damped

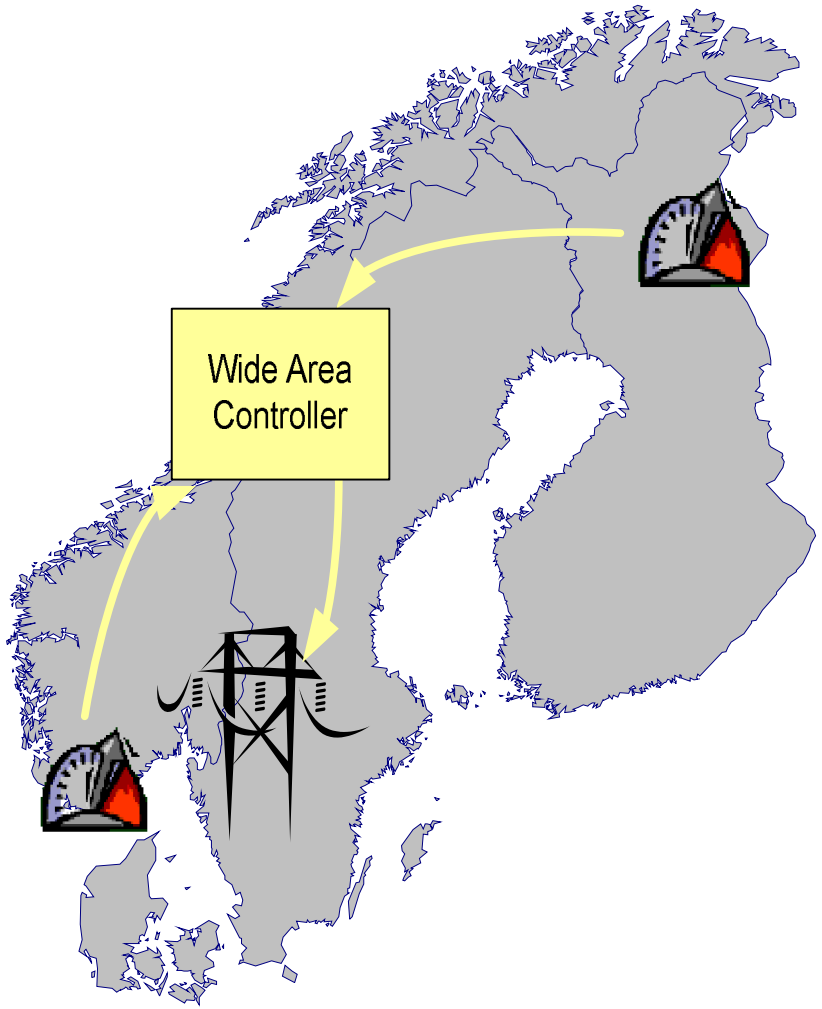
# PDM Results
## II – Time Series



# Wide-area Control
## Pilot Test in Norway

- Wide Area Power Oscillation Damping control WA-POD
- Chose feedback signals from any PMU equipped substation in Nordel
- 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



# Conclusion

- Wide-area Monitoring and Control improves upon traditional SCADA/EMS system with a factor of 10-100 in terms of resolution
- Enables monitoring and control of dynamic (stability) phenomena
- Power damping monitoring validated and transferred to commercial product
- Active control of oscillations demonstrated in pilot test