# Future-Proofing GB's Power System: Reflections on the April 2025 Iberian Event

## Summary

The significant blackout experienced by Spain and Portugal on 28 April 2025 serves as a crucial reminder of the importance of system resilience and the need for continuous improvement as the energy system continues to evolve. The events in Iberia naturally provide a critical opportunity to learn and reflect on where we must continue to support existing work or reinforce where further action may be necessary.

This paper is based on information that has emerged to date hence there is still both unknowns or areas that need greater clarity. We look forward to the ENTSO-E report that will be published later this year. NESO will work with ENTSO-E and neighbouring transmission system operators (TSOs) to understand and learn from the report.

In Great Britain (GB), NESO in conjunction with the energy sector has implemented rigorous planning, testing, monitoring and control measures to ensure the resilience of the power system. These measures include mitigations for some of the key issues reported leading up to and in response to the events of 28 April 2025, including, managing oscillations, voltage control, generator compliance testing, and coordinated restoration plans.

In GB, NESO will continue to build on existing planning, testing, and system monitoring capabilities, particularly in voltage management. Our ongoing stability pathfinder procurement will increase resilience further.  Monitoring, data and asset availability from Transmission Owners (TOs) and driving improvements in this a space are also essential steps. Additionally, resilient communications between control centres, real-time data, and coordination between system operators and network owners must be prioritised.

By addressing these areas, NESO can ensure the continued resilience of the GB power system and maintain our ambition to be able to operate the system carbon-free. The lessons learned from the Iberian blackout will guide NESO in further strengthening our capabilities and ensuring a reliable and resilient power system for the future.

## Introduction

On 28 April 2025 at 12:33 CEST[1], the power systems of Spain and Portugal experienced a blackout. At the time, the system demands were typical considering mild temperatures and time of day. The incident left approximately 60 million people without power across both urban and rural areas. In major cities, the sudden loss of electricity caused widespread disruption. Public transportation systems, traffic lights, bank ATMs and electronic payment systems were rendered inoperative. Emergency services were overwhelmed, and hospitals were reliant on backup generators. Communication was affected as mobile networks and internet services failed.

NESO works closely with its European counterparts and regularly shares perspectives and learnings on both a proactive and retrospective basis. However, we have not approached involved parties whilst they deal with their immediate domestic investigations and their work with ENTSO-E[2]; so this work is based on publicly available information. We will look to work closely with partners once the investigation is concluded to ensure we have a deeper understanding of the incident and develop learning for the GB energy system.

The details of the event are available on the ENTSO-E website[3] but in summary the facts as we understand them at present are as follows:

The incident itself happened across a very short period of time and can be broken down into four phases; due to the technical nature of the assessment, concepts and terms have been explained in Appendix 1.

1. **System Oscillations and Voltage instability 12:00:00 – 12:30:00.** Sub synchronous oscillations are frequency oscillations occurring below the systems standard 50Hz frequency, which left unaddressed can lead to damage to assets or in the worst case, loss of supplies. In this phase, oscillations not atypical for the system were detected and actions were taken to manage these as a priority. These actions dampened the oscillation, however the actions impacted voltage stability across the system.
2. **Generation losses due to high voltage. 12:32:00 – 12:33:18**. Generation has protection settings in place to protect its assets from damage from high system voltage. Where these settings are triggered, i.e. the system volts exceed set limits, the generation will automatically disconnect from the system. Voltage is managed by a combination of network assets and generation with capability to control the voltage. In Spain, a thermal plant has an obligation to regulate voltage dynamically, whereas renewable generation does not as of yet have the same obligation. At this time, the generation mix was 82% renewable, 18% non-renewable. At 12:32 voltages increased rapidly across the whole network, at which point a series of generators disconnected from the system, each in turn exacerbating the high voltages as their capability to regulate voltage was lost.

[1] Central European Summer Time

[2] ENTSO-E, the European Network of Transmission System Operators for Electricity

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

3. **Collapse to zero voltage 12:33:18 – 12:33:30** In sub-second timescales, the cascading loss of generation due to high system voltages, led to the sudden drop in system frequency which then led to demand and generation disconnections, ultimately beyond the limits of the system.
4. **Restoration of supply 12:33:30 – 07:00 (on 29 April).** The restoration approach created various power islands, starting from the synchronous interconnections with France and Morocco along with generation with the ability to restart without supplies. Stable power islands were created which were then joined together once at a sufficient size and stability. By 22:00 50% of demand had been restored and by 07:00 on 29 April, 99.95% of demand was restored.

Already in GB, NESO undertakes rigorous planning, testing and monitoring of the system to ensure the events described in these four phases can be avoided, mitigated and managed. Oscillations occur as normal part of managing a complex power system. In GB, tools are in place to minimise, monitor and manage the impacts. Voltage is managed by a combination of planning, obligations on all generation, compliance testing, network assets and actions taken in control room timescales. Restoration processes are thoroughly prepared, with a series of coordinated restoration plans, testing and training exercises.

NESO's preparations to be able to operate the system carbon-free and our experience of operating the GB system, mean we already have measures in place, or in progress, to support these areas. Nevertheless, the incident is a helpful illustration and source of learning for GB to ensure continued resilience.

In addition to the main causes highlighted, the reporting of the incident also draws out the importance of resilient communications between control centres, real time data and coordination between system operator and network owners.

The key conclusions from the current set of published reports state the blackout was caused by a series of cumulative circumstances, leading to a system overvoltage thus triggering a cascading shutdown of generation. Factors contributing to high voltages and the ability to manage that increase are the most pertinent. Whilst each report analysed goes into detailed findings and recommendations, they can be grouped into the following themes:

- Oscillations
- Voltage
- Restoration

# Comparison of Iberian themes with the GB system

## Oscillations: GB Context

The GB and Spanish systems, like all other transmission systems in Europe normally operate with a balance of generation and demand, at a frequency of 50 Hertz. This means that current flowing in the overhead lines and cables, oscillates, in a controlled manner, 50 times/second. Under certain rare conditions, oscillations from power system sources can be superimposed on the system frequency or voltage. This is not a new occurrence, whilst often unnoticeable it can become amplified if undamped, meaning the oscillations repeat and grow. Like throwing a stone in a pond and the ripple not dying away. Undamped oscillations can result in abnormal voltages and frequency that may cause protection to operate leading to parts of the network disconnecting, generation failures and/or potential demand loss.

Oscillations happen in the system for different reasons and the effectiveness of the actions to mitigate the oscillation depends on whether they address the causes of the oscillations. For the first Iberian oscillation, the investigation suggests that this was a forced oscillation primarily affecting only the Spanish and Portuguese power systems. The second oscillation differed as it was an inter-area oscillation where the whole of the Iberian Peninsula oscillates at a similar amplitude against the rest of Continental European grid. There are two main established mitigating measures: decrease the system impedance by switching on additional lines and/or reduce the flow across the two areas. These mitigation measures dampen the oscillations but can result in voltage increase due to an increase of injected reactive power into the system from the less loaded transmission lines.

In GB, oscillations are normally in the range of 5-12 Hz rather than 0.2-0.6Hz. The main cause for oscillations in GB system is the adverse interaction between a generator control system and the rest of the power system. The most effective measure is to identify the source of the oscillation and retune the generator control system.

NESO has published a Sub-synchronous oscillations report[4] to share our experience and how we tackle the emerging sub-synchronous oscillations challenge with the industry. Also, GB, as discussed later in this document, has obligations on all generation to provide voltage support and thus less likely to experience such widespread voltage issues.

## Oscillations: Current position

NESO leads a cross-industry task force focused on managing and negating the emerging risks of oscillations, working with GB Transmission Owners (TOs) to improve modelling, process, testing, guidance and monitoring. This work has driven new approaches to prevent oscillations occurring

[4] https://www.neso.energy/document/319056/download

and to rapidly resolve them should they occur. NESO monitors the system with new measurement tools that can identify the presence of oscillations. We are also working with the Transmission Operators to prioritise installation of further Phasor Measurement Units (PMUs - devices to monitor the network at chosen locations and help with oscillation identification) which will provide additional capability to monitor and measure oscillations at a national and local level.

Pre-event

- NESO has accurate, advanced modelling tools and a plan to further improve capability in technology, people, and guidance.
- NESO's stability pathfinder procurements[5] will improve the situation as the new assets provide additional damping to the system, as will studies looking into enhanced measurement devices to provide more accurate and timely data. However, NESO is doing more work to drive improvements in data availability.

Real time

- We have coverage of inertia and oscillation monitoring allowing us to provide situational awareness in real time of local or national issues across GB. Today, we are rolling out additional monitoring capability to ensure all substations in England & Wales are covered, as it currently does in Scotland.
- We are developing alarm handling capability to complement real-time identification of system issues and to enable a consistent response to system events.
- Actions could be taken to synchronise additional synchronous plants to increase system damping.
- Where a market participant is not performing as it should, NESO instructs the units to come off the system immediately and does not allow them to return until declared compliant.

Post-event

- We have significantly improved post-event analysis capabilities through development of a new mathematical methodology which identifies root causes of harmful system oscillations and specific locations.
- Market participants in ancillary services are performance monitored for their technical delivery and availability. Markets are competitive with new entrants, so we are improving capability to better identify, monitor and address delivery of contractual requirements.

## Oscillations: Future work

The oscillations observed did not in themselves lead to the blackout. However, it seems the actions taken to address oscillations were a factor leading to the high voltage situation which

[5] https://www.neso.energy/publications/system-operability-framework-sof

contributed to the eventual blackout. This highlights the needs to understand the overall impact on the system of actions taken to address specific operation issues.

This incident further highlights the importance of understanding, monitoring and reducing oscillations through modelling, simulations, testing and compliance. NESO will work with Network Owners to expedite plans to increase real time monitoring across the network.

## Voltage: GB Context

Voltage instability was a key contributing factor to the incident. Key factors cited to date were the lack of delivery of obligated reactive compensation from thermal generation and the lack of dynamic voltage regulation from renewable generation (which was the predominant source of power).  This is not the case in GB. We require reactive capability and voltage control from <u>all</u> generation plants including non-synchronous renewables. Further, we also have compliance testing processes to test this capability ahead of connection to the system and then periodically once connected, NESO has the processes and ability to limit operation of non-compliant generators. These requirements are set out in Grid Code and apply to generators of all sizes and fuel types.

In GB, NESO plans for voltage requirement at various timescales. In the design phase NESO and Transmission Operators have obligations to ensure sufficient reactive capacity will be available for future requirements.  This will be formalised even further within the Centralised Strategic Network Planning (CSNP) process.  The CSNP will ensure that there is a yearly evaluation that will lead to the delivery of the required levels of reactive equipment.  Closer to operational timeframes reactive requirements are assessed in offline models to ensure sufficient reactive capacity is either available or can be scheduled to be available at the time of need.  The operational considerations include ensuring levels of redundancy, in line with the requirements of the GB electricity security standards (NETS SQSS), should any reactive provision become unavailable.

It is reported that the voltage was also impacted by Transmission–Distribution interface points, which in some cases injected MVars onto the Transmission system. The injection of uncompensated reactive power by distribution networks further contributes to an increase in system voltage. In the GB system, whilst there are regional instances where we are experiencing reactive injection from the distribution network at GSPs (Grid Supply Points), we have work underway, in conjunction with Distribution Network Operators, to ensure this is addressed before it is a problem.  NESO are working on how we improve our system models so that our offline analysis more closely reflects our operational experience. This will help ensure that we remain assured of how the network is operating as well as the procurement of further new reactive assets.

There is a suggestion that generators disconnecting from the system at voltage levels lower than the obligated maximums, were material to the incident. This is because the generators were being relied upon for voltage support.

The loss of supply event in GB on 9 August 2019 resulted in NESO driving a shift in GB's approach to fault ride through, including enhancing fault ride through studies, improving the robustness of the modelling process and mandating 5-yearly compliance checks, significantly increasing resilience, etc. As such NESO is mature in its understanding and management of fault ride through performance and has mature compliance processes, through mandating regular testing. This testing can result in non-compliant generation being held off the system and not returning until compliant.  One emerging issue with fault ride through compliance is with distributed connected generators. We must ensure all asset owners, control points, and investors are clear about their obligations under grid code.

A trend toward increasing voltage fluctuations and high voltages is foreseen on the GB system. To ensure GB maintains and improves on capability provided by generators and network assets, NESO has developed new reactive power markets to procure additional voltage regulation services through competition. NESOs stability network services procurements will improve the voltage situation significantly in the short to medium term, providing additional reactive compensation.

Modelling is an area for improvement in medium to long term timescales for both NESO and the Transmission Owners. For example, modelling could be improved to account of market sensitivities and asset availability.

## Voltage: Future work

In GB we recognise the trend toward increasing voltage fluctuations and it is an issue that NESO is taking steps to manage. We continue to develop our modelling capability to enhance our understanding of voltage challenges and continue to push forward our market frameworks for voltage service procurement in the short, medium and long term.

The reactive assets on Transmission Owner networks play a crucial part in managing voltage and ensure compliance with NETS SQSS. It is essential that the status of these assets is monitored and should any faults occur, bringing them back to service should be a priority. Failure to do so reduces system resilience and increases system balancing costs as voltage support must be procured elsewhere.

Finally, the incident reinforces the need for arrangements and planning with the Distribution systems owners to ensure controls are in place to manage the interfaces between the Distribution and Transmission systems and the associated MVAr exchange.

## Restoration: GB Context

The complete details of the Iberian restoration event on 28 April 2025 have yet to be disclosed. Preliminary reports indicate that AC interconnections with France and Morocco were utilised during the initial phases of restoration. Based on this information, the overall event can be characterised as a partial restoration within the broader interconnected European network. These AC links provided essential support not only in terms of active power for energising the transmission system but also contributed voltage, frequency, and inertia support. This enabled a more rapid reconnection of generation units and allowed for demand blocks to be restored at larger scales.

By contrast, the interconnectors between Great Britain and continental Europe are direct current (DC), which, whilst effective in a restoration for provision of active power, they do not offer the same range of voltage, frequency, or inertia support that the AC interconnections with France and Morocco provided to Iberia. There are expected to be valuable insights gained from the Iberian restoration, especially regarding their frameworks, testing processes, and coordination strategies. Once comprehensive information is made available, NESO will assess them to identify any applicable learnings and subsequently inform enhancements to GB's restoration capabilities.

## Restoration: Current Position

Electricity system restoration in GB is governed by the Grid Code and is further supported by business and operational procedures established in agreement with key stakeholders. Together, these elements define a structured, role-based framework for managing the recovery of the electricity network. In the event of a national or regional power outage, NESO will implement a coordinated restoration strategy that includes the use of Local Joint Restoration Plans (LJRPs), clearly defined control room responsibilities, and established communication protocols with Transmission Owners and Distribution Network Operators.

Restoration is carried out using a designated fleet of power stations and interconnectors that are contracted for restoration services. The process starts with the activation of LJRPs in affected areas, or across all seven GB restoration simultaneously. These plans energise transmission corridors, which serve as the foundation for system recovery. As power islands are established and the system stabilises, the control centre makes real-time decisions to expand the islands by adding more generation and demand blocks. These islands are gradually synchronised with neighbouring areas until full system restoration is achieved.

As the generation landscape rapidly evolves, the tools that are used for restoration of the GB power system must evolve with it. To ensure we maintain the capability to restore the system, NESO have adapted our restoration contracting strategy to include a range of new technologies both at Transmission and Distribution level. NESO is mandated to ensure sufficient capability and arrangements are in place by 31 December 2026 to restore 100% of Great Britain's electricity demand within five days. This requirement must also be implemented at a regional level, with an interim target of restoring 60% of regional demand within 24 hours. This new standard represents a significant advancement over the current system restoration expectations for NESO.

To remain proactive in this dynamic environment and achieve these new standards, NESO has implemented a range of initiatives and continues to develop additional capabilities. These efforts include enhanced operational coordination with network companies, procurement of restoration services utilising new technologies, and partnerships with industry and academic institutions for research and development. NESO also engages with international system operators to learn from diverse restoration strategies. Regular testing and readiness assessments of restoration providers are conducted to ensure ongoing preparedness, supplemented by annual cross-industry exercises to evaluate procedures, communications, and training for key personnel.

## Restoration: Future work

Current information suggests that whilst the Iberian Peninsula benefits from the AC interconnection from France and Morocco, the fundamental restoration strategy is comparable to that of Great Britain. Additional details from the ongoing ENTSO-E investigation may provide further understanding of system restoration processes and present opportunities to inform and enhance GB restoration plans.

# Appendix 1. Explainers

## Frequency & Inertia

The GB Power system uses alternating current. This means that the current is alternating between a positive and negative voltage.  This backwards-and-forwards motion or "oscillation" is known as electrical frequency. In the UK, alternating current oscillates 50 times every second, meaning our frequency is 50 hertz (50Hz). In GB, appliances and electrical equipment are designed to work at this frequency.

As supply and demand change, this impacts frequency. If there is more demand for electricity than supply (or generation) then frequency will fall, but if supply is higher than demand, frequency will rise.

NESO manage frequency and are required to maintain frequency within one percent (0.5Hz) of 50Hz, but in aiming to meet that requirement we set ourselves a tighter operational target than required and aim to maintain frequency within 0.2Hz of 50Hz in normal conditions. This is done second by second by balancing supply and demand.  Our control room constantly monitors the frequency ensuring any changes are made swiftly to maintain this critical balance.

Assets connected to the system may also be frequency sensitive and have protection settings to ensure they are not damaged by frequency outside of these limits.

Inertia is an incredibly important to the stable operation of the electricity system. Many generators producing electricity for the grid have spinning parts and they rotate at the right frequency to help balance supply and demand and can spin faster or slower if needed.

The kinetic energy 'stored' in these spinning parts is our system inertia. If there's a sudden change in system frequency, these parts will carry on spinning – even if the generator itself has lost power – and slow down that change (what we call the rate of change of frequency) while our control room restores balance.

Renewables like wind and solar don't synchronise with the grid in a way that provides inertia, so as the older coal and gas plants come off the system NESO replace that inertia using either new assets or existing infrastructure that has been modified.

## Sub Synchronous Oscillations

Sub-synchronous oscillations are power system oscillations at frequencies that are less than the power frequency of 50Hz in GB. They arise from the interactions between certain transmission equipment and typically, the power electronics of non-synchronous generation which convert direct current to the alternating current of the GB System. If left undamped, sub-synchronous oscillations can cause equipment damage, disconnection of generation and in the worst-case scenario loss of supply.

To minimise the occurrence, duration and impact of sub-synchronous oscillations, a robust, multi-layer process is in place.  New connections are designed to ensure that they do not cause or amplify oscillations. Rigorous simulation and testing procedures then demonstrate compliance with the Grid Code and the technical requirements specified by connection agreements.

In operational timescales, NESO ensure that sub-synchronous oscillations are avoided by conducting studies closer to real time and taking appropriate measures to mitigate the risk of sub-synchronous oscillations. The operational measures we may take include requesting the arming/disarming power system stabilisers, management of series compensation schemes, network reconfiguration or managing outages to maintain system strength.

## Voltage

Voltage is what makes electric charges move. It is the 'push' that causes charges to move in a wire or other electrical conductor. Transmission voltages are up to 400,000 volts. Voltages are this high to ensure efficient transmission of power, higher volts mean lower current, which in turn means less energy lost from cables in the form of heat, meaning more energy reaches the other end.

In the same way that NESO must maintain frequency close to 50Hz, we must keep the voltage within a safe range to ensure safety and reliability. Voltage levels across the electricity system can go up and down and may vary across different points of the electricity system.

To keep voltage stable, we can increase it by injecting reactive power and decrease it through absorption of reactive power. Power stations provide reactive power services when they are generating electrical power. The electricity system itself can also be used to provide reactive power; this could come from reactive equipment or from the electrical properties of cables and overhead lines.

## Reactive Power

Reactive power describes the background energy movement in an alternating current (AC) system arising from the production of electric and magnetic fields. Devices that store energy through a magnetic field produced by a flow of current are said to absorb reactive power; those that store energy through electric fields are said to generate reactive power.

Reactive power capability and services are required to make sure voltage levels on the system remain within a given range, above or below nominal voltage levels. We instruct generators or asset owners to either absorb reactive power (decreasing voltage) or generate reactive power (increasing voltage).

The flows of reactive power on the system will affect voltage levels. Unlike system frequency, which is consistent across the network, voltages experienced at points across the system form a 'voltage profile', which is uniquely related to the prevailing real and reactive power supply and demand. NESO must manage voltage levels on a local level to meet the varying needs of the system.  Without the appropriate injections of reactive power at the right locations, the voltage profile of the transmission system will exceed statutory planning and operational limits.

## Appendix 2. Resources and Reference Material

| Organisation | Title | date | Comment |
|---|---|---|---|
| Compass Lexecon and INESC TEC | Analysis of events leading to the peninsular blackout of April 28, 2025 | 28 July 2025 | |
| Non-confidential version of the report from the committee for the analysis of the circumstances that occurred during the electricity crisis of April 28, 2025. | | 18 June 2025 | Redacted and Spanish version only. |
| Red Electrica | Black out in the Spanish Peninsular Electrical System the 28th of April 2025 | 18 June 2025 | |
| ENTSO-E | 28 April 2025 Blackout | Ongoing | Dedicated investigation webpage |