» Grid Incident in Spain and Portugal on 28 April 2025

ICS Investigation Expert Panel

Final Report

20 March 2026

Preamble

This final report is prepared by the Expert Panel established to perform this technical investigation, 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 final report provides a factual, technical, and objective account of the incident to transparently inform stakeholders and governance bodies. Its purpose is to identify the causes of the incident and to recommend measures that strengthen the resilience of the European power system. It aims to support transparency, learning and continuous improvement in system operation across Europe.

The analyses, findings, and recommendations contained in this final report are based on data, documents, and other materials provided by the impacted TSOs and DSOs, as well as some generators and other third parties. While the Expert Panel has exercised due care and applied its best effort in reviewing and evaluating the information received, it does not independently verify, audit, or validate the completeness, accuracy, or reliability of any external data sources. Importantly, the report is not intended to assign liability or responsibility to any party and should not be interpreted as doing so in any way.

This report has been prepared and agreed upon by the Expert Panel. Any analyses, findings, and recommendations set out in this report reflect the Expert Panel's technical assessment at the time of writing and are without prejudice to any investigation or enforcement action that may be taken by the competent authorities.

The recommendations outlined in this report represent a comprehensive set of measures designed to enhance operational robustness, improve cross-stakeholder information exchange, and contribute to maintaining a high level of security of supply across the European power system. The monitoring of the recommendations' implementation provided in this report does not fall within the mandate or remit of the Expert Panel. While voluntary in nature, the recommendations are intended to prompt and support concrete action to help prevent the recurrence of similar events in the future. Any responsibility for the consideration, follow-up and implementation of the recommendations lies with each addressee.

Finally, the recommendations may serve as a basis for future regulatory development, inviting competent authorities to consider, within their respective mandates, possible regulatory or implementation measures, with a view to ensuring that the lessons learned from this incident are duly reflected in the applicable requirements and to establishing a framework aimed at preventing similar incidents in the future.

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CONTENTS

1 MANAGEMENT SUMMARY 6

1.1 Introduction 6
1.2 System and Market Conditions Before the Incident 9
1.3 System Conditions during the Incident 13
1.4 Technical analysis 17
1.5 Restoration Process 25
1.6 Operational Planning 27
1.7 Communication of Synchronous Area Monitors and Between TSOs 27
1.8 Classification of the Incident Based on the ICS Methodology 27
1.9 Conclusions and Recommendations 28

2 SYSTEM AND MARKET CONDITIONS BEFORE THE INCIDENT 29

2.1 Information on Topology 30
2.2 Market Conditions 41
2.3 Active Power Flows Before the Incident 41
2.4 Inertia 50
2.5 Oscillations 54
2.6 Reactive Power and Voltages 80
2.7 Behaviour of the HVDC Link 101
2.8 Annex 111

3 SYSTEM CONDITIONS DURING THE INCIDENT 116

3.1 Dynamic Behaviour of the System During the Incident 116
3.2 Performance of the Protection System During the Incident 140
3.3 System Defence Plan 197
3.4 Impact of the Blackout on System Users on the French Network 205

4 ANALYSIS OF RELEVANT FACTORS 206

4.1 Voltage control 206
4.2 Oscillations 231
4.3 Analysis of Flows Between TSO and DSO Grids in Spain 278
4.4 System Stability and Defence Plans 297
4.5 Management of alarms related to voltage 319
4.6 Root Cause Tree 331

5 RESTORATION PROCESS 336
5.1 Preconditions and strategies for the restoration process 336
5.2 The restoration sequences in the Spanish system 339
5.3 The restoration sequences in the Portuguese system 363
5.4 French local area restoration by RTE 378
5.5 Generation and load recovery 381
5.6 Steps after system restoration 388
5.7 Market restoration 389
5.8 Behaviour of distributed energy resources and load during restoration 390
5.9 Voice communication and remote-control problems during restoration 391
5.10 Conclusion 392

6 OPERATIONAL PLANNING 395
6.1 Introduction 395
6.2 RCC Processes and Investigation 399
6.3 Operational Planning in Spain 421
6.4 Perspectives in forecasting oscillatory phenomena 431

7 COMMUNICATION OF SYNCHRONOUS AREA MONITORS AND BETWEEN TSOs 433
7.1 Communication between TSOs 433
7.2 ENTSO-E Awareness System (EAS) 444

8 CLASSIFICATION OF THE INCIDENT BASED ON THE ICS METHODOLOGY 447
8.1 Scale of the Incident 448
8.2 RCC Investigation Threshold 448
8.3 Scale of all Violations Linked to the Incident 448

9 CONCLUSION AND RECOMMENDATIONS 451
9.1 Summary 451
9.2 Observations on the Applicable Requirements 454
9.3 Recommendations Directly Linked to Root Causes 455
9.4 Recommendations Not Directly Linked to Root Causes 461

LIST OF ABBREVIATIONS 466

REFERENCES 468

EXPERT PANEL MEMBERS 470

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 the most severe and unprecedented blackout that had occurred in Europe in the past 20 years, with a major impact on citizens and society as a whole in both countries. 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.

The blackout occurred after an uncontrolled, rapid rise in system voltage and loss of voltage control on a day with multiple concurrent phenomena, accelerated by rapid generation output reductions and disconnections, leading to voltage instability and cascading generation disconnections in Spain.

Following the incident, the affected transmission system operators (TSOs) REN (Portugal) and Red Eléctrica (Spain) immediately activated their respective system restoration plans. In addition, RTE (France) initiated all necessary procedures and protocols to restore voltage levels in the French electricity system. System restoration in Portugal was completed by 00:22 on 29 April 2025, and in Spain, the transmission system was fully restored by 04:00 on the same day.

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 in accordance with the **Incident Classification Scale (ICS) Methodology**[1]). Consequently, pursuant to the same legal framework, an Expert Panel was set up, which began investigating the incident on 12 May 2025 to deliver the factual report first and the final report thereafter. The reports were prepared in line with the ICS methodology applicable at the time of the incident.

In accordance with the ICS methodology, the Expert Panel comprises representatives from both 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 49 experts: 30 from ACER and NRAs and 19 from TSOs, RCCs, and ENTSO-E bodies across Europe (the complete list of Expert Panel members is available on the final page of this report).

One member from each affected TSO participated and actively contributed to the plenary Expert Panel. In line with the terms of reference, their contribution involved providing input and suggestions but not acting as the primary authors of either the factual or the final reports.

Given the technical complexity of this incident and the numerous aspects to be investigated, the Expert Panel organised its work of analysing the data and drafting this report across several areas (voltage control, oscillations, etc.). Each area was assigned to a specific subgroup of experts reporting to the Expert Panel. Each subgroup was led by a member of the Expert Panel who was not affiliated with the affected TSOs.

In these subgroups, additional experts from affected TSOs participated and contributed via text suggestions, figures, analyses, and/ or other input. Their contribution was assessed by the relevant subgroup of experts before being submitted to the Expert Panel. These measures aim to ensure the neutrality of the final report.

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[1] The ICS Methodology was developed pursuant to Regulation (EC) No 714/2009 of the European Parliament and of the Council of 13 July 2009, as repealed by the Regulation (EU) 2019/943, and updated to fulfil the objectives under Article 15(5) of the Commission Regulation (EU) 2017/1485 of 2 August 2017 establishing a guideline on electricity transmission system operation (SO GL)

This final report builds on the factual report published by the Expert Panel on 3 October 2025, as foreseen by the ICS methodology. For the sake of completeness, almost all data presented in the factual report is also included in the final report, so that the reader does not have to consult both reports in parallel. A limited number of changes were made to the data presented in the factual report, reflecting a deeper understanding of the matter. Furthermore, the final report also includes specific data that were unavailable at the time the factual report was published. These data are included to ensure the highest possible quality and correctness of the final report.

The structure of the final report is similar to the factual report, with two major differences: (i) a new Chapter 4 is added, presenting the detailed analyses performed by the Expert Panel and identifying the root causes of the incident; and (ii) Chapter 9 presents the conclusions of the investigation and the recommendations of the Expert Panel aimed at improving the performance and resilience of the power system across Europe.

This first chapter provides a high-level summary of the report, following the same structure as the report itself. It also includes a specific sub-chapter on data collection, given that collecting complete and 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, this 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 Annexes 1 ("*Common data for reporting*"), 2 ("*Specific data reported for depending on the ICS criterion*") and 3 ("*Additional data for the investigation of scale 2 and scale 3 incidents*"). The methodology also indicates that the Expert Panel shall request additional data and information deemed necessary for the investigation, including data owned by third parties not represented in the Expert Panel (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. 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. Furthermore, given that DSOs did not seem to have access to actual production data from small embedded generators with a production capacity of less than 1 MW (typically rooftop PV), the Expert Panel contacted several manufacturers of PV inverters to obtain such data in an aggregated manner. Two of these companies delivered data in time for the Panel to consider. Finally, the Expert Panel received several voluntary contributions from various third parties (i.e., companies and a trade association).

Data collection from DSOs and significant grid users

Data and information requested from DSOs comprised information on the following, among others:

- any disconnection of generators before the incident;
- the generation mix in the DSO grid before the incident;
- any voltage alarms or exceeded voltage thresholds;
- load shedding;
- the restoration process.

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

- a list of generation facilities in operation on 28 April and any related power system stabilisers;
- information on generation tripping, 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;
- information on the black-start process related to the restoration phase.

In line with the ICS 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 collected the necessary data and transferred it to the Expert Panel in a timely manner. The following parties delivered data:

- DSO in Portugal: E-Redes.
- Generators in Portugal: Akuo, Aquila, Axpo, CWPOWER, Dos Grados, EDP-Produção, EML, 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 from the Expert Panel leaders to the Spanish TSO, Red Eléctrica, on 26 May, and the other from ENTSO-E to the Spanish authorities on 28 May. Following these letters, Red Eléctrica obtained consent from 33 generation companies[2] and DSOs to share all relevant data at its disposal with the Expert Panel, while eight others delivered their data directly to the Expert Panel after being requested by the Panel leaders.

More than 240 emails and letters were exchanged between the Expert Panel leaders and the third parties concerned between 28 June 2025 and 17 February 2026 to finalise the data collection process. Additionally several meetings and workshops were organised with third parties impacted by the incident (DSOs, generators), with the aim to clarify the information submitted to the Expert Panel.

Overall, the following Spanish 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.

Consequently, the Expert Panel collected a significant amount of data from DSOs and significant grid users. However, some data remain missing, particularly for generation trips that occurred before the blackout, which prevented the Expert Panel from identifying the cause of tripping for generation units due to missing or no fault recordings. The concerned parties (namely, the owners of those facilities) all cited the lack of fault record data as the reason they were unable to provide this information to the investigation.

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 of the European Parliament and of the Council of 5 June 2019 on risk preparedness in the electricity sector.
- Several spontaneous submissions, including letters, 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 2025.
- Red Eléctrica report required by the Spanish regulation (Operational Procedure PO 9) published on 18 June 2025.
- Presentations given by E.DSO, EU DSO Entity and Eurelectric during the joint workshops 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 and 13 October 2025.

While the investigation is primarily based on the raw data and information collected at the Expert Panel's request, the Expert Panel also considered these additional external documents in preparing the final report.

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[2] 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.

Treatment of confidential information

The collection of data required for the purposes of this investigation and the drafting and elaboration of the factual and final reports by the Expert Panel have been performed in line with the ICS methodology and the confidentiality requirements established in both the European and relevant national regulatory frameworks. To safeguard confidentiality while upholding transparency, the Expert Panel has adopted a balanced approach, under which any data provided by the affected TSOs linked to individual generators and/or by third parties and classified as confidential has been anonymised. 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 conducted by the Expert Panel, ensuring confidentiality 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 where they are located 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

During its investigation, the Panel has determined that the incident began at 12:32:00 on 28 April 2025. Chapter 2 of the report therefore covers the period prior to that time, starting at 9:00.

The day of the incident was a typical spring day in Spain, with mild temperatures and mostly sunny weather. 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.

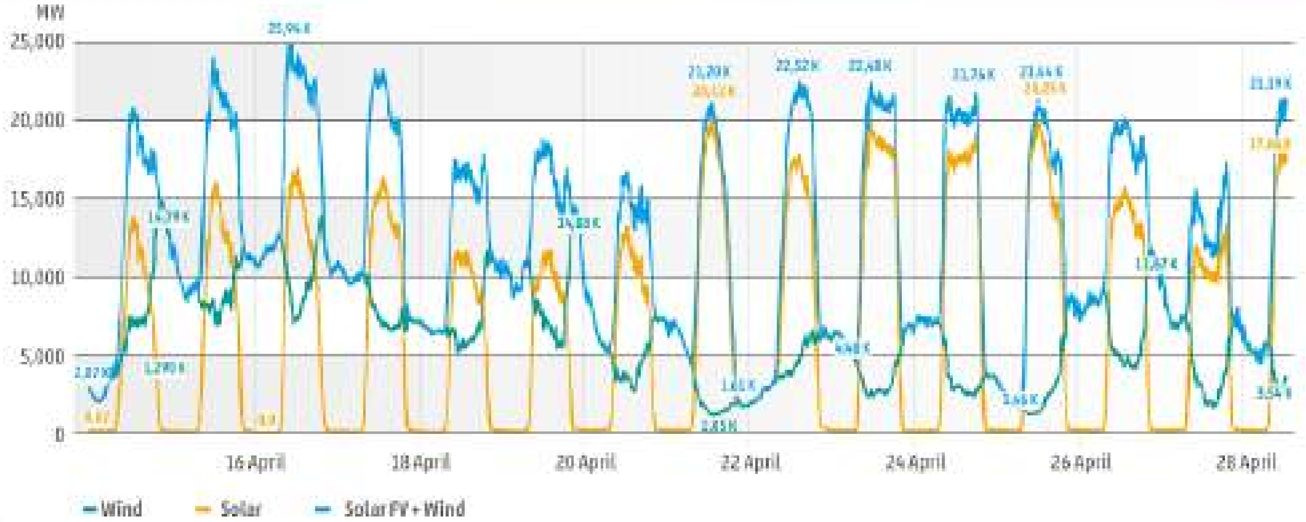


Figure 1-1: Solar and wind production (in MW) in Spain on previous days and the day of the incident, not including small PV units (<1 MW)

The morning hours of 28 April 2025 were characterised by an increasing generation of renewables, which led to lower prices on the day-ahead market and to Spain's exports reaching 5 GW in total. From approximately 09:00, the voltage variability in Spain began to increase, albeit without significant fluctuations, 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.

With the exception of one node (Olmedilla), the voltages in the 400 kV network remained below 435 kV during the period before the incident. Oscillatory behaviour was noted in the morning, but no significant oscillations with amplitudes above 20 mHz were detected until 12:03.

Figure 1- 2 illustrates voltage evolution in the main 400 kV transmission substations (pilot nodes) in Spain from 9:00.

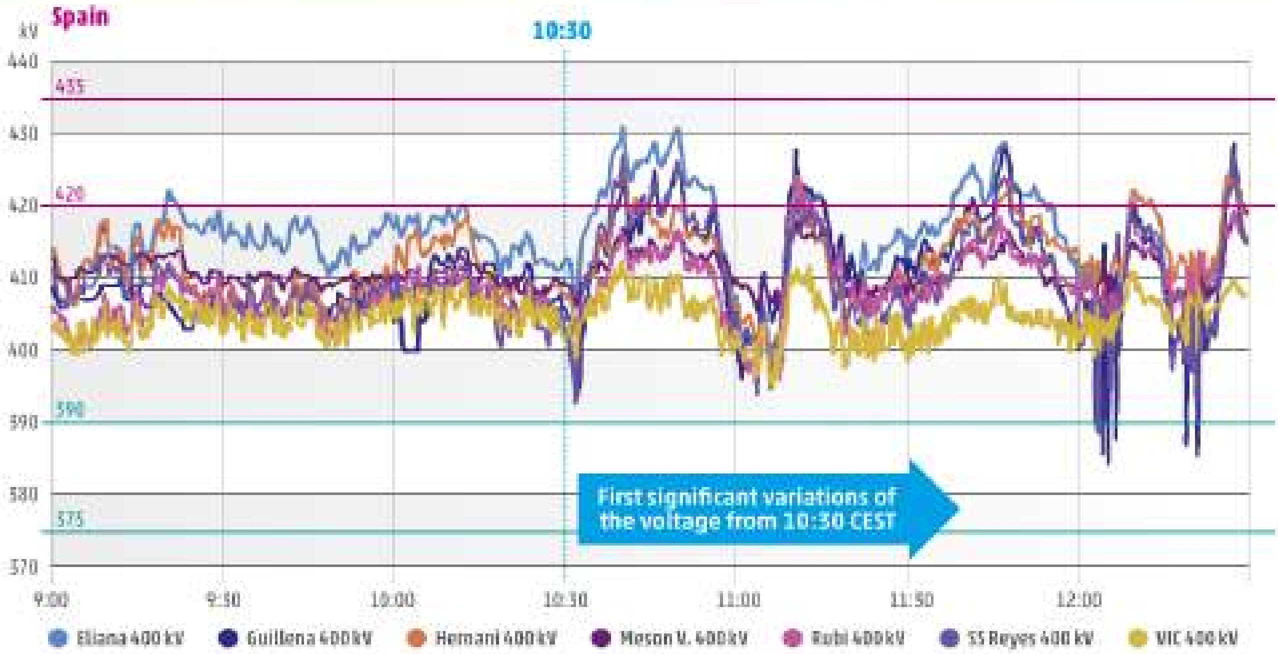


Figure 1-2: Voltage evolution in the main 400kV transmission substations (pilot nodes) in Spain

During the observed time period, the voltage levels on the 400 kV network in Portugal remained within the normal range of operation (380 kV to 420 kV), which differs from the ranges allowed in Spain.

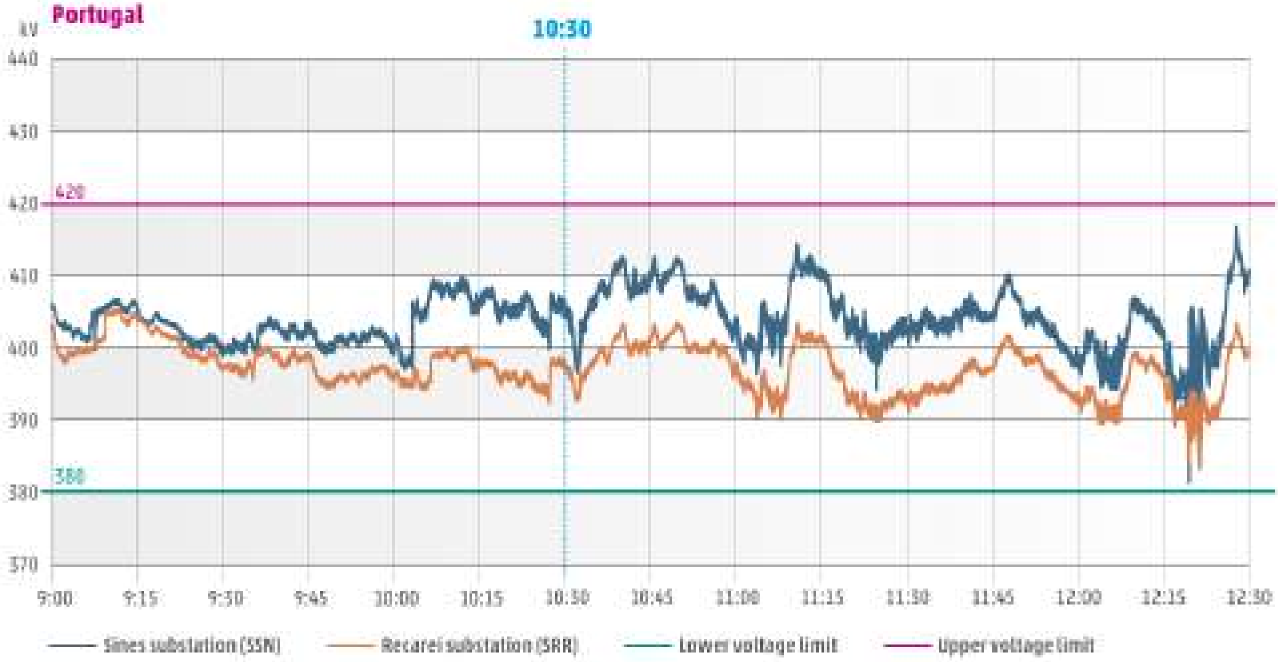


Figure 1-3: Voltage evolution in the main 400kV transmission substations (pilot nodes) in Portugal

An analysis of the geographical distribution of generation and consumption in Spain reveals that electricity production in the south-west of the country was very high relative to consumption in that region. This results in high electricity transit flows from the southwest of Spain to the surrounding areas.

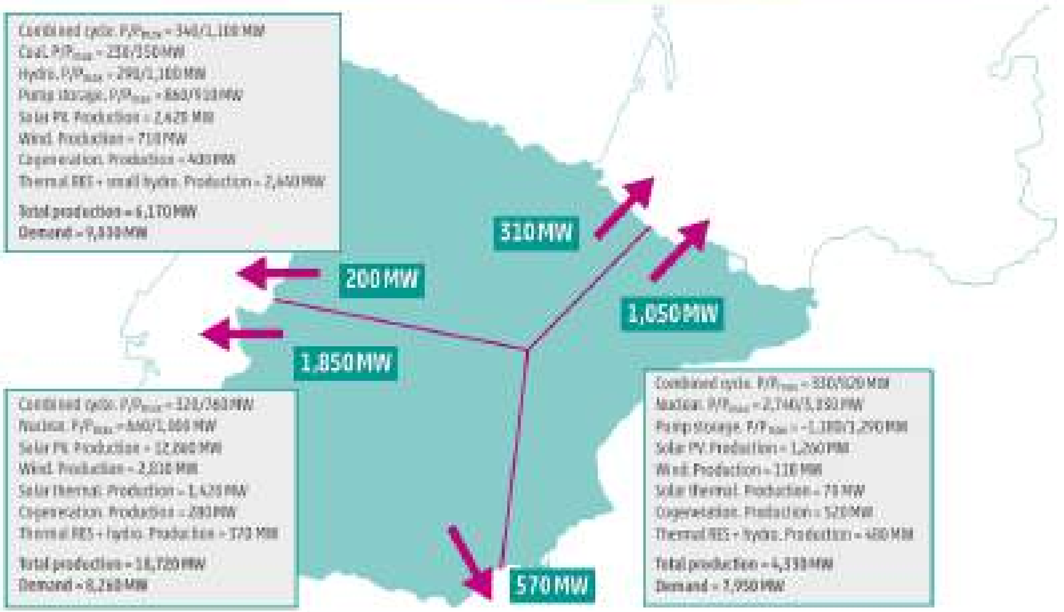
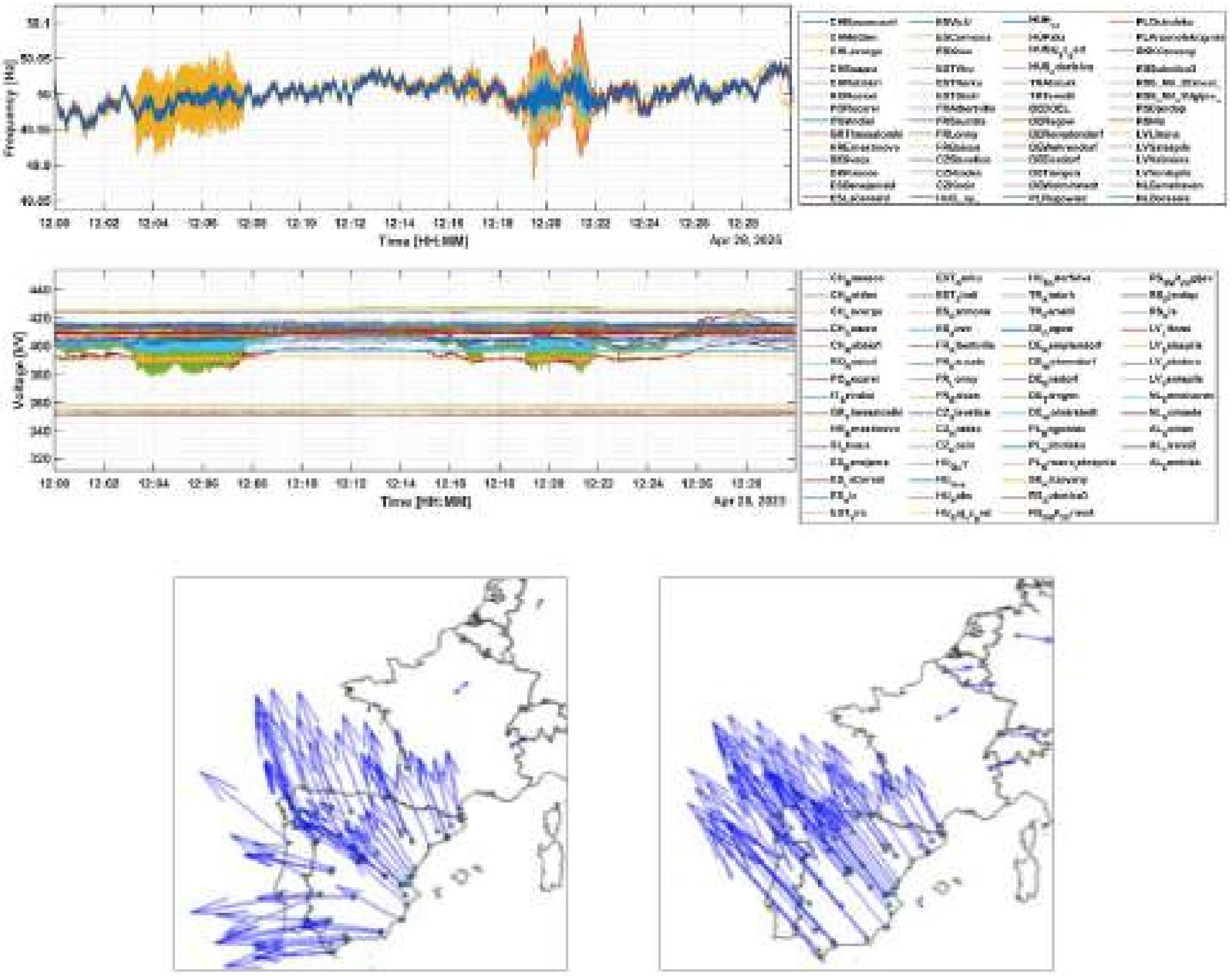


Figure 1-4: Geographical distribution of the generation and consumption in Spain at 12:32

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 classified as converter-driven instability phenomenon primarily affecting the 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 0.2 Hz, corresponding to the East-Centre-West continental mode.



Local oscillation by 0.63 Hz

Inter-area oscillation by 0.2 Hz

Figure 1-5: Oscillatory episodes during the half hour preceding the blackout: Frequency and voltage phasor magnitude measurements from European PMUs (top); mode shapes of the two oscillations (bottom)

To damp these oscillations, the operators in the control rooms of the relevant TSOs took several mitigating measures, such as reducing exports from Spain to France, coupling internal power lines in the South of Spain, and changing the operating mode of the high-voltage direct current (HVDC) link between France and Spain. While these measures effectively mitigated the oscillations, their nature led to an increase in voltage in the Iberian power system.

At 12:32:00 the voltage of the Iberian power system at the 400 kV level was below 420 kV and no notable oscillation with amplitude higher than 20 mHz could be observed. The evolution of the system and market conditions up to this point is explained in further detail in Chapter 2.

1.3 System Conditions during the Incident

After 12:32:00, the voltages at numerous nodes rose, as shown in the Figure 1-6.

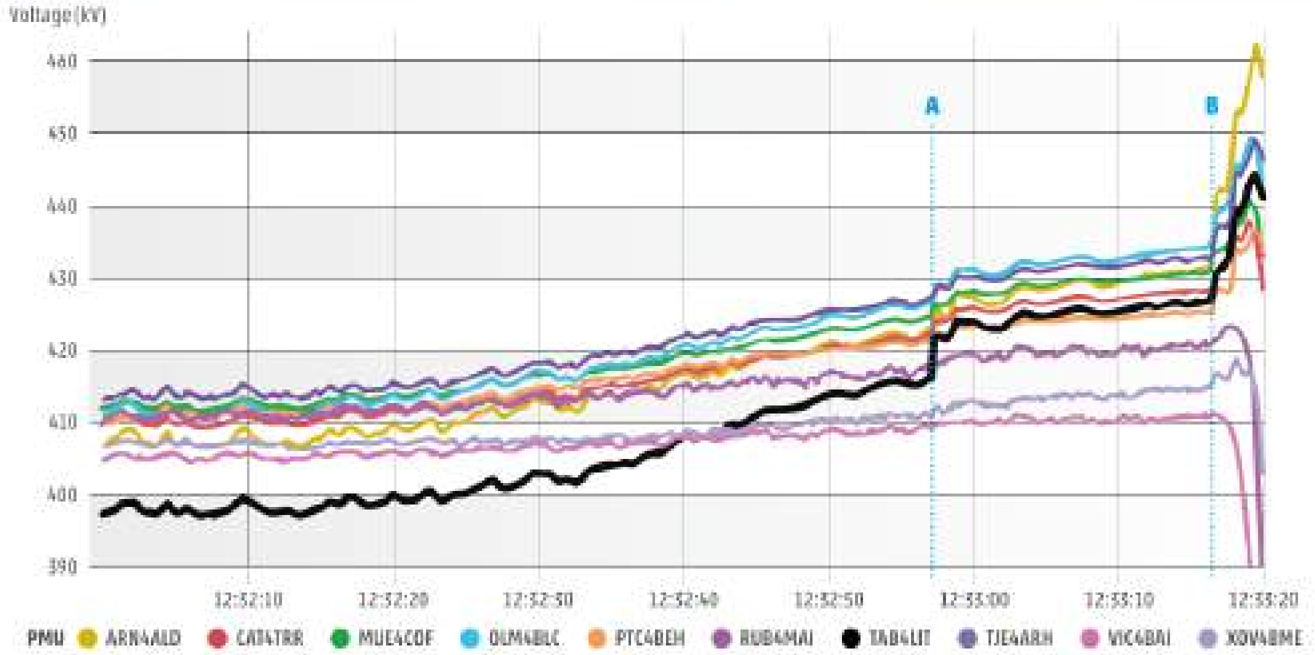


Figure 1-6 : Voltage (positive symmetrical component) evolution in the Spanish power system after 12:32:00 (PMU data). Phase asymmetry (not visible in this chart) was observed in some nodes.

Around 12:30, several generators changed their active power output. From 12:32:00 to 12:32:48, concurrent with the voltage rise shown in Figure 1-6, the active power output of large Renewable Energy Sources (RES) generators (higher than 5 MW) in Spain decreased by approximately 500 MW. The RES power plants maintained a fixed power factor, meaning that changes in active power also affected the generators' reactive power output.

Additional events (mainly generation-related) occurred from 12:32:00 onwards. Between 12:32:00 and 12:32:57, 208 MW of identified distributed wind and solar generating units in northern and southern Spain experienced either a fast downwards change of operating point of a unit without a ramping restriction, or a disconnection of the unit due to unknown reasons.

In the same period, there was an increase in net load in the distribution grids of approximately 317 MW, which can be attributed partly to disconnections of small embedded generators <1 MW (mainly rooftop PV[3]) and partly to an increase in voltage-dependent load as a result of a voltage rise. The exact reasons for some of these events are not known.

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[3] See Section 4.3 for further explanations.

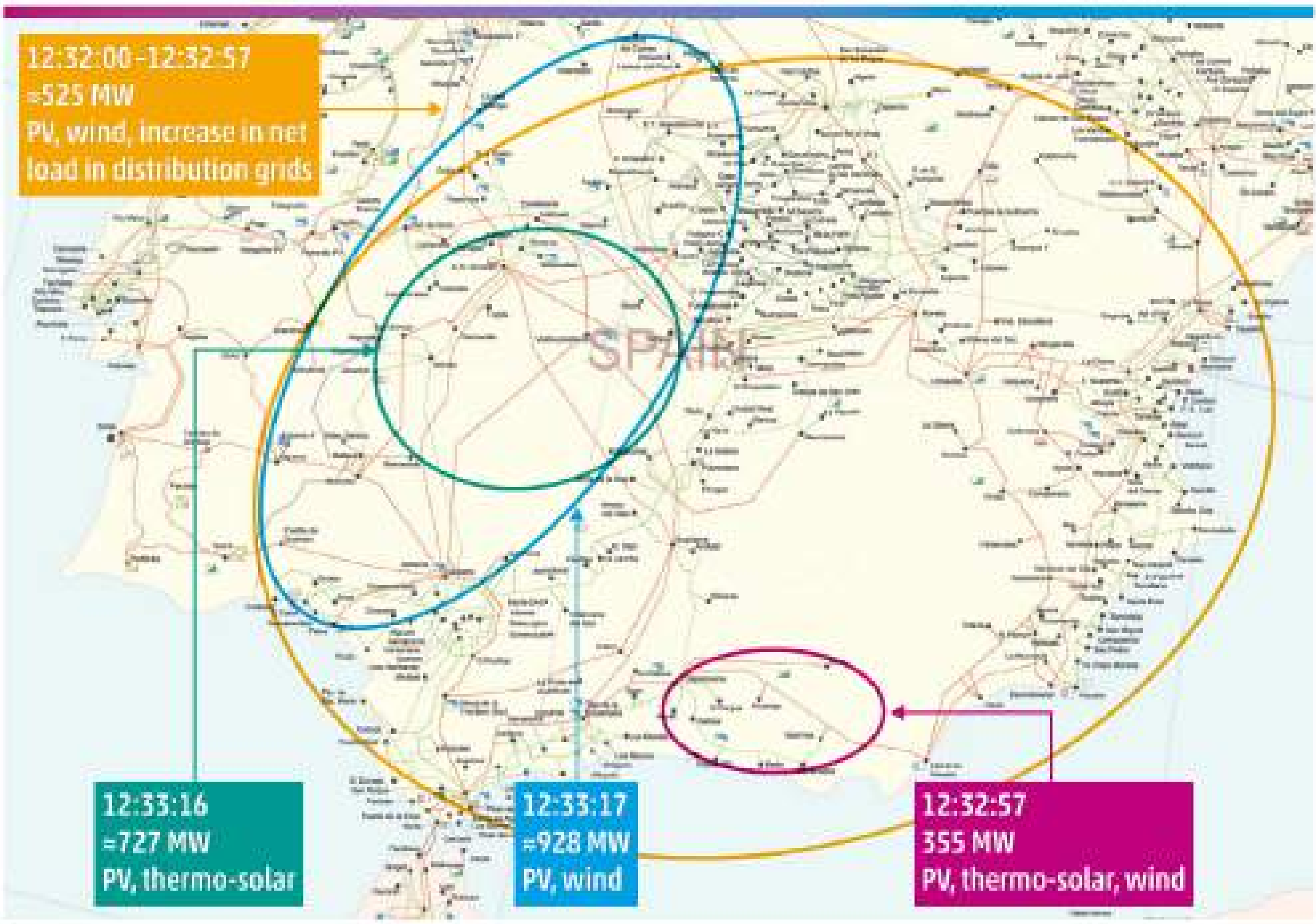

Figure 1-7: Areas of major generation disconnection events in Spain until 12:33:18

From around 12:32:20, a particularly steep rise in local voltage occurred at a substation in the area of Granada (see the nearby PMU coloured in black in Figure 1-6). Some milliseconds after 12:32:57, a 400/220 kV transformer in the same substation tripped due to the activation of an overvoltage protection in the 220 kV side of the transformer, which connects several generation facilities (photovoltaic, wind and thermo-solar) to the transmission grid. Just before the disconnection, the transformer was injecting 355 MW into the grid and absorbing 165 Mvar of reactive energy, and the voltage at the 400 kV level was 417.9 kV. This event created an additional step change in voltage (see Figure 1-6).

The next event consisted of two sets of trips, resulting in an additional loss of 727 MW of PV and thermo-solar facilities connected to two 400 kV transmission substations in the area of Badajoz. At the first substation, an evacuation line tripped at 12:33:16.443 due to the activation of the overvoltage protection. The positive-sequence voltage level at the time of this trip is estimated at 432.4 kV via indirect calculations due to the lack of high-resolution voltage data at the connection point. In the second substation, the trip occurred at 12:33:16.820 due to overvoltage protection.

After that, several trips between 12:33:17 and 12:33:18.020 occurred, leading to the disconnection of wind and solar generation in Segovia, Huelva, Badajoz, Sevilla and Caceres, for a total of 928 MW. Some of these trips occurred due to overvoltage protection, but the Expert Panel was not able to establish the cause of most of these trips. The analysis carried out by the Expert Panel indicates that the overvoltage protection settings at some generation units were set below the voltage limits established in accordance with the applicable requirements.

Figure 1-8 illustrates an increase in voltage beyond 435 kV during this sequence, excluding the 0.5 GW generation schedule changes. The figure therefore shows 317 MW net load increase assumed at 12:32:00, 208 MW fast downwards change of operating point or tripping due to an unknown reason between 12:32:00 and 12:32:57, and identified trips from 12:32:57 onwards until 12:33:18.020, adding up to more than 2.5 GW in total).

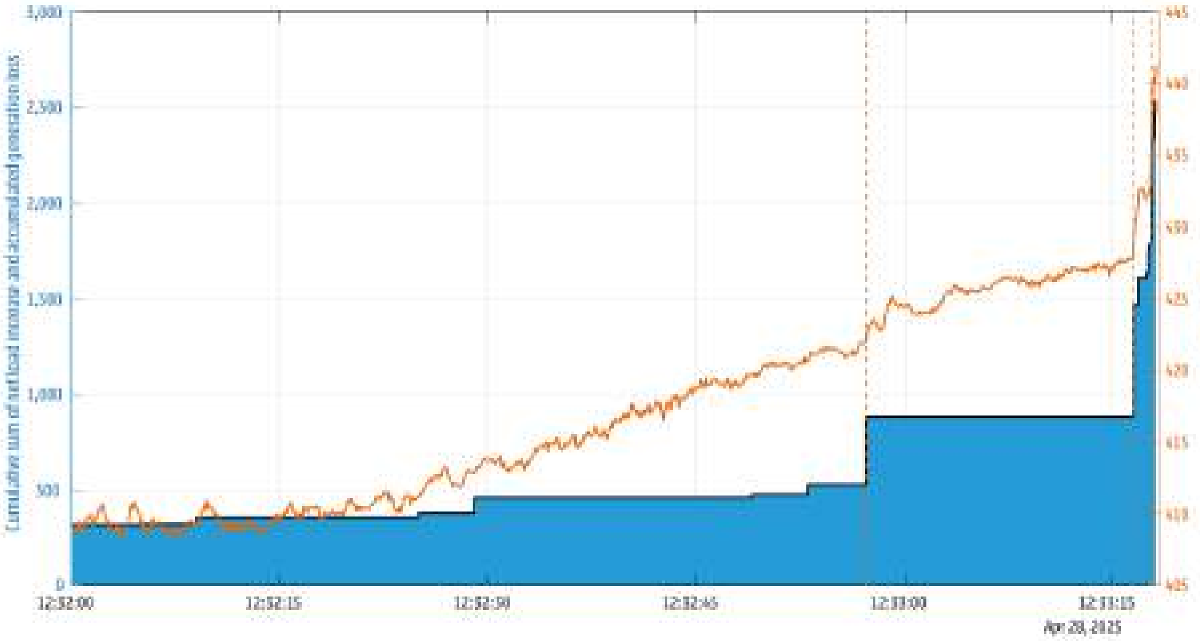

Figure 1-8: Accumulated generation loss combined with net load increase in the Iberian Peninsula system vs voltage at the 400 kV substation in Carmona (Spain). Dotted lines represent the first three main generation disconnection events.

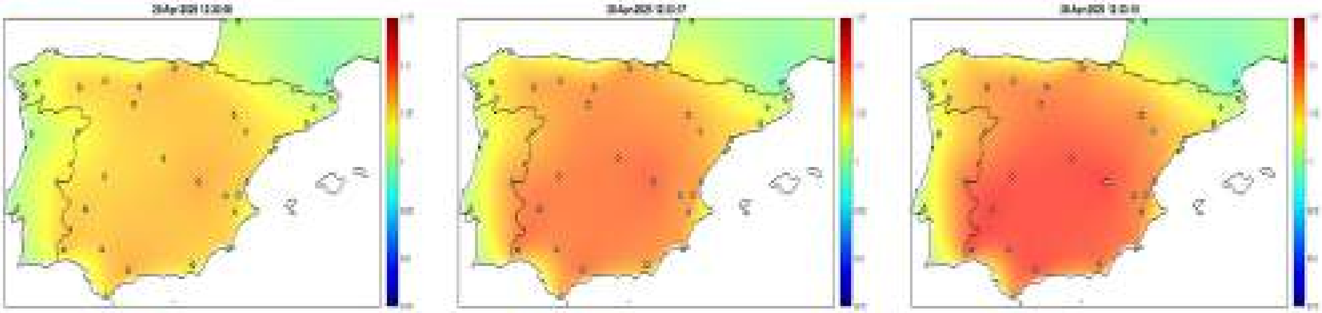

Figure 1-9: Heat map of the Iberian Peninsula for the temporal instants at (a) 12:32:58, (b) 12:33:17, and (c) 12:33:18, showing voltage magnitudes at different substations.

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

Some generation units were consuming reactive power, which reduced the voltage. However, the disconnections of these units without adequate compensation for the loss of reactive power absorption by other resources capable of controlling reactive power led to increased voltages not only in Spain but also in Portugal. Furthermore, the frequency decreased.

Between 12:33:18 and 12:33:21, the voltage in the South of Spain increased sharply, and consequently also in Portugal. The overvoltage triggered a cascade of generation losses, causing the frequency of the Spanish and Portuguese power systems 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 were 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 due to a loss of synchronism, preventing the propagation of the perturbation into the CE power system.

From that moment on, the Spanish and Portuguese grids operated in island mode. After this AC separation of the Iberian Peninsula, the power imbalance continued to grow, leading to a further decline in frequency.

Finally, at 12:33:23.960, the electrical separation of the Iberian system was completed by tripping the HVDC lines that were still transmitting power from Spain to France (due to the constant power mode setting at the time). All system parameters of the Spanish and Portuguese electricity systems collapsed.

Figure 1-10 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 remained 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, indicating that the system conditions had already degraded.

Compared with the blackouts in Spain and Portugal, France was marginally affected by the incident. In addition to a loss of approximately 7 MW of 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.

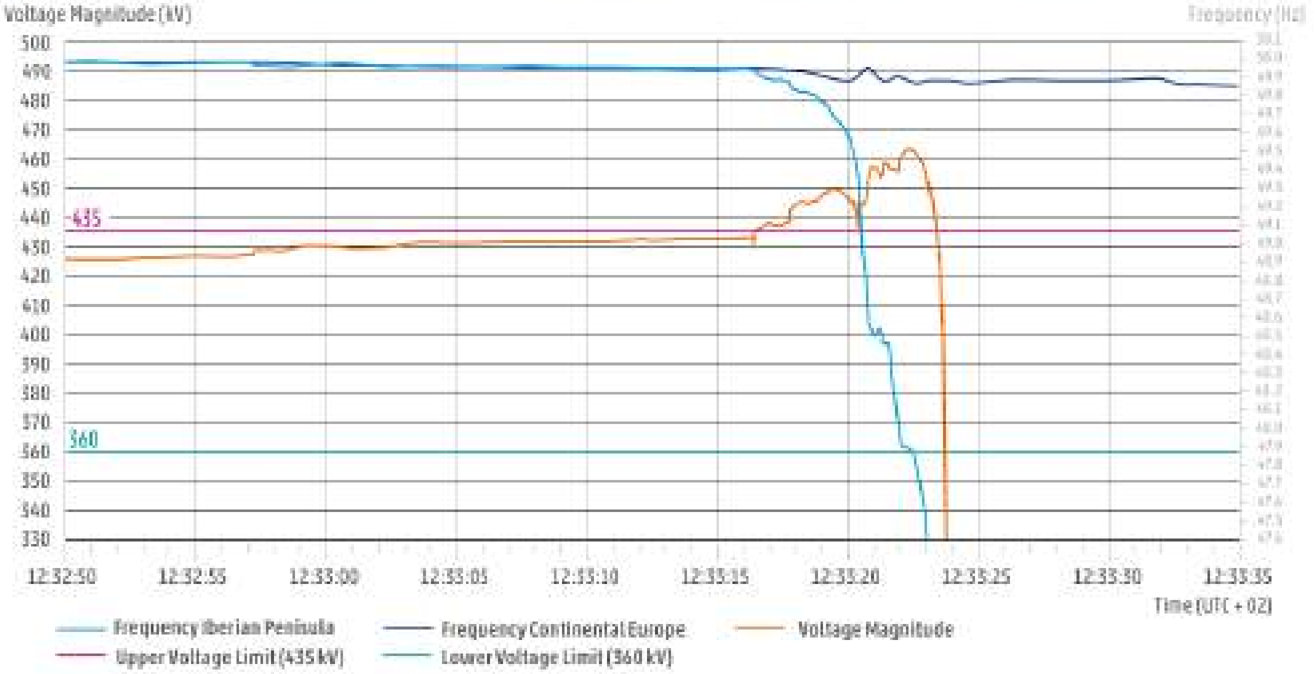

Figure 1-10: Evolution of the frequency and the voltage in the substation of Carmona (Spain) and of the frequency in the rest of Continental Europe (substation of Bassencourt, Switzerland) during the incident.

A comprehensive description of the system conditions during the incident is available in Chapter 3.

1.4 Technical analysis

Chapter 4 of the report presents detailed technical analyses of the phenomena and actions that preceded the blackout, to understand the precise causes of the incident. All these analyses are based on the factual data collected and presented in the relevant chapter of the report. Based on the results of the technical analyses, the Expert Panel established a root cause tree describing the key factors that ultimately led to the blackout.

While the root cause tree analysis describes the role of each element in the tree and the relationship between them, the detailed explanation of the elements is provided in the technical analysis.

It should be noted that these technical analyses focus on the Spanish system, as the facts described in chapters 2 and 3 indicate that the blackout originated in Spain, not in Portugal.

1.4.1 Voltage control

The first area of technical analysis concerns voltage control, which was an important aspect of this incident. The voltage control capability of a system depends on many factors, including the reactive power capacity of the system and the design of the voltage control scheme at all voltage levels (including TSO-operated integrated network components and the requirements applicable to the reactive-power-related behaviour of third parties, particularly generators).

The analysis identifies several factors that contributed to the deterioration of system conditions on 28 April 2025, particularly in the sudden voltage increase observed from around 12:32:00 onwards. They included the following, in no specific order of importance:

- Switching of network components for voltage control, such as shunt reactors, was undertaken manually,[4] which required a certain amount of decision-making and processing time.
  - Some shunt reactors had been previously disconnected due to low voltages during the oscillation episodes up to 12:24.
- According to the requirements applicable on the day of the incident, the RES generators followed a fixed power factor for reactive power provision, thereby not contributing effectively to the voltage control of the system.
  - The fixed power factor mode means that generators absorb reactive power proportionally to active power, and do not respond to voltage fluctuations.
- Regarding conventional synchronous power plants, the analysis shows that the reactive power output of several generators reached Q-reference less than 75 % of the samples (per hour). The reactive power output was not aligned with the TSO expectations based on the requirements under the applicable Operational Procedure 7.4[5].

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[4] The Expert Panel has not comprehensively assessed the approach across all TSOs. Nevertheless, several TSOs participating in the Panel indicated that they only have manual control of shunt reactors, while RTE indicated they have a hybrid approach (combination of manual and automatic control).

[5] This is without prejudice to any potential derogations from the requirements, which the Expert Panel is not competent to assess. The scope of this investigation and the mandate of the Expert Panel do not provide it with any authority or intention to interpret the applicable legislation or to determine liabilities for non-compliance with legal requirements. The analysis is based on RE's SCADA data.

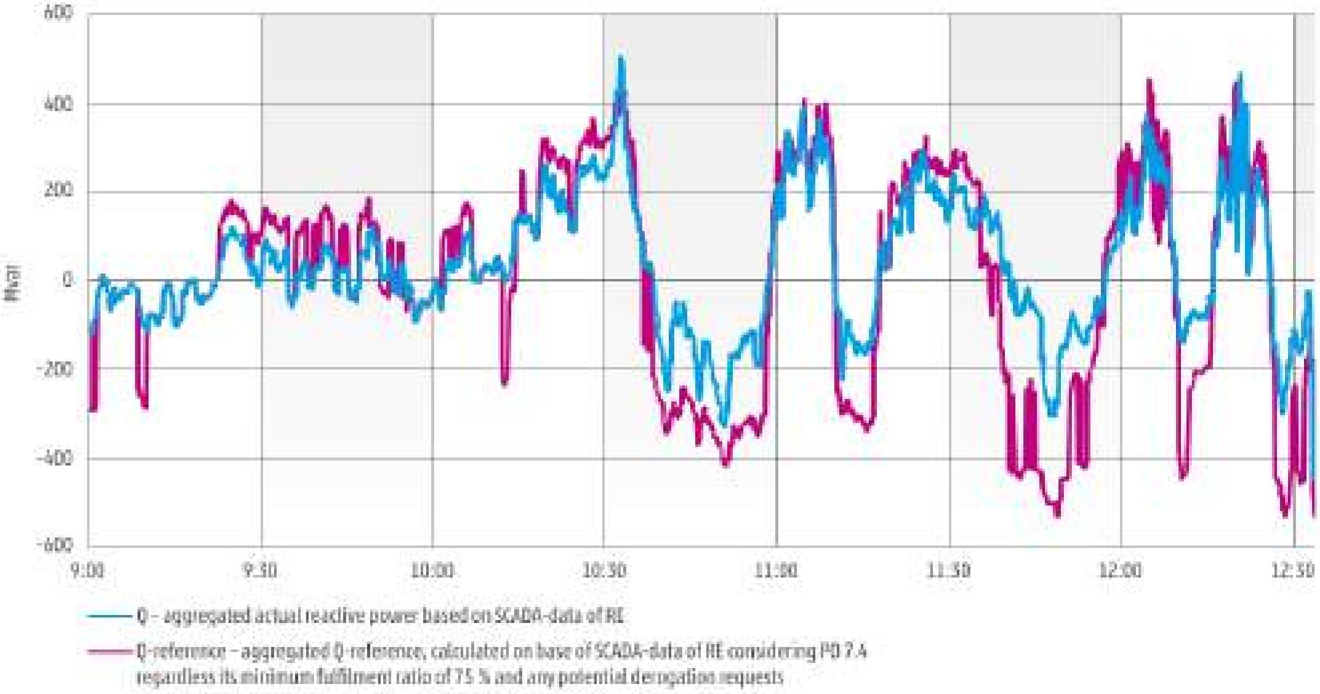

Figure 1-11: Reactive power provided (Q) and the reference reactive power (Q-reference) aggregated for conventional generation units larger than 100 MW of power installed capacity in the centre/southwest area of Spain, based on SCADA data from RE.

- The applicable Operational Procedure 7.4 concerning reactive power provision by synchronous generators did not include explicit specifications concerning dynamic behaviour, and there were no economic consequences if the requirements regarding voltage control were not met.
- The design of voltage control of some local generation networks (extensive grids behind the transmission grid connection point, shared by several generation portfolios) was not aligned with system needs.
  - This also contributed to some of these facilities disconnecting when the voltage at the connection point was within limits.
- Due to Spain's wider operating voltage range of the 400 kV grid compared to the rest of Europe, the margin between the allowed operating voltage limit and the voltage at which generators are allowed to disconnect was very small or non-existent.

Together, the reactive power assets in the system were not able to address the sudden voltage rise. The reactive power absorption status of three asset groups is shown in Figure 1-12. The figure aggregates, by asset group, the total reactive power capacity in the Spanish system on the day of the incident, as well as the actual reactive power absorption at the moment of the incident. However, it should be noted that these categories of assets have different static and dynamic reactive power characteristics: on the day of the incident, conventional synchronous machines (here: PO 7.4 generators) dynamically controlled voltage locally, inverter-based assets (here: a large share of the column RES) contributed with reactive power according to a fixed power factor, and fixed reactive power assets (here: shunt reactors) were manually switched by the TSO to maintain static voltage.

The Expert Panel also assessed the voltage fluctuations that occurred on certain days prior to 28 April 2025, in particular on 22 April. On this day, the voltage reached very high values shortly after 19:00, leading to some disconnections but not to a cascade of overvoltage disconnections, as the system conditions and configuration on that day differed from those on 28 April. In particular, the system did not experience any significant episode of oscillation, either local or inter-area, on 22 April.

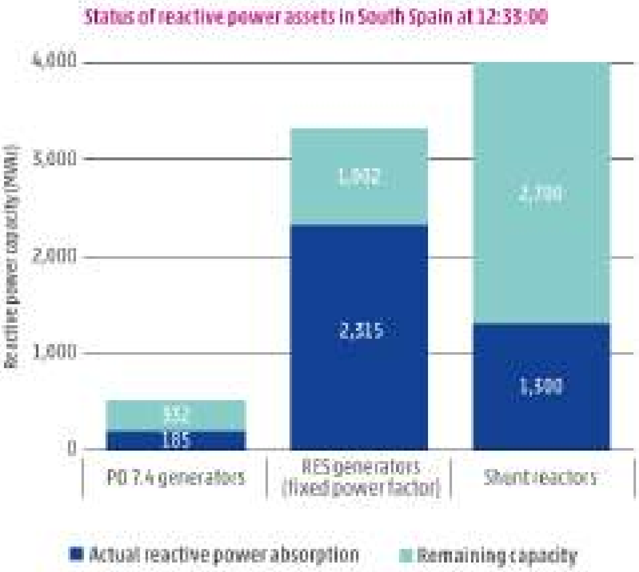

Figure 1-12: Capacity [6] of the different categories of reactive power assets in South Spain at 12:33:00

1.4.2 Oscillations

The second area of technical analysis concerns the two episodes of oscillation that occurred during the half-hour preceding the blackout and are described in Chapter 2. To perform the analysis of these phenomena, the Expert Panel (i) developed a simulation model of the CE power system that can represent the oscillatory behaviour of the system and (ii) used available data from a large number of PMUs located in the Iberian Peninsula and in the rest of the CE synchronous area.

Regarding the first oscillatory episode at 0.63 Hz, the data analysis shows that this mode is mainly located in the Iberian Peninsula, rather than in the rest of the European system, with higher activity in a specific area of Spain between Carmona and Almaraz. It also reveals that this mode is not naturally present in the system. The Expert Panel notes that, in the immediate vicinity of the node where the highest amplitude was observed (jointly with the highest power oscillations), an inverter-based power plant is connected, classified as an existing generator under the applicable requirements in Spain. The analysis concludes that this oscillation is a converter-driven forced oscillation.

The second oscillatory episode at 0.2 Hz was a classic inter-area oscillation of the East-Centre-West mode in the Continental Europe Synchronous Area. The modal analysis of the frequency measurements shows a significant participation of the Iberian Peninsula oscillation, together with the centre of Europe, and the eastern part. The causes of this second oscillation are the combination of different elements that enable the phenomenon. Specific conditions prevailing in the Iberian peninsula created the preconditions to the triggering of the oscillations: the high transmission angle (around 80° between Carmona and S. Llogaia), some lines out of service, the absence of power system stabilisers at some large units, and the insufficient damping of the devices already installed. The simulations carried out also show that the 0.63 Hz oscillation mode can contribute to exciting the 0.2 Hz inter-area oscillation mode, along with other factors.

The Expert Panel also assessed the effectiveness of the measures taken to dampen the oscillations. It concludes that the measures applied during the first oscillatory episode (0.63 Hz), which were not designed to damp oscillations in this frequency range, had a minor, but nevertheless positive impact on the oscillation. On the other hand, the analysis confirms the effectiveness of the operational measures applied during the inter-area oscillation (0.2 Hz).

Finally, the analysis identified several measures to improve the damping of forced and inter-area oscillations, respectively and showed that the measures taken had a positive impact on damping oscillations.

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[6] For explanation of the asterisk, see full Figure note in Section 4.1.2.

1.4.3 Analysis of the flows between TSO and DSO grids in Spain

The Expert Panel conducted a specific analysis to identify the main influencing factors explaining changes in flows between the transmission and distribution grids (hereafter TSO-DSO flows), particularly after the oscillations and during the critical time period from 12:32:00.

Changes in TSO–DSO flows and load result from complex interactions among various factors within the distribution and transmission grids. Changes in distribution grids (e.g., activation of distribution grid-connected units providing balancing services, including automatic frequency restoration reserves (aFRRs) and manual frequency restoration reserves (mFRRs)) can influence TSO–DSO flows, which in turn can impact voltage and regional flows across the transmission system.

There is also feedback from the transmission grid to the distribution grids, e.g. voltage-dependent loads or possible disconnections of small embedded generators due to voltage variations on medium- or low-voltage DSO feeders.

The analysis indicates that:

- » the changes in the total TSO–DSO exchange can only be slightly linked to aFRR or mFRR activations;
- » based on the data provided by two PV-inverter manufacturers, the changes in total TSO–DSO flows can be partially linked to disconnections of small PV installations (<1 MW) connected to low-voltage grids due to activation of over-voltage inverter protection.

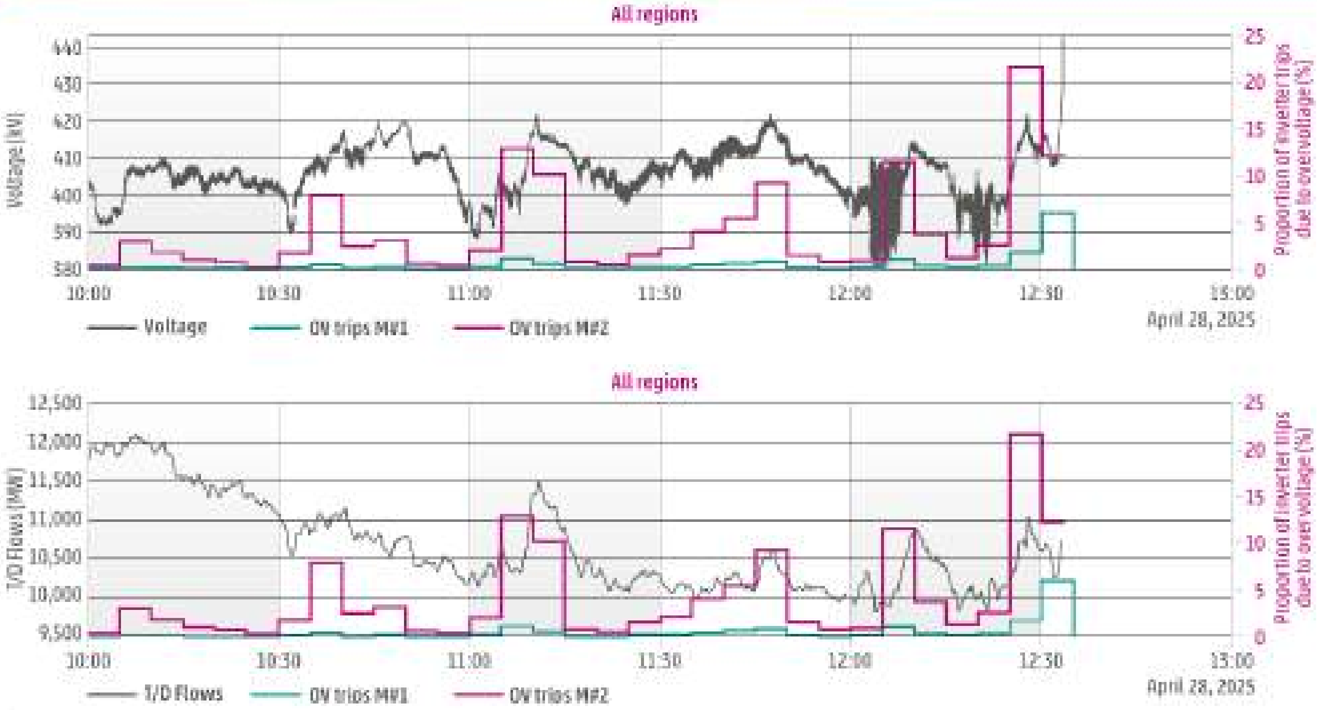

Figure 1-13: Correlation between voltage at the 400 kV substation Carmona , sum of TSO-DSO flows and proportion of inverter trips in Spain by automatic activation of overvoltage protections, aggregated in 5-minute intervals (Source: Red Eléctrica, PV-inverter manufacturers M#1 and M#2)

The data shows a correlation between the proportion of inverter trips and periods when the voltage rises on the transmission grid and when TSO–DSO flows increase. Furthermore, the data provided by one of the two PV-inverter manufacturers also allowed to estimate the total amount of disconnected generation[7]. This amount is highly dependent on the actual number of trips and on the total time between the disconnection and the reconnection of the disconnected inverters.

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[7] The methodology used, described in chapter 4.3, is based on several assumptions and simplifications in the absence of further information. These factors should therefore be taken into account when interpreting the results.

Figure 1-14: Correlation between the TSO–DSO flows and the estimated total amount of disconnected generation in Spain (units <1 MW connected to low-voltage grids)

- Because the voltage dependency of loads is an inherent property of power systems, it can also be linked to a certain extent to the load increase in the distribution grids (and hence to the changes in TSO–DSO flows). Indeed, a correlation is observed between a simplified load model and DSO measurements. However, detailed models, more comprehensive data on load composition, and additional representative measurements from DSOs would be needed to accurately model the behaviour of TSO/DSO interfacing points.

1.4.4 System defence plans

The system defence plans in Spain and Portugal were automatically triggered by the drop in frequency in the final stages leading up to the blackout. They were unable to prevent the system's collapse, despite the fact that their activation proceeded as designed.

The technical analysis of the system defence plan assesses several areas and factors using models suitable for analysing the frequency and voltage stability phenomena, respectively.

The frequency stability analysis includes:

- simulation of a perfectly executed load shedding and hydro-pump plant disconnection;
- the effect of inertia on the frequency variation;
- the role of HVDC power reversal mode.

In particular, the analysis of the impact of inertia indicates that, even with significantly higher inertia values, the loss of system synchronism would not have been avoided, considering the sequence of events. This can be explained by the rapid reduction in synchronising torque in the Iberian Peninsula (due to cascading generator tripping) that led the system to rapidly reach the point of no return.

Furthermore, analysis shows that the rapid intervention on the HVDC interconnection between France and Spain aimed at restoring the Iberian Peninsula's system balance could have worsened system behaviour due to fast transient phenomena.

The second part of the analysis focuses on voltage stability. After the validation of the simulation model, the analysis assesses the sensitivity regarding the following aspects:

- the effect of different parameters (cross-border exchanges, TSO/DSO exchanges, generation changes, connecting transmission lines, connecting/disconnecting shunt reactors) on voltage variations;
- the role of voltage regulation from conventional generators;
- the role of voltage regulation from additional synchronous condensers;
- the role of the defence system.

The simulations demonstrated that, at the time of the incident, the voltage of the Spanish power system was sensitive to any variations – whether related to exchanges with Portugal, France or Morocco, TSO-to-DSO flows, or generation– resulting in significant voltage fluctuations.

The analyses above clearly indicate that the key phenomenon in the incident was the non-effectiveness of voltage control within the Spanish power system. Simulations show that increased reactive power margins could have prevented system collapse, enabling it to operate at lower voltage levels and maintain overall system stability.

Finally, the Expert Panel conducted a detailed analysis of the performance of the Low-Frequency Demand Disconnection (LFDD) scheme. The goal was to verify the load shed at each step, and to identify the exact instant of the trips, and the frequency value at the moment of pickup and tripping of the load shedding relays. Overall, this analysis concludes that the performance of the LFDD scheme at transmission- and distribution-level was in line with the applicable requirements and in accordance with the design.

1.4.5 Management of voltage-related alarms

Given the numerous voltage fluctuations that preceded the blackout, as detailed in Chapter 2, the Expert Panel considered it useful to analyse the voltage-related alarms recorded by the TSOs (in Spain, Portugal and France), DSOs (in Spain and Portugal) and generation control centres (in Spain) in the half-hour preceding the incident, and how they were handled.

The analysis indicates that the distribution of alarms recorded by Red Eléctrica exhibited zonal clustering, with the southern and eastern zones repeatedly prominent for undervoltage alarms, while the interior, southern and northern zones recorded the majority of overvoltage alarms.

The remedial actions taken within the control rooms (coupling and decoupling of reactors, opening and closing of lines, setting HVDC voltage setpoints) were effective in bringing the voltage back under the alarm threshold within minutes in most cases (typically less than 5 minutes). In the last overvoltage episode that preceded the system collapse, Red Eléctrica's dispatchers were unable to implement manual remedial actions due to the rapid development of the incident.

1.4.6 Root cause tree

The analyses summarised above enabled the Expert Panel to develop a root cause tree of the incident. Its purpose is to explain, in schematic, synthetic and simplified form, how the incident unfolded as a result of a combination of key factors, as well as the causal relationships between the various elements.

The root cause tree is presented in Figure 1-15.

Root cause tree

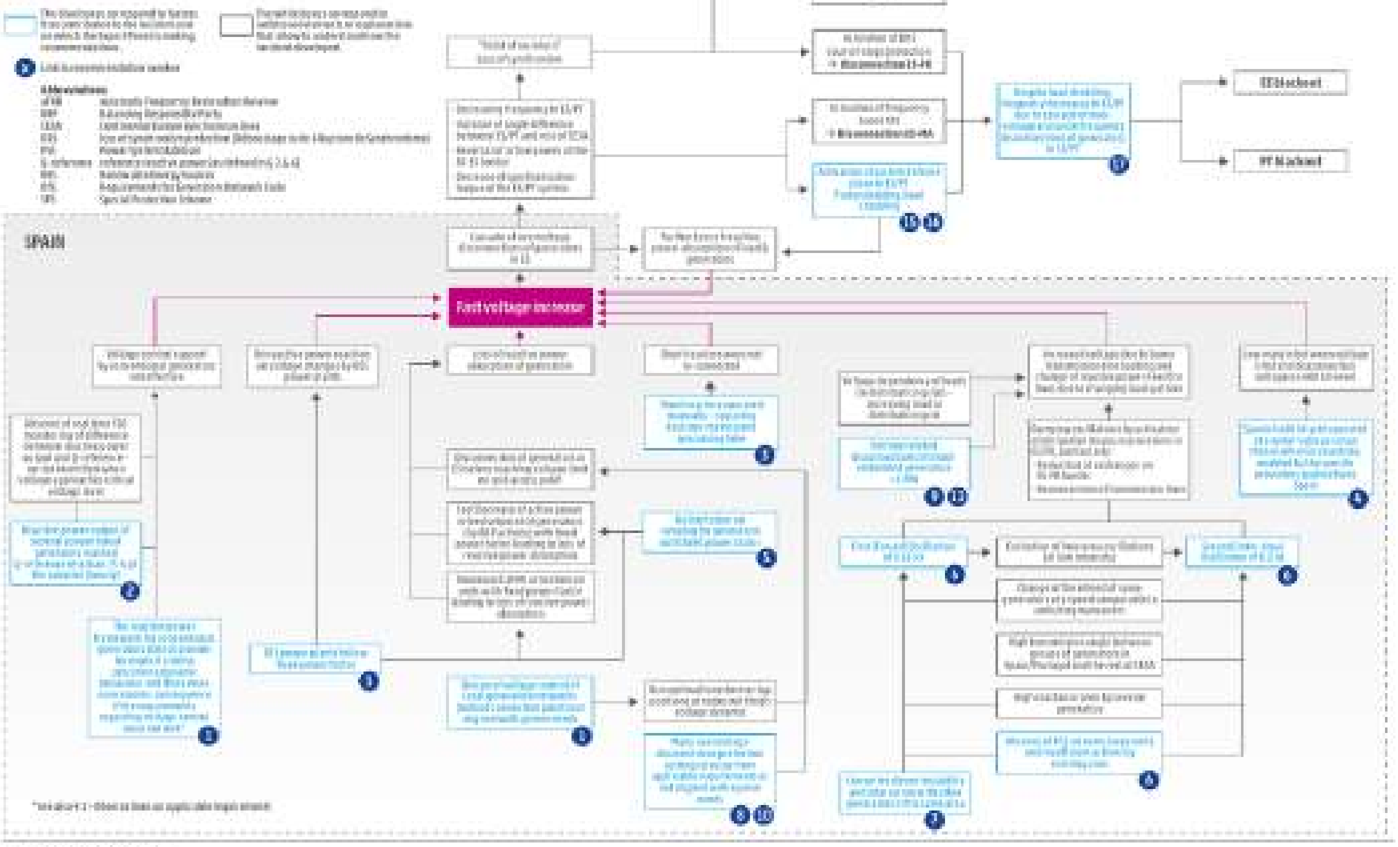

Figure 1-15: Root cause tree

From the tree, it can be seen that the fast voltage increase, which led to the cascade of overvoltage disconnections in Spain and ultimately to the blackout, occurred due to the combination of numerous factors, and particularly (the order in this list does not reflect any particular ranking in terms of criticality):

- the reactive power output of several conventional generators reached Q-reference less than 75 % of the samples (hourly);
- the framework for conventional generators' reactive power output did not include specifications for dynamic behaviour and there were no economic consequences if the reactive power output was not aligned with the 75 % rule;
- the RES power plants followed a fixed power factor;
- the design of voltage control of local generation networks (behind connection point) is not aligned with the system needs;
- there was no limitation on ramping for generators with fixed power factor;
- shunt reactors are operated manually, requiring decision-making and processing time;
- according to data provided and estimations performed, many overvoltage disconnection protection settings diverged from applicable requirements or were not aligned with system needs;
- two oscillatory episodes occurred in the half-hour preceding the blackout: first, a (forced) oscillation of 0.63 Hz, and second, an (inter-area) oscillation of 0.2 Hz:
  - The power system experienced converter-driven instability that interacted with other generators in the same area;
  - There was an absence of PSS at some large units and insufficient damping by the existing ones;
- A certain proportion of small PV units (<1 MW) experienced voltage-related disconnections by activation of inverter protection;
- Spanish 400 kV grid is operated at a wider voltage range than in other EU countries, enabled by specific provisions applicable to Spain;
- the system entered an operating point where, by design, its defence plan was unable to interrupt the cascade of overvoltage disconnections and prevent the total collapse of the Spanish and Portuguese power systems.

More explanation on the root cause tree is provided in Chapter 4.6.

1.5 Restoration Process

Following the incident, each affected TSO immediately activated their respective system restoration plans, implemented in accordance with the applicable requirements, 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 other measures, by activating power system resources, such as black-start processes in certain power plants, and by leveraging existing interconnections with France and Morocco, as schematically illustrated in Figure 1-16.

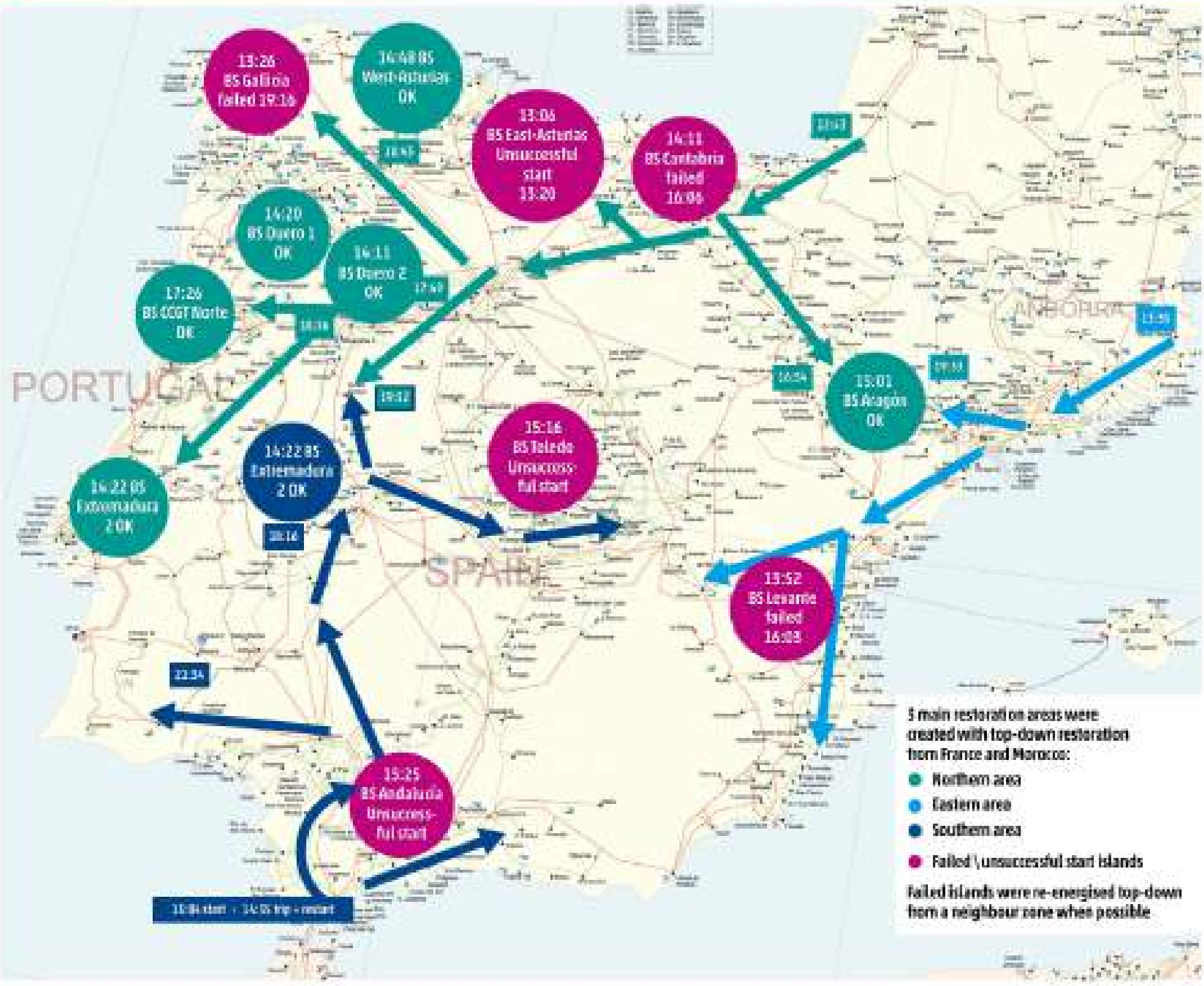

Figure 1-16: Mapping of the main milestones of the restoration process in Spain and Portugal

In Figure 1-16, the green and blue circles represent islands energised "bottom-up" from black-start facilities (some after multiple attempts) and eventually synchronised with a "top-down" re-energised part of the grid (arrows in magenta, green or light blue). The magenta circles indicate islands where bottom-up restoration failed. These areas were re-energised later from one of the "top-down" re-energised grids, from either France (L-400 kV Argia–Hernani energised at 12:43 and L-400 kV Baixas–Vic energised at 13:35) or Morocco.

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

At 15:07, all Spanish nuclear power plants confirmed that they had 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 the Moroccan system could be synchronised with the northern zone connected to CE SA.

At 00:22 and around 04:00 on 29 April 2025, the transmission grid restoration was completed in Portugal and Spain, respectively. Therefore, thanks to comprehensive restoration procedures, fallback strategies, and the full commitment of operators from TSO, DSOs, producers and other parties, the Spanish system was fully restored within 16 hours, while the Portuguese system was back online within 12 hours after the blackout.

Nevertheless, the Expert Panel identified several issues that impacted the restoration process, including difficulties in starting black-start units or maintaining stable islands, problems with the voice communication systems of several DSOs and significant grid users, and insufficient observability of facilities involved in bottom-up restoration scenarios of distribution grids. Chapter 9 of the report includes several recommendations to address these issues.

More details on the restoration process are described in Chapter 5.

1.6 Operational Planning

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 violations of N-1 criteria (no flow congestions and no voltage out of range) 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) conducted 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 conducted before the incident and the operational planning procedures applied in Spain are described in further detail in Chapter 6.

1.7 Communication of Synchronous Area Monitors and Between TSOs

During and after the blackout, communication between TSOs and synchronous area monitors (Swissgrid and Amprion) supported crisis management and restoration coordination. Exchanges via direct calls, ENTSO-E Awareness System (EAS) notifications, and email enabled the 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 synchronous area monitors streamlined information flow, enabling the affected TSOs to focus on urgent operational needs.

This structured, timely communication framework helped manage the incident and restore system stability across the affected regions, as described in further detail in Chapter 7.

1.8 Classification of the Incident Based on the ICS Methodology

The Incident Classification Scale (ICS) Methodology has been developed in accordance with Regulation (EC) No 714/2009 of the European Parliament and of the Council of 13 July 2009, as repealed by the Regulation (EU) 2019/943, and updated to fulfil the objectives under Article 15(5) of the Commission Regulation (EU) 2017/1485 of 2 August 2017 establishing a guideline on electricity transmission system operation (SO GL). The ICS methodology aims to provide a realistic view of system states during incidents. The incident classification criteria are ranked by priority, with the highest-priority criterion determining the incident scale. The methodology stipulates that every incident classified as scale 2 or 3 must be investigated by an Expert Panel.

On 28 April 2025, the scale 3 of incident severity 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 scale of incident severity reached was scale 1 – violation of standards on voltage – due to the high voltage experienced due to the incident. Consequently, the Expert Panel was established based on the requirements of the applicable legislation.

Additionally, the incident met the RCC investigation threshold described in the RCC Post-Operation and Post-Disturbances Analysis and Reporting methodology. This prompted the RCC investigation subgroup to initiate an RCC investigation. Further explanations can be found in Chapter 8.

1.9 Conclusions and Recommendations

The blackout that affected Spain and Portugal on 28 April 2025 was the most severe and unprecedented incident in the European power system for more than 20 years. The investigation conducted by the Expert Panel to establish the most accurate sequence of events possible, to understand the root causes of this incident, and to identify all the factors that contributed to it was also exceptional in terms of its complexity, scope and the nature of the events that led to the blackout.

This final report of the Expert Panel's investigation highlights that the blackout is the result of multiple interacting factors. The incident evolved through a sequence involving a combination of voltage fluctuations and oscillatory phenomena, leading to widespread generation disconnections in Spain, particularly inverter-based resources, followed by a cascade of overvoltage disconnections and culminating in the loss of synchronism of the Iberian system with the Continental Europe Synchronous Area.

The root cause tree provides a comprehensive picture of the causes, their relation and the sequence of events. Despite the correct activation of the system defence plans, the nature and magnitude of the cascading events led to a full collapse of the Spanish and Portuguese systems within seconds. After the blackout, the restoration process began immediately and was completed in 12 hours in Portugal and 16 hours in Spain, thanks to comprehensive restoration procedures, fallback strategies and the full commitment of operators from TSOs, DSOs, producers and other parties.

After analysing all the data at its disposal, establishing the sequence of events, and identifying the causes and other factors that contributed to the incident, the Expert Panel's work has focused primarily on deriving clear, actionable recommendations to reduce the likelihood of similar events and strengthen the overall security and resilience of the European grid.The recommendations are grouped into two categories:

(i) those directly linked to root causes of the incident;

(ii) those not directly linked to the root causes of the incident.

In addition, the report contains several other proposals identified as "areas for improvement" at the end of certain chapters. These proposals are not included among the recommendations, as they do not have a direct or indirect link to the incident. Nevertheless, they have been identified as potentially useful for further consideration. The report also revisits past recommendations from previous ICS investigations that remain relevant to this event, highlighting the importance of implementation and long-term follow-up. In addition, the Expert Panel notes several broader areas where further work by ENTSO-E and third parties could enhance system security.

Finally, the report contains a list of observations concerning the applicable requirements. In line with the scope of the investigation and the mandate of the Expert Panel, these observations do not aim to interpret the applicable legislation or determine liabilities for non-compliance with legal requirements. These observations have been included without prejudice to any inquiries and/or follow-up actions carried out by the competent national authorities.

Ultimately, the recommendations outlined in this chapter represent a comprehensive set of measures designed to enhance operational robustness, improve cross-stakeholder information exchange and help maintain a high level of security of supply across the European power system. As such, they aim to ensure that the lessons learned from this exceptional incident are duly reflected in the applicable requirements on both European and national levels.

The monitoring of the implementation of the recommendations provided in this chapter does not fall within the mandate or remit of the Expert Panel. Any responsibility for the consideration, follow-up and implementation of the recommendations lies solely with each addressee.

Strengthened coordination among TSOs, DSOs, SGUs and other stakeholders is essential to effectively managing complex system events like this one. Sustained efforts to enhance operational practices and information sharing will help maintain the security of supply for all consumers.

All recommendations are detailed in Chapter 9 of the report.

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. 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 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 Section 2.8.1.

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 ACI	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: S22-1 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 section 2.8.2 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:

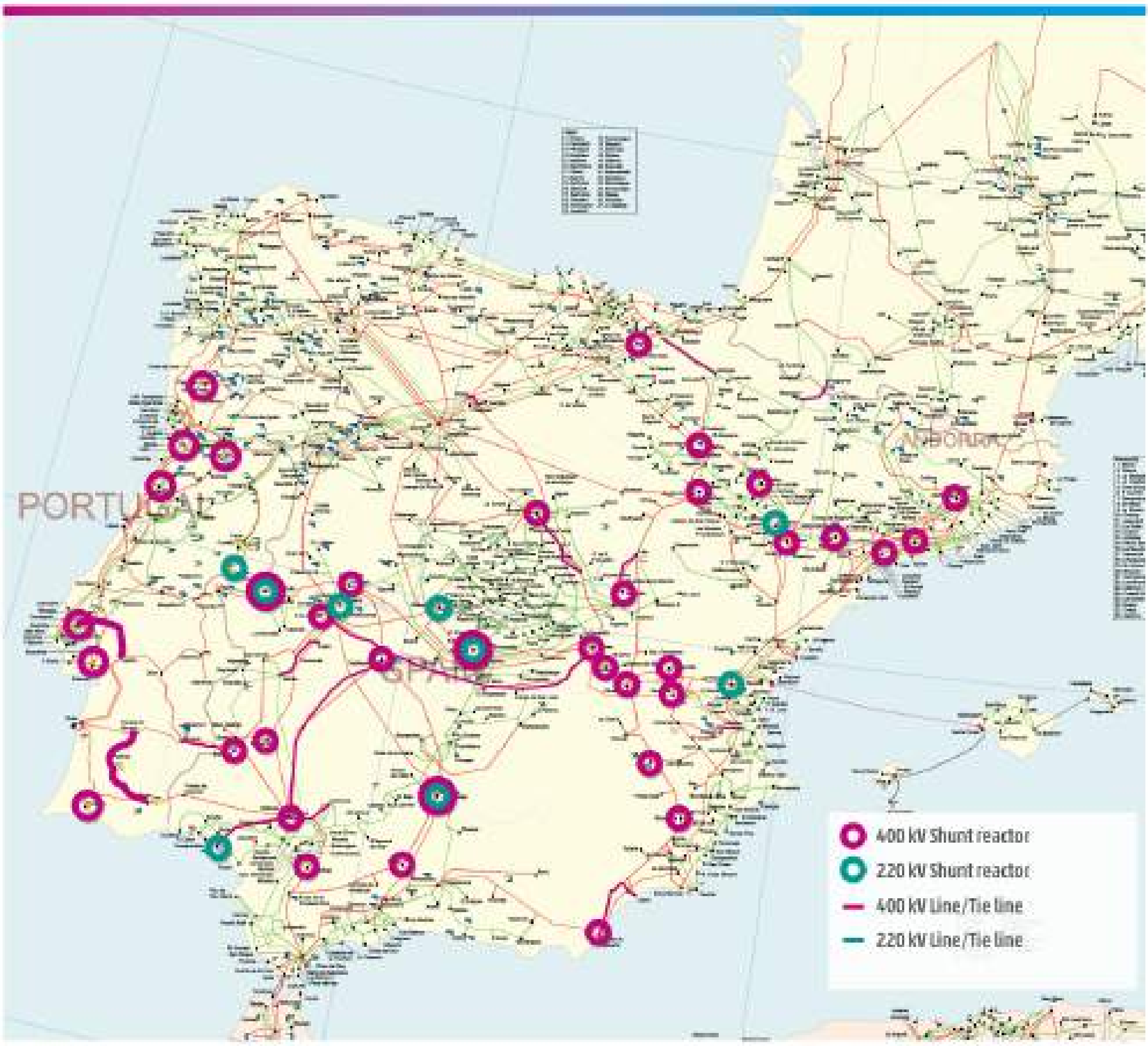

Figure 2-2: Iberian scenario: Open lines and reactances in Portugal and in Spain from 9:00 until 12:32

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 Eléctrica 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 CONDEN 1	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 10:05	28/04 23:33	Manual voltage control
Shunt Reactor	RS1–S. Pedralva 180 Mvar	28/04 10:05	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.

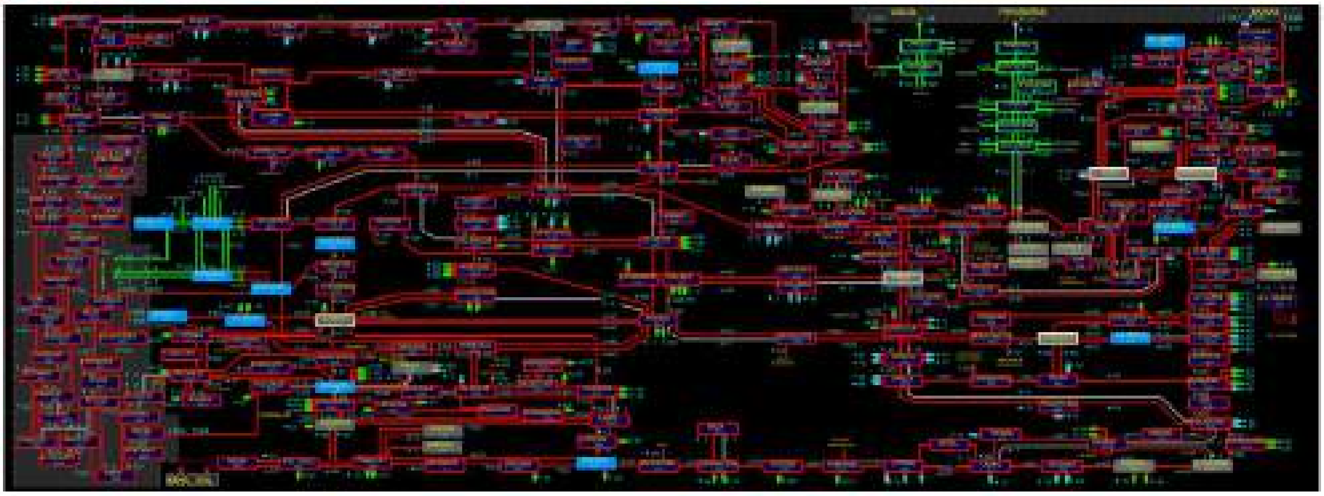

Figure 2-3: Grid topology in Spain at 12:00:00

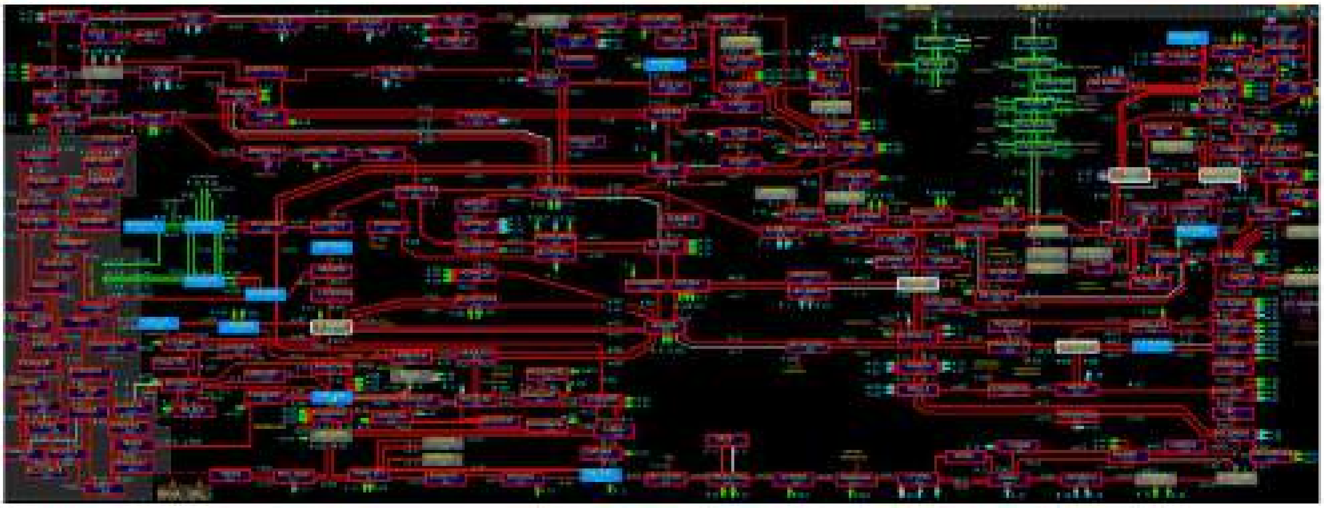

Figure 2-4: Grid topology in Spain at 12:32:00

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.

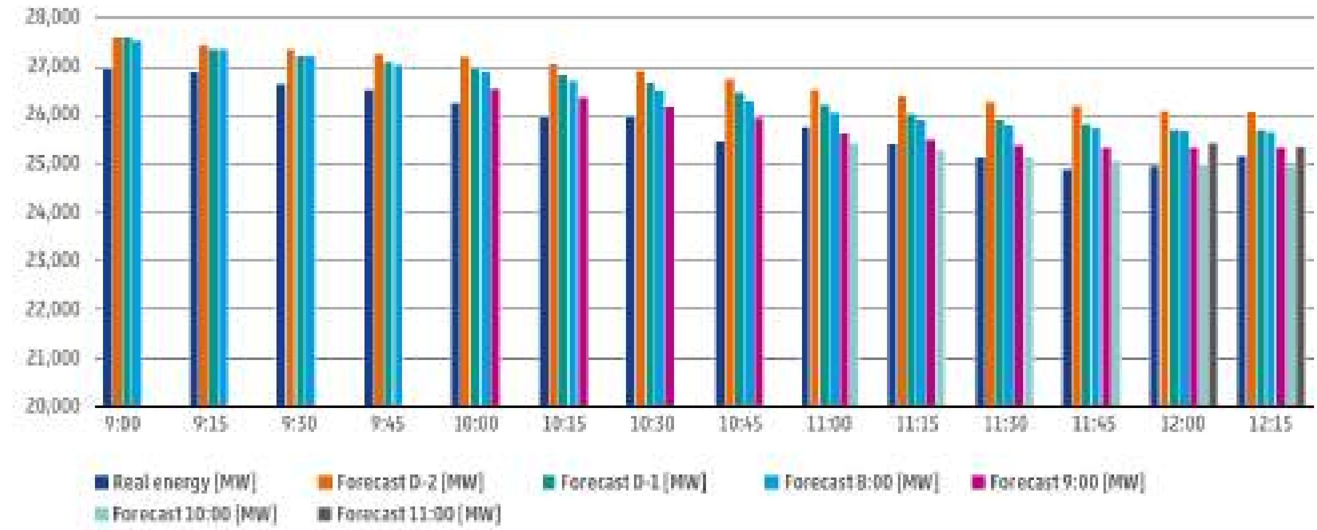

Figure 2-5: Spanish demand forecast

2.1.4.2 Portuguese Demand Forecast

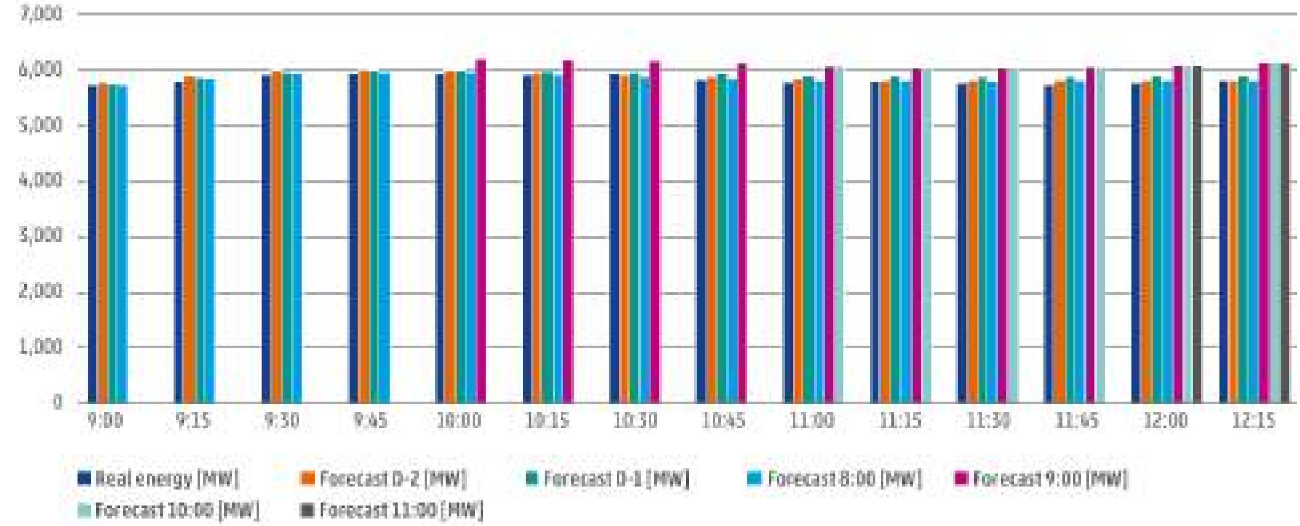

Figure 2-6: Portuguese demand forecast

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.

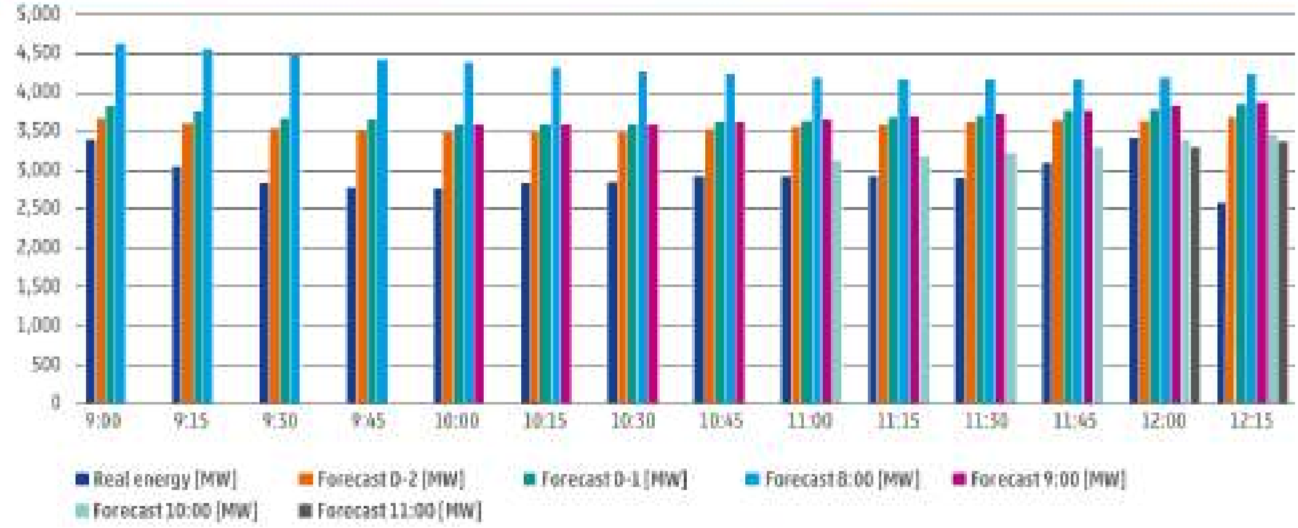

Figure 2-7: Spanish wind forecast

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

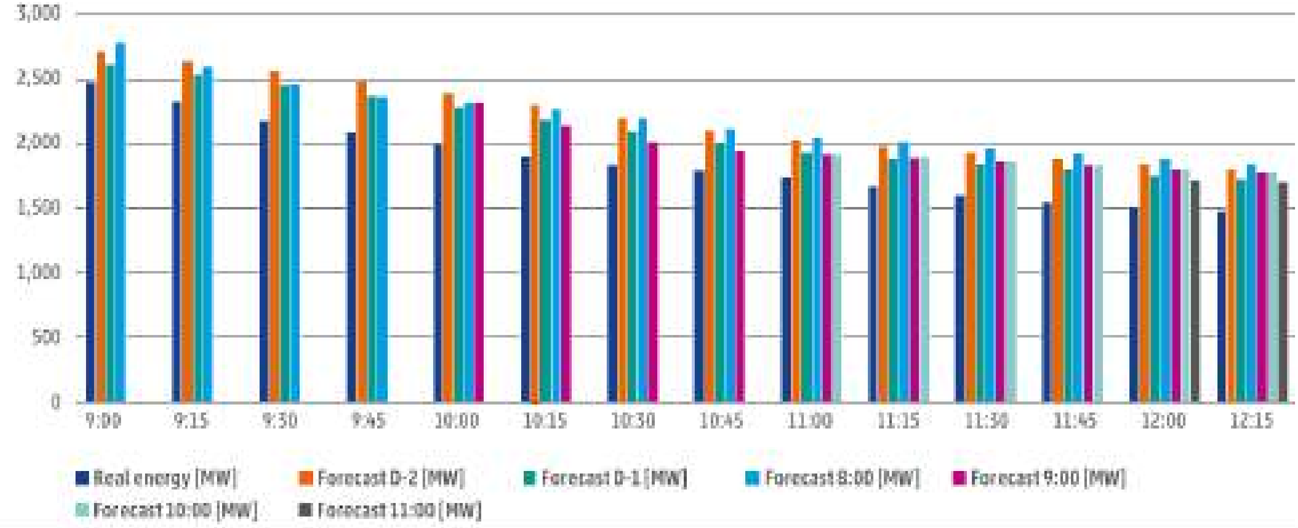

Figure 2-8: Portuguese wind forecast

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.

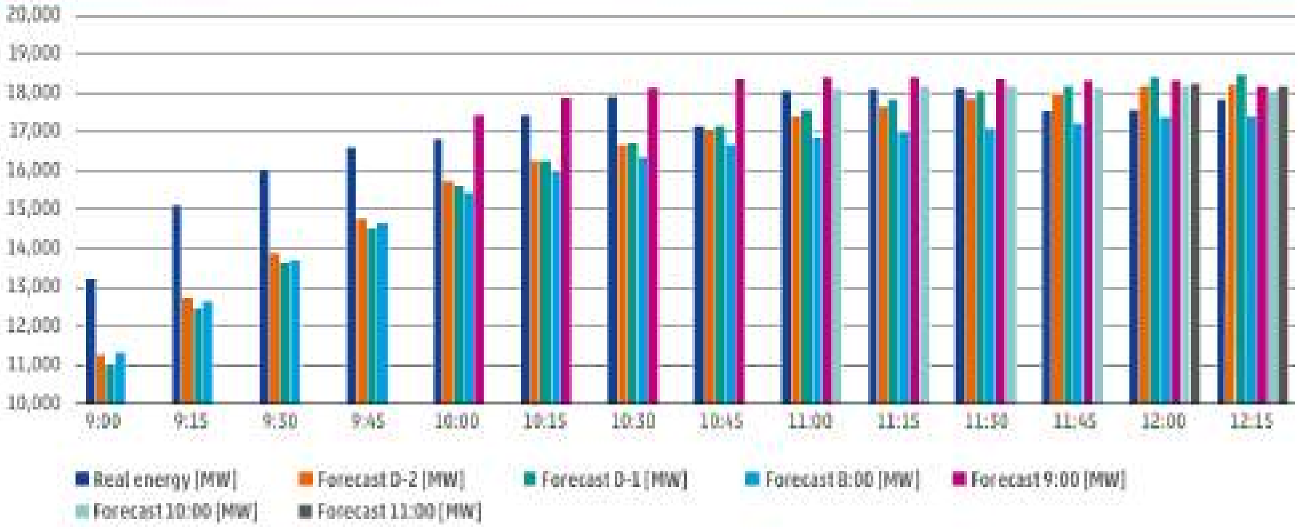

Figure 2-9: Spanish PV forecast (PV installations < 1 MW not considered)

2.1.4.6 Portuguese PV Forecast

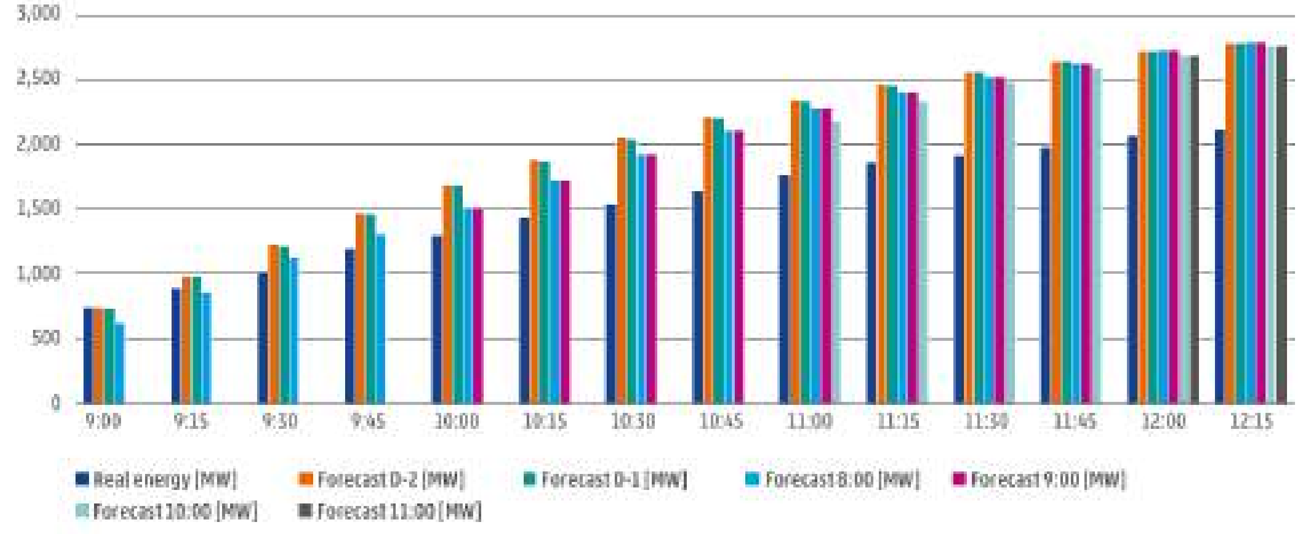

Figure 2-10: Portuguese PV forecast

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.

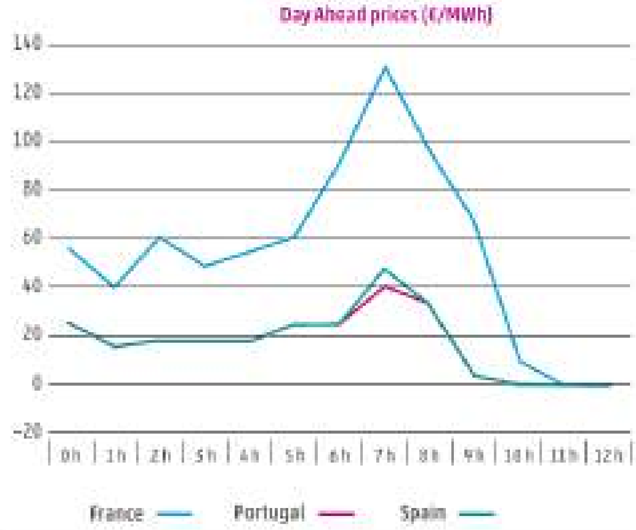

Figure 2-11: Day-ahead prices

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.

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.

Chapter 4.3 provides a more detailed analysis of the TSO-DSO flows and disconnection of small PV units connected to low voltage grids.

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

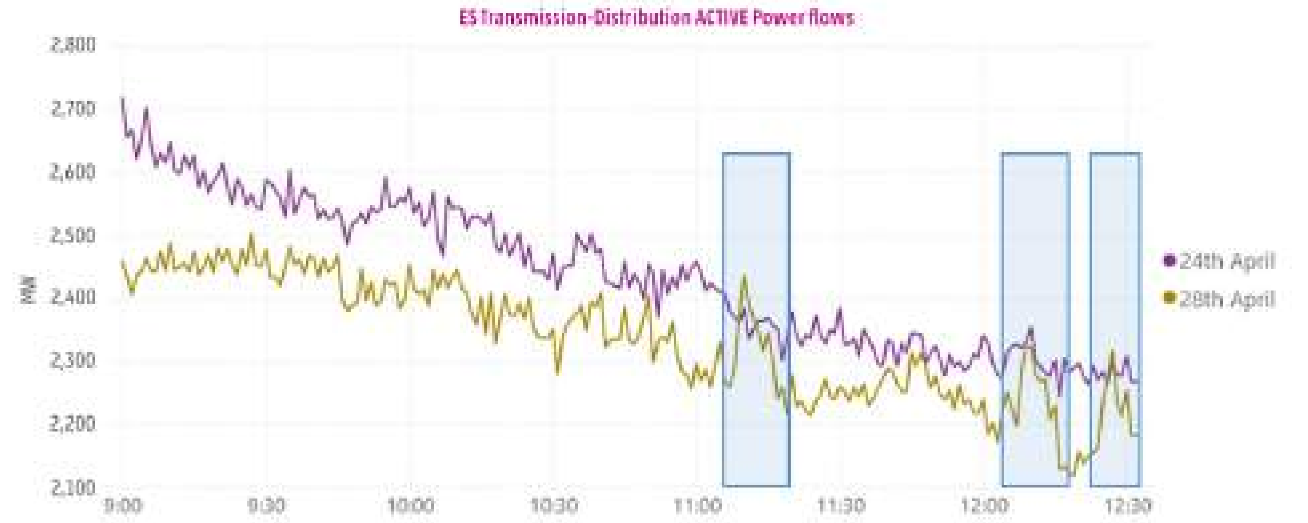

Figure 2-14: Madrid's transmission-distribution flows on 24 and 28 April between 9:00 and 12:32 (Source: RE SCADA)

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.

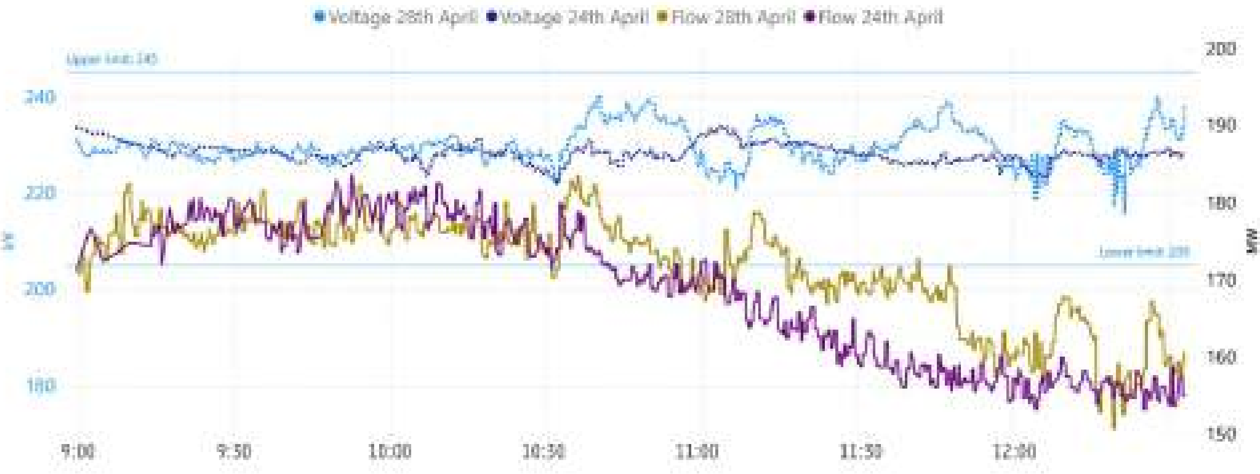

Figure 2-15: Voltage and Active power through the two 220/132 kV transformers at "TS 1-Madrid" between 9:00 and 12:32

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.

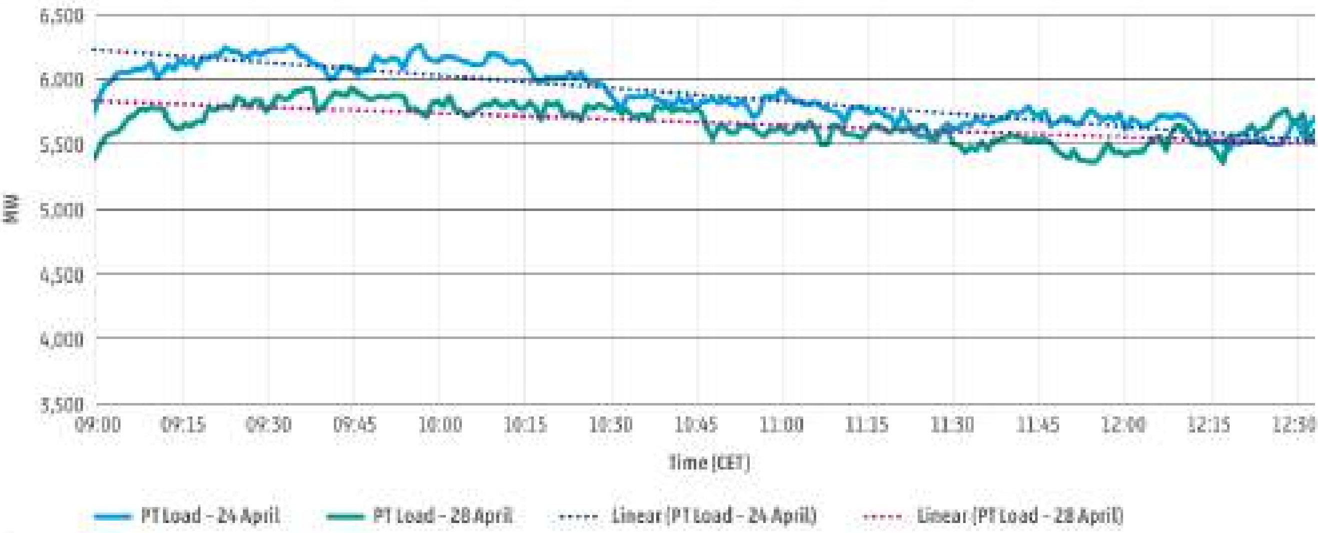

Figure 2-16: Comparison of Portuguese demand evolution on 28 April compared to 24 April between 9:00 and 12:30 (Source: REN's real-time SCADA measurements)

2.3.2 Production Patterns

2.3.2.1 Spanish Generation Mix

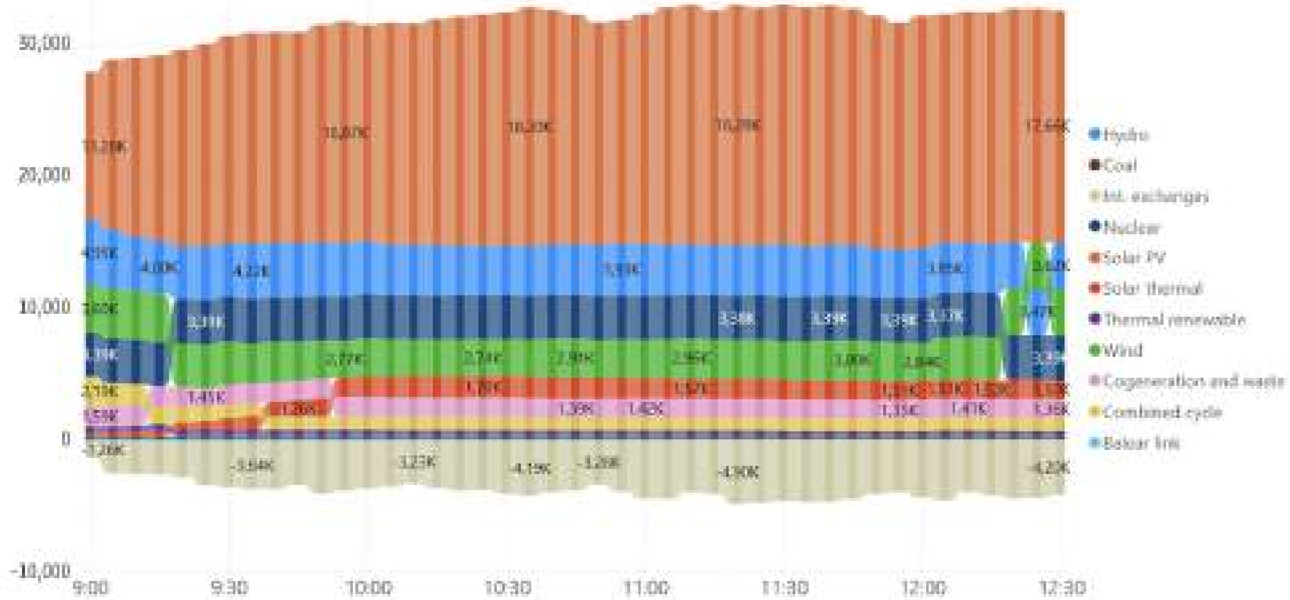

Figure 2-17: Spanish generation mix on 28 April from 9:00 to 12:30 (PV installations < 1 MW not considered)

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.

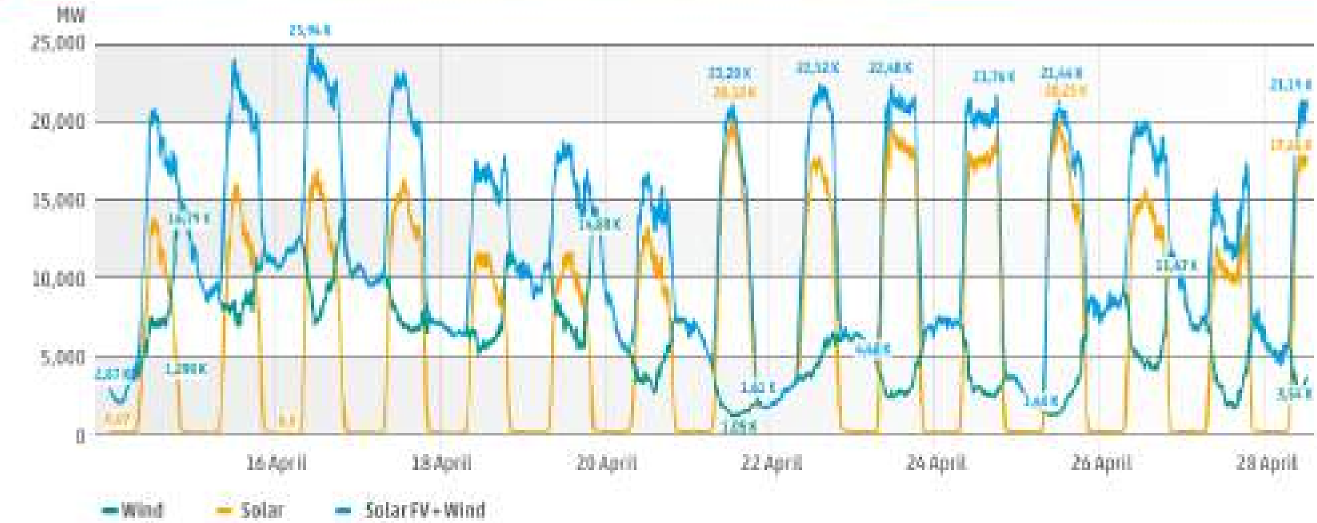

Figure 2-18: Solar PV and wind production in the two weeks in Spain prior to the incident (PV installations < 1 MW not considered)

2.3.2.2 Portuguese Generation Mix

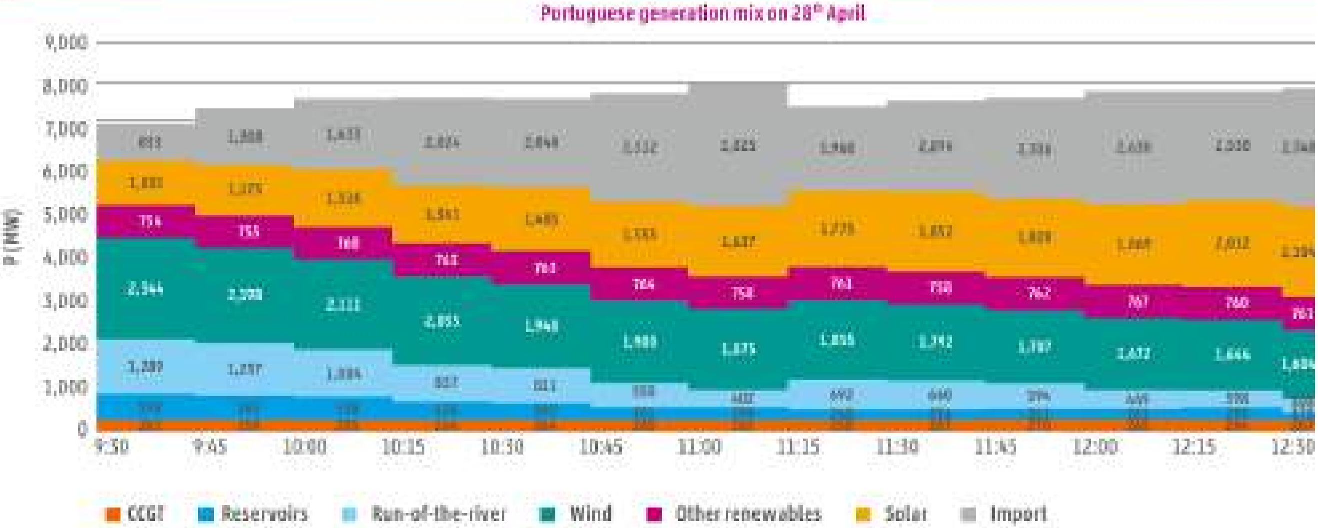

Figure 2-19: Portuguese generation mix on 28 April from 9:30 to 12:30

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.

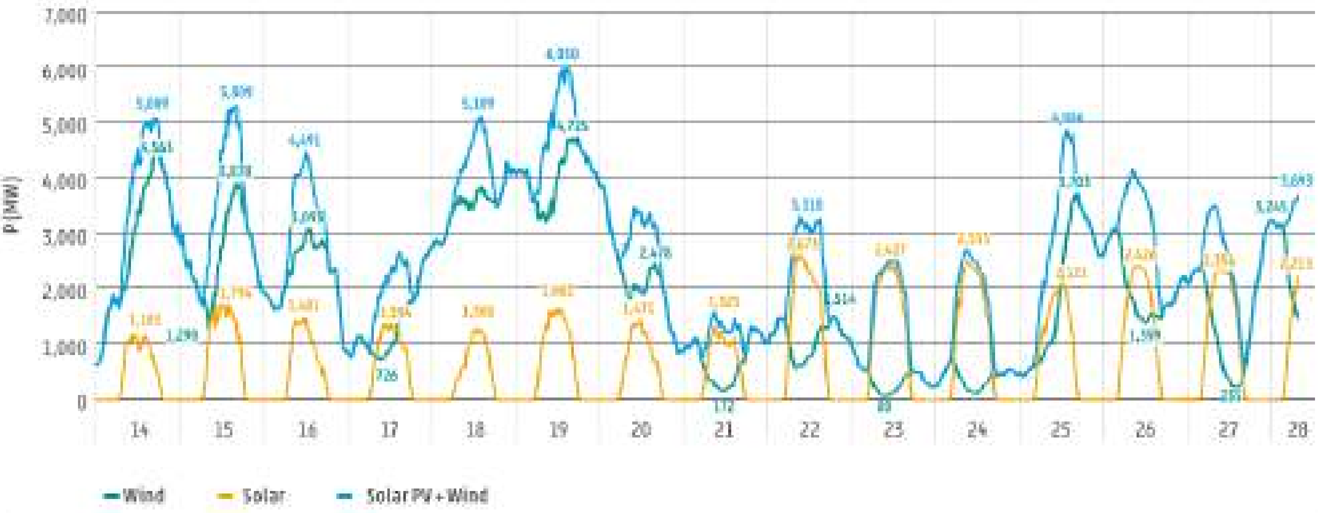

Figure 2-20: Solar PV and wind production in Portugal in the two weeks prior to the incident

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 Eléctrica SCADA with a four-second resolution.

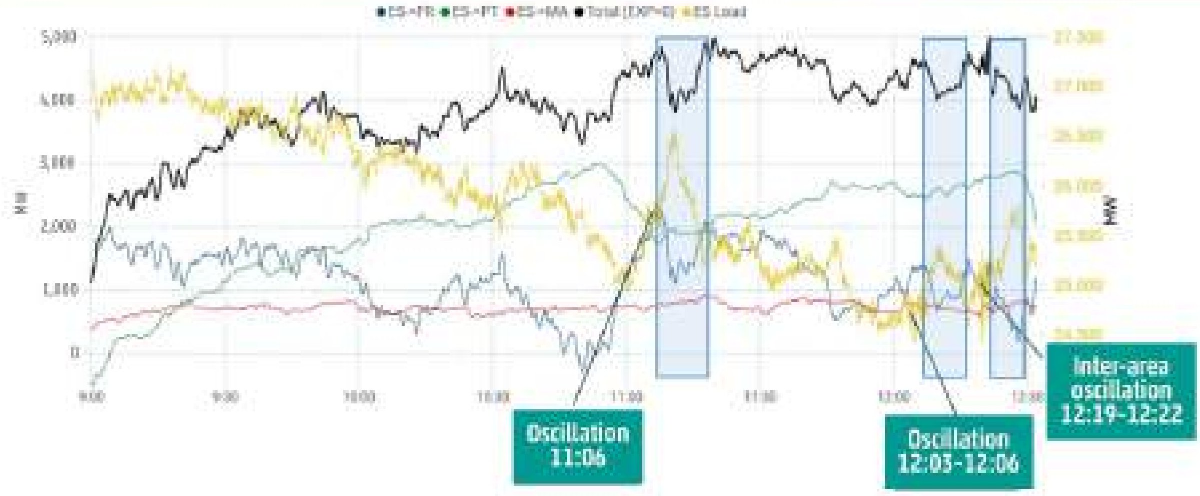

Figure 2-21: Spanish load and physical flows through ES–FR, ES–PT, and ES–MA between 9:00 and 12:32 (source: RE SCADA)

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.

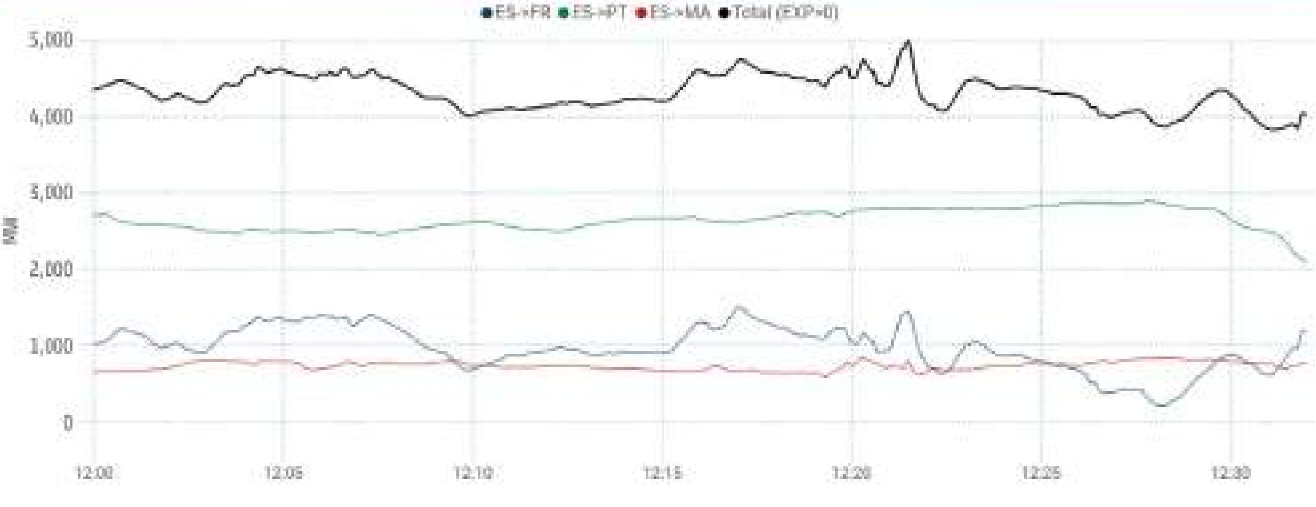

Figure 2-22: Physical flows through ES–FR, ES–PT, and ES–MA between 12:00 and 12:32 (source: RE SCADA)

2.3.4 Scheduled Commercial Exchanges

The cross-border programs are implemented with 10-minute ramps (starting 5 minutes before and ending 5 minutes after the start of the 15 minutes period), except when an urgent measure is required, such as in the case of a counter-trading for security reasons.

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

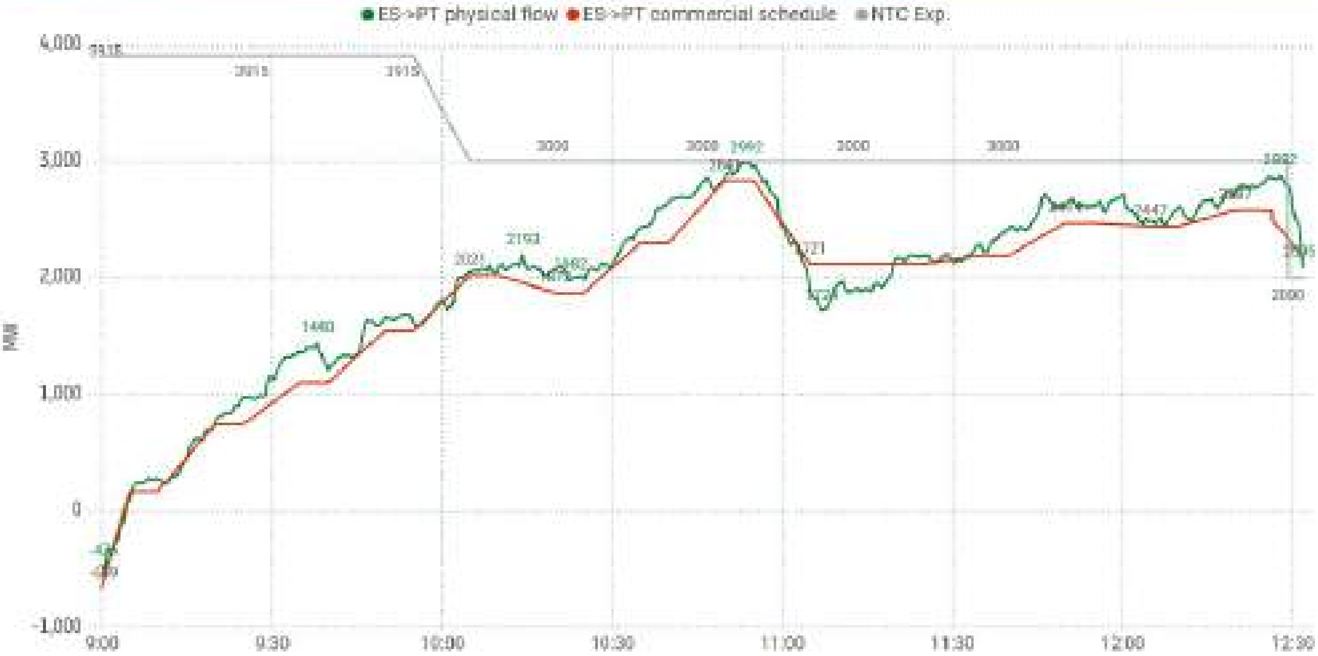

Figure 2-24: Commercial schedule and physical flow through the ES–PT border (source: RE SCADA)

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

Figure 2-25b shows the aFRR demand in Spain throughout the timeframe.

Figure 2-25b: aFRR demand in Spain (source: RE)

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 [1] [2] [3] [4] [5] [6] 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_{sys} (s)	KE (MWs)	H_{sys} (s)	KE (MWs)	H_{sys} (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.

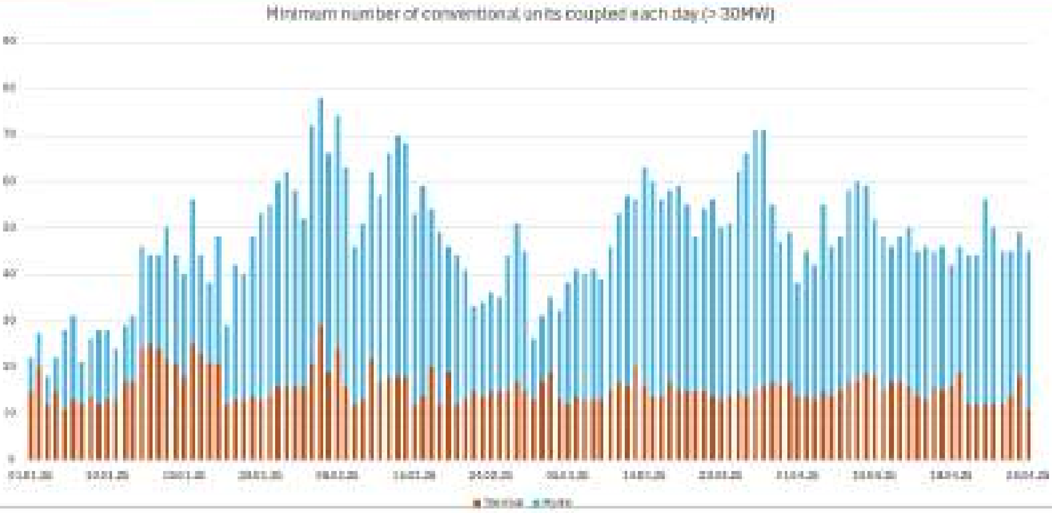

Figure 2-26: Minimum number of conventional units (> 30 MW) coupled to the Spanish network each day from 1 January to 28 April

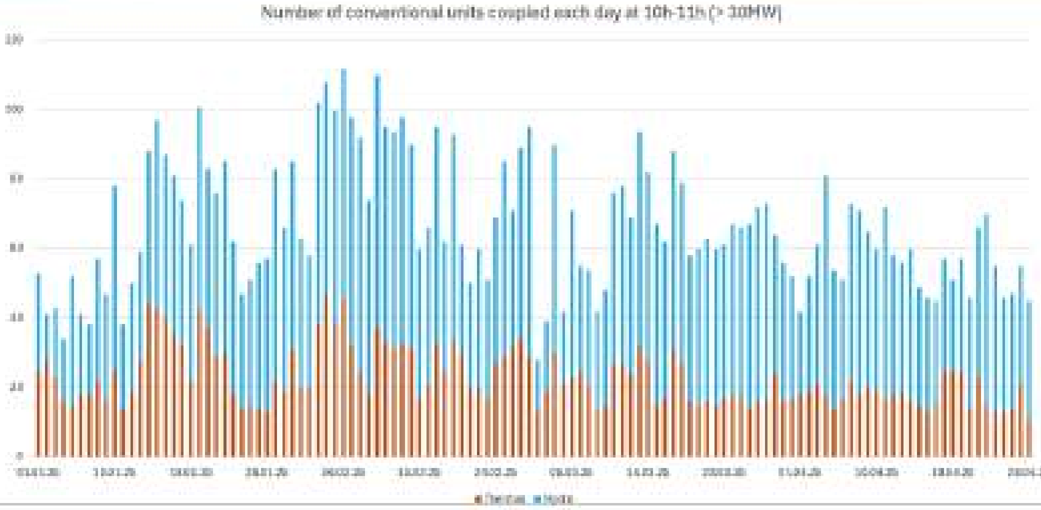

Figure 2-27: Number of conventional units (> 30 MW) coupled to the Spanish network each day in the period from 10:00 to 11:00 (from 1 January to 28 April)

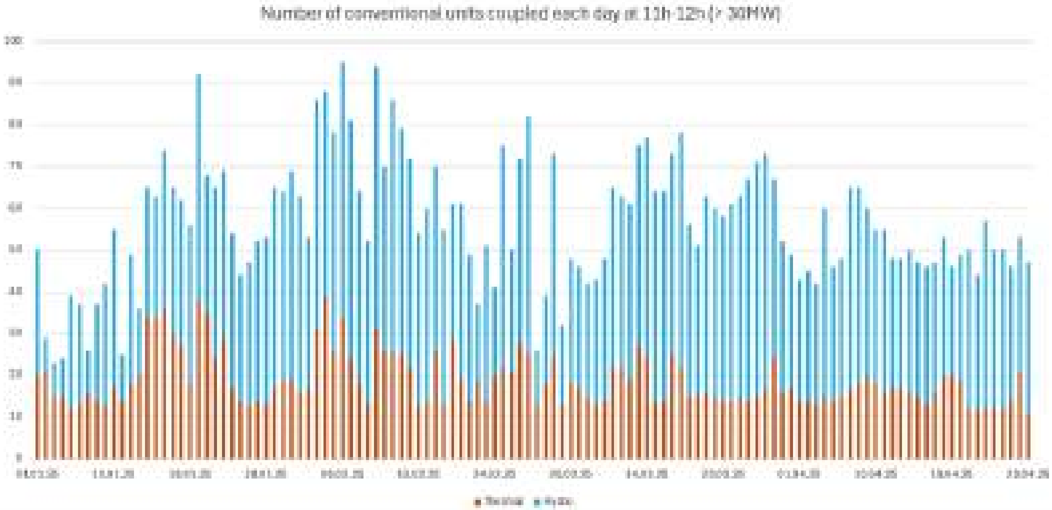

Figure 2-28: Number of conventional units (>30 MW) coupled to the Spanish network each day in the period from 11:00 to 12:00 (from 1 January to 28 April)

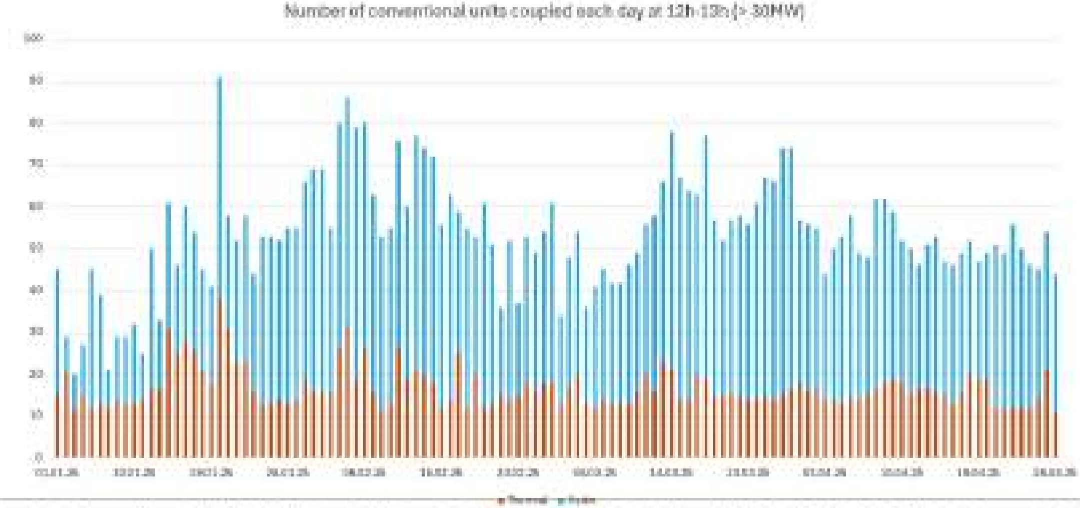

Figure 2-29: Number of conventional units (>30 MW) coupled to the Spanish network each day in the period from 12:00 to 13:00 (from 1 January to 28 April)

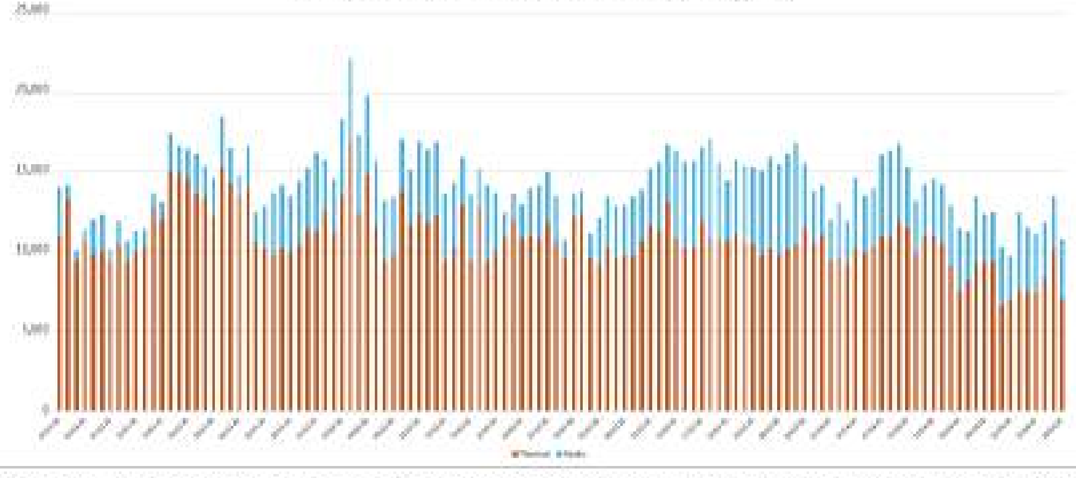

Figure 2-30: Installed power of the conventional units connected to the Spanish network, each time at the hour with the lowest number of coupled units (from 1 January to 28 April)

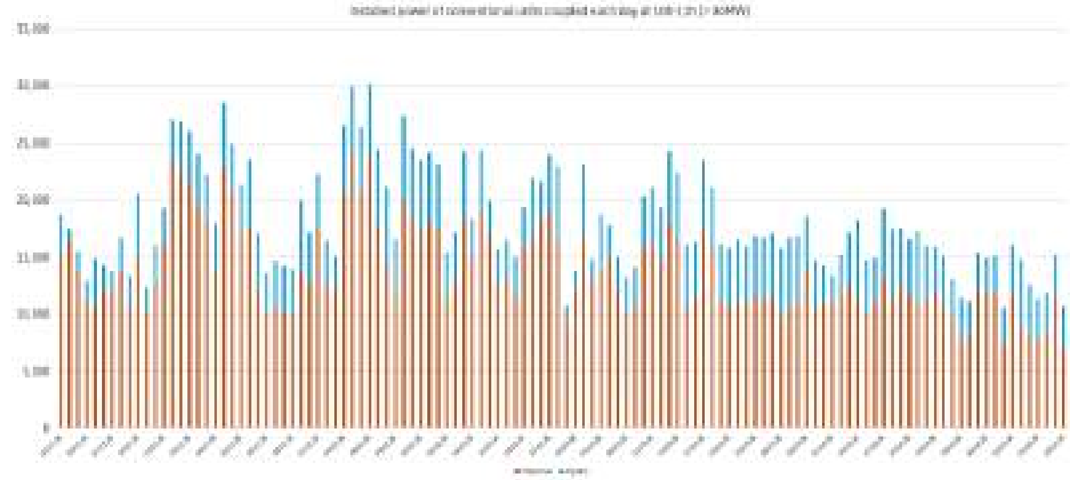

Figure 2-31: Installed power of the conventional units connected to the Spanish network during the period from 10:00 to 11:00 (from 1 January to 28 April)

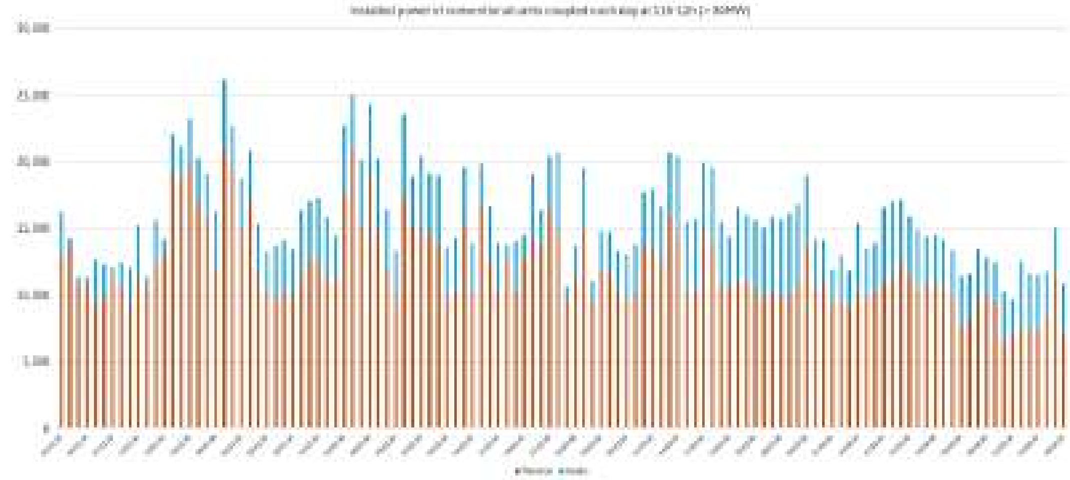

Figure 2-32: Installed power of the conventional units connected to the Spanish network during the period from 11:00 to 12:00 (from 1 January to 28 April)

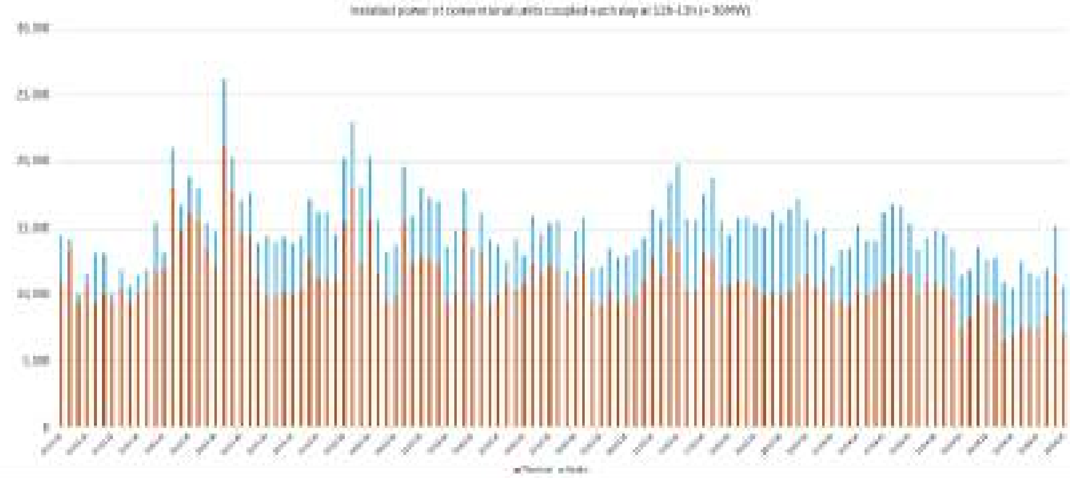

Figure 2-33: Installed power of the conventional units connected to the Spanish network during the period from 12:00 to 13:00 (from 1 January to 28 April)

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[1] 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.

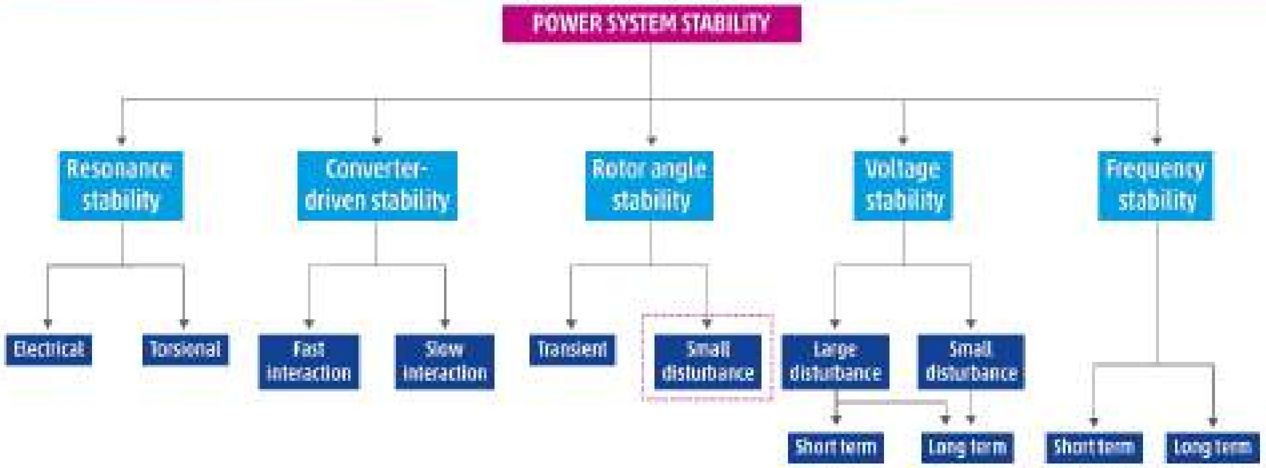

Figure 2-34: Classification of power system stability

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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[1] Stability definitions and characterisation 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:[2] 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. The forced oscillation could be also generated by the interaction between inverter based generators and conventional generators/inverter generators.
- 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[3]). 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.

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

[3] 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 (and consequently significant transmission angles spread)
- 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.

In addition, weak control schemes or failures in generator control systems can also have an impact, since forced oscillations may couple with inter-area modes in different ways:

- forcing oscillatory frequency is very near to the interarea natural frequency, the interarea mode can be excited and amplified
- forcing oscillatory frequency is not coincident with interarea natural frequency, so the interarea mode is excited transiently or quasi permanently but with a smaller amplitude

Historically, the Iberian Peninsula participated to East Central West mode and East West mode in a frequency range between 0.15 Hz and 0.2 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[4] 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:[5]

- 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[6] (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. It is important to underline that the protocol is focused on oscillatory phenomena in the inter-area frequency band 0.15 … 0.3 Hz.

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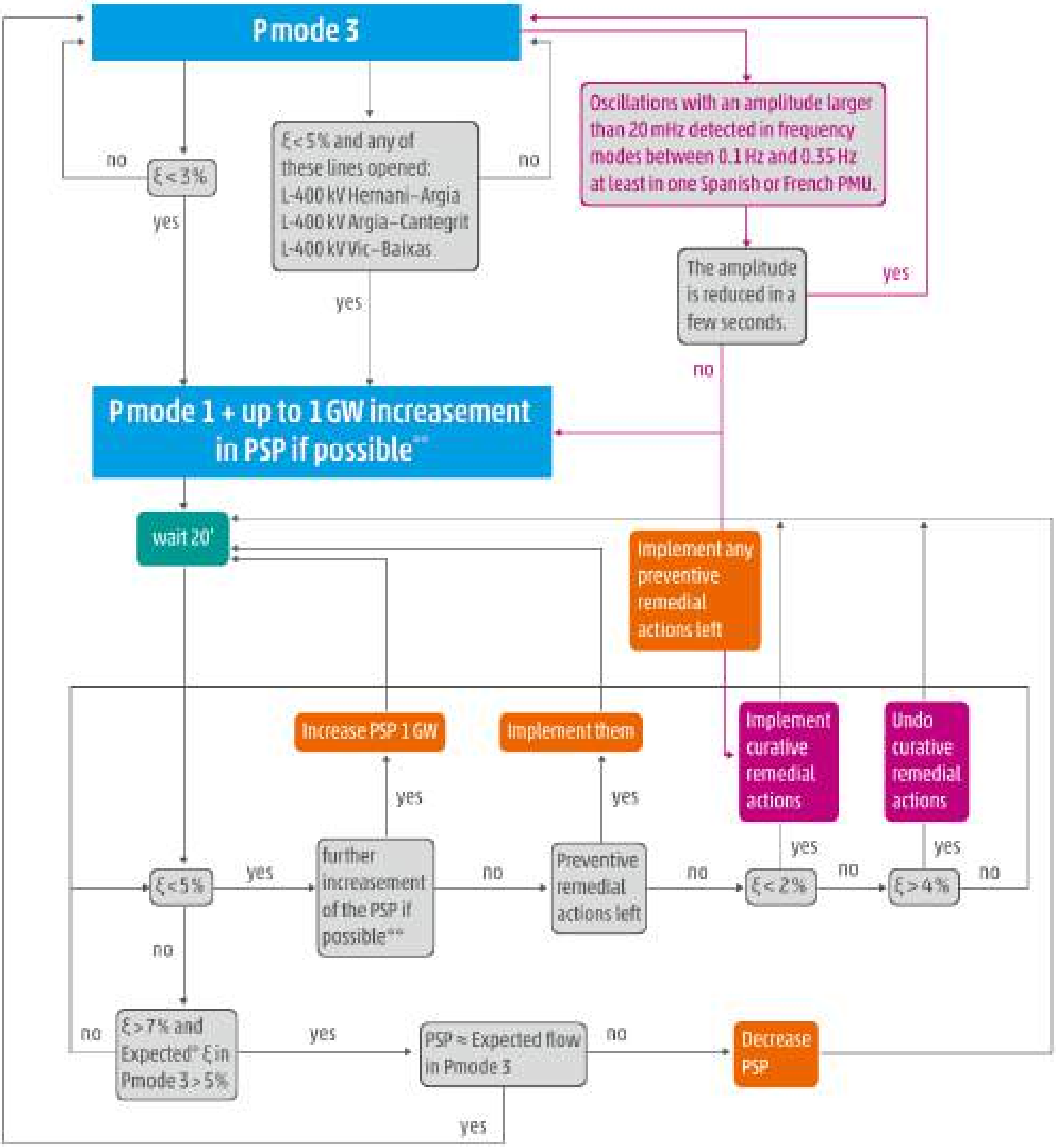
[4] https://eepublicdownloads.entsoe.eu/clean-documents/SOC%20documents/Regional_Groups_Continental_Europe/2017/CE_inter-area_oscillations_Dec_1st_2016_PUBLIC_V7.pdf

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

[6] Hybrid operation implies that active power flowing is $P = P_0 + K \cdot \Delta\theta$ 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[7] 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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[7] Pages 203 and 205 of the **Spanish Transmission network development plan for 2021 – 2026**.

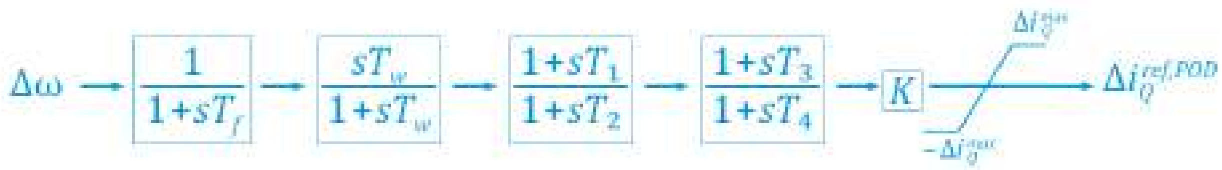

Figure 2-37: Vitoria STATCOM POD block scheme

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.

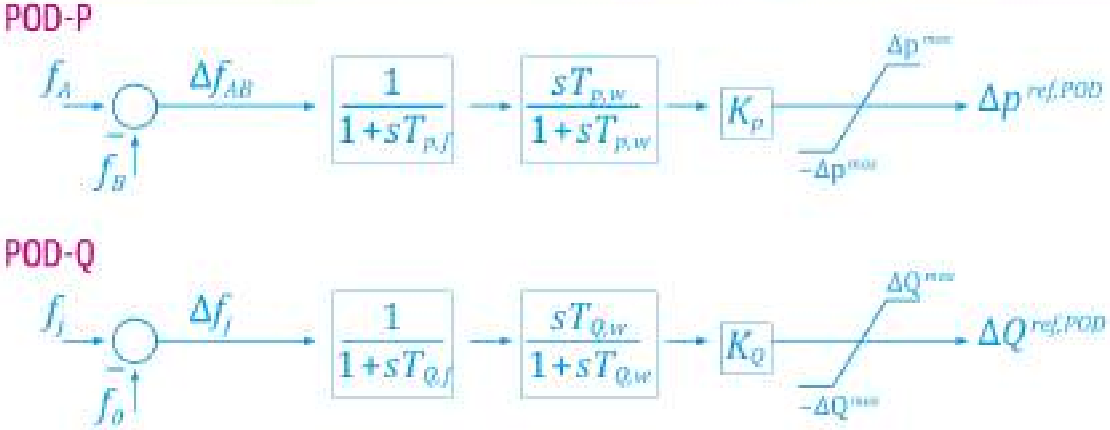

Figure 2-38: INELFE-1 POD block scheme

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_i 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 2-5 and 2-6, for Spain and Portugal, respectively.

Technology	PSS installed	Type	Note
Nuclear	NO		
Hydro	NO		
Pumping storage	YES	PSS2A	One power plant (with five 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 on 28 April 2025

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 on 28 April 2025

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 is 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.

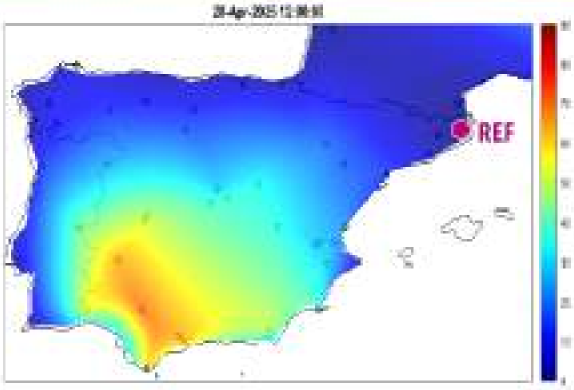

Figure 2-40: Heatmap of angular displacement at 12:00 (source: PMU)

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

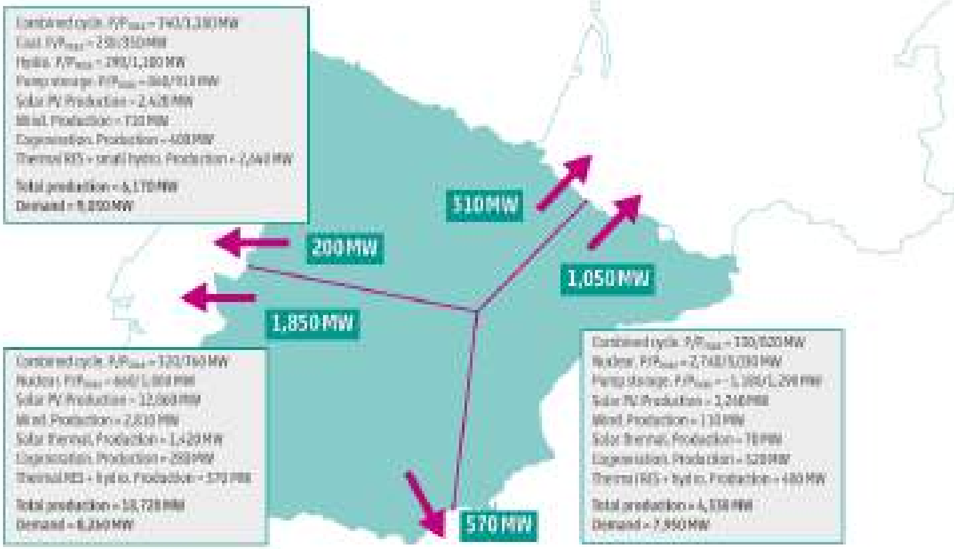

Figure 2-41: Geographic distribution of generation in Spain at 12:32

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).

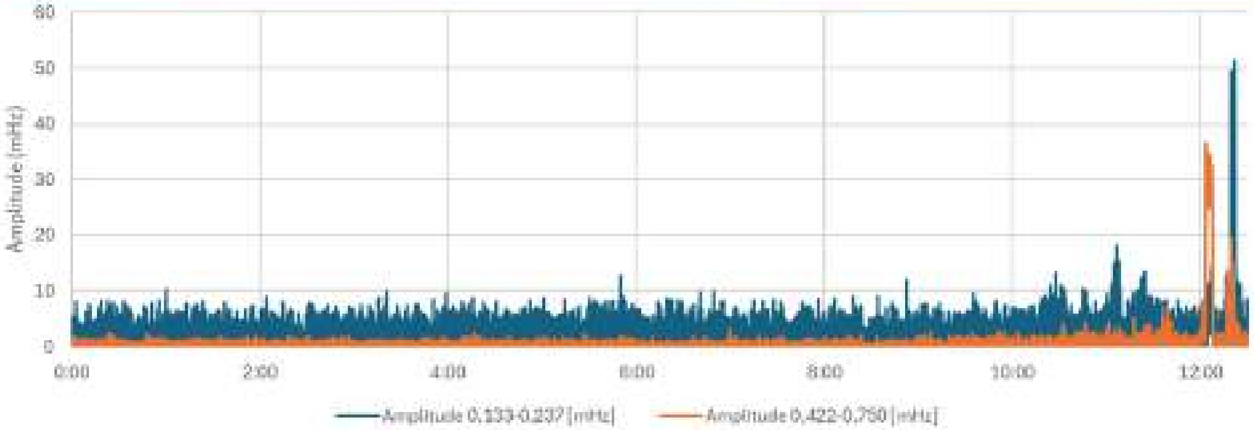

Figure 2-42: Amplitude of modes identified by the modal analysis tool in the RE control room in real time

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.

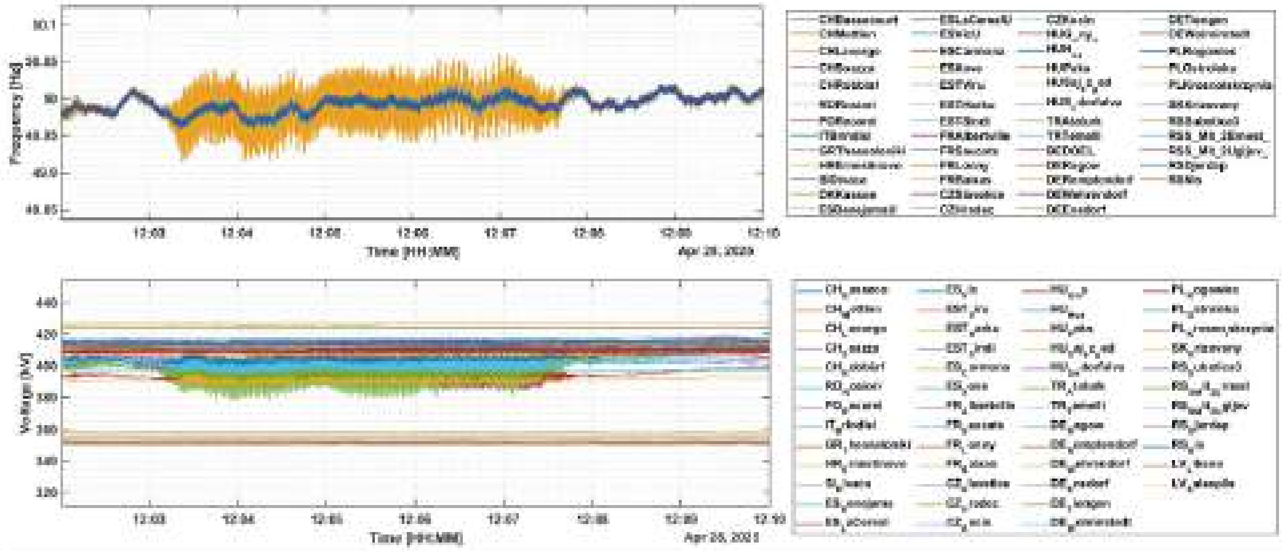

Figure 2-43: Frequency and voltage phasor magnitude measurements from European PMUs

2.5.6.3 Oscillation at 12:03 – 12:08

Oscillatory behaviour with a frequency around 0.63 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).

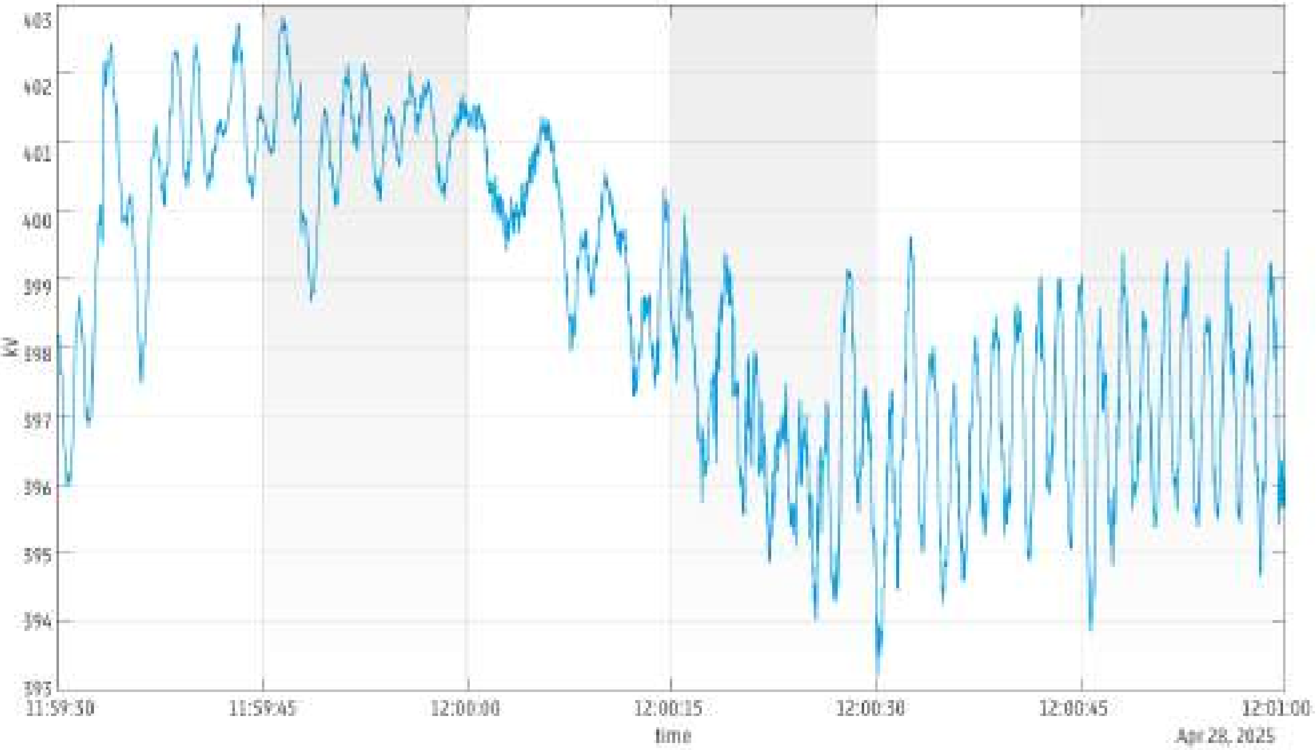

Figure 2-44: Voltage at PMU ONA4DRO, 11:59:30 – 12:01:00

The 0.63 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.[8]

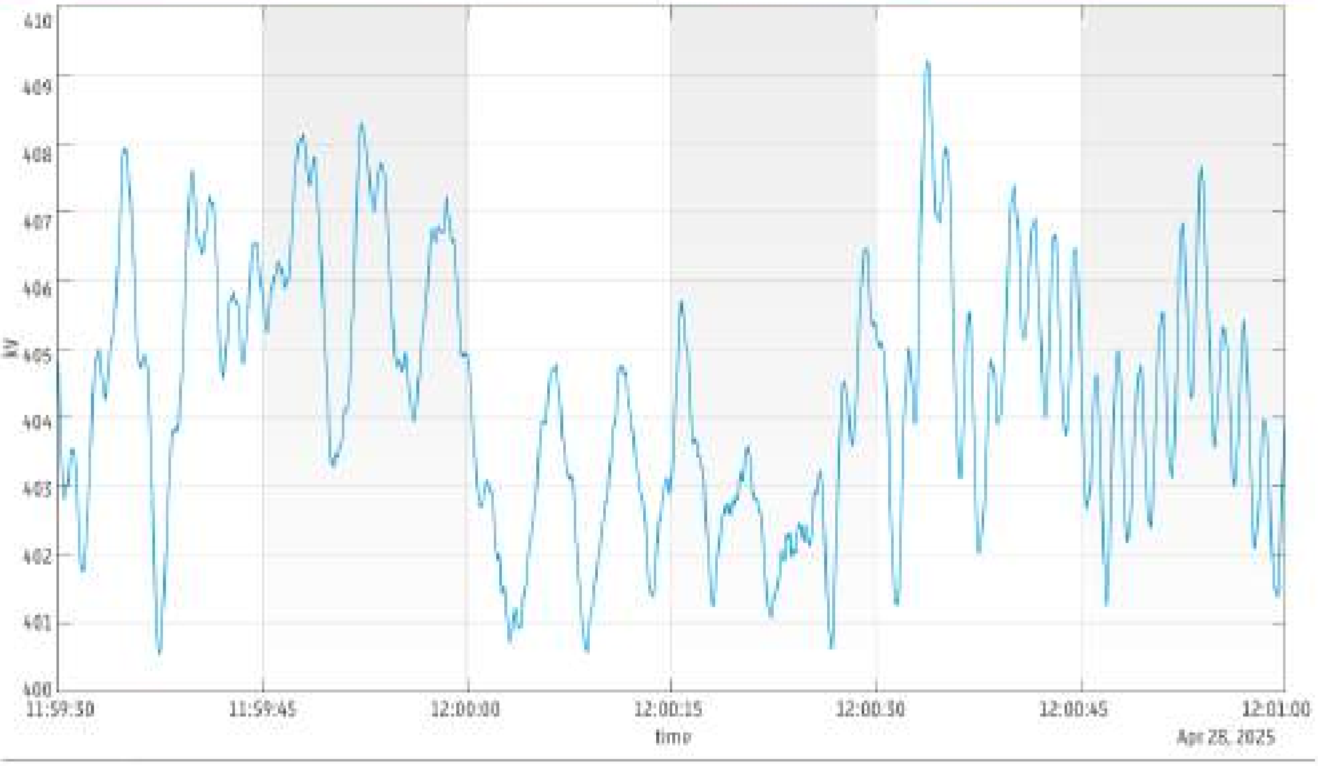

Figure 2-45: Voltage at PMU LLG4ECSL bay 1, 11:59:40 -12:01:00

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[8] 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 0.6Hz 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.

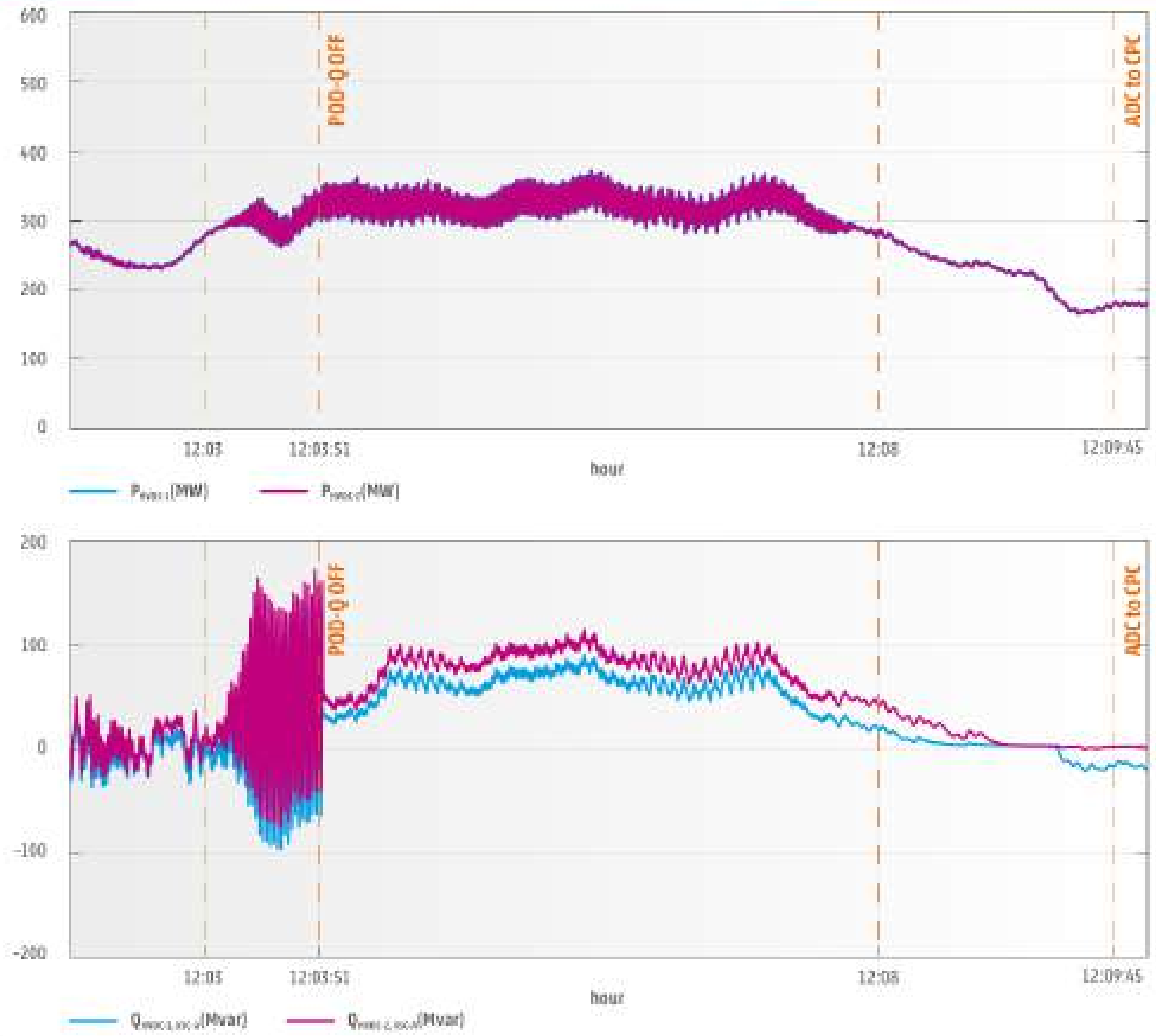

Figure 2-46: Active and reactive power flow at PMU LLG4ECSL bay 1, 12:00:00 – 12:10:00

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.

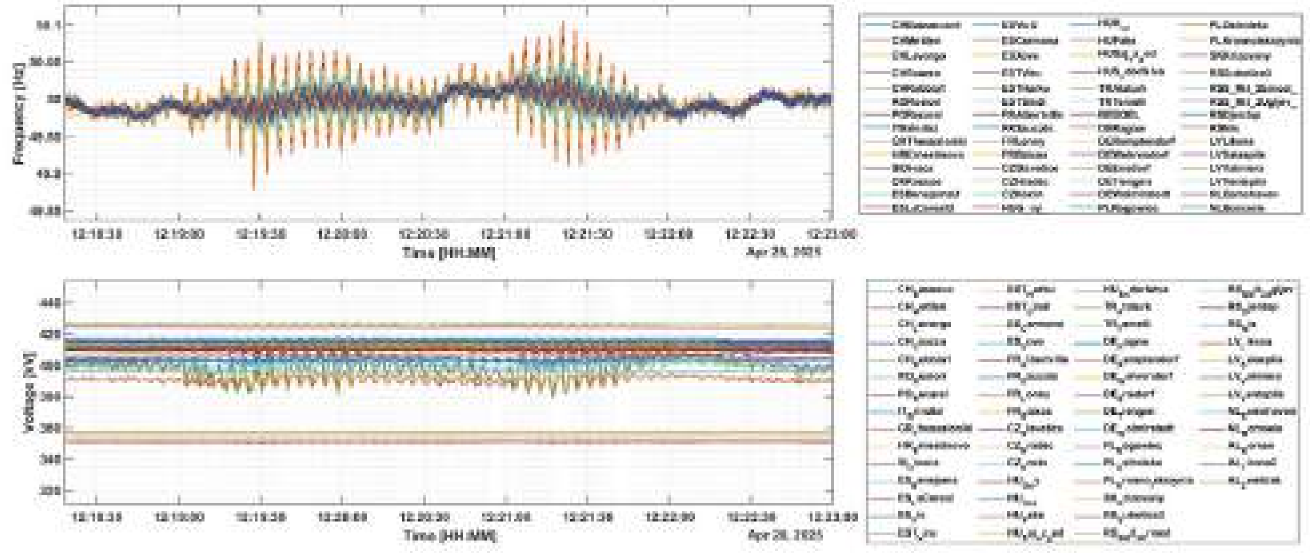

Figure 2-47: Frequency and voltage phasor magnitude measurements from European PMUs

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.

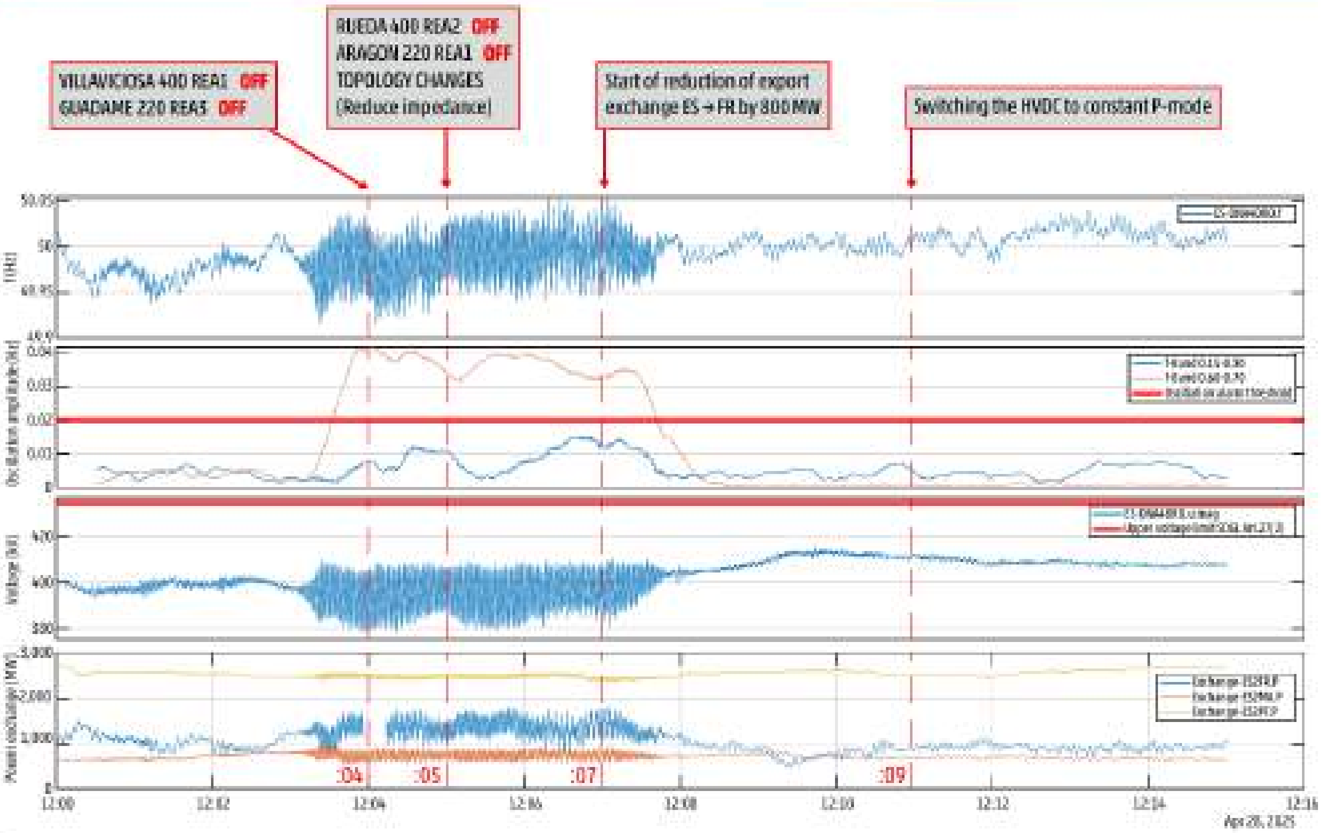

Figure 2-48: Characteristics data of the first oscillations (source: WAMS 100 ms sampling rate in the 6 kV Carmona (Spain) substation) and countermeasures applied

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 0.2 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.

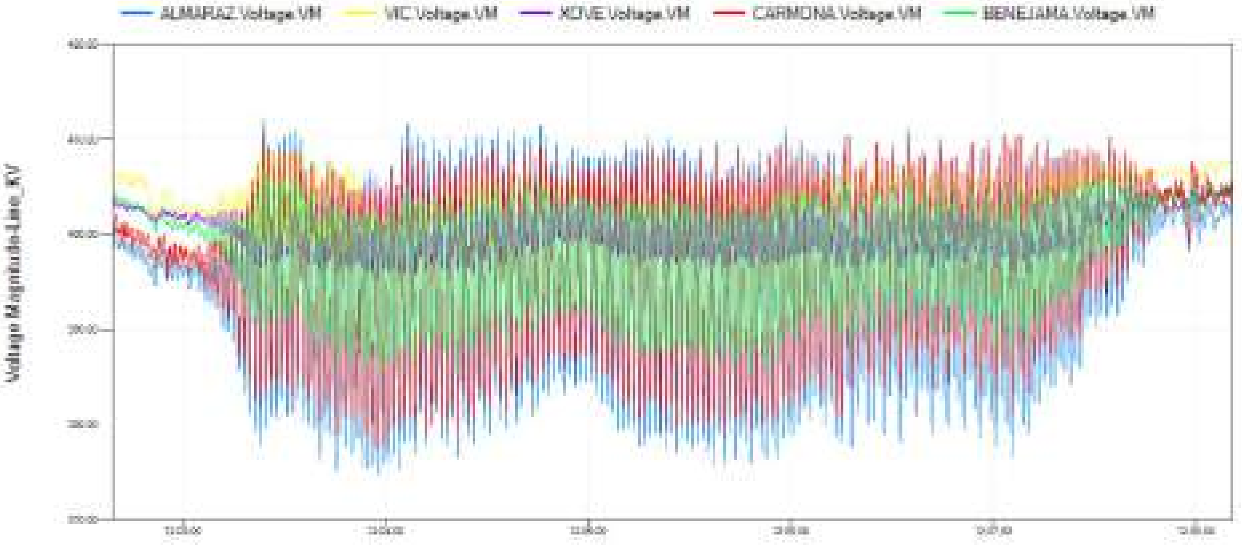

Figure 2-49: Voltage magnitudes in several Spanish substations

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.

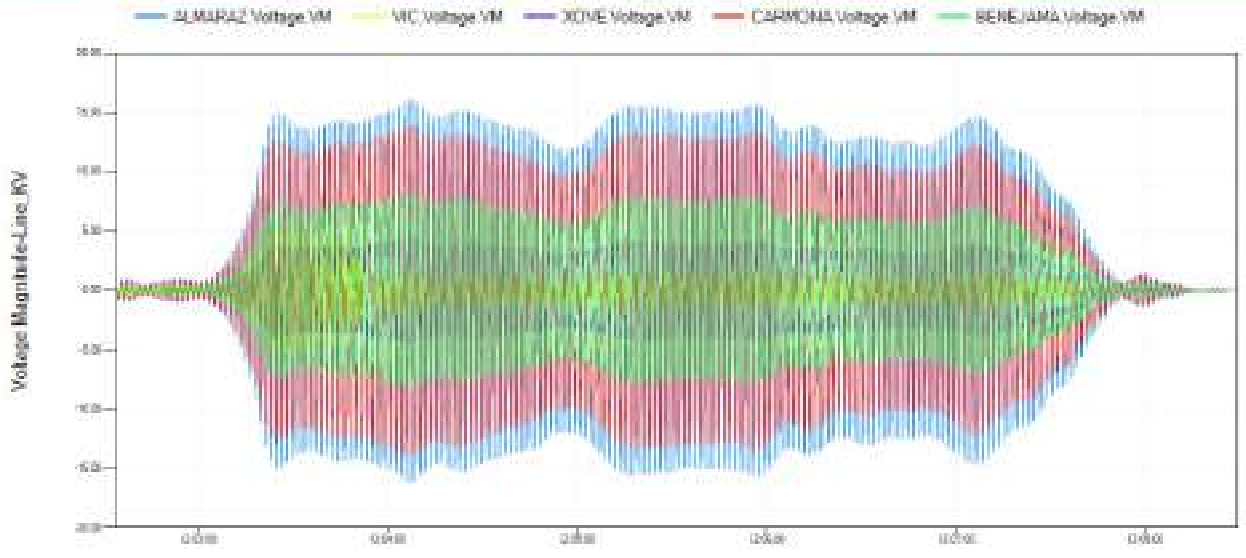

Figure 2-50: Voltage oscillation after apply a pass-band filter [0.55 - 0.70 Hz] in several Spanish substations

After applying a complex principal component analysis algorithm[9] 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).

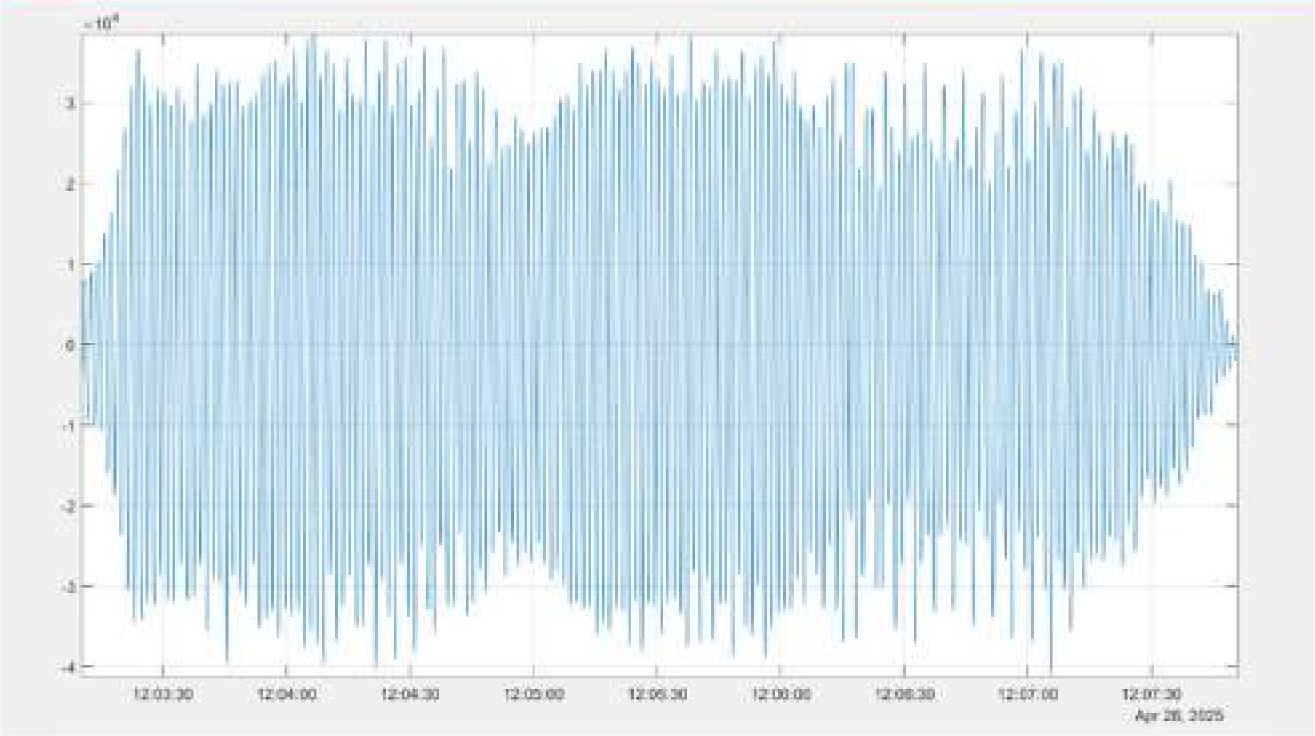

Figure 2-51: Voltage oscillation principal component analysis (PCA)

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[9] 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.

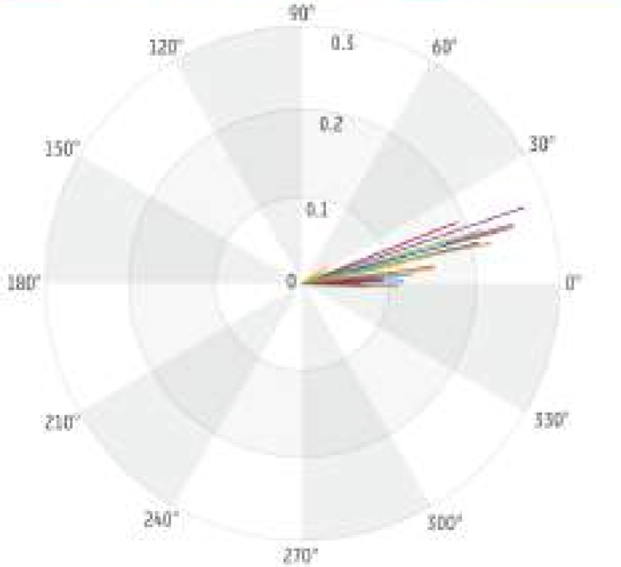

Figure 2-52: Mode shape by complex principal component analysis on PMU voltages normalised (each colour in the polar plot represent a different location)

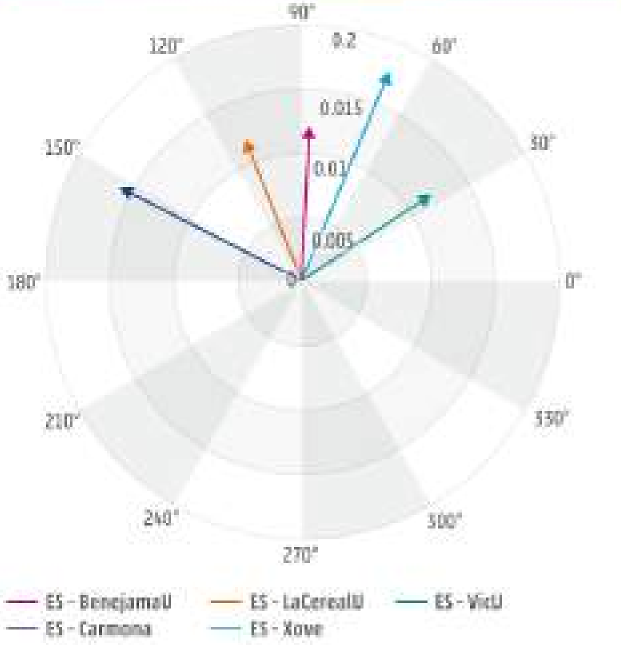

Figure 2-53: Mode shape on PMU frequencies normalised (each colour in the polar plot represents a different location)

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.

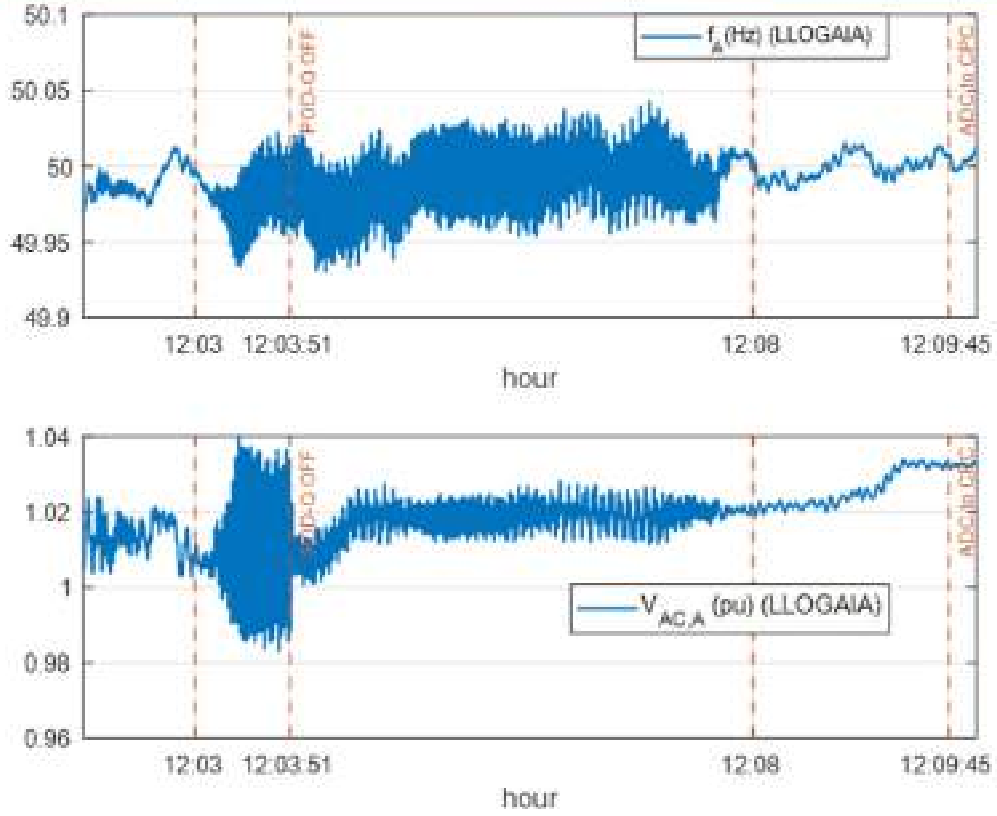

Figure 2-54: First oscillation of 0.63 Hz frequency and voltage at Sta. Llogaia 400 kV substation

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.

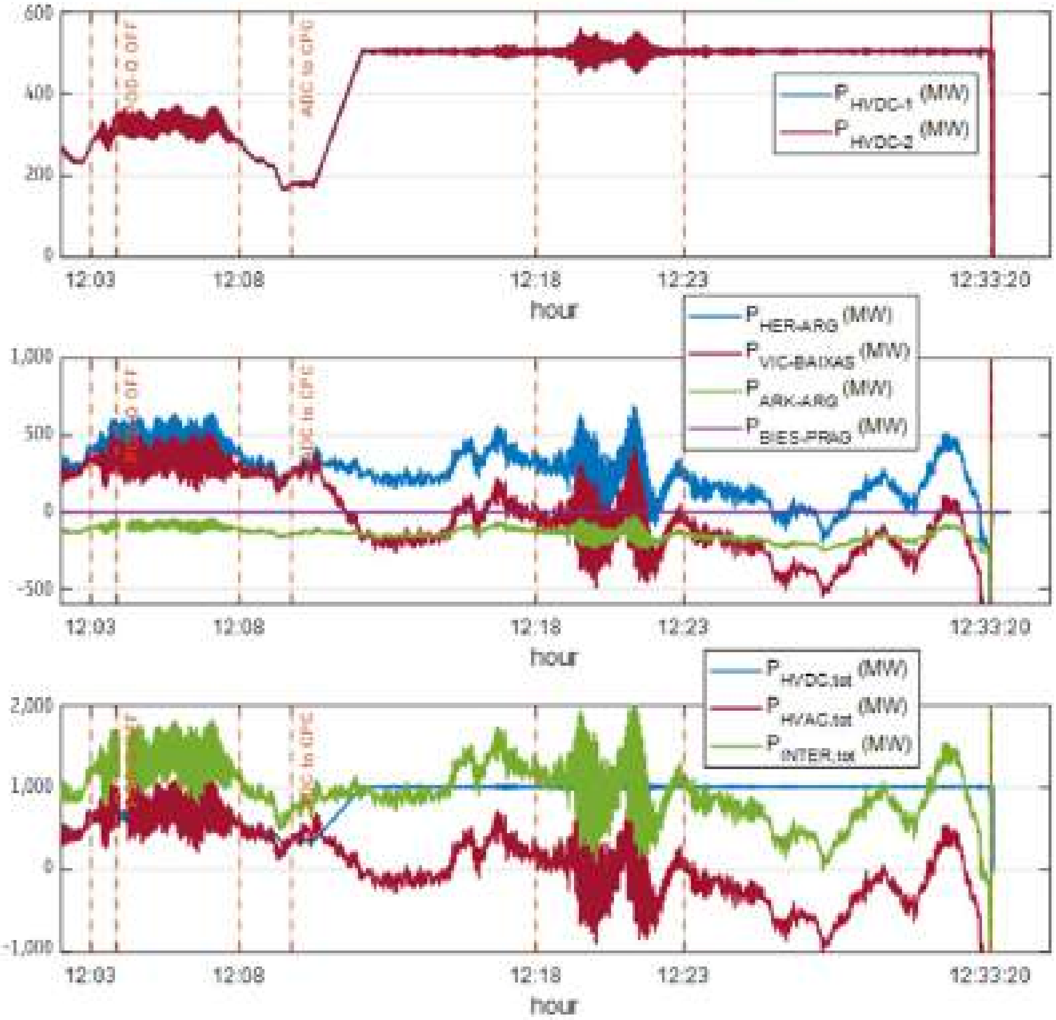

Figure 2-55: Power flows in the Spain–France interconnection (sign criterion: positive = exported from Spain to France)

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.

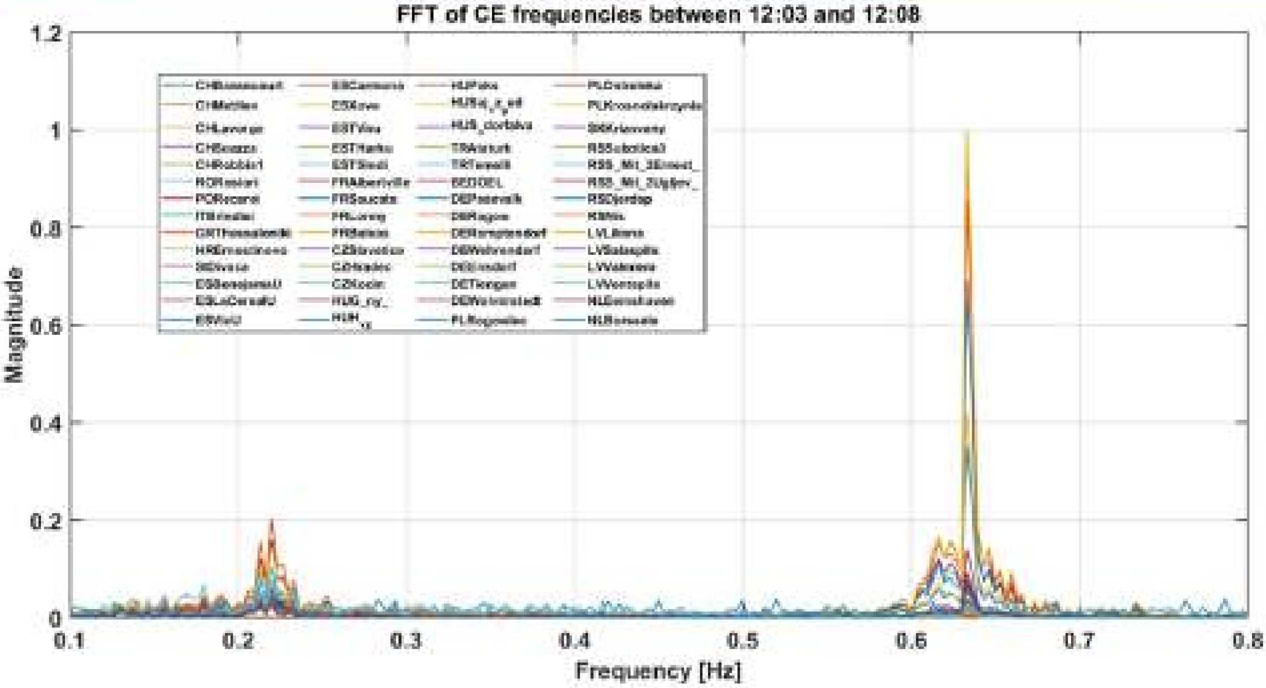

Figure 2-56: Normalised fast Fourier transform of the frequency from various PMUs across Continental Europe between 12:03 and 12:08

To classify this 0.63 Hz oscillation geographical distribution, 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 147°, 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.

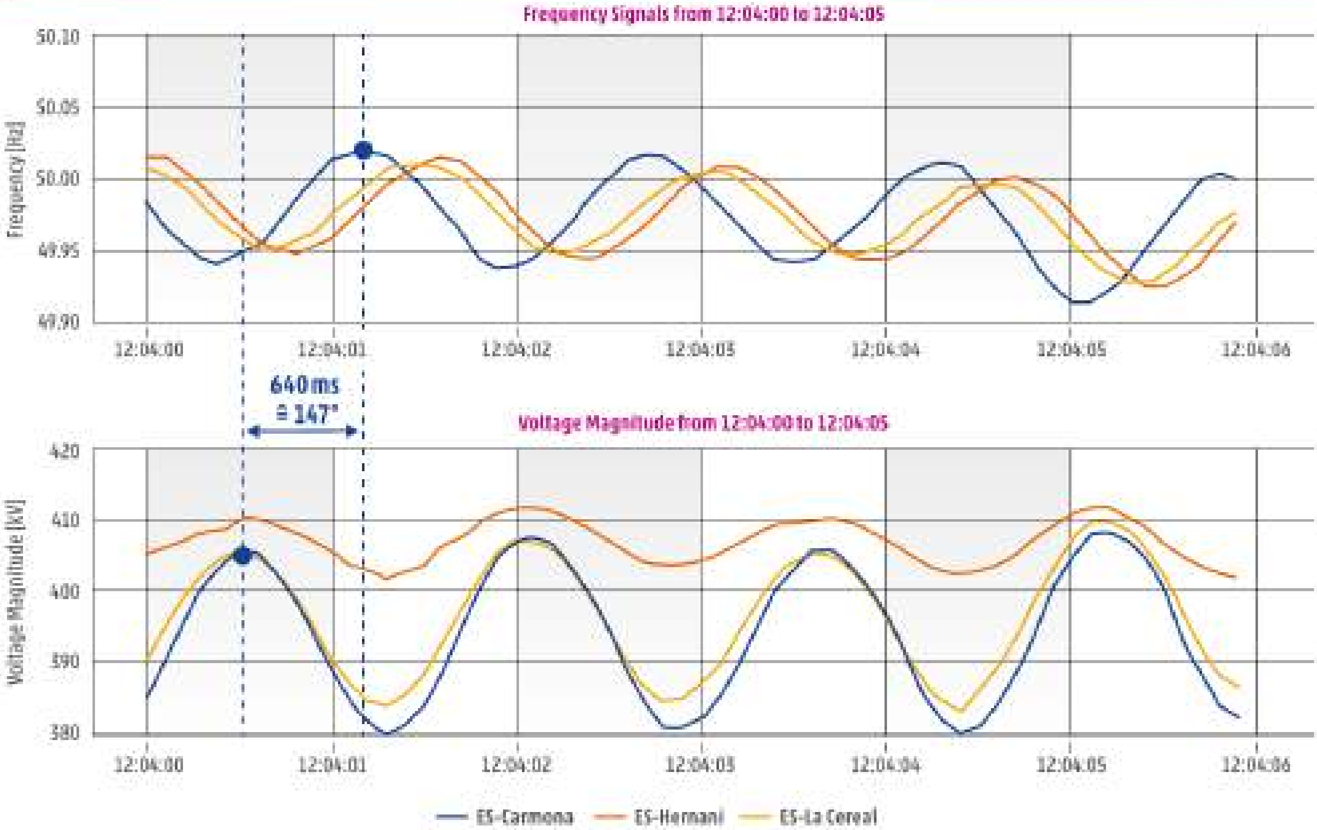

Figure 2-58: Angle between voltages and frequencies

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 2-59 shows fluctuations of active power with a peak-to-peak amplitude of around 0.5 pu and reactive power with a peak-to-peak amplitude of around 0.25 pu, occurring between 12:03 and 12:08.

Chapter 4.2 includes a detailed analysis of the 0.63 Hz oscillations.

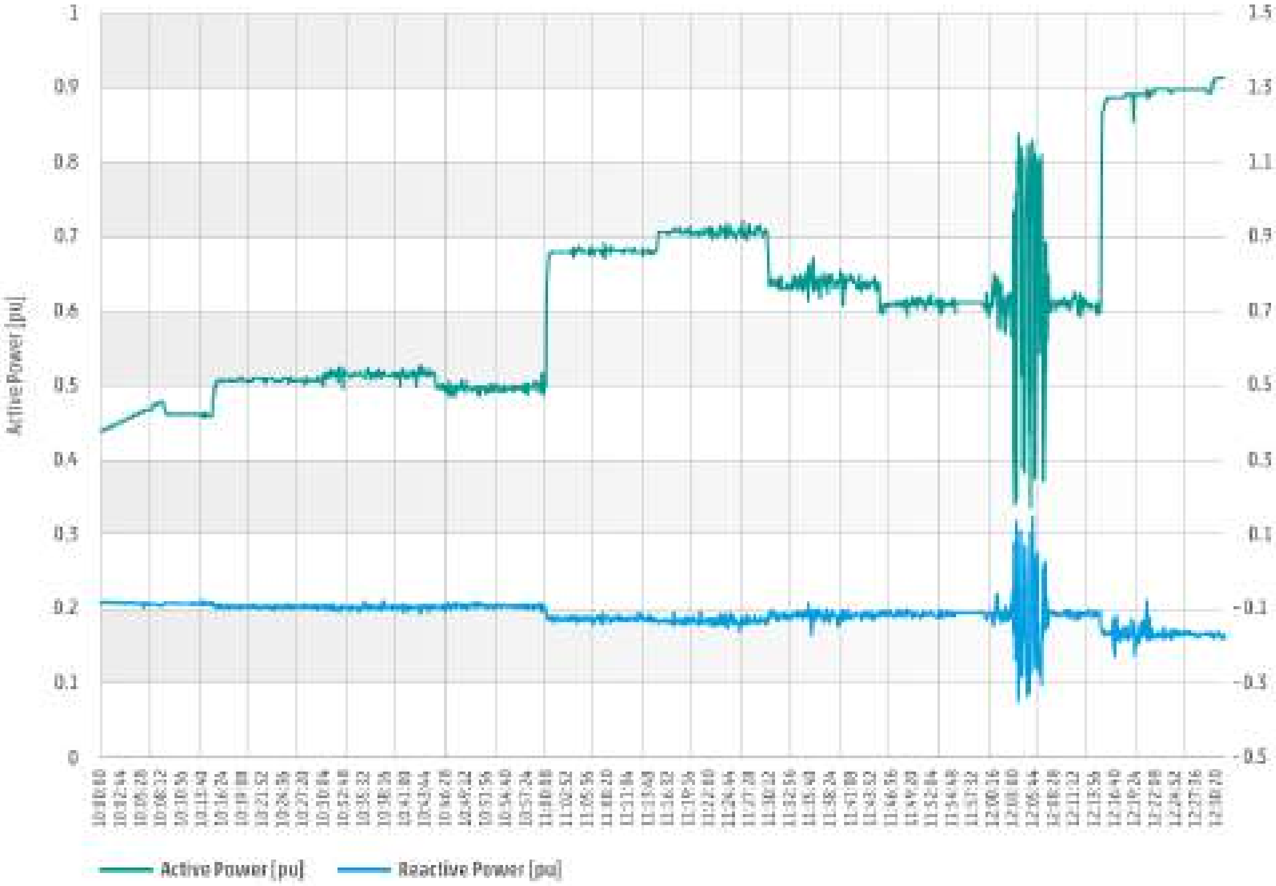

Figure 2-59: Active and reactive power generated by a power plant connected in the province of Badajoz

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.

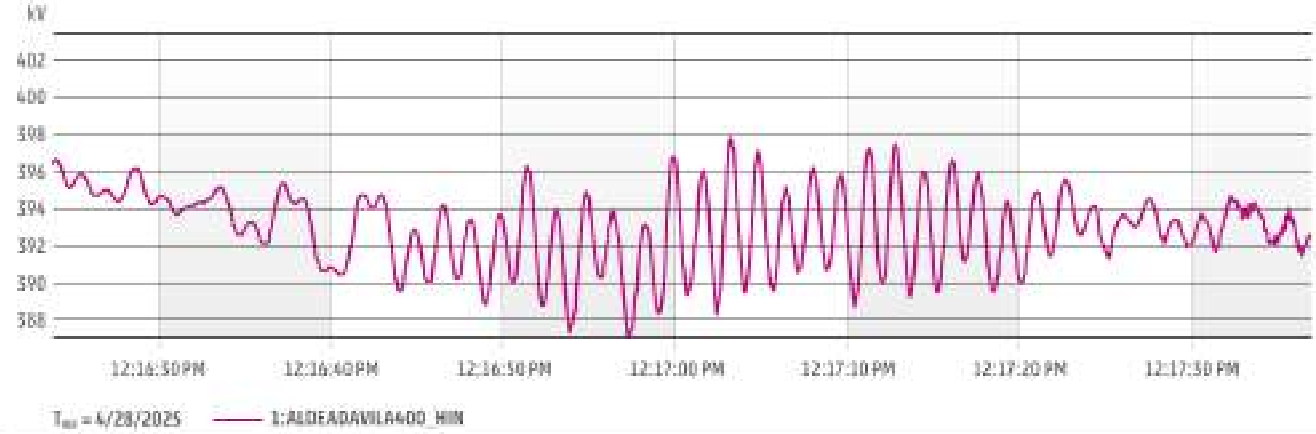

Figure 2-60: Voltage at PMU ALD4HIN between 12:16:30 and 12:17:30

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.

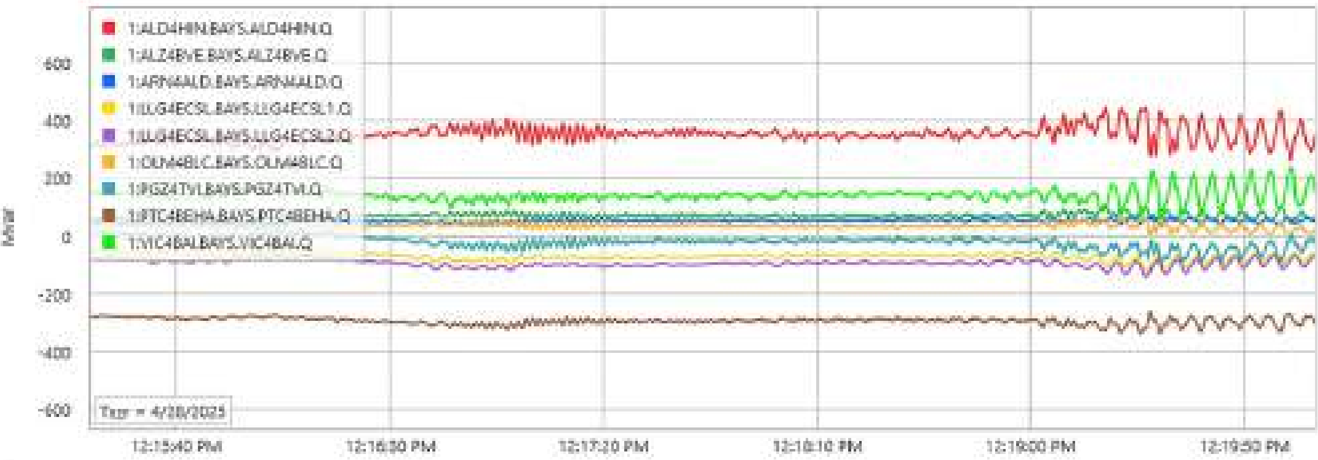

Figure 2-61: Reactive power at various PMUs between 12:15:30 and 12:20:00

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

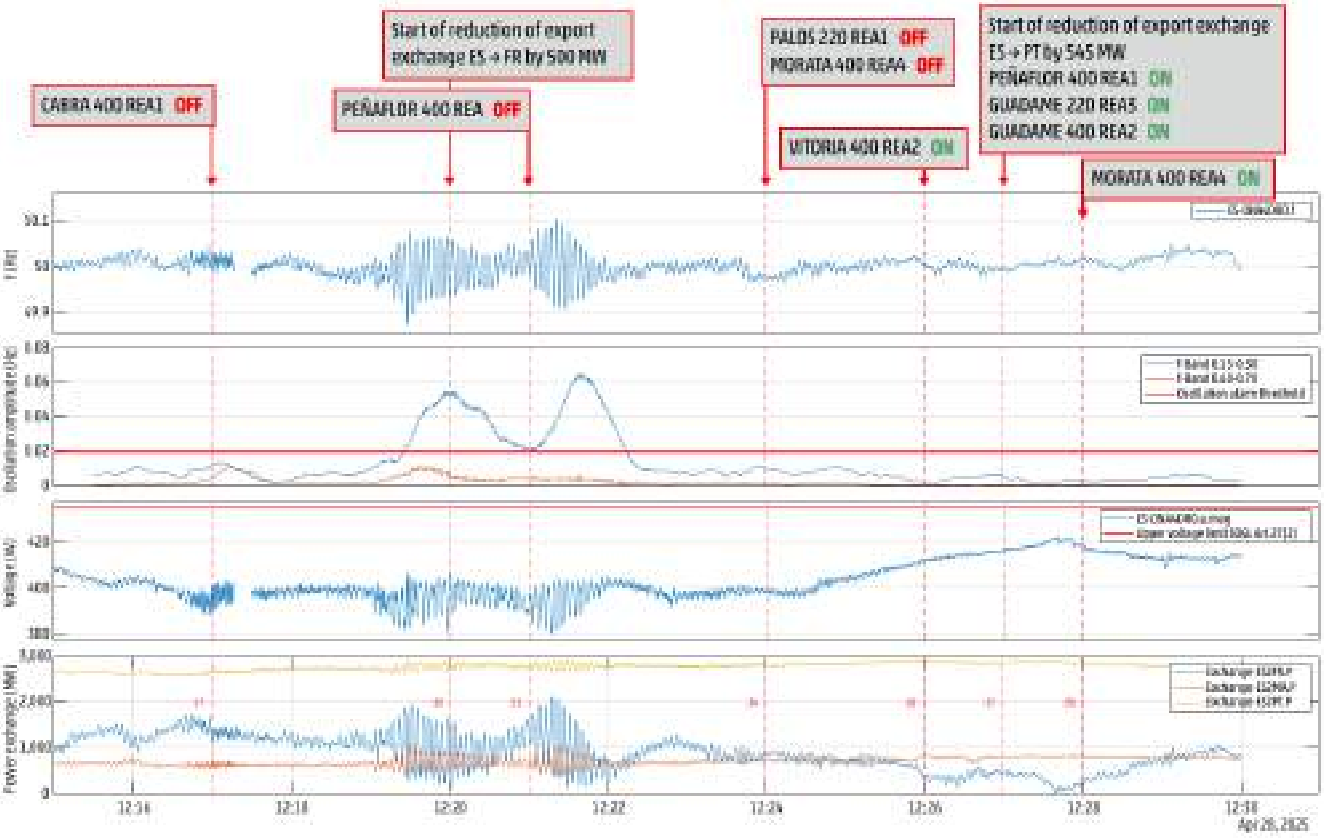

Figure 2-62: Characteristics data of the second oscillations and increasing voltage (source: WAMS 100 ms sampling rate at the 400 kV Carmona substation) and countermeasures

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 0.2 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:

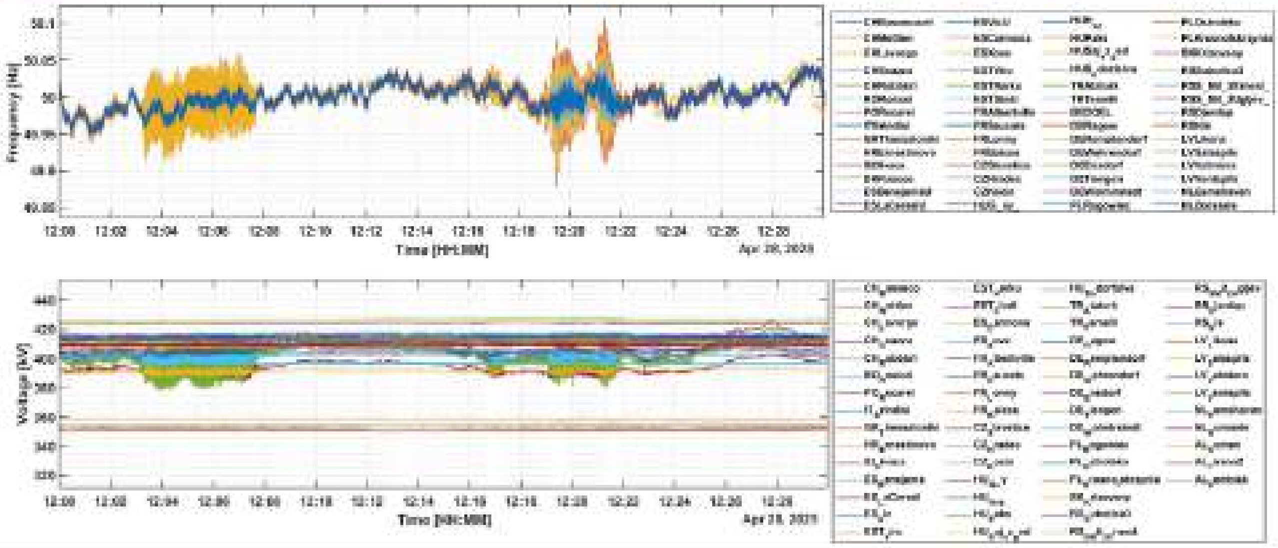

Figure 2-63: Frequency and voltage phasor magnitude measurements from European PMUs

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 shows a spectrogram over all the PMUs of Spain and Portugal available (frequency measurement sampled at 100 ms); it is clearly visible the fingerprint of interarea mode at 0.2 Hz.

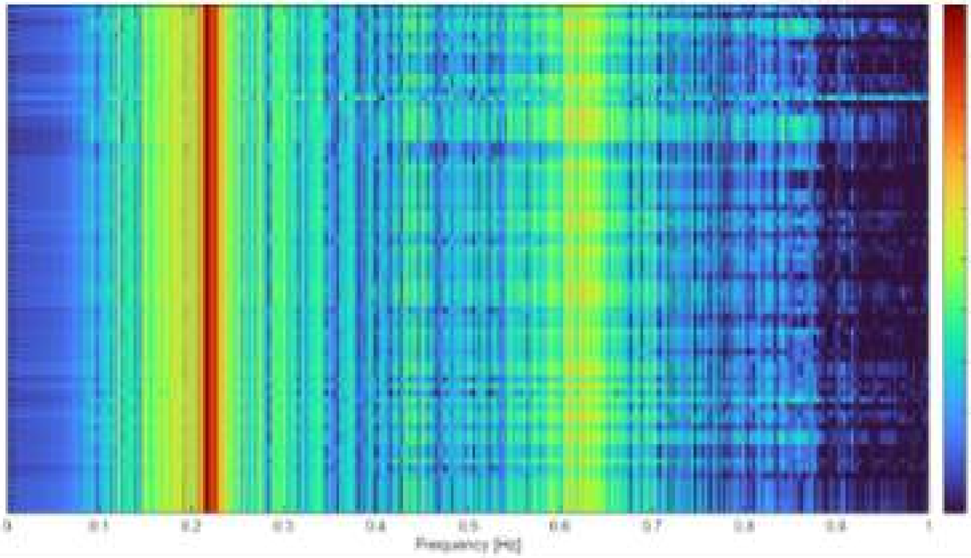

Figure 2-64: Spectrogram of all the Spain/Portugal PMUs during the timeframe of 12:18 to 12:25

The polar plot in Figure 2-65 was obtained processing 128 measurands spreading several European locations; to better readability of the picture, the results of mode shape vectors were aggregated in three main equivalent vectors with a weighting procedure that aggregates vectors with reciprocal phase degrees less than 30°.

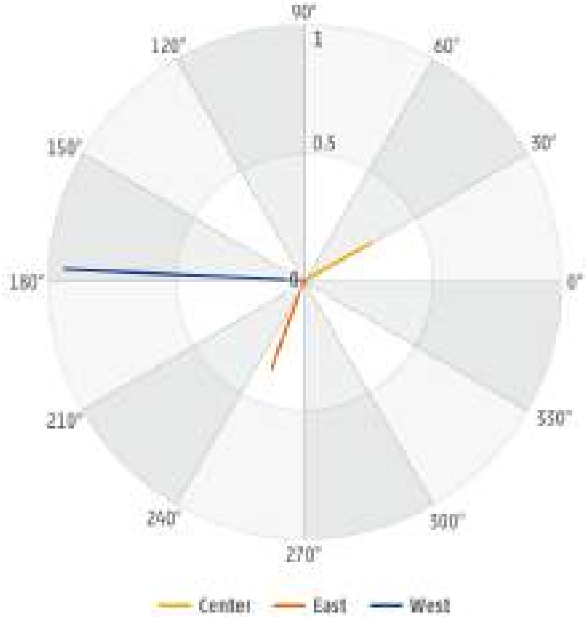

Figure 2-65: Polar plot of the ECW mode at 12:20:00

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[10] (Figure 2-66) show a progressive degradation in the calculated damping of the ECW mode.

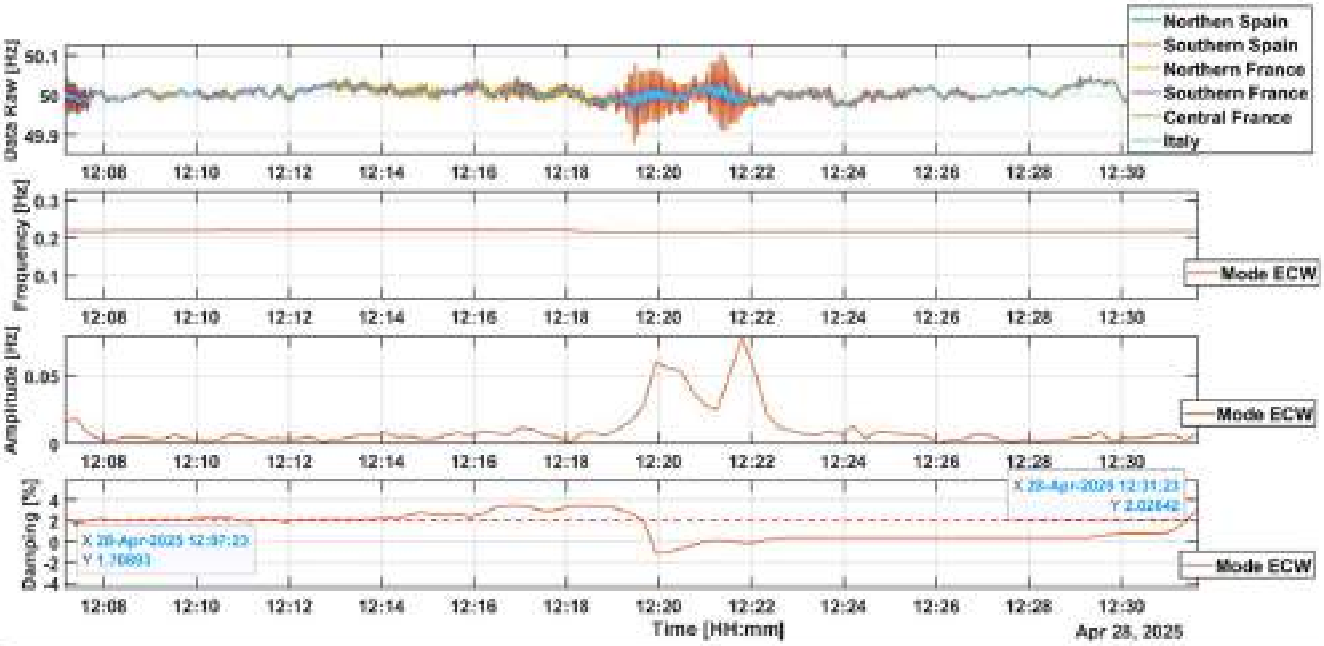

Figure 2-66: Estimated frequency, amplitude, and damping ratio of the dominant oscillation mode over time, obtained using a mode estimation algorithm

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.

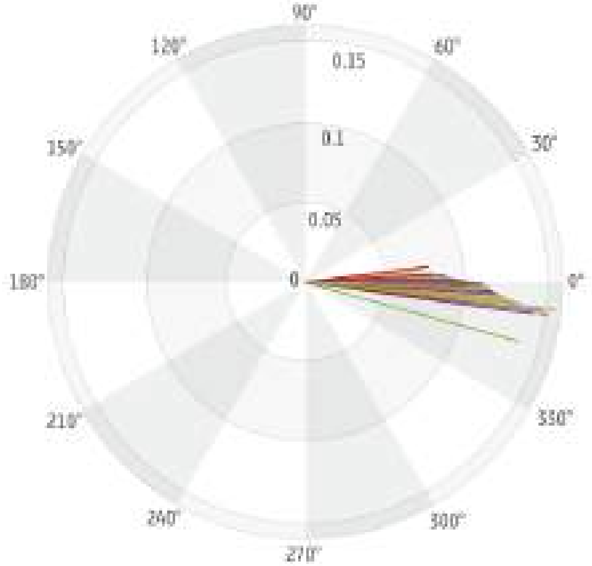

Figure 2-67: Mode shape by complex principal component analysis on PMU normalised voltages (colours in the polar plot represent different locations)

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[10] 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.

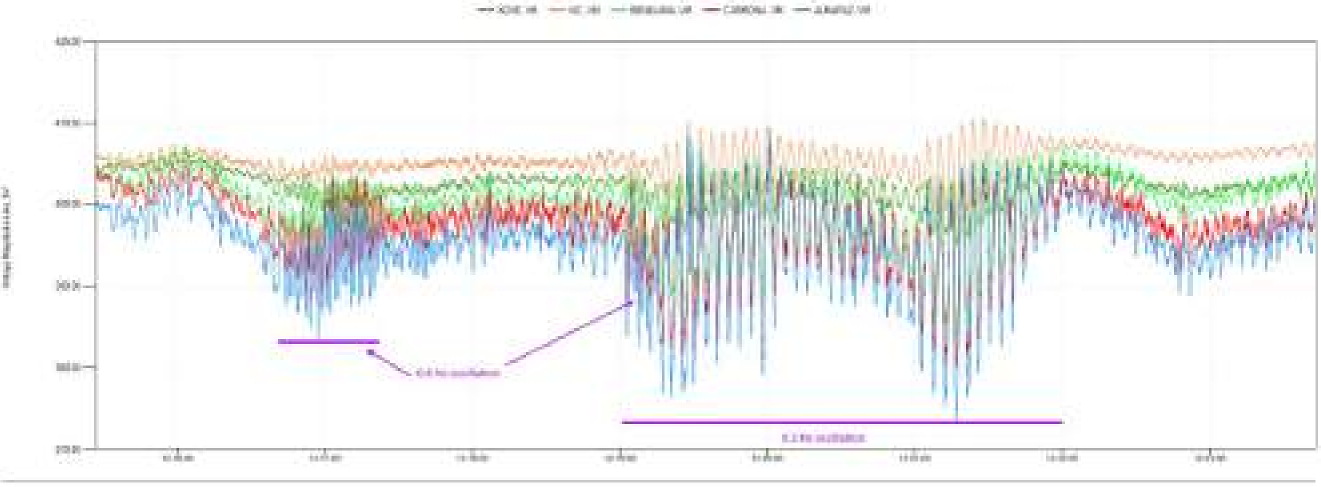

Figure 2-68: Voltage magnitudes at several Spanish substations

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.

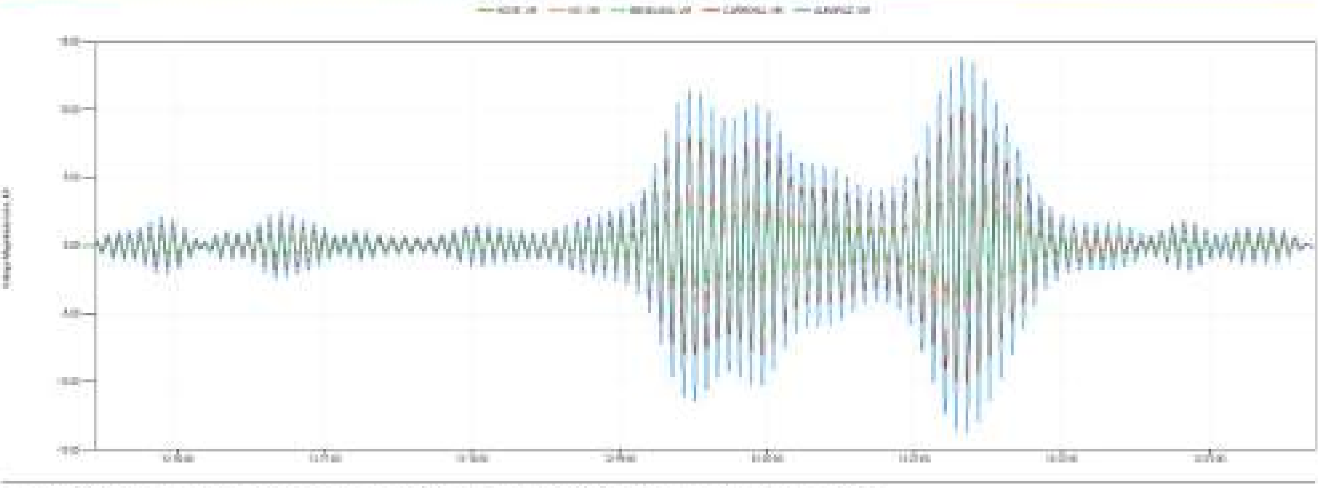

Figure 2-69: Voltage oscillations after applying a pass-band filter [0.18 - 0.25 Hz] at several Spanish substations

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).[11]

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 establish 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[12] (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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[11] In Spain, the following limits apply in accordance with the official Operational Procedure 1.4, § 3.2 (RE 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."*

[12] 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[13] from 1998 are shown in Figures 2-70 and 2-71 (based on data from the Red Eléctrica SCADA system).

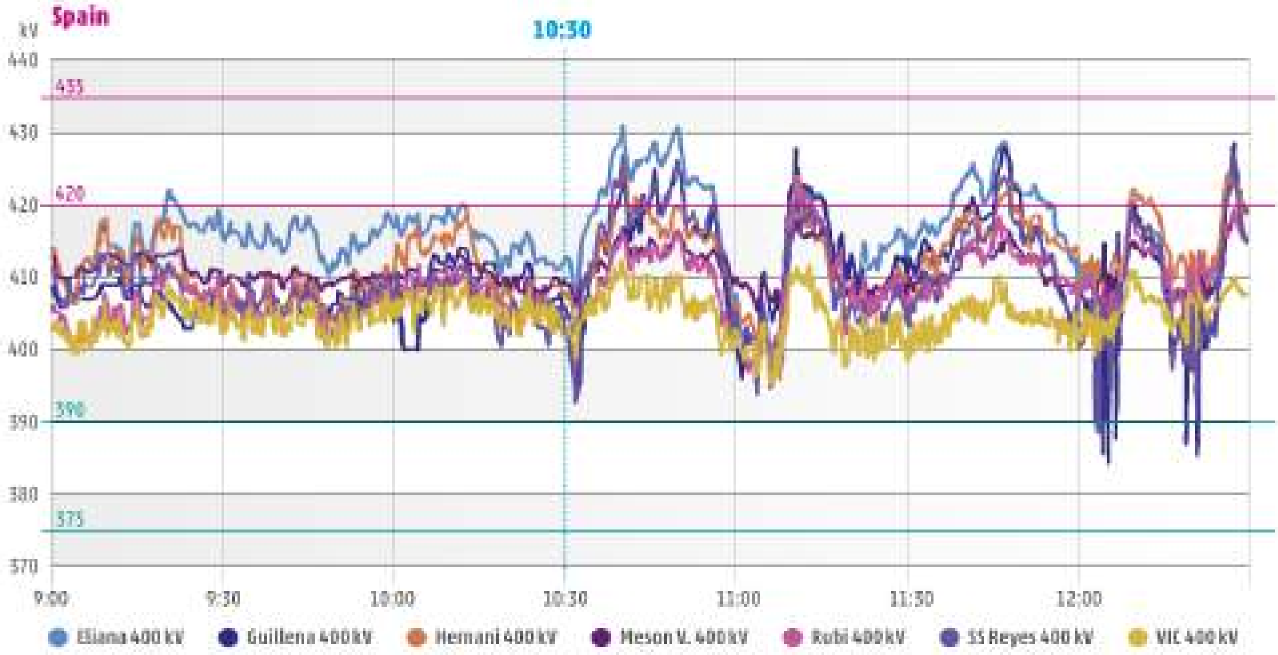

Figure 2-70: Voltage evolution at the main 400 kV transmission substations (pilot nodes) in Spain

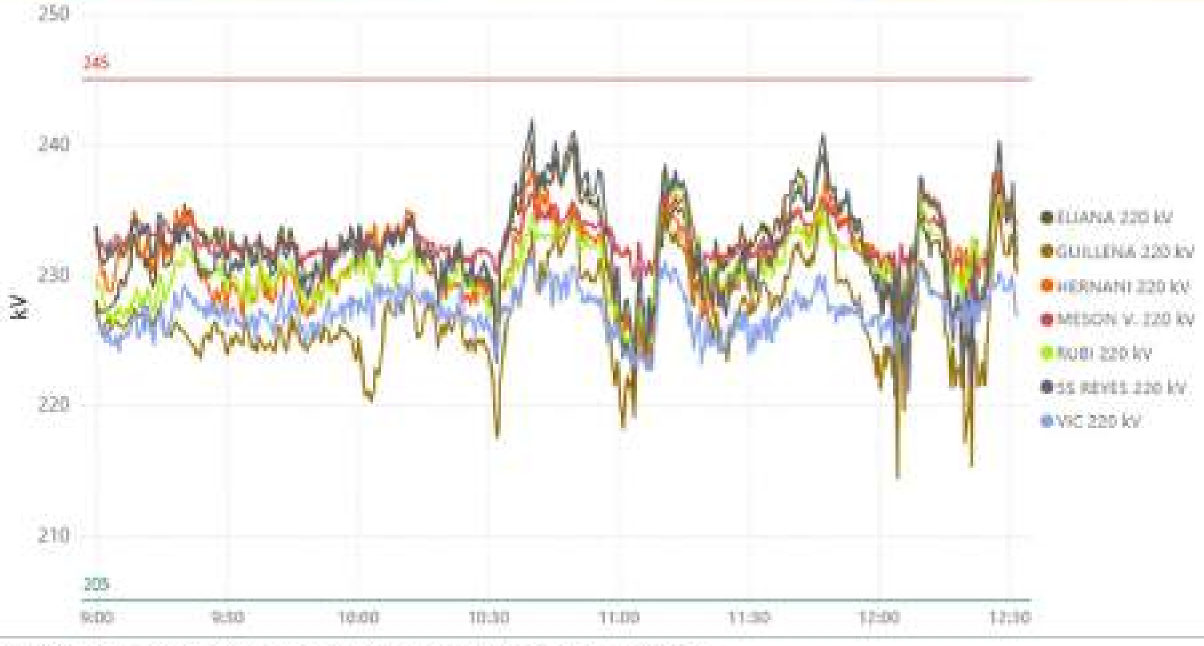

Figure 2-71: Voltage evolution at the main 220 kV transmission substations (pilot nodes) in Spain

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[13] 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.

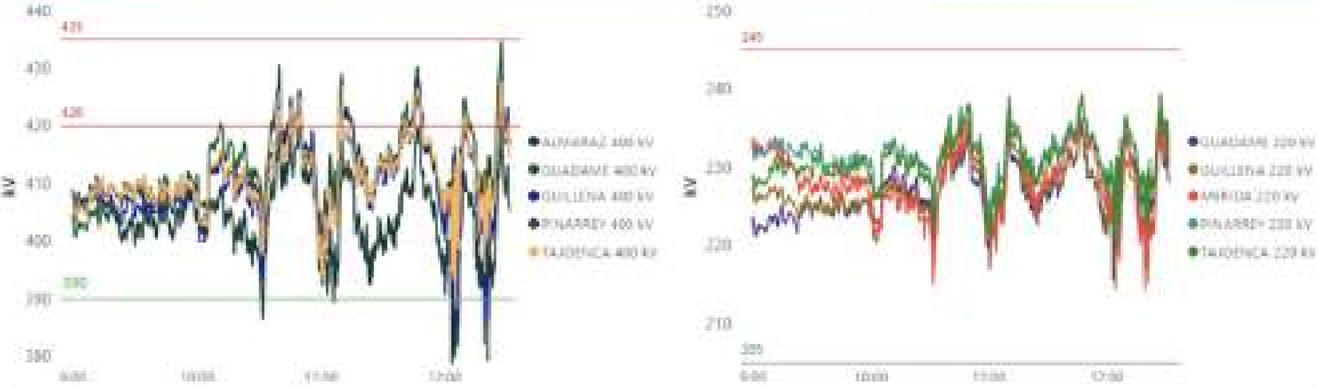

Figure 2-72: Voltage evolution at the main transmission substations (pilot nodes) in the south of Spain

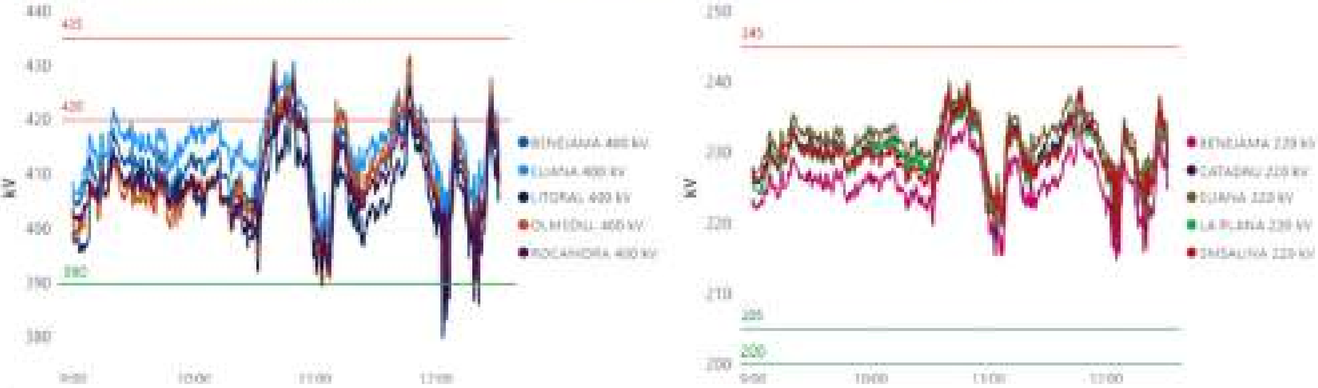

Figure 2-73: Voltage evolution at the main transmission substations (pilot nodes) in the east of Spain

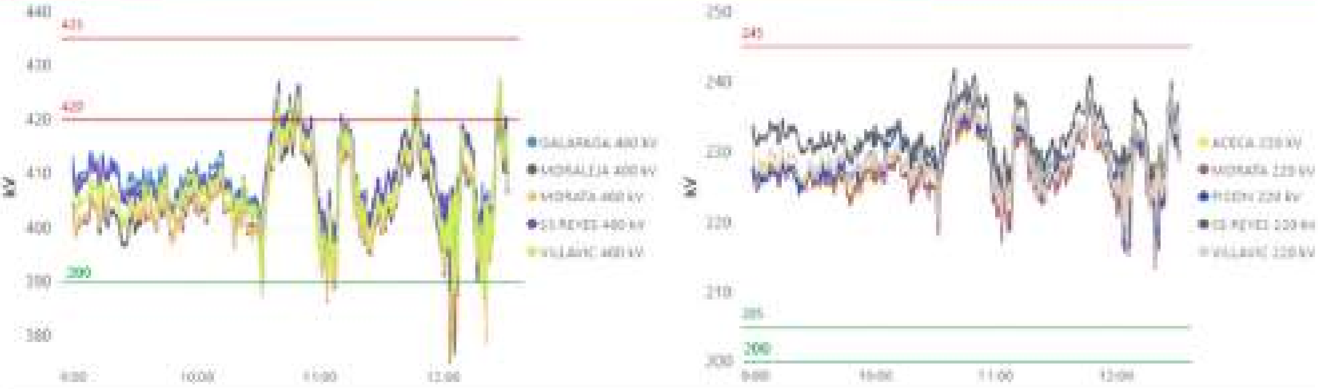

Figure 2-74: Voltage evolution at the main transmission substations (pilot nodes) in the centre of Spain

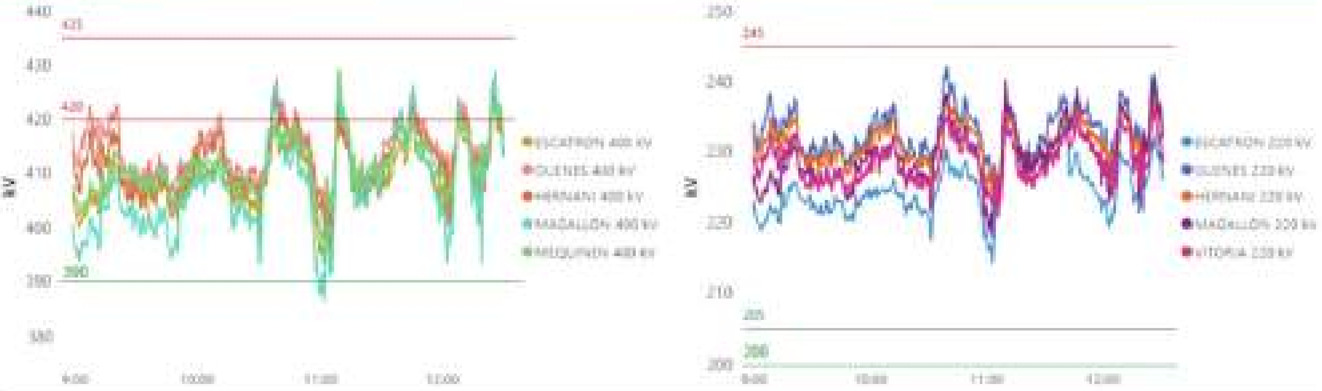

Figure 2-75: Voltage evolution at the main transmission substations (pilot nodes) in the north of Spain

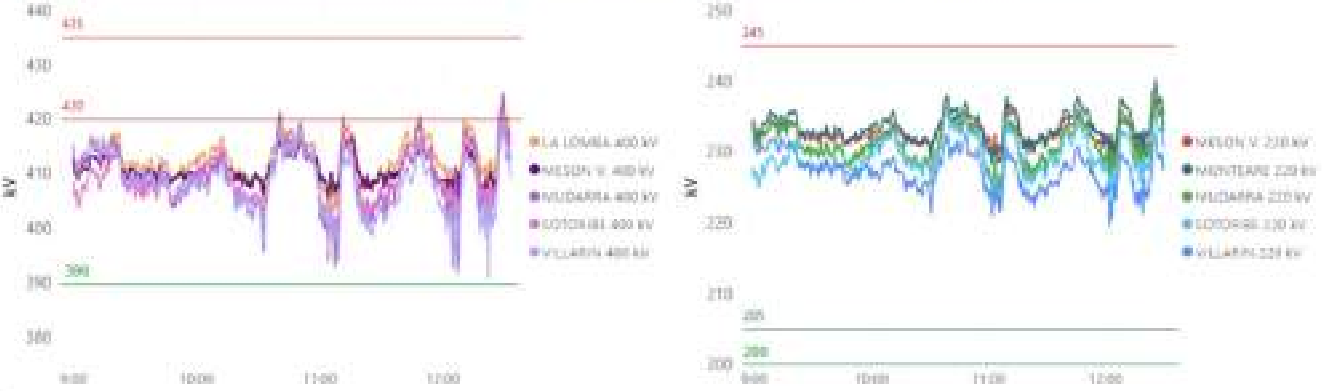

Figure 2-76: Voltage evolution at the main transmission substations (pilot nodes) in the northwest of Spain

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

Chapter 4.1 includes an analysis of these voltage fluctuations and considers also the voltage behaviour observed in Spain on 22 April 2025.

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.

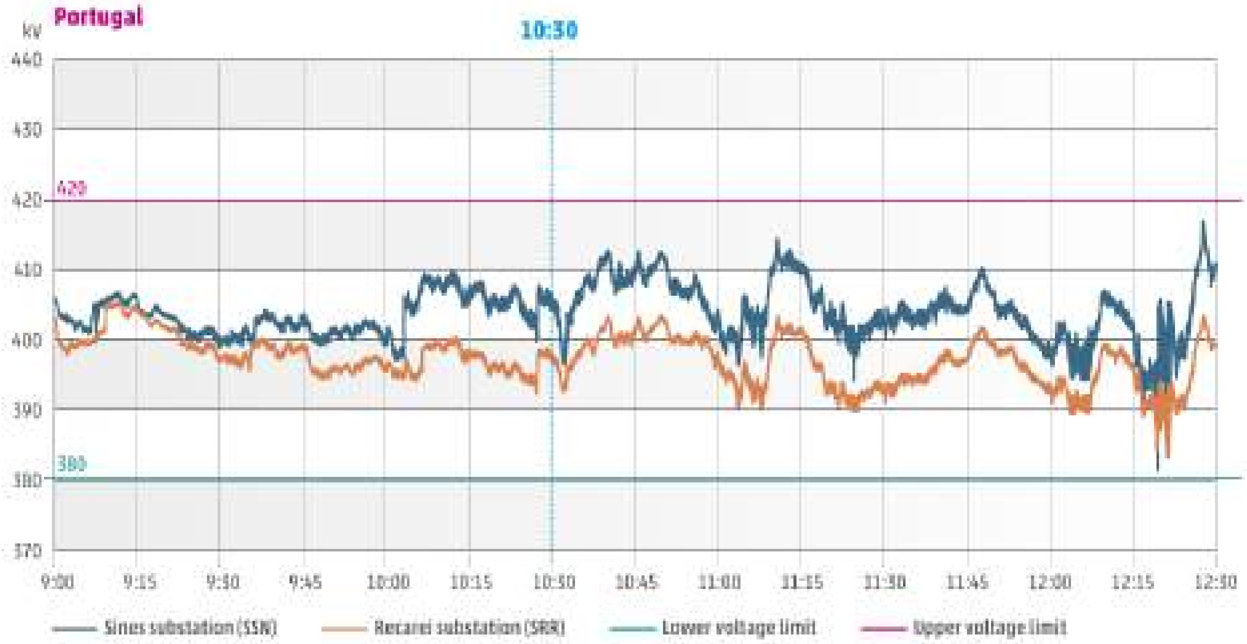

Figure 2-78: Voltage measurements at Sines and Recarei substations (Portugal)

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.

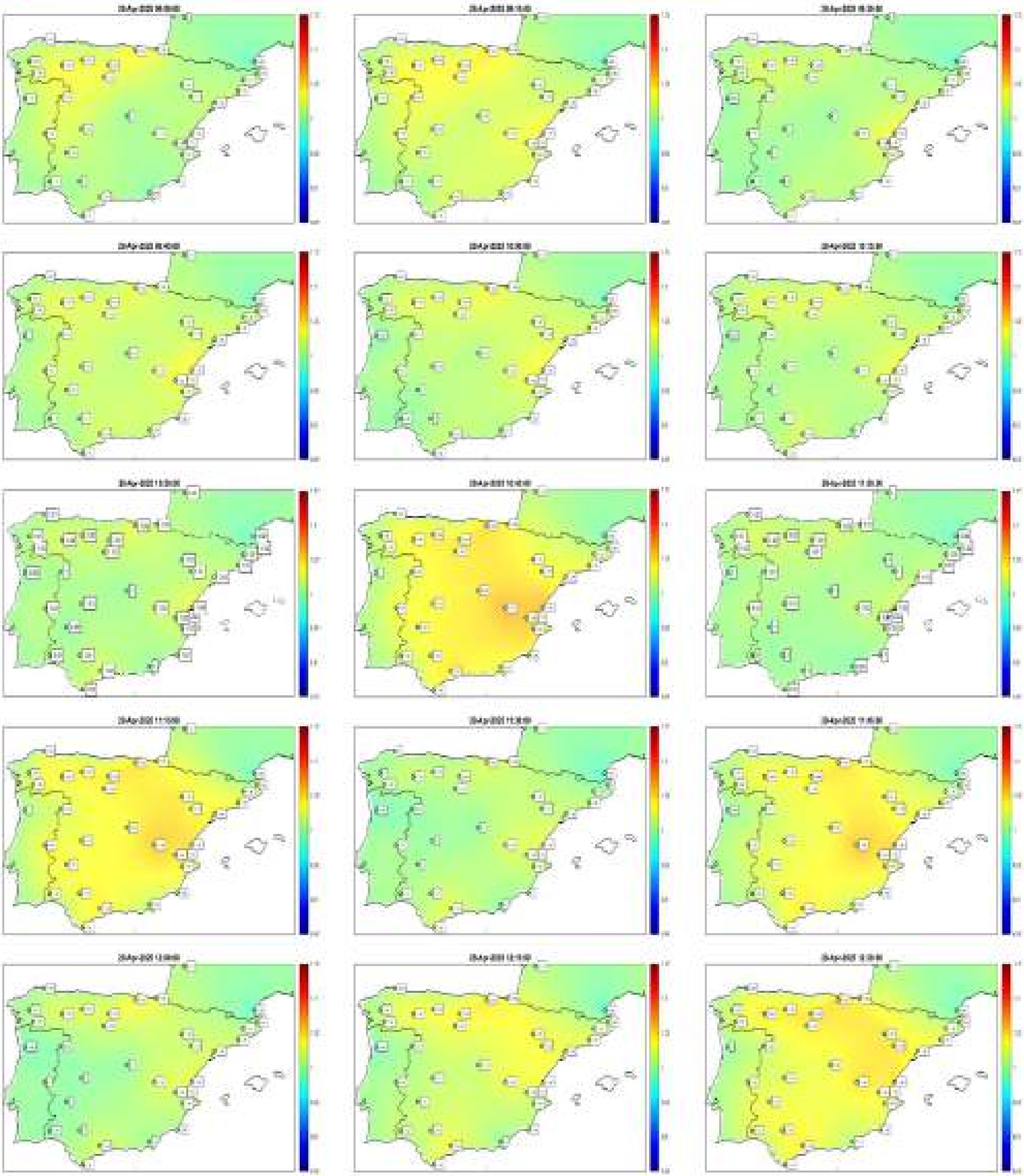

Figure 2-80: Voltage heatmaps of the Iberian Peninsula

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 Eléctrica 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.

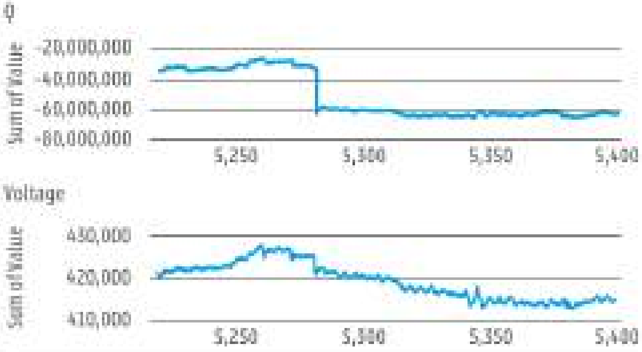

Figure 2-81: Reactive power flow and voltage at PMU MOR4MOT from 12:27:00 to 12:30:00 (x-axis is in seconds in the reference timeframe of the PMU)

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.

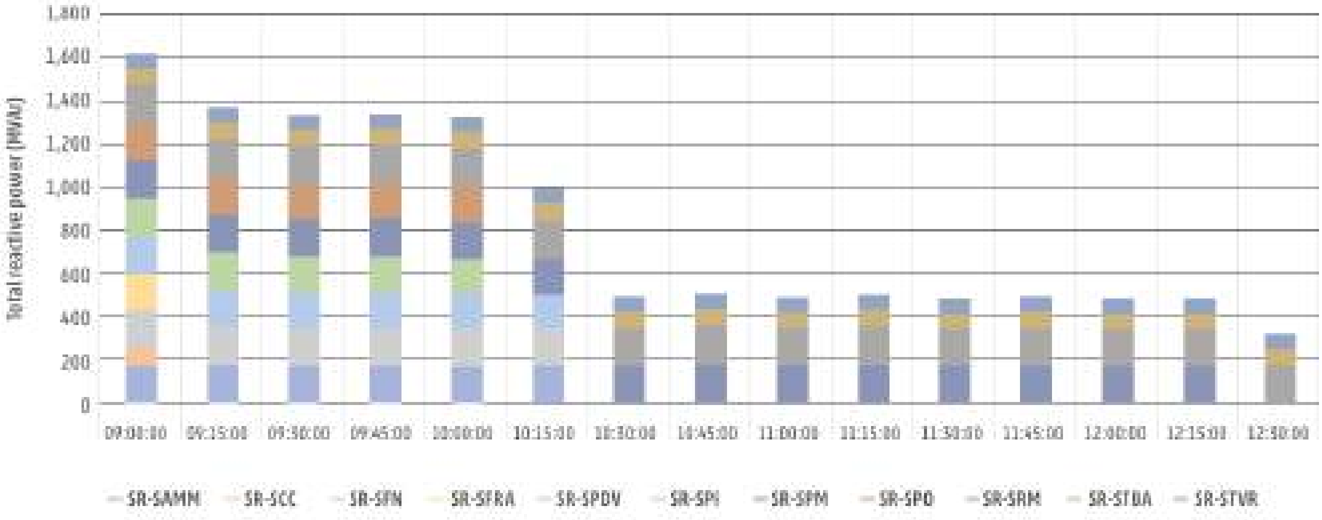

Figure 2-82: Trend of the total reactive power of the shunt reactors in the REN grid

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 from March 2000, which was subsequently **amended** in June 2025.

Operating Procedure (P.O.) 7.4[14] **"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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[14] 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:

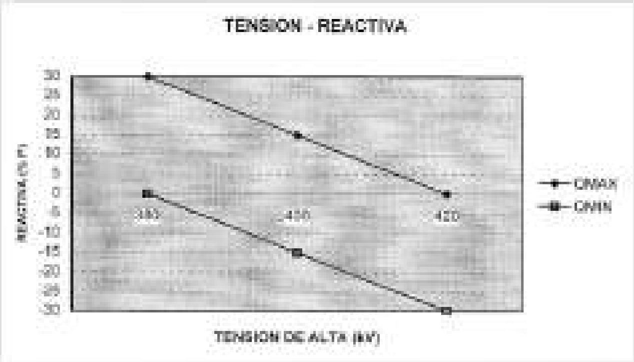
a) *The voltage at the control node assigned to the unit remains within the acceptable variation margins.*
b) *The unit has reached the mandatory reactive power limit or, where applicable, the mandatory limit plus the additional assigned resources, in the appropriate direction.*

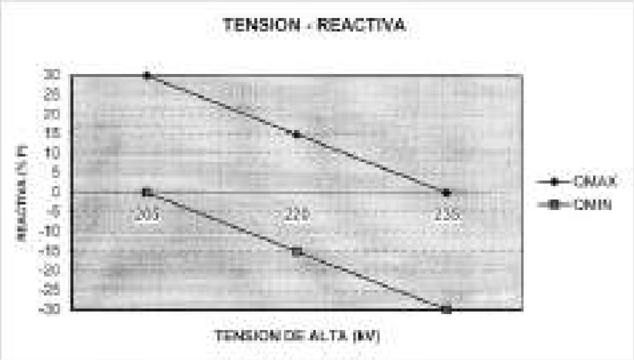
To verify this, it will be checked that the voltage telemetry from the control node – or, if unavailable, the values resulting from state estimation – are within the acceptable band (±2.5 kV around the voltage setpoint established by the System Operator for the control node) in at least 75 % of the sampled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

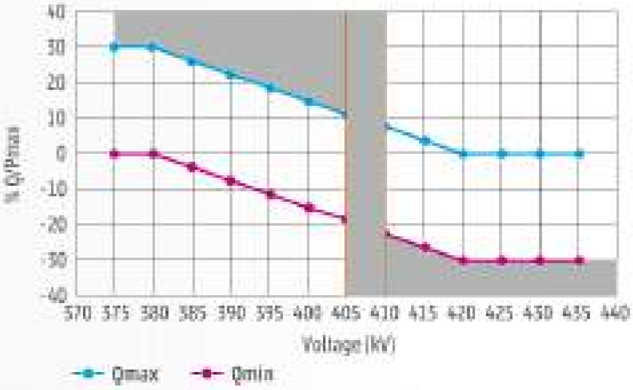
The terms of the service provision are complemented in article 10 of P.O. 7.4. According to article 10.1 of the P.O. 7.4, the service is considered to have been provided adequately if at least 75 % of the values sampled each hour meet one of these two conditions:

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 adequate 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 appropriate 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 appropriate direction in this case), and there is no special requirement 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[15] *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*[16].
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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[15] There is a specific setpoint applicable to Sabón and Meirama.

[16] This has never happened

2.6.5.2 Voltage Regulation Scheme in Portugal

The voltage regulation in the Portuguese transmission system is nodal.

Synchronous power plants (hydro and thermal) can provide reactive power compensation and/or voltage control. Hydro power plants provide this service not only in generation mode but also in pumping/synchronous compensator operation mode, when available. The (voltage and reactive) setpoints are communicated by phone by the TSO. The synchronous generators are obliged to deliver reactive power in order to keep voltage/reactive power at the setpoint defined by the TSO, within the restrictions defined by a P-Q area and as long as the power factor remains higher than 0.90 inductive or 0.95 capacitive. As an exception, one hydro power plant is contracted to provide reactive power control even when not producing active power – thus, it functions as a synchronous compensator. This service uses a reactive power setpoint.

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:

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

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.

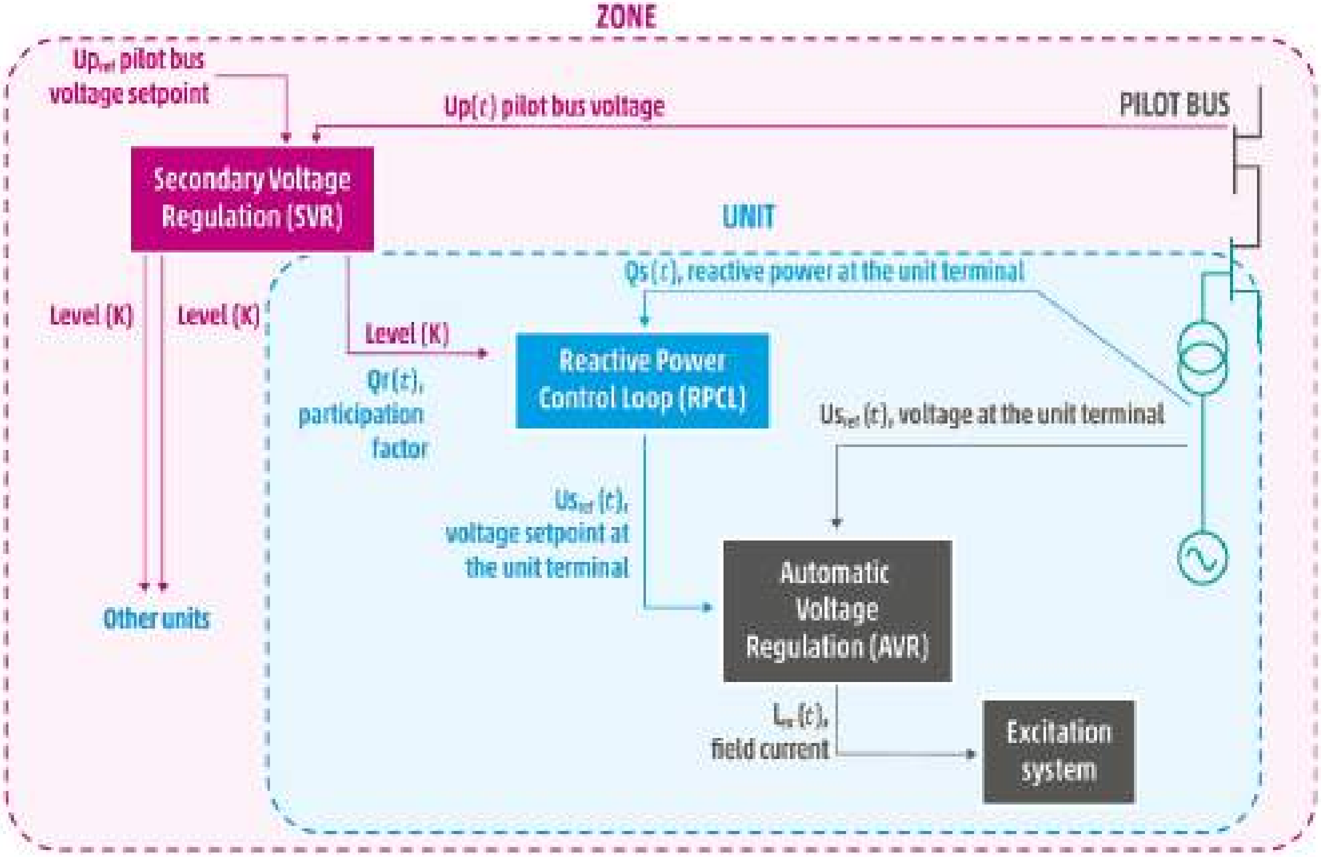

Figure 2-83: SVR principle diagram

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 – 2-86 show per region, the aggregation of the reactive power provided by all conventional synchronous generation units with an installed capacity larger than 100 MW (Q), as well as the aggregation of their reference reactive power (Q-reference), where Q-reference 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). This is without prejudice to the fact that it is permissible, under the Operating Procedure applicable in Spain at the time of the incident, for each unit not to comply with this requirement up to 25 % of the time per hour, and without prejudice to any potential derogations from the requirements, which the Expert Panel is not competent to assess.

For calculation of the aggregated values of Q-reference the individual Q-reference value of a generator was set equal to its actual Q value in periods when voltage was within the permissible variation band (405 – 410 kV) or the generator was in a direct voltage setpoint control mode (pilot project). When the measured voltage crosses the edge of the variation band in either direction, this is reflected in step changes in Q-reference.

Further observations and analysis on the behaviour of conventional synchronous generators regarding reactive power output is described in Chapter 4.1.

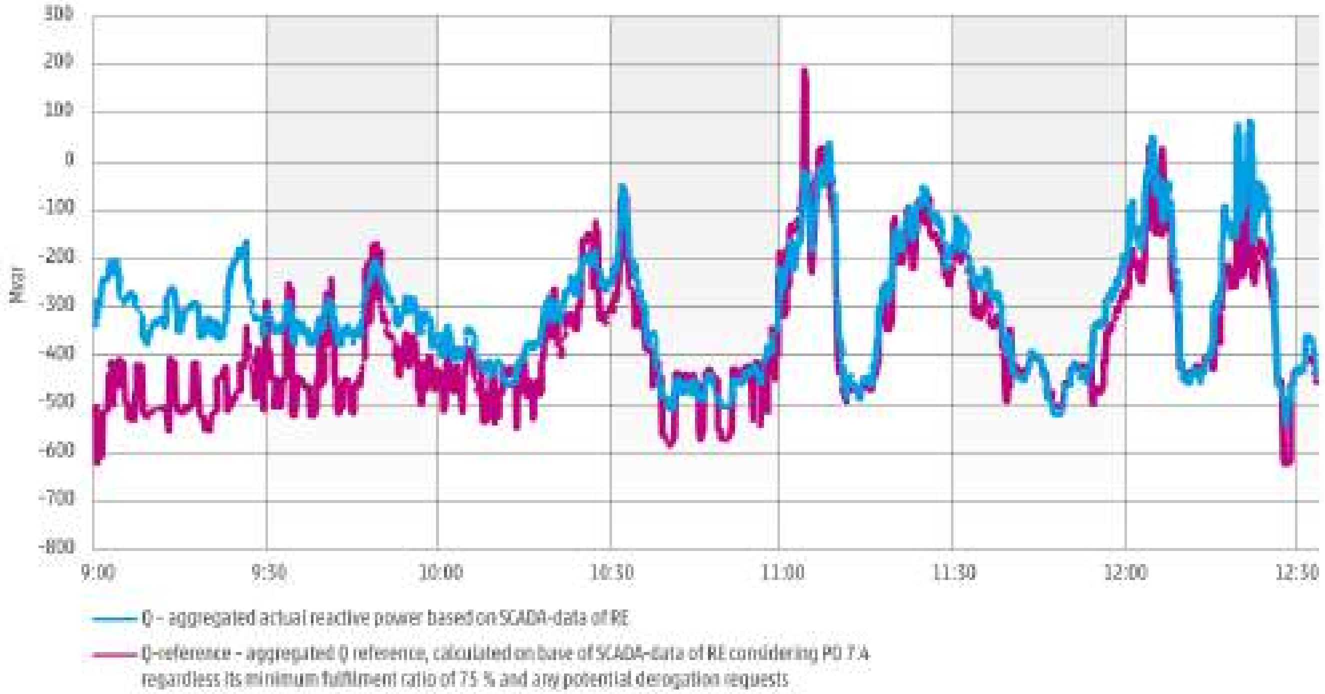

Figure 2-84: Reactive power provided (Q) and the reference reactive power (Q-reference) aggregated for conventional generation units larger than 100 MW of power installed capacity in the north/north-west area of Spain, based on SCADA data of RE

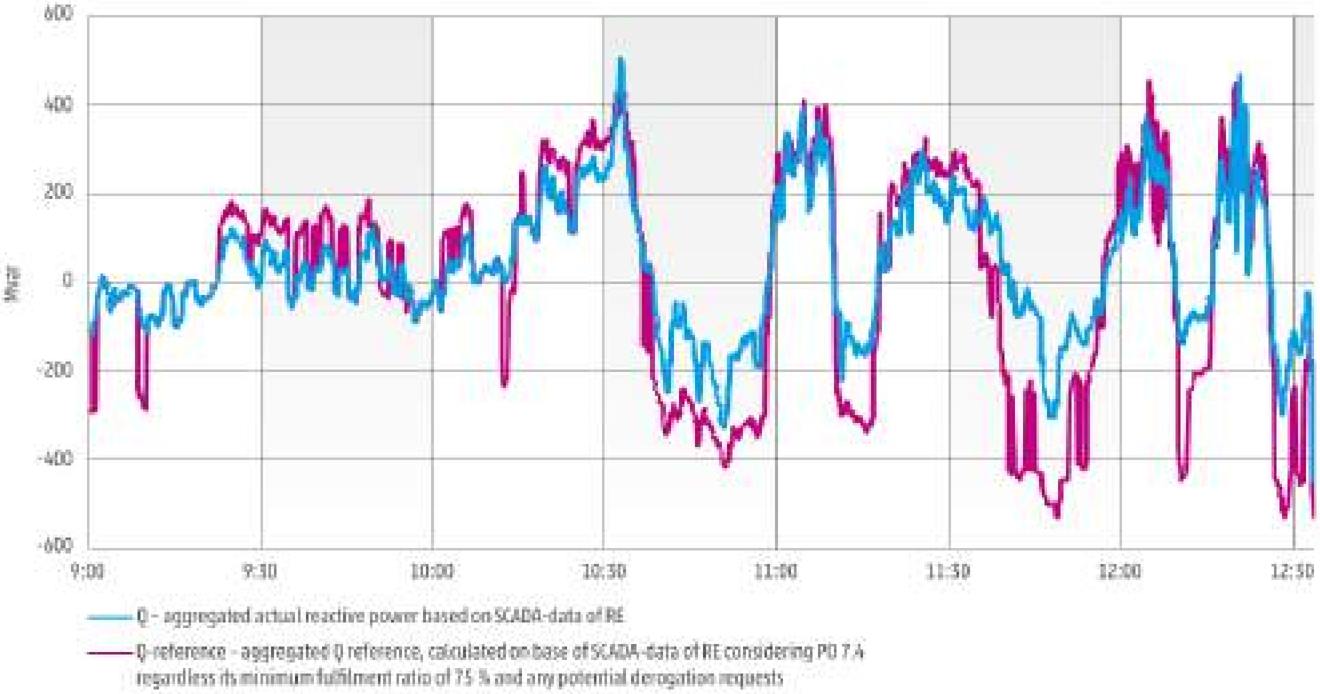

Figure 2-85: Reactive power provided (Q) and the reference reactive power (Q-reference) aggregated for conventional generation units larger than 100 MW of power installed capacity in the centre/south-west area of Spain, based on SCADA data of RE

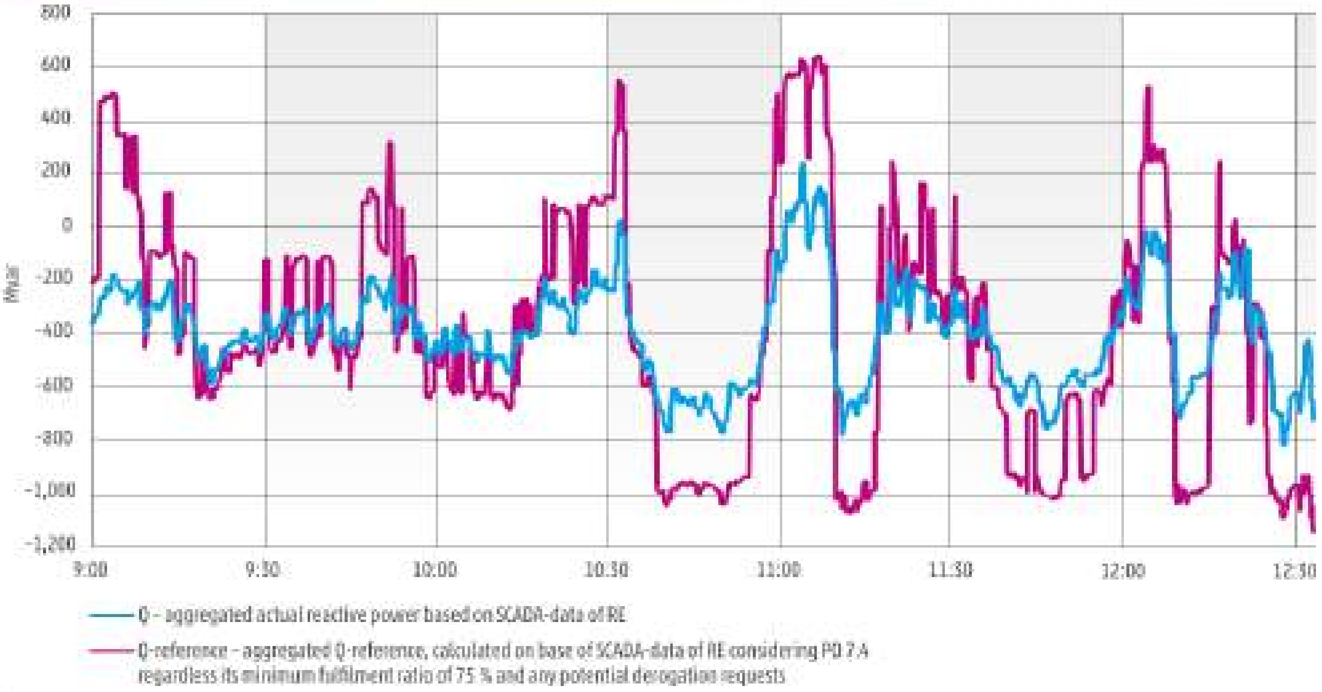

Figure 2-86: Reactive power provided (Q) and the reference reactive power (Q-reference) aggregated for conventional generation units larger than 100 MW of power installed capacity in the east/north-east area of Spain, based on SCADA data of RE

Figures 2-87 and 2-88 show the aggregation of the active and reactive power provided respectively by all PV and wind units >1 MW in Spain.

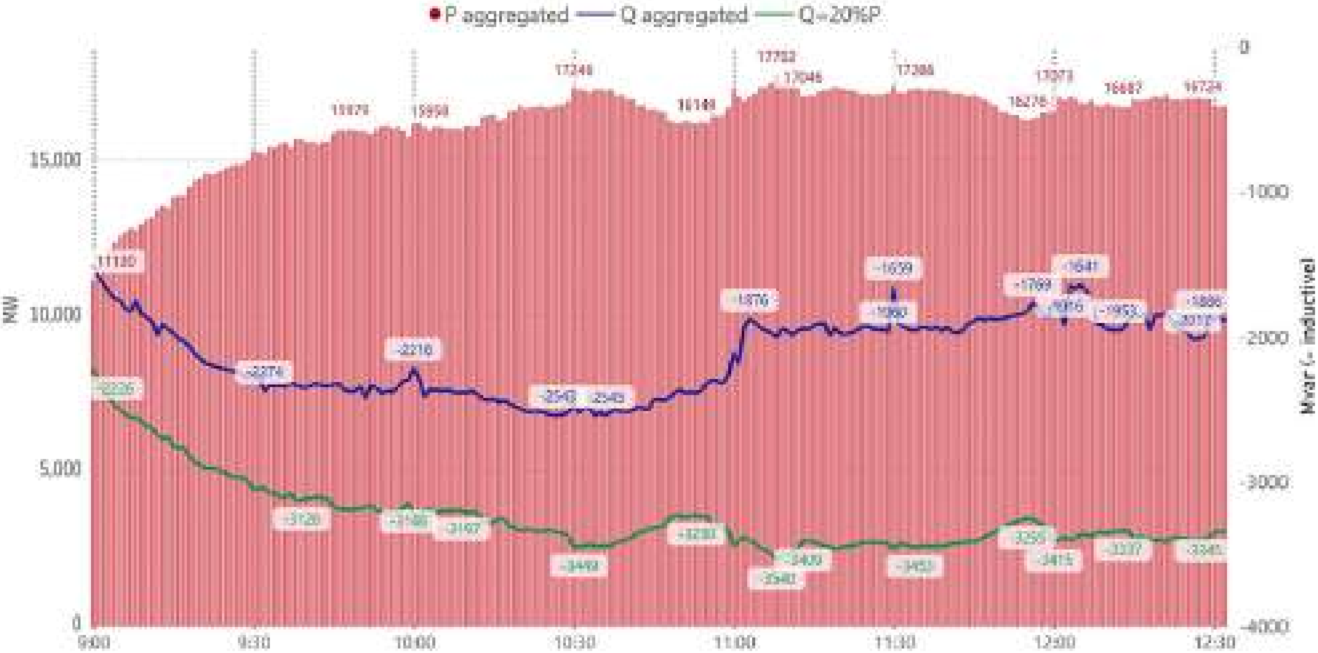

Figure 2-87: Aggregated P and Q of PV generation (facilities or aggregations with installed capacity >1 MW) , based on SCADA data of RE. The green line corresponds to a 0.98 inductive power factor, which is the lowest limit of the generic range defined by the RD 413/2014.

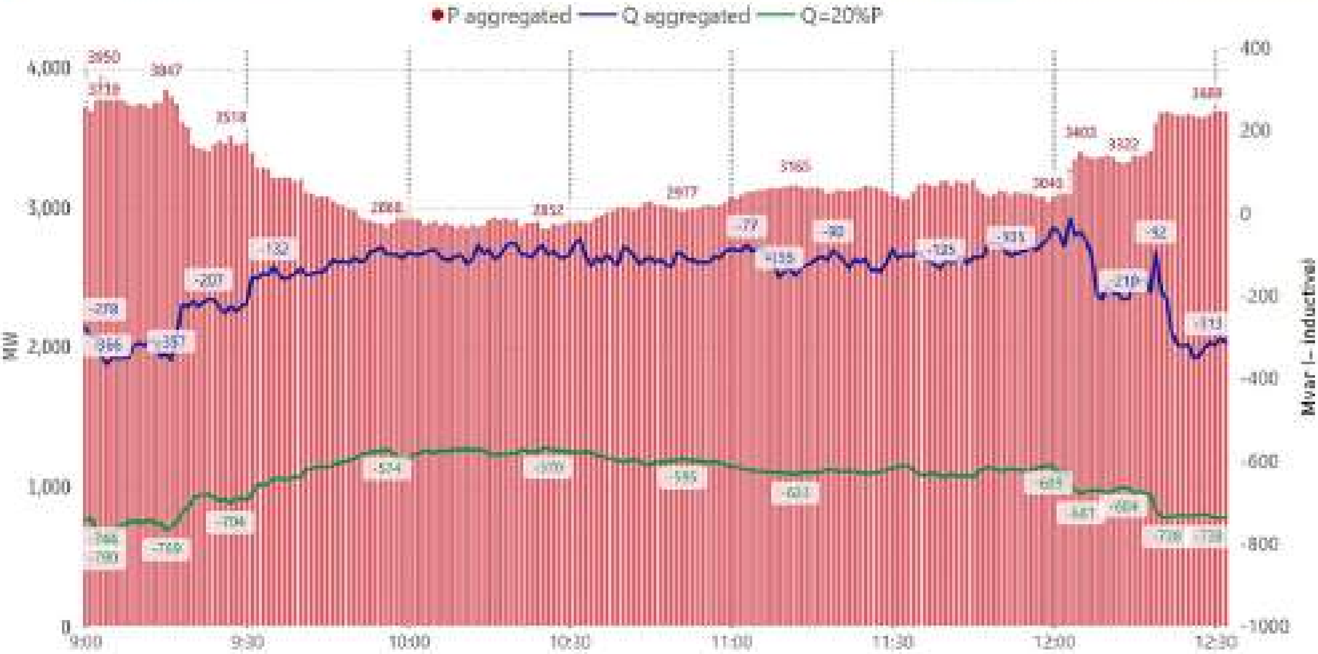

Figure 2-88: Aggregated P and Q of wind generation (facilities or aggregations with installed capacity >1 MW) , based on SCADA data of RE. The green line corresponds to a 0.98 inductive power factor, which is the lowest limit of the generic range defined by the RD 413/2014.

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

Figure 2-89 shows the aggregation of the reactive power provided by generating power plants connected to the 400 kV voltage level 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. Q-reference is calculated taking into account the RfG requirements related to voltage control, complemented by the Portuguese framework "Portaria n.º 73/2020", which defines the reactive power envelope for each generator type. For the Q-reference, REN considers the voltage setpoint that was active at the time, and computes it assuming a 2 % slope and no deadband for the voltage characteristic.

If the voltage at the connection point is above or below 2 % of the voltage setpoint, the unit should provide the maximum reactive power. If voltage on connection point is ±2 % of voltage setpoint, Q-reference is set equal to the actual reactive power (Q), as long as it follows the defined slope.

Due to different approaches to voltage control by synchronous generators in Spain and Portugal, these implementation aspects should be considered when comparing Figure 2-89 to Figures 2-84, 2-85 and 2-86.

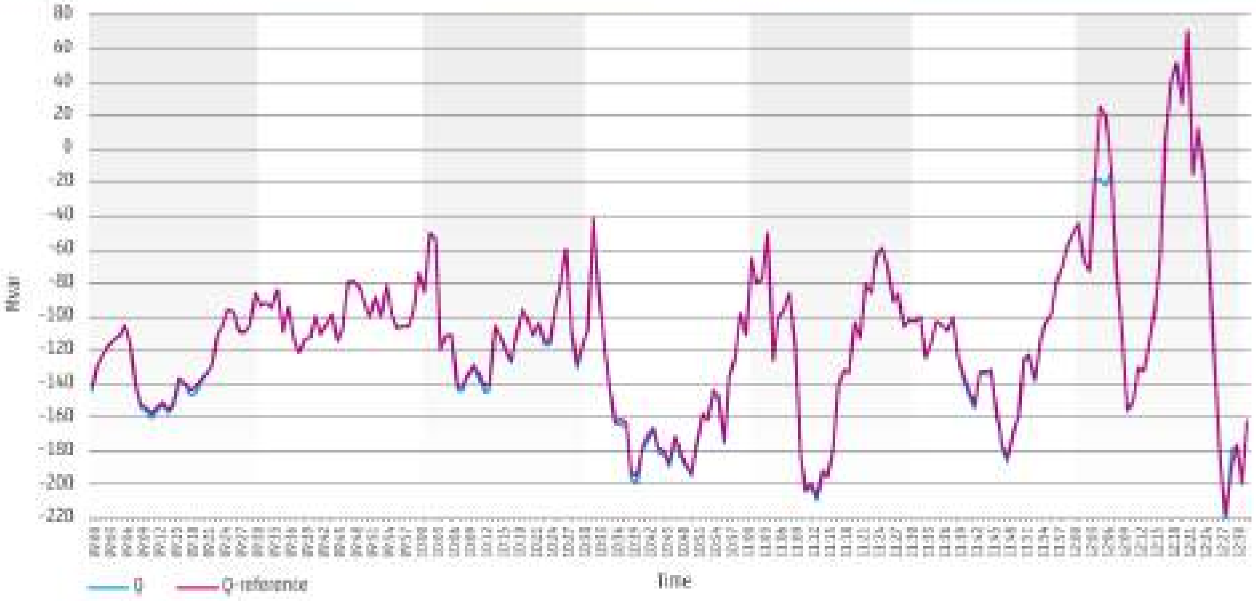

Figure 2-89: Provided reactive power (Q) and reference reactive power (Q-reference) for generating relevant power plants with more than 100 MW of power installed capacity in the south area of Portugal (REN's SCADA measurements)

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.

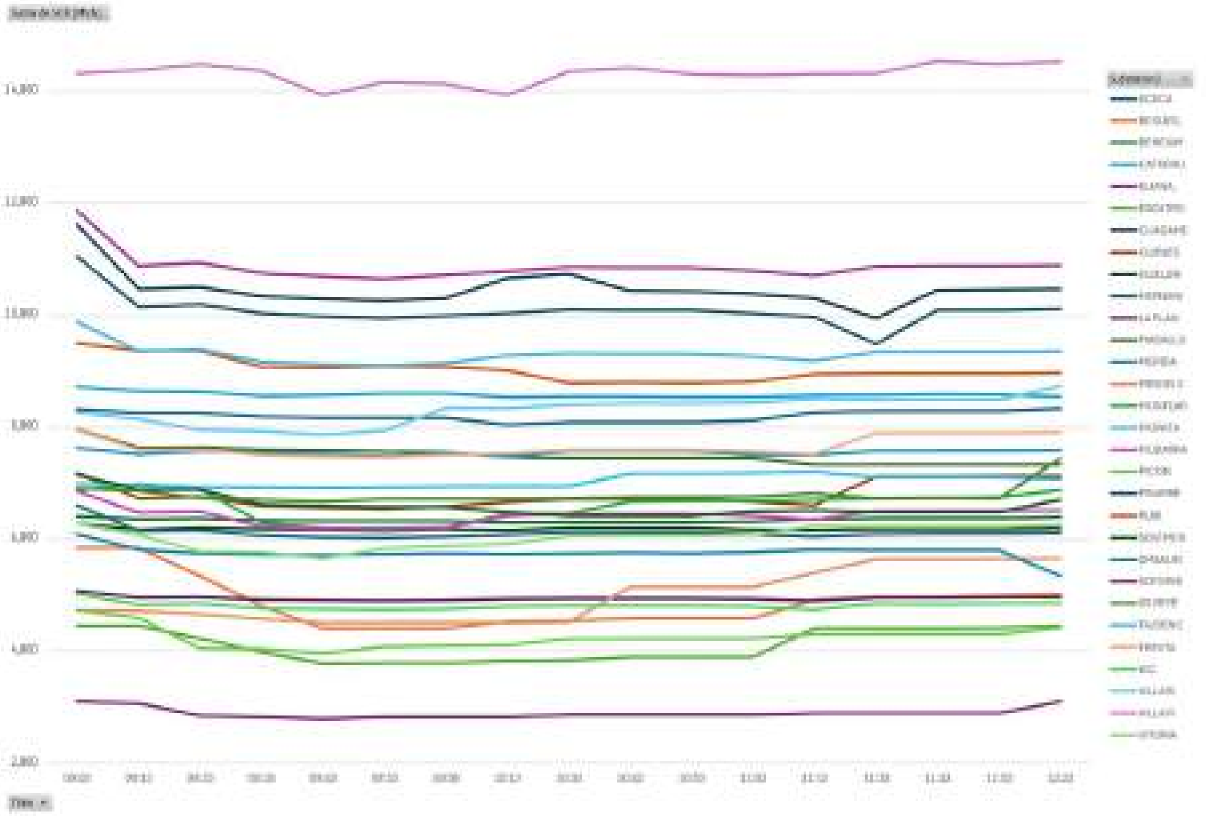

Figure 2-90: Short circuit power evolution in the Spanish 220 kV network (pilot nodes)

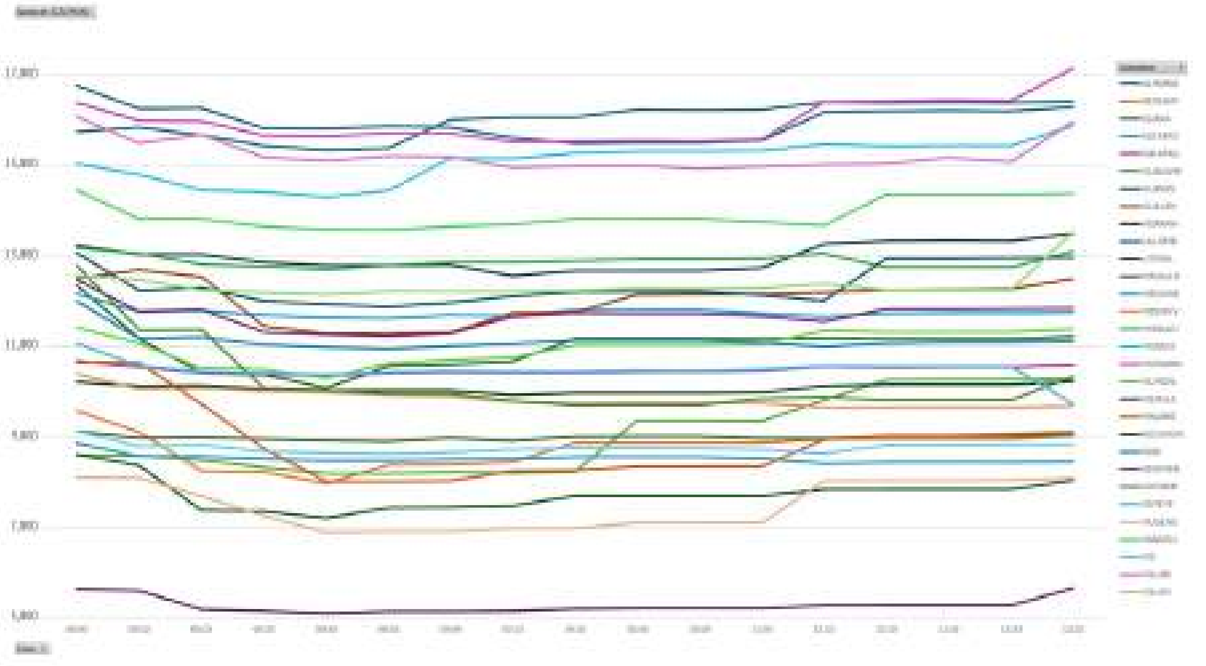

Figure 2-91: Short circuit power evolution in the Spanish 400 kV network (pilot nodes)

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]

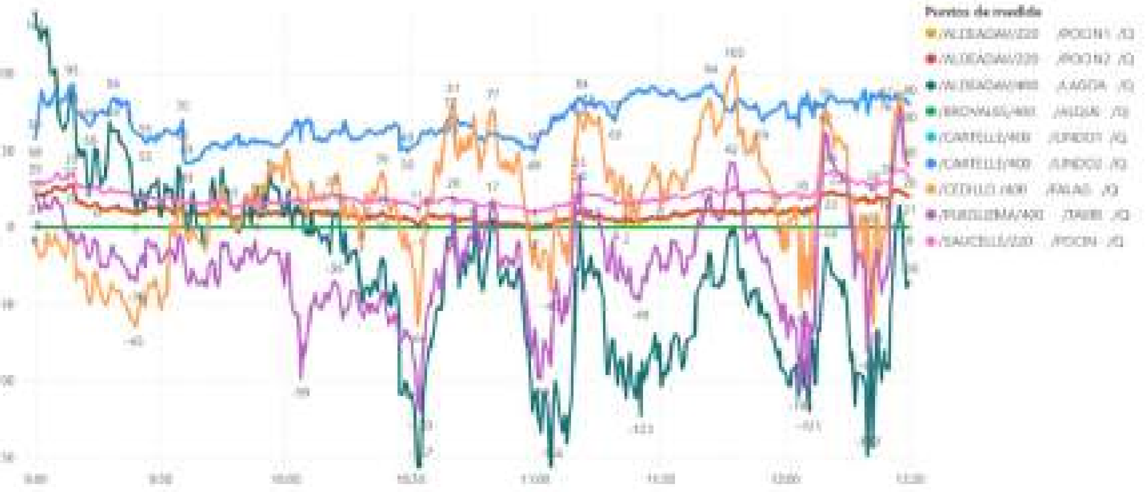

Figure 2-93: AC interconnectors reactive power flow from Spain to Portugal [Mvar]

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