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Blackout in Spanish Peninsular Electrical System the 28th of April 2025

18/06/2025

System Operation Division

June 2025

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1 Introduction

The purpose of this report is to provide a brief explanation of the events of the incident in the Spanish Peninsular Electrical System that took place the 28th of April 2025.

The report has been prepared in compliance with the provisions established in Operating Procedure 9, which states in section 10.6 that, in the case of an incident of special relevance, the System Operator must prepare a written report once it has the definitive information on the matter. This report will include the measures to be taken to prevent the recurrence of the incident or to minimize its consequences in case a similar situation arises again in the future, and it will be sent to the affected agents, the National Commission of Markets and Competition, and the Energy Competent Administration within 60 business days after the occurrence of the incident.

2 Analysis of the incident

After analysing all aspects considered relevant to clarify the incident, with the best information available, this section proceeds to explain the main causes of the blackout in the Spanish electrical system at 12:33:24 on the 28th of April 2025.

Normally, major incidents are usually triggered by a short circuit, a maneuver or an event in general that clearly and unequivocally fixes the origin but in this case, there is no origin produced by some of the causes indicated above.

As will be detailed in the following sections, this incident was the result of a convergence of multiple factors that go beyond the N-1 criterion, which is the standard basis for the design and operation of electrical power systems.

2.1 Initial situation of the system

During the night of the 28th of April 2025, the operating conditions were normal, there was low demand and generation from all technologies in the mix, except photovoltaic solar energy, which began to be connected between 7:15 to 7:20 h and increased its production throughout the morning.

The voltage profile in the Transmission Network remained stable with minimal voltage variations until 6:00 h, coinciding with a change in the interconnection exchange with France. From that moment, voltages dropped at the same time as the demand rose until 9:00 h. During this period, two very low amplitude interarea oscillations appeared in the European system without any consequence, which is within the normal range for an electrical system with the size of the European one.

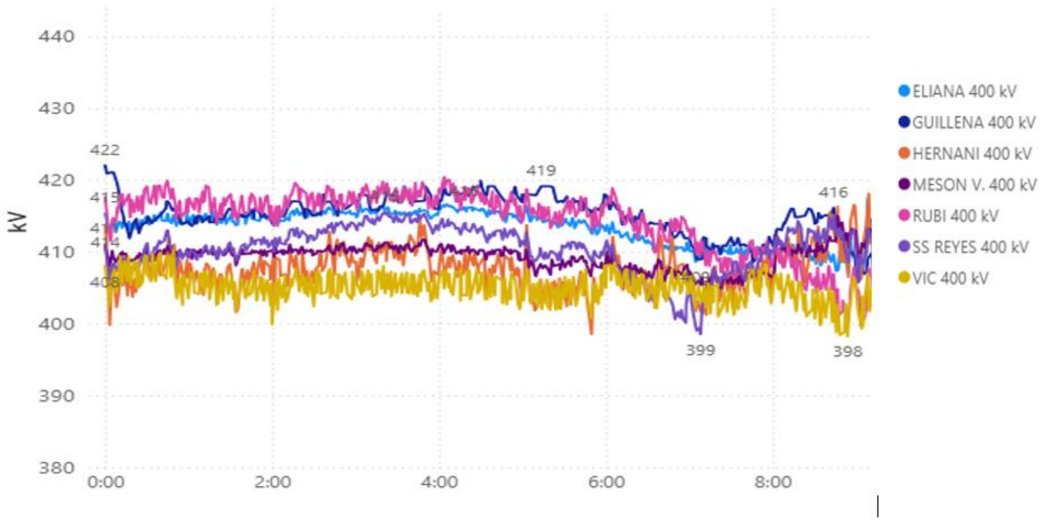

Figure 1. Voltage in 400 kV transmission network from 00:00 to 09:00 h

Between 9:00 h and 9:30 h, solar radiation increased significantly in the country causing a shift in the generation mix towards a predominance of solar generation.

From 9:00 h to 12:00 h, a greater variability in voltages was observed, attributable to the change in the generation mix and demand variations, but without any major excursions. From 10:00 h onwards, coinciding with changes in the interconnection exchange and/or adjustments in balancing energies, voltage variations occurred in the transmission network substations, particularly around 11:00 h, when voltages dropped below 400 kV by about 10 kV.

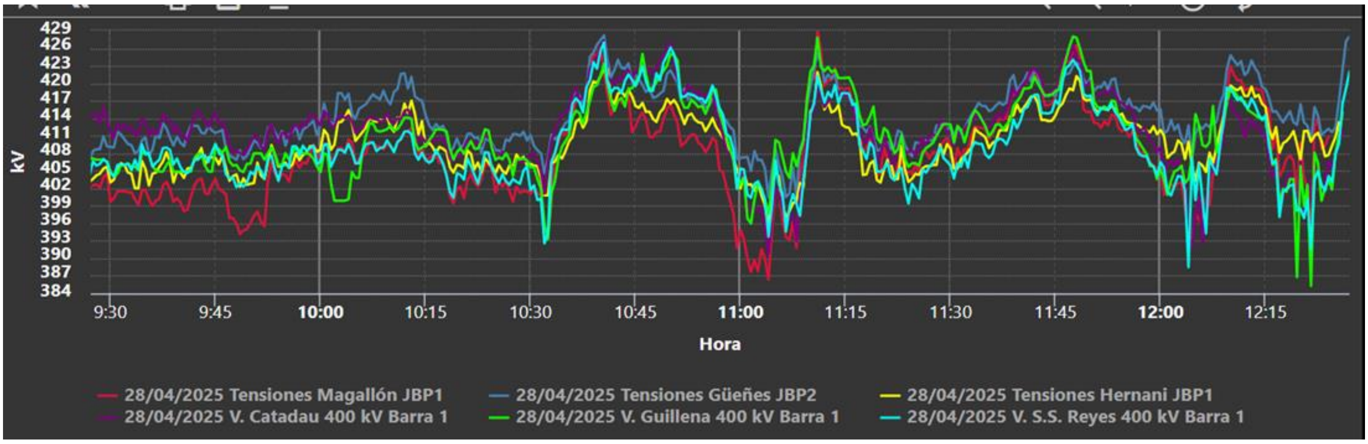

Figure 2. Voltage in 400 kV transmission network from 09:30 to 12:30 h

Subsequently, between 11:04 h and 11:09 h, the voltage recovered rising about 30 kV in some substations, and coinciding with this change, the ADIF[1] transformers connected in Terrer 400 kV and Rueda de Jalón 400 kV substations tripped at the 55 kV voltage level. Both substations are located in Zaragoza. These disconnections occurred with voltages in the Transmission Network substations within range, so it could be inferred that the owner of the transformers didn't adapt the transformer taps quickly enough when the voltage rise started. The situation that occurred with the ADIF transformers, which didn't have major repercussions, can be considered as a prelude of what could have happened later in other substations.

These voltage variations are within the normal operating conditions of the Spanish peninsular electrical system and require control centers to closely monitor and act on the tap changers of their transformers. Likewise, they must be corrected by the conventional generation[2] coupled to the system, which is obliged to regulate voltage at its connection point in compliance with Operational Procedure 7.4. For this purpose, the System Operator (SO) verifies in the technical constraints management process that the generators matched in the market are enough to carry out this control, incorporating those it considers necessary to perform the voltage control function at any given time.

One of the main differences between conventional generation and RCW generation – Renewable, Cogeneration, and Waste – is their operation with respect to voltage control in the substations where are connected, because different regulations applied to them:

- **The generation that must comply with P.O. 7.4 regulates, in a mandatory way, voltage dynamically** and independently of the active power they are generating, thus it ensures stable voltages in the network.
- **RCW generation performs static control in compliance with Royal Decree 413/2014**, which depends on its active power production when operating at a power factor. Therefore, the reactive absorption they typically perform depends on the active power production they have at that moment and not on the existing voltage profile in the network.

Due to this significant difference, the System Operator (SO) determines the minimum non-RCW generation required in the system for voltage control during the 24 hours of each day based on the expected demands,

[1] ADIF: Spanish Railway Infrastructure Manager

[2] Conventional generation according to the Spanish regulation are CCGT, coal, nuclear and large hydroelectric generation plants.

energy exchanges with other countries and available generation. As the day progresses, the available information becomes more accurate, so decisions regarding generation needs can be made more precisely.

In order to rule out the existence of additional overvoltages and oscillations in the network, a thorough review of the entire day from 00:00 h has been carried out. Small amplitude oscillations, with no effect in the system, were identified by the algorithms available in the control center based on the data provided by the PMU installed throughout the system:

- At 10:30 h, an inter-area oscillation in the European synchronous system of 0.2 Hz (typical West-Center-East) appears causing voltage oscillations of up to 4 kV in the 400 kV network, which does not exceed 1% of the nominal voltage.
- At 11:03 h, an inter-area oscillation in the European synchronous system of 0.2 Hz (typical West-Center-East) appears again, causing voltage oscillations of up to 7 kV in the 400 kV network, but does not exceed 2% of the nominal voltage.
- At 11:23 h, an inter-area oscillation in the European synchronous system of 0.2 Hz (typical West-Center-East) appears again, causing voltage oscillations of up to 6 kV in the 400 kV network, thus 1.5% of the nominal voltage.

In conclusion, it has been shown that nothing significant was observed in the system between 00:00 h and 12:00 h. Therefore, the following sections are focused on what happened from 12:00 h onwards.

2.2 Incident description

At 12:00 h, the system conditions were fully compliant with operational procedures. Voltage and frequency levels were within common operation ranges, and the damping for the 0.2 Hz inter-area oscillation mode stood at 20%. In summary, there were no signs or indications that could have remotely predicted the events that followed.

EVENT 1

At **12:03 h, and for a duration of 4 minutes and 42 seconds, a significant 0.6 Hz oscillation** was observed in the electrical system. Coinciding with this, the damping of the 0.2 Hz frequency range dropped from 20% to 5%. Prior to the event, system voltages were close to nominal values, but the **oscillation caused a decrease in average voltage, with fluctuations reaching up to 30 kV** in the most extreme cases, ranging between 375 kV and 410 kV depending on the substation. The oscillation could be seen also in the power exchange with France.

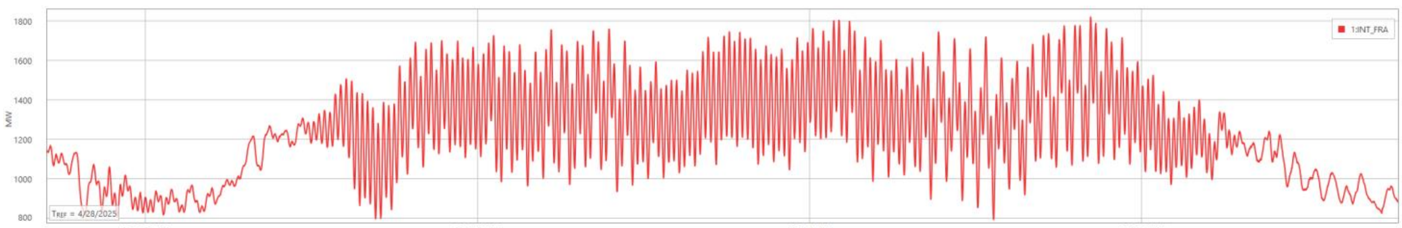

Figure 3. Exchange Spain-France between 12:02 to 12:08 (0.6 Hz oscillation)

Almost at the end of this oscillation also the 0.2 Hz mode could be clearly seen coupled with the 0.6 Hz mode in the power exchange with France.

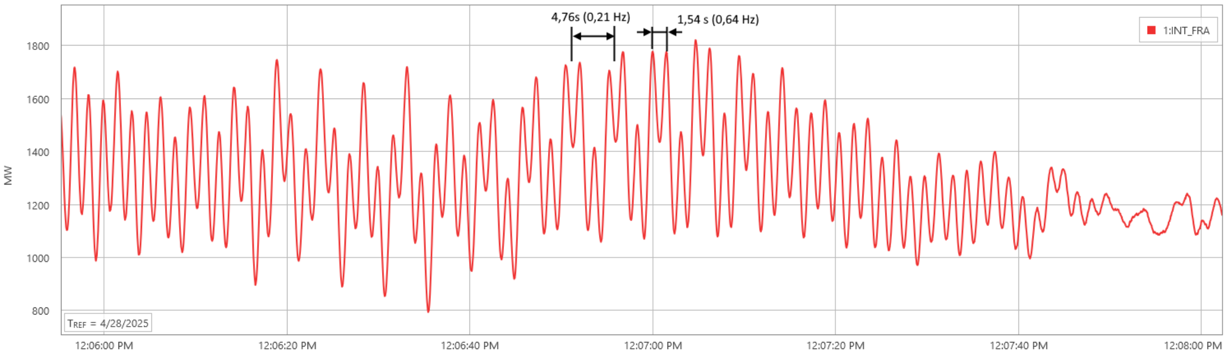

Figure 4. Exchange Spain-France between 12:06 to 12:08 (0.6 Hz oscillation)

In response to this situation, REE Control Center **activated the pre-established measures** to improve oscillation damping and attempt to eliminate it:

- Coupling 400 kV transmission lines to reduce the system impedance.
- Reduction of export exchange with France by 800 MW until setting an export program of 1,500 MW.
- Changing the HVDC link operational mode with France to constant power mode (setpoint: 1,000 MW from Spain to France).

Additionally, due to the voltage drops caused by the oscillations, a series of shunt reactors were disconnected to mitigate the undervoltages.

Once the oscillation was damped, due to the power of the interconnection line with Portugal through Cáceres (400 kV Cedillo – Falagueira) and because the interconnection line with Portugal through Badajoz (400 kV Brovales – Alqueva) was out of service, it became necessary to also reduce the exchange with Portugal to improve damping.

All measures adopted were necessary to mitigate the oscillation, as they enhance damping, which becomes the top priority when such oscillations appear.

The reduction in exchanges implies less power flow to other countries, which in turn increases voltage due to reduction of the power flow on transmission lines. Furthermore, when implementing changes in dispatch programs through the activation of balancing energy, the participating control centers operate as a single node at national level. Therefore, the most competitive offers are selected to meet power reduction needs. In this case, they were concentrated in control centers with renewable energy, mainly photovoltaic, located in the southern part of the country, which presents two effects:

- Due to their location in the southern region, the reduction in load on the transmission lines toward France affects a greater number of lines, thereby exerting a more significant impact on system voltage.
- These are plants within the RCW group that comply with Royal Decree 413/2014, where voltage control is based on power factor, with reactive power absorption proportional to the active power generated. Therefore, when active power production decreases, reactive power absorption is also decreased.

At 12:16 h, the 0.6 Hz oscillation reappeared, causing **voltage** oscillations and **drops, with values ranging between 405 kV and 380 kV** in the most affected substations. Mitigate the oscillation becomes the top priority again.

As voltages dropped again, additional shunt reactors were disconnected to mitigate the resulting low voltages.

All actions taken allowed the situation to be brought under control, however, they tended to increase system voltage. Nevertheless, as previously indicated, the system initially operated with voltages close to nominal, and the oscillations caused voltage drops rather than high voltages.

During the incident analysis, it was determined that the oscillation was not natural to the system but rather forced. This oscillation is observed with significant amplitude at a Photovoltaic Plant located in province of Badajoz (PV Plant A). At the time of the oscillations, the plant was generating approximately 250 MW. Since the oscillation was forced, it ceased once the plant stabilizes it.

An analysis of the network conditions at the point of connection, including short-circuit ratio and voltage level, confirmed that both were within acceptable parameters, so it is therefore likely that the oscillation was originated from an internal control malfunction or anomaly within the plant which should be clarified by its owner. Other plants connected at the same transmission network bay, as well as those in nearby substations, were reviewed, and the only one exhibiting oscillatory behaviour was the aforementioned plant.

EVENT 2

At **12:19 h**, while actions were still being implemented to improve damping following EVENT 1, **a new frequency oscillation** of 0.2 Hz appeared in the system —characteristic of the Western-Central-Eastern European interconnection—. System voltages were close to nominal (between 395 and 410 kV), but **the oscillation caused voltage fluctuations of up to 28 kV at the Almaraz 400 kV substation, with values ranging between 375 kV and 412 kV depending on the substation** —again indicating low voltage conditions—.

A detailed analysis revealed that the oscillation initially began at 0.6 Hz, and quickly afterwards the 0.2 Hz oscillation started. Although PV Plant A had increased its output from 250 MW to 350 MW at 12:15 h and no active power fluctuations were observed, variations in reactive power were indeed detected.

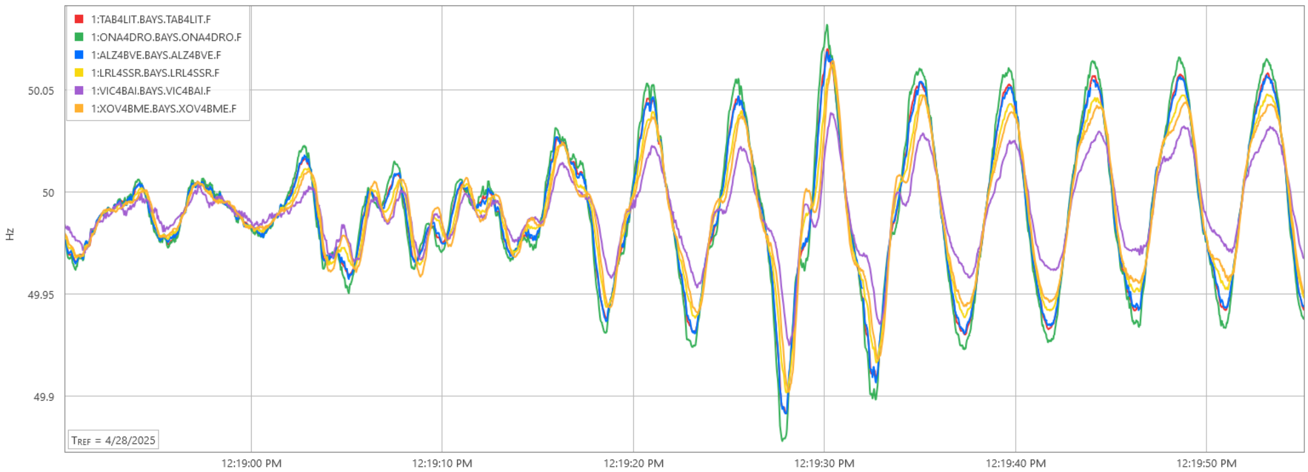

Figure 5. Initial moments of the 0.2 Hz oscillation where 0.6 Hz oscillation can also be observed

Following this finding, the 0.6 Hz oscillation frequency was reviewed across the system, revealing that small-magnitude 0.6 Hz disturbances had been occurring since 10:30 h.

In response to this new oscillation, and in accordance with the protocols already activated at 12:03 h, the following measures were implemented:

- Coupling of 400 kV transmission lines to reduce system impedance.
- Reduction of export exchange with France to 1,000 MW (with the HVDC link set to 1,000 MW from Spain to France, resulting in zero net export via AC lines). This represents a total reduction of 1,300 MW.
- Reduction of export exchange with Portugal from 2,545 MW to 2,000 MW, a decrease of 545 MW.

These three measures contributed to increase the system voltage. The first having an immediate impact, while the two reductions in power exchange progressively raise voltage levels as the dispatch schedules are updated.

At 12:22 h, as the system recovered from EVENT 2, **voltage levels began to rise across the country, though still within operational limits**.

In response, the REE Control Center began coupling shunt reactors at various substations to counteract the voltage rise.

At this point, two noteworthy conditions were observed in the distribution network:

- 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.

Furthermore, considering the measures required to damp the oscillations and the resulting impact of these measures on system flexibility for voltage control and voltage variation management, **a decision was made to connect additional conventional generation units compliant with Operating Procedure P.O. 7.4 —primarily in the southern region—. Start up times were requested, a CCGT plant, in Andalusia, was selected, offering a start up time of 1 hour and 30 minutes, with technical minimum scheduled for 14:00 h**. However, this measure was never implemented due to the blackout.

Coinciding with this decision, it was reported by one control center that one nuclear power plant was experiencing significant oscillations and could potentially trip. As a precaution, a request was made to prepare other CCGT plant in the north for synchronization. Subsequently, other control center indicated that one CCGT plant in Andalusia would require between 2 and 2.5 hours to synchronize and requested a modification of the offer to reduce costs. The first control center later confirmed that its CCGT plant in the north would be ready to synchronize at 15:00 h.

Unfortunately, the required waiting times for these measures could not be fulfilled due to the blackout.

It is worth noting **that no overvoltages were present in the transmission network at this point.** However, voltage variations below nominal values were observed due to the oscillations. This point is particularly relevant to the subsequent developments, in light of what has already been observed in the system.

Summary of the situation at this stage:

- At 12:00 h, the system was in a stable condition, with voltage and frequency within normal operation values.
- The oscillations caused voltage drops, not overvoltages.
- Protocols were activated to mitigate the oscillations, and they were effective on all occasions.
- As typical inter-area oscillations appeared in the system, control center from REE coordinates protocolyzed actions with RTE, to improve damping, like changing the power exchange with France and the operational mode of the HVDC link changing this to constant power mode.
- Generating units compliant to Operating Procedure P.O. 7.4 are required to dynamically regulate system voltage within a defined value, as established by current legislation. This applies to both undervoltages and overvoltages. Voltage variability is closely linked to inadequate response from this type of generation.
- RCW (Renewable, Cogeneration and Waste) generation don't regulate voltage dynamicaly, but must still comply with the specified power factor requirements.

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[3] Demand seen from the transmission network through the interfaces of the transmission network with the distribution network.

[4] Red Eléctrica's Renewable Energy Control Centre

As a result of all the events explained, the system reached an operating state significantly different from the initial conditions, characterized by reduced damping and diminished flexibility in voltage control. The adopted corrective measures could not be fully implemented, as the synchronization of the two groups—intended to enhance voltage stability in the area and to damp potential inter-area oscillations through their Power System Stabilizers (PSS)—.

Starting at 12:27 h, the exchange adjustment with Portugal began, as the change with France had already been underway since 12:22 h.

By 12:30 h, both voltage and frequency remained within the operational limits required by the System Operator (375–435 kV for 400 kV systems and 200–245 kV for 220 kV systems). However, a continued upward trend in voltage levels was observed.

During the program adjustment window, which spans from -5 to +5 minutes, it is common for imbalances to occur between the activation of upward or downward regulation in each country. As a result, voltage fluctuations may arise. These variations must be managed primarily by generating units subject to Operating Procedure P.O. 7.4, which provide dynamic voltage control. This is so because the available resources within the transmission network don't provide dynamic voltage control.

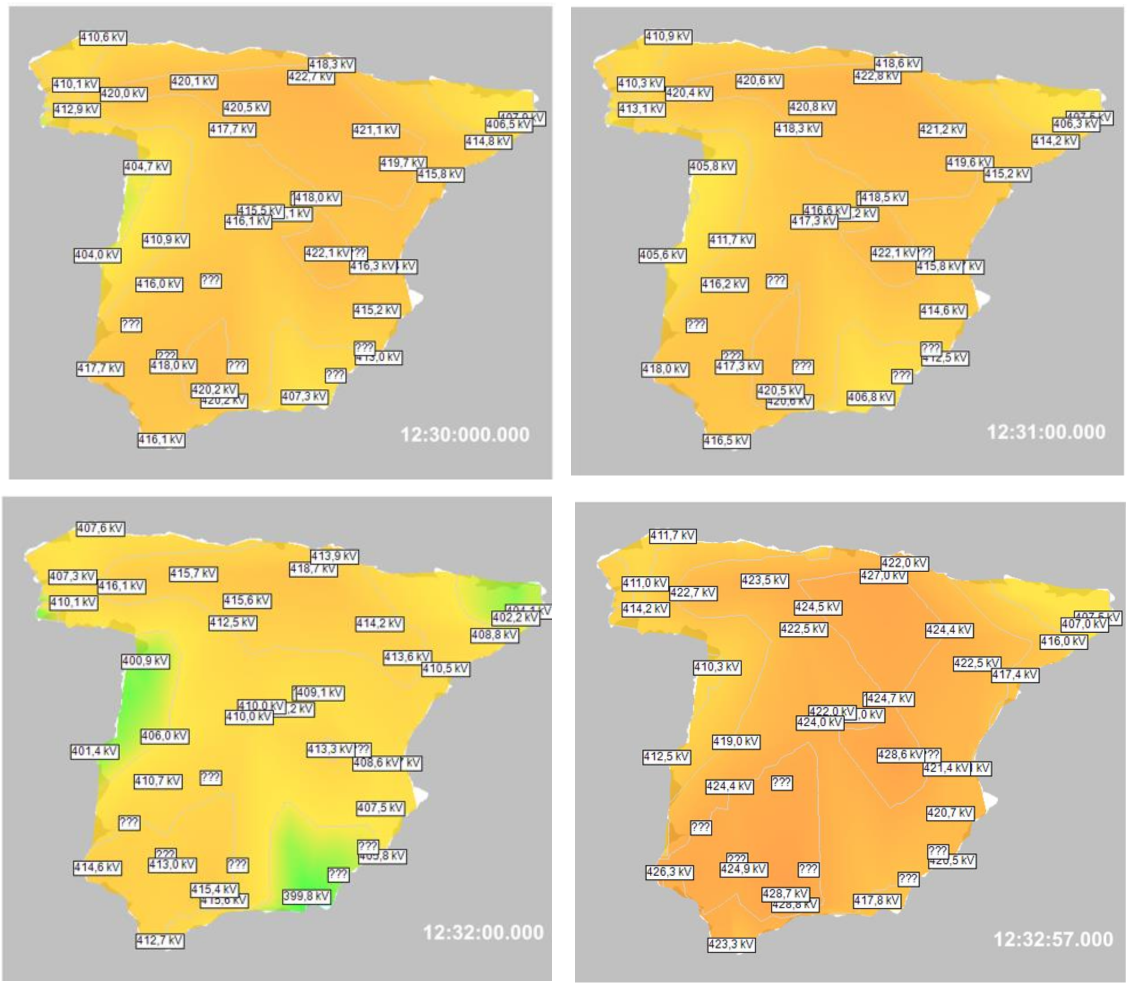

Figure 6. Phase-to-phase voltage in the Spanish 400 kV network

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.

At 12:32:00 h, the export to France reached a peak of approximately 1,500 MW and began to decrease in a quasi-linear manner until 12:32:57 h.

This reduction is explained by several events occurred within those 57 seconds, resulting in a linear increase in voltage across the transmission network:

- To comply with the scheduled dispatch, there **was a reduction in active power output** from RCW generation. Since these units operate under power factor control, this led to a **decrease in reactive power absorption**, thereby causing a voltage rise.
- An additional anomalous **variation in effective demand of approximately 434 MW** was detected. This led to a reduction in energy exports to France, further contributing to the voltage increase in the transmission grid. Abnormal demand increases were observed in Madrid, Alicante, Valencia, Seville, Málaga, Murcia, Cádiz, Toledo, etc. This increase was attributed to a drop in output from a **few distributed generation plants** (around 117 MW). The rest of the variation in demand is attributed to **loss of generation of less than 1 MW or self-consumption**. Given that the system was recovering from low voltage conditions, and voltages were beginning to rise, it is inferred that distribution transformers had tap settings configured to maintain adequate voltage levels. As voltages increased, the tap changers may not have responded quickly enough, potentially resulting in overvoltages in the secondary distribution networks, even though primary voltages remained within acceptable limits.
- Demand is inherently voltage-dependent, thus, as voltage increases, so does demand, further amplifying the previous effect.
- As power flows through the network decreased, transmission lines consumed less reactive power, contributing to the voltage rise.
- Generation units subject to Operating Procedure P.O. 7.4, which are required to provide dynamic voltage control, did not absorb the expected amount of reactive power particularly on the main generators located in Andalusia, Extremadura and Castilla la Mancha. This issue had a significant impact.

EVENT 3

At 12:32:57 PM, a trip occurred at a substation located in the province of Granada involving the 220 kV side of 400/220 kV generation transformer, which at the time was supplying 355 MW to the transmission grid and absorbing 165 Mvar. The voltage at that transmission substation was below 418 kV, within the acceptable range. This is evidenced by the fact that, following the trip, voltages increased to 424 kV.

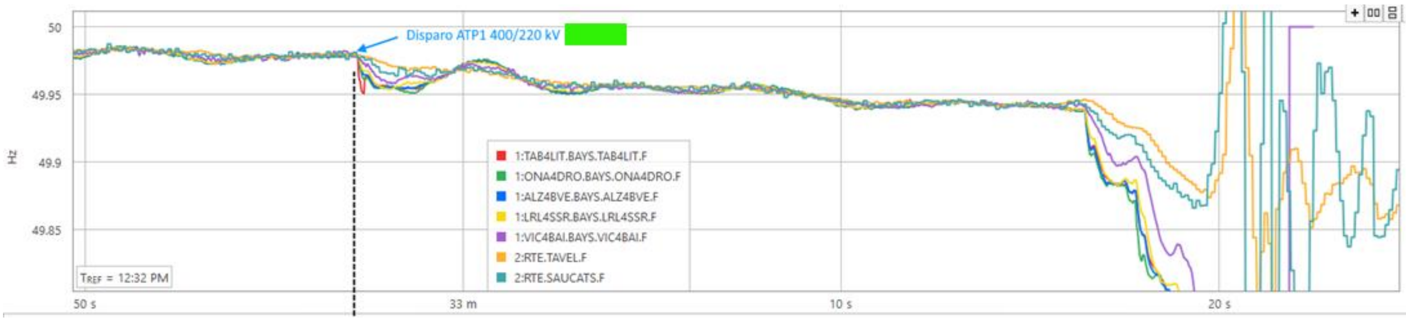

Figure 7. Evolution of the system before and after the trip in Granada

The following figure shows the oscillography recorded by one of the protections of the 400 kV transmission substation where this generation is connected.

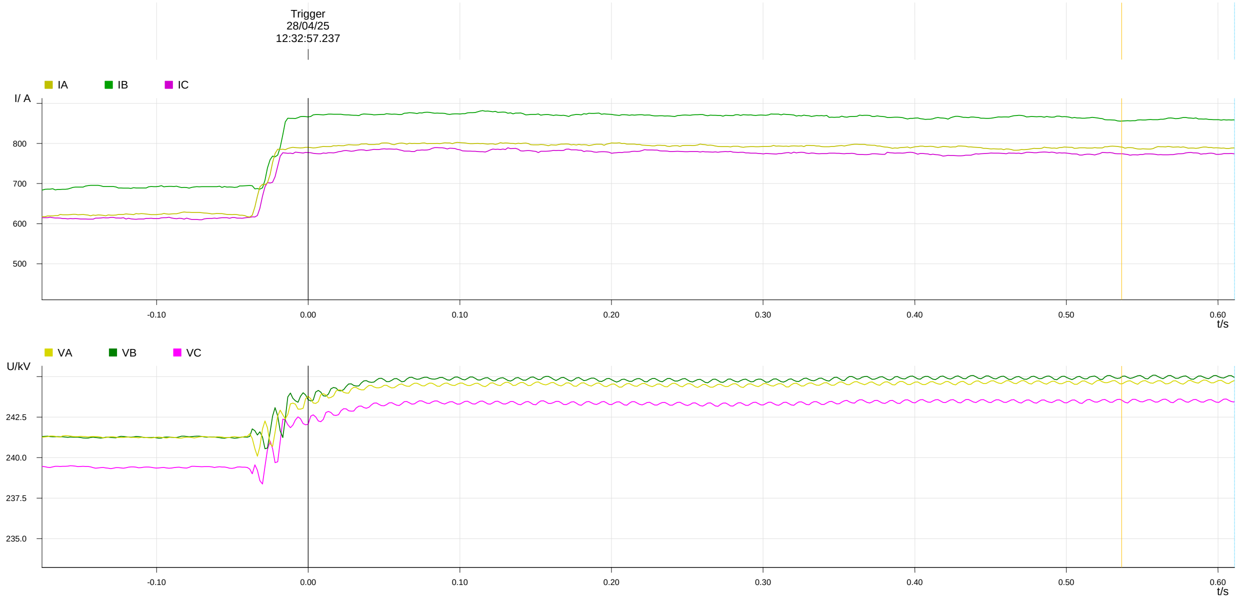

Figure 8. Line protection relay oscillography recorded simultaneously with the transformer trip[5]

Since there were no overvoltages on the transmission network 400 kV side —and the values were well below such thresholds—. It could, once again, be inferred that the cause lies in the generator transformer tap setting. As the system was recovering from previously low voltages, the transformer was likely operating with a tap position configured to maintain appropriate voltage levels at the 220 kV collector substation and the associated evacuation network. As voltages began to rise, the tap changers may not have responded quickly enough, potentially resulting in overvoltages on the secondary side without corresponding high voltages on the primary side of the transformer.

The disconnection of this installation is not correct, as the voltage in the point of connection with the transmission system remains within the limits established in grid codes.

This "Event 3" also contributed to a further increase in system voltage —still within operational limits— due to the same mechanisms previously described: the loss of reactive power absorption from the tripped installation and a reduction in power flow through the transmission network, as generation was lost at a location far from the Spain-France border. The export flow to France, which had been around 450 MW, dropped to nearly zero

[5] Line to Earth voltages are shown in these graphs. To transform to Line to line voltages, a factor of √3 shall be applied

following the trip, due to the loss of generation, changes in system losses, and the ongoing reduction in scheduled exports.

EVENT 4

At 12:33:16.460 h —approximately 19.5 seconds later— a new generation disconnection occurred, this time at province of Badajoz substation, which is connected to a 400 kV transmission network substation (transmission substation B), while generating 582 MW. Subsequently, 360 milliseconds later, a PV photovoltaic plant, connected to a different 400 kV transmission network substation (transmission substation C) also at province of Badajoz, also tripped while generating 145 MW.

Despite no PMU data is available at those two substations the information available indicates that the voltage level was within limits before the disconnections. This evaluation has been made using SCADA values for the substation B, because the voltage magnitude was in a cuasi-steady state since the EVENT 3 and using PMU data (voltage and current) of a different substation that is connected to "substation C".

In total, 727 MW of generation capacity was lost, along with the associated reactive power absorption, leading to effects similar to those observed in the previous event.

Given that there were **no overvoltages or frequency deviations on the 400 kV side**, the root cause could be, once again, attributed to internal conditions within the plants. As the system was recovering from previously low voltage levels, it is inferred that the transformers at generation substation connected to "transmission substation B" were operating with tap settings configured to maintain appropriate voltage at the 220 kV collector substation and the associated evacuation network. As voltages began to rise, the tap changers could not have responded quickly enough, potentially resulting in overvoltages on the secondary side, even though in the transmission substation B voltages remained within acceptable limits. A similar inference applies to the evacuation transformer connected to "transmission substation C".

This new "Event 4" once again contributed to a rise in system voltage due to the same mechanisms previously described: the loss of reactive power absorption and a reduction in northward power transfer from the south. As a result, the interconnection began supplying the northern part of the country, concentrating the operational stress in the southern half of the system.

EVENT 5

At 12:33:17.368 h —approximately 0.98 seconds later— the disconnection of three wind farms occurred. These facilities are connected at 132 kV and evacuate through a 400 kV transmission substation in province of Segovia, resulting in the loss of 23 MW of generation.

Eighty milliseconds later photovoltaic generation connected to the transmission substation B was disconnected due to a trip within its own installations, resulting in a further loss of 118 MW.

Twenty-seven milliseconds after that, an additional 34 MW were lost due to the disconnection of one wind farm and one photovoltaic plant, both injecting into a 220 kV transmission substation in the province of Huelva.

Following this, 233 milliseconds later, a new generation disconnection occurred because of the trip of a link of a generation collector substation in province of Seville, resulting in the loss of 550 MW. The transmission end of the line received a direct transfer trip from the generation end.

Two hundred milliseconds after that a photovoltaic installation tripped in the province of Cáceres. It was injecting 37.5 MW. The generator owner has declared, in a PDF file, that the voltage raised up to a value that is under the voltage threshold that the Order TED/749/2020 stablish that the generation that is connected to a 220 kV POC must withstand at least for 60 minutes -253 kV-.

Finally, 40 milliseconds later, a photovoltaic plant connected to a 220 kV transmission substation in the province of Badajoz tripped. Other additional 72 MW were lost.

In total, an additional 834 MW of generation was disconnected within a 650 ms window, along with the associated reactive power absorption. The estimation derived from the ROCOF suggests that the generation loss during this interval was approximately 1,150 MW, indicating that additional generation may have been lost within this period.

This new “Event 5” once again led to a rise in system voltage due to the same mechanisms previously described: the loss of reactive power absorption and a reduction in south-to-north power transfer. As a result, the interconnection began supplying the northern part of the country, further concentrating operational stress in the southern half of the system.

The system collapse

The Spanish Peninsular Electrical System has lost approximately 2.000 MW of RCW generation in the Transmission network and additional generation connected in distribution grid, which means that the system has lost all the absorpprotion of reactive power of these generators.

Most of the conventional generation equipped with dynamic voltage control did not absorb the reactive power it is obligated to manage according to the Operational Procedures, particularly the generator which was responsible for voltage control in the southern zone, other one located in Extremadura, and the other one which was responsible for voltage control in the central zone of Spain.

Each generation disconnection causes a slight increase of the voltage, which in turn causes the disconnection of other generators, producing a cascading phenomenon.

In this situation, without been able to maintain the voltage within the normal operating values anymore, several simultaneous phenomena occur:

- Increase in the voltage system due to the disconnection of generation.
- Drop in the frequency due to the disconnection of generation.
- Increase in energy import from Europe through the interconnection with France.

In this moment the frequency begins to drop visibly, having the system an overvoltage problem. With each generation disconnection, the system voltage increased and this in turn caused the disconnection of additional generation, therefore the inertia of the system in this incident is irrelevant, since the system was already condemned by the massive loss of generation.

At 12:33:19.620, the maximum import from France is reached, 3.807 MW, with 4.609 MW through the AC network. This situation leads to the loss of synchronism. Only 3,20 seconds have passed since the disconnection which is connected at transmission substation B and 22,5 seconds since the disconnection at the substation located in Granada.

In this situation, the system has the following steps:

- Pump and load shedding in the Spanish and Portuguese system.
- Trip the AC interconnection with France to avoid dragging the French system and to facilitate the system restoration.

As RCW generation continues tripping, the system frequency continues to drop and the voltage rises where it disconnects.

The **undesired disconnection of CCGT located in the east** occurs when the frequency reaches 49.5 Hz and the substation voltage is 419.6 kV. **This loss implies a loss of voltage control and system inertia**.

In this moment, when frequency is 49.5 Hz, **the shedding of coupled pumping is activated**. In the first step, approximately 2,000 MW are shedding, and in the second step activated when frequency reaches 49.3 Hz, another 588 MW of pump generators are shedding. Load shedding of industrial customers connected directly to transmission grid and distribution load shedding continues when the frequency reaches 49 Hz. Approximately the shedding of the consumers connected to transmission grid rise to 1,402 MW.

Load shedding, a universal defence system that helps to restore the frequency in scenarios of severe generation - demand imbalances, causes an increase of the voltage because when a demand is disconnected the voltage naturally rises. This causes an extension of the problem with the voltage control throughout the system, mainly in the northern half of the country and not only in the south, due to the disconnection of RCW plants.

In addition, the **interconnection with Morocco also disconnects** due to the existing under-frequency protections at the Moroccan ends, which trip locally and send remote trips to the ends in the Spanish system. The trip implies losing 314 MW which were imported from Morocco because of the inertial behaviour of the Moroccan system, before the event Spain was exporting energy to Morocco.

When the frequency reaches **48.46 Hz**, **the AC interconnection lines with France trip** preventing expanding the incident further into France and to facilitate its availability for the restoration. The HVDC link, which was in constant power mode, does not disconnect and continues exporting 1.000 MW to France.

From this moment onwards, the **Spanish and Portuguese systems are isolated**, load shedding continues, and generators keep disconnecting, causing voltage to rise and frequency to drop, thereby the **imbalance between generation and demand remains in the system.**

A nuclear generator trips 1,1 seconds later when frequency reaches 47.79 Hz, 758 ms later a **CCGT trips**, 55 ms later other **nuclear generator trips**, 70 ms later two additional **nuclear generators trip**, and 60 ms later other **CCGT trips.** The HVDC link with France disconnects immediately afterward.

At 12:33:24 h the Spanish Iberian Peninsula system collapses. At 12:33:27,300 h the voltage at 400 kV grid is below 1 kV, marking in this moment the **TOTAL BLACKOUT of the system.**

Events in the system

As it was said at the beginning of the report, the electrical system is operated to withstand an N-1 contingency, and in some cases even N-2. For a major incident that results on a total blackout, multiple failures must occur within the system. In this incident, the following circumstances, based on the best available information at this time, have occurred in succession and some of them individually could be assimilated to an N-1 scenario:

1. Forced oscillation at 0.6 Hz, possibly originating in a photovoltaic power plant in the province of Badajoz, triggers system-altering protocolized actions. Shunt reactors are operated, lines are coupled due to oscillations, and schedules are modified. **(N-1)**
2. Natural oscillation at 0.2 Hz triggers further system-altering protocolized actions. Shunt reactors are operated, lines are coupled due to oscillations, and schedules are adjusted. **(N-2).**
3. Generation under P.O. 7.4 does not absorb the required reactive power. **(N-3).**
4. Variations in RCW generation during active power regulation affect voltage control and many of them don´t fulfil their obligations. **(N-4).**
5. The conventional generation requested after the oscillations was not connected.
6. Generation loss in distribution: P < 1 MW and self-consumption of 435 MW before 12:32:57 **(N-5).**
7. Inappropriate tripping of a generation transformer in Granada **(N-6).**
8. Inappropriate tripping of solar thermal generation (Badajoz) and tripping of photovoltaic (Badajoz) without point-of-interconnection data from transmission network **(N-7).**
9. Inappropriate tripping of a photovoltaic power plant connected also in the province of Badajoz but in a different transmission substation **(N-8).**
10. Tripping of three wind farms (Segovia) without point-of-interconnection data from transmission network.
11. Tripping of one wind farm and a PV plant located at the province of Huelva, without point-of-interconnection data from transmission network.
12. Inappropriate tripping of photovoltaic power plant in Seville **(N-9).**
13. Inappropriate tripping a PV generation located in the province of Cáceres **(N-10).**
14. Tripping of PV generation connected to a 220 kV substation located in the province of Badajoz, without point-of-interconnection data from transmission network.
15. Tripping of one CCGT unit located at Valencia **(N-11).**
16. Load shedding of pumping units and loads due to underfrequency results in increased system voltage.
17. The HVDC link operating in constant power mode continues exporting 1,000 MW to France.

18. Tripping of Nuclear Power Plant. **(N-12)**

3 Relevant Aspects

Key findings by area:

Voltage Control

- Generation subject to Operating Procedure P.O. 7.4 failed to comply with its dynamic voltage control obligations, resulting in system voltage levels higher than expected. Moreover, voltage excursions —both upward and downward— tend to be more pronounced due to this non-compliance. Generators typically respond only when voltage deviations become significant, suggesting that their response is primarily driven by internal plant protection mechanisms.
- RCW generation not integrated under P.O. 7.4 failed to meet power factor requirements in approximately 22% of cases. Analysis shows that this non-compliance is concentrated among plants with lower active power output, indicating that compliance with reactive power requirements only begins above a certain active power threshold.
- In some cases, the Transmission–Distribution interface points exhibit highly capacitive behaviour. The injection of uncompensated reactive power by distribution networks further contributes to an increase in system voltage.
- Under Operating Procedure P.O. 7.2, all generation types participate in secondary regulation as a single node at the peninsular level. However, since the updated proposal for Operating Procedure P.O. 7.4 has not been approved, not all generation provides dynamic voltage regulation. As a result, the activation of secondary upward or downward regulation involving RCW generation leads to corresponding increases or decreases in system voltage. In this context, and until Operating Procedure P.O. 7.4 is updated, greater importance is placed on those generating units that do comply with the current procedure.
- P.O.1.4 update has been pending approval since 2021; however, Ministerial Order TED/749/2020 stipulates that generators must withstand voltage rises higher than those specified in P.O.1.4 without disconnecting.
- Schedule changes at interconnection points affect voltage stability, causing transient voltage variations due to the rapid response of certain technologies. Additionally, discrepancies have been observed between the adjustment speeds of the Portuguese and Spanish systems.

Voltage

- Operating Procedure P.O. 1.1, in alignment with the System Operation Guideline, establishes that in the Spanish power system, voltage levels on the 400 kV network may reach up to 435 kV without triggering disconnection (up to 245 and 245.96 kV respectively on the 220 kV network). This does not imply that installations must disconnect at 435.01 kV. Given the measurement errors associated with voltage transformers (VTs) and protection systems, it is necessary to apply a margin above this threshold and implement appropriate time delays to ensure continuous operation. In the observed tripping events, some plants were found to either trip before reaching the specified voltage level or lack the required minimum operating margin, typically >2% or without enough time delay.
- Order TED/749/2020 stipulates that a generator must withstand 440 kV for at least 60 minutes without disconnection, and up to 480 kV on a transient basis, at the point of connection to the 400 kV transmission network. For the 220 kV network, these thresholds are 253 kV and 264 kV, respectively. Some installations were found to have tripped without maintaining the minimum margin required to ensure compliance with the 60-minute criterion. Again, several plants either tripped below the specified threshold or lacked the necessary operating margin, typically >2%, or with a minimum delay.
- The thresholds referenced above represent minimum operational requirements, not protection setpoints. The regulation mandates that installations must remain connected up to those voltage levels and durations; it does not require disconnection once those thresholds are reached.

Frequency

- The 0.6 Hz frequency oscillation observed at 12:02 h is possibly originated in a photovoltaic plant located in the province of Badajoz. This oscillation reappeared a few minutes later and, on the third occurrence, it was detected just prior to the onset of a 0.2 Hz inter-area oscillation. The oscillation from the plant prompted the implementation of mitigation measures aimed at damping the system-wide oscillations, which in turn reduced the system's voltage control margins. It has been observed that the 0.6 Hz oscillation was present at a very low magnitude as early as 10:30 h, which may have contributed to the appearance of the minor oscillations detected between that time and 12:00 h
- The HVDC interconnector operates in two modes: PMODE3, which emulates an AC line based on the angular difference between converter stations (specially defined and designed for this HVDC interconnection), and PMODE1, which corresponds to constant power mode (this is the mode most of the HVDC works with). The HVDC link does not include frequency control capabilities, as RTE declined during the design stage to activate this function. At the time of the event, the link was operating in PMODE1, therefore, despite Spain being in an underfrequency condition and France operating normally, the scheduled power export to France was maintained. As a result, the effective demand in Spain and Portugal at the moment of the AC interconnection trip with France was 1,000 MW higher than the actual demand within the Iberian Peninsula.

Inertia

- The incident was NOT caused by a lack of system inertia. Rather, it was triggered by a voltage issue and the cascading disconnection of renewable generation plants, as previously indicated. Higher inertia would have only resulted in a slightly slower frequency decline. However, due to the massive generation loss caused by voltage instability, the system would still have been unrecoverable.

Transmission Network

- The performance of protection systems within the transmission network is considered correct.
- The disconnection of the interconnections with France successfully prevented the French system from being dragged into the collapse, thereby facilitating and accelerating the subsequent restoration of service.
- The disconnection of the interconnections with Morocco similarly ensured that the Moroccan system remained energized, which also contributed to a faster and more effective recovery process.
- The protection system is not capable of isolating an incident of this nature to a specific portion of the network, due to the meshed topology of the grid within the Iberian Peninsula and the inability to coordinate overvoltage protections. Since the number of affected substations is unknown, the impacted generation and demand are also uncertain, making it impossible to guarantee that the remaining system will not experience a new imbalance leading to a secondary incident.
- Only two overvoltage-related trips were recorded in the transmission network:
  - At 12:33:19,971 h the 220 kV Arganda – Loeches line, due to a voltage transformer measurement error on one phase at Loeches 220 kV substation.
  - At 12:33:23,076 h the 400 kV Valdecaballeros – Maguilla line, during the incident preceding the system collapse, when voltages at Valdecaballeros substation exceeded 480 kV.

Defence Systems

- As previously noted, the disconnection of the French interconnection via loss-of-synchronism protection was appropriate and effective.
- Load-shedding actions within the transmission network were executed correctly. All positions with the function enabled were triggered at the appropriate frequency thresholds and within the required disconnection times.
- No comprehensive data is available to assess load-shedding actions within the distribution network, as the amount of load shed per step and the timing of the disconnections after frequency thresholds

were exceeded have not been provided by the distribution companies. Some of them submitted estimations of total shed demand and a limited number of COMTRADE records from load-shedding relays, but only for a few positions.

4 Recommendations

- Approval of the System Operator's proposal for Operating Procedure P.O. 7.4 regarding voltage control service in the Spanish mainland power system, mandating that all generation units capable of real-time voltage regulation must actively perform such control, and establishing penalties for non-compliance.
- Approval of the System Operator's proposal for Operating Procedure P.O. 1.4 concerning energy delivery conditions at boundary points, to incorporate the voltage values specified in Order TED/749/2020.
- Review of overvoltage protection settings on generation evacuation lines, with the potential adjustment of thresholds to slightly above the maximum limits defined in the operating procedures for the transmission network, in order to prevent unnecessary disconnections when voltages approach those limits.
- Enhancement of system resources for continuous and dynamic voltage control, beyond generation units, through the deployment of synchronous condensers or STATCOMs, rather than relying solely on discrete devices such as reactors or capacitors.
- Extend the ramp times for generation schedule changes to a fixed duration of 10 minutes. It has been demonstrated that the current ramp times of 100 to 120 seconds, as required for facilities subject to Order TED/749/2020, impose stress on the system and have proven to be both unnecessary and detrimental.
- Reinforcement of voltage control capabilities within the distribution network is recommended.
- Upgrade of pre-TED/749/2020 RCW generation units to ensure that production changes follow a controlled ramp profile rather than abrupt step changes occurring within seconds or milliseconds.
- Activation of power-frequency control on existing and future HVDC interconnections.
- Expansion of system capabilities for oscillation damping, including both operational measures and infrastructure enhancements.
- Investigation into the root cause of the forced oscillation originating from the photovoltaic plant in Badajoz, and implementation of corrective actions to prevent recurrence.
- Provide to the System Operator sufficient observability of self-consumption.
- Review and update of technical requirements for self-consumption installations.
- Expansion of the wide area monitoring system (WAMS) through the deployment of PMUs (Phasor Measurement Units), with the objective of installing at least one PMU per transmission substation, where PDCs and communication infrastructure allow.
- Update of operating procedures to define minimum monitoring requirements for incident analysis. These should include, at a minimum: fault records (oscillography), continuous disturbance records with a sampling period of at least 20 ms (50 Hz), and time-synchronized data. These requirements should apply to Type C and D generation facilities, the transmission network, and, within the distribution network, at least to those positions where under-frequency load shedding has been implemented.
- Definition of a procedure for submitting incident analysis data to the System Operator. Additionally, a data collection platform must be developed to ensure that information is provided in a standardized, structured, and clearly identified format, linked to the corresponding installation, while ensuring data confidentiality

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