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Sciences Appliquées

Grid Incident in Spain and Portugal on 28 April 2025: A Focus on Oscillations

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Context

- “On 28 April 2025 at 12:33 CEST, the power systems of Spain and Portugal experienced the most severe blackout incident in the European power system in over 20 years, with major repercussions for citizens and society.” Entso-e, Factual report.
- This presentation aims to provide the potential reasons for this blackout, based on factual data, with a focus on oscillation phenomena.

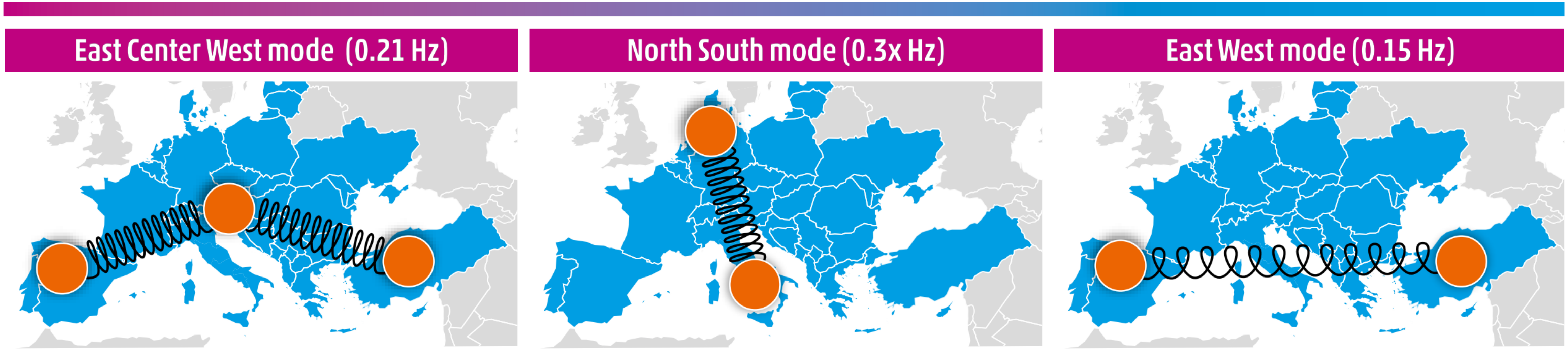
Outline

- Basics about oscillatory stability (small-signal stability)
- State of the system before the incident: Oscillatory stability on 28 April
- Potential causes of the incident
- How to decrease the risk that it happens again?

Basics about oscillatory stability (small-signal stability)

Inter-Area Oscillations

- Large groups of generators in one region start accelerating while those in another region decelerate;
- They oscillate against each other.
- Causes: sudden load changes, or large power transfers across weak transmission corridors*



*https://gilleschaspiere.substack.com/p/understanding-inter-area-electromechanical?r=1yjg9d&utm_campaign=post&utm_medium=web&triedRedirect=true

Local and forced oscillations

- <u>Local oscillations:</u> rotor oscillations of a single power plant against the rest of the power system.

- <u>Inter-plant oscillations:</u> in the same power plant, units oscillate against each other.

Oscillations: Automatic Stabilizing Countermeasures

STATCOM (Static synchronous compensators):

- **a device** that can inject or absorb reactive power almost instantaneously to regulate **voltage**.

- in Q-mode: constant reactive power consumption/production.
- in V-mode: injects a current proportional to the voltage deviation from a reference value.
- Power Oscillation Damping (POD) capability: modulates the reactive power supplied based on the frequency deviation to **damp** electromechanical oscillations.
- Only one STATCOM (± 150 Mvar) was in service in the Spanish grid.

Oscillations: Automatic Stabilizing Countermeasures (2)

<u>HVDC line (VSC-type) between Spain and France, named INELFE-1:</u>

- Rated power of 2 × 1,000 MW

- **POD-P:** measure the frequency at both terminals, calculating the difference, and modulate active power accordingly.

- **POD-Q:** measure local frequency deviation from a reference value, and modulate reactive power accordingly.

Oscillations: Automatic Stabilizing Countermeasures (3)

Power System Stabilisers (PSSs):

- Some synchronous generators modulate excitation to damp oscillations.
- Signal added to the Automatic Voltage Regulator (AVR).
- Positive damping created.

Technology	PSS installed
Nuclear	NO
Hydro	YES
CCGT	YES
Coal	NO

Oscillations: mitigation measures

- Historically: well-damped by synchronous generators thanks to natural damping, and an additional controller (Power System Stabilizer).
- Nowadays: Massive integration of converter-based production units, without damping capabilities.
- Mitigation measures:

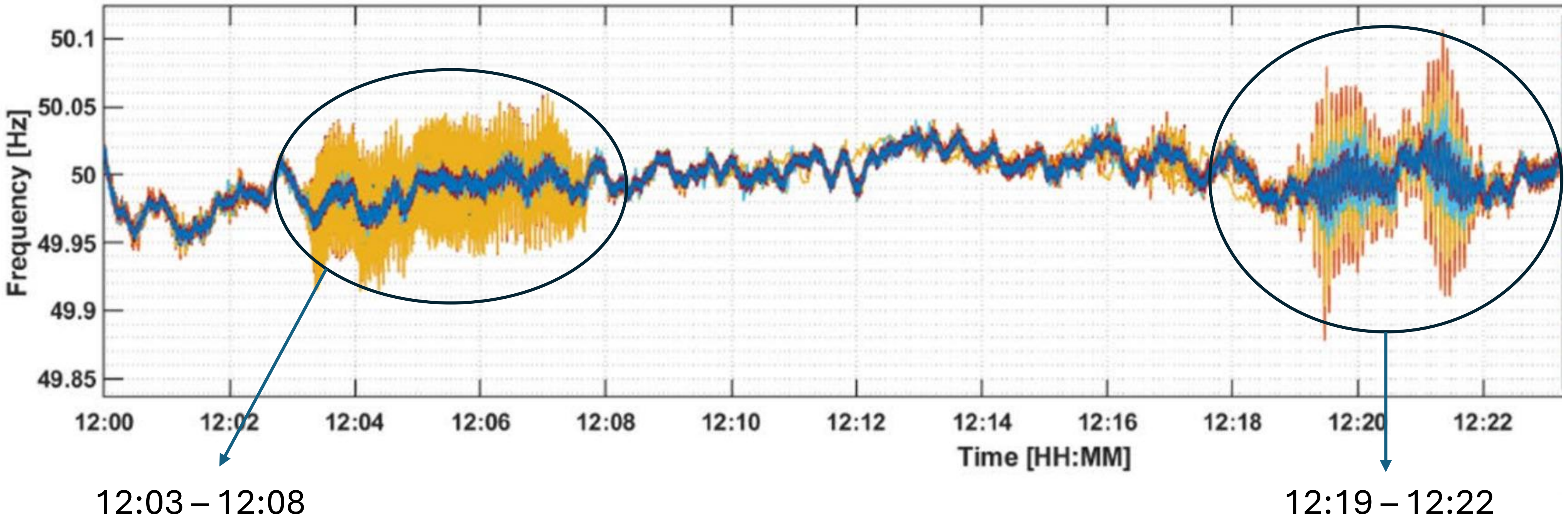
1. Reduction of power exchanges with neighbouring countries.
2. Increasing grid meshing (reduce impedance).

→ Increase voltage!

Oscillatory Stability on 28 April

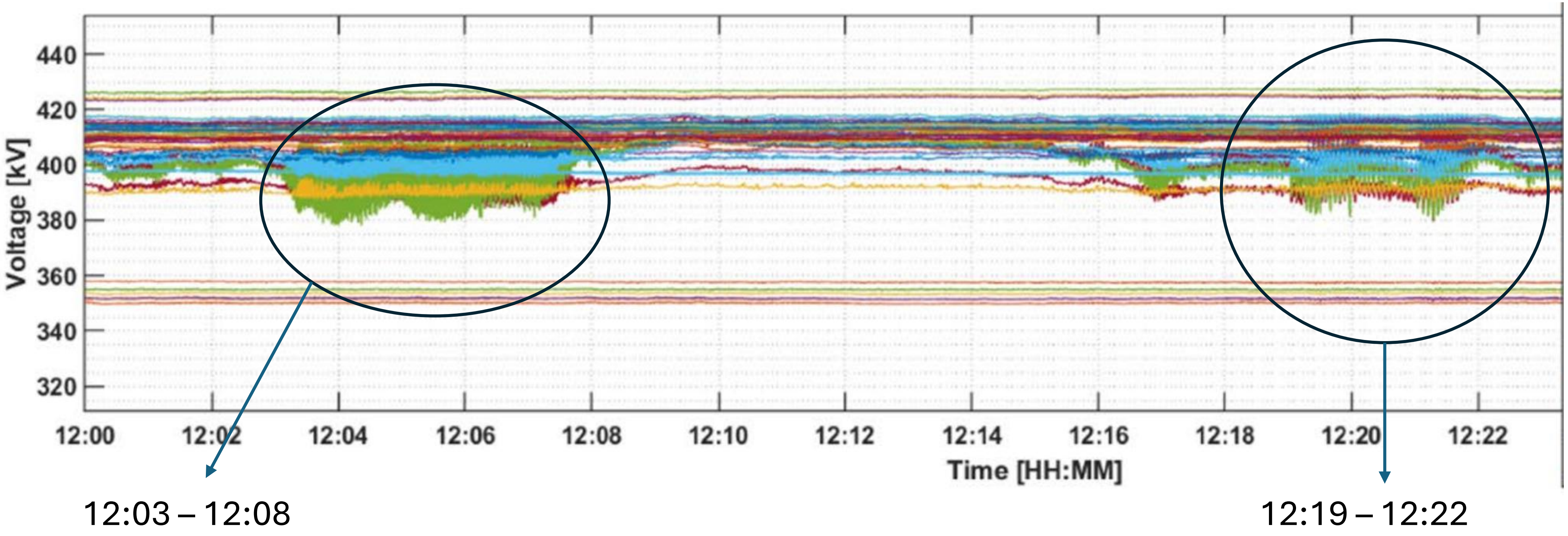
Oscillatory Stability on 28 April (1)

- In the 30 minutes before the blackout event: two prominent oscillation phenomena.
- Periodic fluctuation of all electrical quantities, such as frequency, voltage magnitude, active and reactive power.



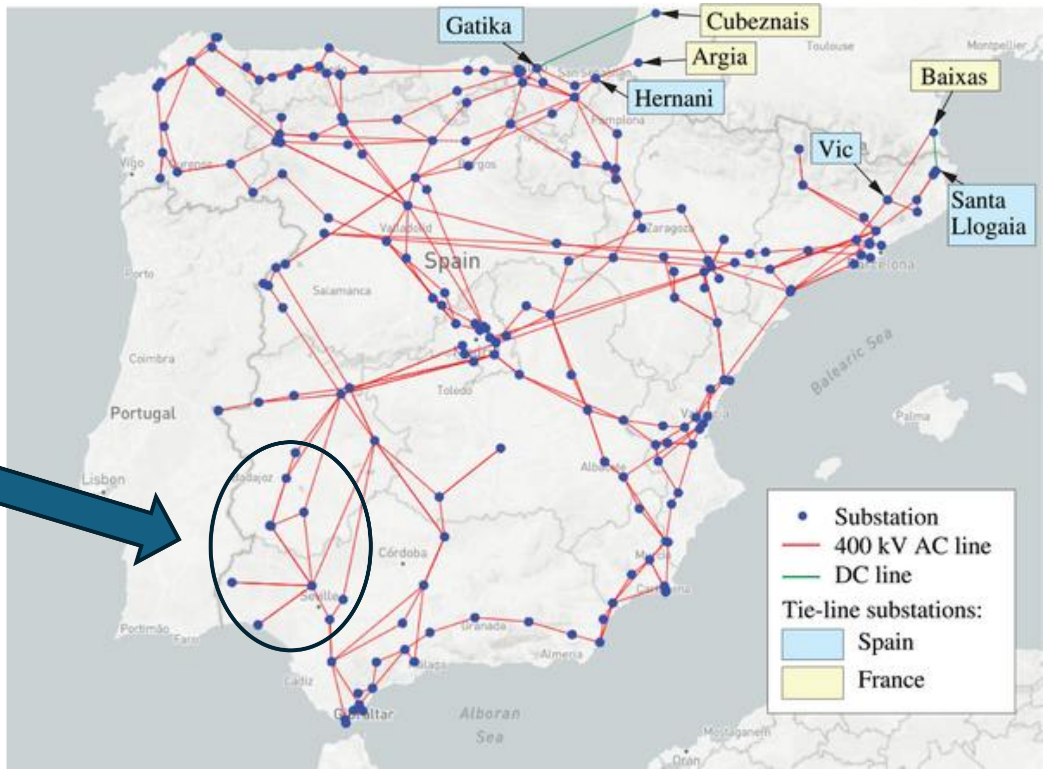
Oscillatory Stability on 28 April (2)

- First oscillation: dominant frequency of 0.63 Hz.
- Second oscillation: dominant frequency of 0.21 Hz.



First oscillation period: 12:03-12:08

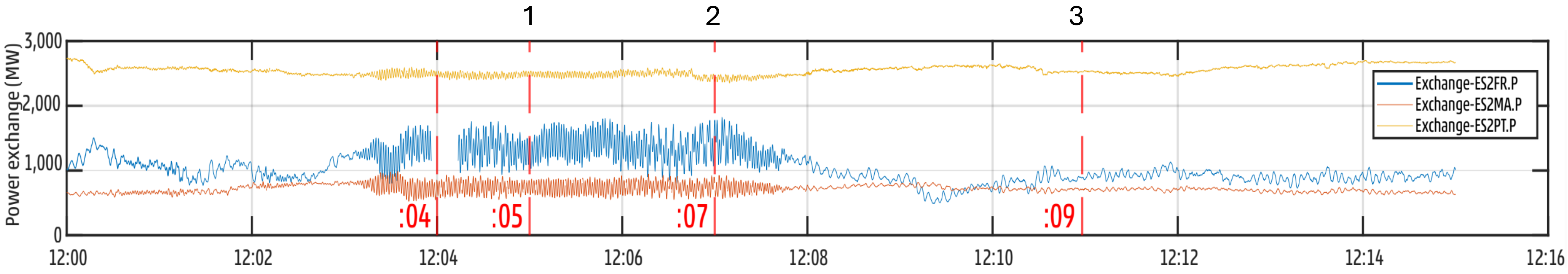
- Local character.
- Most active nodes (in terms of voltage oscillations) in the southwestern area: Almaraz and Puebla de Guzmán.
- Voltage oscillation amplitude reached 30kV peak to peak.



First oscillation period: damping measures

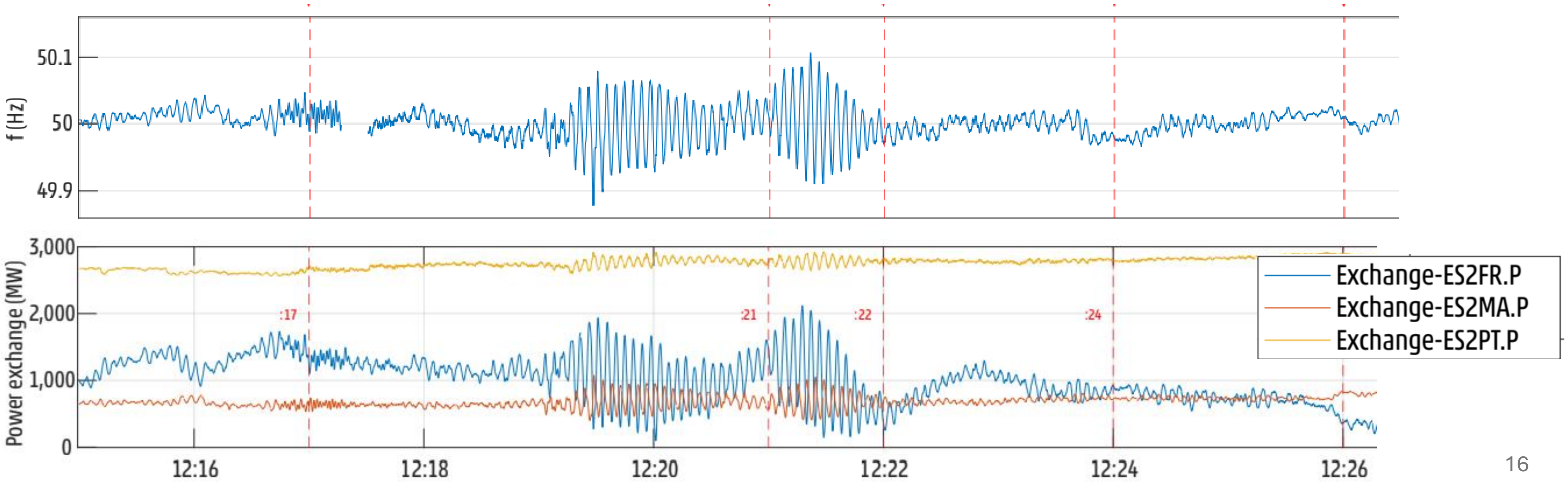
Spanish and French TSOs activated a common protocol:

1. Several topological actions were undertaken, aiming to reduce the impedance of the grid.
2. Reduction of export exchange across the France—Spain borders by 800 MW.
3. Operating mode of HVDC switched to constant power mode.



<u>Second</u> oscillation period: 12:18-12:22

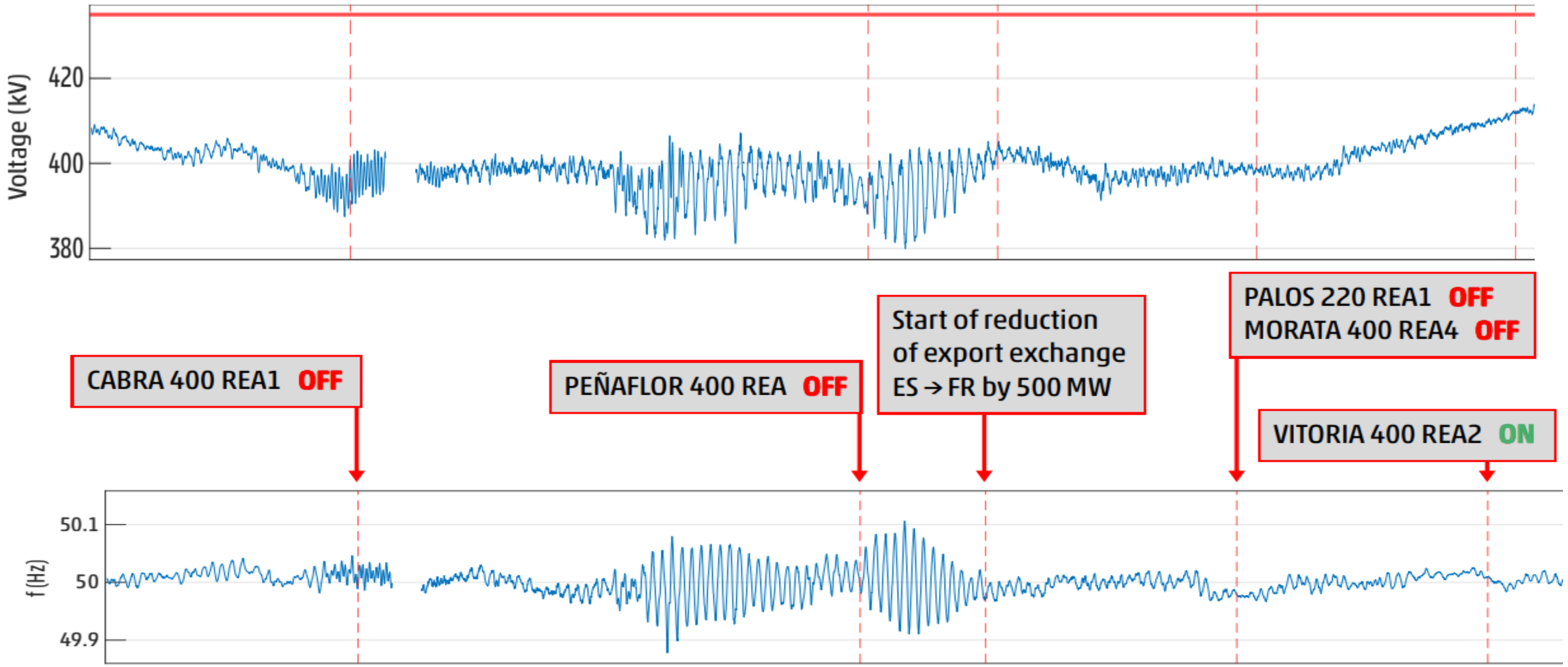
- Inter-area character: East-Center-West mode (0.21 Hz).
- Maximum frequency amplitude of around 200mHz.
- Damping became negative around 12:19.



Second oscillation period: damping measures

Spanish and French TSOs activated (again) a common protocol:

1. Shunt reactors were disconnected (increase in voltage).
2. Reduction of export exchange across the France—Spain borders by 500 MW.



Potential causes of the incident

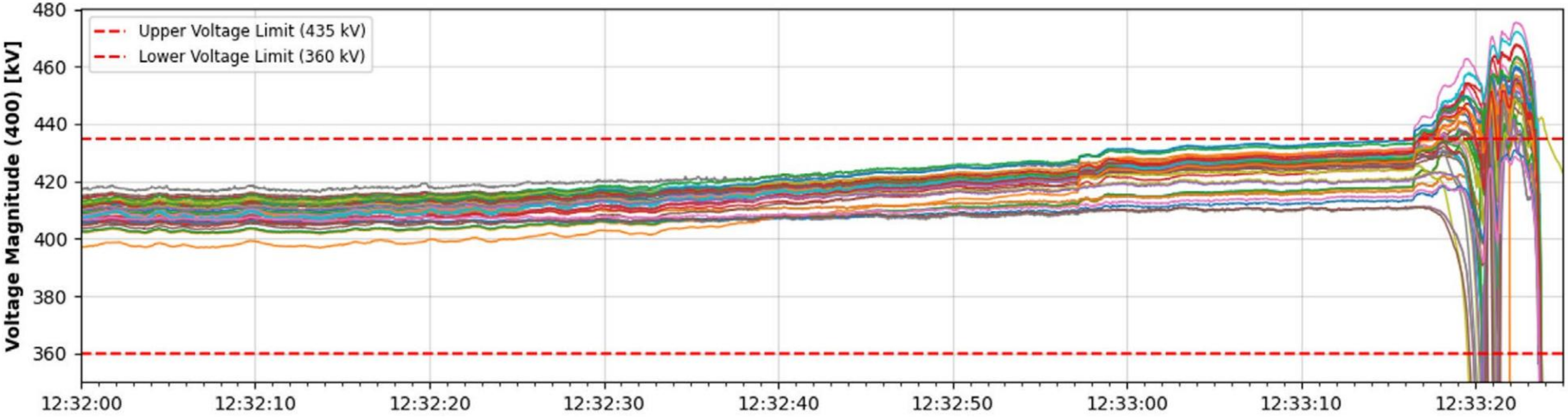
Potential causes of the incident: my theory

Oscillations observed do not seem to have directly induced the incidence.

1. Initially, transmission lines are capacitive (low loading): high voltage.
2. Oscillations detected (both local and inter-area).
3. Mitigation measures led to an increase in voltage.
4. Some generation units and lines tripped because of overvoltage protection.

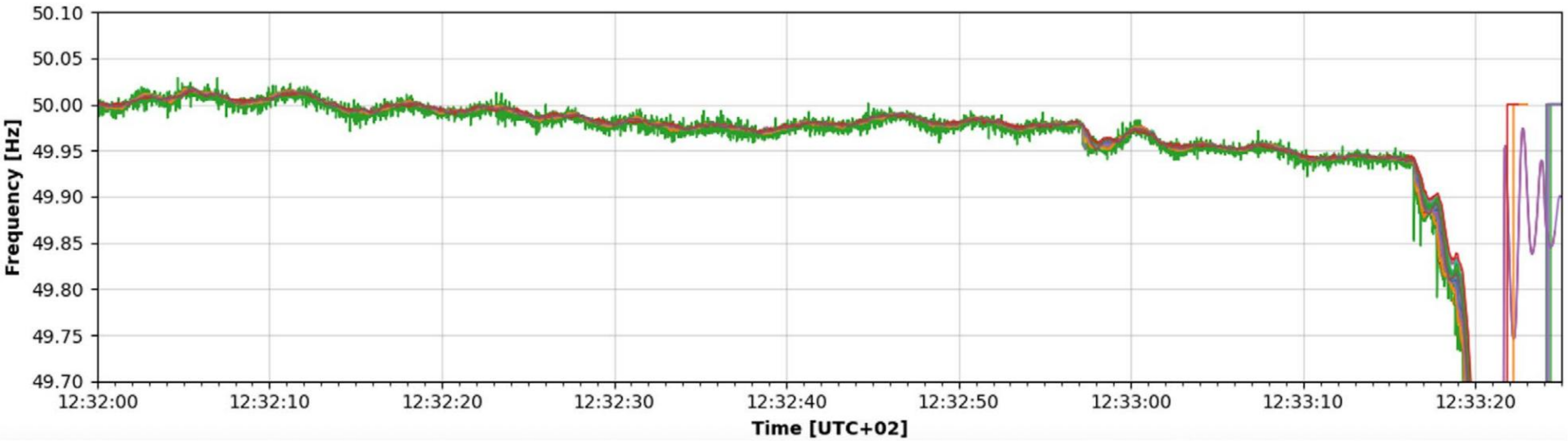
Potential causes of the incident: my theory (2)

Cascading effect: as some of these generators were consuming reactive power, voltage increased even further...



Potential causes of the incident: my theory (3)

Frequency control failed, probably because many generators were already disconnected: loss of synchronism with the rest of the European system and system collapse.



How to decrease the risk that it happens again?

Solutions already implemented

- Only one STATCOM in service (Vitoria 220kV).
- Another 150Mvar STATCOM has been commissioned in Tabernas 220kV after 28 April 2025 and two additional 150Mvar STATCOMs are planned to be commissioned in 2025 (Lousame 220kV and Moraleja 400kV).
- Voltage regulation and oscillations damping capacities are improved.

Proposed solutions

- Instead of installing grid-following converters, grid-forming inverters should be preferred, as it provides:

1. Virtual damping
2. Voltage control

- Wide-Area Damping Controller implementation: Coordinated control using real-time measurements across the grid.

Note regarding first (local) oscillation

- It might be due to a forced oscillatory phenomenon, but still uncertain.
- Additional investigations are required.
- As the most active nodes in the oscillation were identified, the TSO should require conformity tests to synchronous generators connected to these nodes.
- For example, the nuclear power plant connected to the Almaraz node should perform damping tests.

Technology	PSS installed
Nuclear	NO
Hydro	YES
CCGT	YES
Coal	NO

Discussions

- Are STATCOMs and other power-electronics solutions enough to control future grid oscillations, or are alternative approaches needed?

- Does expanding the European grid enhance its robustness, or does it undermine its stability (inter-area oscillations,...)?

- How should coordination practices between TSOs evolve to mitigate these stability issues in the future?

Disclaimer

The views and opinions expressed in this presentation are solely those of the author and do not necessarily reflect those of any affiliated organization or institution. This document is intended for informational purposes only and cannot be used to assess or attribute responsibility to any stakeholder in relation to the blackout event.

References

- European Network of Transmission System Operators for Electricity (ENTSO-E). (2025). *Incident report ES-PT: Blackout in Spain and Portugal on 28 April 2025* [Factual report]. ENTSO-E. https://eepublicdownloads.blob.core.windows.net/public-cdn-container/clean-documents/Publications/2025/entso-e_incident_report_ES-PT_April_2025_06.pdf

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