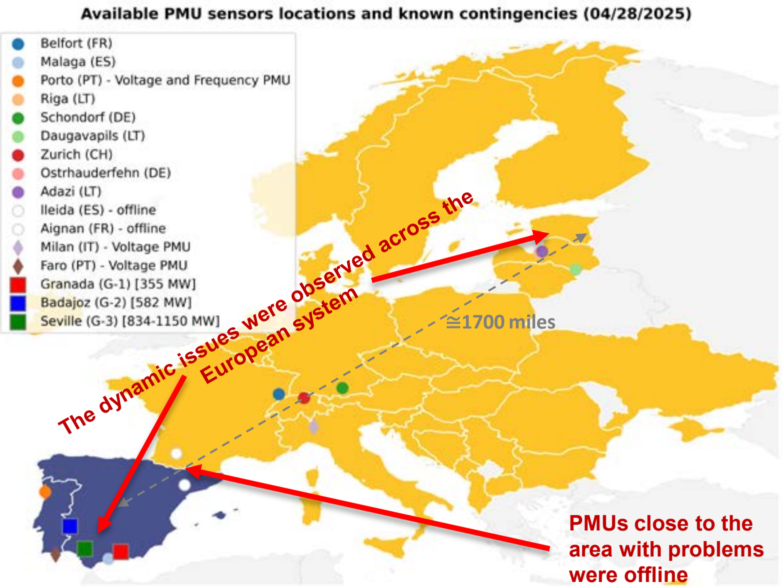
NREL

April 28th 2025 Iberian Blackout: Analysis of available information

Jose Daniel Lara, Ben Kroposki, Tarek Elgindy, Rodrigo Henriquez-Auba, Jarrad Wright

April 28th 2025
Spanish Blackout Analysis Preliminaries

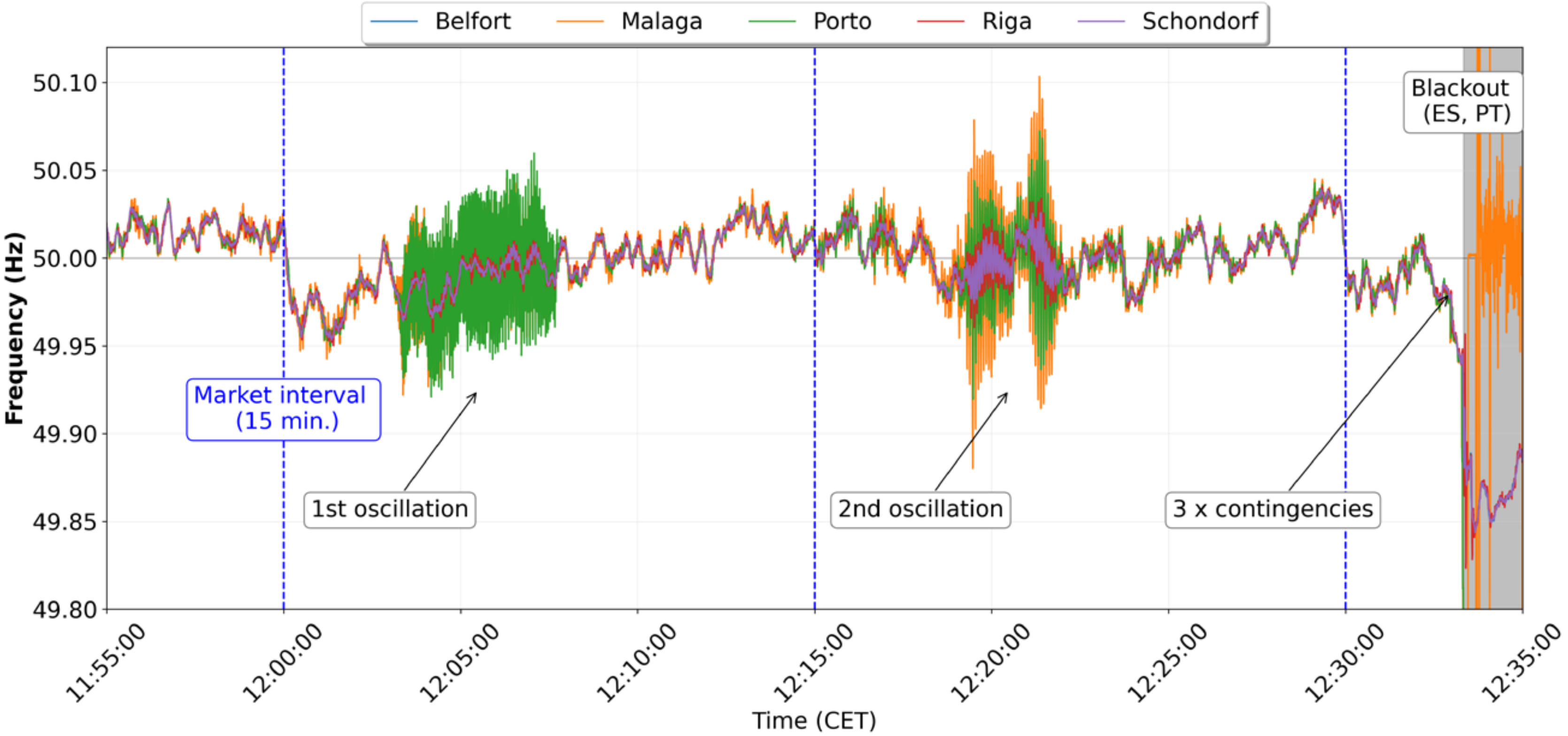
- There are ample figures from the Spanish Operator and ENTSO-E reports included in the report, however official measurements from the operators have not been made available to the public or research community. The official report has been published the Spanish government[1].
- The analysis are based on the following available measurement data for independent analysis:
  - Frequency data for a 2-hour window at the available PMU locations across Europe.
  - Voltage data for for a 2-hour window at near PMU locations in Portugal and Italy.



The findings and statements in this presentation are classified depending on the level of confidence given the available data

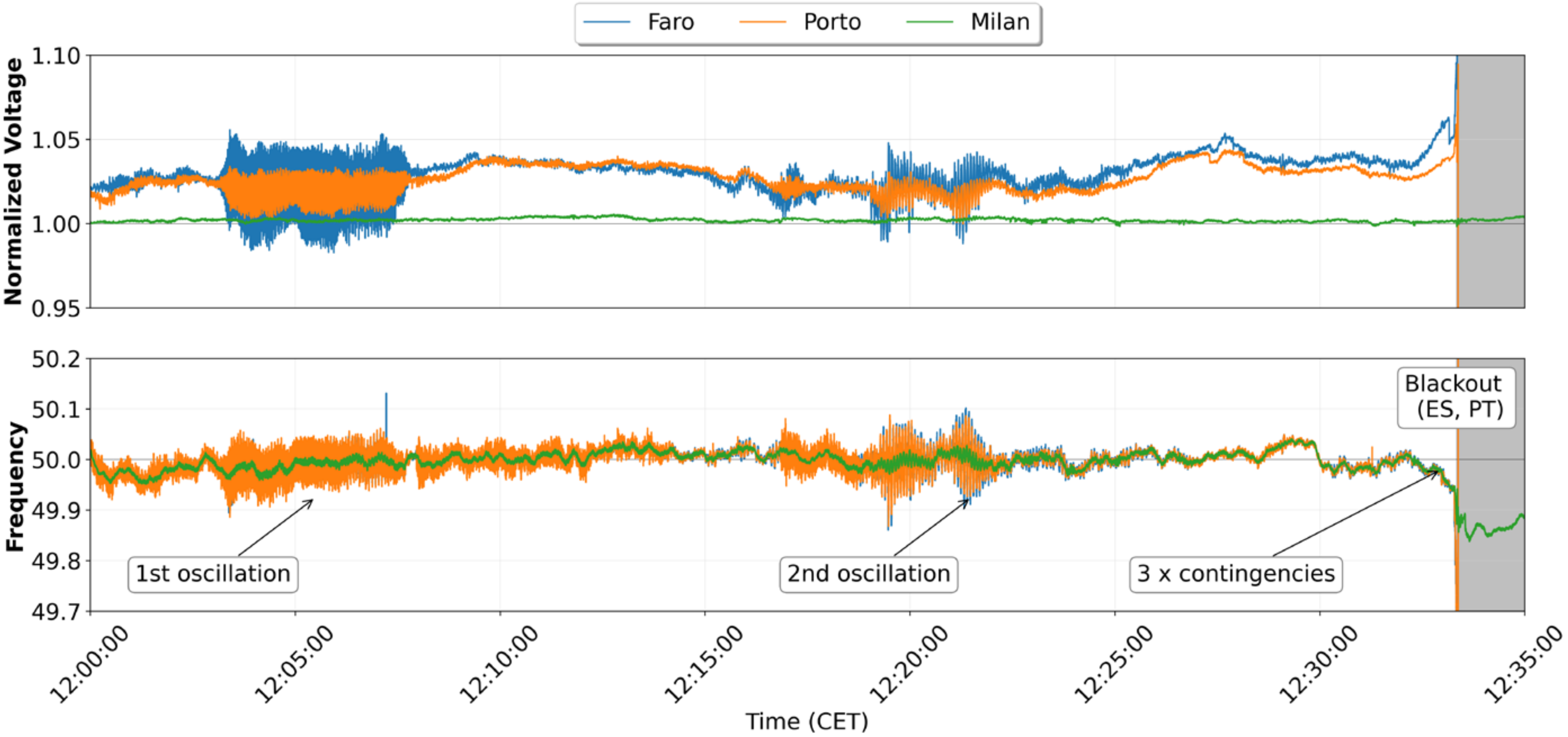
[1]https://www.lamoncloa.gob.es/consejodeministros/resumenes/Documents/2025/Informe-no-confidencial-Comite-de-analisis-28A.pdf

April 28th 2025 Spanish Blackout Analysis Timeline at a Glance



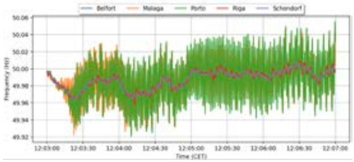
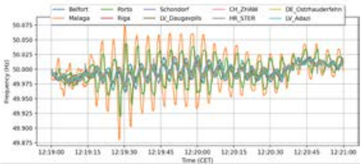
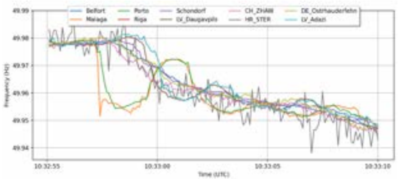
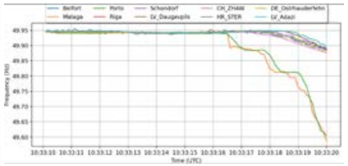
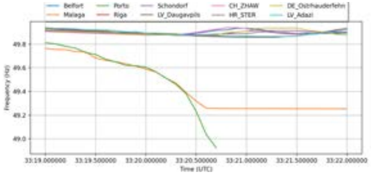
Sources: grid-radar (data), NREL (plots)

April 28th 2025
Spanish Blackout Analysis Timeline at a Glance



Sources: INESC – BR (data), NREL (plots)

April 28th 2025
Spanish Blackout Analysis Timeline at a Glance

12:03 – 12:07

First Oscillation

Low frequency ~0.2 and ~0.6 Hz. 0.6 Hz is dominant.

12:19 –12:21

Second Oscillation

Low frequency ~0.6 and ~0.2 Hz. 0.2 Hz is dominant.

ENTSO-E reported that corrective actions took place to dampen the oscillations.
~~There is no information about which actions were taken~~

~12 Minutes

12:32:57

First Gen Trip

Loss of Generation in Spain. No generation trips were observed in Portugal and France.

12:33:16/12:33:18

Second/Third Gen Trip

Two more generation trips in the span of 2 seconds

12:33:20

Iberia Islanding

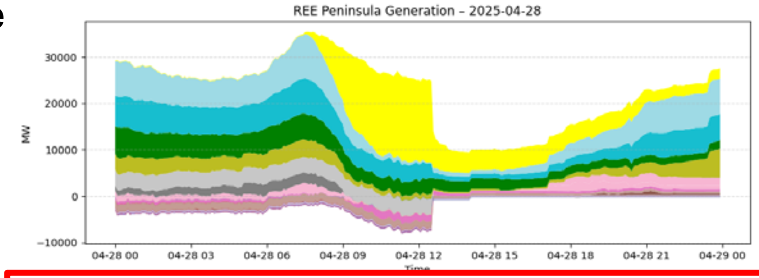
Iberia disconnects; load shedding mechanisms activate but insufficient

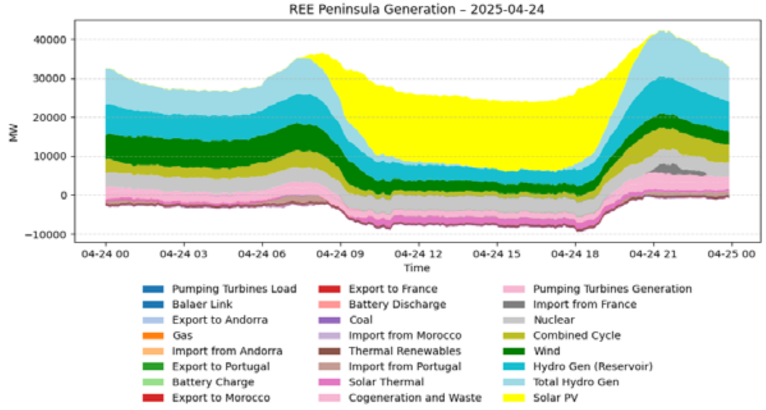
12:33:24

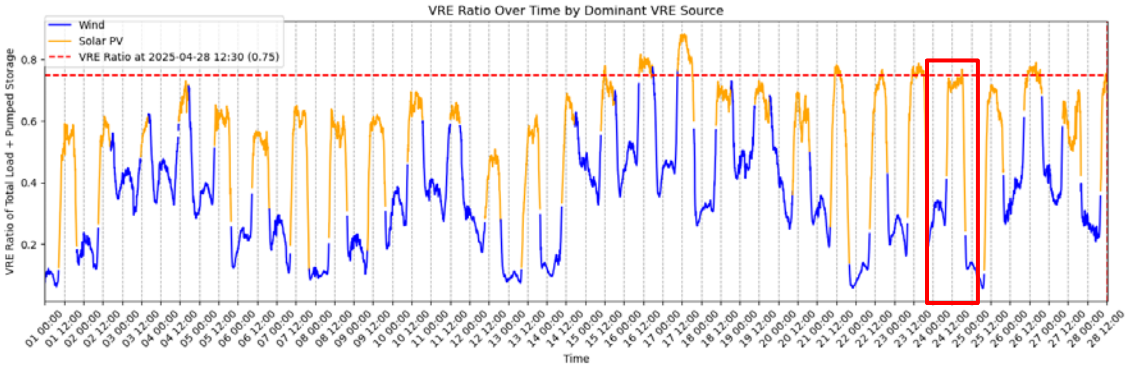
Source: https://www.entsoe.eu/news/2025/05/09/entso-e-expert-panel-initiates-the-investigation-into-the-causes-of-iberian-blackout/

Spanish System Operations on April 28th 2025

- Spain operated with similar shares of VRE during the blackout as it did days prior to the event.
- The total participation of renewable energy was similar through out the month of April as a share of the load plus the hydro pump demand[1].
- Inertia levels reported by the Operator were 2.3 seconds, a value higher than the 2 seconds floor set by the European Operator



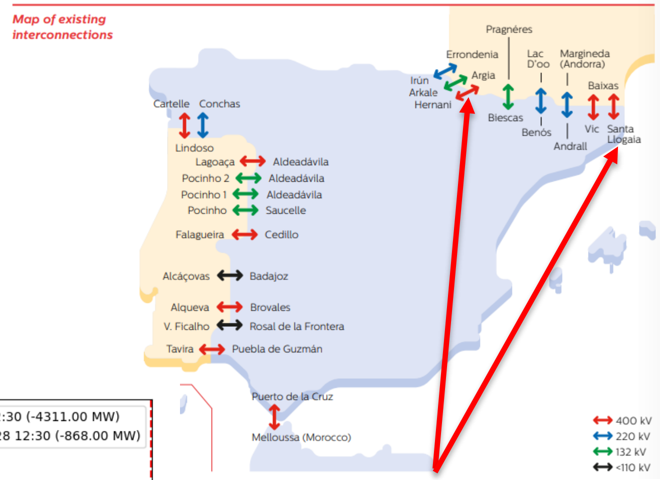




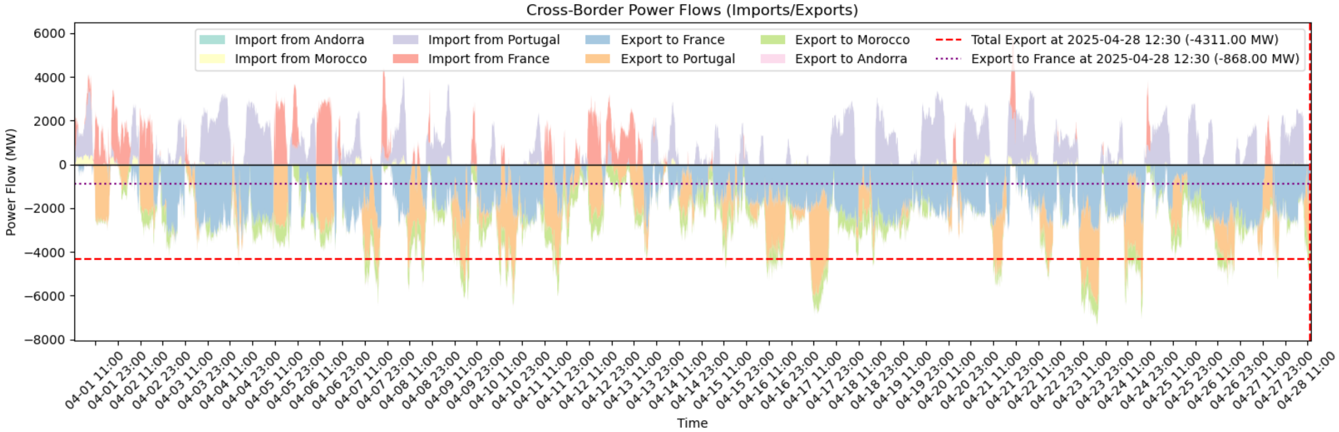
1.Data obtained from Red Electrica API Portal

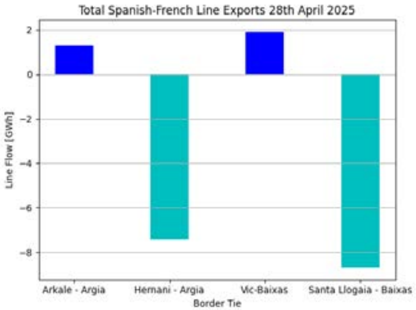
Spanish System Operations on April 28th 2025

- Spain was exporting large amounts of power to France during the blackout at an interconnection that experienced technical challenges before[1].
- The exporting amount were not outside the normal export totals between Spain and France during April[1].
- In 2016 the Iberian peninsula started oscillating with CE Europe after a line trip in France while exporting 2200 MW to the center of the system[2].



Reported Exporting Lines

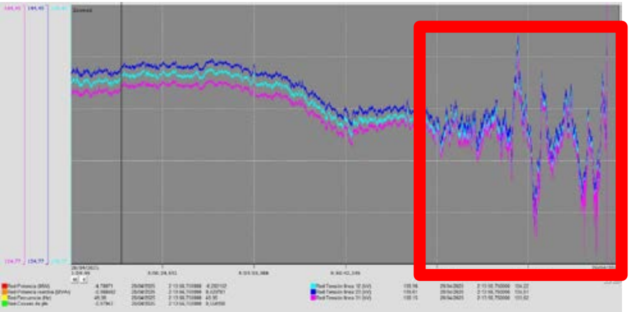


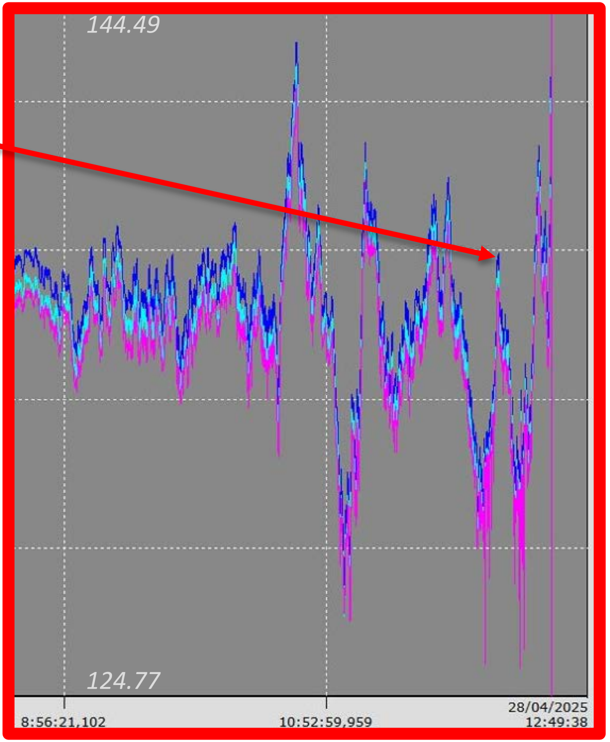


1. Data obtained from Red Electrica API Portal
2. CIGRE Report: Inter-area oscillations in the Continental European power system: events analysis and countermeasures. 2020

Voltage Fluctuations in Cuenca Spain

Approximate initial time the existing event data is available





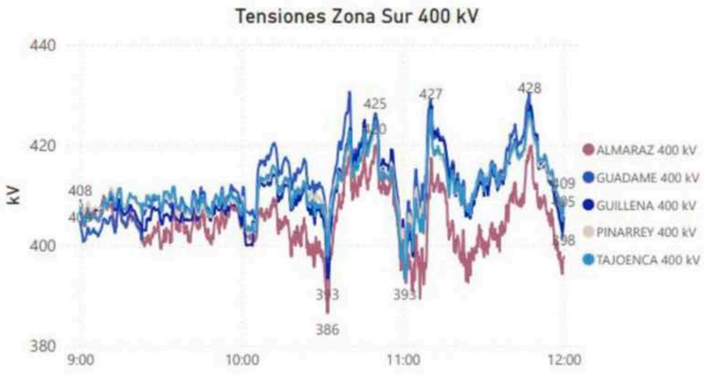
Source: Jorge Gonzalez Sanchez: https://www.linkedin.com/posts/jorge-antonio-gonz%C3%A1lez-s%C3%A1nchez-65396844_apagaejn-postapagaejn-activity-7324734553607012352-rw9Z/

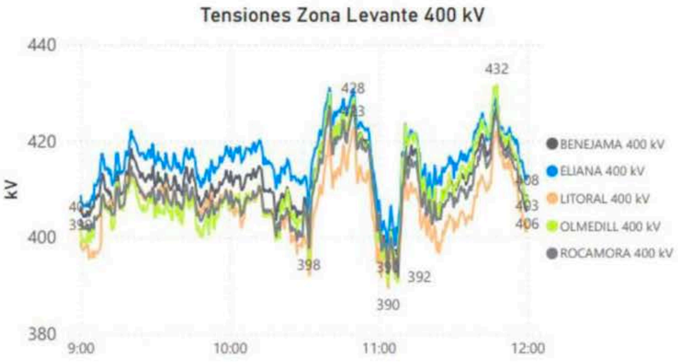
https://www.miteco.gob.es/es/prensa/ultimas-noticias/2025/junio/se-presenta-el-informe-del-comite-de-analisis-de-la-crisis-elect.html

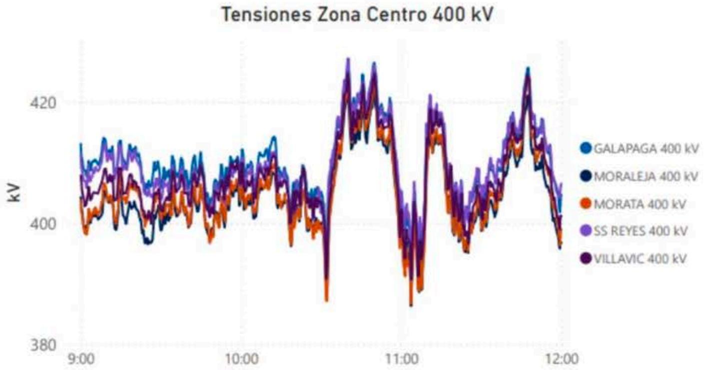
Measurements from a power quality analyzer located 150km east of Madrid, Spain have been shared online and display ~15 kV (11%) voltage fluctuations ~2 hours before the event start.

It is confirmed that the Spanish grid experienced voltage fluctuations in strained transmission corridors, validating prior measurements shared online..

Voltage Fluctuations in Spain as shown in the official reports[1]







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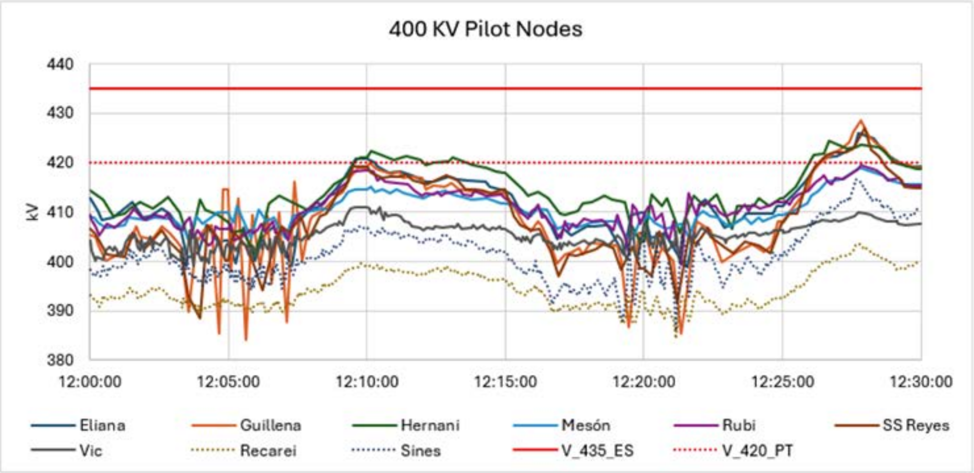
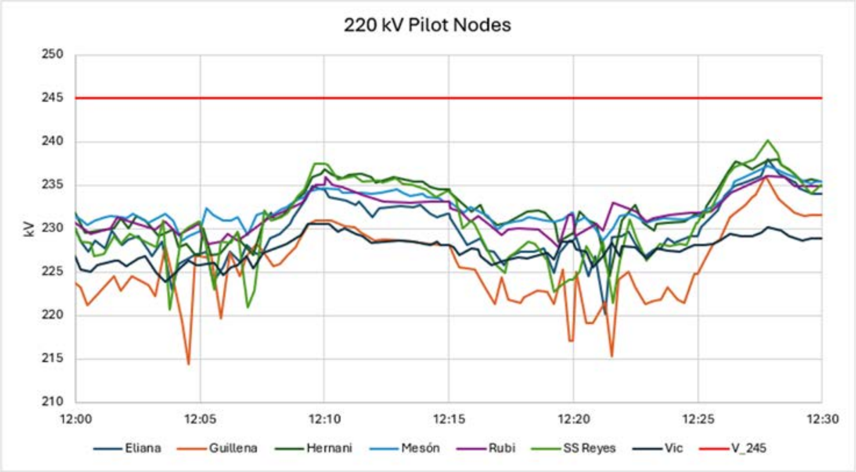
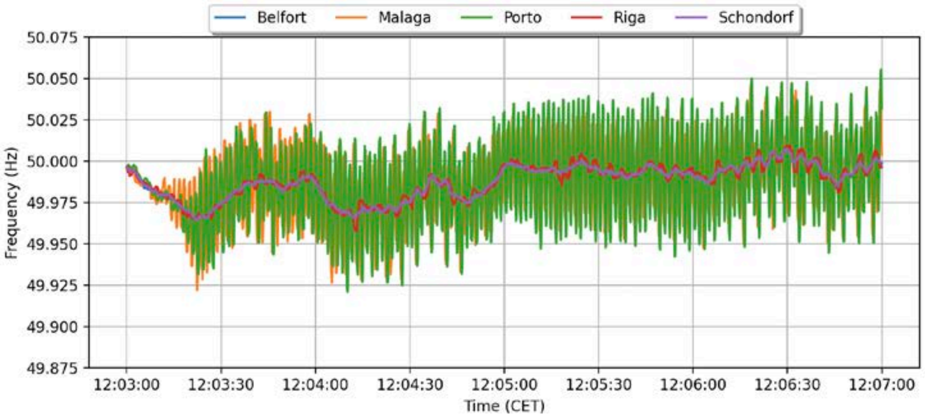


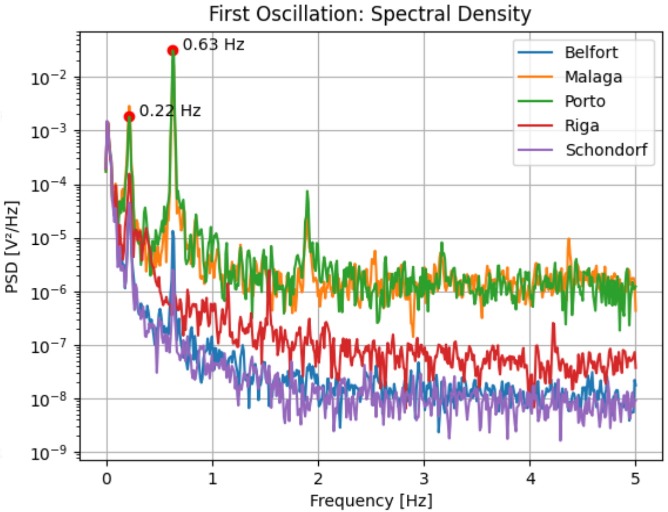


[1]Sources: https://www.entsoe.eu/publications/blackout/28-april-2025-iberian-blackout/

First Oscillation 12:03 – 12:07

12:03 – 12:07





First Oscillation

Low frequency ~0.2 and ~0.6 Hz. 0.6 Hz is dominant.

- Iberias's grid frequency started to oscillate against Latvia's frequency at ~0.6Hz, the oscillation went for 4 minutes.
- The oscillations show a phase difference between ES and PT.
- Relationship between renewable energy and the oscillations is unclear.

First Oscillation 12:03 – 12:07

12:03 – 12:07

First Oscillation

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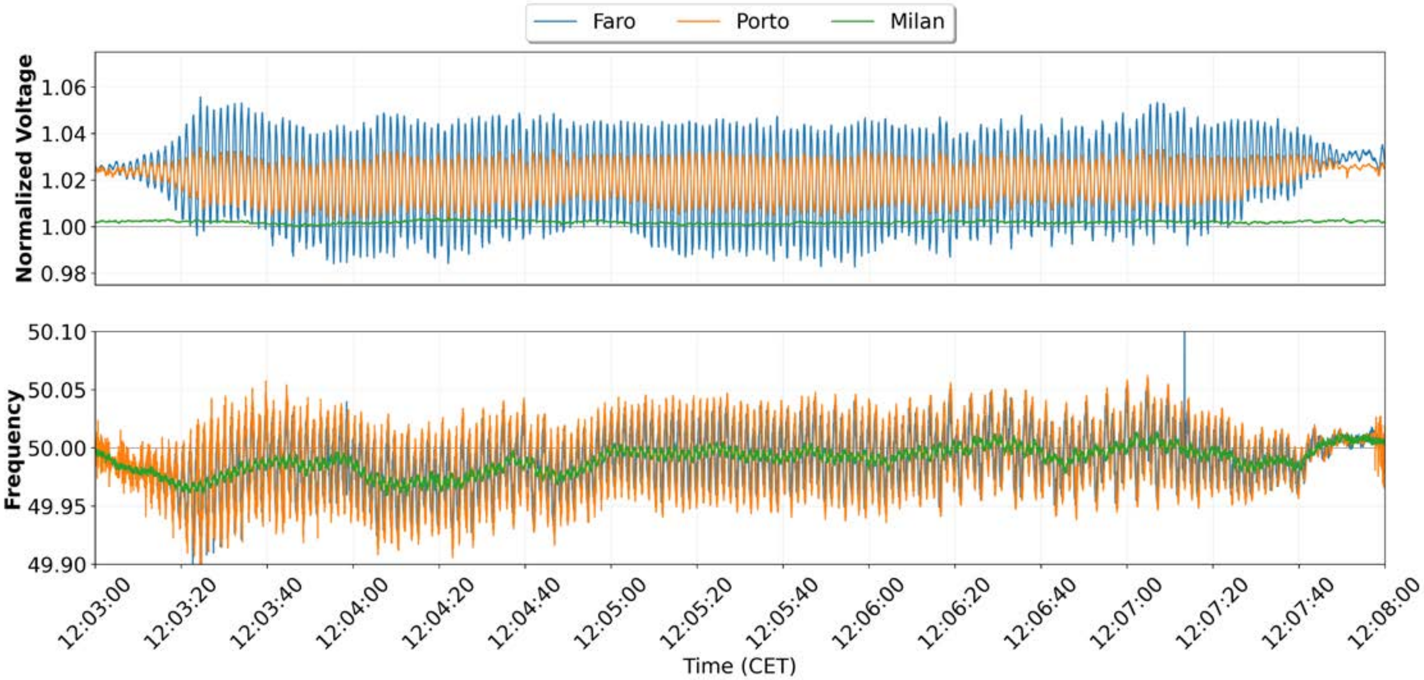
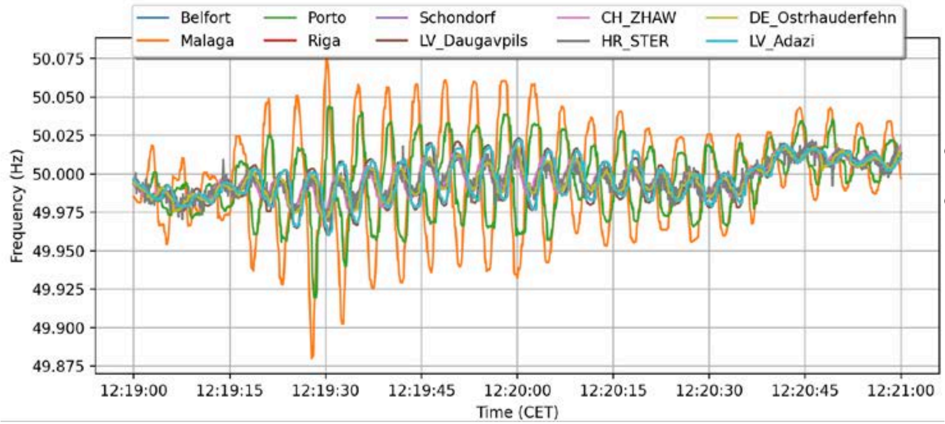
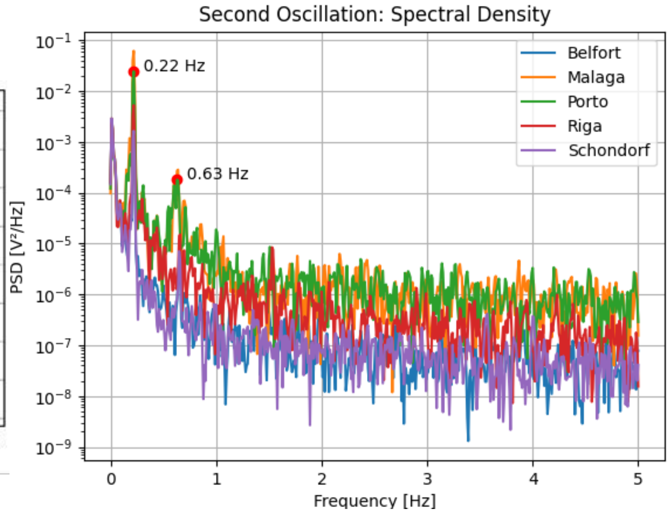


- The Voltage oscillations only manifested locally in Portugal and Spain.

Sources: INESC – BR (data), NREL (plots)

Second Oscillation 12:19 – 12:21





12:19 – 12:21

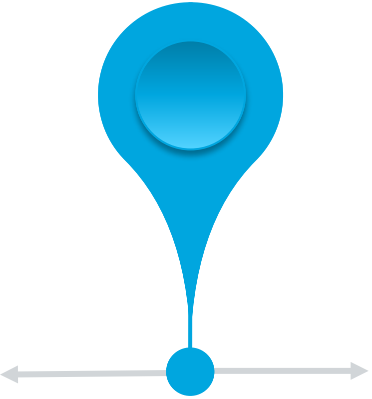
Second Oscillation

Low frequency ~0.6 and ~0.2 Hz. 0.2 Hz is dominant.

- Second oscillation under similar conditions as previous events in 2016 with a 0.2 Hz dominating frequency.
- Iberia is in phase and 180 degrees out of phase from the rest of Europe similar to the 2016 oscillation.

Second Oscillation 12:19 – 12:21

12:19 – 12:21



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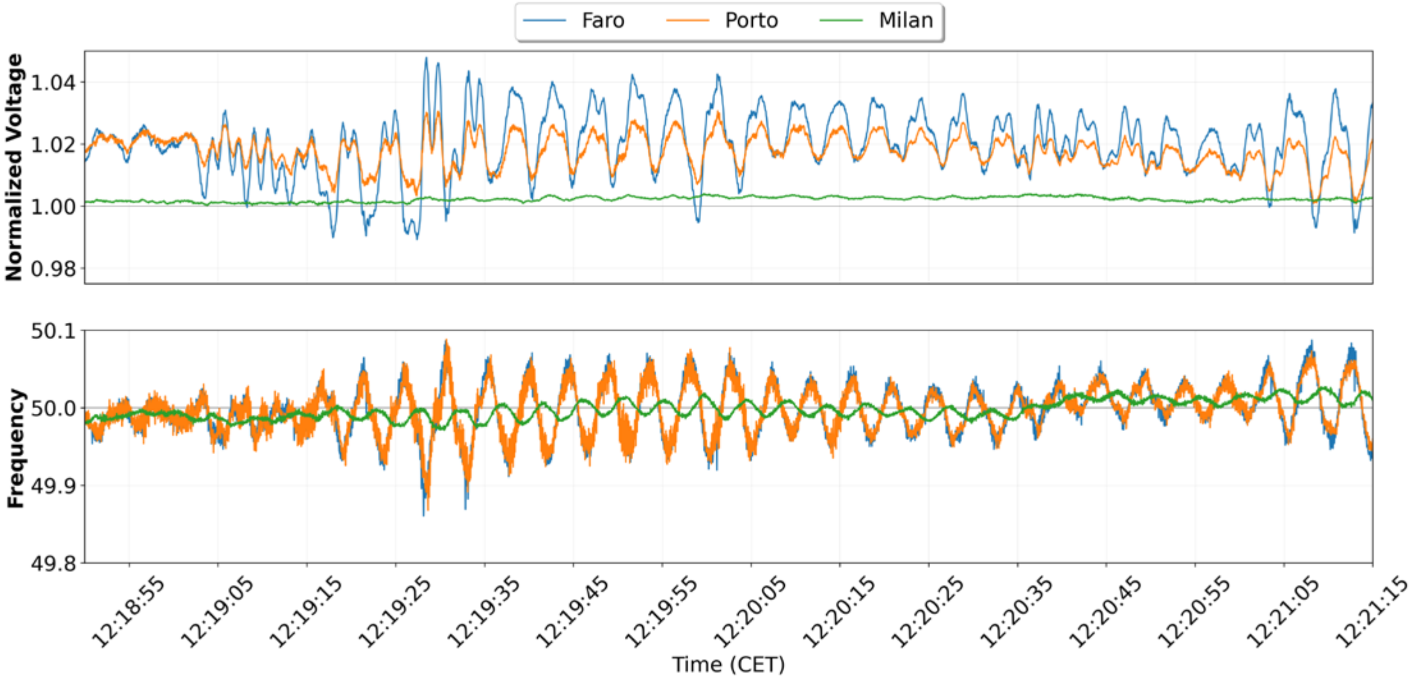
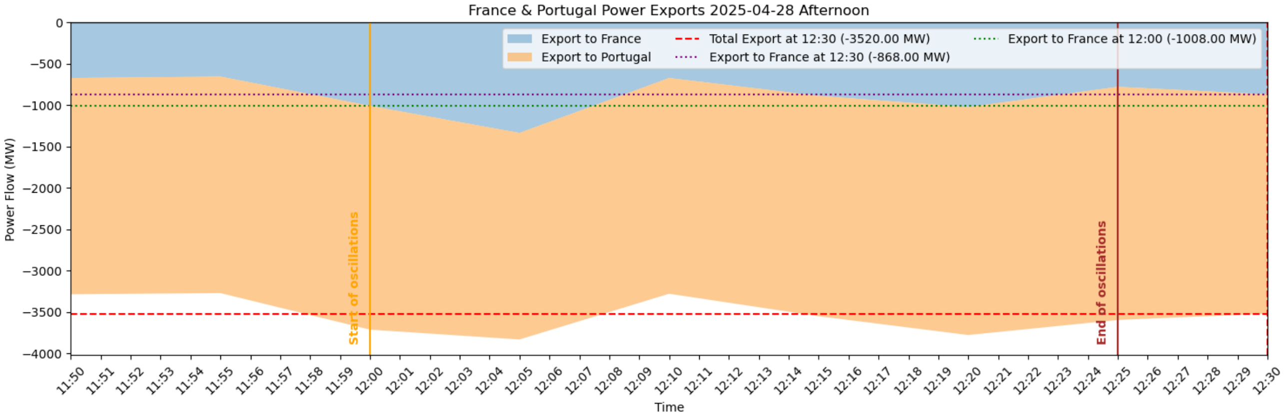


- The operator started reducing exports and attempted to bring another synchronous generator online. The oscillations in 400 kV system in Spain registered ~30 kV fluctuations.

Sources: INESC – BR (data), NREL (plots)

Interconnection changes during the oscillations

- On 1st December 2016 at 11:18 am CET in the French system, the circuit breaker in substation Cantegrit 400 kV Argia bay opened unexpectedly causing the opening of the 400 kV line Argia-Cantegrit which triggered an oscillation when the system was:
  - Exporting power from the Southwestern part to the center of the system
  - France was in a net importing position from the Iberian peninsula.
- In 2016, the Spanish and French operators agreed on reducing the Spain to France exchange from scheduled 2250 MW to 1000 MW to restore N-1 security. The oscillations were completely damped three minutes after this measure.
- On 28 April 2025, at 12:07 the planned interconnection flow gets reduced from 1500 MW to 800 MW to alleviate the oscillations.



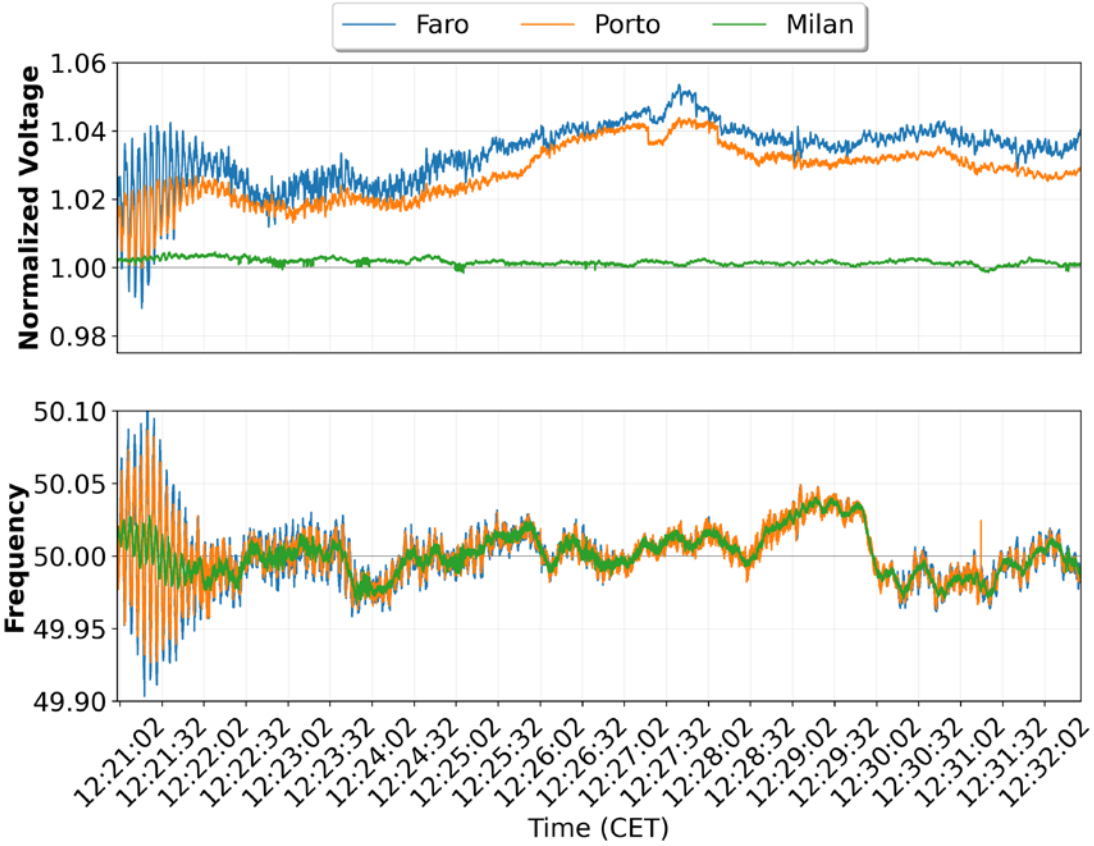
1.Data obtained from Red Electrica API Portal
2. CIGRE Report: Inter-area oscillations in the Continental European power system: events analysis and countermeasures. 2020

Interconnection changes during the oscillations

- After the first oscillation, the operation mode of the HVDC link between Spain and France was changed to fixed power
- The official report shows that the flows between France and Iberia were reversed as part of the market maneuvers which started causing deviations from the plans. The official reports state that these changes are common and that they could have worsened the already present voltage fluctuation problems.
- It isn't clear to date the interactions between the transmission maneuvers and the market changes that lead to the deviations from the planned flows.

Gráfico 45 Intercambio programado (azul) y real (rojo) con Francia el 28 de abril. Fuente: REE

12-Minutes Between the Oscillation and the First Generation Trip

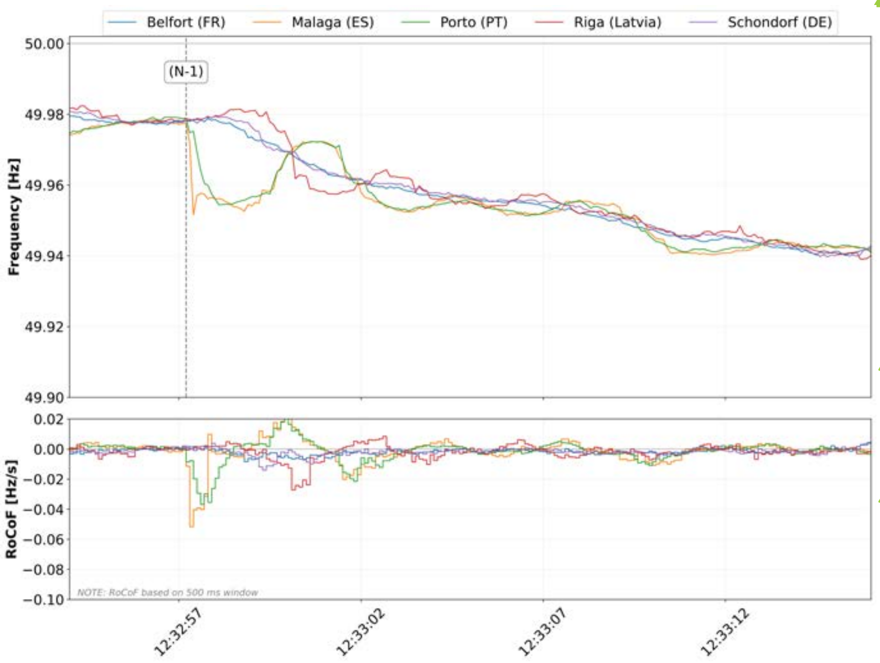


Sources: INESC – BR (data), NREL (plots)

- The actions to reduce oscillations increased voltages.
- The HVDC Links changed operation mode to constant power.
- The “fastest” thermal generator that could be brought online to control voltage required a 90-minute start up.
- The operator connected 5 inductance shunts to bring voltage down.
- The operator closed more circuits to increased transmission capacity (i.e., increase grid strength) and this worsened the voltage problems.

G-1 Loss of Generation and Frequency Response

12:32:57



First Gen Trip

Loss of Generation in Spain. No generation trips were observed in Portugal and France.

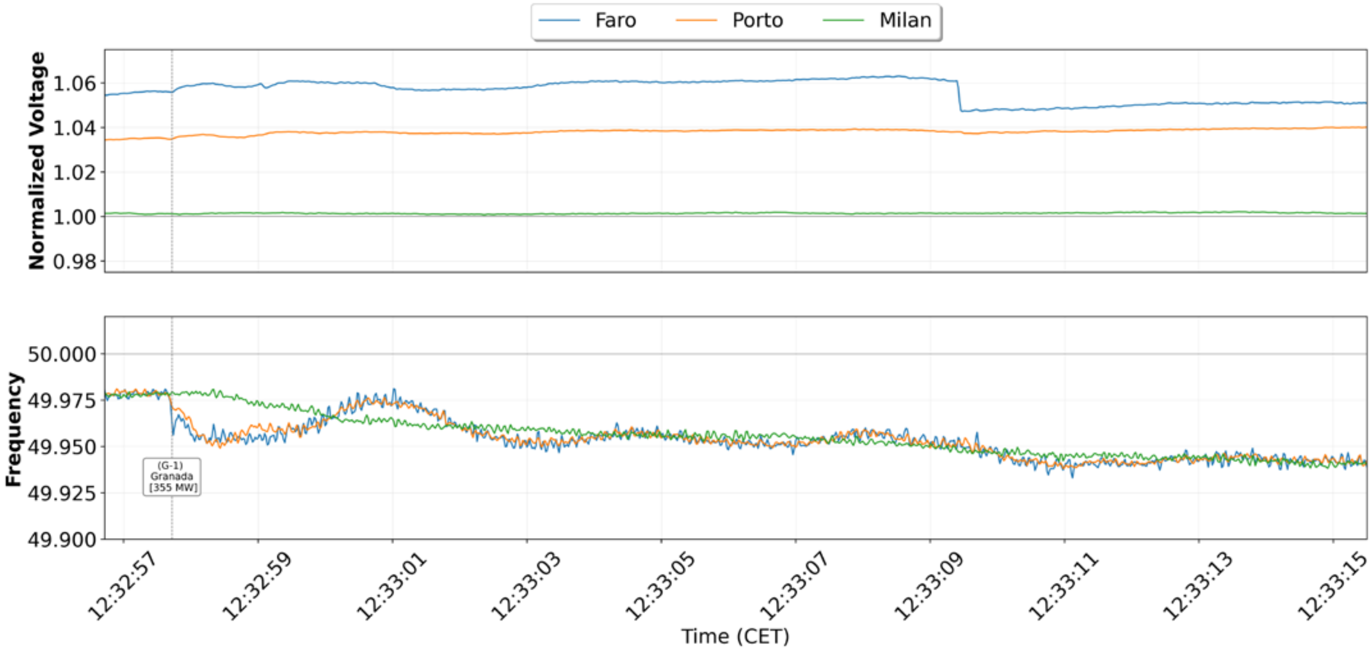
- Between 12:32:00 and the 12:32:55 the operator identified 317 MW of tripped generation from distributed generation smaller under 1 MW in size.
- Frequency delta = -0.023 Hz and recovery time ~0.5 s.
- ROCOF within tolerable parameters. Max value using window of:
  - 100 ms: 0.2 Hz/s
  - 500 ms: 0.05 Hz/s
- ROCOF is below triggering requirement for EU.
- No visible response from secondary reserves deployment. Visible frequency drift possibly due to loss of distributed generation.

G-1 Loss of Generation and Voltage Increases

12:32:57

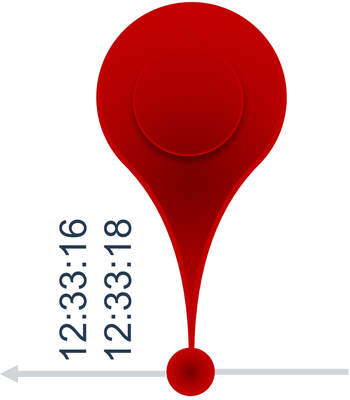
First Gen Trip

Loss of Generation in Spain. No generation trips were observed in Portugal and France.



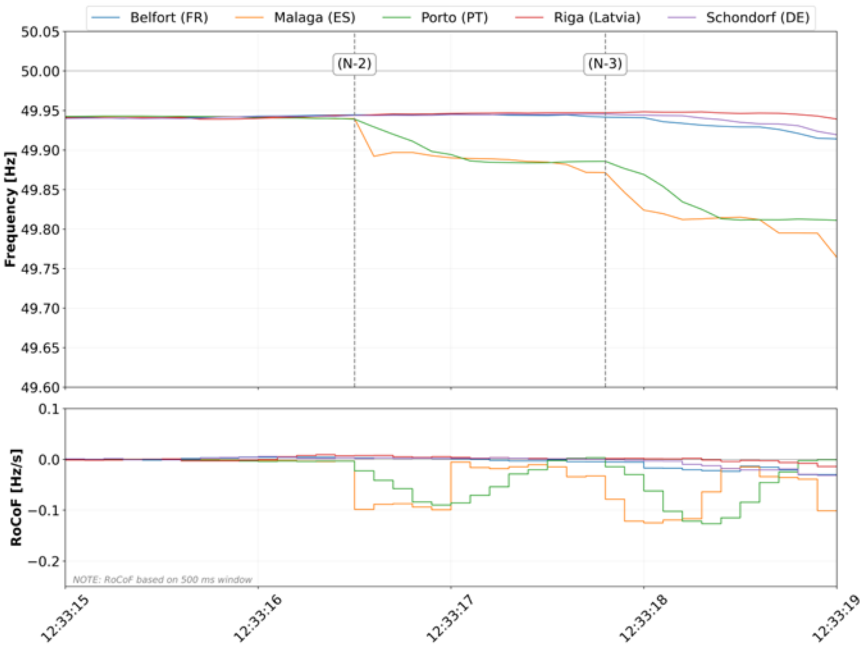
- The G-1 generation trip was producing 355 MW and consuming 165 MVar of reactive power

G-2 and G-3 Loss of Generation and Frequency Response



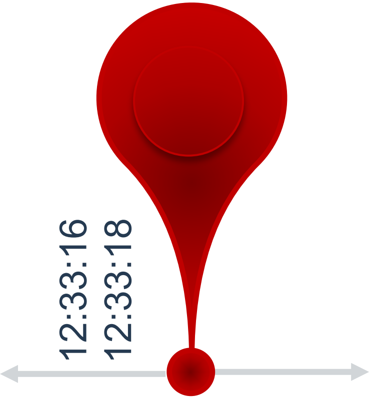
Second/Third Gen Trip

Two more generation trips in the span of 2 seconds



- Second Gen frequency delta = -0.05 Hz and continued to decay.
- Third Gen additional frequency delta = -0.02 Hz, 1.5 seconds later getting to 49.80 Hz and continued to decay.
- ROCOF within tolerable parameters before interconnection trip. Max value using window of:
  - 100 ms: 0.48 Hz/s
  - 500 ms: 0.13 Hz/s
- There is no visible response to recover the frequency from the online generation. Frequency drift over the whole window.

G-2 and G-3 Loss of Generation and Voltage Increases



Second/Third Gen Trip

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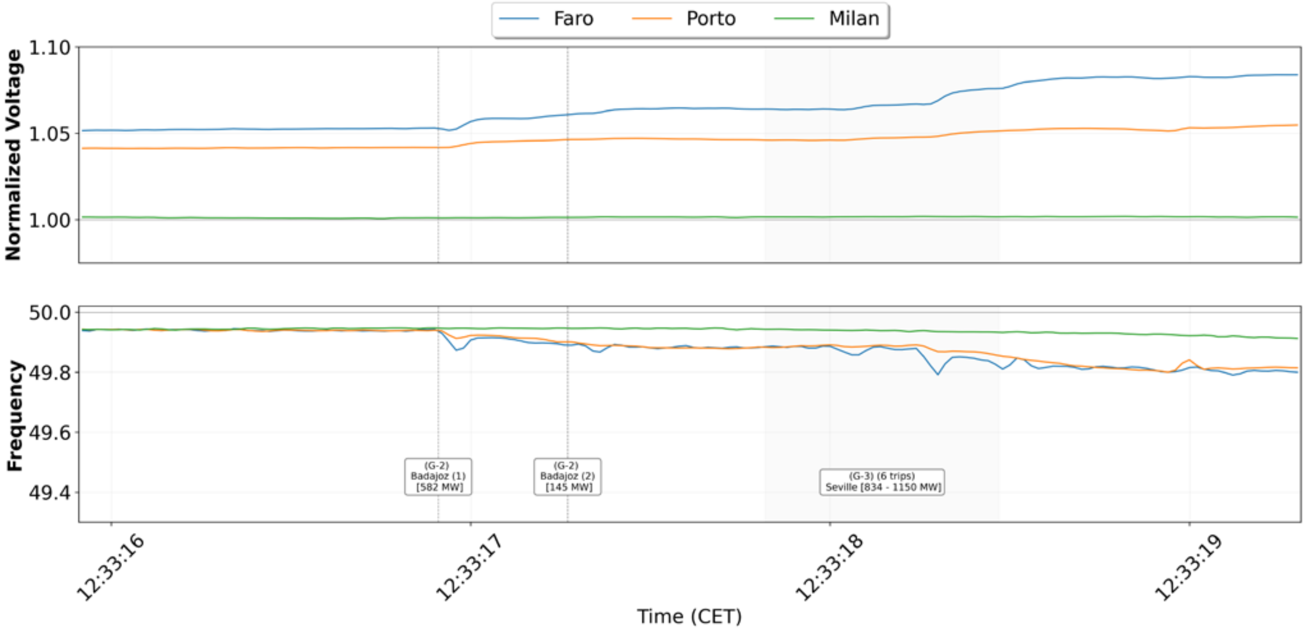
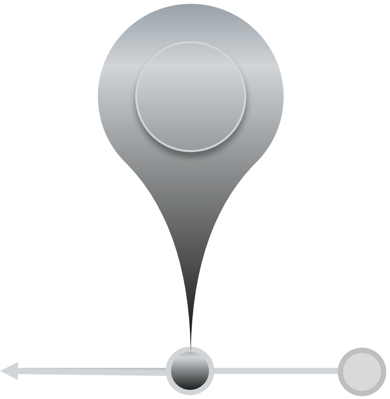


- Additional 730 MW of generation loss in this period (N-2).
- Additional 550 MW of generation loss in this period (N-3).
- Flow reversal with France to import 875 MW and 1500 MW afterwards

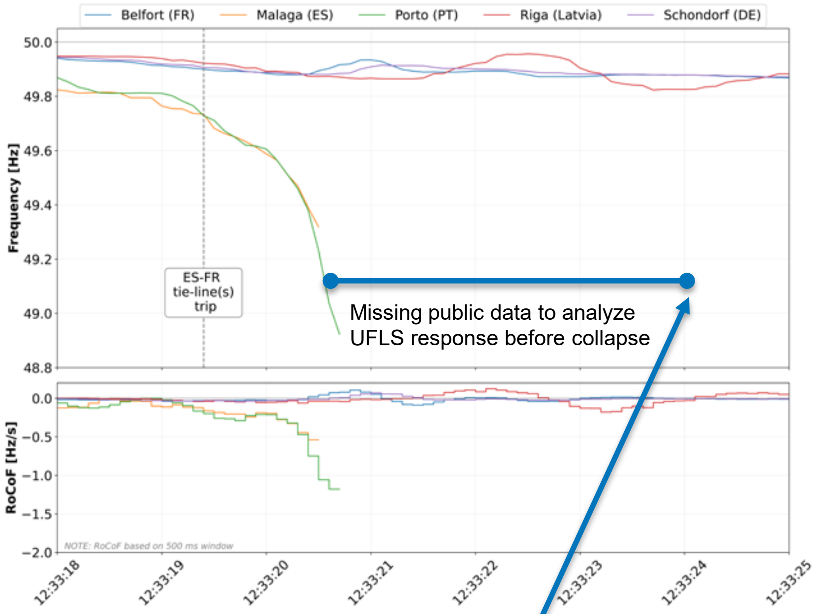
Disconnection from Europe and Under Frequency Load Shedding (UFLS) Trips

12:33:20



Iberia Islanding

Iberia disconnects; load shedding mechanisms activate but insufficient



At 12:33:24 CET, the Iberian electricity system collapsed completely

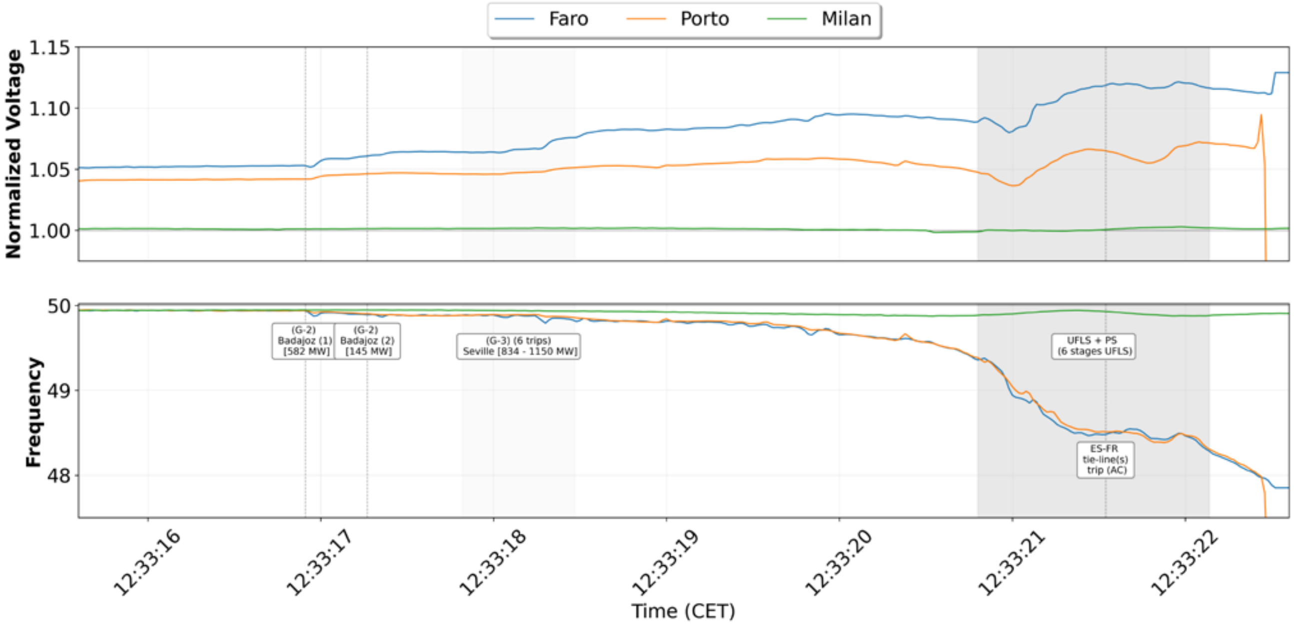
- Continental Europe recovers to normal frequency within 1.5 seconds after disconnection.
- AC overhead lines between France and Spain were disconnected by protection devices against loss of synchronism.
- ROCOF protections start to act on the rest of the Iberian system **AFTER** disconnection.
- UFLS worsen situation by tripping Distributed Gen and more large loads.

Disconnection from Europe and Under Frequency Load Shedding (UFLS) Trips

12:33:20

Iberia Islanding

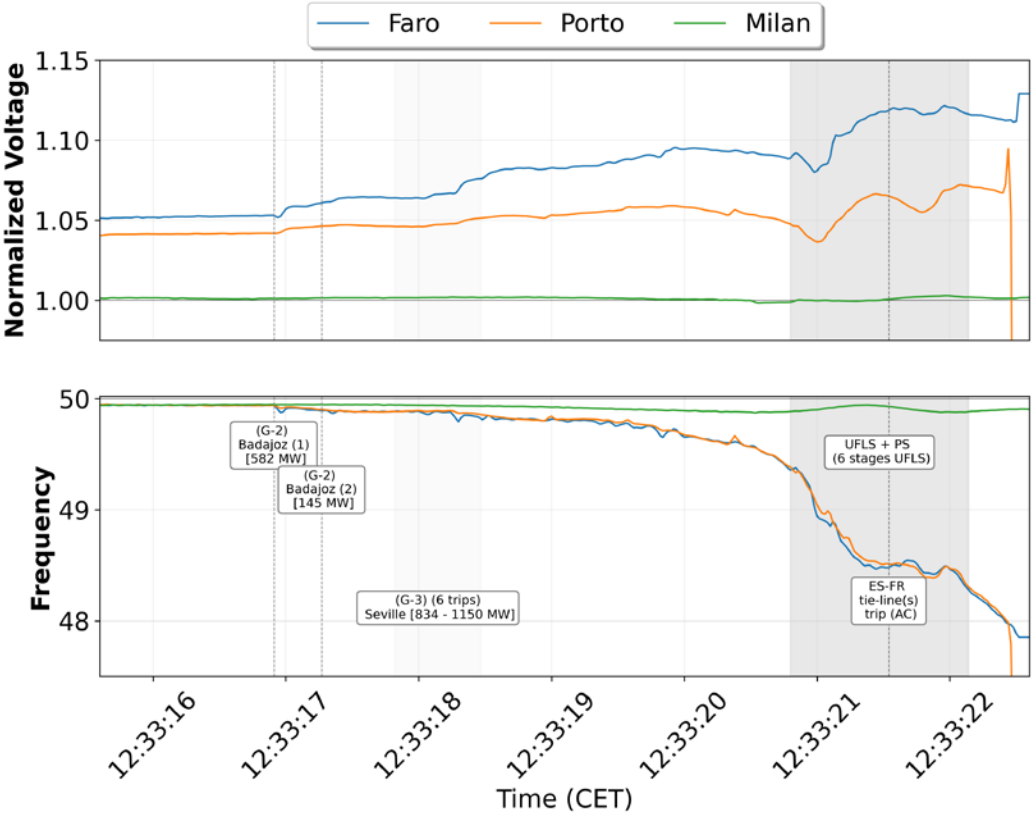
Iberia disconnects; load shedding mechanisms activate but insufficient



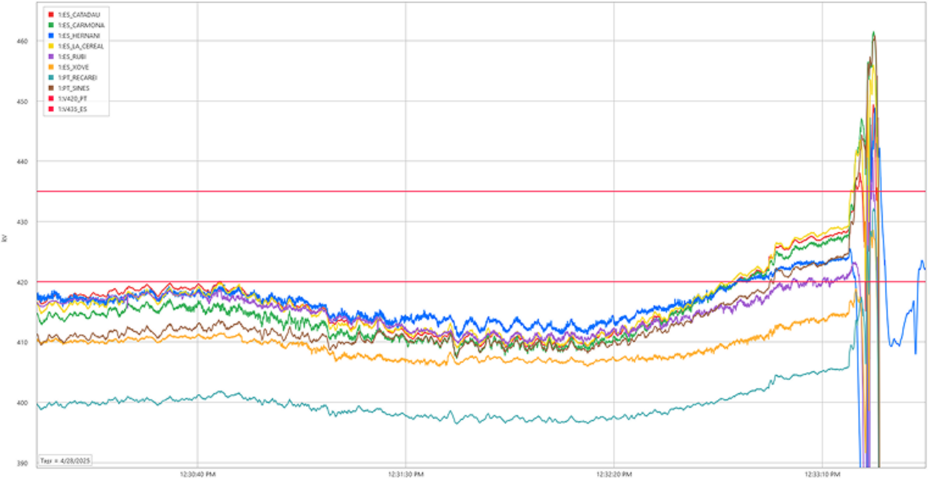
- Overvoltages in Spain reached over 1.14 pu (239,39kV at the 220kV network).
- 12:33:20.180 the pumping load gets disconnected due to underfrequency worsening the voltage problems.

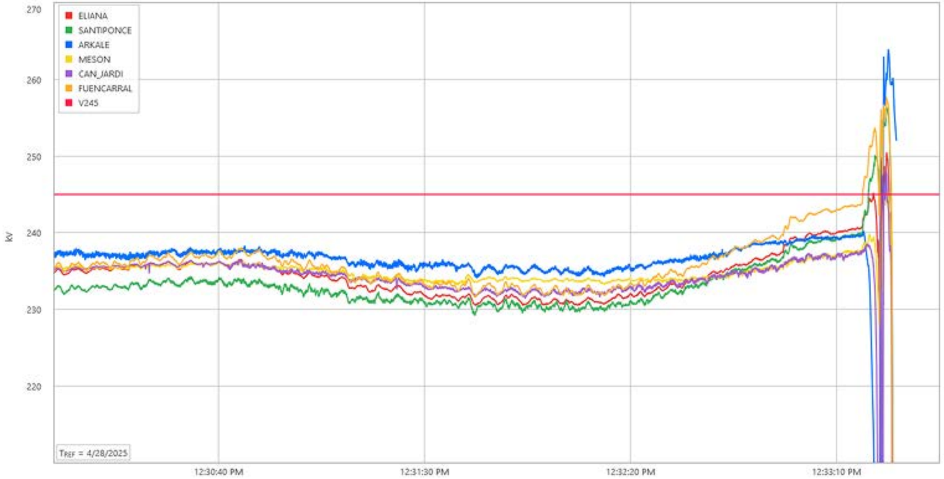
Voltage or Frequency as drivers of the cascading phenomena?

- The event registered decreasing frequency and increasing voltages significantly over 1.05 p.u. **This is a very uncommon set of events for a power system**.
- The explanation to this behavior is that the generation being tripped was under-excited and also providing active power.
- The six stages of load tripping worsen the over-voltage problem. Particularly the tripping of pumped hydro.



Voltage Fluctuations in Spain

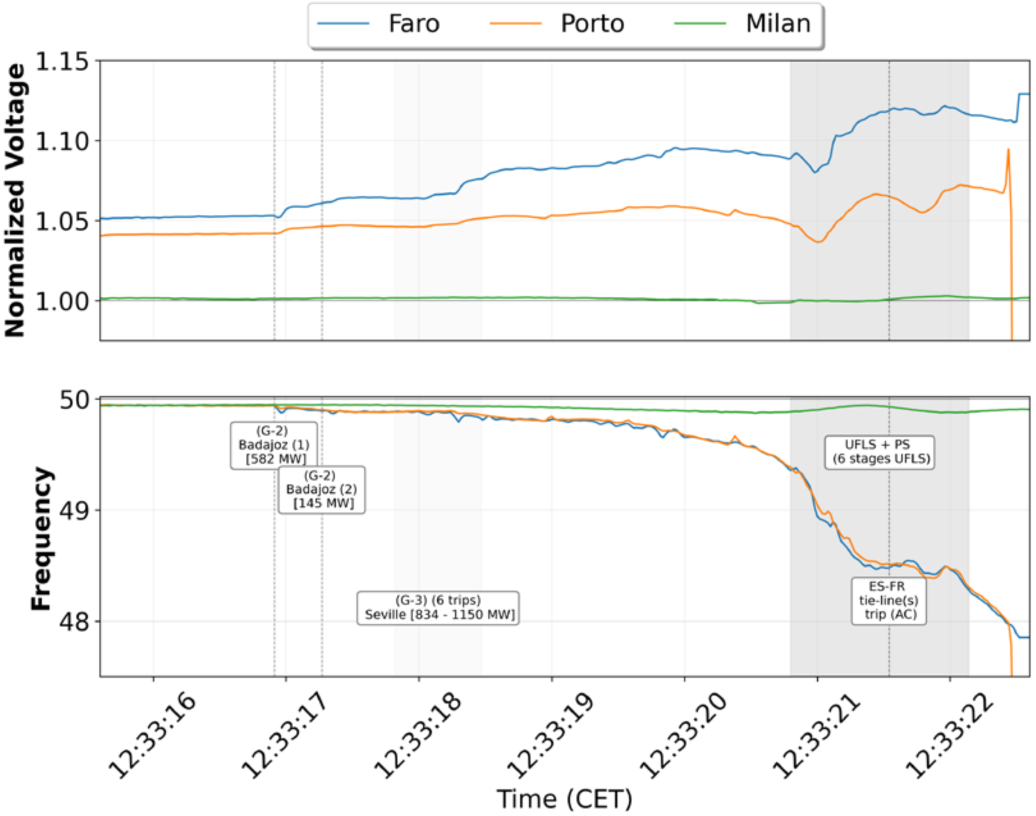




Sources: https://www.entsoe.eu/publications/blackout/28-april-2025-iberian-blackout/

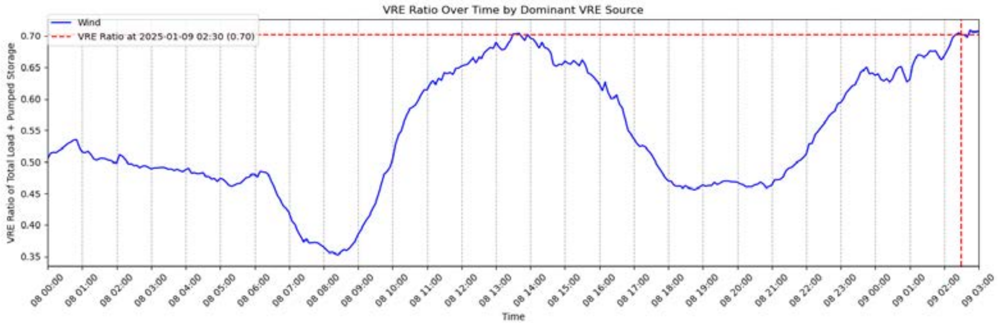
Voltage or Frequency as drivers of the cascading phenomena?

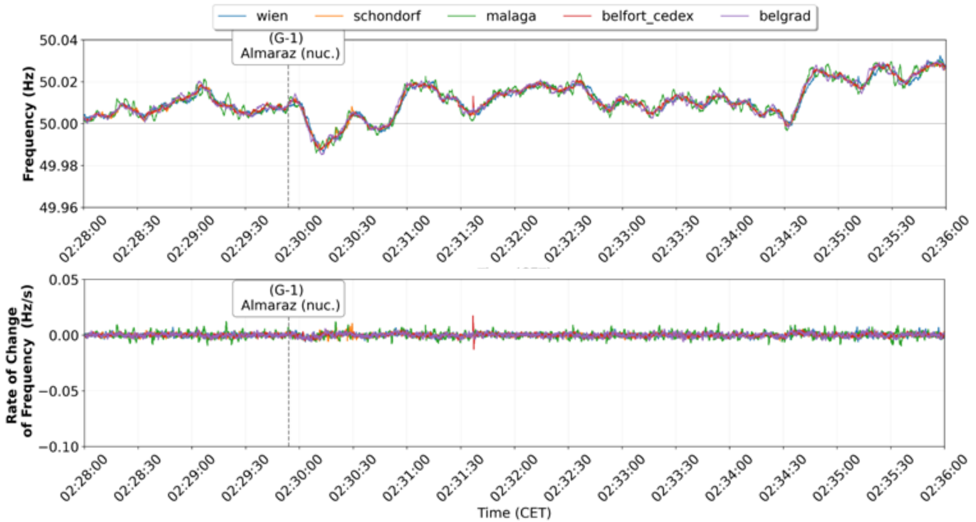
- In the last seven seconds before the blackout the voltage continues to rise through the second two trips and the UFLS actions.
- The continued rise in voltage is consistent with generation trip of units controlling voltage.
- This behavior is a known risk as explained in NERC/FERC PRC-006-1 explicitly requiring utilities to plan for overvoltage control *after* UFLS actions



Nuclear generation trip in January 2025

- On January 9 2025, 2:30 CET, a unit in the Nuclear Plant Almaraz tripped due to an under-excitation protection trigger.
- The incident, which occurred while the unit was operating at 100% power (1 GW), was caused by low excitation in the electric generator during the process of switching the voltage regulator back to automatic mode. **A few hours earlier, the voltage regulator had been switched to manual due to oscillations in the high-voltage grid**[1].
- VRE (wind) supplied 70% of the load at the moment of the generation outage and the frequency was able to come back to normal without registering large ROCOF values





1. https://www.csn.es/documents/10182/2643156/09.01.25%20-%20Información%20sobre%20la%20central%20nuclear%20Almaraz%20II%20(Cáceres)%20-%20INES%200

Oscillations as a symptom and not a cause of the underlying problem

- Under-excitation weakens the rotor's magnetic field. This leads to a weaker magnetic coupling with the stator field.
- If this coupling becomes too weak, the generator can no longer maintain synchronism, especially under load or during system disturbances.
- Under-excited operation of synchronous generators significantly increases their susceptibility to electromechanical oscillations (typically 0.1 to 2 Hz).
- The increased susceptibility is primarily due to the adverse effects of under-excitation on damping torque.

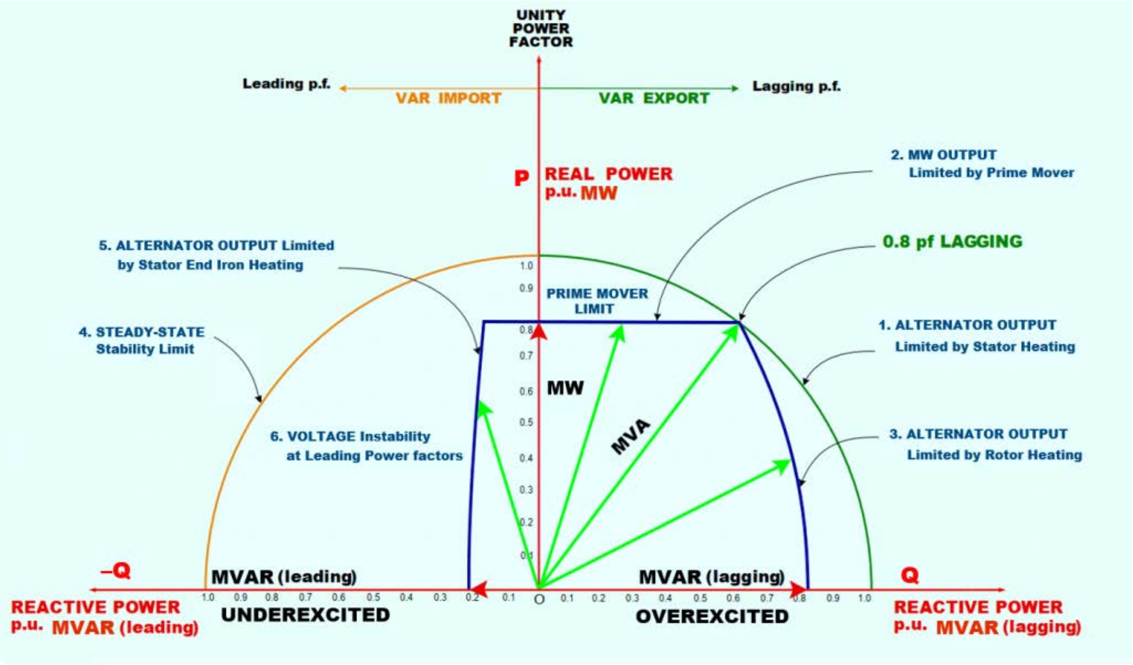


Figure from: https://electengmaterials.com/what-is-generator-capability-curve/

Open Questions About the Event

- Did the oscillations play a role in the generation trips?
- Could a mis-operation of reactive power control plants during the oscillation mitigation actions lead to the first generations' trips?
- What role did the **generation control settings** play in worsening the cascading fault?
- Can the rapid changes in the European system like the massive addition of renewables and the addition of the Baltic countries create unseen dynamic instability conditions?
- Would the addition of **grid enhancing technologies** avoid these issues?

Summary Takeaways from the Available Data

- The Spanish system was operating within normal conditions in terms of renewable penetration and exports before the blackout.
- There were **3 loss of generation events**, and then a complete disconnection from Europe in a short period of time ~20 seconds.
- No system is designed to survive N-3 contingencies plus islanding, under these conditions a blackout is expected.
- **Can we blame "low inertia"?** Unlikely, it is true that after the disconnection the inertia was low in the Spain/Portugal region, but the system had managed to recover frequency during the Almaraz generation trip under similar low load conditions to the blackout.
- Voltage problems in the Spanish grid driven by inadequate reactive power generation control and uncommon collapse conditions are at the core of this event.

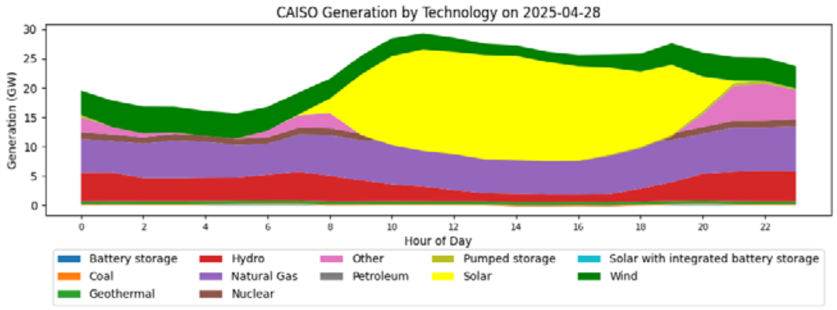
Summary Takeaways from the Available Data

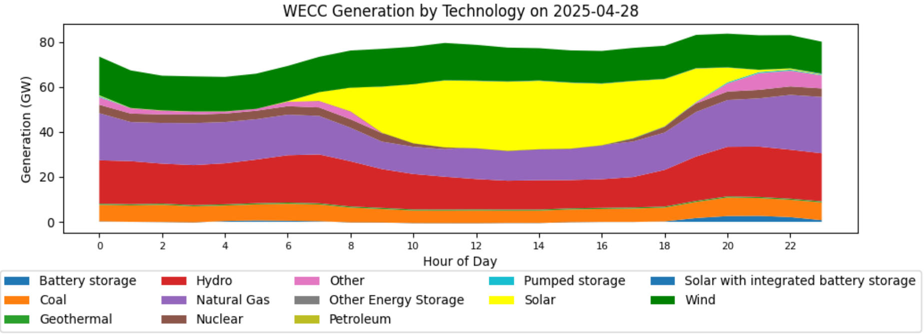
- Overvoltage problems were known. In July 2022 the operator proposed a demonstration to pay for reactive power services including reactive power consumption from PV/Wind systems.
- In Spain the regulation requires renewable generation to operate within +0.98 and -0.98 power factor[1].
- The Chilean blackout earlier this year (February 2025) had a similar sequence of events: high voltages in the north, loss of reactive power control after a line trip and running over-voltages until the system eventually collapsed.
- The operational condition characterized by increased voltage and decreased frequency is seldom examined in system studies. **When integrating significant amounts of inverter-connected generation without reactive power control, especially under low loading conditions, gathering data on new stress scenarios could reduce the probability of major events.**

1. https://www.boe.es/boe/dias/2014/06/10/pdfs/BOE-A-2014-6123.pdf
2. https://www.coordinador.cl/wp-content/uploads/2025/03/EAF-089-2025.pdf

Can an event like this happen in the US? California

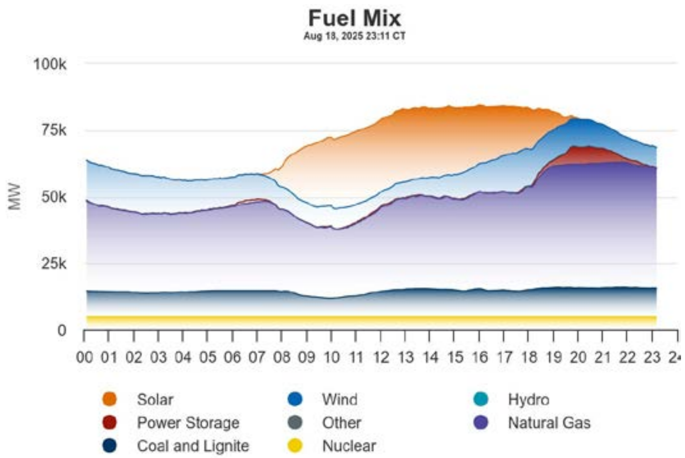
- California's system operates under similar or larger shares of renewable energy as Iberia.
- 56 straight 100% RE days so far in 2025. Average of 4.4 h/day >100% in 2025 v 2.6 h/day 2024[1].
- California's system has a large share of energy storage and hydropower which helps in adding stability to the system. On 20 May 2025, battery discharge crossed the 10 GW mark for the first time ever.
- California is the largest system in WECC which makes it less likely to experience oscillations and overvoltage but studies for future scenarios need to be conducted.

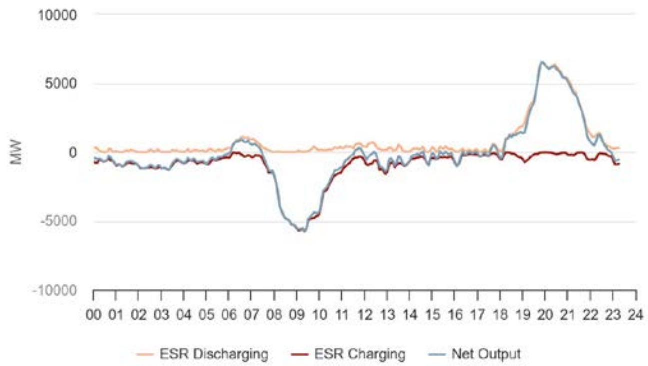




Can an event like this happen in the US? Texas

- Texas's system operates with approximately 50% of the share of renewable energy as in Iberia.
- Inverters with gross rating >20 MVA at the POI must provide Voltage Support Service and follow IEEE 2800-2022 Sections 5, 7, and 9 for voltage control and coordination.
- Texas's system has a substantial share of energy storage as a fraction of the renewable energy, which increases the capability of the system to balance active and reactive power.





Thank You

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