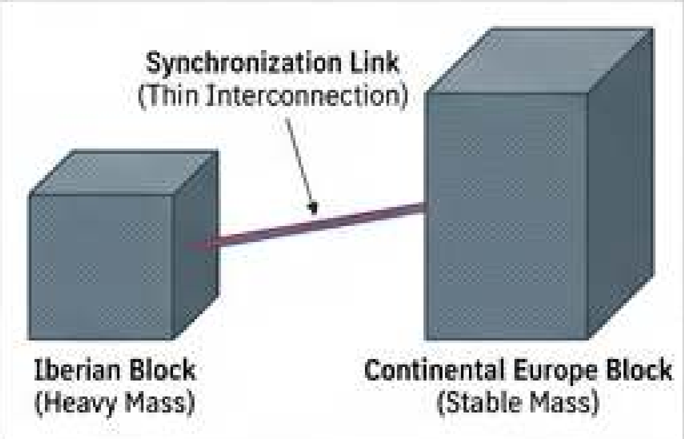
Iberian Peninsula Blackout

A system-level examination of margin, interconnection, and cascading loss of stability

Date of Incident: April 28, 2025
Source: ICS Investigation Expert Panel Factual Report

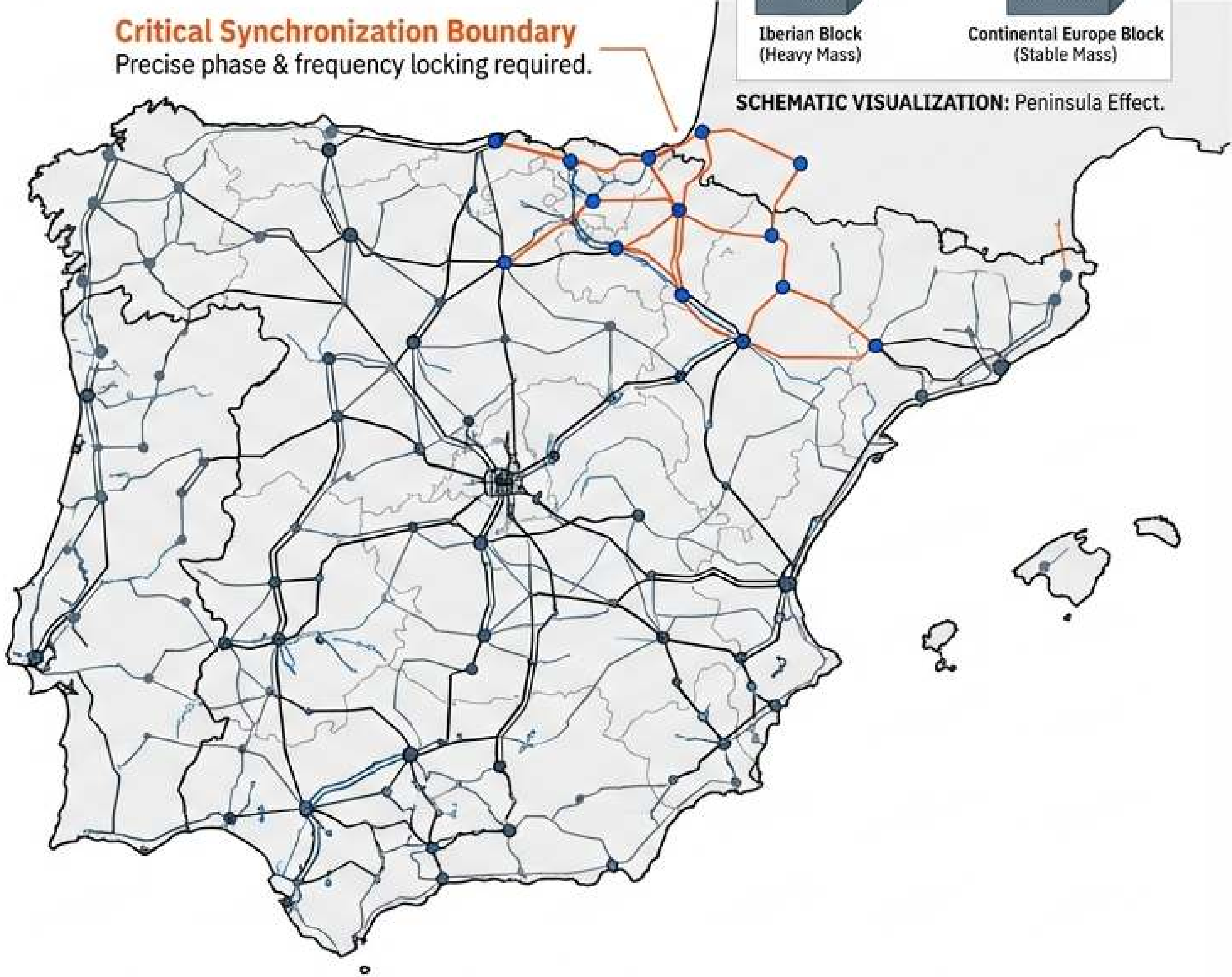
The Topological Reality: An Electrical Peninsula

GRID TOPOLOGY REPORT: IBERIAN PENINSULA & CONTINENTAL EUROPE CONNECTION



SCHEMATIC VISUALIZATION: Peninsula Effect.

- **Domain:** Spain and Portugal operate as a single synchronous block.
- **Interconnection:** Physical connection to Continental Europe (CE) relies entirely on the French transmission border (AC lines and HVDC links).
- **Mass Balance:** Internal generation mass significantly outweighs interconnection capacity.
- **Key Insight:** Stability relies on maintaining precise phase and frequency locking across the Pyrenees boundary.



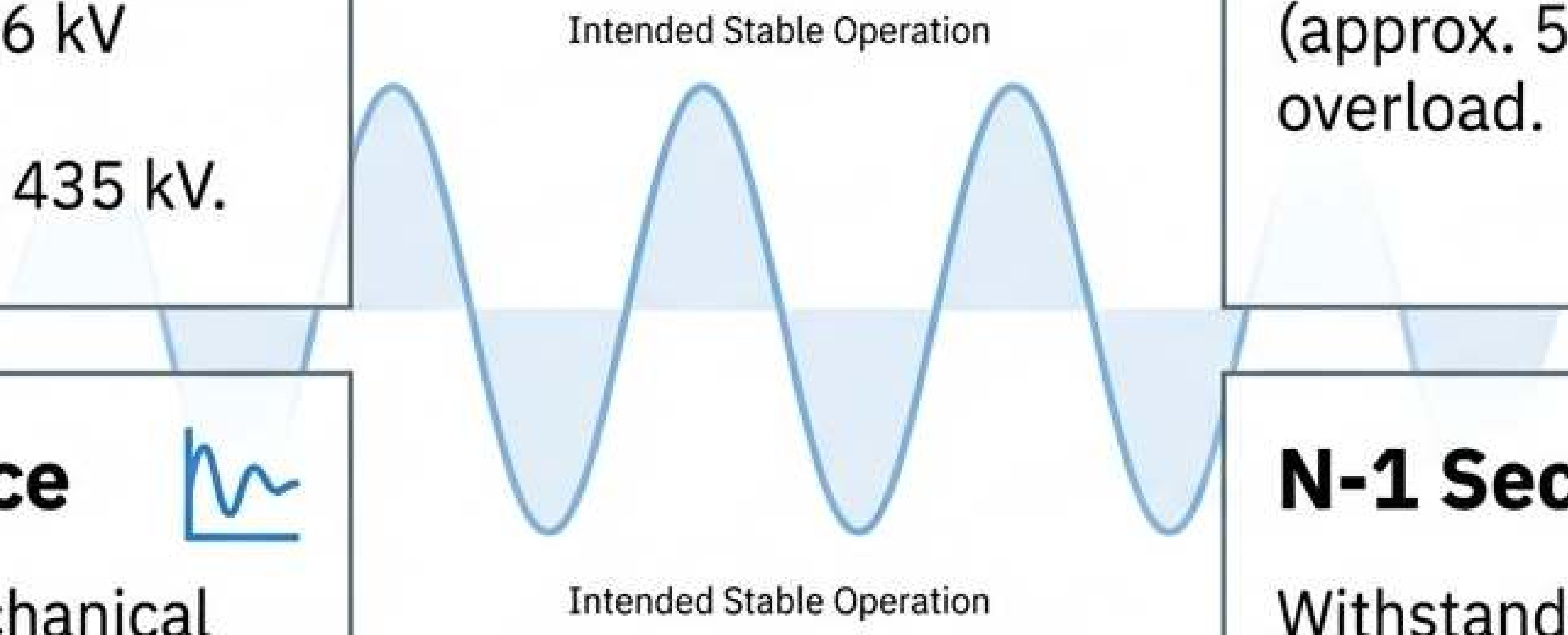
Functional Expectations of the Power System

Voltage Profile

Maintain 400 kV network voltage between 399 kV and 426 kV (nominal).
Upper operational limit: 435 kV.

Export Volume

Facilitate active power export (approx. 5 GW) without thermal overload.



Dynamic Resilience

Damping of electro-mechanical oscillations (0.15–0.21 Hz modes).
Utilization of Power System Stabilizers (PSS).

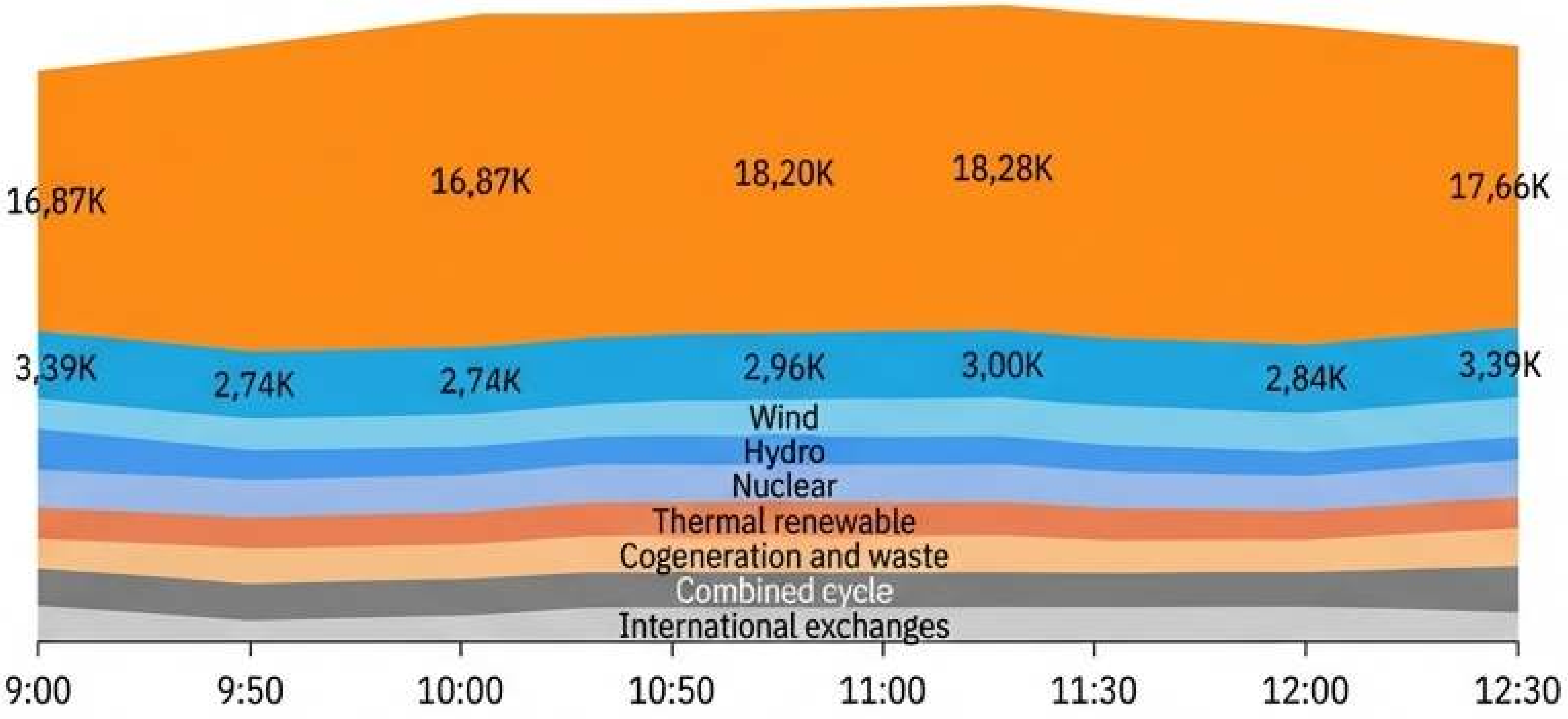
N-1 Security

Withstand loss of single largest line or generator without cascading failure.

Operating Context: High Renewables and Voltage Stress

State at 12:00 CEST

GENERATION MIX



ANALYSIS

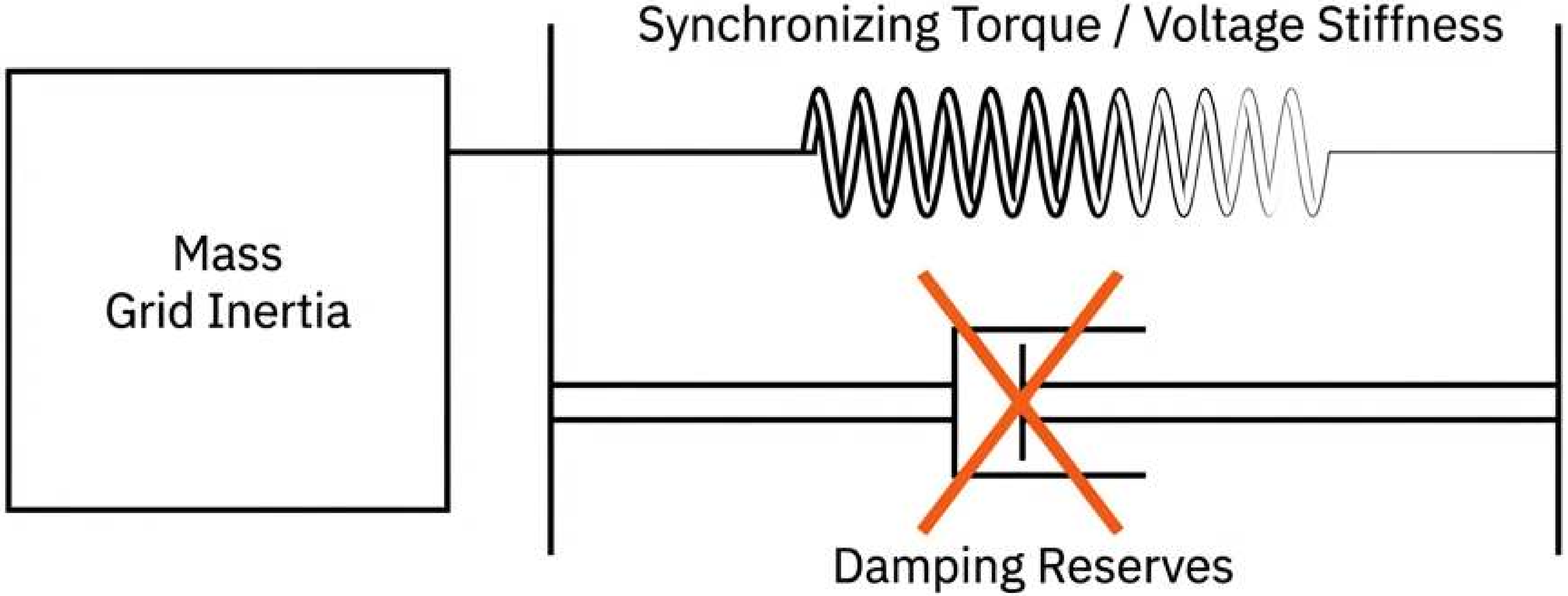
Condition: High renewable penetration + light loading on lines.

Physics: 400 kV lines exhibited capacitive behavior, driving voltage up.

Inertia: Calculated between 2.21 and 2.71 seconds (low historical baseline).

Operator Action: Manual opening of internal transmission lines to reduce voltage.

Functional Failure: Loss of Damping and Stiffness



Loss of Cohesion: Failure to hold phase angle with Europe.

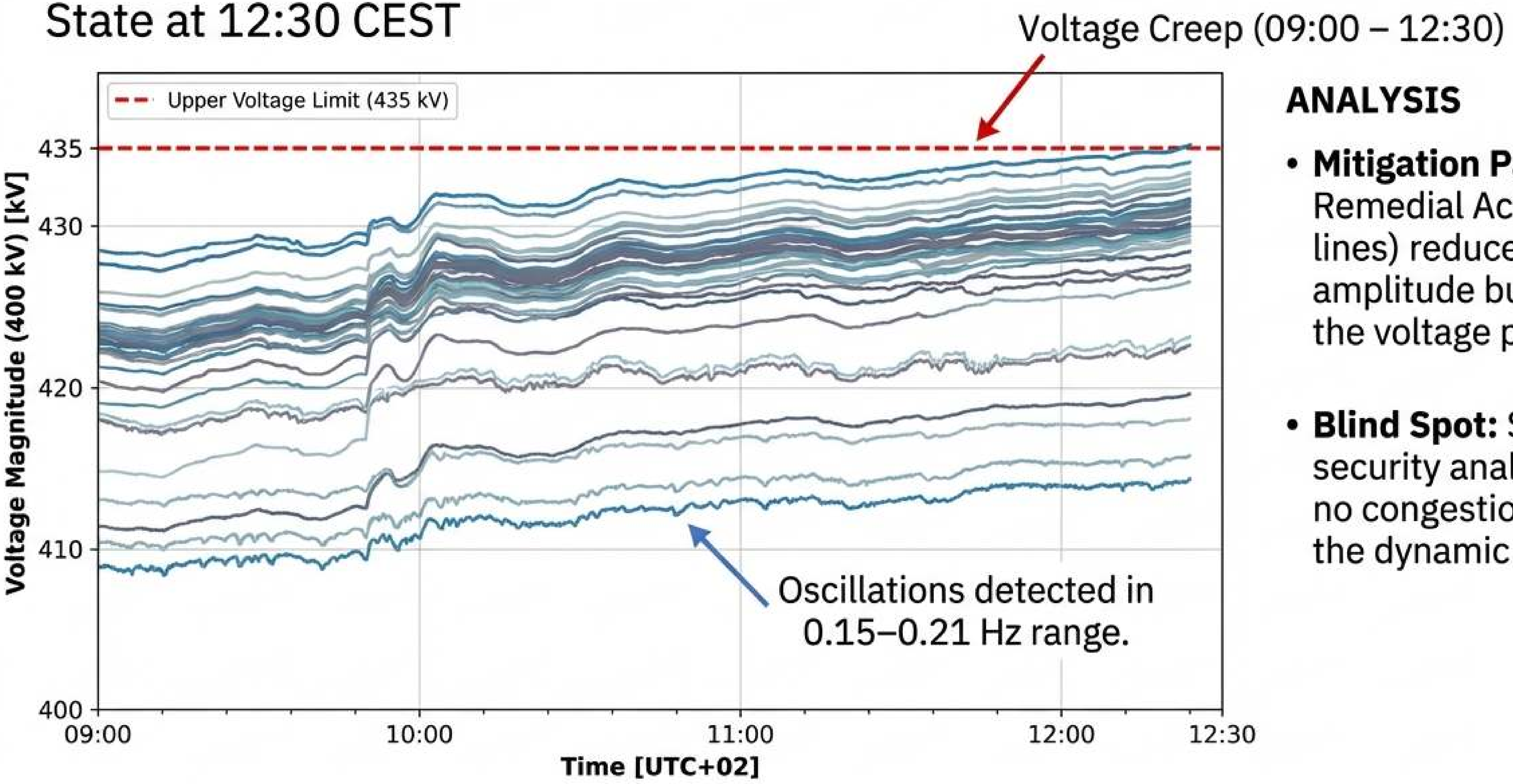
Failure of Damping: Oscillations grow rather than decay.

Failure of Stiffness: Voltage yields to active power shifts.

The system lost its ability to absorb minor shocks. A localized generation loss was not contained; it propagated immediately.

Precursors: Visible Signals of Erosion

State at 12:30 CEST



ANALYSIS

- **Mitigation Paradox:** Remedial Actions (opening lines) reduced oscillation amplitude but increased the voltage profile.
- **Blind Spot:** Standard N-1 security analysis showed no congestions, masking the dynamic degradation.

Mechanisms of Margin Erosion

Operational Actions

- Opening Internal Lines (Topology Change)
- Generators Under-excited (absorbing Reactive Power)

→

Physical Consequences

- Reduced Short-Circuit Strength
- Reduced Dynamic Damping
- Reduced Inertia (Thermal Displacement)

→

System State

- **Brittle Grid**
- Exhausted Reserves
- Susceptible to **Minor Trigger (~317 MW)**

The Cascade: Local Protection, Global Instability

Sequence of Events (12:32:00 – 12:33:18)

12:32:00

Initial **Trigger:** Net load increase / Small Embedded Gen Trip (~317 MW)

12:32:57

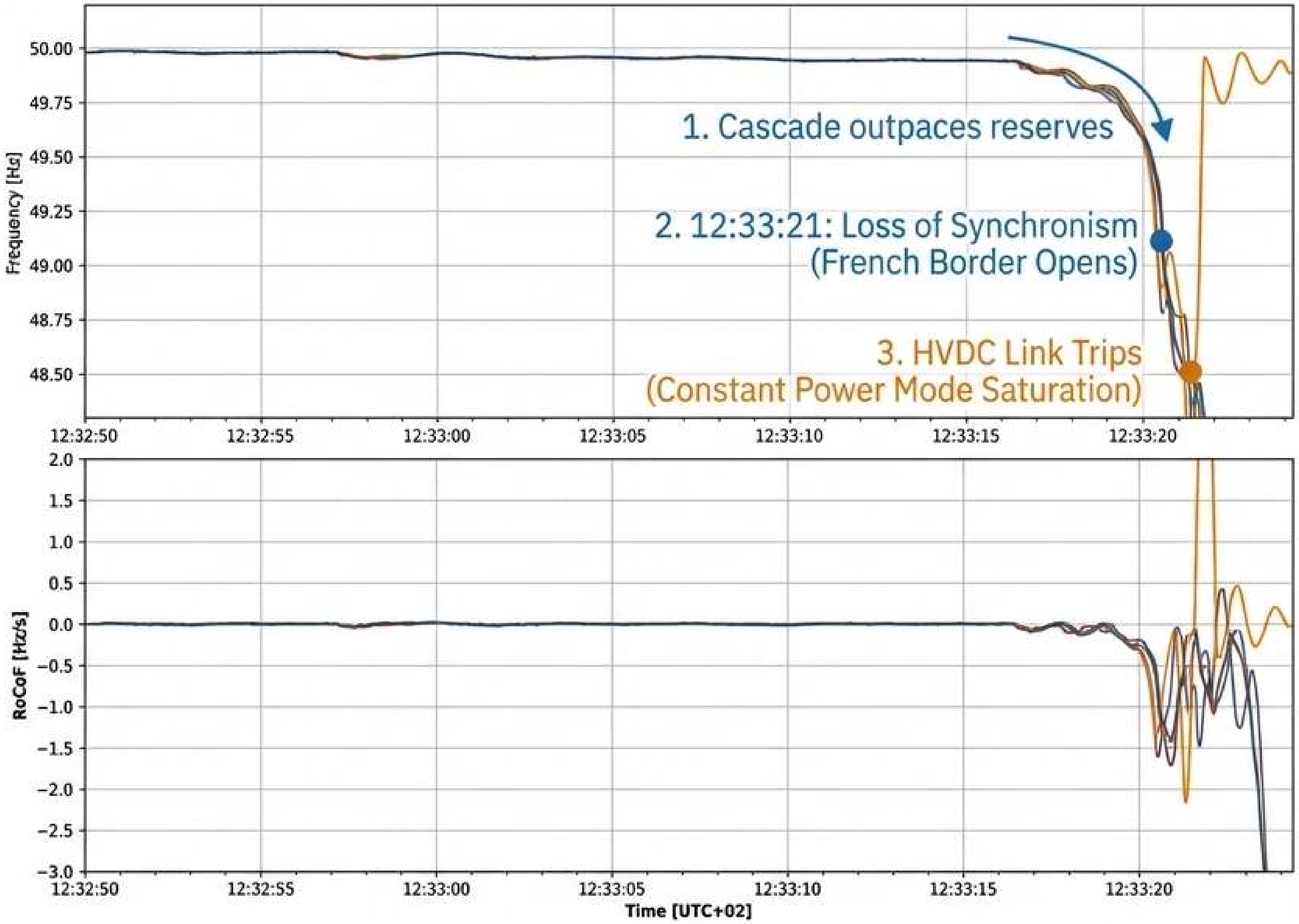
Escalation: 355 MW Trip (PV, Wind, Thermo-solar)

12:33:16 – 12:33:18

Mass Disconnection: >1500 MW Lost
- Granada
- Sevilla
- Badajoz

Voltage instability triggered distributed protection. Over 2 GW disconnected in seconds.

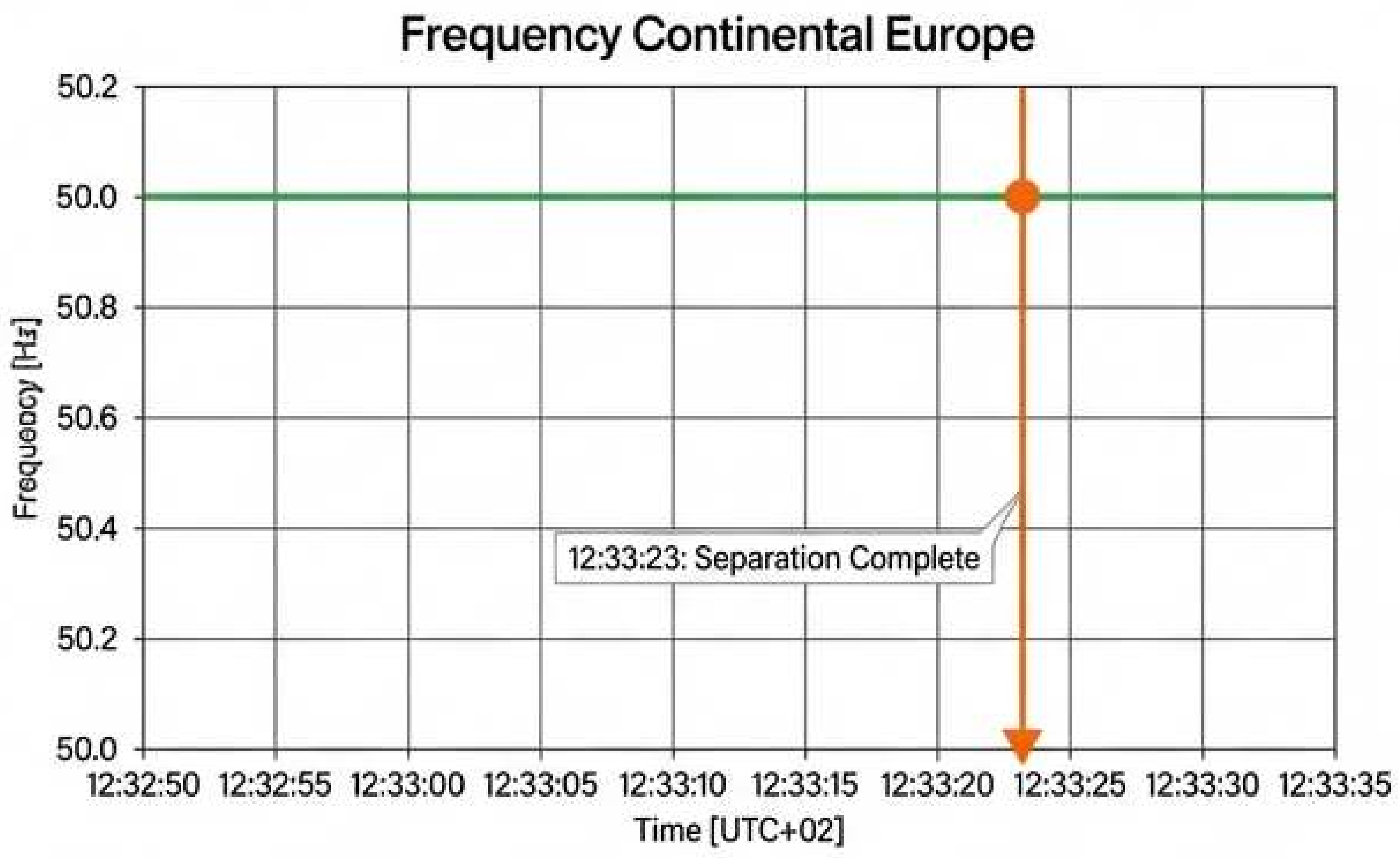
Why Stabilization Failed

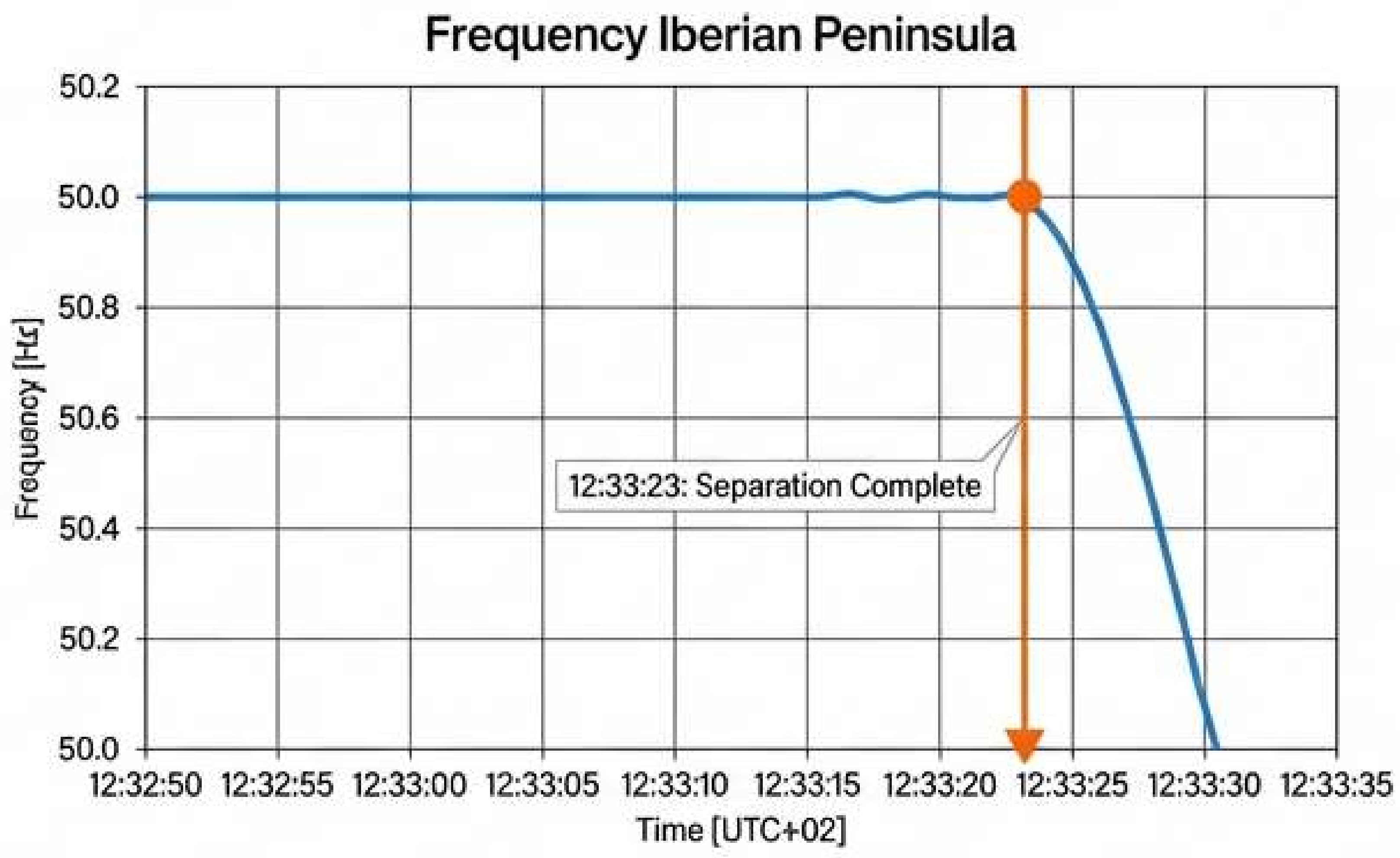


Speed Mismatch: The cascade occurred in seconds, faster than primary frequency containment.

Protection Dominance: Relays operated correctly to isolate the fault, sealing the fate of the peninsula.

System Separation and Collapse





OUTCOME TIMELINE

12:33:23
Total blackout of Spanish and Portuguese transmission systems.

Impact
Suspension of all market activities.

Restoration (Portugal)
Completed 00:22 (Top-down & Bottom-up).

Restoration (Spain)
Completed 04:00 +1 Day

Hidden Risks in Operational Planning

The Blind Spots

	Observation	Hidden Risk
Static vs. Dynamic	Decision to open lines prioritized static voltage limits.	**Eroded** dynamic short-circuit power and **damping**.
Forecast Accuracy	Observation Standard renewable forecasting.	Hidden Risk Underestimation of required inertia for the specific real-time mix.
Tooling Limitations	Observation 'N-1' Security Analysis showed Green.	Hidden Risk Tools measured thermal congestion, not dynamic fragility.

FIGURE 1: FRAGILE GREEN STATUS

Transferable Insights on System Resilience

Non-Linearity

Interconnected systems behave linearly for a long time, then collapse non-linearly when multiple margins (**voltage**, **inertia**, **damping**) erode simultaneously.

Protection as Amplification

Local protection logic (e.g., **PV inverters** tripping on voltage dips) can transform a local disturbance into a **global catastrophe**.

The 'Secure' Illusion

Absence of thermal overloads (**N-1 compliance**) does not guarantee **dynamic stability** in high-renewable, low-inertia environments.

A Closing Reflection

As we optimize our systems for maximum efficiency and renewable penetration, are we inadvertently removing the invisible buffers—damping and inertia—that allow the grid to survive the unexpected?