Inter-Area Oscillations in the European Continental Power System
Challenges and Damping Measures

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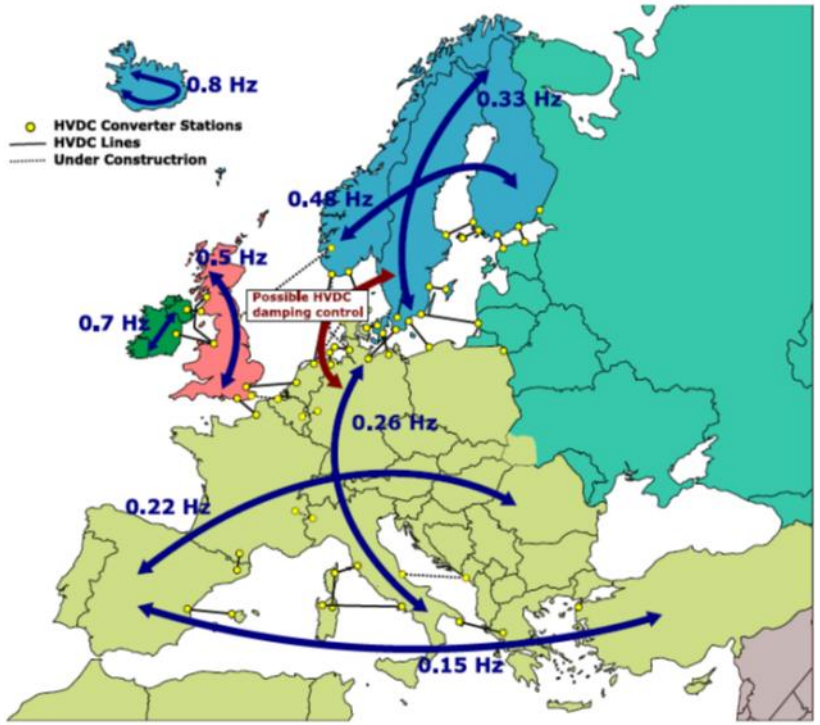
Figure 1. East-Centre-West mode. Mechanical analogy and mode shape (E. Grebe et al.)



Source: ENTSO-E

Agenda

1) Significance of Inter-Area Oscillations – Latest Event
2) Inter-Area Oscillations – Mechanism, Consequences
3) History of CE Power System Extension Steps and Planning of Power System Extensions
4) Recordings of Critical Oscillations
5) Conclusions and Recommendations for the Current and Future of Power System Operation and Control
6) References

1. Iberian Peninsula Blackout from 28.04.2025

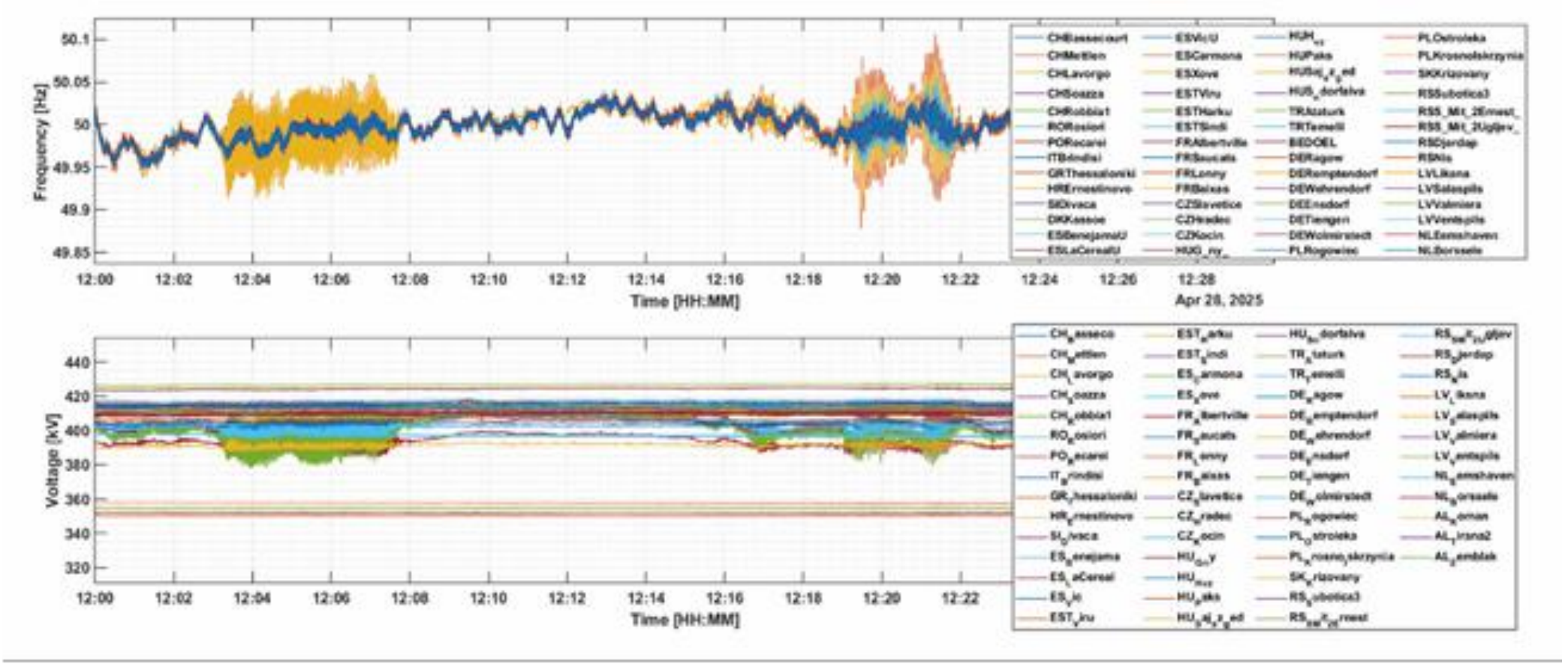
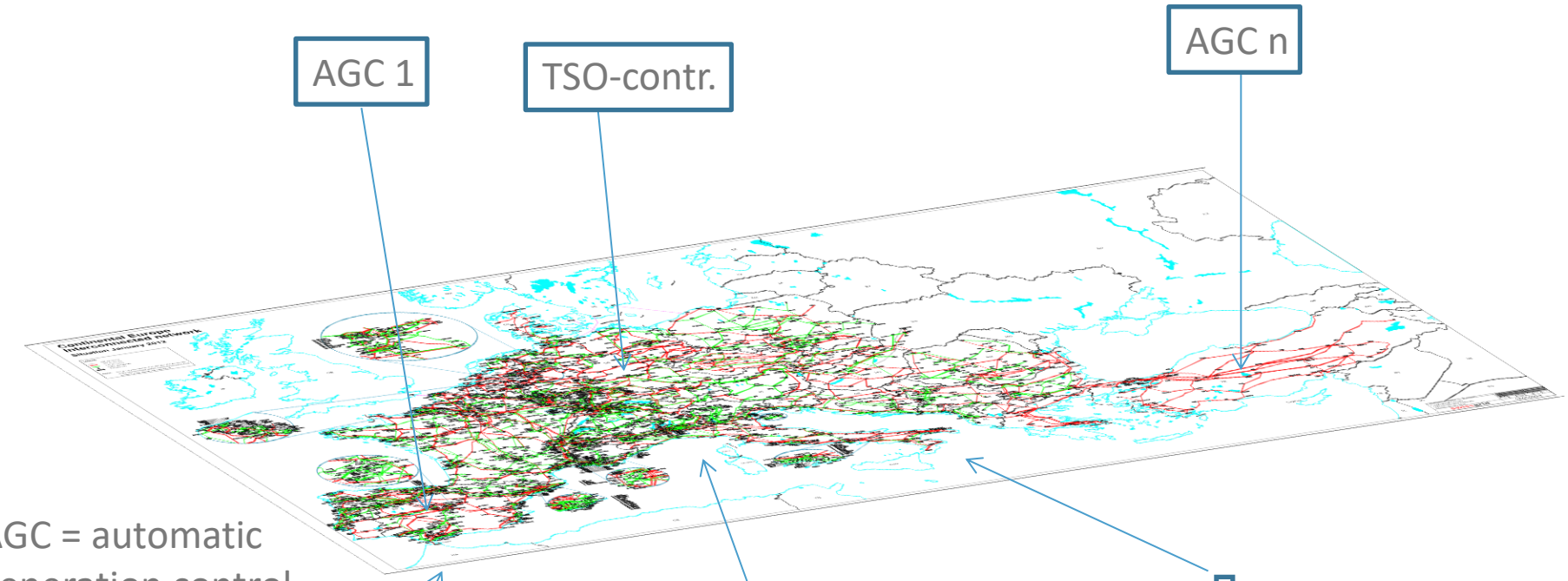


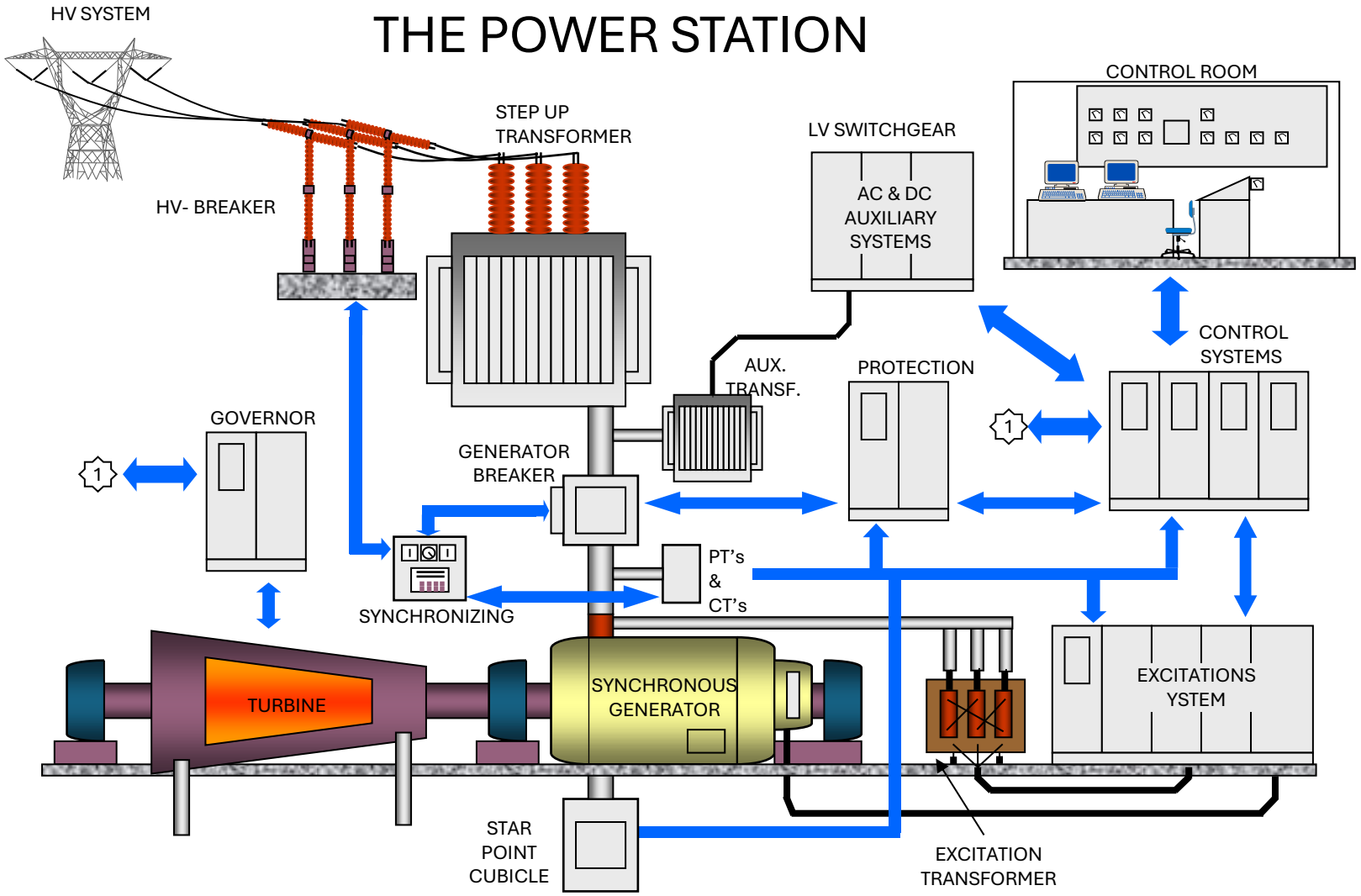
Figure 2-43: Frequency and voltage phasor magnitude measurements from European PMUs

Source: /1/

2.1 The Continental European Power System

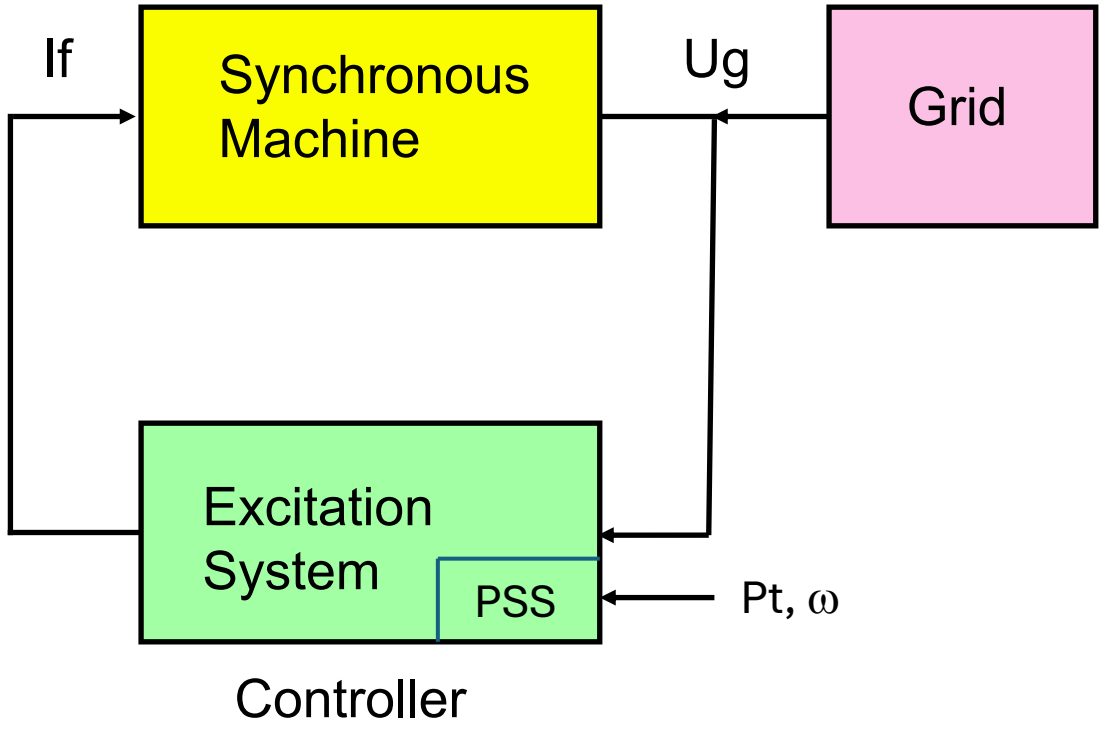


2.2 Classical Power Plant Control Setup

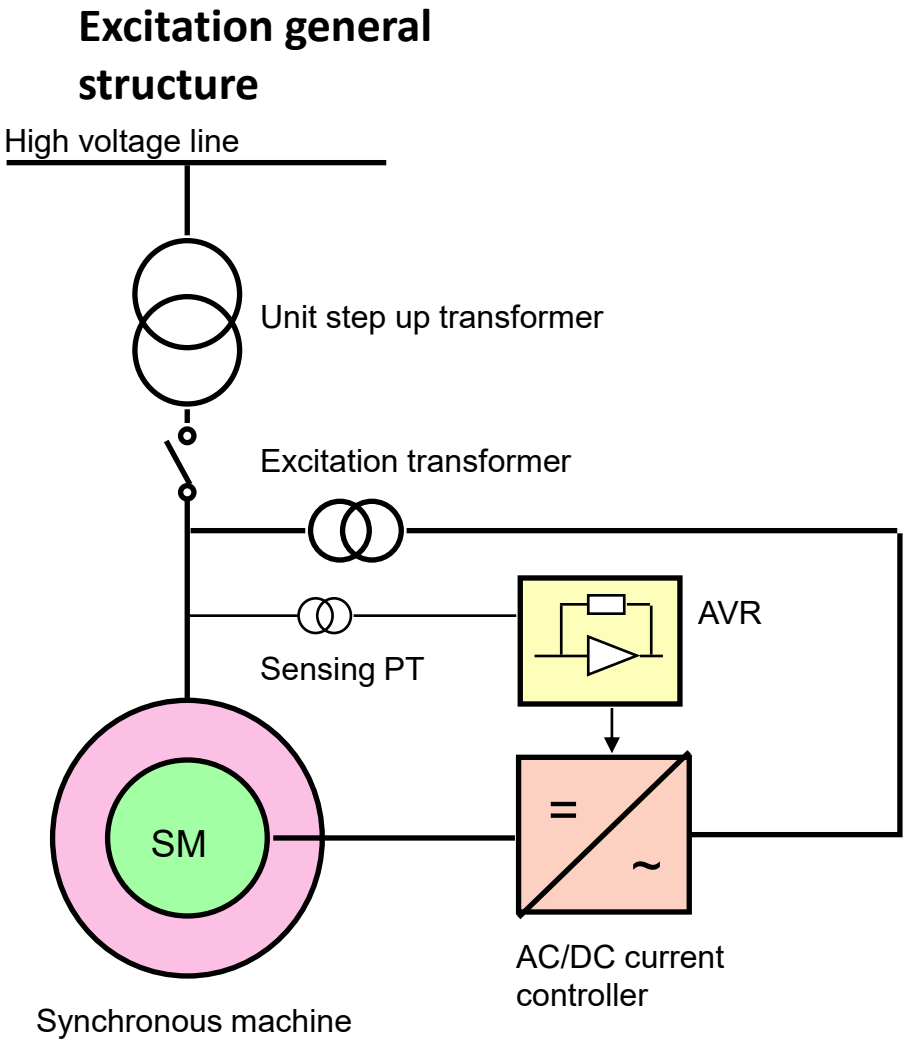


Source:
JT SYSTEMS
Power Engineering

2.3 Classical Generation Voltage Control Loops

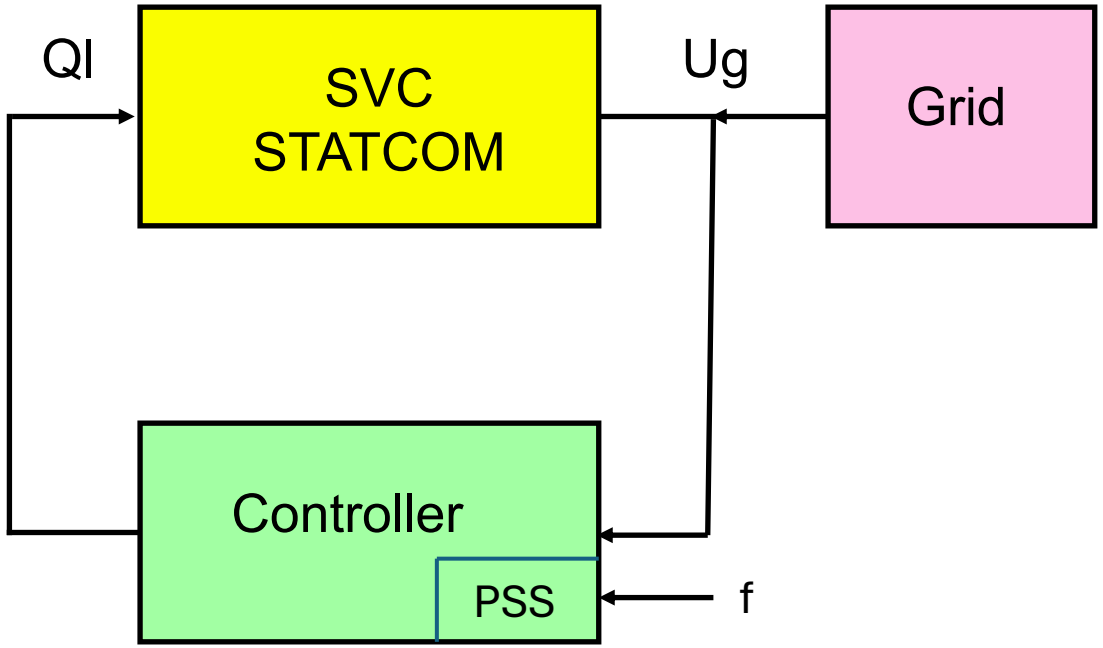


Automatic Voltage Regulator (AVR) and Power System Stabiliser (PSS)



Source:
JT SYSTEMS
Power Engineering

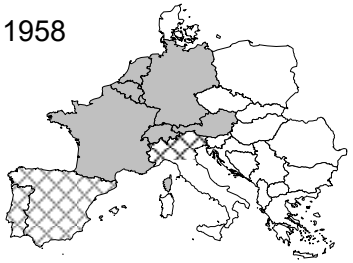
2.4 Classical Load Side Damping Schemes



Static Var Compensator (SVC) and
Static Compensator (STATCOM)

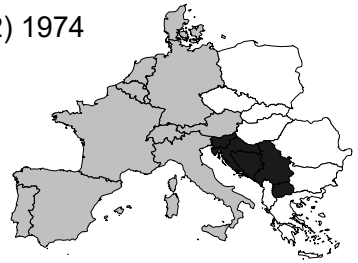
3.1 Continental European Power System Extension Stages

1) 1958



Peak load 32.5 GW

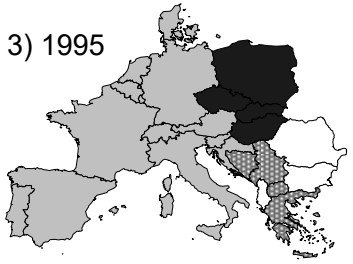
2) 1974



UCTE Member
UCTE asynchronous Member
UCTE synchronous zone
UCTE resynchronisation zone

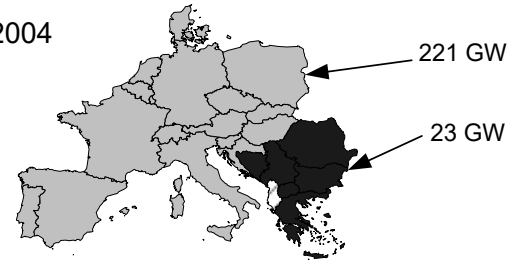
Peak load UCTE 121.5 GW
Max. production of Yugoslavia 6.12 GW

3) 1995

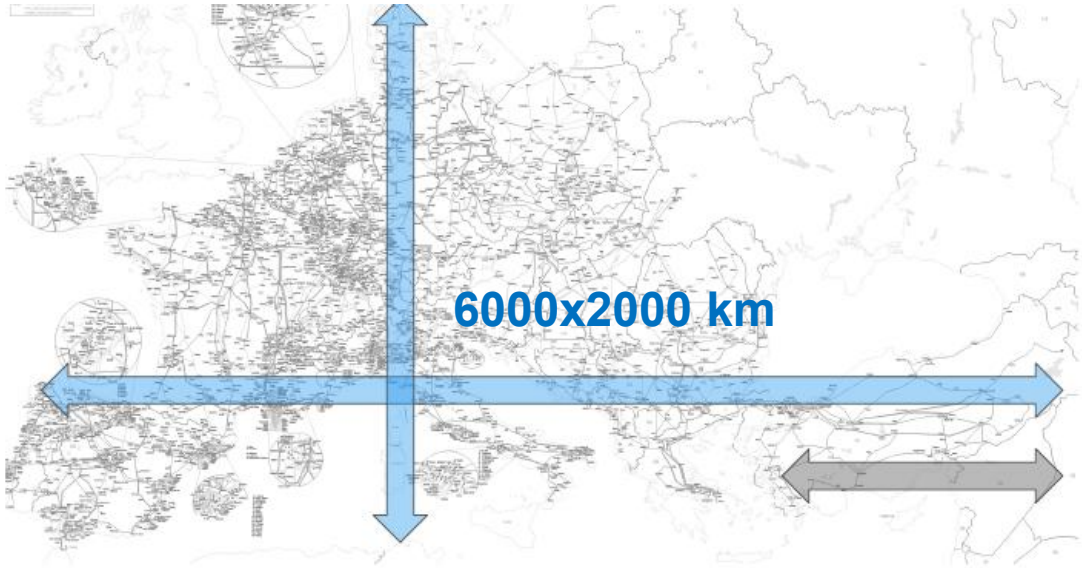


Peak load UCTE 256.7 GW
Peak load Centrel and UCTE ≈ 300GW

4) 2004



Load during resynchronisation 244 GW



5) 2010 Synchronisation of Turkey
+ 50 GW + 1800 km to East

6) 2022 Ukraine / Moldova synchronization + 15 GW + 1600 km to Nord-East

7) 2025 Baltics + 4.6 GW

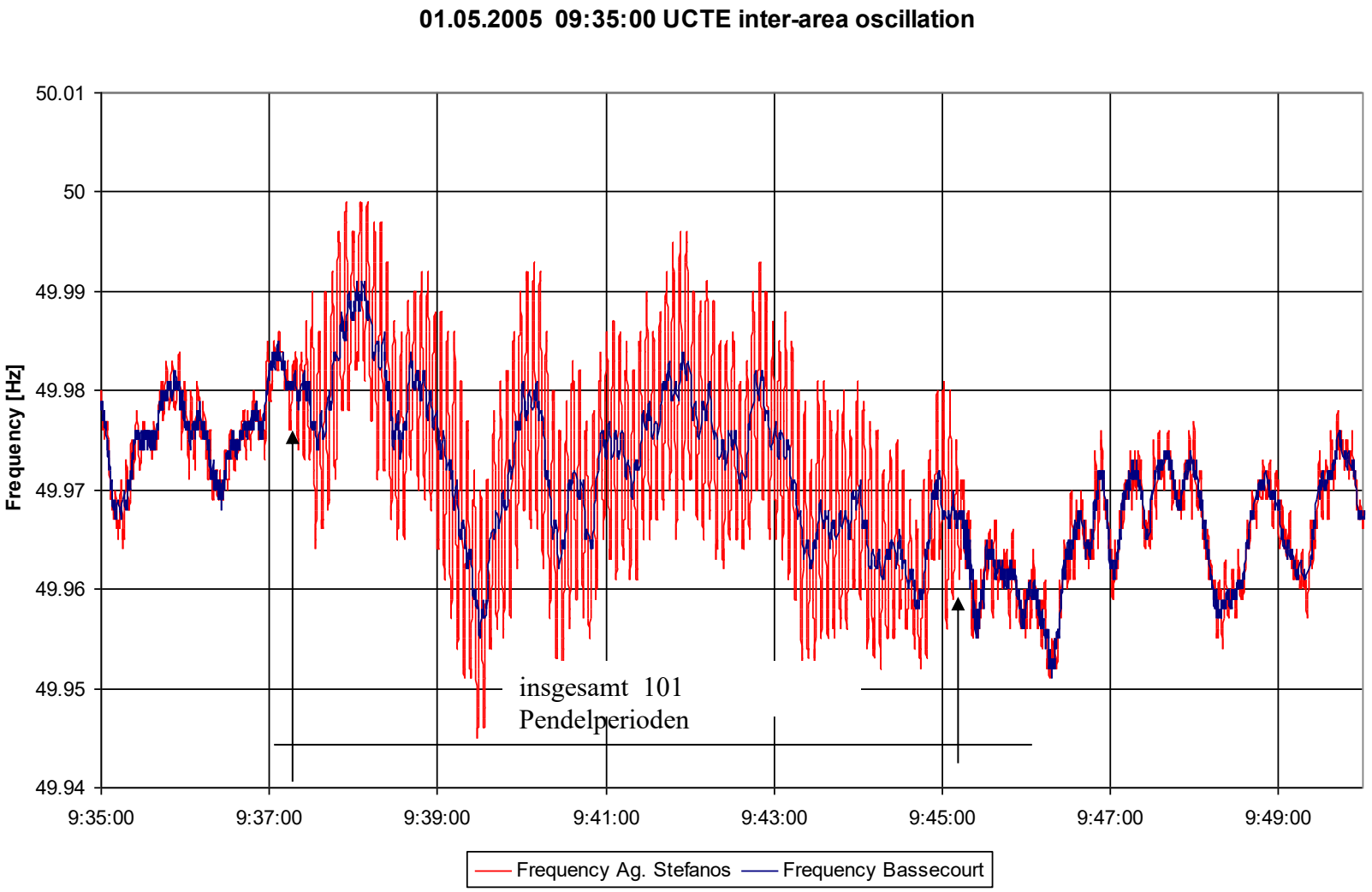
3.2 Power System Extension Planning – Dynamic Aspects

- Power System Dynamic Model Setup and Calibration
- Modal Analysis
- Time Domain Simulations
- Elaboration of power system damping measures
- Re-tuning of control equipment, changes in control mode strategies
- Installation of new damping devices

4. Recordings of Critical Oscillations

1. 01.05.2005 – East-West oscillation
2. 01.04.2007 – North-South oscillation
3. 29.05.2007 – Denmark Mainland disconnection
4. 19.02.2011 & 24.02.2011 – North-South oscillation
5. 01.12.2016 - East-West oscillation
6. 03.12.2017 – North-South oscillation
7. 28.04.2025 – Iberian Peninsula Blackout

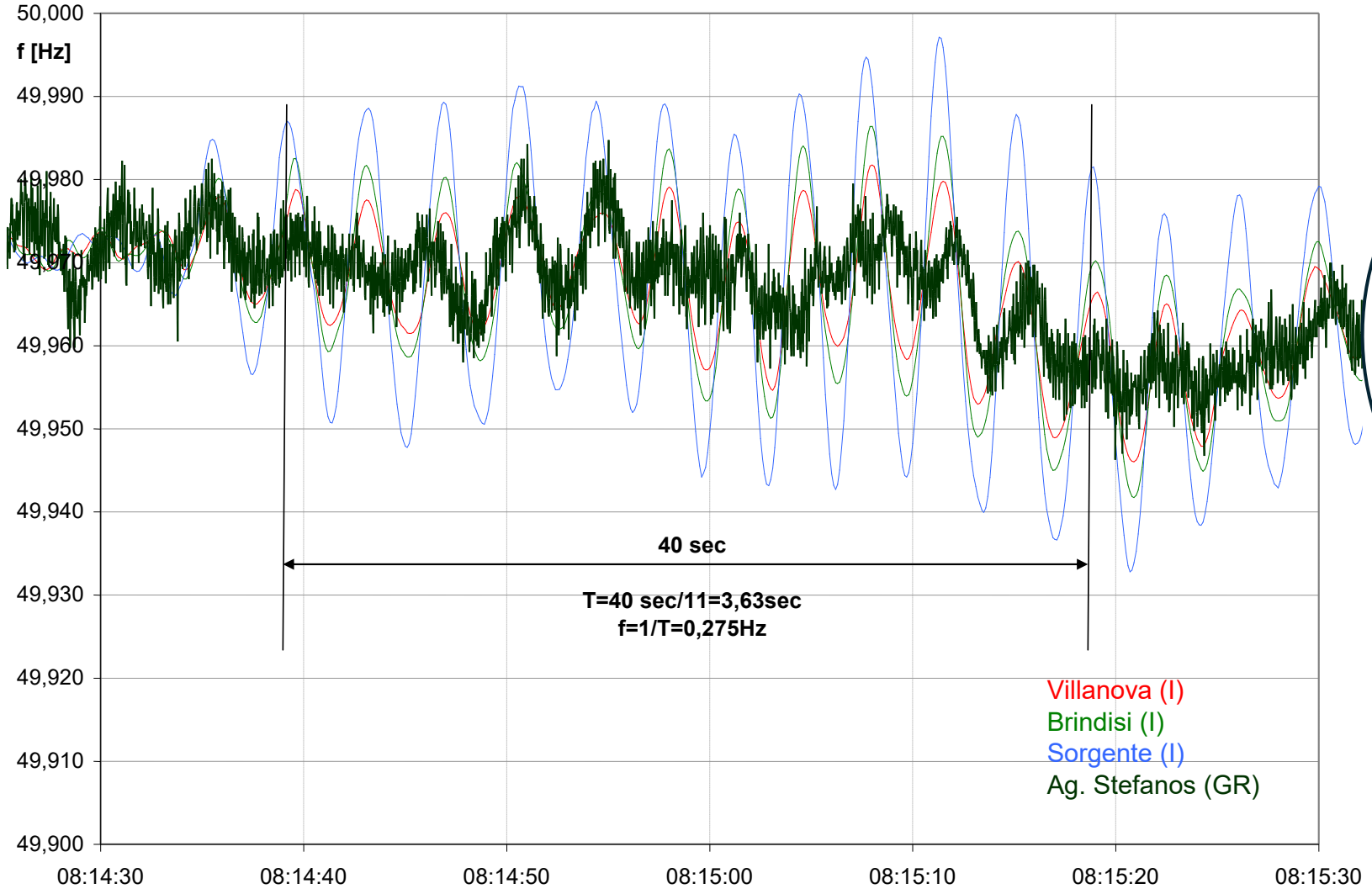
4.1 East-West Oscillation – 01.05.2005



first significant inter-area oscillation after year 2004 system extension

Source: /2/

4.2a North-South Oscillation – 01.04.2007 Frequencies

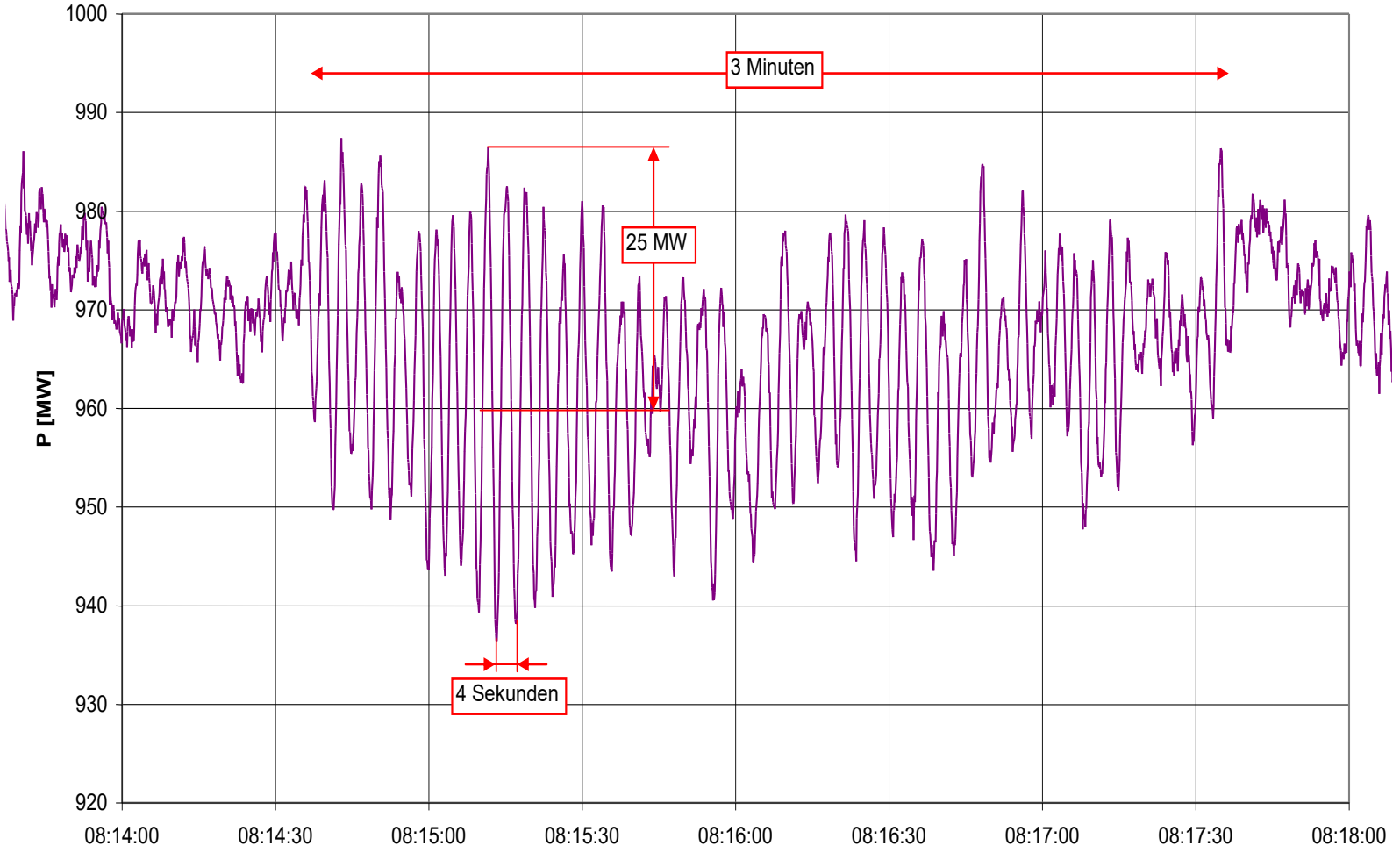


significant North-South inter-area oscillation

oscillating areas

Source: /2/

4.2b North-South Oscillation – 01.04.2007 – Active Power



significant North-South inter-area oscillation

active power close to nodal line

380 kV Mettlen-Lavorgo transmission line

Source: /2/

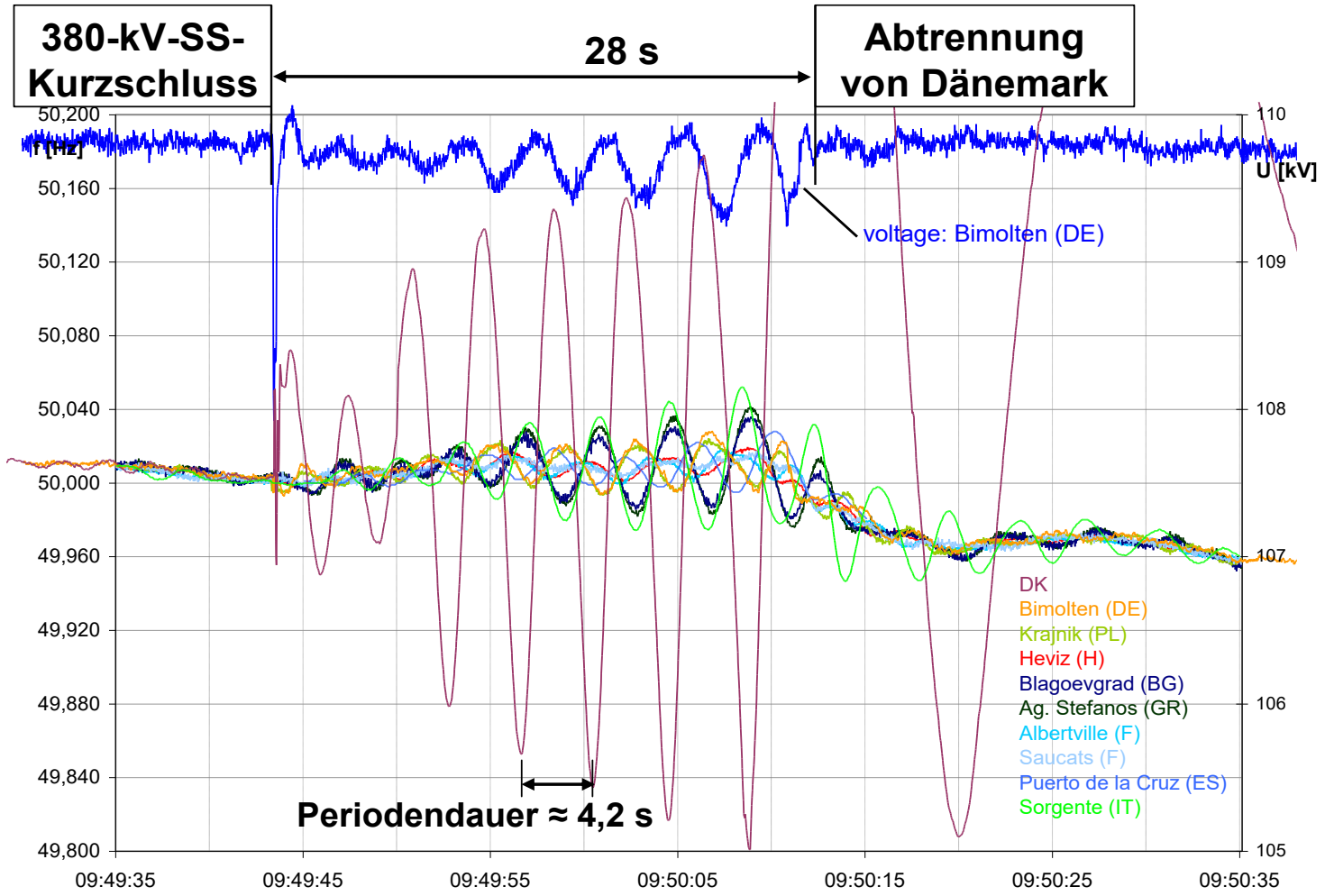
4.3a Denmark M.L. Disconnection – 29.05.2007 - Map

sequence of events:

1. **double busbar failure in 380 kV substation Wilster at 09:49:43h**
2. **disconnection of all 380 kV lines in substation Wilster**
   - **DK + area north of Hamburg connected by remaining two 220-kV-lines**
3. **+28 sec.:**
   • tripping of remaining two 220-kV-lines
   • loss of power import (≈1500MW)
4. **+59 sec:**
   • Baltic cable tripped by emergency protection control
5. **+ 5 min.:**
   • resynchronisation via 380 kV lines

Source: /2/

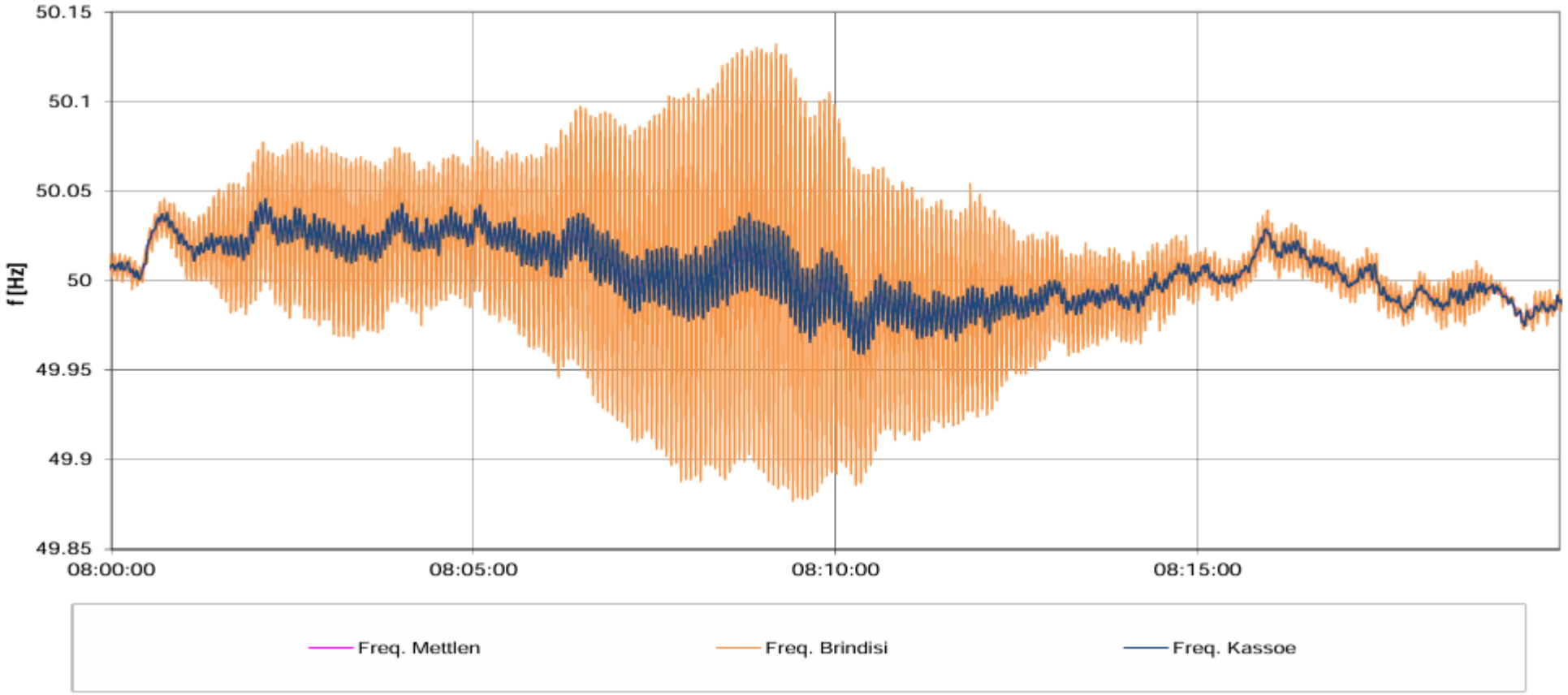
4.3b Denmark M. L. Disconnection – 29.05.2007 Frequencies



first significant CE separation due to critical inter-area oscillations

Source: /2/

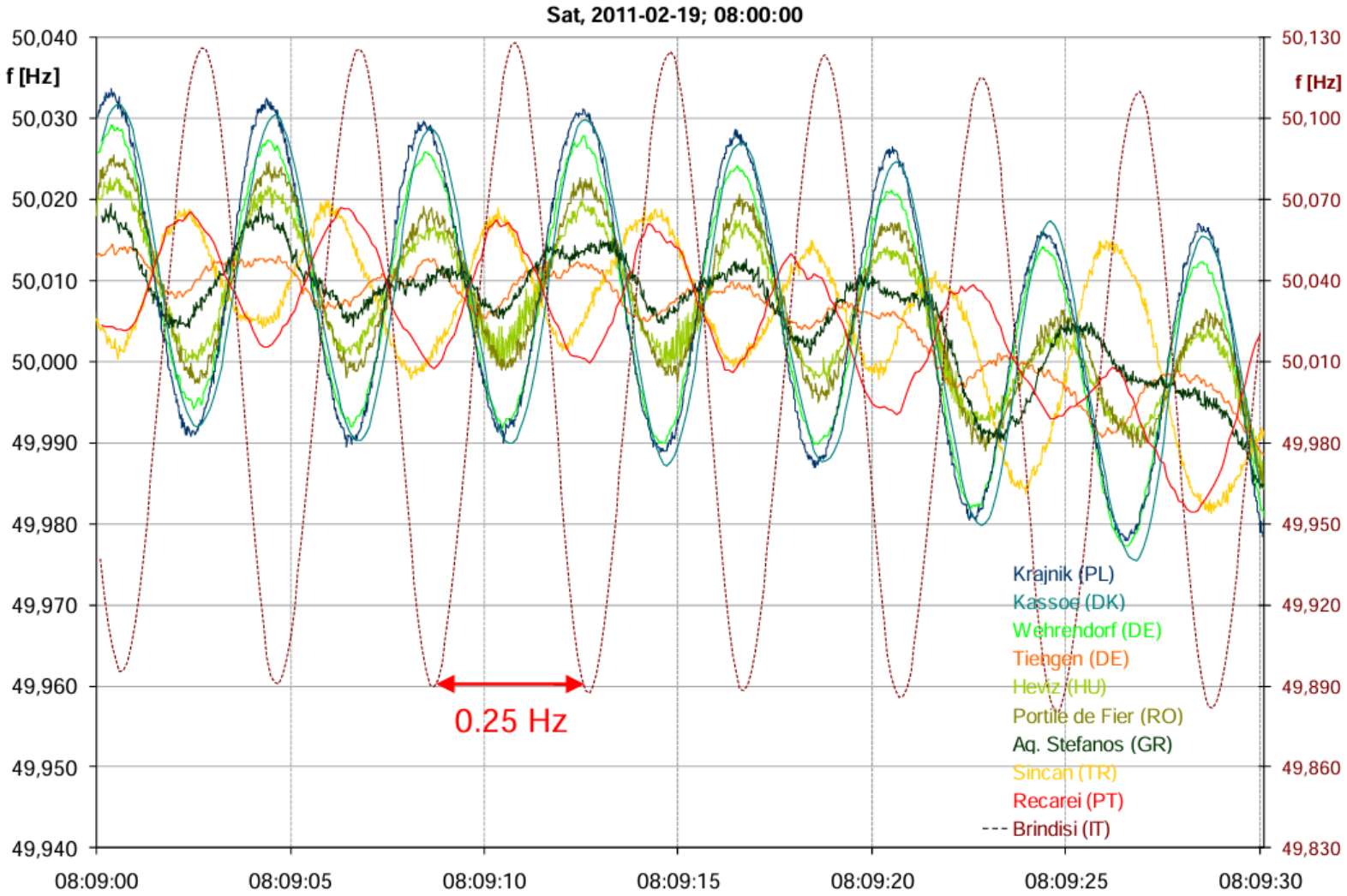
4.4a North-South Oscillation – 19.02.2011 Frequencies



first significant inter-area oscillation after year 2010 system extension

Source: /3/

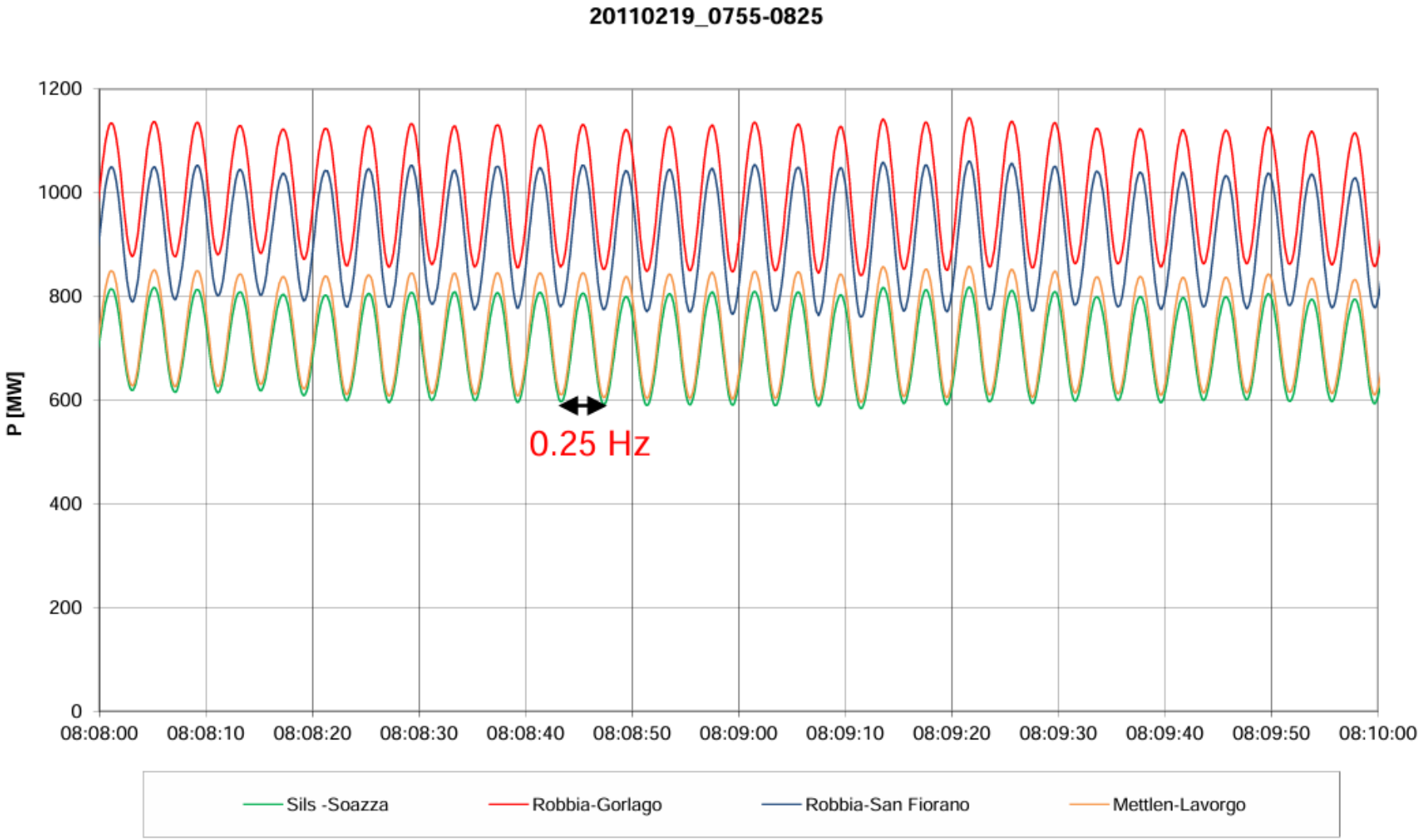
4.4b North-South Oscillation – 19.02.2011 Frequencies Details



Identification of affected oscillation areas and different oscillation modes

Source: /3/

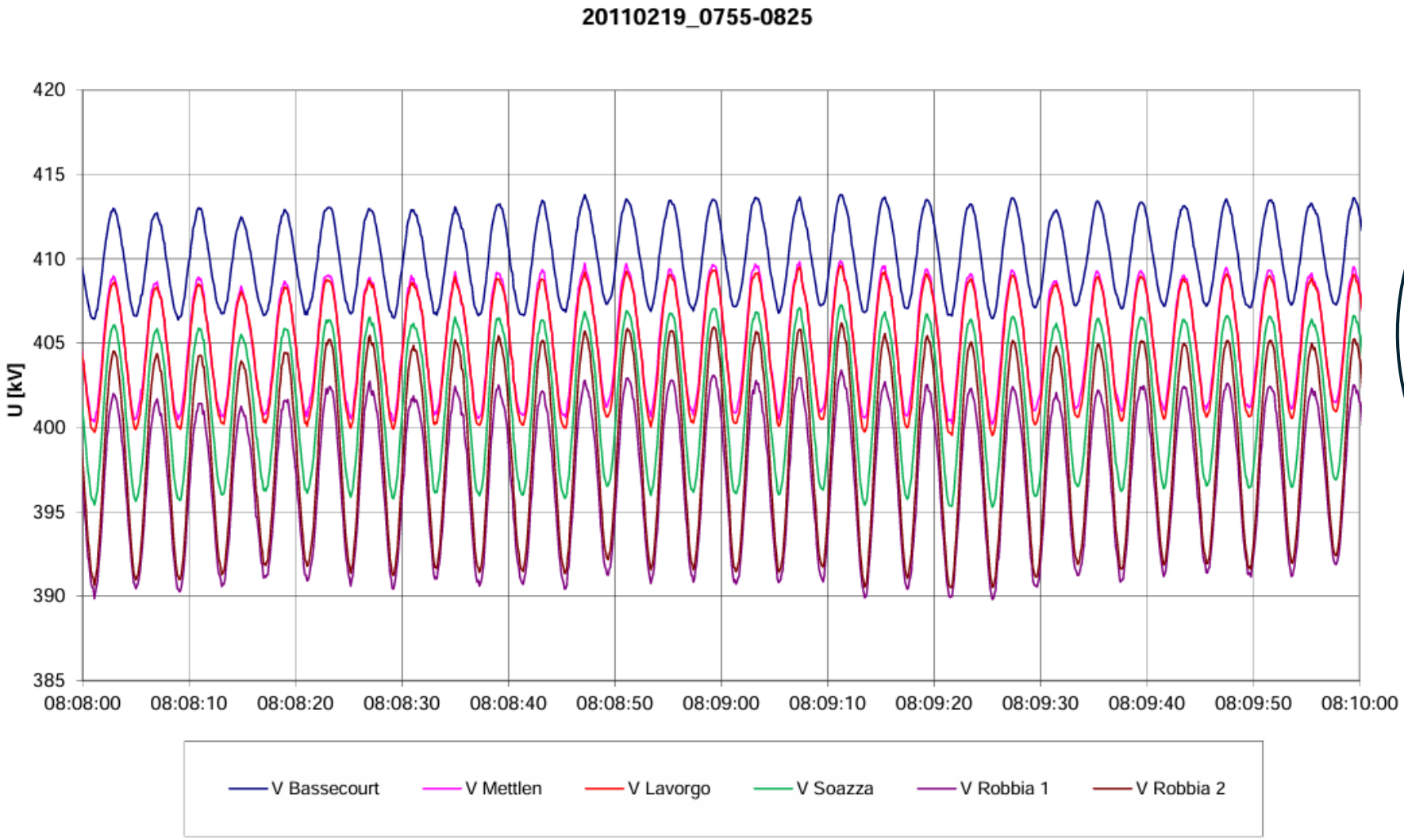
4.4c North-South Oscillation – 19.02.2011 Act. Power Flows



impact of inter-area oscillation on active power flow on single tie-lines

Source: /3/

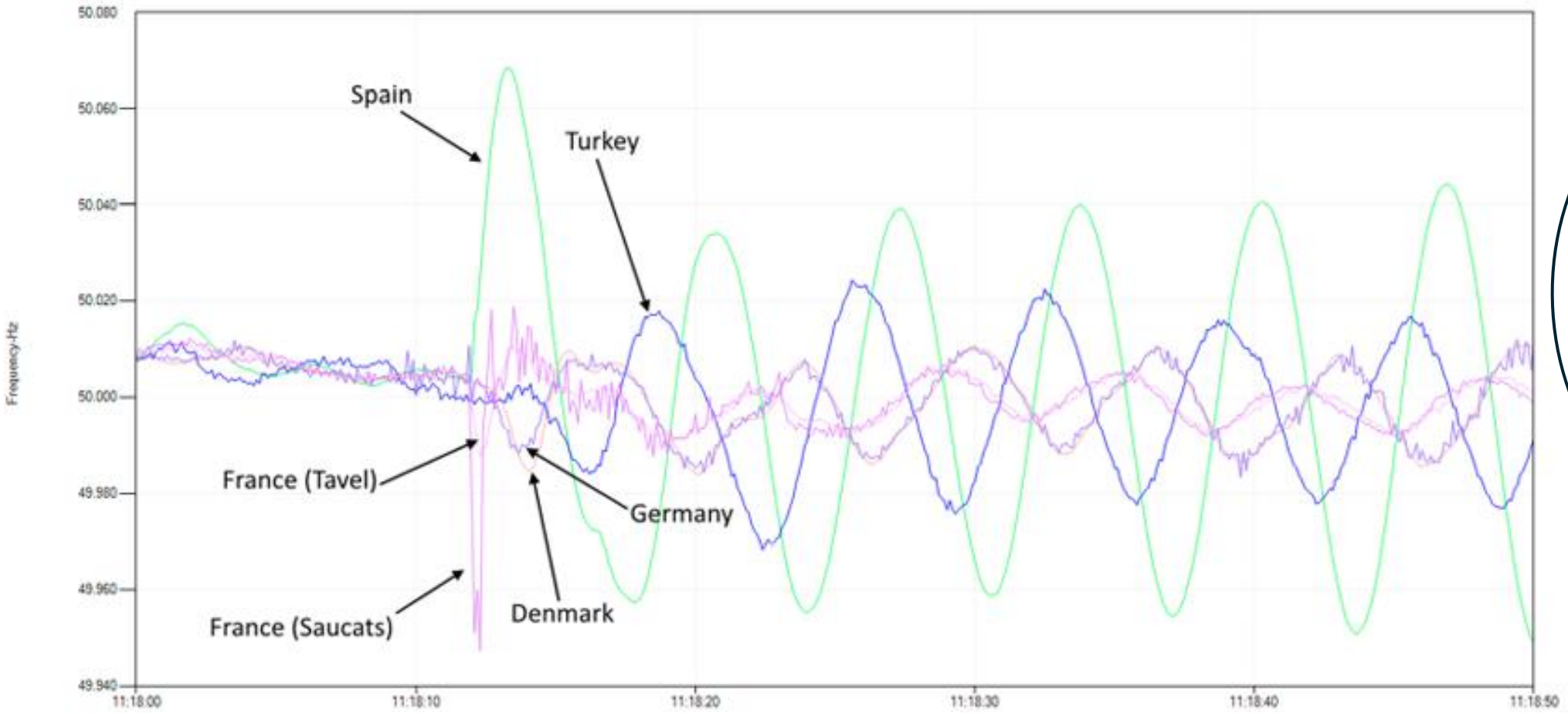
4.4d North-South Oscillation – 19.02.2011 Voltages



impact of inter-area oscillation on busbar voltages and sensitive generation/loads

Source: /3/

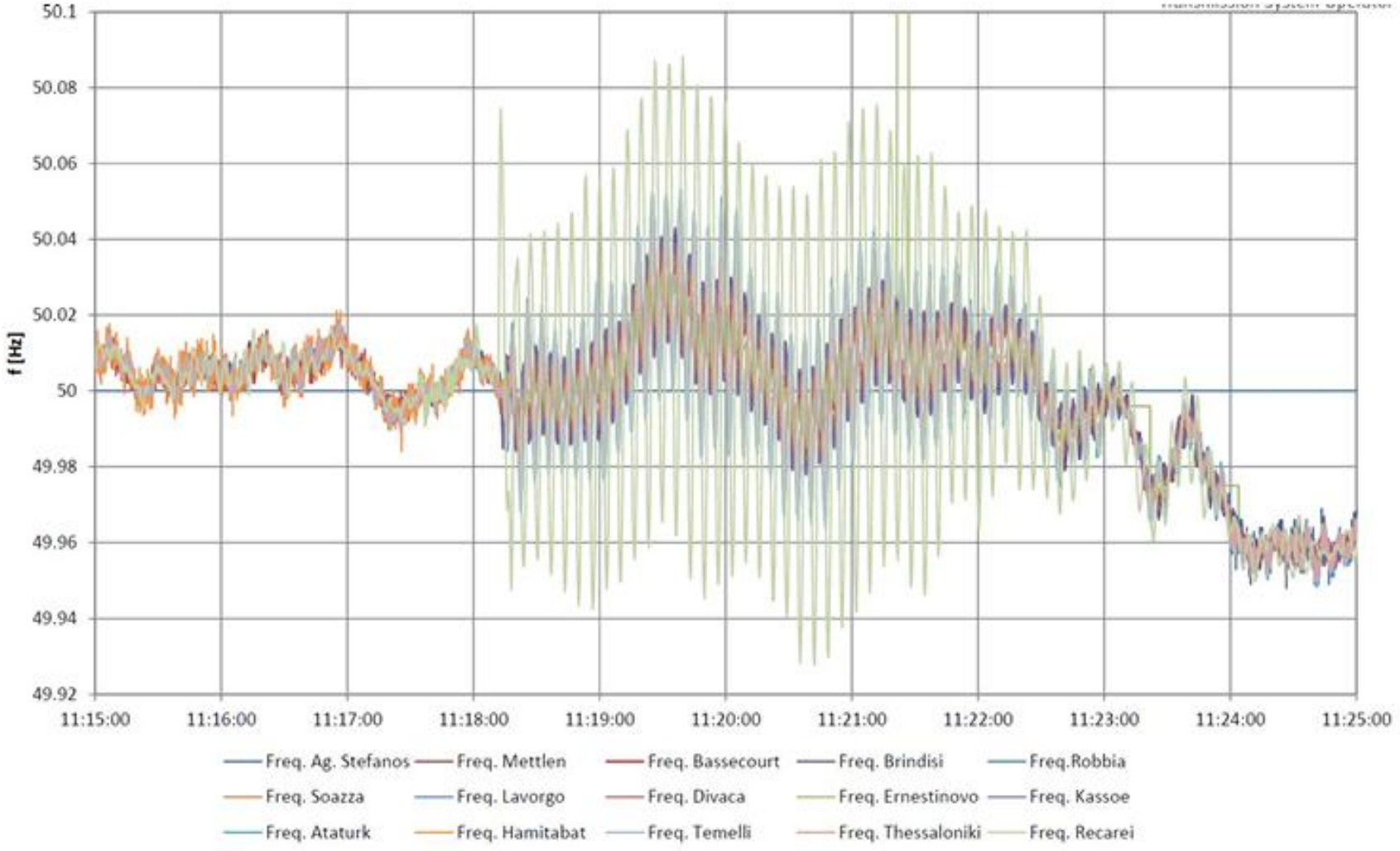
4.5a East-West Oscillation – 01.12.2016 Frequencies



oscillation mode and location determination

Source: /4/

4.5b East-West Oscillation – 01.12.2016 – Freq. Details



significant oscillation region / area

Source: /4/

4.5c East-West Oscillation – 01.12.2016 Freq./Power

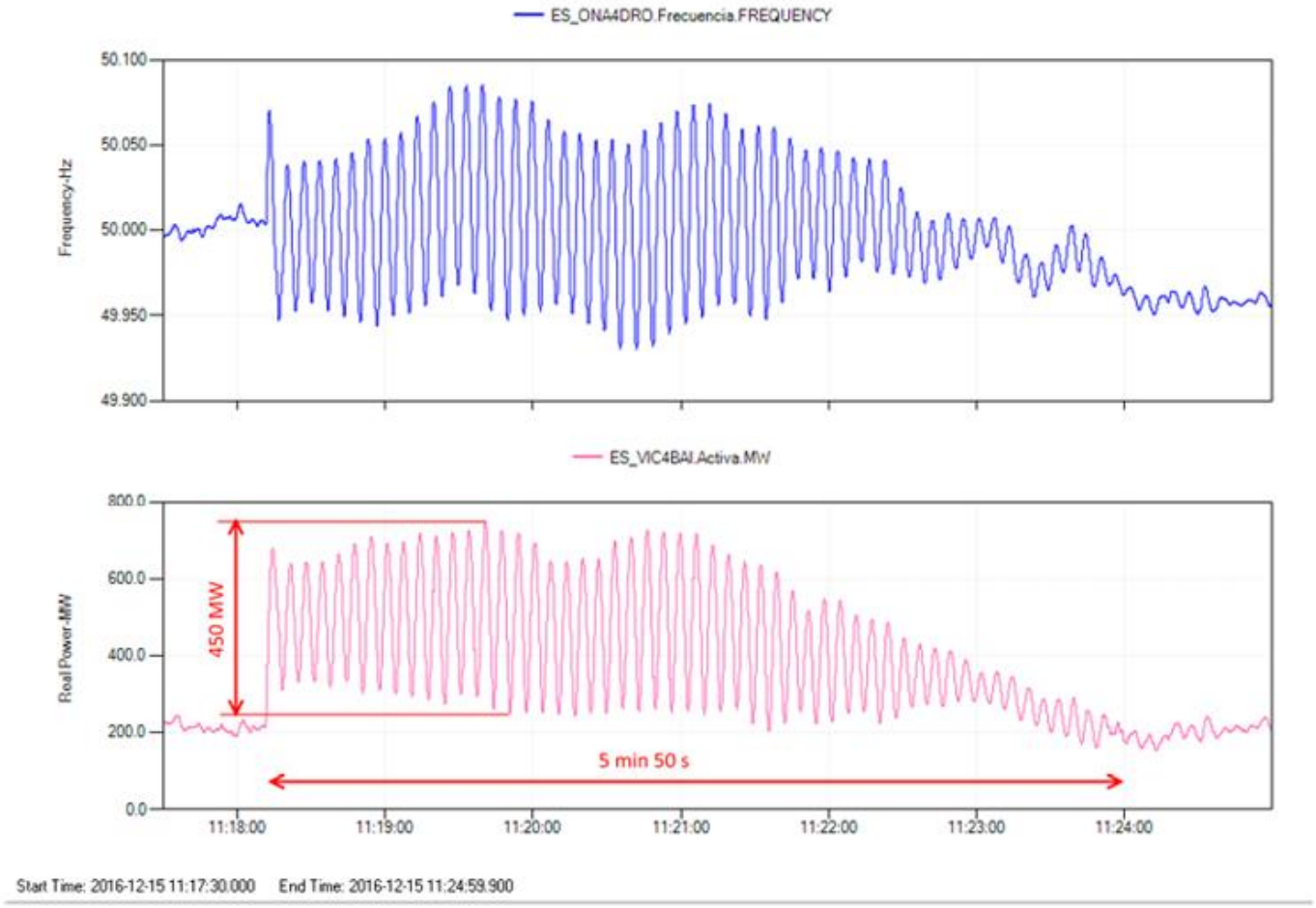
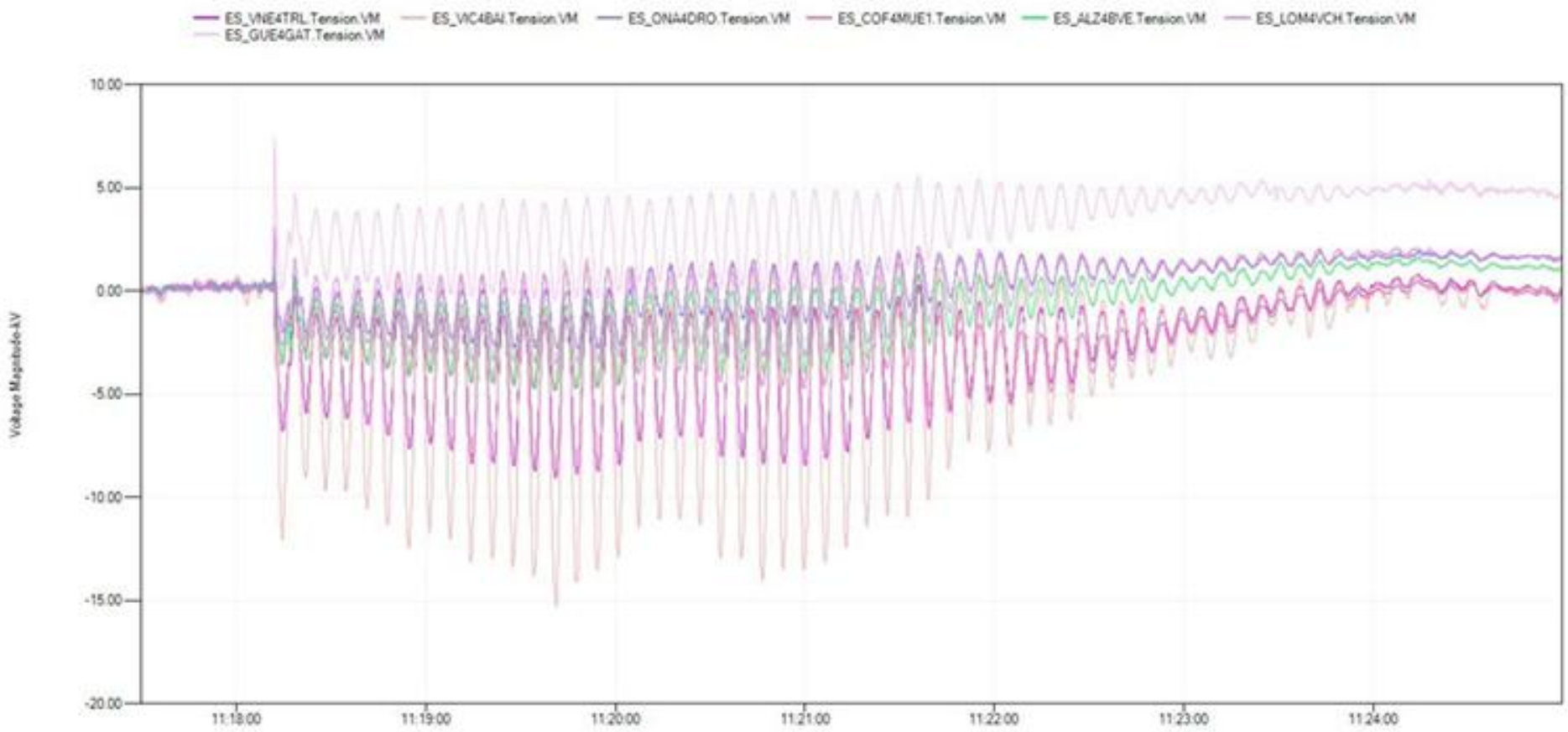


Figure 8. Frequency in Spain and active power through 400 kV Vic-Baixas tie line.

oscillation impact on transmission corridor lines

Source: /4/

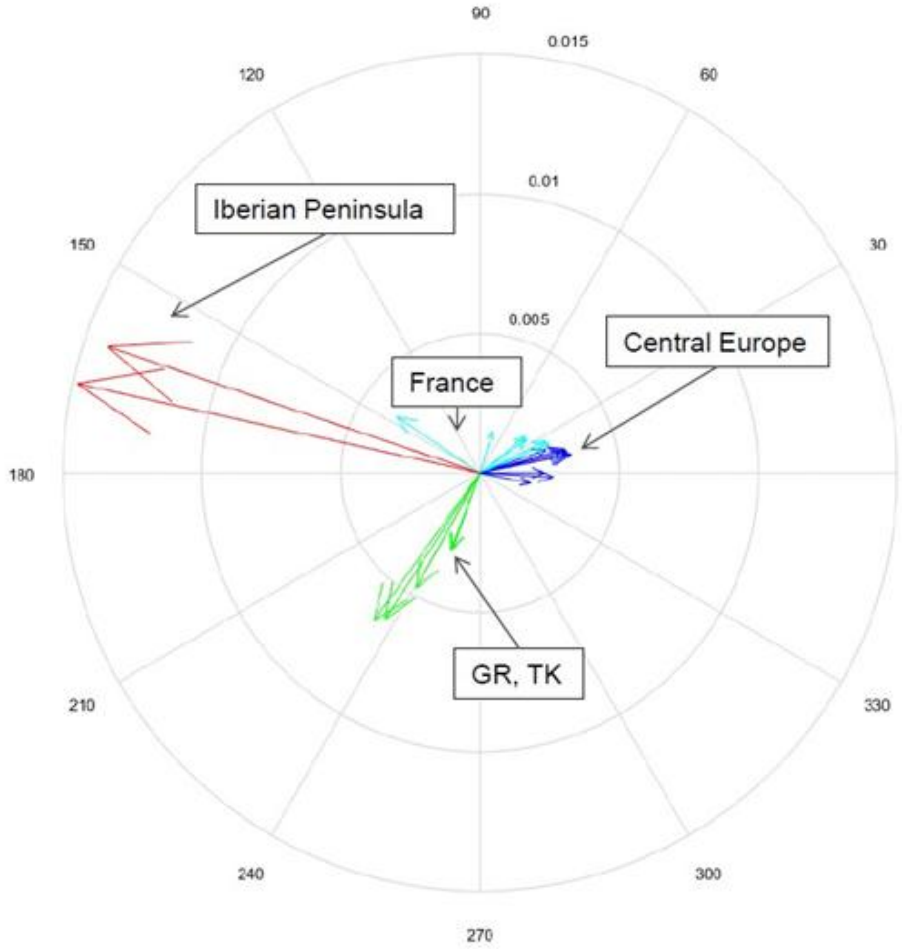
4.5d East-West Oscillation – 01.12.2016 Voltages



impact on substation busbar voltages

Source: /4/

4.5e East-West Oscillation – 01.12.2016 Modal View

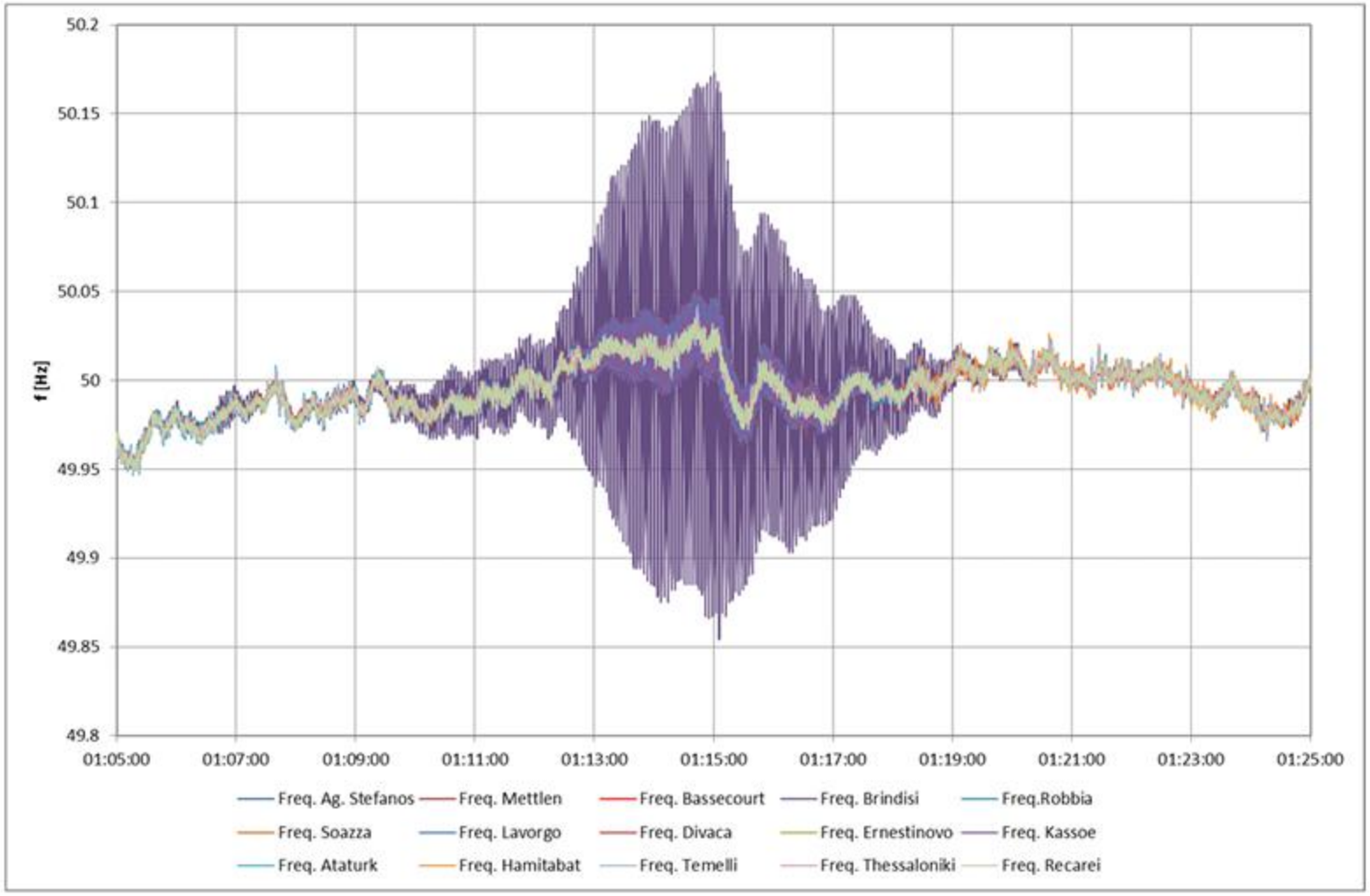


oscillation area participation and mode distribution

Figure 10: Voltage angle differences to the slack node for different European locations in the beginning of the incident.

Source: /4/

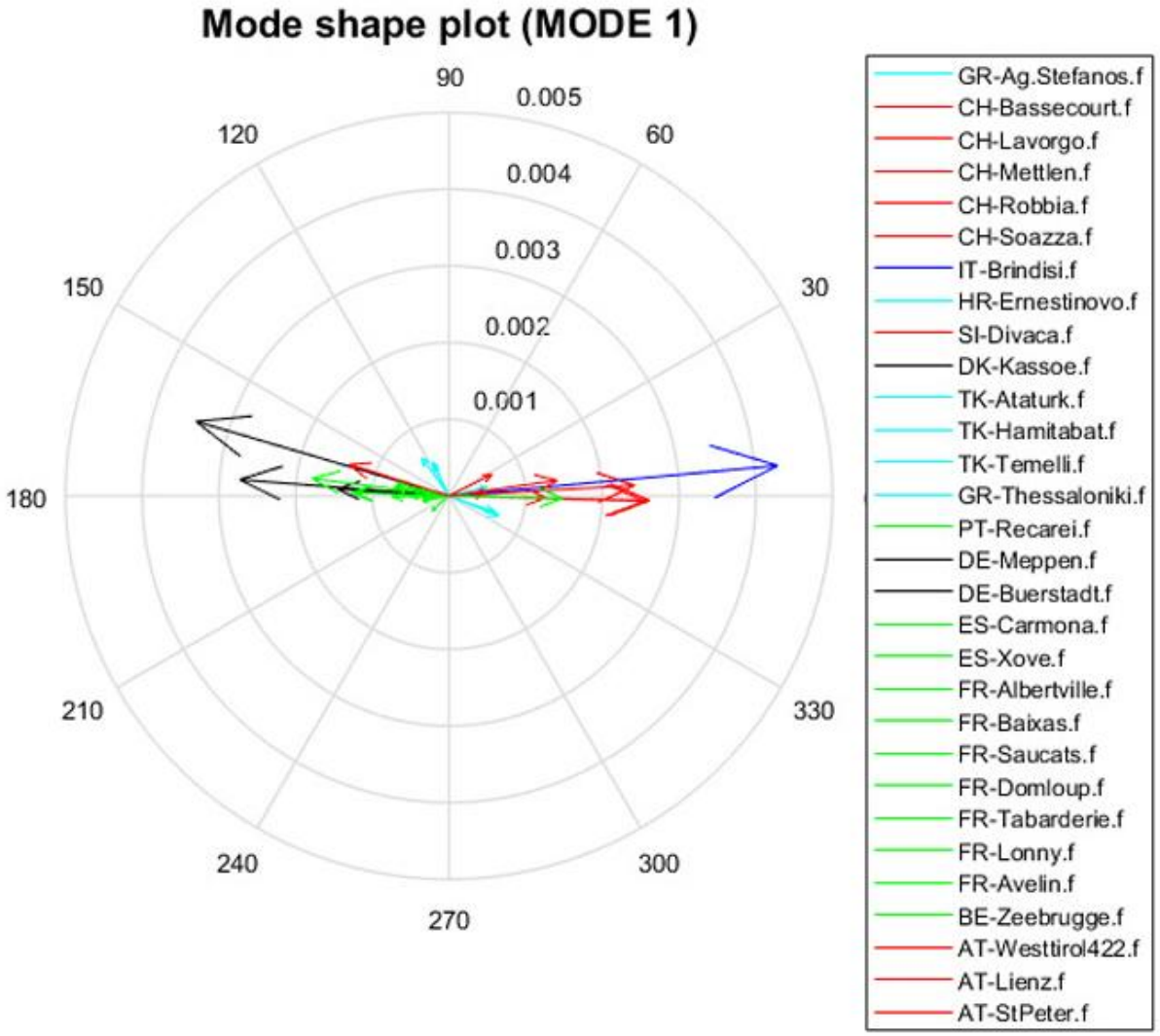
4.6a North-South Oscillation – 03.12.2017 - Frequencies



oscillation amplitude distribution

Source: /5/

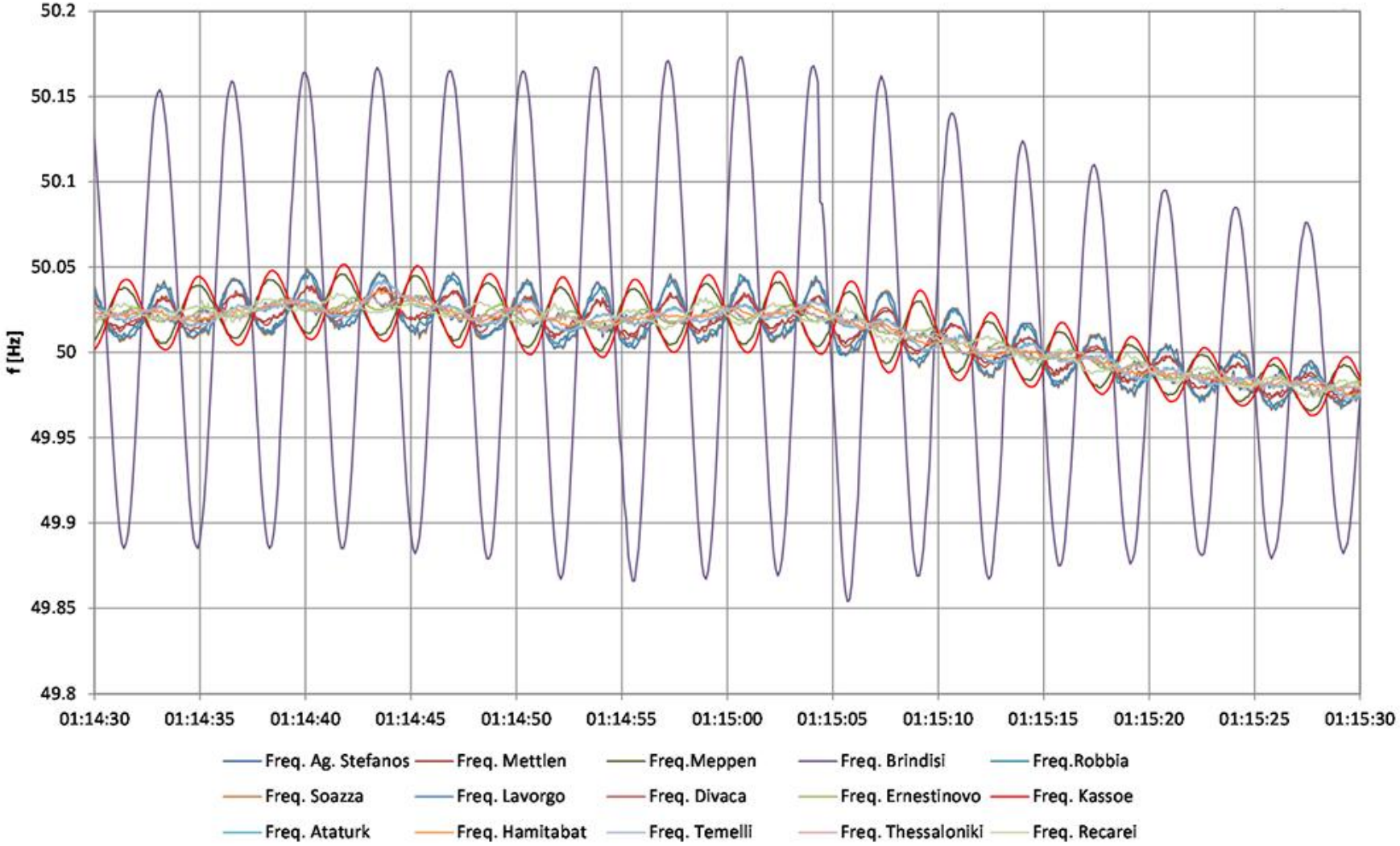
4.6b North-South Oscillation – 03.12.2017 – Mode View



oscillation masses distribution

Source: /5/

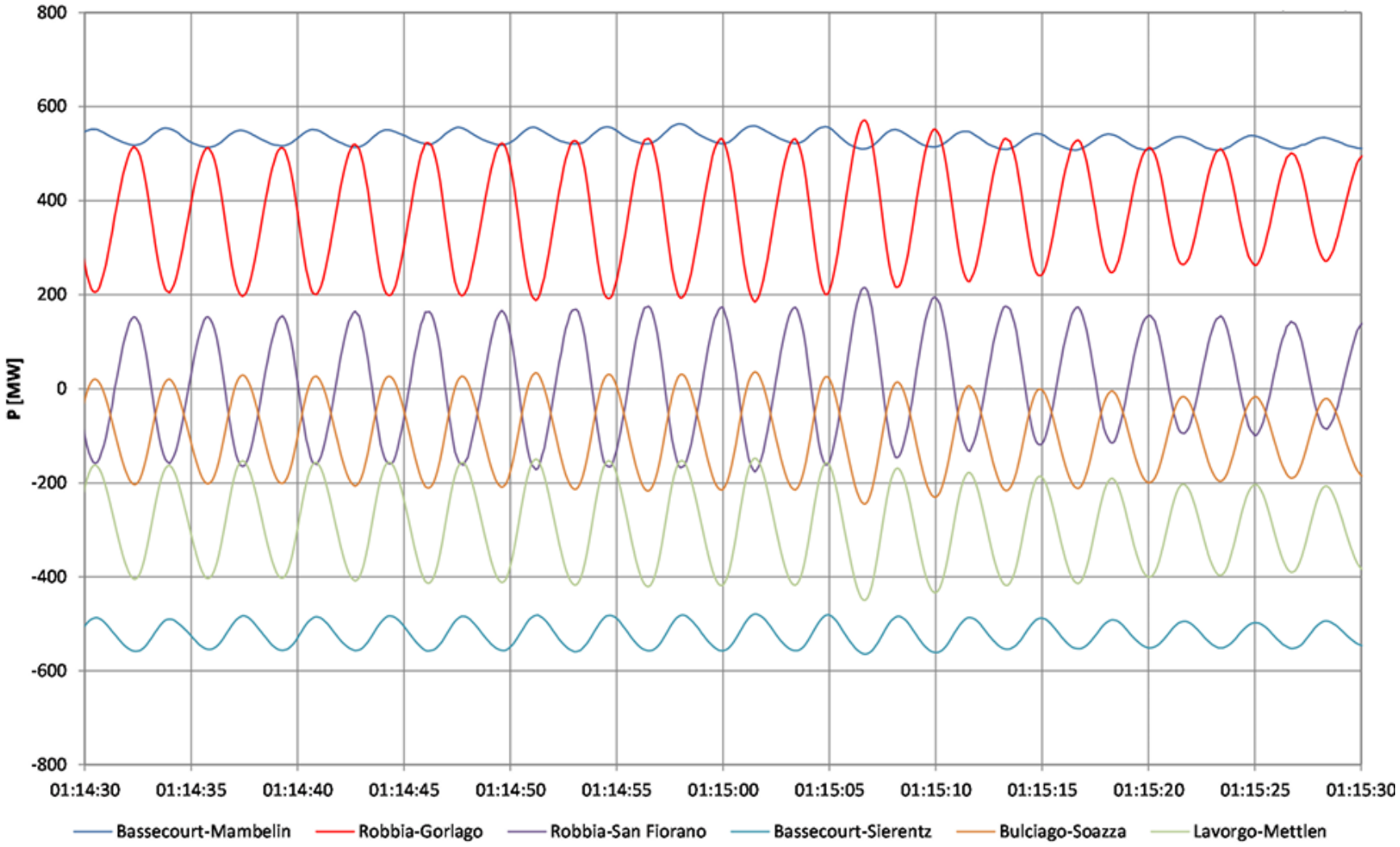
4.6c North-South Oscillation – 03.12.2017 – Freq. Details



oscillation participation distribution

Source: /5/

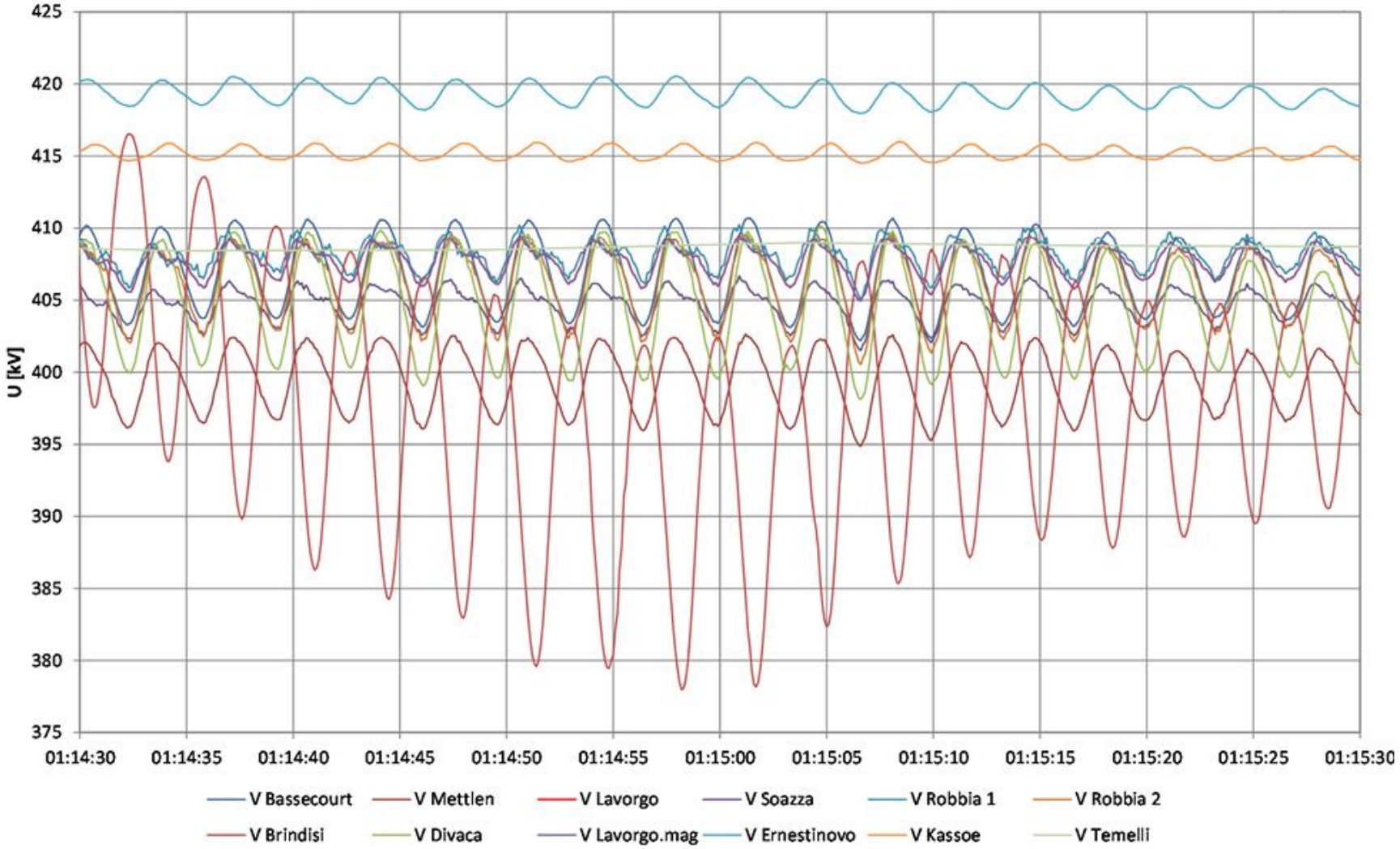
4.6d North-South Oscillation – 03.12.2017 – Active Powers



affected corridor lines on the main oscillation axis

Source: /5/

4.6e North-South Oscillation – 03.12.2017 - Voltages



affected substations with respect to their location

Source: /5/

4.7 Iberian Peninsula Blackout – 28.04.2025 – f/V Phase Shift

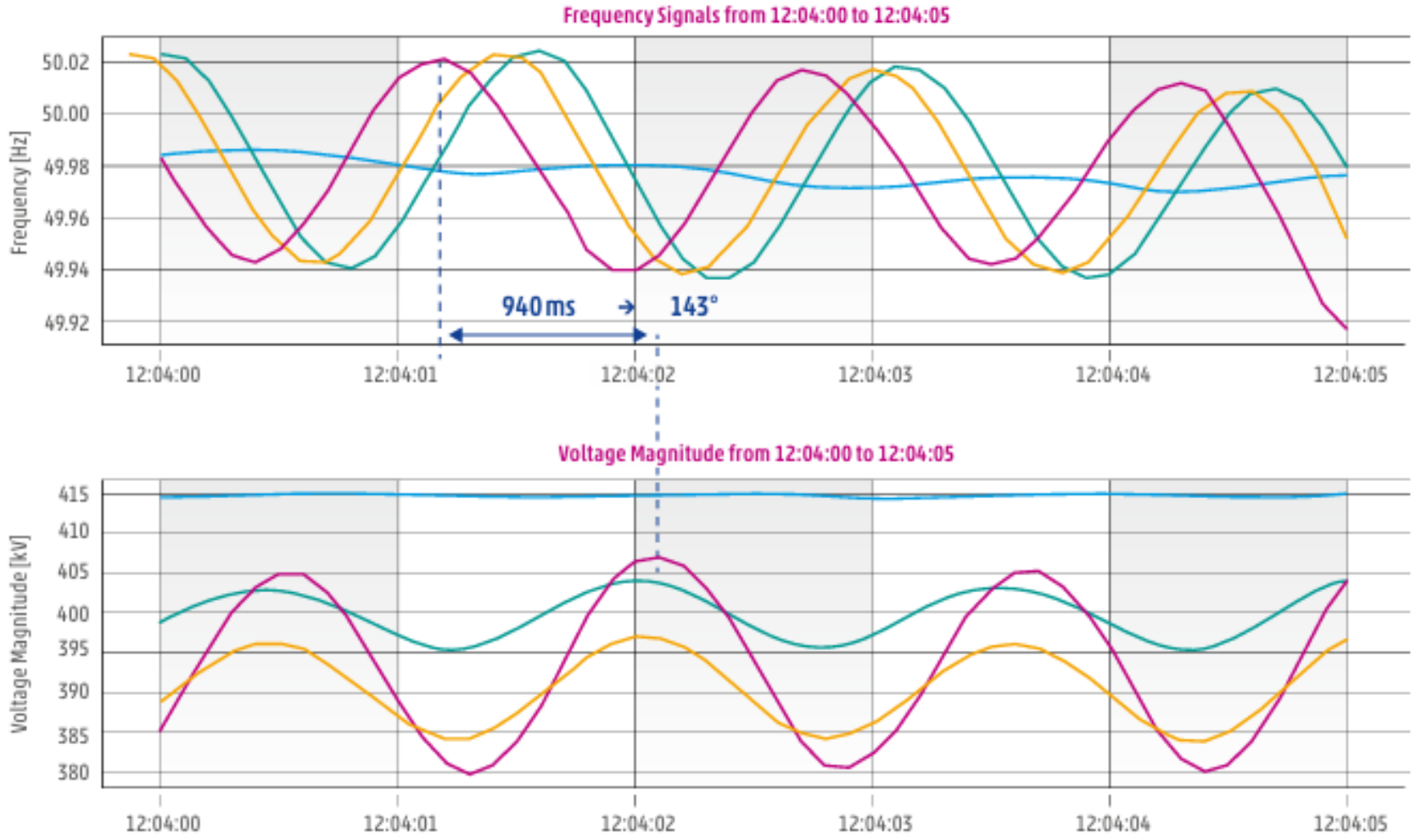


Figure 2-58: Angle between voltages and frequencies

key information with respect to possible/effective damping impact

Source: /1/

5. Conclusions and Recommendations for the Current and Future of Power System Operation and Control

- Power system Operation is becoming more and more challenging.
- The capabilities of the available tools is permanent increasing.
- Monitoring, Modelling => Analysis & Implementation of Improvements are of crucial importance.
- The management of the energy transition is one of the highest priorities for all of us:
  - New generation units will have to be carefully integrated, certain level of system inertia is absolutely needed, e.g. a good mix of synchronous condensers and grid forming converters.
  - The impact of new type of loads as electromobility, heat pumps, electrolysers, air condition shall be considered as well as their potential for their contribution for the power system control and power system protection.
  - The technical needs and consequences shall influence in a better way the political developments.
- The dialogue between all players in the power system, namely generators, consumers, operators, regulators, manufacturers, academia and consulting companies shall be improved and permanently kept ongoing.

6. References

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