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Analysis of the 28 April 2025 Iberian Blackout Based on the ENTSO-E Final Report

Ivan Bednárik
Institute of Power and Applied Electrical Engineering
FEI, STU
Bratislava, Slovakia
ivan.bednarik@stuba.sk

***Abstract*— This paper analyzes the Scale 3 system collapse that occurred on the Iberian Peninsula on 28 April 2025. It examines the pre-incident conditions, characterized by high renewable penetration and low system strength, which facilitated converter-driven and inter-area oscillations. Following a single overvoltage transformer trip, a 20-second cascading generation disconnection led to system separation and full voltage collapse. The core focus of this study evaluates the subsequent 16-hour restoration process, analyzing the tactical execution of top-down re-energization paths versus the severe technical, electrical, and control failures that plagued bottom-up black-start attempts. Finally, the paper assesses TSO operational compliance against national service restoration frameworks and European network codes, detailing the subsequent regulatory overhaul of real-time parameter constraints.**

Keywords—power system stability, voltage instability, cascading failures, Iberian Peninsula blackout (2025), grid resilience, system restoration, black-start capability, ENTSO-E analysis

I. Introduction (*Heading 1*)

On 28 April 2025, at 12:33 CEST, the power systems of Spain and Portugal experienced a Scale 3 major incident—the highest severity level under the Incident Classification Scale (ICS) methodology [1]. This event was characterized by a total loss of demand and system voltage across the continental Iberian Peninsula, representing the most severe system collapse in the European power system in over 20 years. While the blackout primarily affected Spain and Portugal, a localized area in southwest France near the Spanish border also experienced disruptions [1].

Pursuant to the legal framework established by Article 15 of Commission Regulation (EU) 2017/1485 establishing a guideline on electricity transmission system operation (SO GL), an ICS Investigation Expert Panel was convened on 12 May 2025 [1], [5]. This panel was tasked with conducting a technical and objective investigation into the root causes of the incident. The process resulted in a Factual Report published on 3 October 2025 [2], followed by the Final Report on 20 March 2026 [1]. The latter provides an exhaustive analysis of the pre-incident grid state, the complex sequence of oscillatory and voltage phenomena, and the subsequent restoration process, utilizing data provided by Transmission System Operators (TSOs), Distribution System Operators (DSOs), and Significant Grid Users (SGUs) [1].

II. Sequence of Events

For a major system collapse to occur, the transmission network often resides in a degraded or abnormal state that reduces its resilience to cascading failures. In the half-hour preceding the incident, the Iberian power system was subjected to two distinct oscillatory episodes, as shown in Fig. 1. The first, occurring between 12:03 and 12:08 CEST, was a 0.63 Hz converter-driven forced oscillation primarily localized in Spain. The second, from 12:19 to 12:22 CEST, was a 0.2 Hz inter-area oscillation corresponding to the East-Centre-West mode of the Continental Europe Synchronous Area (CE SA) [1].

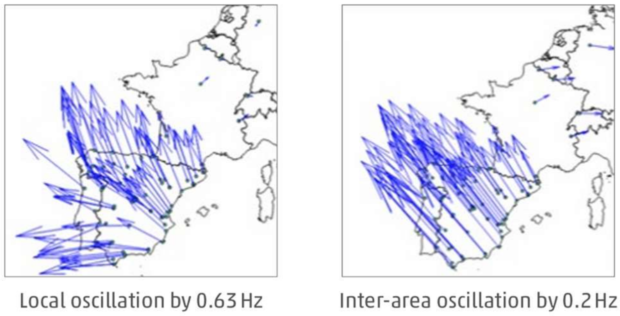

Fig. 1. Oscillatory episodes during the half hour preceding the blackout; mode shapes of the two oscillations [1].

Transmission System Operators implemented several remedial strategies to damp these oscillations, including the reduction of exports from Spain to France and the coupling of internal power lines in Southern Spain to reduce system impedance. Furthermore, the operating mode of the Santa Llogaia-Baixas HVDC link was adjusted. While effective in stabilizing the oscillations, these measures inadvertently increased reactive power production, leading to a steady rise in system voltage. This was compounded by high Renewable Energy Source (RES) penetration, where inverter-based resources were operating under a fixed power factor, rendering them unable to provide dynamic voltage regulation during rapid fluctuations [1].

At 12:32:57 CEST, a critical overvoltage trip of a 400/220 kV transformer in the Granada area (Event ID 3) triggered the collapse sequence [1], [2]. This single event resulted in the immediate loss of 355 MW of generation and 165 Mvar of reactive power absorption. This initiated a cascade where, over the next 20 seconds, approximately 2.5 GW of generation was disconnected across Segovia, Huelva, Badajoz, Sevilla, and Caceres, captured via high-resolution PMU profiles in

Fig. 2, Fig. 3, and Fig. 4. By 12:33:19 CEST, the Iberian Peninsula lost synchronism with the CE SA. The AC overhead lines between France and Spain were disconnected at 12:33:21 CEST by out-of-step protection, resulting in a total voltage collapse and the peninsula entering island mode.

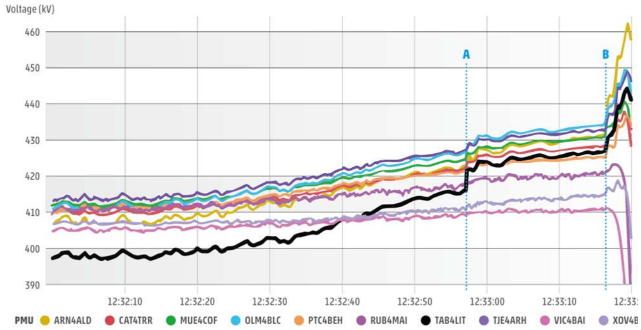

Fig. 2. Voltage (positive sequence) evolution in the Spanish power system after 12:32:00 from PMU data [1].

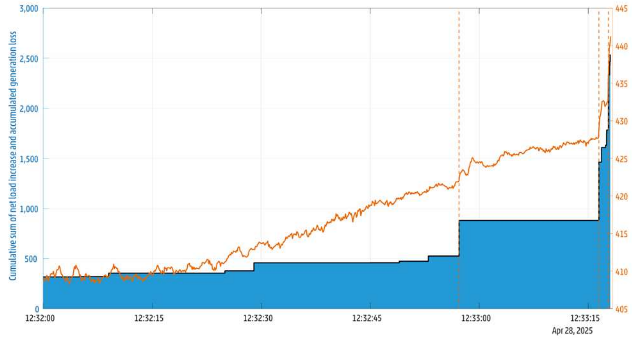

Fig. 3. Accumulated generation loss and net load increase in the Iberian Peninsula vs. voltage at the 400 kV Carmona Substation substation (dotted lines mark major diconnection events) [1].

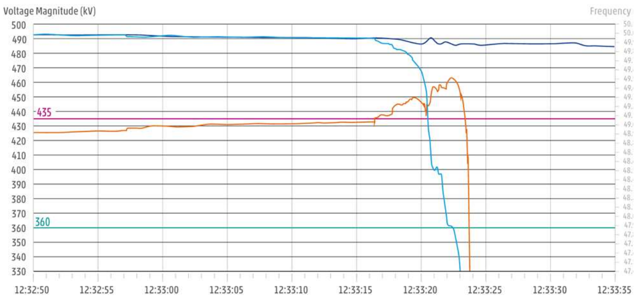

Fig. 4. Frequency and voltage evolution at the Carmona Substation substation and frequency evolution at the Bassencourt Substation substation during the incident [1].

III. Root Cause Synthesis and System Strength Analysis

A central structural factor identified in the Root Cause Tree is the high reactance seen by several generators. This factor is the direct physical consequence of reduced system strength and low Short-Circuit Ratios (SCR) at critical transmission nodes [1]. The investigation established that at the time of the incident, the Iberian grid was characterized by a high displacement of conventional rotating units by static, inverter-based resources. Since SCR depends on the short-circuit power at the connection point—which is inversely proportional to system reactance—the lack of synchronous machines significantly increased the electrical distance between generators and the rest of the system [1].

Within the hierarchy of the Root Cause Tree, this high reactance and corresponding low SCR played a dual role:

- Enabling Oscillatory Instability: The low system strength was a primary driver for the second inter-area oscillation of 0.2 Hz. The high reactance caused generators to operate at suboptimal points for controlling these oscillations, making the East-Centre-West continental mode particularly active within the Iberian Peninsula.
- Exacerbating Voltage Sensitivity: In the technical logic of the tree, these oscillations directly contributed to the fast voltage increase. Because the grid lacked the stiffness provided by a high SCR, the voltage profile became extremely sensitive to even minor reactive power fluctuations [1]. This meant that once the initial oscillations and schedule changes initiated a voltage rise, the weakened grid was structurally unable to damp the excursion.

The Root Cause Tree positions low SCR not as a single trigger, but as the fundamental structural enabler that linked the oscillatory episodes to the uncontrolled voltage rise. This fast voltage increase subsequently led to the cascade of overvoltage disconnections of generators, which the system defense plans—despite being activated correctly—were unable to interrupt. The analysis concludes that without the high reactance seen by generators, the initial disturbances would likely have been damped before reaching the point of no return and the subsequent loss of synchronism.

IV. Restoration Strategy analysis

Following the total system collapse at 12:33 CEST, Transmission System Operators (TSOs) Red Eléctrica (Spain) and REN (Portugal) immediately confirmed a blackout state across the entire Iberian Peninsula. In accordance with the Network Code on Electricity Emergency and Restoration (NC ER - Commission Regulation (EU) 2017/1485), the system was transitioned to an Emergency State. To ensure TSOs maintained absolute control over all restoration assets and grid frequency, all market activities were suspended at 12:44 CEST. This included the cancellation of intraday auctions and the suspension of cross-border balancing platforms such as TERRE and MARI.

The restoration strategy was executed through a hybrid approach of top-down re-energization and bottom-up restoration, visually mapped across the peninsula in Fig. 5:

- Bottom-Up Strategy: Focused on utilizing black-start capable units—primarily Hydropower Plants (HPPs) in Spain and a mix of HPPs and Combined Cycle Gas Turbines (CCGT) in Portugal—to establish localized electrical islands [4].
- Top-Down Strategy: Leveraged healthy interconnections with the Continental Europe Synchronous Area (via France) and the Moroccan system to provide a stable external voltage source and power for gradual re-energization.

A. Chronological Execution of Restoration Milestones

The major events in the restoration strategy are detailed below in chronological order:

- 12:33 CEST: The immediate activation of the National Restoration Plans by Red Eléctrica and REN marked the transition to a hybrid recovery model across the seven designated areas in Spain and the national grid in Portugal [1].
- 12:43 CEST: The initialization of the top-down strategy commenced with the energization of the 400 kV Argia–Hernani interconnection, which utilized stable voltage from the French system to begin re-energizing the Northern Spanish zone.
- 12:44 CEST: A comprehensive suspension of market activities was enacted in accordance with NC ER [4], halting all intraday and adjustment market processes, including TERRE and MARI, to provide TSOs with absolute control over frequency and balancing assets.
- 12:55 CEST: A bottom-up restoration attempt via HPP Extremadura 1 was initiated to provide critical auxiliary services to nearby nuclear facilities, though the resulting electrical island was subsequently lost at 13:56 due to the activation of power reversal protection.
- 13:04 CEST: The receipt of top-down support from the Moroccan interconnection provided a vital voltage source for the Southern zone, despite a temporary trip at 14:27 caused by external frequency imbalances before being successfully restored at 14:34.
- 13:26 CEST: A successful bottom-up restoration in the Galicia area was achieved through HPP Galicia, establishing a stable island for local loads and thermal auxiliaries, which remained operational until a collapse during synchronization at 19:15 [1], [4].
- 13:35 CEST: The expansion of the top-down strategy via the Baixas–Vic link with France provided the Eastern restoration zone with a second external voltage source, significantly stabilizing the recovery of the Cataluña region.
- 15:07 CEST: A major safety milestone was reached with the confirmation of external supply for nuclear auxiliaries, ensuring that all Spanish nuclear power plants had secured stable power for their safety-critical systems.
- 15:25 CEST: The failed bottom-up attempt at HPP Andalucía due to technical issues with lubrication oil flow necessitated a tactical shift, with TSOs prioritizing the top-down recovery of the Southern region through the Moroccan interface.
- 17:01 CEST: A tactical adjustment in the Duero zone was required following frequency control instabilities between local islands, leading to the strategic disconnection of HPP Duero 1 to favor the more stable Duero 2 island.
- 18:36 CEST: The resynchronization of the Portuguese grid with continental frequency was achieved via the 220 kV Aldeadavila–Pocinho 1 interconnector, effectively re-linking the Portuguese system to the 50 Hz European synchronous area.
- 19:32 CEST: The integration of the major restoration zones was finalized by closing the 400 kV Almaraz–C. Rodrigo line, merging the Southern zone (supported by Morocco) with the Northern zone (supported by France) [1].
- 00:22 CEST (29 April): The completion of the Portuguese restoration process occurred approximately 12 hours after the initial collapse, with the national transmission system returning to normal operational status.
- 04:00 CEST (29 April): The final completion of the Spanish restoration was achieved 16 hours post-incident, marking the full recovery of the 400 kV transmission network across the Iberian Peninsula.

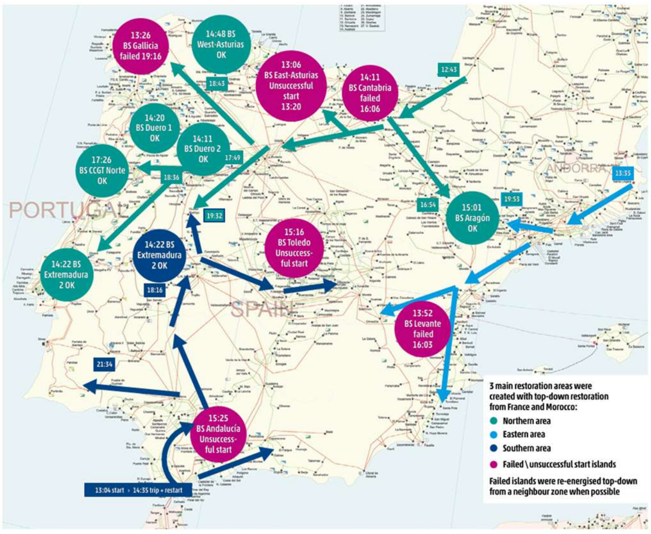

Fig. 5. Main milestones of the restoration process in Spain and Portugal [1].

B. *Technical Root Causes of Island Operational Failures*

Unlike top-down re-energization corridors, multiple bottom-up restoration attempts failed. The islands created in those attempts mainly failed due to frequency control instability and the autonomous reconnection of distributed energy resources (DER), which created load-generation imbalances [1]. The underlying technical failure mechanisms include:

- Active Power and Minimum Stable Generation Mismatches: In the Extremadura 1 island, synchronization of secondary units failed because their minimum stable active power exceeded the net island load. This was exacerbated by the uncoordinated, autonomous reconnection of small-scale distributed energy resources (DER), which reduced the net demand seen by the central hydro plants and triggered reverse power protections.
- Volatile Frequency Excursions and Over-protection: The East Asturias island collapsed due to rapid frequency drops following minor load steps in the 132 kV distribution network. The primary hydro groups tripped at a restrictive threshold of 49.50 Hz, which deviated from the planned 48.00 Hz emergency limits, revealing a lack of protective coordination for islanded states [1], [4].
- Reactive Power and Volt-over-Hertz Violations: In the Levante island, re-energization of long 400 kV lines produced large amounts of capacitive reactive power. As the node voltage surged to 455 kV, the generators

hit their under-excitation limits (UEL), leading to immediate trips via Volt-over-Hertz (V/Hz) protection settings.

- Mechanical and Auxiliary Fluid Dynamics: The Portuguese Centro island experienced an abrupt stop due to low oil levels within the regulation accumulator system. The lack of auxiliary supply post-blackout prevented the oil pumps from maintaining adequate pressure, highlighting a critical vulnerability in black-start physical infrastructure [1].

C. Comparative Engineering Synthesis of Black-Start Island Behaviors

To establish systemic patterns across the failed bottom-up restoration attempts, Table I. categorizes the specific electrical and operational thresholds breached during the creation of local power islands. This comparative matrix isolates the mechanical or electrical limitations that overrode the TSOs' regional defense protocols.

TABLE I. TABLE TYPE STYLES

Restoration Island Zone	Primary Black-Start Asset	Critical Threshold Breached	Dominant Physical Collapse Mechanism
Extremadura 1	Hydro Power Plant	Active Power Balance	Minimum stable generation surpassed net load due to uncoordinated, autonomous distribution-level DER reconnection.
East Asturias	Hydro Power Plant	Frequency Relaying Limit	Frequency dropped under sudden distribution load blocks, tripping at a restrictive 49.50 Hz instead of the planned 48.00 Hz limit.
Levante Zone	Hydro Power Plant	Voltage & Under-Excitation	Unloaded 400 kV line charging capacitance forced generators to their under-excitation limit, causing a Volt-over-Hertz trip at 455 kV.
Centro (Portugal)	Hydro/Thermal Mix	Mechanical /Auxiliary	Prolonged blackout state depleted pressure in the turbine regulation accumulator oil systems, causing an automatic mechanical emergency stop.
Duero Corridor	Hydro Power Plant	Control Loop Stability	Severe structural machine vibrations occurred when attempting to operate primary black-start groups at near-zero active power levels.

The empirical data across these distinct topological zones reveals that bottom-up restoration plans cannot treat electrical islands as static entities. In a compromised synchronous area characterized by low short-circuit power and reduced grid stiffness, the traditional black-start sequence is continuously threatened by a lack of coordinated protection settings. For instance, while the Requirements for Generators (RfG) code establishes clear rules for standard interconnected operations [3], it fails to define the technical parameters needed when a machine must simultaneously balance high line-charging currents and the uncoordinated active power injections coming from low-voltage distribution grids.

Furthermore, the mechanical constraints observed in the Portuguese Centro island underscore a significant operational path dependency: the success of early-stage bottom-up re-energization is rigidly bound to the physical survival time of station auxiliary infrastructure [1]. When auxiliary batteries or oil regulation pumps are starved of power during the initial system separation, the structural window for executing local restoration narrows exponentially. Red Eléctrica’s subsequent restructuring of its defense plan directly addresses this vulnerability by shifting the operational focus away from unstable, isolated hydro islanding, prioritizing instead a reinforced, immediate top-down connection with healthy cross-border interfaces [1], [4].

V. COMPLIANCE WITH TSO RESTORATION PLANS AND EUROPEAN LEGISLATION

The complex operations executed during the 16-hour restoration window provide an essential framework for evaluating TSO adherence to domestic defense rules and European grid codes.

A. National Service Restoration Plans (NSRP)

The operational response by Red Eléctrica and REN demonstrated strict compliance with the structural design of their respective NSRPs. The partitioning of the Iberian mainland into seven autonomous, decentralized restoration zones successfully allowed for parallel recovery tracks. While the tactical environment forced the rapid abandonment of unstable bottom-up islands, the TSOs displayed real-time flexibility by prioritizing top-down re-energization corridors from France and Morocco. This ability to dynamically adapt to unexpected systemic setbacks fully satisfies the core mandates of localized operational resilience embedded in national legislation.

Furthermore, reflecting immediate post-incident lessons, the national regulatory frameworks were aggressively updated. While the CNMC initially approved the restructuring of the Spanish Grid Code Procedimiento de Operación 7.4 (P.O. 7.4) on 12 June 2025 to transition inverter-based resources away from static fixed power factors, the definitive legal execution mechanisms were officially formalized via the CNMC resolution on 19 January 2026. This rapid legislative integration allowed Red Eléctrica to modify its active Restoration Plan, moving beyond old power factor constraints to mandate real-time, dynamic voltage control parameter adjustments across the peninsular generation fleet, setting a precedent for bottom-up island stabilization.

B. Commission Regulation (EU) 2016/631 (Requirements for Generators - RfG)

The TSOs achieved complete compliance with Article 35 of the NC ER code [4]. The complete suspension of all market activities at 12:44 CEST—halting local auctions and disconnecting the transmission networks from cross-border balancing platforms—was operationally and legally justified.

In an isolated, highly volatile network state, commercial market schedules introduce uncontrollable active power deviations. Suspending market operations allowed dispatchers to maintain absolute, centralized authority over frequency balancing assets.

C. Commission Regulation (EU) 2017/2196 (Electricity Emergency and Restoration - NC ER)

The TSOs maintained total regulatory compliance with Article 35 of the NC ER [7]. The complete suspension of market activities at 12:44 CEST—including the formal halting of cross-border intraday allocations and centralized balancing platforms like TERRE and MARI—was legally and technically justified. Under islanded configurations, commercial market mechanisms introduce severe load-frequency balancing risks. Eliminating these market-driven schedules allowed dispatchers to maintain absolute, centralized authority over frequency control assets.

D. Commission Regulation (EU) 2017/1485 (System Operation Guideline - SO GL)

Cross-border coordination via the transmission interfaces with France (RTE) and Morocco (ONEE) strictly adhered to the Coordinated Security Analysis (CSA) protocols mandated by the SO GL [1], [5]. The operational data exchanges executed prior to closing the 400 kV Argia–Hernani and Baixas–Vic interconnectors ensured that top-down re-energization paths did not cause dangerous voltage drops or thermal overloads in the healthy French network, thereby safeguarding the security of the wider Continental Europe Synchronous Area.

E. Regulations (EU) 2019/942, 2019/943, and Directive (EU) 2019/944

The event was properly classified as a Scale 3 incident according to the Incident Classification Scale (ICS) methodology dictated by the Internal Market for Electricity regulations [1], [7]. However, a fundamental regulatory gap was highlighted regarding the interaction with Directive (EU) 2019/944 on common rules for the internal market [8]. The massive, autonomous reconnection of small-scale distributed energy resources (DER < 1 MW) within the distribution grids repeatedly compromised the active power equilibrium of bottom-up islands. This reveals a stark historic mismatch between localized distribution-level connection requirements and the core security intent of modern European market regulations.

VI. Conclusion and Recommendations

The Iberian system collapse of 28 April 2025 serves as a profound technical reference for the vulnerabilities of modern, low-inertia synchronous areas. The technical investigation underscores that a structural reduction in system strength, directly quantifiable by low Short-Circuit Ratios (SCR) at critical transmission nodes, behaves as a critical enabler for cascading voltage instability.

To ensure the long-term resilience of highly decarbonized power systems, the following recommendations are put forward based on the finalized expert panel analyses:

- Harmonization of Overvoltage Over-protection: TSOs must execute an aggressive audit of generation protection settings to ensure that Type D modules incorporate mandatory intentional time delays before executing overvoltage trips, eliminating premature cascading disconnections [3].
- Transition to Dynamic Voltage Support: National regulatory agencies must upgrade grid code requirements to legally transition inverter-based resources from a rigid, fixed power factor operational mode to mandatory dynamic reactive power regulation paths.
- Enhanced Island Testing and DER Coordination: Future revisions of TSO defense and restoration plans must include field testing of black-start hydro units operating at voltages below nominal levels to mitigate capacitive charging on open lines, paired with rigid technical interlocks to prevent the uncoordinated, autonomous reconnection of distribution-level DER during the early stages of island creation [4].

Acknowledgment

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The Role of Low Inertia in the 2025 Iberian Grid Collapse and Restoration

Michal Pecík, E. Vavrinský, D. Vitazkova and H. Kosnáčová (UEF)
Direct and Indirect Respiratory Monitoring Options

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Electrochemical Evaluation of Experimental Supercapacitors in CR2032 Case at High Temperatures

Mayank Jaiswal, Megha Mohan, Sanath Jagannath Shetty and Pavel Veis (FMFI UK)
Optimised Spectral Line Selection and Plasma Diagnostics for Quantitative Analysis of Silicon and Magnesium in Aluminium-Based Alloys by Laser-Induced Breakdown Spectroscopy

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P-N Conductance Type Transition for NH_3 Sensing

Krisztián Kovács, Michal Minárik, Jozef Kozárik nad Juraj Marek (UEF)
Short-Circuit reliability of SiC MOSFETs: Statistical Evaluation under Varying Voltages and Temperatures