Joulen Analysis of Reports into the Spanish Grid Blackout April 2025

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Introduction

Just after midday on the 28th of April 2025, Spain suffered a significant grid failure affecting almost all of the Iberian Peninsula. The blackout caused widespread disruption but recovery was relatively quick with 99.95% of coverage being restored by 7am the following morning.

Since the event several reports have been published by the System Operator and the Spanish Government and the trade association of Spanish Electrical Utilities (Aelec)

We have studied the three reports and the following paper will follow the timeline and causes of the event and the different recommendations of the reports and how they may change the Energy industry going forward.

Root Cause & Timeline of Events

- Initially operating conditions were normal, with low demand and generation in line with historical norms for this time (07:15 - 07:20).
- As Solar PV generation increased, a larger variation of voltages was observed in the

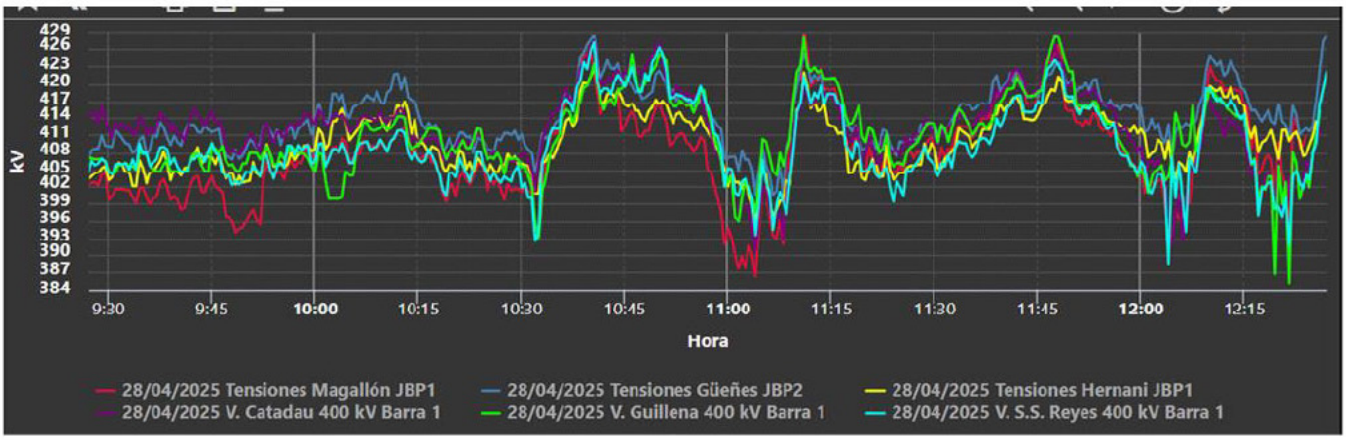

Figure 2. Voltage in 400 kV transmission network from 09:30 to 12 30

- At 11:09 this resulted in two substations tripping as they exceeded their operating voltages, both located in the same regional area (Zaragoza).
- At 12:00 system conditions were still fully compliant and within operational procedures, with no indications of the building issue. However at 12:03 significant frequency oscillations (0.6Hz) were observed in the Spanish-French interconnector.
- This resulted in severe voltage fluctuations, reaching up to 30kV across most substations, with a maximum fluctuation of 410kV being observed (see graphs below).

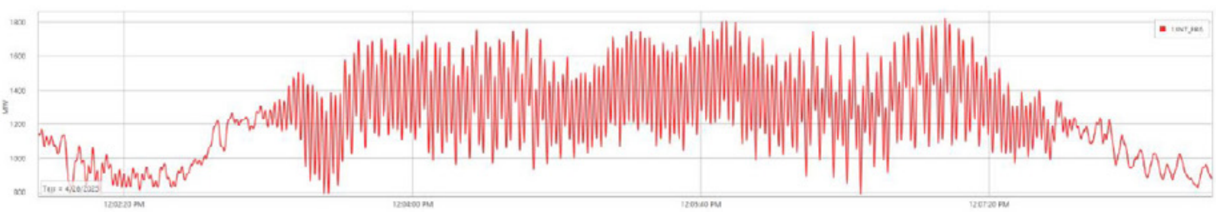

Figure 3. Exchange Spain-France between 12:02 to 12:08 (0.6 Hz oscillation)

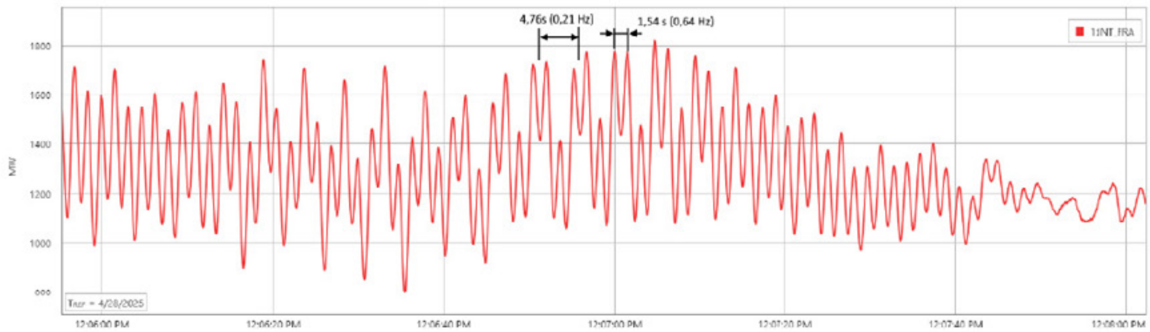

Figure 4. Exchange Spain-France between 12:06 to 12:08 (0.6 Hz oscillation)

• This led to several emergency responses which effectively centred around coupling kV transmission, and reducing interconnector flows to France & Portugal via Spain. Power flows to Portugal were damped because at this time the interconnection line to Portugal via Badajoz was out of service.

• At 12:16 the frequency/voltage oscillations occurred again, with a greater impact on affected substations than before. This led to further disconnects to protect equipment.

• The oscillations appear to have first arisen from a Solar PV plant located in Badajoz (PV Plant A). Oscillations stopped once the power plant was aware and took steps to stabilise these.

• At 12:19 further oscillations were observed with the same magnitude, although these were quickly dampened. PV Plant A generation had increased from 250MW - 350MW, however variations in reactive power elements were still detected (see graph below).

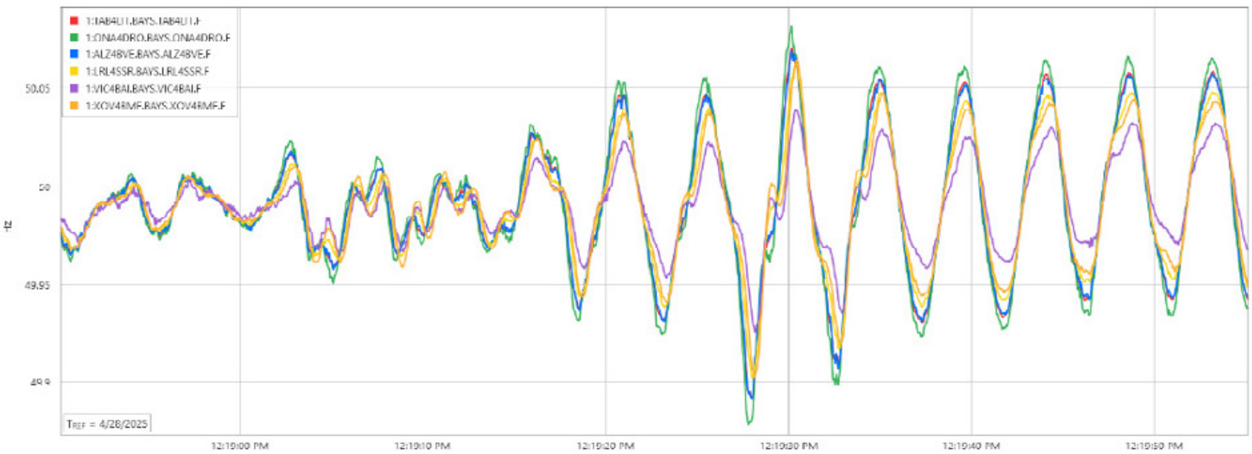

Figure 5. Initial moments of the 0.2 Hz oscillation where 0.6 Hz oscillation can also be observed

• The ongoing issues triggered a further review of the network, which discovered that 0.6Hz oscillations had been occurring since 10:30. This issue was compounded by the previous system disconnects and reduction in power flows, as the system voltage was increasing to mitigate the limits on the network.

• Despite these efforts voltage continued to rise. This has been linked to "an anomalous increase in effective demand of 845MW", which was due to a reduction in output from generation facilities, due to forecasting errors. Of particular importance is that 700MW of the 845MW shortfall can be attributed to facilities with capacities under 1MW (see excerpt below).

- The **distribution network was injecting approximately 760 Mvar into the transmission system nationwide**, with the highest contributions observed in Madrid and Valencia —575 Mvar and 405 Mvar respectively— while in other areas the injection was significantly lower or even negative. This reactive power injection affected voltage levels not only in these regions but also in neighbouring areas.
- An **anomalous increase in effective demand[3] of approximately 845 MW** was detected across the country. Upon further analysis, this increase was traced to two distinct sources within the distribution network:
  - A loss or reduction in the power output of generation facilities with capacities greater than 1 MW, which report telemetry to CECRE[4], amounting to approximately 152 MW.
  - A loss or reduction in the power output from facilities with capacities below 1 MW, unobservable by REE in the distribution network, including of self-consumption, nearly 700 MW.

  This increase in effective demand led to a reduction in energy exports to France, thereby decreasing power flow toward the interconnections and causing a voltage rise in the transmission network.

Excerpt from report discussing anomalous increase in power demand

• In response, two CCGT plants were requested to provide power, however they had a ramp time of between 1.5-2.5 hours, with synchronization not possible until around 15:00.

red eléctrica

It is important to highlight the rate at which generation output can change within the system. New technologies based on power electronic inverters are capable of adjusting their output within a matter of seconds. While this capability is highly beneficial for the economic optimisation of individual generating plants, it is not necessarily ideal from a power system stability perspective in general.

A clear example of this is the rapid schedule changes in photovoltaic generation driven by price fluctuations in electricity markets. From an electrical standpoint, such abrupt changes in inverter-based generation introduce significant imbalances into the system, because regulation mechanisms haven't operated yet. These imbalances must be compensated mainly through interconnections, particularly the one with France.

Severe imbalances lead to drastic shifts in power flows across the network, which in turn alter the capacitive and inductive behaviour of the grid. Consequently, system voltages can vary rapidly. This effect is further exacerbated when such generation operates under power factor control and doesn't provide dynamic voltage control, as it limits the dynamic reactive power support that could otherwise help stabilise voltage.

Excerpt from report discussion generation/demand forecasting impacts

• At 12:32 another substation tripped, which was supplying 355MW whilst absorbing 165MVAr. This led to a cascade effect due to the increased pressure on the network, which was already under extreme stress, with voltages rising after this again.

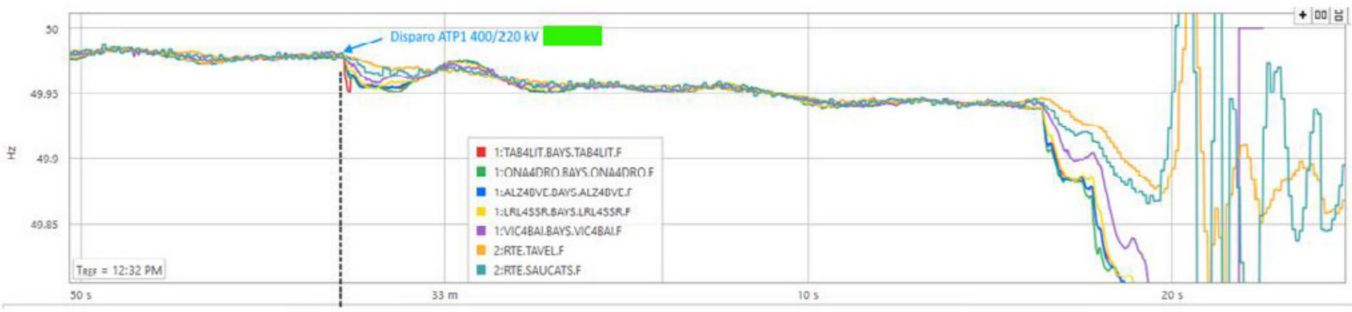

Figure 7. Evolution of the system before and after the trip in Granada

- Following this at 12:33 a second disconnection occurred at the Badajoz substation, removing 582MW from the system. This was immediately followed by a second PV plant in Badajoz tripping, which was currently generation 145MW. This meant that 727MW of generation capacity was lost, along with reactive power elements.

- Approximately 1 second later this led to the loss of further power generation, as wind farms and PV plants in the area began to disconnect. This resulted in an additional 834 MW of generation and reactive elements being lost within a 650ms window. However more recent data suggests this was actually closer to 1150MW.

- This combined loss of approximately 2GW of generation led to increased system voltages and frequency oscillations, which then triggered interconnectors with other countries to trip, further compounding the issue. This subsequently led to large CCGT/Nuclear plants also tripping, as generation inertia at this sites was not able to maintain the required frequency.

REE Report Key Findings by Area

1. Voltage Control:

- Generation sources that were subject to regulations failed to comply with dynamic voltage control obligations, leading to the voltage deviations in the system.

- Renewable, Cogeneration, and Waste (RCW) plants operating failed to meet power factor requirements in 22% of cases as they are required. Non-compliance was identified to be particularly concentrated amount plants with low power outputs. Data suggests reactive power elements were only being accounted for when above certain thresholds, and not continuously.

- Regulations pending from 2021 combined with scheduled changes to interconnection points contributed to transient voltage variations, as discrepancies have been observed before, but not mitigated.

2. Voltage

- Currently voltage levels on the 400kV network are allowed to reach 435kV. Some sites were tripping far too early (as soon as they reached 435kV, and not a sustained level), and measurement/monitoring errors compounded the issue.

- Generators on this network must be able to withstand 440kV for at least 60 minutes without disconnecting, with up to 480kV being requested (Order TED/749/2020). This did not occur indicating widespread non-compliance across the network.

- The thresholds mandated are minimum operational requirements and should not have been breached. This indicates a deeper issue in the industry, most likely due to CAPEX optimisations.

3. Frequency

- Frequency oscillations appear to have originated at a PV plant in Badajoz, however this was not the root cause of the issue. It did however lead to mitigation measures in the area, which when combined with other issues led to the cascading issue. These oscillations appear to have been ongoing since 10:30 and were not identified or resolved.

- Power exports to France of up to 1000MW were maintained even as Spain underwent a underfrequency event. This is due to the French Network Operator (RTE) declining to enable frequency regulation abilities via this interconnector during commissioning.

4. Intertia

- Lack of system inertia did not cause or contribute to this issue in any way, and increasing this would only have somewhat delayed the problem. The primary cause was large voltage deviations causing equipment to trip, leading to a cascade effect.

5. Transmission Network

- Disconnections that occurred were correct and proper, and prevented other EU networks from being "dragged into the collapse". This facilitated quicker restoration of the system across Spain.
- Only two overvoltage trips were recorded in the transmission network, and the main issues with more focused around local transmission and distribution networks

Committee for the Analysis of the Electricity Crisis of April 28th Report

The Spanish Government have released their own report on the events of the 28th of April stating that the blackout was caused by several factors, driven by a combination of technical shortcomings and coordination failures rather than a lack of generation capacity. The three main causes they identified were:

1. Inadequate Voltage Control

- On April 28, the number of synchronous power plants available for voltage regulation was the lowest of the year, despite 10 being scheduled the day before.
- Some plants failed to follow the System Operator's instructions to reduce voltage. In some cases, they even injected reactive power, worsening the situation.

2. Frequency Oscillations

- Unusual oscillations originated from a facility within the Iberian Peninsula.
- These disturbances forced reconfiguration of the grid, making voltage stabilisation even harder.
- A key plant was asked to intervene after the second oscillation but it was impossible to act before the collapse.

3. Improper Disconnection of Generators

- Some generation units disconnected prematurely, before voltage exceeded regulatory safety limits (380–435 kV).
- Others disconnected as expected, to protect equipment once limits were passed.
- Once this chain of disconnections started, system protections could not contain the collapse. In fact, certain protections made the problem worse by unintentionally raising voltages further by discharging the lines as they compensated for the drop in generation instead of managing the voltage.

The Spanish Government paper laid the blame with the System Operator, Red Eléctrica de España (REE) and private conventional power generators, concluding that the root cause was not a lack of generation, but rather a failure to properly programme, coordinate, and execute voltage control. The system had ample resources, but they were poorly deployed and some did not respond as needed.

Report Recommendations

Following its analysis of the April blackout, the Committee has put forward a set of recommendations aimed at preventing similar incidents in the future. These proposals call for stronger oversight across the electricity system to ensure all participants meet their operational responsibilities. A key technical measure involves implementing OP 7.4, which would enable asynchronous facilities to use power electronics solutions to manage voltage more effectively and at lower cost. The recommendations also emphasise the need to boost system flexibility by expanding demand-side participation, increasing storage capacity, and updating regulations around adjustment services. These efforts align with the upcoming 2025–2030 Electricity Planning, which places greater emphasis on industrial energy use. In parallel, the Committee highlights the importance of continuing to expand cross-border interconnections and accelerating the adoption of EU cybersecurity standards, including better network segmentation and advanced event monitoring tools. The report of the Committee for the Analysis of the Electricity Crisis of April 28 is presented

Aelec Statement

The trade association of Spanish Electrical Utilities (Aelec) published it's own statement following the release of the Government and REE's papers, criticising REE's lack of acceptance of responsibility for the events, stating that "the plants managed by our member companies operated normally during the day of 28 April. All of them complied in a timely manner with the orders of the system operator, reacted to the oscillations and increases in voltage observed, and acted as established. The real cause of the blackout was not the performance of the plants, but the manifest insufficiency of units dispatched by the operator to safely cover all the needs of the systems in terms of voltage control and operational stability" Statements in relation to the diagnosis presented by Red Eléctrica de España - aelec

Conclusion

Regardless of who was to blame for the blackout on April 28th, it is clear that there were several key failings leading up to and during the event. Two major elements that were highlighted by all parties was a lack of voltage control in the system and a failure in the wider network to manage these issues. When combined this lead to a cascading effect that would be difficult for anyone to resolve once begun. The recommendations of each report highlight a need to strengthen resilience across the wider network to prevent future occurrences.

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