» Grid Incident in Spain and Portugal on 28 April 2025

ICS Investigation Expert Panel
Factual Report

3 October 2025

Preamble

On 28 April 2025 at 12:33 CEST, the power systems of Spain and Portugal experienced the most severe blackout incident in the European power system in over 20 years, with major repercussions for citizens and society. To prevent similar cases from occurring in the future, a thorough technical analysis of this major incident must be performed.

This factual report describes the system conditions on 28 April 2025 and details the sequence of events that occurred on that day from 9:00 onwards in the electricity systems in Spain, Portugal, and France, as established by the Expert Panel set up in accordance with Article 15 of Commission Regulation (EU) 2017/1485 of 2 August 2017 establishing a guideline on electricity transmission system operation (SO GL) and the Incident Classification Scale (ICS) methodology.

The purpose of this report is to provide a technical and objective account of the incident, based on factual evidence. It aims to support transparency, learning, and continuous improvement in system operation across Europe. While this report is based on most reliable data made available to the Expert Panel by a range of data providers, no representation or warranty, express or implied, is made as to the fairness, completeness or correctness of information and opinions contained in this document. Importantly, the report is not intended to allocate liability or responsibility to any party and may, therefore, not be interpreted in such way. It serves solely as a factual record to transparently inform stakeholders and governance bodies, and to facilitate further discussion and evaluation within the context of the final report referred to hereafter. This report has been agreed and prepared by the Expert Panel and is without prejudice to any investigation or enforcement action that may be taken by the competent authorities.

The factual report will be followed by the final report, which will include an in-depth analysis of the events of 28 April, establish the root causes of the incident, and include recommendations for improving the resilience of the European power system.

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1 MANAGEMENT SUMMARY

1.1 Introduction

On 28 April 2025, at 12:33 Central European Summer Time (CEST), the power systems of Spain and Portugal experienced a blackout. A small area in France near the Spanish border also experienced disruptions for a limited duration. The remainder of the Continental Europe (CE) power system did not experience any significant disturbance.

Following the incident, each affected Transmission System Operator (TSO) – REN (Portugal), RE (Spain), and RTE (France) – immediately activated their respective system restoration plans, as well as any other relevant procedures and protocols for restoring the voltage of the electricity system. The system restoration was completed by 00:22 on 29 April 2025 in Portugal, and by 04:00 on the same day, the transmission system was restored in Spain. This blackout was the most serious incident to occur on the European power system in over 20 years, with a major impact on citizens and society as a whole in Spain and Portugal.

1.1.1 Expert Panel and Structure of Factual Report

The incident has been classified as a scale 3 event – the highest level in terms of severity – following Article 15(5) of the Commission Regulation (EU) 2017/1485 of 2nd August 2017 establishing a guideline on electricity transmission system operation (SO GL) and the **Incident Classification Scale (ICS) Methodology**. Consequently, pursuant to the same legal framework, an Expert Panel was set up, which began investigating the incident on 12 May 2025 with the aim of delivering a factual and final report.

In accordance with the ICS methodology, the Expert Panel comprises representatives from affected and non-affected TSOs, the Agency for the Cooperation of Energy Regulators (ACER), National Regulatory Authorities (NRAs), Regional Coordination Centres (RCCs), and convenors from relevant ENTSO-E bodies. The Panel is led by two experts from TSOs not directly affected by the incident: Klaus Kaschnitz from APG (Austria) and Richard Balog from Mavir (Hungary). Overall, the Expert Panel comprises 45 experts – 28 from ACER and NRAs, and 17 from TSOs, RCCs, and ENTSO-E bodies – from across Europe (the complete list of the Expert Panel members is available on the final page of this report).

While the three affected TSOs actively contribute to the Expert Panel's work, as foreseen by the legal framework, each of them is only represented by one expert in the Panel. Furthermore, in line with the Expert Panel's terms of reference, their contribution involves providing input and suggestions for specific chapters in a transparent and constructive manner, but not acting as the primary authors of the respective chapters where their TSO has been involved in any way in the relevant actions for the event. These measures aim to ensure the neutrality of the reports delivered by the Expert Panel. This factual report – as the first deliverable of the Expert Panel – presents the facts gathered, offering a comprehensive description of the system conditions before the incident, the sequence of events during the incident, the restoration process, and the communication between coordination centres and TSOs. The report also includes an analysis of the incident severity based on the ICS methodology. Finally, the report presents the next steps of the ongoing investigation, which will culminate in the publication of the final report, including recommendations aimed at improving the performance and resilience of the power system across Europe.

The factual report reflects the data and information processed by the Expert Panel up to 22 August 2025. The final report will consider the facts included in this present factual report, as well as any additional information and data related to the circumstances in which the blackout occurred and necessary for the assessment of its causes, that the Panel might deem relevant for a comprehensive investigation. Some of these additional datasets are specified in this report, and some relevant next steps are outlined in Chapter 8 of this factual report.

This first chapter provides a high-level summary of the factual report, following the same structure as the report itself. It also includes a specific sub-chapter on data collection, given that collecting complete, high-quality data proved very challenging for this investigation.

In this report, all times are in CEST, which corresponds to UTC+02:00. Furthermore, when referring to Spain and Portugal as relevant areas, it refers to continental Spain and continental Portugal, respectively.

1.1.2 Data Collection

The ICS methodology provides that an Expert Panel established to investigate a scale 2 or 3 incident carries out its investigation based on data reported by the affected TSOs, as listed in Annex 1 *"Common data for reporting"*, Annex 2 *"Specific data reported for depending on the ICS criterion"* and Annex 3 *"Additional data for the investigation of scale 2 and scale 3 incidents"*. The methodology also stipulates that the Expert Panel shall request additional data and information deemed necessary for the investigation, including data owned by third parties (e.g. Distribution System Operators (DSOs) and generators), to be provided by the affected and other relevant TSOs.

In accordance with this provision, the affected TSOs delivered the required data under the ICS methodology within approximately six weeks following the incident. After the installation of a dedicated confidential data platform and the establishment of rules for the use and distribution of data within the Expert Panel, the data was shared with the entire Expert Panel nine weeks after the incident. To establish the facts directly related to this incident, the Expert Panel also considered it necessary to request and collect specific data from DSOs and significant grid users – especially generation facilities – in the affected countries. Finally, the Expert Panel received several voluntary contributions from various third parties (i.e. ministries, companies, and a trade association).

Data collection from DSOs and significant grid users

Data and information requested from DSOs comprised, among others:

- Information on any disconnection of generators before the incident
- Information on generation mix in the DSO grid before the incident
- Information on any voltage alarms or exceeded voltage thresholds
- Information on load shedding

Data and information requested from significant grid users (generators) comprised, among others:

- List of generation facilities in operation on 28 April and any related power system stabilisers
- Information on generation trippings, including fault recorder files, protection relay settings, and schematic drawings
- Information on any identified malfunctions related to oscillations
- Communications with the TSO before the incident

In line with the methodology and practices applied in previous investigations, the task of collecting data from third parties was entrusted to the affected TSOs.

In Portugal and France, the TSOs were able to collect the necessary data and transfer it in a timely manner to the Expert Panel. The following parties delivered data:

- DSO in Portugal: E-Redes
- Generators in Portugal: Akuo, Aquila, Axpo, CWPOWER, Dos Grados, EDP-Produção, Energi Innovation, Engie, EXUS, Galp, Iberdrola, Powersun Solutions, Neoen, Prosolia, Vector Renewables, Voltalia, Welink, and WiseEnergy
- DSO in France: ENEDIS
- Generators in France: EDF, EDF Renouvelable, and SHEM

In Spain, collecting data from third parties proved more challenging. To facilitate the provision of third-party data to the Expert Panel, two initial letters were sent at the end of May 2025: one by the Expert Panel leaders to the Spanish TSO Red Eléctrica on 26 May and the other by ENTSO-E to the Spanish authorities on 28 May. Following these letters, Red Eléctrica obtained consent from 33 generation companies[1] and DSOs to share all relevant data at its disposal with the Expert Panel, while eight others did not provide their consent. As a next step, the leaders of the Expert Panel requested data directly from the parties that had not given their consent to Red Eléctrica, as well as the parties from which the Panel deemed it necessary to obtain clarifications or additional data.

Overall, more than 150 emails and letters were exchanged between the Expert Panel leaders and the third parties concerned between 28 June and 12 August, with the aim of finalising the data collection process. The following parties have delivered data:

- DSOs: E-Distribucion, Electra Caldense, Electrica Bermejales, Electricas Pitarch, E-Redes, Estabanell, i-DE, Medina Garvey, UFD, and Viesgo
- Generators (including control centres): Acciona, Alpiq, Axpo, Cecovi, Cepsa, Cogen-Energia, EDP España, EDP Renewables, Elawan, Endesa, Energya-VM, Engie, Galp, Gamesa, Gesternova, Gnera, Holaluz, Iberdrola, Ibereolica, Ignis, Magnon, Mercuria Sostenible, Naturgy, Nexus, Norvento, Repsol, RWE, Saica, Samca, SEC Hueneja, Total Energies, and Wind to Market

Overall, the Expert Panel was able to collect a lot of data from TSOs and parties connected to the TSO grids. However, some data remains missing, particularly related to some of the generation trips that occurred before the blackout. Several of the concerned parties (namely the owners of those facilities) informed the Expert Panel that they do not have this fault record data. The present factual report has been prepared based on data provided to the Expert Panel up to 22 August 2025, and the Expert Panel might require additional data to further analyse the event for the final report.

Other contributions

In addition to the raw data collected from TSOs and other parties, the Expert Panel also considered the following additional material:

- Ex-post evaluation reports submitted by Spain and Portugal to the European Commission, prepared pursuant to Article 17 of Regulation (EU) 2019/941 on risk preparedness in the electricity sector.
- Several spontaneous, letters including reports, presentations and other technical documents from various parties: AELEC, E.DSO, Endesa, Eurelectric, Iberdrola, Red Eléctrica, and UFD.
- Spanish government report published on 17 June.
- Red Eléctrica report required by the Spanish regulation (Operational Procedure PO 9) published on 18 June.
- Presentations given by E.DSO, EU DSO Entity and Eurelectric during the joint workshop of the System Operations European Stakeholder Committee (SO ESC) and of the Grid Connection European Stakeholder Committee (GC ESC), chaired by ACER, which took place on 18 July.

While the investigation is primarily based on the raw data and information collected upon the Expert Panel's request, the Expert Panel also took these additional external documents into consideration in preparing the factual report[2].

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[1] Generation control centre: in Spain, all generation facilities with power equal or greater than 1 MW must send real-time information to the TSO. Considering that a very high number of facilities meet this criterion (around 4,200), an additional role has been established based on Operational Procedure 8.2 and RD 413/2014, namely the generation control centre. The generation control centre acts as an intermediary between generation facilities and the TSO control centre to send real-time measurements to the TSO and in the other direction to send to generation facilities the reference power values required by the TSO.

[2] The same will be done for the preparation of the final report.

Treatment of confidential information

The collection of data required for the purposes of this investigation and the conclusion of the factual and final reports by the Expert Panel has been performed in line with the ICS methodology and the confidentiality requirements established in both European and relevant national regulatory framework. To safeguard confidentiality while upholding transparency, the Expert Panel has adopted a balanced approach, based on which any data provided by the affected TSOs linked to individual generators and/or by third parties and classified as confidential has been subject to anonymisation.

Such classification is based on the due justification of the sensitive nature of the specific data by the providing party to the Expert Panel. The anonymisation measures applied are without prejudice to the integrity of the data analysis performed by the Expert Panel, ensuring that confidentiality is protected while preserving the evidential value and robustness of the data provided.

In light of this, this report mentions the technology of individual power plants and – if applicable – the region of their location instead of their names. Furthermore, absolute values of their active or reactive power infeed are replaced by per-unit values.

1.2 System and Market Conditions Before the Incident

The morning hours of 28 April 2025 were characterised by an increasing generation of renewables, having led to decreasing prices on the day-ahead market and increasing exports of Spain up to 5 GW in total. From approximately 09:00, the variability of the voltage in Spain started increasing, albeit without significant variations until shortly after 10:30, when the voltage in a part of the 400 kV transmission network briefly approached – but did not exceed – 435 kV.

The voltages in the 400 kV network remained below 435 kV during the period before the incident. No significant oscillations with amplitudes above 20 mHz could be detected until 12:03.

The following figure illustrates voltage evolution in the main 400 kV transmission substations (pilot nodes) in Spain from 9:00.

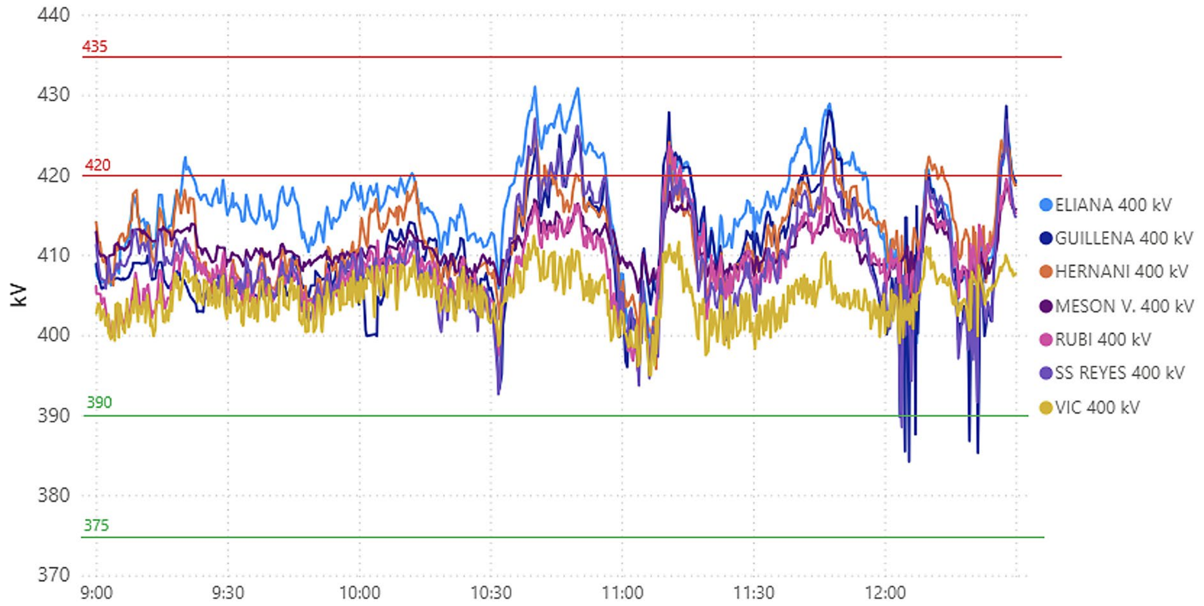


Figure 1-1: Voltage evolution in the main 400 kV transmission substations (pilot nodes) in Spain

During the half hour preceding the blackout, two main periods of oscillations – power, voltage, and frequency swings – were observed in the Continental Europe Synchronous Area (CE SA), the first of which took place from 12:03 to 12:08. The analysis indicates that this oscillation had a local character primarily affecting Spanish and Portuguese power systems with a dominant frequency of 0.63 Hz. The second oscillation occurred between 12:19 and 12:22 as an inter-area oscillation, with a dominant frequency of 0.21 Hz, corresponding to the East-Centre-West continental mode. In order to damp these oscillations, the operators in the control rooms of the relevant TSOs took several mitigating measures, such as reducing the export from Spain to France, coupling of internal power lines in the South of Spain, or changing the operation mode of the HVDC link between France and Spain. While these measures mitigated the oscillations, their nature led to an increase of voltage in the Iberian power system.

At 12:32:00 – the starting point of incident as considered for the purpose of this report – the voltage of Iberian power system at the 400 kV level was below 420 kV and no notable oscillation with amplitude higher than 20 mHz could have been observed. The evolution of the system and market conditions until this point of time is explained in further detail in Chapter 2.

1.3 System Conditions during the Incident

Several important generation trips occurred from 12:32:00 onwards. Between 12:32:00.000 and 12:32:57.000, there was a loss of 208 MW identified distributed wind and solar generators in northern and southern Spain, as well as an increase in net load in the distribution grids of approximately 317 MW, which might be due to the disconnection of small embedded generators <1 MW (mainly rooftop PV) or to an actual increase in load or to a combination of both. The reasons for these events are not known. From 12:32:57.000 until 12:33:18.020, major disconnection events occurred in the regions of Granada, Badajoz, Sevilla, Segovia, Huelva, and Cáceres, which resulted in an additional loss of generation of at least 2 GW (the effects of frequency deviation suggest a loss of even 2.2 GW).

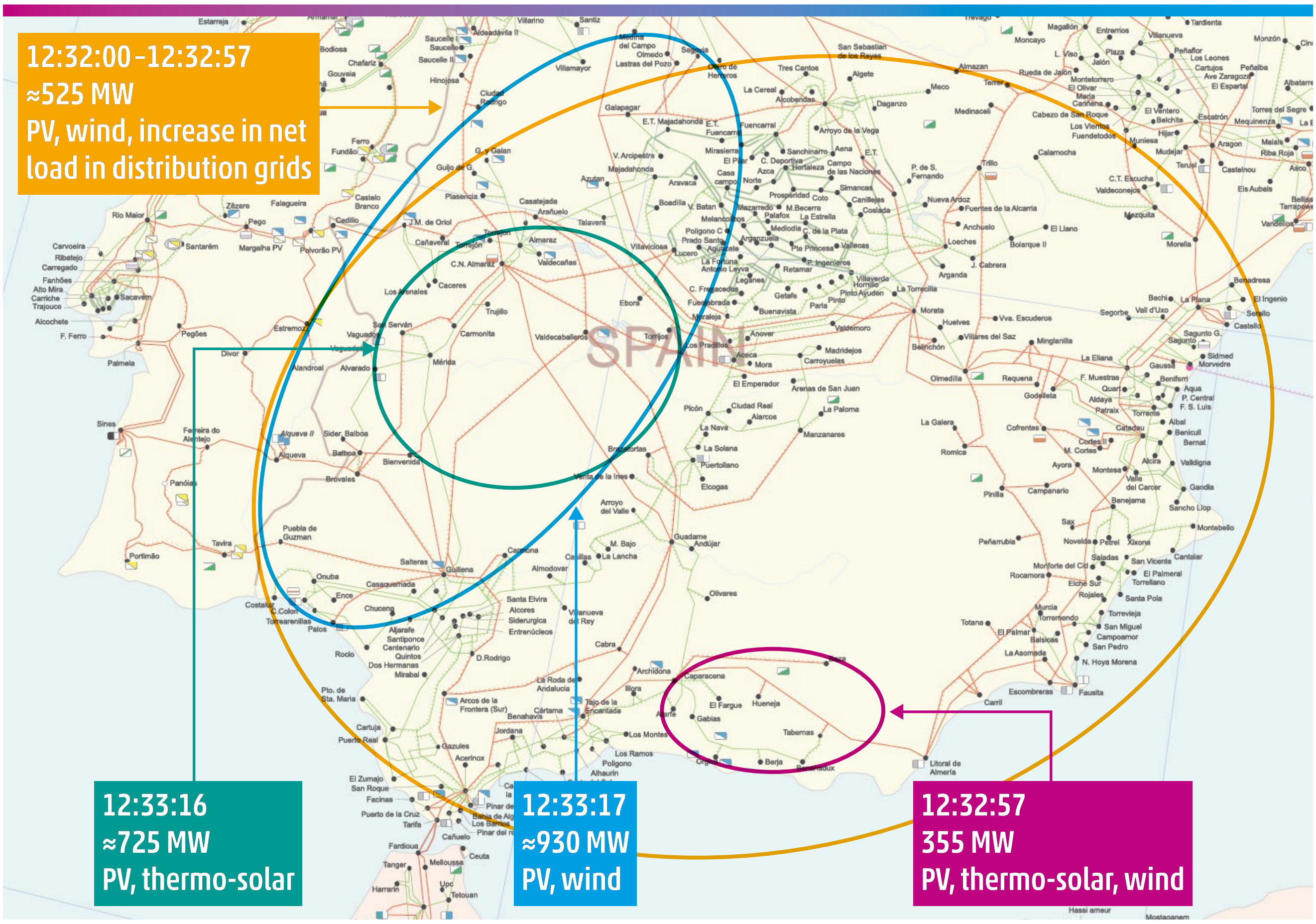


Figure 1-2: Areas of major generation disconnection events in Spain until 12:33:18

This phase of major disconnection events started some milliseconds after 12:32:57 with the tripping of a generation transformer in the region of Granada due to the activation of an over-voltage protection in the 220 kV side of a 400/220 kV transformer, which connects several generation facilities (photovoltaic, wind and thermo-solar) to the transmission grid. The transformer was injecting 355 MW into the grid and the voltage at the 400 kV level was 417.9 kV at this time.

The next event consisted of two sets of trips, resulting in an additional loss of around 725 MW of PV and thermo-solar facilities connected to two 400 kV transmission substations in the area of Badajoz. In the first substation, an evacuation line tripped at 12:33:16.460. The voltage at 400 kV level, at the time of this trip was 435,4 kV but this value, due to the way PMUs calculate and timestamp phasors, could already be influenced by the generation loss. In the second substation, the trip occurred at 12:33:16.820; the reasons for these two trips are not known.

After that several trips between 12:33:17 and 12:33:18.020 occurred that have led to disconnection of wind and solar generation in Segovia, Huelva, Badajoz, Sevilla and Caceres for a total of approximately 930 MW (or even more than 1,100 MW, as implied by the variation of frequency). Some of these trips occurred due to over-voltage protection, but most of trips are not known.

The following figure illustrates the increase of voltage up to a level beyond 435 kV during this sequence of losing generation in Spain of more than 2.5 GW in total until 12:33:18.020.

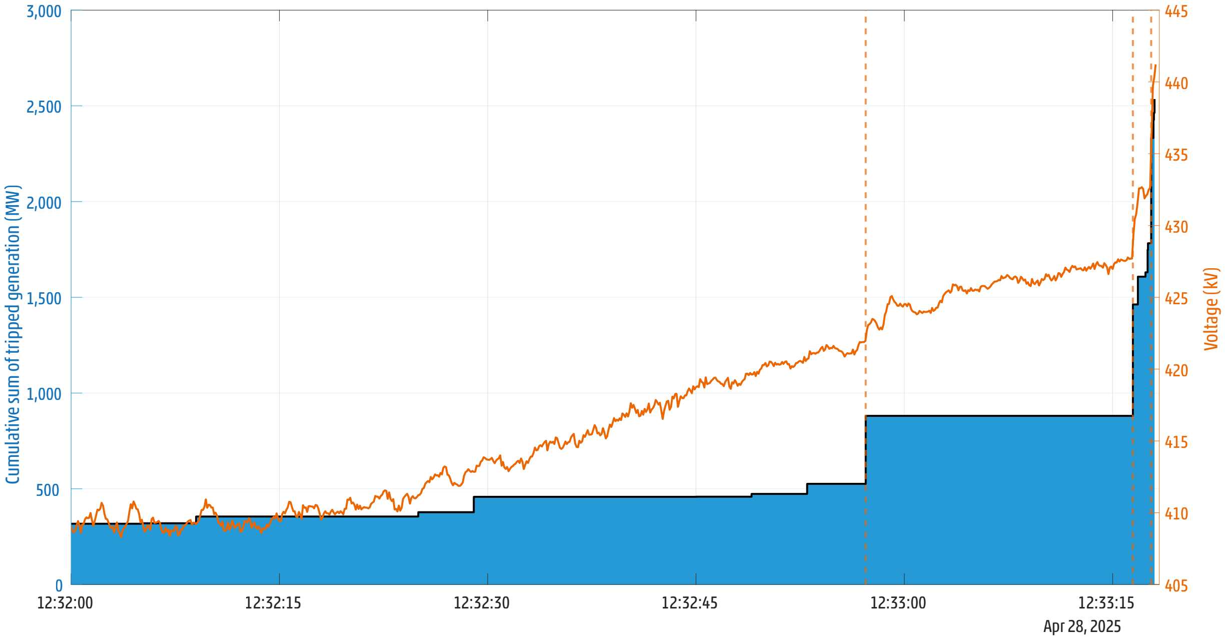


Figure 1-3: Cumulative sum of tripped generation in Spanish system vs voltage at 400 kV substation in Carmona (Spain)

No generation trips were observed in Portugal and France within the 12:32:00 – 12:33:18 timeframe.

As some generation units were consuming reactive power with the effect of reducing the voltage, the disconnections of these units without adequate compensation of loss of reactive power by other resources in the system with the capability to inject/absorb reactive power meant that voltages in the system increased, not only in Spain but also in Portugal. Furthermore, the frequency decreased.

Between 12:33:18 and 12:33:21, the voltage of the South area of Spain sharply increased, and consequently also in Portugal. The over-voltage triggered a cascade of generation losses that caused the frequency of the Spanish and Portuguese power system to decline.

At 12:33:19, the power systems of Spain and Portugal started losing synchronism with the rest of the European System.

Between 12:33:19 and 12:33:22, the automatic load shedding and System Defence Plans of Spain and Portugal – implemented in accordance with Commission Regulation 2017/2196 of 24 November 2017 establishing a network code on electricity emergency and restoration (NC ER) – were activated but unable to prevent the collapse of the Iberian power system.

At 12:33:20.473, the AC interconnection to Morocco tripped due to underfrequency. At 12:33:21.535, the AC overhead lines between France and Spain were disconnected by protection devices against a loss of synchronism. After this AC separation of the Iberian Peninsula, the power imbalance continued to increase, causing the frequency to further decline.

Finally, at 12:33:23.960, the electrical separation of the Iberian system was completed by the tripping of the HVDC lines that transmitted power from Spain to France due to constant power mode at this time, and all system parameters of the Spanish and Portuguese electricity systems collapsed.

The following figure illustrates the evolution of the frequency and voltage in Spain (substation of Carmona) and the frequency in the rest of CE (substation of Bassencourt, Switzerland) during the incident.

The evolution of the Rate of Change of Frequency (RoCoF) in the moments before the blackout indicates that RoCoF in the area remains within the absolute range of 1 Hz/s up until 12:33:20.560, when the frequency was already around 49 Hz. After that, the absolute value of RoCoF exceeded 1 Hz/s, when the system conditions were already degraded.

In comparison to the blackout in Spain and Portugal, France was marginally affected by the incident. Beside a loss of approximately 7 MW load, one nuclear power plant tripped due to the incident.

The evolution of system conditions from 12:32:57 until the blackout is explained in further detail in Chapter 3.

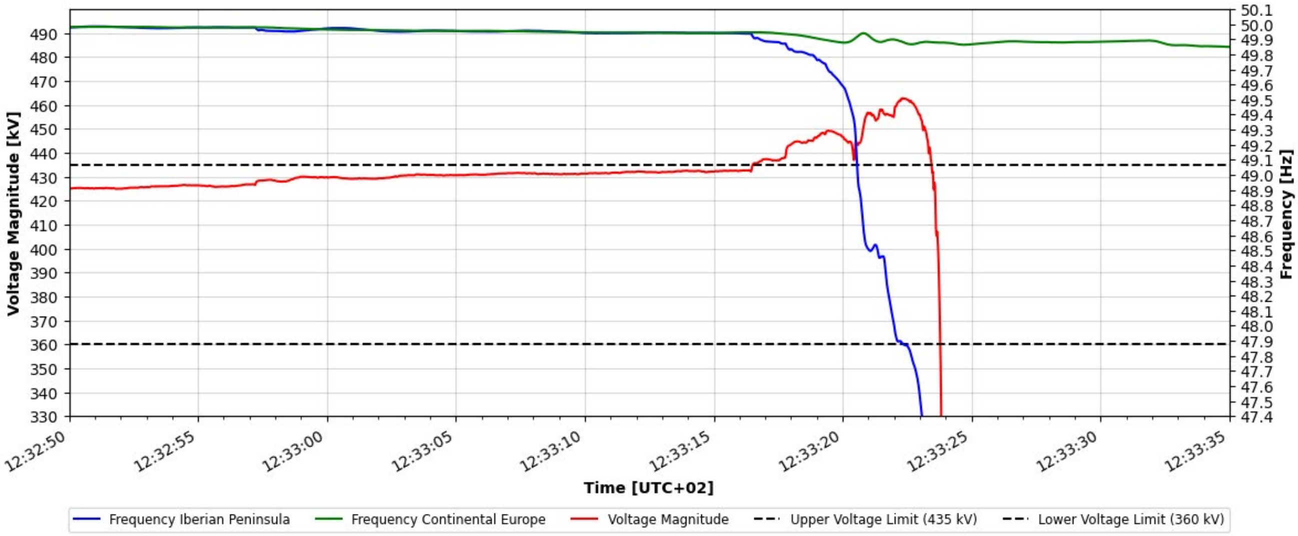


Figure 1-4: Evolution of the frequency and the voltage in the substation of Carmona (Spain) and of the frequency in the rest of Continental Europe (substation of Bassencourt, Switzerland) during the incident

1.4 Restoration Process

Following the incident, each affected TSO immediately activated their respective system restoration plans – implemented in accordance with Commission Regulation (EU) 2017/2196 establishing a network code on electricity emergency and restoration (NC ER) – as well as any other relevant procedures and protocols for restoring the electricity system's voltage. Power system restoration in some regions of the Portuguese and Spanish systems was facilitated – among others – by activating power system resources such as black-start processes in certain power plants, as well as the existing interconnections with France and Morocco.

During the restoration, not all black-start attempts were successful and some electrical islands had to be built up again after tripping. However, until 15:30, eight black-start islands could be built up successfully in Spain and first areas were already connected to rest of CE via interconnectors between Spain and France (L-400 kV Argia—Hernani energised at 12:43 and L-400 kV Baixas—Vic energised at 13:35).

Furthermore, at 13:04, the interconnection between Spain and Morocco was energised, which had to be repeated at 14:34 after tripping at 14:27.

At 15:07, all nuclear power plants confirmed having external supply for their auxiliary services.

At 18:36, the L-220 kV Aldeadavila—Pocinho 1 interconnector between Spain and Portugal was energised and the Portuguese transmission grid received voltage with continental frequency again. In the meantime, two black-start islands could be built up in Portugal.

At 19:32, by switching on the L-400 kV Almaraz—C. Rodrigo line, the Southern zone connected with Moroccan system could be synchronised with the Northern zone connected to CE.

At 00:22 and around 04:00 on 29 April 2025, the restoration process of the transmission grid was completed in Portugal and Spain, respectively. Details of the restoration process can be found in Chapter 4.

1.5 RCC Analysis Before the Incident

The results of the various tasks performed by the RCCs before the incident indicate that the grid was considered secure and no major issues were detected in the affected area during the operational planning phase. The Outage Planning Coordination (OPC) task conducted by SEleNe CC and Coreso to assess outage incompatibilities for transmission elements revealed no congestions (violations of n-1 criteria) for the Iberian Peninsula transmission network.

The Short-Term Adequacy (STA) analysis – led by Nordic RCC – confirmed that the available production capacity could meet the expected consumption. The Coordinated Security Analysis (CSA) – performed by Coreso – revealed no significant operational security risks, and the grid was deemed N-1 secure. The Common Grid Model (CGM) and Coordinated Capacity Calculation (CCC) processes did not reveal any unsafe grid situation. The RCC analysis before the incident is described in further detail in Chapter 5.

1.6 Communication of Synchronous Area Monitors and Between TSOs

During and after the blackout, communication between TSOs and Coordination Centres (Swissgrid and Amprion) supported the crisis management and coordination of restoration. Exchanges via direct calls, ENTSO-E Awareness System (EAS) notifications, and email enabled situational awareness, alignment on cross-border actions, and prioritisation of restoration steps. Key operational measures included adjustments in cross-border exchanges and HVDC interconnection modes to support grid stability.

Unaffected TSOs actively shared information and offered support throughout the incident. The Coordination Centres streamlined the flow of information to enable the affected TSOs to focus on the urgent operational necessities.

This structured and timely communication framework contributed to managing the incident and restoring system stability across the affected regions, as described in further detail in Chapter 6.

1.7 Classification of the Incident Based on the ICS Methodology

The ICS methodology is based on the requirements of Regulation (EC) No 714/2009 and Commission Regulation (EU) 2017/1485, and aims to provide a realistic view of system states during incidents. The criteria for incident classification are ranked by priority, with the highest priority criterion determining the incident scale. An Expert Panel investigates incidents classified as scale 3. On 28 April 2025, the OB3 criterion was met in Spain and Portugal as the result of both loss of demand in the Iberian Peninsula and the total absence of voltage. In France, the highest criterion violated was OV1 (scale 1) due to the high voltage experienced due to the incident. Consequentially, the incident met the RCC investigation threshold, which prompted the RCC investigation subgroup to initiate an RCC investigation by pursuant to Article 7 of the RCC Post-Operation and Post-Disturbances Analysis and Reporting methodology. Further explanations can be found in Chapter 7.

1.8 Next Steps

Following the release of this factual report, the Expert Panel will prepare a final report, which will include further detailed analysis of the events of 28 April regarding:

- 1. Root causes
- 2. Voltage control
- 3. Behaviour of different actors during the incident
- 4. Additional assessments

These categories of further analysis are described in further detail in Chapter 8. The Expert Panel will also consider the incident in a broader context, including by examining the behaviour of the Iberian power system on other days preceding the blackout.

Finally, the final report will also include recommendations to help prevent similar incidents in the future, not only in Spain and Portugal but across the entire European power system.

The final report is expected to be delivered approximately four months after the factual report. However, this timeline is purely indicative as it will largely depend on the complexity of the analyses that the Expert Panel will conduct and the related additional data that the Panel will have to collect accordingly. The final report will be published on the ENTSO-E website and presented to the European Commission and Member States via the Electricity Coordination Group.

2 SYSTEM AND MARKET CONDITIONS BEFORE THE INCIDENT

During the night spanning from 27 to 28 April, the Iberian power system operated normally with voltages in Spain in the range 399–426 kV. This chapter presents the system and market conditions on Monday, 28 April 2025 for the period between 9:00:00 and 12:32:00, without prejudice to relevant events that occurred on previous days, which will be analysed in the final report. Therefore, for the purpose of this report, it is considered that the incident started at 12:32:00.

2.1 Information on Topology

2.1.1 Planned and Unplanned Outages

In this section, all planned outages with an impact on neighbouring systems are presented by the TSO as defined in methodologies for coordinated operations, in accordance with Commission Regulation (EU) 2017/1485 (see Section 2.8.1 in the annex for the detailed list of RTE, RE, and REN outages).

There were no unplanned outages with an impact on neighbours' systems on either RE, REN, or RTE's grid. Therefore, the figure below presents the location of planned outages with an impact on neighbours' systems. Planned outages without an impact on neighbouring systems are listed in Tables 2-9, 2-10, and 2-11 in the annex.

Figure 2-1: Location of planned unavailable elements with an impact on neighbouring systems

Note: The figure shows (in blue colour) all transmission elements with an impact on neighbouring systems that were in planned maintenance on 28 April between 12:00 and 13:00.

From the planned outages with an impact on neighbouring systems, two notable border tie lines were out of service:

- Brovales–Alqueva 400 kV (Spain–Portugal border)
- Biescas–Pragnères 220 kV (France–Spain border)

The Brovales–Alqueva 400 kV (Spain–Portugal) tie line was put into service on 29 April, following the interruption of this outage, initially planned to terminate on 3 May.

Table 2-1 below provides a list of works and manoeuvres from RE between 9:00 and 12:32.

HOUR	ELEMENT	ZONE	COMMENTS
09:00	SE 220 kV SERRALLO	EAST	
09:03	SE 220 kV STA. ELVIRA	SOUTH	
09:16	SE 220 kV ACECA pos PRADILLOS	CENTRE	
09:21	SE 220 kV TORRELLANO	EAST	
09:37	SE 400 kV ALDEADAVILA: JBP2	NORTHWEST	
09:37	SE 400 kV FAUSITA	EAST	
09:52	L-220 kV PRADO SANTO DOMINGO–VILLAVICIOSA	CENTER	
09:52	SE 220 kV VILLAVICIOSA pos ACJ	CENTER	Operation in 2 nodes
09:53	SE 400 kV GUILLENA: L/COLLECTOR 1	SOUTH	
10:46	SE 400 kV PALOS: AT-2 and TM-2	SOUTH	
11:15	L-220 kV VILLAVICIOSA–LUCERO–LEGANES	CENTER	
11:36	SE 220 kV ACECA: 522-1 Switch	CENTER	
12:16	SE 220 kV SS. REYES: L/ PS. FERNANDO split with L/ ALCOBENDAS	CENTER	Topological manoeuvre at SS REYES 220 kV to avoid overload on L-220 kV LOECHES–PS. FERNANDO post contingency at DC-400 kV ALMARAZ–C. RODRIGO/ALDEADAVILA–ARAÑUELO

Table 2-1: List of works and topological manoeuvres from RE

Throughout this document, the following geographic zones are defined:

- South: Andalucía (except Almería) and Extremadura
- Centre: Madrid and Castilla–La Mancha (except Albacete)
- East: Comunidad Valenciana, Murcia, Albacete, and Almería
- North: País Vasco, Navarra, La Rioja, and Aragón
- North East: Cataluña
- North West: Galicia, Asturias, and Cantabria y Castilla León

2.1.2 Topological actions for voltage control

This section lists all manual topological actions taken for voltage control by TSOs (see annex for the detailed list of open lines and RE zonal SCADA images at 12:25). The situation from 9:00 to 12:32 is depicted in Figure 2-2:

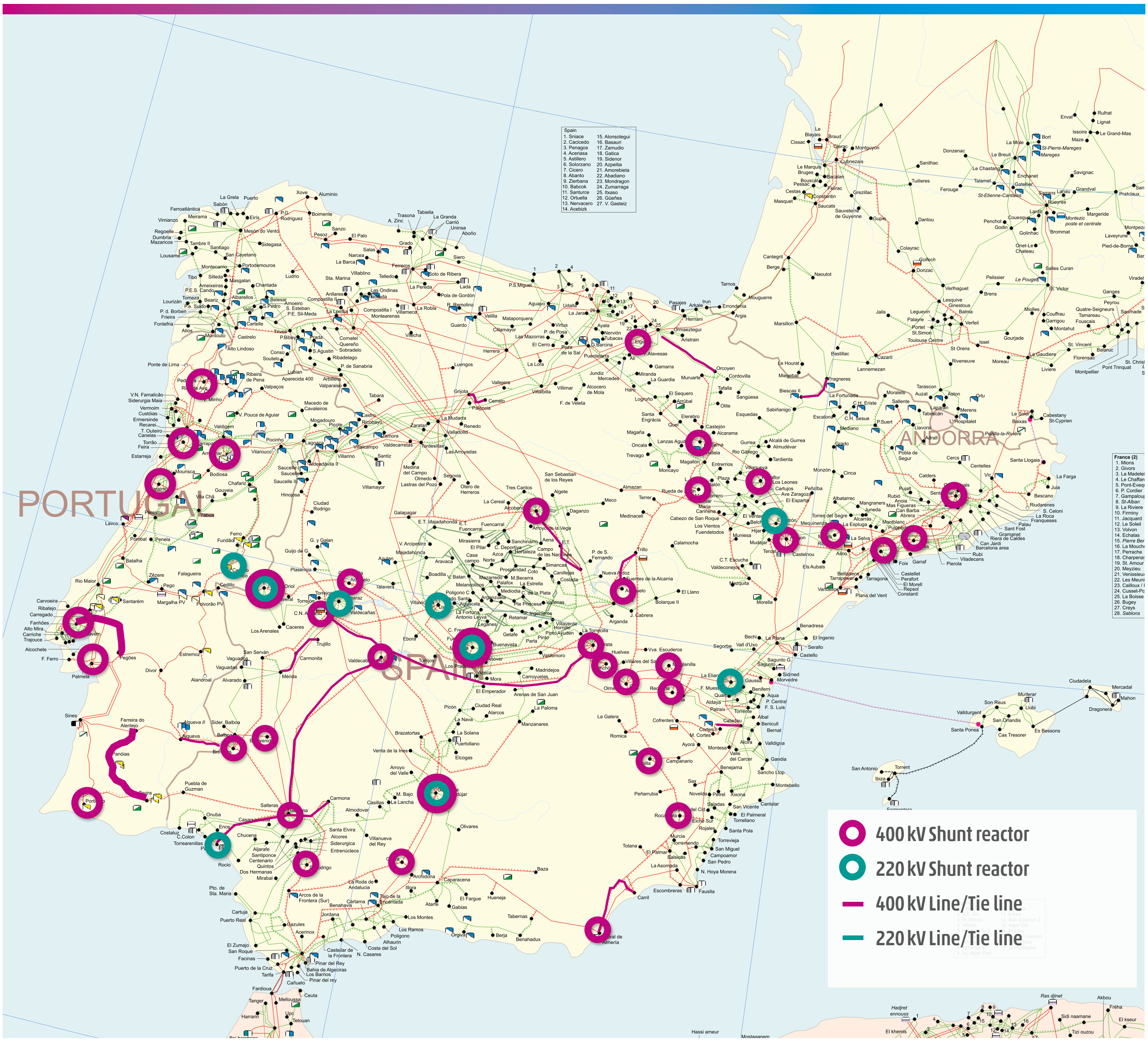


Figure 2-2: Iberian scenario: Open lines and reactances in Portugal and in Spain from 9:00 until 12:32

For context, shunt reactors and lines are connected or disconnected manually based on decisions of the operators in the RE and REN control rooms. Connecting lines decreases system impedance. This action increases damping, and on the other hand increases the reactive power production in the system and hence increases voltage. Disconnecting lines has the opposite effect. Connecting shunt reactors increases reactive power consumption in the system and thus decreases voltage. Disconnecting shunt reactors has the opposite effect.

Additionally, in the table below a list of manoeuvres from Red Electrica before 12:32 is provided. For every manoeuvre, or group of manoeuvres, that it is done in the control room, the decision to perform the manoeuvre is taken either based on the experience of the operator or based on a static power flow simulation performed right before, to check the expected impact of the action on voltages and loads of elements.

HOUR	ELEMENT	NAME	MOVEMENT	ZONE
09:02	LINE	L-400 kV ALMARAZ–SAN SERVÁN 1	SWITCH ON	SOUTH
09:02	SHUNT REACTOR	VALDECABALLEROS 400 REA 2	SWITCH OFF	SOUTH
09:02	SHUNT REACTOR	ANCHUELO REA 1	SWITCH OFF	CENTRE
09:05	SHUNT REACTOR	MINGLANILLA 400 REA 1	SWITCH OFF	EAST
09:08	SHUNT REACTOR	LITORAL 400 REA 1	SWITCH OFF	EAST
09:13	LINE	L-400 kV BRAZATORTAS–MANZANARES 1	SWITCH ON	CENTRE
09:13	LINE	L-220 kV GURREA–VILLANUEVA 1	SWITCH ON	NORTH
09:17	LINE	L-400 kV SALLENTE–CALDERS	SWITCH ON	NORTHEAST
09:13	SHUNT REACTOR	RUEDA 400 REA 2	SWITCH OFF	NORTH
09:14	SHUNT REACTOR	BELINCHON 400 REA 1	SWITCH OFF	EAST
09:22	SHUNT REACTOR	VITORIA 400 REA 2	SWITCH ON	NORTH
09:23	SHUNT REACTOR	GUADAME 400 REA 2	SWITCH OFF	SOUTH
09:24	SHUNT REACTOR	DRODRIGO 400 REA 1	SWITCH OFF	SOUTH
09:25	SHUNT REACTOR	ARANUELO 400 REA 1	SWITCH OFF	SOUTH
09:26	SHUNT REACTOR	BIENVENIDA 400 REA 1	SWITCH OFF	SOUTH
09:27	SHUNT REACTOR	MORALEJA 400 REA 1	SWITCH OFF	CENTRE
09:31	SHUNT REACTOR	JM. ORIOL 400 REA 2	SWITCH OFF	SOUTH
09:32	SHUNT REACTOR	MORALEJA 220 REA 12	SWITCH OFF	CENTRE
09:34	SHUNT REACTOR	ALMARAZ 400 REA 3	SWITCH OFF	SOUTH
09:41	SHUNT REACTOR	VALDECABALLEROS 400 REA 1	SWITCH OFF	SOUTH
09:44	SHUNT REACTOR	BROVALES 400 REA 1	SWITCH OFF	SOUTH
09:49	SHUNT REACTOR	EALMARAZ 220 REA 1	SWITCH OFF	SOUTH
09:52	SHUNT REACTOR	MAGALLON 400 REA 2	SWITCH OFF	NORTH
09:54	LINE	L-400 kV ALMARAZ–MORATA 2	SWITCH ON	CENTRE
10:02	LINE	L-400 kV BROVALES–SAN SERVAN 1	SWITCH OFF	SOUTH
10:04	SHUNT REACTOR	GUILLENA 400 REA 2	SWITCH OFF	SOUTH
10:05	SHUNT REACTOR	CABRA 400 REA 1	SWITCH OFF	SOUTH
10:05	LINE	L-400 kV ARCOS–D. RODRIGO 2	SWITCH ON	SOUTH
10:18	SHUNT REACTOR	JM. ORIOL 220 REA 1	SWITCH OFF	SOUTH
10:19	SHUNT REACTOR	MORALEJA 220 REA 13	SWITCH OFF	CENTRE
10:20	SHUNT REACTOR	OLMEDILLA 400 REA 1	SWITCH OFF	EAST
10:22	SHUNT REACTOR	VILLAVICIOSA 220 REA 2	SWITCH OFF	CENTRE
10:29	SHUNT REACTOR	ROCAMORA 400 REA 1	SWITCH OFF	EAST
10:32	LINE	L-220 kV ACECA–PICON	SWITCH ON	CENTRE
10:32	SHUNT REACTOR	MAGALLON 400 REA 1	SWITCH OFF	NORTH
10:32	SHUNT REACTOR	PINILLA 400 REA 1	SWITCH OFF	EAST
10:32	SHUNT REACTOR	SS REYES 400 REA 3	SWITCH OFF	CENTRE
10:33	LINE	L-400 kV BROVALES–GUILLENA 1	SWITCH ON	SOUTH
10:33	HVDC 320 kV STA. LLOGAIA–BAIXAS	RAISE THE SETPOINT TO 413 kV	SETPOINT	NORTHEAST
10:35	LINE	L-400 kV GUADAME–VALDECABALLEROS	SWITCH ON	SOUTH
10:39	SHUNT REACTOR	MAGALLON 400 REA 2	SWITCH ON	NORTH
10:40	SHUNT REACTOR	GUADAME 400 REA 2	SWITCH ON	SOUTH
10:40	SHUNT REACTOR	PINILLA 400 REA 1	SWITCH ON	EAST
10:40	SHUNT REACTOR	MORALEJA 220 REA 12	SWITCH ON	CENTRE
10:43	HVDC 320 kV STA. LLOGAIA–BAIXAS	REDUCE THE SETPOINT TO 409 kV	SETPOINT	NORTHEAST
10:44	SHUNT REACTOR	RUEDA 400 REA 2	SWITCH ON	NORTH

HOUR	ELEMENT	NAME	MOVEMENT	ZONE
10:44	CONDENSER	JUIA 220 CONDEN1	SWITCH OFF	NORTHEAST
10:45	SHUNT REACTOR	VALDECABALLEROS 400 REA 2	SWITCH ON	SOUTH
10:50	SHUNT REACTOR	CABRA 400 REA 1	SWITCH ON	SOUTH
10:50	SHUNT REACTOR	REQUENA 400 REA 1	SWITCH ON	EAST
10:51	HVDC 320 kV STA. LLOGAIA–BAIXAS	REDUCE THE SETPOINT TO 404 kV	SETPOINT	NORTHEAST
10:59	SHUNT REACTOR	VALDECABALLEROS 400 REA 2	SWITCH OFF	SOUTH
10:59	SHUNT REACTOR	SENTMENAT 400 REA 1	SWITCH OFF	NORTHEAST
10:59	HVDC 320 kV STA. LLOGAIA–BAIXAS	RAISE THE SETPOINT TO 410 kV	SETPOINT	NORTHEAST
11:00	SHUNT REACTOR	GUADAME 400 REA 2	SWITCH OFF	SOUTH
11:01	SHUNT REACTOR	CABRA 400 REA 1	SWITCH OFF	SOUTH
11:02	SHUNT REACTOR	LA SERNA 400 REA 2	SWITCH OFF	NORTH
11:03	LINE	L-400 kV OLMEDILLA–ROMICA 2	SWITCH ON	EAST
11:03	SHUNT REACTOR	BEGUES 400 REA 1	SWITCH OFF	NORTHEAST
11:03	SHUNT REACTOR	REQUENA 400 REA 1	SWITCH OFF	EAST
11:03	SHUNT REACTOR	VITORIA 400 REA 2	SWITCH OFF	NORTH
11:03	SHUNT REACTOR	GUADAME 220 REA 3	SWITCH OFF	SOUTH
11:04	SHUNT REACTOR	ESCATRON 220 REA 1	SWITCH OFF	NORTH
11:04	SHUNT REACTOR	MORALEJA 220 REA 12	SWITCH OFF	CENTRE
11:04	SHUNT REACTOR	PALOS 220 REA 1	SWITCH OFF	SOUTH
11:04	SHUNT REACTOR	RUEDA 400 REA 2	SWITCH OFF	NORTH
11:04	SHUNT REACTOR	MAIALS 400 REA 1	SWITCH OFF	NORTHEAST
11:07	SHUNT REACTOR	MAGALLON 400 REA 2	SWITCH OFF	NORTH
11:07	SHUNT REACTOR	RUBI 400 REA 1	SWITCH OFF	NORTHEAST
11:07	LINE	L-400 kV AGUAYO–ABANTO	SWITCH ON	NORTHWEST
11:07	LINE	L-400 kV GUADAME–CABRA 1	SWITCH ON	SOUTH
11:08	LINE	L-400 kV PINAR–TAJO	SWITCH ON	SOUTH
11:08	HVDC 320 kV STA. LLOGAIA–BAIXAS	RAISE THE SETPOINT TO 413 kV	SETPOINT	NORTHEAST
11:08	SHUNT REACTOR	PINILLA 400 REA 1	SWITCH OFF	EAST
11:09	LINE	L-400 kV MONTEARENAS–MUDARRA 2	SWITCH ON	NORTHWEST
11:10	SHUNT REACTOR	CABRA 400 REA 1	SWITCH ON	SOUTH
11:10	SHUNT REACTOR	GUADAME 220 REA 3	SWITCH ON	SOUTH
11:11	HVDC 320 kV STA. LLOGAIA–BAIXAS	REDUCE THE SETPOINT TO 409 kV	SETPOINT	NORTHEAST
11:11	SHUNT REACTOR	LA SERNA 400 REA 2	SWITCH ON	NORTH
11:12	SHUNT REACTOR	MAIALS 400 REA 1	SWITCH ON	NORTHEAST
11:14	HVDC 320 kV STA. LLOGAIA–BAIXAS	REDUCE THE SETPOINT TO 405 kV	SETPOINT	NORTHEAST
11:17	LINE	L-400 kV ARCOS–CABRA	SWITCH ON	SOUTH
11:18	SHUNT REACTOR	RUBI 400 REA 1	SWITCH ON	NORTHEAST
11:20	LINE	L-400 kV PIEROLA–VANDELLÓS	SWITCH ON	NORTHEAST
11:22	SHUNT REACTOR	ELIANA 220 REA 1	SWITCH OFF	EAST
11:43	SHUNT REACTOR	ELIANA 220 REA 1	SWITCH ON	EAST
11:43	SHUNT REACTOR	ESCATRON 220 REA 1	SWITCH ON	NORTH
11:46	SHUNT REACTOR	SENTMENAT 400 REA 1	SWITCH ON	NORTHEAST
11:47	SHUNT REACTOR	GUADAME 400 REA 2	SWITCH ON	SOUTH
11:47	SHUNT REACTOR	MINGLANILLA 400 REA 1	SWITCH ON	EAST
11:48	SHUNT REACTOR	RUEDA400 REA 2	SWITCH ON	NORTH
11:48	HVDC 320 kV STA. LLOGAIA–BAIXAS	REDUCE THE SETPOINT TO 401 kV	SETPOINT	NORTHEAST

HOUR	ELEMENT	NAME	MOVEMENT	ZONE
11:48	SHUNT REACTOR	EALMARAZ 220 REA 1	SWITCH ON	SOUTH
11:48	SHUNT REACTOR	MORALEJA 220 REA 12	SWITCH ON	CENTRE
11:50	SHUNT REACTOR	PALOS 220 REA 1	SWITCH ON	SOUTH
11:59	HVDC 320 kV STA. LLOGAIA–BAIXAS	RAISE THE SETPOINT TO 406 kV	SETPOINT	NORTHEAST
11:59	SHUNT REACTOR	GUADAME 400 REA 2	SWITCH OFF	SOUTH
12:01	SHUNT REACTOR	EALMARAZ 220 REA 1	SWITCH OFF	SOUTH
12:02	LINE	L-220 kV C.PLATA–VILLAVERDE BAJO 2	SWITCH ON	CENTRE
12:04	SHUNT REACTOR	VILLAVICIOSA 400 REA 1	SWITCH OFF	CENTRE
12:04	SHUNT REACTOR	GUADAME 220 REA 3	SWITCH OFF	SOUTH
12:05	HVDC 320 kV STA. LLOGAIA–BAIXAS	RAISE THE SETPOINT TO 412 kV	SETPOINT	NORTHEAST
12:05	SHUNT REACTOR	RUEDA 400 REA 2	SWITCH OFF	NORTH
12:07	LINE	L-400 kV GRIJOTA–VILLARINO 2	SWITCH ON	NORTHWEST
12:07	LINE	L-400 kV P. GUZMAN–GUILLENA 1	SWITCH ON	SOUTH
12:07	LINE	L-400 kV PALMAR–CARRIL	SWITCH ON	EAST
12:07	SHUNT REACTOR	ARAGON 400 REA 1	SWITCH OFF	NORTH
12:08	LINE	L-400 kV LA ROBLA–MUDARRA	SWITCH ON	NORTHWEST
12:08	LINE	L-400 kV PALMAR–ROCAMORA 2	SWITCH ON	EAST
12:15	LINE	L-400 kV MORATA–VILLAVICIOSA	SWITCH ON	CENTRE
12:17	SHUNT REACTOR	CABRA 400 REA 1	SWITCH OFF	SOUTH
12:21	SHUNT REACTOR	PEÑAFLOR 400 REA 1	SWITCH OFF	NORTH
12:21	LINE	L-400 kV PINILLA–ROMICA 2	SWITCH ON	EAST
12:22	LINE	L-400 kV PINILLA–ROCAMORA 1	SWITCH ON	EAST
12:24	SHUNT REACTOR	PALOS 220 REA 1	SWITCH OFF	SOUTH
12:24	SHUNT REACTOR	MORATA 400 REA 4	SWITCH OFF	CENTRE
12:25	LINE	L-400 kV GUADAME–CABRA 3	SWITCH ON	SOUTH
12:25	LINE	L-400 KV TORDESILLAS–GALAPAGAR	SWITCH ON	CENTRE
12:26	SHUNT REACTOR	VITORIA 400 REA 2	SWITCH ON	NORTH
12:27	SHUNT REACTOR	PEÑAFLOR 400 REA 1	SWITCH ON	NORTH
12:27	SHUNT REACTOR	GUADAME 220 REA 3	SWITCH ON	SOUTH
12:27	SHUNT REACTOR	GUADAME 400 REA 2	SWITCH ON	SOUTH
12:28	SHUNT REACTOR	MORATA 400 REA 4	SWITCH ON	CENTRE
12:32	HVDC 320 kV STA. LLOGAIA–BAIXAS	REDUCE THE SETPOINT TO 409 kV	SETPOINT	NORTHEAST

Table 2-2: List of works and manoeuvres from RE for voltage control

Table 2-3 provides a list of topological actions – shown in Figure 2-2 – taken for voltage control by REN:

Element type	Switched-off element name	Start date and time	End date and time	Reason
Line	Fanhoes–Pegoes 400	26/04 19:46	30/04 06:23	Manual voltage control
Line	Panoias–Tavira 400	27/04 02:18	28/04 09:07	Manual voltage control
Line	Ferreira do Alentejo–Panoias 400	27/04 02:18	28/04 09:07	Manual voltage control
Shunt Reactor	RS1 - S. Feira 180 Mvar	28/04 09:09	29/04 05:24	Manual voltage control
Shunt Reactor	RS1 - S. Castelo Branco 70 Mvar	28/04 09:09	29/04 00:12	Manual voltage control
Shunt Reactor	RS1 - S. Portimão 180 Mvar	28/04 10:03	28/04 23:33	Manual voltage control
Shunt Reactor	RS1 - S. Pedralva 180 Mvar	28/04 10:03	29/04 02:41:	Manual voltage control
Shunt Reactor	RS1 - S. Paraimo 180 Mvar	28/04 10:06	29/04 00:37	Manual voltage control
Shunt Reactor	RS1 - S. Armamar 180 Mvar	28/04 10:27	29/04 02:39	Manual voltage control
Shunt Reactor	RS1 - S. Fanhões 180 Mvar	28/04 10:27	28/04 22:51	Manual voltage control
Shunt Reactor	RS2 - S. Palmela 180 Mvar	28/04 12:19	28/04 23:56	Trip due to low voltage protection

Table 2-3: List of manual topological actions taken for voltage control by REN

2.1.3 Grid Topology Snapshots at 12:00:00 and 12:32:00

The following two figures provide a view of the grid topology in Spain at the time instants of 12:00:00 (Figure 2-3) and 12:32:00 (Figure 2-4). The figure shows all the lines that are connected in that time instance.

The lines that are disconnected (either due to planned maintenance or due to voltage control) are shown on grey colour in the figure.

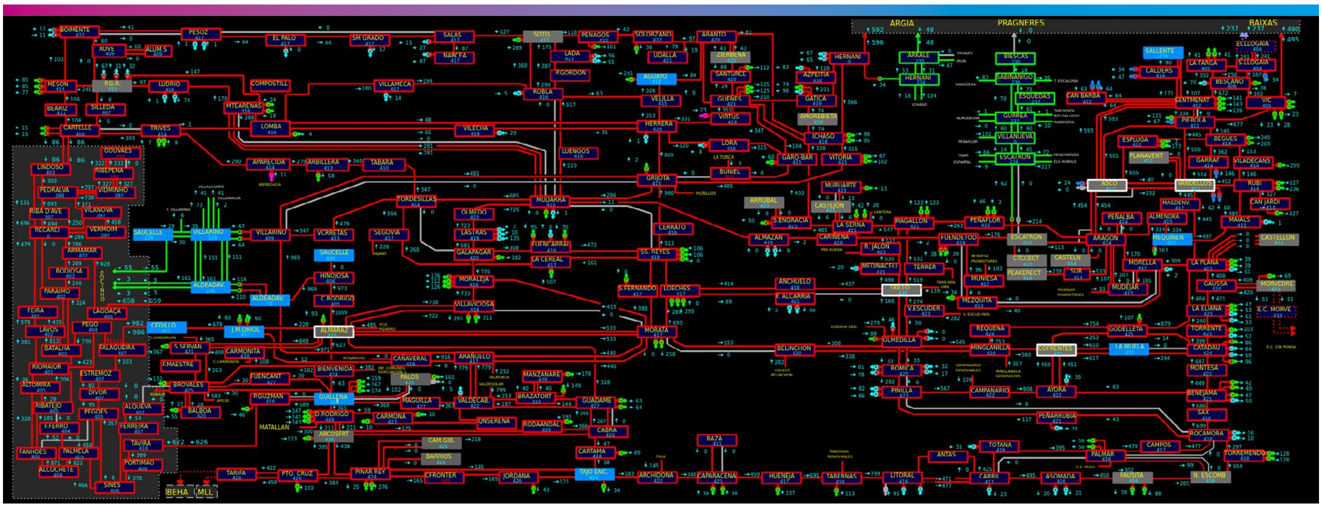


Figure 2-3: Grid topology in Spain at 12:00:00

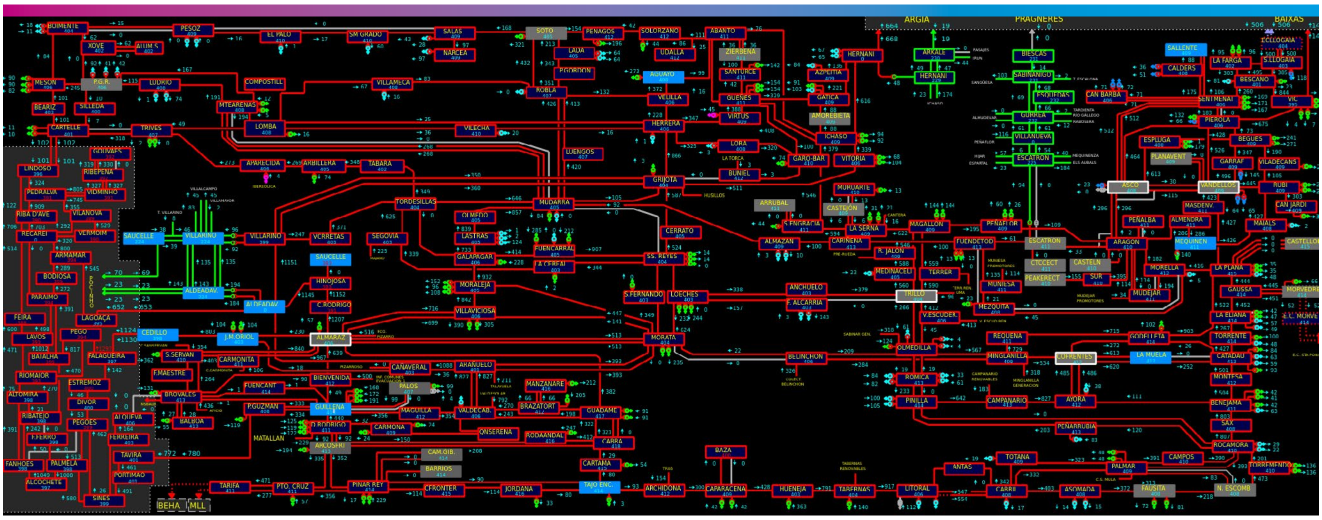


Figure 2-4: Grid topology in Spain at 12:32:00

2.1.4 Demand and Generation Forecasts

The purpose of demand and generation forecasts is to provide the most accurate information possible to support essential security analyses – such as adequacy assessments and N-1 contingency evaluations – and ensure the secure operation of the power system.

Affected TSOs publish renewable generation and electricity demand forecasts, both are carried out in-house, incorporating external weather forecasts. In the case of renewable generation, RE further enhances internal forecasting models with data provided by external suppliers.

Concerning the STA process, forecasts on demand, available generation, and all necessary inputs are provided each D-1 for adequacy analysis. In order to ensure correct delivery, they are sent at 3:00 and again at 8:00. Moreover, a manual check of the correct delivery is performed daily. Concerning the forecasts for the STA process, a time lag – as mentioned in chapter 5 – was detected in the files sent to STA, starting from the date of the hour shift from CET to CEST (30 March).

This bug was detected at the beginning of April and was corrected in May. It only affected STA forecast input files and had no operational impact related to the real-time incident of 28 April.

Concerning N-1 contingency evaluations, the time lag had no impact on 28 April.

The following figures show forecasts estimated by TSOs two days in advance, one day in advance, and the latest available on the same day at 10:00, 11:00, and 12:00:

- » 1) Demand forecast, estimated as generation minus pumping, minus exchanges with other systems
- » 2) Wind forecast
- » 3) PV forecast

2.1.4.1 Spanish Demand Forecast

Demand forecast is generated by combining several proprietary models developed by RE, which use temperature, solar radiation, and labour days demand patterns as exogenous variables, along with real-time demand data.

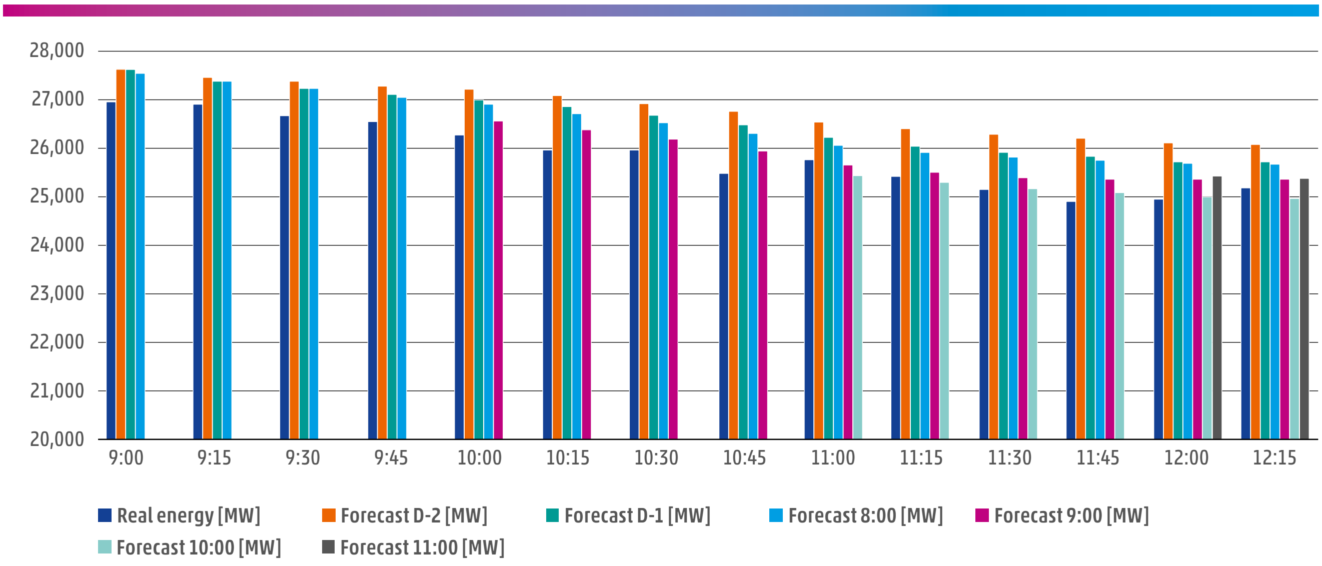


Figure 2-5: Spanish demand forecast

2.1.4.2 Portuguese Demand Forecast

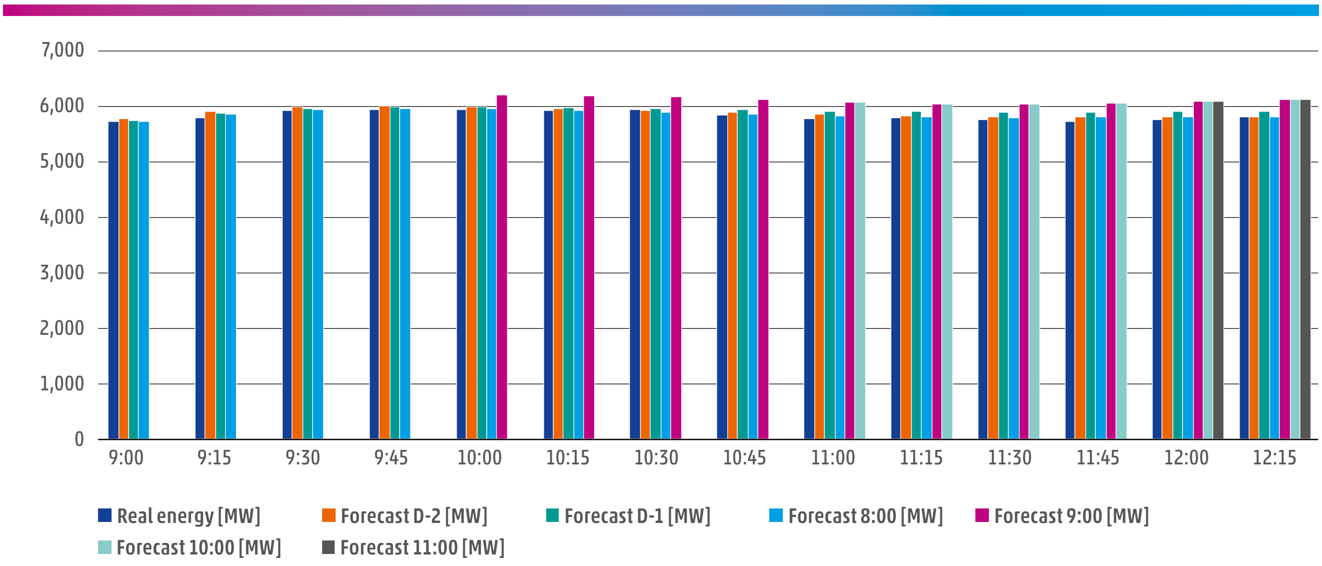


Figure 2-6: Portuguese demand forecast

2.1.4.3 Spanish Wind Forecast

The renewable generation potential forecast – defined as the maximum expected renewable generation based on weather conditions – produced by RE combines its proprietary forecasting models with data from various external providers. For wind generation, forecasting models use wind speed and direction at a height of 100 metres as exogenous variables.

Subsequently, RE refines the abovementioned forecast by applying constraints such as the unavailability of renewable installations and network limitations, which help approximate the potential forecast to the expected actual production. Finally, the forecast is adjusted for the initial time horizons using real-time renewable generation data received via telemetry by RE.

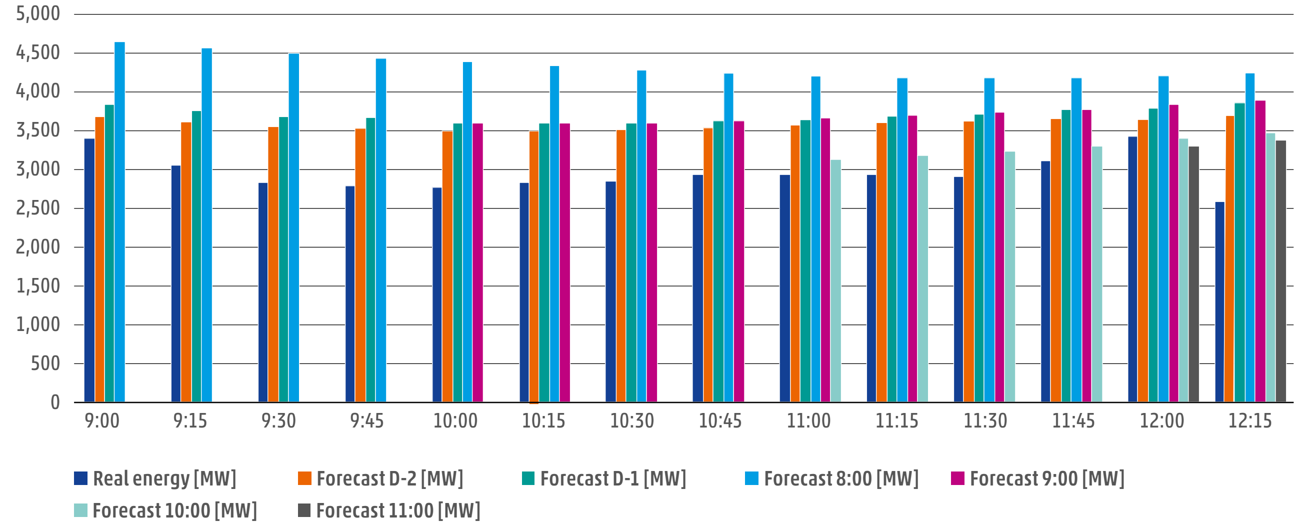


Figure 2-7: Spanish wind forecast

RE corrects these forecasts in their initial horizons using the latest actual production value received. At 08:00, production increased unexpectedly, prompting an upward correction of the forecast. However, at 09:00, production dropped again, whereby the upward correction made at 08:00 resulted in an error.

2.1.4.4 Portuguese Wind Forecast

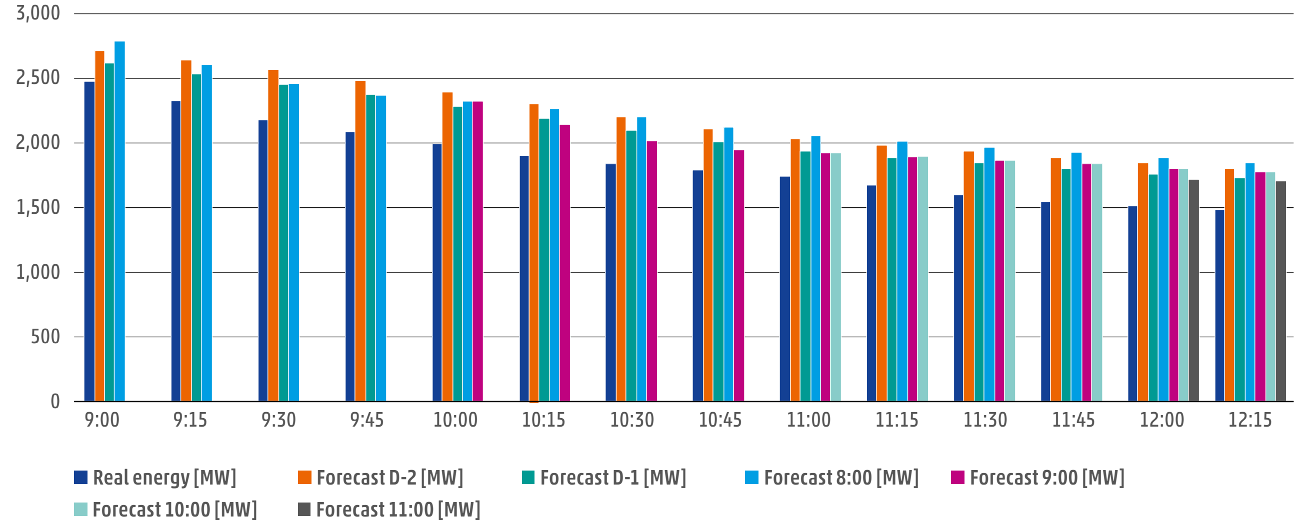


Figure 2-8: Portuguese wind forecast

2.1.4.5 Spanish PV Forecast

The aforementioned renewable generation potential forecast also applies to photovoltaic (PV) generation. In this case, models incorporate global radiation, cloud cover, and temperature.

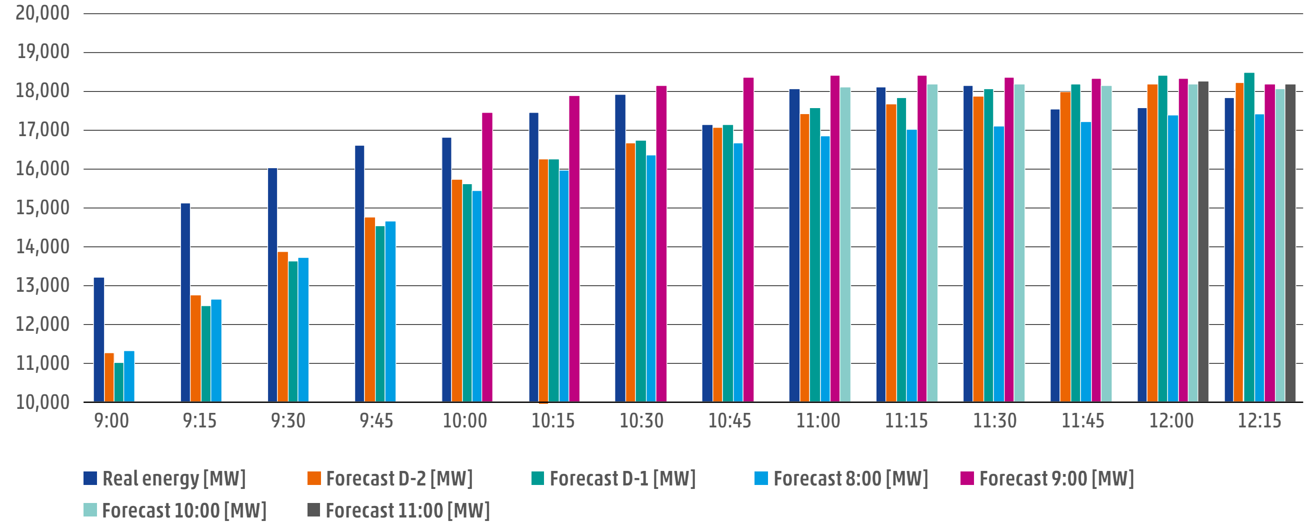


Figure 2-9: Spanish PV forecast

2.1.4.6 Portuguese PV Forecast

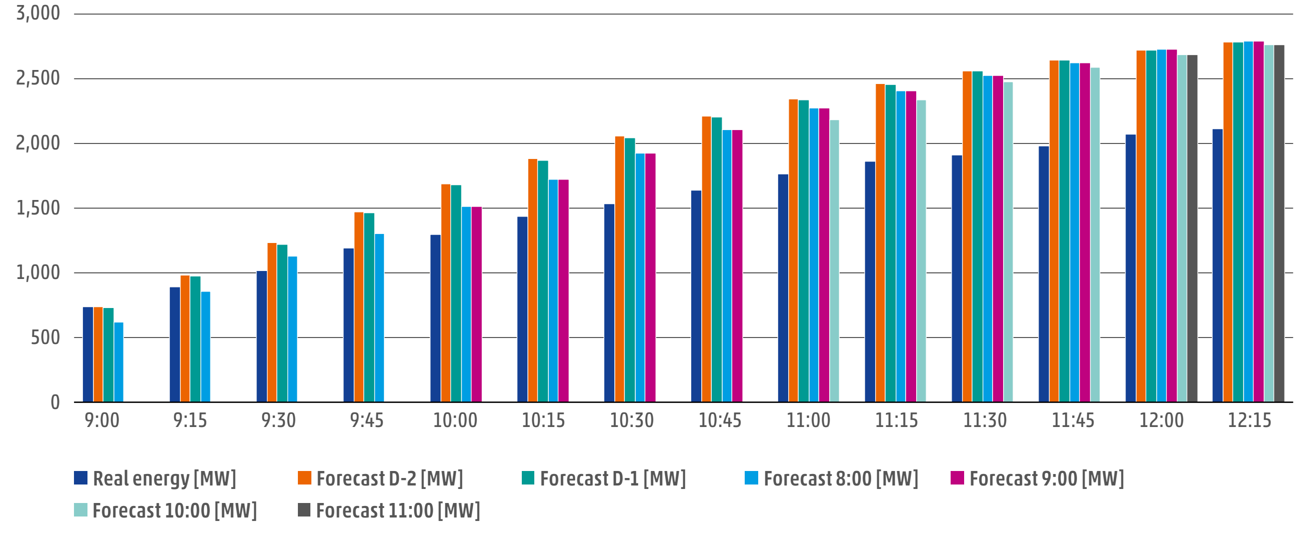


Figure 2-10: Portuguese PV forecast

2.2 Market Conditions

2.2.1 Day Ahead Prices

After the day-ahead market, the prices for delivery before 9:00 settled at low values in Spain and Portugal, in comparison to France. After 9:00, the prices dropped to near 0 €/MWh in the RE price zone.

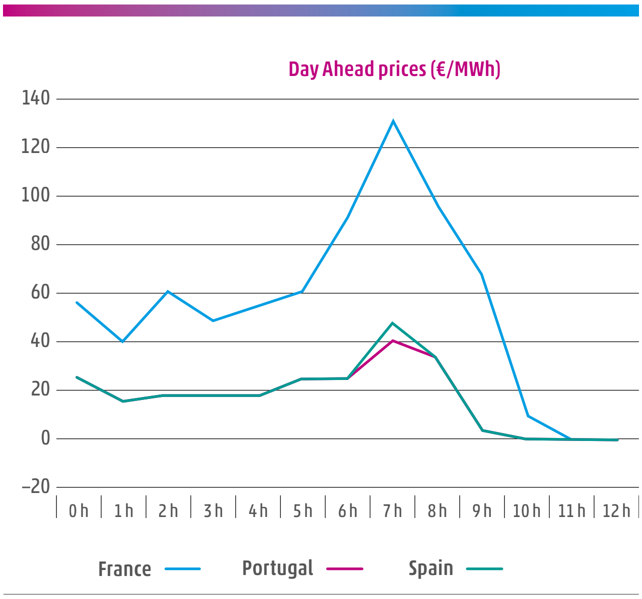


Figure 2-11: Day-ahead prices

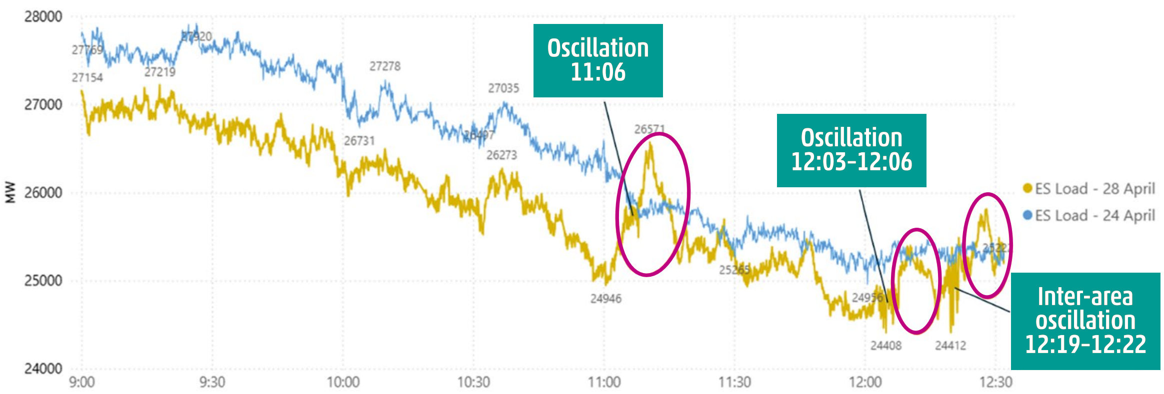
2.3 Active Power Flows Before the Incident

2.3.1 Load Patterns

2.3.1.1 Spanish Total Load

Figure 2-12 below shows the evolution of the total load on the Spanish network from 9:00 to 12:32 on 28 April, as well as the total load on a similar day (24 April). The total load is calculated as the sum of the output of all generation units with a capacity greater than 1 MW connected to the transmission or distribution network, adjusted for net electricity exchanges with the neighbouring TSOs. Hence, it does not include the demand directly supplied by smaller generation units connected to the distribution network. Effectively, if small generation units disconnect, the total load as defined here will increase.

The following figure compares the total load on the day of the incident with the total load for on a similar day (April 24).



Oscillation 11:06

Oscillation 12:03-12:06

Inter-area oscillation 12:19-12:22

Figure 2-12: Total load in Spain on 24 and 28 April between 9:00 and 12:32

This figure shows that three significant temporary total load increases occurred on 28 April but not on 24 April, namely from 11:07 to 11:10, from 12:07 to 12:15, and from 12:25 to 12:29. There is no distinguishable direct cause explaining these patterns, although it can be observed that these three increases in load occurred after three oscillations that took place at 11:06, between 12:03 and 12:06, and between 12:19 and 12:22, respectively, as described in details in Section 2.5.6.

Figure 2-13 shows the power flows between transmission and distribution networks aggregated across continental Spain on the same days (24 and 28 April). It is calculated as the sum of the active power of all transformers 400/132 kV and lower and 220/132 kV and lower connected to the distribution.

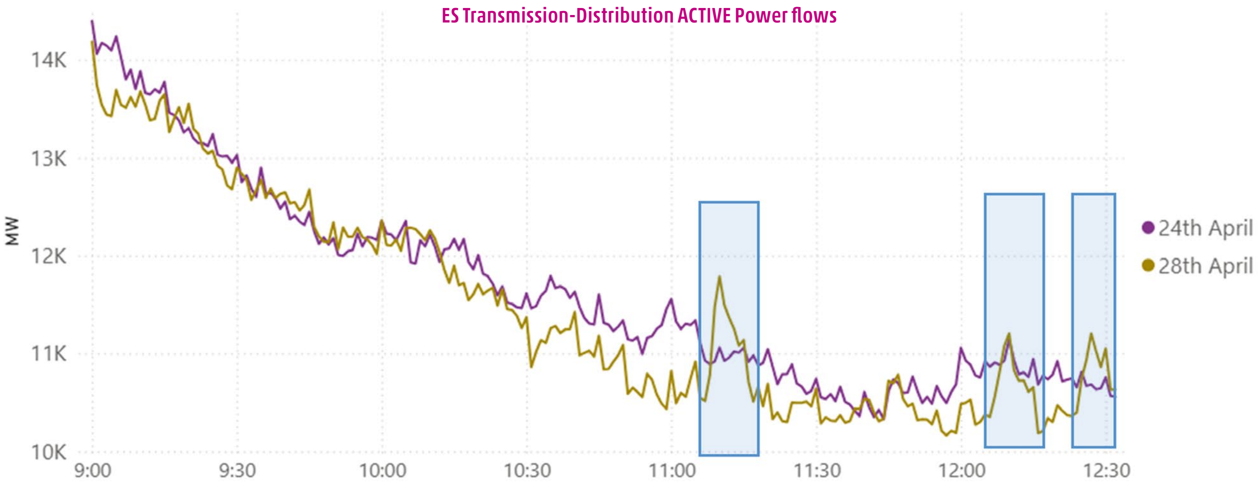


Figure 2-13: Spanish peninsula's transmission-distribution flows on 24 and 28 April between 9:00 and 12:32 (Source: RE SCADA)

The patterns observed in the previous graphs are also visible in this figure, possibly indicating that the total load increases are due to temporary disconnections of small generation units (<1 MW) connected to the distribution networks.

As a regional example, Figure 2-14 presents the power flow in the Madrid area.

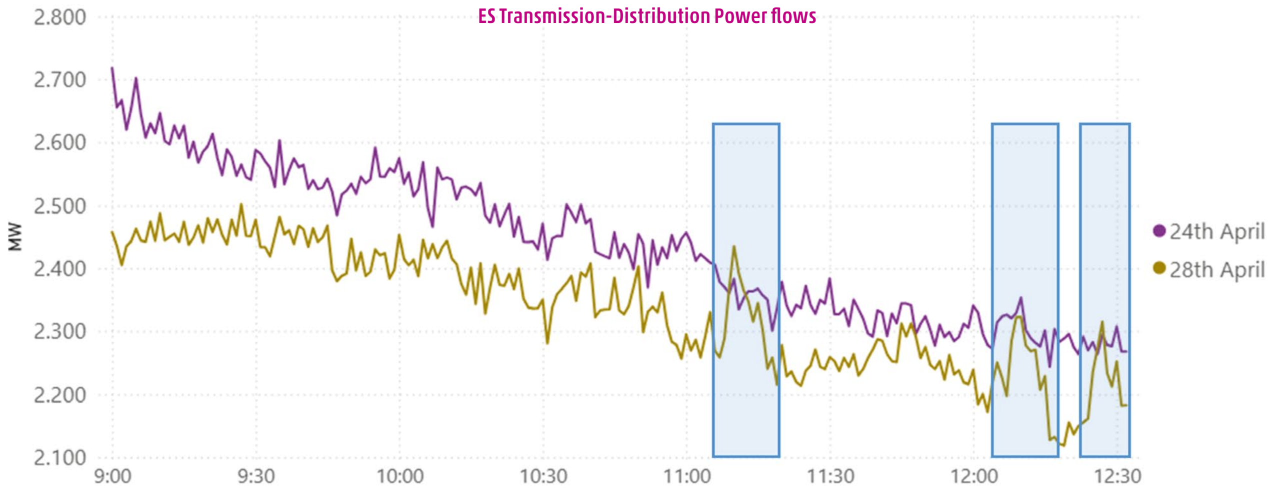


Figure 2-14: Madrid's transmission-distribution flows on 24 and 28 April between 9:00 and 12:32 (Source: RE SCADA)

At the substation level, the active power flow through two transformers in parallel 220/132 kV at "TS 1-Madrid" (located in Madrid) is shown in Figure 2-15 below as an example, compared to the same period on Thursday, 24 April.

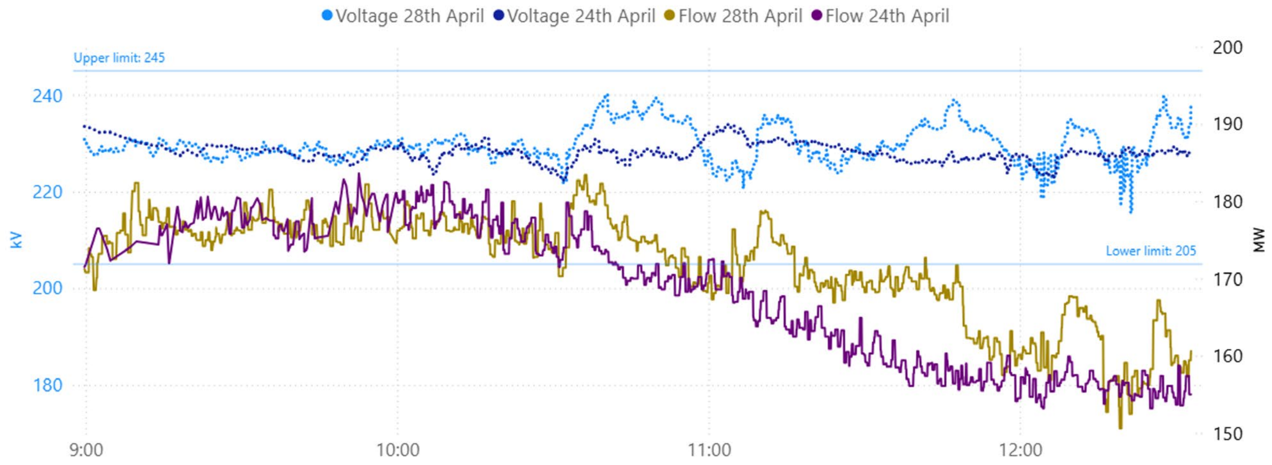


Figure 2-15: Active power through the two 220/132 kV transformers at "TS 1-Madrid" between 9:00 and 12:32

2.3.1.2 Portuguese Load

Concerning the Portuguese system, Figure 2-16 provides a comparison of the demand with a similar day (24 April).

No unusual behaviour regarding Portuguese demand at the transmission network was observed on 28 April prior to the incident.

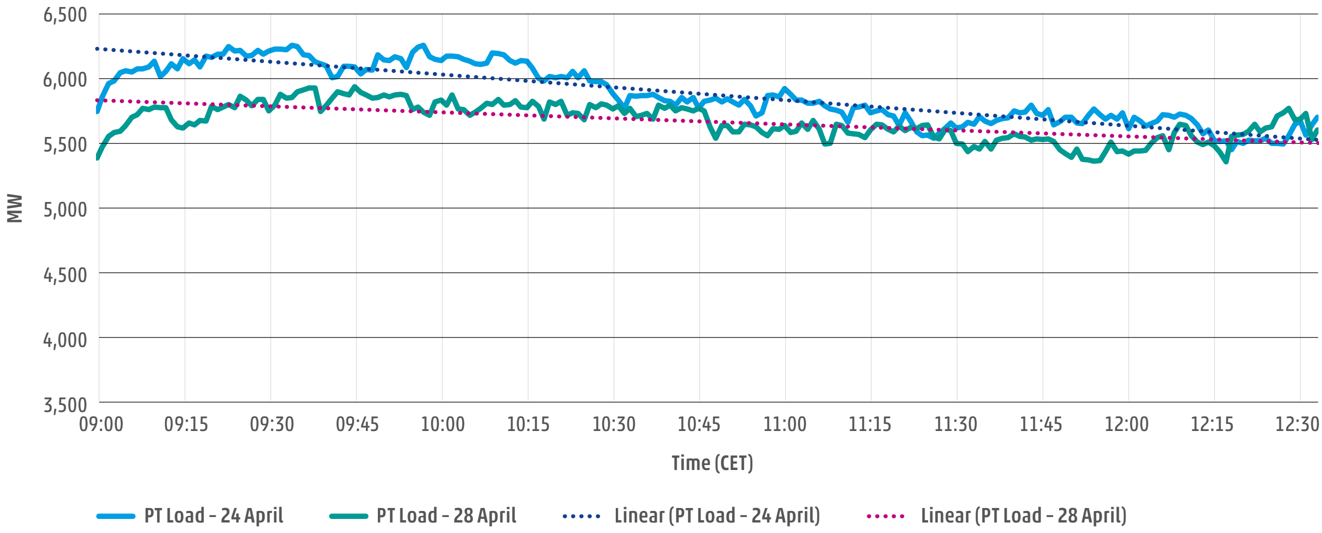


Figure 2-16: Comparison of Portuguese demand evolution on 28 April compared to 24 April between 9:00 and 12:30 (Source: REN's real-time SCADA measurements)

2.3.2 Production Patterns

2.3.2.1 Spanish Generation Mix

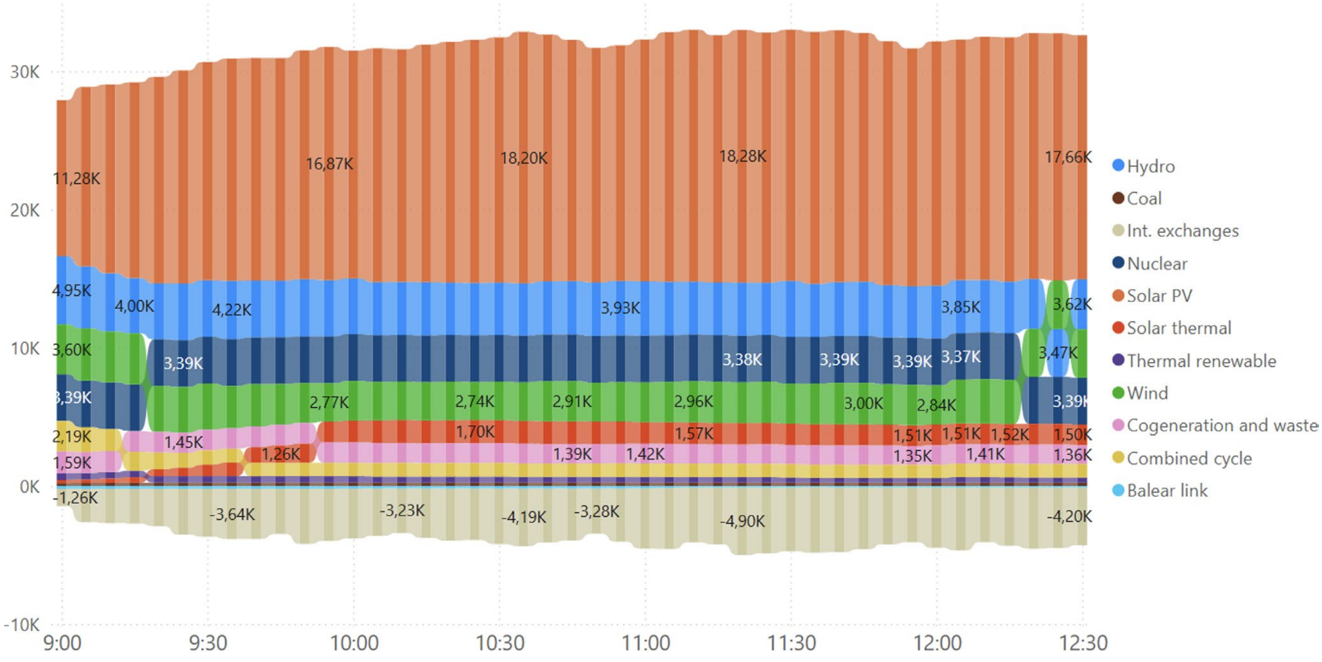


Figure 2-17: Spanish generation mix on 28 April from 9:00 to 12:30

28 April was a typical spring day in Spain, with mild temperatures and sunshine. According to Figure 2-18, the system's solar photovoltaic generation was similar to previous days, while wind generation was more variable but within the ranges observed in previous days.

This behaviour of renewable energies is characteristic of this time of year, where favourable weather maintains consistent solar energy production, while wind generation can fluctuate due to changes in wind speed and direction.

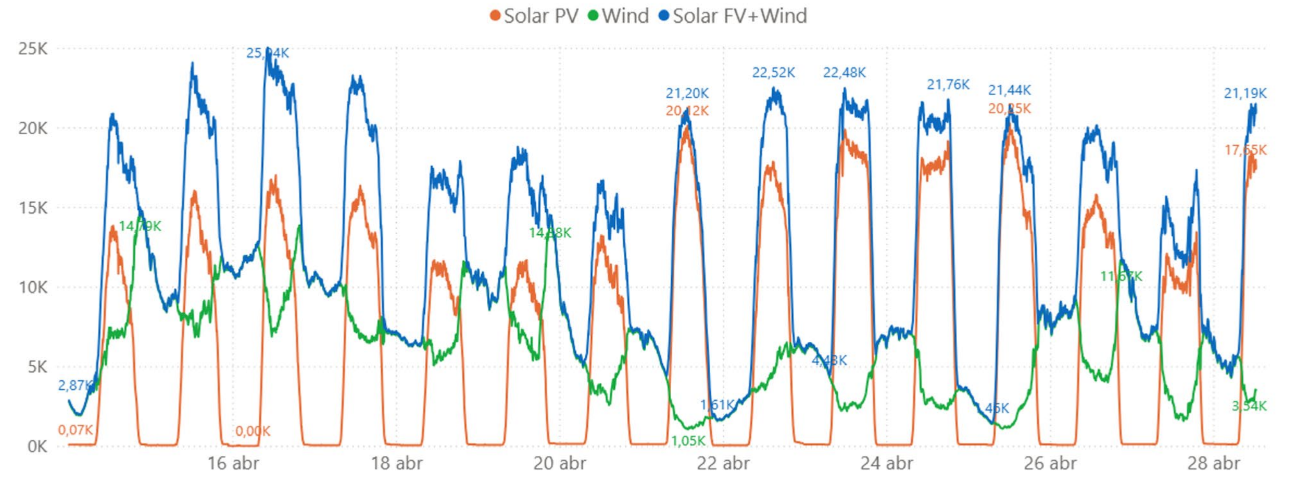


Figure 2-18: Solar PV and wind production in the two weeks in Spain prior to the incident

2.3.2.2 Portuguese Generation Mix

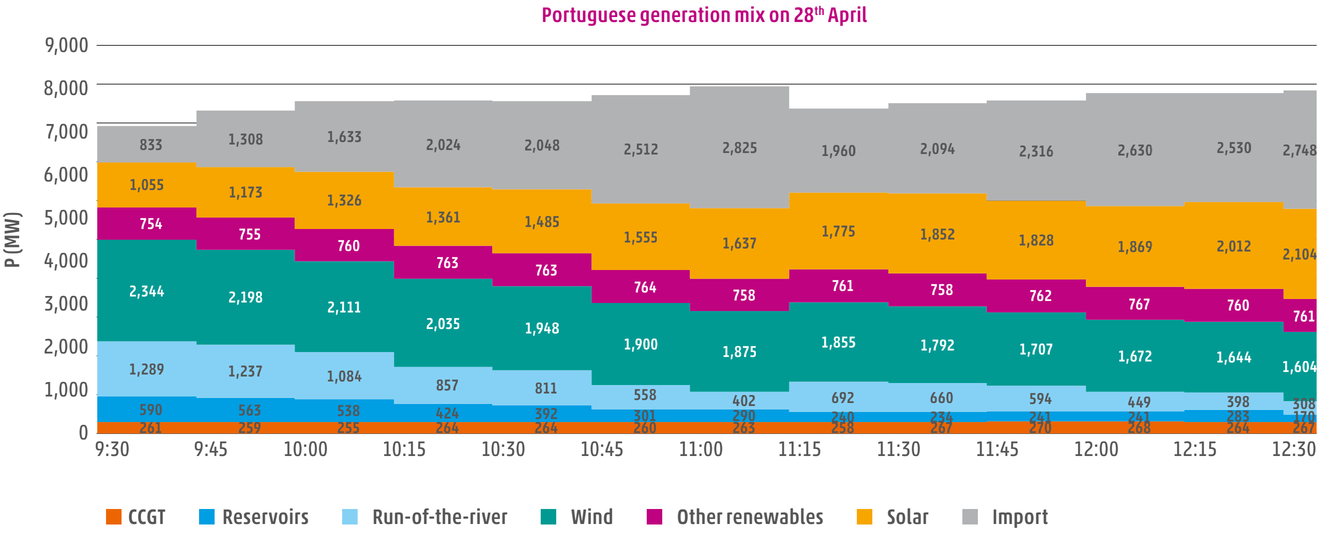


Figure 2-19: Portuguese generation mix on 28 April from 9:30 to 12:30

In Portugal, the temperature and wind speed were relatively moderate on 28 April, with little cloud cover and no precipitation observed. According to Figure 2-20, the photovoltaic generation of the Portuguese system remained stable and showed minimal variation during the days leading up to 28 April.

Wind generation increased in the preceding days due to periods of higher wind speeds, causing slightly more variability in this type of generation. However, these fluctuations remained within the typical range for this time of year.

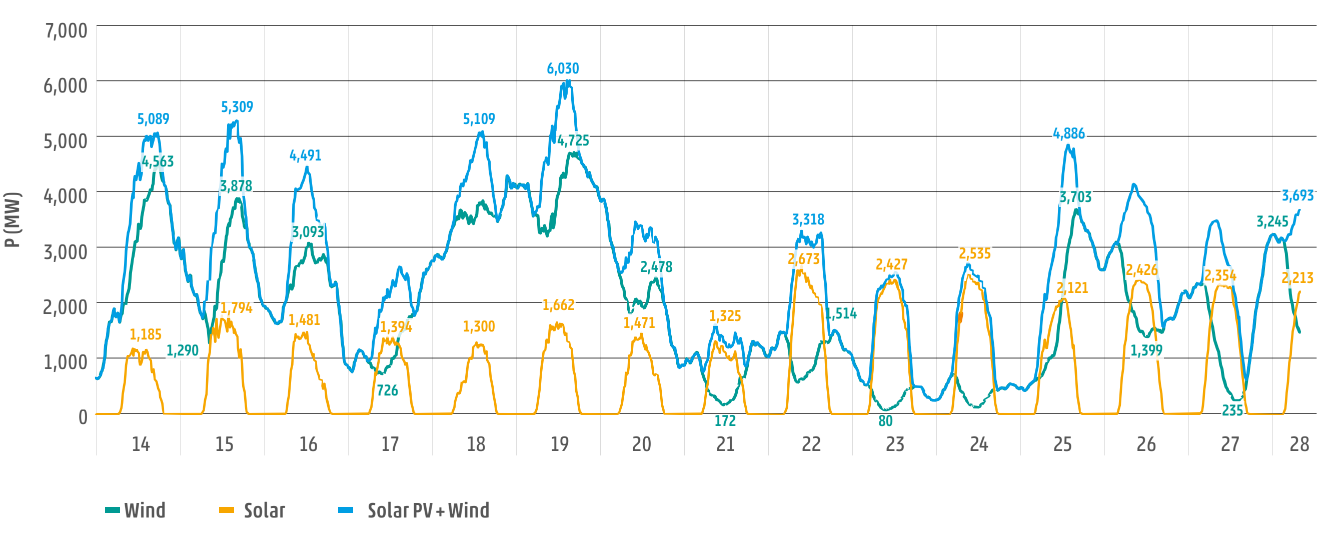
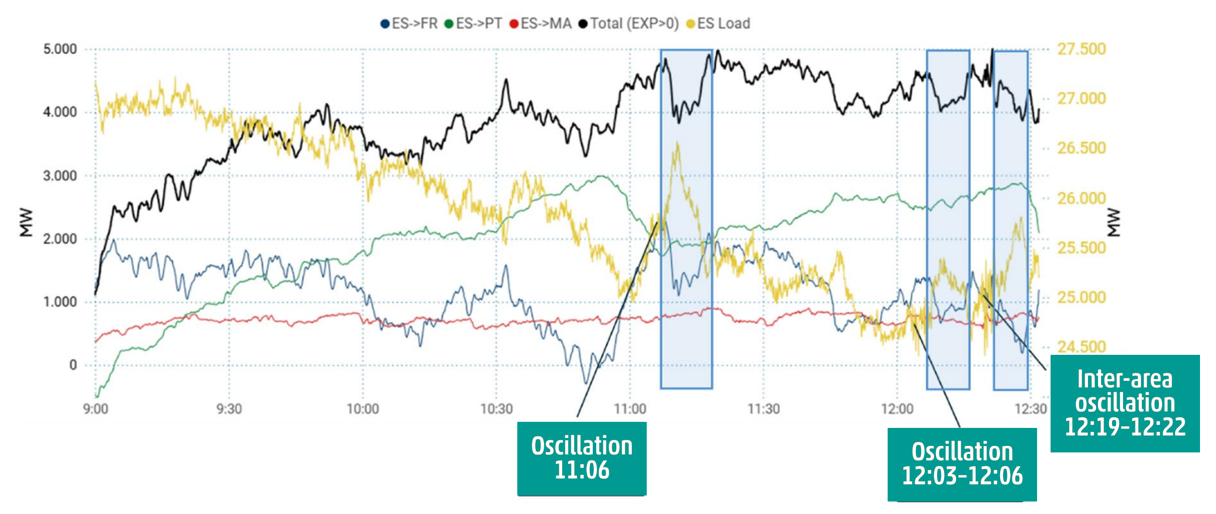


Figure 2-20: Solar PV and wind production in Portugal in the two weeks prior to the incident

2.3.3 Cross-Border Flows

Figure 2-21 shows physical flows through the Spain's interconnections with France, Portugal, and Morocco from 9:00 to 12:32, as well as the total amount. Furthermore, the load curve is presented for reference. The source is Red Electrica SCADA with a four-second resolution.



Oscillation 11:06

Oscillation 12:03-12:06

Inter-area oscillation 12:19-12:22

Figure 2-21: Spanish load and physical flows through ES–FR, ES–PT, and ES–MA between 9:00 and 12:32 (source: RE SCADA)

Figure 2-21 above shows the behaviour of the total load and the exchanges across the three Spanish borders, as well as the sum of these exchanges. Coinciding with the total load increases described above, a reduction of approximately 1,000 MW in the exchange through interconnections is observed during the period between 11:07 and 11:10, declining from 4,800 MW exporting to 3,800 MW exporting (approximate values), and the deviation continued for several minutes. This delay can be explained by the correction value of the International Grid Control Cooperation (IGCC), a real-time process of imbalance netting between TSOs that aims to avoid simultaneous activation of automatic frequency restoration reserves (aFRR) in opposite directions. This process corrects the input of the involved frequency restoration processes accordingly. It can be seen as a transfer of imbalance between TSOs when they are in opposite sign (upward/downward direction).

The IGCC flow during this period increases up to the maximum value of 1,000 MW (the available cross-border capacity limit).

The same behaviour is also observed just after the two subsequent total load increases described above. At 12:07, the value of the export programme with France is 2,000 MW, while the actual exchange with France is around 1,300 MW (see figures in Section 2.4.4). At 12:10, the programme does not change, and the value of the export exchange with France is around 670 MW. Including the interconnections with Portugal and Morocco, this means that the peninsular system reduces its exports by 600 MW (from 4,600 to 4,000 MW).

At 12:24, the value of the export programme with France is 1,000 MW, while the actual exchange with France is 866 MW. At 12:28, the programme does not change, and the value of the export exchange with France is 190 MW (see Figure 2-23). Including the interconnections with Portugal and Morocco, this means that the peninsular system reduces its exports by 513 MW.

Figure 2-22 below focuses on the window from 12:00 to 12:32.

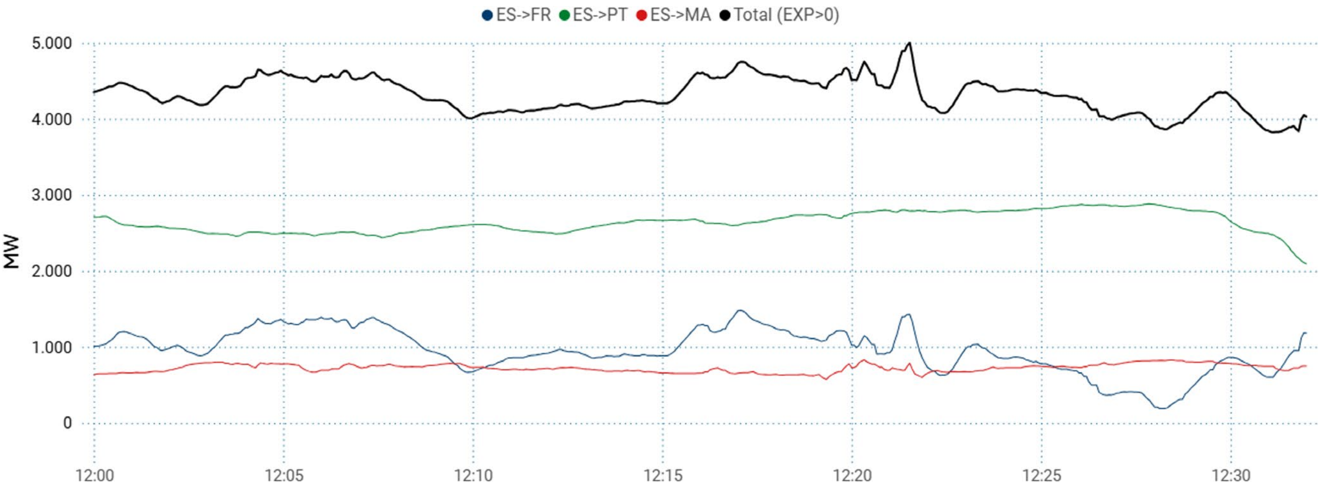


Figure 2-22: Physical flows through ES–FR, ES–PT, and ES–MA between 12:00 and 12:32 (source: RE SCADA)

2.3.4 Scheduled Commercial Exchanges

Figure 2-23: Commercial schedule and physical flow through the ES–FR border (source: RE SCADA)

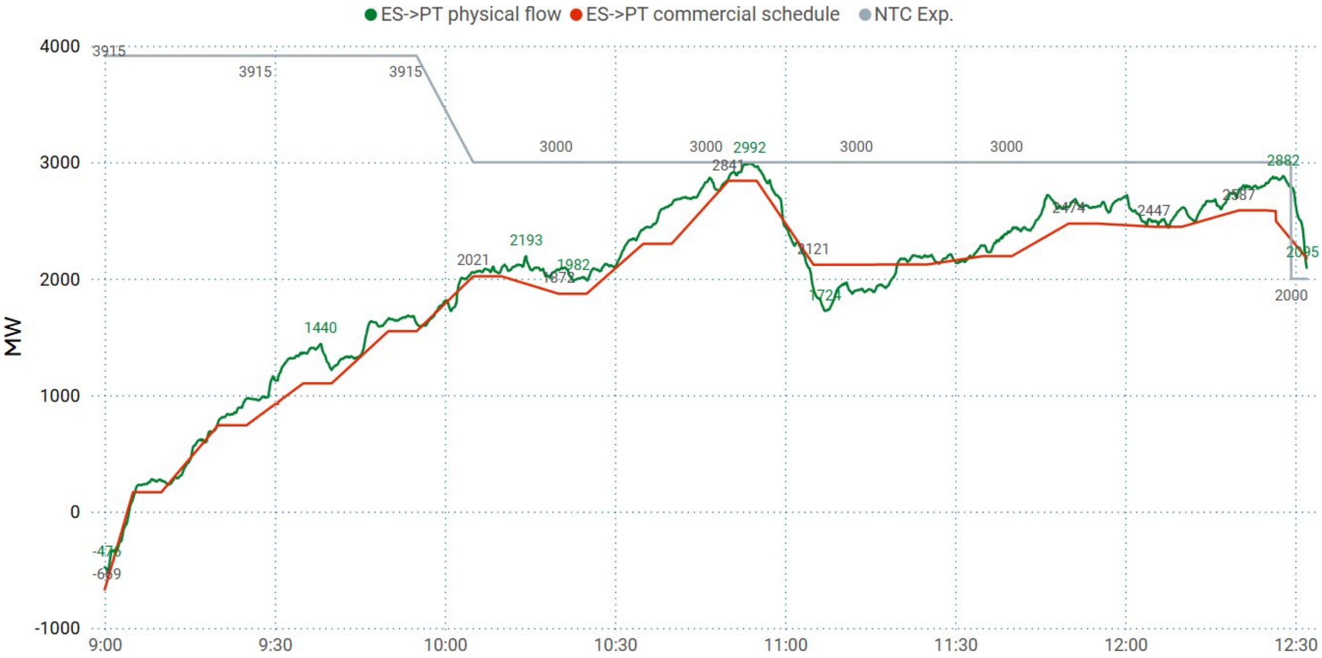


Figure 2-24: Commercial schedule and physical flow through the ES–PT border (source: RE SCADA)

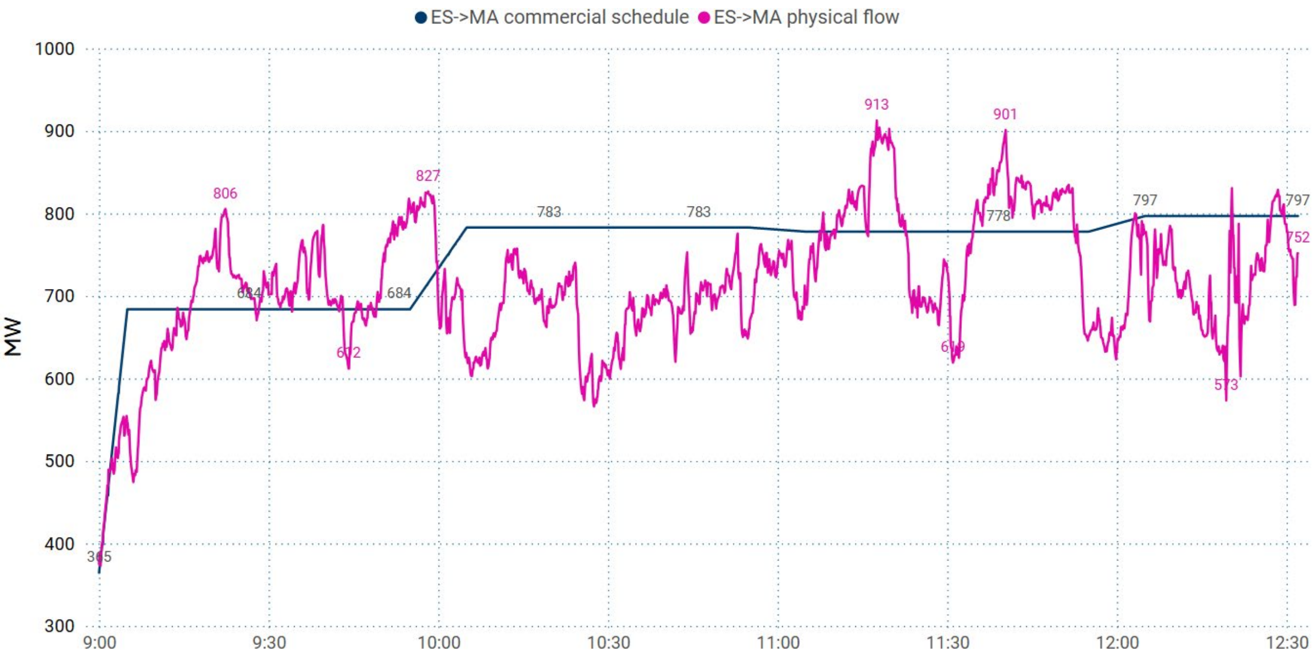


Figure 2-25: Commercial schedule and physical flow through the ES–MA border (source: RE SCADA)

2.4 Inertia

In order to estimate the total inertia of the Iberian Peninsula power system, the following procedure was applied.

For a system comprising N rotating generators, the total stored kinetic energy (KE) is:

$$E_{\text{kin}} = \sum_{i}^{N} H_{\text{gen,i}} S_{\text{gen,i}}$$

Where:

- H is the inertia constant of the i-th generator;
- S is the rated apparent power of the i-th generator.

The equivalent inertia constant is given by

$$H_{\text{eq}} = \frac{\sum_{i}^{N} H_{\text{gen,i}} S_{\text{gen,i}}}{\sum_{i}^{N} S_{\text{gen,i}}}$$

Inverter-based resources such as batteries, wind, and photovoltaic systems do not contribute to system inertia. Thermal solar and certain other renewable sources have a non-zero inertia constant.

With reference to the rated apparent power of inverter-based resources, it is assumed that their energy contribution is approximately equal to the active power P injected into the system. We can assume that the rated power of static generation is approximately equal to the actual delivered active power.

Under these hypothesis, the equivalent inertia of a system where M inverter-based resources are connected and operating is:

$$H_{\text{eq}} = \frac{\sum_i^N H_{\text{gen,i}} \times S_{\text{gen,i}} + \sum_j^N 0 \times S_{\text{inverters},j}}{\sum_i^N S_{\text{gen,i}} + \sum_j^M S_{\text{inverters},j}} = \frac{\sum_i^N H_{\text{gen,i}} \times S_{\text{gen,i}}}{\sum_i^N S_{\text{gen,i}} + \sum_j^M S_{\text{inverters},j}}$$

The scientific literature[3] underlines that the total inertia of the grid must consider the load contribution, namely the effect of rotating machines on industrial and domestic loads. It is worth underlining that inertia calculation is affected by significant uncertainty, mainly for the following reasons:

- The equivalent total inertia is a linearisation of a process affected by several non-linearities.
- The rated inertia of generators, turbines, and other rotating parts is estimated and not precisely calculated in several cases.
- The load's contribution can vary in a wide range depending on the type of loads, aggregations, etc.

Accordingly, the final value for the total inertia will be expressed as a plausible range, rather than a single number.

The total system inertia can thus be expressed as:

$$H_{\text{tot}} = H_{\text{eq}} + H_{\text{loads}}$$

Where the inertial contribution by loads is expressed in the same reference basis of the system. Table 2-4 summarises the main calculated parameters for each electrical system (Spain, Portugal, and the total Iberian Peninsula) immediately prior to the incident at 12:30.

Spain		**Portugal**		**Iberian Peninsula**	
KE (MWs)	H_{tot} (s)	KE (MWs)	H_{tot} (s)	KE (MWs)	H_{tot} (s)
97,590	2.17 - 2.67	21,884	2.45 - 2.95	119,474	2.21 - 2.71

Table: 2-4

The calculation of inertia for days preceding the incident will be implemented in the final report.

The following figures focus on the Spanish network and show for each day from 1 January until 28 April 2025:

- the minimum number of conventional units coupled to the network (>30 MW);
- the number of conventional units coupled to the network (>30 MW) in the time periods 10:00 – 11:00, 11:00 – 12:00 and 12:00 – 13:00;
- the total installed power of the connected conventional units, each time at the hour with the lowest number of coupled units; and
- the total installed power of the connected conventional units, in the time periods 10:00 – 11:00, 11:00 – 12:00 and 12:00 – 13:00.

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[3] [1] P. Kundur: Power Systems Stability and Control. Mc Graw-Hill.
[2] R. Marconato: Electric Power Systems. Second Edition. CEI Editions.
[3] Marina Elenkova, Markos Asprou, Lenos Hadjidemetriou and Christos G. Panayiotou: Estimation of Load Inertia using Ambient Measurements from Synchrophasor Technology. 978-1-6654-8032-1/22 IEEE.
[4] Y. Bian, H. Wyman-Pain, F. Li, R. Bhakar, S. Mishra, and N. P. Padhy, "Demand Side Contributions for System Inertia in the Gb Power System," IEEE Trans. Power Syst., vol. 33, no. 4, pp. 3521–3530, 2018
[5] Wind Energy Technology Institute (WETI), "Determining the Load Inertia Contribution from Different Power Consumer Groups", Henning Thiesen & Clemens Jauch, April 2020
[6] Kumar Prabhakar, Sachin K. Jain, Prabin Kumar Padhy, July 2022, "Inertia estimation in modern power system: A comprehensive review"

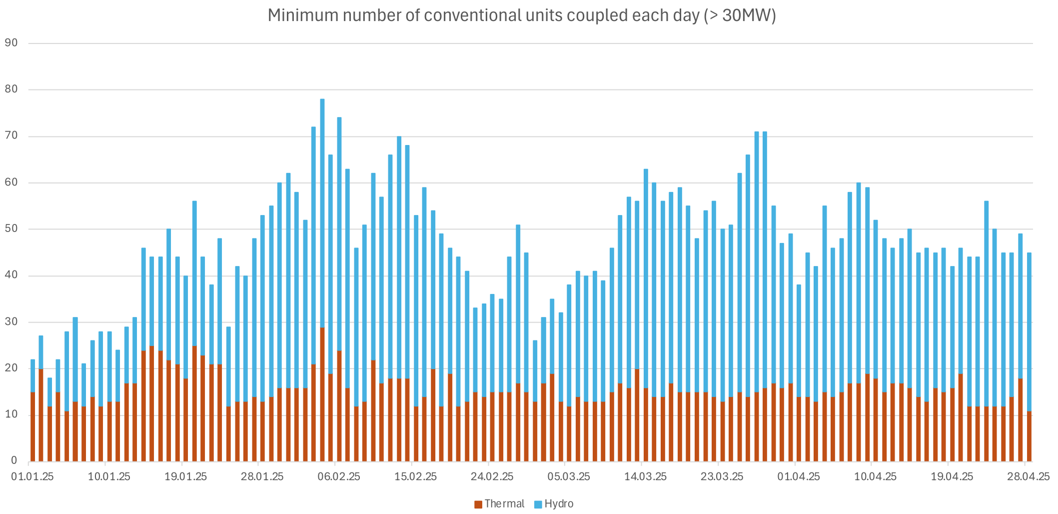

Figure 2-26: Minimum number of conventional units (>30 MW) coupled to the Spanish network each day from 1 January to 28 April

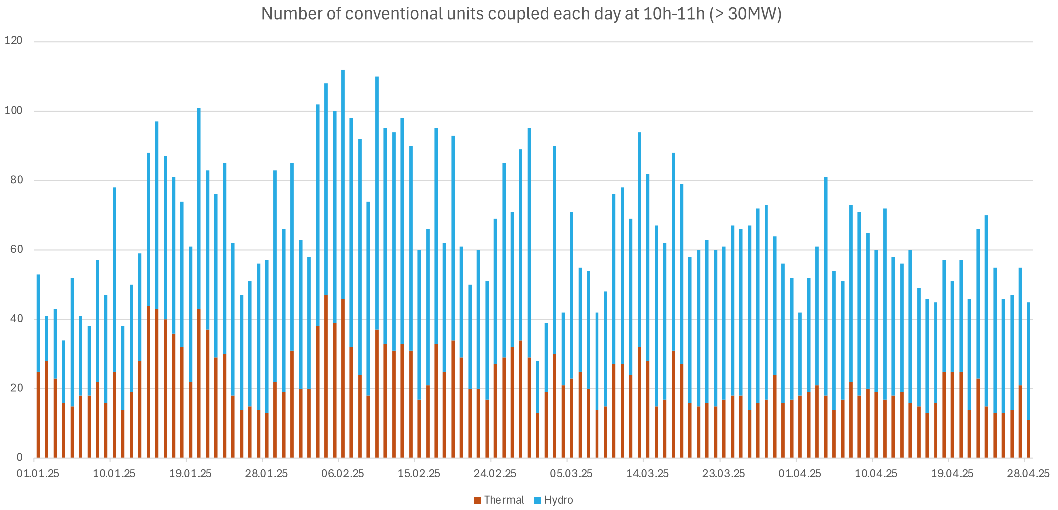

Figure 2-27: Number of conventional units (>30 MW) coupled to the Spanish network each day in the period from 10:00 to 11:00 (from 1 January to 28 April)

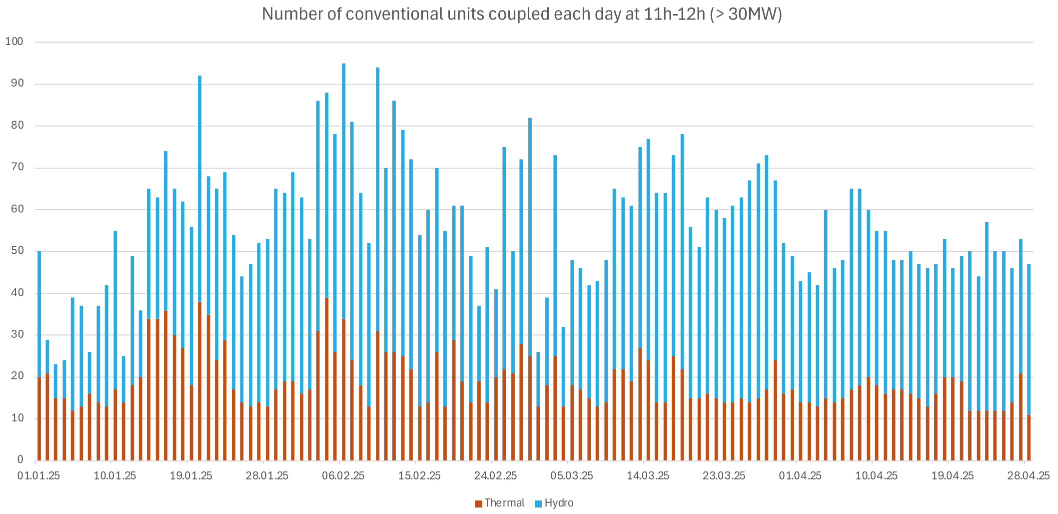

Figure 2-28: Number of conventional units (>30 MW) coupled to the Spanish network each day in the period from 11:00 to 12:00 (from 1 January to 28 April)

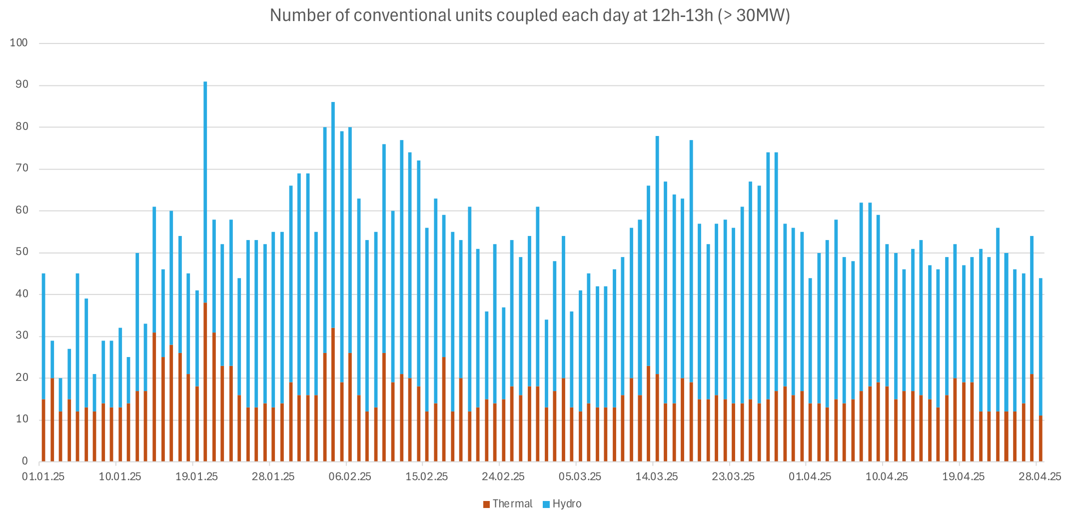

Figure 2-29: Number of conventional units (>30 MW) coupled to the Spanish network each day in the period from 12:00 to 13:00 (from 1 January to 28 April)

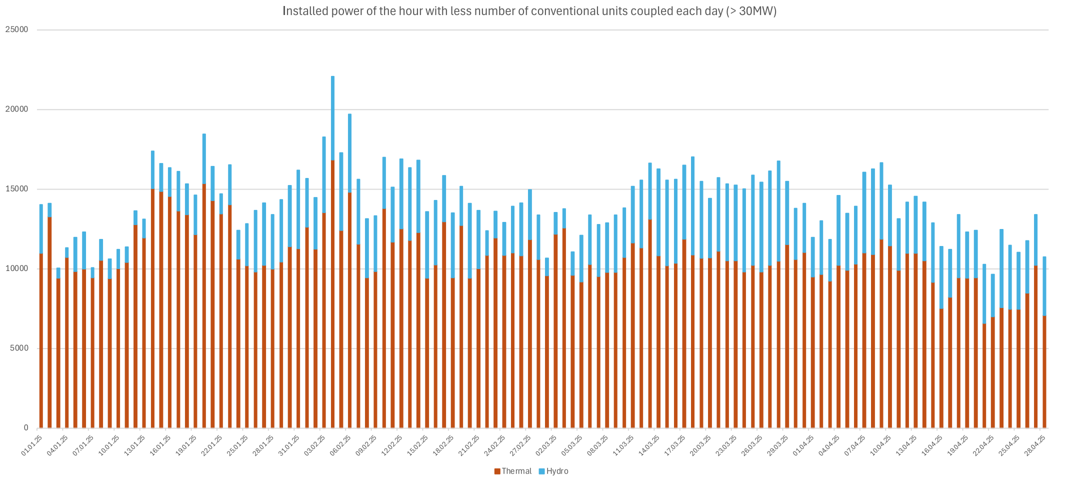

Figure 2-30: Installed power of the conventional units connected to the Spanish network, each time at the hour with the lowest number of coupled units (from 1 January to 28 April)

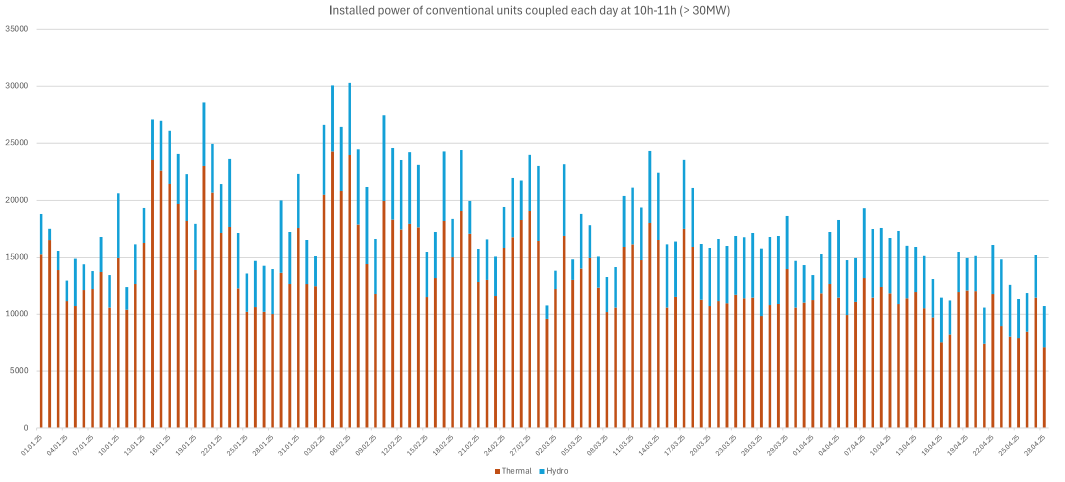

Figure 2-31: installed power of the conventional units connected to the Spanish network during the period from 10:00 to 11:00 (from 1 January to 28 April)

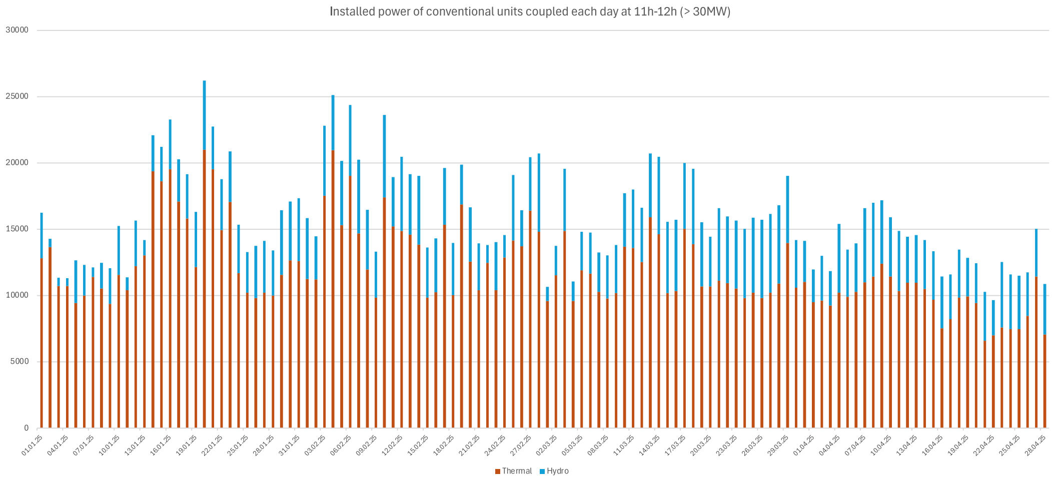

Figure 2-32: Installed power of the conventional units connected to the Spanish network during the period from 11:00 to 12:00 (from 1 January to 28 April)

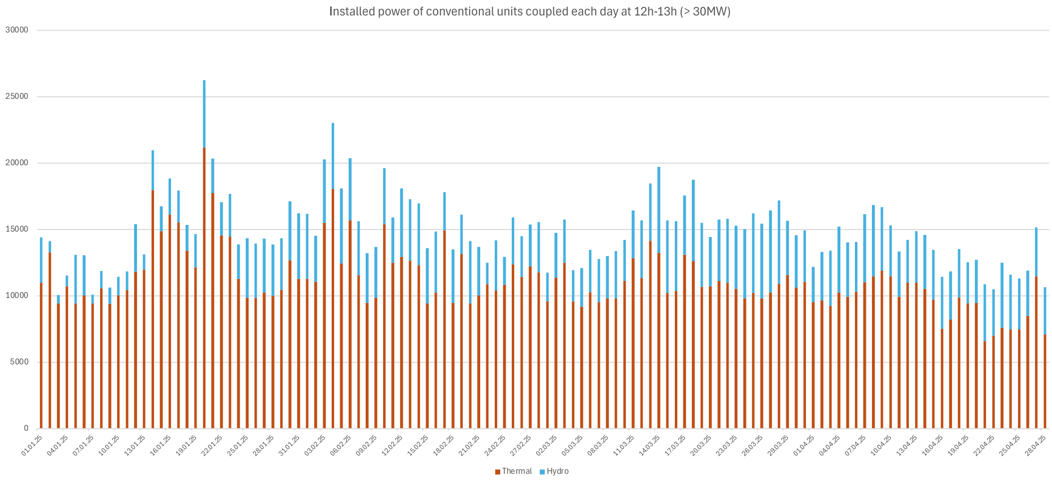

Figure 2-33: Installed power of the conventional units connected to the Spanish network during the period from 12:00 to 13:00 (from 1 January to 28 April)

2.5 Oscillations

2.5.1 Stability Main Concepts

Power system stability phenomena classification involves different branches:

- Frequency stability
- Voltage stability
- Rotor angle stability

The rise in the number and capacity of inverter-based resources (i.a., generators, batteries, HVDC links) recently required the introduction of two new families of dynamic phenomena:

- Resonance stability
- Converter-driven stability

Figure 2-34[4] schematically depicts the different classifications of power system stability.

A subcategory of rotor angle stability is small-disturbance angle stability, defined as the ability to maintain synchronism under minor disturbances. Small-disturbance angle stability can be further divided into non-oscillatory instability (a consequence of a lack of sufficient synchronising torque) and oscillatory instability (resulting from a lack of sufficient damping torque). Minor disturbance rotor angle stability problems (including oscillatory stability) can be either local or global.

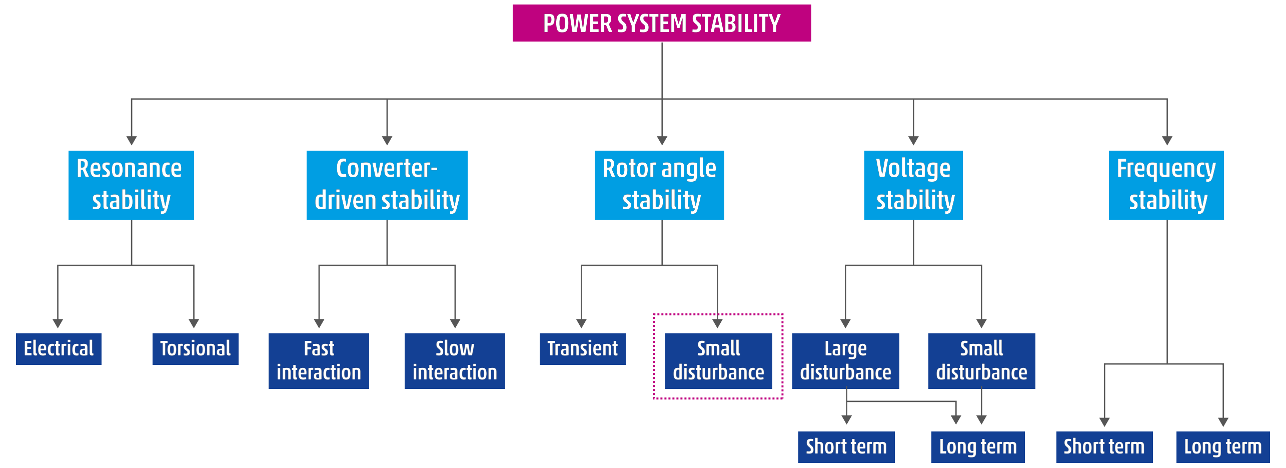

Figure 2-34: Classification of power system stability

Focusing on the oscillatory stability, we can distinguish between different cases. First, depending on the geographical and electrical topological scope, oscillations can be categorised into:

- Inter-plant oscillations: In the same power plant, units oscillate against each other.
- Local oscillations: In a power system, a single generation unit oscillates against the rest of the system.
- Inter-area oscillations: In a power system, a cluster of generation units in one part of the system oscillates against a cluster of generation units in another part, covering a wide extension of the grid.

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[4] Stability definitions and characterization of dynamic behavior in systems with high penetration of power electronic interfaced technologies, IEEE Power and Energy Society, Tech. Rep. PES-TR77, May 2020.

Second, depending on the origin of oscillatory behaviour, oscillations can be:

- Forced:[5] Where the oscillation signal is introduced into the power system by a certain source. For example, a controller in a power plant might malfunction or be improperly tuned. The frequency of such oscillation will depend on the driving source.
- Natural: Where the power system is susceptible to various intrinsic oscillatory modes due to its characteristics, such as topology, generators etc. (such as the 0.15 – 0.30 Hz modes in the Continental Europe grid explained below, or 0.3 – 0.9 Hz modes in the Nordic grid[6]). These oscillation modes are usually sufficiently damped and characterised by low amplitude and energy. They are permanently visible in the system due to the continuous presence of small perturbations owing to normal operational events (manoeuvres, change of topology, load or generation change of path, etc.)

2.5.2 Inter-Area Oscillations

Inter-area oscillatory stability problems are caused by the interaction among large groups of generators and have widespread effects. They involve oscillations between a group of generators in one area and a group of generators in another area. In general, the frequency range depends on the system topology and size. The inter-area oscillations that commonly occur in the Continental Europe (CE) system are characterised by three different modes that physically represent the continuous conversion of kinetic energy of rotating machines into potential energy and vice versa. Figure 2-35 shows the geographical displacement of modes with an equivalent spring mass mechanical analogy to better explain the physics of oscillation. The typical range of inter-area oscillatory modes in the CE system is 0.15 – 0.30 Hz.

It is worth underlining that in a large power system, additional oscillatory frequencies are present with characteristics that are specific to a certain CE system geographic area and not dominant in the dynamics of large parts of the system. Consequently, they are not the object of the present investigation.

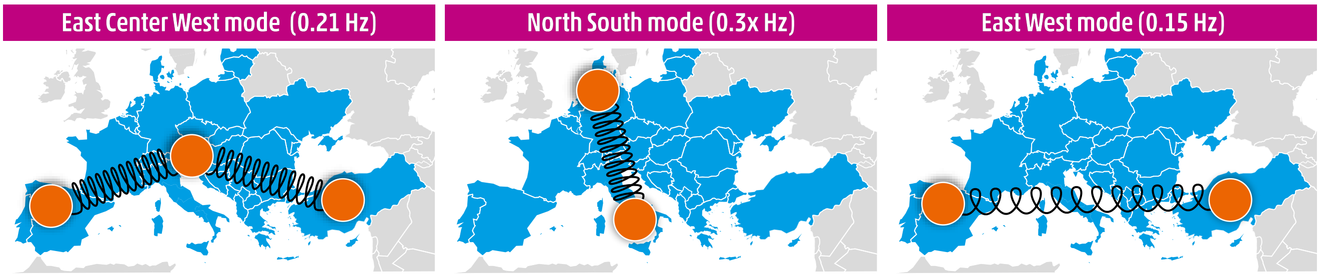
East Center West mode (0.21 Hz)
North South mode (0.3x Hz)
East West mode (0.15 Hz)

Figure 2-35: Inter-area modes representation with equivalent spring mass mechanical analogy

From an operational perspective, oscillatory instability is detected when the main system variables (frequency, voltages, angle differences, etc.) exceed a limit amplitude jointly with a weak damping for a minimum reference time window.

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[5] IEEE PES PSDP/PSSC Task Force on Forced Oscillations

[6] https://www.sciencedirect.com/science/article/pii/S0378779624012525

As mentioned above, intrinsic oscillation modes are always active in the grids, but stable in terms of amplitude and damping. Regarding the inter-area oscillatory stability of the CE SA, worldwide technical literature and continuous monitoring and studies performed by ENTSO-E experts have identified the following factors as important:

- High power flows between two areas of the system from the peripheral parts of the system directed to the centre.
- Increased system impedance due to lines open (i.e. maintenance, voltage control, etc.).
- Underexcitation of generators.
- Power oscillation stabilisers not effective to damp the oscillations.
- Loads as "natural dampers" not sufficient to smooth the oscillation.

Historically, the Iberian Peninsula participated to East Central West mode and East West mode in a frequency range between 0.15 Hz and 0.21 Hz. When higher oscillatory frequencies are detected, it is in general possible – based on signal analysis techniques – to evaluate whether these oscillations have local or inter-area characteristics.

2.5.2.1 Oscillatory Stability Protocol Adopted Between RTE And RE

With reference to the Iberian Peninsula, a significant oscillatory activity was experienced on 1st December 2016, when a 400 kV line was unexpectedly opened at 11:18, triggering a 0.15 Hz oscillation with 0.140 Hz as the maximum amplitude of recorded frequency. The 2016 report[7] concluded that the control rooms (RTE and RE) reacted promptly (two minutes after the oscillation detection), reducing the export flow from Spain to France. The report also concluded that as dynamic stability limits get closer to static limits, N-1 power flow analyses might need to be complemented with dynamic assessments close to real time.

Focusing on HVDC behaviour, after 1 December 2016 event, some studies were carried out to investigate the maximum improvement of stability that could be given by the Llogaia–Baixas HVDC, which led to the following conclusions:[8]

- It was concluded that the Power Oscillation Damping (POD) functionality of the Llogaia–Baixas HVDC (the functionality affects both the active and reactive power of the HVDC) should always be operative. However, the POD functionality of this HVDC alone is insufficient to stabilise inter-area oscillations between the Iberian Peninsula and CE, due to the grid configuration (meshing and load distribution) near the terminals of the link.
- It was also concluded that when stability needs to be improved (i.e. damping of inter-area oscillations needs to be increased), the active power control of the link should be changed. Accordingly, the active power control mode of the link should be changed from the default hybrid mode[9] (which emulates the AC line dynamics and is typically used in voltage source converter HVDCs) to constant power mode.

At present, a specific protocol exists between RTE and RE that outlines all actions to be performed by the control room Operators to increase damping of inter-area oscillations. The relevant part of the protocol regarding logic, conditions and remedial actions is shown in Figure 2-36. Examples of remedial actions including setting the HVDC link to constant power mode, increasing the active power flow through the HVDC, increasing grid meshing, and reducing the active power export from Spain to France.

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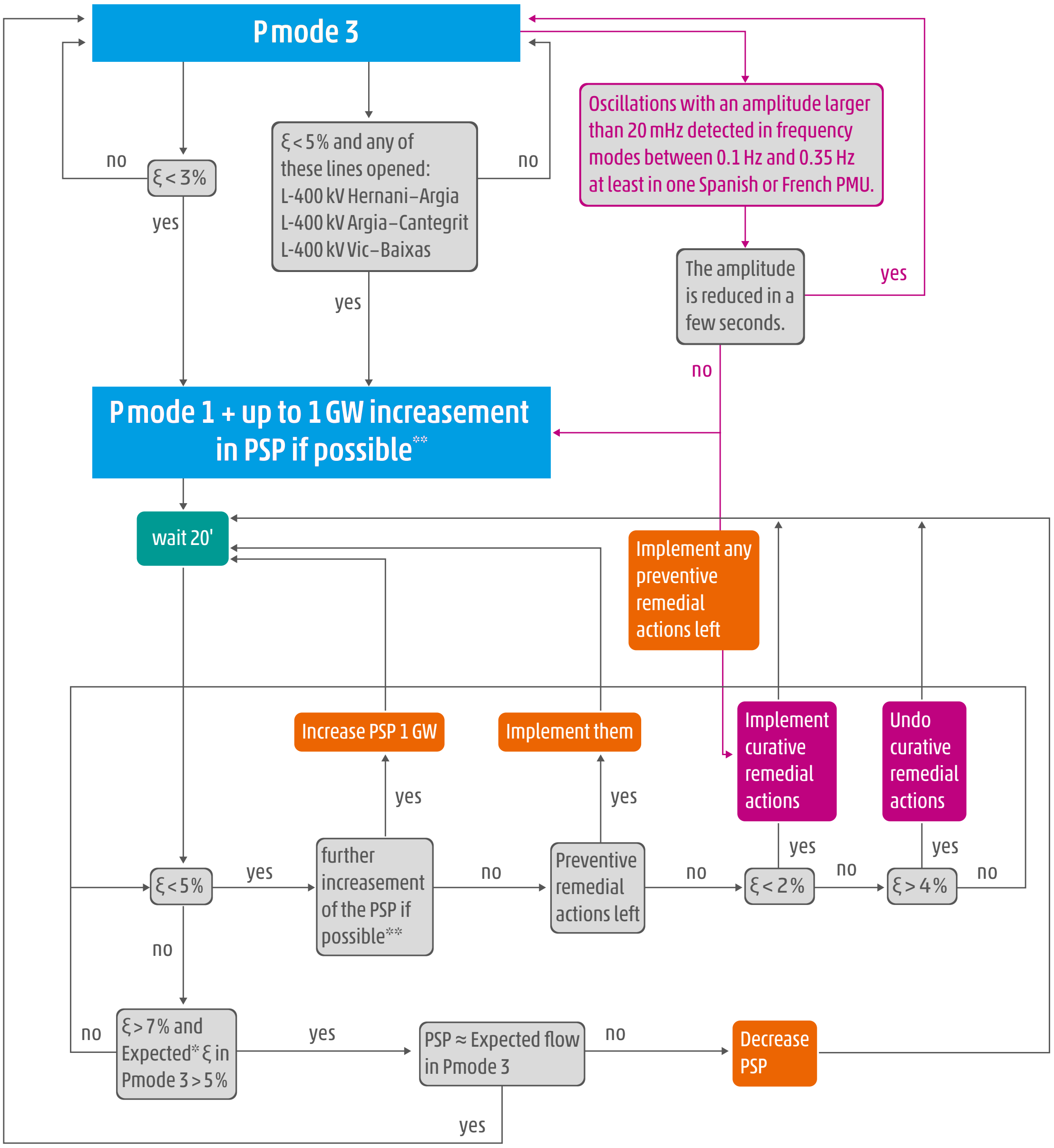
[7] https://eepublicdownloads.entsoe.eu/clean-documents/SOC%20documents/Regional_Groups_Continental_Europe/2017/CE_inter-area_oscillations_Dec_1st_2016_PUBLIC_V7.pdf

[8] "Improvement of the oscillatory behavior of the HVDC link between Spain and France": 2020 CIGRE Paris session.

[9] Hybrid operation implies that active power flowing is $P = P_0 + K \cdot \Delta\vartheta$ with typically $P_0 = 0$. K is a constant and ϑ is angle between the terminals of the link.

Inter-area oscillations Risk management

RE or RTE identifies a constraint on inter-area oscillations when the damping measurement is lower than 3 %, when it is lower than 5 % and any of the following lines are open: Hernani–Argia, Argia–Cantegrit or Vic–Baixas 400 kV or when real time oscillations with an amplitude larger than 20 mHz in oscillation modes between 0.1 Hz and 0.35 Hz are detected and the amplitude is not reduced in a few seconds. The next diagram summarises the decision making.



* Based on machine learning software.

** It reduces power flow through the AC interconnector with increase damping, we consider it is possible when: It does not imply static violations such as overloads or voltages out of ranges in the Spanish or French networks.

Figure 2-36: Flow chart of RTE-RE protocol for inter-area oscillation management

2.5.3 Local Oscillations

Local oscillations concern a small part of the power system and are usually associated with rotor oscillations of a single power plant against the rest of the power system. Such oscillations are generally characterised by a frequency in the range of 0.8 – 2 Hz and observed in a smaller geographical area.

As described in Section 2.5.6.3, detailing the 0.63 Hz oscillation at 12:03 – 12:08 on 28 April, RE explained to the Expert Panel that the control room recognised the presence of an 0.63 Hz oscillation with a low damping (< 1 %), and determined at the moment that applying the countermeasures described in the common protocol (described in Section 2.5.2.1) to be applied in the event of inter-area oscillations with low damping was the most effective action to improve the system stability. The intention was to gain a positive effect by changing the operating point of the system and creating again an increase of intrinsic system damping.

2.5.4 Forced Oscillations

Some oscillation might be forced; for example, caused by inverter-based resources (IBRs). The frequency range for this type of oscillation is more challenging to define, as they are generally driven by their control systems rather than by dynamics based on the physical characteristics of generators, as is mainly the case with synchronous generators. An inverter-based controller that malfunctions and sustains this malfunction could force this effect onto the grid. This might also exacerbate inter-area oscillation modes and induce other generators into oscillation.

2.5.5 Focus on Automatic Stabilising Countermeasures in the Iberian Grid

The aim of this section is to describe the behaviour and status of POD functions over STATCOM and HVDC and power system stabilisers.

2.5.5.1 STATCOMs

The only STATCOM that was in service in the Spanish grid on 28 April is Vitoria 220 kV. The nominal reactive power of this STATCOM is ±150 Mvar (inductive and capacitive), for V = 1 pu in the point of connection. Another 150 Mvar STATCOM has been commissioned in Tabernas 220 kV after 28 April 2025 and two additional 150 Mvar STATCOMs are planned[10] to be commissioned in 2025 (Lousame 220 kV and Moraleja 400 kV).

The steady-state voltage control modes available at STATCOM Vitoria are Q-mode and V-mode. The V-mode was active during the incident and means that STATCOM injects a current proportional to the voltage deviation from a reference value. The reference voltage set by the RE Control Centre at the time of the incident was 222 kV.

Additionally, the POD and Fast Current Injection Controller (FCIC) controls were enabled. The POD modulates the reactive power supplied by the STATCOM based on the frequency deviation to damp electromechanical oscillations in the range of [0.05 – 1.00] Hz, while the FCIC acts in case of large voltage deviations by generating a supplementary reactive current proportional to the difference between the instantaneous voltage and the voltage one second prior to its activation. It acts if phase voltages are outside the range of 0.85 pu to 1.15 pu or voltage variations greater than 0.1 pu in 1 s.

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[10] Pages 203 and 205 of the **Spanish Transmission network development plan for 2021–2026**.

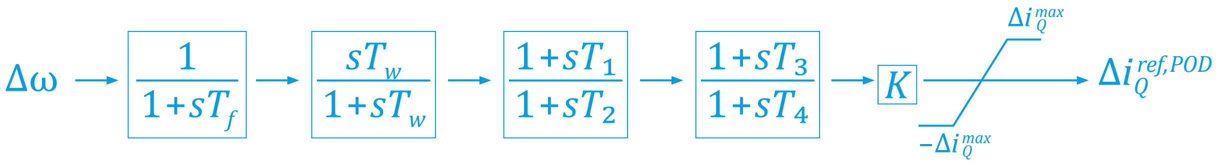


Figure 2-37: Vitoria STATCOM POD block scheme

2.5.5.2 HVDC

There is a HVDC link on the border between France and Spain, named INELFE-1. It has a rated power of 2 × 1,000 MW and is a VSC-type HVDC. Station A of the HVDC is connected to Santa Llogaia 400 kV substation (Spain) and Station B is connected to Baixas 400 kV substation (France). The HVDC is further described in Section 2.7.

With reference to the ability of the link to damp the inter-area oscillations, the HVDC is equipped with a flexible POD function, as detailed in Figure 2-38 below.

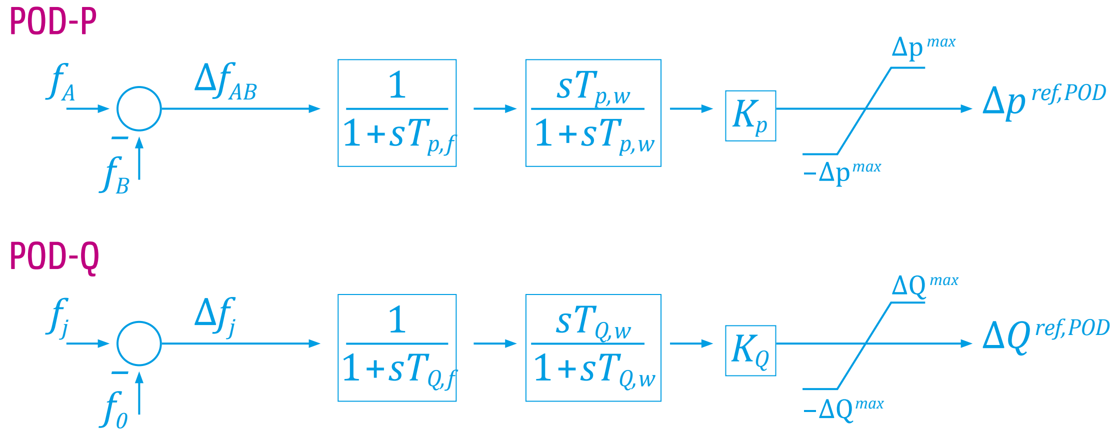


Figure 2-38: INELFE-1 POD block scheme

The POD-P logic processes as input the frequency at terminals A and B, calculating the difference Δf_{AB} for the POD-P or the difference between the frequency in the terminal and the nominal frequency Δf_j for the POD-Q, which is filtered by a cascade of low pass and high pass filters and multiplied by a gain K. POD-Q uses the local frequency deviation from a reference value f0, namely the frequency of terminal A (B) for POD-Q in terminal A (B). The final signal is summed to the HVDC active power and reactive power reference value, respectively. These logics were active during the incident of 28 April 2025. It is important to remark that for safety reasons and to prevent malfunction of the POD, a selective control implemented by the manufacturer prevents operation of POD-Q when the instantaneous output of the controller excessively frequently reaches its limits (±100 Mvar per HVDC pole). If this occurs, POD-Q is disabled, although the total reactive power capacity of the HVDC is not affected (+400/-600 Mvar per HVDC pole).

The POD-Q functionality on the Spanish side remained active from 4 March at 20:03 on Link 1, and from 8 March at 14:34 on Link 2 – the dates on which it was disabled due to works on the links – until 28 April at 12:03:51. After the beginning of the 12:03 episode of the 0.6 Hz oscillation, the POD-Q of HVDC on the Spanish side was automatically blocked., according to manufactured design. This POD-Q remained blocked until the blackout on the Spanish side. The remote reactivation of POD-Q on this side was not applied due to the need to carry out a detailed verification of the cause of the automatic deactivation prior to re-enabling it to preserve the integrity of the HVDC. On the French side, the POD-Q remained active until the blackout.

2.5.5.3 Power System Stabilisers

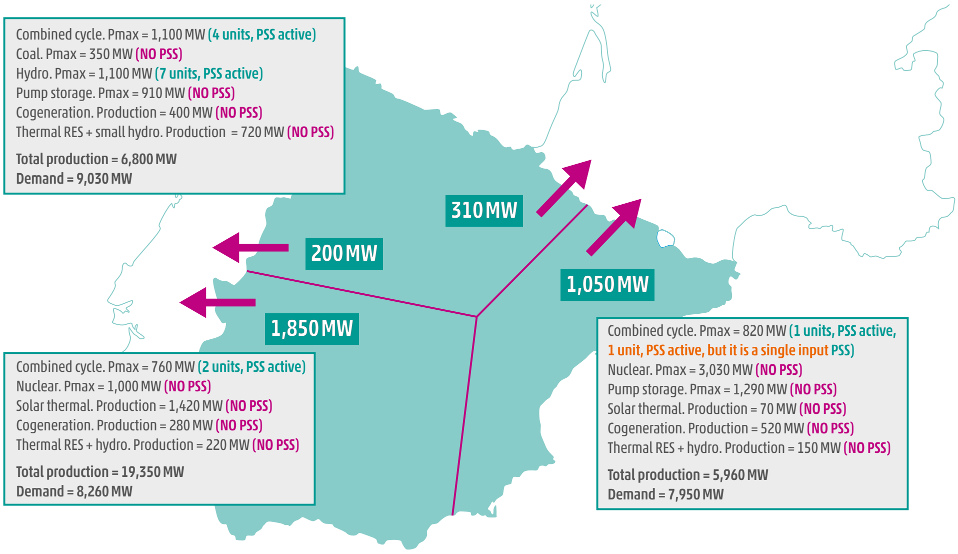
The Power System Stabilisers (PSSs) are the first line of the system defence against inter-area and local oscillations. The installed PSSs are listed in the following Tables 5 and 6, for Spain and Portugal, respectively.

Technology	PSS installed	Type	Note
Nuclear	NO		
Hydro	YES	PSS2A	Two power plants (one with one unit and the other with six units)
CCGT	YES	PSS2A, PSS2B, PSS3B, IEEEST	Six CCGT plants (eight units in total) One CCGT has a single input PSS
Coal	NO		

Table 2-5: Availability of power system stabilisers on the main rotating generators in the Spain grid in operation during the

Technology	PSS installed	Type	Note
Thermal	YES	PSS2A	Only one thermal plant in service
Hydro	YES	PSS2A, PSS2B	Three power plants (two, the largest) out of fourteen with PSSs active
Pumping storage	YES	PSS2A, PSS2B	Nine power plants (seven, the largest) out of fourteen with PSSs active. The PSS is also active in pumping mode

Table 2-6: Availability of power system stabilisers on the main rotating generators in the Portugal grid in operation during the event



Combined cycle. Pmax = 1,100 MW **(4 units, PSS active)**
Coal. Pmax = 350 MW **(NO PSS)**
Hydro. Pmax = 1,100 MW **(7 units, PSS active)**
Pump storage. Pmax = 910 MW **(NO PSS)**
Cogeneration. Production = 400 MW **(NO PSS)**
Thermal RES + small hydro. Production = 720 MW **(NO PSS)**

Total production = 6,800 MW
Demand = 9,030 MW

Combined cycle. Pmax = 760 MW **(2 units, PSS active)**
Nuclear. Pmax = 1,000 MW **(NO PSS)**
Solar thermal. Production = 1,420 MW **(NO PSS)**
Cogeneration. Production = 280 MW **(NO PSS)**
Thermal RES + hydro. Production = 220 MW **(NO PSS)**

Total production = 19,350 MW
Demand = 8,260 MW

Combined cycle. Pmax = 820 MW **(1 units, PSS active, 1 unit, PSS active, but it is a single input PSS)**
Nuclear. Pmax = 3,030 MW **(NO PSS)**
Pump storage. Pmax = 1,290 MW **(NO PSS)**
Solar thermal. Production = 70 MW **(NO PSS)**
Cogeneration. Production = 520 MW **(NO PSS)**
Thermal RES + hydro. Production = 150 MW **(NO PSS)**

Total production = 5,960 MW
Demand = 7,950 MW

Figure 2-39: Geographical displacement of PSSs

Figure 2-39 represents the geographical displacement of PSSs in Spain. The effectiveness of PSSs in RE and REN grids will be assessed in the analysis phase of the investigation.

2.5.6 Oscillatory Stability on 28 April

2.5.6.1 Angular Displacement Before the Oscillations

The heatmaps (Figure 2-40) report the angular displacement between different locations in Spain and Portugal, taking as a reference a PMU in southeast of the interconnection between Spain and France (marked as REF in the figure). It can be observed that maximum angle spread is in the southwest part of Spain.

There were 76 PMUs operational in Spain on 28 April. The extensive PMU coverage in Spain enabled the Expert Panel to establish several relevant facts and enabled producing detailed heatmaps.

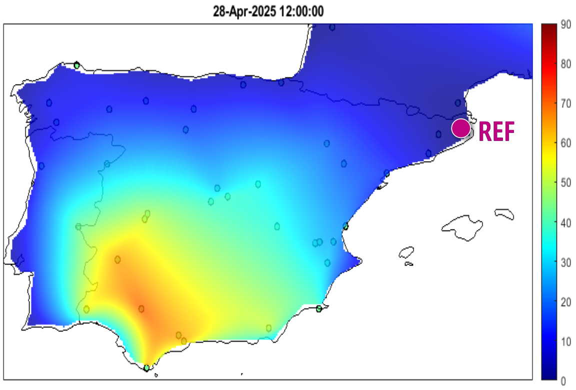


Figure 2-40: Heatmap of angular displacement at 12:00 (source: PMU)

Figure 2-41 helps to interpret the heatmap of the previous figure, aiming to divide the Spanish grid into three equivalent geographic areas in terms of demand and highlight the heterogeneous distribution of generation in Spain before the incident, as well as the generation mix per area. From the numbers indicated in the figure, it can be observed that within the Spanish system, the southwest region is "pushing" active power in the direction of the centre-north and east.

The geographic spread of dominant production capacity can be summarised as follows:

- Renewables (mainly photovoltaic and wind) mainly located in the southwest
- Nuclear in the east and southwest
- CCGT spread across the three regions

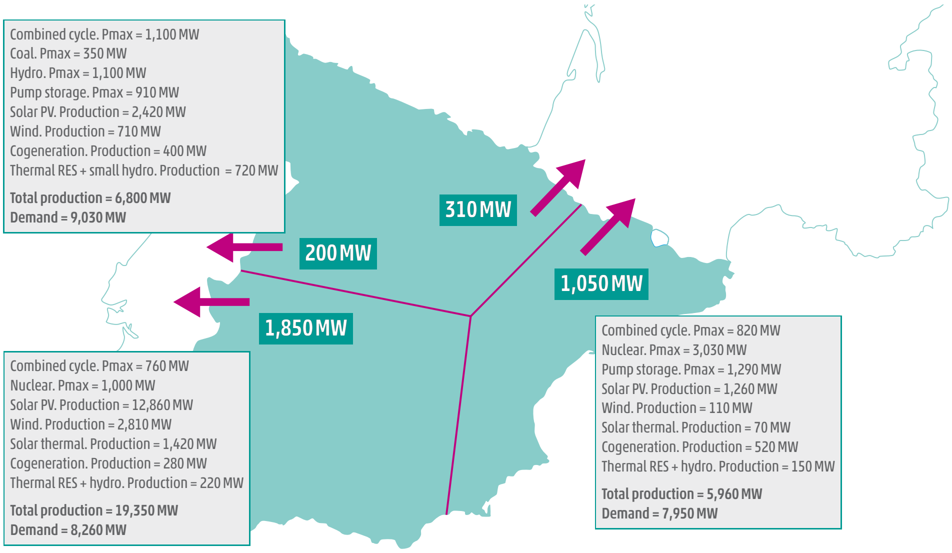


Figure 2-41: Geographic distribution of generation in Spain at 12:32

2.5.6.2 Oscillations

Between 09:00 and 12:00, Figure 2-42 shows some oscillations with small amplitude. In accordance with the common protocol between RTE and RE, no remedial actions were taken to damp these oscillations, including the one at 11:06, because the criteria of the procedure RTE-RE were not met (the damping was higher than 3 % and the amplitude of the oscillations was below 20 mHz). It is also worth specifying that the amplitude in the graphs is not exactly the amplitude of the actual system frequency (expressed in mHz) but rather the output of the modal analysis tool available to the RE control room staff, which provides a value of the estimate mode in a certain range (the actual amplitude in the grid might be higher).

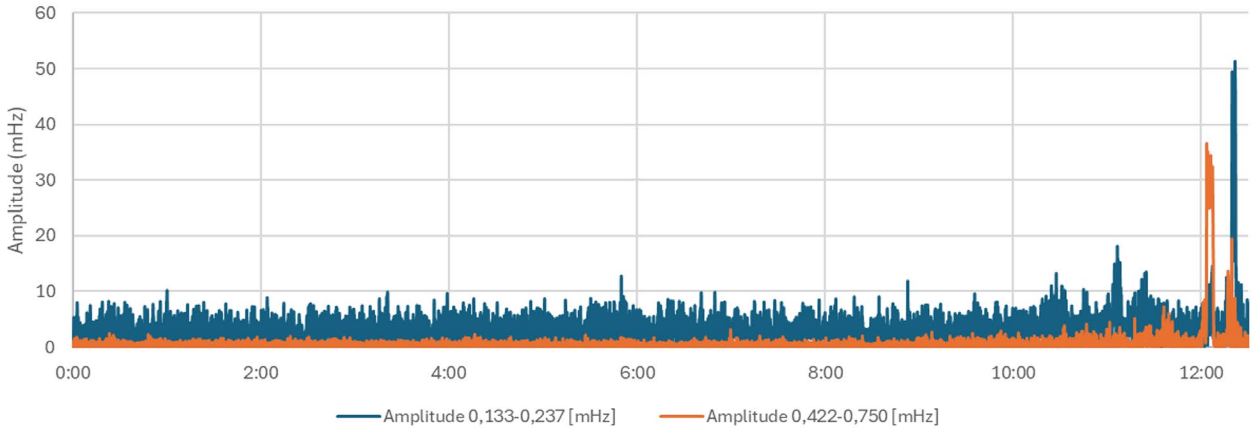


Figure 2-42: Amplitude of modes identified by the modal analysis tool in the RE control room in real time

In the 30 minutes before the blackout event, the Iberian Peninsula was affected by two prominent oscillation phenomena, i.e. periodic fluctuation of all electrical quantities such as frequency, voltage magnitude, active and reactive power. The analyses of these oscillations – conducted by the Expert Panel – are based on two main datasets:

- Frequency PMU measurements in some of the main buses of the CE SA.
- Frequency and voltage PMU recorded in the main buses of Spain, Portugal and South France along the Spanish border grids.

Figure 2-43 depicts frequency and voltage magnitudes from a selection of CESA PMUs, showing the dynamic behaviour of the CE SA between 12:00 and 12:23. These measurements reveal two distinct oscillatory events that affected both frequency and voltage signals, which will be analysed in detail in the following sections. As preliminary remark, it is possible to observe that in terms of amplitude, the first oscillation mainly involves voltages and the second one frequencies.

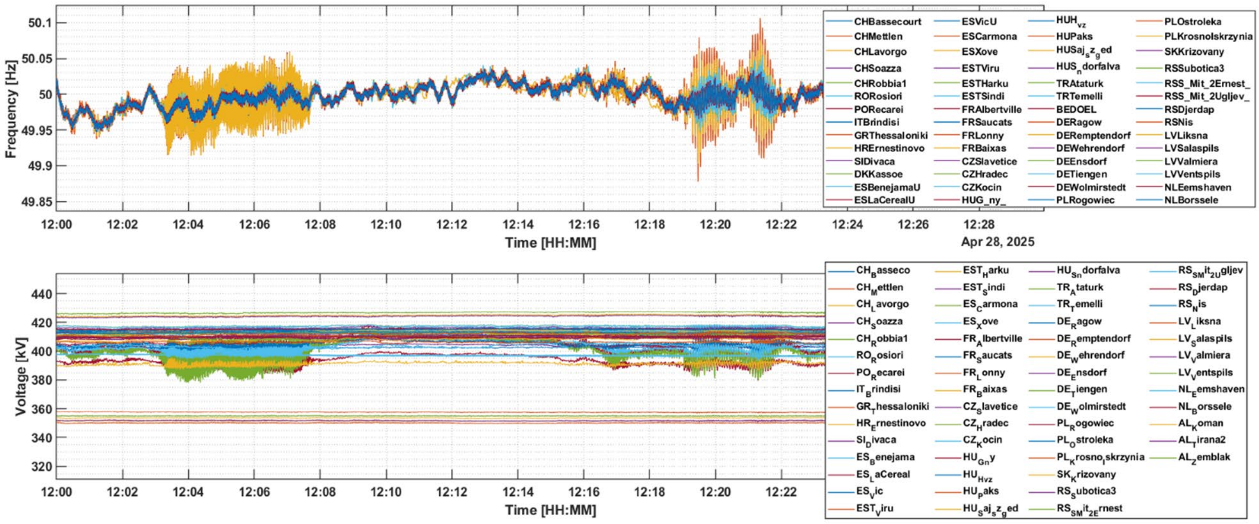


Figure 2-43: Frequency and voltage phasor magnitude measurements from European PMUs

2.5.6.3 Oscillation at 12:03 – 12:08

Oscillatory behaviour with a frequency around 0.6 Hz appears visually discernible in a time series plot at around 12:00:30 in the voltage plot below from PMU in Carmona (Figure 2-44).

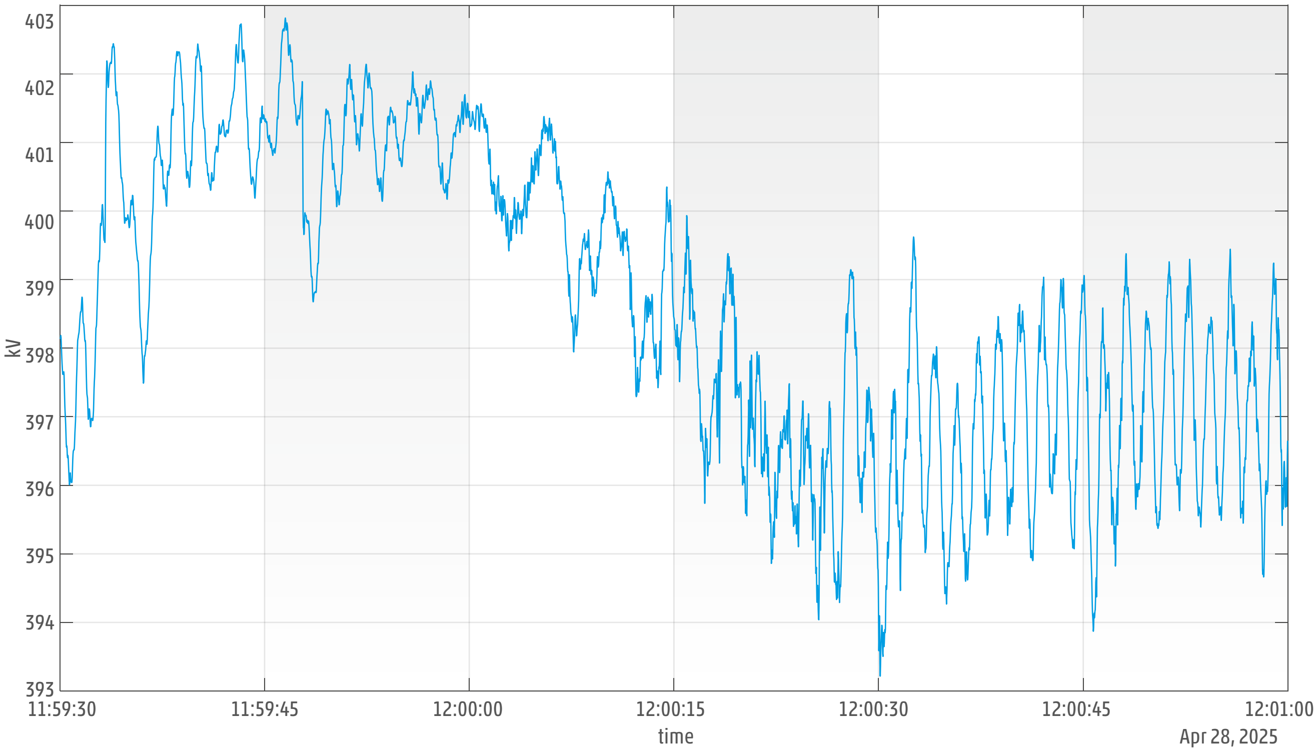


Figure 2-44: Voltage at PMU ONA4DRO, 11:59:30 – 12:01:00

The 0.6 Hz sinusoidal pattern is also visually discernible in the time series plot from around 12:00:30 in the PMU in Santa Llogaia in both the voltage and active power signals, i.e. also in the cross-border power flow on the HVDC. As previously explained, the HVDC link connected at Santa Llogaia is equipped with a POD-Q control system designed to contribute to the damping of oscillations.[11]

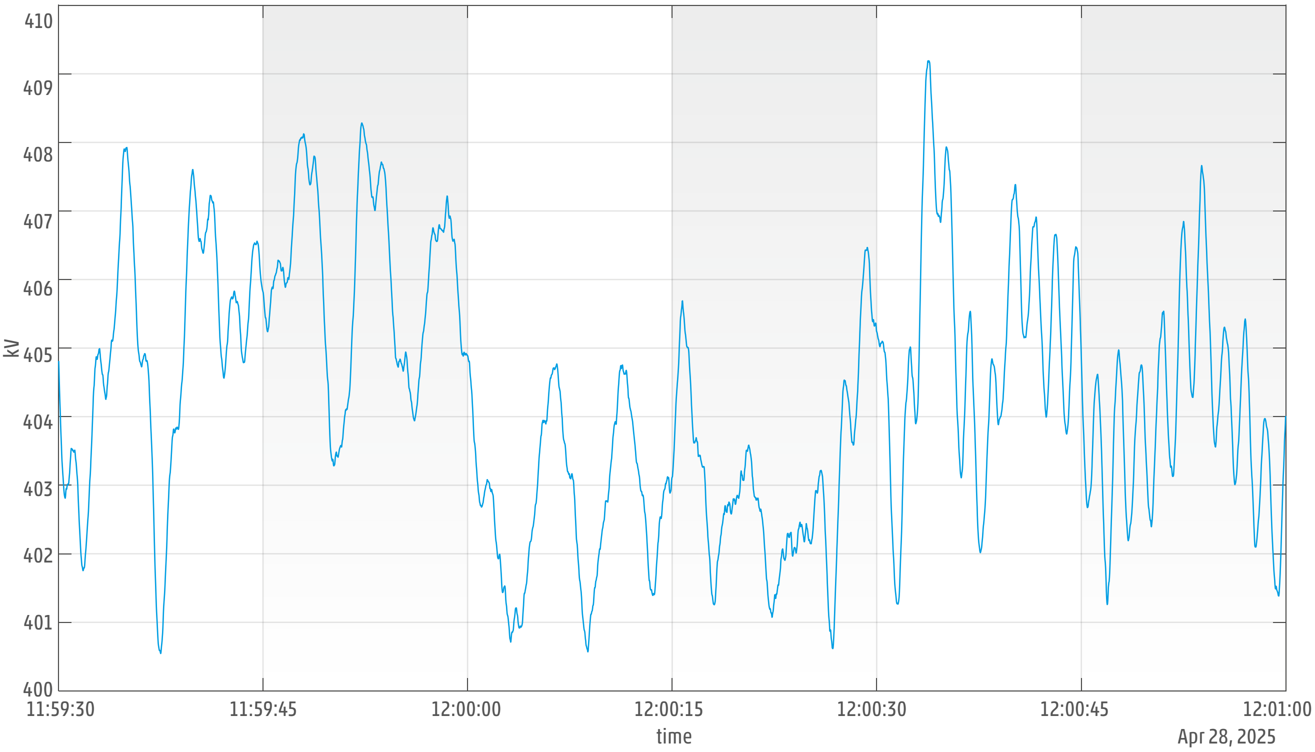


Figure 2-45: Voltage at PMU LLG4ECSL bay 1, 11:59:40 – 12:01:00

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[11] This control modulates reactive power with the aim of adjusting the voltage in the area, thereby influencing local demand and electrical active power of generators nearby to counteract the oscillation. The reactive power modulation performed by the HVDC is what causes the voltage oscillation observed at Santa Llogaia. RE explained that the oscillation in active power through the link is caused by the angle variation that was inducing at the HVDC terminals the 0.6 Hz oscillation. When operating in AC emulation mode, the HVDC transmits power proportionally to the angular difference between Santa Llogaia and Baixas; therefore, any variation in angle results in a corresponding variation in transmitted power. This oscillation in active power is also influenced by the POD-P control, which modulates the active power to mitigate the oscillation currently present in the system.

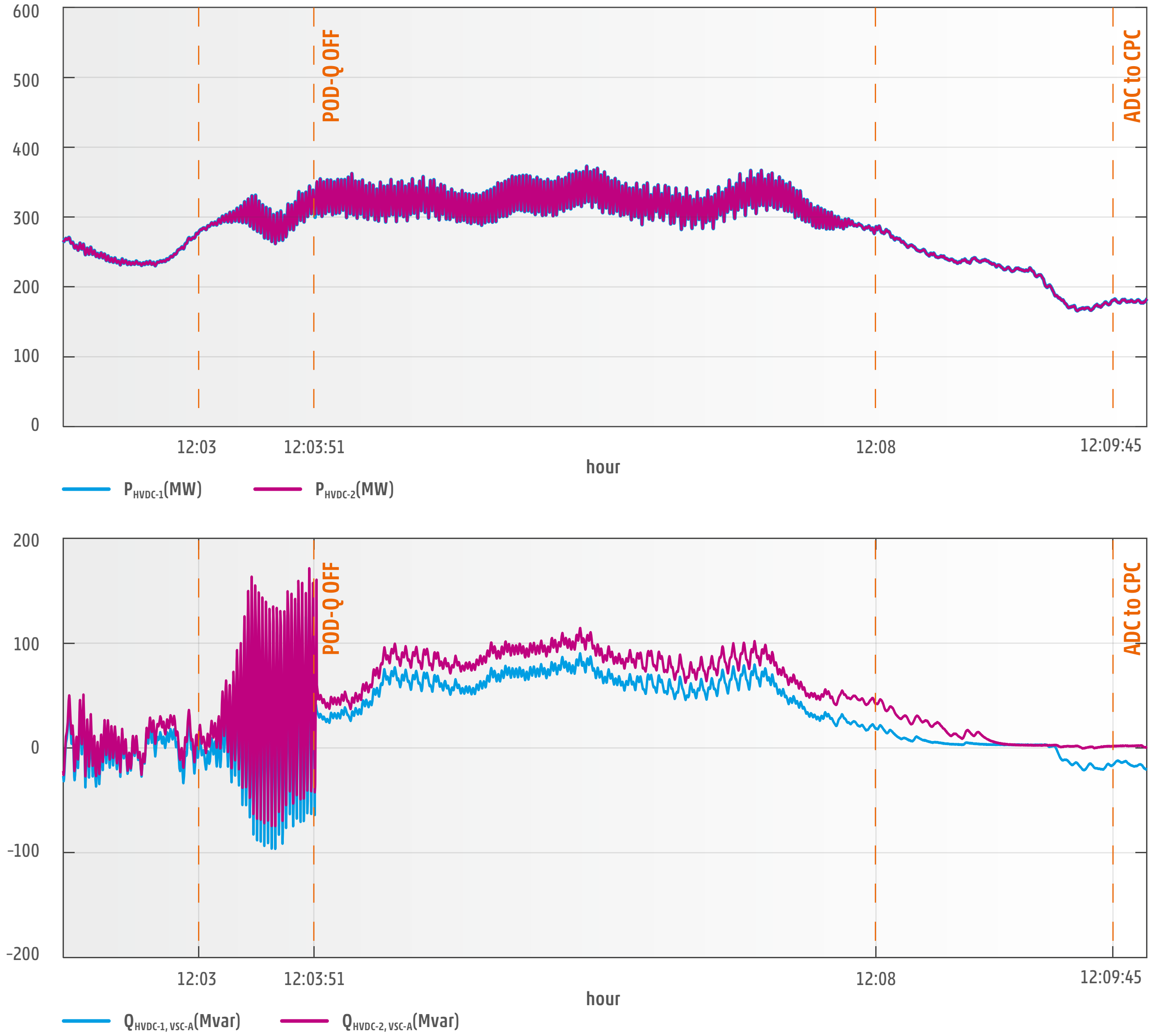


Figure 2-46: Active and reactive power flow at PMU LLG4ECSL bay 1, 12:00:00 – 12:10:00

The oscillation then appeared in all nodes of the system (sustained amplitude higher than 20 mHz) at 12:03 and lasted approximately five minutes, with a maximum peak-to-peak amplitude of 100 mHz in the frequency.

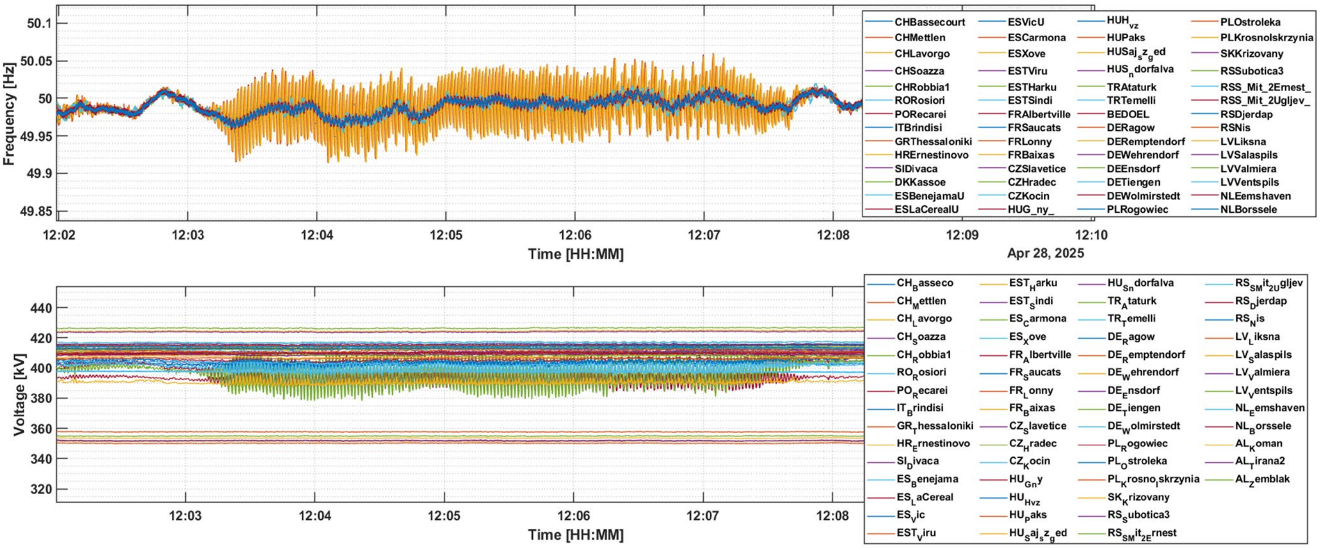
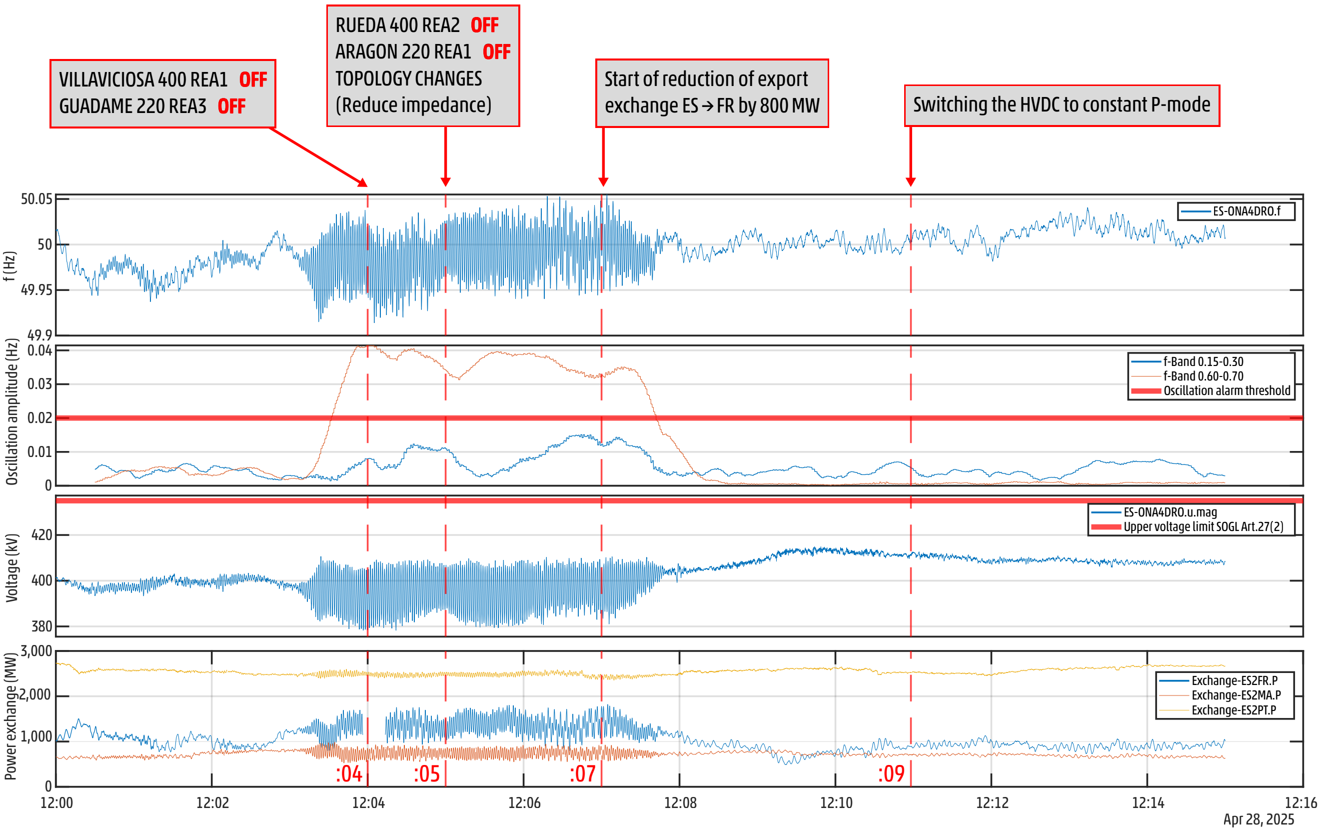


Figure 2-47: Frequency and voltage phasor magnitude measurements from European PMUs

A focused view on Spanish PMU measurements is provided in Figure 2-48, highlighting the system behaviour during the first oscillation and the moments immediately after. The figure displays the evolution of frequency, oscillation amplitude, voltage, and cross-border power exchanges.


VILLAVICIOSA 400 REA1 **OFF**
GUADAME 220 REA3 **OFF**

RUEDA 400 REA2 **OFF**
ARAGON 220 REA1 **OFF**
TOPOLOGY CHANGES
(Reduce impedance)

Start of reduction of export exchange ES → FR by 800 MW

Switching the HVDC to constant P-mode

Figure 2-48: Characteristics data of the first oscillations (source: WAMS 100 ms sampling rate in the 6 kV Carmona (Spain) substation) and countermeasures applied

The second box of Figure 2-48 shows the modal analysis result, demonstrating the dominant presence of a 0.6 Hz component (in orange) and a less prominent component at 0.21 Hz, namely East Central West inter-area oscillation (in blue).

Voltage oscillations were also observed, primarily in the southwestern area. In Figure 2-49, voltages from south-west of Spain (Almaraz and Carmona), north-west (Xove), east (Benejama) and north-east (Vic) are shown. During the oscillation, in certain substations, voltage levels approach the lower threshold established by Spanish regulations of 375 kV, although the highest recorded voltage values barely exceed 410 kV.

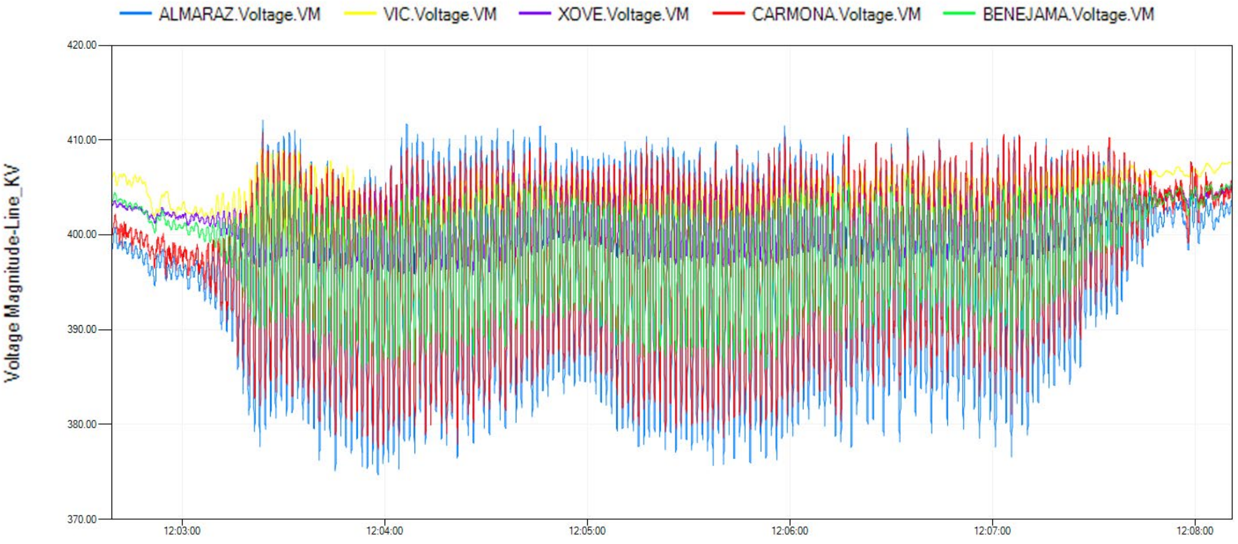


Figure 2-49: Voltage magnitudes in several Spanish substations

Figure 2-50 displays the same voltage values, but after applying a band-pass filter (0.55 to 0.70 Hz), which enhances the visibility of the oscillation amplitude at each substation. It can be seen that the voltage oscillation amplitude reaches 30 kV peak to peak at the Almaraz 400 kV substation.

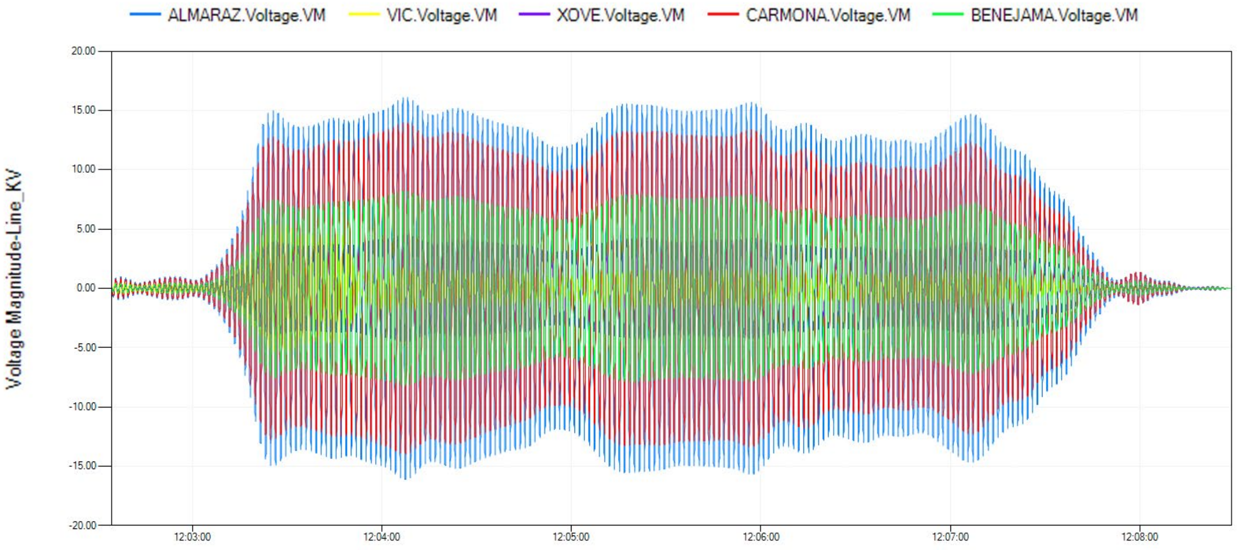


Figure 2-50: Voltage oscillation alter apply a pass-band filter [0.55-0.70 Hz] in several Spanish substations

After applying a complex principal component analysis algorithm[12] to all 400 kV PMUs, it is possible to recreate the finding that the dominant mode is 0.63 Hz. In fact, processing a set of several time series (i.e. voltage, frequency, etc.), the algorithm is able to find a dominant characteristic mode like reported below in Figure 2-51. Observing the sinusoidal path, it is possible to estimate the oscillatory frequency (i.e. measuring time between two adjacent peaks).

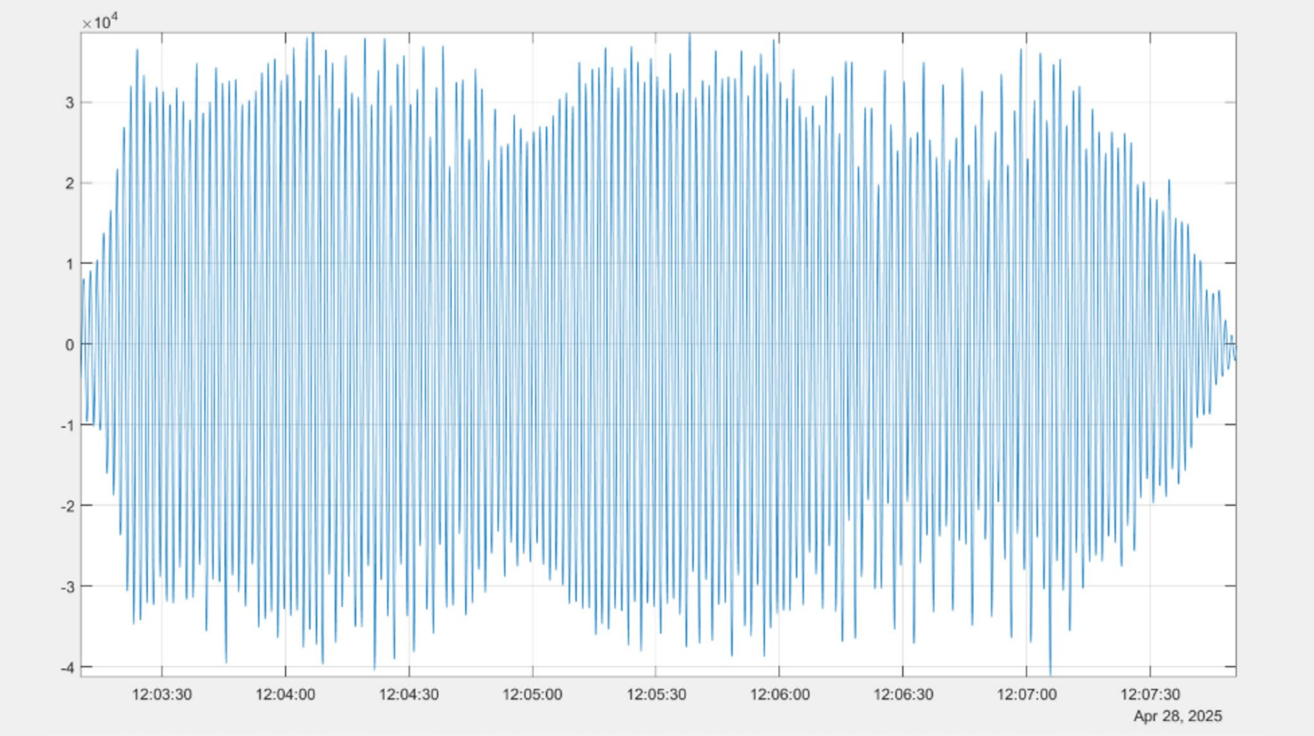


Figure 2-51: Voltage oscillation principal component analysis (PCA)

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[12] Complex principal component analysis is a technique that processes several time series and extracts the dominant components versus time, which enables identifying the frequencies, damping, amplitude and mode shape of the dominant modes. Ref. "Complex Principal Component Analysis: Theory and Examples" by J. D. Horel.

In order to evaluate the 400 kV nodes that are the most active in the 0.63 Hz oscillation, a complex principal component analysis was performed, showing the maximum activity (in this case, voltage amplitudes) in the nodes of Almaraz and Puebla de Guzman.

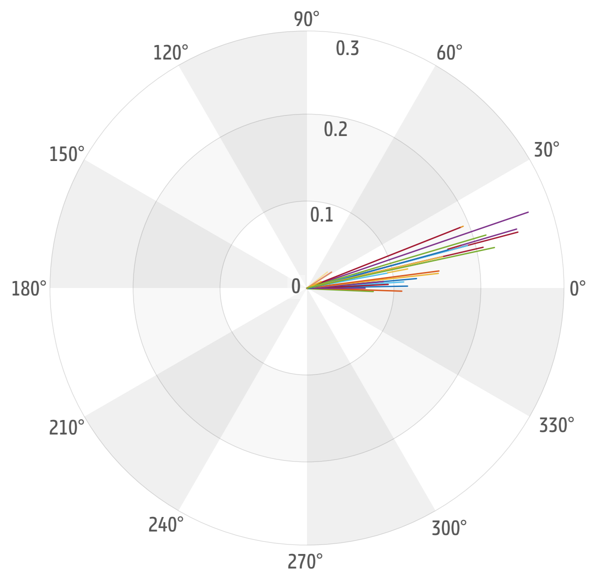

Figure 2-52: Mode shape by complex principal component analysis on PMU voltages normalised (each colour in the polar plot represent a different location)

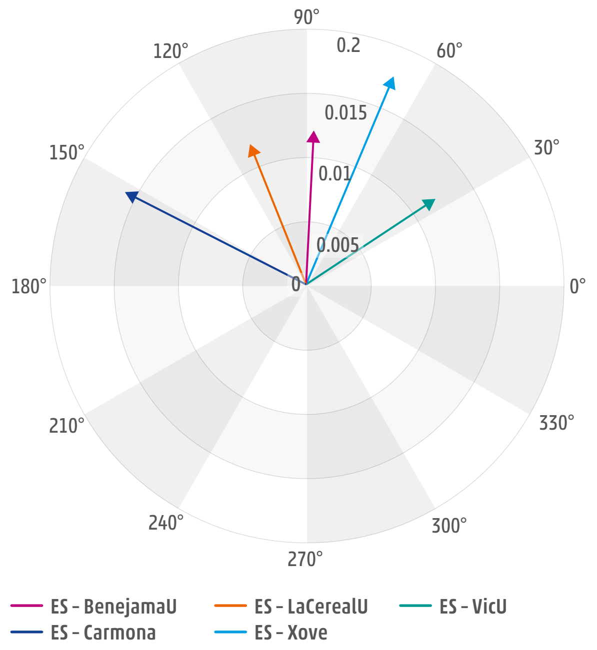

Figure 2-53: Mode shape on PMU frequencies normalised (each colour in the polar plot represents a different location)

Figure 2-53 clearly shows how the significant amplitudes of mode shape are located in Spain and the angle spread is around 120°, with no phase opposition oscillations.

One minute after detecting the oscillation, the control rooms of RE and RTE activated the common protocol described in Section 2.5.2. In terms of event sequence, the RE control room called the RTE control room to initiate the activation of the protocol. The protocol is intended to be applied depending on the damping measurement or when oscillations in the range of 0.1–0.35 Hz and an amplitude higher than 20 mHz are detected.

RE and RTE initiated a change of the operating mode of the HVDC (switching from hybrid mode to constant power mode) and a countertrading procedure involving 800 MW across the France–Spain exchange borders. The countertrading procedure was performed in the following way: as the total imbalance in Spain was negative (i.e. less production in comparison with consumption), there were no need for generators to compensate for countertrading through RR and mFRR allocations.

The imbalance generated by countertrading was compensated with aFRR or reduced the need for mFRR. On the RTE side, countertrading was used to increase French production. This production adjustment was made at the national level, based on electricity market prices using the merit order method. While not part of the oscillation control protocol, four shunt reactors were switched off by RE due to the lower voltages seen in the system during the oscillation:

- » 12:04 Villaviciosa 400 kV REA 1
- » 12:04 Guadame 220 kV REA 3
- » 12:05 Rueda 400 kV REA 2
- » 12:05 Aragón 400 kV REA 1

Furthermore, several topological actions were undertaken, aiming to reduce the impedance of the grid.

Regarding the behaviour of the POD controllers of INELFE HVDC, the POD-P controller remained active during the whole period, while the POD-Q controller was active at the start of the 0.63 Hz oscillation, but disabled at 12:03:51, i.e. approximately 50 seconds after the start of the oscillation. The disabling of the POD-Q was caused by the logic implemented by the manufacturer to prevent its operation when the output of the controller saturates in ±100 Mvar (reaching the upper and lower limit too often).

Figure 2-54 reports the frequency and voltage measured at the Spanish terminal of the HVDC. In the first chart, it can be observed that when the POD-Q is disabled, the amplitude of the frequency oscillation does not change. In the second chart, it can be observed that after the disabling the POD-Q, the amplitude of the local oscillation of voltage at the Llogaia substation decreases. The increase in amplitude of voltage during the POD-Q action is correct, due to the action of the HVDC control aimed at increasing damping. The voltage oscillation amplitude did not change in other substations.

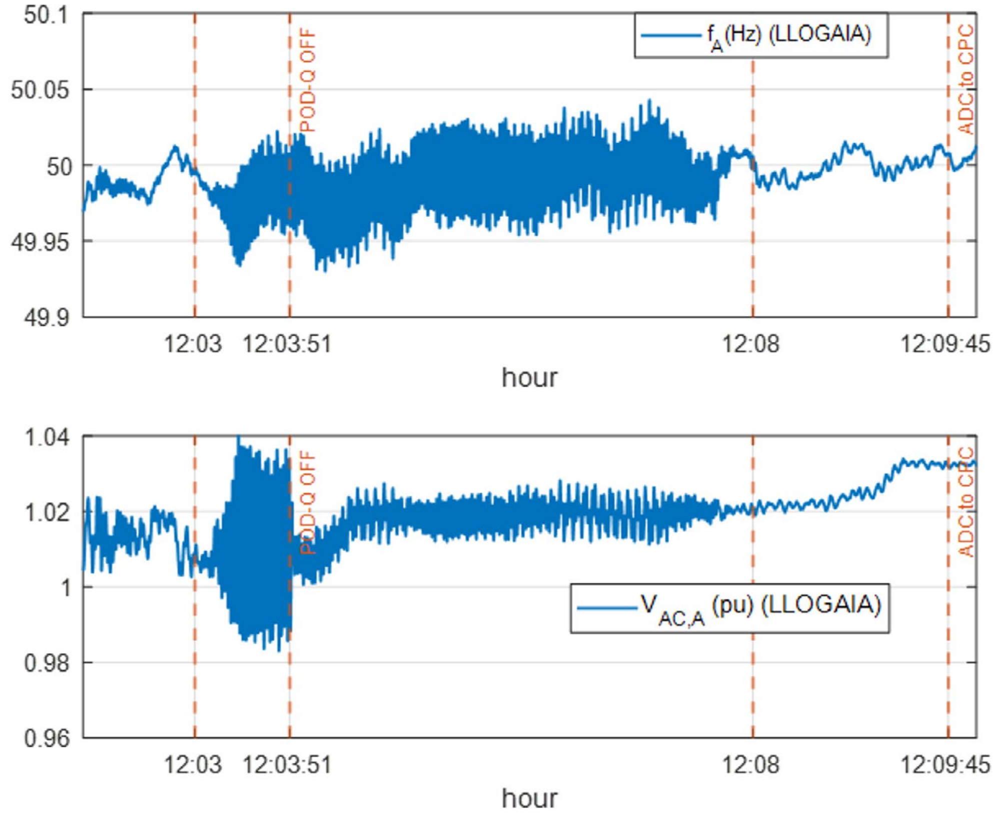

Figure 2-54: First oscillation of 0.63 Hz frequency and voltage at Sta. Llogaia 400 kV substation

The subsequent switch to constant power mode was applied by the control room at 12:09, when the oscillation amplitude was just decreasing. This decision was made by RE/RTE with the aim to further improve the damping. After the power mode was switched to constant power, an additional action was the change of the P set point by increasing it to 1,000 MW in the export direction from the Spanish perspective.

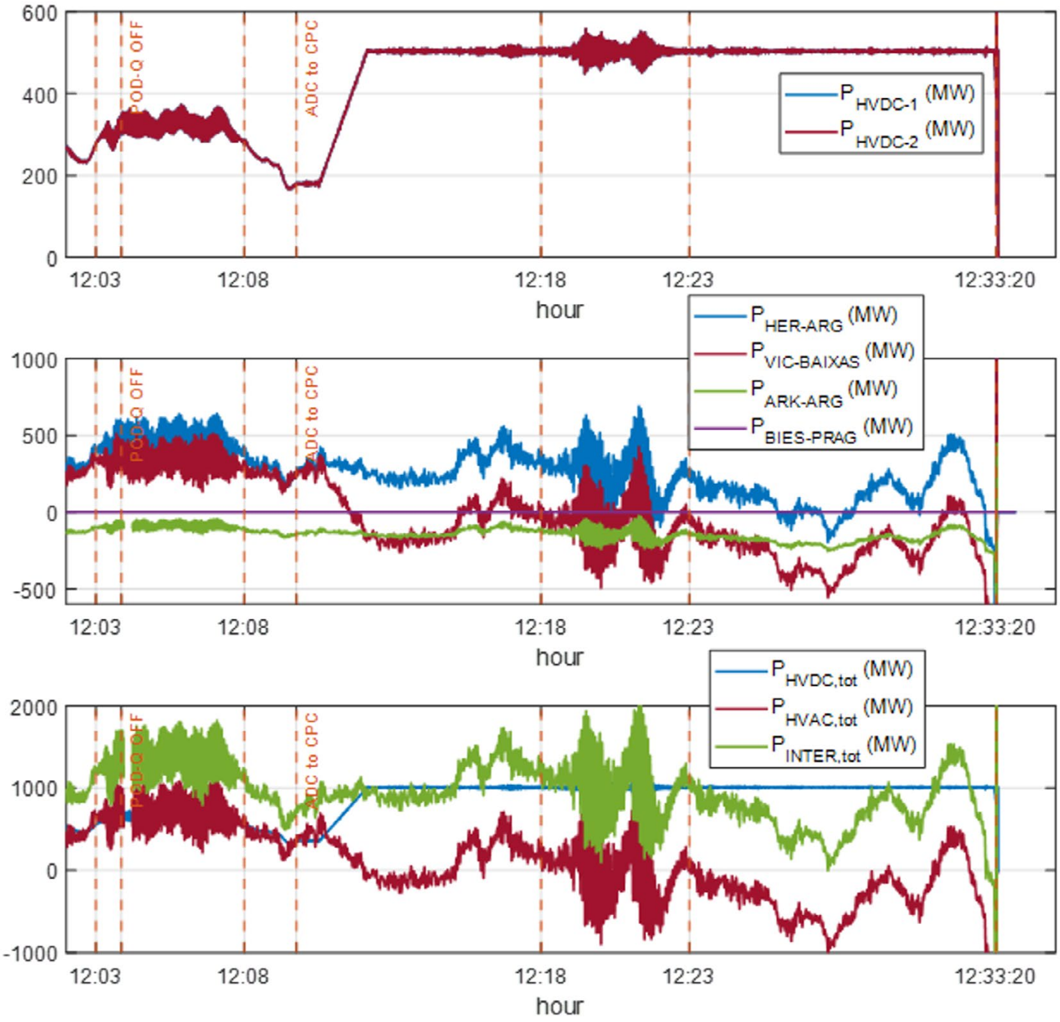

Figure 2-55: Power flows in the Spain–France interconnection (sign criterion: positive = exported from Spain to France)

The frequency domain analysis – performed using a sliding-window fast Fourier transform (FFT) on all PMUs – shows the emergence of a distinct oscillatory mode at approximately 0.63 Hz during the first oscillation.

The FFT results clearly indicate that this mode has a predominant oscillation frequency of 0.63 Hz, most likely corresponding to a local mode.

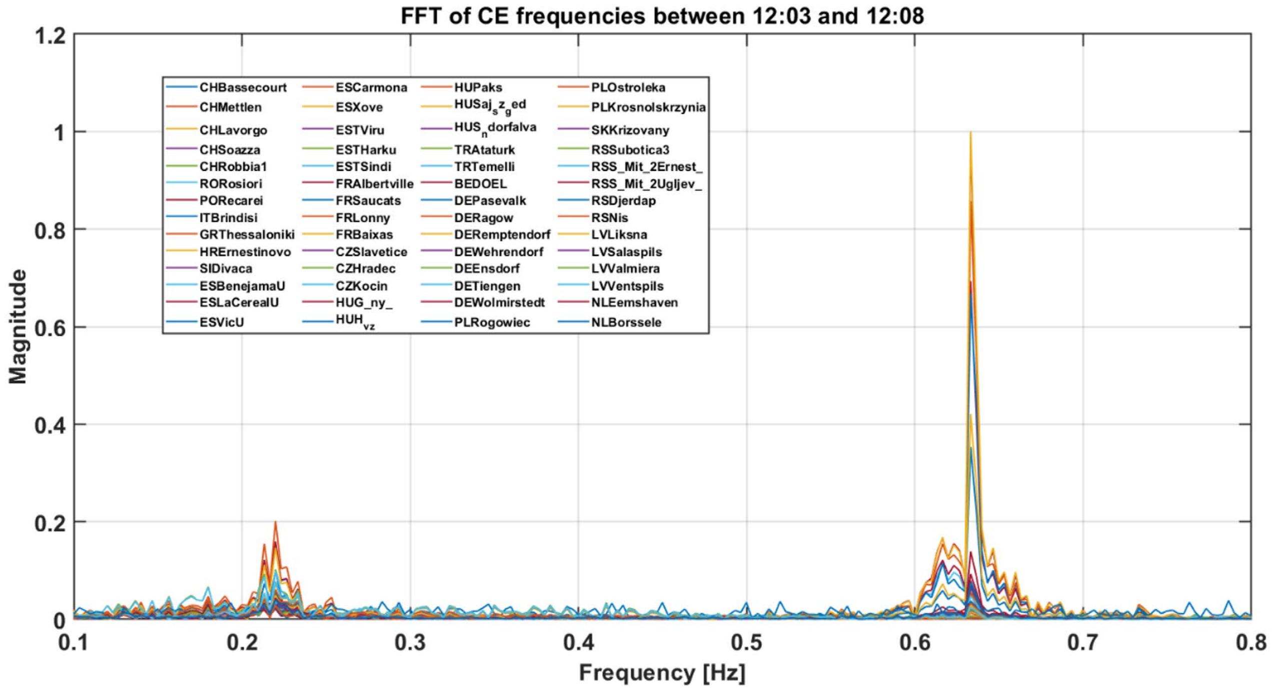

Figure 2-56: Normalised fast Fourier transform of the frequency from various PMUs across Continental Europe between 12:03 and 12:08

To classify this 0.63 Hz oscillation, a mode shape analysis was performed, and the results are showed in Figure 2-57 below.

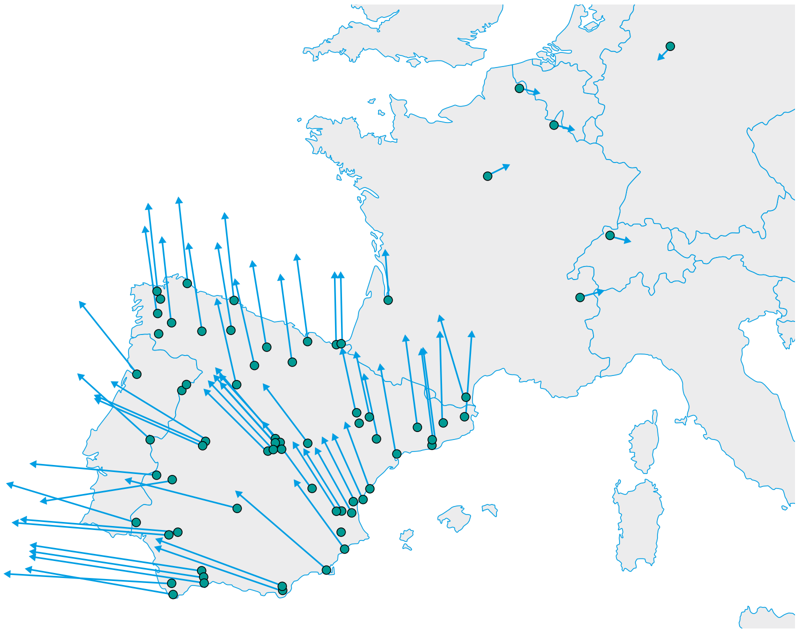

Figure 2-57: Mode shape of the 0.63 Hz oscillation (frequencies)

The arrow in Figure 2-57 above indicates the direction of the oscillation and amplitude. It can be noted that the angular spread of frequencies between north and south of Iberia is around 90° to 100°, with a local geographic displacement.

Figure 2-58 displays a zoom of voltage and frequency at various locations to estimate the angle between the two quantities, which is approximately 143°, confirming unstable behaviour. In fact, the more voltage in a node that is in phase with the frequency, the more the loads can act as a stabilising action.

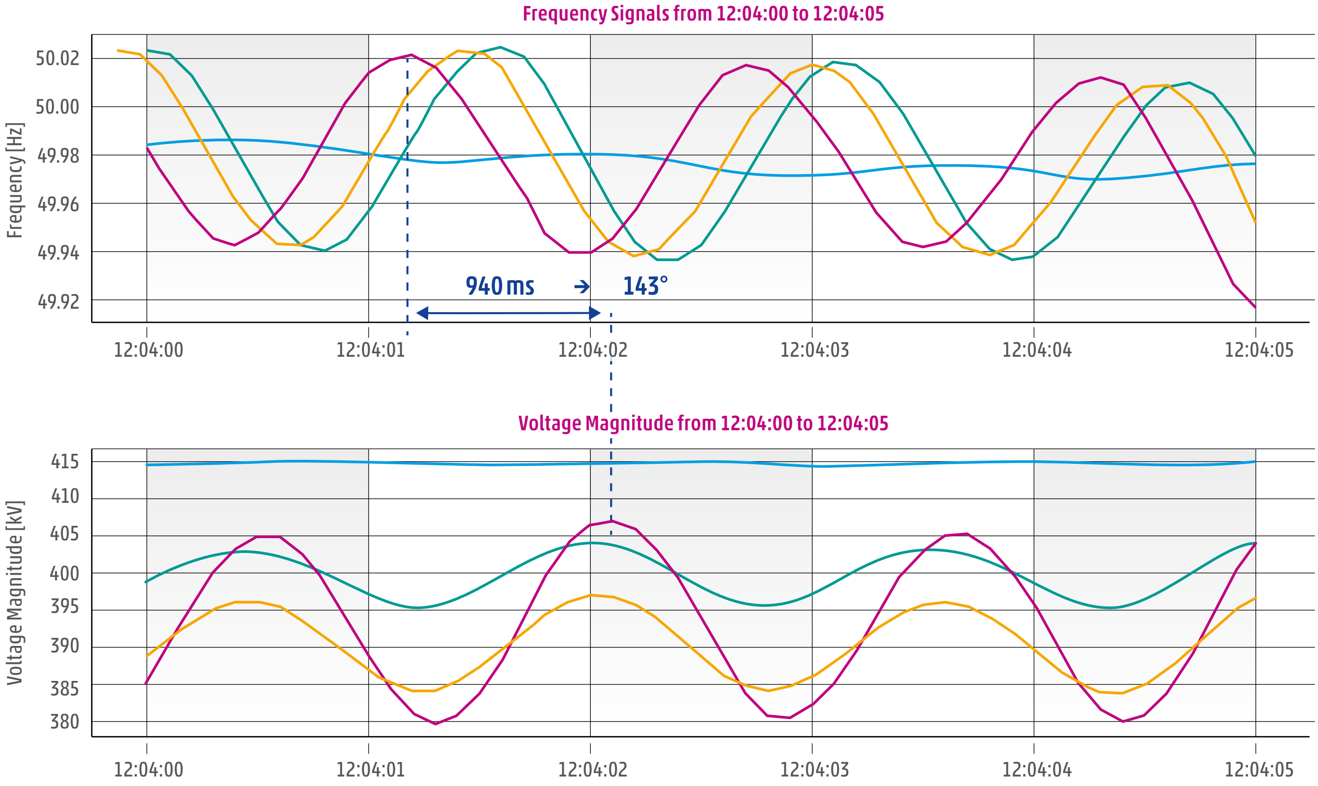

Figure 2-58: Angle between voltages and frequencies

Regarding generation behaviour during oscillations, based on the available data, the maximum resolution available is insufficient to display a clear trend of active, reactive power, and voltage fluctuations for particular generators.

Nonetheless, based on PMU data, it is possible to understand that the dominant content of energy is associated with the reactive power and voltage. In addition, large power fluctuations were detected in the SCADA data of generation in the area of the nodes of Almaraz and Puebla de Guzman. Figure 2-58 shows fluctuations of active power with an amplitude of around 200 MW and reactive power with an amplitude of around 180 Mvar, occurring between 12:03 and 12:08.

All of these elements will be analysed during the investigation to clarify whether any local malfunction could generate a forced oscillatory phenomenon. However, at present, no generator has reported significant malfunctions of reactive power regulation, and thus additional investigations will be conducted in the next analysis phase to confirm the hypothesis of forced oscillation.

In light of all the factors listed in the previous paragraph and the currently available data, the Expert Panel cannot conclude at this stage whether the oscillations were forced or not.

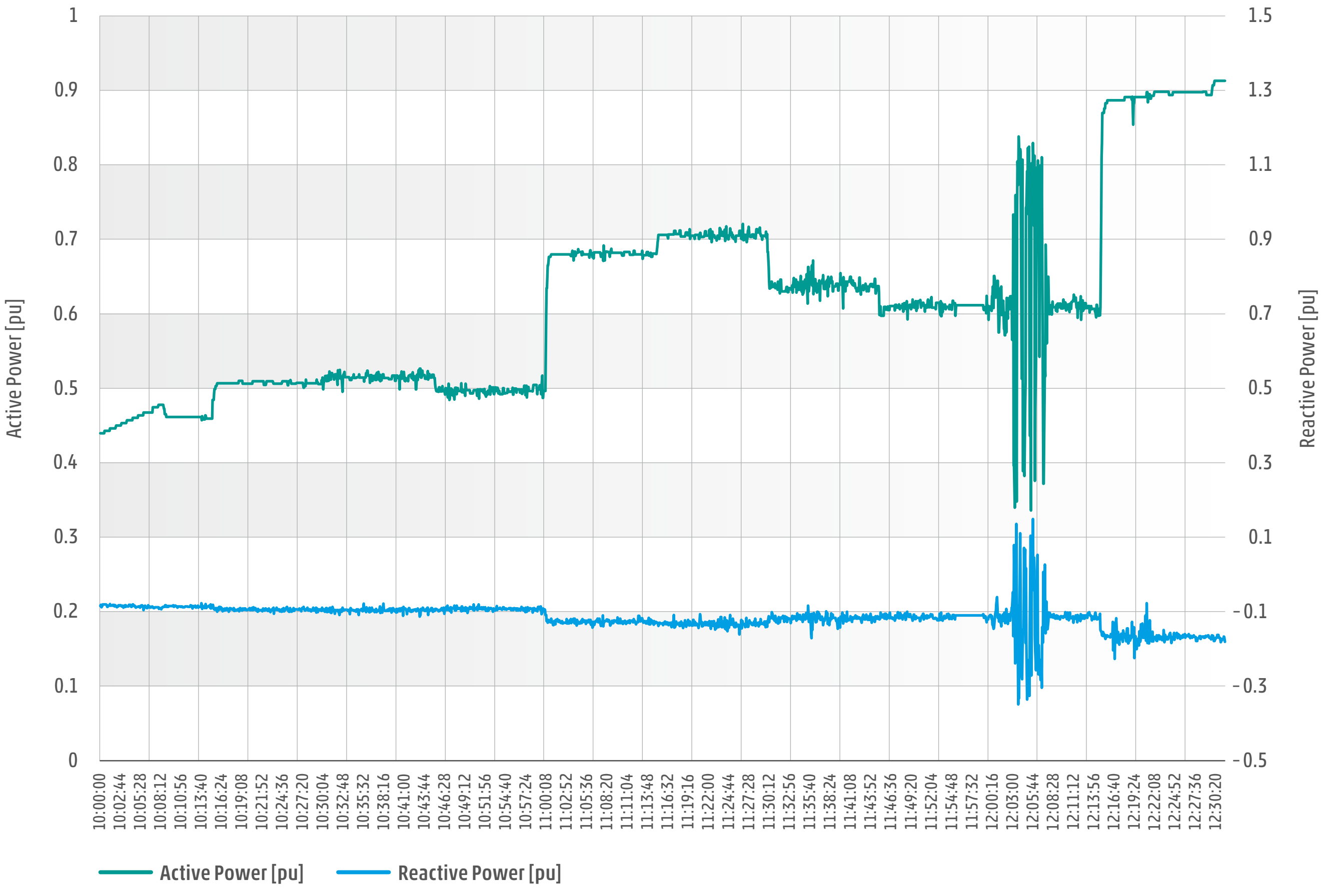

Figure 2-59: Active and reactive power generated by a power plant connected in the province of Badajoz

There have been smaller episodes of oscillatory behaviour registered on some PMUs after the first major oscillation described above and before the second one, which started at 12:19, as shown in Figure 2-60 below, specifically on voltage in PMU ALD4HIN.

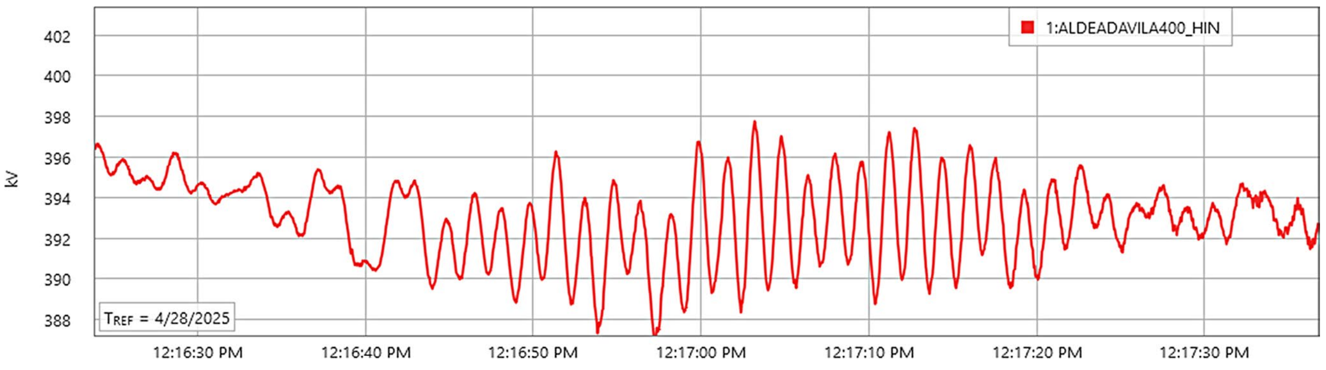

Figure 2-60: Voltage at PMU ALD4HIN between 12:16:30 and 12:17:30

Figure 2-61 shows the period from 12:16:30 to 12:20:00, showing the minor oscillations at the beginning of the interval, as well as the beginning of the 12:19:00 oscillation.

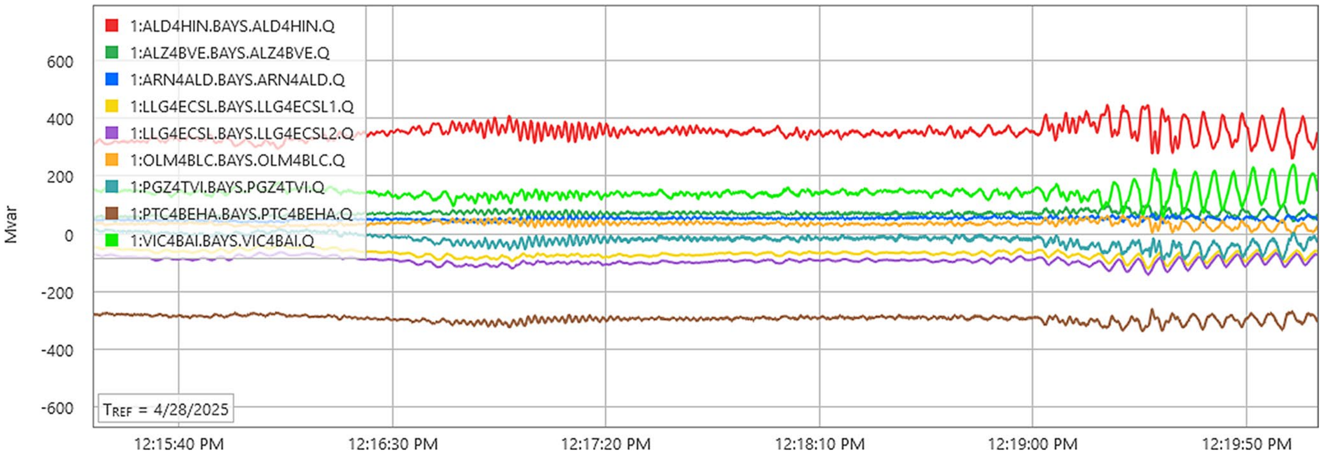

Figure 2-61: Reactive power at various PMUs between 12:15:30 and 12:20:00

2.5.6.4 Oscillation at 12:19 – 12:22

The second major oscillation is considered to have begun (an amplitude higher than 20 mHz) on all PMUs at 12:19.

The 12:19 oscillation is considered to have lasted for approximately three minutes, with a maximum frequency amplitude of around 200 mHz, significantly larger than the 12:03 – 12:08 event.

Following this event, RE and RTE initiated another countertrading procedure involving 500 MW across the France – Spain exchange borders. The countertrading procedure was performed in the following way: as the total imbalance in Spain was negative (i.e., less production in comparison with consumption), there was no need for generators to compensate for countertrading through RR and mFRR allocations.

The imbalance generated by countertrading was compensated with aFRR or reduced the need for mFRR. On the RTE side, countertrading was used to increase French production This production adjustment was made at the national level, based on electricity market prices (mFRR and RR) using the merit order method.

In addition, further actions were adopted on shunt reactors:

- 12:17 Cabra 400 kV REA 1 was disconnected before the second oscillation

Two minutes after the beginning of the second oscillation, the following shunt reactors were disconnected by RE:

- 12:21 Peñaflor 400 kV REA 1
- 12:24 Palos 220 kV REA 1
- 12:24 Morata 400 kV REA 4

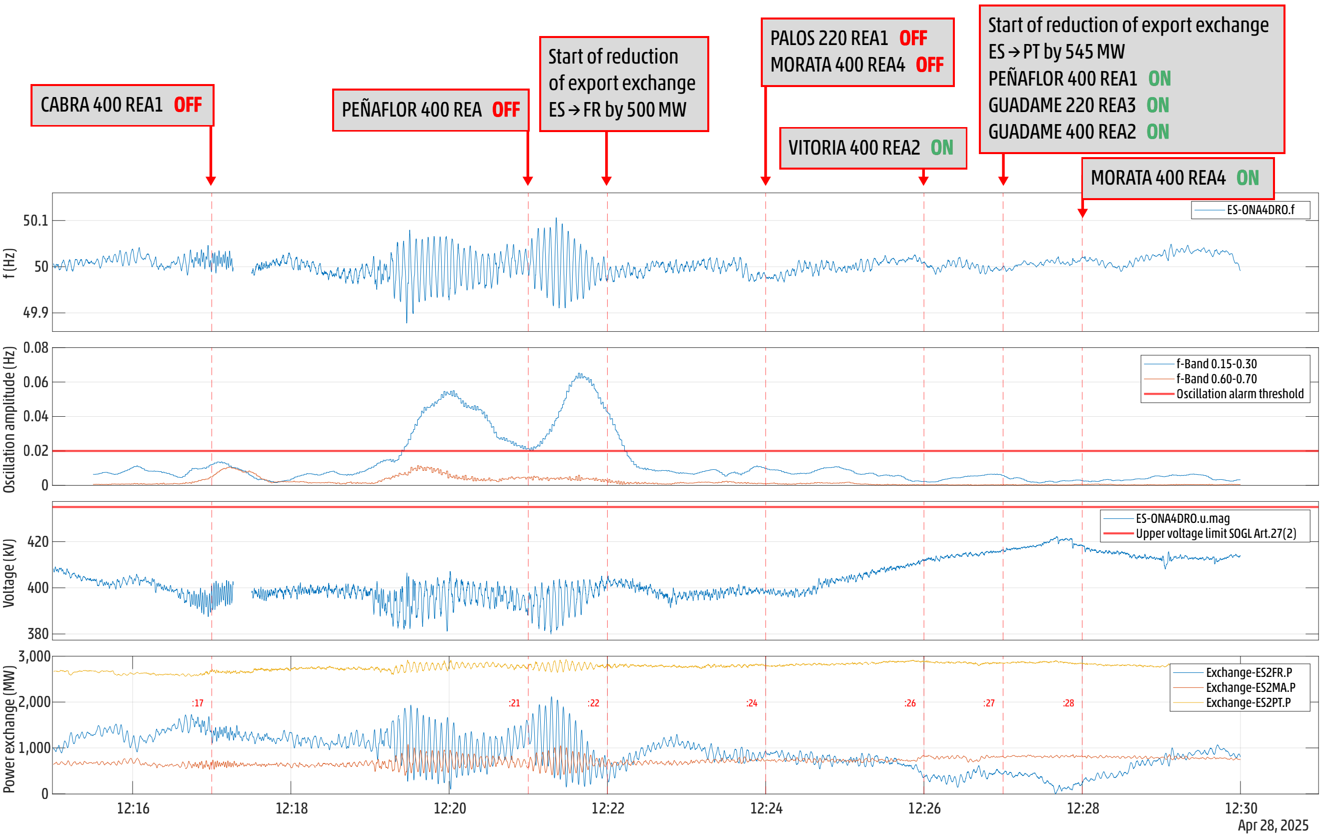

Figure 2-62: Characteristics data of the second oscillations and increasing voltage (source: WAMS 100 ms sampling rate at the 400 kV Carmona substation) and countermeasures

From Figure 2-62, it is possible to observe the frequency behaviour on the first graph. The second graph shows the amplitudes of the two oscillatory frequency components, namely the 0.21 Hz inter-area mode in blue (dominant) and the 0.63 Hz local mode in orange (with smaller amplitude).

Figure 2-63 presents the system-wide trends of frequency and voltage across CE:

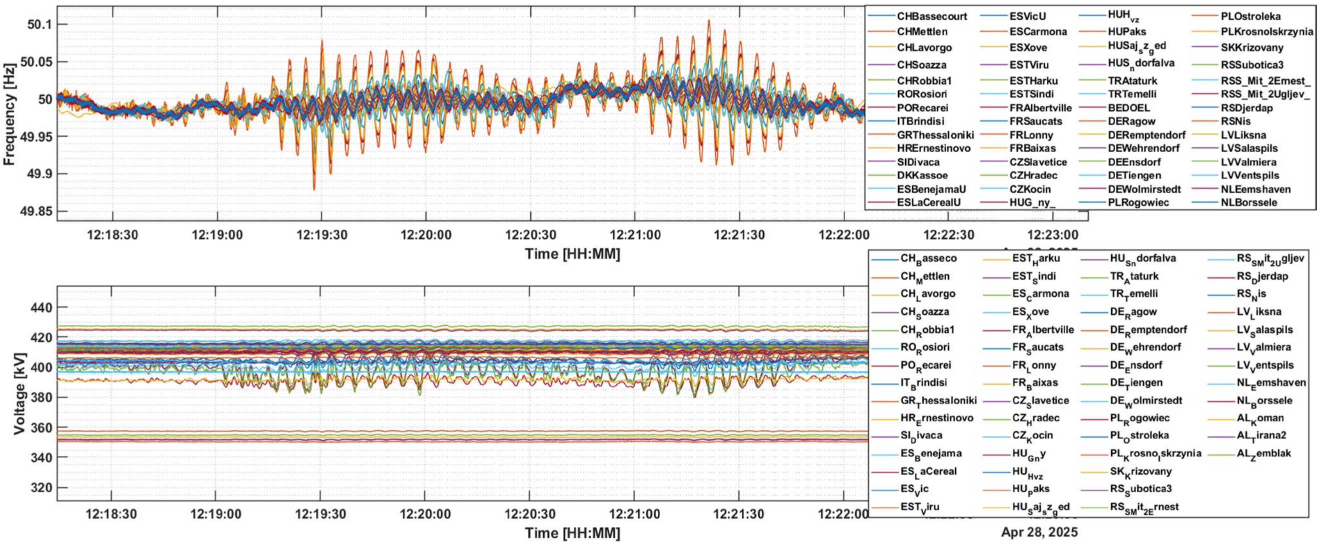

Figure 2-63: Frequency and voltage phasor magnitude measurements from European PMUs

Unlike the first oscillation – which was confined to the Iberian Peninsula in terms of very low amplitude outside the Iberian system – this second event exhibited a clear inter-area character. This is confirmed by both the modal analysis estimates and the polar plot, which indicate that the oscillation corresponds to the ECW mode.

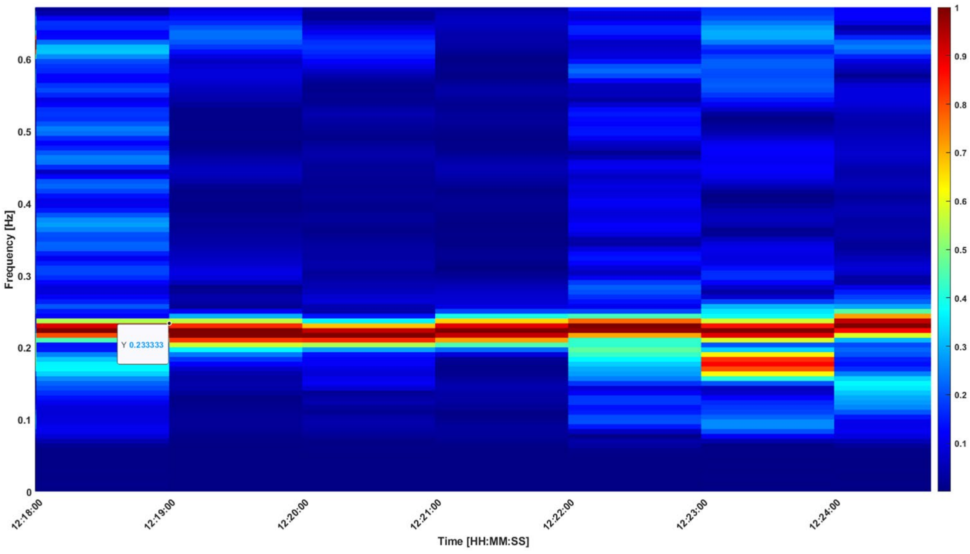

Figure 2-64: Spectrogram from Carmona (ES) PMU during the timeframe of 12:18 to 12:25

In particular, the polar plot in Figure 2-65 reveals a phase opposition between two geographically distinct system clusters:

- The Western cluster (Spain and Portugal), oscillating coherently with a high energy contribution.
- The Eastern cluster (including Estonia, Latvia, Hungary, Poland, and Turkey), moving in opposition.

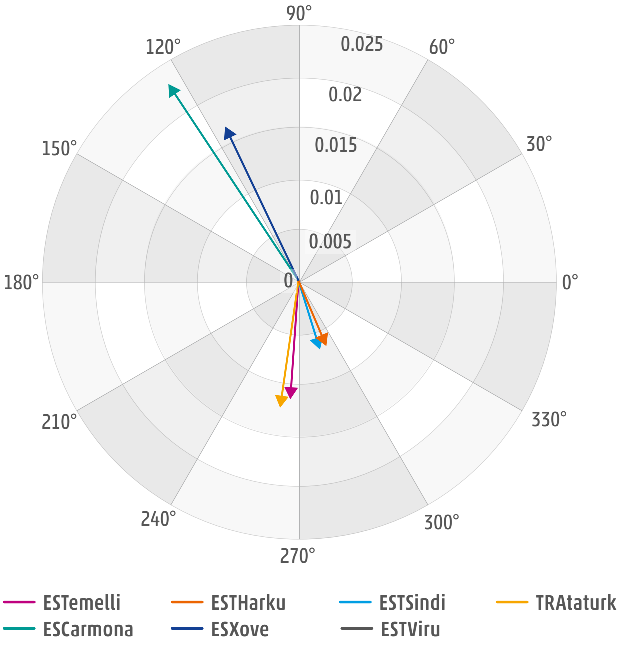

Figure 2-65: Polar plot of the Spanish and Turkish PMUs at 12:20:39.9

The energy distribution across the clusters confirms that the Western area contributed more strongly to this oscillatory mode.

The modal estimates produced using a FFT algorithm[13] (Figure 2-66) show a progressive degradation in the calculated damping of the ECW mode.

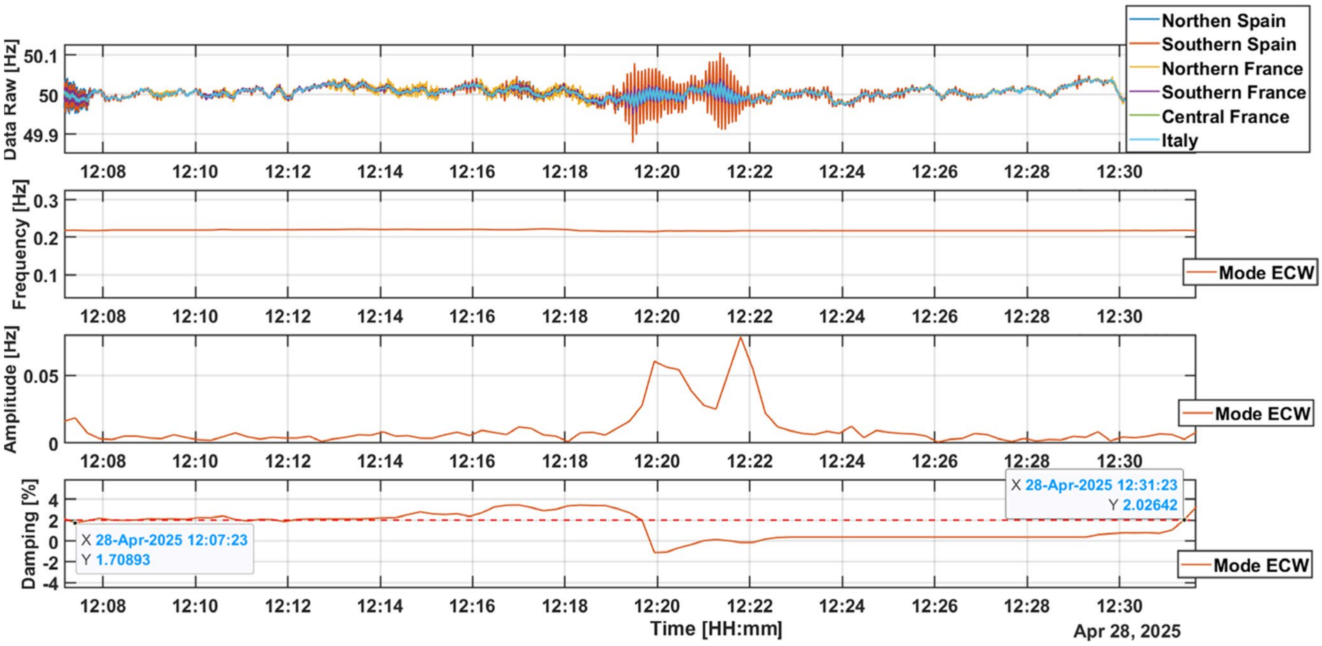

Figure 2-66: Estimated frequency, amplitude, and damping ratio of the dominant oscillation mode over time, obtained using a mode estimation algorithm

Damping remained consistently low for several minutes before becoming negative around 12:19.

This deterioration in damping is accompanied by a marked increase in modal energy, as indicated by the growing amplitude of the oscillation frequency.

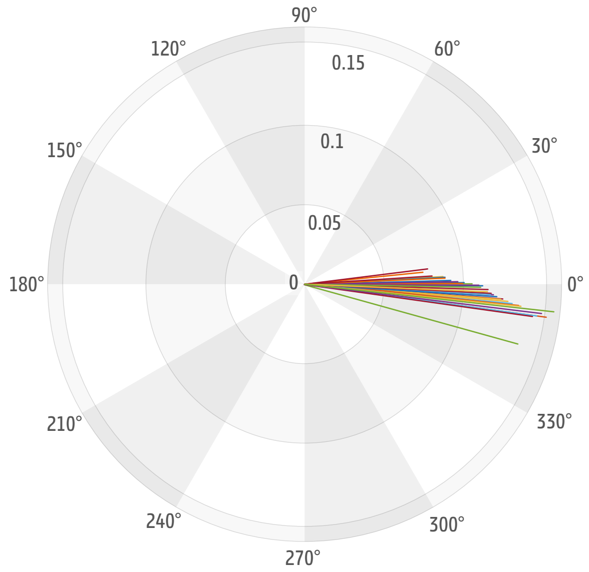

Figure 2-67: Mode shape by complex principal component analysis on PMU normalised voltages (colours in the polar plot represent different locations)

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[13] The adopted technique was based on a fast Fourier analysis on the selected PMUs time series and frequency/damping estimation with the Tufts-Kumaresan algorithm.

In this case, voltage oscillations are also observed, with an amplitude of the same order as those recorded during the 12:03 oscillation, and even slightly lower. Once again, a decrease in the average voltage value is observed.

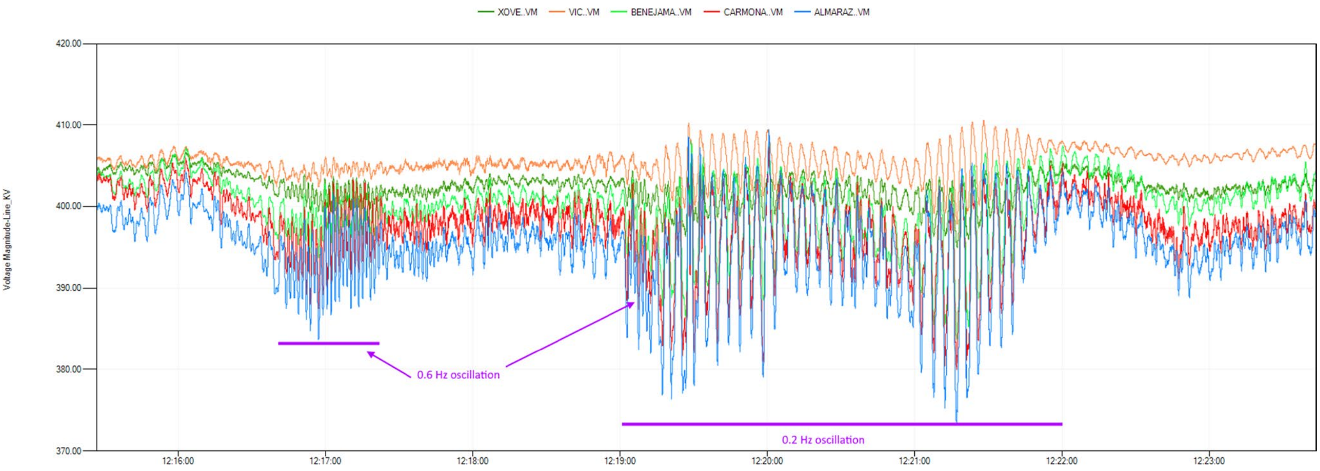

Figure 2-68: Voltage magnitudes at several Spanish substations

Figure 2-69 displays the same voltage values, but after applying a band-pass filter (0.18 to 0.25 Hz), which enhances the visibility of the oscillation amplitude at each substation. It can be seen that the voltage oscillation amplitude reaches 28 kV peak to peak at the Almaraz 400 kV substation.

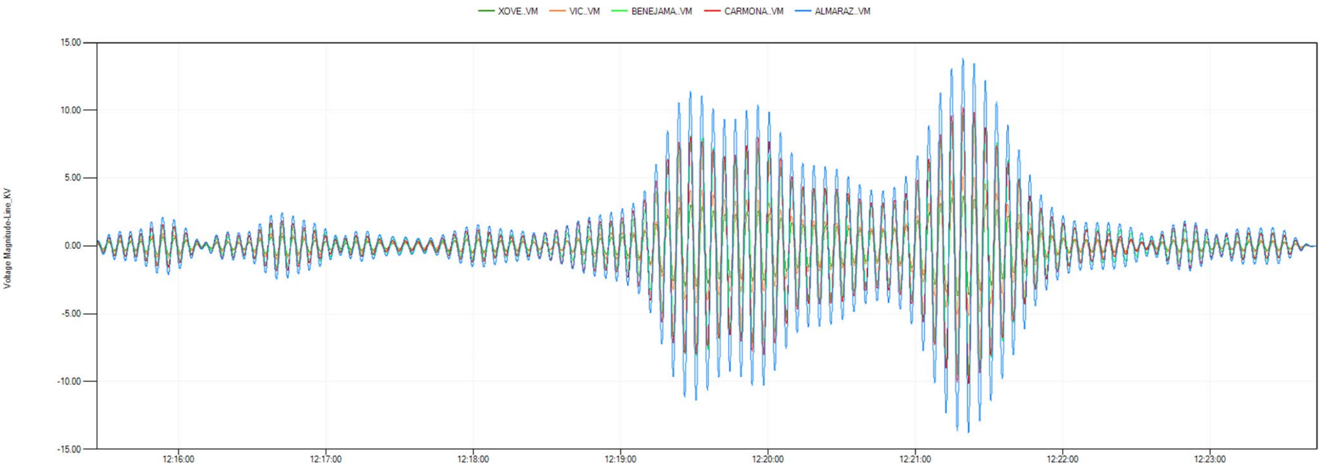

Figure 2-69: Voltage oscillations alter applying a pass-band filter [0.18–0.25 Hz] at several Spanish substations

2.6 Reactive Power and Voltages

2.6.1 Voltage Standards in Spain and Portugal

Voltage standards in Spain are governed by Operational Procedures 1.1, 1.2, and 1.4 from 1998. The Operational Procedure 1.4 mentions two upper voltage limits on the 400 kV grid (420 kV and 435 kV).[14]

Following letters received from two stakeholders, the Expert Panel has formally asked CNMC – the Spanish National Regulatory Authority – to clarify whether the 420 – 435 kV range is only applicable in case of a contingency situation. CNMC responded as follows:

> P.O.1.1 "Performance and safety criteria for the operation of the electrical system" sets the security criteria that must be applied in the operation of the Spanish peninsular electrical system and stablish the limits for contingency situations. This procedure does not set specific voltage limits in normal operation. It refers to local (zonal) procedures that will collect nodal values determined according to the criteria established by PO1.3 "Establishment of permissible voltages at nodes in the network managed by the system operator".
>
> The operational procedure P.O. 1.4 "Energy delivery conditions at the border points of the network managed by the system operator" was passed simultaneously as the P.O. 1.3. This procedure P.O. 1.4 sets that under normal operating conditions, the voltage at the 400 kV level at the border points will range from 390 and 420 kV but eventually maximum levels of 435 kV may be reached. Any installation directly connected to the transmission network must be capable of withstanding these values without damage or disconnection.
>
> Therefore, although the 435 kV limit is consistent with the value regulated in operational procedure P.O.1.1 "Performance and safety criteria for the operation of the electrical system" for contingency situations, the P.O.1.4 does not only link the voltage level of 435 kV to these contingency situations, but to normal operating conditions. Hence 435 kV have to be considered in all type of operation and not only limited to contingency situations.
>
> In this regard, references in European regulations to the possibility that the Spanish TSO may operate the transmission grid at 435 kV (article 27.2 of Regulation (EU) 2017/1485, notwithstanding provisions under article 28) and may oblige generators subject to article 16.2.iii of Regulation (EU) 2016/631 to remain connected at the voltage level of 435 kV for an unlimited time, do not condition it to a contingency either."

In Portugal, voltage standards are defined in Procedure 5 of the "Manual de Procedimentos da Gestão Global do Sistema," where the upper voltage limit on the 400 kV grid is 420 kV. Note that ERSE has published a new version of the code after the 28 April 2025, with new internal numbering.

In terms of deviations from voltage standards reported in the past, RE reported thirteen scale 1 and thirteen scale 0 voltage violations in the 2024 ICS report[15] (related to 2023) and no voltage violations in the 2025 ICS report (related to 2024). REN did not report any voltage violations in 2023 and 2024.

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[14] In Spain, the following limits apply in accordance with the official Operational Procedure 1.4, §3.2 (fRE translation): *"Voltages at the nodes – Under normal operating conditions, the voltage at the 400 kV level at the connection nodes will be between 390 and 420 kV. At the 220 kV level, the voltage will be between 205 and 245 kV. Eventually, maximum values of up to 435 kV and minimum values of up to 375 kV may occur at the 400 kV level. At the 220 kV level, voltages may eventually drop to 200 kV. Any installation directly connected to the transmission network must be able to withstand the above values without damage or disconnection."*

[15] **https://www.entsoe.eu/network_codes/sys-ops/annual-reports/**

2.6.2 Voltage Profiles

2.6.2.1 Voltage Profiles in Spain

In this section, voltage evolution is analysed from 09:00 to 12:32. From 09:00, with the appearance of PV generation in the system, voltage variability increases, albeit without significant excursions. From 10:30, greater excursions are observed. The higher (red lines, 420/245 kV and 435 kV) and lower (green line, 390/205 kV and 375/200 kV) voltage limits mentioned in the Spanish Operational Procedure 1.4[16] from 1998 are shown in Figures 2-70 and 2-71 (based on data from the Red Electrica SCADA system).

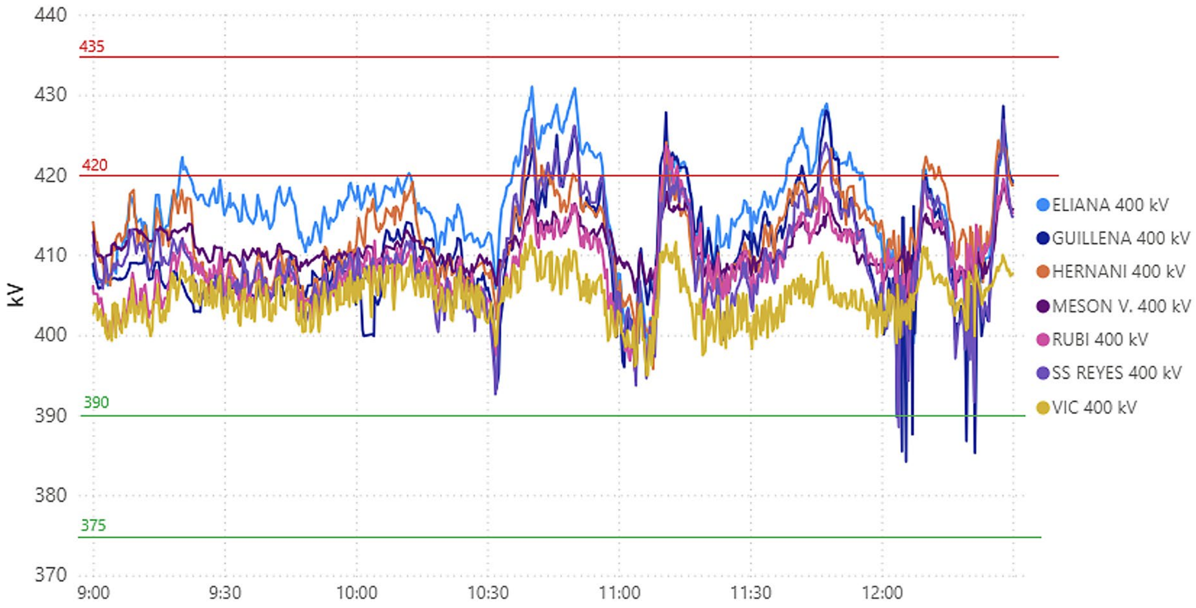

Figure 2-70: Voltage evolution at the main 400 kV transmission substations (pilot nodes) in Spain

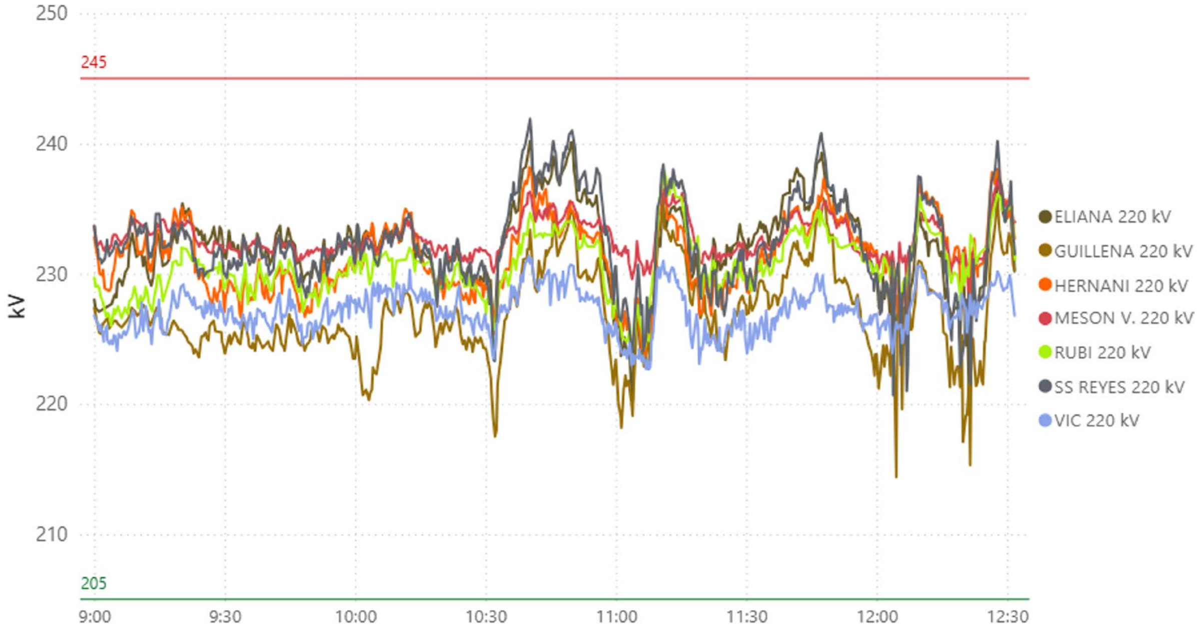

Figure 2-71: Voltage evolution at the main 220 kV transmission substations (pilot nodes) in Spain

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[16] https://www.boe.es/buscar/doc.php?id=BOE-A-1998-20053

In the following, the voltage profile evolution of the main transmission substations are aggregated by area.

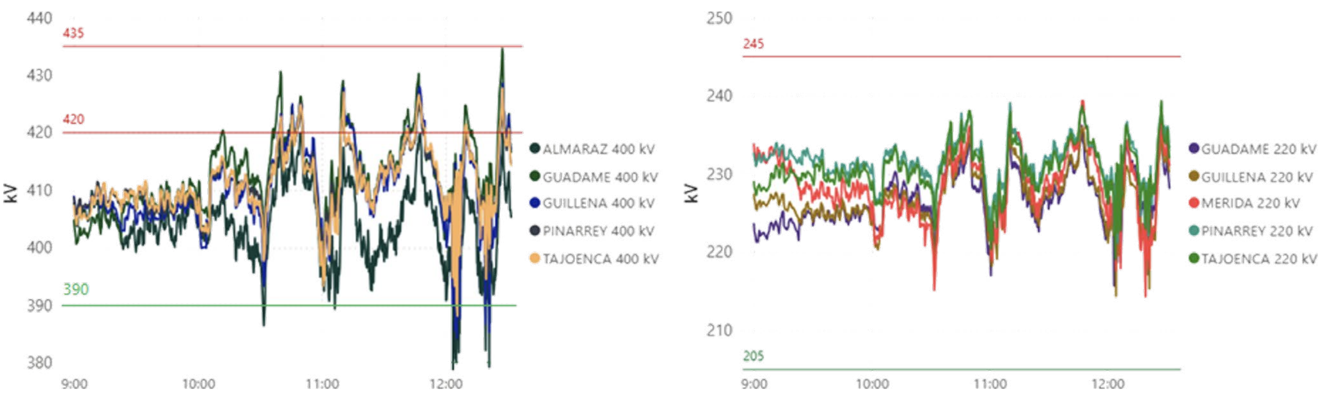

Figure 2-72: Voltage evolution at the main transmission substations (pilot nodes) in the south of Spain

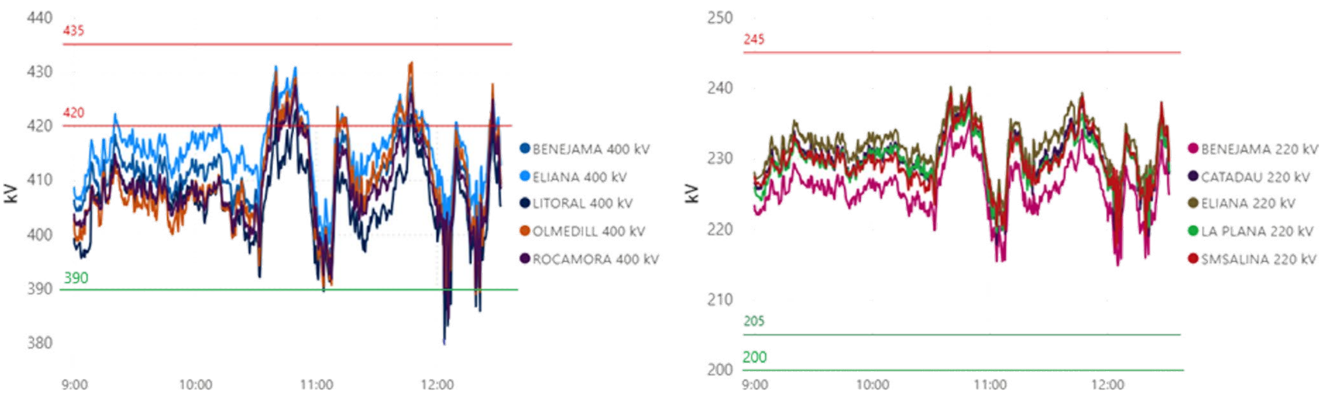

Figure 2-73: Voltage evolution at the main transmission substations (pilot nodes) in the east of Spain

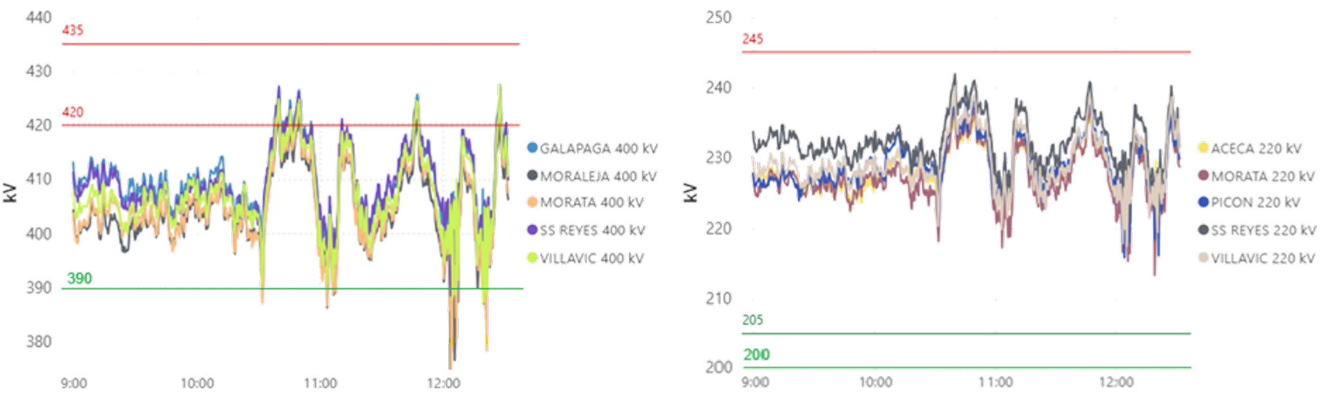

Figure 2-74: Voltage evolution at the main transmission substations (pilot nodes) in the centre of Spain

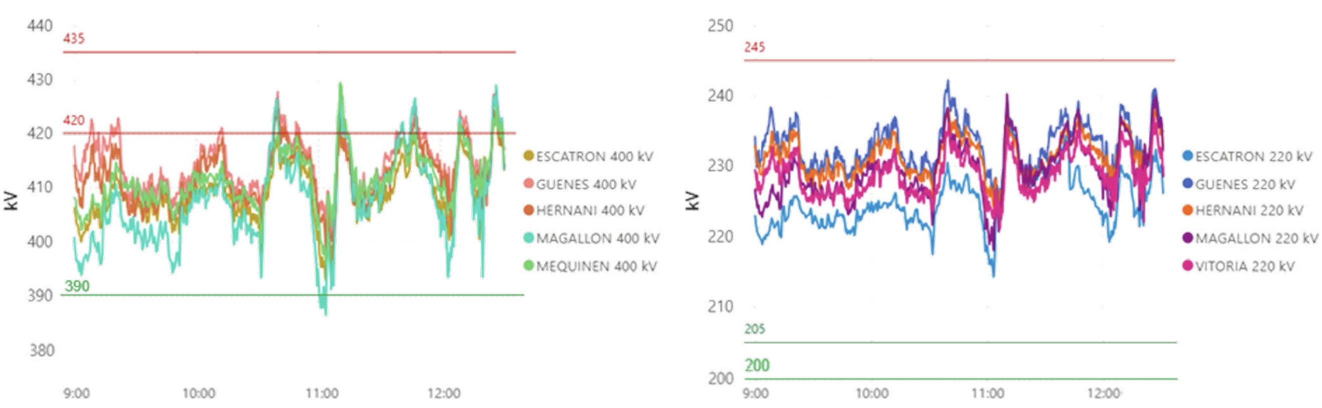

Figure 2-75: Voltage evolution at the main transmission substations (pilot nodes) in the north of Spain

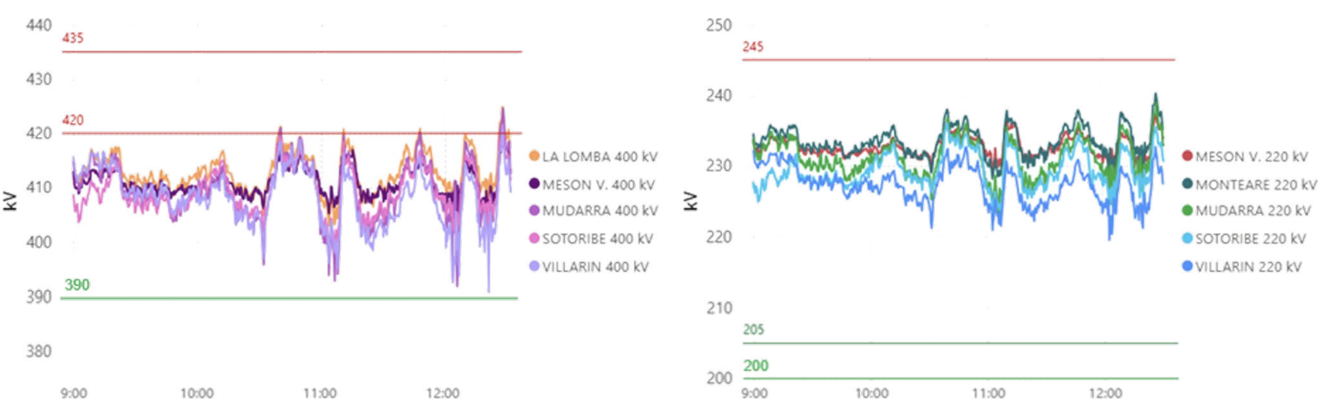

Figure 2-76: Voltage evolution at the main transmission substations (pilot nodes) in the northwest of Spain

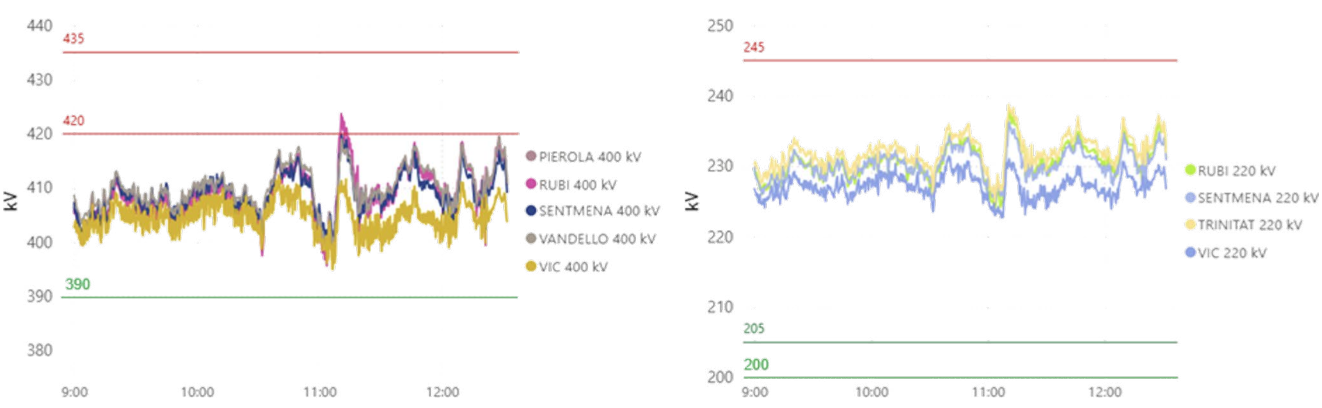

Figure 2-77: Voltage evolution at the main transmission substations (pilot nodes) in the northeast of Spain

In view of its final report, the Expert Panel will further analyse these voltage fluctuations and consider the voltage behaviour observed during the days preceding the blackout.

2.6.2.2 Voltage Profiles in Portugal

In this section, the evolution of voltage in the REN grid is analysed from 09:00 to 12:30 in the substations equipped with available PMU, namely Sines Substation (SSN) and Recarei Substation (SRR). The voltage level is within the nominal values for the observed timeframe.

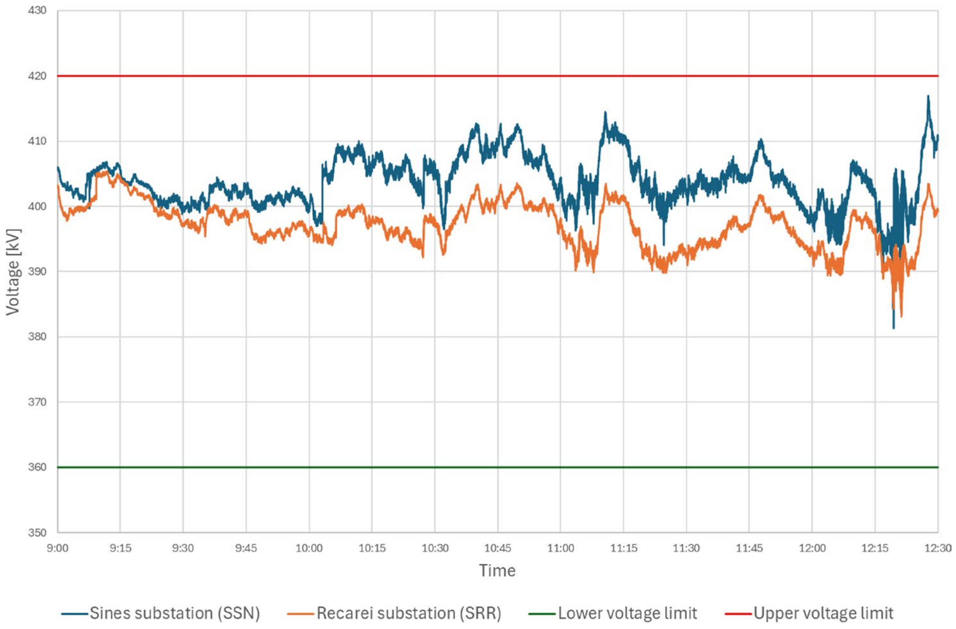

Figure 2-78: Voltage measurements at Sines and Recarei substations (Portugal)

2.6.2.3 Voltage Profiles in France

In this section, the evolution of voltage in the RTE grid is analysed from 09:00 to 12:30 at the Baixas and Saucats substations (southern part of France). The voltage level is within the nominal values for the observed timeframe.

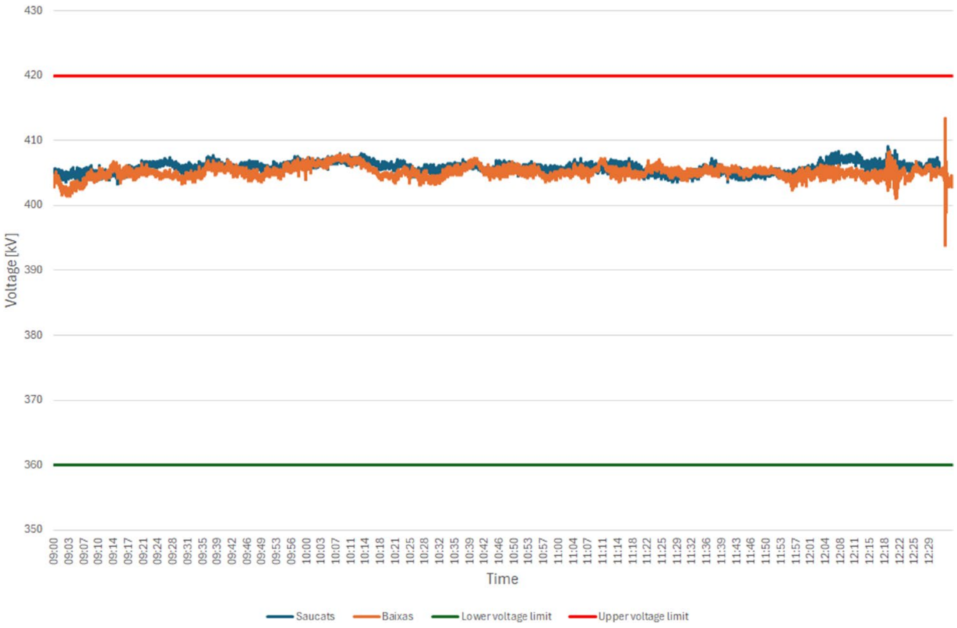

Figure 2-79: Voltage measurements at Baixas and Saucats substations (France)

2.6.3 Voltage Heatmaps of the Iberian Peninsula

In this section, the voltage heatmaps of the Iberian Peninsula are depicted every fifteen minutes from 9:00 to 12:30.

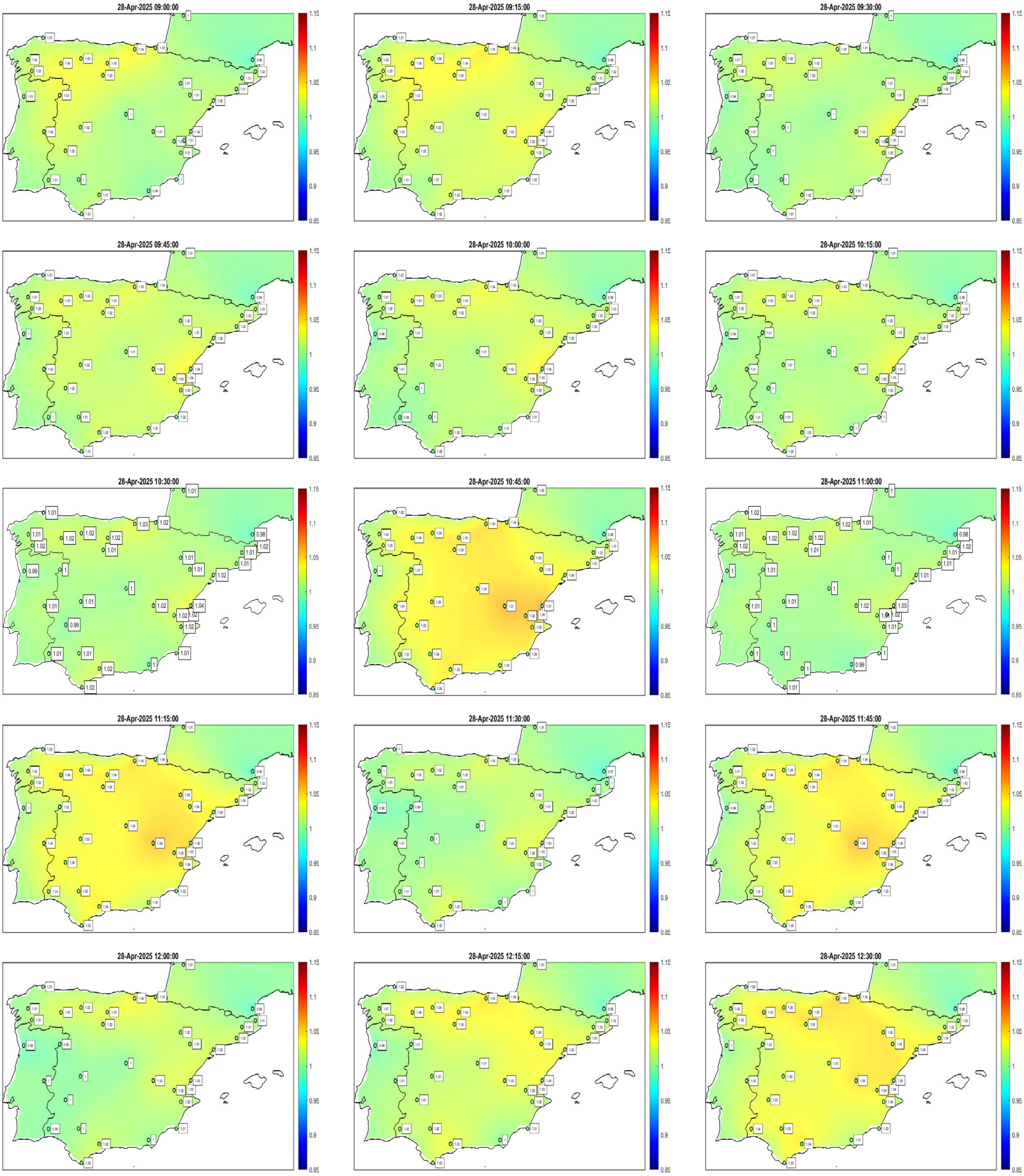

Figure 2-80: Voltage heatmaps of the Iberian Peninsula

2.6.4 Chronology of Voltage Control Actions

2.6.4.1 RE Shunt Reactors, Capacitors, STATCOMs, and HVDC Patterns

The shunt reactors connected to the 400 kV network of Red Electrica have 150 Mvar of reactive power capacity, and the shunt reactors/condensers connected to the 220 kV network have 100 Mvar of reactive power capacity. The shunt reactors are three-phase.

Section 2.1.2 details the effect of connecting shunt reactors and the chronology of the voltage control remedial actions. The example in Figure 2-81 shows the impact of connecting the shunt reactor in the Morata 400 kV substation at 12:28:01, showing the reactive power flow and voltage.

A summary of the shunt reactors and condensers operated by RE is provided in Table 2-7 below, together with the nominal power, location, and position at 12:32:00.

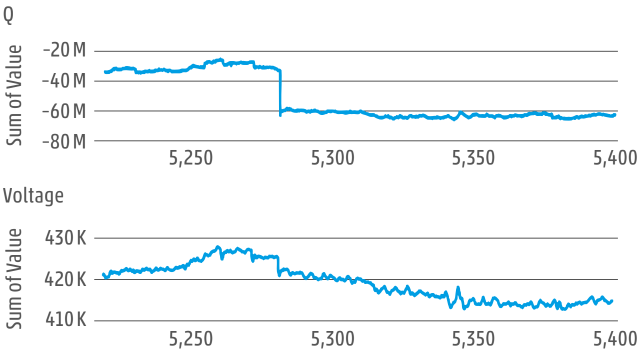

Figure 2-81: Reactive power flow and voltage at PMU MOR4MOT from 12:27:00 to 12:30:00

SHUNT REACTORS and CAPACITORS	Nominal power (Mvar)	Location	Position at 12:32:00
ALMARAZ 400 REA 3	150	SOUTH	Disconnected
ANCHUELO REA 1	150	CENTRE	Disconnected
ARAGON 400 REA 1	150	NORTH	Disconnected
ARANUELO 400 REA 1	150	SOUTH	Disconnected
BEGUES 400 REA 1	150	NORTH-EAST	Disconnected
BELINCHON 400 REA 1	150	EAST	Disconnected
BIENVENIDA 400 REA 1	150	SOUTH	Disconnected
BROVALES 400 REA 1	150	SOUTH	Disconnected
CABRA 400 REA 1	150	SOUTH	Disconnected
DRODRIGO400 REA 1	150	SOUTH	Disconnected
EALMARAZ 220 REA 1	100	SOUTH	Disconnected
ELIANA 220 REA 1	100	EAST	Connected
ESCATRON 220 REA 1	100	NORTH	Connected
GUADAME 220 REA 3	100	SOUTH	Connected
GUADAME 400 REA 2	150	SOUTH	Connected
GUILLENA 400 REA 2	150	SOUTH	Disconnected
JM.ORIOL 220 REA 1	100	SOUTH	Disconnected
JM.ORIOL 400 REA 2	150	SOUTH	Disconnected
JUIA 220 CONDEN1	150	NORTH-EAST	Disconnected
LA SERNA 400 REA 2	150	NORTH	Connected
LITORAL 400 REA 1	150	EAST	Disconnected
MAGALLON 400 REA 1	150	NORTH	Disconnected
MAGALLON 400 REA 2	150	NORTH	Disconnected
MAIALS 400 REA 1	150	NORTH-EAST	Connected
MINGLANILLA 400 REA 1	150	EAST	Connected
MORALEJA 220 REA 12	100	CENTRE	Connected
MORALEJA 220 REA 13	100	CENTRE	Disconnected
MORALEJA 400 REA 1	150	CENTRE	Disconnected
MORATA 400 REA 4	150	CENTRE	Connected
OLMEDILLA 400 REA 1	150	EAST	Disconnected
PALOS 220 REA 1	100	SOUTH	Disconnected
PEÑAFLOR 400 REA 1	150	NORTH	Connected
PINILLA 400 REA 1	150	EAST	Disconnected
REQUENA 400 REA 1	150	EAST	Disconnected
ROCAMORA 400 REA 1	150	EAST	Disconnected
RUBI 400 REA 1	150	NORTH-EAST	Connected
RUEDA 400 REA 2	150	NORTH	Disconnected
SENTMENAT 400 REA 1	150	NORTH-EAST	Connected
SS REYES 400 REA 3	150	CENTRE	Disconnected
VALDECAB 400 REA 1	150	SOUTH	Disconnected
VALDECABALLEROS 400 REA 2	150	SOUTH	Disconnected
VILLAVICIOSA 220 REA 2	100	CENTRE	Disconnected
VILLAVICIOSA 400 REA 1	150	CENTRE	Disconnected
VITORIA 400 REA 2	150	NORTH	Connected

Table 2-7: Main characteristics and status of shunt reactors in RE network

2.6.4.2 REN Shunt Reactor Patterns

In this section, the main characteristics related to shunt reactors of REN are described. The shunt reactors are three-phase.

Substation	Site ID	SR ID	Voltage Level kV	Nominal Power Mvar	Position at 12:32:00
ARMAMAR	SAMM	R1	400 kV	150	Disconnected
CASTELO BRANCO	SCC	R1	220 kV	70	Disconnected
FANHÕES	SFN	R1	400 kV	150	Disconnected
FEIRA	SFRA	R1	400 kV	150	Disconnected
PEDRALVA	SPDV	R1	400 kV	150	Disconnected
PARAIMO	SPI	R1	400 kV	150	Disconnected
PALMELA	SPM	R2	400 kV	150	Disconnected
PORTIMÃO	SPO	R1	400 kV	150	Disconnected
RIO MAIOR	SRM	R1	400 kV	150	Connected
TÁBUA	STBA	R1	220 kV	70	Connected
TAVIRA	STVR	R1	150 kV	75	Connected

Table 2-8: Main characteristics of the shunt reactors in REN data

Section 2.1.2 details the chronology of manoeuvres of shunt reactors by REN. The shunt reactors were gradually disconnected by the control room operator as a normal operation during the observed timeframe, and at 12:19, the Palmela shunt reactor tripped due to undervoltage (the registered voltage value was 379.80 kV, and the protection setting was U = 380 kV and t = 2 s). After the system collapse at 12:33:30, the three remaining shunt reactors of Tabua, Tavira, and Rio Maior were also disconnected. Figure 2-82 depicts the gradual decrease in the amount of inductive reactive power provided by REN's shunt reactors.

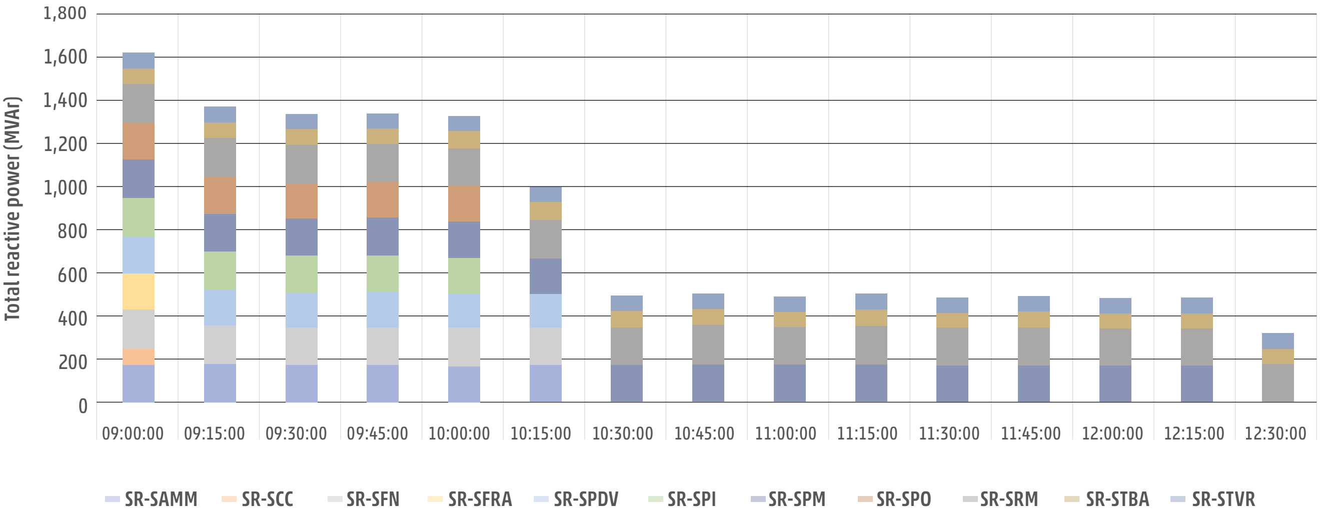

Figure 2-82: Trend of the total reactive power of the shunt reactors in the REN grid

2.6.5 Voltage Regulation Schemes

2.6.5.1 Voltage Regulation Scheme in Spain

In Spain, the voltage regulation at the time of the blackout was governed by the Operating Procedure 7.4[17] from March 2000, which was subsequently **amended** in June 2025.

Operating Procedure (P.O.) 7.4[18] "Ancillary Voltage Control Service of the Transmission Network" applies to conventional generators with an installed capacity equal to or greater than 30 MW connected to buses of the transmission network, transmission operator, consumers connected to the transmission grid with a contracted power equal to or greater than 15 MW, and DSOs.

Below, some literal extracts from Operational Procedure 7.4 are included:

*"**3. Definition***

Voltage control consists of a set of actions involving resources for the generation and absorption of reactive power (generators, reactors, capacitors, etc.) and other voltage control elements, such as transformers with tap changers. These actions are aimed at maintaining voltage levels at the nodes of the transmission network within specified margins to ensure compliance with safety and quality criteria for electricity supply."

*"**4. Service providers***

The service providers shall be:

- *a) All generating units operating under the ordinary regime, with a registered net capacity equal to or greater than 30 MW and directly connected, or connected through a dedicated evacuation line, to nodes of the transmission network. […]*
- *b) Transmission companies.*
- *c) Qualified consumers not covered by a tariff (1), directly connected or connected through a dedicated line to nodes of the transmission network (hereinafter referred to as "service-providing consumers"), with a contracted power equal to or greater than 15 MW.*
- *d) Distribution System Operators […]"*

*"**6. Service provision***

[…]

6.1 Mandatory Requirements

As a technical condition for connection to the transmission network, and to ensure proper operation and system security, providers of this ancillary service must deliver the following minimum services:

6.1.1 Generators

Generators must have a mandatory minimum margin of reactive power capacity, both for generation and absorption, to provide the service. They must adjust their reactive power production and absorption within these limits to help maintain voltage levels at the plant busbars within the variation margins defined by the voltage setpoint and the acceptable variation band established by the System Operator.

For generators, the required minimum reactive power margin at plant busbars at nominal transmission network voltage is defined based on the installed net active power, as recorded in the Administrative Register of Electricity Production Facilities, and the following power factor values:

- a) Capacitive power factor (cos φ) of 0.989 (reactive power generation equivalent to 15 % of maximum net active power).
- b) Inductive power factor (cos φ) of 0.989 (reactive power absorption equivalent to 15 % of maximum net active power).

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[17] Not public

[18] https://www.boe.es/buscar/doc.php?id=BOE-A-2000-5204

This reactive power generation/absorption margin must be deliverable by the unit across the entire range of active power variation, from its technical minimum to its maximum net active power.

These requirements will vary depending on the voltage value at the corresponding node of the transmission network, according to the linear function graphically shown in Annex 6 […]."

"*10. Measurement and Monitoring of Service Compliance*

To monitor compliance with the service, the System Operator will use telemetry data received through the CECOEL real-time energy control system. […]

10.1 Generators

The System Operator will perform sampling every five minutes of the voltage values at the control node and the active and reactive power generated/absorbed by the unit at the plant busbars.

To assess service compliance, an acceptable deviation band of ±2.5 kV around the voltage setpoint established by the System Operator for the control node is defined.

The service will be considered properly delivered when at least 75 % of the sampled values within each hour meet one of the following two conditions:

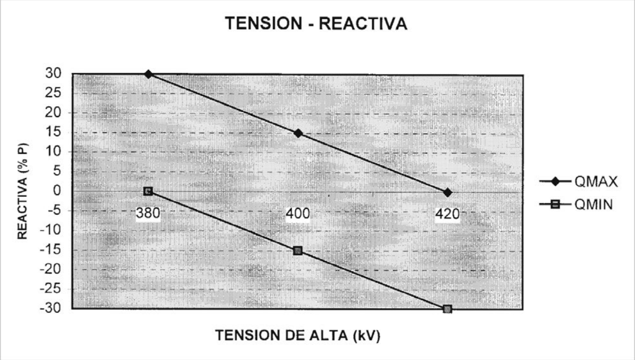
a) *The voltage at the control node assigned to the unit remains within the acceptable variation margins.*
b) *The unit has reached the mandatory reactive power limit or, where applicable, the mandatory limit plus the additional assigned resources, in the appropriate direction.*

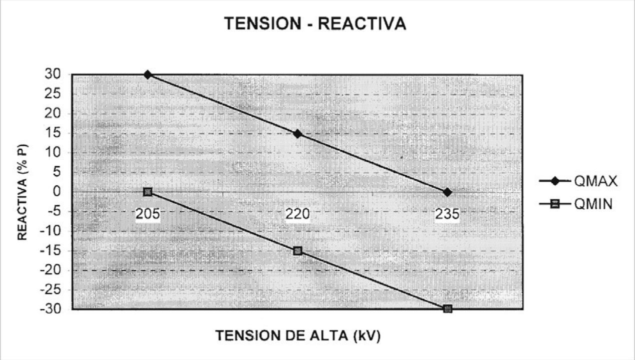
To verify this, it will be checked that the voltage telemetry from the control node – or, if unavailable, the values resulting from state estimation – are within the acceptable band (±2.5 kV around the voltage setpoint established by the System Operator for the control node) in at least 75 % of the sampled values within each hour. If so, the service will be considered properly delivered.

If the voltage has been outside the acceptable band in more than 25 % of the sampled values during the hour, the active and reactive power values at the plant busbars will be analysed. For each set of active power and busbar voltage values, the reactive power limit that the unit should have delivered or absorbed in that situation will be determined, taking into account both the mandatory minimum requirements and, where applicable, the additional assigned resources.

In this latter case, even if the voltage setpoint for the corresponding control node (plant busbars) was not met, as long as the unit has reached the corresponding reactive power limit (mandatory requirements + assigned additional resources) in that situation, in at least 75 % of the samples taken during each hour in which the voltage was out of limits, the service will be considered properly delivered. […]"

ANNEX 6: Variation of Mandatory Requirements for Units Based on the Voltage of the Node of the Transmission Network





Following a presentation shared by a stakeholder, the Expert Panel formally asked CNMC – the Spanish National Regulatory Authority – to explain the figure above ("Annex 6"). More specifically, the Expert Panel asked which of the following two options is correct:

- » Option 1
  - <405 kV: Q has to be at least Qmax (Qmax as minimum generation of reactive power).
  - 405 – 410 kV: No requirement.
  - >410 kV: Q has to be at least Qmin (Qmin as minimum absorption of reactive power).
- » Option 2
  - Q has to be within the range of Qmin and Qmax.

CNMC responded as follows:

"OP 7.4 defines a minimum mandatory capability of reactive power control expressed as a margin both in generation and absorption for the provision of the service. Generators must be able to modify their production and absorption of reactive power within these limits (Qmax, Qmin), so that they contribute to maintain the voltage within the variation margins defined by the voltage setpoint value (400 kV) and the permissible variation band around it established by the System Operator (405 – 410 kV).

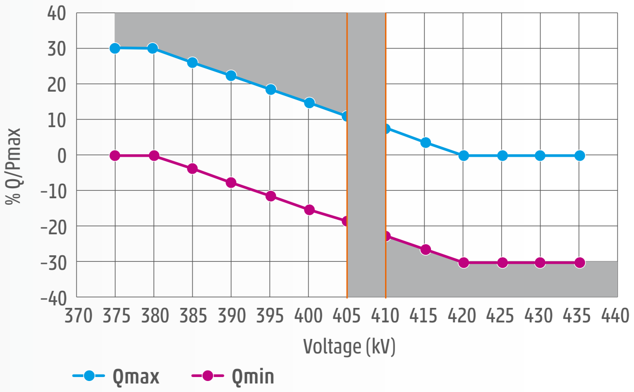
The terms of the service provision are complemented in article 10 of P.O. 7.4. According to article 10.1 of the P.O. 7.4, the service is considered to have been provided adequately if at least 75 % of the values sampled each hour meet one of these two conditions:

a) The voltage is maintained within the permissible variation margins (405 – 410 kV for the voltage level of 400 kV).

b) The group has reached the mandatory reactive power limit or, where applicable, the mandatory limit plus the additional limit assigned, in the appropriate direction.

Based on the above, for an adecuate compliance with the requirements of the service, when the voltage level is under 405 kV generators must generate a reactive power of at least the generation limit of its reactive capacity (the appropiate direction in this case), when the voltage level is over 410 kV they must absorb at least the absorption limit of its reactive capacity (the appropiate direction in this case), and there is no special requeriment of reactive power when the level voltage is between 405 – 410 kV.

Grey area in the figure below shows the right area, that is, Option 1 in your question, without prejudice that compliance allows a time margin of 25 % outside that area."



Document: “Voltage Setpoints in the Transmission Network” (PCT-0-006: submitted to voltage control service providers in December 2011):

Below some literal extracts from PCT-0-006 are included:

“ANNEX 2:

The purpose of this document is to publish the voltage setpoints applicable for the provision of the Voltage Control Service on the transmission network, which will be in effect from January 1, 2012, until further notice from Red Eléctrica.

GENERAL SETPOINTS

The voltage setpoints to be used as reference[19] *during the different peak, flat, and off-peak periods are as follows:”*

400 kV		
PEAK	**FLAT**	**OFF-PEAK**
405 - 410	405 - 410	405 - 410

220 kV		
PEAK	**FLAT**	**OFF-PEAK**
225 - 230	225 - 230	225 - 230

[...]”

Royal Decree 413/2014 *applies to electricity generation facilities using renewable energy sources, cogeneration, and waste-to-energy (RCR). Section 7 of the regulation establishes the following mandatory voltage control requirements:*

1. *Facilities must maintain a power factor within the range of 0.98 inductive to 0.98 capacitive on an hourly basis. Accordingly, they must inject or withdraw reactive power depending on their active power output within this range, which can be modified annually by resolution of the Secretary of State for Energy, upon proposal by the TSO according to system needs*[20].
2. *Facilities with an installed capacity equal to or greater than 5 MW must follow the instructions issued by the TSO to adjust their power factor within the established range, based on system requirements. The TSO gives inductive power factor instructions by email to these facilities so that they absorb as much reactive power as possible, respecting the maximum inductive limit of 0.98 set by the Royal Decree, which corresponds to 20 % reactive power relative to the active power generated. The TSO can update its instructions when necessary and requests the facility owner to implement the change within a few days.*
3. *In cases where the facility is connected to the distribution network, any modification to the power factor range must take into account the limitations that might be established by the distribution system operator for the safety of its network. For this purpose, the distribution network operator may propose specific instructions to the TSO that must be considered.*

It is worth noting that Royal Decree 413/2014 includes a penalty of 0.261 c€/kWh (2.61 €/MWh) for non-compliance with the hourly obligations established for RCR generators.

Article 9, Section 5 of **CNMC Circular 3/2020** *– which establishes the methodology for calculating electricity transmission and distribution tariffs – includes a billing term for reactive energy applicable to all consumers, except those connected at low voltage with a contracted power of 15 kW or less.*

The reactive power billing term applies to all time periods except period 6, provided that reactive energy consumption exceeds 33 % of active energy consumption during the billing period (i.e., power factor ≤ 0.95) and only affects such excesses. During period 6, consumers must maintain a power factor greater than 0.98 capacitive, although no penalty is currently associated with non-compliance for this period.

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[19] There is a specific setpoint applicable to Sabón and Meirama.

[20] This has never happened

2.6.5.2 Voltage Regulation Scheme in Portugal

The voltage regulation in the Portuguese transmission system is nodal.

Reactive power compensation and voltage control are provided by synchronous generation (hydro and thermal) and pumping hydro power plants. The setpoints are communicated by phone by the TSO.

The old wind power plants provide reactive power compensation (predefined tan(φ) between −0.2 and 0.2, which that means the ratio between reactive and active power outputs is predefined).

Solar power plants with an installed capacity larger than 1 MW (as do new wind power plants) provide automatic voltage/reactive power control, receiving real-time setpoints sent by REN's SCADA for voltage control or reactive control (the voltage control setpoint is the most commonly used). Note that service is provided during the daylight period and in night operation mode.

REN uses the measure of the connection point of the power plant as a reference. The power plants have a closed-loop voltage regulation on the high voltage side.

2.6.5.3 Voltage Regulation Scheme in France

Figure 2-83 provides an overview of the voltage regulation system in France. The reactive power requirement of each control zone – calculated by the secondary voltage regulator (SVR) – is expressed as a per-unit value K, ranging from −1 to +1. This value is transmitted from the control centre to the local regulating units. The communication delay of approximately ten seconds is determined by the SCADA system's sampling rate.

In accordance with French grid connection requirements, all generation units with an installed capacity above 50 MW are mandated (with remuneration) to participate in the SVR scheme. This ensures a broad and distributed contribution to voltage regulation across the transmission network.

At the unit level, a reactive power control loop (RPCL) receives the K value from the SVR and computes a voltage reference Usref (t), which is then sent to the automatic voltage regulator (AVR). The RPCL can be modelled as a proportional-integral (PI) controller, which regulates the generator's terminal reactive power output Qs(t) to follow a time-varying reference Qcs(t), defined as:

$$Q_{cs}(\mathrm{t}) = K(\mathrm{t}) \times Q_{\mathrm{r}}(\mathrm{t})$$

Here, Qr(t) represents the unit's maximum reactive power capability (either injection or absorption) at a given time, acting as a participation factor.

For thermal units, Qr is typically considered constant and proportional to the nominal reactive power of the alternator (e.g., Qr = 1.4 × Qnom). However, in practice, the actual reactive power capability can vary depending on the unit's operating conditions, such as terminal voltage and active power output. This discrepancy can lead to situations where the reactive power output Qs(t) does not reach the theoretical maximum even when K = ±1, due to physical limitations such as rotor current or internal angle constraints.

In terms of dynamic response, each control block in Figure 2-83 operates on a different time scale:

- The AVR is the fastest, with a response time in the order of seconds.
- The RPCL follows, with a typical response time of approximately 10 seconds.
- The SVR is the slowest, with a response time on the order of 100 seconds.

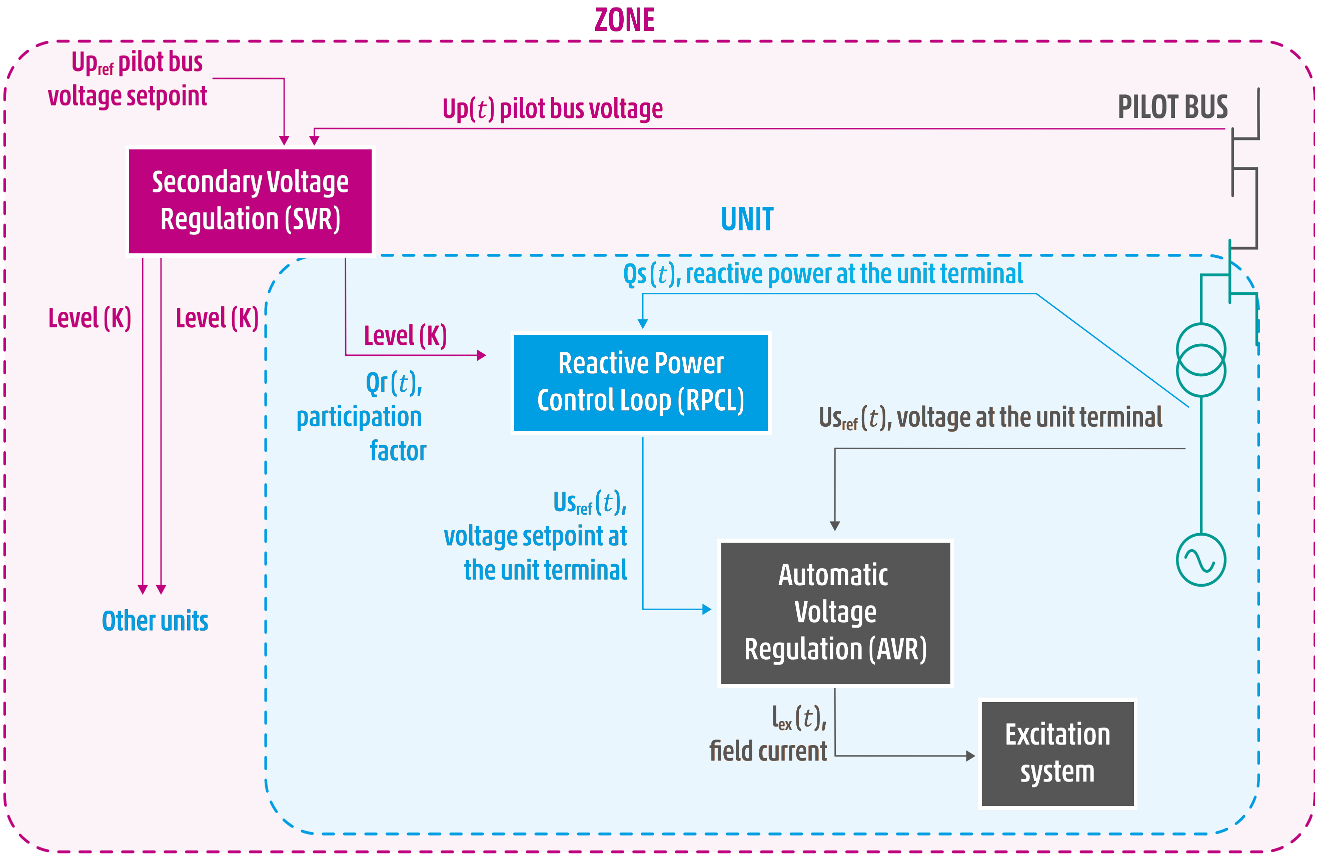

Figure 2-83: SVR principle diagram

2.6.5.4 Voltage Regulation by the HVDC Baixas Santa Llogaia

See Section 2.7.

2.6.6 Aggregated Data from Power Plants Connected to the Spanish Transmission Network

Figures 2-84 – 2-88 show per region, the aggregation of the reactive power provided by all conventional generation units with an installed capacity larger than 100 MW (Q)[21], as well as the aggregation of their reference reactive power (Qreference), where Qreference corresponds to the minimum reactive power that a generation unit must generate or absorb, based on CNMC's explanation of Operating Procedure 7.4 applicable at the time of the incident (see Section 2.6.5.1), without prejudice to the fact that it is permissible for each unit not to comply with this requirement up to 25 % of the time per hour.

In view of its final report, the Expert Panel will further analyse these data and consider the reactive power behaviour observed in the past, as well as the measures taken following these observations.

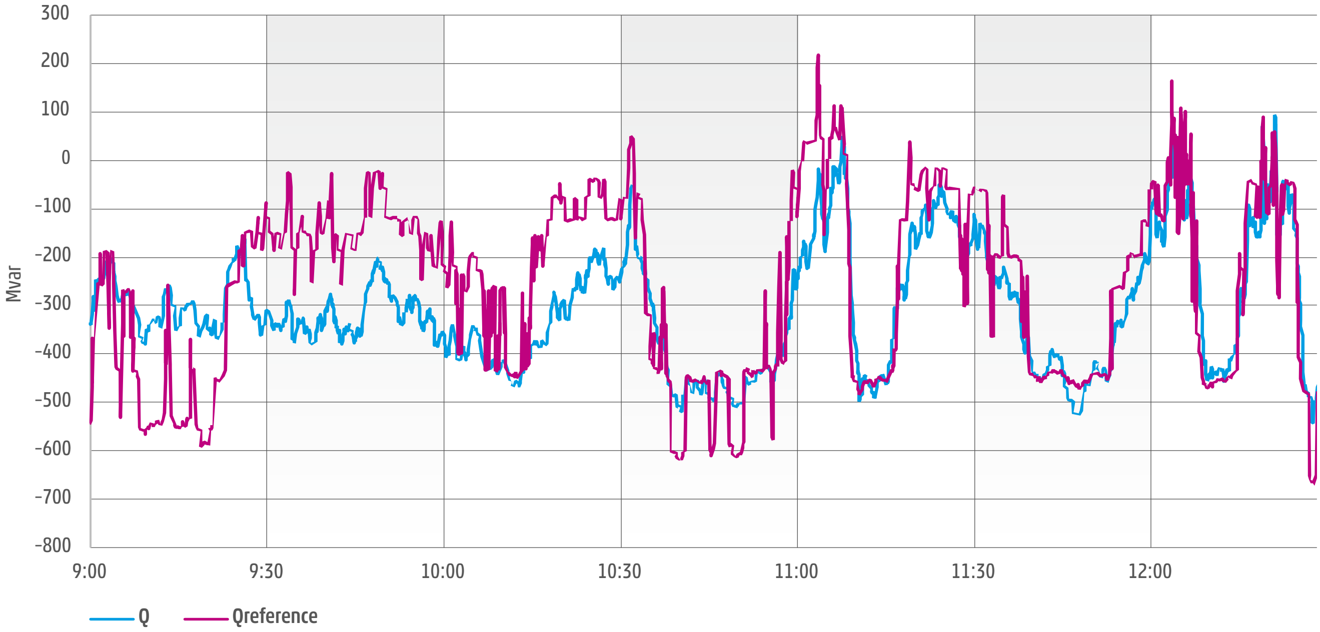

Figure 2-84: Reactive power provided (Q) and the reference reactive power (Qreference) aggregated for conventional generation units larger than 100 MW of power installed capacity in the north/north-west area of Spain

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[21] The reactive power provided by each generation unit is measured by the TSO with a time interval that varies from 4 to 20 seconds between two measurements. To build the curves Q in these graphs, a linear interpolation has been undertaken between two consecutive measurements.

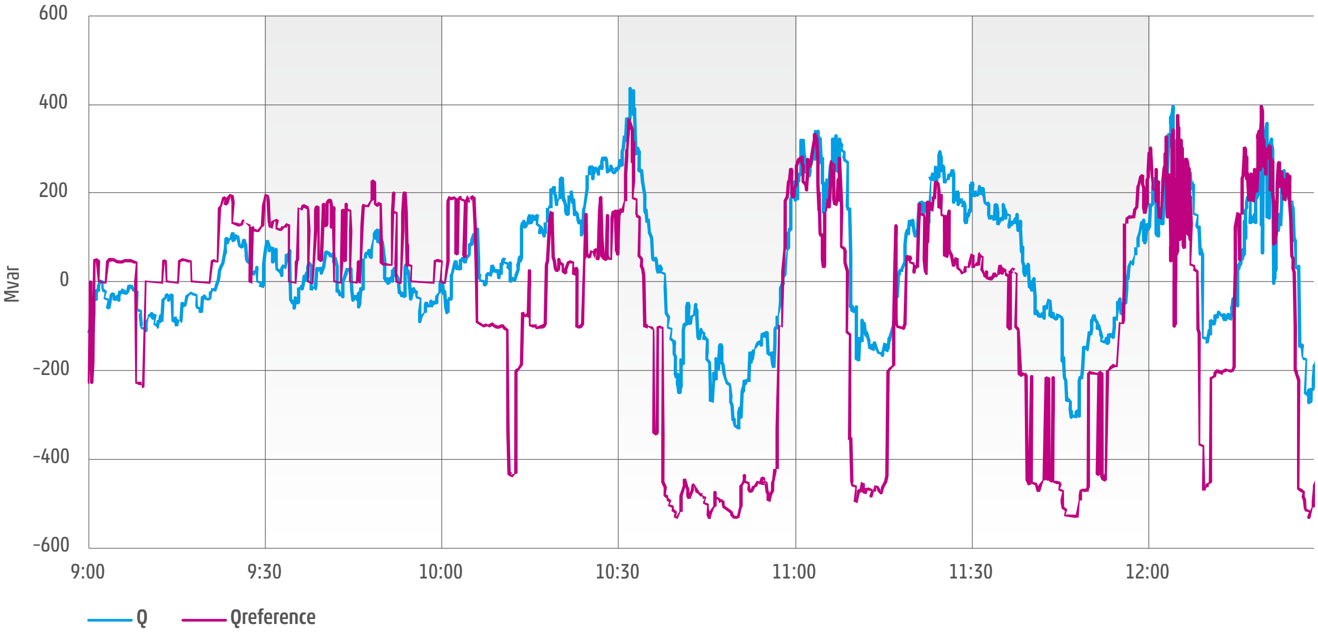

Figure 2-85: Reactive power provided (Q) and the reference reactive power (Qreference) aggregated for conventional generation units larger than 100 MW of power installed capacity in the centre/south-west area of Spain

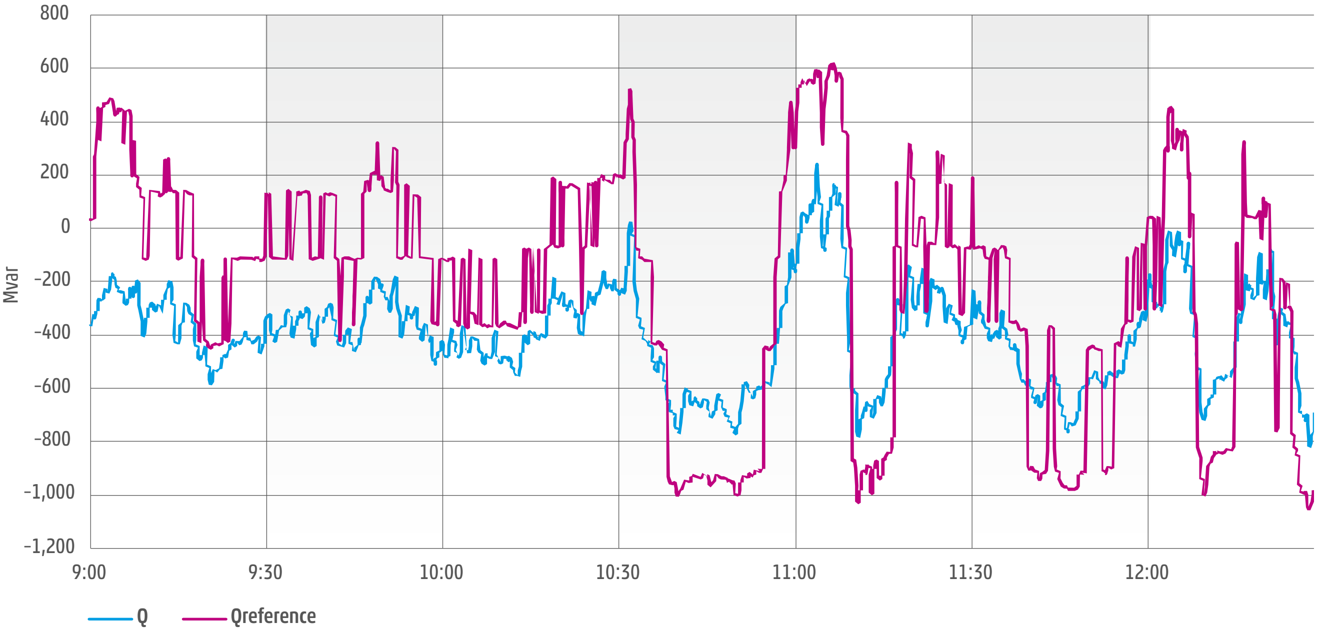

Figure 2-86: Reactive power provided (Q) and the reference reactive power (Qreference) aggregated for conventional generation units larger than 100 MW of power installed capacity in the east/north-east area of Spain

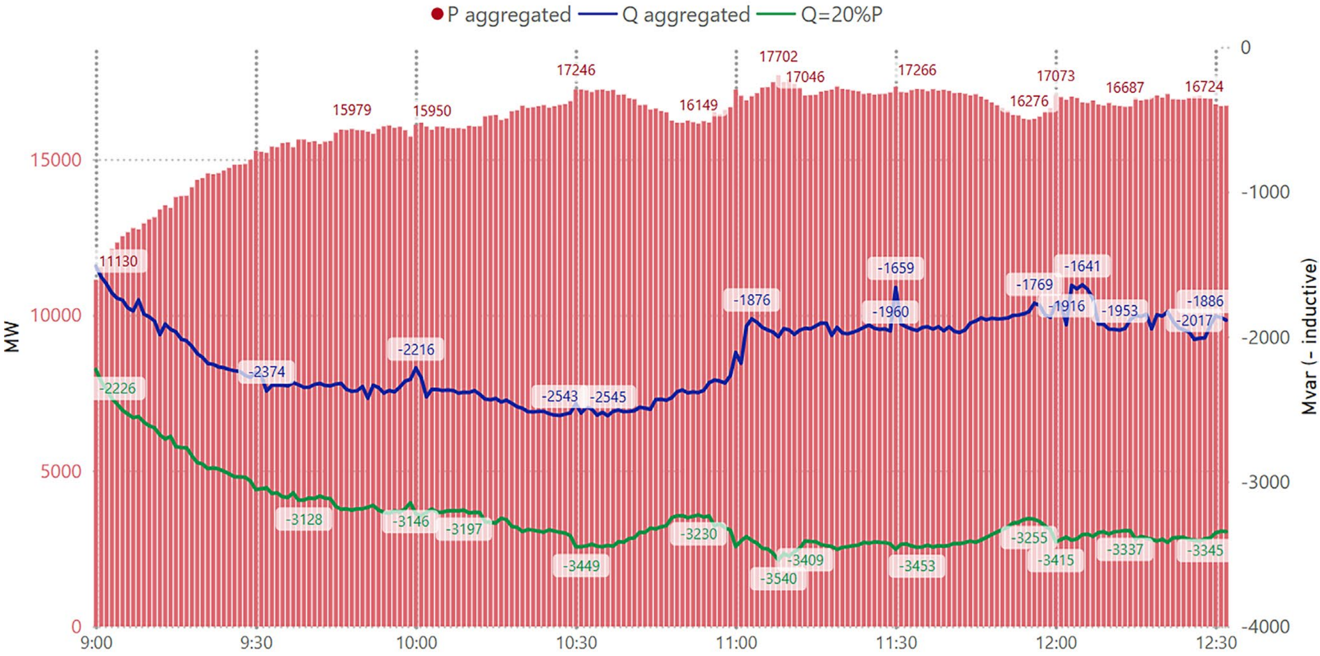

Figure 2-87: Aggregated P and Q of PV generation (facilities or aggregations with installed capacity >1 MW). The green line corresponds to a 0.98 inductive power factor, which is the lowest limit of the generic range defined by the RD 413/2014.

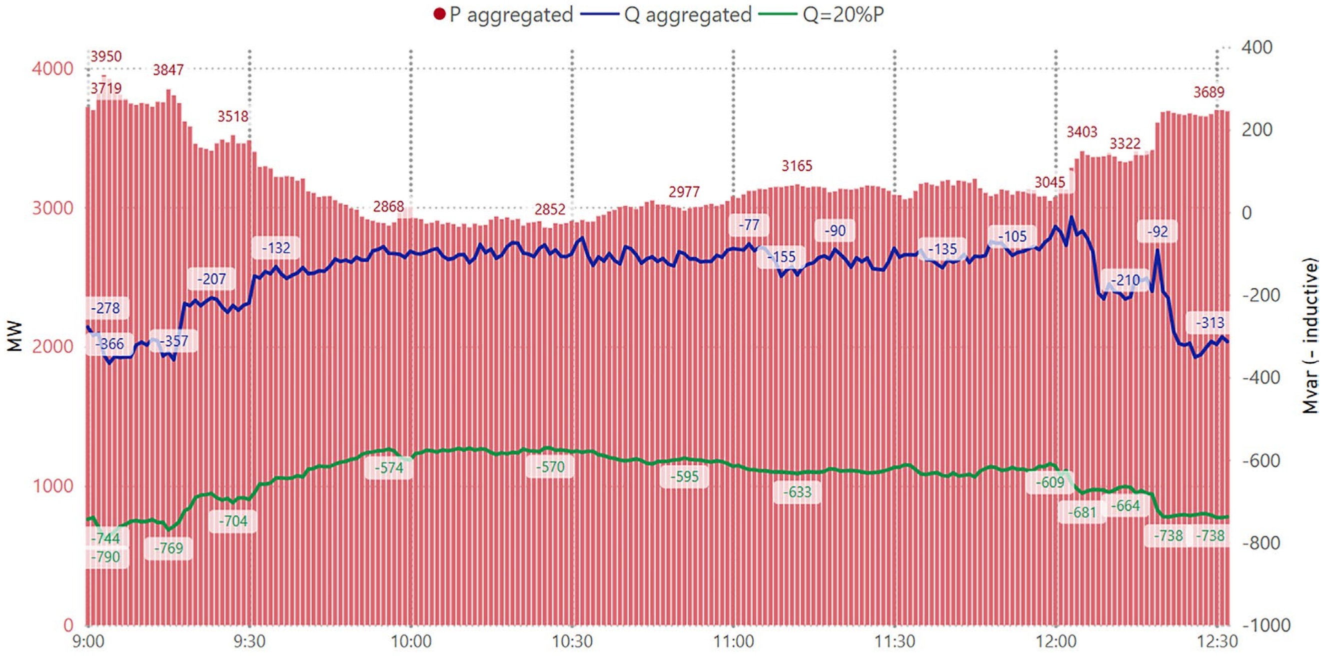

Figure 2-88: Aggregated P and Q of wind generation (facilities or aggregations with installed capacity >1 MW). The green line corresponds to a 0.98 inductive power factor, which is the lowest limit of the generic range defined by the RD 413/2014.

2.6.7 Data from Relevant Power Plants Connected to the Portuguese Transmission NetworkA

Figure 2-89 shows the aggregation of the reactive power provided by relevant generating power plants with a power installed capacity of more than 100 MW in the south area of Portugal, as well as the aggregation of their reference reactive power.

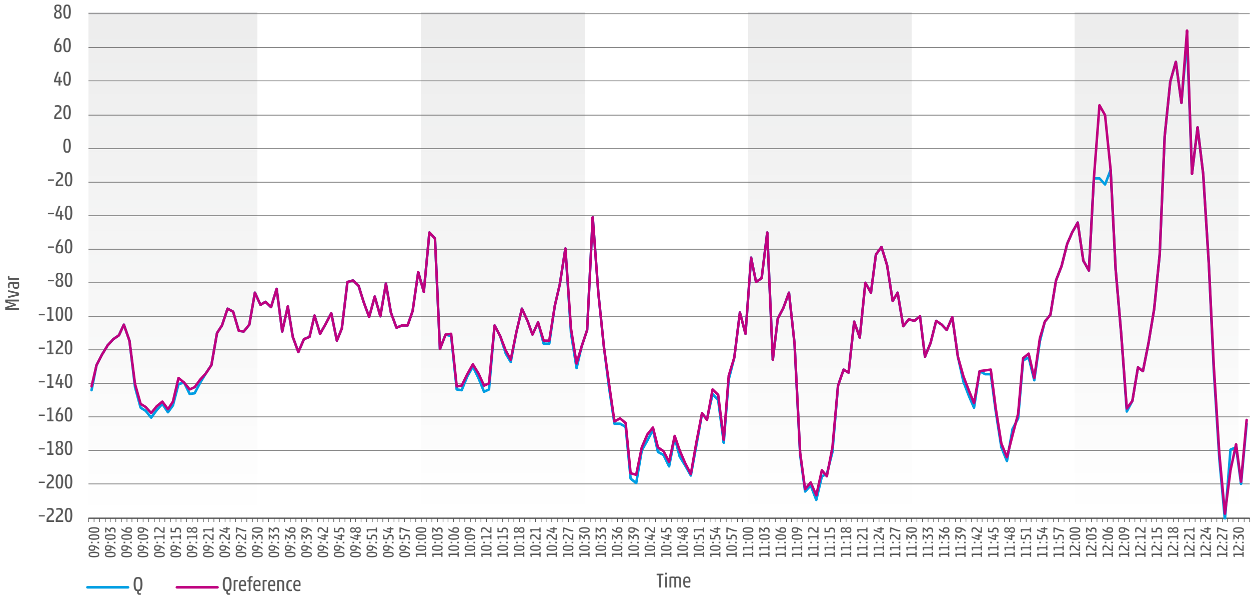

Figure 2-89: Provided reactive power (Q) and reference reactive power (Qreference) for generating relevant power plants with more than 100 MW of power installed capacity in the south area of Portugal (REN's SCADA measurements)

2.6.8 Technical Constraints in Spain

The technical constraints solving process in Spain is described in Operational Procedure 3.2 "Technical restrictions" (the latest amendment was published on 17 March 2025 and includes adjustments for a fifteen-minute market timeframe). This process has two differentiated parts, one of which is undertaken after the day-ahead market gate closure time, and another is performed continuously in real time to solve remaining issues. The objective is to guarantee security with the minimum and more economical number of changes to the results that come out of the daily market This process allows the Spanish TSO to introduce any change that it considers justified to guarantee the security of supply in the scheduling of the generation and storage units (and consumers on voluntary bases), connected to both transmission and distribution networks, including the dispatch of any power plant not scheduled by the market but needed by the system to provide services such as voltage control or balancing. Needs for maintaining security in distribution are assessed and communicated to the TSO by the DSO. The process has two differentiated parts: one of them taken care after the day ahead market, with the aim of guaranteeing the physical feasibility of the economic dispatch of the market, and another one under continuous bases to solve any constraint found in real-time operation. The TSO must choose the group of actions that solves the security issues (mainly congestion and voltages out of range) at the lowest possible cost. The cost of this process is daily transferred to the consumers (directly to consumers for those who buy directly in the wholesale market and through suppliers for the rest), in proportion to their consumption, as part of the cost of energy. However, the TSO is financially neutral and has no budget limit, so it has no direct economic impact if it reduces the costs.

After the D-1 results are published, situations such as unexpected unavailability or changes in the forecasts can occur that need to be solved in the real-time constraint resolution process. In general, this process implies continuous monitoring and adjustment, and it offers the advantage of less uncertainty due to being closer to real time.

Even if there was not a remunerated voltage control service in place, power plants scheduled by the TSO under PO3.2 to solve situations of lack of dynamic voltage control receive the technical constraints remuneration (pay as bid) for their active power redispatch. In security studies conducted on 27 April, for 28 April, the combined cycle "Thermal 4–Centre /South-West" was scheduled for the entire day to regulate voltage in Western Andalusia. At 19:52 on 27 April, the unit was declared unavailable due to an internal problem, initially until 22:00 on 27 April and later extended to 00:00 on 30 April.

The connection of "Thermal 5–Centre/South-West" was extended during the night to secure voltages. During the morning of 28 April, RE considered that the "Thermal 5–Centre/South-West" plant was not needed.

There is no operational procedure approved in Spain where a minimum number of generation units coupled is required, and there is also no maximum limit. The criterion to decide the coupling of an additional generation unit is the fulfilment of Operational Procedure 1.1 with foreseen scenarios (generation, demand, and network).

At 12:20 on 28 April, RE ordered the connection of an additional thermal power plant equipped with PSS, following the detection of system oscillations. The selected group was a combined-cycle gas plant in centre/south-west, which indicated that it could be connected in 90 minutes. At 12:26, the confirmation was issued to the power plant to connect at 14:00. Due to the blackout occurring before 14:00, this connection never occurred. In general, RE is aware of the start-up times of the combined-cycle gas plants in its control area.

2.6.9 Short Circuit Power

Figures 2-90 and 2-91 plot the calculated short circuit power over time, demonstrating that most trends appear to be uniform during the observed timeframe.

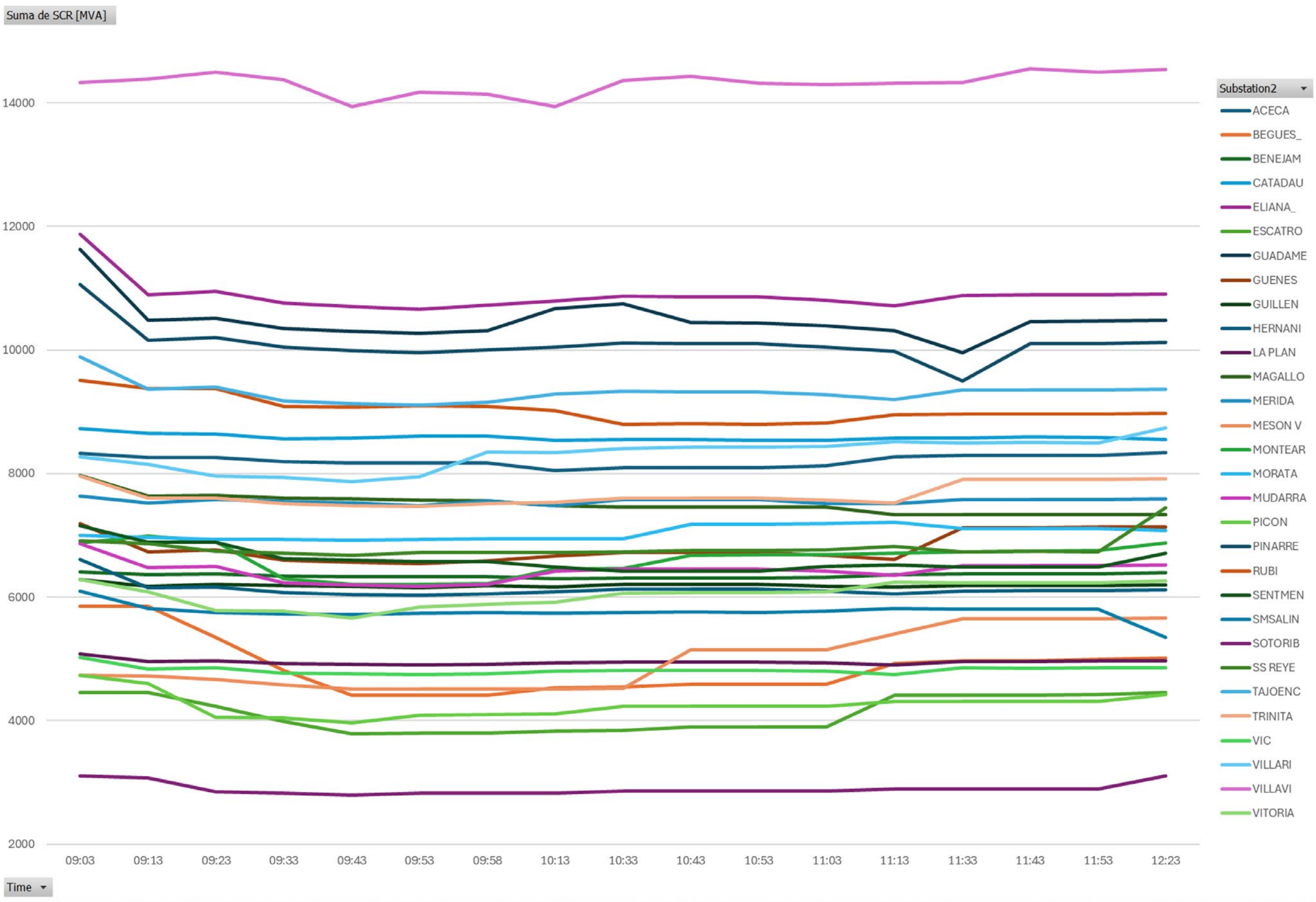

Figure 2-90: Short circuit power evolution in the Spanish 220 kV network (pilot nodes)

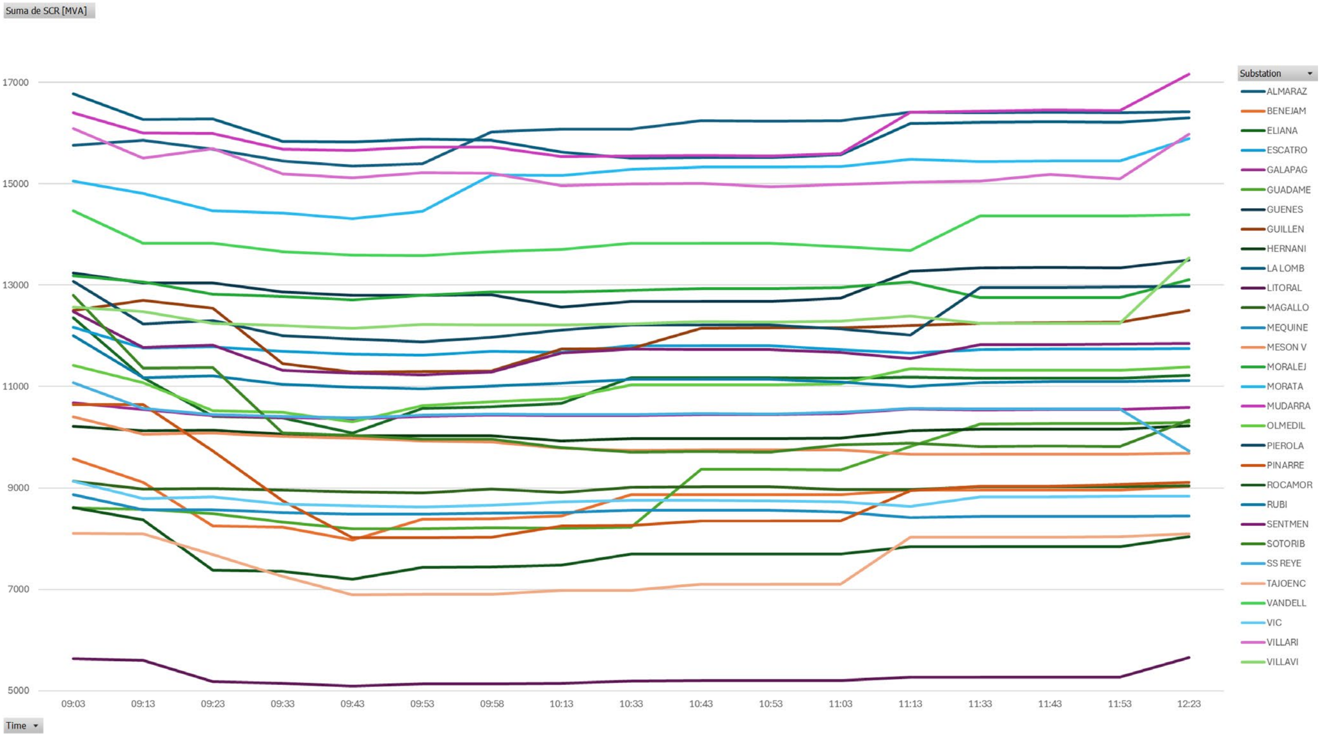

Figure 2-91: Short circuit power evolution in the Spanish 400 kV network (pilot nodes)

2.6.10 Reactive Power Flows with Neighbouring TSOs

Figures 2-92 – 2-94 plot profiles of the reactive power flows with the neighbouring TSOs.

Figure 2-92: AC interconnectors reactive power flow from Spain to France [Mvar]

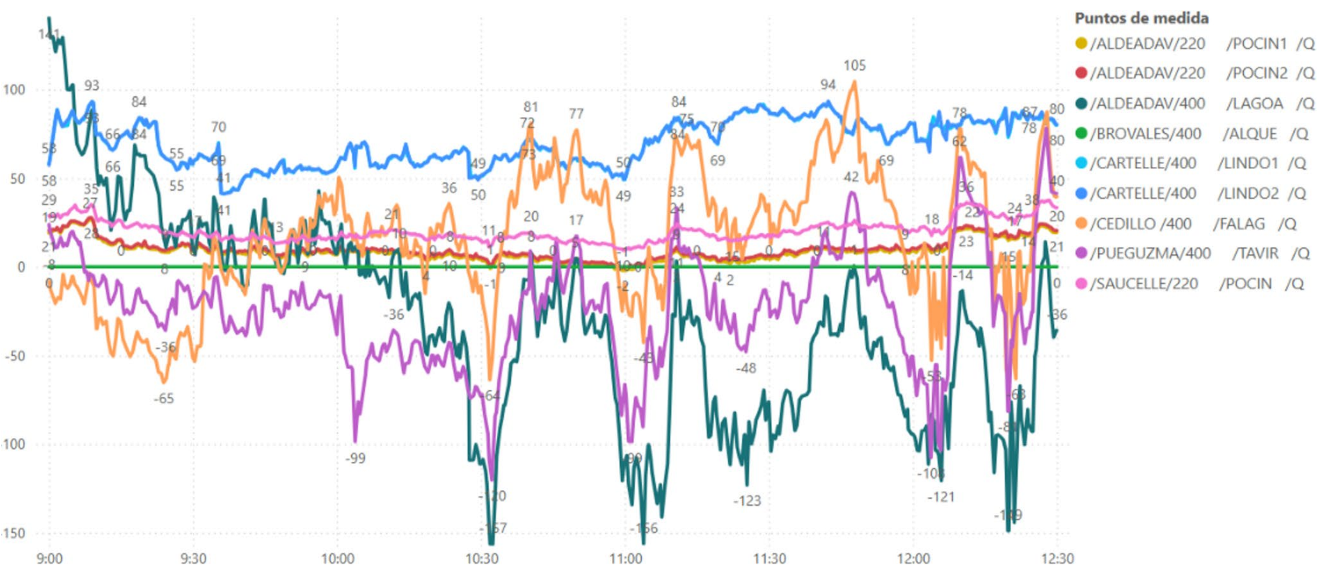

Figure 2-93: AC interconnectors reactive power flow from Spain to Portugal [Mvar]

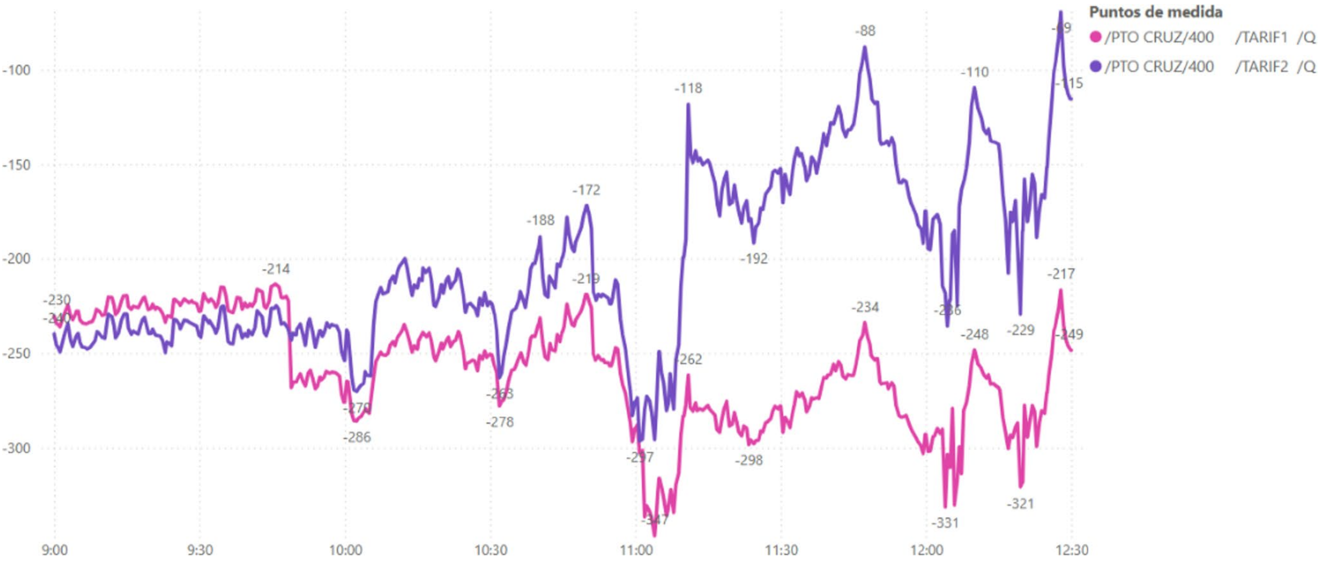

Figure 2-94: AC interconnectors reactive power flow from Spain to Morocco [Mvar]

2.7 Behaviour of the HVDC Link

The Santa Llogaia–Baixas HVDC link is a VSC-type HVDC with transmission capacity of 2 × 1,000 MW commissioned in 2015. In 2019, it was the VSC HVDC with the highest transmission capability.[22]

A VSC-type HVDC is a relatively new HVDC technology, as opposed to the classic LCC. VSC can control active and reactive power independently, provide black start capability, and work as a STATCOM.

This HVDC connects the substations of Santa Llogaia 400 kV (in Spain) and Baixas 380 kV (in France). It runs almost in parallel with the Vic–Baixas 400 kV AC interconnection line, forming an AC-DC corridor.

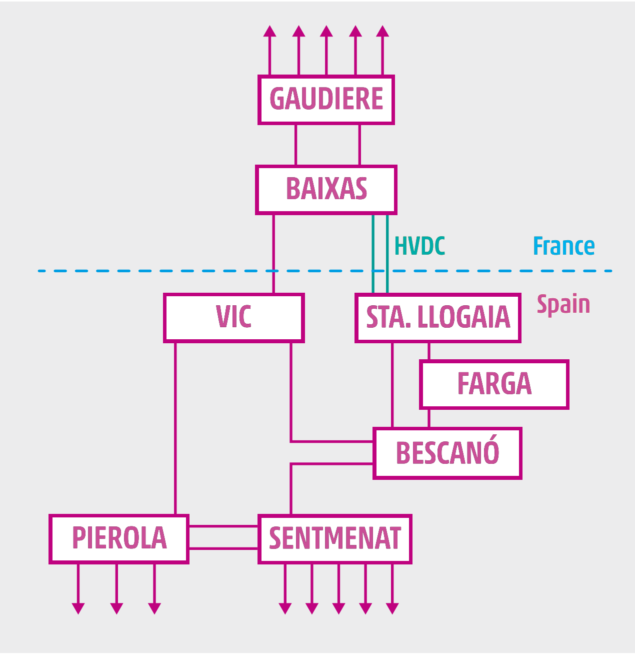

Figure 2-95: 400 kV grid in the area of the HVDC Baixas–Santa Llogaia

2.7.1 HVDC Control

The operator of a VSC-based HVDC independently controls the active and reactive power at both HVDC terminals, with a priority assigned to one of these controls if needed in extreme operating points.

In terms of active power control, the operator of a VSC HVDC sets the active power reference point. This active power setpoint is achieved based on either the desired real power flow, desired DC voltage, or desired frequency. For each moment in time, in one of the two terminals, Psetpoint will be determined. In the other terminal, the DC line voltage depends on the Psetpoint and will be set in accordance. The maximum active power capability is 2 × 1,000 MW.

On the Santa Llogaia–Baxias HVDC, the active power setpoint is determined for the Spanish and French ends and based on one of the three modes. In PMODE1, a fixed active power transmission value and its direction are determined. In PMODE2, the HVDC active power setpoint depends on an external analogue signal, which is intended to be the active power flow on several lines. This mode is not used in operation. The third mode – PMODE3 – is an AC emulation mode, where the active power setpoint is calculated based on the difference in angles between the HVDC terminals. Effectively, in this mode, the flow on the HVDC will resemble the flow on an AC line.

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[22] See ENTSO-E's 2019 report " HVDC links in system operations" available at https://eepublicdownloads.entsoe.eu/clean-documents/SOC documents/20191203_HVDC links in system operations.pdf.

The function for PMODE3 on the Santa Llogaia–Baixas HVDC is as follows:

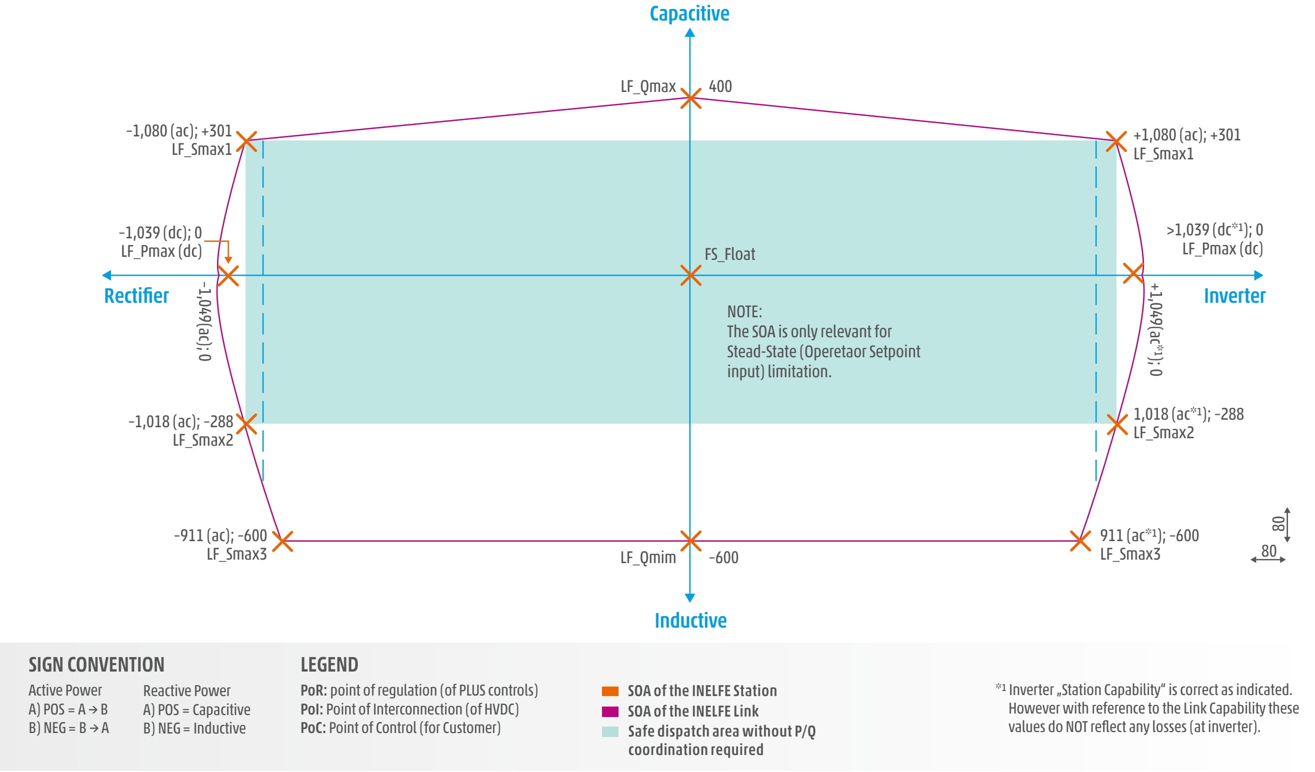
$$P_{setpoint} = P_0 + (K / (1 + sT) * (\delta_A - \delta_B)$$

The values for P_0, K and T are as follows: $P0 = 0$, $K = 360$ MW/º, $T = 50$ s. The angles δ_A and δ_B are measured at substations 400 kV Baixas in France and 400 kV Santa Llogaia in Spain.

In terms of **reactive power control**, the operator of a VSC HVDC sets the reactive power reference point. This reactive power setpoint is achieved based on either the desired reactive power flow or desired AC voltage.

For each moment in time, in each of the terminals independently, the reactive power setpoints Qsetpoint will be determined.

Each HVDC link is capable of generating up to 400 Mvar and absorbing up to 600 Mvar in each of the terminals. Working both links together can generate up to 800 Mvar and absorb up to 1,200 Mvar in each of the terminals. These maximum capabilities can be limited by the active power transmitted by the link. The maximum capability of Q depending on the transmitted P is shown in the guaranteed operation area curve in Figure 2-96. This implies that in terms of control priority, the Santa Llogaia–Baxias HVDC prioritises active over reactive power.



NOTE:
The SOA is only relevant for Stead-State (Operetaor Setpoint input) limitation.

Figure 2-96: Guaranteed operation area curve

On the Santa Llogaia–Baxias HVDC, the reactive power setpoints on the French and Spanish sides vary. On both sides, the reactive power setpoint is determined based on a $V_{setpoint}$.

On the French side, the $V_{setpoint}$, is controlled by the secondary voltage control. This means that measurements from several substations in the French power systems are collected, and a voltage setpoint at the HVDC terminal calculated based on a pre-determined approach.

On the Spanish side, the Vsetpoint is manually inserted by the control room. The management of the HVDC voltage setpoint is integrated within the northeast area to ensure coordination with other voltage control devices operating in that region. On 28 April, the setpoint was set as outlined in Figure 2-97.

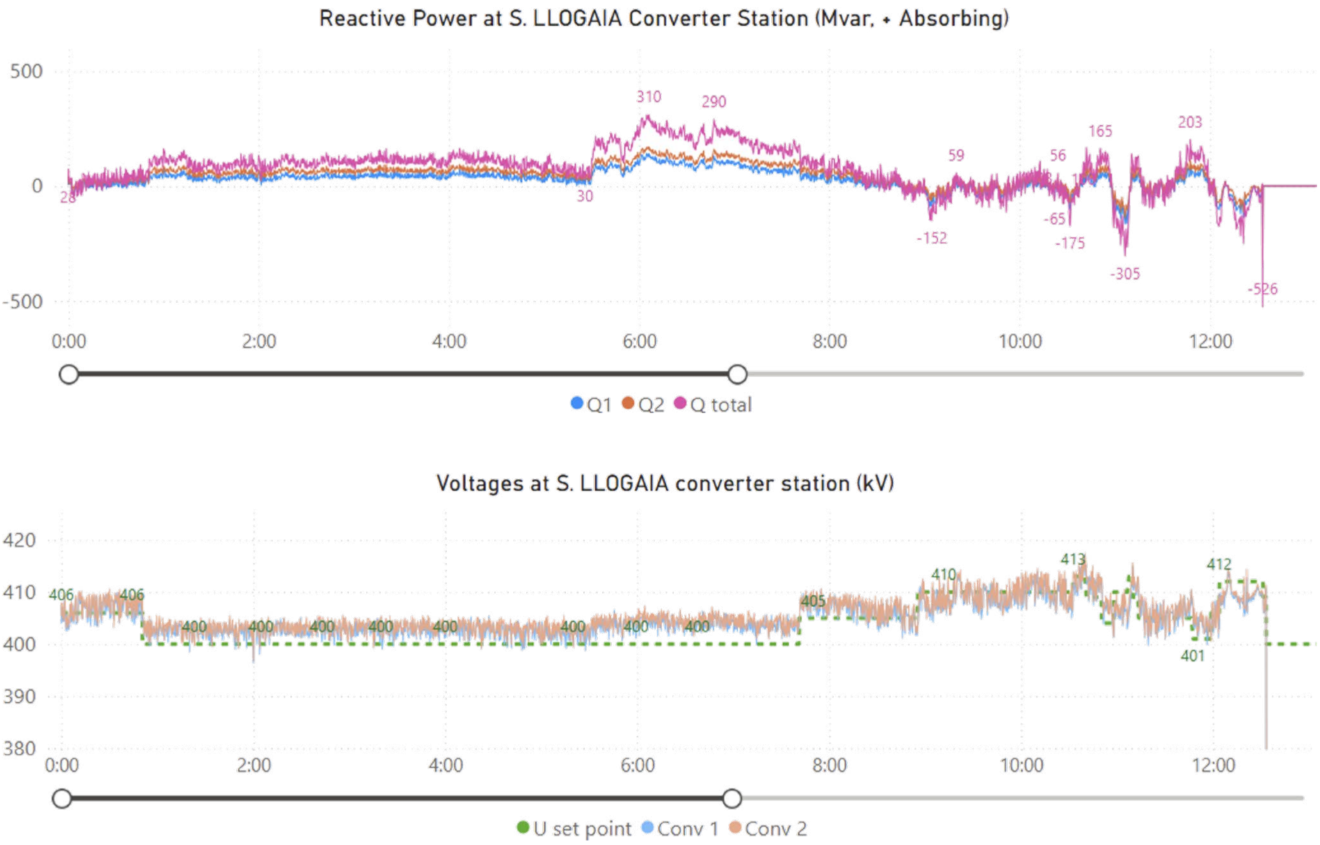


Figure 2-97: Reactive power and voltages at the Santa Llogaia converter station on 28 April (source: RE SCADA)

2.7.1.1 Voltage and Reactive Power Flows at HVDC Terminals

This section describes the behaviour of the HVDC link, with a focus on voltage and reactive power at the terminals on both the French and Spanish sides.

The observed timeframe is 11:30:00–12:00:00, with a focus on 11:35:20–11:36:20 (a minor oscillation with amplitude around 0.6 Hz can also be observed in this latter timeframe).

2.7.1.1.1 French side

It is observed that in the period 11:30:00 – 12:00:30, the reactive power at a HVDC node (Baixas 1) varies between +340 and +443 MVar (both generating). The voltage is a minimum of 388 kV and a maximum of 394 kV.

It is observed that in the period from 11:35:20 to 11:36:20, the reactive power at a HVDC node (Baixas 1) varies between +372 and +395 MVar (both generating). The voltage is a minimum of 389 kV and a maximum of 392 kV.

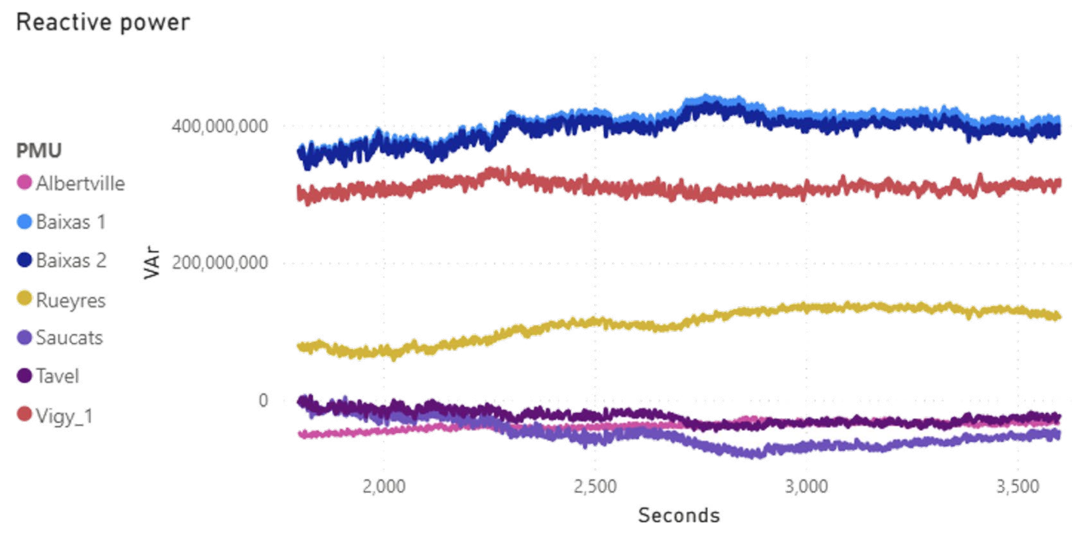


Figure 2-98: Reactive power flow measured by a set of PMUs in France, 11:30:00 – 12:00:00

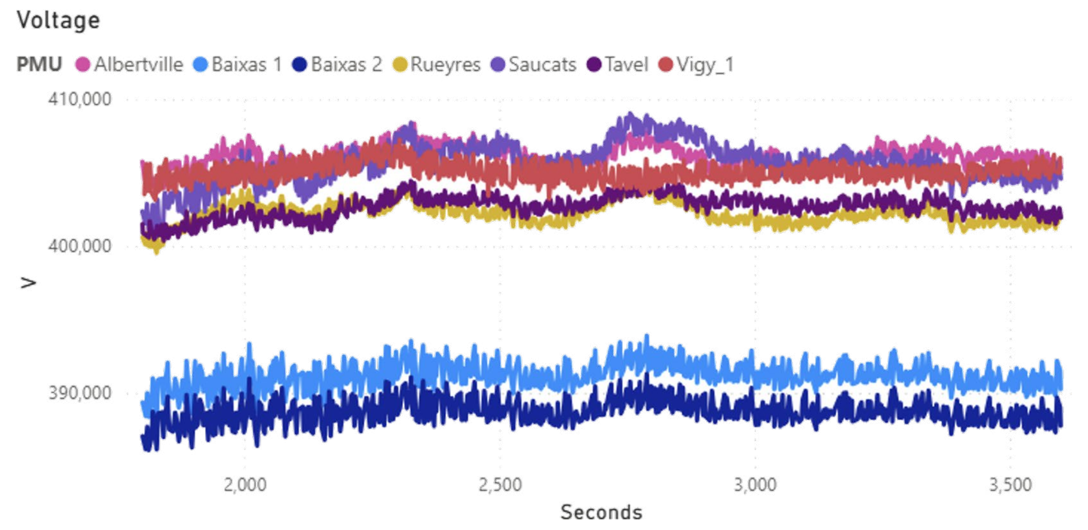


Figure 2-99: Voltage measured by a set of PMUs in France, 11:30:00 – 12:00:00

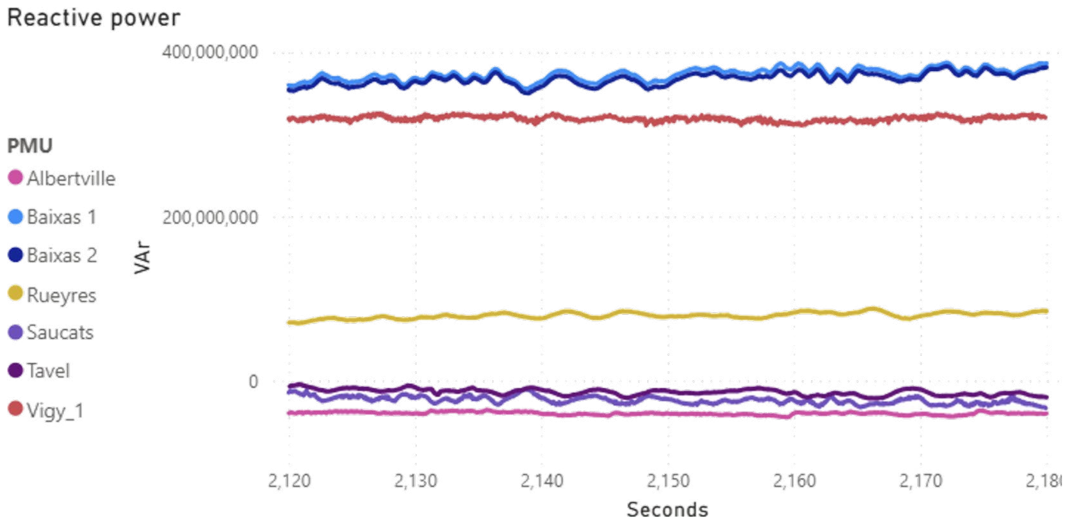


Figure 2-100: Reactive power flow measured by a set of PMUs in France, 11:35:20 -11:36:20

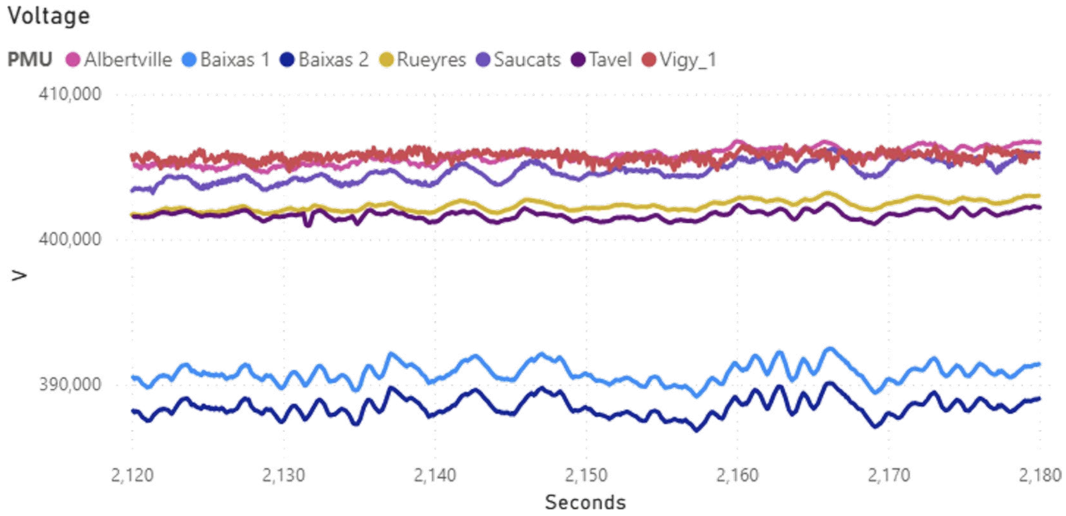


Figure 2-101: Voltage measured by a set of PMUs in France, 11:35:20 -11:36:20

2.7.1.1.2 Spanish side

It is observed that in the period from 11:30:00 to 12:00:00, the reactive power at a HVDC node (Santa Llogaia 1) varies between −51.6 MVAr (absorbing) and +128.4 MVar (generating). The voltage is minimum 398 kV and maximum 411.0 kV.

It is observed that in the period from 11:35:20 to 11:36:20, the reactive power at a HVDC node (Santa Llogaia 1) varies between −43.6 MVAr (absorbing) and +35.7 MVar (generating). The voltage is a minimum 400.5 kV and maximum 408.6 kV.

It is observed from Figures 2-98 and 2-100 that the variation of reactive power is the highest at the PMU corresponding to the HVDC node. Figure 2-102 shows that in the Spanish HVDC node, reactive power fluctuates between positive and negative values. It is also observed from Figure 2-105 that the variation of voltage in the PMU corresponding to the Spanish HVDC node is higher than the variation of voltage in adjacent PMUs (Vic and Rubi).

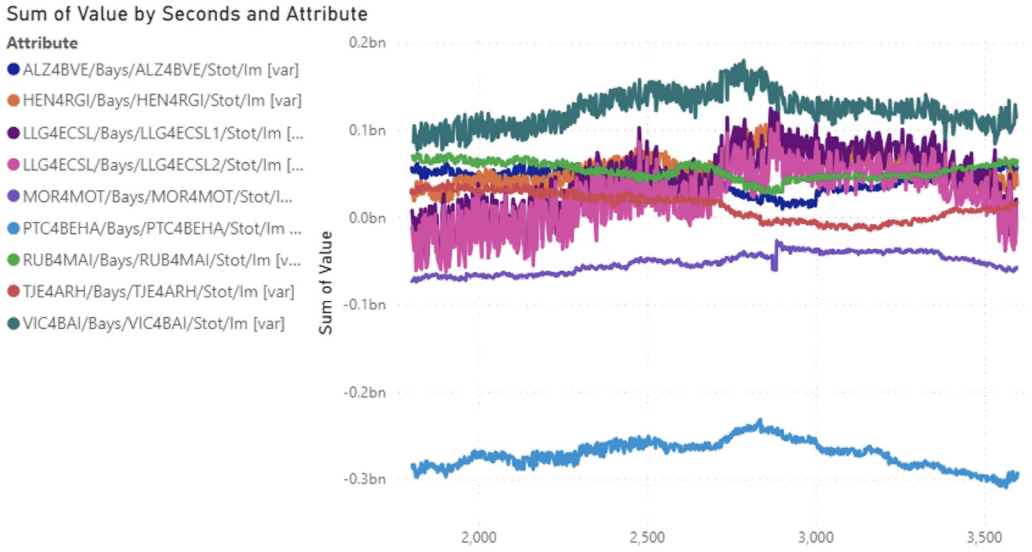


Figure 2-102: Reactive power measured by a set of PMUs in Spain, 11:30:00 – 12:00:00

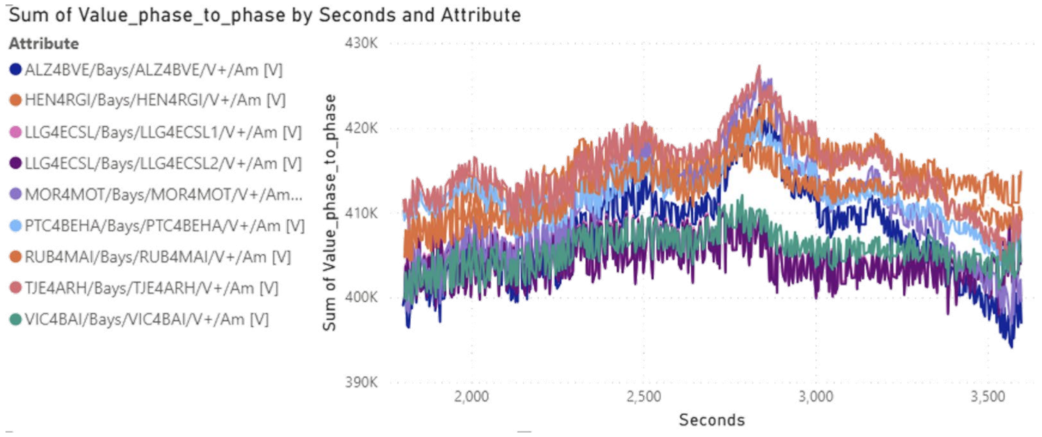


Figure 2-103: Voltage measured by a set of PMUs in Spain, 11:30:00 – 12:00:00

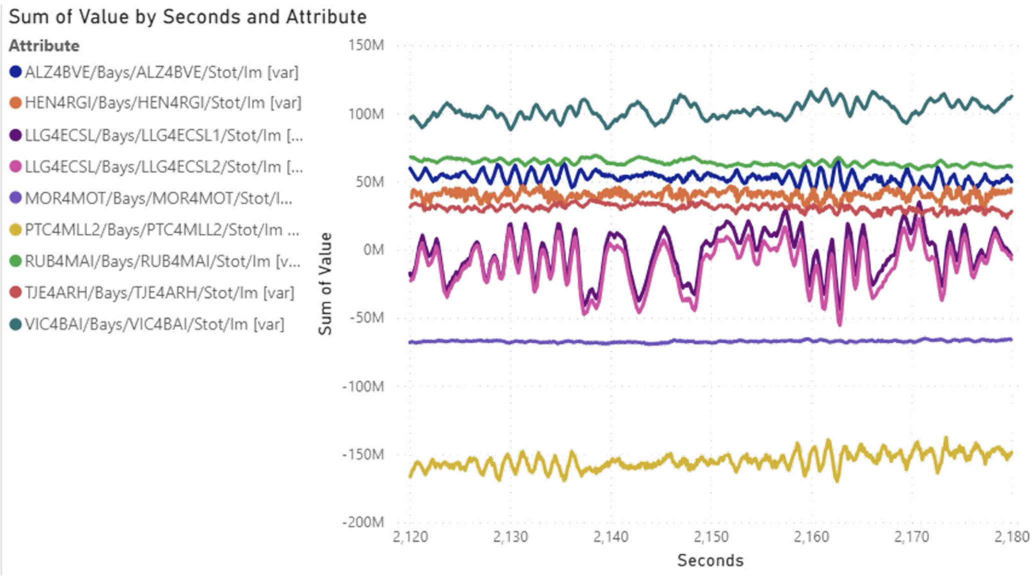


Figure 2-104: Reactive power measured by a set of PMUs in Spain, 11:35:20 – 11:36:20

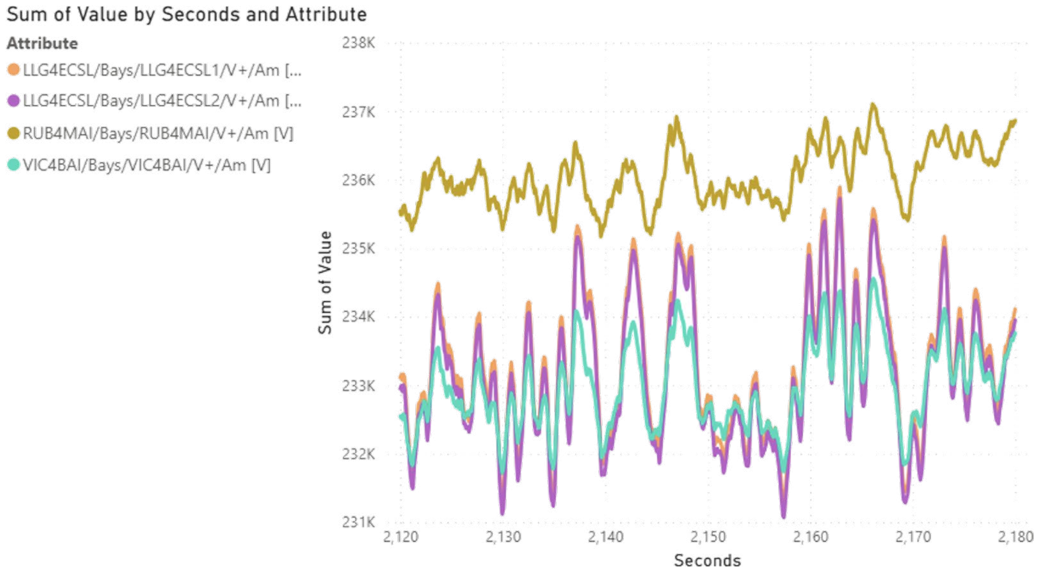


Figure 2-105: Voltage measured by a set of PMUs in Spain (the HVDC node and two nodes in the geographical vicinity), 11:35:20 – 11:36:20

2.7.1.2 Active and Reactive Power Flows and Voltage at HVDC Terminals

This section describes the behaviour of the HVDC link, with a focus on active power, reactive power, and the AC voltage at the Spanish end. Figures 2-106 – 2-108 show the time series from 12:00:00 to 12:16:00.

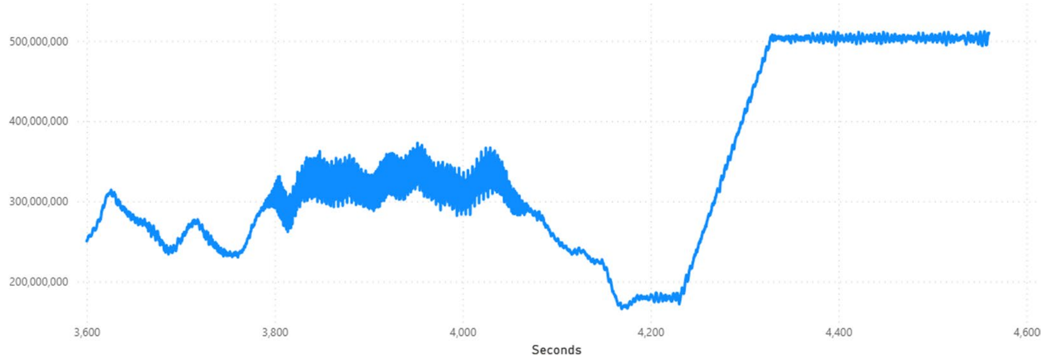


Figure 2-106: Active power flow, Llogaia bay 1, 12:00 – 12:16

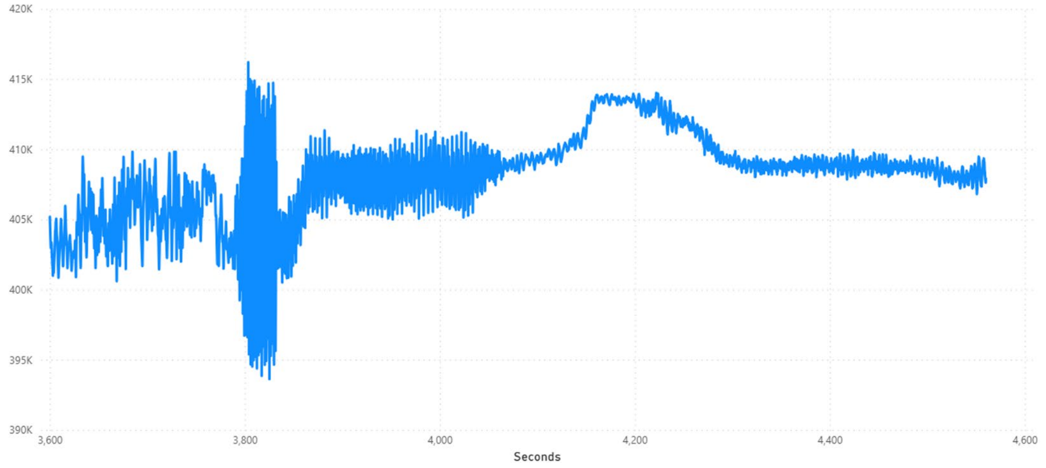


Figure 2-107: AC voltage, Llogaia bay 1, 12:00 – 12:16

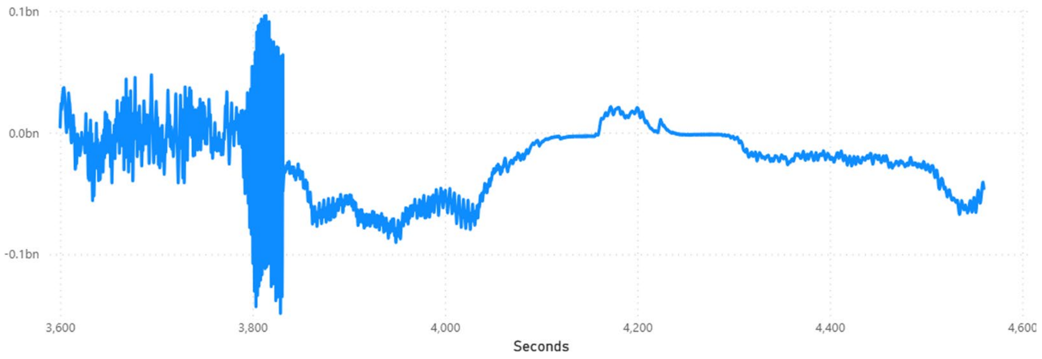


Figure 2-108: Reactive power flow, Llogaia bay 1, 12:00 – 12:16

Figures 2-109 – 2-111 show the data from 12:16:00 to 12:32:00.

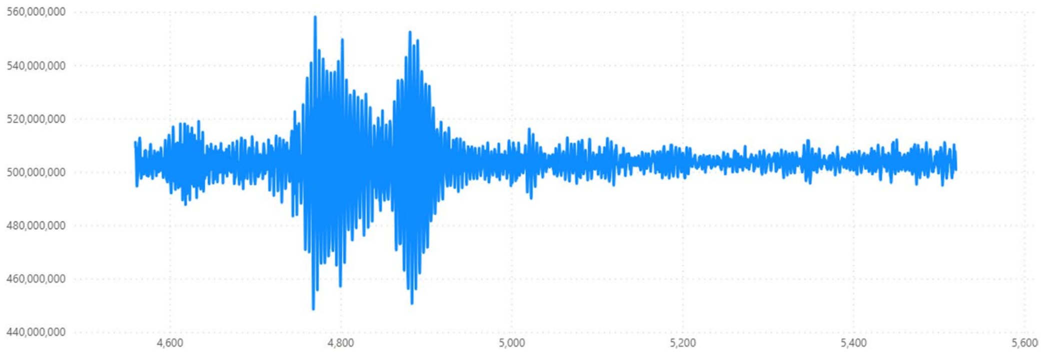


Figure 2-109: Active power flow, Llogaia bay 1, 12:16 - 12:32

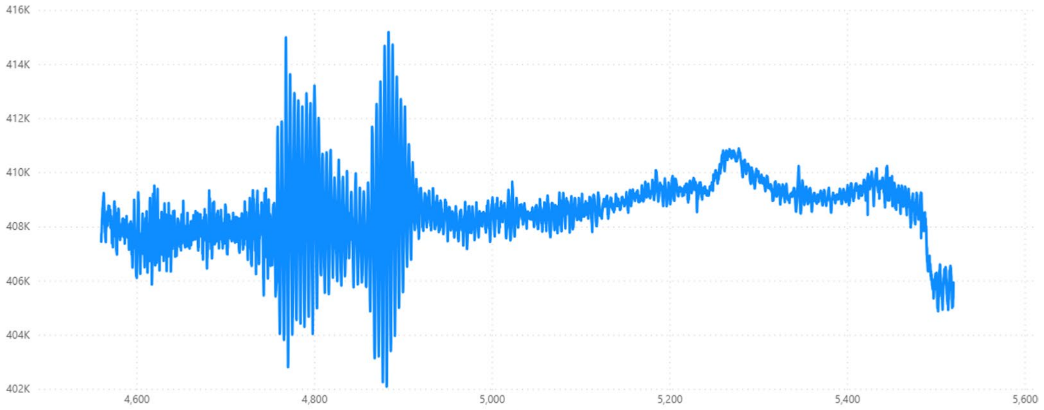


Figure 2-110: AC voltage, Llogaia bay 1, 12:16 - 12:32

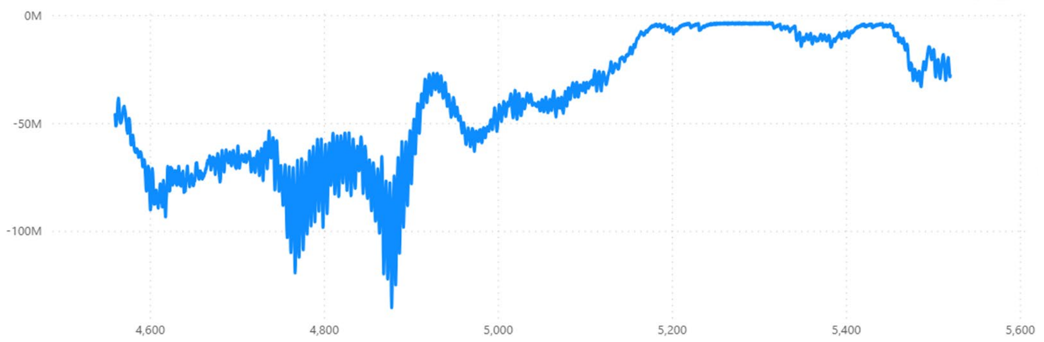


Figure 2-111: Reactive power flow, Llogaia bay 1, 12:16 - 12:32

2.7.2 HVDC Oscillation Damping

The output of active and reactive power of the HVDC can be altered by the output of POD control loops. The final voltage and current signals produced by the HVDC depend on all inner control loops and how they are prioritised. Section 2.5.5.2 describes the POD functionalities of the HVDC.

2.7.3 Additional functionalities

Besides the functionalities mentioned earlier in the chapter, the Santa Llogaia–Baxias HVDC is also capable of the following functions:[23]

- special protections scheme run-back/run-up (meaning a rapid decrease or increase in power flow to stabilise grids during emergencies);
- providing frequency containment reserves in case of a system split;
- island detection.

The HVDC has the capability to automatically adjust the active power flow or active power parameters in response to an external signal. This functionality is referred to as modulation modules (power run-up/run-down). The modulation modules (MMs) are a station control functionality, meaning that they are independently defined in each converter station (Santa Llogaia and Baixas).

In normal operation, MMs are only used on the Spanish side, and the external signal is associated with predefined contingencies. The MMs considered at Santa Llogaia end have the following features:

- **MM1:** Switch to Pmode1 under the contingency of double circuit 400 kV Santa Llogaia–Bescanó/Santa Llogaia–La Farga
- **MM2:** Switch to Pmode1 under the contingency N-1 400 kV Bescanó–Sentmenat
- **MM3:** Switch to Pmode1 under the contingency of double circuit 400 kV Bescanó–Sentmenat/Vic–Pierola
- **MM4:** Switch Pmode1 under the contingency N-1 400 kV Bescanó–Vic
- **MM5:** Switch to Pmode1 under the contingency of double circuit 400 kV Bescanó–Sentmenat/Bescanó–Vic
- **MM6:** Limiting Operating Power Range (OPR) under the contingency of double circuit 400 kV Bescanó–La Farga/Bescanó–Santa Llogaia
- **MM7:** Limiting OPR under the contingency of double circuit 400 kV La Farga–Santa Llogaia/Bescanó–Santa Llogaia

The HVDC control system automatically activates the relevant MM and adjusts the active power transmitted through the link when both of the following conditions are satisfied:

- The relevant MM is enabled.
- The line(s) for this MM tripped.

In real-time operation, MMs are enabled depending on network conditions. Because enabling or disabling them affects power levels, these actions are coordinated with RTE.

At 12:32, the MMs enabled at the Santa Llogaia end were:

- MM1
- MM3
- MM5
- MM6

None of the aforementioned MMs were activated during the day.

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[23] Per Table 3 of https://eepublicdownloads.entsoe.eu/clean-documents/SOC documents/20191203_HVDC links in system operations.pdf

2.8 Annex

2.8.1 Detailed List of All Planned Outages

Element type	Hour (from – to)	Switched off element name
Tie-line	All Day	400 kV BROVALES – ALQUEVA
Line	All Day	400 kV BUNIEL GRIJOTA 1
Line	09 to 18	400 kV ALMARAZ CN MORATA 2
Line	09 to 24	400 kV CATADAU MUELA 1
Line	All Day	400 kV CARRIL LITORAL 1
Line	All Day	400 kV FUENTES DE LA ALCARRIA TRILLO
Line	All Day	400 kV LOECHES SS.REYES
Line	All Day	400 kV SAN FERNANDO SS.REYES 1
Line	All Day	400 kV BROVALES ALQUEVA
Line	09 to 24	400 kV PALOS GUILLENA 2
Line	All Day	400 kV CARMONA VALDECABALLEROS
Line	09 to 18	220 kV ATIOS PAZOS DE BORBEN
Line	09 to 24	220 kV HARO LAGUARDIA
Line	All Day	220 kV ITXASO ORCOYEN 2
Line	09 to 18	220 kV ORTUELLA SANTURCE
Line	09 to 24	220 kV VALLADOLID NUEVO ZARATAN 2
Line	All Day	220 kV BADALONA GUIXERES 1
Line	09 to 18	220 kV ABRERA GIS RUBI
Line	All Day	220 kV BEGUES CAN JARDI
Line	All Day	220 kV BIESCAS PRAGNERES
Line	09 to 24	220 kV EIXAMPLE VILANOVA
Line	All Day	220 kV LA ESPLUGA JUNEDA
Line	09 to 24	220 kV LA FARGA JUIA 1
Line	09 to 24	220 kV CAN JARDI CERVELLO
Line	09 to 18	220 kV ACECA PRADILLOS
Line	All Day	220 kV ALDAIA QUART DE POBLET
Line	All Day	220 kV CASA DE CAMPO NORTE
Line	All Day	220 kV ANTONIO LEYVA PARQUE INGENIEROS
Line	09 to 18	220 kV LA PLANA EL SERRALLO 1
Line	09 to 24	220 kV LEGANES T DE LEGANES
Line	09 to 24	220 kV LUCERO T DE LEGANES
Line	09 to 24	220 kV PRADO VILLAVICIOSA
Line	All Day	220 kV LA TORRECILLA VILLAVERDE BAJO
Line	09 to 24	220 kV VILLAVERDE BAJO T DE LEGANES
Line	09 to 24	220 kV ALCORES SANTA ELVIRA 2
Line	16 to18	220 kV CARTUJA DON RODRIGO
Line	09 to 18	220 kV DON RODRIGO ALJARAFE
Line	09 to 13	220 kV DON RODRIGO DOS HERMANAS 2
Line	All Day	220 kV MERIDA TRUJILLO
Line	16 to 18	220 kV ALJARAFE CHUCENA 1
Line	09 to 15	220 kV ALJARAFE SANTIPONCE
Line	All Day	132 kV IRUN ERRONDENIA
Transformer	09 to 24	AT ESCATRÓN 400/220 kV
Transformer	09 to 24	AT PALOS 400/220 kV
Transformer	All Day	AT LITORAL 400/132 kV

Table 2-9: RE planned outages

Element type	Switched off element name	Start date/time CET	End date/time CET	Reason
Line	Paraimo–Pereiros 1 220 kV	06/01 09:10	14/08 18:35	Upgrade line capacity
Line	Fernao Ferro–Ribatejo 400 kV	07/03 08:53	11/07 18:00	Upgrade line capacity
Line	Palmela–Fernão Ferro 2 150	31/03 16:02	24/05 14:18	Palmela substation remodulation
Transformer	Auto Transformador 4 400/150 kV Subestação Ferreira do Alentejo	07/04 09:39	31/10 18:00	Ferreira Alentejo substation remodulation
Line	Recarei–Vermoim 3 400 kV	14/04 09:12	22/09 18:00	Recarei substation remodulation
Line	Tunes–Estoi 150 kV	16/04 18:01	22/09 18:00	Tunes substation remodulation and line maintenance
Tie-line	Brovales–Alqueva 400 kV	24/04 09:04	29/04 13:40	Corrective maintenance, installing bird diverters after a protected species collision
Line	Fanhões–Carriche2 220	28/04 07:59	02/05 18:12	Creation of safety conditions for other company work near the line
Line	Alto Mira–Carriche/Trajouce 220	28/04 08:02	29/04 18:58	Substation maintenance
Line	Chafariz–Vila Cha 1/Ramal Gouveia 220 kV	28/04 09:52	29/04 09:15	Other company works

Table 2-10: REN planned outages

Element type	Switched off Element name	Start date	End date	Reason
Tie-line	225 kV Biescas Pragnères	22/04	02/05	PST maintenance
Line	400 kV Eguzon Valdivienne 2	08/04	06/06	Switch replacement
Line	400 kV Braud Cubnezais 4	28/04	05/05	Preventive and curative maintenance
Line	440 KV Breuil Marmagne	28/04	30/04	Curative maintenance
Busbar	Valdivienne 2A	08/04	02/05	Development of the grid
Busbar	Granzay 1B	22/04	28/04	Preventive maintenance
Busbar	Marsillon 1	14/04	28/04	Development of the grid

Table 2-11: RTE planned outages

2.8.2 Detailed List of Open Lines for Voltage Control

Element name	Date start Time	Hour start time	Date end time	Hour End Time	Zone
L-400 kV MORELLA–MUDEJAR 1	15/03	23:49	29/04	20:32	NORTH
L-400 kV ARAGÓN–PEÑALBA 2	31/03	23:12	29/04	20:37	NORTH
L-400 kV CASTEJON–MURUARTE 1	07/04	22:27	29/04	19:38	NORTH
L-400 kV PALMAR–ROCAMORA 2	13/04	00:20	28/04	12:08	EAST
L-400 kV PALMAR–CARRIL	13/04	02:59	28/04	12:07	EAST
L-400 kV CARTELLE–TRIVES 1	14/04	23:21	28/04	21:30	NORTH WEST
L-400 kV LA ROBLA–MUDARRA 1	14/04	23:24	28/04	12:08	NORTH WEST
L-400 kV BAZA–CAPARACENA 2	16/04	01:53	29/04	21:04	EAST
L-220 kV TALAVERA–VILLAVERDE	16/04	15:55	28/04	16:54	CENTRE
L-400 kV N.ESCOMBRERAS–PALMAR 2	17/04	01:55	28/04	18:55	EAST
L-400 kV PINILLA–ROMICA 2	17/04	23:44	28/04	12:21	EAST
L-400 kV MONTEARENAS–MUDARRA 1	19/04	03:07	30/04	06:52	NORTH WEST
L-400 kV PINILLA–ROCAMORA 1	19/04	23:59	28/04	12:22	EAST
L-400 kV MONTEARENAS–MUDARRA 3	20/04	00:38	28/04	05:20	NORTH WEST
L-400 kV TORDESILLAS–GALAPAGAR	20/04	01:37	28/04	12:25	CENTRE
L-220 kV RUBI–GRAMANET 2	20/04	13:55	28/04	15:38	NORTH-EAST
L-220 kV MARAGALL–TRINITAT1	20/04	13:55	02/05	11:36	NORTH-EAST
L-400 kV BOIMENTE–PESOZ 2	21/04	16:09	29/04	01:58	NORTH WEST
L-400 kV SALAS–PESOZ	21/04	16:12	29/04	01:59	NORTH WEST
L-400 kV BROVALES–GUILLENA1	21/04	18:43	28/04	10:33	SOUTH
L-400 kV GUADAME–CABRA 1	23/04	00:21	28/04	11:07	SOUTH
L-220 kV GURREA–VILLANUEVA 1	23/04	03:57	28/04	09:13	NORTH
L-400 kV ARCOS–CABRA	23/04	19:23	28/04	11:17	SOUTH
L-400 kV MUDARRA–S. SEBASTIÁN	23/04	23:00	30/04	06:30	NORTH WEST
L-400 kV PINAR–TAJO	23/04	23:48	28/04	11:08	SOUTH

Element name	Date start Time	Hour start time	Date end time	Hour End Time	Zone
L-400 kV GUADAME–CABRA 3	24/04	19:47	28/04	12:25	SOUTH
L-400 kV GUADAME–VALDECABALLEROS 2	24/04	19:52	28/04	10:35	SOUTH
L-400 kV BELINCHON–MORATA 1	24/04	23:55	29/04	20:35	CENTRE
L-400 kV AGUAYO–ABANTO	25/04	16:16	28/04	11:07	NORTH WEST
L-400 kV P.GUZMAN–GUILLENA 1	25/04	20:09	28/04	12:07	SOUTH
L-400 kV OLMEDILLA–ROMICA 2	25/04	23:57	28/04	11:03	EAST
L-400 kV MORATA–VILLAVICIOSA	26/04	00:52	28/04	12:15	CENTRE
L-400 kV DON RODRIGO–ARCOFRONT 2	26/04	01:01	28/04	10:06	SOUTH
L-400 kV MONTEARENAS–MUDARRA 2	26/04	15:59	28/04	11:09	NORTH WEST
L-400 kV HERRERA–LOMBA	26/04	18:06	28/04	06:14	NORTH WEST
L-400 kV GRIJOTA–VILLARINO 2	26/04	19:51	28/04	12:07	NORTH WEST
L-400 kV ALMARAZ–MORATA 2	26/04	19:56	28/04	09:54	CENTRE
L-400 kV GUILLENA–PALOS 2	27/04	00:15	28/04	08:19	SOUTH
L-220 kV AENA–SS REYES 2	27/04	00:26	14/05	15:08	CENTRE
L-400 kV RUBÍ–VANDELLÓS	27/04	01:14	28/04	07:37	NORTH-EAST
L-400 kV COFRENTES–LA MUELA 1	27/04	03:06	28/04	14:01	EAST
L-400 kV CATADAU–LA MUELA 1	27/04	03:10	28/04	09:38	EAST
L-400 kV PIEROLA–SENTMENAT 2	27/04	11:28	28/04	15:20	NORTH-EAST
L-400 kV PIEROLA–VANDELLÓS	27/04	12:40	28/04	11:20	NORTH-EAST
L-400 kV SALLENTE–CALDERS	27/04	12:47	28/04	09:17	NORTH-EAST
L-400 kV ABANTO–ICHASO 1	27/04	15:14	28/04	06:20	NORTH
L-400 kV BRAZATORTAS–MANZANARES 1	27/04	15:17	28/04	09:13	CENTRE
L-220 kV BESOS NUEVO–VILANOVA	27/04	17:09	28/04	06:39	NORTH-EAST
L-400 kV BROVALES–SAN SERVAN1	27/04	19:55	28/04	10:02	SOUTH
L-400 kV ALMARAZ–S.SERVAN 1	27/04	19:56	28/04	09:02	SOUTH
L-400 kV ARAÑUELO–MORATA 2	27/04	20:02	28/04	07:29	CENTRE

Element name	Date start Time	Hour start time	Date end time	Hour End Time	Zone
L-400 kV ARAÑUELO–VALDECABALLEROS 2	27/04	20:07	28/04	07:23	SOUTH
L-400 kV FUENDETODOS–MEZQUITA	27/04	20:09	28/04	20:29	NORTH
L-400 kV MEZQUITA–MORELLA 1	27/04	20:09	29/04	20:33	NORTH
L-400 kV ALMARAZ–VILLAVICIOSA 2	27/04	22:48	28/04	07:17	CENTRE
L-400 kV BIENVENIDA–GUILLENA	27/04	23:01	28/04	07:48	SOUTH
L-400 kV ARCOS–RODA	27/04	23:03	28/04	06:14	SOUTH
L-400 kV ALMARAZ–GUADAME	27/04	23:29	28/04	07:09	SOUTH
L-220 kV CERRO PLATA–VILLAVERDE BAJO 2	28/04	00:45	28/04	12:02	CENTRE
L-220 kV ACECA–PICON	28/04	00:46	28/04	10:32	CENTRE
L-220 kV PICON–PUERTOLLANO	28/04	00:46	28/04	22:00	CENTRE
L-400 kV LA CEREAL–SEGOVIA	28/04	00:47	28/04	06:59	CENTRE
L-400 kV SALLENTE–SENTMENAT	28/04	01:14	28/04	06:47	NORTH-EAST
L-400 kV ALMARAZ–C. RODRIGO	28/04	03:39	28/04	05:28	SOUTH
L-400 kV ALDEADAVILA–HINOJOSA	28/04	03:40	28/04	05:27	NORTH WEST

Table 2-12: RE list of open lines for voltage control

3 SYSTEM CONDITIONS DURING THE INCIDENT

Subchapter 3.1 presents the dynamic behaviour of the system during the incident. For the purposes of this report, the incident began at 12:32:00.

In Section 3.1.1, a sequence of events is provided in both tabular and graphical form. They are grouped in so-called "event clusters" for easier geographical identification on maps presented later in the section. The next section (3.1.2) presents the evolution of the main electrical quantities in the affected TSO networks that characterised the event, including voltage magnitude, frequency, rate of change of frequency (RoCoF), and active power. Section 3.2 covers protection behaviour, including an analysis of generation trips, and is preceded by a summary of general requirements for generators to ensure grid code compliance. Section 3.3 provides information on system defence plans for the affected TSOs. Where PMU measurements are considered in this chapter, it should be noted that PMUs have a temporal accuracy of approximately ±30 ms.

3.1 Dynamic Behaviour of the System During the Incident

This subchapter provides a factual representation of the evolution of the system during the event. As described above, this section deals with all the events that occurred between 12:32:00 and 12:34:00. The time before this period is covered in the previous chapter.

3.1.1 Sequence of Events

This section describes the sequence of events that led to the separation of the Iberian Peninsula power system from the Continental Europe Synchronous Area and Morocco, and to the subsequent blackout.

Table 3-1 lists the following types of events: generation loss (including type of generation), line trip, hydro Pump trip, and load shedding, along with the estimated value of lost power (country abbreviations used in Table 3-1: ES = Spain, PT = Portugal, IP = Iberian Peninsula). Causes are not included in the table as they are unknown in most cases. The known causes are reviewed in Section 3.2. In the final report, causes will be estimated in cases where no factual information is available.

The events in Table 3-1 are grouped according to geographical, temporal, event-type, and energy-source criteria. The resulting clusters are displayed on the network map (Figure 3-1), showing either the specific location of the affected plant or substation, or the centroid when events within the same cluster occurred across different geographical areas.

It is worth noting that many events occurred within a very short time frame, making it difficult to determine their exact sequence, as not all data is time-synchronised with sufficient accuracy. In addition, some of these events occurred in parts of the system that are not fully observable[24] from the TSO perspective, requiring estimation of the imbalance caused by the disconnection of certain power plants. Therefore, the events listed in Table 3-1 represent the best available measurements and estimations at the time of publication.

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[24] In Spain and Portugal, all generation facilities greater than 1 MW must send production in real time to the TSO. Smaller facilities do not have this obligation.

Event Cluster	Country	Time (CEST)	Event Type	Description	Electrical Power Imbalance (MW)
1	ES	12:32:00.000 - 12:32:57.000	Net load increase	Disconnection of small embedded generators and/or actual increase of load at the distribution level	317.30
2a	ES	12:32:05.000	Generation loss	Wind	2.57
2a	ES	12:32:09.000	Generation loss	Wind	21.62
2a	ES	12:32:09.000	Generation loss	Wind	5.89
2a	ES	12:32:25.000	Generation loss	Wind	19.21
2a	ES	12:32:29.000	Generation loss	Wind	22.42
2a	ES	12:32:29.000	Generation loss	Wind	55.63
2a	ES	12:32:45.000	Generation loss	PV	0.59
2a	ES	12:32:49.000	Generation loss	Wind	13.35
2a	ES	12:32:49.000	Generation loss	PV	1.14
2a	ES	12:32:53.000	Generation loss	PV	11.94
2a	ES	12:32:53.000	Generation loss	Wind	19.98
2b	ES	12:32:09.000	Generation loss	Wind	4.79
2b	ES	12:32:09.000	Generation loss	Wind	2.86
2b	ES	12:32:25.000	Generation loss	Wind	3.43
2b	ES	12:32:29.000	Generation loss	Wind	2.26
2b	ES	12:32:53.000	Generation loss	Wind	4.78
2b	ES	12:32:53.000	Generation loss	Wind	10.01
2b	ES	12:32:53.000	Generation loss	Wind	5.99
3	ES	12:32:57.220	Generation loss due to power transformer trip	PV, wind, and thermo-solar	355.00
4a	ES	12:33:16.460	Generation loss	PV and thermo-solar	582.00
4b	ES	12:33:16.820	Generation loss	PV	145.00
5a1	ES	12:33:17.368	Generation loss	Wind	22.87
5a2	ES	12:33:17.780	Generation loss	PV	550.00
5a3	ES	12:33:17.940	Generation loss	Wind	94.00
5b1	ES	12:33:17.520	Generation loss	PV	118.00
5b2	ES	12:33:17.547	Generation loss	Wind and PV	33.73
5b3	ES	12:33:17.975	Generation loss	PV	37.50
5b4	ES	12:33:18.020	Generation loss	PV	71.90
6a1	ES	12:33:18.102	Generation loss	PV	3.00
6a2	ES	12:33:18.220	Generation loss	PV	20.00
6a3	ES	12:33:18.360	Generation loss	PV	16.00
6a4	ES	12:33:18.410	Generation loss	PV	41.00
6a5	ES	12:33:18.540	Generation loss	PV	63.00
6a6	ES	12:33:18.630	Generation loss	PV	25.70
6a7	ES	12:33:18.680	Generation loss	PV	127.50
6a8	ES	12:33:18.846	Generation loss	PV	154.00
6a9	ES	12:33:19.000	Generation loss	PV	16.00
6b	ES	12:33:18.951	Generation loss	PV	530.00
7a	PT	12:33:19.000	Load shedding	Pump	–221.00
7b	PT	12:33:19.090	Load shedding	Pump	–124
7c	PT	12:33:19.332	Load shedding	Pump	–113.00
8a	ES	12:33:19.095	Generation loss	PV	150.00
8a	ES	12:33:19.320	Generation loss	PV	0.71

Event Cluster	Country	Time (CEST)	Event Type	Description	Electrical Power Imbalance (MW)
8a	ES	12:33:19.339	Generation loss	Wind	11.17
8a	ES	12:33:19.380	Generation loss	Wind	6.21
8b	ES	12:33:19.252	Generation loss	Wind	364.00
8b	ES	12:33:19.260	Generation loss	PV	70.00
8b	ES	12:33:19.396	Generation loss	PV	509.00
8b	ES	12:33:19.407	Generation loss	PV	63.30
8b	ES	12:33:19.920	Generation loss	PV	72.00
8b	ES	12:33:19.951	Generation loss	PV	12.00
8b	ES	12:33:19.960	Generation loss	PV	22.30
8b	ES	12:33:19.973	Generation loss	PV	24.60
9	ES	12:33:19.971	Line trip	Loeches (RE)–Arganda (RE) 220 kV	-
10	ES	12:33:20.000	Pump disconnection	Pump	–102.00
11	PT	12:33:20.000	Load shedding	Pump	–219.00
11	PT	12:33:20.000	Load shedding	Pump	–219.00
11	PT	12:33:20.102	Load shedding	Pump	–207.00
11	PT	12:33:19.520	Load shedding	Pump	–18
11	PT	13:33:19.780	Load shedding	Pump	–18
11	PT	12:33:20.540	Load shedding	Pump	–74
11	PT	12:33:20.660	Load shedding	Pump	–75
12a	ES	12:33:20.020	Generation loss	PV	313.00
12a	ES	12:33:20.040	Generation loss	PV and thermo-solar	50.30
12a	ES	12:33:20.100	Generation loss	Wind	48.90
12a	ES	12:33:20.100	Generation loss	Combined cycle	165.00
12b	ES	12:33:20.175	Generation loss	PV	75.80
12b	ES	12:33:20.200	Generation loss	PV	305.00
12b	ES	12:33:20.235	Generation loss	PV	139.50
12b	ES	12:33:20.300	Generation loss	PV and thermo-solar	35.00
12b	ES	12:33:20.420	Generation loss	PV	131.00
12b	ES	12:33:20.476	Generation loss	PV	212.40
13a	ES	12:33:20.133	Load shedding	Pump	–69.00
13a	ES	12:33:20.180	Load shedding	Pump	–129.00
13a	ES	12:33:20.193	Load shedding	Pump	–139.00
13a	ES	12:33:20.320	Load shedding	Pump	–26.00
13a	ES	12:33:20.367	Load shedding	Pump	–25.00
13a	ES	12:33:20.405	Load shedding	Pump	–201.00
13a	ES	12:33:20.416	Load shedding	Pump	–131.00
13a	ES	12:33:20.418	Load shedding	Pump	–130.00
13a	ES	12:33:20.423	Load shedding	Pump	–130.00
13a	ES	12:33:20.506	Load shedding	Pump	–69.00
13b	ES	12:33:20.224	Load shedding	Pump	–89.00
13b	ES	12:33:20.243	Load shedding	Pump	–414.00
13b	ES	12:33:20.254	Load shedding	Pump	–79.00
13b	ES	12:33:20.259	Load shedding	Pump	–192.00
13b	ES	12:33:20.285	Load shedding	Pump	–51.00
13b	ES	12:33:20.306	Load shedding	Pump	–192.00

Event Cluster	Country	Time (CEST)	Event Type	Description	Electrical Power Imbalance (MW)
13b	ES	12:33:20.480	Load shedding	Pump	–78.00
14	ES	12:33:20.353	Load shedding	Pump	–103.00
14	ES	12:33:20.476	Load shedding	Pump	–53.00
15	ES	12:33:20.370	Load shedding	Pump	–75.00
16a	ES	12:33:20.229	Tie-line trip	Puerto de la Cruz (RE)–Beni Harchane (ONEE) 400 kV	–
16b	ES	12:33:20.473	Tie-line trip	Puerto de la Cruz (RE)–Mellousa (ONEE) 400 kV	–
17	ES	12:33:20.561	Load shedding	Pump	–181.00
17	ES	12:33:20.605	Pump disconnection	Pump	–30.00
18	IP	12:33:20.574	Load shedding 49.0 Hz	Distribution	–448.8
19	ES	12:33:20.650	Generation loss	PV	167.70
20	ES	12:33:20.650	Load shedding	Demand	–970.10
20	ES	12:33:20.810	Load shedding	Demand	–181.70
21	ES	12:33:20.740	Generation loss	PV	89.00
21	ES	12:33:21.080	Generation loss	PV	170.67
21	ES	12:33:21.254	Generation loss	PV	129.00
22	IP	12:33:20.788	Load shedding 48.8 Hz	Distribution	–1,733.39
23	ES	12:33:20.800	Load shedding	Pump	–68.00
24	PT	12:33:21.000	Generation loss	Distributed generation on DSO side (estimate)	1,073.00
25	PT	12:33:21.048	Net load disconnection	Unexpected trip due to improper activation of load shedding function	110.00
26	ES	12:33:21.060	Load shedding 48.7 Hz	Distribution	–71.03
27	PT	12:33:21.155	Load shedding	Pump	–337.00
28	ES	12:33:21.168	Load shedding	Demand	–250.70
29	IP	12:33:21.300	Load shedding 48.6 Hz	Distribution	–1,495.9
30	PT	12:33:21.390	Net load disconnection	Unexpected trip due to improper activation of load shedding function	17.00
31a	ES	12:33:21.407	Line trip	Baixas (RTE)–Vic (RE) 400 kV	–
31b	ES	12:33:21.437	Line trip	Arkale (RE) – Argia (RTE) 220 kV	–
31b	ES	12:33:21.535	Line trip	Argia (RTE)–Hernani (RE) 400 kV	–
32	ES	12:33:21.440	Generation loss	PV	26.00
32	ES	12:33:21.503	Generation loss	PV	140.00
33	IP	12:33:21.537	Load shedding 48.4 Hz	Distribution	–1,809.09
34	PT	12:33:21.562	Load shedding	Pump	–30.00
34	PT	12:33:21.782	Load shedding	Pump	–329.00
35	IP	12:33:21.838	Load shedding 48.2 Hz	Distribution	–1,582.3
36a	ES	12:33:21.872	Generation evacuation line trip	Pinar del Rey (RE)–San Roque 1 220 kV	–
36b	ES	12:33:21.980	Generation evacuation line trip	Olmedilla (RE)–Sabinar 400 kV[25]	–
37	IP	12:33:22.080	Load shedding 48.0 Hz	Distribution	–1,566.1
38a	ES	12:33:22.160	Generation loss	PV	55.00
38a	ES	12:33:22.460	Generation loss	PV	52.00
38a	ES	12:33:22.470	Generation loss	Wind and PV	114.00
38a	ES	12:33:22.860	Generation loss	PV	57.00
38b	ES	12:33:22.600	Generation loss	PV	117.50

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[25] At the time of the trip, the line's active power flow was null.

Event Cluster	Country	Time (CEST)	Event Type	Description	Electrical Power Imbalance (MW)
39	PT	12:33:22.213	Load shedding	Pump	–114.00
40	ES	12:33:22.330	Generation loss	Wind and PV	54.00
40	ES	12:33:22.900	Generation loss	PV	170.50
41a	ES	12:33:22.702	Generation loss	Nuclear	1,045.00
41b	ES	12:33:23.460	Generation loss	Combined cycle	166.00
41c	ES	12:33:23.515	Generation loss	Nuclear	653.00
42	ES	12:33:23.076	Line trip	Maguilla (RE)–Valdecaballeros (RE) 400 kV	–
43a	ES	12:33:23.140	Generation loss	PV	125.00
43a	ES	12:33:23.360	Generation loss	PV	117.50
43a	ES	12:33:23.360	Generation loss	PV	167.50
43b	ES	12:33:23.400	Generation loss	PV	380.00
43a	ES	12:33:23.260	Generation loss	PV	57.00
44	PT	12:33:24.519	Generation loss	Hydro	86.19
45	ES	12:33:23.520	HVDC block	HVDC Iberian Peninsula (RE)–Majorca (RE)	–
46	ES	12:33:23.590	Generation loss	Nuclear	1,692.00
47	ES	12:33:23.648	Generation loss	Combined cycle	87.00
48	PT	12:33:23.644	Generation loss	Combined cycle	330.69
48	PT	12:33:23.790	Generation loss	Hydro	64.76
49	PT	12:33:23.837	Generation loss	Hydro	40.12
49	PT	12:33:23.845	Generation loss	Hydro	39.62
50	ES	12:33:23.883	Pump disconnection[26]	Pump	–78.00
50	ES	12:33:23.888	Pump disconnection[27]	Pump	–78.00
51	ES	12:33:23.960	HVDC block	HVDC Iberian Peninsula (RE)–France (RTE)	–
52	PT	12:33:23.954	Line trip	Mogadouro (REN)–Central da Valeira (REN) 220 kV	
53	PT	12:33:24.195	Generation loss	Hydro	65.34
54	ES	12:33:24.230	Generation loss	Combined cycle	78.00
54	ES	12:33:24.725	Generation loss	Combined cycle	83.00
54	ES	12:33:24.800	Generation loss	Combined cycle	140.00
55a	ES	12:33:25.060	Tie-line trip	Aldeadávila (RE)–Lagoaça (REN) 400 kV	
55b	ES	12:33:25.144	Tie-line trip	Cartelle (RE)–Lindoso (REN) (ckt 2) 400 kV	
55c	ES	12:33:25.183	Tie-line trip	Cartelle (RE)–Lindoso (REN) (ckt 1) 400 kV	
55d	ES	12:33:25.325	Tie-line trip	Cedillo (RE)–Falagueira (REN) 400 kV	
55e	ES	12:33:25.410	Tie-line trip	Saucelle (RE)–Pocinho (REN) 220 kV	
55f	ES	12:33:26.165	Tie-line trip	Aldeadávila (RE)–Pocinho (REN) (ckt 1) 220 kV	
56	PT	12:33:24.434	Line trip	Lagoaça (REN)–Armamar (REN)	
57	PT	12:33:26.078	Generation loss	Hydro	45.81
57	PT	12:33:26.080	Generation loss	Hydro	45.82
57	PT	12:33:26.081	Generation loss	Hydro	45.96
58	PT	12:33:27.154	Generation loss	Hydro	24.10
59	PT	12:33:29.225	Generation loss	Hydro	39.36
59	PT	12:33:29.317	Generation loss	Hydro	61.40
60	PT	12:33:37.800	Generation loss	Hydro	49.04

Table 3-1: Sequence of events (imbalances shown in red for >500 MW, in orange for >50 MW, and in yellow for the remainder)

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[26] This pumping unit was tripped by the undervoltage protection function, without the underfrequency protection function having been triggered beforehand.

[27] This pumping unit was tripped by the loss of synchronism protection function, without the underfrequency protection function having been triggered beforehand.

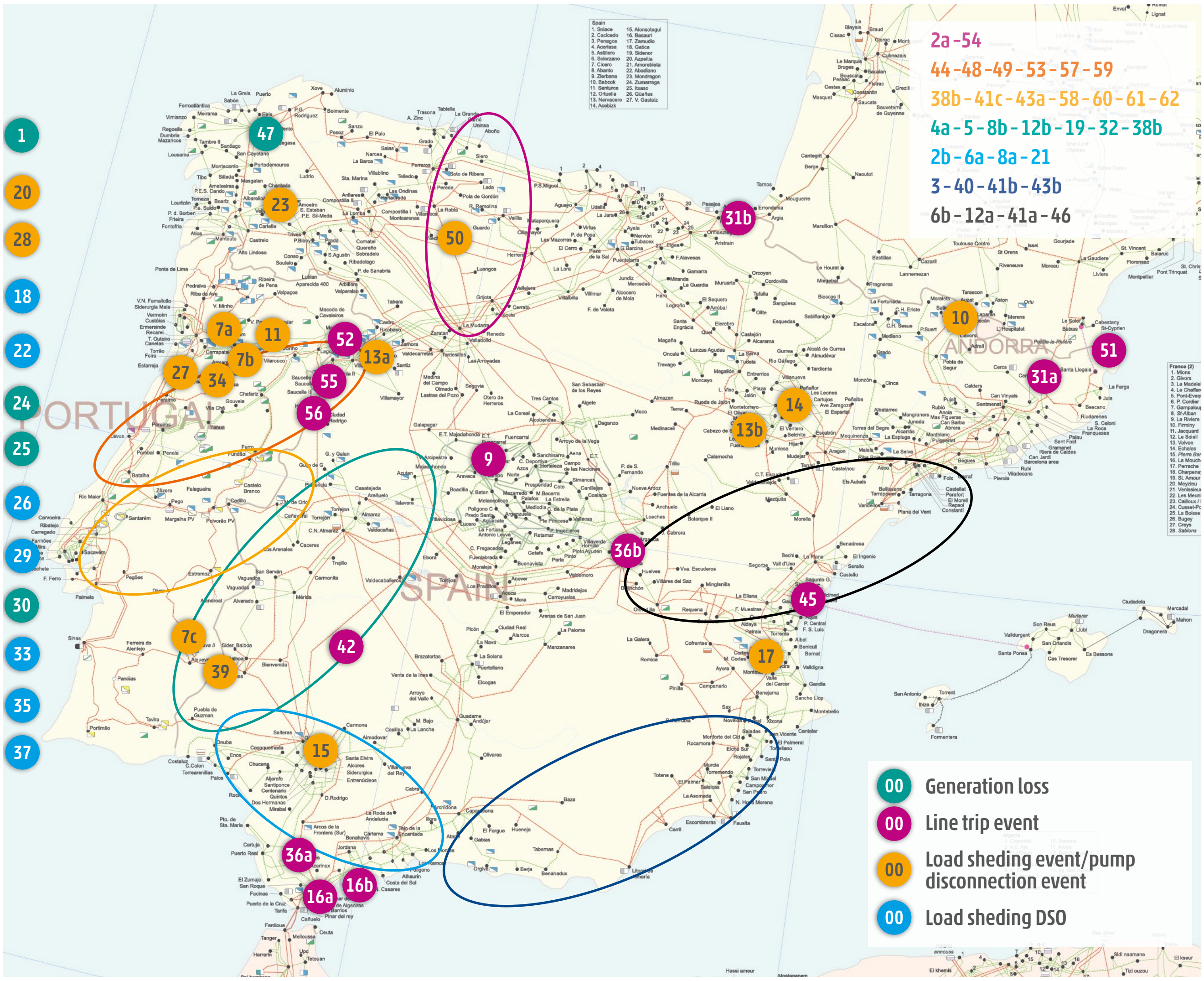

Figure 3-1: Temporal and spatial representation of the events in the Spanish and Portuguese power system. The events noted on the left side of the map refer to distributed resources. The events mentioned on the top-right corner of the map are not precisely located on the map for confidentiality reasons: their approximate location is indicated by the circled area in the corresponding colour (e.g. event 2b is located in the area outlined in blue)

The sequence of the main events can be summarised as follows:

- From 12:32:00.000 to 12:32:57.000, there was a net load increase of approximately 317 MW on the distribution grids (**event 1**) as well as a loss of approximately 208 MW of distributed wind and solar generation facilities >1 MW, in both northern (**event 2a**) and southern (**event 2b**) Spain.

  At the time of writing, the cause and exact location of these events remain unknown, due to the TSO's limited observability[28] at the medium/low voltage level. Estimates were made using phasor measurement units (PMU) measurements at the interconnections, along with known variations in generation (aFRR). In particular, the Expert Panel has not yet determined whether the increase in net load (event 1) is due to the disconnection of small embedded generators <1 MW (mainly rooftop PV) or to an actual increase in load or to a combination of both.

- Some milliseconds (ms) after 12:32:57, a generation evacuation power transformer owned by a third party A and operated by third party B in the 400 kV transmission substation (TS) 1 – Granada tripped (**event 3**). This transformer transfers power from several wind and solar power plants to the Spanish transmission system. At the moment of the trip, the active power flow on this transformer was approximately **355 MW**, from the 220 kV side to the 400 kV side.

  The owner reported the cause of the trip as the overvoltage function on the 220 kV side of the transformer. As reported by the owner, at 12:32:57.155, the protection equipment on the 220 kV side recorded a voltage of 242.9 kV on phase B and tripped (the protection setting for the overvoltage protection relay was Ut = 110 % Un (242 kV), t = 0 s). At 12:32:57.215, coinciding with the transient associated with the circuit breaker opening, phases A and C tripped (at registered voltage 244.3 kV).

  The owner provided no voltage measurement for the 400 kV side of the transformer. A COMTRADE recording is available at the 400 kV TS 1 – Granada, coinciding with the tripping of the 220 kV transformer circuit breaker. This recording was captured by a transmission line protection system at the aforementioned substation: the voltage value observed in this record at the moment of the transformer trip was 417.9 kV.

  In a facility connected downstream of the 400/220 kV transformer that tripped, and linked via a 500-metre line to the 220 kV Generation substation 1 – Granada, an oscillography record is available with voltage measurements at the 220 kV level, showing that the voltage was 237.5 kV at the moment of the transformer trip. According to SCADA data, the reading at 12:32:56 was 233.4 kV (1.061 pu) at the transformer on the 220 kV voltage side.

- In the 12:33:16–12:33:17 time frame, an additional **725 MW** of thermo-solar and PV generation tripped in 400 kV TS 1 – Badajoz and 400 kV TS 2 – Badajoz in central-southern Spain (**event 4**).

  In the 400 kV generation substation (GS) 1 – Badajoz, an evacuation line tripped at 12:33:16.460 for unknown reasons. GS 1 – Badajoz is a collector substation for generation evacuation, with its connection point located at the 400 kV TS 1 – Badajoz. At the time, the disconnected generation plants were injecting 582 MW into the grid. Immediately afterwards, the generation connected downstream of the transformer disconnected due to overfrequency.

  The transmission line monitored by the PMU at 400 kV TS 1 – Badajoz was out of service during the event; therefore, no PMU measurements from this substation are available. The last SCADA voltage reading in substation 400 kV TS 1 – Badajoz (at an unknown phase) at 12:33:10 was 434.0 kV at evacuation bay, 430.5 kV at busbar 1, and 429.9 kV at busbar 2.

  At 12:33:16.420, the positive sequence voltage in the PMU at 400 kV TS 3 – Cáceres was 431.72 kV, and the voltage measure in phases A, B, and C in the same PMU were 428.1, 436.8, and 430.2 kV, respectively.

  At 12:33:16:460, the positive sequence voltage at 400 kV TS 3 – Cáceres was 435.4 kV, while the power flow was 851.7 MW towards a substation in the north. These values already reflected the changes caused by the generation loss. At 12:33:16.680, the positive sequence voltage at this substation reached 440.0 kV. The voltage measured by the PMU then remained above 440 kV until 12:33:23.600.

  A PV power plant connected to it, 400 kV TS 2 – Badajoz, tripped at 12:33:16.820 for unknown reasons. At the time, the plant was injecting 145 MW into the grid.

  The PMU located in the substation was out of service at the time of the event. The last SCADA voltage reading in the substation was 436.1 kV at 12:33:16.

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[28] Generation larger than 1 MW must send real-time data on production with a granularity of 12 seconds to the TSO through the SCADA.

- In the 12:33:17–12:33:18 time frame, approximately **930 MW**[29] of wind and solar generation disconnected in the 400 kV TS 1—Segovia, 400 kV TS 1—Seville (event 5a), 400 kV TS 1—Badajoz, 220 kV TS 1—Huelva, 220 kV TS 1—Cáceres, and 220 kV TS 3—Badajoz (**event 5b**).

  After event 5b, the high voltage and low frequency profiles in the Spanish transmission system led to cascading tripping of many other generators, both conventional and renewable.

- At 12:33:20.473, the AC interconnection to Morocco tripped due to underfrequency (the frequency threshold of the protection is 49.5 Hz). At the same time, pump storages disconnected both in Spain and Portugal in line with the underfrequency defence plan schemes.

- At 12:33:21.535, the AC interconnection to France was lost, leading to a system split between the Iberian Peninsula and the CE SA due to a loss of synchronism relay intervention.

- After the AC separation of the Iberian Peninsula caused by the AC synchronism loss, the power imbalance continued to increase, causing the frequency to drop further. The HVDC link between Santa Llogaia and Baixas tripped at 12:33:23.960, completing the electrical separation of the Iberian Peninsula from France.

3.1.2 Evolution of Electrical Quantities During the Incident

This subchapter describes the evolution of the main quantities that characterise the event in the main high voltage (HV) buses of the affected TSO networks (i.e. voltage magnitudes and phases, frequency, and active power in the minute before the blackout event).

The data used for these factual analyses are collected from PMUs installed across the affected TSOs grid.

Figure 3-2 shows voltage magnitude heat maps at various moments in the Iberian Peninsula and southern France. The figure clearly shows the increase of voltage magnitudes starting in the Spanish network. At 12:32:58, the positive sequence voltage magnitudes were over 1.05 pu. At 12:33:17, maximum voltage magnitudes reached 442.5 kV (1.106 pu) in the Spanish grid. One second later, at 12:33:18, voltage magnitudes reached 451.4 kV (1.128 pu), with higher values in the southern part of Spain.

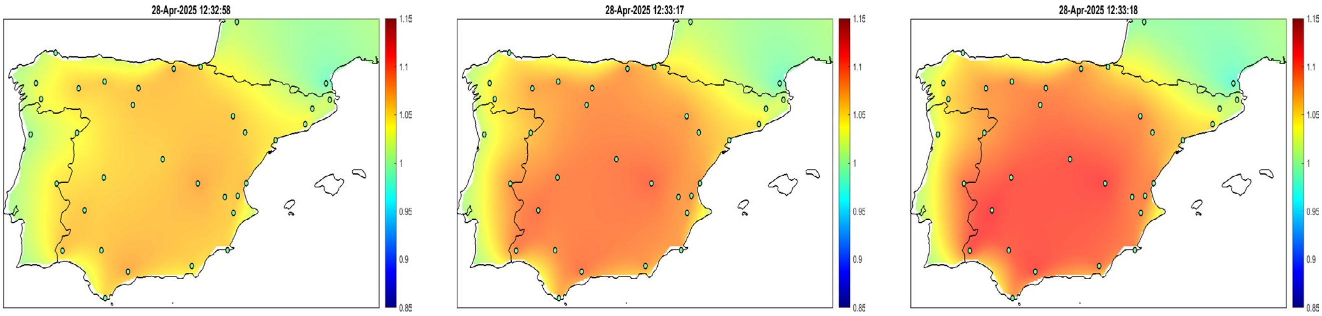

Figure 3-2: Heat map of the Iberian Peninsula for the temporal instant (a) 12:32:58, (b) 12:33:17, and (c) 12:33:18 showing voltage magnitudes at different substations

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[29] This is the total amount of power that could be estimated based on measurements. However, the effects on frequency deviation suggest that this trip could have been up to 1,100 MW.

3.1.2.1 Spain

The dataset used for the analysis reported in this section comes mainly from Spanish PMU devices located as shown in Figure 3-3.

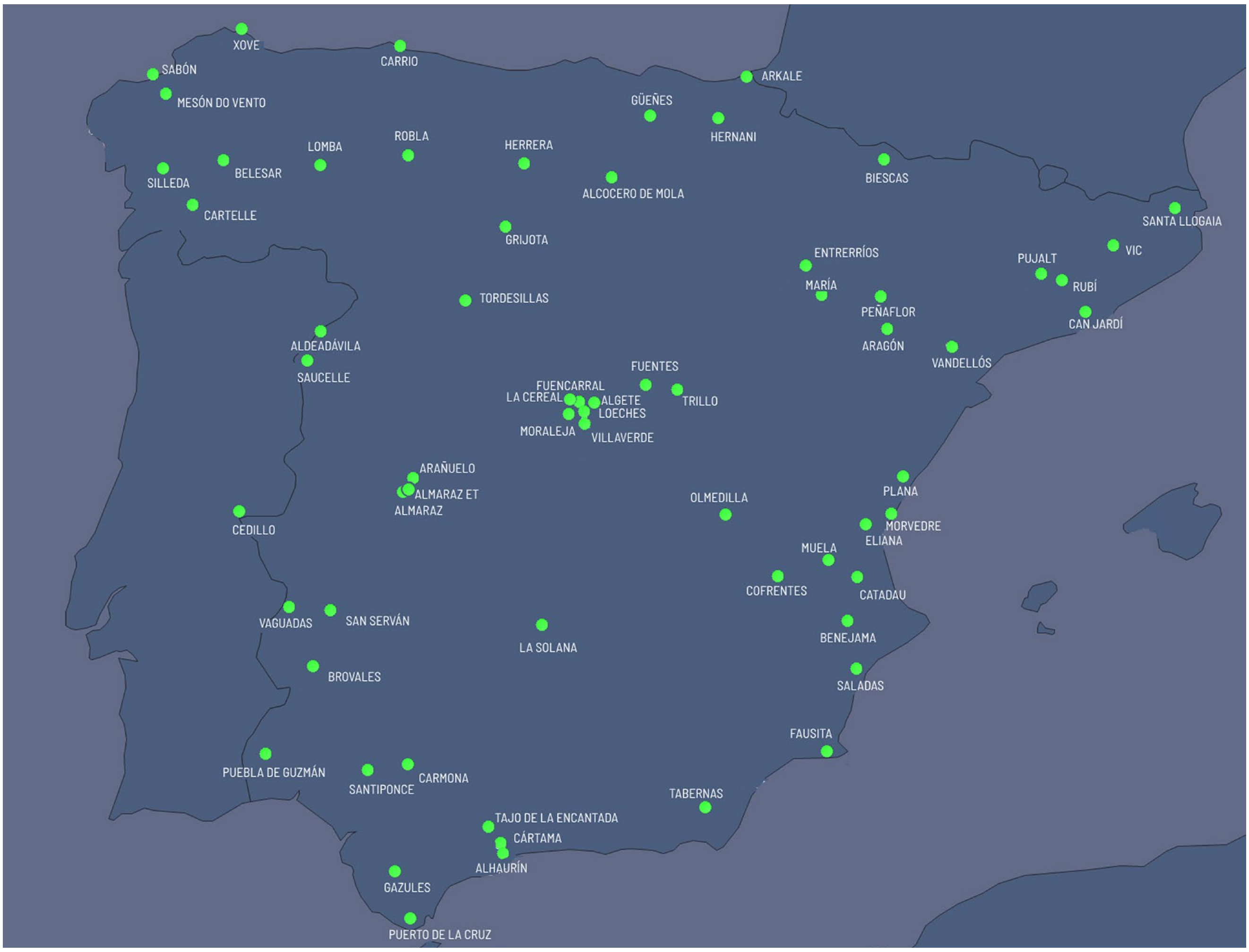

Figure 3-3: Location of PMU devices in the Spanish power system

Figure 3-4 shows the evolution of the electrical quantities in the main buses of the Spanish power system from 12:32:00 to 12:33:25 on 28 April 2025.

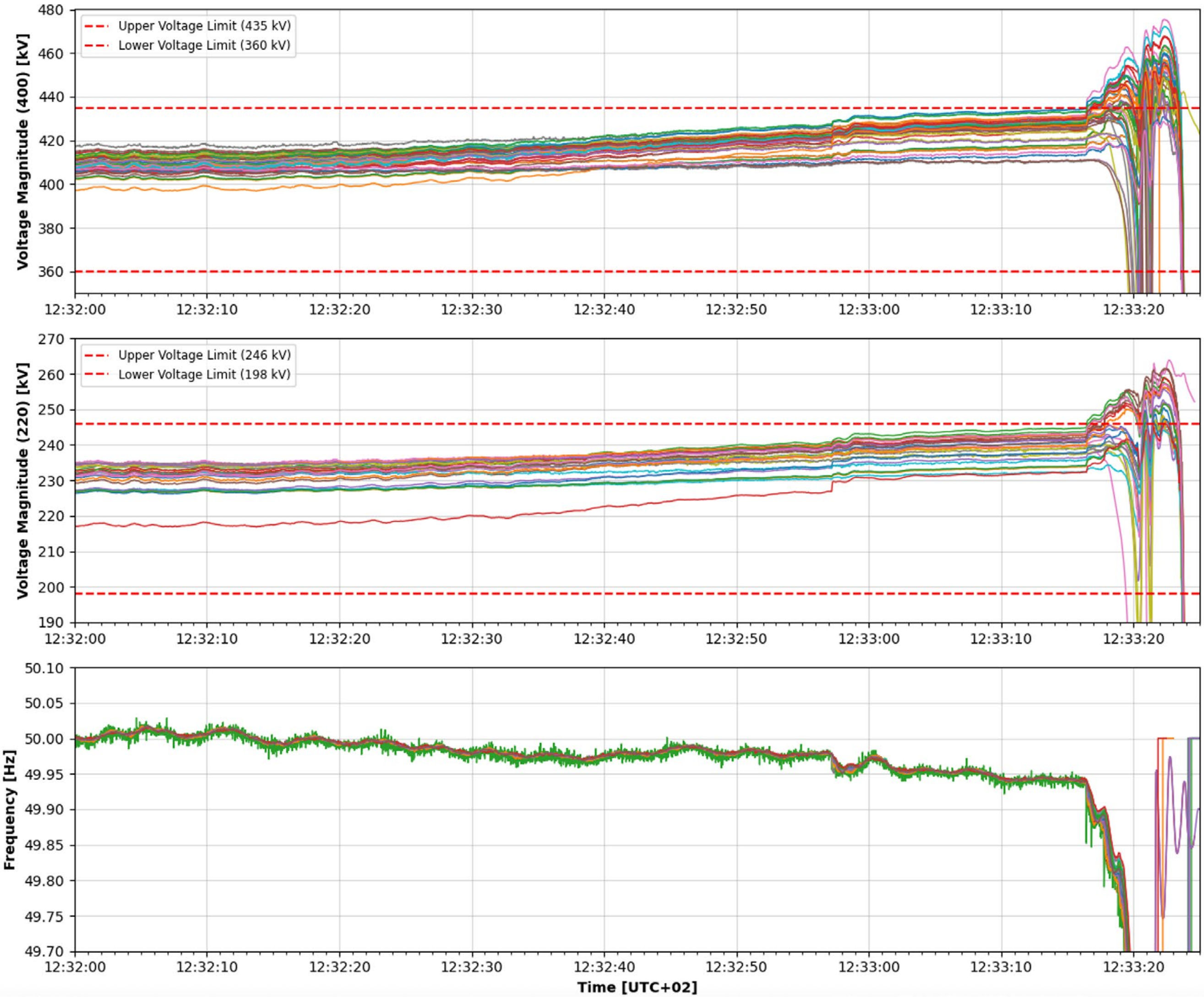

Figure 3-4: Evolution of the electrical quantities in the Spanish power system during the event

3.1.2.1.1 Voltage

Admissible voltage ranges in the Spanish transmission system

More detailed explanation of voltage limits in Spain is included in Chapter 2, Section 2.6. According to these prescriptions, voltage in Spain can range:

- from 375 to 435 kV for the 400 kV network
- from 200 to 245 kV for the 220 kV network

Voltage profiles in the Spanish transmission system

Unless otherwise specified, references to PMU voltage values in this section refer to the positive symmetrical voltage component, defined as $V_+ = {}^1/_3 \times (V_a + a \times V_b + a^2 \times V_c$, where $a = e^{j120°}$.

Voltage protection of transmission lines is based on the measurement of phase-to-ground voltage. Voltage magnitude profiles, shown in Figure 3-5, indicate that voltages at the measuring points on the transmission system remained within operational limits until 12:33:16 (event 4) at all buses in the observed perimeter, both on the 400 kV and 220 kV voltage levels. At 12:32:00, voltage began to increase rapidly, possibly also due to the progressive disconnection between 12:32:00 and 12:32:55 of 208 MW of wind and solar generation connected to the distribution grids, along with an increase of 317 MW in net load that cannot be directly identified but possibly involve rooftop PV generation (total disconnection of roughly 525 MW). The Expert Panel made this preliminary assessment based on the flows measured by PMUs at the borders with neighbouring countries.

At 12:32:57, the trip of a power transformer in the "400 kV TS 1 – Granada" (event 3) caused the disconnection of 355 MW generation from PV, wind, and thermo-solar power plants. The reactive power being absorbed through this transformer was 165 Mvar. At that time, the voltage in the HV network further increased almost instantaneously, while remaining below 435 kV (i.e. within operational limits).

At 12:33:16.680, after the disconnection of generation connected to "400 kV TS 1 – Badajoz", the positive sequence voltage in at least one bus in the Spanish system exceeded 440 kV (1.10 pu). The disconnections in the "400 kV TS 2 – Badajoz" substation at 12:33:16.820 (completing event 4) led to voltage beyond operational limits at several buses in the Spanish transmission system. The loss of reactive power absorption at those two substations was 165 and 38 Mvar, respectively.

At 12:33:17, the disconnection of approximately 930 MW of PV, and wind power plants connected to several 400 kV and 220 kV substations led to voltages exceeding 440 kV in several substations.

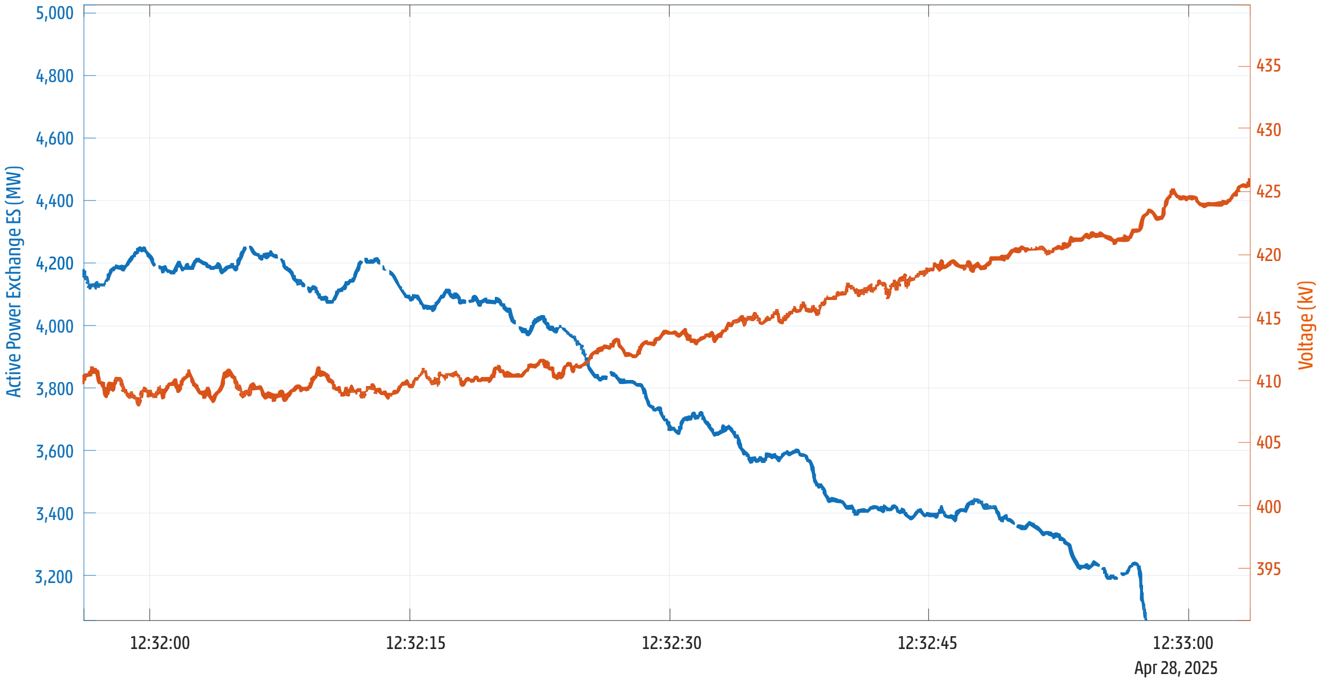

Figure 3-5: Evolution of the voltage in the Carmona substation and of the net active power exchange position between Spain and neighbouring countries between approximately 12:32:00 and 12:33:00 (source: PMU data from Red Eléctrica)

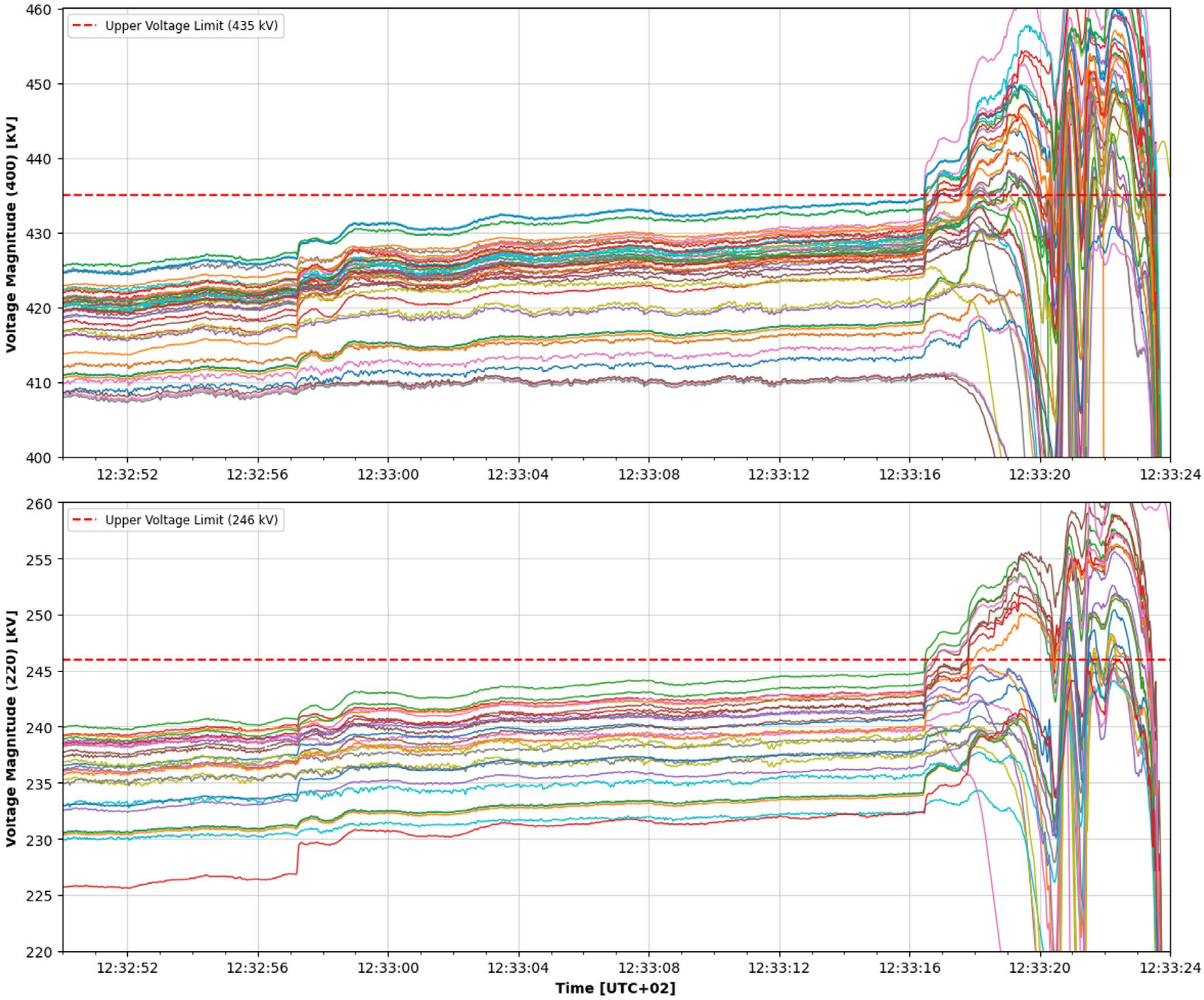

Figure 3-6: Voltage in the Spanish power system during the incident

At this stage, voltage control was fully lost, with cascading disconnection of further power generators leading to the loss of synchronism of the Iberian Peninsula with continental Europe. The low frequency (49.5 Hz) triggered underfrequency protection in Morrocco, and the border was opened at 12:33:20.4.

The loss of synchronism triggered DRS (*Débouclage suite à Rupture de Synchronisme, translated in this document as loss of synchronism protection* – see Section 3.2.2.4) on the France—Spain border, leading to the AC separation of the Iberian Peninsula from the French power transmission system at 12:33:21.5, disconnection of the ES—FR HVDC at 12:33:23.960, and blackout at 12:33:27.

Figure 3-7 depicts the overall accumulated generation loss[30] in the Iberian Peninsula system and the maximum voltage profile on the 400 kV network.

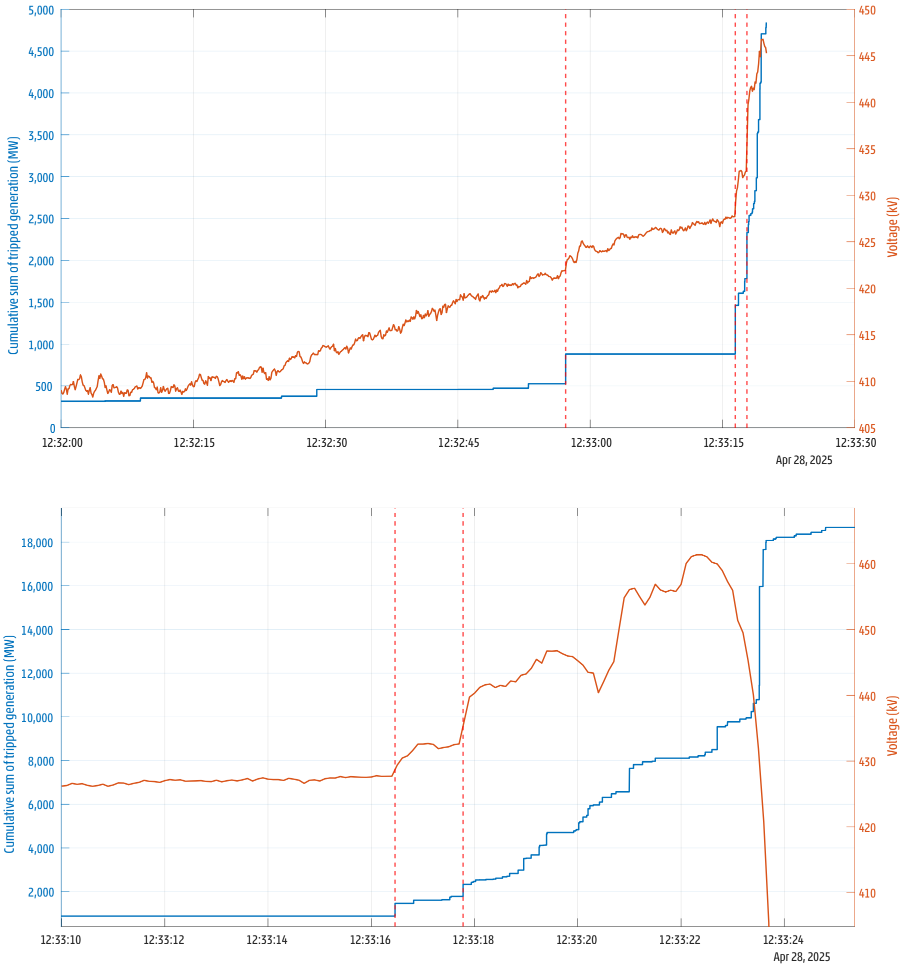

Figure 3-7: Accumulated generation loss in the Iberian Peninsula system vs 400 kV maximum voltage. Dotted lines represent the three main generation disconnection events (event 3, event 4, and event 5).

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[30] Accumulated generation loss is based on the events reported in Table 3-1. It is important to note that this is to the best of the Task Force's and affected TSOs' knowledge; some additional generation or load trips may be missing, as the events occurred within a very short time frame, and the grid is not fully observable with high-resolution monitoring systems.

3.1.2.1.2 Frequency and Rocof

The sequence of events caused the frequency in Spain to rapidly deteriorate after the loss of generation. Figure 3-8 shows the frequency measurements and RoCoF in the last minute before the blackout. The RoCoF was calculated using a 500 ms sliding window accordingly to the best practices suggested by ENTSO-E.

Figure 3-8: Frequency and RoCoF in the Spanish power system during the incident

In the minutes before the event, the frequency in Spain was stable, with typical fluctuations for a large, interconnected system. Before 12:32:00, the frequency was around the nominal value of 50 Hz. Following the progressive increase in net load (event 1) and loss of generation (events 2a and 2b) at distribution level, the frequency began to decrease, dropping to 49.98 Hz from 12:32:00 to 12:32:55.

At 12:32:57, the sudden disconnection of 355 MW of generation (event 3) caused the frequency to drop further, to 49.94 Hz.

At 12:33:16, the loss of an additional 725 MW of generation (event 4) led the frequency to further decrease, to around 49.9 Hz. From that point onwards, the frequency in Spain and Portugal began deviating from that of continental Europe and did not return to synchronism.

At 12:33:17, the disconnection of at least 930 MW of generation (event 5) led to frequency values of around 49.8 Hz in Spain and Portugal.

Before 12:33:20, at least 2,600 MW more generation was disconnected, and the frequency in the Iberian Peninsula dropped to 48.5 Hz. At the same time, the frequency in continental Europe reaccelerated towards 50 Hz. The AC interconnection lines between France and Spain were still in service at that time, but the Iberian Peninsula lost synchronism with continental Europe at around 12:33:19.62. The loss of synchronism caused large amplitude swings in electric power across the AC interconnection lines between Spain and France, as shown in Figure 3-10 (middle).

In the following five seconds, cascading events caused a further ~–8,000 imbalance within the Iberian Peninsula transmission system, caused by the disconnection of ~7,000 MW of generation and the disconnection of ~15,000 MW of loads and pumping hydro from the defence system. Table 3-2 shows a breakdown of the disconnected power by type of energy source.

Type of energy source	Aggregated disconnected power (MW)
Combined Cycle	719.0
Load	-8,504.3
Nuclear Power Plant	3,390.0
Pumped Hydro	-2,756.0
PV	3,198.1
PV and Thermo-Solar	85.3
Wind	48.9
Wind and PV	168.0
Total generation	7,609.3
Total demand + Pump	-11,260.3

Table 3-2: Focus of power disconnection from 12:33:20 to 12:33:25

Figure 3-9 depicts the overall generation loss in the Iberian Peninsula system and the frequency trajectory during the incident.

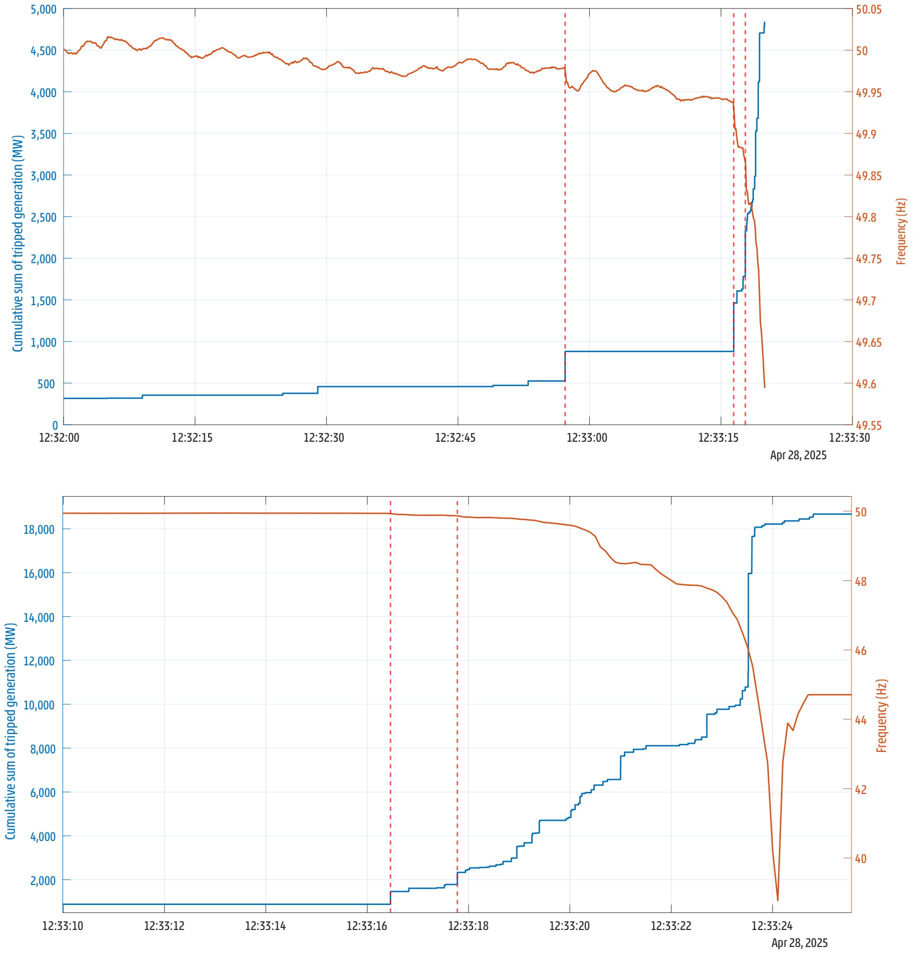


Figure 3-9: Cumulative power imbalance in the Iberian Peninsula system vs average frequency.

Figure 3-10 shows frequency and RoCoF in the Spanish transmission system estimated over a 500 ms sliding window, as suggested by the most relevant scientific literature and ENTSO-E best practices on the topic.

It can be observed that immediately after 12:33:20, the absolute values of RoCoF were well beyond 1 Hz/s.

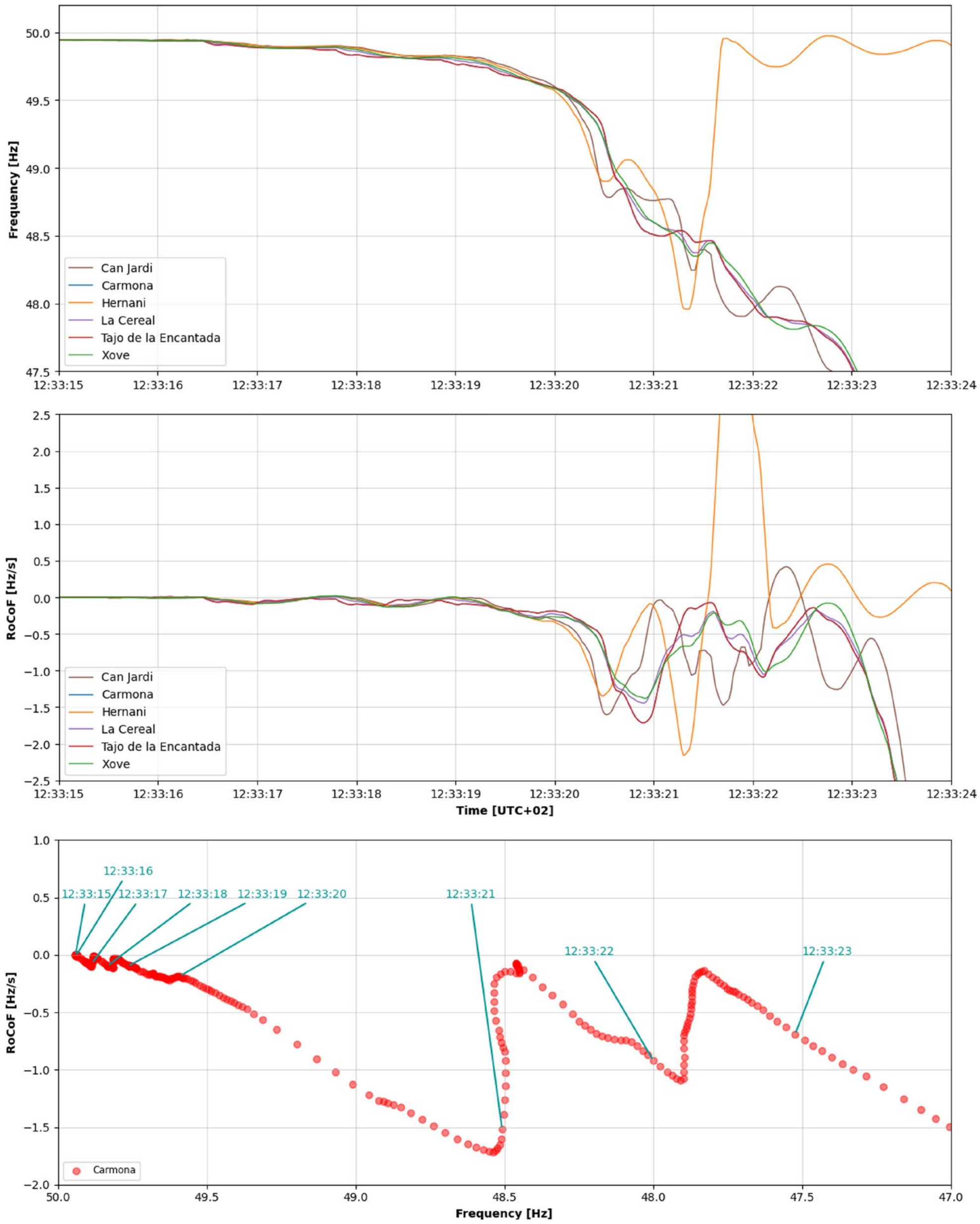


Figure 3-10: Frequency and RoCoF in the Spanish transmission system

Figure 3-10 shows how in certain substations near the France–Spain border, high RoCoFs were observed during the transient caused by the loss of synchronism. During the transient associated with the loss of synchronism, significant frequency drops were recorded in the border area when power was flowing from Spain to France; conversely, when power was flowing from France to Spain, sharp frequency increases were observed. Therefore, the RoCoFs observed near the France–Spain border were not only caused by the demand generation imbalance within the Iberian Peninsula but were also strongly influenced by the transient associated with the loss of synchronism. This occurred due to the loss of a massive amount of generation in the Iberian Peninsula, which led to such a high level of active power import from France that the stability angle (90°) in the border was exceeded. Beyond this angle difference, any further increase results in a decrease in imported power rather than an increase, thereby worsening the generation-demand imbalance in the system. When the angle difference reaches 270°, at which point electricity exports from Spain to France reach their maximum level, power exports from Spain to France begin to decrease. This leads to a reversal in the direction of cross-border flows, with power starting to be imported from France into Spain. This process continues to repeat with increasing speed due to the growing frequency difference between systems, until the systems are fully separated.

To more accurately assess the impact of the demand generation imbalance on frequency during the early stages, Figure 3-11 shows the frequency and RoCoF at the La Cereal substation, located in the north of Madrid – therefore near the centre of the Iberian Peninsula – along with the total power exchange between the Iberian Peninsula and France and Morocco.

Figure 3-11 shows that the RoCoF of −1 Hz/s was reached at 12:33:20.560. At that moment, Spain had experienced the disconnection of at least 5,750 MW of generation and the load shedding of nearly 2,500 MW from pumped-storage facilities. In Portugal, 2,100 MW of pumped-storage load had also been shed. Additionally, due to the loss of synchronism, the Iberian Peninsula was exporting 5,440 MW – representing a difference of approximately 5,000 MW compared to the value at 12:33:16.460 – thus further increasing the existing demand generation imbalance in the Iberian Peninsula. Therefore, at the moment when the rate of change of −1 Hz/s was first reached, the demand generation imbalance in the Iberian Peninsula amounted to at least 6,150 MW.

The actual imbalance at that moment may have been even greater, as the precise disconnection times for most of the generation could not be determined, and it is also possible that rooftop PV were disconnected at that time Figure 3-11 also shows that the RoCoF threshold of −2 Hz/s – established in the Spanish TED 749/2020 Order and Portuguese regulation Portaria 73/2020 as the value that generation units should withstand – is reached at approximately 12:33:23.360, nearly seven seconds after event 4a occurred (it should be noted that only power generation modules (PGMs) connected after the regulation's entry into force are required to comply with this threshold). Following the disconnection of a large amount of generation triggered by the overvoltage event in the system, the estimated RoCoF value during the transient exceeded the withstand capabilities for which the large new generators were designed.

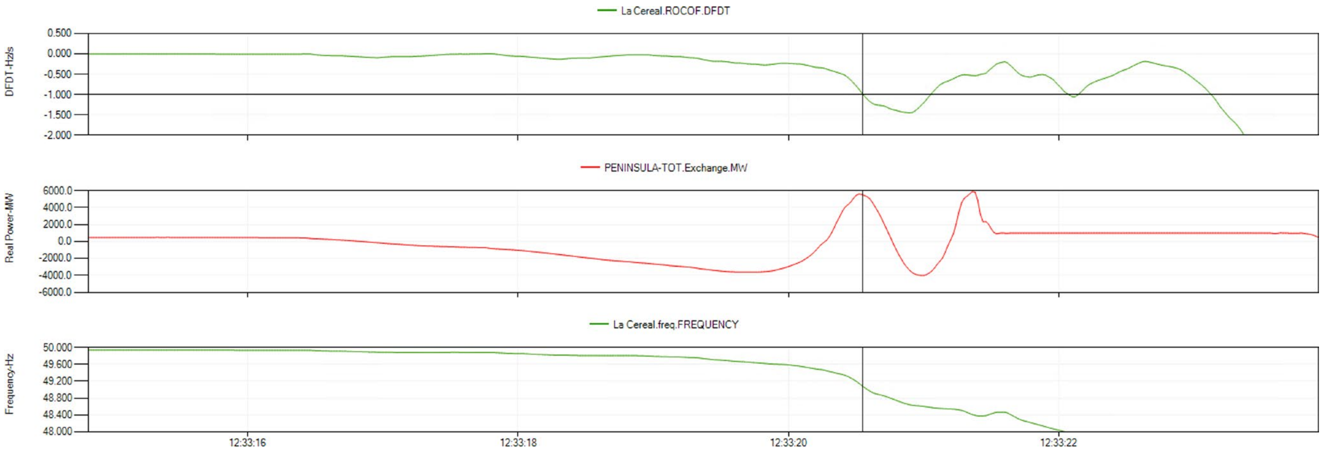


Figure 3-11: RoCoF and frequency in the La Cereal 400 kV substation and total exchange between the Iberian Peninsula and France and Morocco.

3.1.2.1.3 Active Power Flow on the Border

Figure 3-12 depicts the evolution of active power flows on the Spanish power system borders to France, Portugal, and Morocco. Positive values are exports from Spain.

The connections with Morocco and Portugal did not experience any changes – the flows remained constant throughout the pre-event period at a stable value of 750 MW and 2,100 MW, respectively. On the border with France, active power flows exhibited a visible change (a decrease of 1,500 MW) between 12:32:00 and 12:33:00.

After the 4a event, Spain began importing until the lines with France and Morocco tripped due to the intervention of loss of synchronism relays.

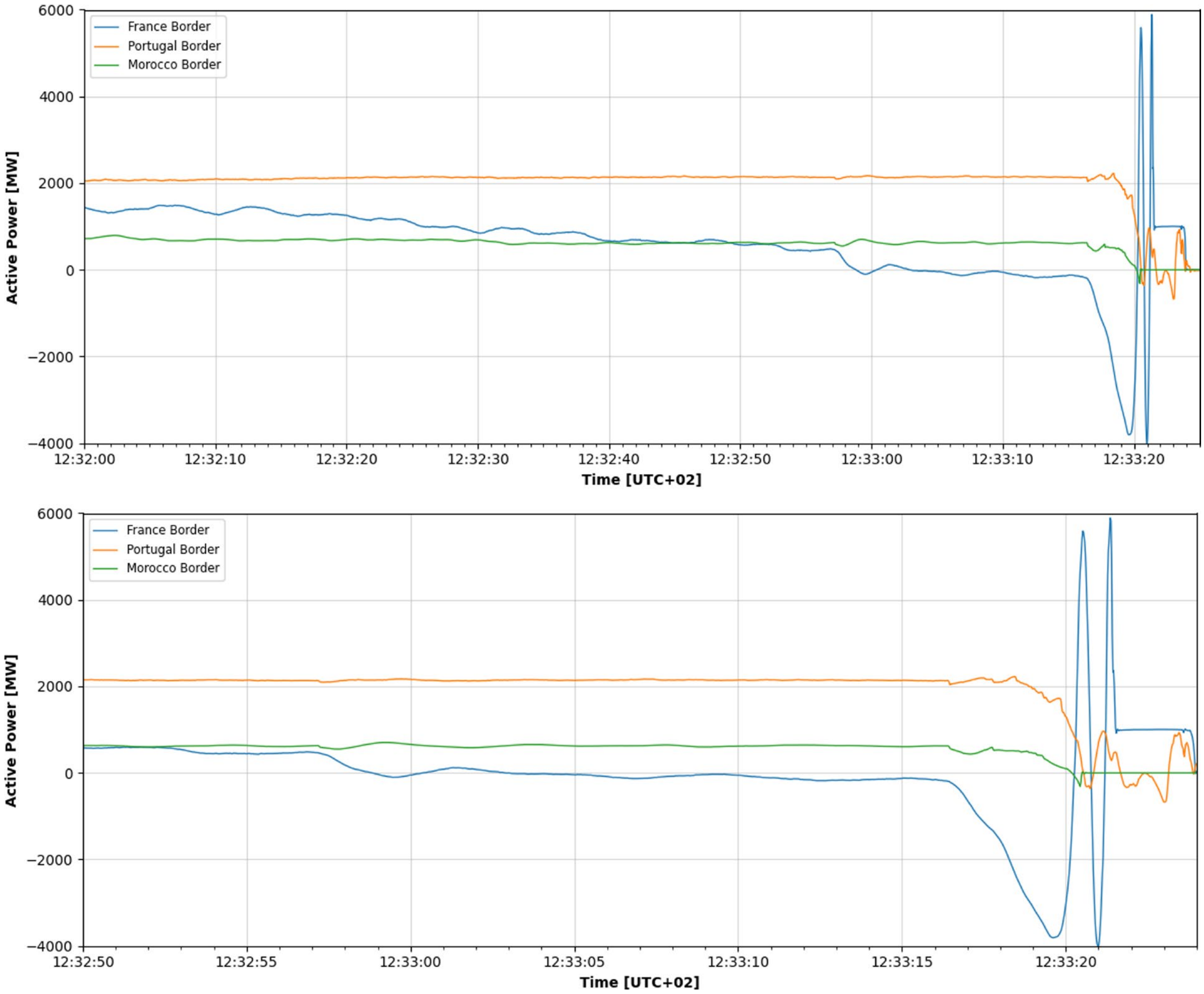


Figure 3-12: Active power on the Spanish power system borders.

Figure 3-13 shows the correlation between voltage magnitude and angle with respect to the net position of the Spanish grid (which is mainly influenced by the exchange with France). The graphs show that as soon as exchange began to decrease – due to the events 1, 2a and 2b – the voltage increased noticeably.

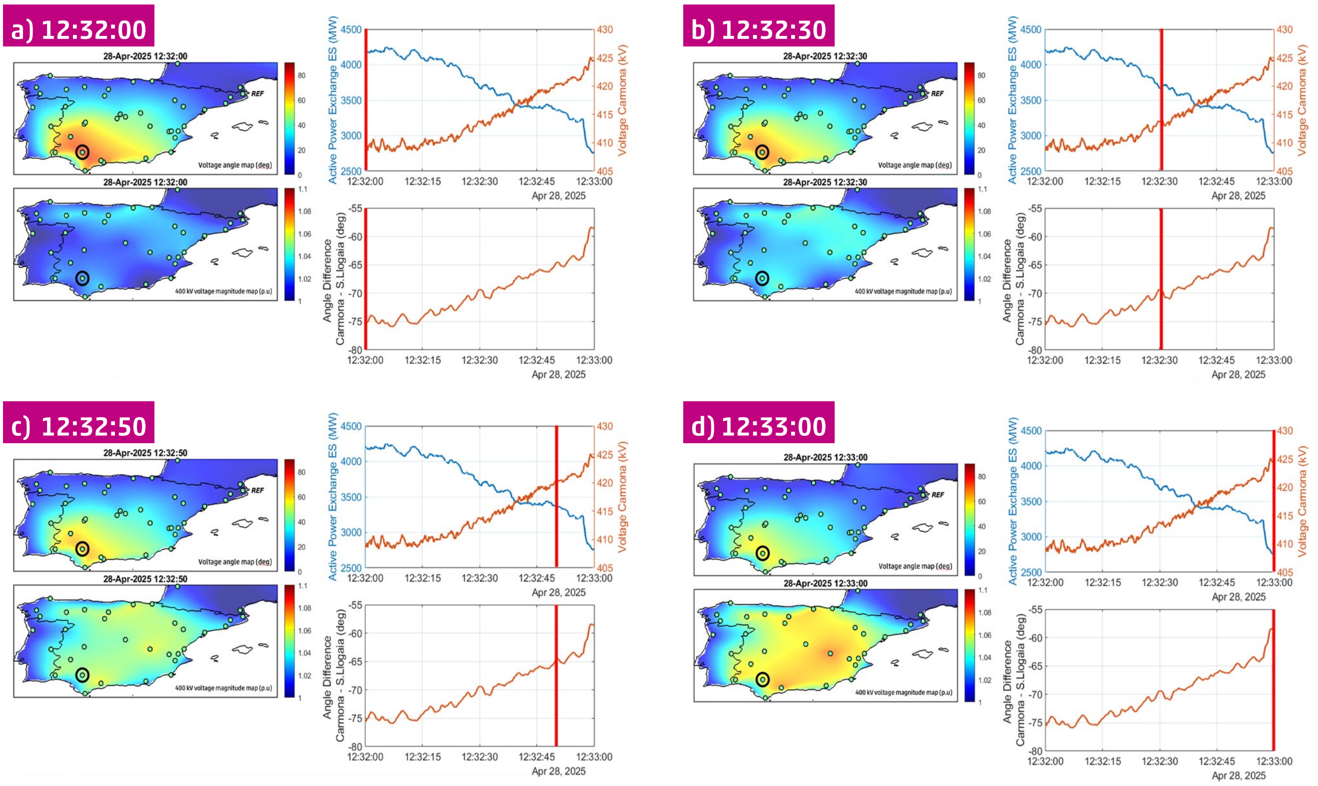


Figure 3-13: Voltage phasors vs physical net position of Spain (the reference angle is indicated in the maps as REF)

3.1.2.2 Behaviour of the HVDC link

This section presents the behaviour of the HVDC link Santa Llogaia–Baixas. At the time the incident began (12:32:00), the HVDC was set to the following setpoints:

- Active power: 2 × 500 MW in the Spain to France direction
- AC voltage setpoint at the Spanish end: 405 kV
- AC voltage setpoint at the French end: 395 kV

Figure 3-14 shows the power flow and AC voltage on the PMU in Santa Llogaia from 12:32:00 to 12:33:25.

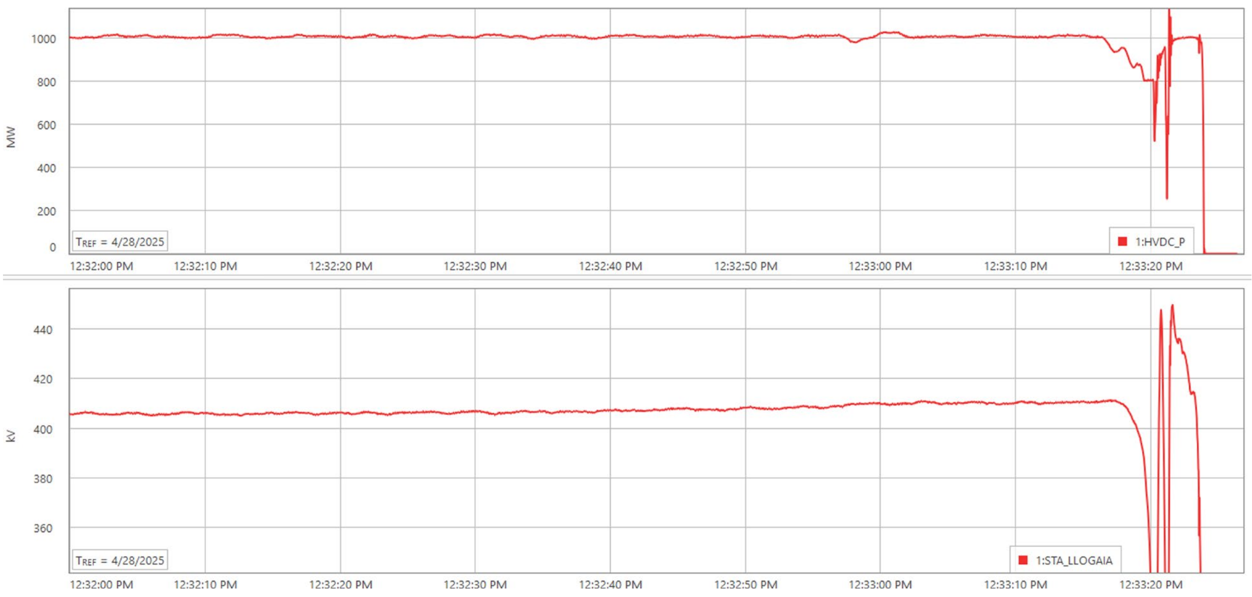


Figure 3-14: Active power through the both HVDC links and voltage at Santa Llogaia 400 kV

With regard to the power flow on the France–Spain border, Figure 3-15 complements Figure 3-12, showing the active power flow on the wo HVDC pole and in the 3 AC lines in service (2 of 400 kV and 1 of 220 kV) for the time frame 12:33:15 - 12:33:25. The chart shows the flow on the AC lines dropping to 0 MW at 12:33:21 following the line trips triggered by the loss of synchronism protections. The HVDC continued exporting energy from Spain to France until 12:33:24, when the flow on the HVDC line dropped to zero as well, after the voltage collapse in Santa Llogaia.

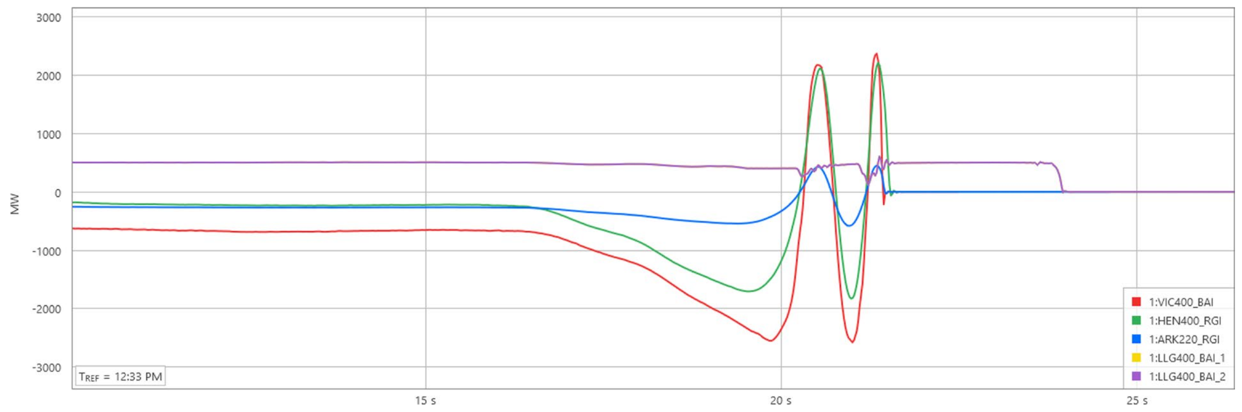


Figure 3-15: Active power through France–Spain interconnections (positive indicates power flow from Spain to France)

At 12:33:00, the voltage at the HVDC nodes was 393 kV in Baixas and 410 kV in Santa Llogaia. The HVDC was absorbing 2 × 440 Mvar of reactive power on the French side and injecting 7.7 Mvar of reactive power on the Spanish side.

3.1.2.3 Portugal

The dataset used for the analysis reported in this section comes from five PMU devices located in the Portuguese power system. Figure 3-16 depicts the evolution of the electrical quantities in the main buses of the Portuguese power system during the event.

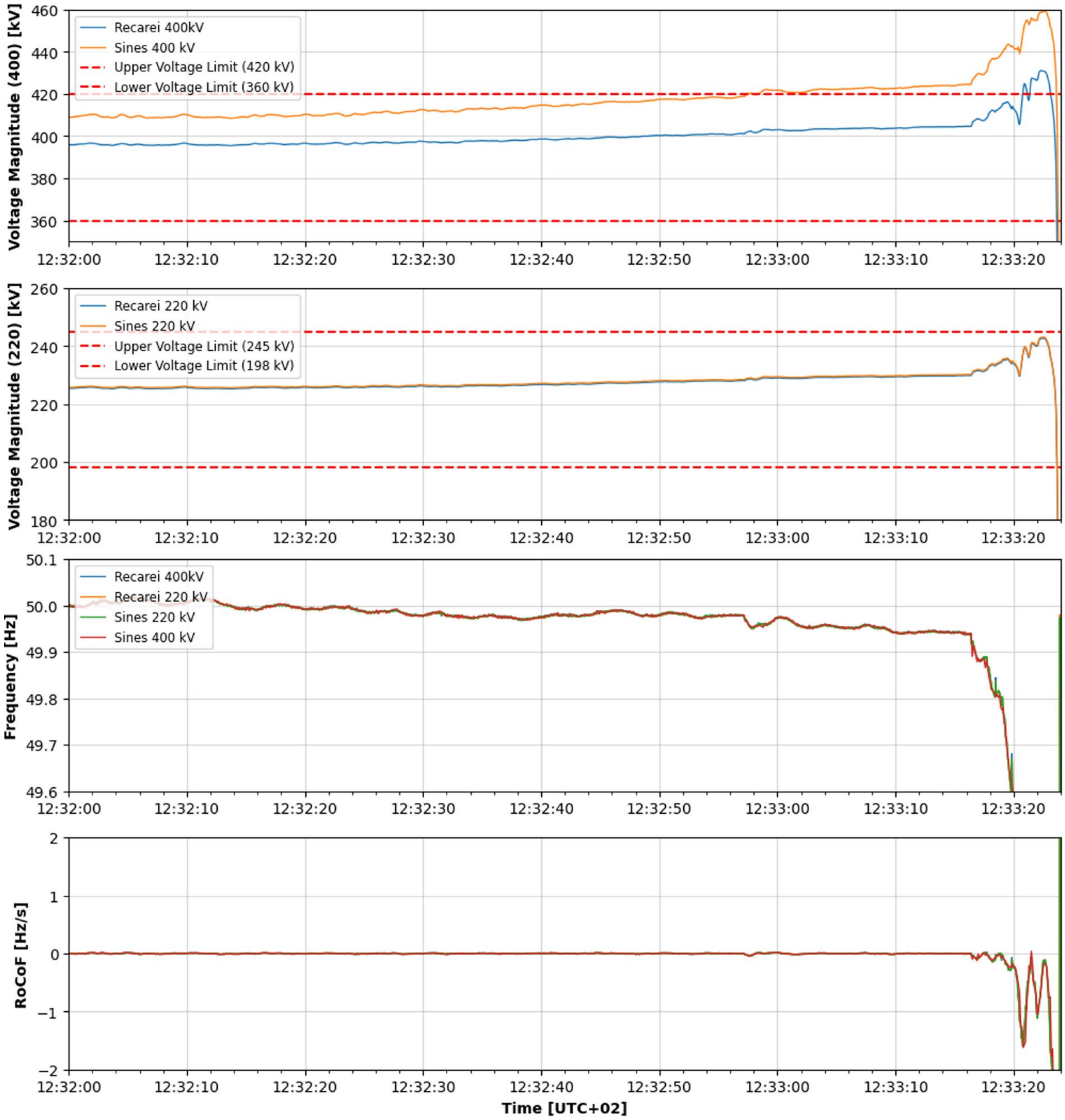


Figure 3-16: Evolution of the electrical quantities in the Portuguese power system during the event

Looking at the voltage magnitude profiles on the transmission system, it can be observed that from 12:32:00 to 12:32:57, voltages rose on average by 3 % at 400 kV buses and 5.5 % at 220 kV buses within the observed perimeter, while remaining within normal operating limits.

Regarding frequency and RoCoF, the same considerations for Spain apply. Portuguese regulation Portaria 73/2020 of 16 March, which corresponds to the national implementation of the EU Requirements for Generators (RfG 2016/631), establishes the same RoCoF limit of 2 Hz/s.

3.1.2.4 France

The dataset used for the analysis reported in this section comes from PMU devices located as shown in Figure 3-17.

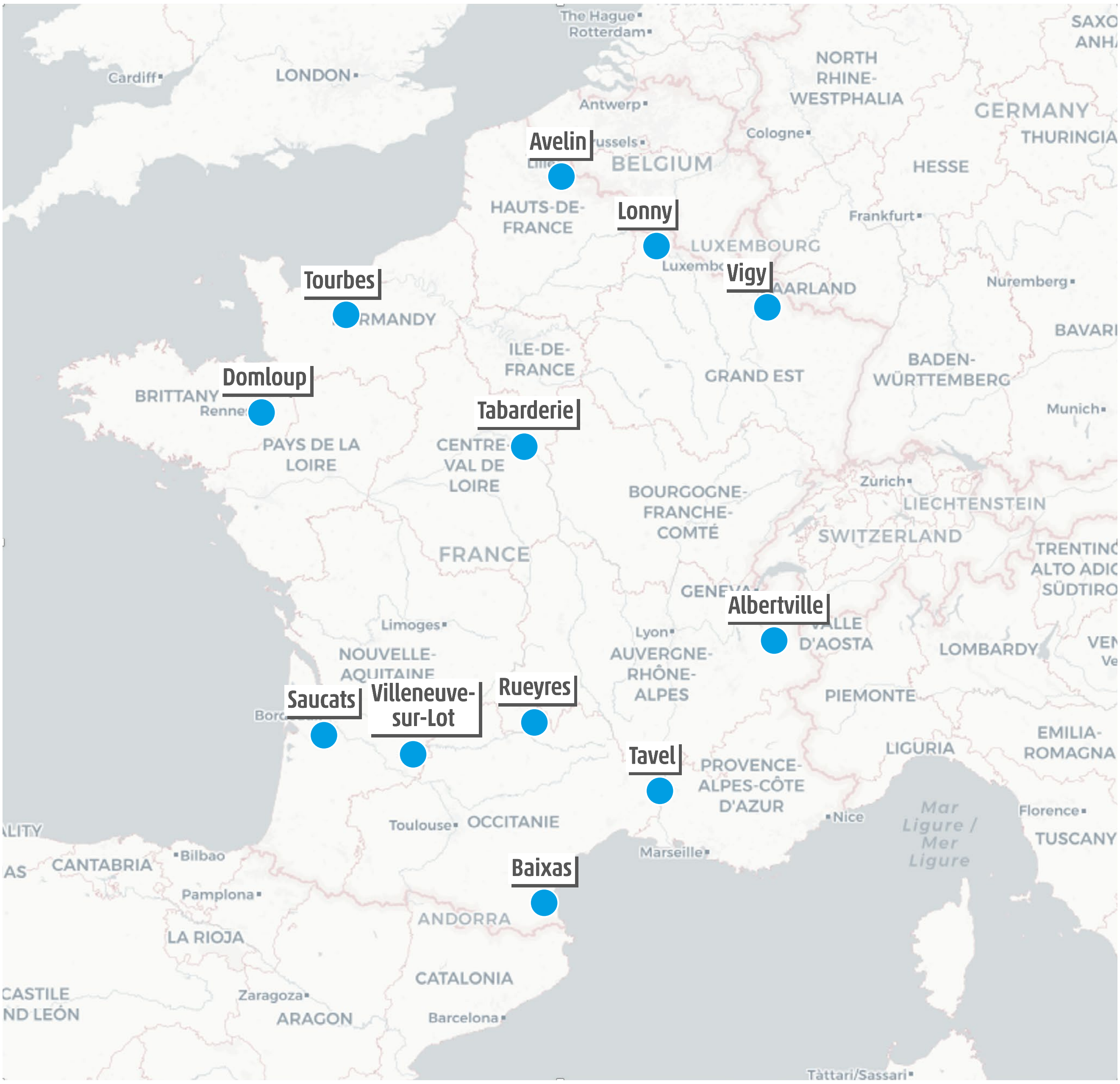


Figure 3-17: Location of PMU devices in the French power systems

Figure 3–18 depicts the evolution of the electrical quantities in the main nodes of the French power system during the incident.

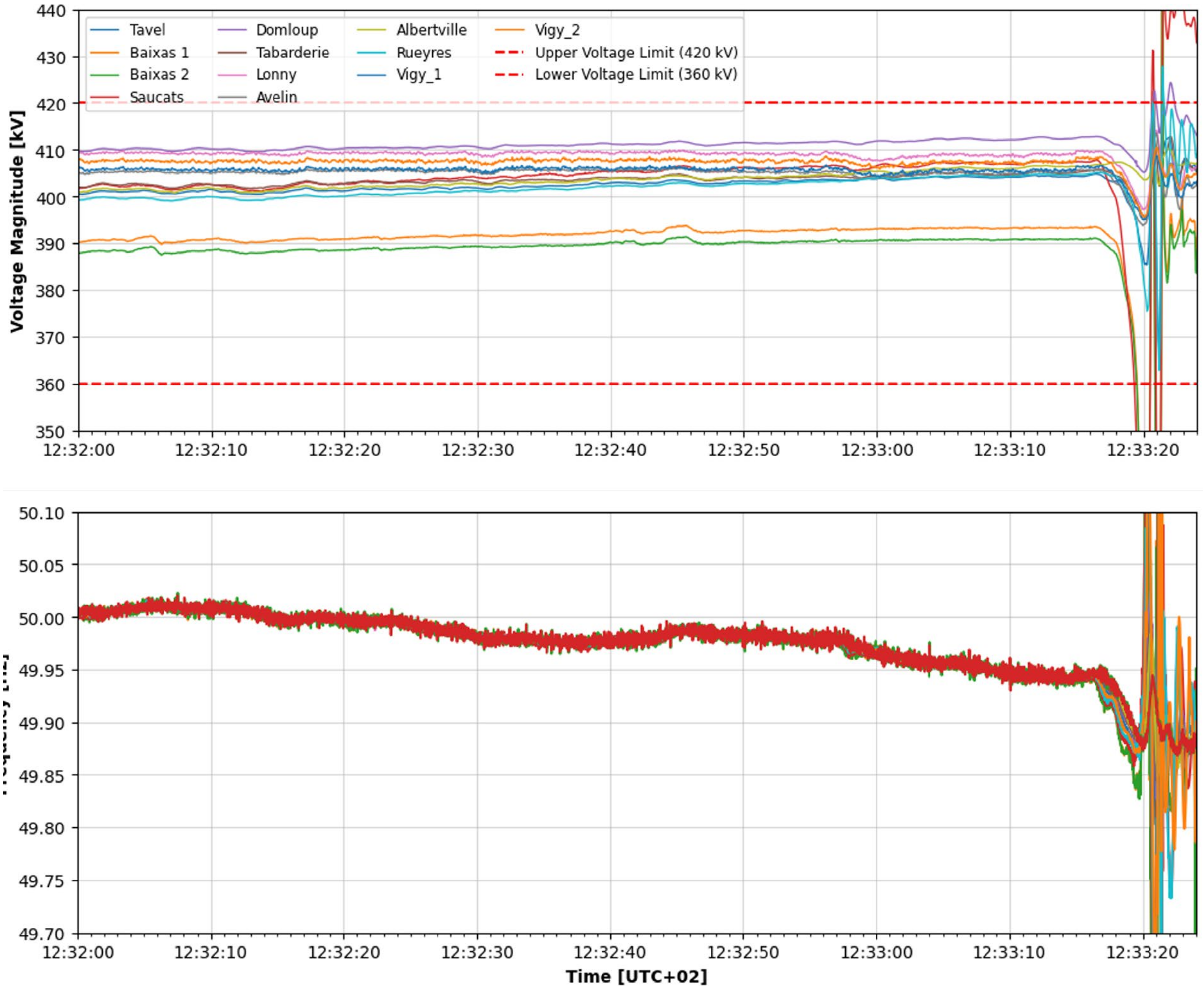


Figure 3-18: Evolution of the electrical quantities in the French power system during the incident

At 12:35, at least six 400 kV substations were above 430 kV (the upper voltage limit on the RTE grid is 420 kV), and one substation was above 435 kV (Baixas 440 kV).

More than 10 225 kV substations were above 260 kV (the upper voltage limit on the RTE grid is 245 kV) on the southwest part of the RTE network.

Loss of voltage control capacities (value)

- Golfech 1 nuclear power plant was absorbing 426 Mvar at 12:33.
- One unit out of the four Montezic hydraulic power pumps was absorbing 27 Mvar at 12:33.
- HVDC Baixas Santa Llogaia was absorbing 870 Mvar at 12:33:29 (based on measurements from French PMU).

3.2 Performance of the Protection System During the Incident

The objective of designing, setting up, and maintaining a protection system is to prevent dangerous situations for people, limit damage to electrical system components when an anomaly or failure occurs, minimise the consequences of service discontinuities in any network situation, and reduce the risk of transient instability in the transmission network.

Reconstructing system operation actions, comparing them with operational planning results, and assessing the utilisation of system elements are essential for analysis. Events such as the blackout on 28 April 2025 must be thoroughly analysed and investigated to understand their causes and the sequence of events, and to identify corrective actions that could help prevent similar incidents in the future.

This section analyses the protection's operation (tripping) using the available data: mainly the SCADA event lists and the disturbance fault recordings (DFRs).

3.2.1 Generation Protection Behavior During the Incident

3.2.1.1 Requirements for Generators for Grid Code Compliance in Spain

In Spain, the technical requirements for generation facilities regarding voltage and frequency depend on their commissioning date, with the following main categories:

- Facilities commissioned before the application date of the EU RfG (i.e. before 27 April 2019), which are subject to the technical requirements published in 1998 in Operating Procedure 1.4 for voltage requirements and to the System Operation Guideline.
- Facilities commissioned after the application of the EU RfG (27 April 2019) and before the entry into force of Order TED 749/2020 (8 January 2021), which are subject to the exhaustive requirements of the RfG.
- Facilities commissioned after the entry into force of Order TED 749/2020 (8 January 2021).
- Renewable energy production facilities commissioned after the entry into force of Royal Decree 413/2014 (11 June 2014).

Accordingly, the following operating voltage ranges are distinguished (labelled for the purpose of this report with V1–V5). For voltage values that are not listed in any of the ranges listed for each category, generators are allowed to disconnect:

- **Category V1:** Facilities commissioned prior to 27 April 2019 (Operating Procedure 1.4 and System Operation Guideline apply):
  - Generator connected to a voltage of 400 kV:
    - 390–420 kV: Normal operation, generators must stay connected for an unlimited time
    - 375–390 kV and 420–435 kV: Occurs eventually, generators must stay connected for an unlimited time

  - Generator connected to a voltage of 220 kV:
    - 205–245 kV: Normal operation, generators must stay connected for an unlimited time
    - 200–205 kV: Occurs eventually, generators must stay connected for an unlimited time

- **Category V2:** Facilities commissioned after 27 April 2019 (exhaustive RfG criteria apply) that are type D electricity generation modules must be able to remain connected to the grid and operate within the voltage ranges (at the connection point and expressed in per unit values relative to the base) for the minimum time periods listed below:
  - Type D electricity generation module connected to 110 kV ≤ V < 300 kV:
    - 0.85–0.90 pu: 60 minutes
    - 0.90–1.118 pu: Unlimited time
    - 1.118–1.15 pu: Minimum 20 minutes, maximum 60 minutes

  - Type D electricity generation module connected to 300 kV ≤ V ≤ 400 kV:
    - 0.85–0.90 pu: 60 minutes
    - 0.90–1.0875 pu: Unlimited time (including the Spanish exception)
    - 1.0875–1.10 pu: Minimum 20 minutes, maximum 60 minutes

- **Category V3:** Facilities commissioned after 8 January 2021 (Order TED 749/2020 applies) that are type D electricity generation modules must be able to remain connected to the grid and operate within the voltage ranges (at the connection point and expressed in per unit values relative to the base) for the minimum time periods listed below:
  - Type D electricity generation module connected to 110 kV ≤ V < 300 kV:
    - 0.85–0.90 pu: 60 minutes
    - 0.90–1.118 pu: Unlimited time
    - 1.118–1.15 pu: 60 minutes

  - Type D electricity generation module connected to 300 kV ≤ V ≤ 400 kV:
    - 0.85–0.90 pu: 60 minutes
    - 0.90–1.0875 pu: Unlimited time
    - 1.0875–1.10 pu: 60 minutes

- **Category V4:** Facilities commissioned after 8 January 2021 that are type B, C, and D electricity generation module connected to a radial distribution network with a voltage below 110 kV (note: the operator of the distribution grid has the right to define different disconnection times in accordance with the TSO):
    - < 0.85 pu: 1.5 seconds
    - 0.85–1.10 pu: Unlimited time
    - 1.10–1.15 pu: 1 second
    - > 1.15 pu: 0.2 seconds

- **Category V5:** Facilities commissioned prior to 27 April 2019 that are connected to voltages lower than 220 kV (hence out of scope of category V1). There is no national voltage withstand requirement for generators in this category.

The required operating frequency ranges are (labelled for the purpose of this report with F1–F4):

- **Category F1:** Facilities prior to 11 June 2014: Protection settings are based on the characteristics of each facility, considering their technical capabilities.

- **Category F2:** Renewable energy facilities commissioned after 11 June 2014 (Royal Decree 413/2014 applies):
  - < 48 Hz: 3 seconds
  - 48–51 Hz: Unlimited time
  - 51 Hz: 0.5 seconds

- **Category F3:** Facilities after 27 April 2019 (exhaustive RfG criteria apply) that are type A, B, C, and D electricity generation modules must be able to remain connected to the grid and operate within the frequency ranges referred to below:
  - 47.5–48.5 Hz: Non-exhaustive time (minimum 30 minutes)
  - 48.5–49.0 Hz: Non-exhaustive time (minimum 30 minutes)
  - 49.0–51.0 Hz: Unlimited time
  - 51.0–51.5 Hz: 30 minutes

- **Category F4:** Facilities after 8 January 2021 (Order TED 749/2020 applies) that are type A, B, C, and D electricity generation modules must be able to remain connected to the grid and operate within the frequency ranges referred to below:
  - 47.5–48.5 Hz: 30 minutes
  - 48.5–49.0 Hz: Unlimited time
  - 49.0–51.0 Hz: Unlimited time
  - 51.0–51.5 Hz: 30 minutes

Additionally, Order TED (749/2020) establishes that for type A, B, C, and D electricity generation modules commissioned after 8 January 2021, the requirements for combined frequency and voltage variations are defined such that the frequency ranges indicated in the previous point are modified according to the voltage. The following figures show, for each combined frequency–voltage range, the minimum time that an electricity generation module must remain connected to the grid.

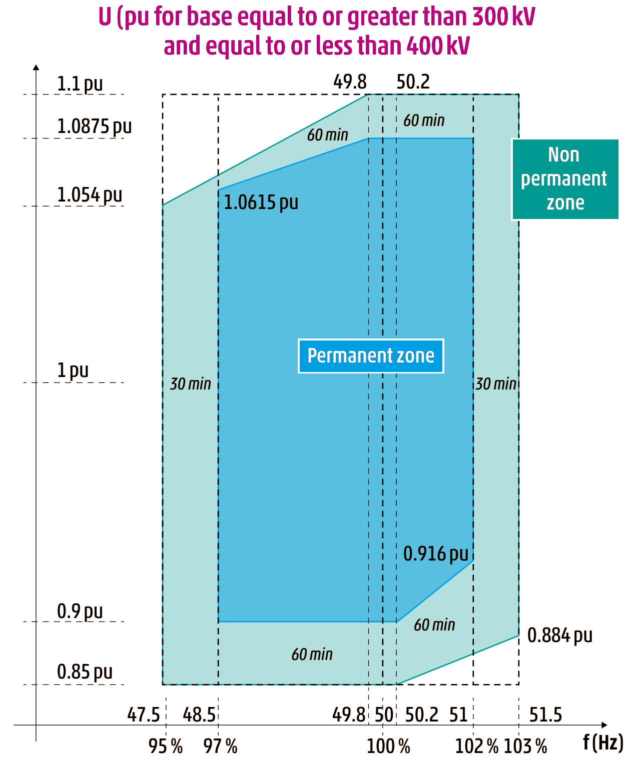


Figure 3-19: Minimum time periods during which an electricity generation module must be able to operate without disconnecting from the grid, for different combined values of frequency and voltage, when the nominal voltage of the connection point is equal to or greater than 300 kV and equal to or less than 400 kV

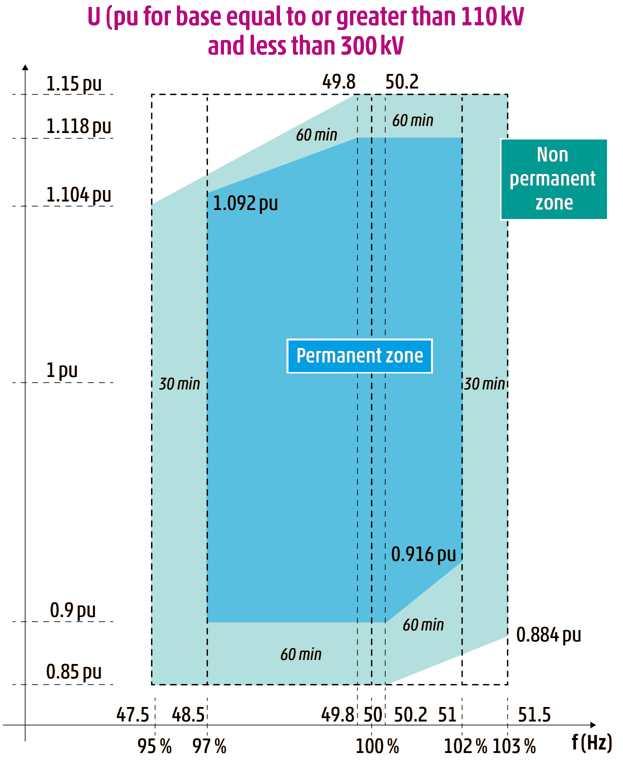
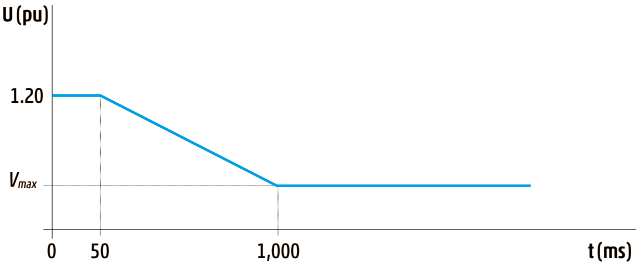


Figure 3-20: Minimum time periods during which an electricity generation module must be able to operate without disconnecting from the grid, for different combined values of frequency and voltage, when the nominal voltage of the connection point is equal to or greater than 110 kV and less than 300 kV

Likewise, Order TED/749/2020 established that electricity generation modules of types B, C, and D, with a commissioning date later than 8 January 2021, must comply with requirements to withstand temporary overvoltages. They must remain connected to the grid and continue operating stably during temporary overvoltage events, in accordance with Figure 3-21 and Figure 3-22.



V_{max}: Highest admissible voltage considered within the voltage ranges and minimum durations that must be withstood without disconnection, in accordance with Regulation (EU) 2016/631 of 14 April 2016, or, if this regulation is not applicable, the highest admissible voltage considered within the normal operating ranges.

Figure 3-21: Minimum overvoltage durations at the point of connection (RMS voltage to ground in one or all phases, expressed in per unit of the voltage base at the point of connection) that a type D power park module connected to the transmission network must be capable of withstanding without disconnection

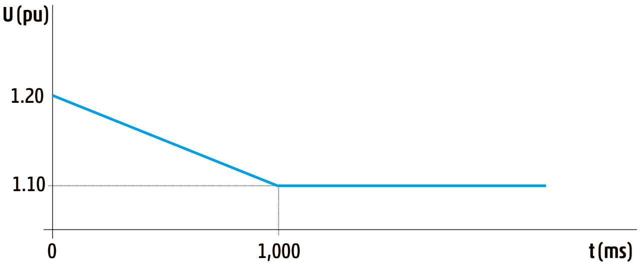


Figure 3-22: Minimum overvoltage durations at the point of connection (RMS voltage between any pair of phases, expressed in per unit of the voltage base at the point of connection) that a type B, C, or D power park module not connected to the transmission network must be capable of withstanding without disconnection

Regarding the requirement to maintain and provide records enabling the analysis of generation dynamics and the operation of protection systems, Spanish regulations establish the following:

- Spanish Operating Procedure 9 (P.O. 9) stipulates that when an incident occurs, as defined in Section 10.3 thereof, the owner of the facilities or the party responsible for the affected supply must provide the system operator (SO) with a preliminary report of the event based on the best available information. Additionally, the SO may request further clarification regarding the contents of the report and gather the information outlined in Annex V that has not yet been received and is deemed necessary.
- Annex V of P.O. 9 specifies the requirement to provide oscillographic records, protection event logs, and chronological records from the control systems of substations affected by the incident, as well as the complete configuration files of the protection devices that were triggered. The same procedure establishes that oscillographic data must be submitted in electronic format, preferably in COMTRADE format (as defined in IEEE Standard C37.111).
- Furthermore, Regulation EU RfG 2016/631 states: "power-generating facilities shall be equipped with a facility to provide fault recording and monitoring of dynamic system behaviour. This facility shall record the following parameters: voltage, active power, reactive power, and frequency".
- Spanish Order TED 749/2020 establishes: "In the case of type C and D power-generating modules, the activation of any protection relay must be recorded along with the oscillographic data. The owner of the power-generating module shall be obliged to provide to the relevant system operator the fault record and oscillographic data upon request".

3.2.1.2 Requirements for Generators for Grid Code Compliance in Portugal

In Portugal, generator requirements are aligned with the EU RfG 2016/631, complemented by national legislation, specifically Portaria No. 73/2020 from 16 March covering the non-exhaustive requirements for grid connection.

Regarding frequency range withstand capability requirements, these two regulations define the operational frequency ranges that generating modules must be capable of supporting:

- 47.5 Hz – 48.5 Hz: 30 minutes
- 48.5 Hz – 49.0 Hz: Unlimited time
- 49.0 Hz – 51.0 Hz: Unlimited time
- 51.0 Hz – 51.5 Hz: 30 minutes

Similarly, regarding voltage range withstand capability requirements, the operational voltage ranges that generating modules must be capable of supporting are as follows:

For voltage base values from 110 kV to 300 kV

- 0.85 pu – 0.90 pu: 60 minutes
- 0.90 pu – 1.118 pu: Unlimited time
- 1.118 pu – 1.15 pu: 20 minutes

For voltage base values from 300 kV to 400 kV

- 0.85 pu – 0.90 pu: 60 minutes
- 0.90 pu – 1.05 pu: Unlimited time
- 1.05 pu – 1.10 pu: 20 minutes

Without prejudice to the above voltage levels required to be supported, type D power park modules (PPMs) shall be capable of withstanding transient overvoltages and must remain connected to the grid for at least the following values of transient overvoltage amplitude and duration:

- 1.25 pu during 100 ms and 1.20 pu during 5 s

Facilities commissioned before the application date of the EU RfG and Portaria No. 73/2020 must comply with requirements established in Portaria No. 596/2010 from 30 July, which approved and published the national Transmission Grid Regulation and Distribution Grid Regulation. In those cases, the applicable requirements for the frequency and voltage withstand capability ranges are similar to the current requirements.

3.2.1.3 Generation Disconnection in Spain During the Incident

The generation disconnections in Spain until 12:33:19.000 are listed in Table 3-3. The identification of the events is in line with the sequence of events provided in Table 3-1.

These events will be analysed in the following subchapters.

Event ID	Time (CEST)	Substation	Voltage Level (kV)	Technology	Production disconnected (MW)
3	12:32:57.220	400kVTS1-Granada	400	PV, wind and thermo-solar	355
4a	12:33:16.460	400kVTS1-Badajoz	400	PV, thermo-solar	582
4b	12:33:16.820	400kVTS2-Badajoz	400	PV	145
5a1	12:33:17.368	400kVTS1-Segovia	400	wind	22.87
5b1	12:33:17.520	400kVTS1-Badajoz	400	PV	118
5b2	12:33:17.547	220kVTS1-Huelva	220	Wind and PV	33.73
5a2	12:33:17.780	400kVTS1-Sevilla	400	PV	550
5a3	12.33:17.940	400kVTS1-Segovia	400	Wind	94
5b3	12:33:17.975	220kVTS1-Cáceres	220	PV	37.5
5b4	12:33:18.020	220kVTS3-Badajoz	220	PV	71.9
6a1	12:33:18.102	220kVTS2-Sevilla	220	PV	3
6a2	12:33:18.220	220kVTS3-Badajoz	220	PV	20
6a3	12:33:18.360	220kVTS3-Badajoz	400	PV	16
6a4	12:33:18.380	400kVTS2-Cáceres	400	PV	41
6a5	12:33:18.540	400kVTS1-Murcia	400	PV	63
6a6	12:33:18.630	220kVTS1-Cádiz	220	PV	25.7
6a7	12:33:18.680	220kVTS1-Cádiz	220	PV	127.5
6a8	12:33:18.846	400kVTS1-Málaga	400	PV	154
6b	12:33:18.951	400kVTS1-Cuenca	400	PV	530

Table 3-3: Generation disconnection in Spain

3.2.1.3.1 Event ID 3: "400 kV TS 1—Granada" 355 MW disconnection

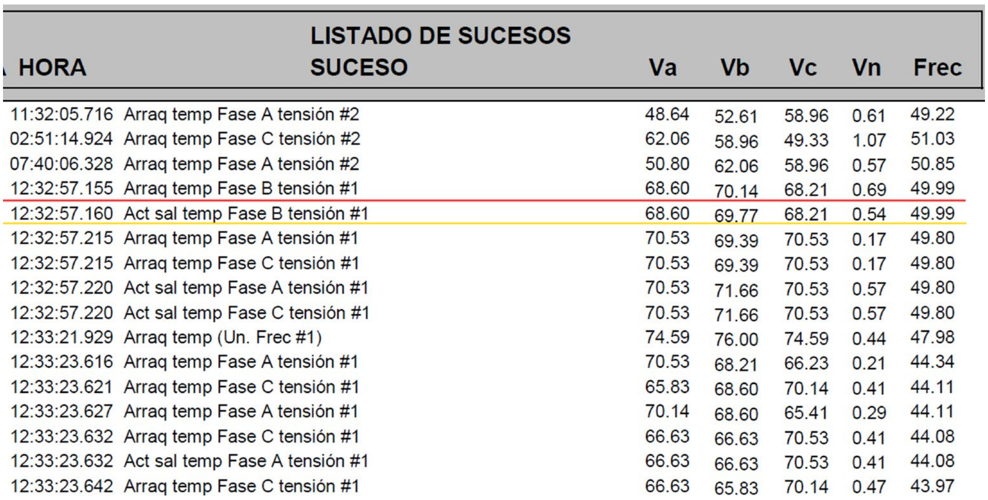
At 12:32:57.220, in GS 1—Granada (Spain), the generation evacuation transformer 400/220 kV tripped at the 220 kV level. This caused the loss of 355 MW of active power generation and 165 Mvar of reactive absorption.

During the investigation, the loss of this generation was identified based on the alarms available to Red Eléctrica. This identification was confirmed to be consistent with observations from PMU measurements, and an oscillographic record on the 400 kV substation coinciding with the tripping was also available. However, this oscillography is from a line within the substation and therefore does not include direct measurements from the transformer itself. Nonetheless, it is possible to observe changes in the substation voltage, and in the current flowing through the line, resulting from the generation loss.

The tripped 400/220 kV evacuation transformer does not belong to the transmission grid, as it is owned by a consortium of companies comprising several entities that inject power through the transformer. There are various facilities downstream of this transformer. Some are not required to comply with either the TED Order or the RfG, meaning that they belong to Category V1 (523 MW). However, there are also several facilities (total: 127 MW) downstream that must comply with TED Order 749/2020 (they belong to category V3). This is outlined in the last paragraph of this subsection.

No oscillographic records from the protection system that operated were delivered to the Expert Panel. However, the owner of this transformer reported that the cause of the trip was overvoltage and that the trip occurs when the 220 kV side of the 400/220 kV transformer reaches 242 kV (1.10 pu), with no delay (t = 0 s). This trip setting was set by the owner. The trip setting was not reviewed by the TSO because it was not needed to coordinate with transmission protection (short-circuit protections).

The owner of the transformer provided an event record showing that the voltage exceeded the setting threshold (70 secondary volts or 140 kV primary phase-to-ground or 242 kV primary phase-to-phase). Five ms later, the activation of the output contact was issued, which means that the trip signal was initiated. At that moment, the voltage was already below the tripping threshold. Fifty-five ms after this activation, new operations of the overvoltage function were observed, which may coincide with the breaker opening transient.



LISTADO DE SUCESOS

HORA	SUCESO	Va	Vb	Vc	Vn	Frec
11:32:05.716	Arraq temp Fase A tensión #2	48.64	52.61	58.96	0.61	49.22
02:51:14.924	Arraq temp Fase C tensión #2	62.06	58.96	49.33	1.07	51.03
07:40:06.328	Arraq temp Fase A tensión #2	50.80	62.06	58.96	0.57	50.85
12:32:57.155	Arraq temp Fase B tensión #1	68.60	70.14	68.21	0.69	49.99
12:32:57.160	Act sal temp Fase B tensión #1	68.60	69.77	68.21	0.54	49.99
12:32:57.215	Arraq temp Fase A tensión #1	70.53	69.39	70.53	0.17	49.80
12:32:57.215	Arraq temp Fase C tensión #1	70.53	69.39	70.53	0.17	49.80
12:32:57.220	Act sal temp Fase A tensión #1	70.53	71.66	70.53	0.57	49.80
12:32:57.220	Act sal temp Fase C tensión #1	70.53	71.66	70.53	0.57	49.80
12:33:21.929	Arraq temp (Un. Frec #1)	74.59	76.00	74.59	0.44	47.98
12:33:23.616	Arraq temp Fase A tensión #1	70.53	68.21	66.23	0.21	44.34
12:33:23.621	Arraq temp Fase C tensión #1	65.83	68.60	70.14	0.41	44.11
12:33:23.627	Arraq temp Fase A tensión #1	70.14	68.60	65.41	0.29	44.11
12:33:23.632	Arraq temp Fase C tensión #1	66.63	66.63	70.53	0.41	44.08
12:33:23.632	Act sal temp Fase A tensión #1	66.63	66.63	70.53	0.41	44.08
12:33:23.642	Arraq temp Fase C tensión #1	66.63	65.83	70.14	0.47	43.97

Figure 3-23: Event record of GS 1 – Granada transformer protection

An oscillographic record corresponding to this trip is available, captured by one of the line protection relays at the 400 kV TS 1 – Granada, the point of connection. This record (see Figure 3-24) shows that the maximum phase-to-ground voltage prior to the trip was 241.3 kV, which corresponds to a phase-to-phase voltage of 417.9 kV (1.045 pu). The same voltage was measured in phases A and B.

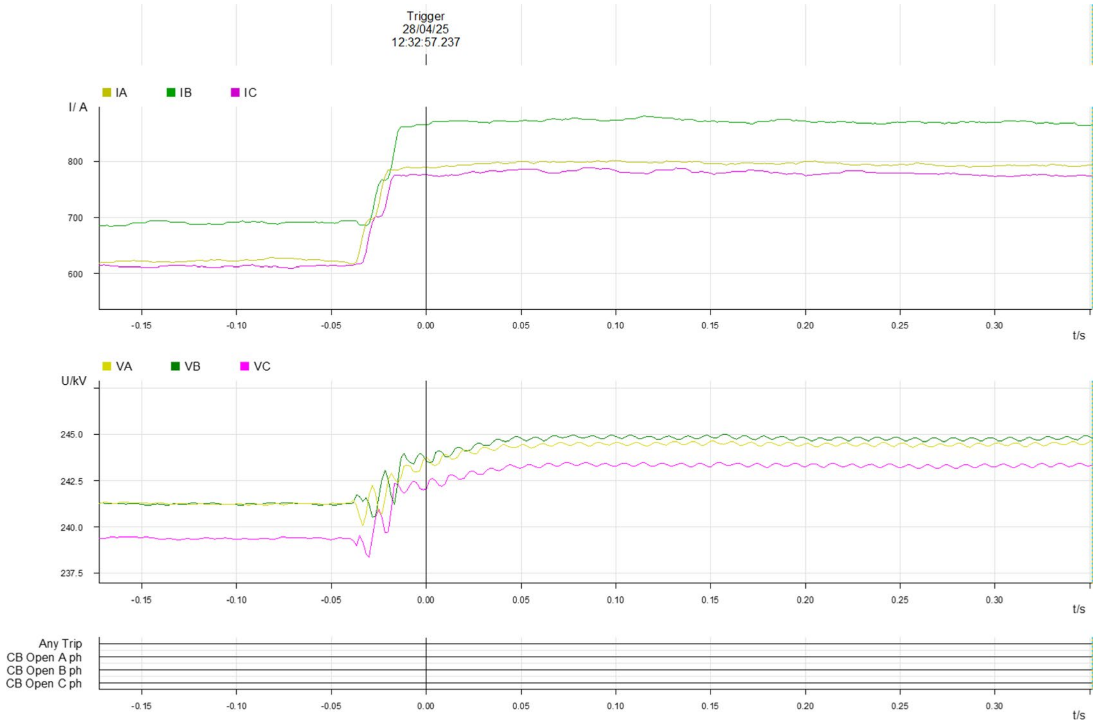


Figure 3-24: Oscillographic record from a line protection in 400 kV TS 1 – Granada

Although no oscillographic records are available from the relay that caused the trip at the 220 kV level, a record is available from a plant located downstream from this substation, approximately 500 meters from 220 kV GS 1 – Granada, where the voltage at the 220 kV level can be observed. Figure 3-25 shows this record, indicating that the phase-to-ground voltage was 137.1 kV, which corresponds to a phase-to-phase voltage of 237.5 kV (1.079 pu).

The secondary voltage values of phases A and C in this COMTRADE record (68.55 V secondary in phase A and 68.05 V secondary in phase C) are consistent with those observed in the event log shown in Figure 3-23. However, the 5 ms transient in phase B that triggered the transformer overvoltage protection is not observed. Following the upstream circuit breaker trip, an increase in voltage is observed at the register due to the loss of the evacuation path.

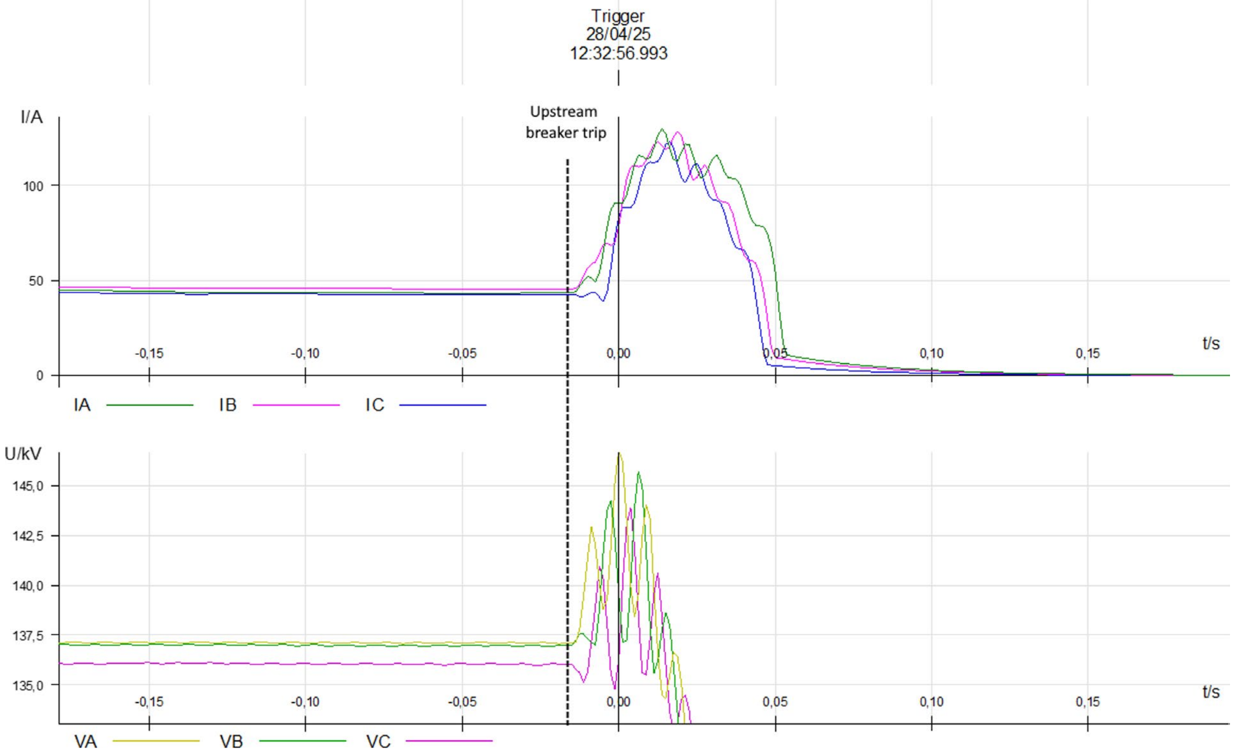


Figure 3-25: Oscillographic record of a generation evacuation line connected downstream of 220 kV GS 1 – Granada

The breakdown of the installed capacity of the generation connected downstream of the tripped element, in terms of the voltage withstand capabilities (described in Section 3.2.1.1) is as follows

- Category V1: 523 MW
- Category V2: 0 MW
- Category V3: 127 MW
- Category V4: 0 MW
- Category V5: 0 MW

3.2.1.3.2 Event ID 4a: 400 kV TS 1—Badajoz 582 MW Disconnection

At 12:33:16.460, at 400 kV GS 1—Badajoz, the evacuation line to 400 kV GS 2—Badajoz tripped. This caused the loss of 582 MW of active power generation and 165 Mvar of reactive absorption.

Several oscillographic records from one downstream operator indicate that, at this moment, an upstream collector installation was lost, as evidenced by the occurrence of overfrequency immediately afterwards. Additionally, a chronological log provided by another downstream operator shows the opening of circuit breakers on a line at the 400 kV GS 1—Badajoz, which connects to the substation where the generation loss occurred.

Although there are facilities that were commissioned prior to the entry into force of the RfG, there are two facilities whose commissioning took place afterwards, and which also obtained certification as compliant with TED Order 749/2020.

No oscillographic records from the protection system that operated, nor the settings of that relay, were delivered to the Expert Panel. It is unclear whether the relay that tripped was the one located at 400 kV GS 1—Badajoz or the one at the remote end in GS 2—Badajoz, which could have sent a transfer trip signal to GS 1—Badajoz. However, what is available is an event log showing the opening of circuit breakers 521-1 and 520-2 at 400 kV GS 1—Badajoz at that moment.

There is no high-resolution voltage data available at the connection point, 400 kV TS 1—Badajoz. The only data available is from the SCADA system. The SCADA voltage value registered at 12:33:10 at the TS 1—Badajoz generation evacuation bay was 434.0 kV, 430.5 kV at busbar 1, and 429.9 kV at busbar 2. An examination of PMU measurements from four nearby substations shows that from 12:33:04 – corresponding to the moment of lowest voltage around 12:33:10 – the maximum voltage increase up until the moment of the trip was 3.3 kV.

The distribution over voltage withstand requirements for generation connected downstream of the tripped element is as follows:

- V1: 556 MW
- V2: 0 MW
- V3: 69 MW
- V4: 0 MW
- V5: 0 MW

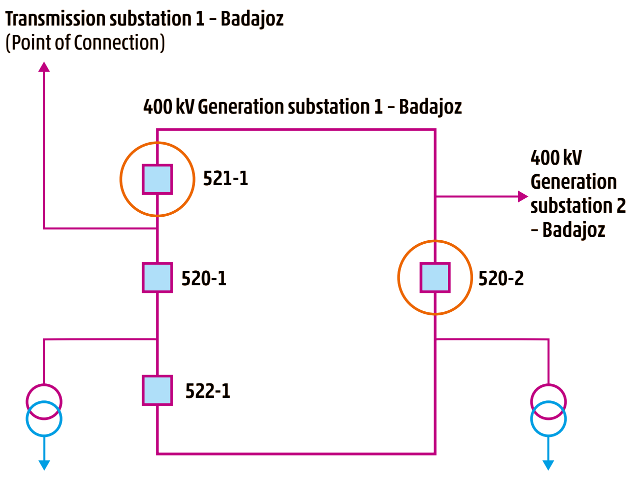


Figure 3-26: Single line diagram of generation evacuation substation 400 kV GS 1—Badajoz

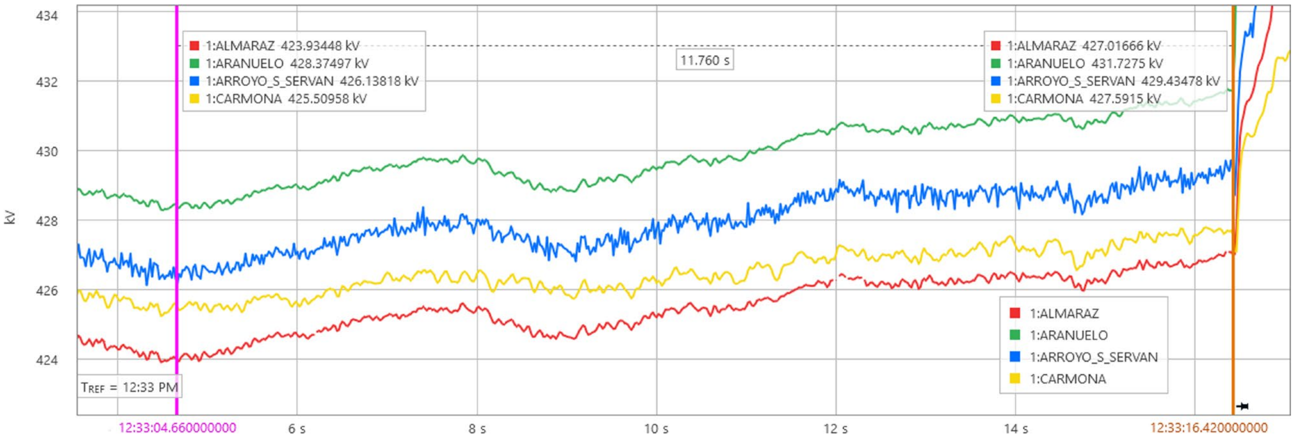


Figure 3-27: Voltage measurements from PMUs at 400 kV substations in the vicinity of TS 1—Badajoz

3.2.1.3.3 Event ID 4b: 400 kV TS 2—Badajoz 145 MW Disconnection

At 12:33:16.820, a PV plant connected to 400 kV TS 2 – Badajoz tripped. This PV plant was generating 145 MW and absorbing 37 Mvar. This PV plant was certified as compliant with Order TED 749/2020.

The last voltage values registered by the SCADA system were 427.7 kV at 12:32:52 and 436.1 kV at 12:33:16.

A file containing samples with a refresh rate of one second was delivered to the Expert Panel by a third party. The samples cease to update at time stamp 12:33:17. A COMTRADE record was also received from the line connecting the collector substation, which is part of the generation evacuation network, to the PV plant. This record corresponds to the end located at the collector substation. The record shows that the trip occurred when the system frequency was approximately 49.85 Hz, which corresponds approximately to the time stamp 12:33:17.920. At that moment, and during the 200 ms prior as recorded in the COMTRADE file, the current through the position was already zero, indicating that the trip must have occurred before 12:33:17.720. A PMU is available on one of the lines of the substation but located at the opposite end (400 kV TS 2—Cáceres bay to 400 kV TS 2—Badajoz). A change in active power on this line was identified at time stamp 12:33:16.820, around the time when the samples ceased to update. A power system simulation confirmed that the power change observed in the PMU was consistent with a generation loss of 145 MW at 400 kV TS 2—Cáceres.

No oscillographic records from the protection system that operated were delivered to the Expert Panel. The oscillographic record received from the collector substation end indicates that the initial trip must have occurred at the PV plant end. The settings received from the collector substation end indicate that two thresholds are configured for the overvoltage protection function. The first threshold is set at 435.6 kV phase-to-phase (1.089 pu), with a time delay of 1.5 seconds, and the second threshold is set at 455.4 kV phase-to-phase (1.1385 pu), with a time delay of 0.2 seconds.

The COMTRADE record shows that, at the moment immediately prior to the circuit breaker opening, the voltage was 449.0 kV. Furthermore, considering the timing configuration of this protection, it is known that the voltage threshold of 435.6 kV was exceeded 1.5 seconds before the opening of this position, at approximately time stamp 12:33:16.420, which corresponds to 400 ms prior to the trip of the PV plant.

Figure 3-27 shows the oscillographic record of the line protection that tripped at the collector substation end before the trip of the other line end.

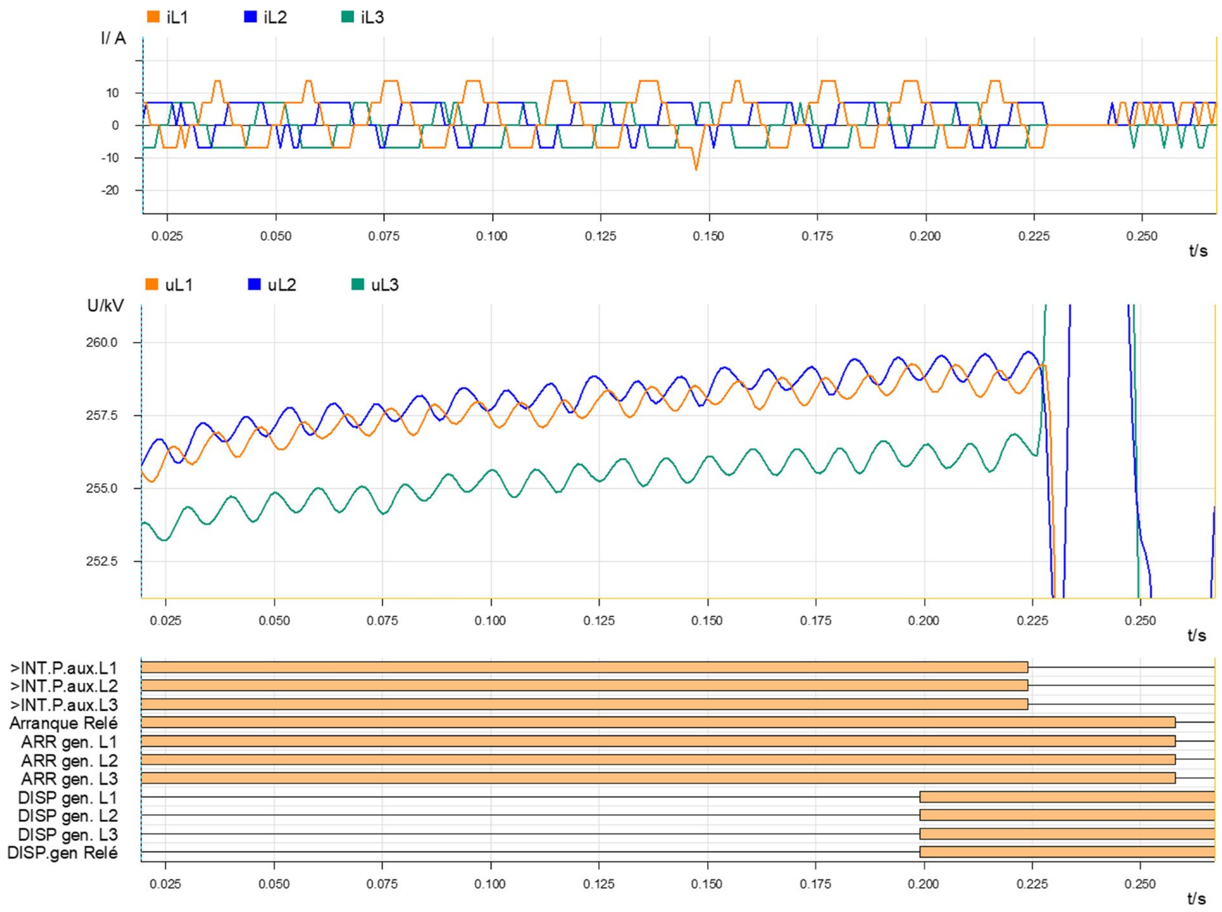


Figure 3-28: Oscillographic record of the protection system for the line connecting the PV plant to the collector substation at the collector substation end

The distribution over voltage withstand requirements for generation connected downstream of the tripped element is as follows:

- V1: 0 MW
- V2: 0 MW
- V3: 150 MW
- V4: 0 MW
- V5: 0 MW

3.2.1.3.4 Event ID 5a1: 400 kV TS 1 – Segovia 22.9 MW Disconnection

At 12:33:17.368, three wind farms connected to a 132 kV evacuation grid that is connected to 400 kV TS 1 – Segovia were disconnected due to the tripping of an element in the upstream section of the generation collector network. This caused the loss of 22.9 MW of active power generation and the loss of 12.3 Mvar in reactive power absorption. These three wind farms were commissioned before the RfG entered into force.

The generation loss was identified through the oscillographic record of a collector transformer. The synchronisation of the recording was verified by analysing the frequency of the voltage signal.

No oscillographic records from the protection system that operated, nor the settings of that relay, were delivered to the Expert Panel. However, an oscillographic record was received from the 400/132 kV generation transformer at TS 1 – Segovia, in which the voltage levels at both 400 kV (connection point) and 132 kV can be observed at the time of the trip. The phase-to-ground voltage measured at the 400 kV level at the time of the trip is 252.0 kV, which corresponds to a phase-to-phase voltage of 436.5 kV. The phase-to-ground voltage measured at the 132 kV level was 83.3 kV, corresponding to a phase-to-phase voltage of 144.3 kV.

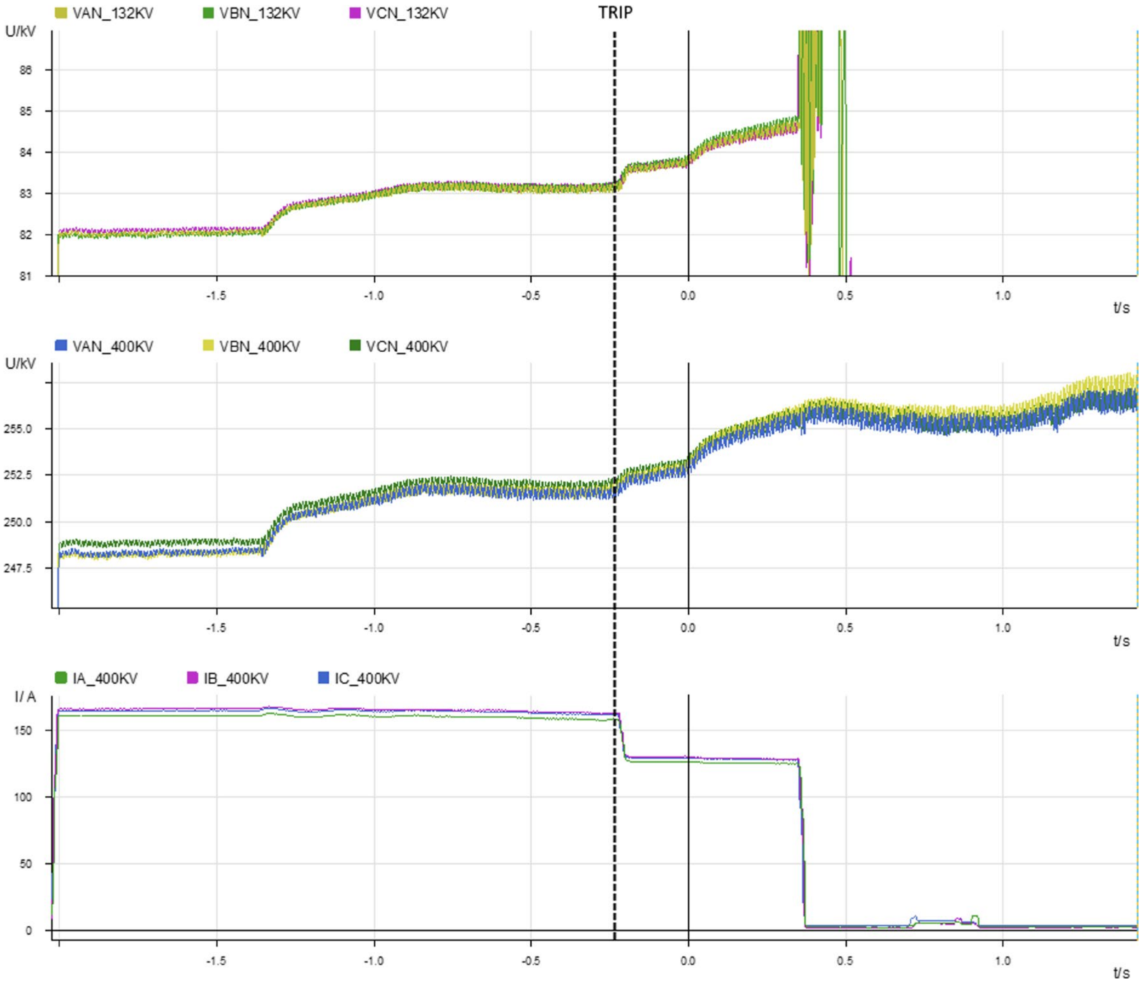


Figure 3-29: Voltage at the 400 kV and 132 kV voltage levels of the TS 1 - Segovia generation transformer and transformer current at the 400 kV level

The distribution over voltage withstand requirements for generation connected downstream of the tripped element is as follows:

- V1: 49 MW
- V2: 0 MW
- V3: 0 MW
- V4: 0 MW
- V5: 0 MW

3.2.1.3.5 Event ID 5b1: 400 kV TS 1—Badajoz 118 MW Disconnection

At 12:33:17.520, the evacuation line to 400 kV TS 1–Badajoz tripped in 400 kV GS 1—Badajoz. This generation evacuation network has its point of connection at 400 kV TS 1—Badajoz. This caused the loss of 118 MW of active power generation and the loss of 22 Mvar in reactive power absorption.

The generation loss was identified through an oscillographic record from the transformers at the GS 1—Badajoz and an event log.

It is inferred that the relay that operated was the line relay, as the circuit breaker that opened is the one shared between the line and Transformer 1 (520-1, see Figure 3-26). However, the circuit breaker shared between Transformer 1 and Transformer 2 is 522-1 (see Figure 3-26), which was recorded to have opened approximately 1.5 seconds later due to the undervoltage function.

The disconnected facility must comply with Order TED 749/2020.

No oscillographic records from the protection system that operated, nor the settings of that relay, were delivered to the Expert Panel. The owner of the transformers sent oscillographic records from the transformers, which show that the overvoltage function only initiates during the trip transient, and that it is the undervoltage function that triggers 1.5 seconds after the line circuit breaker opens. In this record, there is a voltage channel that, although identified as phase-to-ground voltage, appears to correspond to phase-to-phase voltage, which measured 443 kV at the moment of the trip. This voltage was measured at the 400 kV GS 1—Badajoz, not the 400 kV TS 1—Badajoz, which is the connection point to the transmission grid.

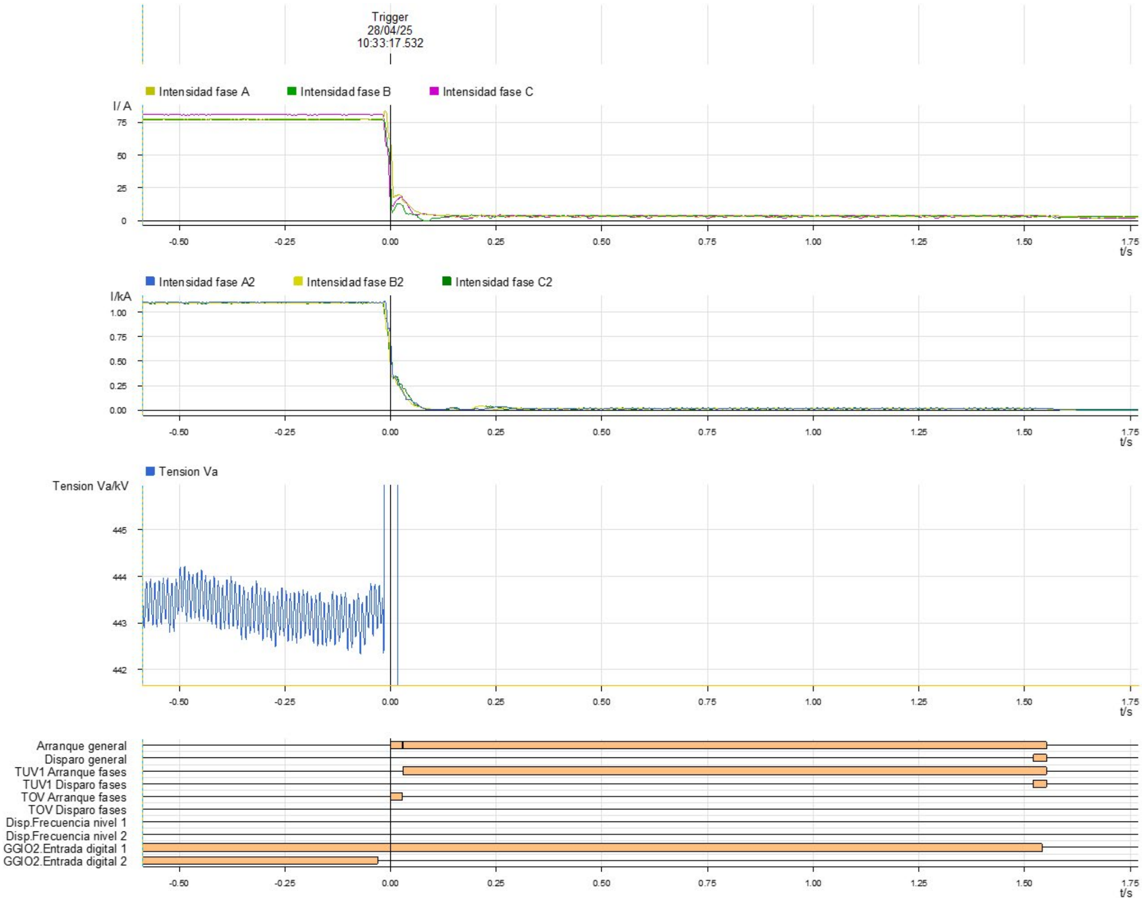


Figure 3-30: Oscillographic record from Transformer 1 at GS 1—Badajoz

The distribution over voltage withstand requirements for generation connected downstream of the tripped element is the following:

- V1: 0 MW
- V2: 0 MW
- V3: 206 MW
- V4: 0 MW
- V5: 0 MW

3.2.1.3.6 Event ID 5b2: 220 kV TS 1—Huelva 33.7 MW Disconnection

At 12:33:17.547, two PV plants connected to 220 kV TS 1–Huelva were disconnected.

These two disconnected facilities must comply with Order TED 749/2020.

To determine the timing of the generation loss, events provided by the control centre were used. It was verified that, at that moment, a voltage step is observable in the PMU measurements from 400 kV TS 1—Huelva.

No oscillographic records from the protection system that operated, nor the settings of that relay, were delivered to the Expert Panel.

The control centre associated with this connection point indicated that the cause of the trip was the overvoltage protection function, and that the voltage reached was 267 kV at the 220 kV level and 76 kV in the 66 kV evacuation network. However, since no oscillographic data were provided, it is not possible to determine whether this voltage was reached before the trip, during the trip transient, or after the trip. For instance, the 220 kV level remained connected for several seconds after the event, and significant overvoltage was recorded in this voltage level following that moment.

The distribution over voltage withstand requirements for generation connected downstream of the tripped element is as follows:

- V1: 17 MW
- V2: 0 MW
- V3: 42 MW
- V4: 0 MW
- V5: 0 MW

3.2.1.3.7 Event ID 5a2: 400 kV TS 1—Seville 550 MW Disconnection

At 12:33:17.780, the generation–transmission interface line tripped at the end corresponding to the generation evacuation network and additionally sent a remote trip signal to the transmission network substation end (400 kV TS 1—Seville). This caused the disconnection of several PV plants, resulting in the loss of 550 MW of active power injection and absorption of 195 Mvar of reactive power.

All PV plants connected to this point of connection must comply with Order TED 749/2020.

An oscillographic record was available from the evacuation facility at the transmission network end, which was used to identify the generation loss.

Figure 3-31 shows the oscillographic record captured by the line protection system at the transmission substation (400 kV TS 1—Seville), which received the remote trip signal from the opposite end. It shows that the maximum phase-to-ground voltage recorded at the time of the trip was 252.7 kV, which corresponds to 437.7 kV phase-to-phase.

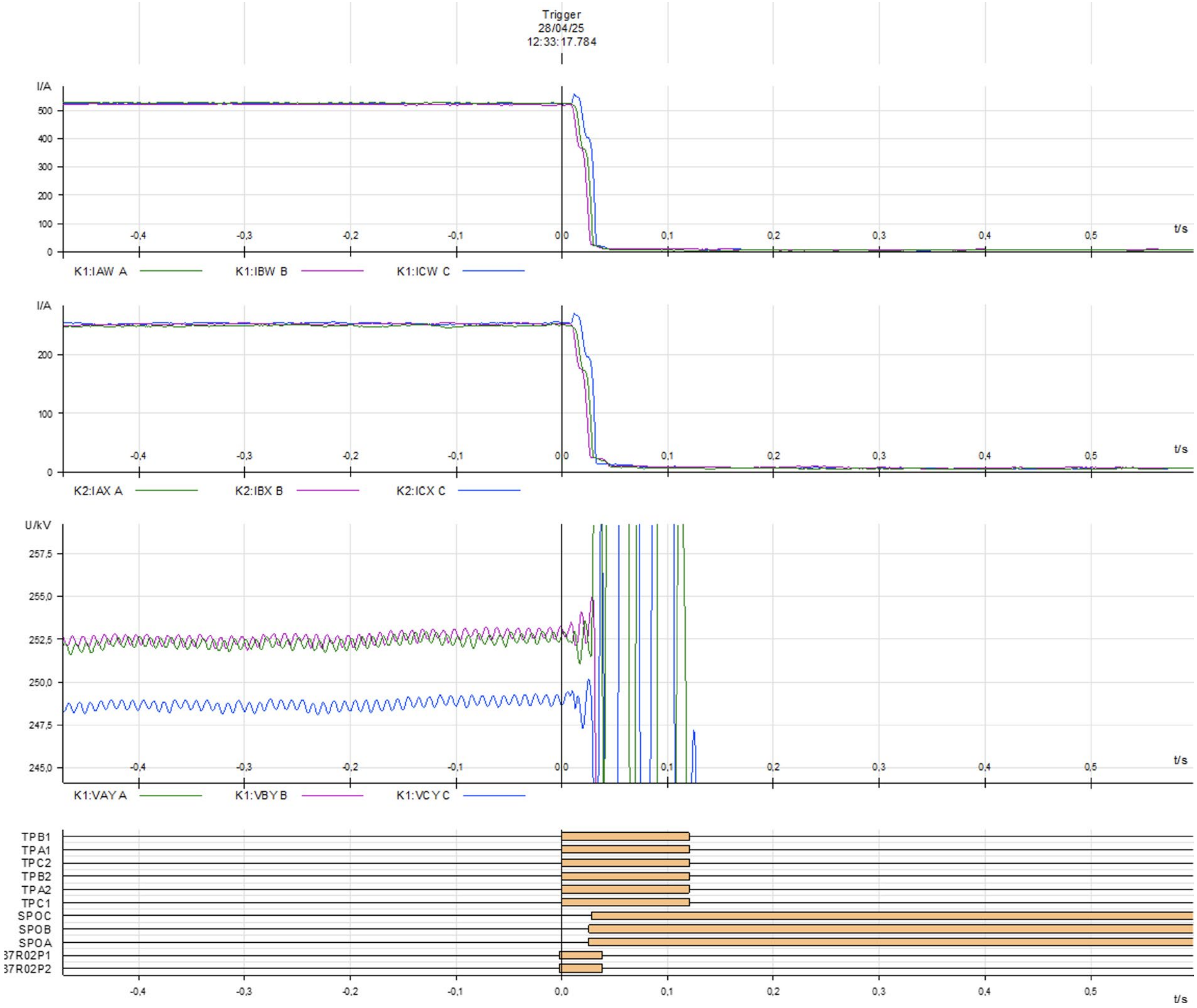


Figure 3-31: Oscillographic record from 400 kV TS 1-Seville substation, 400 kV GS 1-Seville bay (TPX1: breaker 1 trip of each phase, TPX2: breaker 1 trip of each phase, SPOX: Single pole open of each phase, 87R02P1: transfer trip received through communication channel 1, 87R02P2: transfer trip received through communication channel 2

No oscillographic records from the protection system that operated at the generation end were provided. However, oscillographic data were delivered to the Expert Panel from the other line protection system, where the voltage at the generation end can be observed at the time of the trip. It has also been indicated that the overvoltage protection function was the cause of this trip. The overvoltage settings of this protection function, as reported, are 436.6 kV (1.09 pu) one second.

Figure 3-32 shows the oscillographic record from one of the line protection systems at the 400 kV GS 1 – Seville end. It can be observed that the maximum phase-to-ground voltage measured at the time of the trip was 251.4 kV, which corresponds to 435.4 kV phase-to-phase.

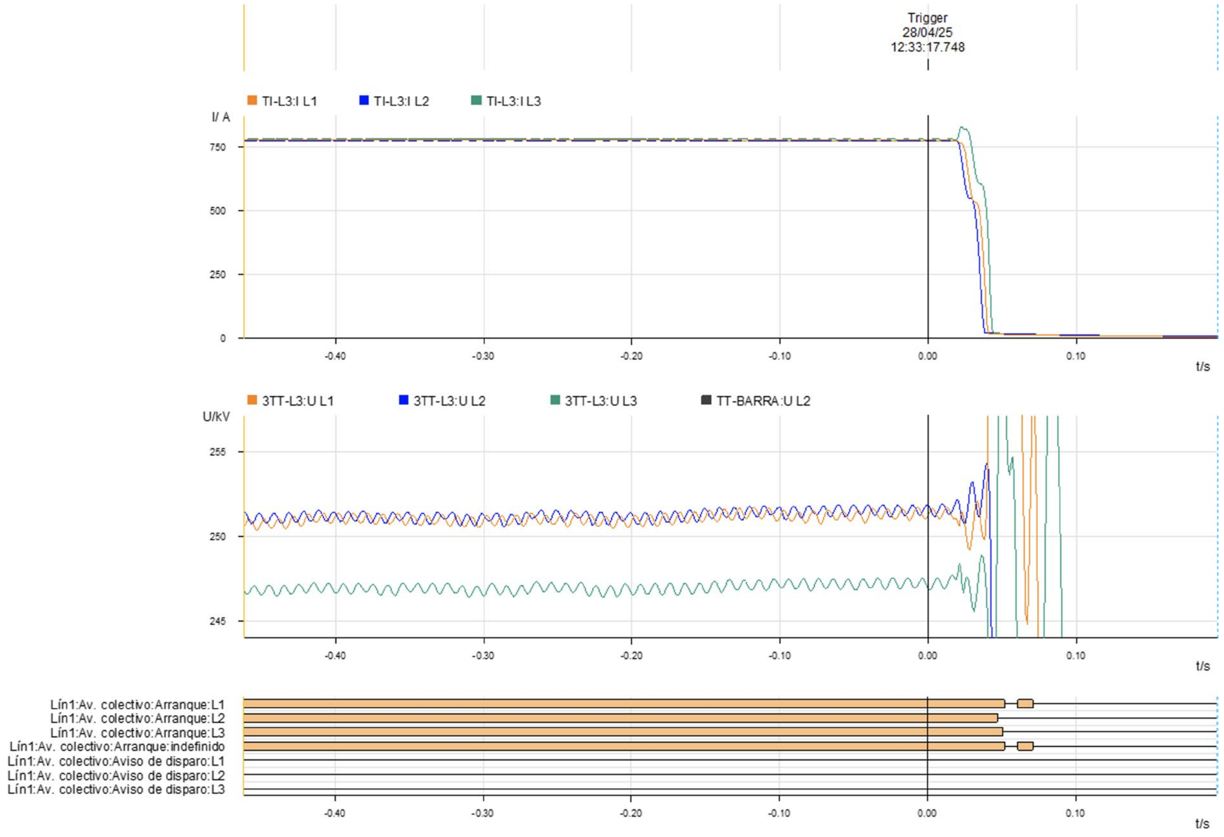


Figure 3-32: Oscillographic record from 400 kV GS 1 – Seville substation TS 1 – Seville Bay

The distribution over voltage withstand requirements for generation connected downstream of the tripped element is as follows:

- V1: 0 MW
- V2: 0 MW
- V3: 698 MW
- V4: 0 MW
- V5: 0 MW

3.2.1.3.8 Event ID 5a3: 400 kV TS 1—Segovia 94 MW Disconnection

At 12:33:17.940, at 400 kV TS 1—Segovia, the generation evacuation transformer 400/132 kV tripped in the 132 kV level. This caused the loss of 94 MW of generation and the loss of 26.5 Mvar in reactive power absorption.

All facilities downstream from this installation were commissioned prior to the entry into force of the RfG.

No oscillographic records from the protection system that operated were provided. However, an oscillographic record was delivered to the Expert Panel from the 400/132 kV transformer at 400 kV TS 1—Segovia, in which the voltage levels at both 400 kV (connection point) and 132 kV can be observed at the moment of the trip. The phase-to-ground voltage measured at the 400 kV level at the moment of the trip was 256.0 kV, which corresponds to 443.4 kV phase-to-phase. The phase-to-ground voltage measured at the 132 kV level was 84.7 kV, which corresponds to 146.7 kV phase-to-phase. The settings received for the overvoltage function include a voltage threshold of 1.1 pu with a time delay of 0.5 seconds.

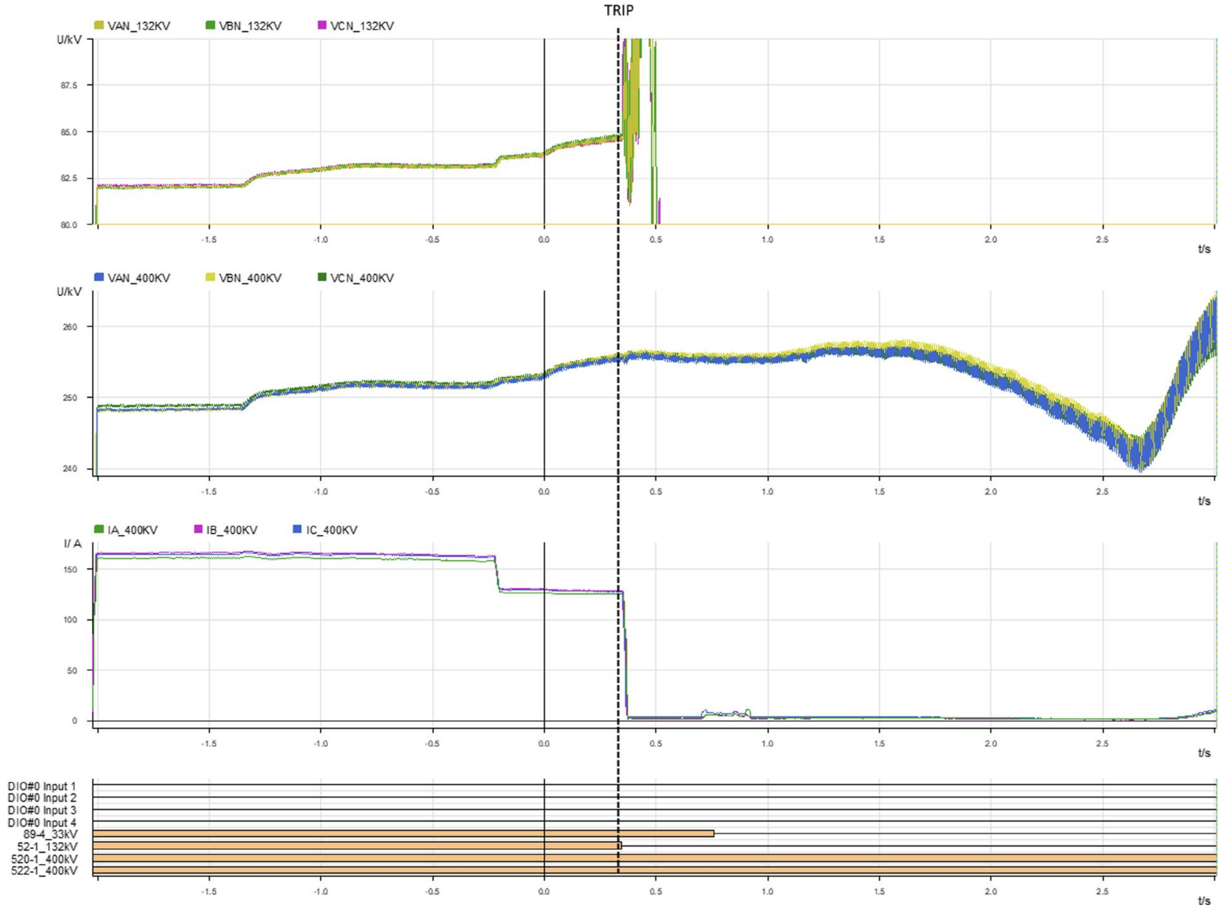


Figure 3-33: Voltage at the 400 kV and 132 kV voltage levels of the TS 1—Segovia generation transformer and transformer current at the 400 kV level

The distribution over voltage withstand requirements for generation connected downstream of the tripped element is as follows:

- V1: 230 MW
- V2: 0 MW
- V3: 0 MW
- V4: 0 MW
- V5: 0 MW

3.2.1.3.9 Event ID 5b3: 220 kV TS 1—Cáceres 37.5 MW Disconnection

At 12:33:17.975, one PV plant connected to 220 kV TS 1—Cáceres was disconnected. This caused the loss of 37.5 MW of generation and 7 Mvar in reactive power absorption.

This PV plant must comply with Order TED 749/2020.

To determine the timing of the generation loss, events provided by the responsible control centre were used. It was verified that approximately at that moment, a voltage step is observable in the PMU measurements from 220 kV TS 4—Cáceres. This is the closest PMU available, although it is located slightly less than 100 km away.

No oscillographic records from the protection system that operated were delivered to the Expert Panel.

According to the information received, the trip was caused by an overvoltage condition. The setting of this protection function at the time of the incident was 110 % of 220 kV, with a time delay of 1.5 seconds. Likewise, the owner has reported that the voltage reached at the moment of the trip was 250.39 kV.

The distribution over voltage withstand requirements for generation connected downstream of the tripped element is as follows:

- V1: 0 MW
- V2: 0 MW
- V3: 106 MW
- V4: 0 MW
- V5: 0 MW

3.2.1.3.10 Event ID 5b4 220 kV TS 3—Badajoz 71.9 MW Disconnection

At 12:33:18.020, three PV plants connected to 220 kV TS 3—Badajoz were disconnected due to the tripping of an upstream element. This caused the loss of 71.9 MW of generation and 16 Mvar in reactive power absorption. All PV plants connected to this point of connection must comply with Order TED 749/2020.

No oscillographic records from the protection system that operated, nor the settings of that relay, were delivered to the Expert Panel.

However, oscillographic records were received from the PV plants coinciding with the trip of the upstream facility. These records were likely synchronised using the nearest PMU frequency to time-align data. They show that the phase-to-ground voltage at the plant's location reached 147.2 kV, which corresponds to 254.9 kV phase-to-phase. High-resolution records are not available at the connection point (220 kV TS 3—Badajoz).

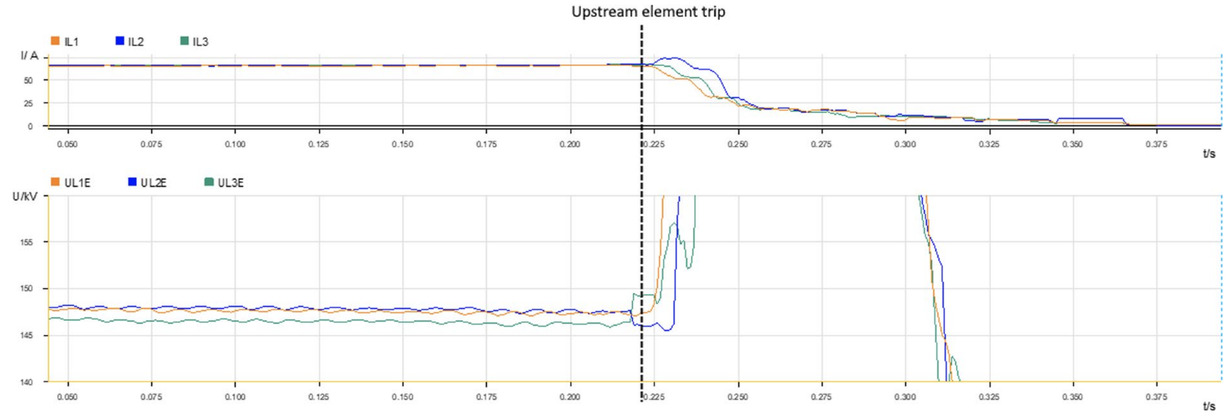


Figure 3-34: Oscillographic record from one PV plant with a point of connection in 220 kV TS 3—Badajoz

The distribution over voltage withstand requirements for generation connected downstream of the tripped element is as follows:

- V1: 0 MW
- V2: 0 MW
- V3: 124 MW
- V4: 0 MW
- V5: 0 MW

3.2.1.3.11 Event ID 6a1 220 kV TS 2—Seville 3 MW Disconnection

At 12:33:18.102, the generation–transmission interface facility tripped at the end corresponding to the generation evacuation network and additionally sent a remote trip signal to the transmission network substation end (220 kV TS 2—Seville). This caused the disconnection of 3 MW of PV plants. This plant must comply with Regulation (EU) 2016/631 (RfG).

No oscillographic records from the protection system that operated, nor the settings of that relay, were delivered to the Expert Panel. However, an oscillographic record is available from the end connected to the transmission network, where it can be observed that the voltage at the moment of the trip was 142.3 kV, which would correspond to a phase-to-phase voltage of 246.5 kV.

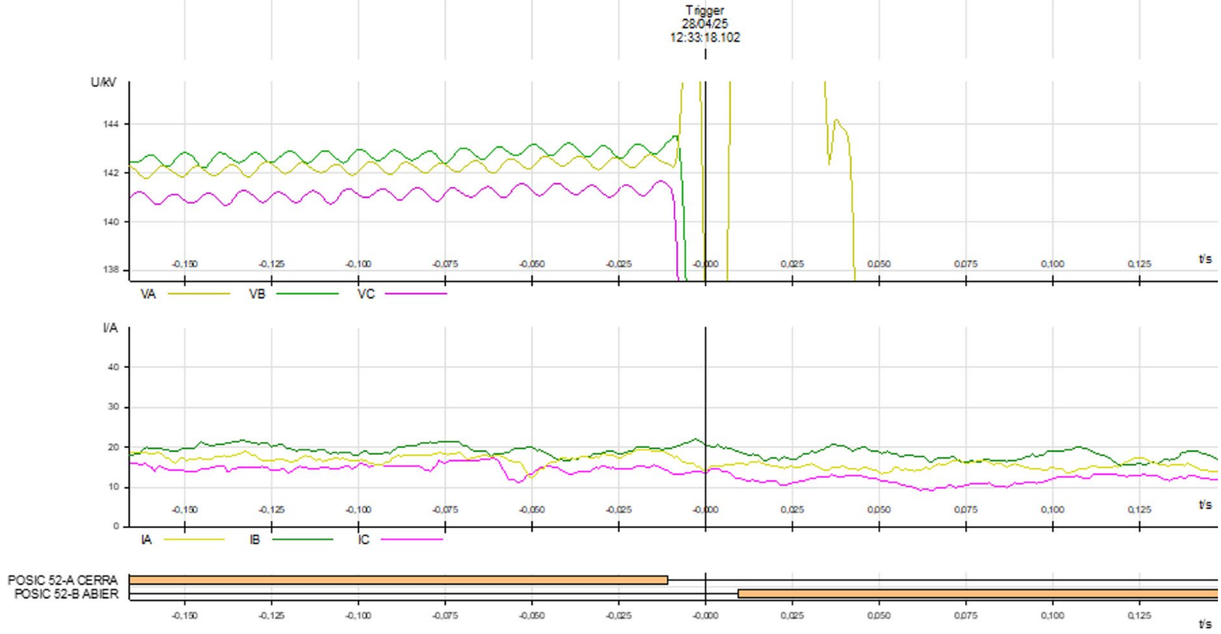


Figure 3-35: Oscillographic record from "220 kV TS 2—Seville" collector bay

The distribution over voltage withstand requirements for generation connected downstream of the tripped element is as follows:

- V1: 0 MW
- V2: 100 MW
- V3: 0 MW
- V4: 0 MW
- V5: 0 MW

3.2.1.3.12 Event ID 6a2 220 kV TS 3—Badajoz 20 MW Disconnection

At 12:33:18.220, 20 MW of power injection reduction was observed due to a link facility at a 220 kV substation located in the province of Badajoz.

All PV plants connected to this point of connection must comply with Order TED 749/2020.

No oscillographic records from the protection system that operated, nor the settings of that relay, were delivered to the Expert Panel.

The distribution over voltage withstand requirements for generation connected downstream of the tripped element is as follows:

- V1: 0 MW
- V2: 0 MW
- V3: 292 MW
- V4: 0 MW
- V5: 0 MW

3.2.1.3.13 Event ID 6a3 400 kV TS 3—Badajoz 16 MW Disconnection

At 12:33:18.360, a 16 MW reduction was observed due to a link facility at substation 400 kV TS 3—Badajoz and a 4 Mvar absorption reduction. This was measured by a PMU that is connected at the transmission end of the line, but there is no information on which exact plant was disconnected.

All PV plants connected to this point of connection must comply with Order TED 749/2020.

No oscillographic records from the protection system that operated, nor the settings of that relay, were delivered to the Expert Panel.

Figure 3-36 shows the power and voltage measured by the PMU installed at that line position. Subsequent reductions in power injection down to zero can also be observed. The phase-to-phase voltage at the moment of the first observed disconnection was 447.7 kV.

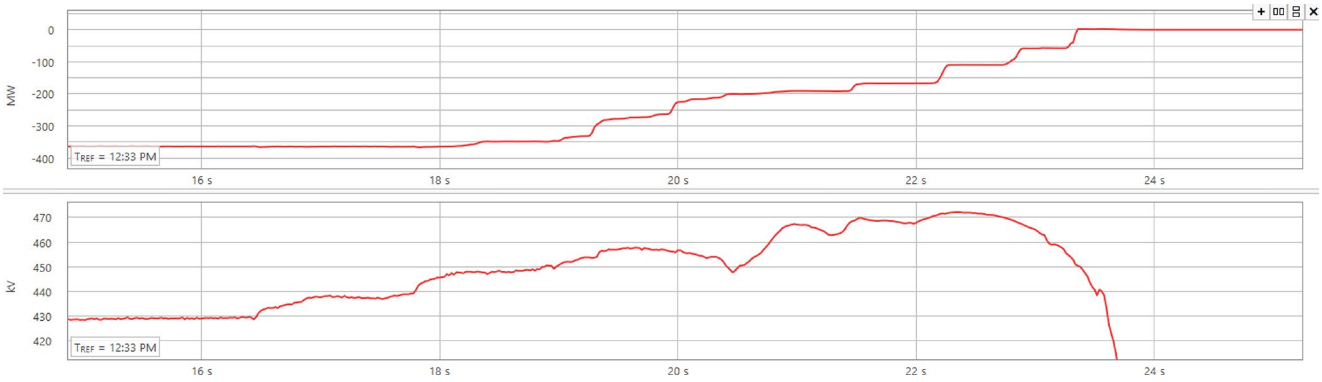


Figure 3-36: PMU measurements at the 400 kV TS 3—Badajoz collector bay

The distribution over voltage withstand requirements for generation connected downstream of the tripped element is as follows:

- V1: 0 MW
- V2: 0 MW
- V3: 369 MW
- V4: 0 MW
- V5: 0 MW

3.2.1.3.14 Event ID 6a4 400 kV TS 2—Cáceres 41 MW Disconnection

At 12:33:18.410, a PV plant connected to 400 kV TS 2—Cáceres tripped. This PV plant was generating 41 MW. This plant must comply with Order TED 749/2020.

No oscillographic records from the protection system that operated, nor the settings of that relay, were delivered to the Expert Panel.

The phase-to-phase voltage at the moment of the first observed disconnection was 443.7 kV at 400 kV TS 2—Cáceres.

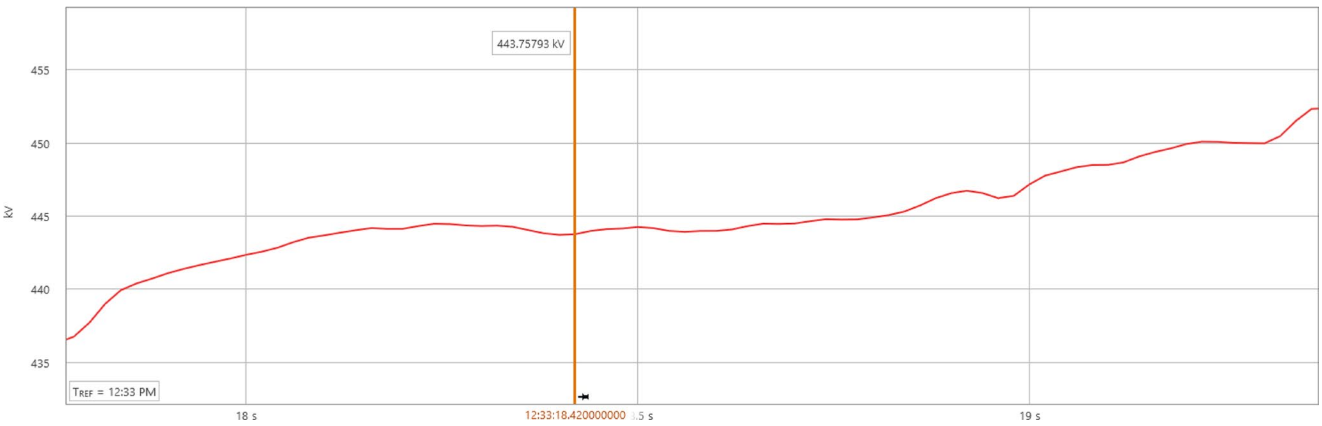


Figure 3-37: PMU voltage measurement at 400 kV TS 2—Cáceres

The distribution over voltage withstand requirements for generation connected downstream of the tripped element is as follows:

- V1: 0 MW
- V2: 0 MW
- V3: 42 MW
- V4: 0 MW
- V5: 0 MW

3.2.1.3.15 Event ID 6a5 400 kV TS 1 – Murcia 63 MW Disconnection

At 12:33:18.540, a PV plant connected to a 132 kV distribution network close to 400 kV TS 1 – Murcia tripped when it was generating 63 MW. This plant must comply with the Spanish Operational Procedure 1.4. The settings of that relay have not been received.

The cause of the trip was overvoltage. The phase-to-phase voltage at the 132 kV substation was 147.3 kV.

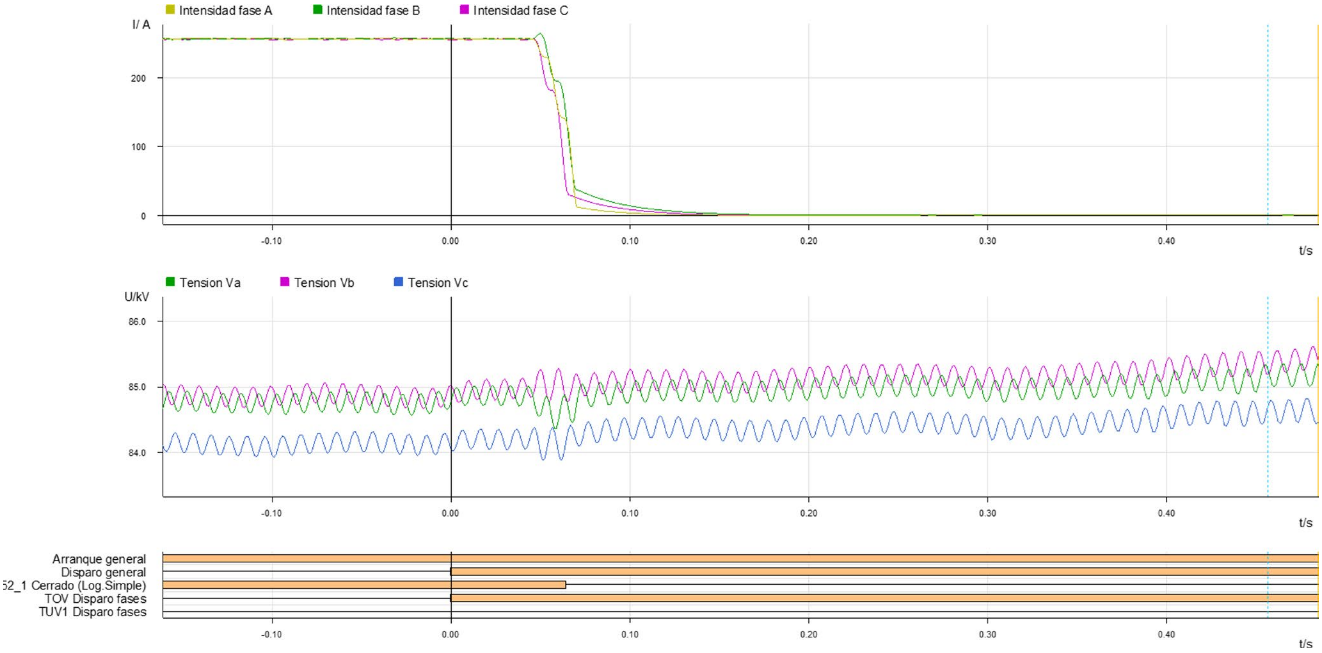


Figure 3-38: Oscillographic record from the PV plant

The distribution over voltage withstand requirements for generation connected downstream of the tripped element is as follows:

- V1: 0 MW
- V2: 0 MW
- V3: 0 MW
- V4: 0 MW
- V5: 74 MW

3.2.1.3.16 Event ID 6a6 220 kV TS 1—Cádiz 26 MW and ID 6a7 220 kV TS 1—Cádiz 128 MW Disconnection

At 12:33:18.630, a transformer connected to 220 kV GS 1—Cádiz tripped, and 25.7 MW were lost. After 50 ms, the evacuation line to 220 kV TS 1—Cádiz tripped at the generation end, and an additional 127.5 MW were disconnected. There are wind farms and PV plants connected to 220 kV TS 1—Cádiz through this evacuation line. Some of these plants were commissioned before the RfG came into force, others afterwards, and some after the entry into force of the TED 749 Order.

No oscillographic records from the protection system that operated, nor the settings of that relay, were delivered to the Expert Panel. However, an oscillographic record was received from the bay protection system at the circuit breaker corresponding to the evacuation line towards the transmission network.

There are no high-resolution records from the transmission substation that is the point of connection. However, the phase-to-ground voltage recorded at the generation substation was 143.3 kV, which corresponds to a phase-to-phase voltage of 248.0 kV.

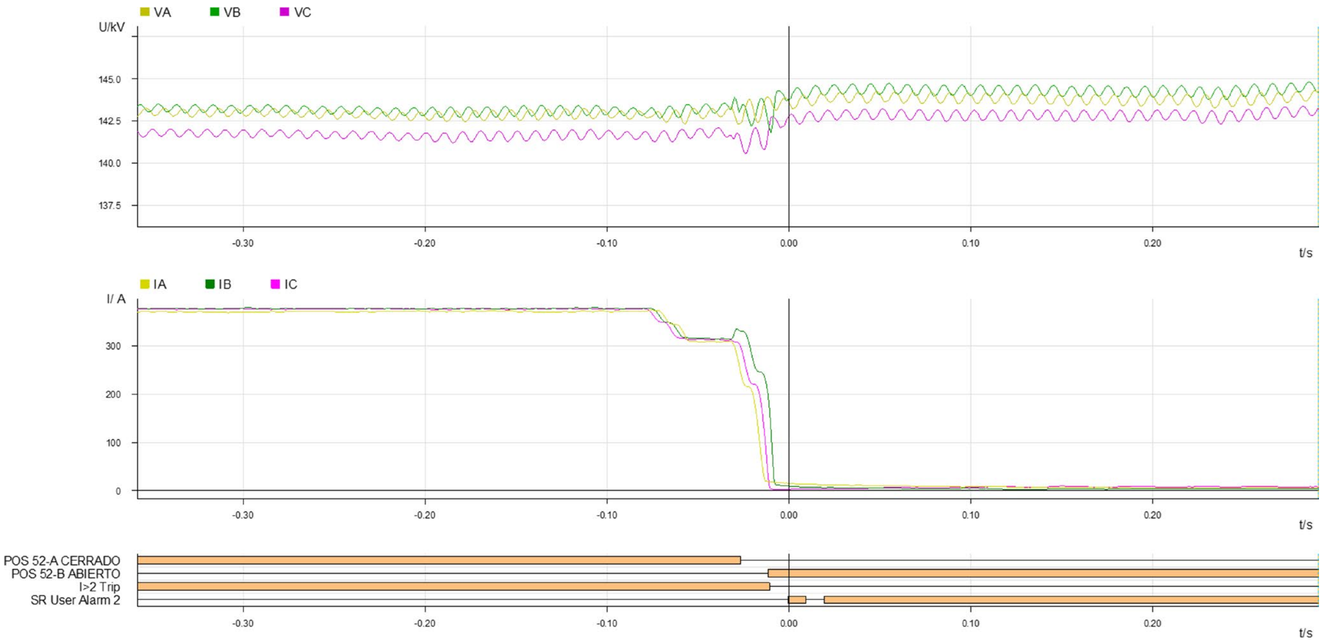


Figure 3-39: Oscillographic record from the 220 kV GS 1—Cádiz bay to TS 1—Cádiz

The distribution over voltage withstand requirements for generation connected downstream of the tripped element is as follows:

- V1: 100 MW
- V2: 8 MW
- V3: 88 MW
- V4: 0 MW
- V5: 0 MW

3.2.1.3.17 Event ID 6a8 400 kV TS 1—Málaga 154 MW Disconnection

At 12:33:18.846, the generation–transmission interface line tripped at the end corresponding to the generation evacuation network and additionally sent a remote trip signal to the transmission network substation end (400 kV TS 1—Málaga). This caused the disconnection of several PV plants with a total production of 154 MW.

All PV plants connected to this point of connection must comply with Order TED 749/2020.

The received settings indicate that the overvoltage function is configured at 439.56 kV phase-to-phase (1.0989 pu) with a time delay of one second. Additionally, the oscillographic record from the tripping relay was delivered to the Expert Panel, showing that at the moment of the trip, the voltage of all three phases was above 1.1 pu. Figure 3-40 shows the oscillographic record that tripped the line at the generation end.

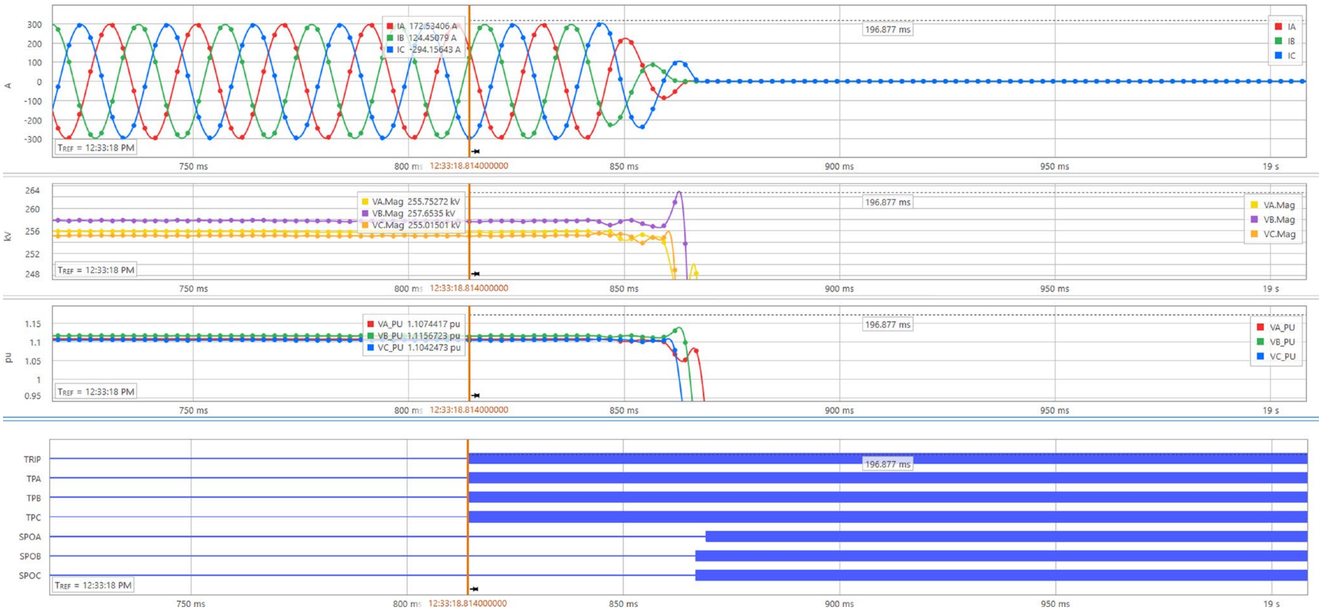


Figure 3-40: Line protection oscillographic record from the generation end

Figure 3-41 shows the oscillographic record obtained at the transmission end. The phase-to-phase voltage at the time of the trip was 448.6 kV.

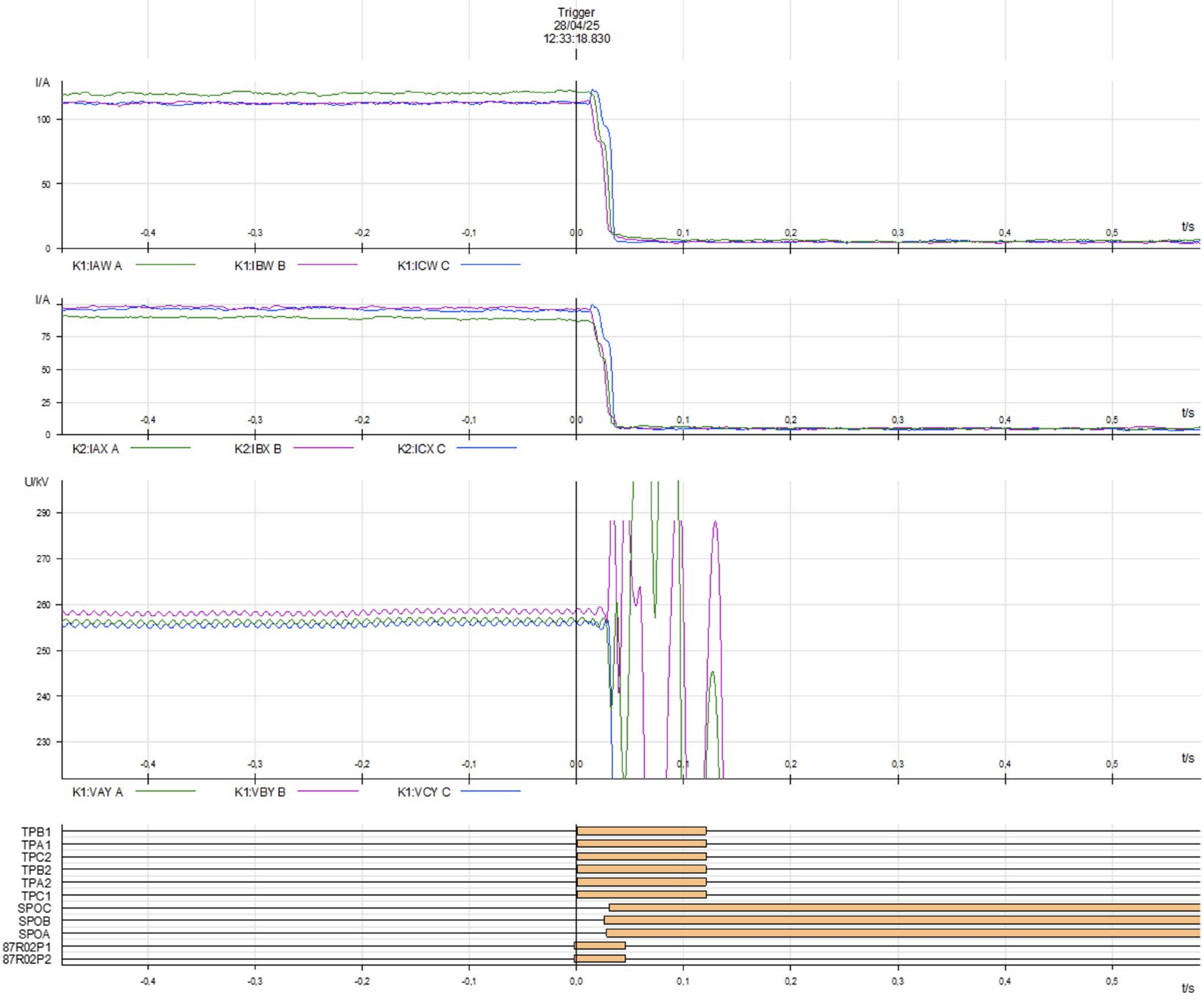


Figure 3-41: Oscillographic record from 400 kV TS 1 – Málaga, collector bay (TPx1: breaker 1 trip of each phase, TPx2: breaker 2 trip of each phase, SPOx: Single pole open of each phase, 87R02P1: transfer trip received through communication channel 1, 87R02P2: transfer trip received through communication channel 2)

The distribution over voltage withstand requirements for generation connected downstream of the tripped element is as follows:

- V1: 0 MW
- V2: 0 MW
- V3: 174 MW
- V4: 0 MW
- V5: 0 MW

3.2.1.3.18 Event ID 6b 400 kV TS 1—Cuenca 530 MW Disconnection

At 12:33:18.951, the generation–transmission interface line tripped at the end corresponding to the generation evacuation network and additionally sent a remote trip signal to the transmission network substation end (400 kV TS 1—Cuenca). This caused the disconnection of several PV plants with a total production of 530 MW.

All PV plants connected to this point of connection must comply with Order TED 749/2020.

The settings delivered to the Expert Panel for these relays show two stages for the overvoltage protection function: a first stage with a voltage threshold of 1.088 pu and a time delay of 60 minutes, and a second stage with a voltage threshold of 1.11 pu and a time delay of 1.2 seconds. The COMTRADE record of the relay that tripped at the generation substation end shows that the maximum phase-to-ground voltage measured at the time of the trip was 257.8 kV (1.116 pu), which corresponds to a phase-to-phase voltage of 446.6 kV

Figure 3-42 shows the record of the generation side.

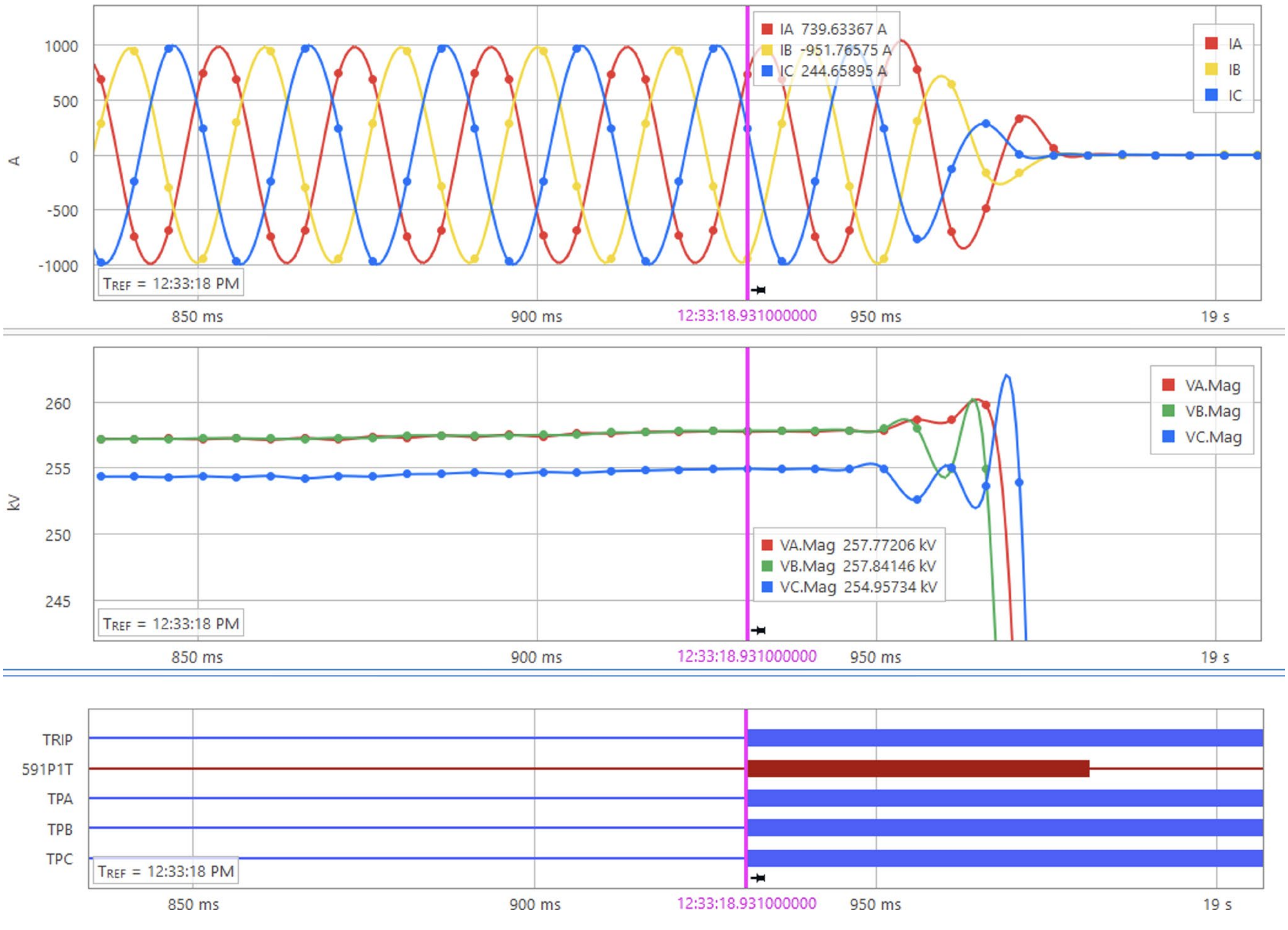


Figure 3-42: Oscillographic record from 400 kV GS 1—Cuenca, TS 1—Cuenca bay (591P1T: overvoltage trip)

Figure 3-43 shows the oscillographic record corresponding to the transmission substation end. It shows that the phase-to-ground voltage measured at the moment of the trip was 259.0 kV, which corresponds to a phase-to-phase voltage of 448.6 kV.

It should be noted that the ripple observed in the image in the RMS voltage values is caused by the fact that the system frequency at that moment was not 50 Hz, but approximately 49.8 Hz. This necessitated adjusting the time window used for filtering and calculating this value to align with the actual system frequency. However, the visualisation software is not capable of performing this adjustment. The same behaviour has been observed in previous records.

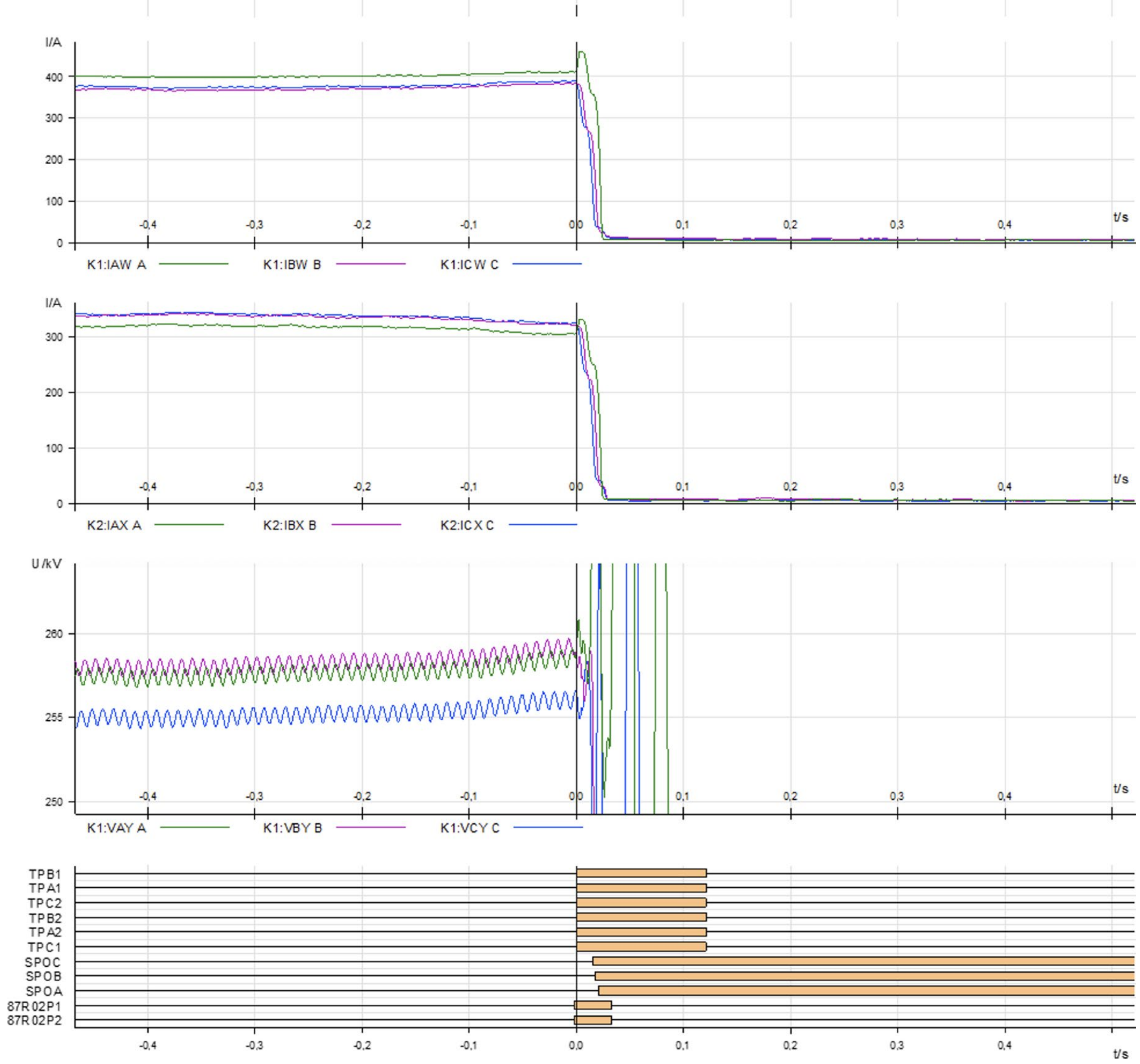


Figure 3-43: Oscillographic record from 400 kV TS 1–Cuenca transmission substation, GS 1–Cuenca bay (TPx1: breaker 1 trip of each phase, TPX2: breaker 1 trip of each phase, SPOx: Single pole open of each phase, 87R02P1: transfer trip received through communication channel 1, 87R02P2: transfer trip received through communication channel 2)

The distribution over voltage withstand requirements for generation connected to the 400 kV TS 1–Cuenca substation is as follows:

- V1: 0 MW
- V2: 0 MW
- V3: 664.85 MW
- V4: 0 MW
- V5: 0 MW

3.2.1.4 Generation Disconnections in Portugal

In Portugal, the disconnection of generating units connected to the transmission grid that occurred between 12:33:23 and 12:33:37 was caused by a frequency drop below 47.5 Hz.

This response was compliant with the regulations outlined in the previous chapter.

Concerning generating units connected to the distribution grid, some of them disconnected before 12:33:23, and the total amount is under evaluation.

3.2.1.5 Generation Disconnections in France

Below is a detailed list of impacts on generation units and network elements.

Tripping time	Generation unit	Type	P lost (MW)	Q lost (Mvar)	Voltage level (kV)	Cause of the trip
12:33:19.850	Hydro 1 South-West of France	Hydro	3.5	0	63	Under investigation
12:33:19.850	Hydro 2 South-West of France	Hydro	3.5	0	63	Under investigation
12:33:19.850	Hydro 3 South-West of France	Hydro	3.5	0	63	Under investigation
12:33:20.900	Hydro 4 South-West of France	Hydro	-35	0	225	Under investigation
12:33:23.307	Hydro 5 South-West of France	Hydro	28	-17	225	Under investigation
12:33:23.460	Hydro 6 South-West of France	Hydro	-210	27	400	Under investigation
12:33:23.863	Hydro 7 South-West of France	Hydro	6	?	150	Under investigation
12:33:23.857	Hydro 8 South-West of France	Hydro	1.8	0	63	Under investigation
12:33:23.857	Hydro 9 South-West of France	Hydro	1.8	0	63	Under investigation
12:33:30	Hydro 10 South-West of France	Hydro	5	-2	63	Under investigation
12:33:35.759	Nuclear 1 South-West of France	Nuclear power plant	1,290	-430	400	Internal Protection trip
12:33:36	Hydro 11 South-West of France	Hydro	7	0	63	Under investigation
12:35:53.189	Hydro 12 South-West of France	Hydro	17	-2	63	Under investigation

Table 3-4: List of production tripping in France

3.2.1.5.1 Nuclear 1 South-West of France

The nuclear reactor one of Golfech power plant (1,290 MW) disconnected at 12:33:35.759 due to the trip of an internal protection.

3.2.1.5.2 Solar 1 South-West of France

Production decreased from 16 to 7 MW. As the voltage increased, production progressively recovered.

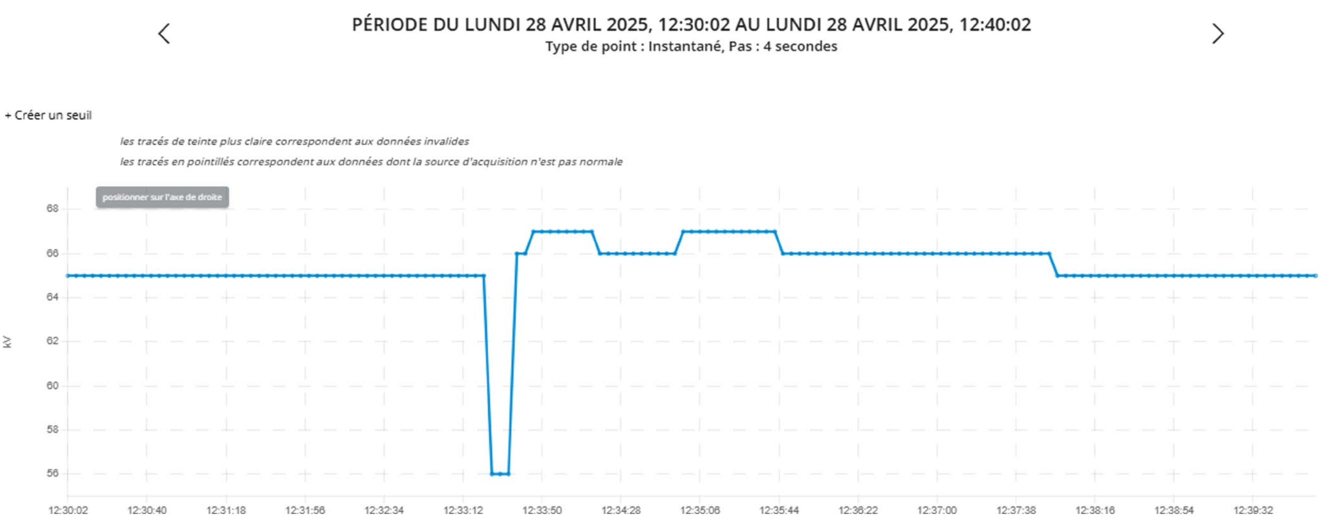


Figure 3-44: Solar 1

3.2.1.5.3 Solar 2 South-West of France

There was a decrease in production from 23 to 4 MW, along with an increase in the voltage (see Figure 3-45).

Figure 3-45: Solar 2a (blue) and Solar 2b (red)

3.2.1.5.4 Battery 1 South-West of France

A rise in voltage was seen at 12:33:26, as shown in Figure 3-46.

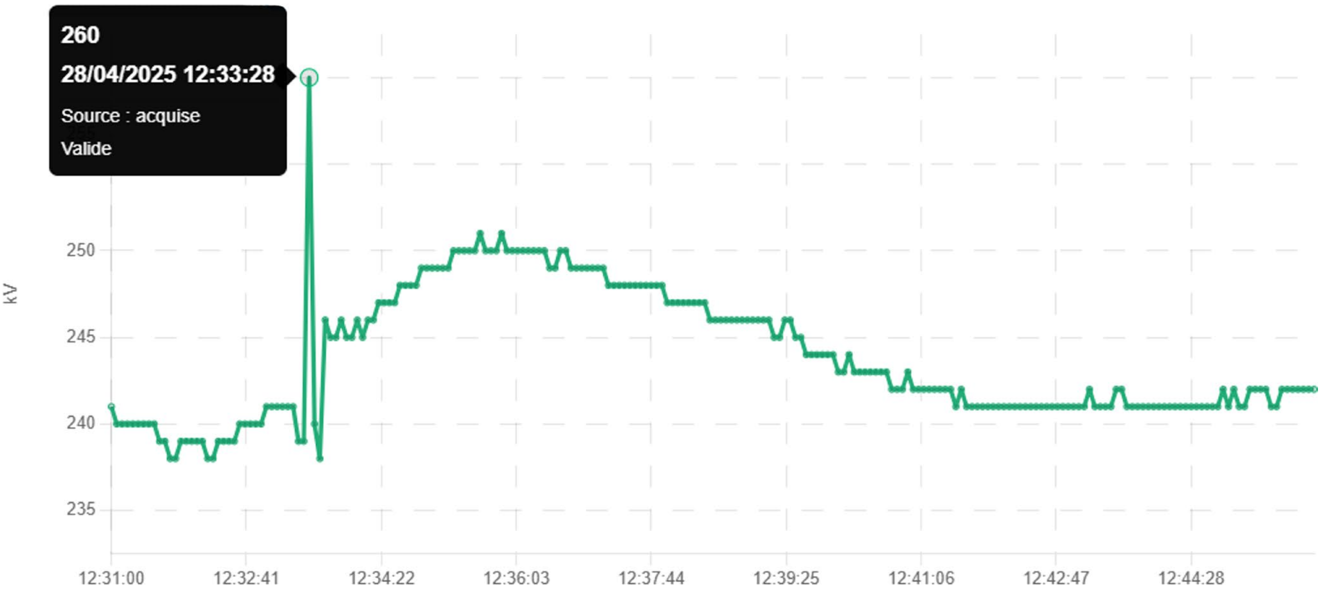


Figure 3-46: Battery 1

3.2.2 Transmission System Protection Behaviour During the Incident

The events that will be analysed are listed in Table 3-5. The identification of the events is in line with the sequence of the events presented in Table 3-1.

Event	Time (CEST)	Substation A (TSO)	Substation B (TSO)	Voltage Level (kV)	Asset Type	Relay Trigger	Cause of Tripping	Tripped Phases	Relay Parameter Settings
9	12:33:19.971	Arganda (RE)	Loeches (RE)	220	OHL	OV	Incorrect measurement from phase B voltage transformer in Loeches substation	3 phase	V > 120 % Vnominal time delay = 1 s
16a	12:33:20.229	Puerto de la Cruz (RE)	Beni Harchane (ONEE)	400	OCHL-TIE	UF	Low frequency function at Morocco side and transfer trip to Spain	3 phase	f < 49.5 Hz
16b	12:33:20.473	Puerto de la Cruz (RE)	Melloussa (ONEE)	400	OCHL-TIE	UF	Low frequency function at Morocco side and transfer trip to Spain	3 phase	f < 49.5 Hz
31a	12:33:21:407	Baixas (RTE)	Vic (RE)	400	OHL-TIE	OST	Loss of synchronism	3 phase	2 beats
31b1	12:33:21.437	Argia (RTE)	Arkale (RE)	220	OHL-TIE	OST	Loss of synchronism	3 phase	2 beats
31b2	12:33:21.535	Argia (RTE)	Hernani (RE)	400	OHL-TIE	OST	Loss of synchronism	3 phase	2 beats
42	12:33:23.076	Valdecaballeros (RE)	Maguilla (RE)	400	OHL	OV	Overvoltage	3 phase	
52	12:33:23.954	Mogadouro (REN)	Central da Valeira (REN	220	OHL	DIST	Distance Z1 trip due to unstable voltage conditions protection	3 phase	Z < 80 % line
55b	12:33:25.144	Cartelle (RE)	Lindoso (REN) (ckt 2)	400	OHL-TIE	DIST	Z1 trip due to voltage and frequency collapse	3 phase	Z < 80 % line
55c	12:33:25.183	Cartelle (RE)	Lindoso (REN) (ckt 1)	400	OHL-TIE	DIST	Z1 trip due to voltage and frequency collapse	3 phase	Z < 80 % line
55d	12:33:25.325	Cedillo (RE)	Falagueira (REN)	400	OHL-TIE	DIST	Z1 trip due to voltage and frequency collapse	3 phase	Z < 80 % line
55e	12:33:25.410	Saucelle (RE)	Pocinho (REN)	220	OHL-TIE	DIST	Z1 trip due to voltage and frequency collapse	3 phase	Z < 80 % line
56	12:33:25.434	Lagoaça (REN)	Armamar (REN)	400	OHL	DIST	Distance Z1 trip due to unstable voltage conditions	3 phase	Z < 80 % line
55f	12:33:26.165	Aldeadávila (RE)	Pocinho (REN) (ckt 1)	220	OHL-TIE	DIST	Z1 trip due to voltage and frequency collapse	3 phase	Z < 80 % line

Table 3-5: Performance of the protection system of lines in the sequence of events, abbreviations: OHL: overhead line, OCHL: overhead-cable hybrid line, OHL-TIE: overhead line tie line, OCHL-TIE: overhead-cable hybrid line tie line, DIST: distance protection, UF: under frequency protection, OST: Loss of synchronism protection, OV: over voltage protection

3.2.2.1 Event ID 9: 220 kV Arganda (RE)—Loeches (RE)

At 12:33:19.971, the Arganda (RE)—Loeches (RE) 220 kV overhead line (OHL) tripped. The overvoltage function caused the trip; during the high voltage situation, an incorrect measurement from the phase B voltage transformer in the Loeches substation was the cause of the overvoltage function trip. The relay protection system of the OHL operated according to its settings (1.2 pu, one-second delay).

In Figure 3-47, the upper chart shows the voltage measured at the Loeches substation, where the overvoltage was detected, and the lower chart shows the voltage measured at the Arganda substation. Arganda relays did not trip, but the breaker opened because they received a transfer trip signal.

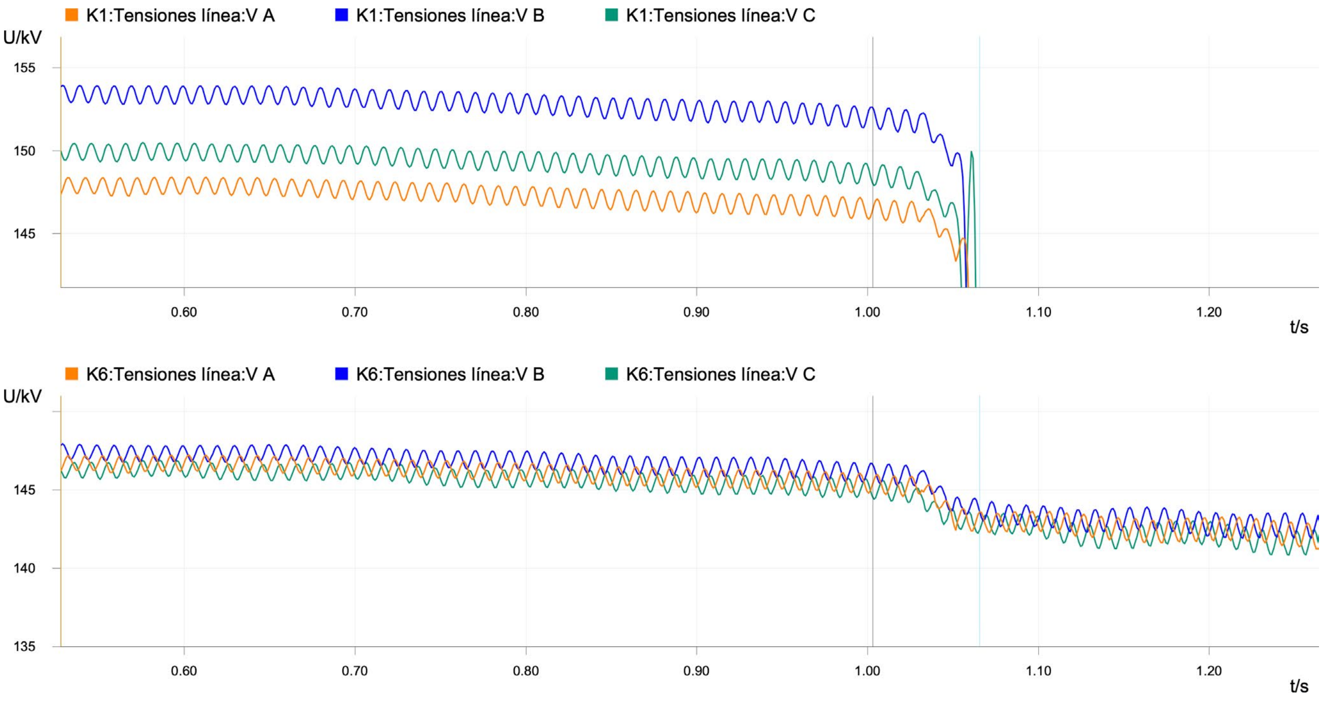


Figure 3-47: RMS Voltages in Loeches substation (upper chart) and in Arganda substation (lower chart)

Figure 3-47 shows that the voltage measurements in the different phases at the Loeches substation vary significantly from one phase to another. This anomaly suggests that the voltage transformer was exhibiting abnormal behaviour. Additionally, the fact that no other lines in the substation tripped, when all have the same overvoltage settings, leads to the conclusion that the voltage measurement at the Loeches substation was not correct.

3.2.2.2 Event ID 16a: 400 kV Puerto de la Cruz (RE)—Beni Harchane (ONEE)

At 12:33:20.229, the Puerto de la Cruz (RE)—Beni Harchane (ONEE) 400 kV tie-line opened in Beni Harchane due to an underfrequency protection and also sent a direct transfer trip to the Spanish side (Puerto de la Cruz) that opened 161 ms later.

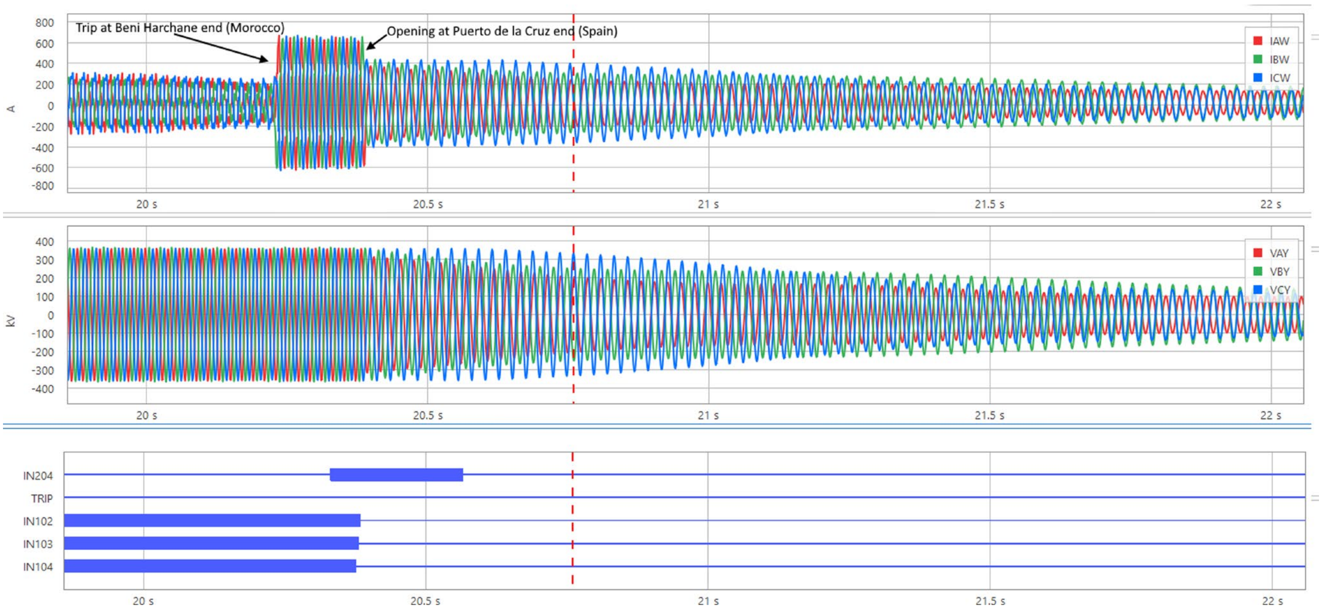


Figure 3-48: Beni Harchane bay at Puerto de la Cruz 400 kV substation relay recording (IN102, IN103, and IN104: breaker position, IN204: direct transfer trip reception)

3.2.2.3 Outage ID 16b: 400 kV Puerto de la Cruz (RE)—Melloussa (ONEE)

At 12:33:20.473, the Puerto de la Cruz—Melloussa 400 kV line opened in Melloussa due to an underfrequency protection and also sent a direct transfer trip to the Spanish side (Puerto de la Cruz) that opened 91 ms later.

Figure 3-50 shows the recording of the protection installed in the Melloussa bay at the Puerto de la Cruz 400 kV substation. The recording shows how the Moroccan end of the line tripped and indicates that it sent a direct transfer trip to the Spanish end. In addition, Figure 3-49 shows a trip signal, but this operation occurred when the breaker was already opened. This relay operation was caused by the discharge of the submarine cable on the reactor, as there was current with a low voltage.

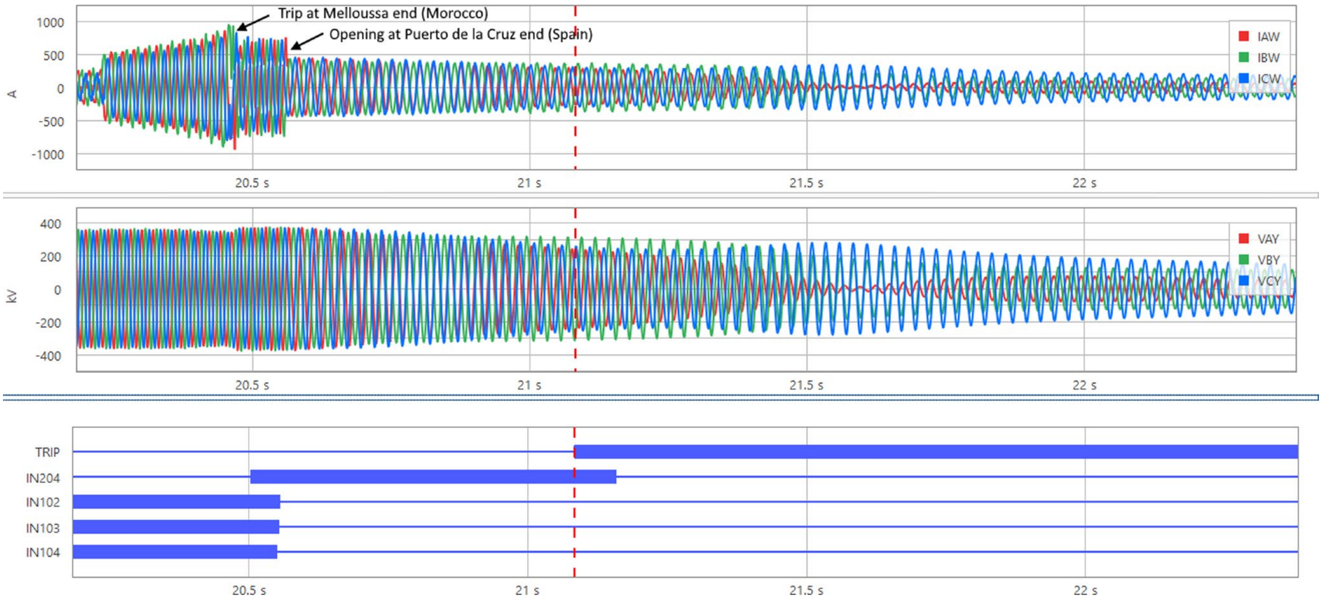


Figure 3-49: Melloussa bay at Puerto de la Cruz 400 kV substation relay recording (IN102, IN103, and IN104: breaker position, IN204: direct transfer trip reception)

3.2.2.4 Event ID 31a: 400 kV BAIXAS (RTE)—Vic (RE)

At 12:33:21.407, the Baixas (RTE)—Vic (RE) 400 kV line opened in Baixas (RTE) due to the tripping of the loss of synchronism protection. The Vic (RE) end tripped 35 ms later. The loss of synchronism protections on both sides are set for two beats (swing), which means that they trip after two swings (see Figure 3-50 and the explanation accompanying Figure 3-52).

Figure 3-50 shows the oscillography recorded by the distance protection of Baixas bay at Vic 400 kV substation because loss of synchronism protections are not able to record oscillography.

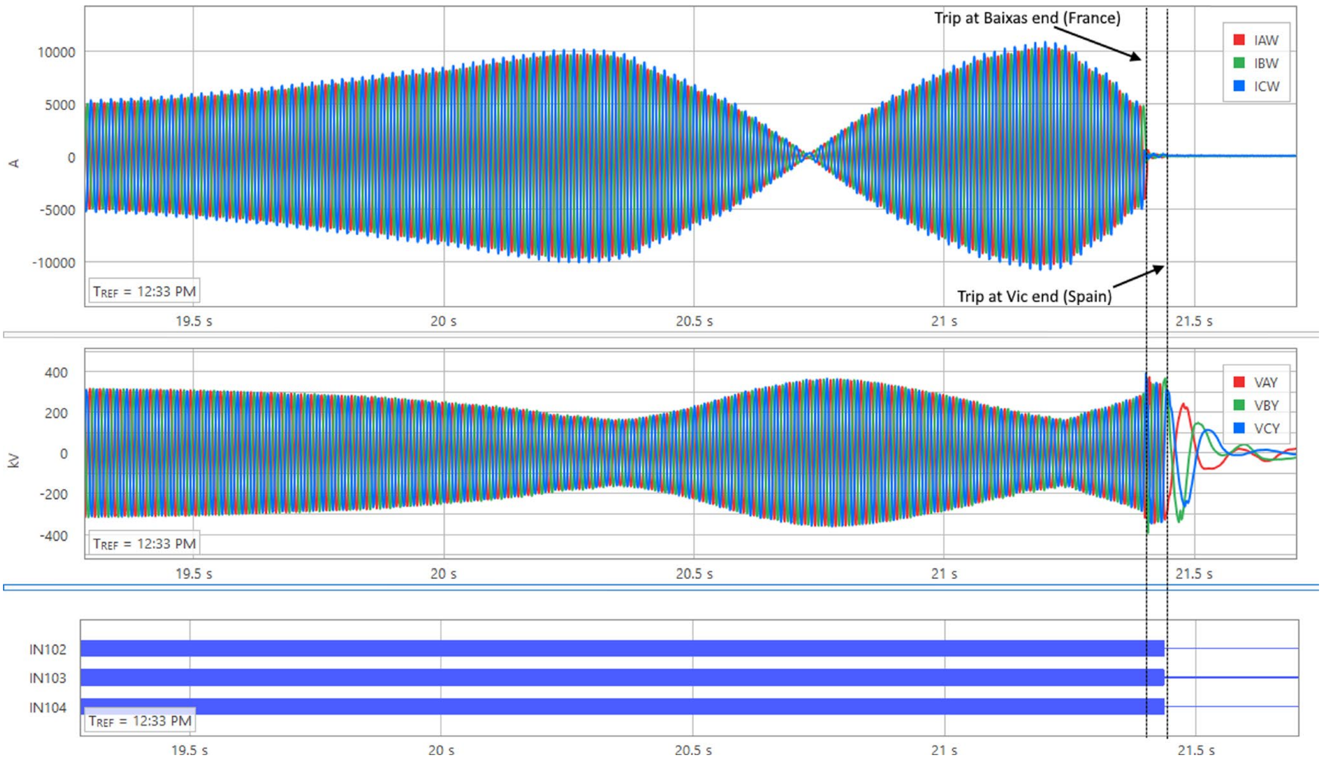


Figure 3-50: Baixas bay at Vic 400 kV substation distance relay recording (IN102, IN103 and IN104: breaker position).

Figure 3-51 illustrates the impedance evolution observed at Baixas bay at the Vic 400 kV substation using PMU data. It depicts the initial conditions, the changes following the first and second generation loss (events 3 and 4a, respectively), and the subsequent evolution at one-second intervals after the second generation loss.

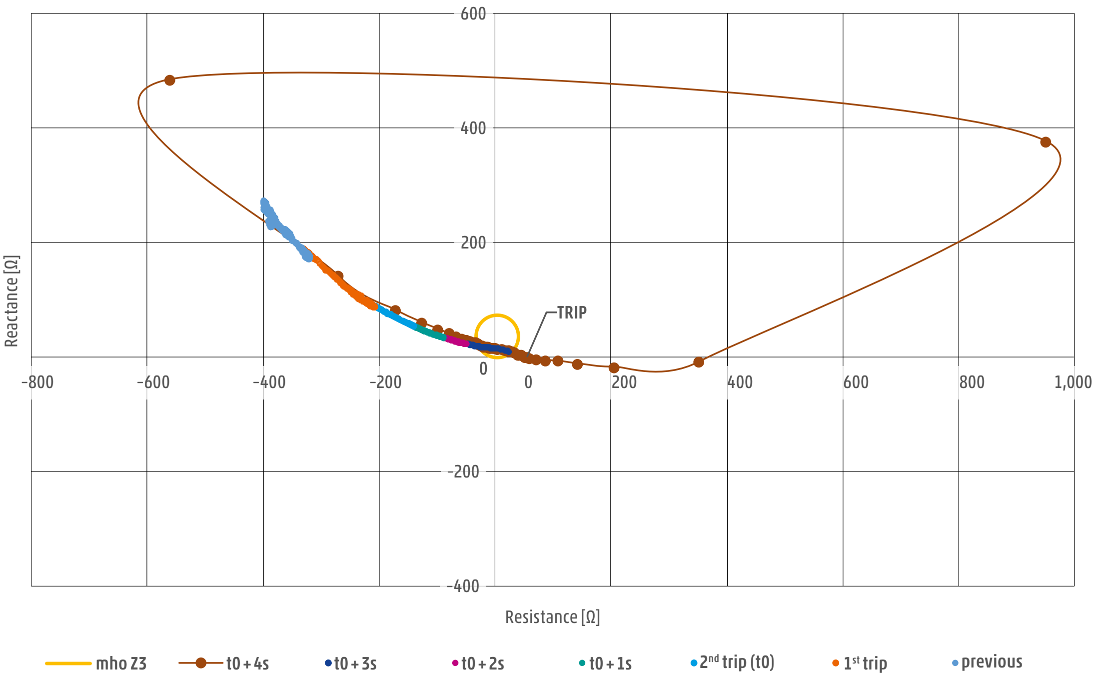


Figure 3-51: Baixas bay at the Vic 400 kV substation: Impedance evolution using PMU data

Explanation of the Operation of DRS Loss of Synchronism Protection

DRS loss of synchronism protection permanently measures the voltage peak values. When the relay measures at least 10 consecutive decreasing peaks followed by four consecutive increasing peaks, it detects one beat if the minimum voltage reached is below a configured voltage threshold. After detecting the configured number of beats, the relay is ready to trip, and it will trip after a time delay that starts when the average RMS voltage during the oscillation is exceeded, as seen in Figure 3-52.

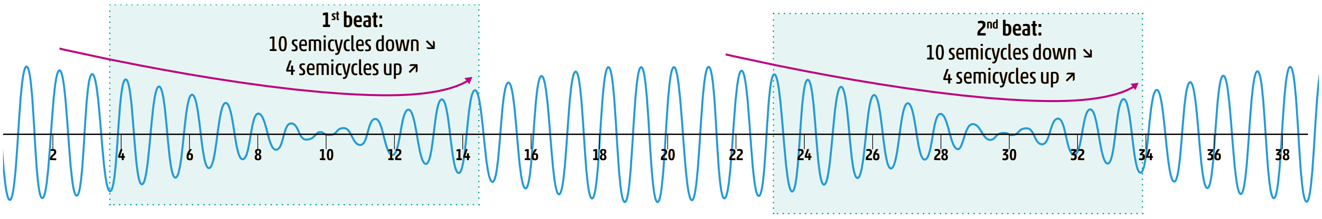


Figure 3-52: DRS loss of synchronism protection operating principle

3.2.2.5 Event ID 31b1: 220 kV ARGIA (RTE)—Arkale (RE)

At 12:33:21.437, the Argia (RTE)—Arkale (RE) 220 kV line opened in Arkale (RE) due to the tripping of the loss of synchronism protection. The Argia (RTE) end did not trip because of the voltage fall (trip on the Spanish side); therefore, the loss of synchronism protection lost the count of the pulse (see Figure 3-53).

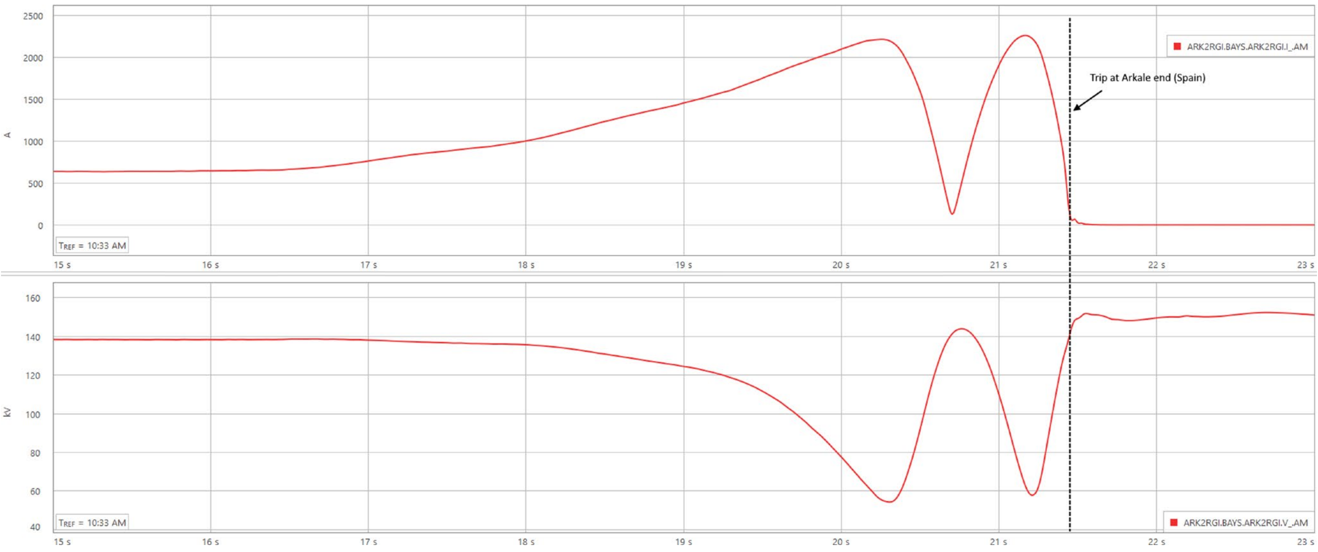


Figure 3-53: Argia bay at Arkale 220 kV PMU data

Figure 3-54 illustrates the impedance evolution observed at Argia bay at the Arkale 220 kV substation using PMU data. It depicts the initial conditions, the changes following the first and second generation loss (events 3 and 4a, respectively), and the subsequent evolution at one-second intervals after the second generation loss.

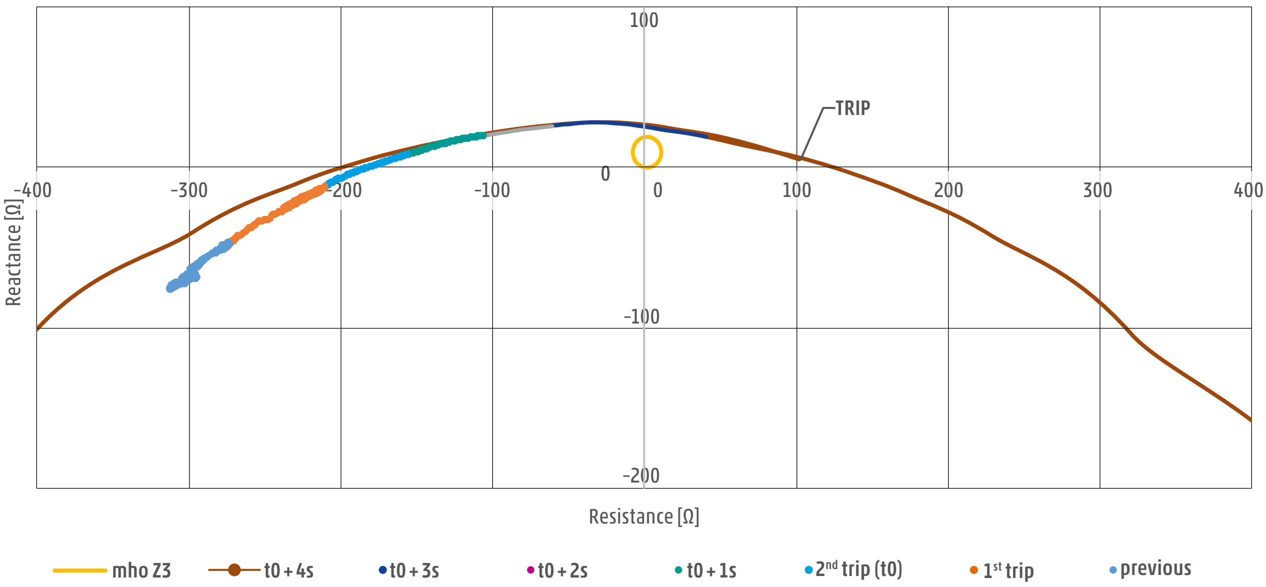


Figure 3-54: Argia bay at Arkale 220 kV substation: Impedance evolution using PMU data

3.2.2.6 Event ID 31b2: 400 kV ARGIA (RTE)—Hernani (RE)

At 12:33:21.535, the Argia (RTE)—Hernani (RE) 400 kV line opened in Hernani (RE) due to the tripping of the out-of-step function of the distance protection, whose operating principle is based on monitoring the trajectory of the impedance seen by the relay. The Argia (RTE) end did not trip because of the voltage fall (trip on the Spanish side); therefore, the loss of synchronism protection lost the count of the pulse.

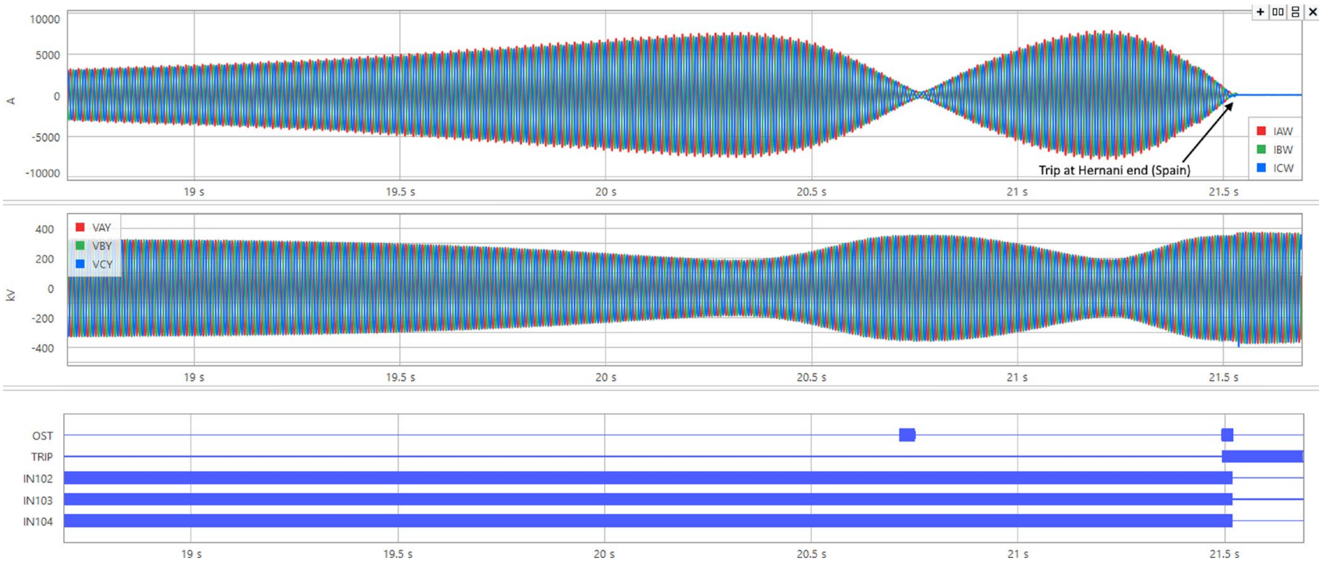


Figure 3-55: Argia bay at Hernani 400 kV substation recording (IN102, IN103, and IN104: breaker position)

Figure 3-56 shows the voltage drop due to the trip on the other end of the line.

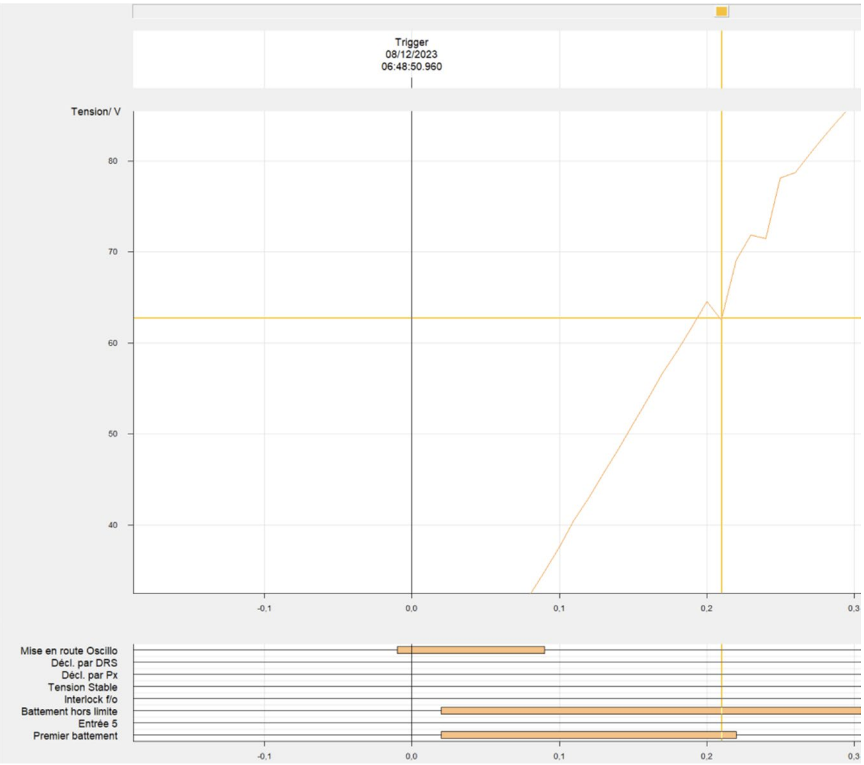


Figure 3-56: Hernani bay at Argia 400 kV substation recording

Figure 3-57 illustrates the impedance evolution observed at Argia bay at the Hernani 400 kV substation using PMU data. It depicts the initial conditions, the changes following the first and second generation loss, and the subsequent evolution at one-second intervals after the second generation loss.

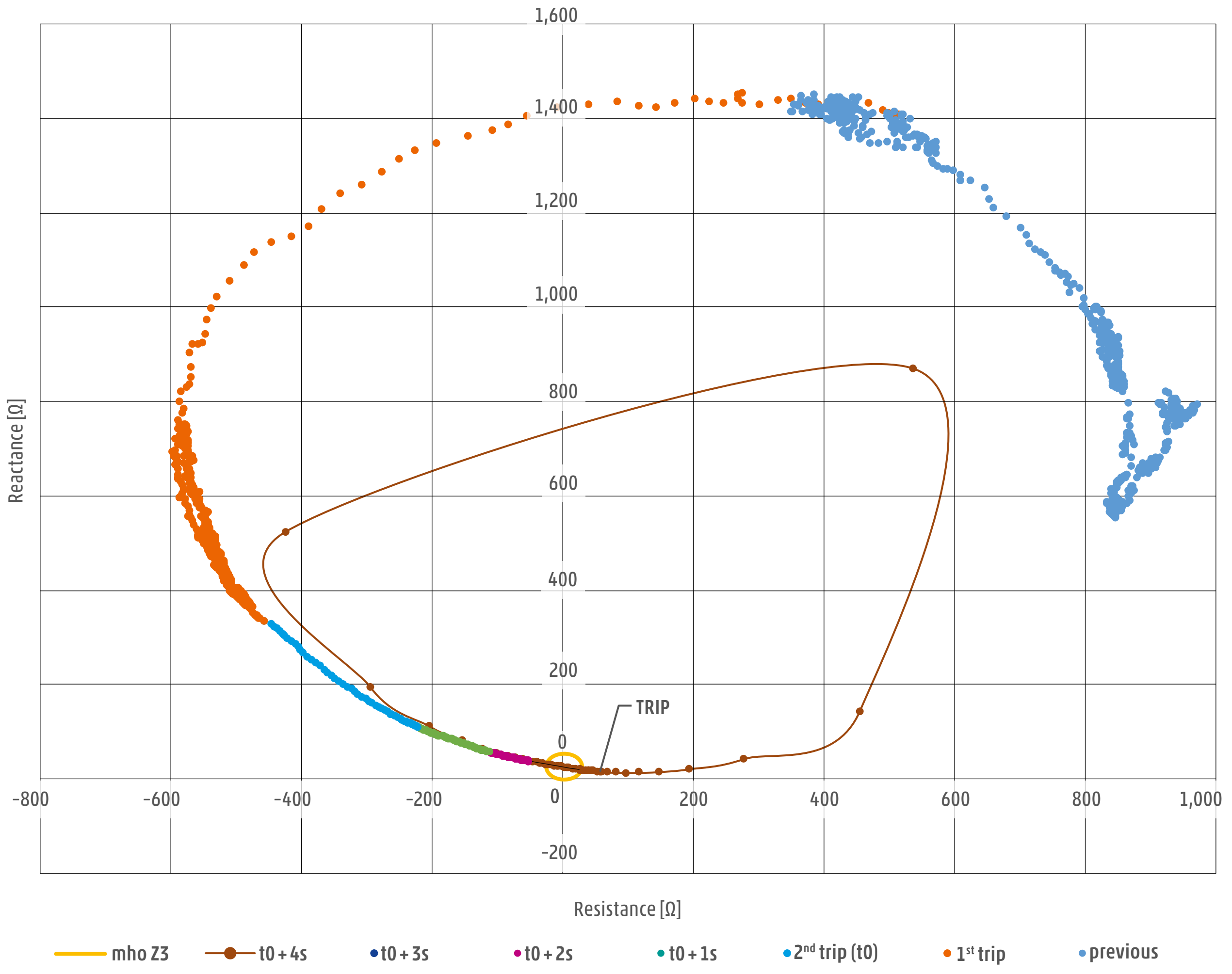


Figure 3-57: Argia bay at Hernani 400 kV substation: Impedance evolution using PMU data

3.2.2.7 Other Transmission Trips in Spain

After 12:33:23.750, with the frequency already below 44 Hz, several transmission network lines tripped due to the operation of zone 1 of the distance protections. Two main factors caused the operation of these protections: very low system frequency, sometimes even outside the limits established for their correct operation, and low voltages, in some cases almost zero while there was still current through those lines. When these protection systems tripped, the system conditions were so degraded that, although there was no short circuit in these elements, the operation of the protections cannot be considered incorrect. In addition, these trips did not contribute to aggravating the incident because, at that moment, the Iberian electrical system was not recoverable.

As an example of this, there are the trips on the Spanish side of six tie-lines with Portugal, as shown in Table 3-5. Figure 3-58 shows the trip of the Lindoso 2 bay in the Cartelle 400 kV substation.

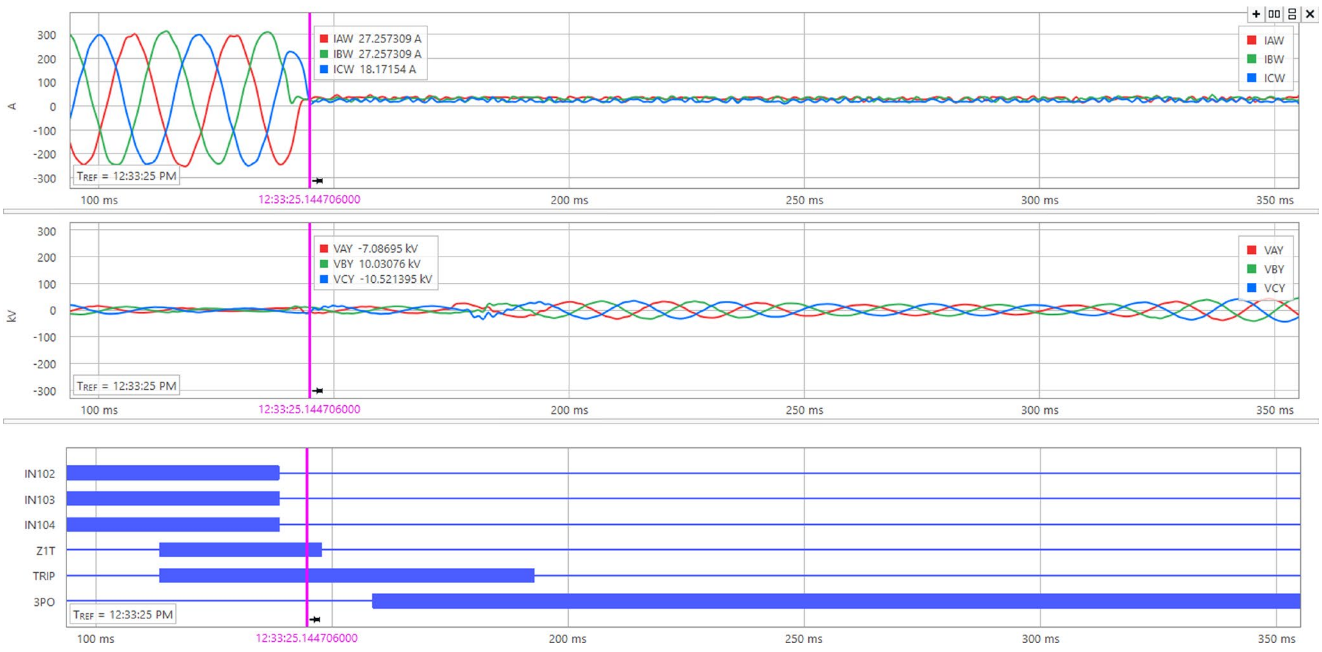


Figure 3-58: Lindoso 2 bay at Cartelle 400 kV substation relay recording (IN102, IN103, and IN104: breaker position, Z1T: distance zone 1 trip, 3PO: 3 pole open)

After 12:33:27, all circuit breakers belonging to the transmission network in Spain tripped due to the undervoltage function. This function trips all the circuit breakers with a time delay of four seconds when the voltage drops below 65 % of the nominal voltage. The purpose of this function is to open all circuit breakers in an area when a blackout occurs in that area to facilitate a faster and more orderly service restoration. In some circuit breakers, this function is disabled because of the design of the service restoration plans; in those cases, these circuit breakers remained closed.

3.2.2.8 Other Transmission Trips in Portugal

Within the Portuguese transmission network, the protection systems do not have the following protection functions enabled at the transmission level: out-of-step, over/underfrequency (except at 60 kV), and over/undervoltage (except for undervoltage protection applied to shunt reactors). As a result, during the blackout event, no trips were initiated by these functions.

Two transmission lines tripped due to the operation of zone 1 of the distance protection function. This trip was caused by unstable voltage conditions. Under these circumstances, the distance protection algorithm was unable to maintain a reliable voltage reference, which compromised its ability to operate correctly.

Although no fault was detected in the system, the behaviour observed does not indicate a malfunction of the protection system. Instead, it reflects a limitation in the algorithm's performance under low-voltage dynamic conditions.

As illustrated in Figure 3-59, voltage and current oscillations were recorded prior to the trip. These oscillations differ from a typical power swing. In this case, the voltage drop is accompanied by a simultaneous current drop, and the same pattern is observed during current increases. The affected lines were Lagoaça – Armamar 400 kV (trip at 12:33:25.434) and Mogadouro – Central da Valeira 220 kV (trip at 12:33:23.95). These trips did not contribute to the deterioration of system conditions, as they occurred after the voltage collapse.

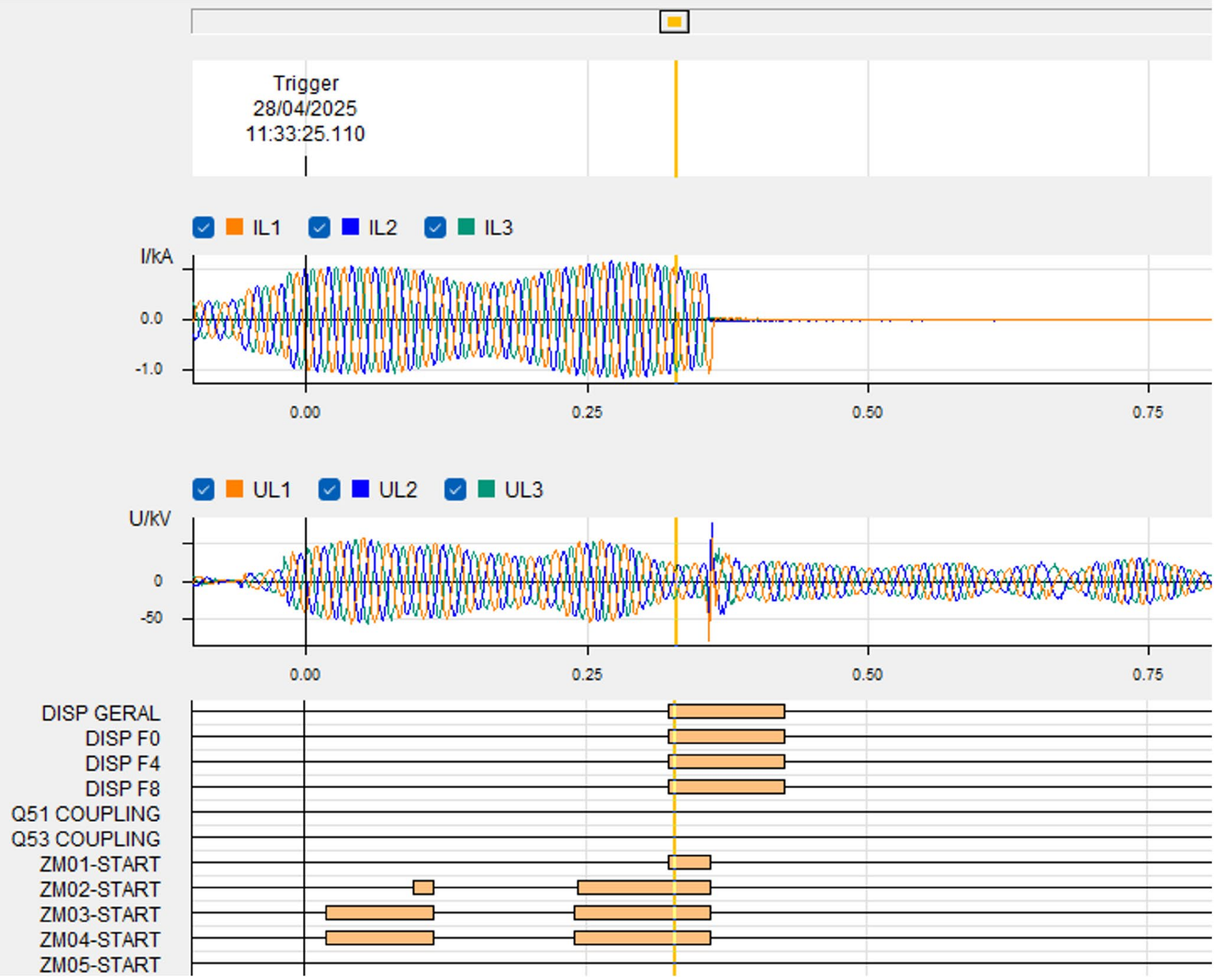


Figure 3-59: Z1 Trip of Lagoaça – Armamar line in the Lagoaça 400 kV substation due to unstable conditions

The remaining transmission network circuit breakers that were energised prior to the blackout were opened by a control logic known as "zero voltage cut-off, top = 6 s" This function issues a trip command to the circuit breaker if the measured voltage remains below 30 % of the nominal value for a continuous duration of six seconds.

3.2.2.9 Other Transmission Trips in France

Time (CEST)	Substation A (TSO)	Substation B (TSO)	Voltage Level (kV)	Asset Type	Relay Trigger	Cause of Tripping	Tripped Phases	Relay Parameter Settings
12:33:20:298	Mousserolles (RTE)	Borderes et Lamesant (RTE)	63	OHL	DIST	Distance protection tripped the line incorrectly.	3 phase	overreach zone Z < 120 % line
12:33:20:518	Mouguerre (RTE)	Lussagnet (RTE)	63	OHL	OST	Loss of synchronism	3 phase	1 beat
12:33:20:551	Dax (RTE)	Transformer 1 400/63 kV	63	OCHL	OST	Loss of synchronism	3 phase	1 beat
12:33:20:572	Aire-Sur-Adour (RTE)	Transformer 3 400/63 kV	63	OHL	OST	Loss of synchronism	3 phase	1 beat
12:33:20:583	Midour (RTE)	Usson (RTE)	63	OCHL	OST	Loss of synchronism	3 phase	1 beat
12:33:21:280	Issel (RTE)	Marsillon (RTE)	400	TR	OST	Loss of synchronism	3 phase	2 beats
12:33:21:280	Issel (RTE)	Orlu (RTE)	400	TR	OST	Loss of synchronism	3 phase	2 beats
12:33:21:382	Lavelanet (RTE)	Bus coupler	63	OHL	OST	Loss of synchronism	3 phase	2 beats
12:33:21:404	Berge (RTE)	Porta (RTE)	225	OHL	OST	Loss of synchronism	3 phase	2 beats
12:33:21:410	Nentilla (RTE)	Cantegrit (RTE)	150	OHL	OST	Loss of synchronism	3 phase	2 beats
12:33:21:418	Argia (RTE)	Berge (RTE)	225	COUPLER	OST	Loss of synchronism	3 phase	2 beats
12:33:21:423	Latour-de-Carol (RTE)	PORTA (RTE)	63	OHL	OST	Loss of synchronism	3 phase	2 beats
12:33:21:427	Marsillon (RTE)	CANTEGRIT (RTE)	225	OHL	OST	Loss of synchronism	3 phase	2 beats
12:33:21:451	Marsillon (RTE)	BERGE (RTE)	225	OHL	OST	Loss of synchronism	3 phase	2 beats

Table 3-6: List of tripped lines in France

3.2.2.9.1 63 kV MOUSSEROLLES (RTE)—LE BOUCAU (RTE)

At 12:33:20:298, the Mousserolles (RTE)—Le Boucau (RTE) 63 kV line opened in the Mousserolles substation. The distance protection tripped the line because the measured impedance crossed the characteristic. In this case, the protection should have been in blocking state (power swing blocking) and not tripped. The malfunction of the distance relay is currently under investigation at RTE.

3.2.2.9.2 63 kV MOUGUERRE (RTE)—GUICHE (RTE)

At 13:33:20.518, Mouguerre (RTE)—Guiche (RTE) 63 kV OHL opened in the Mouguerre substation due to the loss of synchronism protections function trip. The loss of synchronism protection function is set to trip on the first beat (swing) of voltage if the voltage dip reaches the preset value. The protection system of the OHL tripped according to its settings.

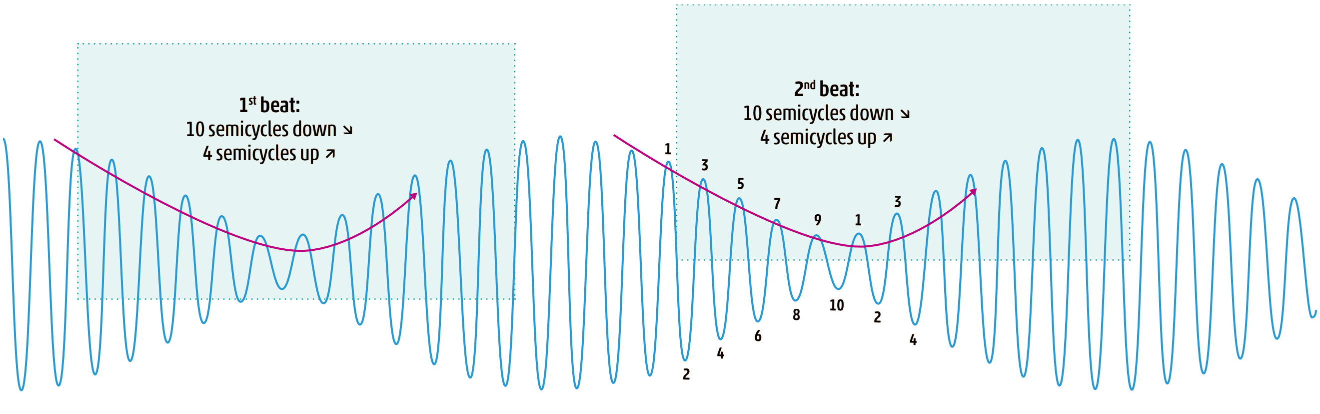


Figure 3-60: DRS loss of synchronism protections operating principle

Explanation of the operation of the loss of synchronism protection: the loss of synchronism protection permanently measures the voltage peak values. When the relay measures at least 10 consecutive decreasing peaks followed by four consecutive increasing peaks, it detects one beat if the minimum voltage reached is below a configured voltage threshold. After detecting the configured number of beats, the relay is ready to trip, and it will trip after a time delay that starts when the average RMS voltage during the oscillation is exceeded, as seen in Figure 3-60.

3.2.2.9.3 63 kV DAX (RTE)—ARRIOSSES (RTE)

At 13:33:20.551, Dax (RTE)—Arriosses (RTE) 63 kV OHL opened in the Dax substation due to the loss of synchronism protection function trip. The loss of synchronism protection function is set to trip on the first beat (swing) of voltage if the voltage dip reaches the preset value. The protection system of the OHL tripped according to its settings.

3.2.2.9.4 63 kV AIRE SUR ADOUR (RTE)—BORDERES ET LAMESANT (RTE)

At 13:33:20.572, Aire sur Adour (RTE)—Borderes et Lamesant (RTE) 63 kV OHL opened in the Aire sur Adour substation due to the loss of synchronism protection function trip. The loss of synchronism protection function is set to trip on the first beat (swing) of voltage if the voltage dip reaches the preset value. The protection system of the OHL tripped according to its settings.

3.2.2.9.5 63 kV MIDOUR (RTE)—LUSSAGNET (RTE)

At 13:33:20.583, Midour (RTE)—Lussagnet (RTE) 63 kV OHL opened in the Midour substation due to the loss of synchronism protection function trip. The loss of synchronism protection function is set to trip on the first beat (swing) of voltage if the voltage dip reaches the preset value. The protection system of the OHL tripped according to its settings.

3.2.2.9.6 400 kV/63 kV Transformer 1 at ISSEL (RTE) substation

At 12:33:21:290, the 400 kV/63 kV Transformer 1 at Issel (RTE) substation tripped on 400 kV due to the loss of synchronism protection function operation. The protection tripped on the second beat (swing) of voltage on 400 kV because at the first beat, there was not enough voltage dip according to the settings, as shown in Figure 3-61 the protection system of the transformer operated according to its settings.

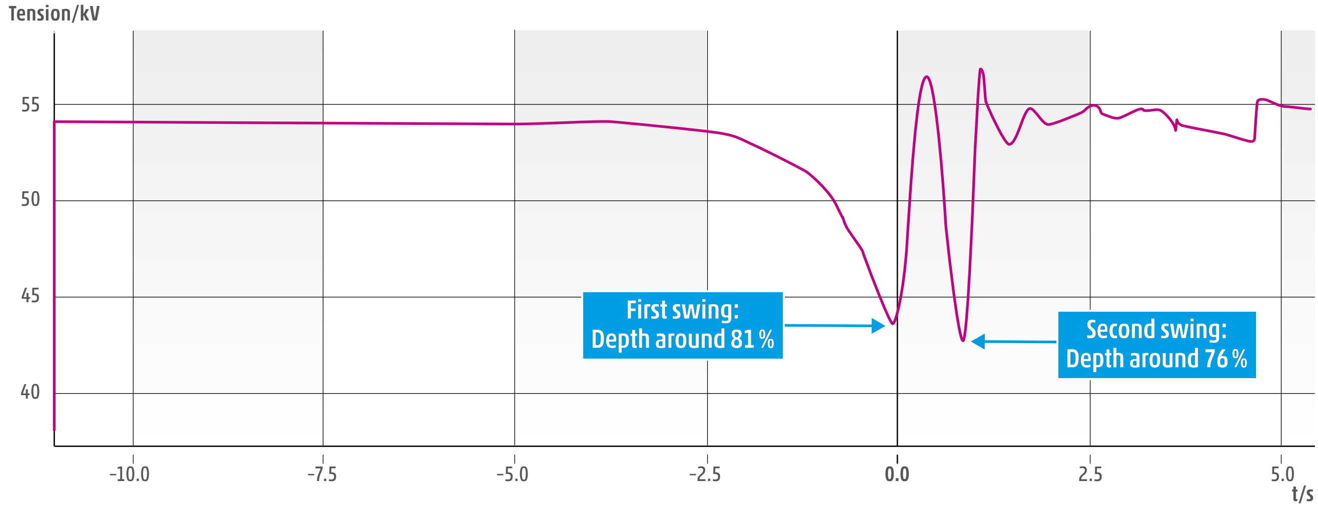


Figure 3-61: The voltage dip in the first and second swing on the Transformer 1 at Issel (RTE) substation.

3.2.2.9.7 400 kV/63 kV Transformer 3 at Issel (RTE) substation

At 12:33:21:310, the 400/63 kV Transformer 3 at Issel (RTE) substation tripped on 400 kV due to the loss of synchronism protection function operation. The protection tripped on the second beat (swing) of voltage on 400 kV because at the first beat, there was not enough voltage dip according to the settings. The protection system of the transformer operated according to its settings.

3.2.2.9.8 63 kV LAVELANET (RTE)–USSON (RTE)

At 13:33:21.382, Lavelanet (RTE)–Usson (RTE) 63 kV OHL opened in the Lavelanet substation due to the loss of synchronism protection function trip. The protection tripped on the second beat (swing) of voltage because at the first beat, there was not enough voltage dip according to the settings, as shown in Figure 3-62. The protection system of the OHL tripped according to its settings.

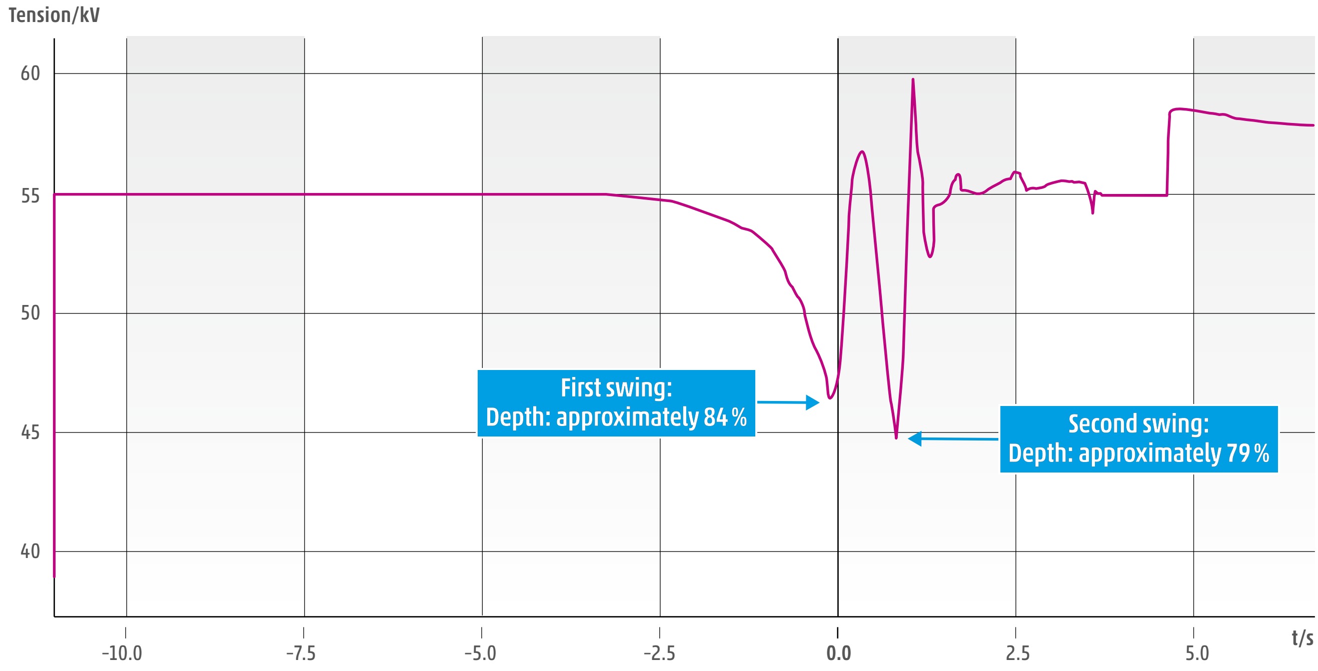


Figure 3-62: The voltage dip in the first and second swing at Lavelanet (RTE) substation.

3.2.2.9.9 225 kV BERGE (RTE)—MARSILLON (RTE)

At 13:33:21.404, Berge (RTE)—Marsillon (RTE) 225 kV OHL opened in the Berge substation due to the loss of synchronism protection function trip. The protection tripped on the second beat (swing) of voltage at 65 % voltage dip. The beats (swings) are much deeper in the Berge substation than on the other end of the line. Figure 3-63 shows that the first beat was not deep enough to trigger the protection. The protection triggered on the second beat, which is much deeper, in line with its settings.

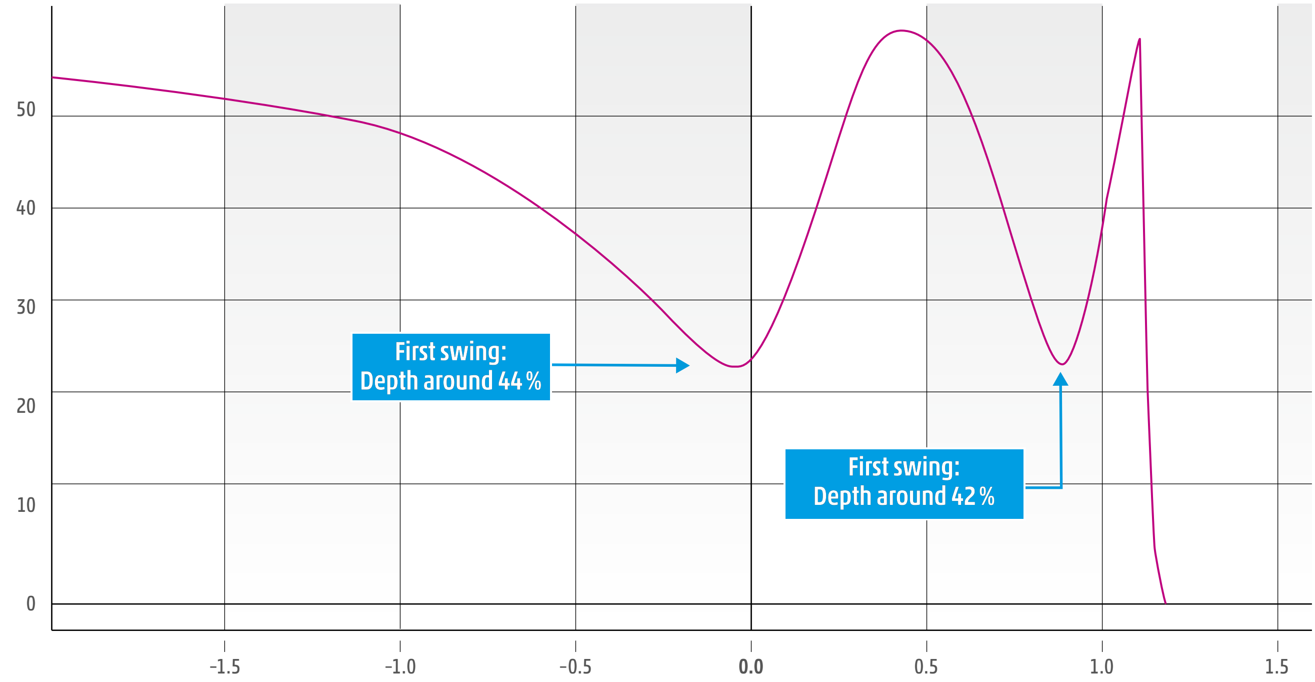


Figure 3-63: Voltage pulse on the Berge—Marsillon lines

3.2.2.9.10 150 kV NENTILLA (RTE)—ORLU (RTE)

At 13:33:21.410, Nentilla (RTE)—Orlu (RTE) 150 kV OHL opened in Nenti substation due to the loss of synchronism protection function trip. The protection tripped on the second beat (swing) of voltage because at the first beat, there was not enough voltage dip according to the settings. The protection system of the OHL tripped according to its settings.

3.2.2.9.11 225 kV ARGIA (RTE)—Bus Coupler

At 13:33:21.418, Argia (RTE) 225 kV bus coupler circuit breaker opened due to the loss of synchronism protection function trip. The protection tripped on the second beat (swing) of voltage. The protection system of the OHL tripped according to its settings.

3.2.2.9.12 63 kV LATOUR-DE-CAROL (RTE)—PORTA (RTE)

At 13:33:21.423, Latour-de-Carol (RTE)—Porta (RTE) 63 kV OHL opened in the Latour-de-Carol substation due to the loss of synchronism protection function trip. The protection tripped on the second beat (swing) of voltage because at the first beat, there was not enough voltage dip according to the settings. The protection system of the OHL tripped according to its settings.

3.2.2.9.13 225 kV MARSILLON (RTE)—CANTEGRIT (RTE)

At 13:33:21.427, Marsillon (RTE)—Cantegrit (RTE) 225 kV OHL opened in the Marsillon substation due to the loss of synchronism protection function trip. The protection tripped on the second beat (swing) of voltage. The protection system of the OHL tripped according to its settings. The loss of synchronism protection of Cantegrit had tripped previously, but subsequently opened the breaker at 12:33:21:437.

3.2.2.9.14 225 kV MARSILLON (RTE)—BERGE (RTE)

At 13:33:21.451, Marsillon (RTE)—Berge (RTE) 225 kV OHL opened in the Marsillon substation due to the loss of synchronism protection function trip. The protection tripped on the second beat (swing) of voltage. The protection system of the OHL tripped according to its settings.

3.3 System Defence Plan

Commission Regulation (EU) 2017/2196 of 24 November 2017 established the Network Code on Electricity Emergency and Restoration (NC ER). This regulation outlines the rules for (i) safeguarding operational security, (ii) preventing the propagation and deterioration of an incident, (iii) avoiding widespread disturbance and the blackout state, and (iv) allowing the efficient and rapid restoration of the electricity system from emergency and/or blackout states.

Section 2 of the regulation establishes the requirements for the design and implementation of the System Defence Plan. In particular, Article 15 sets out the requirements for the automatic underfrequency control scheme.

3.3.1 Spanish System Defence Plan

The Spanish defence plan for a situation involving a sudden drop in system frequency due to an imbalance between production and consumption includes the following two strategies, in accordance with Article 15 of the NC ER:

» 1. Automatic low frequency pump-storage disconnection plan

» 2. Automatic low frequency demand disconnection strategy.

The first strategy consists of two steps, with activation thresholds of 49.5 Hz and 49.3 Hz. The second strategy defines six frequency thresholds, beginning at 49 Hz and decreasing in 0.2 Hz intervals down to 48 Hz. At each threshold, portions of demand are progressively disconnected, as shown in Table 3-7 and Figure 3-64.

Step	Threshold (Hz)	Demand disconnected (% of total load)
1st	49.0	6
2nd	48.8	9
3rd	48.6	8
4th	48.4	8
5th	48.2	7
6th	48.0	7

Table 3-7: Low Frequency demand disconnection plan

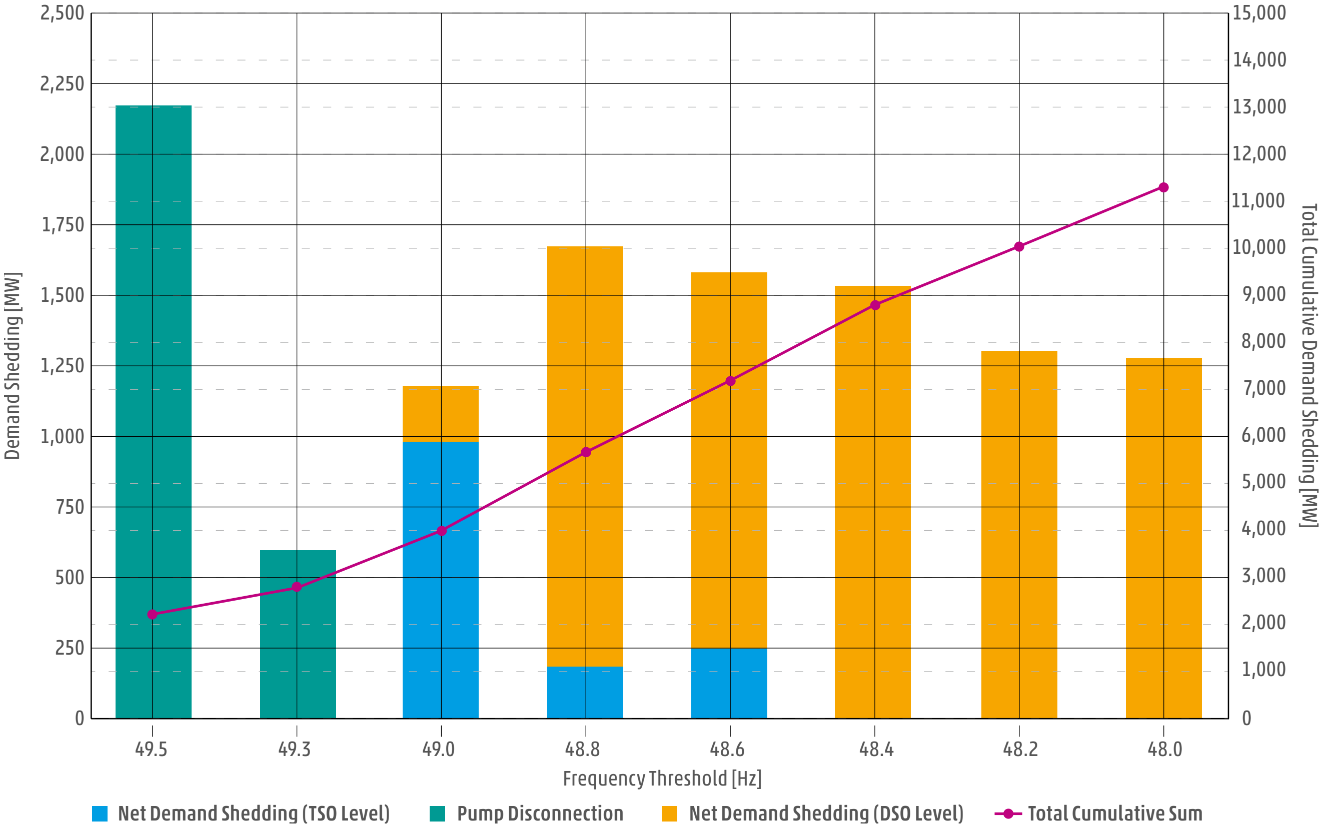


Figure 3-64: Activation of the Low Frequency Demand Disconnection Plan for RE.

The Spanish defence plan has incorporated demand across different frequency steps, taking into account its geographical location to ensure a balanced impact on both congestion and voltage levels. The plan does not have specific measures related to voltage; it is primarily designed to maintain the balance between generation and demand, which is reflected in the change of frequency.

Per the Spanish defence plan, the LFDD demand disconnected at each frequency level is, in some cases, physically disconnected at the connection point of specific load units, while in others, it is physically disconnected at the distribution connection points. This means that a specific section of the distribution system is disconnected in its entirety, regardless of whether active/reactive power is being injected or absorbed by that section.

3.3.1.1 Automatic Low Frequency Disconnection of Pump Storage

Before the incident, the total power from pumping units was 3,031 MW, of which 2,365 MW came from pumping associated with the first frequency threshold (49.5 Hz) and 666 MW with the second frequency threshold (49.3 Hz).

At 12:33:20.180, the system frequency fell below 49.5 Hz, triggering the first step of the automatic low frequency disconnection of pump-storage units. The disconnection associated with this initial threshold was effective between 12:33:20.133 and 12:33:20.800. At that time, 24 pumping units were available, 20 of which were tripped. However, two of these were disconnected due to unrelated causes, before the operation of the underfrequency relay. Of the remaining four units, one was disconnected at 12:33:23.888 due to loss of synchronism. No information is available for the disconnection of the remaining three. The total pump-storage power disconnected at this frequency threshold amounts to **2,168 MW** out of 2,365 MW (91 %).

At 12:33:20.500, the frequency fell below 49.3 Hz, triggering the activation of the second step. At this stage, six pump units were available. However, one pump-storage unit disconnected at 12:33:24.000 due to undervoltage issues. At this frequency threshold, the total power disconnected amounts to **588 MW**.

Considering both frequency thresholds, the pump storage disconnection amounts to **2,756 MW**.

Table 3-8 shows the pump storage disconnection for both steps.

Pump-storage	Step [Hz]	P Tripped
Pump 1	49.5	Y
Pump 2	49.5	Y
Pump 3	49.5	Y
Pump 4	49.5	No information available
Pump 5	49.5	No information available
Pump 6	49.5	Y
Pump 7	49.5	Y
Pump 8	49.5	Y
Pump 9	49.5	Y
Pump 10	49.5	Y
Pump 11	49.5	Y
Pump 12	49.5	Y
Pump 13	49.5	No information available
Pump 14	49.5	Y
Pump 15	49.5	Y
Pump 16	49.5	Y
Pump 17	49.5	Y
Pump 18	49.5	Y
Pump 19	49.5	Y
Pump 20	49.5	Y
Pump 21	49.5	Y
Pump 22	49.5	Y
Pump 23	49.5	Y
Pump 24	49.5	Y
TOTAL at 49,5 Hz (MW)		**2,168**
Pump 25	49.3	Y
Pump 26	49.3	Y
Pump 27	49.3	Y
Pump 28	49.3	failed
Pump 29	49.3	Y
Pump 30	49.3	Y
TOTAL at 49,3 Hz (MW)		**588**
TOTAL (both steps) (MW)		**2,756**

Table 3-8: Pump storage disconnection for the Spanish system

3.3.1.2 Low Frequency Automatic Demand Disconnection

On 28 April 2025 at 12:30:00, the total consumption in Spain reached **25,184 MW**, as shown in Figure 2-5 of Chapter 2, representing the total load estimate closest to the instant of LFDD activation. It is currently not clear whether distributed generation was also disconnected in any LFDD step (this will be assessed in the final report). From 12:33:20.600 onwards, the six frequency steps of the low frequency automatic demand disconnection plan were activated as follows:

- At 12:33:20.600, the system frequency dropped below 49.0 Hz, triggering the activation of the first step of load shedding. During this step, a total of 1,175.9 MW of load was disconnected.
- At 12:33:20.760, the system frequency dropped below 48.8 Hz, triggering the activation of the second step of load shedding. The total load shed in this step was 1,669.1 MW.
- At 12:33:21.000, the system frequency dropped below 48.6 Hz, triggering the activation of the third stage of load shedding. The total amount of load disconnected in this stage was 1,574.6 MW.
- At 12:33:21.380, the system frequency dropped below 48.4 Hz, triggering the activation of the fourth step of load shedding. The total load shed in this step was 1,523.9 MW.
- At 12:33:21.820, the system frequency dropped below 48.2 Hz, triggering the activation of the fifth step of load shedding. The total load shed in this step was 1,294.3 MW.
- At 12:33:22.040, the system frequency dropped below 48.0 Hz, triggering the activation of the sixth step of load shedding. The total load shed in this step was 1,267.1 MW.

Notably, two DSOs reported that a few underfrequency relays had not yet been adapted to the agreed low frequency demand disconnection scheme. As a result, 71.03 MW were disconnected at 48.7 Hz, although they are currently programmed to activate at 48.6 Hz. Therefore, the 71.03 MW at 48.7 Hz were added to the 48.6 Hz frequency threshold.

The total disconnected demand was **8,504.9 MW**, representing approximately 34 % of the prior total consumption. This value falls short of the theoretical target set by the defence plan, which establishes a range with a minimum of 38 %. This includes the load from consumers connected at the transmission grid and at the distribution grid. Table 3-9 presents the net demand disconnected during the six steps.

Step	Threshold (Hz)	Load disconnected (MW)	Real (% of total load)	Plan (% of total load)
1st	49.0	1,176	4.7	6
2nd	48.8	1,669	6.6	9
3rd	48.6	1,575	6.3	8
4th	48.4	1,524	6.1	8
5th	48.2	1,294	5.1	7
6th	48.0	1,267	5.0	7
	TOTAL	8,505	33.8	45.0

Table 3-9: Demand disconnection for the Spanish System (preliminary estimation)

3.3.2 Portuguese System Defence Plan

The frequency drop activated the underfrequency defence plan of the Portuguese electrical system, in accordance with Article 15 of Regulation (EU) 2017/2196 issued by the Commission on Emergency and Restoration. The plan foresees progressive load shedding based on frequency thresholds, described as follows:

- From 49.8 Hz to 49.3 Hz, the defence plan automatically shed the hydroelectric units in pumping mode.
- At 49.2 Hz, the defence plan shed the electro-intensive industrial load at the TSO and DSO level.
- From 49.0 Hz to 48.0 Hz, the defence plan shed distribution-connected consumers.

According to REN and E-REDES data, the total shed active power was:

» Hydroelectric units in pumping mode:	2,098 MW
» Electro-intensive industrial consumers:	218 MW
» Distribution network consumers:	1,955 MW.

On 28 April 2025 at 12:33:00, the total consumption in Portugal amounted to 5,865 MW.

The preliminary estimation of the total demand disconnected as part of LFDD, between 49.0 Hz and 48.0 Hz, amounted to 1,955 MW, representing 33.3 % of the prior total consumption. Considering the 218 MW of electro-intensive industrial consumers disconnected at 49.2 Hz, the total disconnected demand represents 37.1 % of prior total consumption. This value falls short of the theoretical target set by the defence plan, which establishes a range with a minimum of 38 %. Details can be found in Table 3-10, Table 3-11, Table 3-12, and Figure 3-65.

The Portuguese defence plan is designed to shed consumption in different frequency steps. Geographical dispersion of the consumption to be shed in each frequency step is assured, mitigating the impacts of congestions and voltages in the grids.

Per the Portuguese defence plan, the LFDD demand disconnected at each frequency level is, in some cases, physically disconnected at the connection point of specific load units, while in others, it is physically disconnected at the distribution grid and at transmission connection points with the distribution grid. This means that a specific section of the distribution system is disconnected in its entirety, regardless of whether active/reactive power is being injected or absorbed by that section.

Pump-storage	Step (Hz)	P previous (MW)	P tripped (MW)
Pump 1	49.8	18	18
Pump 2	49.8	18	18
Pump 3	49.8	124	124
Pump 4	49.8	0	0
Pump 5	49.8	0	0
Pump 6	49.8	221	221
Pump 7	49.8	0	0
Pump 8	49.8	0	0
TOTAL at 49.8 Hz		**381**	**381**
Pump 9	49.7	0	0
Pump 10	49.7	113	113
Pump 11	49.7	337	337
TOTAL at 49.7 Hz		**450**	**450**
Pump 12	49.6	0	0
Pump 13	49.6	0	0
Pump 14	49.6	219	219
Pump 15	49.6	219	219
TOTAL at 49.6 Hz		**438**	**438**
Pump 16	49.5	0	0
Pump 17	49.5	114	114
Pump 18	49.5	74	74
Pump 19	49.5	75	75
Pump 20	49.5	207	207
TOTAL at 49.5 Hz		**470**	**470**
Pump 21	49.4	0	0
Pump 22	49.4	0	0
Pump 23	49.4	0	0
Pump 24	49.4	0	0
TOTAL at 49.4 Hz		**0**	**0**
Pump 25	49.3	30	30
Pump 26	49.3	0	0
Pump 27	49.3	329	329
TOTAL at 49.3 Hz		**359**	**359**
TOTAL (all steps)		**2,098**	**2,098**

Table 3-10: Pump storage disconnection for the Portuguese system

Threshold (Hz)	Electro-intensive load disconnected (MW)
49.2	218

Table 3-11: Disconnection of electro-intensive industrial consumers for the Portuguese System

Threshold (Hz)	Load disconnected (MW)	Real (% of total load)	Planned (% of total load)
49.0	315	5.3	6.7
48.8	293	5.0	6.6
48.6	315	5.3	6.9
48.4	323	5.5	6.6
48.2	282	4.8	6.4
48.0	427	7.3	9.7
TOTAL	**1,955**	**33.3**	**42.9**

Table 3-12: Demand disconnection as part of the LFDD plan for the Portuguese system (preliminary estimation)

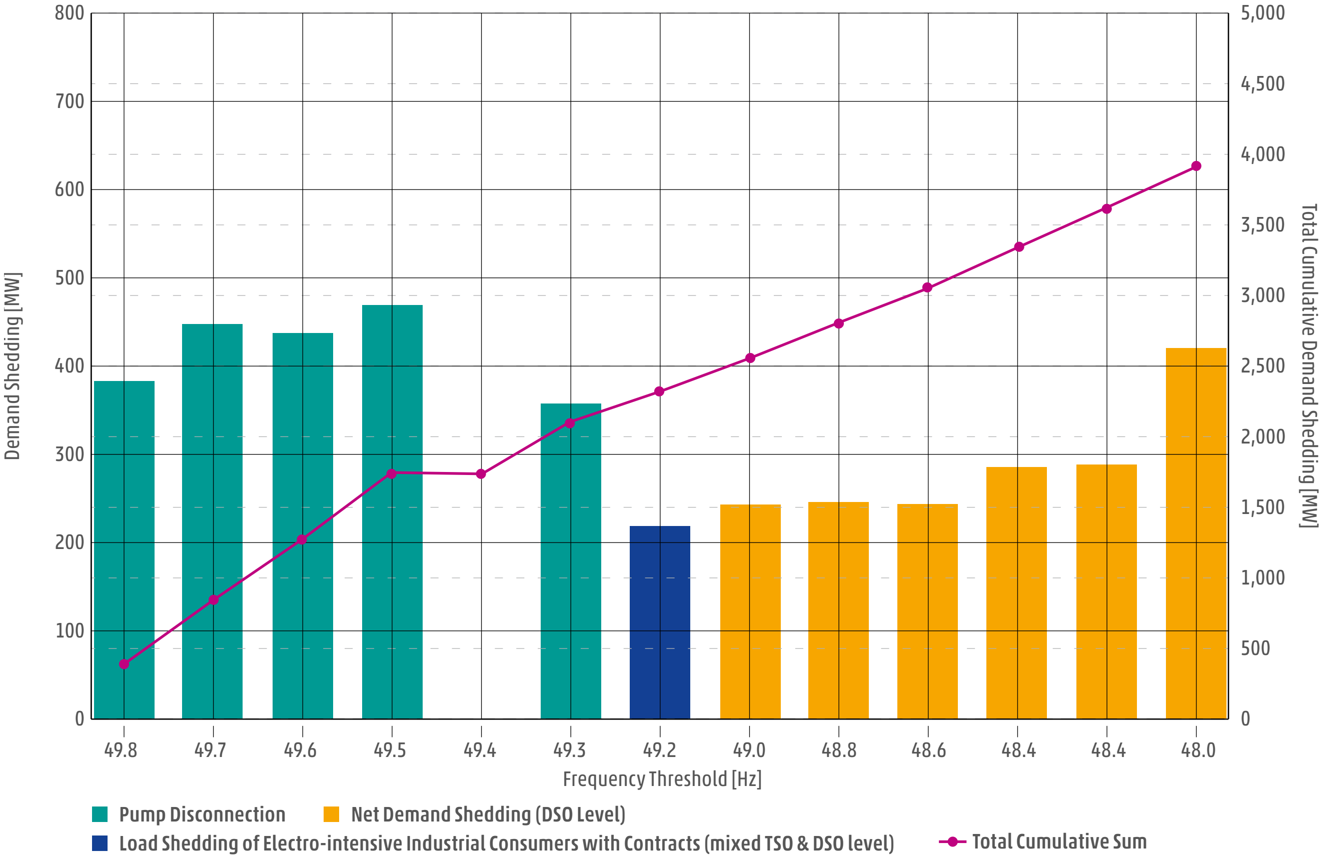


Figure 3-65: Activation of the low frequency demand disconnection plan for REN

3.3.3 French System Defence Plan

The French defence plan of RTE includes the following mechanisms:

- A load shedding plan on a frequency criterion aimed at fighting frequency collapses, which sheds 45 % of the total load in six steps between 49 and 48 Hz.

Step	Threshold (Hz)	Demand disconnected (% of total load)
1st	49.0	5
2nd	48.8	8
3rd	48.6	8

Step	Threshold (Hz)	Demand disconnected (% of total load)
4th	48.4	8
5th	48.2	8
6th	48.0	8

Table 3-13: Low Frequency demand disconnection plan

- Local relays called DRS (Débouclage suite à Rupture de Synchronisme – see Section 3.2.2.4), a French acronym for area islanding protections in case of loss of synchronism, should detect any loss of synchronism and immediately isolate the ill network portion from the healthy one. To accomplish this, the defence plan defines a synchronism zone, with loss of synchronism protection (DRS) installed at the border of this zone.

As presented in Section 3.2, the French defence plan worked as expected. Many losses of synchronism protection (DRS) were triggered at the boundary of the synchronism zone defined in the defence plan, as shown in Figure 3-66.

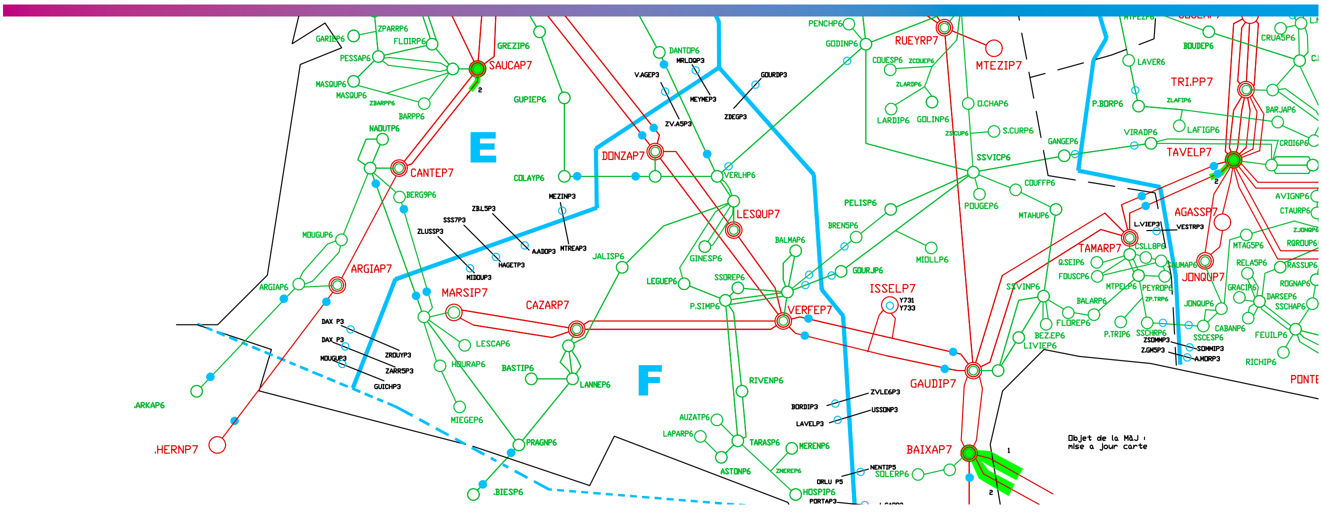


Figure 3-66: Defence plan synchronism zone on the southwest of France

On the other hand, some load shedding based on the frequency criterion occurred in the Basque Country, in accordance with the plan.

3.3.4 Overview of Pump-Storage Shedding

Before the incident, 5,129 MW of pump-storage units were connected: 3,031 MW in the Spanish network and 2,098 MW in the Portuguese network. As a result of the underfrequency condition, 2,756 MW of pump storage disconnected in Spain and 2,098 MW of pump storage disconnected in Portugal, with a total power of 4,854 MW, to support the restoration of the generation–demand balance.

Table 3-14 shows the frequency thresholds and the pump storage disconnected in each step. Notably, the load shedding relays of some units experienced delays in their proper operation.

System	Frequency threshold (Hz)	Disconnected load (MW)
PT	49.8	381
PT	49.7	450
PT	49.6	438
ES	49.5	2,168
PT	49.5	470
PT	49.4	0
ES	49.3	588
PT	49.3	359
	TOTAL	4,854

Table 3-14: Pumped storage tripped per frequency threshold

3.3.5 Overview of Load Shedding

Due to the underfrequency condition in the Iberian Peninsula, all the frequency thresholds defined in the system defence plan in Portugal and Spain were reached, and the pump-storage and load shedding were activated to try to restore generation–demand balance. In particular:

- In Spain, 8,505 MW of consumption were disconnected, including 1,402.5 MW from industrial consumers connected to the transmission grid and 7,102.4 MW of load in the distribution network.
- In Portugal, 2,173 MW of consumption were disconnected, including 218 MW from industrial consumers and 1,955 MW of load in the distribution network.

The effective load shedding in Portugal and Spain reached 10,678 MW, as shown in Table 3-15 and Figure 3-67.

The values for the transmission load shedding in the Spanish system were obtained mainly from COMTRADE files and verified against previous SCADA values. There are no COMTRADE files available from load shedding in the distribution network in the Portuguese and Spanish systems. Distribution load shedding values were provided by the DSOs.

	Electro-intensive Industrial Consumers (MW)		Other Load (MW)		
Threshold (Hz)	**PT**	**ES**	**PT**	**ES**	**TOTAL**
49.2	218				218
49.0			315	1,176	1,491
48.8			293	1,669	1,962
48.6			315	1,575	1,890
48.4			323	1,524	1,847
48.2			282	1,294	1,576
48.0			427	1,267	1,694
TOTAL	**218**		**1,955**	**8,505**	**10,678**

Table 3-15: Load shedding for ES and PT

Threshold (Hz)	DSO1 (ES) (MW)	DSO2 (ES) (MW)	DSO3 (ES) (MW)	DSO4 (ES) (MW)	DSO5 (ES) (MW)	E-REDES (PT) (MW)	Total DSO (MW)
49.0	85.1	23.7			97.0	315.0	520.8
48.8	529.9	190.0			767.5	293.0	1,780.4
48.7	49.6				21.4		71.0
48.6	423.9	195.7		5.2	628.1	315.0	1,567.9
48.4	633.8	216.8		21.6	651.7	323.0	1,846.9
48.2	412.3	220.3	60.4	12.2	589.1	282.0	1,576.3
48.0	544.1	218.2	0.7	11.6	492.5	427.0	1,694.1
TOTAL	**2,678.7**	**1,064.7**	**61.1**	**50.6**	**3,247.3**	**1,955.0**	**9,057.4**

Table 3-16: Distribution load shedding per frequency threshold

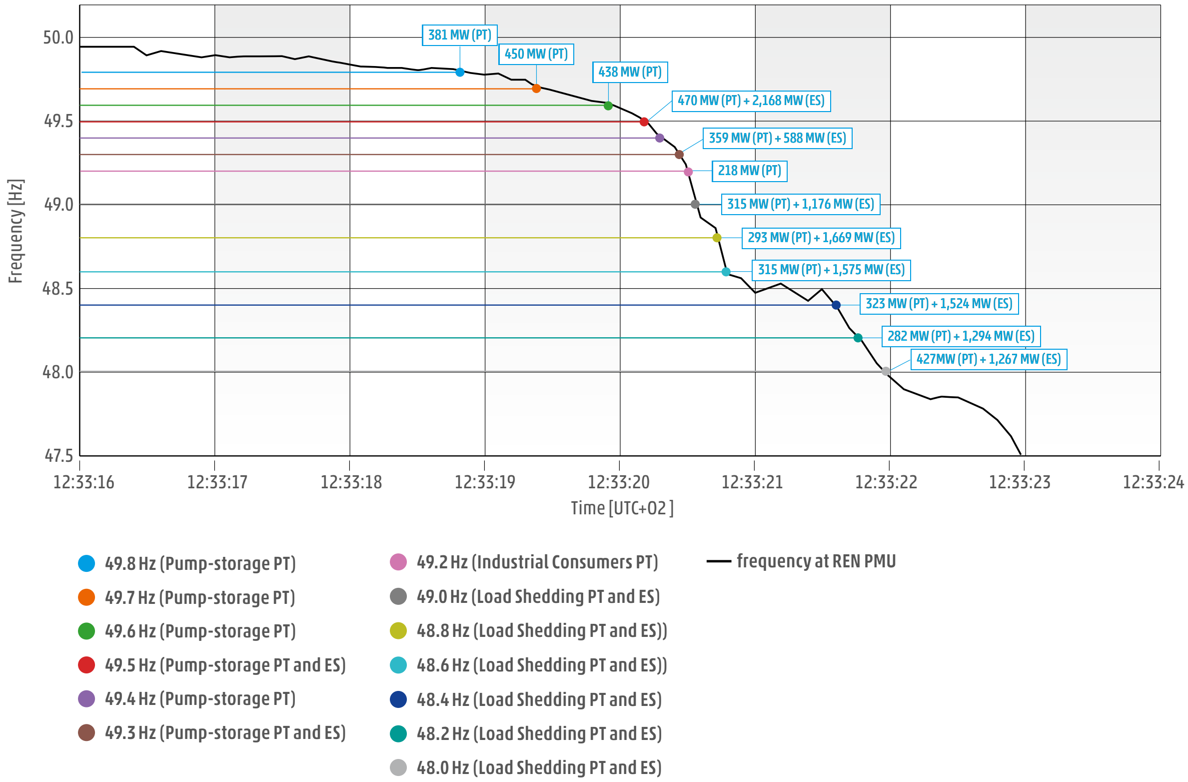


Figure 3-67: System defence plan threshold, grid tripping, load and pump-storage shedding

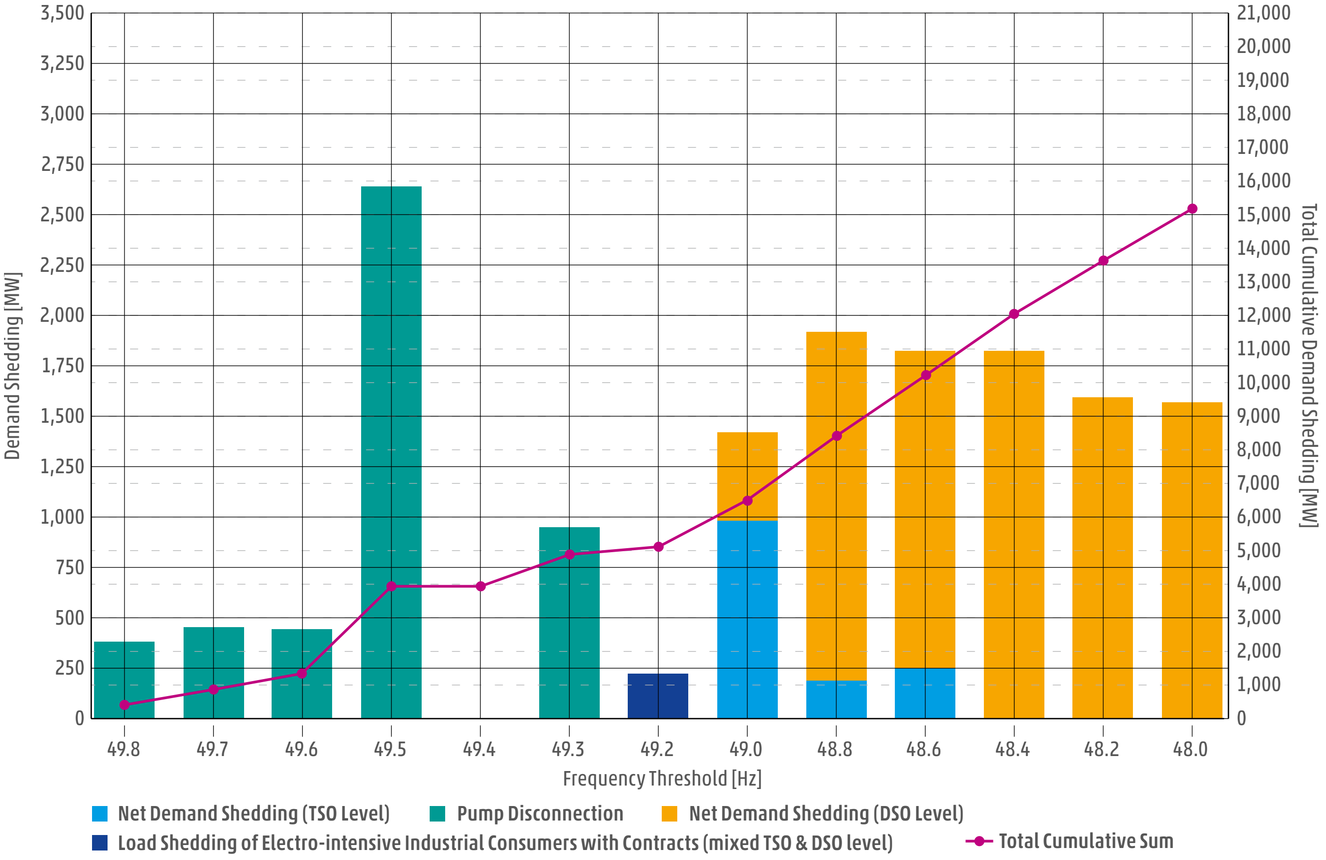


Figure 3-68: Activation of the low frequency demand disconnection plan for the Iberian Peninsula.

3.4 Impact of the Blackout on System Users on the French Network

The blackout incident of 28 April had a significant impact on multiple system users connected to the French power grid. The impact was related to overvoltage incidents, as well as the observed oscillations when the loss of synchronism occurred.

This impact was mainly concentrated in the southwest area of France.

Regarding the load impact, two substations at the distribution level in the Basque Country were impacted by the dynamic phenomena during the collapse phase.

The first substation was shed due to the frequency load shedding defence plan.

The second substation lost supply due to the activation of the loss of synchronism protection.

The total unsupplied power amounted to 7 MW. System users were restored within 15–20 minutes.

Regarding the impact on industrial system users, approximately 15 experienced total or partial process interruptions due to the activation of their own protections (related to voltage or oscillations).

Some suffered equipment damage, while others experienced a slow restart following necessary cleaning procedures. Additional users experienced voltage dips.

On the generation side, one nuclear power plant experienced an automatic interruption of the reactor, and around 20 other generation facilities connected to the transmission grid, as well as additional power plants on the distribution grid, tripped.

This was related either to:

- Low transient frequency
- High current level on the stator side
- Loss of synchronism

Other generation facilities tripped due to high voltage levels. This was the case for two hydraulic power units, as well as some PV and wind turbines. The two hydropower pumps were consuming around 200 MW.

Generation facilities connected to networks below 45 kV were disconnected due to the activation of protections, primarily related to overvoltages.

Finally, a few batteries that were connected before the event were disconnected very briefly. The total loss of supplied power was minor (around 5 MW), and the restart took between one and three minutes.

4 RESTORATION PROCESS

The objective of this chapter is to explain the restoration process in the systems affected by the incident, namely the Portuguese and Spanish systems. In the case of the French system, the incident only impacted a local area, as described in Section 4.3.

This chapter is divided into five sections:

4.1 Preconditions and strategies for the restoration process

Restoring electrical grids in continental Europe after significant disruptions occur is a complex and coordinated process. TSOs work collaboratively in accordance with Regulation (EU) 2017/2196, which established the Network Code on Electricity Emergency and Restoration (hereinafter NC ER) to re-establish electricity supply through a mixture of "top-down" and "bottom-up" approaches. The top-down approach utilises voltage from neighbouring, healthy parts of the network, while the bottom-up approach relies on the black-start capability of power plants. Black-start capability enables certain power plants to start up independently without an external power supply, which is vital for gradual restoration when no external voltage is available.

4.1.1 Red Eléctrica preconditions and strategies for the restoration process

The restoration process in Spain used a combination of top-down and bottom-up restoration strategies. For the top-down strategy, support was activated through the neighbouring countries, creating three zones with stable frequency and voltage that progressed and subsequently synchronised with the remaining areas. Specifically, the following supports were activated:

- » Support from France through the interconnections via the País Vasco
- » Support from France through one of the interconnections via Cataluña
- » Support from Morocco through one of the interconnections via Andalucía

In parallel, the bottom-up strategy was implemented by initiating re-energisation through hydropower plants (HPP) with black-start capability.

The restoration plan for the Spanish peninsular (i.e. mainland) electrical system divides the network into seven specific areas, as shown in Figure 4-1. Each area contains at least two HPPs with black-start capability, with one serving as backup to the other. This design is in accordance with Article 23(4)(f) of the NC ER.

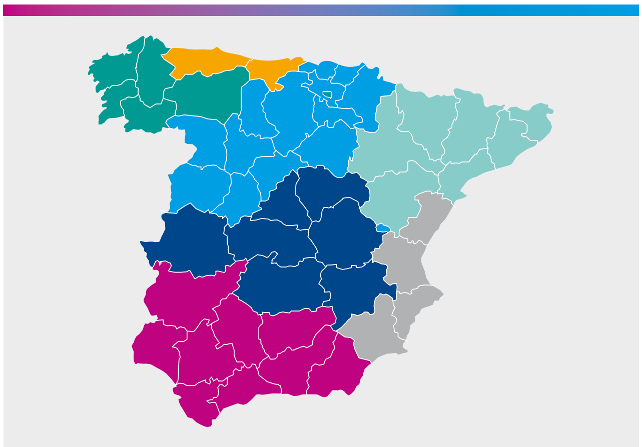


Figure 4-1: Specific restoration plans for the Spanish system – Red Eléctrica

Restoration process timeline

- At 12:33, restoration service plans were activated in all seven areas.
- At 12:34, REN was contacted to confirm that the entire Portuguese electrical grid was without voltage, as indicated by the Red Eléctrica control system. Additionally, it was confirmed that they had initiated the process of restoring the Portuguese electrical system.
- At 12:36, Red Eléctrica communicated the situation in its control area to the rest of the European system operators (TSOs), changing the system state from normal to blackout via the ENTSO-E Awareness System (EAS). Almost immediately, the state was changed again to restoration state.
- At 12:36, RTE was contacted to confirm that their transmission network had not experienced any incidents, as indicated by the Red Eléctrica control system. Additionally, RTE was requested to send support to Red Eléctrica through the 400 kV Argia–Hernani and Baixas–Vic lines.
- At 12:44, market activities were suspended in accordance with Article 35 of Regulation (EU) 2017/2196 and Operating Procedure 3.9. In coordination with the NEMO (OMIE-Operador del Mercado Ibérico de Energía), intraday markets and adjustment services markets were suspended.
- At 12:47, L'Office National de l'Électricité et de l'Eau potable (ONEE) in Morocco was contacted to confirm that their transmission network had not experienced any incidents, as indicated by the Red Eléctrica control system. It was also agreed to provide support up to 100 MW through one of the submarine cables that connects Morocco with Spain.

4.1.2 REN: preconditions and strategies for the restoration process

Plan "Plano Nacional de Reposição de Serviço". This procedure establishes the restoration strategies following a generalised blackout of the Portuguese system. The strategies used differ depending on whether the generalised shutdown is national (top-down restoration, with support from the Spanish system) or Iberian (bottom-up restoration, without support from the Spanish system).

In line with Article 23(4)(f) NC ER, the Portuguese system has two power plants with black-start capability, one serving as backup to the other. The National Service Restoration Plan foresees the restoration of the Portuguese system from one of these power plants, or from the start-up of both, depending on operational conditions.

Therefore, Red Eléctrica could provide no support during the first hours, and the restoration had to be started by the two power plants with black-start system capability in Portugal (bottom-up strategy): Combined Cycle Gas Turbine Powerplant (CCGT) 1-Norte, located near the Oporto area, and HPP 1-Centro near Lisbon.

To restore the system as soon as possible, the dispatch centre operators (located in Sacavém) and network operation centre operators (located in Vermoim) were divided into two teams: the first team was in charge of establishing an electrical island with HPP 1-Centro, and the second team was in charge of establishing an electrical island with CCGT 1-Norte.

In a phone call at 12:34, it was verified with Red Eléctrica that the blackout affected the entire Iberian Peninsula.

At 12:38, the Portuguese system state was changed from normal to blackout state in the EAS. At 17:04, it was changed to the restoration state.

As a result of this incident, REN requested that the NEMO (OMIE):

- Cancel "in advance" the first intraday auction for 29 April
- Halt the negotiation on the continuous intraday market
- Cancel "in advance" the second intraday auction for 29 April
- Cancel "in advance" the third intraday auction for 29 April

Additionally, REN suspended the transactions on:

- TERRE (Trans European Replacement Reserves Exchange): The hour between 13:00 and 14:00 on 28 April was the last period during which transactions were established on TERRE.
- MARI (Manually Activated Reserves Initiative): The quarter-hour between 12:45 and 13:00 on 28 April was the last period during which transactions were established on MARI.
- National aFRR capacity market and national redispatch markets for the remaining periods on 28 April and all periods on 29 April.

4.1.3 RTE preconditions and strategies for the restoration process

There was only one 63 kV substation (SS) without voltage on the RTE grid (Arriosse), as shown in Figure 4-2, which had a limited impact on customers, as they were already supplied via the DSO network at 12: 49. Therefore, the restoration plan was not activated, and this SS was re-energised at 13:57.

The nuclear power plant that tripped also had a limited impact. Therefore, the restoration plan was not activated, and the plant was re-energised on the next day, 29 April, at 16:15.

Figure 4-2: Location of Arriosse SS (63 kV) on RTE grid

4.2 Restoration sequences

This section describes the restoration sequences in detail, from the first actions until the total restoration of the Spanish, Portuguese, and French systems.

4.2.1 Spanish system restoration by Red Eléctrica

Restoration process timeline

- At 12:43, the L-400 kV Argia–Hernani interconnection was energised, initiating the top-down re-energisation strategy, as established in the procedure for mutual support of the Spanish and French systems after incidents. This marked the beginning of the restoration of the **Northern zone** with voltage from France.
- At 12:55, the HPP Extremadura[31] 1, with black-start capability, was started to supply auxiliary services to a nuclear power plant and stabilise the load at the 220 kV Talavera SS. At 13:56, the group tripped, losing the created electrical island.
- At 13:00, HPP Duero[32] 1, with black-start capability, was started, initiating the **Duero 1 electrical island** to supply critical loads, other HPPs, and synchronisation with the **Northern zone**. At 13:12, the group tripped. It was started up again at 14:20.
- At 13:04, voltage was received from Morocco, initiating the restoration of the **Southern zone**. It was agreed with ONEE to provide support up to 100 MW through one of the submarine cables connecting the two systems. After the disconnection,[33] caused by an underfrequency relay trip at 14:27, voltage was restored from Morocco at 14:34. The network energisation from the 400 kV Tarifa SS was restarted to enable voltage supply to the thermal groups in the area.
- At 13:06, HPP East Asturias, with black start-up capability, was started. At 13:20, the group tripped, preventing the initiation of the **East Asturias electrical island** from the start-up of this HPP.
- At 13:26, HPP Galicia, with black-start capability, was started, initiating the **Galicia electrical island** to supply load in Galicia and critical loads, and to attempt to energise the auxiliary services of several thermal power plants (TPPs).
- At 13:35, the L-400 kV Baixas–Vic interconnection was switched on in Cataluña, starting the top-down re-energisation strategy in the Cataluña area, as established in the procedure for mutual support of the Spanish and French systems after incidents. This marked the beginning of the restoration of the **Eastern zone** with voltage from France. The main objectives were to supply auxiliary services for TPPs, supply critical loads, and synchronise with the other areas.
- At 13:52, HPP Levante, with black-start capability, was started, initiating the **Levante electrical island** to attempt to energise the auxiliary services of the TPPs in the northern Levante area.
- At 14:11, HPP Duero[32] 2, with black-start capability, was started, initiating the **Duero 2 electrical island** to supply critical loads, other HPPs, and synchronise with the **other islands**.
- At 14:11, HPP Cantabria, with black-start capability, was started, initiating the **Cantabria electrical island** to supply load in the Cantabria area, supply auxiliary services for several TPPs, and synchronise with the islands created in the Asturias area.
- At 14:22, HPP Extremadura[31] 2, with black-start capability, was started using a soft-start process[34] to supply the auxiliary services of a nuclear power plant and create the **Centro electrical island**, enabling load stabilisation and the connection of the remaining HPPs and TPPs.
- At 14:28, HPP West Asturias, with black-start capability, was started, initiating **the West Asturias electrical island** in the 132 kV distribution network to supply load in the Asturias area, connect other HPPs, and synchronise with the **East Asturias** and **Cantabria electrical islands**. At 15:01, HPP Aragón, with black-start capability, was started, initiating the **Aragón electrical island** to connect other nearby HPP and supply the auxiliary services of several TTPs.

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[31] HPP Extremadura 1 and Extremadura 2 are in the same area, with one serving as backup for the other.

[32] HPP Duero 1 and Duero 2 are in the same area, with one serving as backup of the other.

[33] The cause of underfrequency situation is still to be determined. Load restoration in the Spanish system had been halted a few minutes before the trip.

[34] The process of energising the grid with gradually increasing voltage.

- At 15:07, all nuclear power plants confirmed having external supply for their auxiliary services.
- At 15:25, an attempt was made to start the available HPP with black-start capability of Andalucía without success. Taking into account the proximity and progress of the **Southern zone**, the re-energisation of the Andalucía area from the zones with stable voltage and frequency was prioritised to speed up the restoration of the zone.
- At 15:16, HPP Madrid, with black-start capability, started. After several attempts, it was not possible to create the island, whose objective was to supply the auxiliary services of a TPP and some stabilisation loads in the Toledo area.

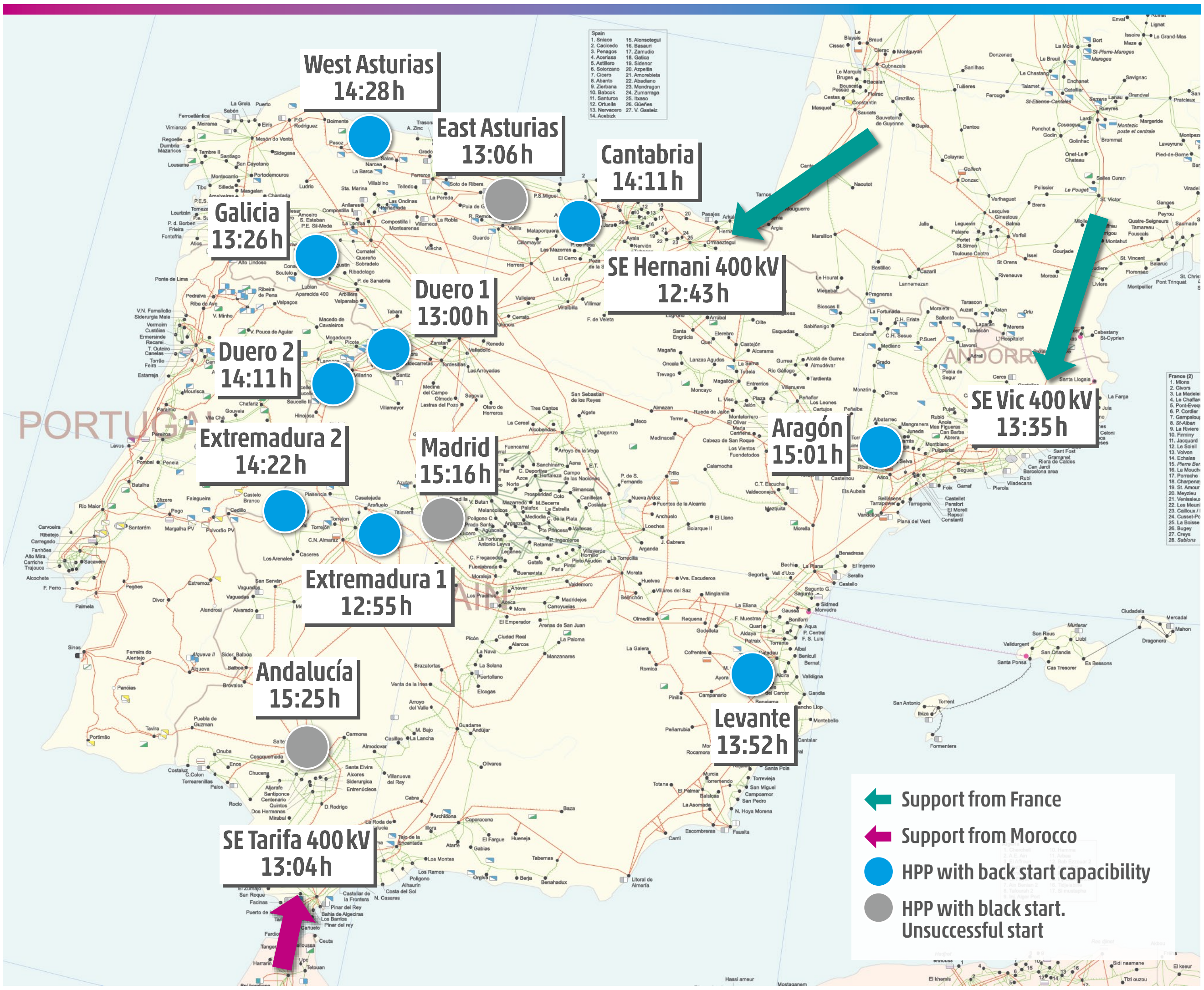


Figure 4-3: Starting time of HPP with black-start capability and supports from interconnections with France and Morocco – Red Eléctrica

To speed up the restoration process, re-energisation from the zones with stable voltage and frequency to the others was prioritised as much as possible.

At 15:14, the first TPP was connected in the Southern zone.

Figure 4-4 shows the evolution of the restoration in the transmission network and black-start islands through 15:30.

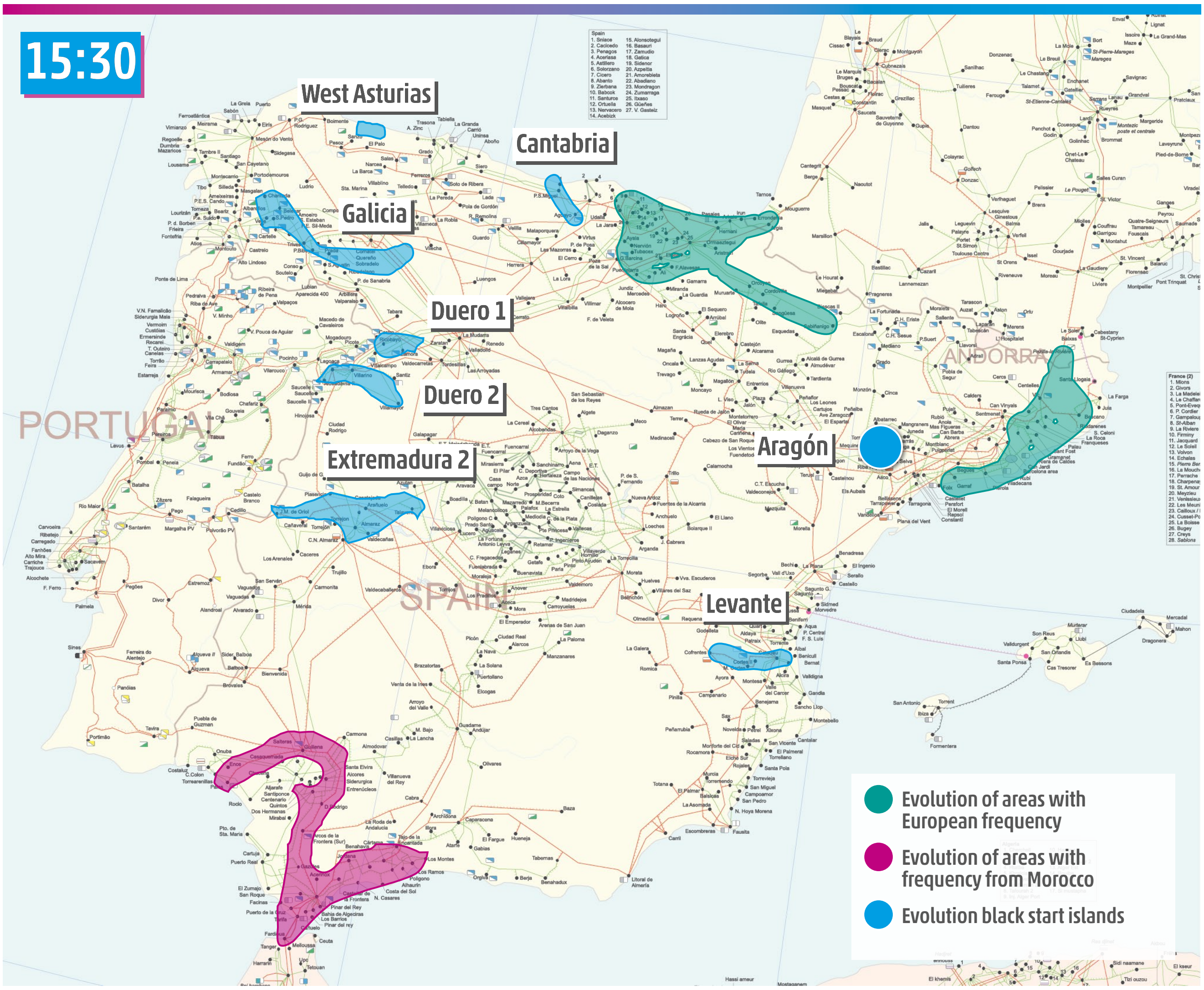


Figure 4-4: Evolution of the restoration in the transmission network and black-start islands through 15:30 (1,952 MW of load supplied) – Red Eléctrica

Restoration process timeline

- At 15:59, one link of the HVDC Baixas–Sta. Llogaia interconnection was switched on.
- At 16:03, the HPP Levante tripped, losing the **Levante electrical island**.
- At 16:06, the HPPs Cantabria tripped, losing the **Cantabria electrical island**. Taking into account the proximity and progress of the Northern zone, the re-energisation of the Cantabria area from the zones with stable voltage and frequency was prioritised to speed up the restoration of the zone.
- At 16:20, the first TTP was connected in the **Northern zone**.
- At 16:21, L-400 kV Aguayo–Abanto was energised from the **Northern zone**. Subsequently, the HPPs of Cantabria were re-connected. From this point, once synchronised with continental Europe's frequency, the restoration of the Cantabria area and the supply of auxiliary services to TTPs in the area were resumed.
- At 16:34, the L-400 kV La Plana–Masdenvergue was switched on to initiate the restoration process in the **Levante zone** with stable voltage and frequency from the **Eastern zone**. Subsequently, the auxiliary services of the TPPs in the northern Levante area were supplied.
- At 16:43, a new attempt was made to create the **Levante electrical island** from HPP Levante, without success. At 17:23, the 400 kV SS La Muela was energised from the Eastern zone, and the HPPs were connected to it.
- At 16:54, the **Northern** zone was synchronised with the **Aragón electrical island** through the L-220 kV Escatrón–Villanueva. The situation is represented in Figure 4-5.

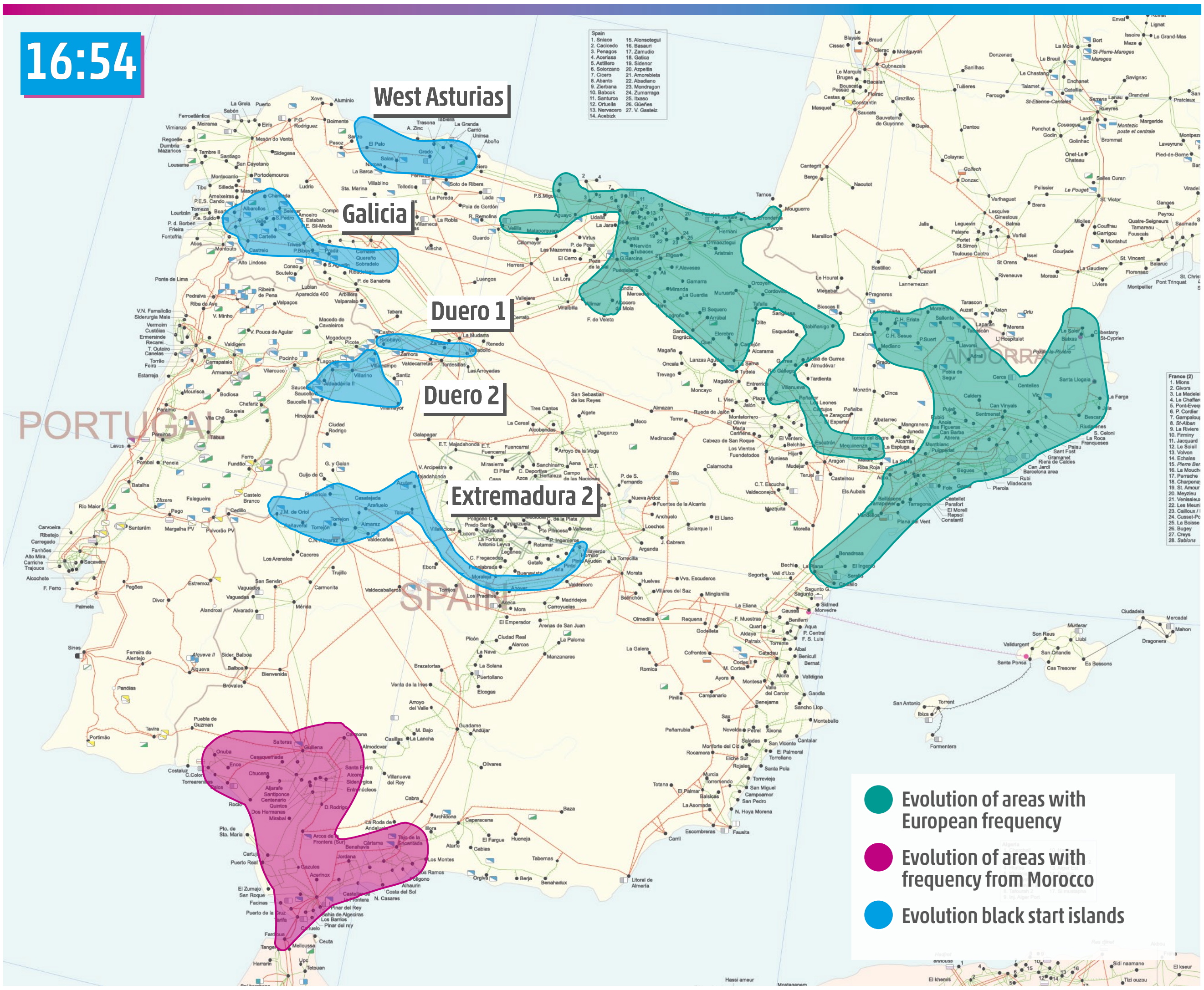


Figure 4-5: Evolution of the restoration in the transmission network and black-start islands through 16:54 (3,303 MW of load supplied) – Red Eléctrica

- At 17:01, after several failed attempts to synchronise the **Duero 1 electrical island** and the **Duero 2 electrical island**, it was decided to disconnect the HPP Duero 2. Synchronisation was not possible due to the frequency difference between the islands and the inability of the groups to regulate it.
- At 17:49, the **Duero 1 electrical island** was synchronised with the **Northern zone** through the L-220 kV Arroyadas–Tordesillas, connecting the Duero area to continental Europe's frequency. The situation is represented in Figure 4-6.

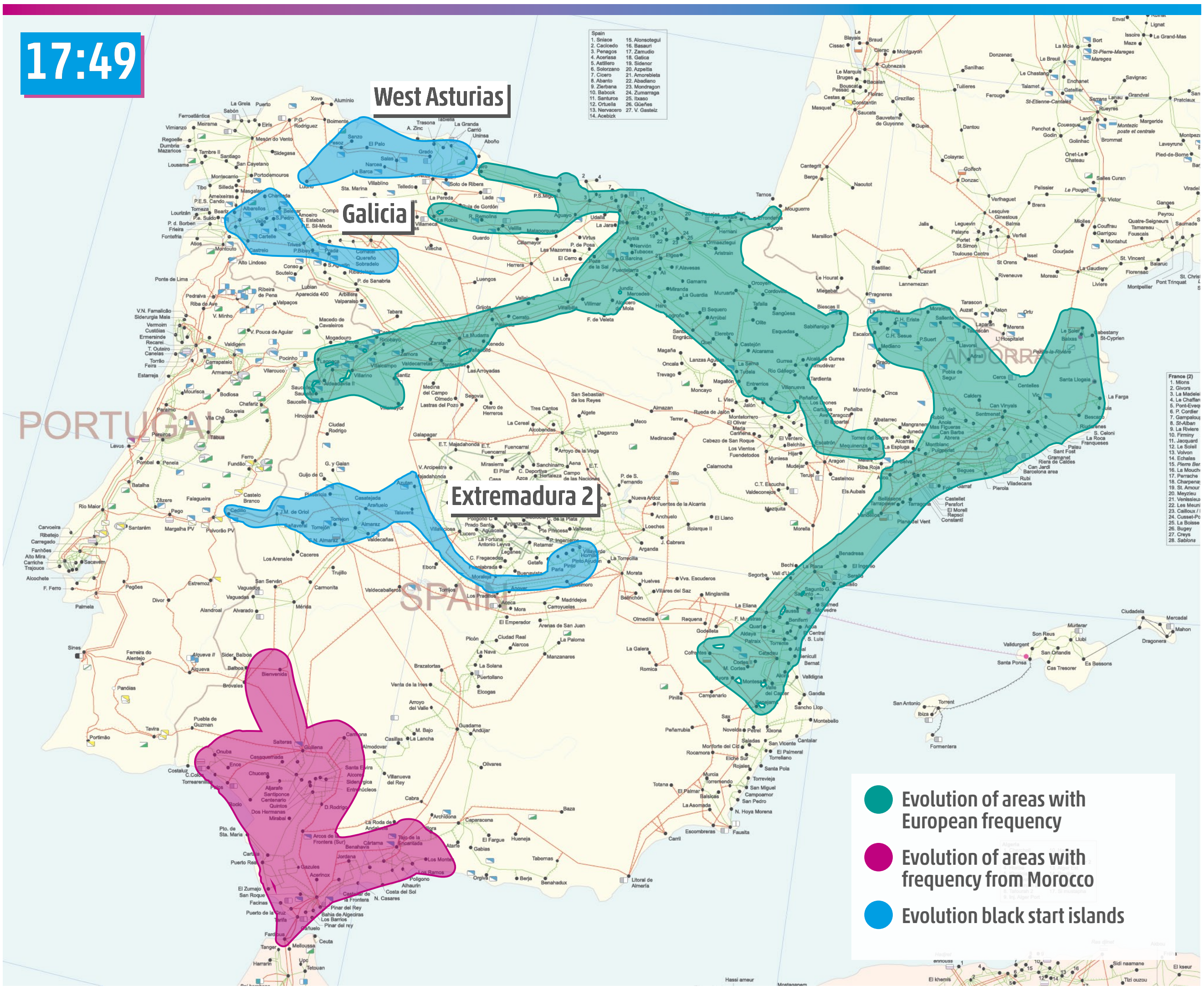


Figure 4-6: Evolution of the restoration in the transmission network and black-start islands through 17:49 (5,565 MW of load supplied) – Red Eléctrica

- At 18:16, the L-400 kV Bienvenida–Almaraz was switched on, synchronising the **Southern zone** with the **Centro electrical island**. At that time, several HPPs were connected within the **Centro electrical island** and had extended their supply to the Madrid area. The situation is represented in Figure 4-7.

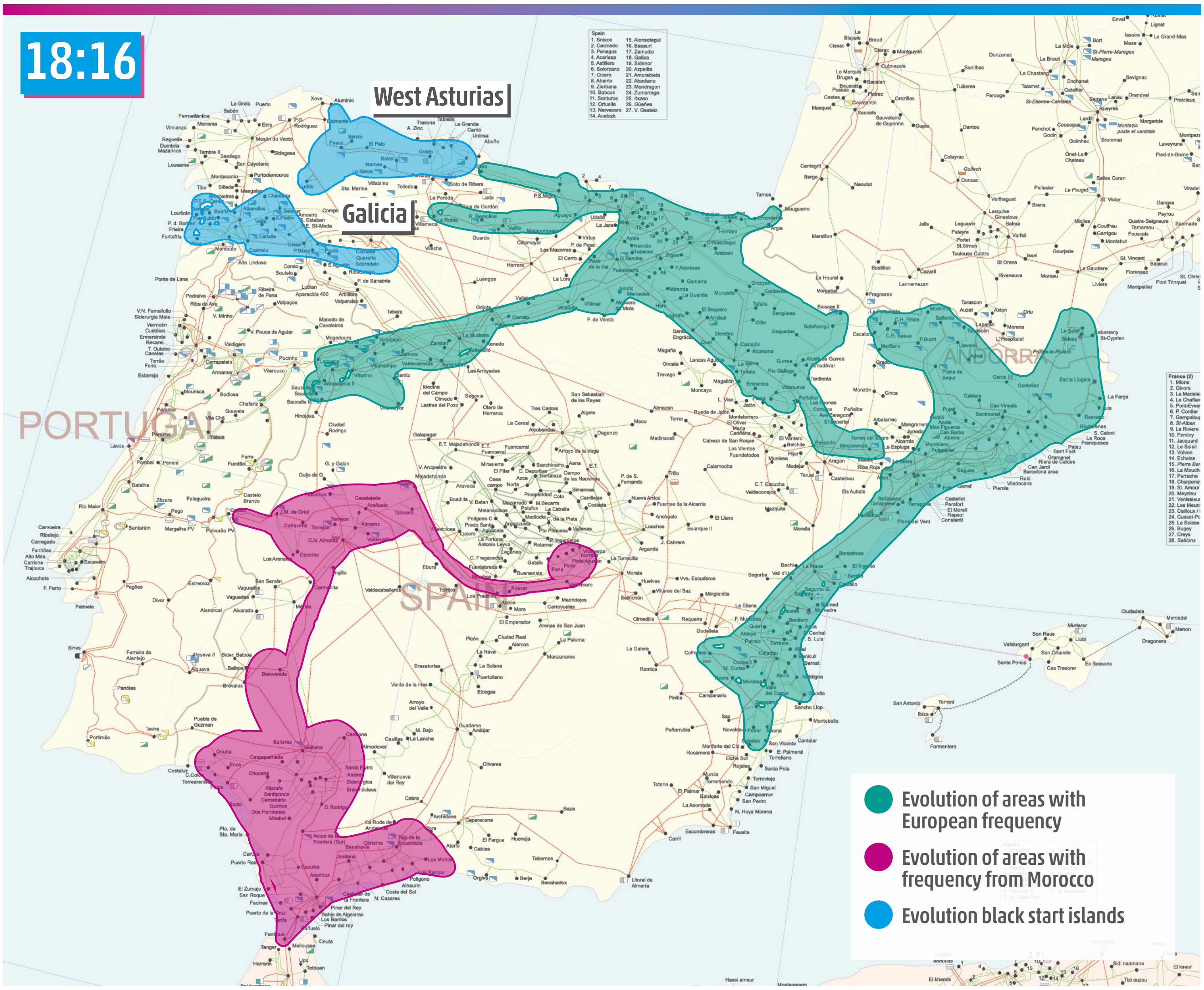


Figure 4-7: Evolution of the restoration in the transmission network and black-start islands through 18:16 (6,809 MW of load supplied) – Red Eléctrica

- At 18:36, from the **Northern zone**, the L-220 kV Aldeadávila–Pocinho 1 interconnection was switched on, sending voltage to the Portuguese electrical system for the first time in the restoration process. From this point, REN received voltage with continental European frequency.
- At 18:43, the **West Asturias** electrical island, initiated in the Asturias distribution network, was synchronised with the **Northern zone** through the ATP1 220/132 kV Siero. The situation is represented in Figure 4-8.

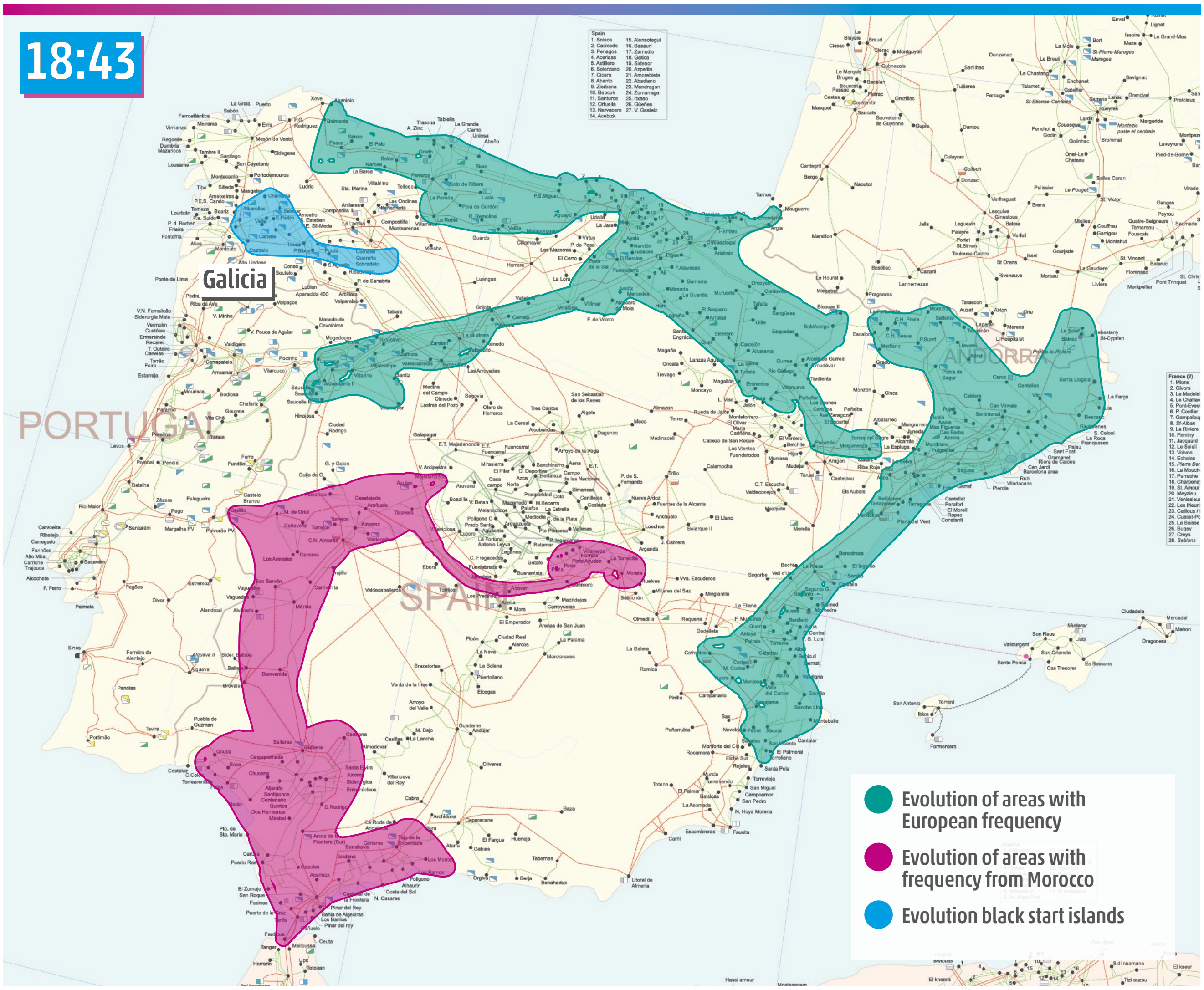


Figure 4-8: Evolution of the restoration in the transmission network and black-start islands through 18:43 (7,470 MW of load supplied) – Red Eléctrica

» At 19:15, the **Galicia electrical island** tripped. Due to the proximity of voltage from the Northern zone, it was decided not to restart the island.

» At 19:18, the 220 kV Tordesillas-Valparaíso–Arbillera was switched on to initiate the re-energisation of the Galicia area from the **Northern zone**, with stable voltage and frequency to speed up the restoration of the zone. The situation is represented in Figure 4-9.

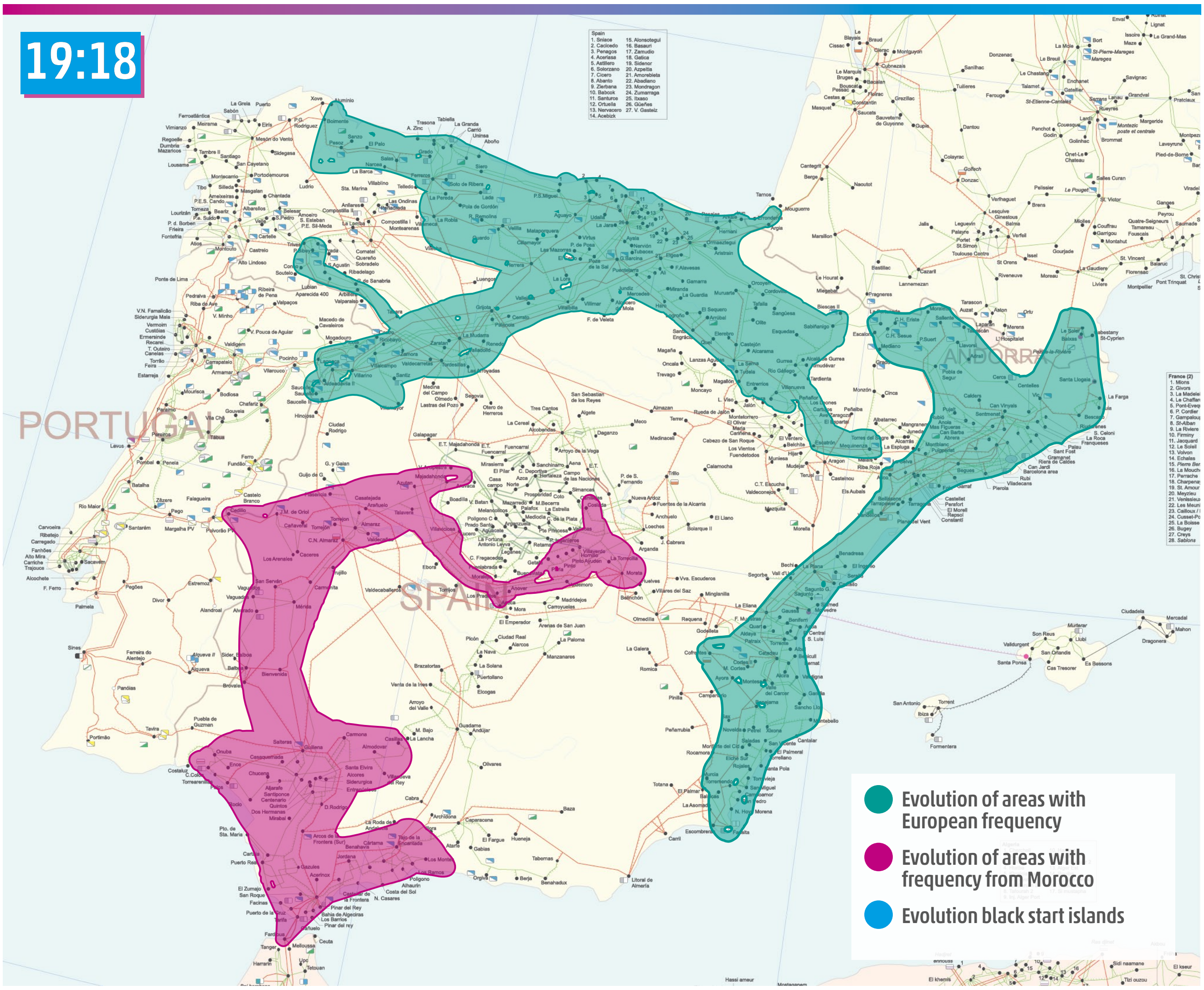


Figure 4-9: Evolution of the restoration in the transmission network and black-start islands through 19:18 (8,612 MW of load supplied) – Red Eléctrica

» At 19:32, L-400 kV Almaraz—C. Rodrigo was switched on, synchronising the **Northern zone**, which at the time primarily comprised País Vasco, Navarra, La Rioja, Castilla León, Cantabria, Asturias, and Galicia, with the **Southern zone**, composed of Andalucia, Extremadura, Castilla la Mancha, and Madrid. The synchronisation was accomplished without problems thanks to the use of a synchro-check device, which assesses the synchronisation conditions for three parameters: difference of voltage magnitude, difference of frequencies, and difference of phase angles. The situation is represented in Figure 4-10.

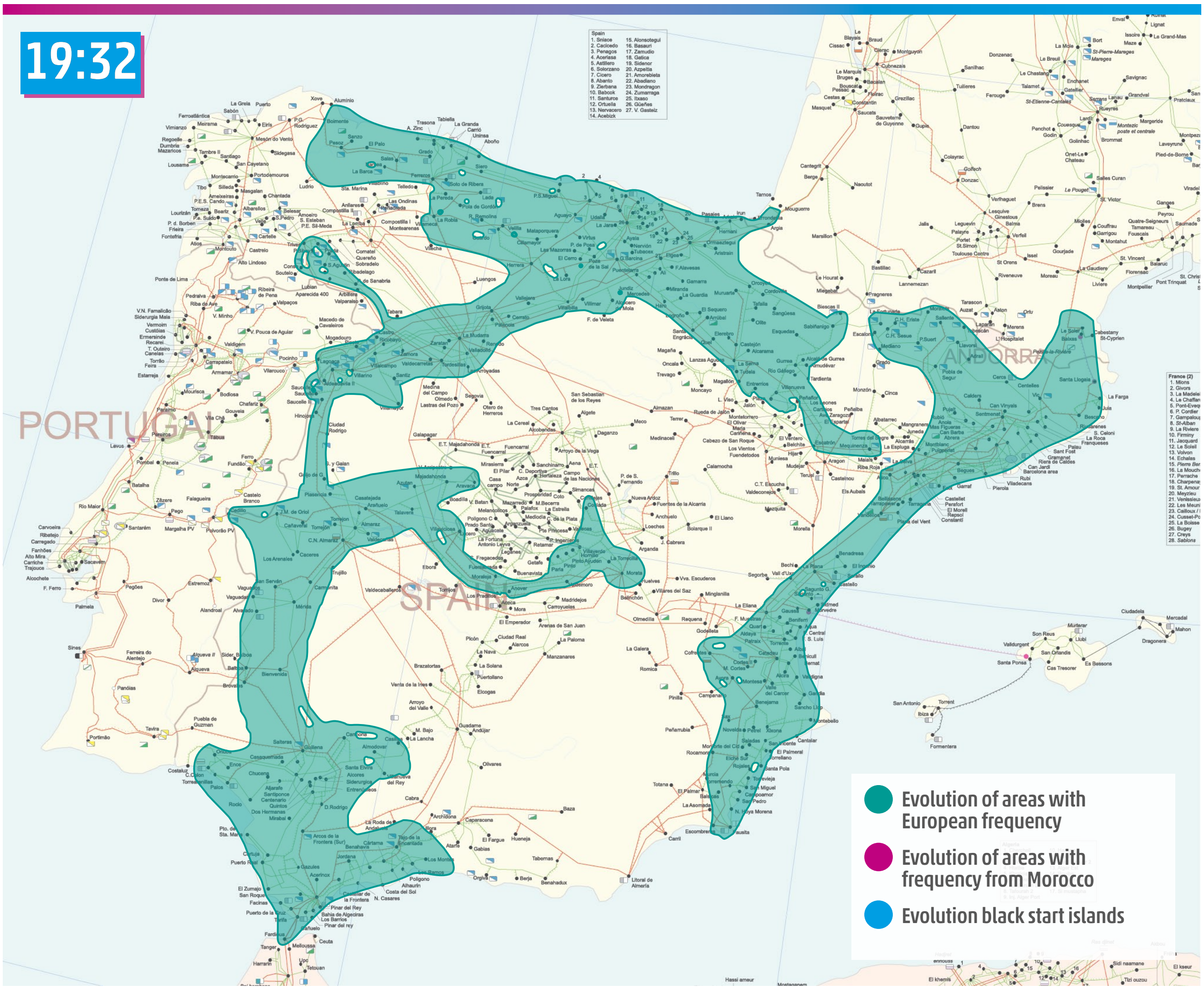


Figure 4-10: Evolution of the restoration in the transmission network through 19:32 (8,827 MW of load supplied) – Red Eléctrica

» At 19:53, L-400 kV Peñaflor–Aragón was switched on, connecting the Northern and Eastern zones and creating a single restoration area in the Spanish peninsular electrical system. The situation is represented in Figure 4-11.

» At 19:57, L-220 kV Saucelle–Pocinho was switched on, reinforcing the interconnection in the Northern zone of Portugal with Spain. At 19:58, the L-220 kV Aldeadávila–Pocinho 2 was also switched on.

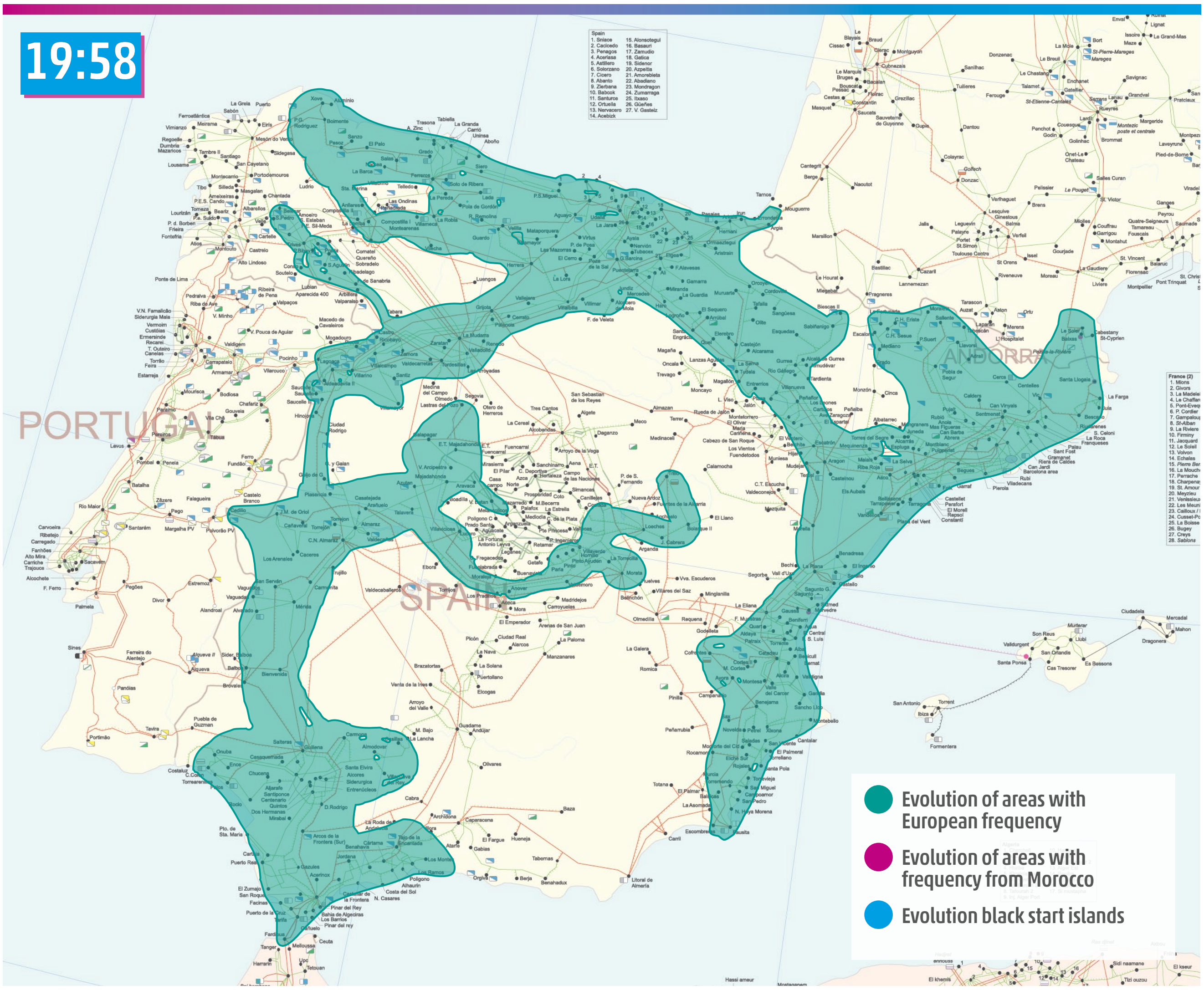


Figure 4-11: Evolution of the restoration in the transmission network through 19:58 (9,566 MW of load supplied)

With all the areas of the Spanish peninsular system connected to the European synchronous system, the restoration process of the transmission network accelerated substantially. The transmission network equipment's autonomy ensured proper functioning of the voice communication system, telemetry, and remote control until the completion of the restoration process.

Cooperation among Red Eléctrica, REN, and RTE, as well as distribution and generation control centres, was continuous throughout the entire restoration process.

It should be noted that the restoration of the load in some areas of the Spanish system progressed more slowly due to voice communication system problems at some distribution and generation control centres, which made it difficult to contact them from the Red Eléctrica control centres. Additionally, some of these distribution companies experienced issues receiving telemetry and remote-control signals at their facilities.

From this moment on, the rest of the available TPPs and HPPs were progressively connected to the system.

Below are some of the most notable milestones:

- At 21:20, 13 TPPs were connected to the Spanish peninsular electrical system.
- At 21:58, the second link of the HVDC Baixas–Sta. Llogaia interconnection began to exchange power in AC emulation mode.
- At 21:34, the L-400 kV Tavira–Puebla de Guzmán was switched on to reinforce the interconnection between Spain and Portugal in the southern zone.

Figure 4-12 shows the evolution of the restoration in the transmission network through 22:33.

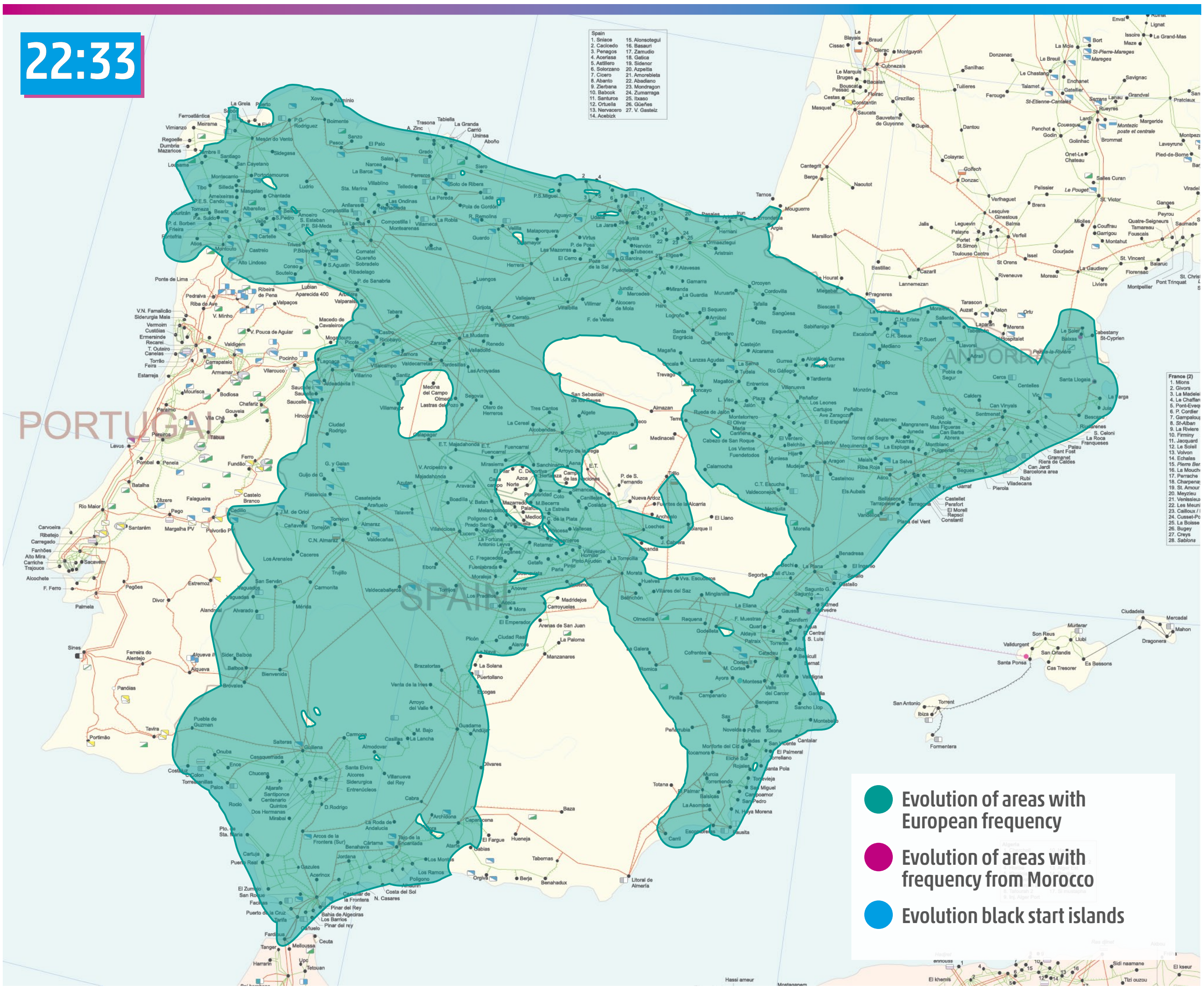


Figure 4-12: Evolution of the restoration in the transmission network through 22:33 (14,760 MW of load supplied)

- At 23:32, 21 TPPs were connected to the Spanish peninsular electrical system.
- At 00:06 on 29 April, the master aFRR controller was started, initiating load-frequency control.
- From 01:38, the Renewable Energy Control Center (CECRE) progressively sent instructions to allow the production of renewable, cogeneration, and waste (RCW) generation units. At 07:05, instructions were released to all RCW generation units.
- At 02:18, it was agreed with ONEE to end the emergency energy transfer from Morocco.
- At 02:59, in coordination with REN, the EAS state was changed from restoration to emergency.
- At 03:09, 31 TPPs were connected to the Spanish peninsular electrical system.
- At around 04:00, 100 % of the transmission network was restored.
- At 10:56, voltage was sent to Andorra through the double circuit 132 kV Margineda–Adrall.

- At 11:39, market participants were informed through the markets information system (eSIOS) that, in coordination with the NEMO, market activities were to be restored.
- At 14:13, the Peninsula–Balearic interconnection was energised.
- At 14:34, the result of the daily market for 30 April was published.
- At 14:36, in coordination with REN, the EAS state was changed from emergency to alert.

4.2.2 Portuguese system restoration by REN

At 12:35, REN requested the black-start mode start-up of HPP 1-Centro. At 12:43, REN requested the black-start mode start-up of CCGT 1-Norte. Following the restoration plan, the black-start operation mode was carried out with one generation unit in each of these power plants to establish electrical islands. At 12:45, HPP 1-Centro was operating in black-start mode with voltage on the 220 kV Busbar of Zêzere SS. When connecting the 220/60 kV Transformer 4 of Zêzere SS with a rated power of 170 MVA, HPP 1-Centro tripped at 12:49, which also caused a complete failure of the auxiliary services of the power plant. Subsequently, the producer initiated several attempts to start the auxiliary services of HPP 1-Centro. These efforts were unsuccessful due to problems starting up auxiliary small hydro units.

In the first hours, CCGT 1-Norte was unsuccessful in closing the generator circuit breaker to energise the unit transformer due to unexpected problems in the control and command systems in the power plant SS.

Restoration process timeline

- At 15:40, HPP 1-Centro started and propagated voltage to the 220 kV Busbar of Zêzere SS, leading to the creation of the first restoration area. Then at 15:51, the first load in the Zêzere SS were connected, with HPP 1-Centro tripping at 15:55 with 5 MW.
- At 16:13, HPP 1-Centro started and propagated voltage to the 220 kV Busbar of Zêzere SS, re-establishing the first restoration area. At 16:26, there was a progressive load restoration in Zêzere SS (60 kV) and propagation of voltage to HPP 2-Centro and HPP 3-Centro HPPs at 150 kV.
- At 16:38, CCGT 1-Norte started and propagated voltage to the 220 kV Busbar of the power plant SS.
- At 16:54, voltage was propagated to Canelas and Recarei SSs, and there was a progressive load supply. Then at 17:23, a synchronous compensator was started using Unit 2 of Torrão HPP to support voltage control in the island, as foreseen in the National Service Restoration Plan, coinciding with the tripping of CCGT 1-Norte.
- At 17:26, CCGT 1-Norte started again and propagated voltage to the 220 kV Busbar of power plant SS, leading to the creation of the second restoration area.

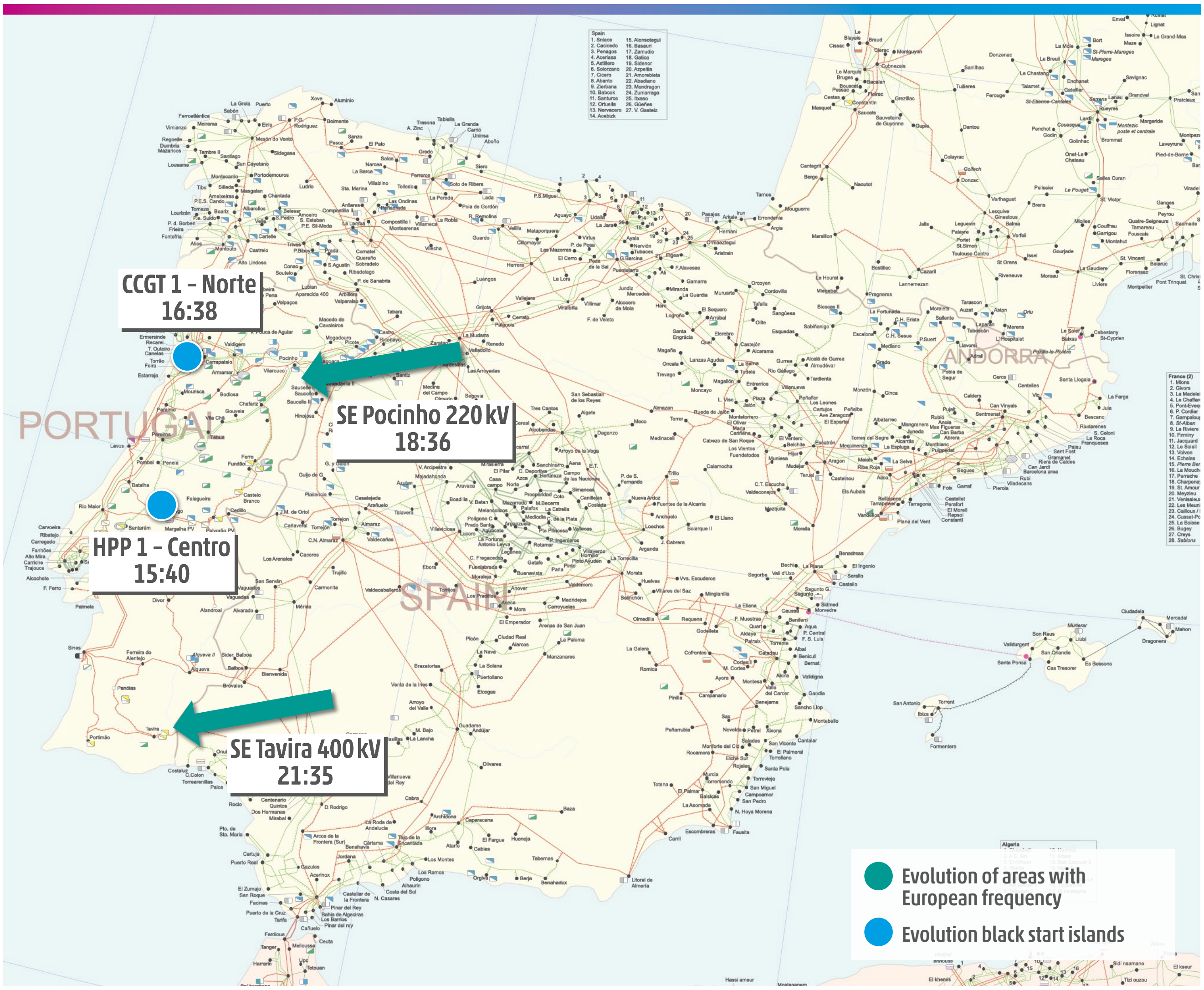


Figure 4-13: Starting time of power plants with black-start capability and later-stage support from interconnections with Spain – REN

» At 18:32, the Oporto region had voltage available in a relevant set of injection SSs of the distribution network, allowing E-Redes (the Portuguese DSO) to continue with the progressive load supply in this geographic area.

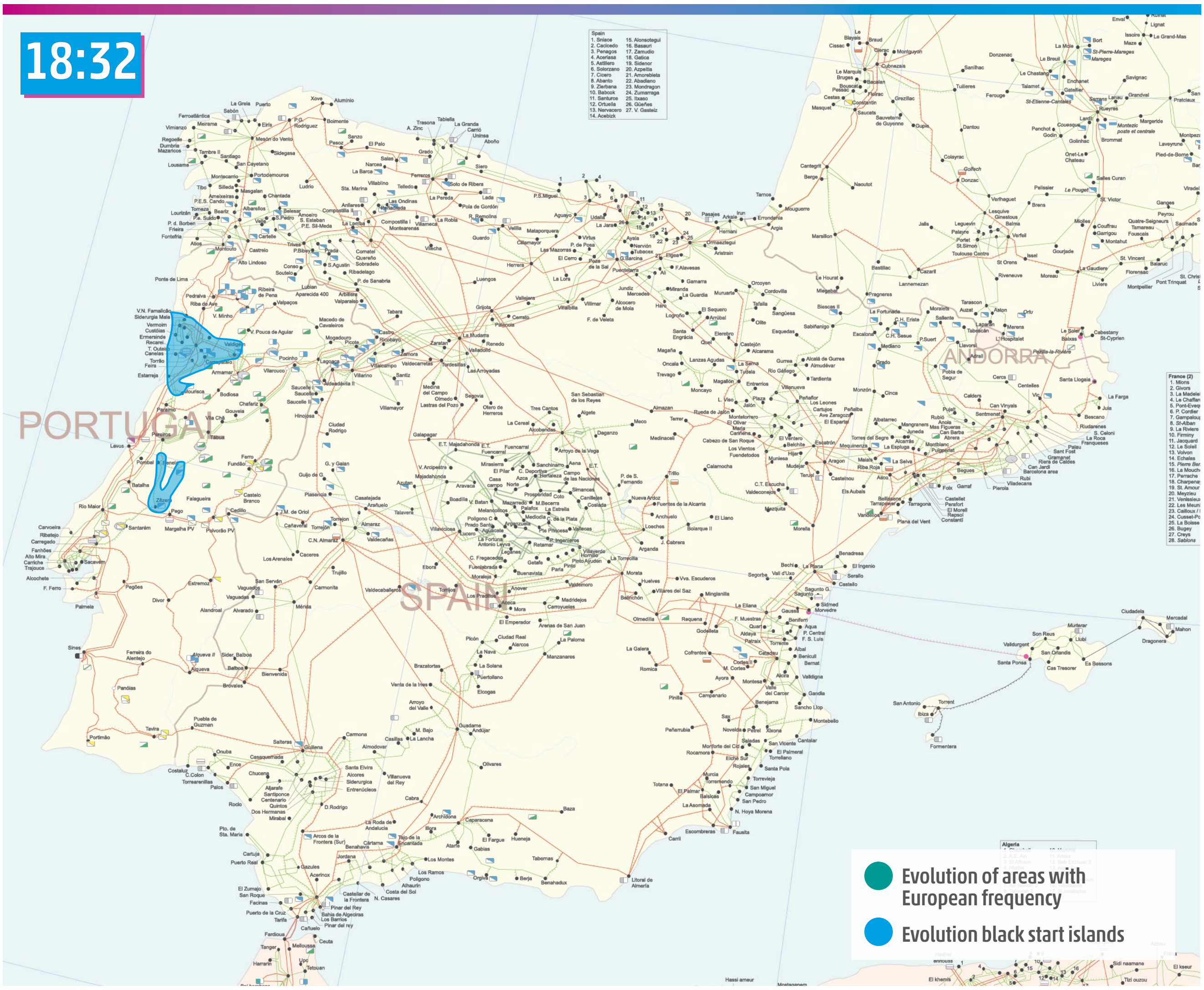


Figure 4-14: Evolution of the restoration in the black-start islands through 18:32 (120 MW of load supplied) – REN

» Then, at 18:36, voltage was propagated to the 220 kV busbar of Pocinho SS from the Spanish Aldeadávila SS (Pocinho–Aldeadávila 1 tie-line at 220 kV), leading to the creation of the third restoration area. This constituted the first synchronous connection with the continental European system through the Spanish electrical system.

At the time, the Portuguese system was being restored in three different electrical islands:

- First by HPP 1-Centro
- Second by CCGT 1-Norte
- Third by interconnection with Spain (synchronous restoration)

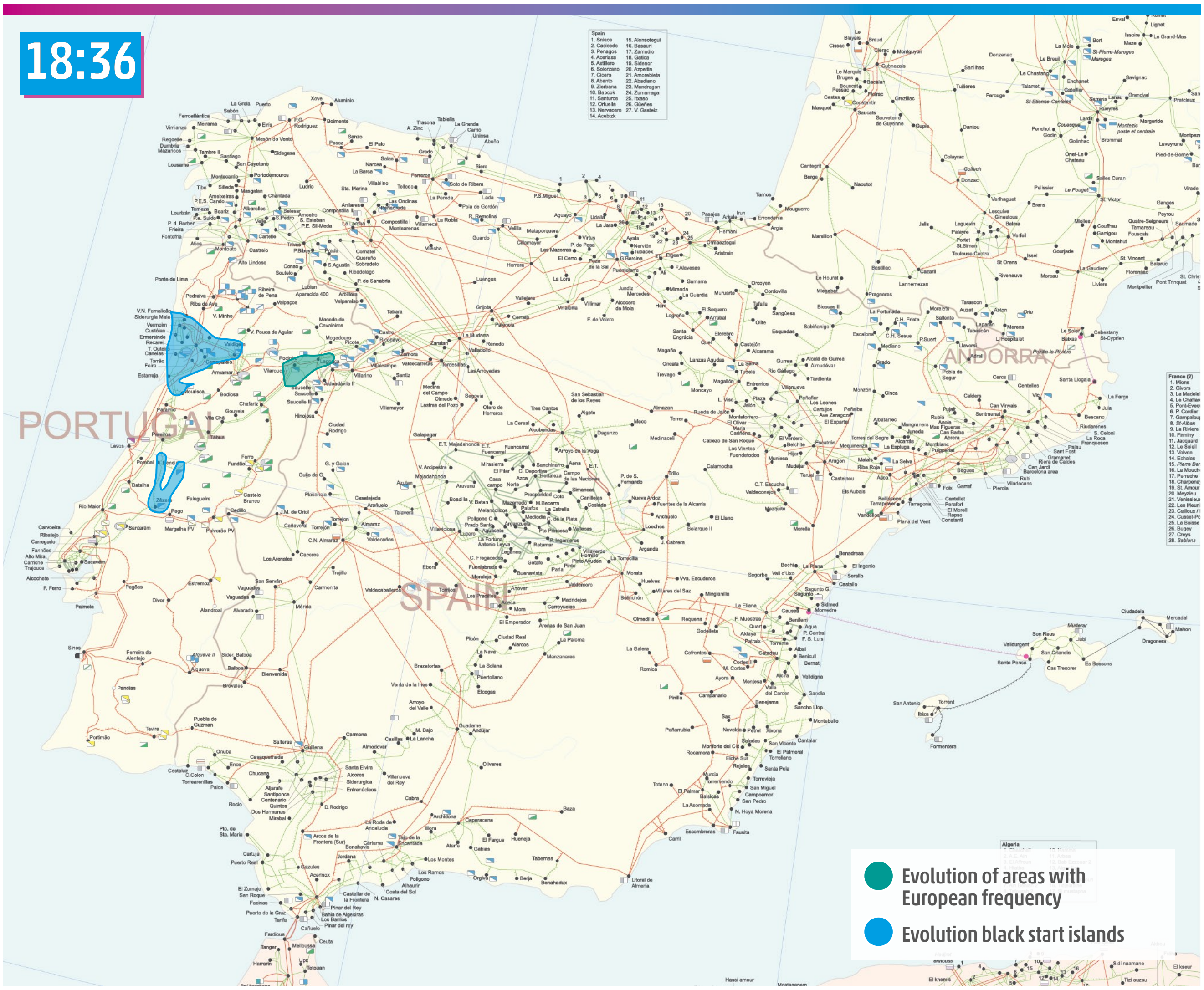


Figure 4-15: Evolution of the restoration in the transmission network and black-start islands through 18:36 (120 MW of load supplied) – REN

- At 19:00, voltage was propagated, enabling progressive load supply and generation restoration along the corridors leading to the Zêzere SS, extending the third restoration area (synchronous with the Spanish/ continental European region).
- At 19:58, the connection with the Spanish system was reinforced, connecting both the Pocinho–Aldeadávila 2 and Pocinho–Saucelle lines at 220 kV.
- Then at 20:01, the electric island powered by HPP 1-Centro was synchronised with the Spanish system, leading to the successful synchronisation of the first and third restoration areas with the continental European region. The synchronisation was accomplished without problems with the use of a synchro-check device, which assesses the conditions for synchronization (difference of voltage magnitude, difference of frequencies and difference of phase angles). At this point, there were 18 HPP units connected to the grid: 10 in the third restoration area, two in the first restoration area, and six in the second restoration area.

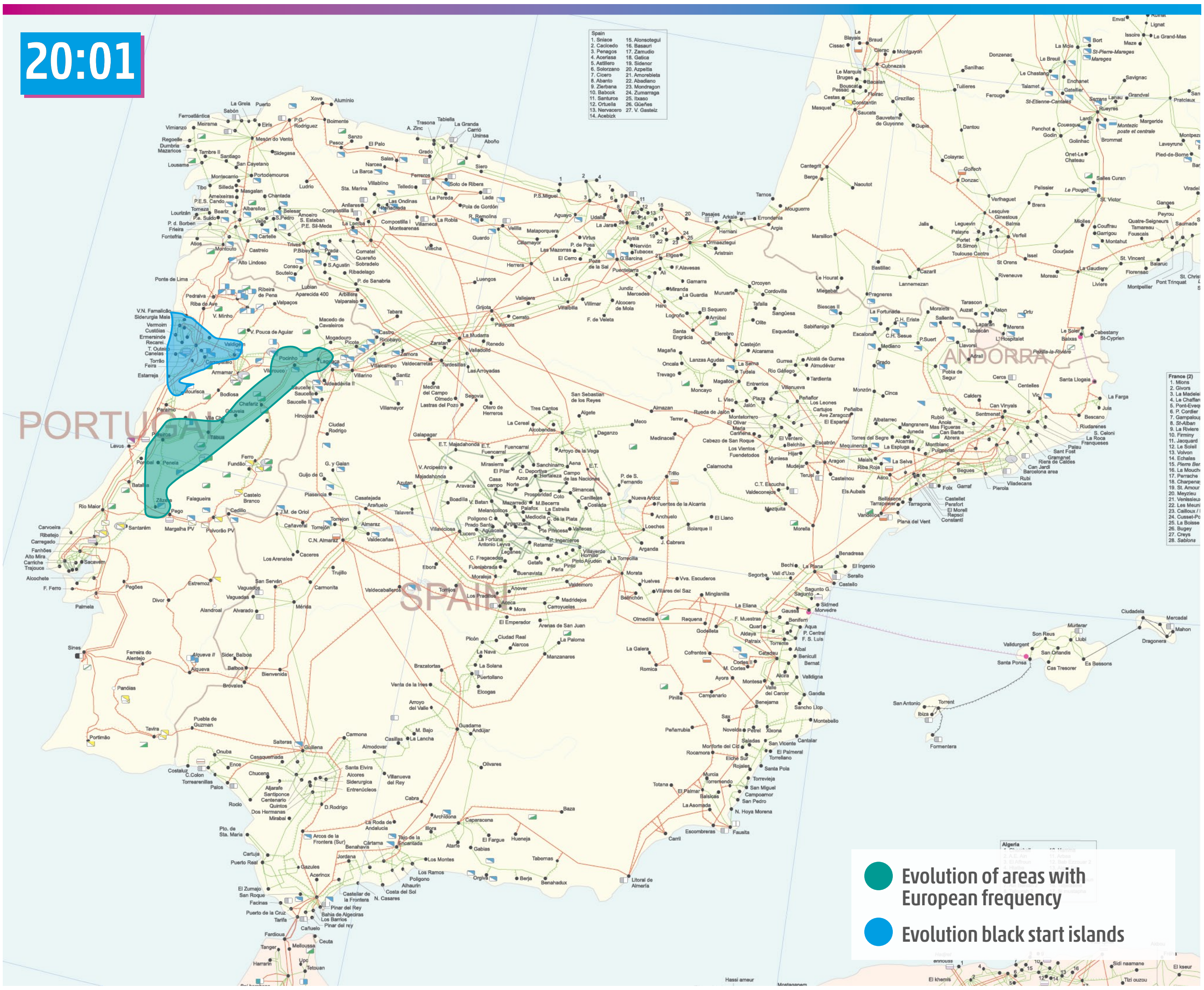


Figure 4-16: Evolution of the restoration in the transmission network and black-start islands with the synchronisation of the electric island powered by HPP 1-Centro through 20:01 (376 MW of load supplied) – REN

- At 20:22, the synchronisation of the electrical island powered by CCGT 1-Norte with the Spanish/continental European region was achieved, leading to the successful synchronisation of the second restoration area with the first and third areas, which were already synchronous with the continental European region. The synchronisation was accomplished without problems with the use of a synchro-check device.

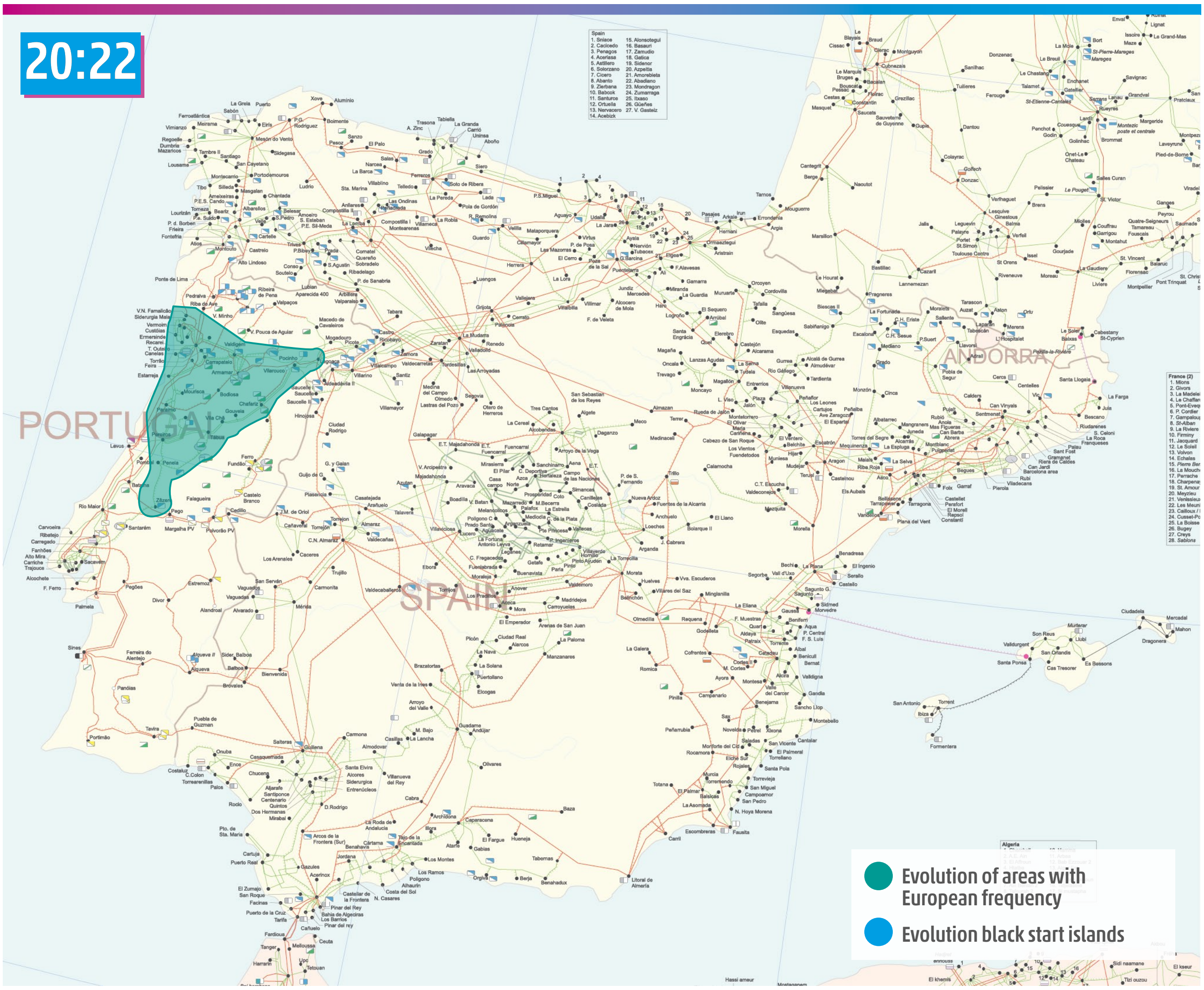


Figure 4-17: Evolution of the restoration in the transmission network with the synchronisation of the electric island powered by CCGT 1-Norte through 20:22 (457 MW of load supplied) – REN

With all areas of the Portuguese system connected to the Spanish/European synchronous system, the restoration process of the transmission network accelerated substantially. The transmission network equipment's autonomy ensured proper functioning of the voice communication system, telemetry, and remote control until the restoration process was completed. Permanent coordination and cooperation were established between REN, Red Eléctrica, E-REDES, (Portuguese DSO) and all national producers, namely significant grid users (SGU), during the Portuguese restoration process.

- At 20:25, automatic generation control (AGC) was activated, following an interconnection schedule program of 0 MW (as agreed with Red Eléctrica) to balance the Portuguese system by automatically adjusting generation to match load.
- At 20:26, voltage propagation, progressive load supply, and generation restoration were occurring nationwide in the northern and central regions of Portugal.
- At 20:47, the interconnection with the Spanish grid was strengthened with the connection of the Lagoaça–Aldeadávila tie-line at 400 kV.
- At 20:57, the restoration of the main loads in the Lisbon region began, with voltage propagated to the Sacavém SS (REN's National Control Centre).

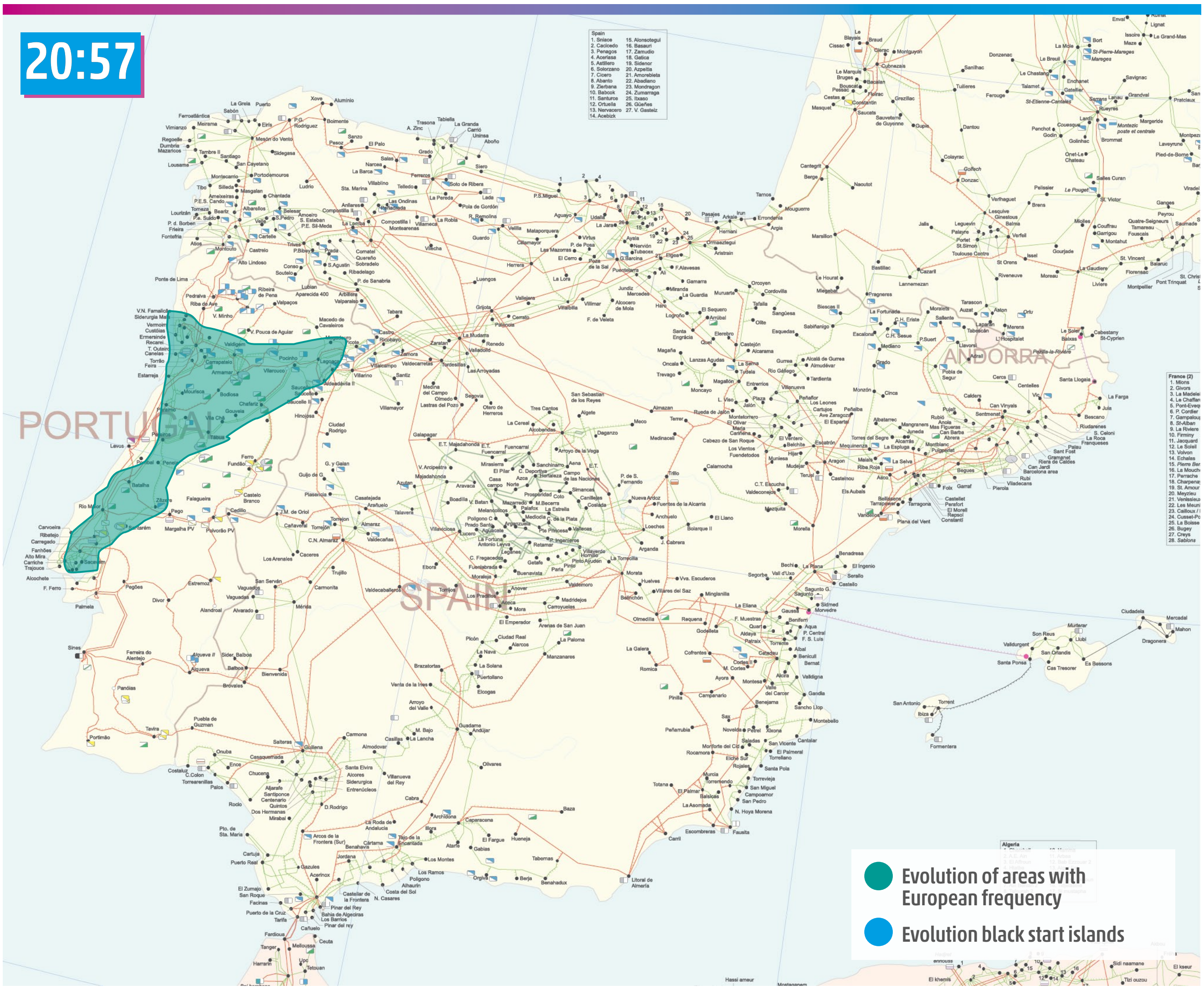


Figure 4-18: Evolution of the restoration in the transmission network through 20:57 (715 MW of load supplied) – REN

- By 21:11, the Lisbon region had voltage available in a relevant set of injection SSs in the distribution network, allowing E-REDES to continue progressive load restoration in this geographic area.
- At 21:35, the 400 kV Tavira–Puebla de Guzmán tie-line was connected, initiating voltage propagation and progressive load supply in the Algarve and Alentejo areas, leading to the creation of the fourth restoration area through synchronous connection with the continental European region (through the Spanish system).

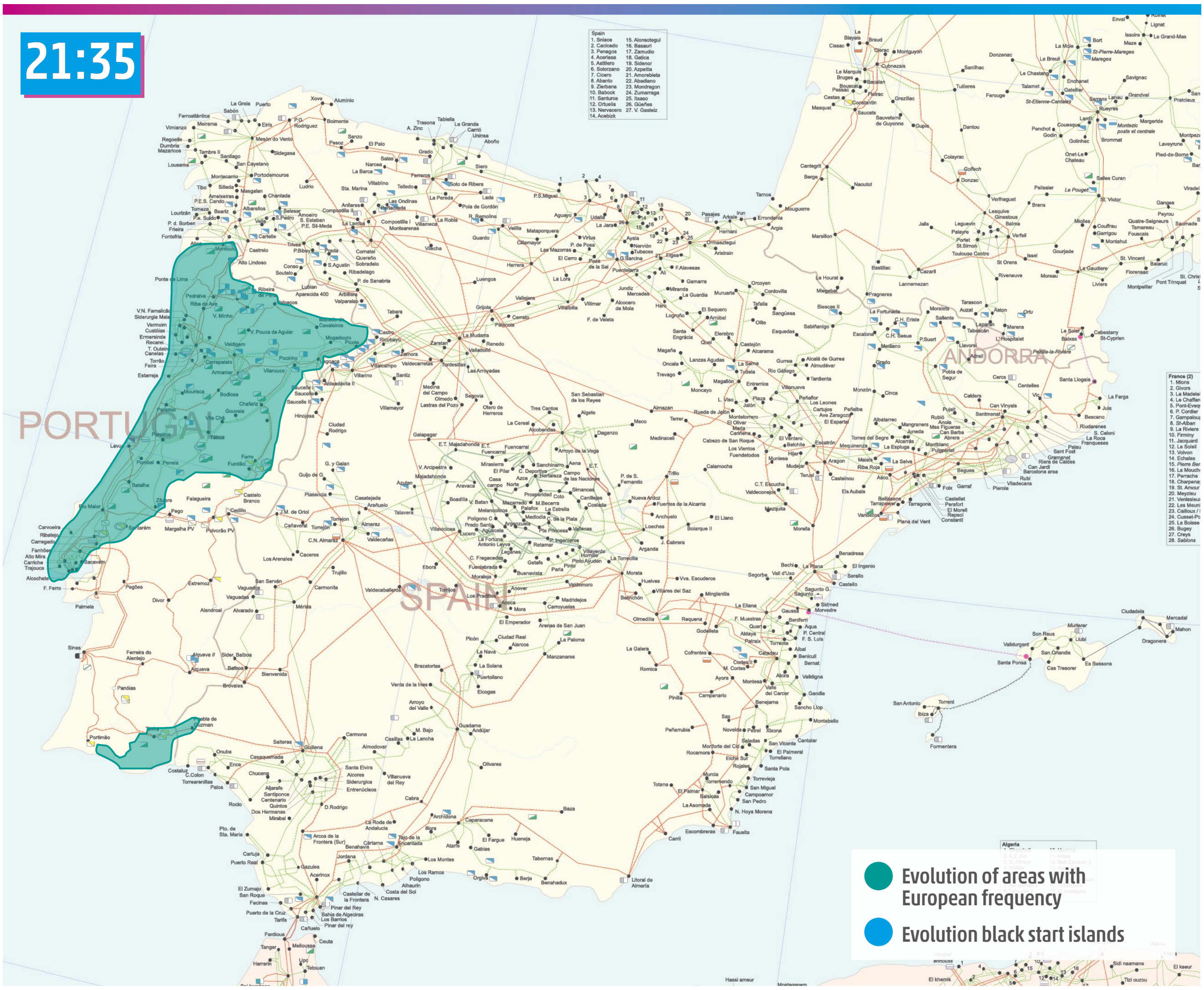


Figure 4-19: Evolution of the restoration in the transmission network through 21:35 (1,244 MW of load supplied) – REN

- At 21:37 and 22:23, the interconnection with the Spanish system (synchronous with the continental European region) was strengthened with the connection of the 400 kV Alto Lindoso – Cartelle and Falagueira – Cedillo tie-lines, respectively.
- At 22:28, there was voltage propagation and progressive load supply in the Setúbal peninsula area from the extension of the 400 kV for the Lisbon region.
- At 23:19, the Algarve and Alentejo region was connected with the rest of the network, leading to a successful merge of the main grid area with the fourth restoration area.
- By 00:22, TSO grid restoration was completed with the connection of the last delivery point, the Divor SS.

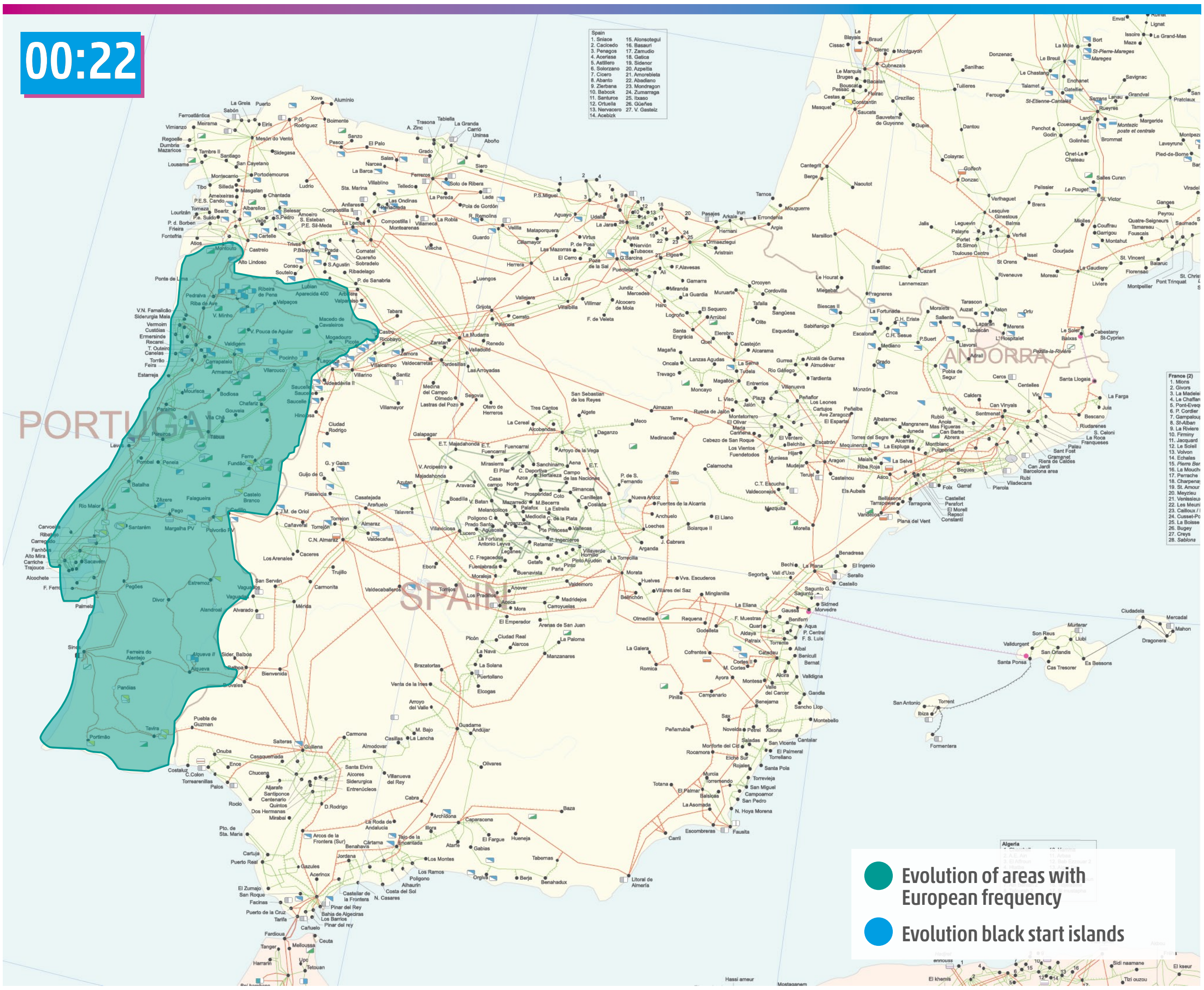


Figure 4-20: At 00:22, the restoration of the transmission network was completed (4,237 MW of load supplied) – REN

- At 02:13, in coordination with Red Eléctrica, the Portuguese system state in the EAS was changed from restoration to emergency.
- At 14:37, in coordination with Red Eléctrica, the Portuguese system state in the EAS was changed from emergency state to alert state.
- At 14:43, validation of the results of the daily market for 30 April was concluded from the REN side.
- At 16:23, market participants were informed through a statement and the publication of an urgent market message that market activities were to be resumed for the delivery periods relating to 30 April.

4.2.3 French local area restoration by RTE

At 12:35: Operators from the Nantes control room checked that every shunt reactor available was in operation and asked every generation unit available to absorb maximum reactive power.

- At 12:38: Three 400 kV overhead lines were opened to control voltage.
- At 12:45: Two more 400 kV overhead lines were opened to control voltage.
- At 15:03: The HVDC unit at Baixas was energised.
- At 15:15: The HVDC unit at Baixas was absorbing enough reactive power to clear the remaining high voltage constraints, marking the end of the voltage-limit violation on the RTE network.

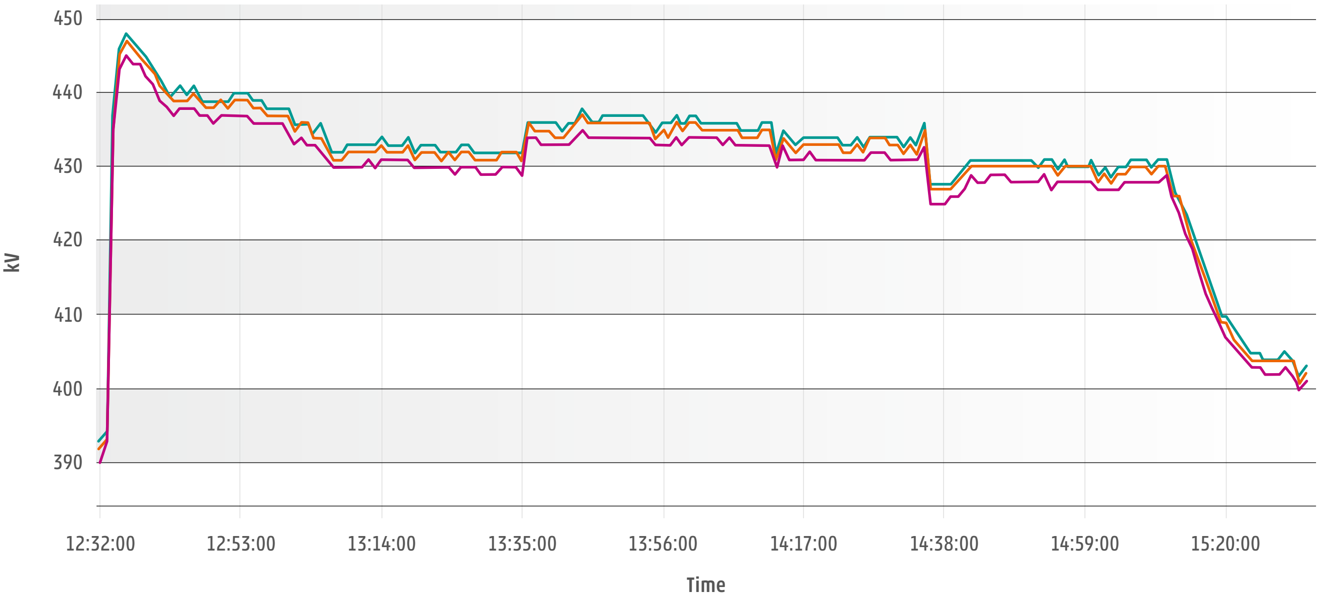
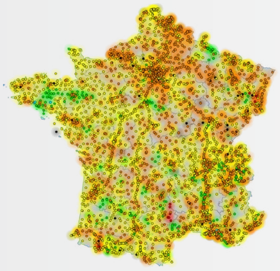


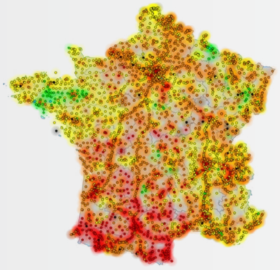
Figure 4-21: Voltage for 400 kV Baixas on 28 April

Voltage heat map evolution



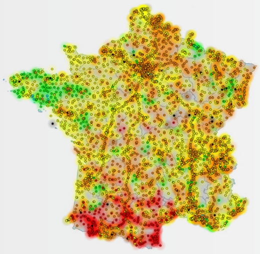
» **12:30**

Situation before the separation of the Iberian Peninsula from the rest of continental Europe.



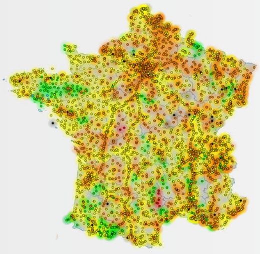
» **12:35**

After the tripping of the Golfech 1 power plant and the HVDC Baixas–Santa Llogaia, high voltages spread through all of southwest France.



» **12:40**

Seven minutes after the separation, and after several mitigation actions, the high-voltage episode was under control, except for close to the Spain–France border.



» **15:20**

After the connection of the HVDC in voltage control, voltage was back within normal range.

Legend

400 kV	225 kV	150 kV	90 kV	63 kV
🟩 396 < U ≤ 404	218 < U ≤ 227	147 < U ≤ 153	88 <U ≤ 91	62 < U ≤ 64
🟨 404 < U ≤ 412	227 < U ≤ 236	153 < U ≤ 159	91 < U ≤ 94	64 < U ≤ 66
🟧 412 < U ≤ 420	236 < U ≤ 245	159 < U ≤ 165	94 < U ≤ 97	66 < U ≤ 68
🟥 420 < U	245 < U	165 < U	97 < U	68 < U

Figure 4-22: Voltage heat map evolution in France

Power was available on the west part of the border via the 400 kV Argia–Hernani and 225 kV Argia–Arkale tie-lines. In coordination with Red Eléctrica, these tie-lines were brought into service at 12:43 (400 kV Hernani–Argia) and 12:54 (220 kV Arkale–Argia).

On the eastern part of the border, the 400 kV Baixas Vich tie-line was energised at 13:35.

Restoration process timeline

- At 13:27, a maximum transit of 950 MW on the border was agreed upon with Red Eléctrica.
- At 14:41, a maximum transit of 1,200 MW on the border was allowed.
- At 15:59, the HVDC Baixas—Santa LLogaia 1 link was put into operation, followed by link 2 at 21:58.
- At 17:30, a maximum transit of 1,500 MW on the border was allowed.
- At 18:19, a maximum transit of 2,000 MW on the border was allowed until 23:59.
- At 22:33, an agreement was reached for a cross-border exchange from France to Spain of 1,400 MW, scheduled from 00:00 to 03:00.
- At 07:00 on 29 April, the maximum transit on the border rose to 1,500 MW for 08:00.
- At 09:37, an agreement was reached to reduce the cross-border exchange from France to Spain to 800 MW from 10:00 to 11:00.
- At 10:05, an agreement was reached to reduce the cross-border exchange from France to Spain to 0 MW as of 11:00. This value was maintained until 23:00.
- At 22:00, an agreement was made to open the Spain-to-France intraday allocation (XBID) at 23:00.

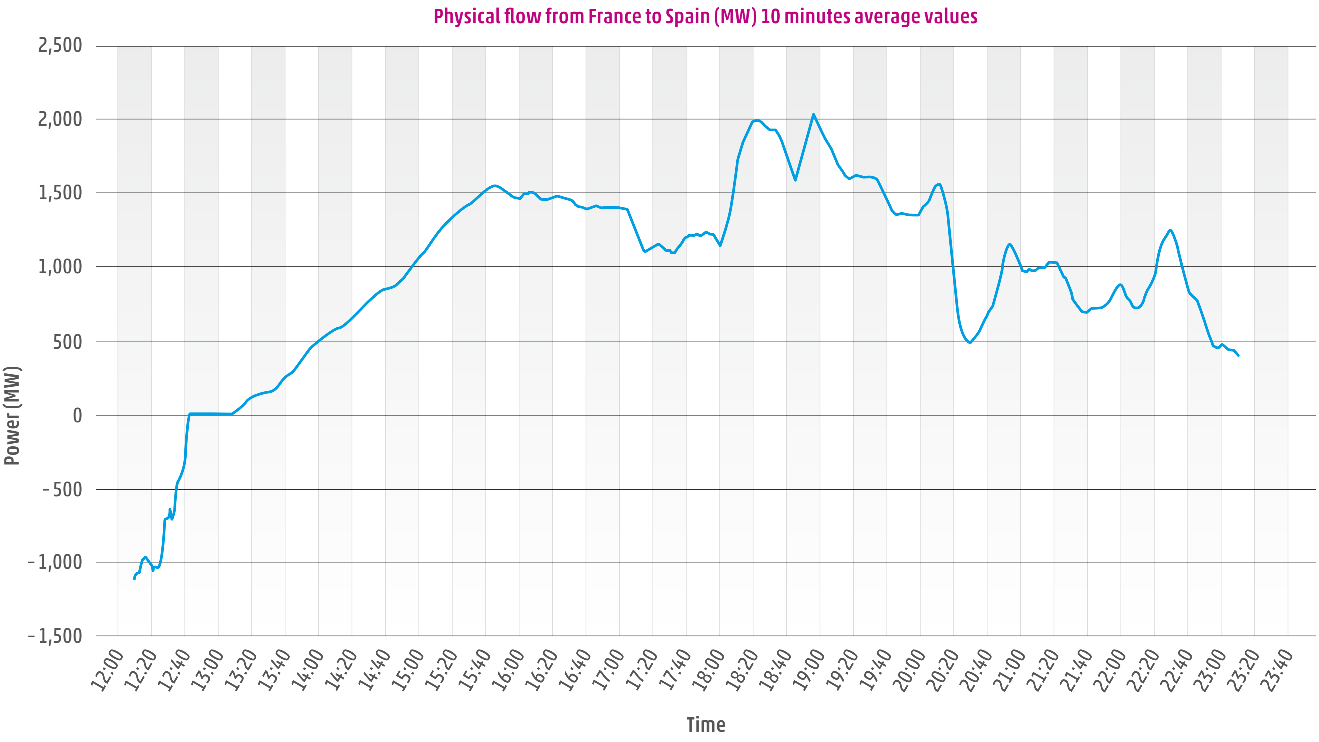


Figure 4-23: Physical flow from France to Spain (MW) in 10-minute average values

4.3 Generation and load recovery

The restoration of electrical grids after a total blackout is a complex and demanding coordinated process. TSOs worked collaboratively to re-establish electricity supply through a mixture of top-down and bottom-up approaches. Generation and load recovery occurred simultaneously as the grid was being restored. This sub-chapter describes the generation and load recovery once system balance was achieved.

In the following sections, it is noted that several islands tripped during the restoration process and/or that black-start attempts were unsuccessful. Unless otherwise specified, the reasons for the trips are not yet known to the Expert Panel and will be investigated in the final report.

4.3.1 Spain

The restoration of the Spanish transmission system from the Red Eléctrica side was concluded at 04:00 on 29 April. The restoration continued at the distribution system level, concluding at 07:00 on 29 April.

Evolution of the generation and load during and after restoration

The restoration of the interrupted power supply began at 12:43 with the support received through the Spain—France interconnection. Additionally, as noted in the previous sections, in the minutes following the incident, islands were created from hydroelectric plants with autonomous start-up across different electrical zones.

From 13:04, support was established through the Spain—Morocco interconnection. Subsequently, starting at 15:14, combined-cycle plants progressively connected to contribute to the restoration of power supply.

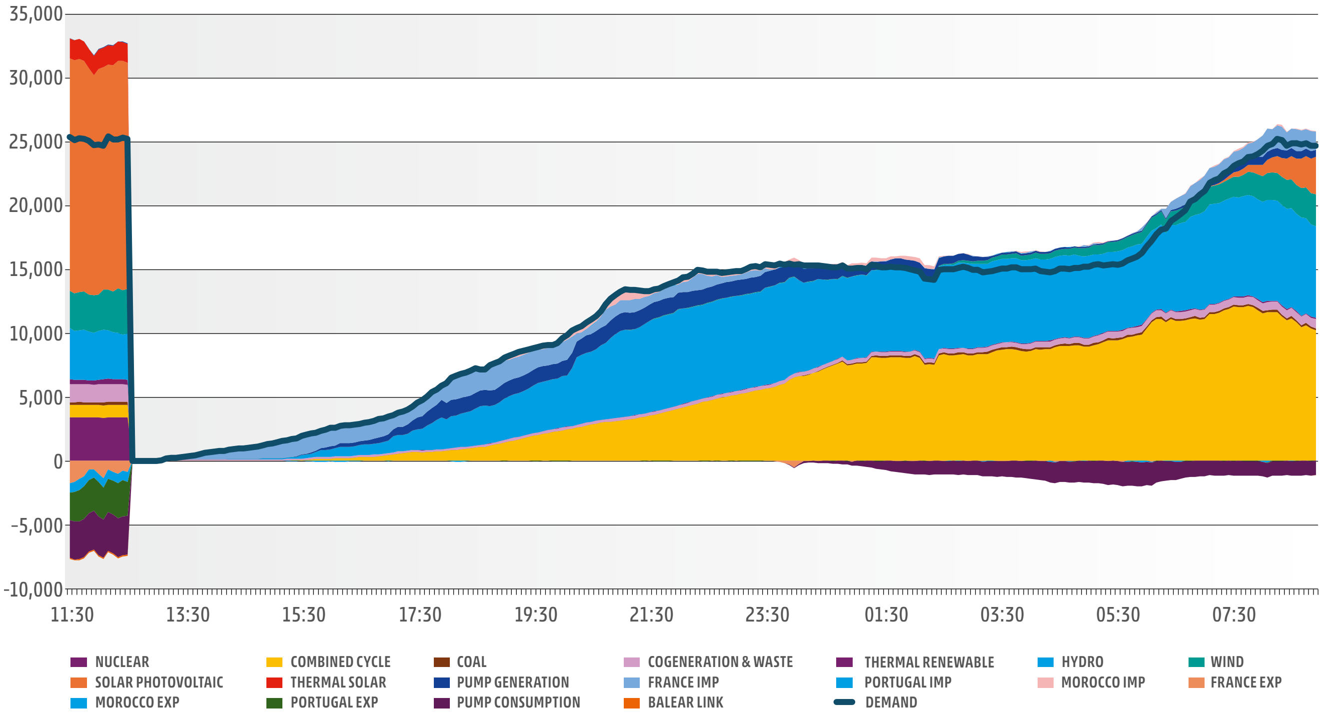


Figure 4-24: Evolution of generation and load of the Spanish system during the restoration phase – Red Eléctrica

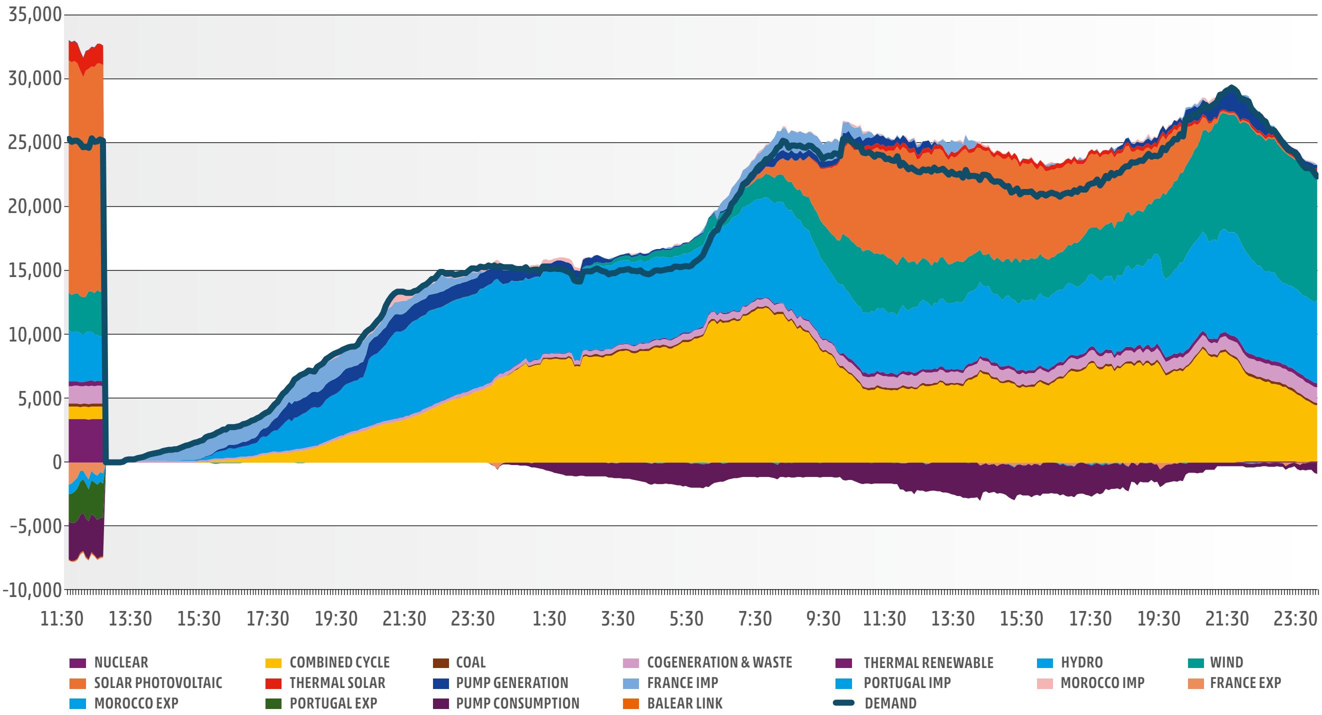


Figure 4-25: Evolution of generation and load of the Spanish system until the end of 29 April – Red Eléctrica

Evolution of renewable generation during restoration

Supervision and control of RCW in the Spanish electrical system is carried out by CECRE, commissioned in June 2006.

Under Spanish regulation established in Royal Decree 413/2014, all single RCW facilities, or clusters sharing the same connection point with a total installed power greater than 1 MW, are required to send real-time telemetry of active power produced to CECRE. Additionally, all single RCW facilities, or clusters with a total installed capacity greater than 5 MW, receive active power setpoints from CECRE, with which they must comply.

Therefore, CECRE receives real-time telemetry from RCW facilities and can issue real-time limits for maximum production of RCW facilities connected to both the transmission and distribution network.

This real-time information is collected from the plants by the Renewable Energy Control Centres (RESCCs) and channelled via the ICCP links connecting these control centres to CECRE.

To minimise the number of points of contact with CECRE, the RESCC serves as the sole real-time interface with the Spanish TSO. In other words, RESCCs act as intermediaries between CECRE and the RCW facilities. Each RCW facility is free to choose its preferred RESCC, regardless of the technology it uses or its connection point to the network.

Generation control is managed by CECRE, which sets individual limits for each facility through its RESCC.

Therefore, on one hand, RESCCs collect real-time information from RES facilities and send it to CECRE (supervision), and on the other hand, they collect the setpoints established by CECRE and send them to the facilities (control).

After the incident, at 13:38, CECRE sent a setpoint of 0 MW to all RCW facilities.

Once it was determined that RCW generation could be safely incorporated into the Spanish electrical system without affecting the restoration process, the setpoints were released as follows. It is important to note that setpoints refer to the installed power of RCW generation:

Time	Setpoint for maximum production for RCW generation (MW)	% of total installed power
01:38	1,000	1.4
01:55	2,000	2.9
02:50	3,000	4.3
03:37	4,000	5.7
04:06	5,000	7.1
04:33	6,000	8.6
05:02	7,000	10
05:29	8,000	11.4
05:59	10,000	12.8
06:08	12,000	17.1
06:13	15,000	21.4
06:16	19,000	27.1
06:18	24,000	34.2
06:28	29,000	41.4
06:36	34,000	48.6
06:43	41,000	58.5
06:51	49,000	70.0
06:58	57,000	81.3
07:04	limitations released	100

Description of the evolution of balancing compensations from neighbouring TSOs

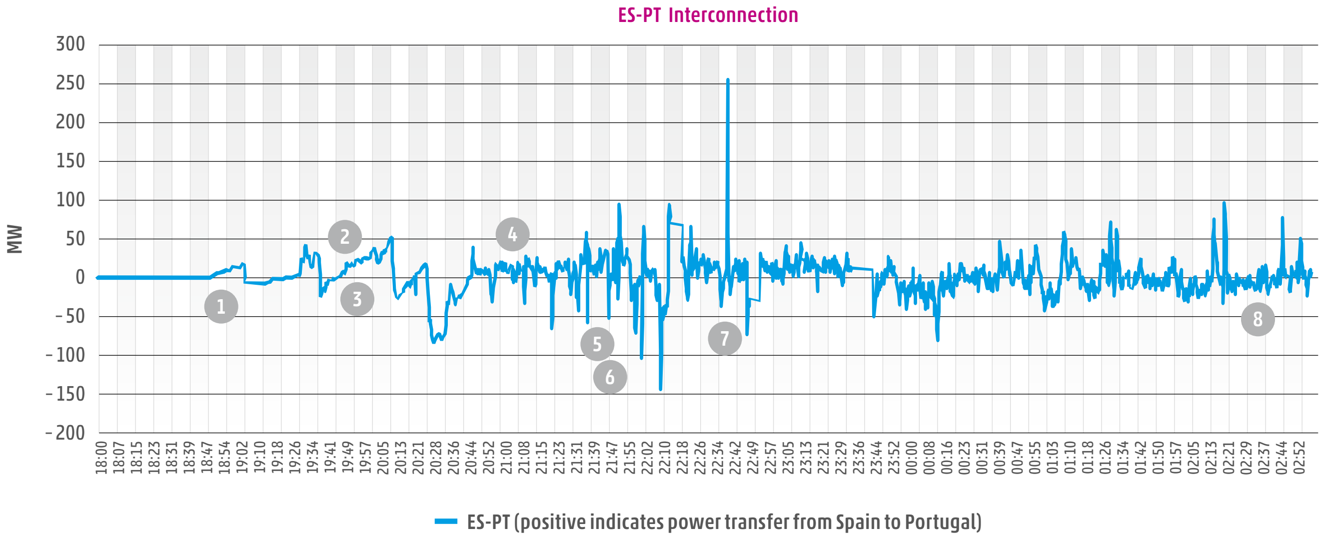


Figure 4-26: Active power exchange on the Spain–Portugal interconnection

1. At 18:36, the L-220 kV Aldeadávila–Pocinho 1 interconnection was switched on, sending voltage to the Portuguese electrical system for the first time during the restoration process. From this point, REN received continental European frequency.
2. At 19:57, the L-220 kV Saucelle–Pocinho interconnection was switched on.
3. At 19:58, the L-220 kV Aldeadávila–Pocinho 2 interconnection was switched on.
4. At 20:47, the L-400 kV Aldeadávila–Lagoaça interconnection was switched on.
5. At 21:34, the L-400 kV Puebla de Guzman–Tavira interconnection was switched on.
6. At 21:37, the L-400 kV Cartelle–Lindoso 1 interconnection was switched on.
7. At 22:33, the L-400 kV Cedillo–Falagueira interconnection was switched on.
8. At 02:37, the L-400 kV Cartelle–Lindoso 2 interconnection was switched on.

The interconnection between Spain and Portugal through the 400 kV Brovales–Alqueva line was unavailable due to maintenance work at the time of the incident. The return of the line was requested, ending the outage. This interconnection was switched on at 13:39 on 29 April.

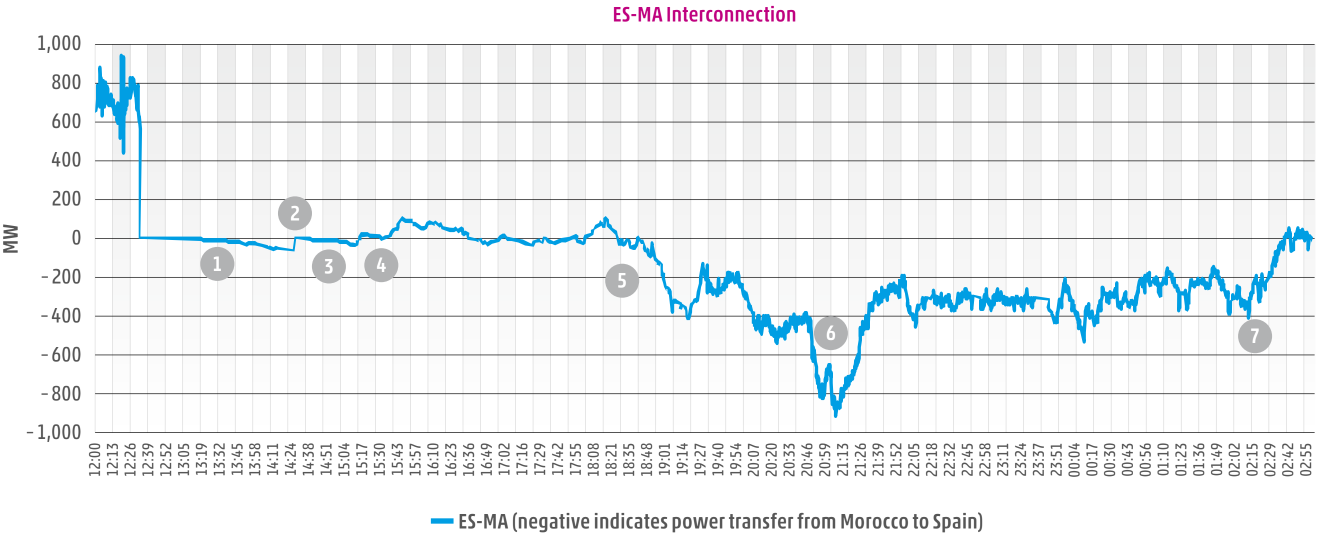


Figure 4-27: Active power exchange on the Spain–Morocco interconnection

1. At 13:04, support was received from Morocco through the L-400 kV Pto. de la Cruz–Mellousa 2 (ESMA 2) interconnection.
2. At 14:27, the interconnection with Morocco was disconnected due to an underfrequency relay trip, causing the disconnection of all the load supplied up to that moment.
3. At 14:34, voltage was resumed from Morocco through the L-400 kV Pto. de la Cruz–Mellousa 1 (ESMA 1) interconnection.
4. At 15:14, the first TTP was connected in the Southern zone.
5. At 18:16, the L-400 kV Bienvenida–Almaraz was switched on, synchronising the Southern zone with the Centro electrical island.
6. At 20:59, the L-400 kV Pto. de la Cruz–Mellousa 2 (ESMA 2) interconnection was switched on.
7. At 02:18, it was agreed with ONEE to discontinue emergency support from Morocco.

4.3.2 Portugal

Evolution of generation and load during and after restoration

As mentioned in the previous sections, the restoration of the supply began at 15:40 with the successful start-up of the first power plant in black-start mode. No support from the Spanish system was possible at that moment.

At 18:36, support was established through the 220 kV Spain–Portugal interconnection to synchronise the two islands with the continental European power system, significantly increasing network stability, which enabled accelerated restoration of the Portuguese system. No energy support was needed between the Spanish and Portuguese systems, and the interconnection capacity between Portugal and Spain was set at 0 MW in import and export directions.

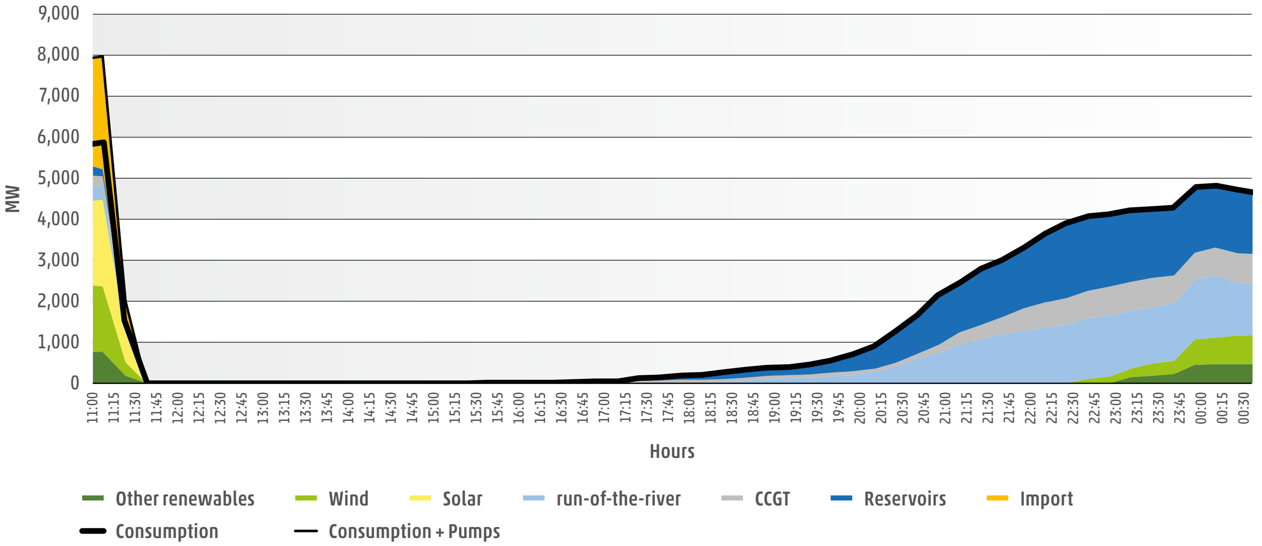


Figure 4-28: Evolution of generation and load of the Portuguese system during the restoration phase – REN

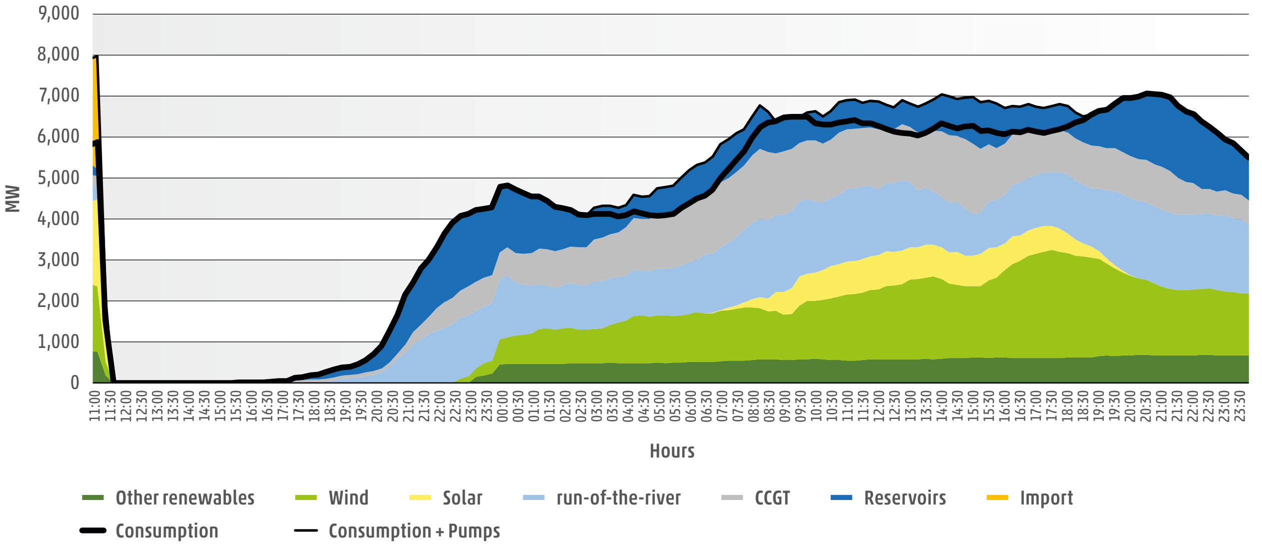


Figure 4-29: Evolution of generation and load of the Portuguese system until the end of 29 April – REN

The restoration of the Portuguese transmission system from the REN side was concluded at 00:22. At the distribution system level, the restoration continued, ending at 04:00 on 29 April.

Evolution of renewable generation (wind and solar) during restoration

- According to established Portuguese regulations, all renewables single power plants, or set of power plants sharing the same connection point with a total installed power greater than 1 MW, should have observability and controllability (by setpoints) from REN's National Control Centre. However, no setpoint was sent to limit renewable production during the restoration phase.
- According to the National Service Restoration Plan, the connection points of the renewable power plants (solar and wind generation) connected to the transmission system were not energised during transmission system restoration. They were energised by REN after the restoration throughout the day on 29 April, and instructions for production permission were provided by phone. For the wind generation connected to the transmission system (2,774 MW of installed capacity), production permissions were given from 16:00, while solar generation (1,767 MW of installed capacity) received permission from 21:00 on 29 April.
- The renewable power plants connected to the distribution system began to be energised shortly before the end of the transmission system restoration, in coordination between REN and E-REDES. For the wind and solar generation connected to the distribution system (2,634 MW and 2,620 MW of installed capacity, respectively), production permissions were given from 23:00 on 28 April.

4.3.3 France

The D-1 commercial nomination on the Spain–France border for business day 28 August was scheduled from France to Spain (up to 1,688 MW) between 13:00 and 15:00, and then from Spain to France between 16:00 and 21:00 (1,800 MW from 16:00 to 18:00, then 3,000 MW).

As RTE supplied Red Eléctrica in the afternoon and evening of 28 April and in the morning of 29 April, RTE activated bids on the French balancing mechanism (up to 4,500 MW, total activated energy for 28 and 29 April: 51.9 GWh) and sought support from other TSOs (up to 500 MW, 3,000 MWh from Swissgrid on 28 April and 8,850 MWh from Amprion on 28 and 29 April).

4.4 Steps after system restoration

This section describes the steps taken to ensure system balance after the network restoration.

4.4.1 Spain

The day-ahead market session for 29 April was conducted, but its results were not applied in system operation. The remaining electric market activities for 29 April in the Spanish system were suspended. They were re-established for 30 April. As the system restoration progressed, orders were given to synchronise all available hydraulic and thermal generators in the system. As they were synchronised, instructions were given to each of these generators by phone to adjust their generation to demand.

The master aFRR controller was connected at 00:06 on 29 April, and the synchronised hydraulic and thermal generators with secondary regulation capacity were included in this system, thereby providing a significant volume of secondary regulation to manage demand and generation variations.

From 01:38 to 07:00, the limitations on RCW generation were progressively removed to allow their inclusion in the system as described in section 4.3.

Throughout 29 April, synchronised hydraulic and thermal generators were instructed by phone to adjust their generation to demand and maintain adequate levels of secondary reserve.

From 00:00 to 24:00 on 29 April, export capacities with France, Portugal, and Morocco were reduced to 0 MW to enable all system demand to be supplied with the available generation.

From 06:30 to 11:00, due to insufficient synchronized generation to supply the demand, a support import program was requested from France (800 MW from 06:30 to 08:00 and from 10:00 to 10:30, 1,500 MW from 08:00 to 10:00, and 400 MW from 10:30 to 11:00).

In the last hours of 29 April, hydraulic and thermal generators were instructed to adjust their generation to their market programs starting from 00:00 on April 30.

4.4.2 Portugal

The day-ahead market session for 29 April was conducted, but the results were not applied in system operation. The remaining electric market activities for 29 April in the Portuguese system were suspended. They were re-established for 30 April.

As the system restoration progressed, HPPs and TPPs were given instructions by phone (non-market-based central dispatch). As they were synchronised, each of these generators received instructions by phone to adjust its generation to demand.

During the afternoon of 29 April, the production limitations on renewable generation (wind and solar) connected to the transmission grid were progressively removed to allow their inclusion in the system as described in section 4.3.

Throughout 29 April, instructions were issued by phone to the synchronised hydro and thermal generators to adjust their generation to demand and maintain adequate secondary reserves. The AGC was put into service at 20:25 on 28 April, following an interconnection schedule program at 0 MW, as agreed with Red Eléctrica.

4.5 Market restoration

This section describes the restoration of market activities in Spain and Portugal after the restoration and stabilisation of the systems.

4.5.1 Spain

On the morning of 29 April, the Iberian NEMO was informed by phone of the forecast for completing the system restoration and the resumption of market activities, starting with the clearing of the daily market for energy delivery on April 30.

At 11:39 on 29 April, in coordination with the Iberian NEMO, the Spanish system operator published a statement in the System Operator Information System (ESIOS) to all actors indicating that the restoration state would last until 23:59 that same day:

> *Following the incident in the peninsular electricity system that occurred at 12:33 p.m. yesterday, April 28, and until 11:59 p.m. today, April 29, market activities are suspended in accordance with Operating Procedure P.O.3.9. Therefore, no energy or capacity schedules or allocations made through market mechanisms for the periods within this time frame will be considered valid.*
>
> *The energy settlement will be carried out in accordance with sections 5 and 6 of the aforementioned procedure.*
>
> *The system operator has already informed the NEMO that market activities will resume starting with the day-ahead market for energy delivery April 30.*

This information was also published on the privileged information platform of the system operator.

> *Due to the incident in the Spanish Peninsular electrical system at 12:33 PM on April 28th, market activities for delivery April 29th are suspended, following both Article 35 of Commission Regulation (EU) 2017/2196 and Spanish Operational Procedure 3.9. Market activities for delivery April 30th have been restored.*

In particular, the following milestones are highlighted:

- Participation in the single day-ahead coupling took place on 29 April at 12:00 for energy delivery on 30 April. For 30 April, the interconnection capacity between Spain and France, as well as between Spain and Portugal, was limited.
- The intraday market for 30 April was enabled at 23:00 on 29 April.
- Connection to the European platform for mFRR (MARI) at 00:15 on 30 April.
- Connection to the European platform for RR (TERRE) at 00:26 on 30 April.
- Connection to imbalance netting platform (IGCC) at 11:55 on 30 April.

4.5.2 Portugal

On 29 April at 16:23, REN published a statement and an urgent market message indicating that the restoration and stabilisation of the system would last until 23:59 that same day:

Following the blackout situation that occurred on 28 April 2025, in the Portuguese electrical system and the subsequent, ongoing process of restoration and stabilisation that is taking place on 29 April, it is reported that:

- *The interconnection capacity between Portugal and Spain will be set on 30 April (CEST – Central European Summer Time), at 0 MW in the import and export direction.*
- *Transactions will resume in the day-ahead market, intraday market sessions, and the continuous intraday market for the delivery periods relating to 30 April (CEST)*
- *Contracts will resume, inclusive from 30 April (CEST), in the various markets and processes managed by REN – Rede Eléctrica Nacional, S.A., namely the processes for resolving technical restrictions, the replacement reserve (RR) market, the frequency restoration reserve market with manual activation (mFRR) and the secondary regulation band market*

Additionally, on 29 April at 18:26, a notification was sent to all market players stating that the restoration state would last until 23:59 that same day.

REN reconnected to the balancing platforms on:

- IGCC: The reconnection occurred on 30 April at 19:08.
- TERRE: REN started to submit needs for RR for the delivery periods between 03:00 and 04:00 on 30 April.
- MARI: The reconnection occurred on 30 April for the quarter-hour from 19:30 to 19:45.

5 RCC ANALYSIS BEFORE THE INCIDENT

5.1 Introduction

5.1.1 Role and Scope of RCCs in Incident Investigations

In Europe, there are five Regional Coordination Centres (RCCs) and one Regional Security Coordinator (RSC), each performing their prescribed tasks in their designated geographical regions. The RCCs are Baltic RCC, TSCNET, SEleNe CC, Coreso, and Nordic RCC, while the RSC is SCC. The RCC tasks are listed in the Electrical Regulation (EU Reg 2019/943 Art. 37). In this report, both RSCs and RCCs will be referred to as RCCs for ease of reading the document, and the term "RCC task" will be used for both RSC services and RCC tasks.

Relevant to this investigation, RCCs are required to conduct post-operation and post-disturbances analysis and reporting tasks (also known as regional incident analysis and reporting or RIAR) per EU regulation 2019/943, Article 37.1 (i), based on the methodology approved by ACER on 31 March 2022. As with all RCC tasks, the RIAR investigation is carried out independently of both individual national interests and those of transmission system operators (TSOs) (Art. 35 (4) of EU Regulation 2019/943) and interacts with the investigation executed by the Incident Classification Scale (ICS) Expert Panel.

An RCC Investigation Subgroup is created within the ICS Expert Panel when the RCC investigation threshold is met. The RCC investigation threshold has been met as per ICS classification, as detailed in Chapter 7. The following sections provide an overview of the different RCC tasks and their outcome connected with this incident. The final report will also include an assessment, recommendations, and a conclusion from the RCC perspective.

The incident in question concerned the South West Europe (SWE) capacity calculation region (CCR) which includes Portugal, Spain, and France. The RCC responsible for this CCR, and therefore the affected RCC, is Coreso.

5.1.2 High Level Description of RCC Tasks

RCC tasks are relevant to the operational planning phase and focus on steady state analysis rather than dynamic analysis of the European power system.

Article 37.1 of the EU Regulation 2019/943 prescribes the following RCC tasks:

EU REGULATION 2019/943 ARTICLE 37.1	TASK
a	Coordinated capacity calculation (CCC)
b	Coordinated security analysis (CSA)
c	Common grid model (CGM)
d	Consistency assessment of defence and restoration plans
e	Short-term adequacy (STA)
f	Outage planning coordination (OPC)
g	Training and certification of staff working for RCCs (TCI)
h	Supporting the coordination and optimisation of regional restoration as requested by TSOs
i	Carrying out post-operation and post-disturbances analyses and reporting
j	Regional sizing of reserve capacity
k	Facilitating the regional procurement of balancing capacity
l	Supporting TSOs, at their request, in the optimisation of inter-transmission system operators' settlement
m	Carrying out tasks related to the identification of regional electricity crisis scenarios if, and to the extent, they are delegated to the RCCs
n	Carrying out tasks related to the seasonal adequacy assessments if, and to the extent, they are delegated to the RCCs
o	Calculating the value for the maximum entry capacity available for participation of foreign capacity in capacity mechanisms
p	Carrying out tasks to support TSOs in identifying the need for new transmission capacity, upgrades to existing capacity, or suitable alternatives

Table 5-1: List of mandated RCC tasks

Of these tasks, the ones carried out for the SWE region are listed in Section 5.1.3. RCC tasks identified as relevant for this incident are outlined in Section 5.2.

5.1.3 Regional Coordination for South West Europe

The SWE system operation region (SOR) includes Portugal, Spain, and France, and the RCC responsible is Coreso. The region covers southwest France and the Iberian Peninsula, as its geographical characteristics impact the electrical grid's layout and operation.

Both Spain and Portugal have significant installed renewable generation capacity, meaning that cross-border electricity flows are highly dependent on renewable generation patterns, particularly wind and solar, including their forecasts. Due to the intermittent nature of these energy sources, it is common for intraday (ID) markets to alter the conditions initially anticipated during the planning stages, such as the day-ahead (DA) market. In scenarios with high renewable output, Renewable Energy Sources (RES) curtailment is often necessary. When this occurs alongside low demand periods (like Sundays, holidays, or nighttime), REN or RE may report a forecast of tight downward generation margins, which is provided to Coreso at the beginning of the security analysis (SA) DA SWE process or in weekly calls between TSOs hosted by Coreso. Furthermore, since generation centres in Spain are usually far from consumption hubs due to demographic and industrial factors, these circumstances introduce an additional challenge: voltage and reactive power management. Under low loading conditions, the extensive 400 kV lines tend to exhibit capacitive behaviour, which increases the voltage. To counteract this effect, RE and REN apply remedial actions (RAs) by opening internal lines to redistribute loading and increase the loading on the remaining lines, thus reducing the voltage in the transmission grid. This can result in more lines out of service in DA grid models than those initially reported as planned outages in the week-ahead (W-1) models (exchanged in the context of outage planning coordination (OPC)).

The two borders within the SWE region (PT–ES and ES–FR) are analysed separately from a capacity calculation perspective, as the impact of one border on the other is minimal due to the Spanish grid lying between them. This results in a different approach compared to other European regions: Capacity calculation in SWE is based on net transfer capacity (NTC) rather than flow-based methods. From an SA standpoint, the interaction between the two borders remains limited. However, the worst-case scenarios typically occur when energy flows from Portugal to France through Spain during periods of high wind generation – or conversely, when wind generation in both Spain and Portugal is low. In these cases, certain transmission corridors within Spain and along the western segment of the Spain–France border may experience congestion.

RCC activities usually focus on specific areas of the three TSOs' grids. For SA and regional OPC services, these areas are defined in Table 5 2. Based on its cross-border relevance, each element will be included in each list (interest, observability or none). The elements within each list are treated differently during SA and regional OPC processes, as described in Table 5 2. The table also provides an overview of key indicators related to the elements included in these lists.

The concept of interest/observability areas is actively used during interactions with TSOs and is part of existing procedures. Coreso does not assess security of all the national grids, but instead focuses on an agreed area close to the borders. Thus, grid elements are assigned to interest/observability areas based on their cross-border relevance. More details about Interest Areas will be provided in the final report.

	Interest		Observability		
	400 kV Substations	**220 kV Lines**	**400 kV Substations**	**220 kV Substations**	**220 kV Lines**
RTE	8	7	11	16	0
RE	45	23	(all other 400 kV substations)	0	2
REN	28	17	0	0	0
Impact[35]	Report constraints and find remedial actions when loading >100 %		Report constraints when loading >100 %. If loading is above 120 % for RTE or 115 % for RE, simulate the tripping, and if the cascading effect has consequences on the area of interest, find remedial actions.		

Table 5-2: Number of elements included in interest and observability lists in the scope of SA and regional OPC services

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[35] Impact with regards to considering these elements in OPC and SA task

5.2 RCC Tasks Relevant to the Investigation

For this investigation, this report will focus on the tasks relevant to the specific hour of the event, which occurred on 28 April 2025 at around 12:33. These tasks are listed in Table 5-3 and further detailed in Sections 5.2.1 through 5.2.6. In all processes, no issues were forecasted in the SWE region concerned. A schematic of the time horizons for the relevant RCC tasks is shown in Figure 5-1.

Task	RCC	Area	Time frame	Result	References to the chapters in this document
OPC	SeleneCC (SCC)	Europe	Week-Ahead 25.04.2025 13:00	OK	
	Coreso	SWE (Regional)	Week-Ahead 25.04.2025 11:30		
STA	Nordic RCC (SCC)	Europe	Week-Ahead (27.04.2025 09:50)	OK	
CGM	Coreso, SCC	Europe, CGMES format	D-2, D-1, N/A	NOT OK, No Impact	5.2.3.1
	TSCNET, Baltic RCC	Europe, CGMES format	Intraday 28.04.2025 07:51 (Baltic) 11:12 (TSCNET)	OK	
	Coreso	SWE, CGMES format	D-2, D-1 (26.04.2025 18:30, 27.04.2025 18:00)	OK	
	Coreso	Continental Europe, UCTE DEF	D-1, ID (27.04.2025 18:30, 28.04.2025 03:30)	OK	
CCC	Coreso	SWE (regional)	D-2, D-1 (27.04.2025 08:00, 27.04.2025 22:00)	NOT OK, No impact	5.2.4
CSA	Coreso	SWE (regional)	D-1 (27.04.2025 23:00)	OK	
E&R	Coreso	SWE region	Every five years, completed in October 2024	OK	
Crisis Scenarios	Coreso	SWE region	Every four years, completed in September 2024	OK	
RIAR	ALL RCCs	Europe	Upon demand	N/A	

Table 5-3: Overview of the status from RCC tasks (according to the rotational calendar[36])

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[36] The common grid model (CGM) (common grid model exchange specification (CGMES) format), OPC, and short-term adequacy (STA) tasks are carried out at the pan-European (PE) level, with RCCs executing them in rotation according to a pre-agreed calendar that designates a main and backup RCC for security purposes. OPC and STA tasks are executed using a centralised PE tool, whereas for CGMES format CGMs, each RCC deploys its individual European merging function (EMF) tool.

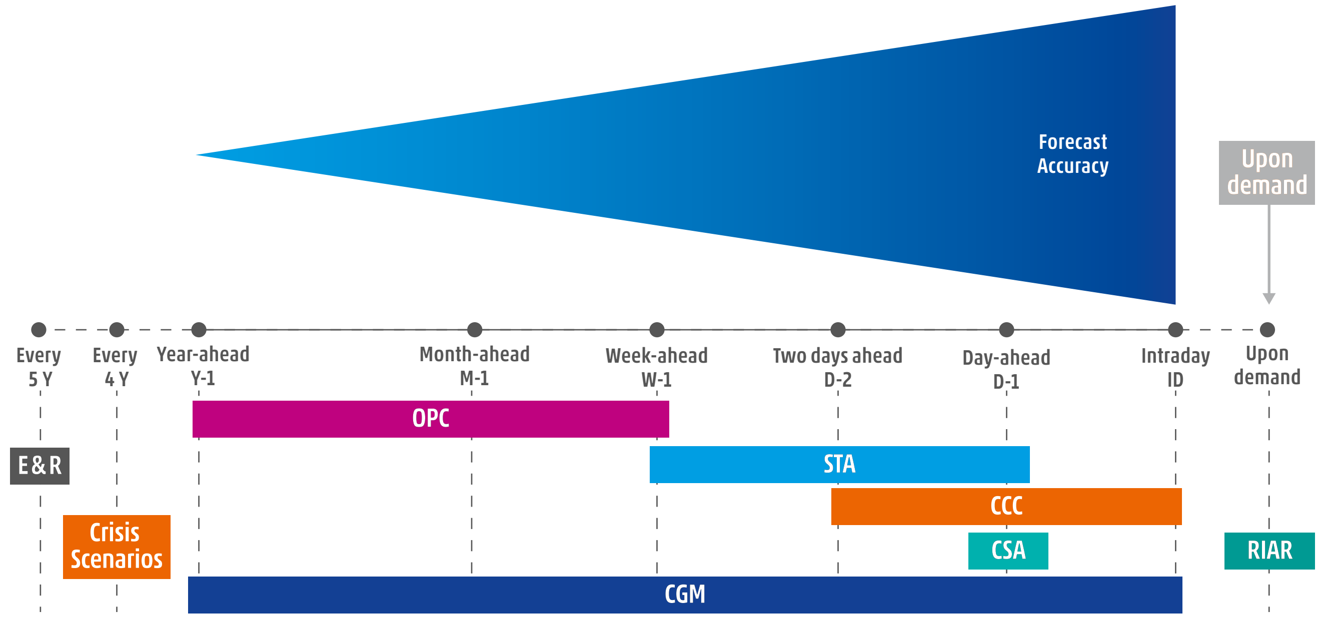

Figure 5-1: Relevant RCC tasks and their time horizons

5.2.1 Outage Planning Coordination

The OPC process is designed to support the planning of grid element outages while ensuring the operational security of the interconnected European power system. This is achieved through procedures carried out at both the pan-European (PE) and regional levels.

Building on the PE OPC process, RCCs also conduct regional OPC processes, commonly referred to as regional outage planning incompatibility (OPI) assessments. These aim to evaluate whether the outage plans of European TSOs are feasible from a grid security perspective. If potential congestions are identified, the process involves proposing RAs, verifying the feasibility of the coordinated unavailability plan with respect to security limits, and issuing recommendations to address any detected incompatibilities in outage planning.

5.2.1.1 Pan-European OPC Process

The PE OPC tool supports the coordination of outages by enabling the exchange of unavailability asset plans (UAPs) and maintaining a database of relevant assets. Relevant assets are grid elements that TSOs deem critical for regional coordination. A standardised procedure ensures data quality and consistency through the validation of planned statuses for cross-border lines managed by TSOs. All RCCs carry out the PE OPC process on a rotational basis. During the week of this incident, the RCC acting as merge operator was SEleNe CC.

The W-1 OPC cycle covers Saturday to Friday, with TSOs required to submit preliminary disconnection plans by Wednesday at 12:00. After a series of validations and merges (first at 12:00, second at 16:00), RCCs perform security assessments. TSOs can adjust plans and request further analysis until Thursday at 16:00 (third merge). Final plans are reviewed in the weekly operational teleconference (WOPT) on Fridays at 10:25 for the Core, Italy North (IN), and SWE regions, moderated by TSCNET. Final changes must be submitted by Friday at 13:00 (fourth merge), which defines the official plan. Outages submitted after that are deemed unplanned. RCCs use common grid models (CGMs) to evaluate outage impacts and propose RAs or cancellations if operational security limits are at risk.

The W-1 merges for BW18, which includes business day 28 April 2025, were performed successfully as follows:

» First Merge:	23.04.2025 12:00
» Second Merge:	23.04.2025 16:00
» Third Merge:	24.04.2025 16:00
» Fourth Merge:	25.04.2025 13:00

The latest UAP updates were submitted by RE, REN, and RTE on 25 April 2025 after the fourth merge was performed. Remaining tie-line inconsistencies (TLIs) were not related to the event, as outage inconsistencies were due to end after 28 April. The list of the outages declared in the PE OPC tool as relevant to the SWE region is presented in Table 5-4.

The PE OPC tool currently considers only transmission assets in UAPs and not generation and demand assets. TSOs do not own these assets and cannot submit outage details for them. Further refinement of the PE OPC tool would be required to process such assets.

TSO	Voltage level	Name	OPC	From	To	RT
ES	220	Badalona–Guixeres 1	OUT	LT (Long Term)		OUT
ES	220	Itxaso–Orcoyen 2	OUT	21.04.2025	02.05.2025	OUT
ES	400	Puentes G.R.–Xove	OUT	21.04.2025	15.05.2025	OUT[37]
ES/FR	220	Biescas–Pragnères	OUT	22.04.2025	02.05.2025	OUT
ES/PT	400	Brovales–Alqueva	OUT	24.04.2025	30.04.2025	OUT
ES	400	Almaraz CN–Morata 2	OUT	28.04.2025	28.04.2025	IN
FR	400	Braud–Cubnezais 4	OUT	28.04.2025	05.05.2025	OUT
PT	400	Fernao Ferro–Ribatejo	OUT	07.03.2025	11.07.2025	OUT
PT	220	Chafariz–Vila Cha 1/Ramal Gouveia	OUT	28.04.2025	28.04.2025	OUT

Table 5-4: Outage list relevant for the SWE region (Source: PE OPC UAP)

5.2.1.2 Regional Outage Planning Incompatibility (OPI) Assessment for SWE

As explained in Section 5.2.1.1, the PE OPC process merges individual UAPs four times. Once the second merge UAP is available, regional OPI assessment starts at Coreso for all relevant regions.

The main steps performed by the OPC operator at Coreso include:

- Building the single OPC scenario to be analysed in detail for all regions. This is based on two main factors: the level of exchanges from reference cases provided by TSCNET and the volume of simultaneous relevant planned outages from TSOs. The operator selects a time stamp (TS) that reflects the most critical scenario – typically with the highest exchanges and most outages.
- Identifying any outage planning security constraints (OPSC) or OPIs at the regional level by running an SA using a contingency list supplied by TSOs (the same list used in SA DA SWE).
- Proposing solutions to TSOs when constraints are found, prioritising non-costly RAs (e.g. Phase Shifting Transformer (PST) tap changes or outage rescheduling). Costly measures like generation redispatch or commercial exchange adjustments are considered only when necessary. The key distinction is that OPIs may involve costly measures and could even result in the cancellation of planned outages by the respective TSO.
- Sharing results during the WOPT and coordinating with other RCCs/TSOs when issues affect multiple regions, ensuring transparency and third-party awareness.
- Publishing regional OPSC/OPI reports for each region. These reports summarise the analysed outages, cross-border physical flows, contingency outcomes, and proposed solutions. They are also shared internally to support upcoming Capacity Calculation (CC) and SA processes, especially for tracking postponed outages or agreed RAs.

The W-1 process is repeated weekly and remains flexible to accommodate last-minute changes, including urgent outage notifications requiring ad hoc analysis.

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[37] The line feeds an industrial consumer that was forecasted to demand 0 MW across all time frames (W-1, D-2, and D-1), so the line was in service with 0 MW flow at all times. However, according to RE, in real time, the line carried 70 MW but was not reflected in RTSN due to an issue in SCADA.

Focus on Business Day 28 April, TS 12:30

The W-1 regional OPI assessment for Week 18 was carried out on Thursday and Friday, 24–25 April 2025. Results were distributed to all participating TSOs immediately after completion.

For week 18, the RCC identified Monday BD 28/04 at TS 12:30 as the single (most critical, see bullet point 1 in the list above) scenario for the CORE, IN and SWE regions. This was based on the level of exchanges (considering those of BD 21/04, TS 18:30) and the amount of relevant planned outages across all 3 regions. All important parameters were within limits in the assessment.

The exchanges in the SWE region used during the regional OPI assessment process are displayed in Table 5-5, including details on the actual physical cross-border flows in real time for comparison purposes.

	OPC: commercial schedules (MW)	Real-Time physical flows (MW)
FR → ES	2,271	–960
ES → PT	1,243	2,453

Table 5-5: Commercial exchanges in the SWE region in the grid model used during the OPC regional process. Real-time physical cross-border flows are displayed for comparison purposes (Source: RTSN, BD 28/04 at TS 12:30)

The location of relevant outages is illustrated in Figure 5-2.

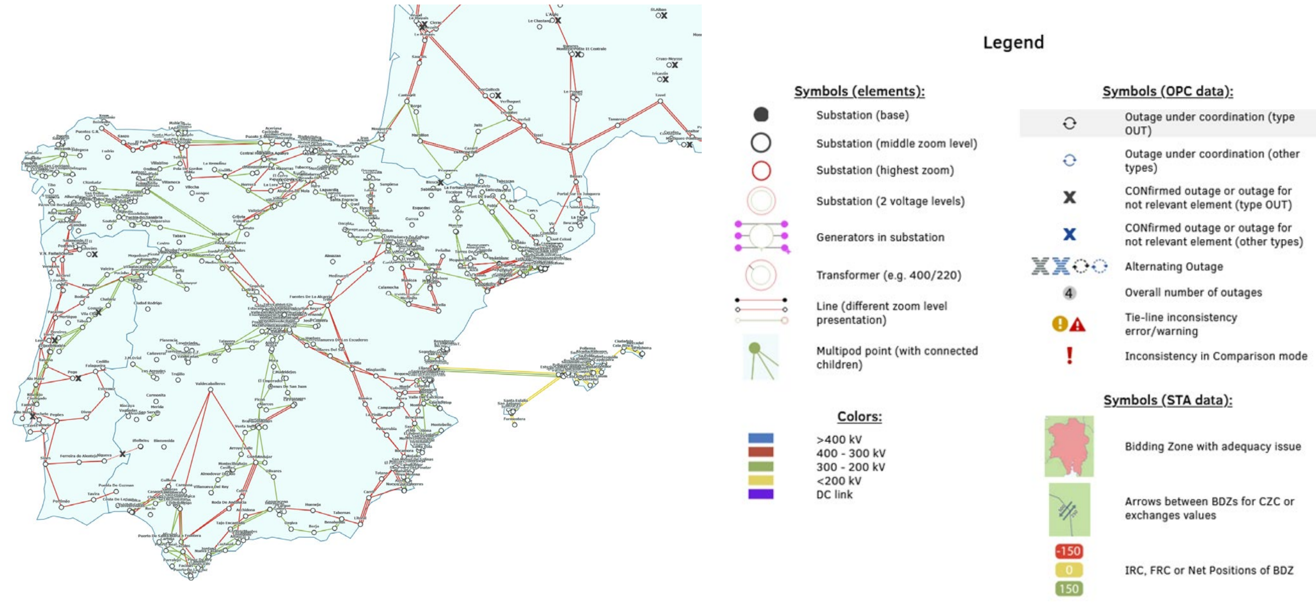


Figure 5-2: Visualisation of planned outages in the SWE region for BD 28/04 (Source: PE OPC tool)

The W-1 regional OPI SA revealed no major violations arising from the planned outages requiring costly RAs; thus, the OPC report for the SWE region recorded no OPIs. The only OPSC detected is displayed in Table 5-6.

TSO	Contingency			Constraint				Remaining after RA
	U (kV)	Substation 1	Substation 2	U (kV)	Substation 1	Substation 2	Overload	
RTE/RE	400	Hernani	Argia	220	Arkale	Argia	172 %	96 %
	Remedial action: 220 kV PST Arkale (Tap change): 17 → 9							

Table 5-6: OPSC detected during the regional OPC process for the SWE region

5.2.2 Short-Term Adequacy

The short-term adequacy (STA) service investigates whether the reliable available expected production capacity can meet the expected consumption using both upward and downward regulations. The calculation takes place daily, with a time horizon of D-7 to D-1 for the process. Although this incident was not related to any adequacy issues, a summary of the STA data and results is provided in the following sections.

All SWE TSOs (RTE, RE, and REN) and RCCs participate in the PE (also known as cross-regional) STA process. For the daily process, all TSOs are required to submit input data for the calculations. The process is then executed automatically and monitored by the main or backup RCC.

The regional STA process can also be triggered if the results of the deterministic calculation indicate inadequacy, for a time horizon of D-3 or shorter. This is a situation that rarely occurs. Nordic RCC was the main adequacy assessment agent (AAA) for the PE process in the week when the incident happened. No regional process was triggered in the days preceding the incident, and the focus of the analysis will be the process of the previous day. The process did not detect any adequacy issues for the day of the incident.

5.2.2.1 Input data

The input data (net transfer capacity (NTC) files, W-1 generation, and W-1 load files) relevant for all affected and neighbouring TSOs were received before the STA calculations were performed on 27 April 2025 (the day before the incident). These files successfully passed validation and were used in the calculation.

It is worth mentioning that the first file uploaded by RE for the W-1 generation was rejected, as it lacked information on installed generation for biomass, oil, pumped storage, water reservoir, other renewable, and waste. The reason was related to a time series for a specific type of generation. The files sent subsequently passed validation, resulting in no issues with the process.

To verify the quality of some of the input data provided by the affected TSOs, the STA input data was compared to the realised values obtained from the ENTSO-E Transparency platform. The quality of two data groups was assessed: forecast solar and wind generation.

The comparison results for the affected regions are presented in Figure 5-3. The yellow area represents the forecasted probability range, where:

- the lower bound corresponds to the P05 value (5 % probability the real value will be below this threshold)
- the higher bound corresponds to the P95 value (95 % probability the actual value will be below this threshold),
- The centre line corresponds to the P50 (median forecast; 50 % probability of being above or below)

The forecasted values were used as input for the PE STA tool and formed the basis for the STA calculations. The observed values (blue line) are based on data retrieved from the ENTSO-E Transparency platform and represent average power values for each corresponding hour. Due to Portugal's data being reported on an hourly basis, the final data point shown at 12:30 reflects the average for 12:00 – 13:00, which includes the time frame during which the blackout occurred.

In general, the forecasted values for solar generation display narrow confidence ranges, indicating high certainty in unverified predictions. In contrast, the wind generation forecasts for Spain and France show broader confidence intervals, suggesting greater uncertainty. Across all TSOs and both forecast types, there is a discrepancy between observed values and forecasted ranges. Specifically for solar generation in Spain, there appears to be a consistent one-hour time lag between the forecasted and actual values. The influence of data quality on the process outcomes shall be explored further in the final report for this incident. However, it is important to clarify that the real-time incident is not associated with adequacy.

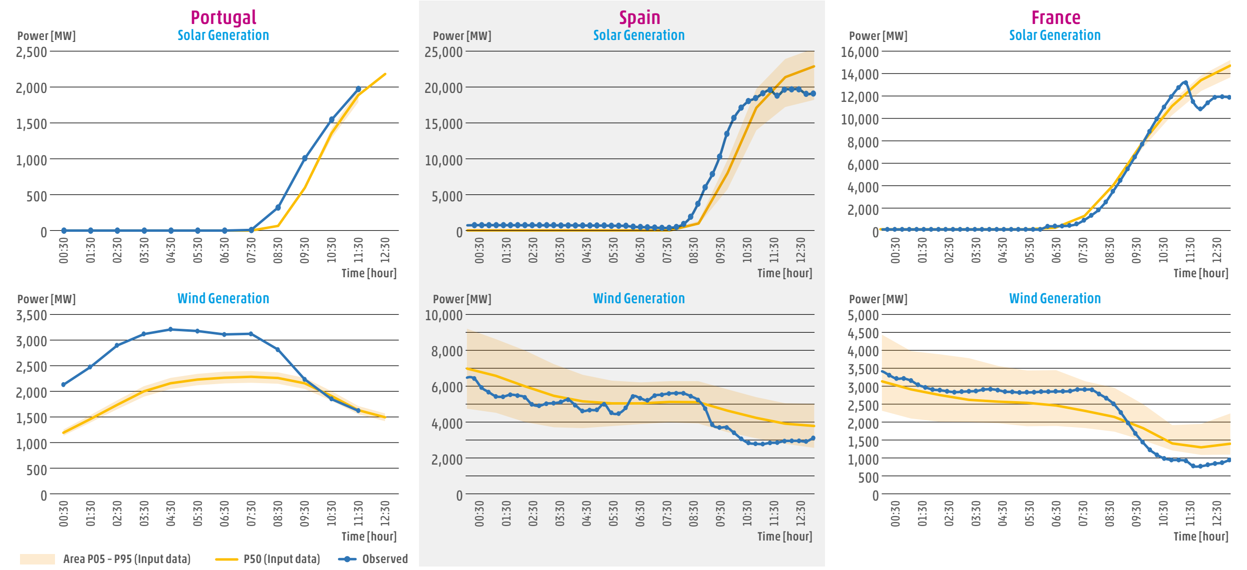


Figure 5-3: Graphs comparing forecasted input data of STA with observed values (average hourly values for Portugal), according to the ENTSO-E Transparency platform, for solar and wind generation in the affected regions (PT-ES-FR)

5.2.2.2 Calculation Results

STA calculations were completed within the standard time frame typical for the daily STA process. The automatic deterministic and probabilistic calculations were triggered at 09:00, finishing at 09:05 and 09:20, respectively.

The entire STA process was completed successfully, with no system failures or issues reported through the STA tool's ticketing system. The deterministic results for the period did not reveal any adequacy issues in affected and neighbouring TSOs after the STA calculation. Final exchanges between affected TSOs and remaining capacities (RCs) after the calculation are presented in Figure 5-4. As part of the daily procedures, the Nordic RCC operator on duty reviewed the deterministic results and emailed the rest of the RCCs along with the TSOs facing adequacy issues. RE, REN, and RTE were not among the countries identified as having adequacy concerns.

Regarding the probabilistic calculations from the PE tool, no inadequacy was identified for the SWE region during the relevant time frame.

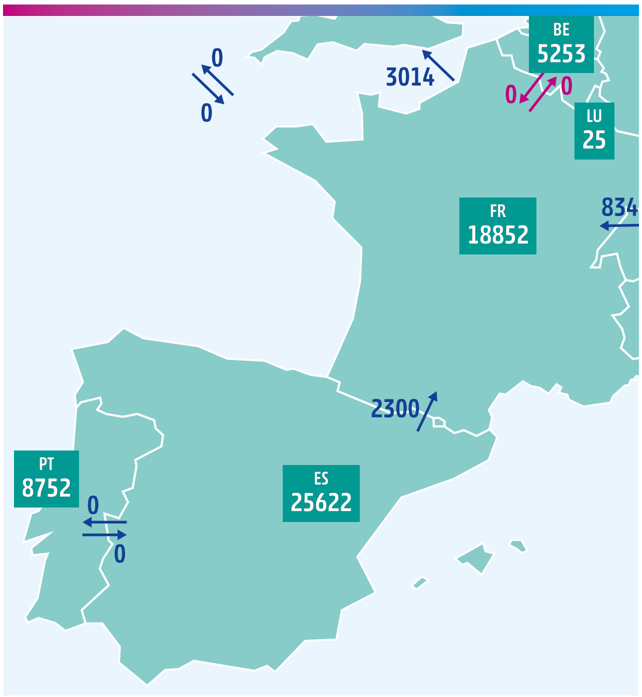


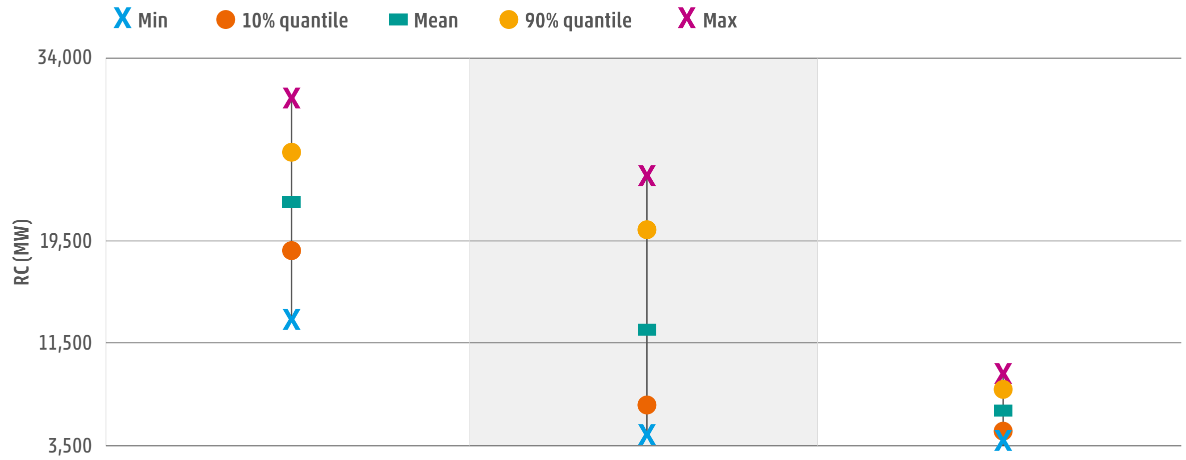
Figure 5-4: Final exchanges and remaining capacities in SWE 28/04/25 @ 12:30

It is worth noting that, based on the input data received, the STA calculations showed a scenario with cross-border power flows between PT and ES and ES and FR that did not align with the real-time conditions. This will be investigated further in the final report.

	STA prevision (MW)	Real-time physical flows (MW)
FR→ES	2, 200	-960
ES→PT	0	2,453

Table 5-7: Benchmarking between forecast and real time flows

Nevertheless, the results for all the SWE TSOs showed considerably high RCs, as shown in Figure 5-5. RC represents each TSO's ability to meet its load using the available generation. These results indicate no adequacy issues and no reliance on imports from neighbouring areas.



	ES	FR	PT
X **Min**	11,583	4,387	4,068
● **Q10**	17,856	6,542	4,431
▬ **Mean**	22,377	12,347	6,238
● **Q90**	26,678	20,382	8,327
X **Max**	30,559	24,873	9,431

Figure 5-5: Remaining capacity statistic – final state per BDZ in SWE for the period 28/04/25 to 03/05/25

A recently developed feature in the STA process allows the assessment of potential curtailment at the bidding zone level. This assessment is optional for TSOs, and only some currently use it. This analysis depends on input data classified as inflexible generation – generation that must run. The calculations then assess whether curtailment might be needed and identify any surplus inflexible generation that cannot be consumed, while also considering the capacity to export this excess.

Among the SWE TSOs, only RE does not provide data compatible with this feature. For RTE, the results indicated no need for curtailment, as the inflexible generation remained below the expected load. In the case of REN, the tool encountered a calculation error, so no meaningful results were available.

5.2.3 Common Grid Model

As outlined in Table 5-1, the creation of CGMs is a responsibility assigned to RCCs under EU Regulation 2019/943, Article 37(d). This task must be carried out in accordance with the methodologies and procedures established under the System Operation Guidelines (SO GL), developed pursuant to Regulation (EC) No 714/2009, as well as capacity allocation and congestion management (CACM) and forward capacity allocation (FCA). CGMs serve as the foundation for regional and PE processes such as coordinated security analysis (CSA), OPC, and coordinated capacity calculation (CCC), and are produced by merging the individual grid models (IGMs) provided by TSOs.

An IGM is a detailed model of a TSO's control area, containing information on network topology, load, generation, and relevant operational data. Each TSO is responsible for creating and maintaining its own IGM using a standardised format to ensure compatibility with other TSOs' models. Currently used standards include the Union for the Co-ordination of Transmission of Electricity data exchange format (UCTE DEF) and common grid model exchange standard (CGMES). UCTE DEF is a legacy standard created by UCTE, which was the predecessor organisation to ENTSO-E, while CGMES is an International Electrotechnical Commission (IEC) technical specification based on the IEC CIM (Common Information Model) family of standards.

In sum, a CGM is a consolidated network model produced by merging multiple IGMs from different TSOs. This provides a representation of a larger, interconnected portion of the power system, which is then utilised for system-wide processes. The CGM merging processes for different time horizons and regions are described in the following subsections.

5.2.3.1 Pan-European CGM

The PE CGM is created by merging the IGMs of European TSOs while considering reference data programs (Pan European Verification Function (PEVF) or Common Grid Model Alignment (CGMA) files) and boundary sets (BDSs). It is created for four different time horizons (ID, D-1, D-2, and year-ahead (YA)).

In accordance with System Operation Committee (SOC) Decision Number 11 dated 4 December 2019, the CGM is developed based on a rotational principle. Under this approach, CGM creation responsibilities are divided into groups based on time frames: Group 1 handles the DA and two-day-ahead (D-2) time frames, Group 2 is responsible for the ID time frame, and Group 3 manages the YA time frame. Each group operates with two roles: main and backup.

At any given time, one RCC assumes one role within a specific group and carries out the CGM creation accordingly. The rotation among RCCs occurs every four weeks – except for the YA time frame, which rotates annually following a predefined schedule. The use of both main and backup roles ensures redundancy, as two RCCs work in parallel on the same time frame, ensuring that at least one CGM will always be available even when the main RCC is facing issues.

The CGMES merging process is still facing challenges, primarily related to the required quality and complexity of input data. As such, convergence issues are often encountered, and certain CGMs are not published. During the development phase, a tactic to identify problematic input files entailed excluding them, allowing the quality assessment of the process with the remaining files. To comply with the CGM methodology, RCCs jointly decided to discontinue this practice in the production environments as of Q3 2024. Discontinuing this pre-emptive exclusion practice resulted in low publication rates for CGMES CGMs. However, the published CGMs were considering all input data and European merging function (EMF) requirements.

According to the Common Grid Model Methodology (CGMM) and following the adopted timings in the CGM building process (implemented on 21 April 2025), the day-ahead congestion forecast (DACF) CGMES process begins at 18:00 – by which time all IGMs should be submitted – and concludes by 18:30, when validated CGMs for the relevant scenario become available via Operational Planning Data Environment (OPDE). Similarly, the D-2 Congestion Forecast; DA (D2CF) CGMES process starts at 19:50 and ends at 20:10, with validated CGMs also made available through OPDE. For both processes, according to the rotation calendar, Coreso acted as the main RCC responsible for the merging, while SCC served as the backup RCC.

The Intraday Congestion Forecast (IDCF) process operates on an hourly basis, with validated CGMs released every hour via OPDE. TSCNET served as the main RCC for the IDCF CGMES process, and Baltic RCC acted as the backup.

For the 28 April 2025 business day, all three SWE TSOs submitted valid D-2 and D-1 IGMs on time. However, 11 TSOs from other regions did not provide D-2 IGMs, and five TSOs did not provide D-1 IGMs. Coreso's D-1 merge was successful for eight out of 24 TSs, while the remaining 16, including the 12:30 TS, were non-convergent. The backup D-1 model from SCC for 12:30 was also non-convergent. For the D-2 process, neither Coreso's nor SCC's models converged for any TS.

For the ID merge, RTE and RE delivered three packages of eight IGMs, while REN delivered twice 24 IGMs and once 12 IGMs. The transition to more frequent ID models is pending. Seven other TSOs did not deliver any valid ID IGMs for this business day. TSCNET, as the main merge operator, performed hourly merges for the business day, which were all non-convergent. In the 11:12 merge, the last merge before the incident occurred, the IGMs from all but two TSOs were older than one hour. The Baltic RCC, as the backup merge operator, was able to create a convergent model at 07:51 by substituting models based on additional validation rules, which still needed to be aligned on a European level. This was the latest convergent PE CGMES CGM before the incident.

Overall, the PE CGMES merging process is still undergoing improvements, and the resulting models were of limited use. Since all regional and cross-regional assessments are still either based on the legacy UCTE DEF merge or a regional CGMES merge, this did not directly impact the incident. All security assessments could be performed using other models. The missing input data from other regions had no relevant impact on SWE.

In conclusion, while there were no available D-1 and D-2 CGMs in CGMES format for the time of the incident, this would not have made a difference unless they had been used for SA and OPC purposes. The same applies to the CGMES format ID CGM, which was available but outdated, having been produced hours before the incident.

5.2.3.2 Regional CGMES CGM

In addition to the PE CGMs, Coreso carries out a regional merge of the D-2 and D-1 CGMES IGMs from REN, RE, and RTE on a daily basis, producing CGMs that are mandatory inputs for the DA and ID capacity calculations, respectively. These CGMs are produced each evening for six TSs (02:30, 05:30, 09:30, 12:30, 15:30, and 19:30) and are shared with the TSOs as part of the process outputs. The latest regional SWE CGMES merge was completed before 19:30 on Sunday. All required input data was valid and delivered on time. The merge and load flow simulations were successfully executed for both time horizons.

5.2.3.3 Continental Europe UCTE CGM

The **UCTE DEF** is a legacy standard previously used for data exchange in various processes. One major difference between the UCTE DEF and the CGMES-based PE CGM implementation lies in the modelling approach: in UCTE DEF, models are built for all of continental Europe, with each RCC additionally generating CGMs for their specific regions. For example, for the DACF, Coreso produces a DA CGM for the SWE region (including applied model improvements), while Selene CC creates CGMs for Southeast Europe. In this way, each RCC is responsible for developing CGMs tailored to its specific region.

The process of submitting and merging these individual models includes data validation. Detected issues are categorised by severity, which impacts the data's suitability for analysis:

- **Informational:** Indicates minor data conditions or deviations that do not prevent the use of the model.
- **Warning:** Signifies data inconsistencies or potential inaccuracies. Models with warnings may be used, but the associated data should be treated with caution.
- **Fatal Error:** Denotes a data issue that makes the model unusable for its intended purpose. Processing is typically halted until the error is rectified.

Currently, UCTE CGMs are merged by synchronous area; for example, the UCTE CGM containing Spain, Portugal, and France does not include Nordic or Baltic countries. This subsection presents the availability, validation of the affected TSO IGMs, and the merge for the continental Europe UCTE CGM.

Since IGMs serve as the starting point, the delivery of IGMs across different time horizons is shown in Table 4-7. Each process has a different expected frequency of IGM creation: for D-1 and real-time snapshot (RTSN), one IGM per TS is expected, whereas for ID, delivery can occur hourly before real time. For example, after 12:30, new ID IGMs for 12:30 are not expected.

As shown in Table 5-7, most IGMs were valid, indicating that no fatal errors were present. The missing values occur because REN does not provide ID or RTSN IGMs, and RE does not provide RTSN IGMs, as the provision of RTSN files is not mandatory. From the valid IGMs, both informational and warning messages are included. The only invalid IGM was submitted by RE for the ID time horizon one hour before real time; the model for TS 12:30 was generated at 11:16, which was the last ID IGM submitted for TS 12:30, as RE does not provide IGMs hourly. Regarding RTSN, both REN and RE provided RTSN models generated on demand for the incident investigation.

TSO	D-1	ID	RTSN
REN	1/1	–	–
RE	1/1	4/5	–
RTE	1/1	19/19	1/1

Table 5-8: Delivery of valid IGMs for the D-1, ID, and RT time horizons for business day 28.04.2025, TS 12:30 during the processes

convergence in RE's legacy power system analysis tool and, consequently, in the UCTE IGM model either. Due to a malfunction in the RE tool responsible for modelling the status of reactors, high voltage shifts were provided (e.g. a 400 kV busbar operating at 280 kV). Therefore, UCTE IGM load flow results are no longer valid for operational SA. Similar problems were observed on three separate days in the month: on 4 April (one ID IGM), 14 April (two ID IGMs), and 28 April (five ID IGMs). On 28 April, out of the five affected models, four corresponded to the 10:30 TS and one to the 12:30 TS.

Concerning the CGMs, the DA IGMs are utilised for the DACF process. Coreso is the RCC performing the SA for the SWE region, which is further described in Section 5.2.5. During the DACF process, four CGMs were created, at 18:00, 18:27, 19:57, and 20:10.

CGMs were created based on all the provided ID IGMs. All CGMs created that day for the TS 12:30 were convergent. Invalid IGMs were excluded, and the latest provided IGM was used instead – for example, for the last ID CGM[38] reated at 12:15, the ES IGM generated at 10:16 was utilised.

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[38] According to TSCNET merging.

5.2.4 Coordinated Capacity Calculation

The capacity calculation process described in this section refers to the regulated task that follows the CACM Guideline EU 1222/2015. As explained in Section 5.1.3, the SWE region has some specificities that define how cross-border capacities are calculated. Coreso performs the NTC-based capacity calculation using a coordinated methodology developed by SWE TSOs (REN, RE, and RTE), approved by ACER and the NRAs. This task is currently performed for the following time frames:

- CCC Long Term (LT) SWE: Currently performed on the TSO side. Under development at Coreso.
- CCC DA SWE: Performed two days ahead, calculates total transfer capacities (TTC) for six TSs for the DA market.
- CCC ID SWE: Two different runs apply:
  - First run: Performed one day ahead; calculates TTC for six TSs for ID market.
  - Second run: Performed on the same day; calculates TTC for three TSs in the afternoon for the remaining ID market gates. Currently in parallel run, therefore results are not being sent to the market and thus not applicable.

Additional Contraints (CRACs), all in CGMES format), Coreso calculates TTC for a limited number of TS (02:30, 05:30, 09:30, 12:30, 15:30, and 19:30) and for each border and direction independently. The calculated TTCs are sent as a proposal to the TSOs, which validate the proposal and allocate capacities for the 24-hour period by extrapolation. Coreso then processes the TSOs' feedback to determine the final TTC for each border and direction. To calculate the final output sent to markets, NTC, the following formula and parameters are applied:

- NTC = TTC – transmission reliability margin (TRM)
- TRM is 7.5 % of TTC for the Spain–France border, with a minimum of 200 MW.
- TRM is 10 % of TTC for the Portugal–Spain border, with a minimum of 100 MW.

The calculated TTC values are compared with the parameters above. In cases where fallbacks are applied, it might result in the following:

- If CCC DA SWE cannot compute TTC, or if TTC < TRM: LT TTC values are applied
- If CCC ID SWE cannot compute TTC, or if TTC < TRM: DA TTC values are applied

introduction of a new tool for the CCC DA process, replacing the previous technology. The former tool is maintained as a backup and is used when the main tool fails to publish all the required results.

In contrast, for the CCC ID process, the new tool was launched in March 2025. Unlike the DA process, no backup tool is currently in place for ID.

Focus on Business Day 28 April, TS 12:30

Table 5-9 below provides an overview of the proposed capacities for the market directions observed on 28 April.

Process	Direction	Calculated TTC (MW)	CNEC	Proposed TTC (MW) and reason
CCC DA	ES → FR	0	N-1 Braud–Preguillac 1 led to divergence	2,500 (LT TTC values applied)
CCC DA	ES → PT	3,900	N-2 Alto Lindoso–Cartelle 400 kV overloads Aldeadávila–Lagoaça 1 400 kV	3,900
CCC ID	ES → FR	100	N-1 Braud–Preguillac 1 overloads Braud–Preguillac 2	2,500 (D2 TTC values applied due to TTC < TRM)
CCC ID	ES → PT	4,050	N-2 Alto Lindoso–Cartelle 400 kV overloads Aldeadávila–Lagoaça 1 400 kV	4,050

Table 5-9: Overview of proposed TTC (MW) per process and direction. Only the real-time market directions are depicted; all calculated capacities refer to the dedicated subchapters 5.2.4.2. and 5.2.4.3.

5.2.4.1 Long-term Capacity Calculation

The LT capacity calculation process for yearly, quarterly, and monthly time frames is currently being developed. The go-live of this process is expected in Q1 2026 (at the time of reporting).

Until then, the LT values used as backup for the CCC DA SWE process are inputs received from RE based on a bilateral monthly process among SWE TSOs (RE and REN for the ES–PT border, RE and RTE for the ES–FR border). Table 5-10 shows the provided values by RE for this business day for 12:30.

ES → FR	2,300 MW
ES → PT	3,500 MW
FR → ES	2,400 MW
PT → ES	2,200 MW

Table 5-10: Long-term NTC values provided for 28/04 TS 12:30 (Source: RE)

5.2.4.2 Day-ahead Capacity Calculation

The DA capacity calculation for business day 28 April was performed on the evening of 26 April and concluded on 27 April at 08:00 with the validation from TSOs. The results are presented in Table 5-10.

	TTC (MW)	Contingency	CNE (Limiting element)
PT → ES	3,785	N-2 Alto Lindoso–Cartelle 400 kV	Angle constraint
ES → PT	3,900	N-2 Alto Lindoso–Cartelle 400 kV	Aldeadávila–Lagoaça 1,400 kV
FR → ES	2,500	N-1 Argia–Arkale 1,220 kV	Argia–Hernani 400 kV
ES → FR	2,500	N-1 Braud–Preguillac 1 led to divergence	LT TTC values applied

Table 5-11: Proposed TTC for TS 12:30 after CCC DA SWE calculation for BD 28/04, with limiting element and reason

Further analysis was conducted to determine the final direction of exchanges observed in real time on 28 April at 12:30. Regarding the ES → FR direction, with 0 MW exchange, there was a violation in the model after N-1 Braud–Preguillac 1. Therefore, no TTC was computed with either tool (live or backup), and the LT TTC value (2,500 MW) was applied for this direction and TS. During the validation phase, TSOs did not decrease the proposed value, so it was confirmed as the final TTC value.

Regarding the ES → PT direction, the limiting element is Aldeadávila–Lagoaça 1 400 kV after N-2 Alto Lindoso–Cartelle 400 kV, resulting in a TTC value of 3,900 MW. During the validation phase, TSOs did not decrease the proposed value, so it was confirmed as the final TTC value.

Focusing on the capacities provided in the directions taken by markets in the ID time frame and to provide some context, the final TTC provided during CCC DA SWE were within normal values relative to those provided during 2025 so far, as illustrated in the figures below. In the Spain-to-France direction, the provided 2,500 MW belongs to the 16th percentile (see Figure 5-6), while for the Spain-to-Portugal direction, the provided 3,900 MW belongs to the 22th percentile (see Figure 5-7) of this year's distribution.

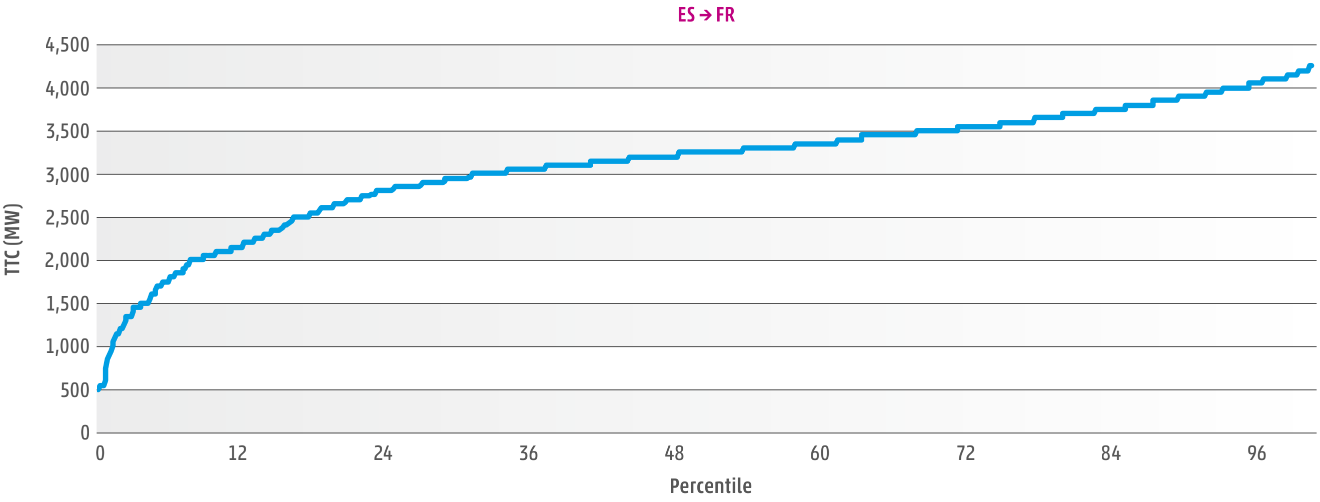

Figure 5-6: Proposed TTC values for the DA process and the ES → FR direction since January 2025, sorted from lowest to highest

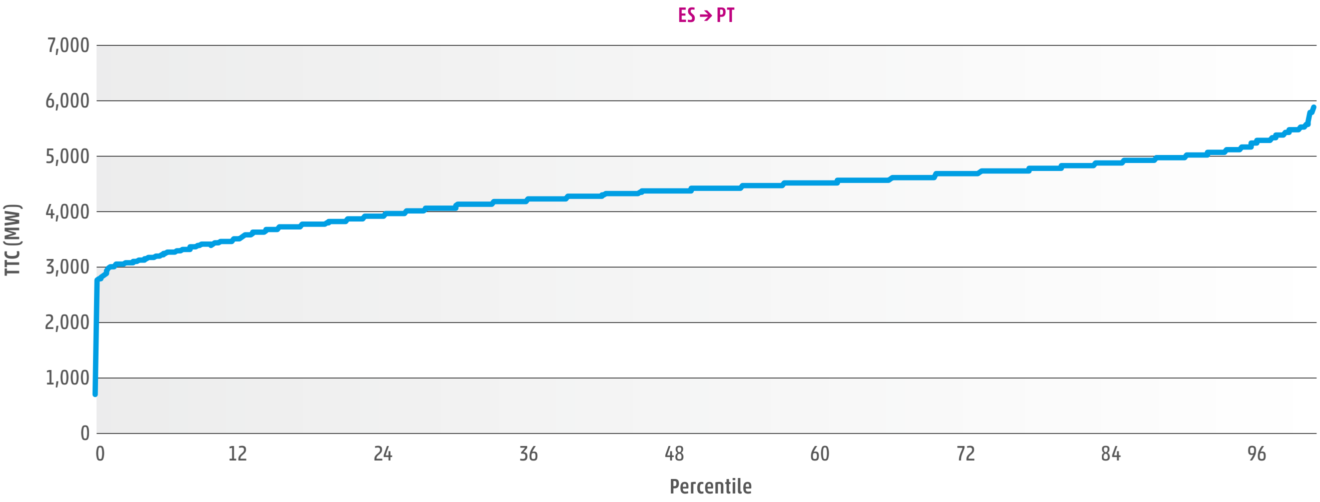

Figure 5-7: Proposed TTC values for the DA process and the ES → PT direction since January 2025, sorted from lowest to highest

5.2.4.3 Intraday Capacity Calculation, First Run

The ID capacity calculation is performed in D-1, so for business day 28 April, the calculation was performed in the evening of 27 April, providing results by 22:00. The results can be observed in Table 5-12.

	TTC (MW)	Contingency	CNE (Limiting element)
PT→ES	3,050	N-2 Alto Lindoso–Cartelle 400 kV	Angle constraint
ES→PT	4,050	N-2 Alto Lindoso–Cartelle 400 kV	Aldeadávila–Lagoaça 1,400 kV
FR→ES	2,600	Base case	Argia–Hernani 400 kV
ES→FR	2,500 (D2 TTC values applied due to TTC < TRM)	Base case divergence	D-2 TTC values applied

Table 5-12: Proposed TTC after CCC ID SWE calculation for BD 28/04, with limiting element and reason.

Regarding the ES→FR direction, the computed TTC was 100 MW (i.e. lower than TRM) due to N-1 Braud–Preguillac 1 overloading Braud–Preguillac 2. Therefore, DA TTC values (2,500 MW) were applied. During the validation phase, TSOs did not decrease the proposed value, so it was confirmed as the final TTC value.

Regarding the ES→PT direction, the limiting element is Aldeadavila–Lagoaça 1 400 kV, considering the N-2 Alto Lindoso–Cartelle 400 kV, resulting in a TTC value of 4,050 MW. During the validation phase, TSOs did not decrease the proposed value, so it was confirmed as the final TTC value.

5.2.5 Coordinated Security Analysis

The implementation of the CSA methodology via the ROSC (regional operational security coordination) process will eventually replace the current SA service; however, it is still under development, with a Q1 2027 expected go-live for the SWE region. SA for the SWE region is conducted by Coreso daily using the DACF grid models in the DA time frame. This analysis is based on coordinated procedures and relies on the continental Europe CGM in UCTE format, as described in Section 5.2.3. On these models, security analyses are run for the whole day, and RAs are proposed by Coreso operators for the worst TS for each constraint, in close coordination with the SWE TSOs. Currently, security analyses in the ID time frame are not operational for the SWE region.

The DA Security Analysis process for the Core, IN, and SWE regions unfolded in a tightly coordinated sequence beginning the day before 16:00 and concluding by midnight

- It started with the delivery of IGMs from the TSOs and the availability of market results, which serve as the foundational inputs for the process. By 18:00, the first version of the CGM (CGM V1) was generated. This version was then refined through several targeted improvements per region. For the SWE region, for example, Coreso adapted the tap position of the PSTs on the FR–ES border depending on N-state loading and TSO operational guidelines to ensure the base case reflected a realistic scenario.
- At 18:15, a second, enhanced version of the CGM (CGM V2) was produced, incorporating these improvements. The process continued at around 18:30 – 18:45 with the launch of the security analysis for all regions and 24 TSs, where the system's robustness was assessed against potential contingencies.

- Once the security analysis results were available, the operator interpreted them and identified the most relevant constraints within the interest and observability area for the SWE region, as detailed in Section 5.1.3. Once selected, the worst-case TS for each constraint was analysed, addressing N-1 violations through the implementation of RAs. The applicability of these proposed actions was then verified through direct communication with the relevant TSO operators. If confirmed, the actions were documented in the report; if not, the Coreso operator sought and proposed alternative solutions.
- By 21:00, Coreso, in collaboration with the TSOs, evaluated and coordinated RAs to address any identified issues. At 21:00, the Daily Operational Planning Teleconference (DOPT) was used to exchange and consolidate relevant cross-border data. The process then moved into the impact and deviation assessment phase at 22:00, which included a specific study for the Central Eastern Europe (CEE) region.
- A combined DACF CGM was built with the CGMs of Coreso and TSCNET that included all the agreed preventive RAs from the study. At 22:30, the proposed RAs were confirmed with the TSOs, ensuring alignment and readiness.
- Finally, before midnight, the comprehensive DA report (summarising the entire SA, including all assessments and confirmed actions) was published, marking the conclusion of the SA DA process.

As mentioned earlier, for the SWE region, no SA ID process is operational on the RCC side; instead, it is performed solely on the TSO side. These are used to reassess the security situation with updated inputs, thus enabling more accurate results and solutions. Coreso provides SA ID services for the Core and IN regions and supports TSOs from these regions in the close-to-real-time time frame as part of continuous monitoring and when requested. However, these services are not provided for the SWE region, as IDCF and RTSN are not available. The potential impact of these services in the scope of the event of business day 28 April will be addressed in the final report.

5.2.5.1 Conclusion for Business Day 28 April, TS 12:30

For the 12:30 TS on 28 April, the DA CGM used was the last one created around 18:00 on the previous day, following the standard procedure for DA SA activities. The study reveals that TS 12:30 was a non-stressed TS, meaning that no need for RA coordination was forecasted in the DA time frame.

5.2.5.2 Overview of the Study for Business Day 28 April

The study concluded that critical constraints were detected on the France–Spain (FR–ES) border, requiring countertrading of up to 300 MW at 05:30, along with extreme curative tap positions in the Arkale PST to resolve the issue. Additional constraints were identified on the Spain–Portugal (ES–PT) border and within the internal Spanish grid. These were manageable through the usual topological RAs and internal redispatch.

Additional relevant information used during the SA of the DA SWE were the planned outage of 220 kV Biescas–Pragnères (ES–FR) and 400 kV Brovales-Alqueva (PT–ES) tie-lines, and the tight downwards generation margin announced by REN. There was no specific request to study N-2 contingencies, as the weather forecast was favourable.

TSO	Generation margins	Peak load (MW) and time
RE	Sufficient	30,800 at 21:30
REN	Tight–Downward	6,820 at 21:30
RTE	Sufficient	48,800 at 13:00

Table 5-13: Load and generation margin forecast declared by SWE TSOs at the start of the SA DA SWE process

Day-ahead commercial exchanges overview

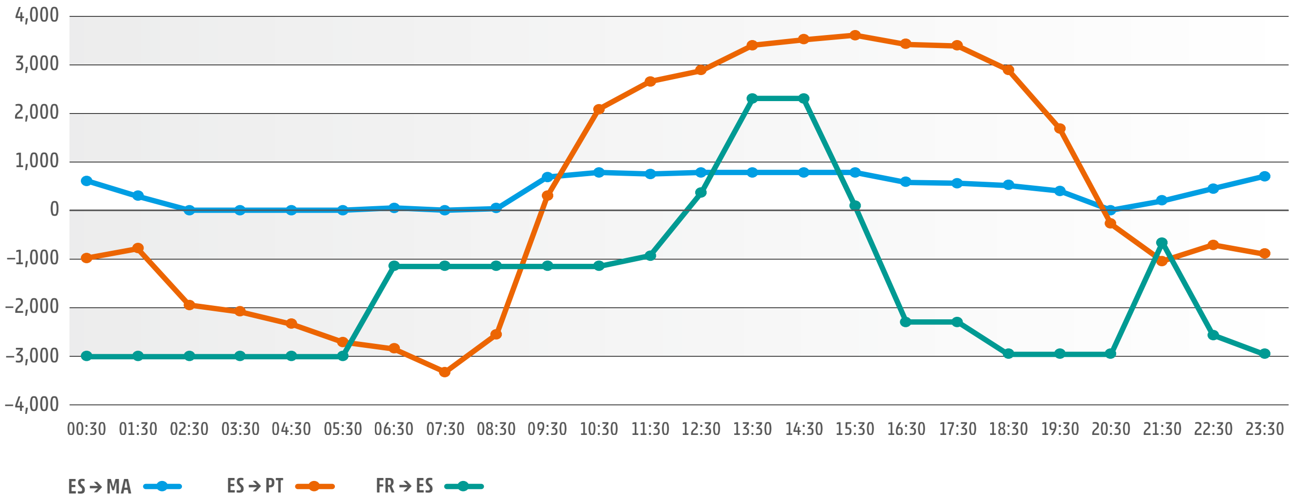

Figure 5-8: Commercial exchanges in the DA time frame for BD 28/04 (MW)

On 28 April, the commercial exchanges in DA showed Spain mostly exporting to France, except around midday, when it briefly imported up to 2,300 MW. Portugal exported to Spain overnight, but flows reversed in the morning, with Spain exporting up to 3,531 MW during the afternoon before Portugal resumed exports in the evening.

Some deviations between DA commercial flows and physical cross-border flows in the DA CGM were foreseen, particularly during the midday hours. On the Portugal–Spain border, key interconnectors such as Cedillo–Falagueira and Puebla de Guzman–Tavira were expected to play a central role in the midday export to Portugal (mostly due to the planned outage of Brovales–Alqueva), while Aldeadavila–Lagoaca and Cartelle–Alto Lindoso were forecasted to handle the bulk of the export flows from Portugal during the night and early morning.

	00:30	01:30	02:30	03:30	04:30	05:30	06:30	07:30	08:30	09:30	10:30	11:30	12:30	13:30	14:30	15:30	16:30	17:30	18:30	19:30	20:30	21:30	22:30	23:30
ARKALE PST [1–33]	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	17	16	17	17	17
	–316	–309	–306	–301	–306	–319	–174	–180	–175	–132	–68	–66	50	220	214	–24	–161	–179	–262	–302	–265	–116	–284	–308
	56.2	54.9	53.8	53.1	54.1	56.6	34.3	34.5	33.6	27.9	20.7	20.4	14.1	37.3	36.5	14.9	30.2	33.6	47.5	54.5	48.9	28.9	52.8	55.7

Figure 5-9: N-state overview for Arkale PST, with details of tap (top row), active power in MW (middle row) and loading in % (bottom row). Positive values of active power mean flow from FR to ES. Yellow cells indicate loading over 50 %.

N-state physical flows

As explained earlier, the SWE region consists of two borders that interact with each other to a lesser degree than in other regions, such as Core. The main consequence is that typically there is a lower difference between commercial and physical flows. Consistent with the previous section, the highest N-state flows observed on the main corridors of the Spain–France border were all in the Spain-to-France direction, either in the early morning or evening (see Table 5-14).

Tie-line	Highest N-state loading	Time stamp	Direction
400 kV Argia–Hernani	1,395 MW (91 %)	20:30	Spain to France
220 kV Argia–Arkale	316 MW (74 %)	05:30	Spain to France
220 kV Biescas–Pragneres	-	-	-
400 kV Baixas–Santa Llogaia 1 & 2	2 x 620 MW (63 %)	18:30	Spain to France
400 kV Baixas–Vic	514 MW (32 %)	18:30	Spain to France

Table 5-14: Highest level of N-state loading on the Spain-France tie-lines, sorted from west to east (note that the 220 kV Biescas–Pragneres tie-line was in planned outage)

on Arkale PST. Since the capacity calculation processes took this planned outage into account, however, the given capacities did not require high tap adaptation to manage flows on Arkale PST, and could be kept at a stable tap position of 17 (neutral tap) except for a brief adjustment to tap 16 at 20:30 (see Figure 5-9).

The Spain–Portugal border has a high level of transfer capacity due to the nine tie-lines in operation. However, their distribution along the border is uneven, with denser meshing in the north than in the south. Table 5-15 presents the highest N-state loading for each tie-line, including the details of the TS and flow direction.

Tie-line	Highest N-state loading	Time stamp	Direction
400 kV Alto Lindoso–Cartelle 1 & 2	2 × 532 MW (35 %)	07:30	Spain to Portugal
400 kV Aldeadávila–Lagoaça	1,374 MW (86 %)	06:30, 07:30	Portugal to Spain
220 kV Aldeadávila–Pocinho 1 & 2	159 MW (39 %)	06:30	Portugal to Spain
220 kV Saucelle–Pocinho	157 MW (45 %)	08:30	Portugal to Spain
400 kV Cedillo–Falagueira	1,087 MW (78 %)	17:30	Spain to Portugal
400 kV Brovales–Alqueva	-	-	-
400 kV Puebla de Guzman–Tavira	673 MW (54 %)	18:30	Spain to Portugal

Table 5-15: Highest level of N-state loading on the Spain-Portugal tie-lines, sorted from north to south (note that the 400 kV Brovales–Alqueva tie-line was in planned outage)

The lower meshing in the southern part of the border means that the planned outage of 400 kV Brovales–Alqueva (located in the south) is quite impactful both for the N-state and N-1 loadings of tie-lines nearby (400 kV Cedillo–Falagueira and 400 kV Puebla de Guzman–Tavira). Additionally, it is worth mentioning the apparent loop in physical flows in the northern part of the Spain–Portugal border during the morning, with some tie-lines exporting while others import. This behaviour is quite common in this part of the border due to the high level of meshing.

Since none of the values in Table 5-14 or Table 5-15 involve hours close to 12:30, the main conclusion is that this period was indeed less constrained in the DA time frame.

SA DA study results

Constraints were detected either in the morning or evening hours, mainly on the FR-ES (Argia–Hernani, Arkale–Hernani, Hernani–Itxaso) and ES-PT borders (Falagueira–Cedillo, Aldeadavila–Lagoaca). They were resolved using 300 MW countertrading (FR↑, ES↓), PST tap changes at Arkale (from 17 to 1 in steps), transformer disconnections at Argia, and internal redispatch by RE (400 MW) and REN (800 MW).

Coreso proposed that RAs bring all N-1 loadings below the 100 % threshold. For each of the detected contingency constraints for business day 28 April, the following figures show an overview of the N-1 loading for all 24 TSs, while the tables show the proposed solution for the worst TS.

N-1 400 kV Argia–Hernani on 220 kV Argia–Arkale

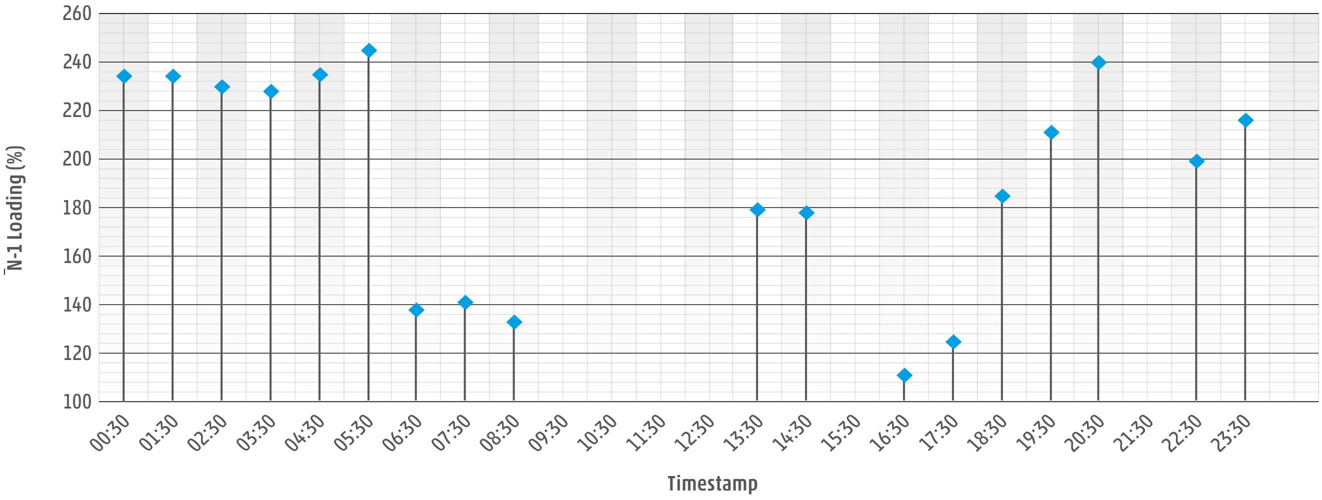

Figure 5-10: Overview of loading as % of PATL of 220 kV Argia–Arkale after the trip of 400 kV Argia–Hernani (before application of RAs)

TSO	Contingency		Constraint		Max. constraint (%, TS)	Remaining after RA
	U (kV)	Element	U (kV)	Element		
RTE/RE	400	Argia–Hernani	220	Argia–Arkale	245 %, 05:30	98 %

Remedial actions:
PRA: Countertrading (RE, RTE) 300 MW [FR↑,ES↓]
CRA: 220 kV Arkale PST: Tap change (17→15) [To avoid PST block]
CRA: 220 kV Arkale PST: Tap change (15→5) [Automatic]
CRA: 220 kV Arkale PST: Tap change (5→1) [Manual]

Table 5-16: Proposed RAs to solve the constraint on 220 kV Argia–Arkale after the trip of 400 kV Argia–Hernani

N-1 220 kV Argia – Arkale on 400 kV Argia – Hernani

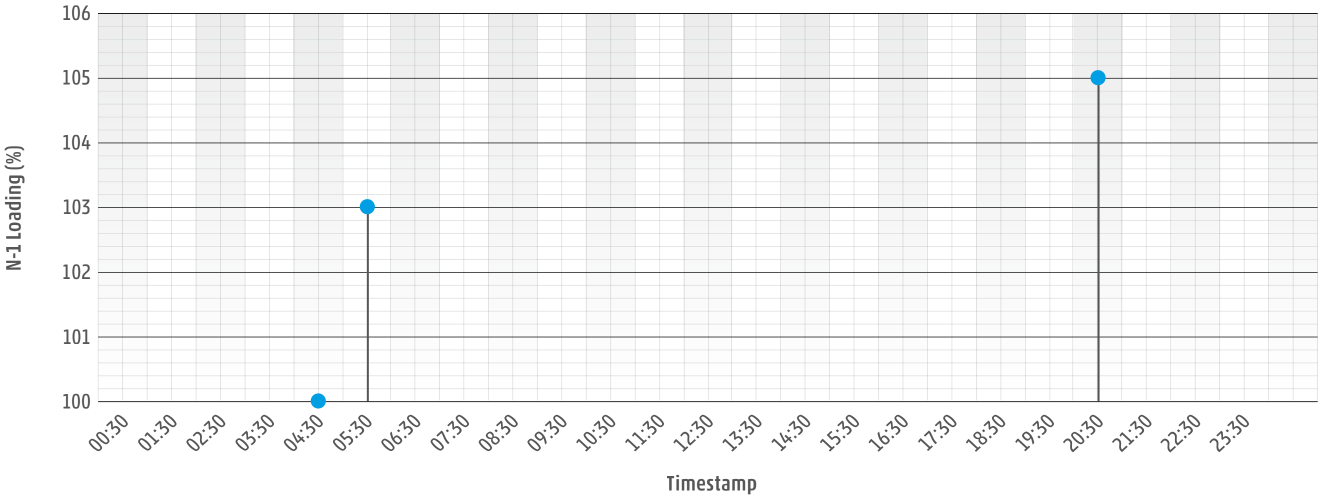

Figure 5-11: Overview of loading as % of PATL of 400 kV Argia – Hernani after the trip of 220 kV Argia – Arkale (before application of RAs)

TSO	Contingency		Constraint		Max. Overload (%, TS)	Remaining after RA
	U (kV)	Element	U (kV)	Element		
RTE/RE	220	Argia – Arkale	400	Argia – Hernani	105 %, 20:30	99 %

Remedial actions:
PRA: Countertrading (RE, RTE) 150 MW [FR↑,ES↓]
CRA: 400/220 kV TF Argia 1, 2: Switch Off

Table 5-17: Proposed RAs to solve the constraint on 400 kV Argia – Hernani after the trip of 220 kV Argia – Arkale

N-1 400 kV Grijota–Villarino on 400 kV Valdecarretas–Villarino

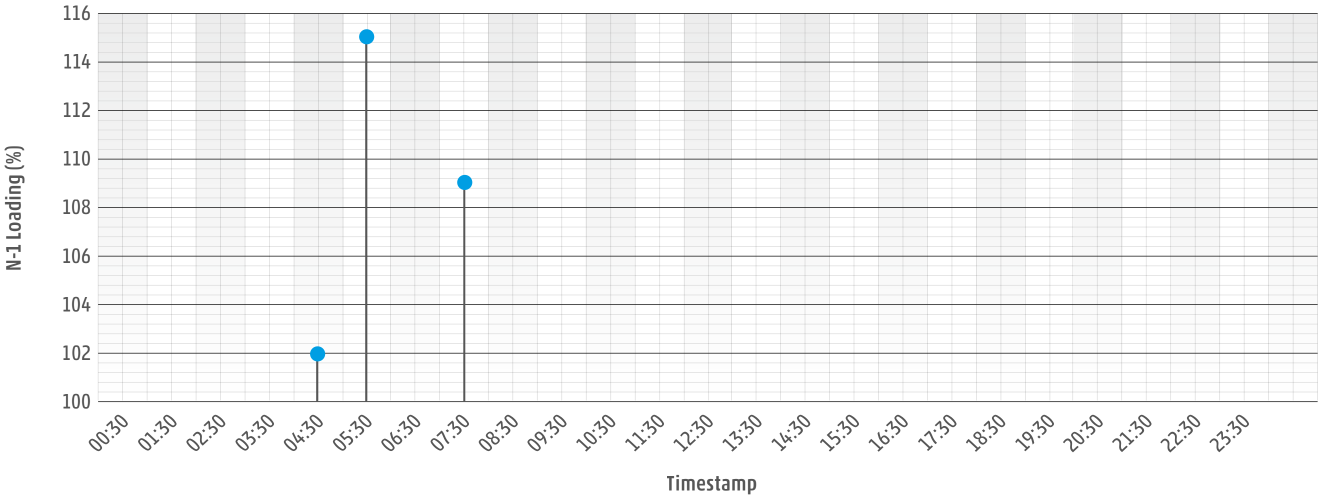

Figure 5-12: Overview of loading as % of PATL of 400 kV Valdecarretas–Villarino after the trip of 400 kV Grijota–Villarino 1 (before application of RAs)

TSO	Contingency		Constraint		Max. Overload (%, TS)	Remaining after RA
	U (kV)	Element	U (kV)	Element		
RTE/RE	400	Grijota–Villarino 2	400	Valdecarretas–Villarino 1	115 %, 05:30	86 %
Remedial actions: CRA: 400 kV Grijota–Villarino 1: Switch On						

Table 5-18: Proposed RAs to solve the constraint on 400 kV Valdecarretas–Villarino after the trip of 400 kV Grijota–Villarino 2 (in this case, note that the 400 kV Grijota–Villarino 1 line was sent out of service for reactive power control)

N-2 400 kV Arañuelo–Aldeadávila and Hinojosa–Aldeadávila on 400 kV Cedillo–Falagueira

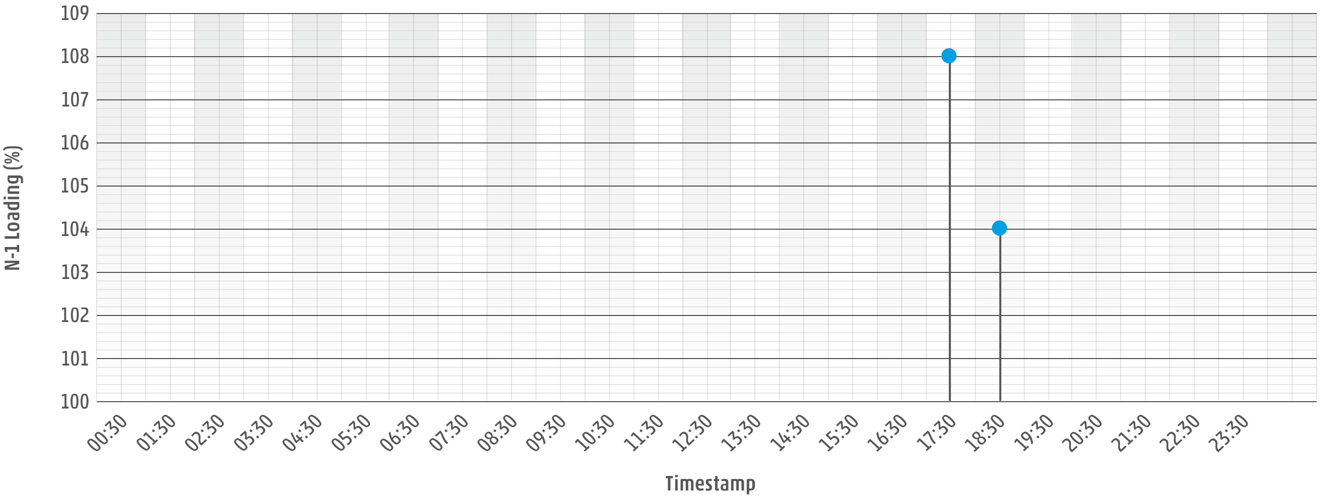

Figure 5-13: Overview of loading as % of PATL of 400 kV Cedillo–Falagueira after the double trip (N-2) of 400 kV Arañuelo–Aldeadávila and Hinojosa–Aldeadávila (before application of RAs)

TSO	Contingency		Constraint		Max. Overload (%, TS)	Remaining after RA
	U (kV)	Element	U (kV)	Element		
REN/RE	400	Arañuelo–Aldeadávila and Hinojosa–Aldeadávila (N-2)	400	Cedillo–Falagueira	108 %, 17:30	99 %
Remedial actions: CRA: Internal Redispatch (RE) 400 MW [ReduceGen on J.M.Oriol]						

Table 5-19: Proposed RAs to solve the constraint on 400 kV Cedillo–Falagueira after the double trip (N-2) of 400 kV Arañuelo–Aldeadávila and Hinojosa–Aldeadávila.

N-2 400 kV Alto Lindoso–Cartelle (1, 2) on 400 kV Aldeadávila–Lagoaça

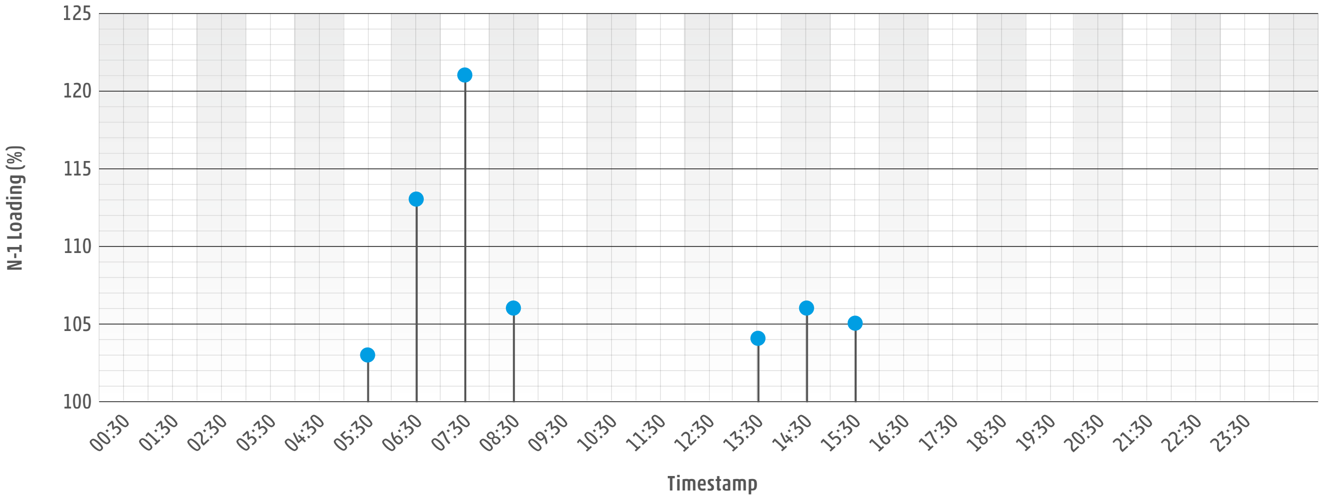

Figure 5-14: Overview of loading as % of PATL of 400 kV Aldeadávila–Lagoaça after the double trip (N-2) of 400 kV Alto Lindoso–Cartelle (before application of RAs)

TSO	Contingency		Constraint		Max. Overload (%, TS)	Remaining after RA
	U (kV)	Element	U (kV)	Element		
REN/RE	400	Alto Lindoso–Cartelle (N-2)	400	Aldeadavila–Lagoaca	121 %, 07:30	99 %
Remedial actions: CRA: Internal Redispatch (REN) 800 MW [Dec Gen Bemposta and Picote]						

Table 5-20: Proposed RAs to solve the constraint on 400 kV Aldeadavila–Lagoaca after the double trip (N-2) of 400 kV Alto Lindoso–Cartelle (before application of RAs)

5.2.6 Other RCC Tasks

5.2.6.1 Emergency and Restoration Plans Consistency Check

In accordance with Article 6 of the Network Code on Electricity Emergency and Restoration (NC ER), TSOs shall review their defence and restoration plans at least every five years with a subsequent consistency assessment. RCCs are responsible for evaluating the coherence of specific measures, including inter-TSO assistance, frequency management, active power support, and top-down re-energisation. Following this consultation, the relevant RCC will prepare a technical report assessing the consistency of the measures implemented by the TSOs.

This task was last performed and completed in 2024, for the second time since it was established. Coreso evaluated the defence and restoration plans of the SWE region and verified the existence of the necessary agreements outlining the relevant procedures to be applied in emergency, blackout, or restoration states by Red Eléctrica, REN, and RTE. TSOs have provided Coreso with the references to the most recent versions of these documents, and no inconsistencies were identified between RTE and Red Eléctrica, or between Red Eléctrica and REN.

5.2.6.2 Regional Incident Analysis and Reporting

Regional Incident Analysis and Reporting (RIAR) is the RCC task based on the requirement from Article 37(1)(i) of EU Regulation 2019/943 and the ACER decision 04/2022. In this task, all RCCs jointly investigate the role of RCC tasks connected with incidents above a specific threshold. Since the establishment of the RCCs in 2022, the only incident before April 2025 that was above the threshold was the Scale 3 incident (blackout) in South East Europe (SEE) on 21 June 2024. The system split on 24 July 2021 occurred before the establishment of RCCs.

The investigation into the SEE blackout was completed on 25 February 2025 with the publication of the final report. With this report, the RCCs issued two recommendations for all ENTSO-E TSOs connected to the RCC tasks, one aiming at a more frequent update of ID IGMs, the other addressing the voltage accuracy of the grid models. Both recommendations are also applicable to SWE but expected only until mid-2026. Until 28 April 2025, they were still pending – in line with the recommended timeline.

The TSOs added an additional recommendation affecting the RCC tasks, aimed at resolving tie-line rating inconsistencies in the SWE area. Generally, such inconsistencies are not limited to SEE but are also present in SWE. However, the recommendation only addressed the affected TSOs and did not include other TSOs. Contrary to the system split on 4 November 2006 in Germany, the tie-line rating inconsistencies did not contribute to the incident in SEE. Since RCCs generally consider the lower limits in regional processes, the impact of such inconsistencies is limited to local processes and not considered critical for RCC processes.

In addition to the mandatory RCC task of RIAR, Coreso offers its shareholders an additional voluntary service: a "post-event analysis" that provides basic investigations for incidents below the threshold and may also include the use of post-operational data such as RTSN.

5.2.6.3 Crisis Scenarios

The RCCs have a defined role in ENTSO-E's process of identifying regional crisis scenarios. This role is described in the **risk preparedness regulation** and further elaborated in the **methodology** for identifying regional electricity crisis scenarios, which was amended in 2023 by ENTSO-E and the RCCs and submitted to ACER. The **amended methodology** was approved by ACER on 8 March 2024 and clarifies the role of RCCs in the various stages of updating the regional crisis scenarios. It outlines four stages in updating regional electricity crisis scenarios:

- Establishing a list of regional electricity crisis scenario candidates, using the previous list of regional electricity crisis scenarios as a starting point and providing updates
- Compiling a list of regional electricity crisis scenarios for evaluation
- Evaluating and ranking electricity crisis scenarios
- Reporting on the most relevant regional electricity crisis scenarios

In all stages, RCCs support ENTSO-E, and TSOs are consulted or informed. ENTSO-E has the final responsibility for the report and various process steps. This process delivers the most severe regional electrical crisis scenarios every fourth year. The TSOs are required to include the regional electrical crisis scenarios in their risk preparedness plans.

The regional electrical crisis scenarios were updated in 2024, which resulted in the analysis of 23 scenarios with different root causes, including natural (weather, earthquakes, etc.), anthropogenic (physical attack, etc.), or others. So far, the investigation has identified no correlation between the incidents listed and the scenarios analysed.

6 COMMUNICATION OF SYNCHRONOUS AREA MONITORS AND BETWEEN TSOs

This chapter outlines the key communications between synchronous area monitors (SAMs) and the affected Transmission System Operators (TSOs) during the incident, highlighting the exchanges that supported situational awareness and operational coordination. In addition to these interactions, it also includes messages exchanged via the ENTSO-E Awareness System (EAS) platform, as well as email correspondence between SAMs and the TSOs related to this event.

To maintain conciseness, the focus is on communications between TSOs; however, communications with significant grid users were also reviewed and considered during the analysis, despite not being detailed in this section.

6.1 Communication between TSOs

Within the Synchronous Area Continental Europe, control actions and reserves are organised in a hierarchical structure with scheduling areas, monitoring areas, load-frequency control (LFC) areas, LFC blocks, and the synchronous area with two coordination centres. The coordination centres facilitate communication and cooperation among TSOs, helping solve inter-TSO issues, and coordinate responses to potential disruptions or changes in power demand and generation. The coordination centres' role is carried out simultaneously by the TSOs Swissgrid and Amprion, with each responsible for a specific geographic portion of the synchronous area, ensuring that each TSO communicates with only one coordination centre. The TSOs affected by the incident on 28 April 2025 are all serviced by Swissgrid.

In continental Europe, coordination centres also fulfil SAM obligations according to Article 133 of the System Operation Guidelines (SO GL). In this role, they monitor the synchronous area's frequency and other parameters and initiate international coordination, if needed. The SAM role is performed by Swissgrid in even-numbered months and by Amprion in odd-numbered months; therefore, Swissgrid was the active SAM during the event.

In the following, calls shown in blue are those with the SAMs designated for the Continental Europe Synchronous Area, namely Swissgrid or Amprion.

» **28 April, 09:08:**

RTE informed Swissgrid of notable frequency fluctuations observed in their network prior to the hourly change. No alarms were triggered at Swissgrid's control centre, and the oscillations were not clearly communicated by RTE, resulting in no immediate action.

» **28 April, 12:05:**

RE asked RTE to reduce cross-border exchange due to oscillations. Net transfer capacity (NTC) was set to 1,500 MW until 13:00.

» **28 April, 12:08:**

RE asked RTE to switch the HVDC interconnection Baixas (RTE)–Santa Llogaia (RE) system from PMode3 [ed. emulating an AC line] to PMode1 [ed. constant power set point] due to oscillations. RTE accepted.

» **28 April, 12:08:**

RE and REN coordinated on managing voltage oscillations and cross-border power flows. Initially, RE requested countertrading between 13:00 and 15:00 to reduce Portuguese imports, which REN accepted.

» **28 April, 12:11–12:13:**

RE contacted REN to request the cancellation of the previously agreed countertrading. Both parties agreed that REN would operate in TERRE (Trans European Replacement Reserves Exchange) while maintaining current import levels. REN then requested and received approval from RE to place 700 MW of replacement reserve needs in TERRE for the 13:00–14:00 period.

» **28 April, 12:14:**

RTE called RE to confirm the NTC value of 1,500 MW, which had not been updated via the tools.

» **28 April, 12:17:**

RE called REN to reinstate a countertrading request from 13:00 to 14:00 to reduce imports and alleviate power flows in Spain's 400 kV corridors. REN accepted.

» **28 April, 12:19:**

RE requested that RTE reduce NTC from 1,500 MW to 1,000 MW due to newly observed oscillations, with the reduction to remain in effect until 14:00. RTE accepted.

» **28 April, 12:20–12:27:**

RE requested that REN bring forward the countertrading originally scheduled for 13:00–14:00 [ed. final values activated were 13:00–13:15 with 507 MW, 13:15–13:30 with 590 MW, 13:30–13:45 with 531 MW, 13:45–14:00 with 538 MW] by adding quarter-hourly countertrading for the periods 12:30–12:45 with 247 MW and 12:45–13:00 with 88 MW to reduce Portuguese imports and alleviate power flows in Spain's 400 kV corridors. REN accepted both requests.

» **28 April, 12:34:**

RE informed RTE of a total blackout in the Iberian Peninsula and the initiation of system restoration. RE requested a gradual supply of 400 MW, which RTE agreed to, and both parties decided to set cross-border exchanges to 0 MW temporarily.

» **28 April, 12:34:**

Amprion reported a system split to Swissgrid and initiated discussions on coordinating with RE and REN, who were initially unable to communicate due to the blackout. It was noted that Swissgrid had attempted to reach the affected TSOs.

» **28 April, 12:34–12:36:**

RE called REN to confirm that both systems were in a blackout situation. RE and REN agreed to set cross-border exchange schedules to 0 MW and initiate restoration with black-start units and the assistance of the French system.

» **28 April, 12:37:**

RE requested RTE to energise the 400 kV TIE Baixas (RTE)—Vic (RE). RTE Toulouse was required to consult RTE Paris.

» **28 April, 12:39–12:40:**

RE requested RTE to restore voltage at the Hernani substation from the Argia substations. RTE successfully put the 400 kV TIE Argia (RTE)—Hernani (RE) into service.

» **28 April, 12:39:**

Amprion confirmed to Swissgrid that they, as SAM, would also issue the RG CE system split announcement within the EAS according to the system split procedure.

» **28 April, 12:41:**

Swissgrid contacted RTE for updates on the blackout; RTE confirmed plans to supply up to 400 MW to RE.

» **28 April, 12:41:**

RE asked RTE to initiate the agreed 400 MW exchange from France to Spain via AC, and both parties committed to expediting the process.

» **28 April, 12:47:**

TERNA called RTE to offer help.

» **28 April, 12:47:**

RE contacted ONEE and agreed to receive up to 100 MW of power from Morocco via one of the submarine cables connecting the two systems.

» **28 April, 12:47:**

RE informed Swissgrid of a blackout situation and shared initial restoration plans. No additional support was needed at that time.

» **28 April, 12:49:**

RE requested RTE to close the 400 kV TIE Baixas (RTE)—Vic (RE), but RTE clarified that the operation fell under the responsibility of their Paris control centre and not the control centre of Toulouse, which was called.

» **28 April, 12:49–12:54:**

Swissgrid and Amprion confirmed the blackout in Spain and Portugal. They defined RE as the frequency leader for the Iberian Peninsula, Swissgrid for the rest of continental Europe, and RTE as the resynchronisation leader according to the role definitions of the system split procedure.

» **28 April, 12:51:**

RTE informed RE that staff were being dispatched to Baixas to restore the HVDC interconnection Baixas (RTE)—Santa Llogaia (RE), which could not be restarted automatically due to protection system constraints.

» **28 April, 12:57:**

Swissgrid confirmed to RTE the role assignments and that LFC controllers would remain unchanged.

» **28 April, 13:20:**

RE asked RTE about any issues or incidents on the tie-lines. RTE confirmed that no anomalies or incidents were observed. RE suggested that RTE send staff to close these tie-lines in case of remote-control failure.

» **28 April, 13:24:**

RTE informed Swissgrid that it had received too little information from Spain to assess the extent of the blackout. RTE reported Iberian frequencies around 50.3–50.4 Hz. It was still unclear to the RTE operator whether the French supply of power would be via AC or DC lines.

» **28 April, 13:27:**

RE asked RTE about the issue related to the lack of voltage transmission on the 400 kV TIE Baixas (RTE)—Vic (RE). RTE was seeing high voltages. It was agreed to energise the line. RE would adjust a load of 100 MW to help reduce the voltage. Additionally, it was agreed to increase NTC to 950 MW.

» **28 April, 13:36:**

RE provided an updated assessment, confirming a total blackout across the Iberian Peninsula, with all regions affected. The cause remained unknown.

» **28 April, 13:40:**

RTE contacted Swissgrid to request information on available capacity to support their system.

» **28 April, 13:40:**

RTE reported to RE that the HVDC interconnection Baixas (RTE)—Santa Llogaia (RE) could be started and voltage regulated, requesting a switch to PMode3 [ed. emulating an AC line]. However, RE indicated that the mode change was not feasible due to the network's weakened condition.

» **28 April, 13:41:**

REN enquired if RTE had already started the Spanish grid restoration. RTE confirmed that it was in progress.

» **28 April, 13:45:**

REN informed Swissgrid that Portugal was experiencing a nationwide blackout. REN attempted grid restoration using two black-start units, with no immediate support from Spain. One unit had failed multiple times. The cause of the blackout was still unknown.

» **28 April, 13:50:**

Swissgrid informed Amprion that RE was energised by RTE and REN was restoring bottom-up.

» **28 April, 14:02–14:04:**

RE informed RTE of their ability to regulate voltage via the HVDC interconnection Baixas (RTE)—Santa Llogaia (RE) at Baixas and planned to activate the STATCOM function at Santa Llogaia. To support this, RE requested switching Link-2 from "Standby" to "Decoupled", which RTE approved.

» **28 April, 14:14:**

Swissgrid asked RTE about the grid situation in France, Spain, and Portugal. RTE reported a 600 MW exchange with Spain, with two interconnections [ed. 400 kV TIE Argia (RTE)—Hernani (RE) and 400 kV TIE Baixas (RTE)—Vic (RE)] already in service, and a third line expected to follow. RTE wanted to send 400 additional MW through the HVDC line.

» **28 April, 14:17:**

RTE asked RE if the 220 kV TIE Biescas 2 (RE)—Pragneres (RTE) could be put into service. RE answered that it would try to find out and then inform RTE.

» **28 April, 14:20:**

RE informed RTE about the closing of a switch at the converter and notified them of the move to "Stopped" and then "Decoupled" mode to regulate voltage as STATCOM.

» **28 April, 14:34:**

In response to the request made at 14:17, RE informed RTE that it was not possible to put the 220 kV TIE Biescas 2 (RE)—Pragneres (RTE) into service due to ongoing work.

» **28 April, 14:35:**

RE contacted ONEE and requested renewed voltage from the Moroccan electrical system.

» **28 April, 14:41:**

RE requested RTE to increase the cross-border exchange from 950 to 1,200 MW. RTE agreed with a 1,200 MW NTC.

» **28 April, 14:54:**

RE informed RTE that they could move Link-2 to "Stopped", which required a coordinated manoeuvre. RTE performed the manoeuvre first, followed by RE. RE and RTE then agreed to change to "Decoupled" mode without needing to coordinate operation in "STATCOM" mode.

» **28 April, 15:00:**

TERNA asked RTE about the situation at the Spanish border.

» **28 April, 15:01:**

RE asked if REN already had generation in service. REN reported that black-start capacity power plants were experiencing issues and that it was waiting for these power plants to be successfully started up and connected to the grid.

» **28 April, 15:06:**

Swissgrid informed Amprion that two tie-lines between France and Spain were back in operation and 600 MW were being exchanged. Amprion informed Swissgrid in its role as frequency leader that the Temelin power plant tripped in the Czech Republic, but that this was probably not linked to the blackout.

» **28 April, 15:13:**

Swissgrid enquired with RTE about a missing file with the scheduled exchange. There were misunderstandings between SG and RTE during the call. RTE confirmed that it would send the missing file.

» **28 April, 15:20:**

RTE reported to RE an exchange of 1,391 MW with an NTC of 1,200 MW. RE suggested increasing the cross-border exchange to 1,400 MW and NTC to 1,500 MW until 17:00.

» **28 April, 15:31:**

RTE informed RE that the 400 kV TIE Argia (RTE)–Hernani (RE) N-1 was causing an overload on the 220 kV TIE Argia (RTE)–Arkale (RE) due to the 220 kV PST Arkale (RE) being out of service.

» **28 April, 15:32:**

RE requested RTE to connect Link-1 from HVDC interconnection Baixas (RTE)–Santa Llogaia (RE) for power transmission. Coordination was confirmed.

» **28 April, 15:35:**

RE informed RTE that the 220 kV PST Arkale (RE) [ed. and the 220 kV TIE Argia (RTE)–Arkale (RE)] would be put into service, establishing tap 17.

» **28 April, 15:37:**

REN reported issues with starting black-start plants to RE. RE could not assist REN at the time.

» **28 April, 15:39:**

RE informed RTE that they had found issues with docking the 220 kV PST Arkale (RE) and indicated that it may be necessary to open the line [ed. 220 kV TIE Argia (RTE)–Arkale (RE)].

» **28 April, 15:43:**

Swissgrid informed Amprion that three tie-lines between France and Spain [ed. 220 kV TIE Argia (RTE)–Arkale (RE), 400 kV TIE Baixas (RTE)–Vic (RE) and 400 kV TIE Argia (RTE)–Hernani (RE)] were back in operation.

» **28 April, 15:50:**

Amprion questioned RTE about a 2,500 MW demand on PICASSO. RTE mentioned a negative price and said that 500 MW would be coming back online soon. RTE noted that there would be an excess of power after 16:00. Amprion asked RTE about the situation in Spain, but RTE had no further information.

» **28 April, 15:52:**

RE requested power from RTE via the HVDC interconnection Baixas (RTE)–Santa Llogaia (RE) Link-1 in PMode3 [ed. the line was switched back to PMode1 after 1 min]. RE took the master control to make the changes.

» **28 April, 15:56:**

RE informed RTE that the 220 kV TIE Argia (RTE)–Arkale (RE) had to be decoupled to connect the PST.

» **28 April, 16:02:**

RTE reported to RE that the flow through Santa Llogaia was moving from Spain to France.

» **28 April, 16:04:**

RE informed RTE of the intention to change the flow direction at the HVDC interconnection Baixas (RTE)–Santa Llogaia (RE). RTE confirmed and agreed to open the 220 kV TIE Argia (RTE)–Arkale (RE).

» **28 April, 16:09:**

Swissgrid asked RTE about the current grid situation and offered support. France did not require assistance at that time.

» **28 April, 16:13:**

RE informed RTE that the 220 kV TIE Argia (RTE)–Arkale (RE) and 220 kV PST Arkale (RE) were now operational. RE reported that power transmission had stopped due to an angular difference issue.

» **28 April, 16:13:**

Swissgrid asked RE about the current status of the system reposition and whether all transmission interconnection lines with France had been reconnected. RE confirmed that restoration efforts were ongoing and all interconnection lines with France were operational. The network was radial, and efforts were being made to create a mesh configuration. The exchange capacity stood at 1,500 MW. Swissgrid further enquired if any black-start power plants were in operation. RE said that one unit was active in the southern region, and more groups were expected to start up shortly. RE reported that an area had been connected to Morocco. Swissgrid asked about the situation at the border with Portugal, and RE conveyed that REN had reported issues with black-start plants. RE had several isolated zones, and once these were connected, RE would be able to provide voltage support to REN.

» **28 April, 16:39:**

Swissgrid enquired with RTE regarding the current grid situation, and there was no news to report.

» **28 April, 16:55:**

Swissgrid provided Amprion with clarification regarding the current grid situation for the restoration of the Iberian Peninsula.

» **28 April, 16:56:**

ONEE called RE and offered to provide up to 200 MW of support from its system. The offer was accepted on the same call.

» **28 April, 16:58:**

RTE informed RE their intention to couple busbars in ARGIA 220 kV. Approval was given.

» **28 April, 17:30:**

RTE informed RE that from 20:00, the cross-border exchange would proceed as scheduled before the incident, with 3,000 MW. RTE suggested informing its balance team to extend the 1,500 MW until midnight.

» **28 April, 17:35:**

Swissgrid provided Amprion with clarification regarding the current grid situation for the restoration of the Iberian Peninsula.

» **28 April, 18:06:**

RTE informed Swissgrid that as of 19:00, they would no longer be able to balance themselves due to a lack of energy from Spain and requested a countertrade of 500 MW.

» **28 April, 18:07:**

ONEE contacted RE to ask if the Spanish electricity system was divided into several electrical zones or if all electrical zones were connected. RE explained that it was divided, with the northern zone of the Spanish system connected to the European grid via the French grid, and the southern zone connected to the Moroccan grid.

» **28 April, 18:09:**

RTE reported a flow of 1,900 MW instead of 1,500 MW to RE. RE would regulate it.

» **28 April, 18:11:**

RTE informed RE that 1,700 MW was available until midnight.

» **28 April, 18:19:**

RTE reported to RE that the flow was 2,000 MW. RE would adjust it. RTE proposed increasing NTC to 2,000 MW.

» **28 April, 18:23:**

Swissgrid provided Amprion with clarification regarding the current grid situation for the restoration of the Iberian Peninsula.

» **28 April, 18:34:**

RE called REN and offered to energise the 220 kV TIE Aldeadávila I (RE)–Pocinho (REN), providing voltage support from its system (up to 20 MW of power support). The offer was accepted on the same call.

» **28 April, 19:08:**

ONEE contacted RE to request that no more load be taken from Morocco via ESMA1 due to low frequency. RE asked ONEE if it could continue taking 300 MW, and ONEE agreed, but instructed them not to exceed 300 MW.

» **28 April, 19:21:**

ONEE contacted RE to enquire about the progress of the restoration of the Spanish electricity system, specifically whether generation had been restored and whether the load on ESMA 1 would rise above 370 MW. RE advised that generation was gradually being restored and that the load on ESMA 1 was not expected to exceed that value.

» **28 April, 19:22:**

Swissgrid enquired with REN about the current grid situation. REN reported that there were three restoration areas, one of which was being supported by RE. At that time, 170 MW of load was being supplied.

» **28 April, 19:45:**

Swissgrid provided Amprion with clarification regarding the current grid situation for the restoration of the Iberian Peninsula.

» **28 April, 19:49:**

REN requested that RE reconnect the 220 kV tie-lines, specifically the 220 kV TIE Aldeadávila II (RE)–Pocinho (REN) or the 220 kV TIE Pocinho (REN)–Saucelle 1 (RE), with a preference for including both if feasible. RE suggested the reconnection of the 400 kV TIE Cedillo (RE)–Falagueira (REN). REN indicated that the reconnection of the 400 kV TIE Cedillo (RE)–Falagueira (REN) would occur at a later stage, and that they preferred to connect the 220 kV lines at that time. RE accepted.

» **28 April, 20:00–20:11:**

RTE requested emergency reserves from Amprion. It was agreed to deliver 400 MW from Germany to France from 21:00 until midnight.

» **28 April, 20:23:**

RE requested that RTE change the state of Link-2 from “Decoupled” to “Coupled” to enable power transmission. RE indicated a preference for receiving power through the HVDC interconnection Baixas (RTE)–Santa Llogaia (RE) rather than charging the 400 kV TIE Baixas (RTE)–Vic (RE). RTE agreed.

» **28 April, 20:31:**

RE reported to RTE that they had changed the power setpoint (PSP) from 600 MW to 300 MW for the HVDC interconnection Baixas (RTE)–Santa Llogaia (RE) Link-1. RE confirmed no exchange variation, only the recovery of Link-2. RTE noted a 1,300 MW deviation [ed. Between the 2,000 MW schedule and the 700 MW physical flow] that may affect frequency.

» **28 April, 20:35:**

RE requested RTE to adjust the cross-border exchange to 800 MW from that moment on due to the existing deviation to maintain frequency stability. RTE approved the change.

» **28 April, 20:49:**

RE requested RTE to adjust the cross-border exchange to 1,400 MW due to the reduced imbalance. RTE approved.

» **28 April, 20:53:**

RE requested ONEE to reduce the cross-border exchange to the 300 MW agreed in the initial program. ONEE reported frequency issues as the reason for the higher flow and agreed to reduce generation.

» **28 April, 21:01:**

RE requested ONEE to close the second Spain–Morocco tie-line. RE energised the line and ONEE closed the line, reducing load on the other interconnection.

» **28 April, 21:02:**

Swissgrid provided Amprion with clarification regarding the current grid situation for the restoration of the Iberian Peninsula.

» **28 April, 21:08:**

ONEE informed RE that 900 MW was too much for their system and it was experiencing overloads.

» **28 April, 21:11:**

RE requested RTE to change the HVDC interconnection Baixas (RTE)–Santa Llogaia (RE) from "Decoupled" to "Stopped", waiting for 20 minutes, and then moving it to "Coupled" to put it into service. The manoeuvre was completed.

» **28 April, 21:13:**

ONEE asked RE about the interconnection between Spain and France. RE requested ONEE to regulate the 300 MW cross-border exchange, while ONEE asked RE to reduce production.

» **28 April, 21:14:**

Swissgrid contacted RTE for an assessment of the current situation. RTE reported that the frequency was stable and the situation at the border with Spain was under control. It confirmed that activation of the remaining power from Spain could continue.

» **28 April, 21:18:**

RTE informed RE that they planned to set the scheduled exchange to zero to regulate imbalances. They noted that increasing cross-border exchange could cause overloads when connecting two zones in a loop. RTE asked for cross-border exchange values for 29 April, suggesting 2,000 MW from France to Spain and 0 MW from Spain to France. RE confirmed these values.

» **28 April, 21:19:**

Swissgrid provided Amprion with clarification regarding the current grid situation for the restoration of the Iberian Peninsula.

» **28 April, 21:25:**

REN requested RE to connect the 400 kV TIE Puebla de Guzman (RE)–Tavira (REN) to begin supplying consumption in the Algarve (southern region of Portugal). RE accepted.

» **28 April, 21:26:**

ONEE asked RE about the deviation in the 300 MW exchange.

» **28 April, 21:31:**

RTE reported to Swissgrid that they had set the scheduled export value to Spain to 0 MW to better regulate with secondary control because otherwise, the scheduled cross-border values would change too frequently. The original scheduled exchange (without incident) with Spain was 3,000 MW from Spain to France, but with Spain now importing about 1,000 MW, RTE was buying 4,000 MW from Germany and Switzerland. Amprion and Swissgrid remained available to assist with any balancing issues.

» **28 April, 21:41:**

Swissgrid asked RE about nuclear plant issues or safe mode status. RE confirmed they were all in safe mode. Regarding the exchange with France, RE reported 1,400 MW. Swissgrid asked if RE was still in restoration mode and if assistance was needed. RE answered that the restoration was still ongoing and that no assistance was needed.

» **28 April, 21:41:**

RE requested RTE for information regarding the Link-2 manoeuvre. The waiting period had elapsed, and ready status could be applied. The manoeuvres were executed, and power transmission began. HVDC interconnection Baixas (RTE)—Santa Llogaia (RE) was normalised in PMode3 [ed. emulating an AC line], but PODP (power oscillation damping P) remained disabled.

» **28 April, 21:43:**

Swissgrid provided Amprion with clarification regarding the current grid situation for the restoration of the Iberian Peninsula.

» **28 April, 21:47:**

Swissgrid asked REN to confirm the existence of a synchronous connection from FR to PT.

» **28 April, 21:48:**

RE requested Coreso to validate the value provided by RTE, with an export of 0 MW and an import of 2,000 MW. Coreso confirmed.

» **28 April, 21:49:**

Swissgrid asked RE to verify if Portugal was connected to France through Spain and if Portugal was operating at the European frequency. The affected TSOs confirmed the existence of a synchronous connection from France to Portugal.

» **28 April, 21:50:**

Swissgrid provided Amprion with clarification regarding the current grid situation for the restoration of the Iberian Peninsula.

» **28 April, 21:52:**

ONEE asked RE about the need for additional energy. RE responded that no further energy was currently required.

» **28 April, 22:03:**

ONEE asked RE about the connection between Spain and France. Information was provided, along with frequency measurements.

» **28 April, 22:10:**

REN informed RE that grid conditions were fulfilled for the connection of the 400 kV TIE Cedillo (RE)—Falagueira (REN) and requested the connection. RE accepted.

» **28 April, 22:28:**

RE informed REN that they would change their LFC to peninsular mode. REN agreed.

» **28 April, 22:33:**

RTE enquired with RE about cross-border exchange capacities for 29 April. RE confirmed that the capacity from Spain to France was 0 MW and reported readiness to reconnect secondary regulation. RTE requested information about the schedule to achieve balance. Both parties agreed on a 1,400 MW exchange from France to Spain between 00:00 and 03:00.

» **28 April, 22:34:**

RTE requested Amprion to extend and increase emergency power. It was agreed to continue with 400 MW from 00:00 until 01:00 on 29 April and then 650 MW from 01:00 to 10:00.

» **28 April, 22:50:**

RTE informed Swissgrid that the Spanish load frequency controller would soon be operational. Subsequently, the exchange program from France to Spain would be increased from 0 MW to 1,400 MW. However, RTE noted that the exchange program would remain unchanged for the next few hours to allow for better frequency regulation.

» **28 April, 22:55:**

RTE thanked Amprion for their support. RTE received a schedule and entered it into their system.

» **28 April, 23:14:**

Amprion confirmed to Swissgrid the delivery from Amprion to RTE for the next hours: 400 MW from 00:00 to 01:00 and 650 MW from 01:00 to 10:00.

» **28 April, 23:27:**

ONEE enquired with RE about the restoration process. RE stated that it was ongoing and could not provide a status update.

» **28 April, 23:41:**

RE informed RTE that the LFC would be reconnected with a 100 MW schedule and then revert to 1,400 MW. RTE required one hour's notice to adjust its system and did not support changes before 00:30. A 0 MW schedule from 0:00 was agreed, allowing the connection of the LFC.

» **28 April, 23:52:**

ONEE enquired with RE about the situation, and RE explained about the connections with other TSOs and noted that the restoration process had not yet been completed.

» **28 April, 23:55:**

REN and RE agreed to change their LFC mode to power and frequency control, with scheduled programs on the PT—ES border at 0 MW.

» **29 April, 00:03:**

RTE expressed concerns to Swissgrid about its ability to maintain balancing at the border with Spain. Swissgrid offered RTE the option of activating power via the Stage 2 frequency procedure in an emergency. RTE would respond promptly if necessary.

» **29 April, 00:08:**

RE informed RTE that the LFC in Spain has been successfully activated. RTE confirmed that frequency regulation in Spain was now being managed by the Spanish system. RE reported that it had recovered 70 % of the load. No information was available about the REN restoration.

» **29 April, 00:11:**

RTE announced to Swissgrid that the grid controller in Spain was in operation. The initial exchange program [ed. schedule agreed before the blackout] indicated 0 MW from Spain to France and 3,000 MW from France to Spain. RTE had no information about the LFC in Portugal.

» **29 April, 00:17:**

Swissgrid provided Amprion with clarification regarding the current grid situation for the restoration of the Iberian Peninsula.

» **29 April, 00:47:**

REN asked RE to establish contact between the NCC management teams of REN and RE using the phone consoles in the control rooms. REN confirmed that it was already supplying all transmission substations with consumption and provided a summary of the generation profile (solar and wind connected to the transmission grid with restrictions). REN reported their intention to change the EAS state to emergency (red).

» **29 April, 01:54:**

REN informed RE that they were performing LFC regulation at 0 MW (schedule program) and asked for the match confirmation of the cross-border exchange schedule. RE confirmed that they would keep the scheduled programs (Spain to Portugal) at 0 MW on 29 April. RE reported that they would impose an NTC at 0 MW (Spain to Portugal) for 30 April. REN reported that they would continue limiting renewable (wind and solar) production connected to the transmission grid for better regulation. REN suggested changing the EAS status from the restoration to the emergency state, maintaining the suspension of energy markets. RE reported that they would remain in the restoration state for the time being.

» **29 April, 02:05:**

RE requested confirmation from REN regarding the scheduled exchanges from Portugal to Spain for 29 April. REN confirmed that the scheduled program would be 0 MW.

» **29 April, 02:16:**

RE informed ONEE that the supporting cross-border exchange was no longer required, and it was agreed to set it to 0 MW.

» **29 April, 02:19:**

Swissgrid asked REN for confirmation concerning the end of the restoration state of the Portuguese system. REN confirmed and reported that all transmission substations with consumptions were supplied.

» **29 April, 02:20:**

REN and RE called about an EAS malfunction. RE was seeing the Portuguese system in normal state when REN had switched to emergency state.

» **29 April, 02:22:**

Swissgrid informed RE that Portugal has updated the status in EAS to alert and confirmed that all loads were connected to the grid. Swissgrid requested information regarding the restoration process status in Spain. RE indicated that the restoration process was in its final stages. However, certain loads had not yet been recovered due to issues encountered by some DSOs when doing so. RE anticipated that all loads would likely be connected shortly.

» **29 April, 02:23:**

REN and RE called again about the EAS malfunction. RE was seeing the Portuguese system in normal state when REN had switched to emergency state.

» **29 April, 02:24:**

Swissgrid asked RTE for a general update. RTE confirmed ongoing stable border exchanges between Spain and France.

» **29 April, 02:25:**

REN and RE called again about an EAS malfunction. RE was viewing normal state of the Portuguese system when REN had changed to emergency.

» **29 April, 02:29:**

RTE asked RE about the status of the network restoration. RE reported that the transmission grid restoration was completed, and they were waiting for the restoration of loads at lower voltage levels. RE reported uncertainty about generation volume.

» **29 April, 02:29:**

REN and RE called again about the EAS malfunction. REN confirmed the end of the restoration state in the Portuguese system, switching to emergency state. REN confirmed that all transmission substations with consumptions were supplied.

» **29 April, 02:30:**

RE confirmed to REN that they were seeing the Portuguese system in emergency state in the EAS.

» **29 April, 02:44:**

Swissgrid provided Amprion with clarification regarding the current grid situation for the restoration of the Iberian Peninsula.

» **29 April, 03:11:**

Swissgrid asked RE about the EAS emergency status. RE confirmed all loads were connected, generation was stable, and there were no incidents. However, markets in the Iberian Peninsula remained suspended as a precaution. Swissgrid asked about next steps for balancing and exchange schedules. RE stated that the market was currently halted but expected normalisation by 30 April.

6.2 ENTSO-E Awareness System (EAS)

The EAS is activated in response to critical incidents, facilitating a coordinated and timely response among multiple TSOs within the ENTSO-E framework. This mechanism not only supports operational collaboration but also ensures effective communication of status assessments across Europe, enhancing situational awareness and enabling informed decision-making. Below is a detailed overview of the changes in system states as well as the information communicated through EAS for each affected TSO during the sequence of events.

» **28 April, 12:40:**
REN – Normal state to blackout state

» **28 April, 12:40:**
RE – Normal state to blackout state

» **28 April, 12:49:**
Swissgrid (as CC South) – Normal state to emergency state

» **28 April, 12:49:**
Amprion (as CC North) – Normal state to emergency state

» **28 April, 12:50:**
RTE – Normal state to emergency state

» **28 April, 13:08:**
RTE – Info: French synchronous leader for the split grid between France and Spain

» **28 April, 13:10:**
RE – Blackout state to restoration state

» **28 April, 13:20:**
Swissgrid (CC South) – Info: Swissgrid is the frequency leader of the main South Island, Spain is the frequency leader of their island, and France is the resynchronisation leader

» **28 April, 14:35:**
RTE – Emergency state to alert state

» **28 April, 17:05:**
REN – Blackout state to restoration state

» **29 April, 02:13:**
REN – Restoration state to emergency state

» **29 April, 03:00:**
RE – Restoration state to emergency state

» **29 April, 11:15:**
Swissgrid (as CC South) – Emergency state to normal state

» **29 April, 11:15:**
Amprion (as CC North) – Emergency state to normal state

» **29 April, 11:20:**
RTE – Alert state to normal state

» **29 April, 14:40:**
RE – Emergency state to alert state

» **29 April, 14:40:**
REN – Emergency state to alert state

» **30 April, 12:40:**
RE – Alert state to normal state

» **30 April, 12:50:**
REN – Alert state to normal state

6.3 Email Communications between SAM and the TSOs

This section includes the official email communications between SAM and the TSOs.

28 April, 12:53: From Swissgrid to all TSOs:

> *Dear Colleagues*
>
> *We announce that a system split is occurred in RG CE. The "procedure in case of system separation and resynchronisation of separated grid areas" is started.*
>
> *Details of the system split (number, borders, and TSOs of islands) and future information are shared via European Awareness System (EAS).*
>
> *If the system split is inside of your control area or on your tie lines please set EAS to emergency state: critical event and separation from the grid (Flow chart: step 4).*
>
> *Kind regards*

28 April, 22:14 – From Swissgrid to all TSOs:

> *Update!*
>
> *Dear Colleagues*
>
> *RTE is still balancing the Iberian peninsula via aFRR/mFRR activations. RTE has to activate the difference to the scheduled values (up to 3,000 MW export Spain → France) as well. Currently the margins are sufficient.*
>
> *In case there is a lack of balancing energy, Amprion and Swissgrid are ready to support RTE and stabilize the system frequency.*
>
> *Kind regards*

28 April, 23:20 – From Swissgrid to all TSOs:

> *Information!*
>
> *Dear colleagues,*
>
> *since 28.04.2025 23:17 (CET) we observed a permanent steady state frequency deviation with a fast-growing grid time deviation of +6 sec in the last 4 hours and a total grid time deviation of +4.27 sec.*
>
> *The cause of the frequency deviation could be identified (reason: restoration state Spain and Portugal).*
>
> *The Coordination Centres [ed. SAMs] will further monitor the situation.*
>
> *If the situation is not getting worse no actions are necessary by uninvolved TSOs until further notice.*
>
> *Thank you all for your collaboration.*
>
> *Kind regards*

29 April, 02:48 – From Swissgrid to all TSOs:

> *Information!*
>
> *Dear colleagues,*
>
> *from 28.04.2025 23:17 to 29.04.2025 02:45 (CET) we observed a permanent steady state frequency.*
>
> *The grid time deviation in the last 4 hours is now: +1.93 sec*
>
> *Total grid time deviation is now: +5.55 sec*
>
> *Now the alarm is cancelled.*
>
> *Reason for cancellation: grid time deviation is decreasing (≤2sec in the last 4 hours)*
>
> *No further action is needed.*
>
> *Thank you all for your collaboration.*
>
> *Kind regards*

7 CLASSIFICATION OF THE INCIDENT BASED ON THE ICS METHODOLOGY

The ICS methodology was originally developed in accordance with Regulation (EC) No 714/2009 of the European Parliament and of the Council of 13 July 2009, as repealed the by Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal market for electricity (recast), and updated to fulfil the objectives and the security indicator requirements laid out in Article 15 of Commission Regulation (EU) 2017/1485 of 2 August 2017 establishing a guideline on electricity transmission system operation (SOGL). The definitions and concepts in this methodology are in line with Articles 15 and 18 of the SOGL and further extended to describe the real-time situation of the TSO's system.

Scale 0 **Noteworthy incident**		**Scale 1** **Significant incident**		**Scale 2** **Extensive incident**		**Scale 3** **Major incident / 1TSO**	
Priority / Short definition (Criterion short code)		**Priority / Short definition (Criterion short code)**		**Priority / Short definition (Criterion short code)**		**Priority / Short definition (Criterion short code)**	
#20	Incidents on load (L0)	#11	Incidents on load (L1)	#2	Incidents on load (L2)	#1	Blackout (OB3)
#21	Incidents leading to frequency degradation (F0)	#12	Incidents leading to frequency degradation (F1)	#3	Incidents leading to frequency degradation (F2)		
#22	Incidents on transmission network elements (T0)	#13	Incidents on transmission network elements (T1)	#4	Incidents on transmission network elements (T2)		
#23	Incidents on power generating facilities (G0)	#14	Incidents on power generating facilities (G1)	#5	Incidents on power generating facilities (G2)		
		#15	N-1 violation (ON1)	#6	N violation (ON2)		
#24	Separation from the grid (RS0)	#16	Separation from the grid (RS1)	#7	Separation from the grid (RS2)		
#25	Violation of standards on voltage (OV0)	#17	Violation of standards on voltage (OV1)	#8	Violation of standards on voltage (OV2)		
#26	Reduction of reserve capacity (RRC0)	#18	Reduction of reserve capacity (RRC1)	#9	Reduction of reserve capacity (RRC2)		
#27	Loss of tools and facilities (LT0)	#19	Loss of tools and facilities (LT1)	#10	Loss of tools and facilities (LT2)		

Figure 7-1: Incident classification scale

Figure 7-1 shows the criteria from the methodology and the corresponding scale, ordered by descending priority. An incident can comprise multiple events and meet various criteria. In this case, the highest criterion decides the scale of the incidents. In the case of a scale 2 or 3 event, an investigation is conducted by an Expert Panel.

While only the highest priority criterion is relevant for deciding the scale, the other criteria are also assessed.

7.1 Scale of the Incident

The highest-violated ICS criterion during this incident was a scale 3 blackout (OB3). This criterion is met if there is a loss of more than 50 % of demand or a total absence of voltage for at least three minutes, assessed based on the TSO's control area. The lost load on 28 April 2025 was as follows:

- 25,638 MW for Spain (100 % of the demand in the Spanish Peninsula before the incident)
- 5,900 MW for Portugal (100 % of the demand in mainland Portugal before the incident)
- 7 MW for France (0.01 % of the demand before the incident).

Spain and Portugal also suffered a total absence of voltage. Therefore, both the loss of load and voltage criteria for OB3 were met.

For France, the lost load was below 100 MW and therefore no L criterion was met. France's highest criterion violation was an OV1 due to high voltage during the incident.

7.2 RCC Investigation Threshold

The RCC post-operation and post-disturbances analysis and reporting (RIAR) methodology has been developed to define the respective RCC task in accordance with Article 37(1)(i) of the Regulation (EU) 2019/943 of the European Parliament and of the Council of 5 June 2019 on the internal market for electricity. This methodology foresees an RCC investigation in addition to the work of the Expert Panel if both of the following criteria are met:

a. a TSO has moved from a normal or alert system state to an emergency system state as a result of actions taken by another TSO being in emergency, blackout, or restoration system state, and
b. the incident has been confirmed as at least a scale 2 incident as defined by the ICS methodology.

Post-analysis confirmed that Spain and Portugal were in a blackout and restoration state during the incident, meaning that the incident met the RCC investigation threshold to initiate the investigation. The conclusions of the RCC investigation are added as a dedicated chapter in the final report.

7.3 Scale of all Violations Linked to the Incident

The OB3 was the most severe criterion violated during the incident in Spain and Portugal. Several other criteria were violated before the blackout occurred, which are presented in Table 7-1 and summarised below. When an incident meets several criteria, it is classified according to the criterion with the highest priority. Additionally, all sub-criteria information (i.e., ICS violations or events) is also collected. Figure 7-2 presents a timeline view of the ICS criteria violated during the incident. It should be noted that the violations of the criteria regarding loss of generation facilities (G) and loss of load (L) have been separated into smaller violations to better visualise the sequence of events and correlate the impact of these violations with the measured frequency and voltage during the incident. The following paragraphs consolidate the violations according to the ICS methodology and therefore do not fully align with the detailed timeline presented in Figure 7-2.

In Spain, there was a loss of generation facilities (G0) at 12:32, followed by a transformer trip at 12:32:57, which is classified as a scale 0 loss of network element (T0) violation, and a further 355 MW of generation tripped. Approximately 20 seconds later, at 12:33:16, there were successive trips of power generation facilities. These generation trips are classified as one G2 incident as they occurred within fifteen minutes and were greater than 3,000 MW. Further T incidents occurred with the loss of tie lines and transmission lines in Spain. The trip of the HVDC interconnector was classified as a T2 ICS violation due to the impact on a neighbouring TSO with OV (voltage) violations in France. The disconnections of all tie lines between France and Spain split the Iberian Peninsula from CE (involving more than one TSO with a load larger than 5 % of the total load of the synchronous area before the separation, thus violating the RS2 criterion). The loss of load (L2) criteria was met after the generation loss, as automatic TSO system defence measures were activated with the tripping of pumps and distribution load shedding.

There was high-voltage violations in Spain during the incident that contributed to the trip of generation, although they did not meet the time threshold for a voltage violation as defined in the ICS methodology. Voltage was above 1.1 per unit for 16 seconds, whereas the ICS methodology requires a time of greater than 30 seconds. The subsequent voltage collapse is captured under the OB3 (blackout) criteria.

Portugal experienced high voltage and – similarly to Spain – the duration did not reach the time thresholds specified in the ICS methodology, and therefore there were no OV incidents. There was a significant loss of load (L2) as pumps and industrial consumers were disconnected, as well as the distribution load. There were two T0 events with the loss of a transformer and an overhead line. Additionally, a G2 violation was recorded at the time of the blackout, as all generation facilities were disconnected.

The highest criteria experienced in France by RTE was scale 1 related to OV1. France also had G0 and T0 violations.

Frequency degradation (F) ICS criteria violation was a below scale (BS) violation (FBS). The reason is that the frequency deviation magnitude thresholds were met, but – similarly to the ICS voltage criteria (OV) – the duration of the deviations were not sufficiently long to be registered at a higher scale. Furthermore, the frequency deviations are registered at a synchronous area level, even if local anomalies might occur.

All oscillations that occurred prior to the blackout – as detailed in this report – did not cause any ICS criteria violations.

Criterion	Scale	Red Eléctrica	REN	RTE
OB	3	×	×	
L	2	×	×	
	1			
	0			
F	2			
	1			
	0			
	BS	×		
T	2	×		
	1			
	0	×	×	×
G	2	×	×	
	1			
	0			×
	BS			
ON	2	Not Violated		
	1			
RS	2	×	×	
	1			
	0			
OV	2	Not violated because the time threshold was not reached		
	1			×
	0			
	BS			
RRC	2	Not Violated		
	1			
	0			
LT	2	Not Violated		
	1			
	0			

Table 7-1: ICS criteria violations by TSO

Note: Each violated ICS criterion has an X in the cell. The scales shown are 0–3 and below scale (BS). There was no violation of the ICS ON, RRC, and LT criteria.

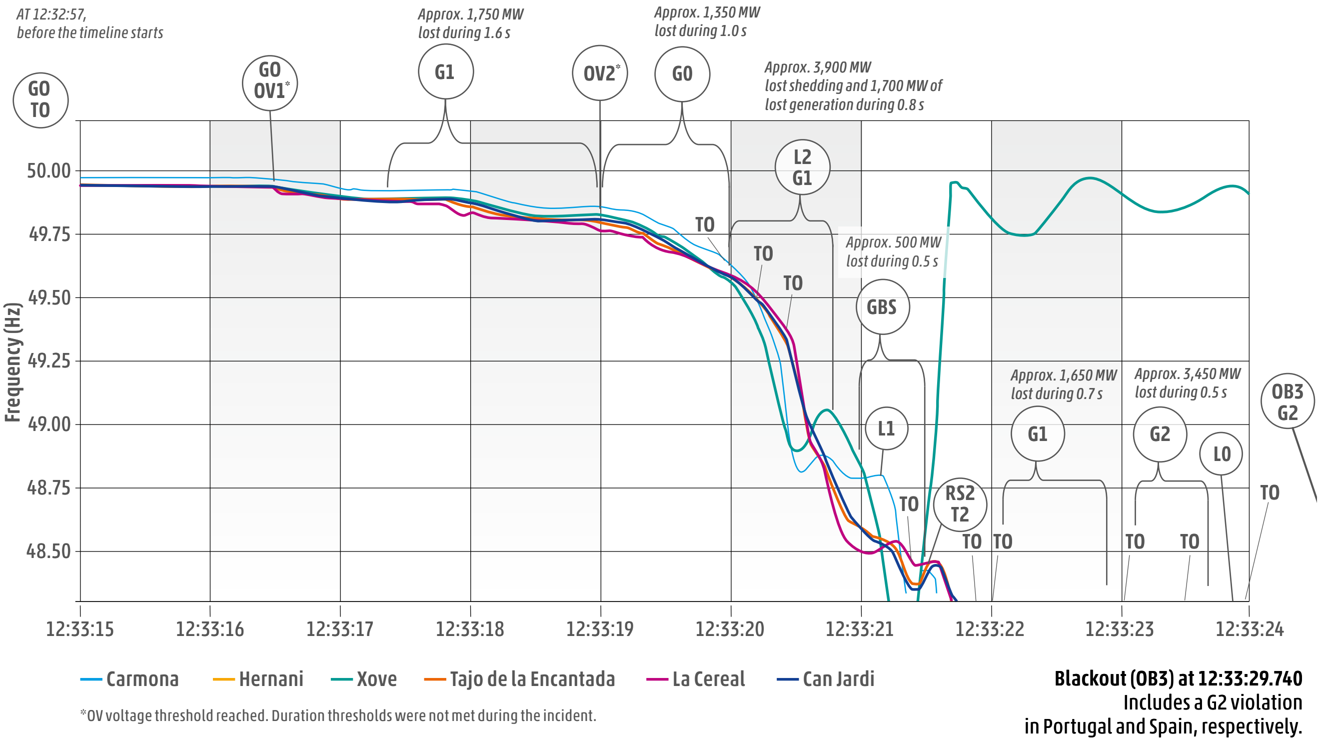

Figure 7-2: ICS criteria violations for Portugal and Spain during the incident
Note: All sub-ICS criteria violations for tripped generation facilities (G) and loss of load (L) are included in the graph but reported as a single G or L violation for Portugal and Spain. When the G and L criteria are regarded as a whole, Spain and Portugal each had a G2 violation, as the generation trips occurred within 15 minutes and amounted to more than 3,000 MW, and a blackout (OB3) due to the total loss of voltage in the control area. The L2 criterion was reached at one point, but after more than 50 % of the load is lost in the control area, the L2 becomes an OB3 violation.

8 NEXT STEPS

This factual report highlights the exceptional and unprecedented nature of this incident, as it is the first time that a cascading series of disconnections of generation components along with voltage increases has been part of the sequence of events leading to a blackout in the Continental Europe Synchronous Area. Therefore, a timely and comprehensive determination of causes and future recommendations is crucial.

Following the delivery of this factual report, in accordance with the ICS methodology, the Expert Panel investigating the blackout that occurred in Spain and Portugal on 28 April 2025 will develop a final report, which will notably cover the following:

1. Root causes

- determine and analyse the root causes and contributing factors to the incident.

2. Voltage control

- assess the operational planning procedures and voltage management tools and how they were applied on 28 April.
- assess the operation of tap-changing transformers and its impacts.
- assess the performance of generators regarding voltage.

3. Behaviour of different actors during the incident

- determine the voltage withstand capabilities that the generators were required to withstand for the relevant disconnection event, as well as whether disconnections were conforming.
- assess the impact of small generators connected to the DSOs grid, including whether additional actions and procedures are necessary to monitor and remedy a broader range of frequency oscillations.
- investigate the performance of the system defence plans.
- analyse the various steps of the restoration phase, including the efficacy of black-starts and the performance of the initial electricity islands.
- analyse alarm handling in control centres of affected TSOs, DSOs and generators.

4. Additional assessments

- assess voltage fluctuations that occurred on certain days prior to 28 April to better understand the circumstances occurred 28 April.
- assess the operation of the HVDC link on 28 April.
- assess the relevance of studies (including short-circuit, load flows, dynamic, oscillations) performed by TSOs, DSOs and operators of private networks.
- assess the actions undertaken by the TSOs to mitigate oscillations during 28 April, as well as how these actions affected voltage conditions.
- assess the cause(s) of the increased load on the transmission network concurrent with three episodes of frequency oscillations.
- analyse additional datasets mentioned in other chapters of the factual report.
- assess the security analyses from operational planning and real-time.

The Expert Panel will also assess – to the maximum extent possible – whether the most relevant requirements for this incident arising from European and/or national regulations and contracts – such as those in the SO GL, the Connection Network Codes (e.g. RfG and DCC), the Emergency and Restoration Network Code (ER NC), Synchronous Area Framework Agreement (SAFA), national regulations (e.g. voltage control and voltage operational limits) or the TSO-DSO protocol on voltage control – were fulfilled, or whether any failures contributed to the incident possibly meaning that any future processes might require adjustment.

Additionally, the final report will also establish recommendations to help prevent similar incidents in the future, not only in Spain and Portugal but across the entire European power system. As part of preparing the final report, the Expert Panel will invite key stakeholders to discuss the factual report and share their suggestions regarding the recommendations to be developed in the final report.

The Expert Panel envisages completing the final report within approximately four months following the publication of this factual report. **However, this timeline is purely indicative as it will largely depend on the complexity of the analyses that the Expert Panel will conduct and the related additional data that the Panel will need to collect accordingly.**

LIST OF ABBREVIATIONS

AAA	Adequacy Assessment Agent
ACER	Agency for the Cooperation of Energy Regulators
aFRR	automatic Frequency Restoration Reserves
AGC	Automatic Generation Control
AVR	Automatic Voltage Regulator
BS	Below Scale
CACM	Capacity Allocation and Congestion Management
CC	Capacity Calculation
CCC	Coordinated Capacity Calculation
CCGT	Combined Cycle Gas Turbine Powerplant
CCR	Capacity Calculation Region
CE	Continental Europe
CE SA	Continental Europe Synchronous Area
CECRE	Renewable Energy Control Center
CEE	Central Eastern Europe
CEST	Central European Summer Time
CGM	Commong Grid Model
CGMA	Common Grid Model Alignment
CGMES	Common Grid Model Exchange Standard
CGMM	Common Grid Model Methodology
CIM	Common Information Model
CRACs	Contingency List, Remedial Action and Additional Contraints
CSA	Coordinated Security Analysis
DA	Day-ahead
DA2CF	D-2 Congestion Forecast;
DACF	Day-ahead Congestion Forecast
DFR	Disturbance Fault Recording
DOPT	Daily Operational Planning Teleconference
DSO	Distribution System Operator
EAS	ENTSO-E Awareness System
EMF	European Merging Function

FCA	Forward Capacity Calculation
FCIC	Fast Current Injection Controller
FFT	Fast Fourier Transform
GC ESC	Grid Connection European Stakeholder Committee
GS	Generation substation
HPP	Hydropower Plant
HV	High Voltages
IBR	Inverter-Based Resource
ICS	Incident Classification Scale
ID	Intraday
IDCF	Intraday Congestion Forecast
IEC	International Electrotechnical Commission
IGCC	International Grid Control Cooperation
IGM	Individual Grid Model
KE	Kinetic Energy
LFC	Load-frequency Control
LFDD	Low Frequency Demand Disconnection
LT	Long term
MARI	Manually Activated Reserves Initiative
mFRR	manual Frequency Restoration Reserve
MMs	Modulation Modules
NC ER	Network Code on Emergency and Restoration
NRA	National Regulatory Authority
NTC	Net transfer capacity
OHL	Overhead Line
OMIE	Operador del Mercado Ibérico de Energía
ONEE	L'Office National de l'Électricité et de l'Eau potable
OPC	Outage Planning Coordination
OPDE	Operational Planning Data Environment
OPI	Outage Planning incompatibility
OPR	Operating Power Range

OPSC	Outage Planning Security Constraints
PCA	Principle Component Analysis
PE	Pan-European
PEVF	Pan European Verification Function
PGM	Power Generation Module
PI	Proportional-Integral
PMU	Phasor Measurement Unit
POD	Power Oscillation Damping
PSS	Power System Stabiliser
PST	Phase Shifting Transformer
PV	Photovoltaic
RA	Remedial Action
RCC	Regional Coordination Centre
RCW	Renewable, cogeneration, and waste
RE	Red Eléctrica
REN	Rede Eléctrica Nacional
RES	Renewable Energy Sources
RG CE	ENTSO-E Regional Group Continental Europe
RIAR	Regional Incident Analysis and Reporting
RoCoF	Rate of Change of Frequency
ROSC	Regional Operational Security Coordination
RPCL	Reactive Power Control Loop
RR	Replacement reserve
RSC	Regional Security Coordinator
RTE	Réseau de Transport d'Electricité
RTSN	Real-time-snapshot
SA	Security Analysis
SAFA	Synchronous Area Framework Agreement
SAM	Synchronous Area Monitor
SCADA	Supervisory Control And Data Acquisition
SEE	South-East-Europe
SGU	Significant Grid Users
SO	System Operator
SO ESC	System Operation European Stakeholder Committee
SOC	ENTSO-E System Operation Committee
SOGL	System Operation Guidelines
SS	Substation
STA	Short-term adequacy
SVR	Secondary Voltage Regulator
SWE	South West Europe
TCI	Training and certification of staff working for RCCs
TERRE	Trans European Replacement Reserves Exchange
TLIs	Tie-line Inconsistencies
TPP	Thermal Power Plant
TRM	Transmission Reliability Margin
TS	Transmission Substation
TS	Only for Chapter 5: Timestamp
TSO	Transmission System Operator
TTC	Total Transfer Capacity
UAP	Unavailability Asset Plan
UCTE DEF	Union for the Co-ordination of Transmission of Electricity Data Exchange Format
WOPT	Weekly Operational Teleconference
YA	Year-ahead

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