Iberian blackout: why it happened, will there be another one?

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Reports

red eléctrica
Una empresa de Redeia

Incidente en el Sistema Eléctrico Peninsular Español el 28 de abril de 2025

June 18, 2025

GOBIERNO DE ESPAÑA | CONSEJO DE SEGURIDAD NACIONAL | COMITÉ PARA EL ANÁLISIS DE LAS CIRCUNSTANCIAS QUE CONCURRIERON EN LA CRISIS DE ELECTRICIDAD DEL 28 DE ABRIL DE 2025

Versión no confidencial del informe del comité para el análisis de las circunstancias que concurrieron en la crisis de electricidad del 28 de abril de 2025

17 June 2025

» Grid Incident in Spain and Portugal on 28 April 2025

ICS Investigation Expert Panel
Factual Report

3 October 2025

ENTSOE: factual report

» Grid Incident in Spain and Portugal on 28 April 2025

ICS Investigation Expert Panel
Final Report

20 March 2026

ENTSOE: final report

Iberian blackout 28 April 2025

- Blackouts are fascinating: engineering + economics + politics
- The largest blackout in Europe since 2003 Italy
- 55M people affected, over 30GW lost
- Spain, Portugal a small bit of France

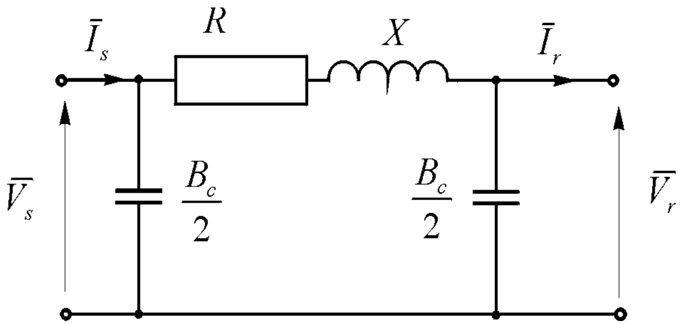
Suddenly, knowing a lot about the U.S. power grid became sexy at cocktail parties.

What has happened?

- More technical than usual blackouts caused by cascaded line tripping (US/Canada 2002, Italy 2003, Europe 2006 etc)
- Direct cause of the blackout:
  - Overlooked interactions between power system oscillations and voltage stability
- First a quick tutorial on voltage control and power system oscillations
- No equations!

Voltage (V) and reactive power (Q)

- Voltage control is closely related to controlling reactive power Q in the system
- Reactive power exists only in AC circuits: inductors and capacitors
- Convention: Q is “produced” by capacitors and “absorbed” by inductors
- Production of (capacitive) Q causes voltages to increase, while consumption of (inductive) Q causes voltages to drop
- Loads are typically inductive (many machines) – cause the voltage to drop
- Transmission lines may produce or consume Q depending on the line current
    - When the current is low (e.g. at night), the net effect is capacitive and voltages rise
    - When the current is high (e.g. during the day) , the net effect is inductive and voltages drop



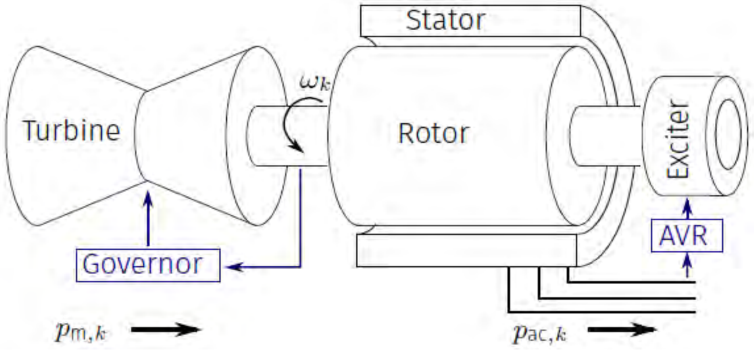
Equivalent circuit of a transmission line

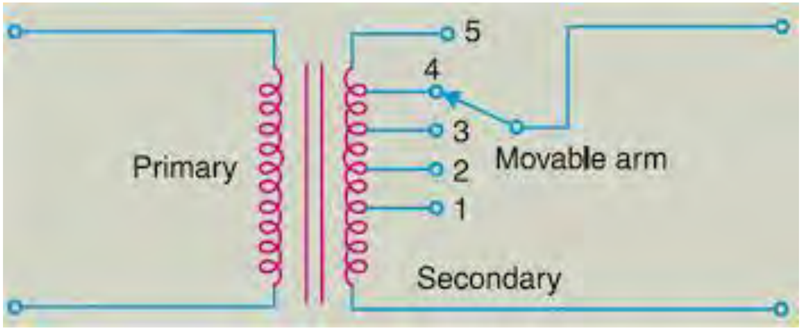
$Q_{cap} \propto V^2 \approx$ const

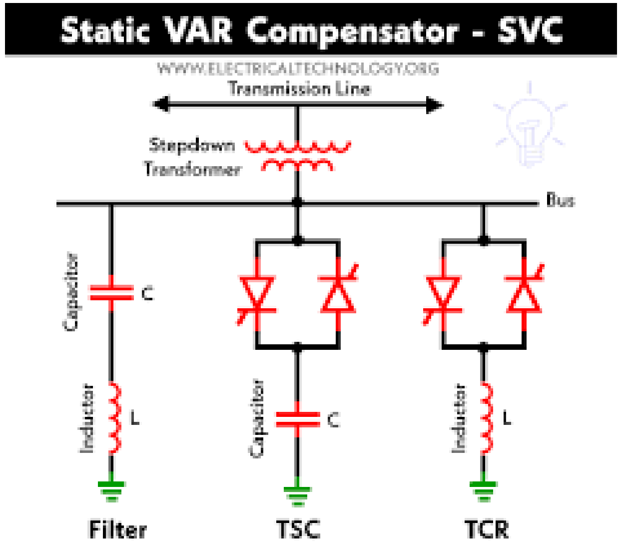
$Q_{ind} \propto I^2 \approx$ variable

How to control voltage

- Synchronous machines in traditional plants are the main providers of continuous dynamic voltage control
  - Q depends on the rotor (excitation) current – Automatic Voltage Regulator (AVR)
  - Smooth, continuous control
- Static compensators: reactors (inductors), capacitors, Static VAR Compensators (SVC)
  - Step-wise control
- Tap-changing transformers that connect high-voltage transmission to lower voltage distribution networks:
  - Taps change the transformation ratio to keep the distribution voltages within limits

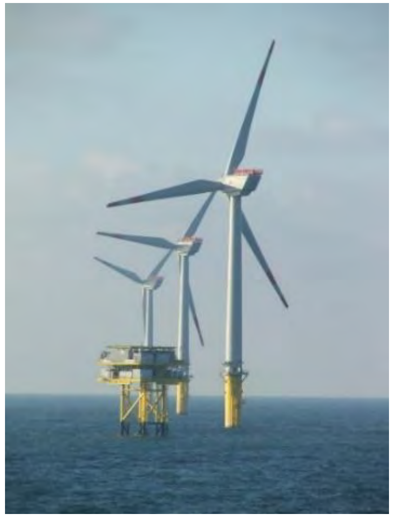






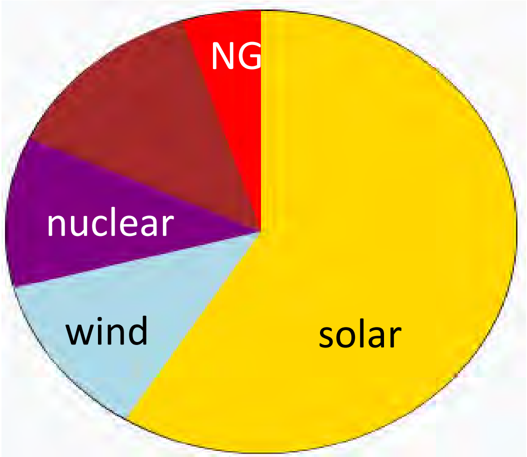
Voltage control using Inverter-Based Resources (IBRs)

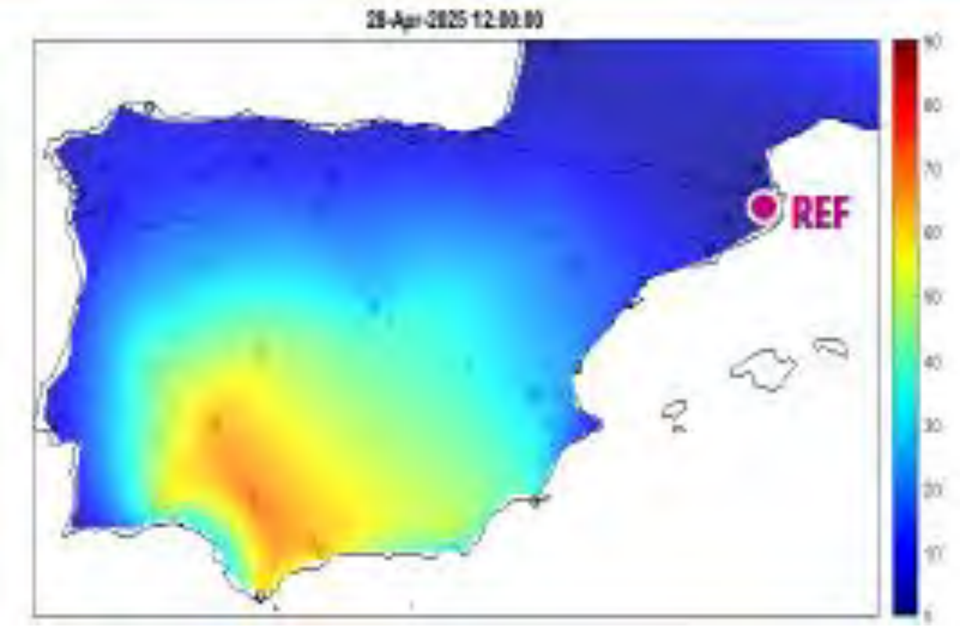
- Wind, PV solar and batteries produce DC electricity so they are connected to the AC grid using power electronic devices called inverters (converters) – Inverter-Based Resources (IBRs)
- IBRs also include EVs, data centres, HVDC converter stations etc
- Inverters can provide voltage support (within limits) by producing/consuming Q
  - Opportunity cost
- Many countries (including Portugal) with high IBR penetration require IBRs to contribute to automatic voltage control
  - Portugal didn’t experience voltage problems but was brought down by Spain
- In Spain IBRs are required to operate at a constant (inductive) power factor so Q is not controllable - it depends on real power P produced
  - A major contributing factor to the blackout



Conditions before the blackout

- About 70% wind + solar generation in Spain, exports to France, Portugal, Marocco
- Wind and solar mainly in the southwest, pushing power towards centre-north and east
- Inertia more than adequate – no role in the blackout
- Voltages within the limits
- Only 10 traditional plants (fewer than usual) provided dynamic voltage control
  - Mainly center and the north
  - But voltage is a local problem!
- Oscillations appeared at 12:03 (1/2h before the blackout)

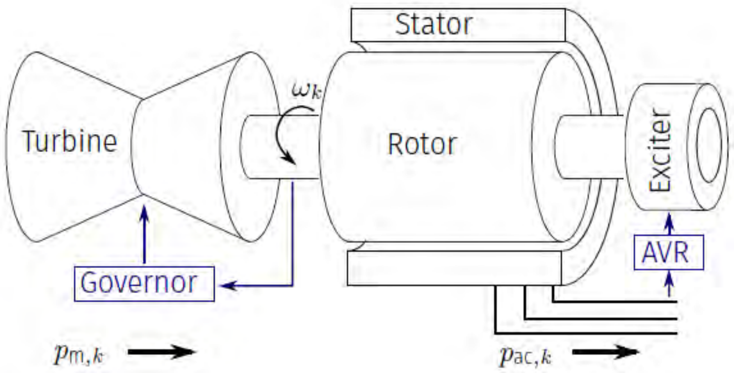




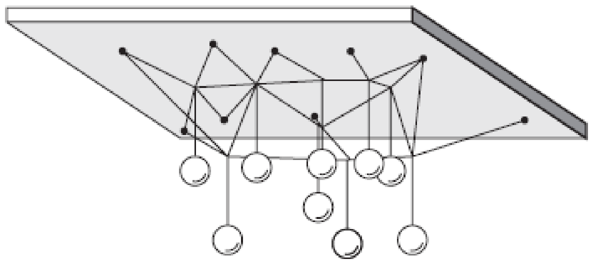
Heatmap of angular displacement at 12:00

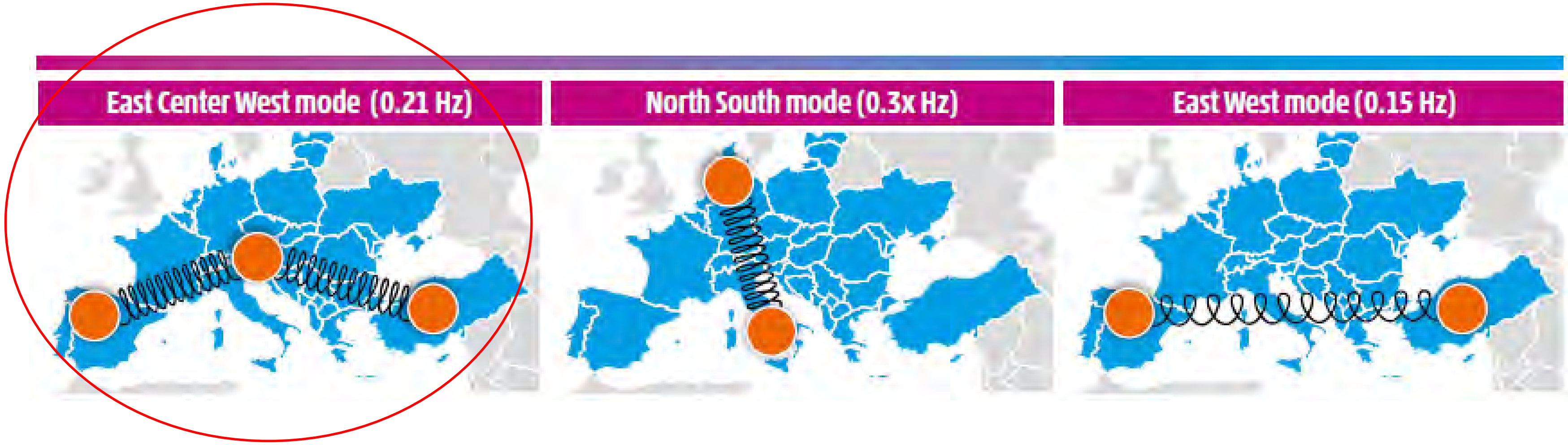
What are power system oscillations?

- In traditional systems, oscillations between rotors of synchronous machines
  - Spring-like mechanism
  - Occur when weak transmission links between regions
- Well-known European inter-area modes of oscillations



Source: D. Gross

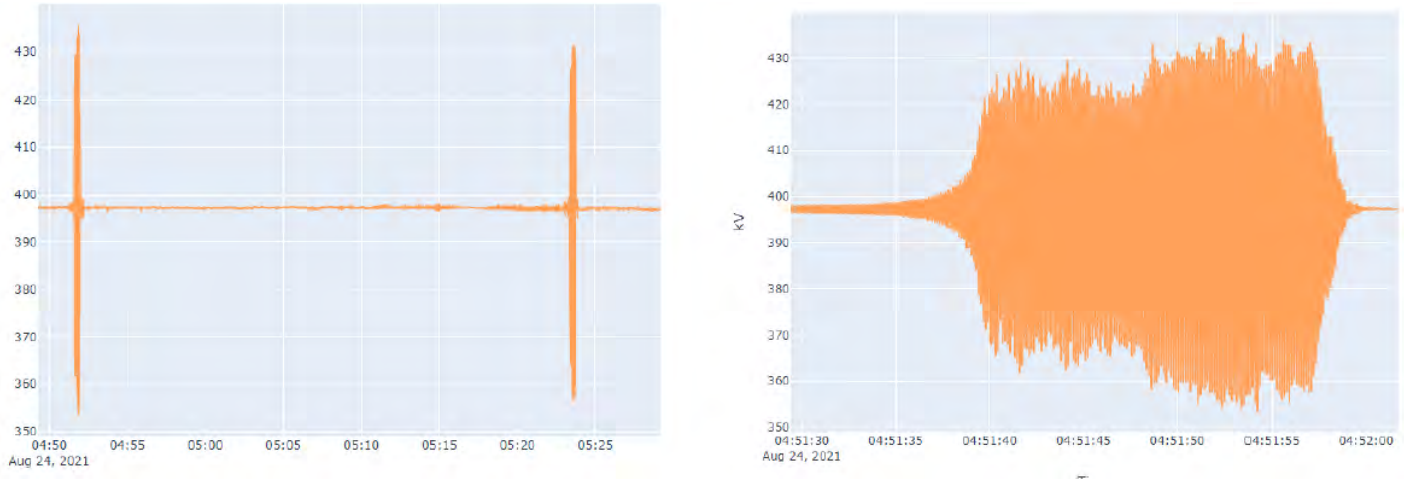




A new kid on the block: Sub Synchronous Oscillations (SSO)

- Inverter Based Resources (IBRs) replace synchronous machines
  - Fully programmable
  - May malfunction in a “weak” grid
  - Many additional control loops
  - Possible inadvertent harmful interactions
- Many cases of spontaneous oscillations around the world
  - Not well understood

Scotland 2021



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1st oscillation: 0.63 Hz, 12:03-12:08

½ hour before the blackout, about 5 mins duration

A local Iberian oscillation – not affecting Europe

A forced SSO caused by a malfunction of controls of a (unnamed) PV plant

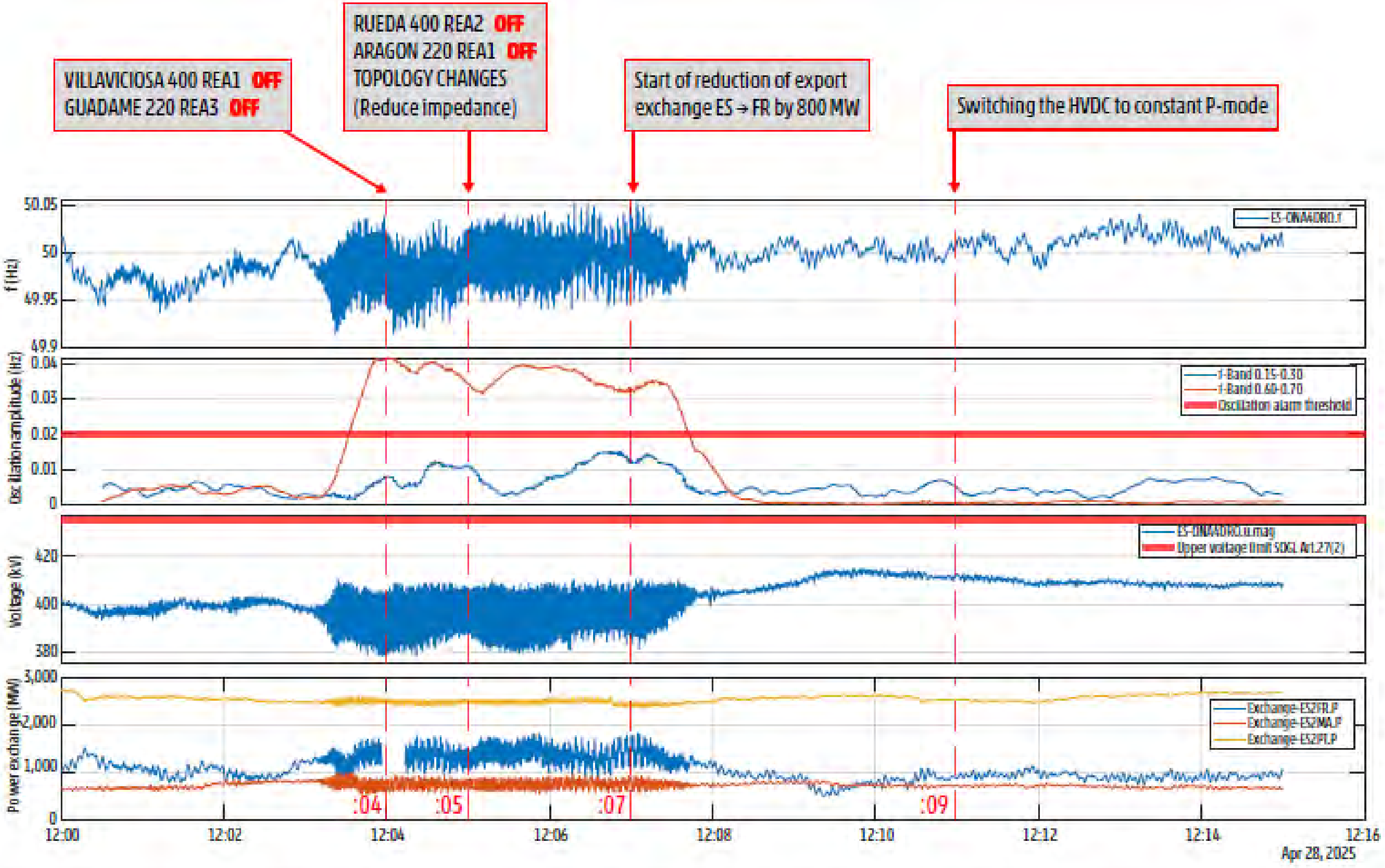
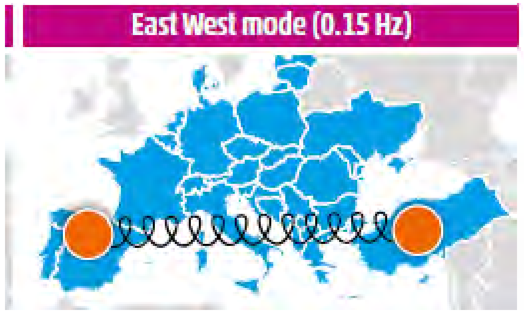


Figure 2-48: Characteristics data of the first oscillations (source: WAMS 100 ms sampling rate in the 6 kV Carmona (Spain) substation) and countermeasures applied

2nd oscillation, 0.21 Hz, 12:19-12:22

- a well-known inter-area electromechanical mode
- 3 mins duration
- Iberia vs Eastern Europe (Baltics, Hungary, Poland, Turkey)



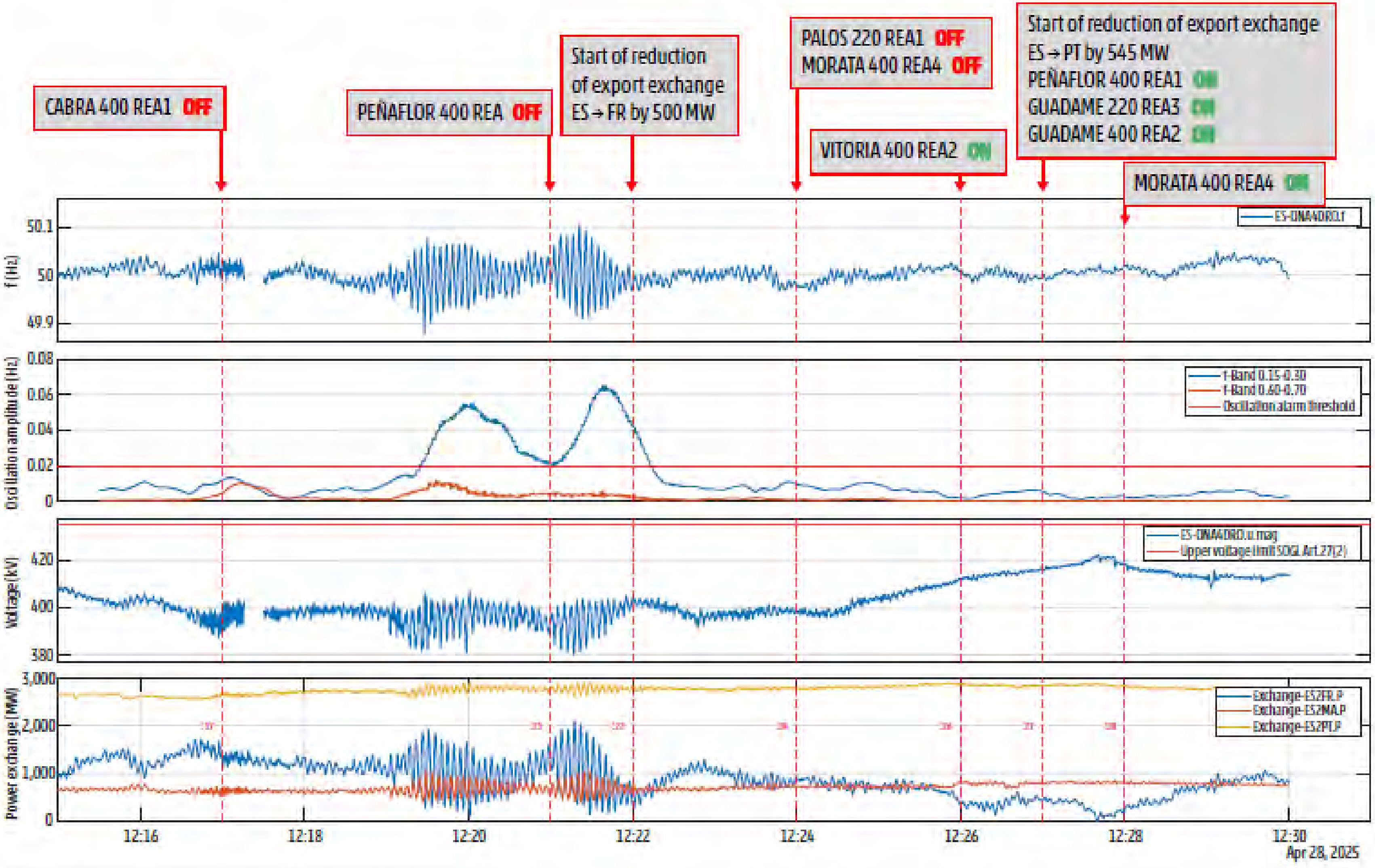
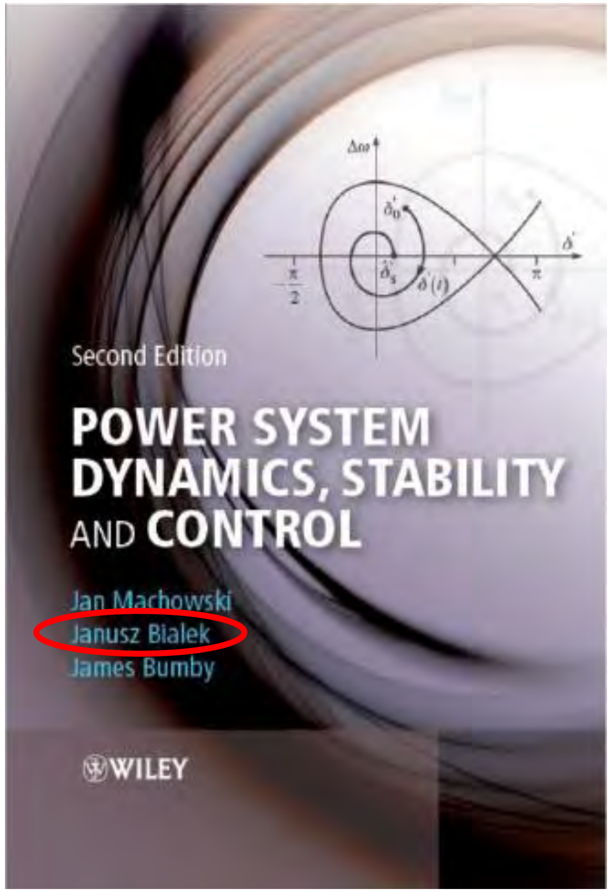


Figure 2-62: Characteristics data of the second oscillations and increasing voltage (source: WAMS 100 ms sampling rate at the 400 kV Carmona substation) and countermeasures

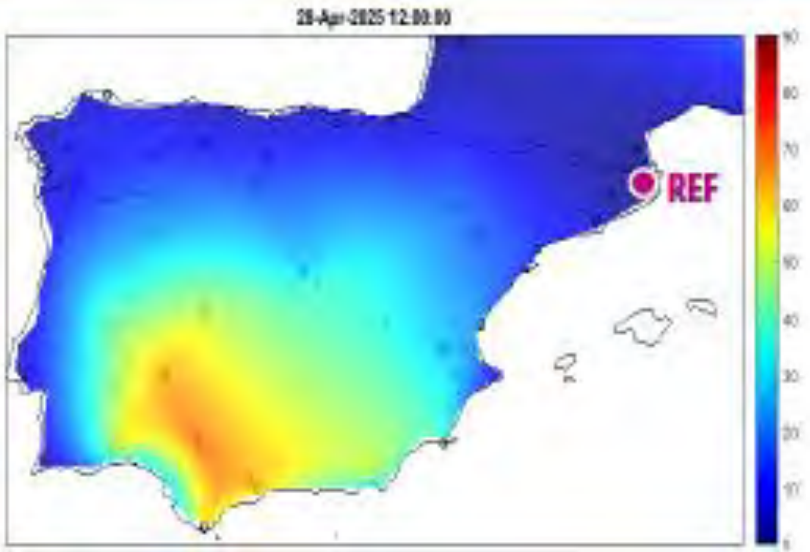
How to damp electromechanical oscillations

- Increase voltages
- Strengthen the network (connect more lines)
- Reduce inter-area flows

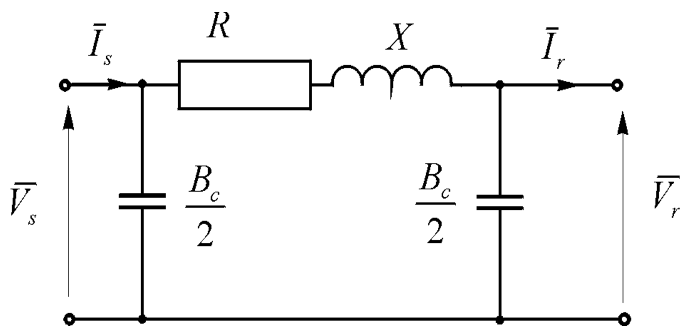


And that’s what they did!

- Ten 400 kV lines were reconnected to strengthen the network
  - Average loading on lines has decreased
  - Side effect: reduced reactive power consumption, V↗
- Export to France was reduced by reducing southern PV generation
  - Side effect - further reduction of line loadings across Spain, V↗
- Some reactors were switched off to increase the voltage, V↗
- Some other control actions not affecting voltages



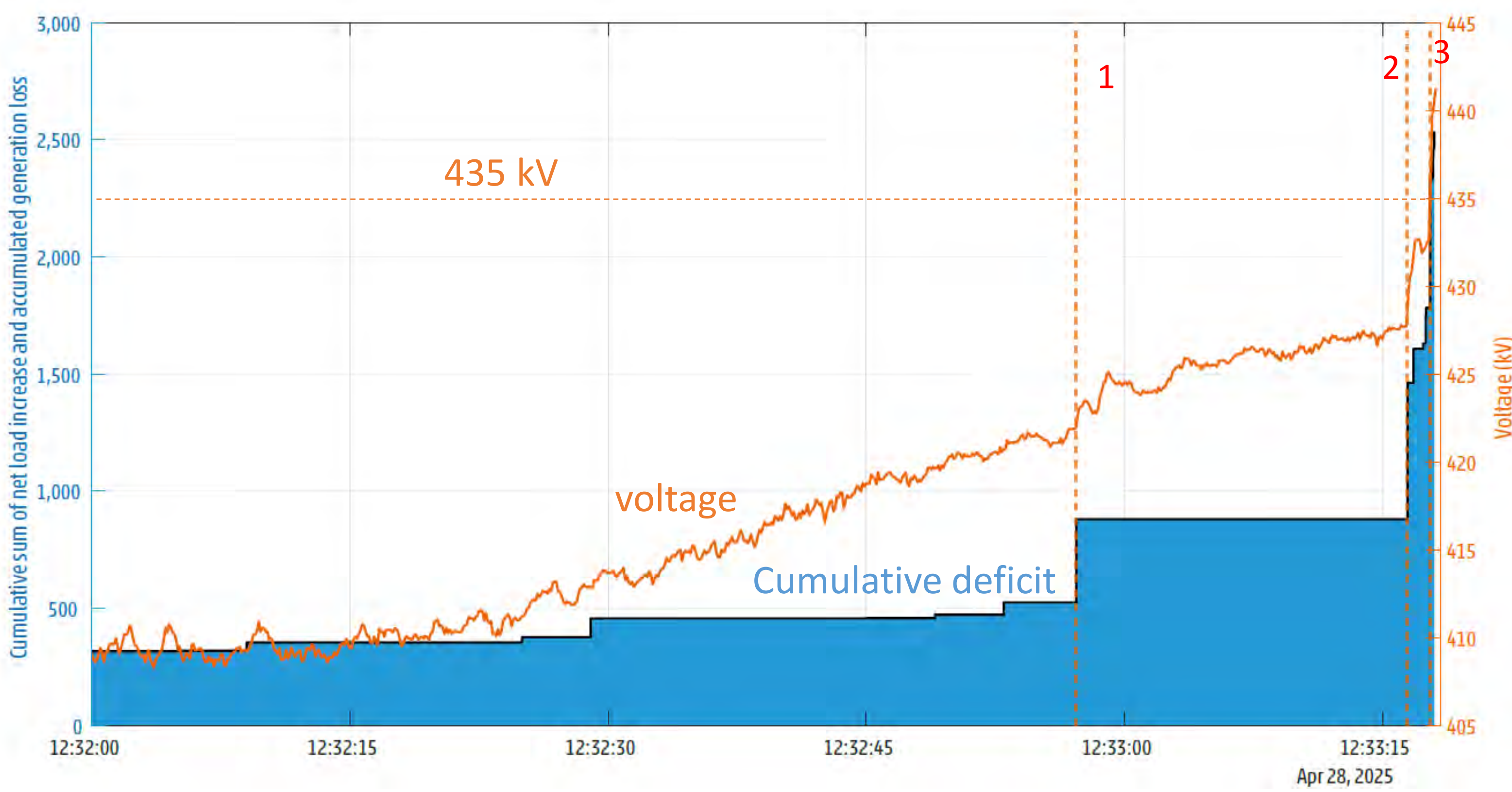
Heatmap of angular displacement at 12:00



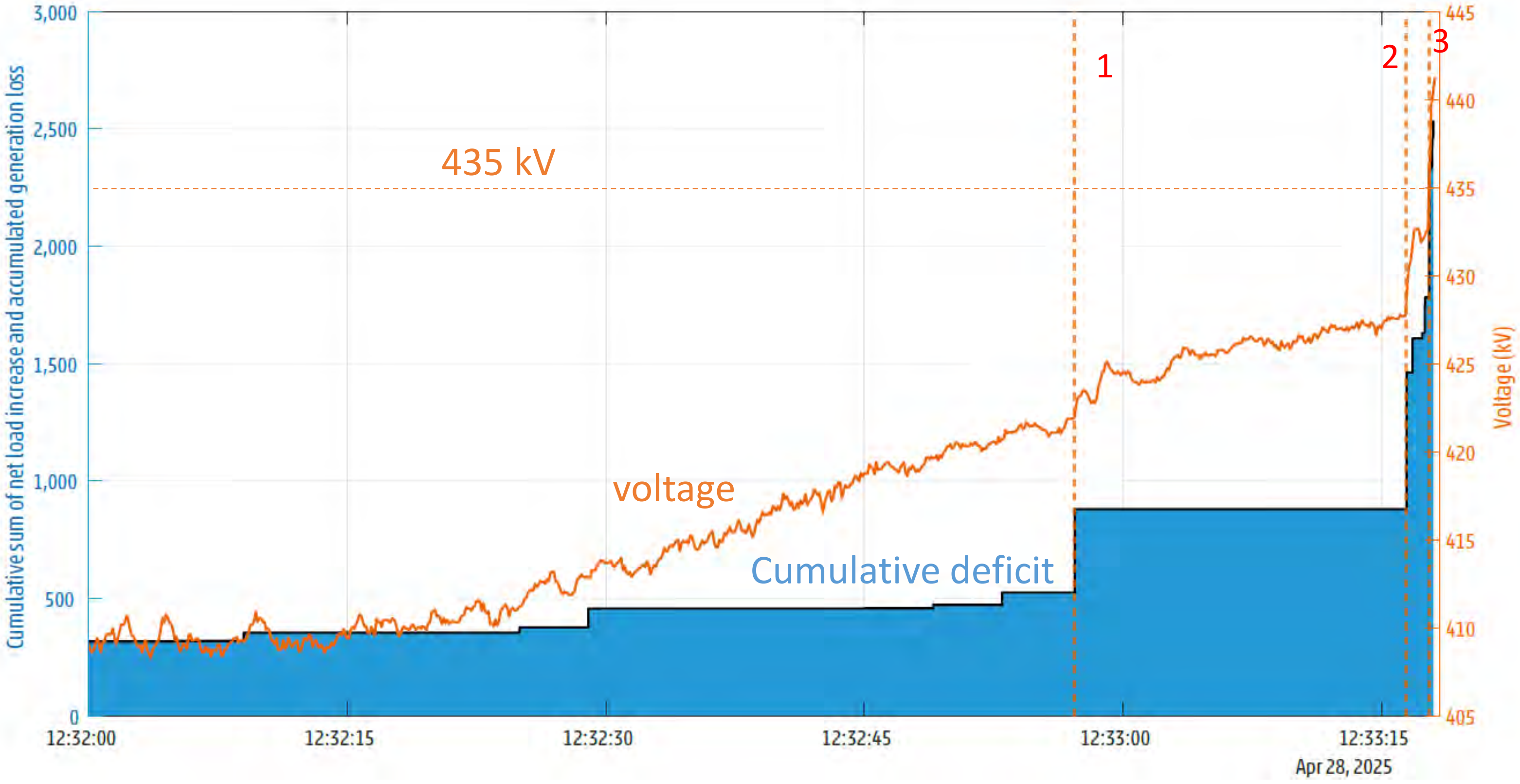
Equivalent circuit of a transmission line
$Q_{cap} \propto V^2 \approx$ const
$Q_{ind} \propto I^2 \approx$ variable

A vicious circle of generation trips

- Fast voltage rise led to generation trips
- A wind/PV solar generation trip causes V↗ due to
    - Reduction of line flows
    - Reduction of Q consumption by RES (constant power factor)
- This causes further overvoltage and consequent trips



Generation trips



- Causes of many trips are still unknown due to poor observability of Distributed Generation
- 1: in 1 minute, about 1 GW imbalance
  - distributed wind and PV tripped due to unknown reasons
  - Rooftop PV tripped
  - Demand increase due to increased voltage
- 2: 20 secs - overvoltage trips of a transformer with its connected generation, wind and solar plants; cumulative total about 1.5 GW
- But transmission voltage still < upper limit of 435 kV!
- 3: 1 sec - Voltage increases triggering further trips of RES and conventional generation in Spain: 2.5 GW total
- No trips in Portugal or France so far

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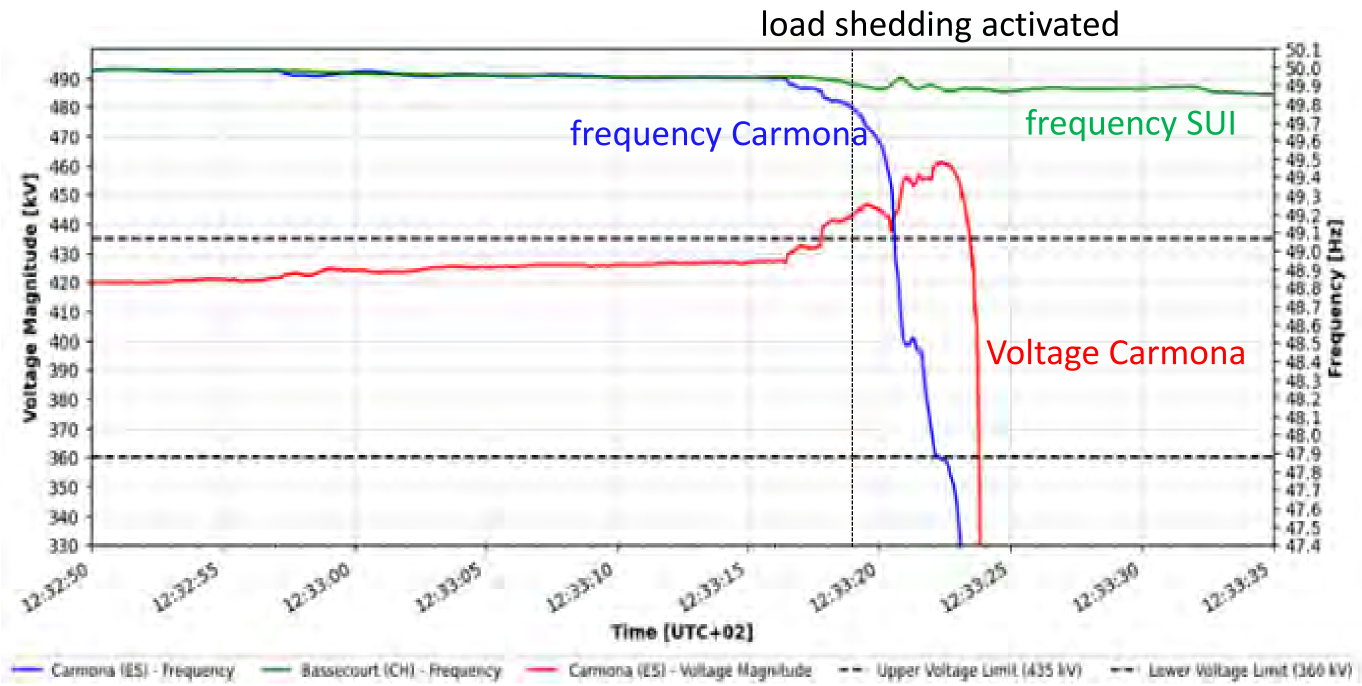
- frequency was dropping so automatic load shedding in Iberia was activated at 23:33:19
    - Inadvertent loss of Q consumption, V↗
    - Further reduction of line flows and V↗
- Further generation trips and frequency drop
- trips of interconnectors to Marocco and France
- total collapse of the Iberian system in less than 1.5 minute after the first plant trip
- Restoration was relatively quick: up to 12 hours in Portugal and 16 hours in Spain (but many areas were connected quicker)



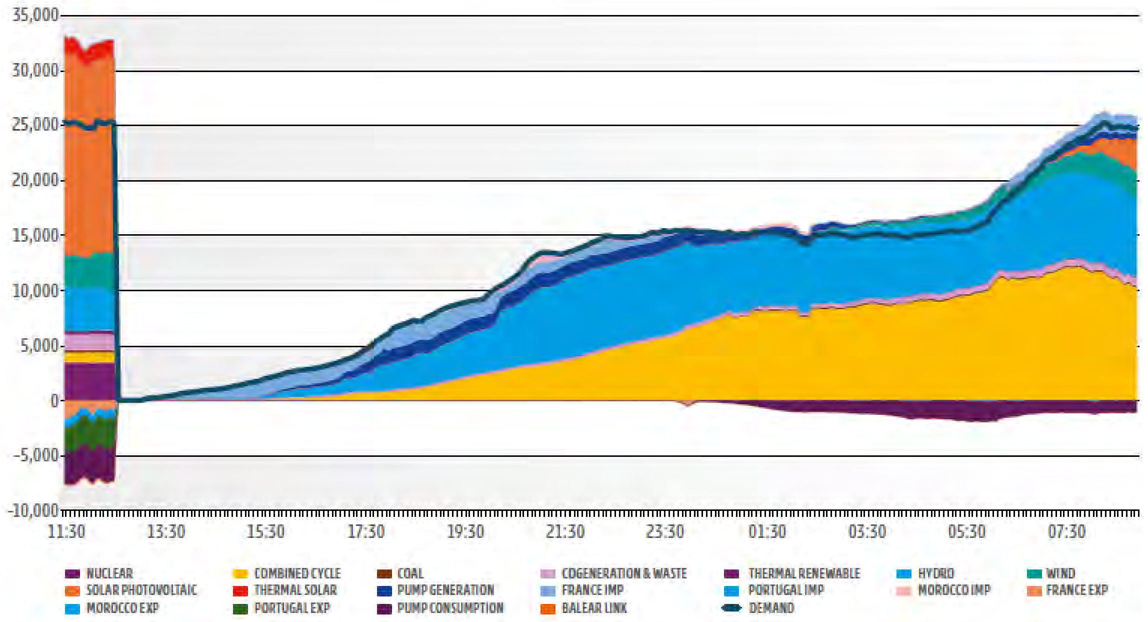
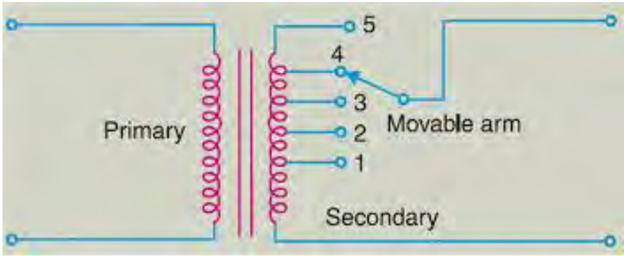


Figure 4-24: Evolution of generation and load of the Spanish system during the restoration phase - Red Eléctrica

Why the reaction to rising voltages was slow and inadequate?



- The rise in voltage was NOT unexpected
- Why slow? Technical reasons
    - Tap-changing transformers operate with dead-zones and delays to avoid unnecessary operation
    - Shunt reactors are manually operated in Spain
- Why inadequate?
    - Non-compliance of traditional gens (below 75% of required reaction)
        - No penalties for non-delivery
    - Poor design of voltage control in local generation networks
    - Poor design of overvoltage protection of wind and PV
- Too few means for dynamic voltage control
    - Only 10 conventional plants providing dynamic voltage support with few in the south
    - RES plants operating at a constant power factor

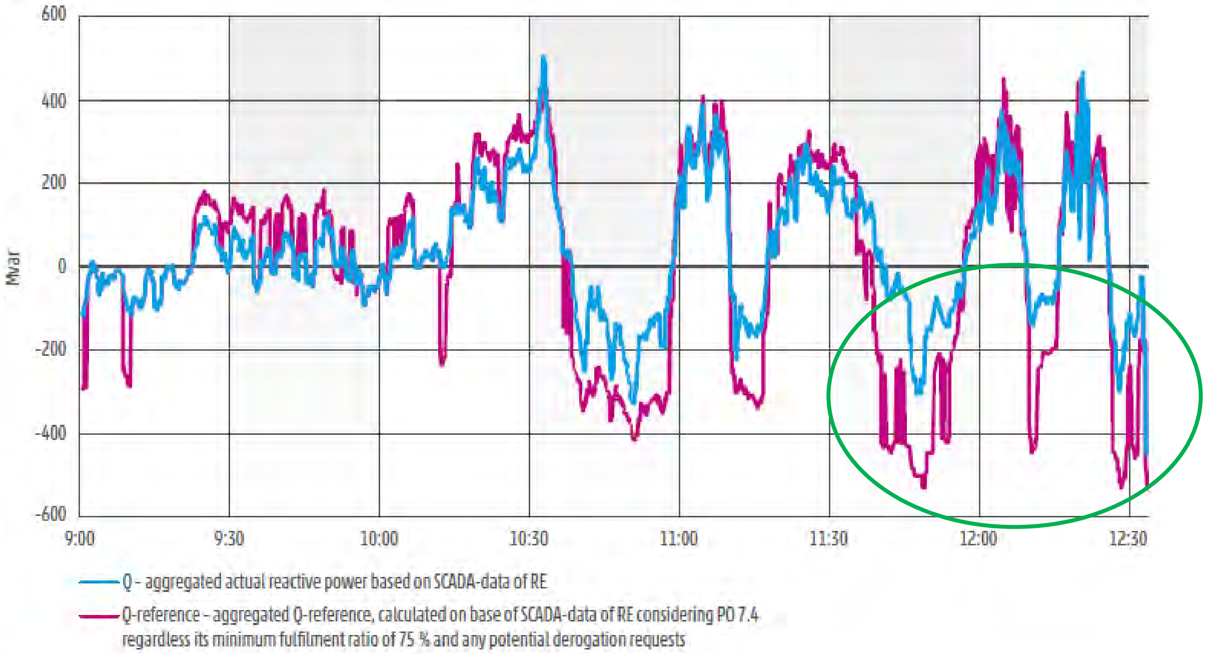


Figure 1-11: Reactive power provided (Q) and the reference reactive power (Q-reference) aggregated for conventional generation units larger than 100 MW of power installed capacity in the centre/southwest area of Spain, based on SCADA data from RE.

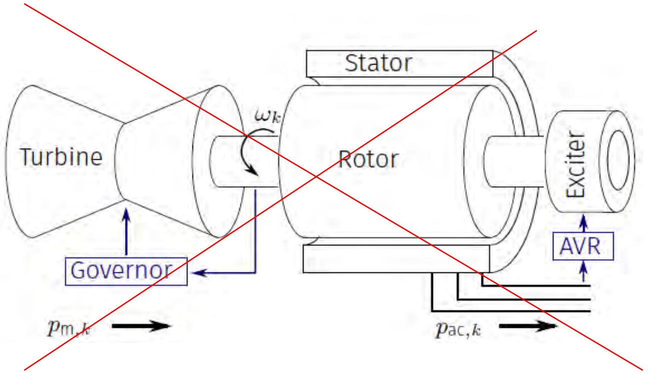
Regulatory reaction to the blackout

- The system operator began authorising renewable plants to provide voltage control.
- Additional rules were adopted to further strengthen voltage control and grid stability
- In April 2026, National Markets and Competition Commission (CNMC) opened a probe into:
    - REE over “very serious” alleged infringements
    - power companies over “serious” breaches of the law

Underlying reasons for the blackout

- The direct reasons for the blackout
  - Overlooked interactions between oscillations and voltage control
  - Inadequate voltage control arrangements in Spain
- But what were the main underlying reasons?
  - The emphasis was on fast growth of RES in Spain
  - System controls have not been sufficiently adapted to a high penetration of RES
  - One cannot operate the same way as a traditional grid
  - Other countries have adapted better (Portugal, GB, Ireland, Australia, et al)

Conclusions



- The Iberian blackout was a warning shot
- Are we in danger too?
- It was a particular Spanish mishap but …
- Fast penetration of IBRs changes the fundamental system characteristics
  - Synchronous machines are replaced by power electronics
  - Physics-based operation replaced by software-based
  - Physics never fails but software can
  - Poorly understood phenomena
  - A lot of “unknown unknowns” – we don’t know what can hit us next
  - System operators are scared
  - More research is needed!
- When and where will be the next one?
- I don’t know but I hope before I retire

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