Elförmörkelsen på Iberiska halvön den 28 april 2025

Iberian Peninsula Blackout – 28 April 2025

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(Engineering HVDC)



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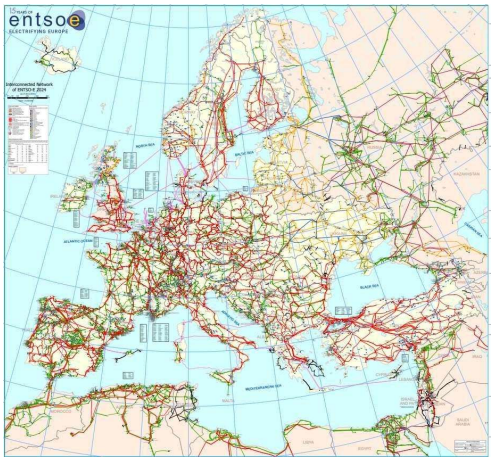
Executive Summary

- Zero voltage event at 12:33:30 on 28 April 2025
- Disconnection from European grid
- Multidisciplinary investigation by Committee 28 (Government in Spain) and ICS Investigation Expert panel (ENTSO-E)
- No cyberattack; Cascading overvoltage



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Two stage investigation

Government in Spain:

- GTOSE: Electrical System Operation
- GTCSD: Cybersecurity & Digital Systems

Report review and investigation by Expert Panel (ICS) by ENTSO-E:

- Factual report 10 November, 2025.
- Recommendations in Final report 20 Mars 2026.

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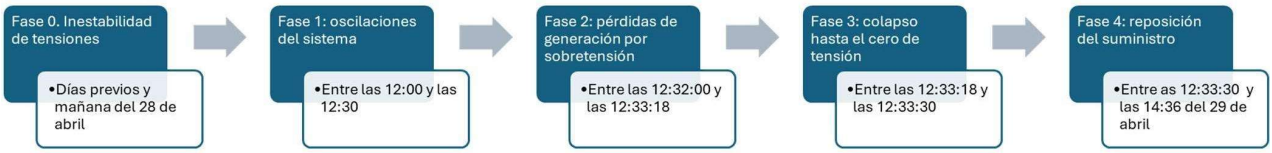
Timeline of Events

- Phase 0: Precursor voltage sensitivity
- Phase 1: Poorly damped oscillations (0.2 Hz & 0.6 Hz)
- Phase 2: Overvoltage-induced generation losses
- Phase 3: System collapse to zero voltage
- Phase 4: Restoration completed by 29 April, 14:36



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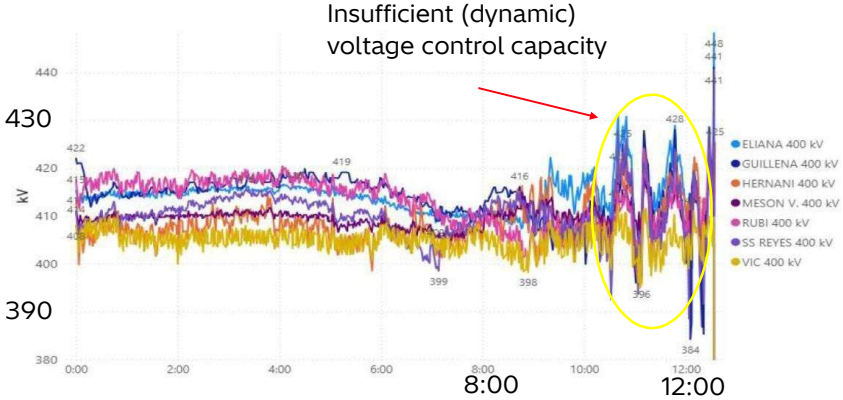
System Conditions on 28 April

- Low demand, high renewable penetration (82%)
- One planned voltage controlling unit out of service

- Voltage sensitive
(• low inertia)
- Limited flexibility for voltage control

Large amplitude voltage variations in short periods of time throughout the morning

Insufficient (dynamic) voltage control capacity



Graph 3 Voltage evolution in the 400 kV network from 00:00 on 28 April. Source: REE

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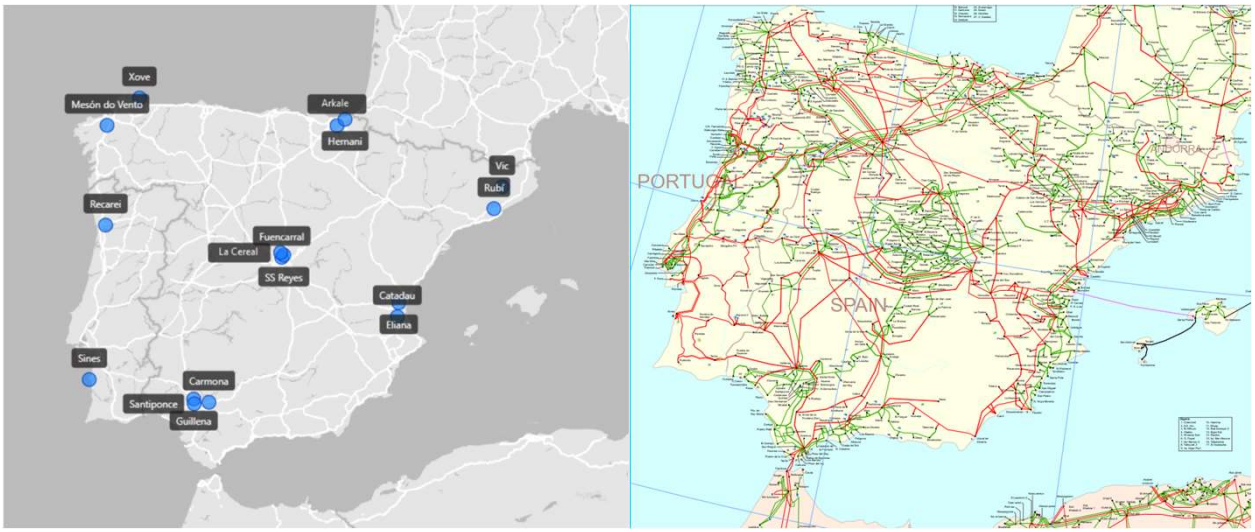

9 **Figure 3 - Location of substations where the voltage was measured.**

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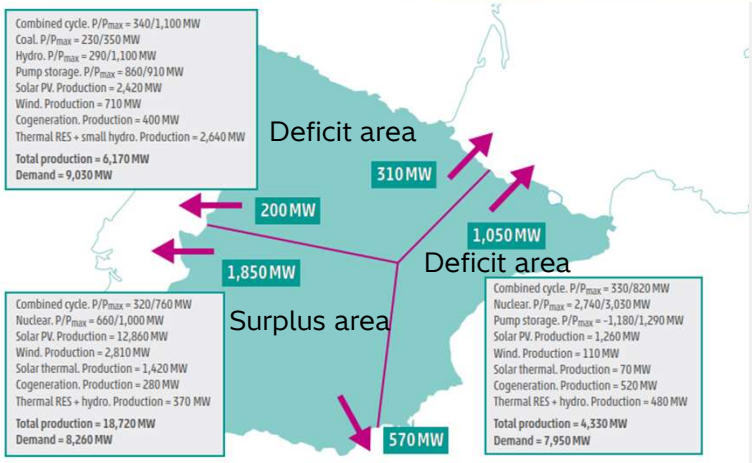
Production and demand in different areas



Factors affecting damping

- Weakly connected groups of generators
- *Power transmission from a smaller to a larger sub-system*
- Voltage regulators
- Damper windings in generators
- Turbine governing
- Loads
- SVC (Static Var Compensation)
- PSS (Power System Stabilizer)
- HVDC – modulation/damping control – effects depends on network location

11 Figure 1-4: Geographic distribution of generation and consumption in Spain at 12:32

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Oscillations before 12:00 and beyond

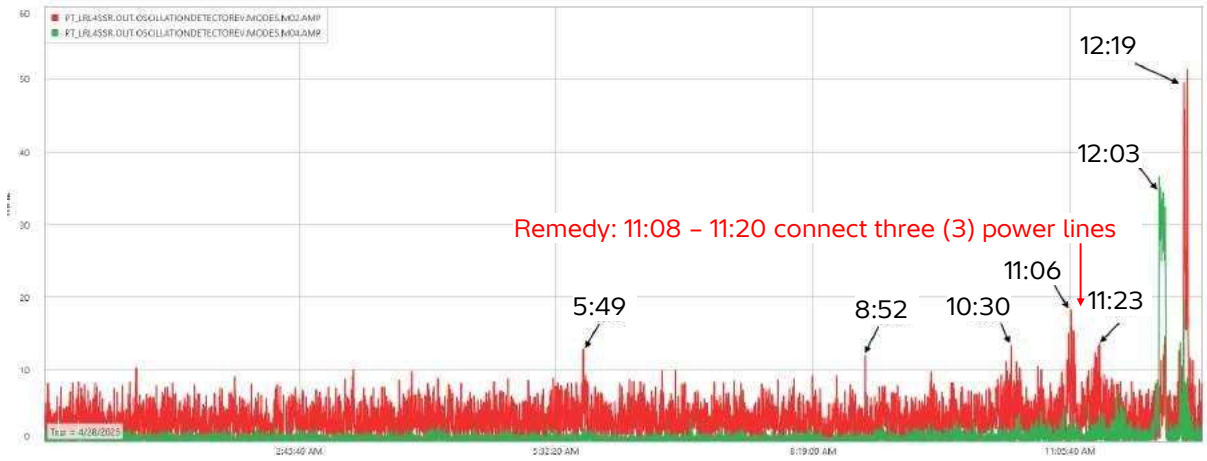

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Figure 6 Oscillations recorded on 28 April, 0.2 Hz (red) and 0.6 Hz (green). Source: REE

Poorly Damped Oscillations and remedies

- 12:03 – 12:08: 0.63 Hz oscillation (local origin). Converter-driven instability phenomenon.
- 12:19 – 12:22: 0.21 Hz East-Center-West mode (inter-area mode)
- To increase damping: *power exchange adjustments, meshing*

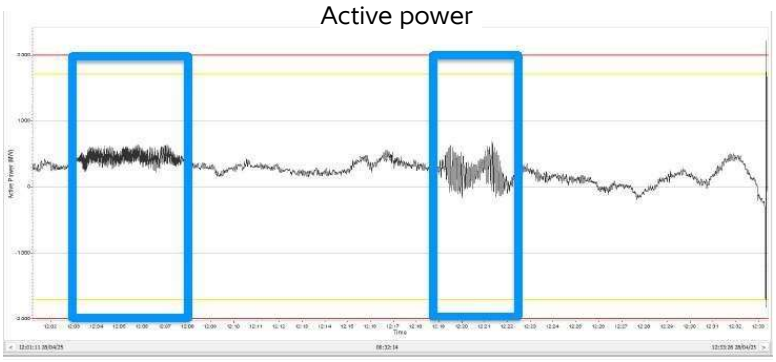

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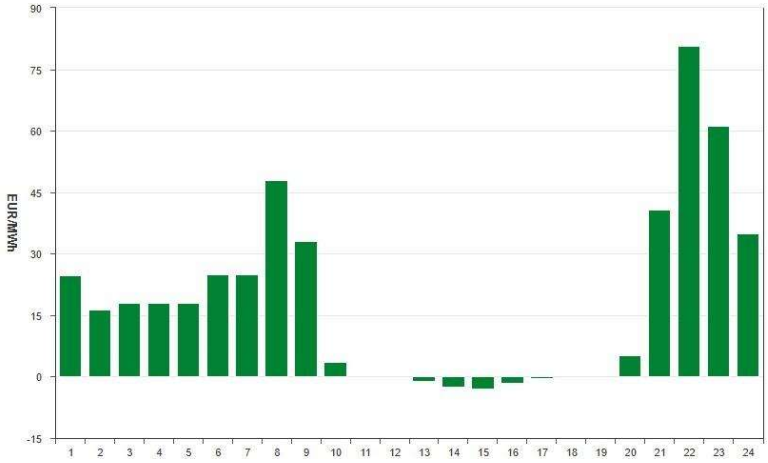
Figure 7 Recorded oscillations between 12:00 and 12:30 on 28 April. Source: REE

To reduce power export - reduction of solar in South due to best price



Poorly damped oscillation remedy: reduce power exchange. In addition, set INELFE HVDC in Pctrl.

Chart 1 Hourly spot market prices (OMIE) on 28 April. Source: OMIT

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First significant oscillation

Remedy: Connect five (5) power lines

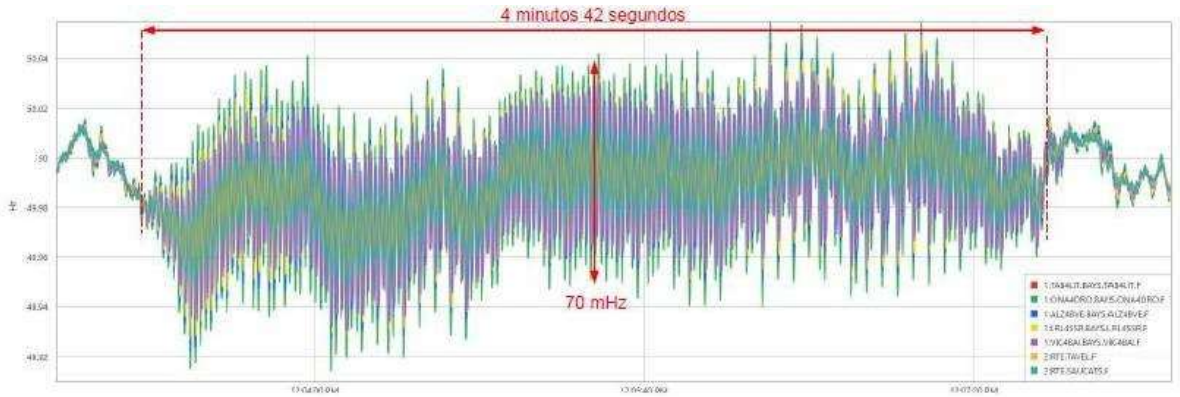

Figure 8 First oscillation (12:03). Source: REE

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Second significant oscillation

Remedy: Connect two (2) power lines and further reduce power exchange



Graph 12 Second oscillation (12:19). Source: REE

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Voltage sags during first oscillation

Remedy: Disconnect four (4) shunt reactors. 12:20 request to connect unit with dynamic voltage control and Power System Stabilizer (PSS) (takes 1:30 hours to connect)

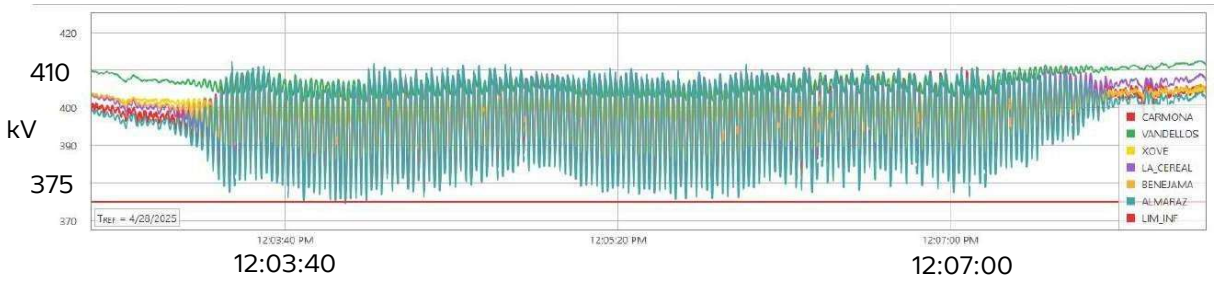

Figure 9 Voltages at the 400 kV nodes during the first oscillation (12:03). Source: REE

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Voltage sags during second oscillation

Remedy: Disconnect additional four (4) shunt reactors

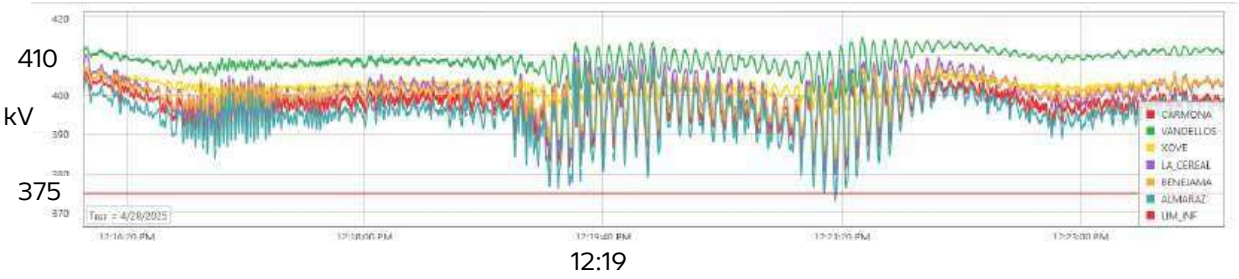

Figure 13 Voltages at 400 kV nodes during the second oscillation (12:19)
Source: REE

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Remedy: 12:26-12:28 connect five (5) shunt reactors

Remedy: 12:04-12:24 connect power lines and disconnect shunt reactors

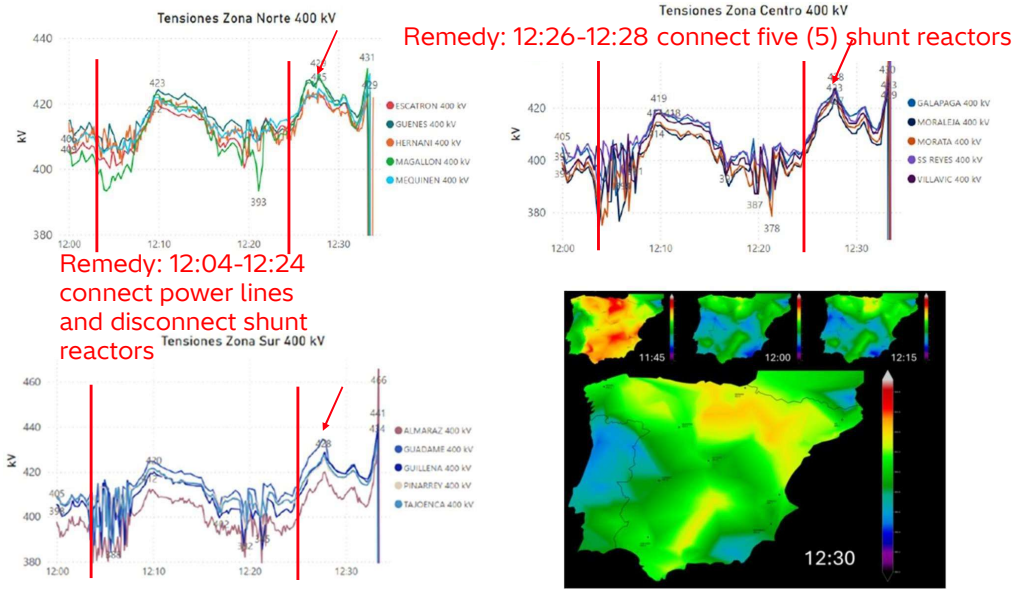

Figure 14 Voltage evolution in the 400kV network between 12:00 and 12:35. Together with heat map between 11:45 and 12:30.
Source: REE

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Loss of small embedded generation units in the distribution network between 11:00-11:10, 12:07-12:15 and 12:25-12:29

...which are re-connected...

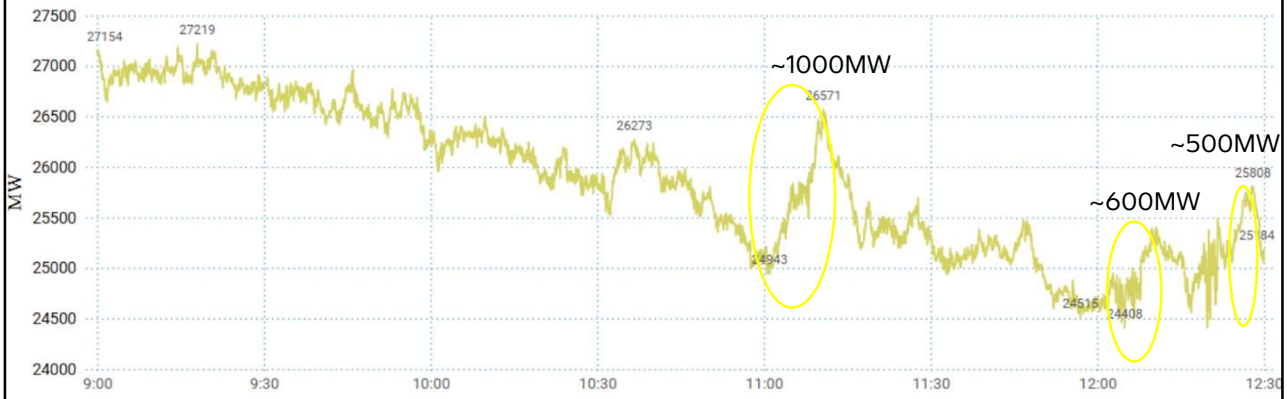

Figure 11. Load supplied by the Spanish grid between 9:00 and 12:30 CEST

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Conditions after oscillations (Phase 1) due to remedies during 11:08 – 12:28

- Ten (10!) more lightly loaded power lines
- Much less power transfer in transmission system
- Five (5) shunt reactors instead of eight (8)
- Still waiting for additional unit with voltage control and PSS to connect

- 50 Hz, still low damping
- more transmission line reactive power surplus and reactive power flows
- Less local reactive power absorption by reactors and generators

More voltage sensitive network with limited flexibility for voltage control

At 12:30, 410 - 420 kV, downward trend, but too late, too high voltages in the distribution system...

30 PSS = Power System Stabilizer

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Overvoltage and Generation Losses (Phase 2)

- Small power generation starts tripping
- Voltage rise from 12:32:00
- Three major generation disconnection events in <30 seconds
- Overvoltage → generation loss → more overvoltage

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Starts with small power generation losses

The 208 MW of generation disconnection identified

Instant	Upstream substation	Lost generation	Technolog
12:32:05,000		2,6	
12:32:09,000		21,6	
12:32:09,000		5,9	
12:32:09,000		4,8	
12:32:09,000		2,9	
12:32:25,000		19,2	
12:32:25,000		3,4	
12:32:29,000		22,4	
12:32:29,000		55,6	
12:32:29,000		2,3	
12:32:45,000		0,6	
12:32:49,000		13,3	
12:32:49,000		1,1	
12:32:53,000		11,9	
12:32:53,000		20,0	
12:32:53,000		4,8	
12:32:53,000		10,0	
12:32:53,000		6,0	

12:32:00 - 12:32:57

Small power generation losses of 525 MW distributed throughout the territory

355 MW from distributed generation <1 MW (power factor controlled).

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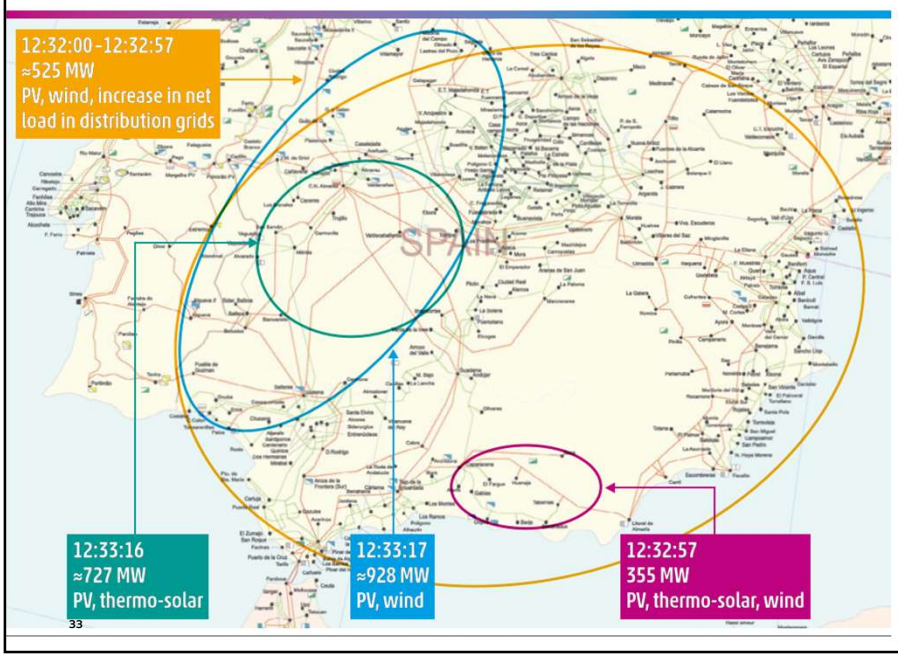

Figure 1-7: Areas of major generation disconnection events in Spain until 12:33:18

Due to activation of Overvoltage protection

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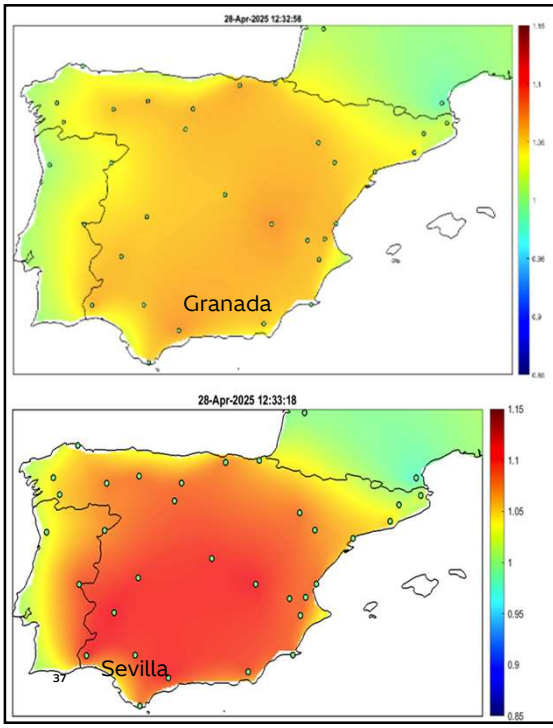

Figures 12a, 12b & 12c – Heat maps of the voltage in the 400 kV network (in p.u.) one second after each of the first three generation trips (source: PMU data from Red Electrica, REN and RTE)

Rapid voltage increase in transmission system due to loss of generation (transmission) and reactive power control

until 12:33:18.020, adding up to more than 2.5 GW in total (FiR)

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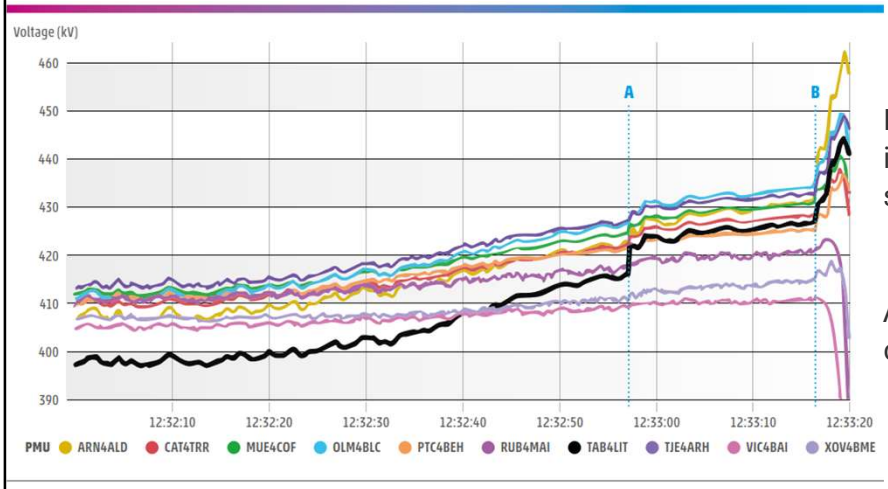

Figure 1-6: Voltage evolution in the Spanish power system after 12:32

A: 12:32:57 tripping of one 400/220 kV transformer

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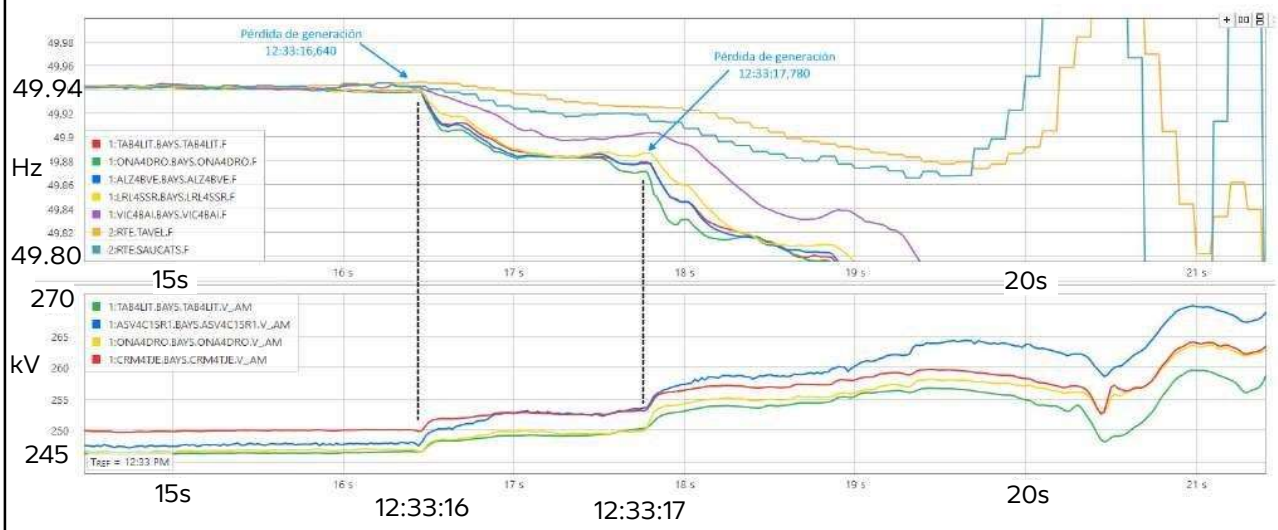

Graph 18 Variation in frequency (above) and voltage (below), indicating the timing of Events 2 and 3.
Source: REE

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Collapse (Phase 3) and restoration (Phase 4)

- Cascade of generation losses due to over-voltages (between 12:33:18 and 12:33:21)
- Rapid angle increase and loss of synchronism between Spain and France around 12:33:19
- Full system collapse by 12:33:30

- Blackstart and restoration via France, Morocco, hydro
- 99.95% restored by 07:00 on 29 April

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Cybersecurity Findings

- No evidence of cyberattack
- Risks: weak authentication, weak segmentation, outdated systems, poor logging

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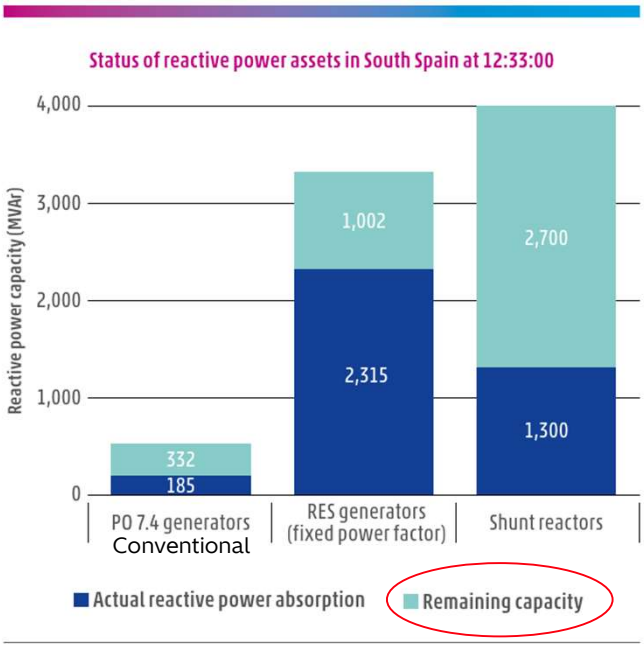
Root Causes

- Insufficient dynamic voltage control
- Inadequate local reactive power absorption
- Countermeasures to increase oscillation damping amplified the inadequacy

Led to overvoltage → generation loss → more overvoltage → collapse



[42] Figure 1-12: Capacity of the different categories of reactive power assets in South Spain at 12:33:00

Proposed Measures

- Voltage and reactive power assessment
- Regulatory: Implementation of the new voltage control service regulated in operation procedure 7.4.
- Harmonised voltage range in ENTSO-E, i.e. also for Spain: 380 – 420kV.
- Inter-area oscillations mitigation, FACTS, PSS/POD, including monitoring and detection (PMUs)
- High-voltage ride-through requirement for Type A power-generating modules

- TSO/DSO/PGM monitoring and data governance
- ENTSO-E common grid model
- Black-start and island-mode real tests

[43]

Q/A

45

Power oscillation versus voltage

Factors affecting damping

- *Weakly connected groups of generators*
- *Power transmission from a smaller to a larger sub-system*
- Voltage regulators
- Damper windings in generators
- *Generators absorbing reactive power*
- Turbine governing
- Loads
- SVC (Static Var Compensation)
- PSS (Power System Stabilizer)
- *HVDC – modulation/damping control – effects depends on network location*

Factors increasing voltage

- *Connection of power lines*
- *Lightly loaded power lines*
- Local reactive power surplus
- Loss of reactive power absorption (e.g. power generation trips and/or disconnection of shunt reactors)
- Generators with limited reactive power absorption
- Tap-changers
- Loads: type, voltage dependence and dynamic properties
    - HVDC - constant power “load”

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Transformer tap-changer and load influence

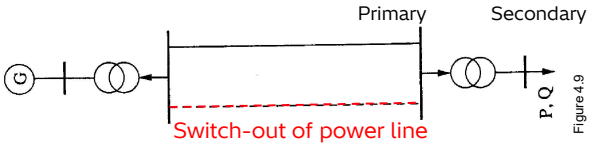


Figure 4.9

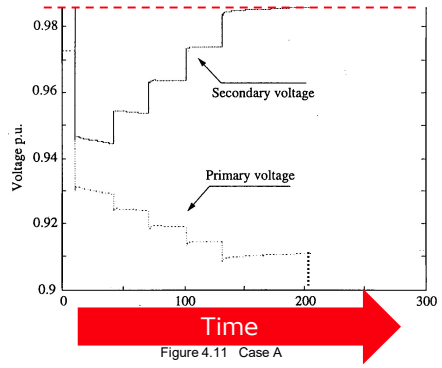


Figure 4.11 Case A

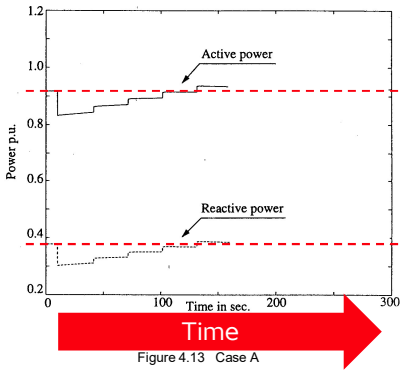


Figure 4.13 Case A

Cascaded transformers with tap-changer can also give overshoots

Time direction for **voltage step decrease** in transmisson system (primary voltage)

47 Picture/Figure from Stefan Johansson, Fredrik Sjögren Voltage Collapse in Power Systems, Chalmers, No 192L, 1995

47

Transformer tap-changer and load influence

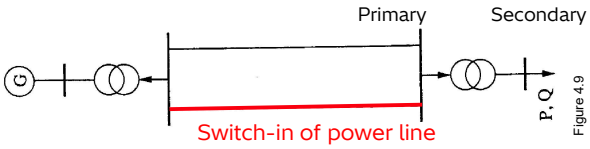


Figure 4.9

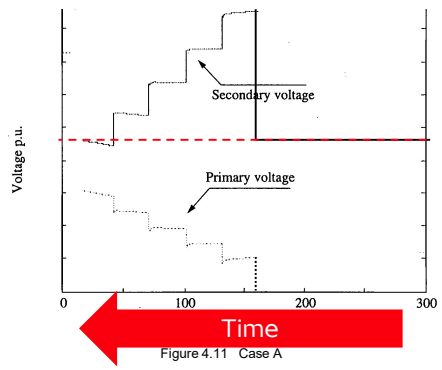


Figure 4.11 Case A

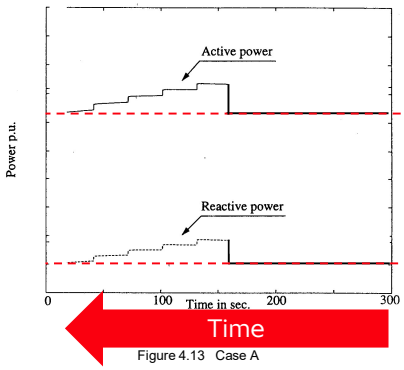


Figure 4.13 Case A

Cascaded transformers with tap-changer can also give undershoots

Time direction for **voltage step increase** in transmisson system (primary voltage)

48 Using picture/figure from Stefan Johansson, Fredrik Sjögren Voltage Collapse in Power Systems, Chalmers, No 192L, 1995

48

Post-incident network simulations and analysis

"The simulations demonstrated that, at the time of the incident, the voltage of the Spanish power system was sensitive to any variations – whether related to exchanges with Portugal, France or Morocco, TSO-to-DSO flows, or generation – resulting in significant voltage fluctuations."

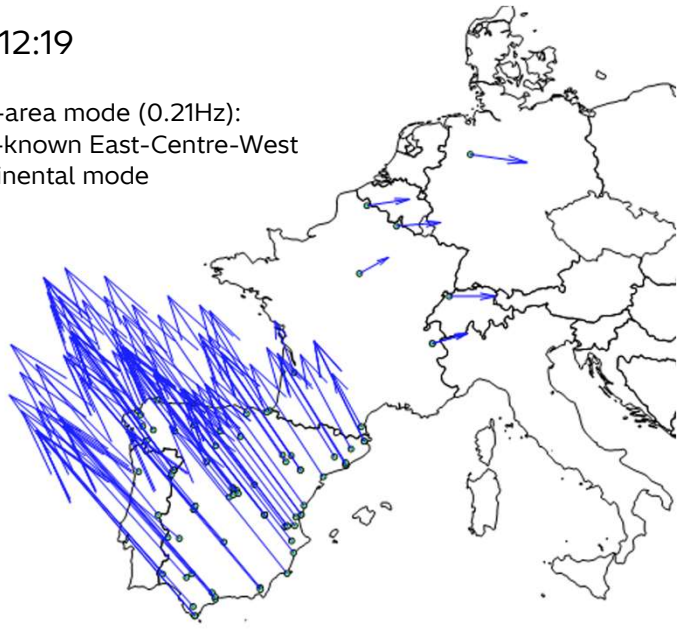
"The analyses clearly indicate that the key phenomenon in the incident was the non-effectiveness of voltage control within the Spanish power system. Simulations show that increased reactive power margins could have prevented system collapse, enabling it to operate at lower voltage levels and maintain overall system stability."

"The remedial actions taken within the control rooms (coupling and decoupling of reactors, opening and closing of lines, setting HVDC voltage setpoints) were effective in bringing the voltage back under the alarm threshold within minutes in most cases (typically less than 5 minutes). In the last overvoltage episode that preceded the system collapse, Red Eléctrica's dispatchers were unable to implement manual remedial actions due to the rapid development of the incident."

49 Qoutes from" Final Report on the Grid Incident in Spain and Portugal on 28 April 2025", ICS investigation Expert panel, ENTSO-E, 2026

At 12:19

Inter-area mode (0.21Hz):
Well-known East-Centre-West Continental mode



Remedies:

Reduce the exchange with France

Reduce the exchange with Portugal

Connecting two other 400kV circuit

Figure 8 – mode shapes of the second oscillation (source : WAMS measurements of Red Eléctrica, REN and other Continental Europe TSOs)