TRANSPOWER

Iberian Peninsula Blackout - 28 April 2025

Overview of the event and the lessons for NZ

System Operator
June 2026

IMPORTANT

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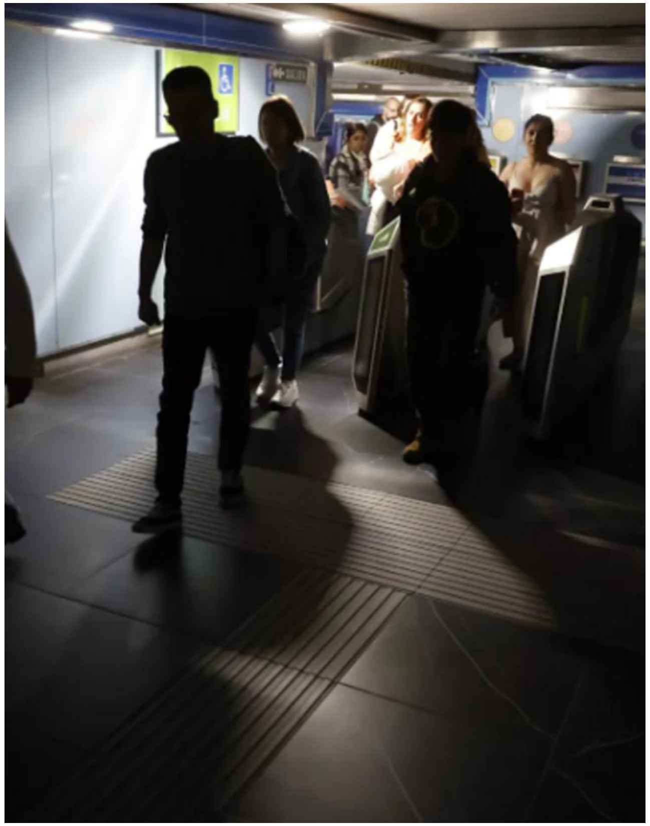
1 Introduction

On 28th April 2025 at 12:33 pm Spain and Portugal experienced a full blackout. Some areas of the peninsular were without power for over 16 hours. This was the most severe blackout in Europe in 20 years.

Large blackouts are rare but cause widespread impacts extending to loss of public transport, impacts on water services and air traffic control. When they happen overseas, they provide an opportunity to learn. In our role as System Operator we monitor international events for lessons improve our own operations processes and prevent similar failures from occurring in New Zealand.

Several reports have been released explaining the cause of the blackout, but the most detailed analysis report, on the root causes and recommendations, was released by ENTSO-E in March 2026. This review focuses on the root causes identified by ENTSO-E and the high-level lessons for NZ.



1.1 What this paper covers

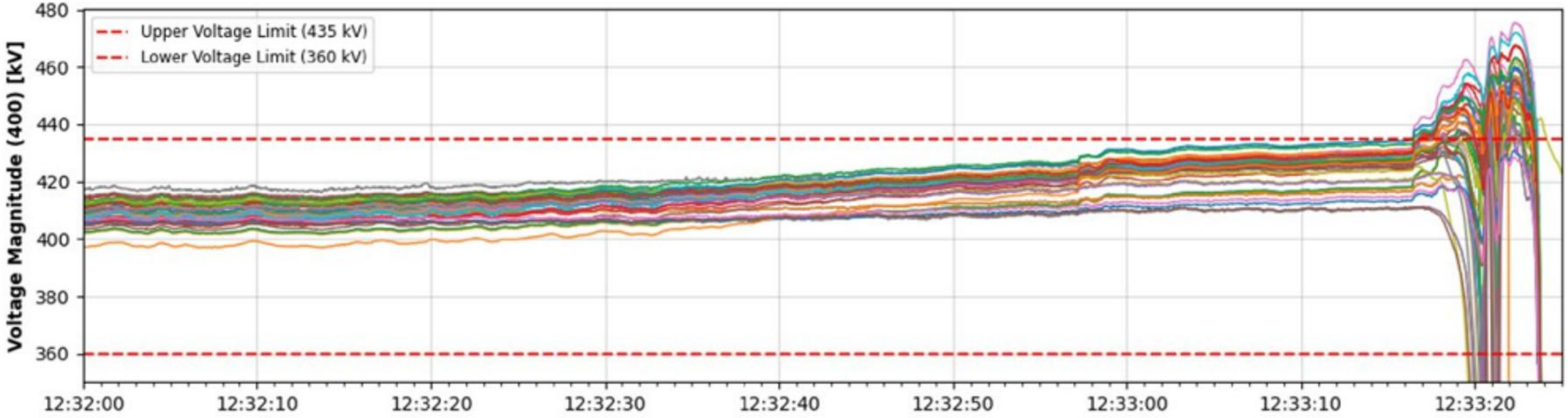
1. An overview of the blackout and the Iberian Power System
2. Overview of oscillations prior to the power system collapse
3. Overview of system collapse
4. Root causes for the blackout
5. Recommendations given by ENTSO-E and how they apply to NZ

2 Overview 28 April 2025 black out

The morning: The day began as normal. Weather was mild and sunny, wind and solar generation were typical for the season and Spain was exporting several GW of power to other regions. Voltage levels were within acceptable bounds but showing increasing variability from around mid-morning. There was no single warning sign—just a slightly "restless" voltage profile developing through the morning. The penetration of renewables, particularly solar, was climbing up to about 55% by the time of the event. By late morning, the system was technically stable, but with reduced resilience—particularly to disturbances.

The 'midday' Oscillations, actions to dampen them and climbing voltages: At around 12:00 noon, the system operator observed two distinct oscillation events. The first had a mode around ~0.6 Hz, driven by a solar PV plant in Badajoz, Spain, and seen locally. The second (≈12:19–12:22) was a known inter-area oscillation (~0.21 Hz) across wider Europe. Operators acted to damp the oscillations by reducing cross-border exports and by reconnecting lines to reduce impedance. Whilst these actions helped stabilise the second set of oscillations, they had the unintended consequence of pushing voltages higher across the Iberian system. By around 12:30–12:32: Oscillations had stopped, but voltage had become dangerously high and poorly controlled.

Over-voltages and system collapse: What happened next was fast. Voltage rose toward operational limits and appears to have triggered initial generator disconnections. Each generator that tripped or ramped down removed reactive power absorption and caused voltage to increase further. This triggered even higher voltage, more trips, interconnectors were disconnected to protect other regions, and the system collapsed.



3 Peninsula – the system prior to event

The Iberian peninsular network at the time had a load of ~31 GW – around four times higher than the NZ winter peak load. Immediately prior to the blackout, around 55% of the generation was solar. The network includes a number of connections with the rest Europe.

Tie lines to Morocco:

- 2x 400 kV AC
- 1400 MW total capacity

Source: ENTSO-E Grid Maps

Tie lines to France:

- 2x 400kV AC, 2x 220 kV AC,
- 1 HVDC.
- 2800 MW total capacity.
- 1 of the 220 kV lines (in red) was on planned outage prior to the blackout.

Load at time of event

Spain: ~25,200 MW

Portugal: ~5,500 MW

4 ‘Midday’ Oscillations prior to the blackout

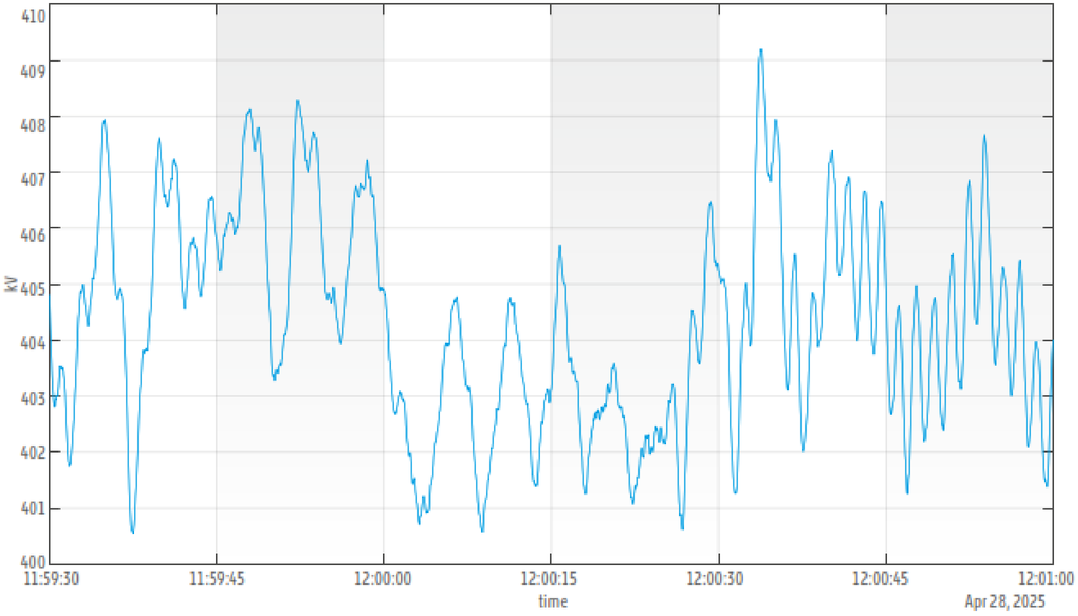
Prior to the blackout, the system was approaching high solar export in the middle of the day. The system began experiencing oscillations, and operators in control rooms took actions to mitigate these. While the oscillations did not cause the blackout, the actions taken to mitigate them helped lead to the conditions that allowed the blackout to occur.

Oscillations are when one part of a power system fluctuates against another part of the system, which are seen as the system voltage or system frequency oscillating at with a frequency (or mode) that is different to the nominal frequency of the system. They can be local, where one unit oscillates against the rest of the system, or be wider inter-area where a group of generators in one part of the system oscillates against a group in another part of the system. These are more likely when a region is experiencing low system strength – at periods of weak voltage control. The oscillations on this day were:

- 0.63 Hz oscillations in frequency and voltage in the Iberian Peninsula system. These were analysed post-event and determined to be local oscillations, likely generated from a control system injecting a periodic disturbance.
- A second 0.21 Hz oscillation 12 minutes later, corresponding to a known European inter-area mode, involving groups of generators.

Actions taken to mitigate these included reducing exports to France and reconnecting transmission lines within Spain.

Reducing exports helped reduce the interarea oscillations, and reconnecting lines helped reduce impedance and damp electro-magnetic oscillations. Both these actions worked to worsen voltage control, and push voltages higher. The reduced power transfers reduced current flows and reduced the consequent voltage drops along the lines. Both the reduced transfers and reconnected transmission lines acted to reduce reactive power absorption within the system.



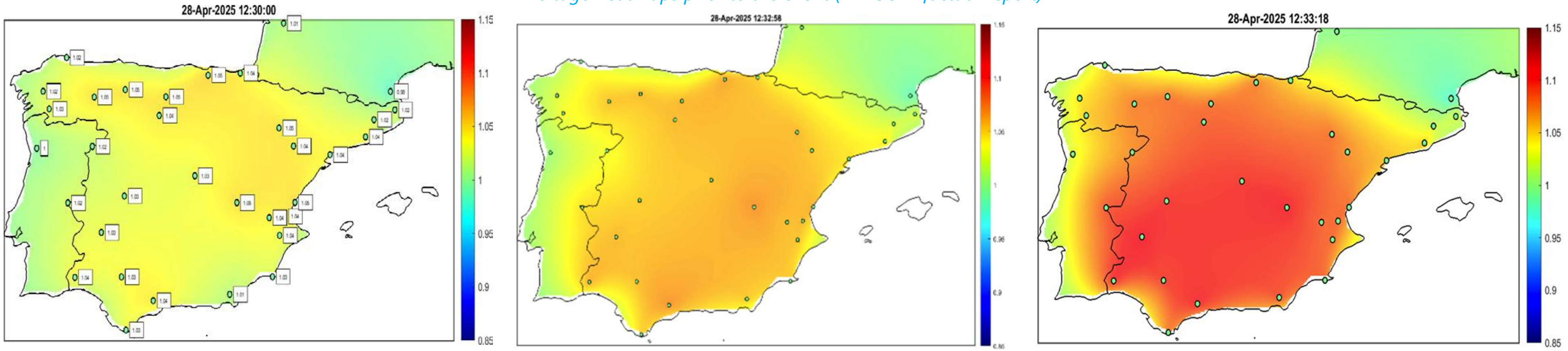
0.63 Hz voltage oscillations prior to the event.
Source: ENTSO-E final report

5 Events leading into the blackout

As a result of actions taken to avoid oscillations, voltage began increasing. At 12:33, generation began tripping on over-voltage. Further generation tripping caused overvoltages over the next two minutes and the system collapsed.

- The first generation transformer tripped in Southern Spain on overvoltage while the grid voltage was still within limits, removing ~355 MW of generation. This had the effect of increasing voltage further by reducing reactive power absorption.
- A further 725 MW generation tripped in Southwest Spain, leading to even higher voltages.
- A further 1100 MW generation tripped around the south and southwest of Spain.
- Over-voltages from the loss of these generators caused cascade generation over-voltage tripping through Spain.
- Spanish/Portuguese AUFLS equivalent activated, but this was insufficient to prevent collapse of the system.
- The Iberian Peninsula was disconnected from the rest of the European grid by protection action on HVDC links and AC interconnections. Spain and Portugal power systems blacked out.

Voltage heatmaps prior to the event (ENTSO-E factual report)

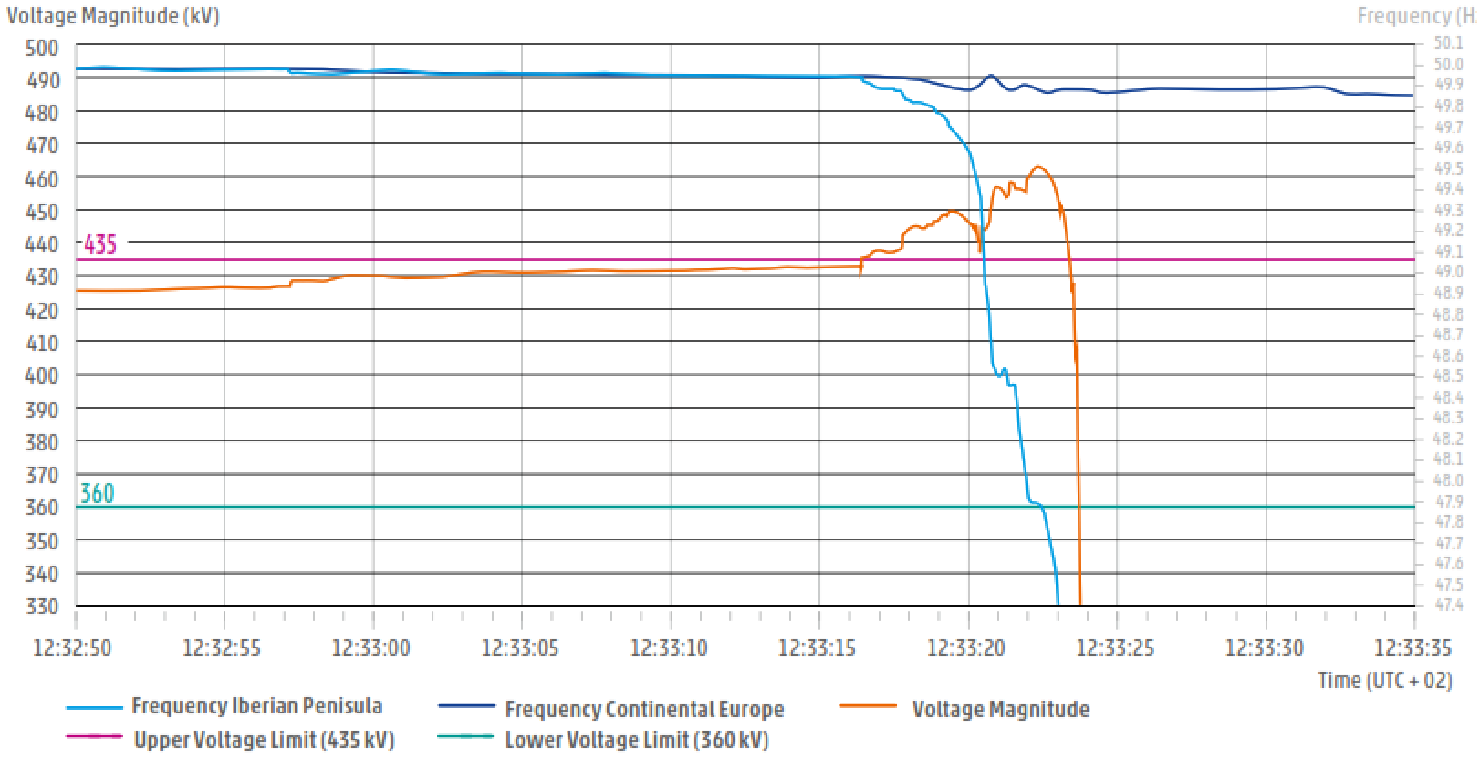


6 Root causes of the cascade system collapse

The ENTSO-E report sets out 14 root causes; these are summarised here and provided in more detail in the reference slides.

The trigger for the collapse was rapidly increasing voltage with three high-level groups of factors:

1. The Iberian system ran out of reactive margin (spare reactive power capacity) to control the voltage.
2. The Spanish 400 kV system was operated at a much wider voltage range than other countries which left little to no margin before generators were required to trip
3. Overvoltage protection settings for generators and networks were not aligned with system needs.



Evolution of frequency and voltage in Carmona (Spain) against frequency in Continental Europe.
Source: ENTSO-E Final Report

7 Fast voltage rise: root causes

The Iberian system ran out of reactive margin (spare reactive power capacity) to control the voltage.

- Control room actions taken to mitigate oscillatory behaviour (switching lines back into service, reducing flows from Spain to France) caused an increase in the steady-state voltage of the grid.
- Shunt reactors were all switched manually, instead of being part of automatic control schemes, requiring human processing time to switch in/out.
- Only one STATCOM was in operation, with another undergoing the final testing before commissioning.
- Solar and other inverter-based renewable sources were operated in fixed power factor mode, so were unable to respond to the increase in voltage by absorbing further reactive power. Reduction in active power output also caused reduction in reactive power being absorbed.
- Conventional generation ran out of reactive margin – the ability to absorb further reactive power.

Spain's 400 kV grid operated at a wider voltage range than other countries

- Spain's 400 kV grid was operated at 380 kV to 435 kV which left little to no margin before generators were required to trip (at 435 kV or 400kV)

Overvoltage protection settings for many generators and networks were not aligned with system needs.

- Some generators were set to trip with zero delay once the voltage went outside the allowable voltage range, instead of having fixed time settings based on voltage level or similar.
- In some cases, the protection settings were not set to co-ordinate with the VT nominal voltage ratio, leading to settings that picked up while the voltage was within the allowable voltage range

8 Key recommendations and significance to NZ

8.1 Voltage control

Voltage Control Recommendations	New Zealand comparison and key lessons (in bold)
Generators should use **voltage-control mode** wherever possible	Recent Electricity Industry Participation Code updates require all new generators over 10 MW, as well as existing generators above 30MW, to operate in voltage control mode to provide voltage support regardless of fuel type. **However, it is important to maintain monitoring and compliance around these requirements.**
In planning, Transmission companies should **design the system** so it can operate in expected uncertainties through use of static and dynamic reactive power sources	Transpower's System Planning team considers voltage control in system design, as seen with recent investment into STATCOMs in the Upper North Island and further proposed investment into more reactive plant to help the Upper South Island.
In operational planning and real-time, system operators **should account for potential rapid voltage slopes** from active and reactive power ramping, build in sufficient margins, and monitor the performance of reactive power resources	Remaining margin on dynamic reactive plant is considered in operations planning studies, to avoid these plant operating at their extremes. Dynamic reactive plant are also operated as close to the middle of their ranges as practical in real-time under. Real-time contingency analysis assesses and provides visibility on enough reactive margin needed to regulate system voltage.
Automation of reactive power support	New Zealand has reactive power controllers (RPCs) in service in various places around the country to automate switching of shunt devices.
Use an **appropriate voltage operating range** with sufficient voltage margin	New Zealand has the same voltage operating ranges across both the North and South Island and is not operated as close to the extremes of these ranges under normal circumstances. Over-voltage protection settings are outside these margins.
Consider and avoid **ramping that is faster than voltage control**. This is particularly important for Spain where fixed power factor was used.	Maximum active power ramp rates are agreed with new connections before commissioning to reduce frequency swings from dispatch changes, and they operate in voltage control mode reducing the impact on voltage deviation with changes in active power. **We are assessing how ramp rates of intermittent generation affect system frequency when constraints are lifted and deciding the next steps.**

8.2 Disconnections

Disconnections	New Zealand comparison and key lessons (in bold)
Validate the protection settings for generation and other assets	Under the Code, asset owner protection systems must undergo routine testing, with verification provided to the System Operator that the protection systems meet their obligations under the Code. **However, it is worth considering whether to re-validate over-protections during routine testing**
Require high voltage ride-through capability for type A generation (0.8 kW-1MW, connected below 110 kV)	DER installed after 2020 must comply with AS/NZS 4777.2:2020, which specifies voltage limits where the installation must remain in continuous operation.
Putting controls in place after trippings during events to check asset owner capabilities	We investigate unexpected tripping as part of our event investigation process to determine whether a plant was complying with their Code obligations. **However, as for the voltage support obligations, it is important to maintain monitoring and compliance for fault ride through**
Investigate connection and reconnection behaviour of non-observable DER	AS/NZS 4777.2 also requires DER installations to have an automatic disconnection device, as well as specifying connection and reconnection procedures for DER.

8.3 Oscillations and data

Oscillations	New Zealand comparison and key lessons (in bold)
Establish a framework for inter-area oscillations including defining damping required, modelling and studies	**This is an increasingly important area internationally with the increase in inverter-based resources generally. In NZ we need to upskill our engineers in assessing and analysing oscillatory stability. We also need to develop processes to help assess oscillatory stability and keep abreast of industry best-practice in analysis techniques as these are also rapidly developing.**
Enhance monitoring and real-time detection	**Some sub-synchronous oscillations have been detected on the NZ system via 25 high-resolution PMUs spread across 17 sites throughout the country. However, we do not have visibility across a large range of frequency and have no visibility in our control rooms. We are investigating tools and techniques to assess converter stability and are also working with our transmission business to accelerate offline assessment and to introduce real-time monitoring capability**

Post event data	New Zealand comparison and key lessons (in bold)
Create snapshots of the system after a significant event to allow accurate simulations – this is specifically for oscillations	Snapshots of the system are taken every 4 minutes automatically for the real-time voltage stability analysis tool. In addition, snapshots from SCADA data can be brought into our Powerfactory, DSA Tools, and PSCAD models for offline analysis.
Establish a standardised framework for data provision during incident investigations covering the data types and formats, latency, data sharing and legal provisions removing the need for ad hoc negotiations	Updates to the Code and Connected Asset Commissioning, Testing and Information Standard (CACTIS) will require new generators to install automatically triggered high-speed data monitors to provide post-event data with specified formats and quantities for analysis. Obtaining this data for existing assets will continue to require ad-hoc negotiation.

8.4 System defence and restoration

System Defence	New Zealand comparison and key lessons (in bold)
Implement an adaptive Automatic Load Shedding Scheme to take account of DER	**NZ's AUFLS scheme has been updated to provide more granularity in response and to include responses triggered by the rate of change of frequency. Going forward, as increasing resources are connected on distribution feeders or at household level, it will be important to assess the effectiveness of the AUFLS scheme, to establish the level of visibility required at feeder level and be prepared to modernise our backstop defence systems. Work to establish operating roles, data sharing between the system operator and DSOs is important to progress.** **The Electricity Authority is working with the system operator and distributors to improve management of reactive power flow through GXPs**
Real-time visibility at feeder level including flows, DER status and Automatic Load Shedding status	
Modernise system defence plan to reflect high IBR and DER environment to cover fast voltage change, oscillations, rapidly changing power flows	

Restoration	New Zealand comparison and key lessons (in bold)
Run periodic black start and island-mode tests	We require the four black-start providers to test their capability every two years. **However, going forward we will need to review our black start and restoration processes generally to take account of increased DER and new technologies.**
Define a framework for DER controlled reconnection and DSO visibility	AS/NZS 4777.2 specifies the conditions under which new DER installations can reconnect to the local network, and minimum and maximum ramp rate limits to return to nominal active power output post reconnection.
Enhance restoration industry trainings	An industry exercise is carried out annually to practice the response from the control rooms across the industry to a simulated major event. Transpower, its service providers and large generator shave at least 24 hours black-out proof communications, and critical tools (including Cell phones, satphones and fleet link). It is not clear if all distributors have the same level of emergency communications. We have an ongoing comms project which should deliver one-to-one and one-to-many messaging and is intended to be relatively low cost so distributors can implement.
Ensure at least 24 hours black-out proof communication and critical tools	

9 Key actions for New Zealand

While the standards and regulations in Europe differ from New Zealand, asset owner compliance the visibility and co-ordination of DER, and oscillations and inverter behaviour are areas that could increase risks to New Zealand. We have identified key actions which we are addressing and have built these into our strategy development.

Voltage control and generation requirements

ACTION: Strengthen Asset Owner Compliance and Testing Processes

As System Operator we have strengthened our commissioning and testing processes, and worked with the Authority on the new CACTIS. We need to follow these improvements with improved monitoring, and compliance controls.

We are looking at opportunities to build more monitoring (for example of secondary tripping) that can cope with the increased volumes of both smaller generators and compliance requirements, and provide a focus on highest-risk non-compliance.

ACTION: Increase DER visibility and coordination, and coordination of reactive power flows across GXPs

The Authority is progressing work on Future System Operations, which is considering models for distribution system operations. In the meantime, the System Operator requires increased visibility and coordination of DER. We are preparing a paper on the key requirements to maintain system security. We are been actively involved in industry forums such as Flex Forum and have included some communication requirements in the CACTIS. We are also involved in voltage management coordination work with the Authority and Distributors.

ACTION: Consider validating generation over-voltage protection settings during routine testing

Oscillations, inverter behaviour, and the speed of transition to a more IBR-dominated network are areas that could increase risk to New Zealand.

ACTION: Accelerate System Monitoring Work

The System Operator has completed initial scoping of work required to lift system monitoring. This will include short term improvements to monitor system inertia, frequency and voltage deviations. It also requires acceleration of high-resolution Grid and generator monitoring equipment installation. We particularly need to develop high speed monitoring and analytics to ultimately have real-time visibility of oscillatory behaviour. The System Monitoring work will also consider the availability and requirements for post-event data, noting there are already requirements for data built into the CACTIS.

ACTION: Accelerate work on system strength and inverter interactions

We are progressing work on tools, processes and upskilling on system stability and inverter interactions. We are carefully monitoring international developments and will involve overseas expertise to assist us in developing guidelines and assessment capabilities. We are also working with the Authority on system strength under the Future Security and Resilience programme.

System defence and restoration (future actions)

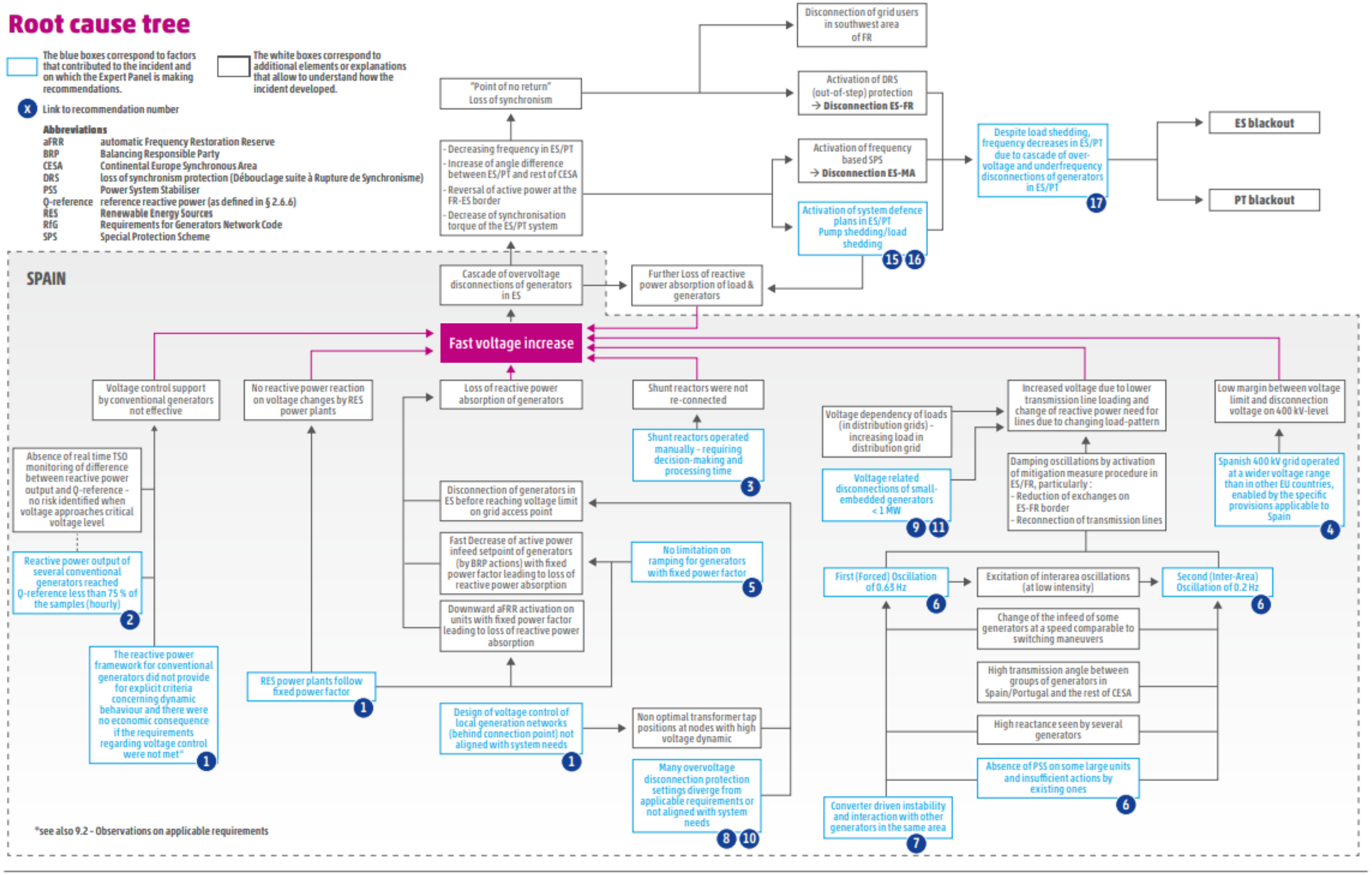
ACTION: Review AUFLS in light of increased DER

This will involve reviewing the effectiveness of the Automatic Underfrequency Load Shedding Scheme (AUFLS) with increased generation and other DER connecting at feeder level.

ACTION: Review restoration and black-start plans

We regularly run black start exercises (every 6 months), simulated restoration exercises, and an annual industry exercise for a significant event. However, as more DER, including behind-the-meter resources connect we will review our procedures to take account of increased DER.

Reference Material



Root cause tree

The blue boxes correspond to factors that contributed to the incident and on which the Expert Panel is making recommendations.

The white boxes correspond to additional elements or explanations that allow to understand how the incident developed.

Ⓧ Link to recommendation number

Abbreviations

aFRR	automatic Frequency Restoration Reserve
BRP	Balancing Responsible Party
CESA	Continental Europe Synchronous Area
DRS	loss of synchronism protection (Débouclage suite à Rupture de Synchronisme)
PSS	Power System Stabiliser
Q-reference	reference reactive power (as defined in § 2.6.6)
RES	Renewable Energy Sources
RfG	Requirements for Generators Network Code
SPS	Special Protection Scheme

*see also 9.2 - Observations on applicable requirements

Figure 4-124: Root cause tree linked with recommendations

Source: ENTSO-E final report

Key root cause factors in ENTSO-E report in more detail

Numbers match the final ENTSO-E report (Summarised from pp 333, 334)

Factors influencing fast voltage increase

Related to Voltage control - Non-effective voltage control by conventional generators, no voltage support from renewable plants, and voltage control for some local generation networks not aligned with needs

1. Several conventional units provided less reactive power support than the operational procedure in Spain required – more reactive power absorption would have led to a decrease in voltages
2. The reactive power framework for these generators did not provide explicit criteria concerning dynamic behaviour, and there were no consequences if voltage control requirements were not met
3. Renewable energy power plants followed fixed power factor which meant they provided no reactive support to compensate for voltage fluctuations.
4. Some local generation network design did not support system voltage control and disconnection settings meaning(– a combination of lack of voltage control from generators, fast generation ramps, disconnections and low tap changing transformers)
5. No limitation on ramping for generators with fixed power factor – fast ramping down of these units resulted in fast increase in voltage.
6. Shunt reactors, which would have absorbed reactive power and reduced voltage, operating manually – requiring decision-making and processing time.
7. Many overvoltage disconnection protection setting diverged from requirements or not-aligned with system needs (generator tripped earlier than required or needed)

Noted here for ease of understanding – voltage-related disconnections of small embedded generators 1 MW

Factors Related to oscillations

8. Converter-drive instability and interaction with other generators in the same area led to forced oscillations which endangered the system as frequency and voltage can severely fluctuate within seconds
9. Absence of Power System Stablisers on some large units and insufficient actions by existing ones. These stabilisers are able to damp oscillations.
10. The two oscillations led to mitigations which damped the oscillations but contributed to increased voltage

Spanish 400 kV grid operational range

11. The Spanish Grid was operated at a wider voltage range than other countries, (380 kV to 435 kV – with generators to remain connected up to 435 kV or 440 kV. This means the voltage margin was almost non existent.

Factors related to Defence Systems

12. Activated load shedding included automatic disconnections of some plants that were absorbing reactive power
13. Despite load shedding, frequency continued to decrease doe to cascade overvoltage and underfrequency disconnections of generators.

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