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The blackout of the Iberian Peninsula on April 28, 2025

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ICREPQ'26
Santander, 10-12 June 2026

comillas.edu

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- Voltage instability
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Introduction

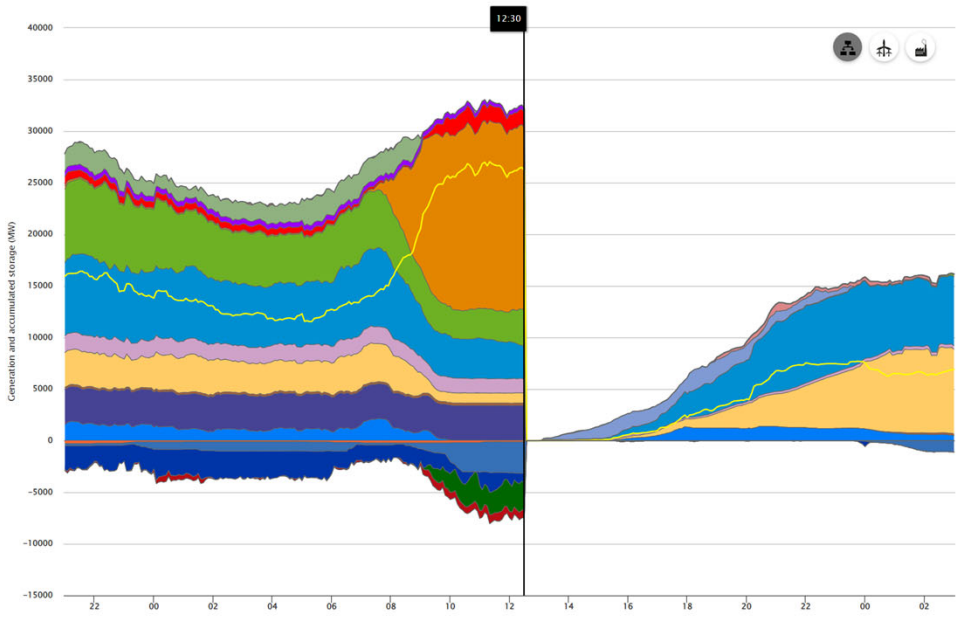
- At 12:33 on April 28, 2025, a blackout occurred in the Iberian electricity system. Sixty million people lost the electricity supply.
- This is the first time in the history of the Spanish peninsular electricity system that a blackout has occurred. The most serious incidents in the peninsular system (July 1977, October 14, 1987, and August 24, 1994) never resulted in a blackout in the Iberian system.
- It is only comparable in continental Europe, in terms of severity, with the blackout of the Italian system on September 28, 2003.
- On April 30, the Spanish government established a committee to analyze the electricity crisis, chaired by the Third Vice President and Minister for Ecological Transition and Demographic Challenge. On June 17, the Council of Ministers approved the report drawn up by this Committee.
- On June 18, Red Eléctrica, the Spanish TSO, presented its report on the events.
- On May 9, ENTSO-e established a panel of experts to investigate the incident. ENTSO-e presented its factual report on October 3. ENTSO-e presented its final report on March 20, 2026.

Introduction

- The generation portfolio through April 28, 2025, and at 12:30

Generation structure and progressive cumulative storage (MW) at the 12:30 - 04/28/2025

Demand	26203	- (%)
Importation Morocco		(%)
Importation Portugal		(%)
Importation France		(%)
Biofuel	377	1.17 (%)
Solar thermal	1498	4.65 (%)
Solar PV	17657	54.86 (%)
Wind	3499	10.87 (%)
Hydro	3172	9.86 (%)
Cogeneration and waste	1356	4.21 (%)
Combined cycle	982	3.05 (%)
Coal	229	0.71 (%)
Nuclear	3387	10.52 (%)
Pumping Turbine	28	0.09 (%)
Battery delivery		(%)
Balear link	-102	- (%)
Battery charging	-8	- (%)
Pumping consumption	-3030	- (%)
Exportation France	-868	- (%)
Exportation Portugal	-2652	- (%)
Exportation Morocco	-782	- (%)
Exportation Andorra	-9	- (%)



Introduction

- Endesa and Iberdrola commissioned Comillas to elaborate an independent report on the blackout of the Iberian Peninsula on April 28, 2025.
- Professors Rouco, Lobato, and Echavarren have prepared a report and a summary of it, with the most relevant results.
- This report is preliminary in nature.
- Endesa and Iberdrola sent this summary to ENTSO-e on September 16, 2025.
- The report has been prepared using information on the electricity system provided by Endesa and Iberdrola, to which they have access as agents of the system.
- This report could not have been prepared using public information.

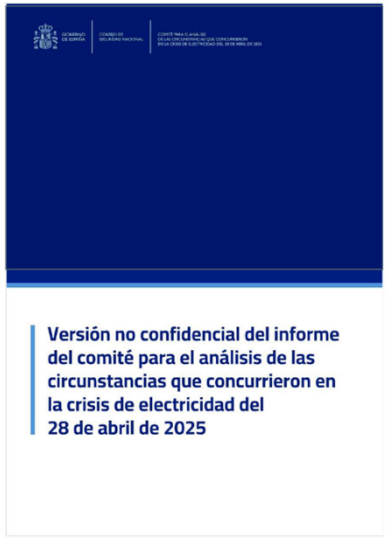
Introduction

- The summary of the report was made public on September 29, 2025.
- This presentation shows the results contained in the summary of the report.
- The fundamental conclusions of our analysis have not been affected by the published reports.
- Moreover, some of them have been reinforced.

Introduction

- Reports

Spanish Government

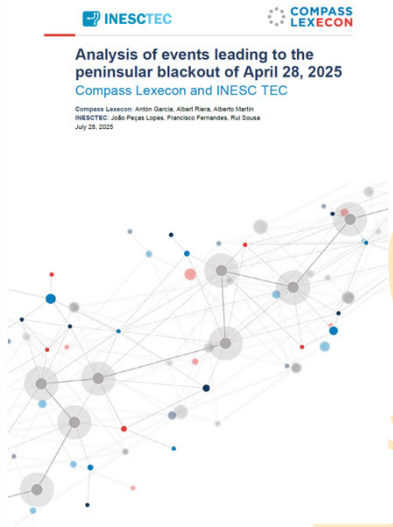


https://www.lamoncloa.gob.es/consejodeministros/resumenes/Documents/2025/Informe-no-confidencial-Comite-de-analisis-28A.pdf

Spanish TSO

https://www.ree.es/en/press-office/news/press-release/2025/06/red-electrica-presents-report-incident-28-april-and-proposes-recommendations

INESCTEC and CompassLexecon for the Spanish Association of Electric Utilities

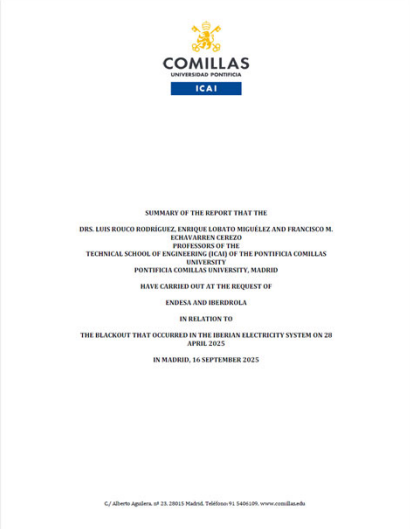


https://aelec.es/wp-content/uploads/2025/08/20250729_Report-CL-INESC-TEC_Analysis-events-leading-to-BO.pdf

Introduction

- Reports

Comillas-IIT for Endesa and Iberdrola



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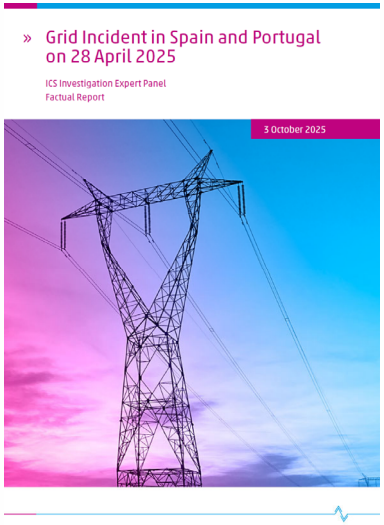
ENTSO-e factual report

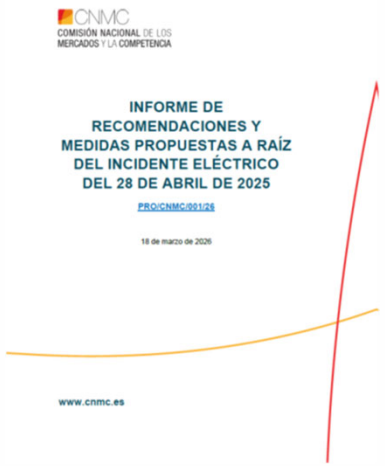


https://eepublicdownloads.blob.core.windows.net/public-cdn-container/clean-documents/Publications/2025/entso-e_incident_report_ES-PT_April_2025_06

Introduction

- Reports

Spanish National Commission of Markets and Competitiveness



https://www.cnmc.es/sites/default/files/6463458.pdf

ENTSO-e final report

https://eepublicdownloads.blob.core.windows.net/public-cdn-container/clean-documents/Publications/2025/iberian-blackout/entso-e_incident_report_ES-PT_April_2025_06.pdf

Phases of the event according to the Analysis Committee

- **Phase 0**: Voltage instability phenomena (the preceding days and the morning of the 28th between 9:00 and 12:00)
- **Phase 1**: System oscillations (between 12:00 and 12:30)
- **Phase 2**: Generation tripping due to overvoltage (between 12:32:00 and 12:33:18)
- **Phase 3**: System collapse (between 12:33:18 and 12:33:30)
- **Phase 4**: Restoration of supply from 12:33:30 p.m. on April 28 to 7:00 a.m. on April 29 for 99.95% of demand

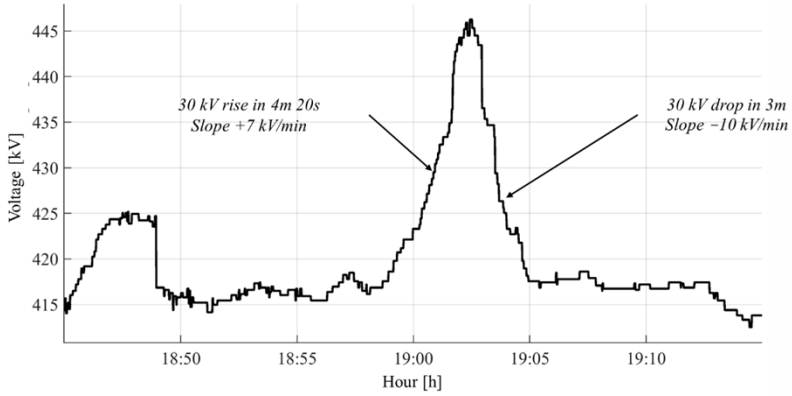
Phase 4 will not be included in our analysis

Voltage instability phenomena

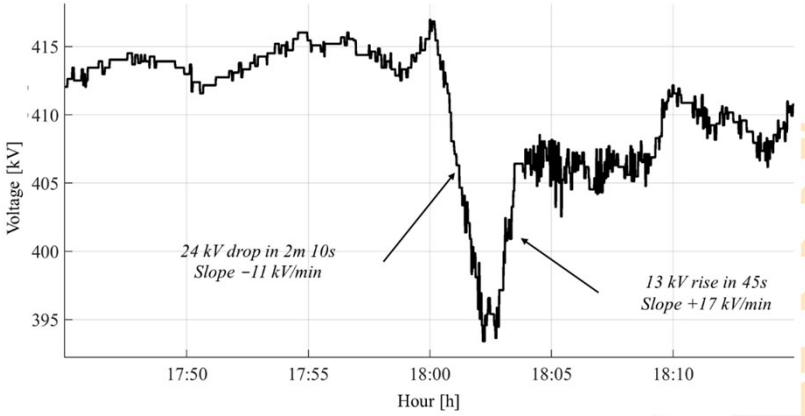
- According to the Analysis Committee
  - "Some agents have reported **previous episodes of voltage instability** this year, citing January 31, March 19, and April 22 and 24, and have linked the situation on the 28th to these precedents, particularly those of April 22 and 24."
  - "From 9:00 a.m. onwards, **greater variability in voltages** was observed, initially without significant excursions. It was from 10:30 a.m. onwards that a greater excursion was observed, i.e., larger variations in voltage values with respect to standard values."
  - "According to data provided by both the System Operator and the distribution network operators, although significant voltage variations were observed in the early hours of the morning of the event, **voltage levels in the transmission network appear to have remained within the levels** set by operating procedures 1.1 and 1.3 (between 380 and **435 kV** in the 400 network, and between 205 and 245 kV in the 220 network) throughout the period until 12:30 p.m."

Voltage instability phenomena

- The events on April 22 and 24 were characterized by variations (**up and down ramps**) of tens of kV in a few minutes.
  - Records at a 400 kV substation in Extremadura



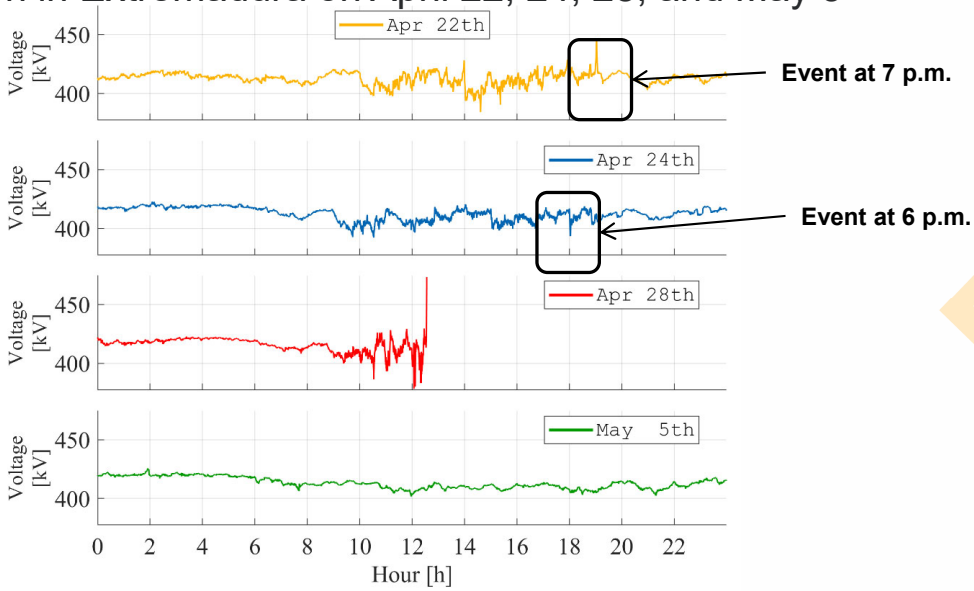
April 22



April 24

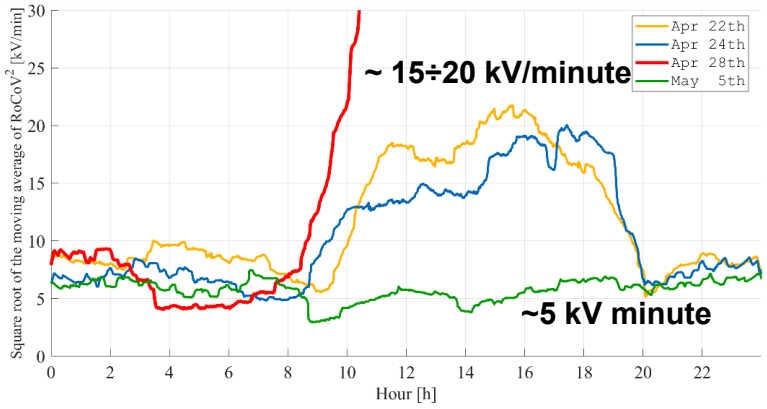
Voltage instability phenomena

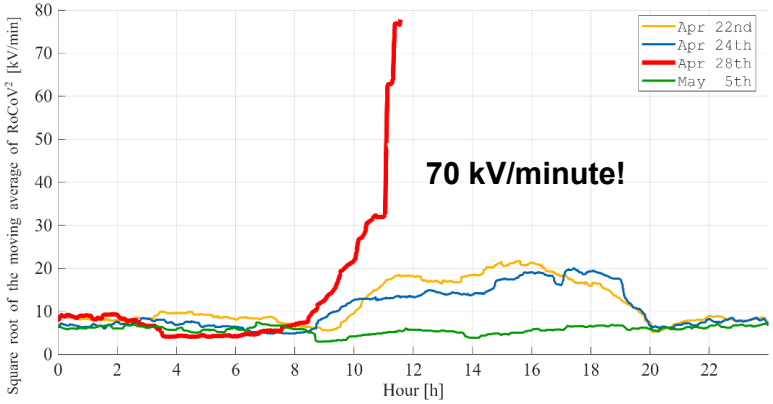
- **Simply** inspecting the temporal evolution of voltages does not provide information on the state of the system.
  - Records at a 400 kV substation in Extremadura on April 22, 24, 28, and May 5



Voltage instability phenomena

- A metric based on **voltage rate-of-change** clearly shows the phenomena noted by the Analysis Committee and how they disappeared after April 28.
  - Metric evolution through the day on April 22, 24, and 28 and May 5





Increasing the y-axis scale to see the last value calculated on April 28

Voltage instability phenomena

- The instability phenomena on the preceding days and on the morning of the 28th between 9:00 and 12:00 show that the **transmission grid voltage control system** (with very high penetration of renewable generation controlled with a constant power factor) **was not performing its function properly**.

- What is the **function of the transmission grid voltage control system**?
  - To ensure that **voltages follow the setpoints** regardless of the shape of the setpoints themselves, external disturbances, or any changes in the grid.

- Why?
  - Because **synchronous generation with dynamic voltage control in the south and center** was **low**.
    - Renewable generation is under **power factor control**.

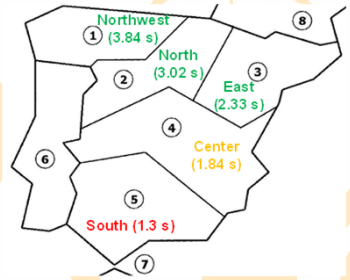
Low synchronous generation in the south and center areas and the weakness of the transmission network

- According to the Analysis Committee
  - "The **final number of thermal units coupled** at 12:30, just before the event, was 11, a figure that **has not been recorded on any other day of the year**."

Low synchronous generation in the south and center areas and the weakness of the transmission network

- Inertia is not distributed uniformly across the Spanish peninsular system.
  - The inertia of the southern and central areas is lower than that recommended by ENTSO-e (2 seconds).
  - **The inertia in the south area** (1.3 seconds) **is 35% lower** than that recommended by ENTSO-e.

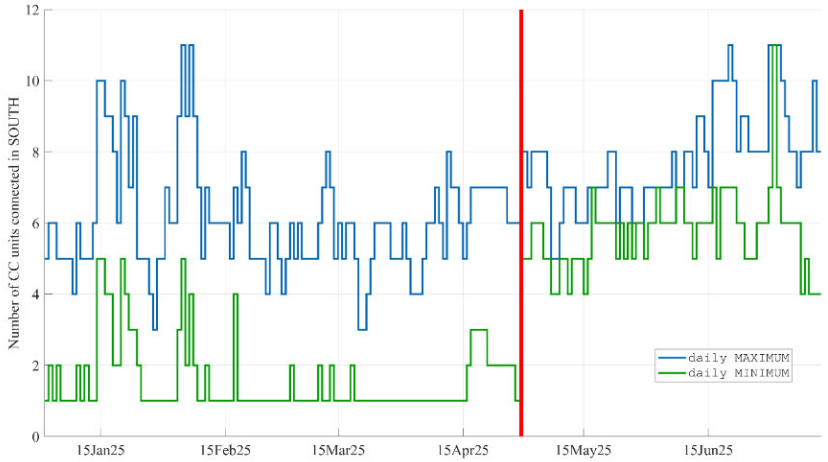
Area	Kinetic Energy [MWs]					Demand			Inertia [s]
	Nuclear	CCGT	Coal	Hydro	Total	Raw file e-sios [MW]	Raw file e-sios [%]	Estimation [MW]	
NORTHWEST	0	3714	1746	6652	12111	3194	13%	3152	3,84
NORTH	0	2995	0	7843	10837	3633	15%	3585	3,02
EAST	9642	0	0	4105	13747	5988	24%	5909	2,33
CENTER	2906	8875	0	4204	15984	8780	35%	8664	1,84
SOUTH	0	2881	0	1535	4417	3443	14%	3398	1,30
TOTAL	12547	18465	1746	24339	57097	25038	100%	24708	2,31



The calculated value of the inertia of the Spanish peninsular system (2.31 s) is within the range providen by ENTSO-e (2.14-2.64 s).

Low synchronous generation in the south and center areas and the weakness of the transmission network

- The **minimum number of combined cycle units connected in Andalusia has changed** significantly since April 28.



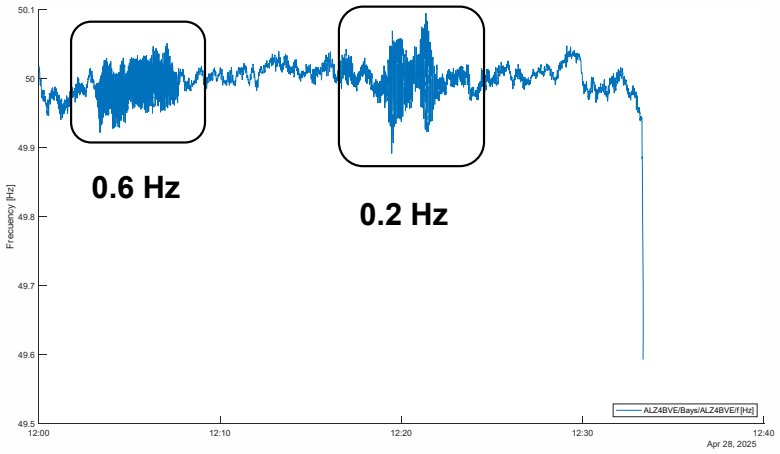
Low synchronous generation in the south and center and the weakness of the transmission network

- The weakness of the transmission network
  - **Thirty-five percent of the 400 kV network was disconnected** at 9:00 in the center and south areas.

AREA	% km of opened lines due to voltage control at 9:00			% km of unavailable lines			% km lines with planned works starting at 9:00			% km all causes	
	220 kV	400 kV	Total	220 kV	400 kV	Total	220 kV	400 kV	Total	220 kV	400 kV
NORTHWEST		20,74%	10,5%	2,5%	0,9%	1,7%				2,5%	21,7%
NORTH		14,4%	7,3%	0,7%	1,6%	1,2%				0,7%	16,0%
EAST	1,5%	8,5%	5,7%	2,8%	4,8%	4,0%	0,3%	1,3%	0,9%	4,6%	14,6%
CENTER	7,0%	26,7%	16,2%	5,6%	2,2%	4,0%	0,4%	5,4%	2,7%	13,0%	34,3%
SOUTH		27,5%	12,6%		8,3%	3,8%					35,8%
TOTAL	1,8%	18,4%	10,3%	2,3%	3,8%	3,1%	0,2%	1,4%	0,8%		

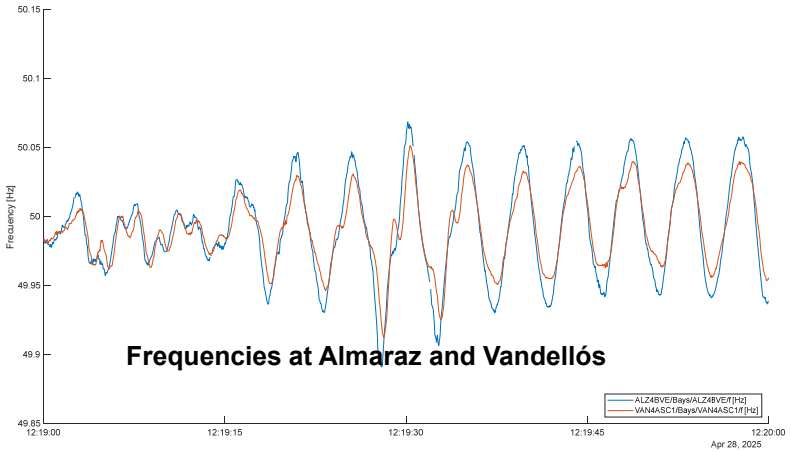
System oscillations

- Between 12:00 and 12:30, two events of very poorly damped oscillations occur (1%, less than the 5% established in Operating Procedure 13.1).
  - In general, oscillations occur due to **"high" power transfers** through **"weak" networks**.
  - Red Eléctrica connects 11 lines during this period to damp these oscillations.
  - The **favorable effect of connecting these lines** confirms the **weakness of the network**.

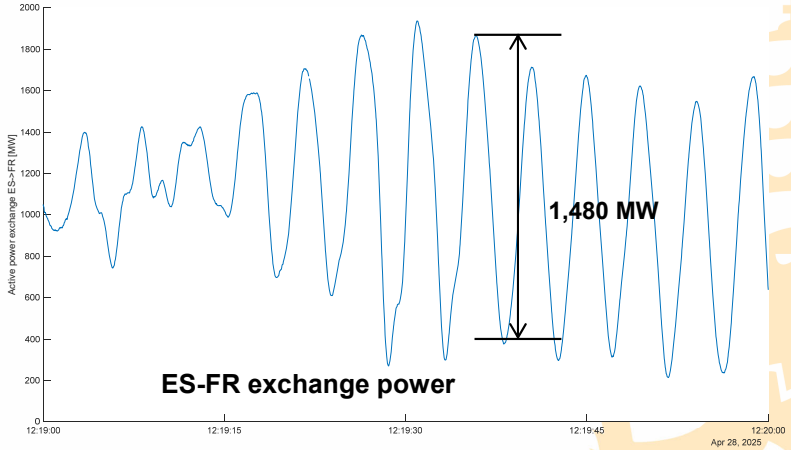


System oscillations

- **The 0.2 Hz oscillation** results in a peak-to-peak oscillation of **1,480 MW** in the exchange power with France.
  - The **generators on the Iberian Peninsula** oscillate in phase and **exchange energy with the generators in the rest of the European continental system**.



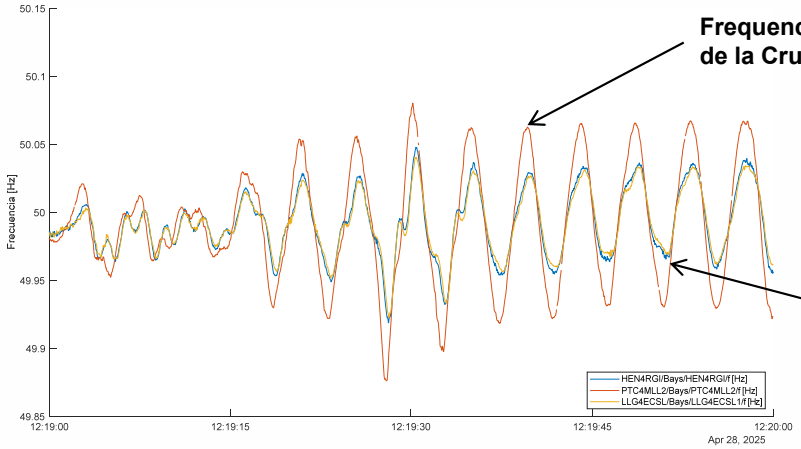
Frequencies at Almaraz and Vandellós

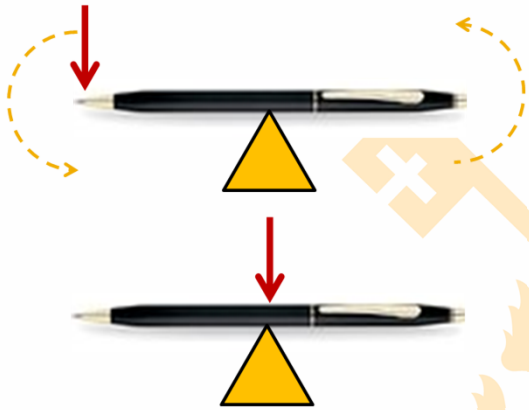


ES-FR exchange power

System oscillations

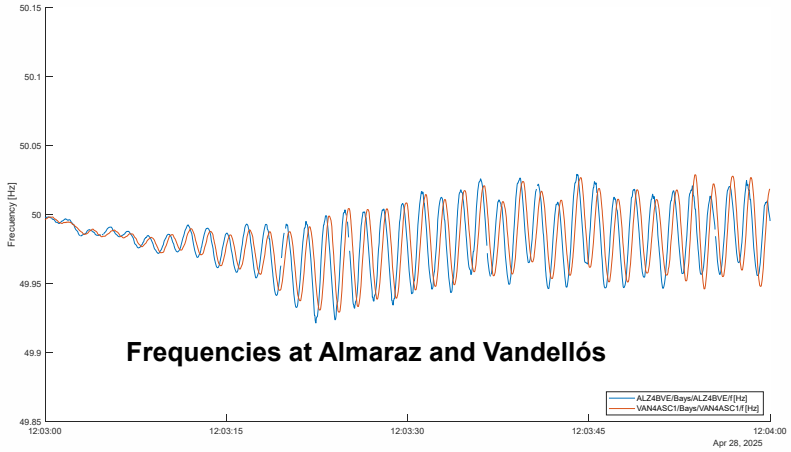
- The **combined cycle units in Andalusia** play a **very important role** in **damping** the 0.2 Hz oscillation because
  - being equipped with power system stabilizers (PSSs), and
  - exhibiting greater observability of the 0.2 Hz oscillation.





System oscillations

- **The 0.6 Hz oscillation** results in an oscillation of around **470 MW** in the exchange power with France.
  - The **generators on the Iberian Peninsula** oscillate almost in phase and **exchange energy with the generators in the rest of the European continental system**.



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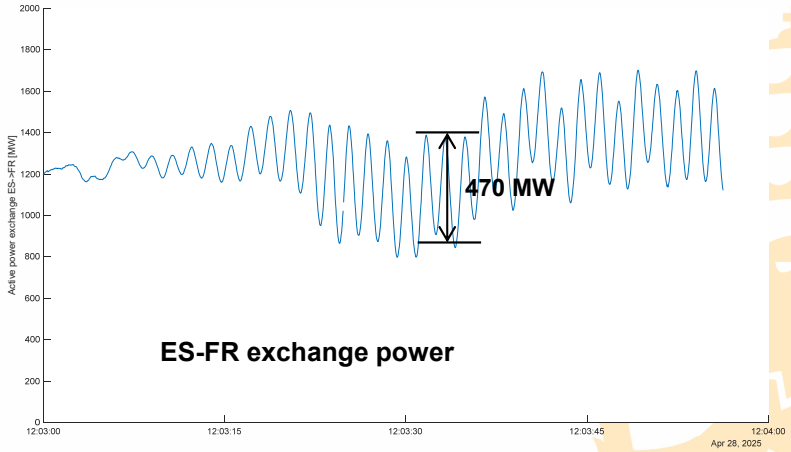


ES-FR exchange power

Generation disconnections and collapse due to overvoltage

- Generation disconnections due to overvoltage
  - According to the Analysis Committee

Description	Time	Location	Power [MW]	Accumulated power [MW]
Event 1	12:32:57,140	Granada	355	355
Event 2	12:33:16,460	Badajoz	730	1085
Event 3	12:33:17,780	Sevilla	550	1635

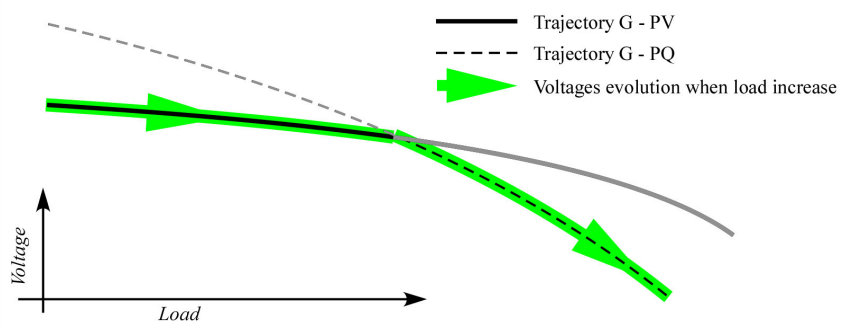
  - According to Operating Procedure 13.1 and the Detailed Specifications for calculating the access capacity of generation to transmission and distribution networks, the system must withstand the loss of 3,000 MW of generation following a three-phase clear fault lasting 250 milliseconds.

Generation disconnections and overvoltage collapse

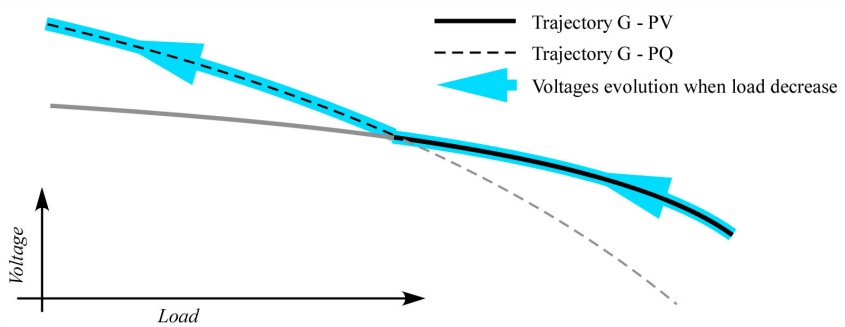
- ENTSO-e has stated:
  - "The Expert Panel is looking particularly at the **cascading series of generation disconnections and voltage increases as the most probable trigger for the blackout**. Such cascading voltage increases have never before been linked to a blackout in any part of the European power system. If confirmed, this high-voltage blackout mode will require a thorough analysis and investigation by all power system experts of the ENTSO-E community."

Generation disconnections and overvoltage collapse

- **Overvoltage collapse** versus **undervoltage collapse**



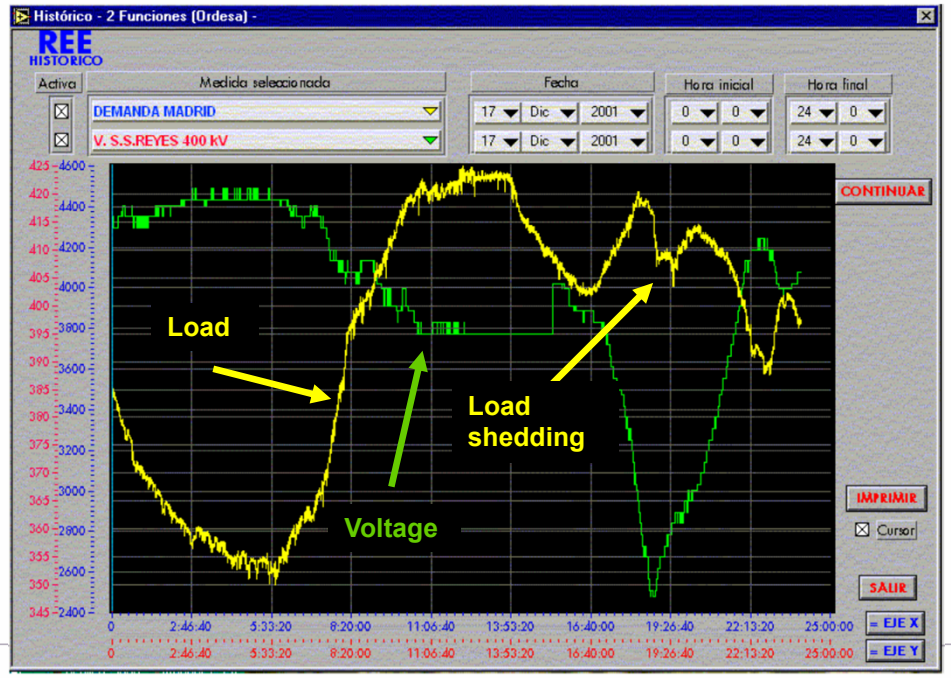
Undervoltage collapse: voltage decreases as system load increases



Overvoltage collapse: voltage increases as system load decreases

Generation disconnections and collapse due to overvoltage

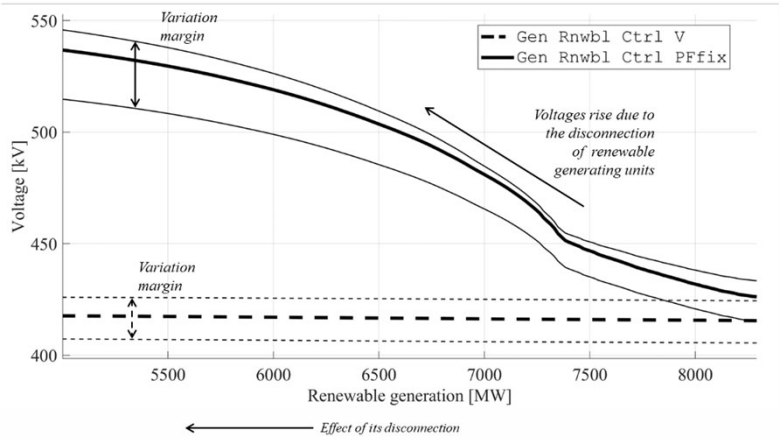
- Near collapse due to undervoltage on December 17, 2001, in the Spanish peninsular system



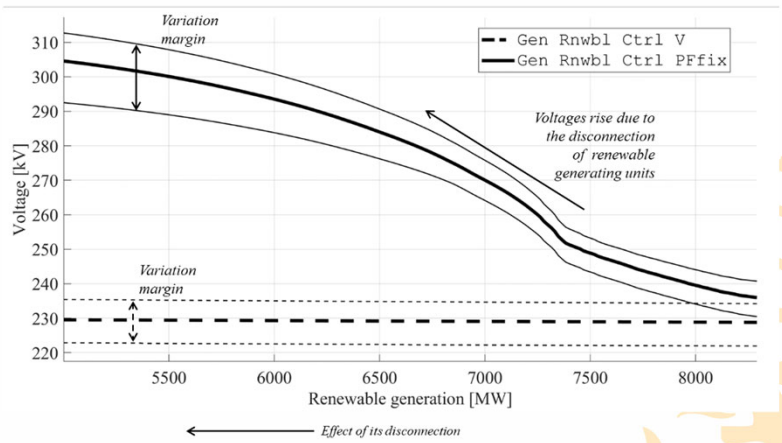
Voltage drops as a result of increased load and insufficient reactive power resources near the load

Generation disconnections and collapse due to overvoltage

- **Voltages are rising as renewable generation is** gradually **being** disconnected in Extremadura and Andalusia.



Carmona 400 kV

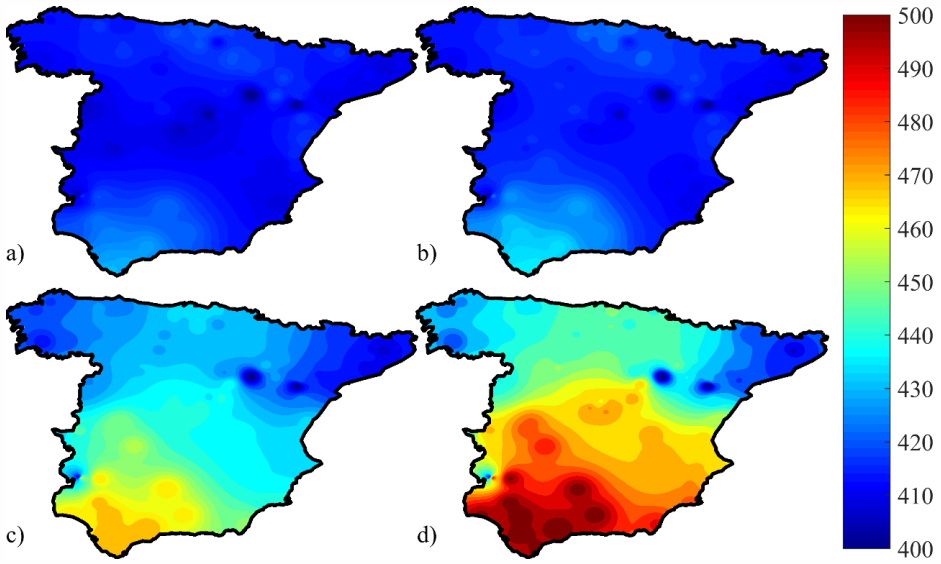


Guillena 220 kV

The simulations were performed on a snapshot of the electrical system's operation at 12:30 p.m., reconstructed from data available from the agents (raw cases from e-sios, daily operation report, and daily restrictions report).

Generation disconnections and overvoltage collapse

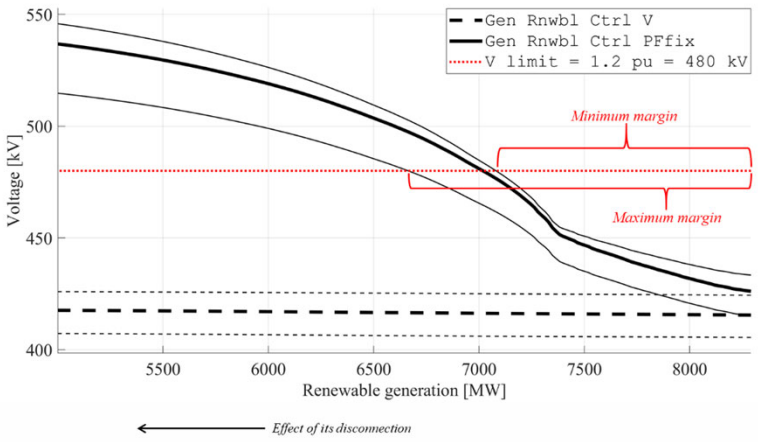
- **Voltage maps** for **the three** generation **disconnections** identified by the Analysis Committee



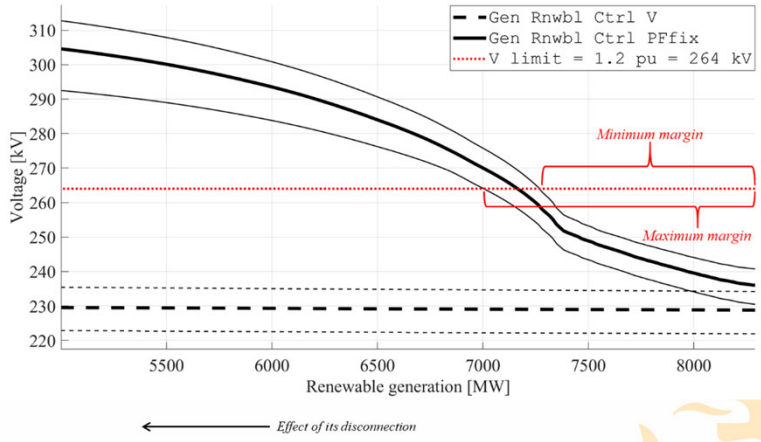
The third event causes overvoltages throughout practically the entire peninsular system except Catalonia, thanks to its nuclear power plants and the HVDC link with France.

Generation disconnections and overvoltage collapse

- **Overvoltage collapse margin**



Carmona 400 kV



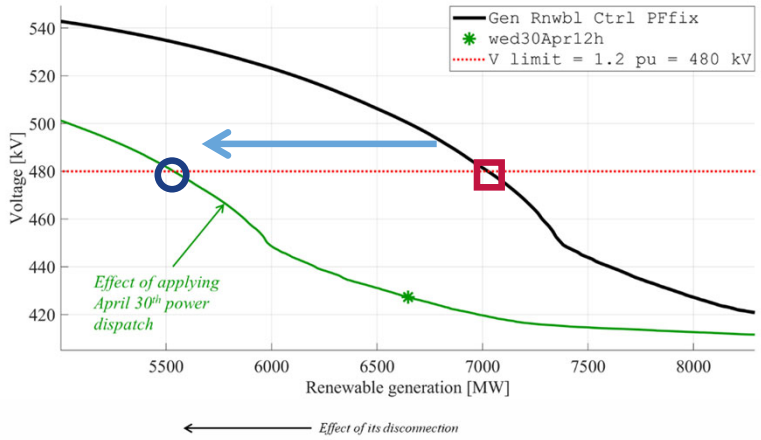
Guillena 220 kV

Nivel	Margen superior [MW]	Margen nudo seleccionado [MW]	Margen inferior [MW]
400	1625	1268	1213
220	1286	1199	1019

Generation disconnections and overvoltage collapse

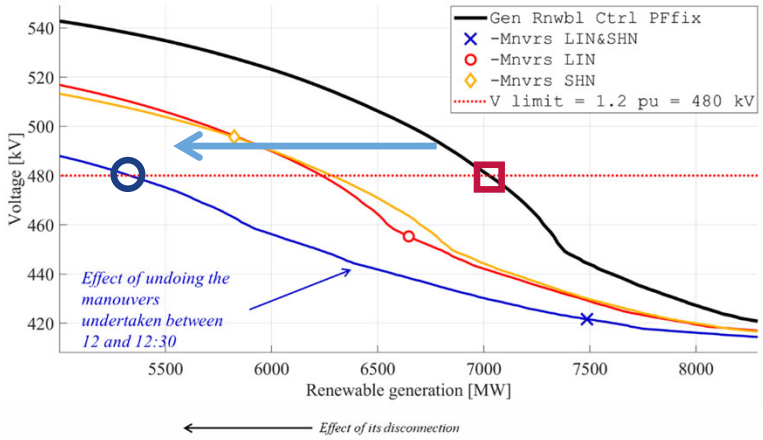
- How does the **margin to collapse due to overvoltage** evolve if **the dispatch of April 30** is applied, **in which five combined cycle units were connected in Andalusia** in the process of solving technical restrictions?

  - The **margin to overvoltage collapse** in Carmona 400 kV **would have gone** from **1,268 MW** to **2,758 MW**.



Generation disconnections and overvoltage collapse

- How would the **margin to collapse due to overvoltage have evolved** if **the line and reactor maneuvers** carried out by Red Eléctrica between 12:00 and 12:30 p.m. **had been reversed**?
  - The **margin to collapse due to overvoltage** in Carmona 400 kV **would have gone** from **1,268 MW** to **2,964 MW**.



Conclusions

- A **novel metric** has confirmed the occurrence of **voltage instability phenomena** on April 22 and 24 and on the morning of April 28.
- **Low synchronous generation** in the southern and central areas and the **weakness of the** transmission **network** in those areas have been made clear by measuring them with **quantitative indicators**.
- **Low synchronous generation with dynamic** voltage **control** is behind the **voltage instability phenomena**.
- The **oscillations** occur due to **"high" power transfers** through **"weak" networks**.
- The **combined cycle groups in Andalusia** play a **very important role** in **damping the** 0.2 Hz **oscillation.**
- The **favorable effect of line connections in damping oscillations** confirms the **weakness of the network**.

Conclusions

- The phenomenon of **collapse due to overvoltage** explains the increase in voltages as renewable generation is disconnected in Andalusia and Extremadura.
- At 12:30 p.m., **there was no margin for overvoltage collapse** to accommodate the disconnection of generation due to overvoltage.
- The **line and reactor maneuvers** carried out by Red Eléctrica between 12:00 and 12:30 p.m. created a great reactive power unbalance in the transmission grid.
- The **application of the dispatch on April 30**, in which five combined cycle units were connected in Andalusia, **would have increased the margin for overvoltage collapse**, allowing the disconnection of generation due to overvoltage to be absorbed.
- The **lack of sufficient synchronous generation with dynamic voltage control** in the south and center areas was the **cause of the blackout** on April 28.