SUMMARY OF THE REPORT THAT

DRS. LUIS ROUCO RODRÍGUEZ, ENRIQUE LOBATO MIGUÉLEZ AND FRANCISCO M. ECHAVARREN CEREZO
PROFESSORS OF THE SCHOOL OF ENGINEERING OF THE COMILLAS PONTIFICAL UNIVERSITY

HAVE CARRIED OUT AT THE REQUEST OF

ENDESA AND IBERDROLA

IN CONNECTION WITH

THE BLACKOUT THAT OCCURRED IN THE IBERIAN ELECTRICITY SYSTEM ON 28th APRIL 2025

IN MADRID, 1st OCTOBER 2025

SUMMARY

Introduction

At 12:33 on 28th April 2025, a blackout occurred in the Iberian electricity system. On the ENTSO-e incident classification scale, this corresponds to a "blackout" (grade 3 on a scale of 0 to 3).

This is the first time in the history of the Spanish peninsular electricity system that a blackout has occurred. The most serious incidents in the peninsular system (6th July 1977, 14th October 1987, and 24th August 1994) never led to a blackout in the Iberian system. From our point of view, it is only comparable in continental Europe, in terms of severity, with the blackout of the Italian system on 28th September 2003.

On 30th April, the Spanish government set up a committee to analyse the electricity crisis, chaired by the Third Vice-President and Minister for Ecological Transition and the Demographic Challenge. On 17th June, the Council of Ministers approved the report drawn up by this Committee. On 18th June, Red Eléctrica presented its report on the events.

On 9th May 2025, ENTSO-e set up a panel of experts to investigate the event. ENTSO-e regularly updates the progress of its investigation.

Endesa and Iberdrola have requested an independent report from the Institute for Research in Technology (IIT) of the ICAI Engineering School of the Comillas Pontifical University to assess the facts and circumstances that led to the blackout in the Iberian electricity system on 28th April 2025.

This document contains a summary of the report carried out by Drs. Luis Rouco Rodríguez, Enrique Lobato Miguélez, and Francisco M. Echavarren Cerezo, Professors of the School of Engineering, at the request of Endesa and Iberdrola, on the facts and circumstances that led to the blackout in the Iberian system on 28th April 2025.

Although the report addresses all the facts and circumstances that led to the blackout, this summary aims to bring to the reader's attention novel analyses that offer well-founded answers to unresolved questions arising from a careful study of the reports issued. In preparing the report, the authors have used non-public data provided by Endesa and Iberdrola.

In particular, we would like to offer our contribution to the challenge posed by ENTSO-e in its press release of 16th July 2025:

> *The Expert Panel is looking particularly at the cascading series of generation disconnections and voltage increases as the most probable trigger for the blackout. Such cascading voltage increases have never before been linked to a blackout in any part of the European power system. If confirmed, this high-voltage blackout mode will require a thorough analysis and investigation by all power system experts of the ENTSO-E community.*

We also provide our quantitative analysis on two key points highlighted by the Analysis Committee: the Phase 0, characterized by voltage instability during the week preceding and the morning of the event, between 9:00 and 12:00, and the low connection of thermal synchronous generation.

Additionally, the document examines the nature of the oscillations that occurred between 12:00 and 12:30, as well as their relationship to the synchronous generation situation in the south and central areas, and the transmission network.

Voltage instability phenomena

The anomalous voltage variations of 22nd April (which led to disconnections due to overvoltage protection of 10 Adif substations, nine generation bays, and the Repsol refinery in Cartagena) and 24th April highlighted the limitations of the voltage control system of the Spanish peninsular power system, in which renewable generation, controlled with power factor, had reached a very high penetration.

The mere inspection of the temporal evolution of voltages is insufficient to reveal the system's state. However, an in-depth analysis of the time evolution of voltages with appropriate metrics (seeFig.1 the evolution of the square root of the moving average of the square of the voltage derivative) on 22, 24 and 28 April and 5 May (one week after the blackout when Red Eléctrica was already applying the so-called reinforced operation of the electricity system) shows the anomalous situation of the voltage control of the transmission grid in the Spanish peninsular system before 28th April, the extreme anomaly on 28th April and the recovery to normality on 5th May. The evolution of the metric on 28th April shows that the voltage instability phenomena began around 9:00 and increased as the morning progressed.

In summary, the stress instability phenomena were present before 28th April and from 9:00 on 28th April.

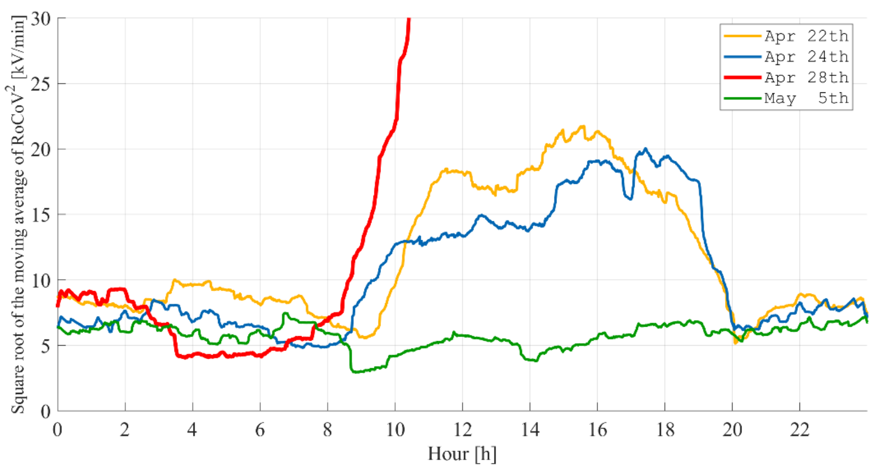

Fig.1: Evolution of the metric proposed for measuring the voltage control condition applied at Núñez de Balboa 400 kV on 22, 24 and 28 April, and 5 May.

The combination of low synchronous generation in the south and center areas and the weakness of the transmission network in those areas

We propose using area inertia to measure the geographical distribution of synchronous generation that provides dynamic voltage control. The inertia in the south area was equal to 1.3 seconds, while in the center area it was 1.84 seconds. Both are lower than the ENTSO-e recommendations (2 seconds). These values indicate the low synchronous generation in the south area (only one combined cycle unit was coupled in Andalusia) and the center area (only one of the nuclear units was coupled), and therefore, the scarcity of means to carry out dynamic voltage control.

The evolution of the number of combined cycle power units connected in Andalusia from 1st January 2024 to 30th June 2025 has also been shown. The change that has taken place since 28th April has been noted.

The extension of the peninsular 400 kV network, open for various reasons (voltage control, unavailability, and programmed work), reached 22.9% on 28th April at 9:00 am. It should be noted that 35.8% and 34.3% of the 400 kV grid extension in the south and center areas, respectively, were offline. With more than one-third of the 400 kV grid disconnected, it is evident that the transmission grid in the southern and central areas is weak.

The occurrence of poorly damped oscillations with a weak grid and low synchronous generation (combined cycle power plants) in Andalusia is therefore not surprising, as all combined cycle power plant units are equipped with Power System Stabilisers (PSSs) whose task is to dampen oscillations. The importance of combined cycle power plant units in damping inter-area oscillations stems from their high observability of these oscillations. On the other hand, the damping effect of the manoeuvres carried out by Red Eléctrica between 12:00 and 12:30 is not surprising either.

System oscillations
It is not surprising that poorly damped oscillations (barely 1%, which is less than the 5% established in PO 13.1) occur with a weak grid and low synchronous generation (combined cycle power plants) in Andalusia.

On the one hand, all combined cycle power plant units are equipped with Power System Stabilizers (PSSs) whose mission is to dampen oscillations. The combined cycle power plant units in Andalusia play a very important role in damping the 0.2 Hz oscillation because they are located at one end of the European continental system, where they are highly observable.

Furthermore, the dampening effect of the maneuvers carried out by Red Eléctrica between 12:00 and 12:30, when it connected 11 lines, should come as no surprise.

The 0.6 Hz oscillation (which occurred from 12:03 onwards) is an inter-area oscillation between generators in the Iberian system and generators in the rest of the European continental system, since the amplitude of the active power exchange oscillation (470 MW peak to peak) is comparable to the amplitude (1480 MW peak to peak) of the 0.2 Hz oscillation (which occurred from 12:19 onwards).

The statements by Red Eléctrica and ENTSO-e regarding the forced nature of this 0.6 Hz oscillation are not supported by evidence and/or analysis. Even if it were a forced oscillation due to a specific installation, it should not be forgotten that the amplitude of the oscillations caused by a forced oscillation depends on the proximity of the frequency of the forced oscillation to the frequency of one of the natural oscillations of the system and on the damping of the latter.

The phenomenon of overvoltage collapse and the margin to collapse
This paper has shown both the concept of overvoltage collapse caused by the disconnection of generation with power factor control and a method for calculating the margin to overvoltage collapse developed by the authors. The concept developed allows for understanding the phenomenon of generation disconnection due to overvoltage. The method for calculating the margin allows tackling the impact of various operational decisions that configured the situation of the Iberian system at 12:30 on 28th April.

The conceptual model has been implemented into a simulation model that allows tracing the evolution of voltages when the progressive disconnection of controlled generation with constant power factor occurs, starting from the instantaneous operation of the Iberian electricity system at 12:30 (load flow case). It should be noted that the load flow case constructed only approximately reflects the situation of the Iberian electricity system at 12:30, as Red Eléctrica has not provided either Endesa or Iberdrola with the load flow output cases of its state estimator for reasons of confidentiality.

Fig.2 shows the voltage growth when renewable generation (controlled with constant power factor) is disconnected homothetically at all nodes in Andalusia and Extremadura. This is certainly not what happened. However, it is the usual method used in the literature to study the margin to undervoltage collapse, and it provides a good illustration of the phenomenon.

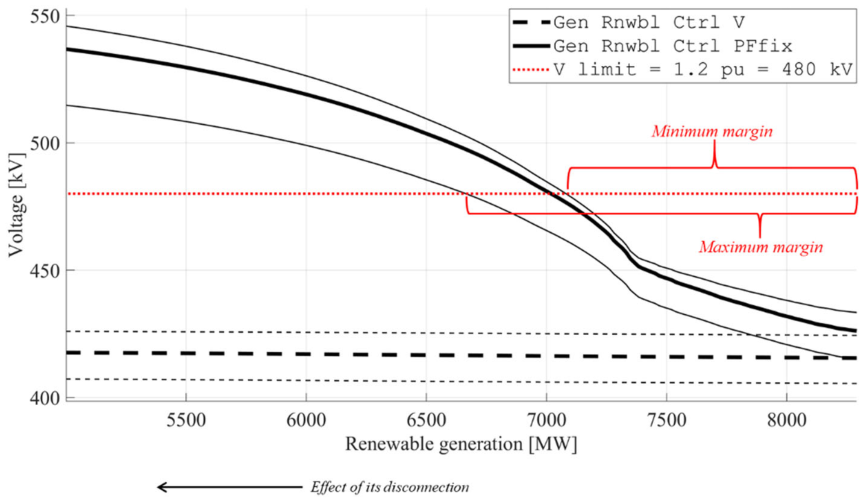

Fig.2: Effect on voltage at Carmona 400 kV of controlled generation disconnection with constant power factor and voltage variation margins at 400 kV.

To quantify system security, we have proposed a measure known as the *overvoltage collapse margin*. The overvoltage collapse margin can be defined as the volume of generation that can be disconnected until the overvoltage protection tripping threshold is reached. According to the general protection criteria of the Spanish peninsular system, the overvoltage protection tripping threshold will be between 110% and 120% of the nominal voltage. For illustrative purposes, we will take 120% (1.2 pu). As there is a different voltage variation at each node of the network, we will provide maximum and minimum values of the margin for each voltage level.

Table 1 details the ranges of variation of the overvoltage collapse margin in the 400 and 220 kV networks, as well as in two selected nodes of these networks (Carmona 400 kV and Guillena 220 kV). The most restrictive network is the 220 kV network. The safety margin was 1019 MW, while there were disconnections of at least 1615 MW, with the system having to withstand disconnections of 3000 MW as established in OP 13.1 on criteria for the development of the transmission grid and in the detailed specifications for the calculation of generation access capacity to the transmission and distribution grids.

Tab. 1: Safety margins at 120% of nominal voltage.

Level	Upper margin [MW]	Selected node margin [MW]	Lower margin [MW]
400	1625	1268	1213
220	1286	1199	1019

If the synchronous generation scheduling carried out by Red Eléctrica on 30th April, connecting seven groups of combined cycle power plants in Andalusia, had been carried out on 28th April, the uncontrolled growth of voltages produced by the possible loss of generation controlled with power factor would not have occurred as shown in Fig.3. For example, the safety margin at Carmona 400 kV would have increased from 1268 MW to 2758 MW.

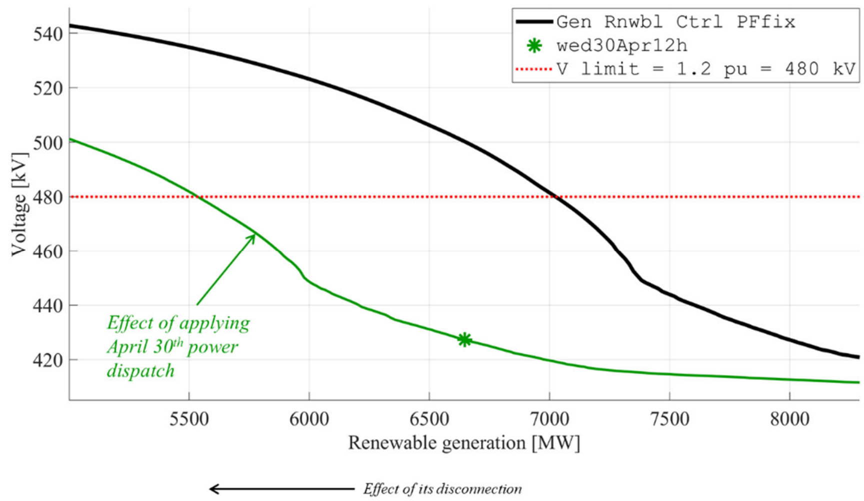

Fig.3: Effect on voltage at Carmona 400 kV of controlled generation disconnection with constant power factor and voltage variation margins at 400 kV.

It has also been found that the switching of lines and reactors carried out by Red Eléctrica between 12:00 and 12:30 (adding 1,050 Mvar reactive injection to the grid) causes the safety margin at Carmona 400 kV to decrease from 2,964 MW to 1,268 MW.

According to the simulations carried out, the scarce connection of synchronous generation equipped with dynamic voltage control in the southern (only one combined cycle unit in Andalusia was online) and central areas (only one of the nuclear units was online) is the reason why the disconnection of renewable generation, controlled with constant power factor, leads to an uncontrolled growth of voltages or *overvoltage collapse* phenomenon.

Conclusion

The voltage instability phenomena noted by the Analysis Committee in the days prior to 28th April and from 9:00 on the 28th, have been confirmed.

The situation of weakness in the transmission grid (35.8% of the 400 kV grid in the south area was disconnected) and in the system (unusually low synchronous generation in the south and centre areas) has also been confirmed.

The concept of overvoltage collapse and collapse margin has been proposed to understand the phenomenon and evaluate the sensitivity of what happened in relation to various actions, such as the connection of synchronous generation in Andalusia or the maneuvers carried out by Red Eléctrica between 12:00 and 12:30.

It can be concluded that there is an insufficient safety margin for the overvoltage collapse caused by the disconnection of renewable generation with power factor control. It can also be concluded that the adverse effect of the maneuvers carried out by Red Eléctrica between 12:00 and 12:30.

TABLE OF CONTENTS

1 INTRODUCTION

1.1 Background

At 12:33 on 28th April 2025, a blackout occurred in the Iberian electricity system. On the ENTSO-e incident classification scale [1], it corresponds to grade 3 on a scale of 0 to 3.

This is the first time in the history of the Spanish peninsular electricity system that a blackout has occurred. The most serious incidents in the peninsular system (6th July 1977 [2], 14th October 1987 [3], and 24th August 1994 [4]) never led to a blackout. The blackout of the Iberian system is only comparable in continental Europe, in terms of its severity, with the blackout of the Italian system on 28th September 2003 [5].

On 30th April, the Spanish government set up a committee to analyse the electricity crisis, chaired by the Third Vice-President and Minister for Ecological Transition and Demographic Challenge. On 17th June, the Council of Ministers approved the report drawn up by this committee [6]. On 18th June, Red Eléctrica presented its report on what had taken place [7].

On 1st May 2025, ENTSO-e set up a panel of experts to investigate the event [8]. ENTSO-e regularly updates the progress of its investigation [9].

Endesa and Iberdrola have requested an independent report from the Institute for Research in Technology (IIT) of the ICAI Engineering School of the Comillas Pontifical University to assess the facts and circumstances that led to the blackout in the Iberian electricity system on 28th April 2025.

1.2 Object

This document contains a summary of the report carried out by Drs. Luis Rouco Rodríguez, Enrique Lobato Miguélez, and Francisco M. Echavarren Cerezo, Professors of the School of Engineering, at the request of Endesa and Iberdrola, on the facts and circumstances that led to the blackout in the Iberian system on 28th April 2025.

Although the report addresses all the facts and circumstances that led to the blackout, this summary aims to bring to the reader's attention novel analyses that offer well-founded answers to unresolved questions that arise from careful study of the reports issued.

In particular, we would like to offer our contribution to the challenge posed by ENTSO-e in its press release of 16th July 2025:

> *The Expert Panel is looking particularly at the cascading series of generation disconnections and voltage increases as the most probable trigger for the blackout. Such cascading voltage increases have never before been linked to a blackout in any part of the European power system. If confirmed, this high-voltage blackout mode will require a thorough analysis and investigation by all power system experts of the ENTSO-E community.*

This paper will show both the concept of overvoltage collapse caused by generation disconnection with power factor control and a method for the calculation of the margin to overvoltage collapse developed by the authors. The concept developed will help to understand the phenomenon of generation disconnection due to overvoltage. The method for calculating the margin will make it possible to assess the impact of various decisions that marked the situation of the Iberian power system at 12:30 on 28th April.

The document will also show how the mere inspection of the evolution of voltages over time is insufficient to show the phenomena of voltage instability during the week prior to and during the morning of the event between 9:00 and 12:00, and how a more sophisticated metric shows them clearly.

The report will also analyze and quantitatively measure the generation situation in the southern and central areas of the Spanish peninsular system and its transmission grid on 28 April.

In addition, the document will discuss the nature of the oscillations that occurred between 12:00 and 12:30 and their relationship to the synchronous generation situation in the south area and the transmission network.

In summary, the document will analyze three circumstances that, from our point of view, are key to explaining what happened:

1. The voltage instability phenomena during the week prior to and during the morning of the event between 9:00 and 12:00.
2. The combination of low synchronous generation in the southern and central areas with a weak transmission grid.
3. The insufficient safety margin against overvoltage collapse (caused by the disconnection of renewable generation with power factor control).

1.3 Organisation of the document

The document contains 9 sections. Section 2 contains a list of acronyms. Section 3 analyses the voltage instability phenomena during the previous week and during the morning between 9:00 and 12:00. Section 4 analyses the generation situation in the south and center of the Spanish peninsular system and its transmission grid. Section 6 introduces the concept of overvoltage collapse and the calculation of the overvoltage collapse margin. Section 7 presents the conclusions. Section 8 contains the literature references consulted. Section 9 contains the ratification of the report.

1.4 Disclaimer

In accordance with the practices of the scientific community, the conclusions and opinions stated in the reports and results belong to the authors and in no way do they bind or obligate Comillas Pontifical University, any of its centers or institutes, nor the rest of its lecturers and researchers.

Therefore, any citation or reference made to the results drawn from this collaboration must always explicitly cite the name of the authors, and under no circumstances may they exclusively mention Comillas Pontifical University.

2 ACRONYMS

ADIF, Administrador de Infraestructuras Ferroviarias (Administrator of Railway Infrastructures)

CNMC, Comisión Nacional de los Mercados y la Competencia, Spanish National Markets and Competition Commission

ENTSO-e, European Network of Transmission System Operators for Electricity

e-SIOS, System Operator's Information System

PSS, Power System Stabilizer

PSS/e, Power System Simulator for Engineering

PO, Operating Procedure

RCR, Renewables, Cogeneration and Waste

RD, Royal Decree

3 VOLTAGE INSTABILITY PHENOMENA

The Analysis Committee has identified a phase 0 in the electricity crisis of 28th and 29th April 2025 that is characterized by voltage instability during the week prior to and during the morning of the event between 9:00 and 12:00. However, Red Eléctrica does not recognize the existence of the aforementioned phase 0 on the grounds that, according to its assessment, the voltages were within the admissible margins established in the Operating Procedures (OPs).

The correct operation of an electricity system requires that the variables that characterize it (voltage and frequency) must be within narrow margins, so that the normal disturbances that can occur in a power system do not lead it to an alert or even an emergency condition. The purpose of power system control systems is to ensure that these variables are within narrow operating margins.

Therefore, it is just as important that the voltages vary "little" and "slowly" as it is that the voltages are within the admissible margins. If, for example, voltages are close to their upper limit and "fast" variations are experienced, these variations can lead to the tripping of overvoltage protections. Red Eléctrica had reported the increasing untimely tripping of overvoltage protections when launching the need for a new OP 7.4 on voltage control of the transmission grid [10].

This section presents in detail the views of the Analysis Committee and Red Eléctrica, our vision of voltage instability phenomena, and our proposal for a quantitative analysis method that consists of moving from the mere visual inspection of the time evolution of voltages to the use of a more sophisticated metric. We will see that this physically meaningful metric will reveal the existence of voltage instability phenomena.

3.1 The view of the Analysis Committee and Red Eléctrica

The Analysis Committee has identified voltage instability phenomena as the voltage variations occurring between 9:00 and 12:00 due to their high variability and amplitude.

> *From 9:00 onwards, greater voltage variability is observed, initially without significant excursions. It is from 10:30 h onwards that a greater excursion is observed, i.e. variations of greater amplitude in the voltage values with respect to the standard values.*

The Analysis Committee insists on the occurrence of relevant voltage variations, although within the margins established in Operating Procedures (OP) 1.1 [11] and 1.3 [12].

> *According to the data provided by both the System Operator and the distribution network operators, although relevant voltage variations were observed in the early morning hours of the event, the voltage levels in the transmission grid seem to remain within the levels set by operating procedures 1.1 and 1.3 (between 380 and 435 kV in the 400 kV grid, and between 205 and 245 kV in the 220 kV grid) throughout the period up to 12:30h.*

The Analysis Committee makes a questionable interpretation of the OPs 1.1, 1.3, and 1.4 [12] on the admissible margins of the voltages, which agrees with the interpretation of Red Eléctrica. According to our interpretation, the admissible margins in normal operation in the 400 kV grid are 390 kV and 420 kV. Our interpretation is shared by Red Eléctrica when it proposed the need for a new OP 7.4 on voltage control of the transmission grid [10]. Although ENTSO-e had initially adopted Red Eléctrica's interpretation, it has recently requested the CNMC to interpret the OPs.

Red Eléctrica, in its report, does not recognize the existence of phase zero: it does not mention what happened in the past days and simply points out that

> *From 9:00 h to 12:00 h there is greater variability in voltages, which is attributable to the change in the generation mix and variations in demand, but without major excursions.*

Red Eléctrica acknowledges that in 5 minutes, the voltage at some 400 kV grid nodes varied by 30 kV (7.5%).

> *Then, between 11:04 h and 11:09 h, the voltage recovered, rising by 30 kV at some nodes.*

We must understand that Red Eléctrica considers that a variation of 7.5% in 5 minutes (6 kV/minute) is a normal variation. We do not agree.

3.2 Our method of quantitative analysis

On 22 and 24 April, there were anomalous voltage variations. In particular, at around 19:00 on 22 April, the overvoltage protections of ten Adif substations, nine generation positions, and the Repsol refinery in Cartagena were disconnected due to overvoltage tripping.

To shed light on what happened, the voltages of several 400 and 220 kV grid nodes in Andalusia and Extremadura (epicenter of the event) were analyzed on the days prior to 28th April (22nd and 24th April), on 28th April itself and on 5th May (one week after the blackout, when Red Eléctrica was already applying the so-called reinforced operation of the electricity system).

In this summary document, we will focus on the observations made at Núñez de Balboa 400 kV as an illustrative example. The conclusions drawn at Núñez de Balboa 400 kV are reproduced in the rest of the nodes considered.

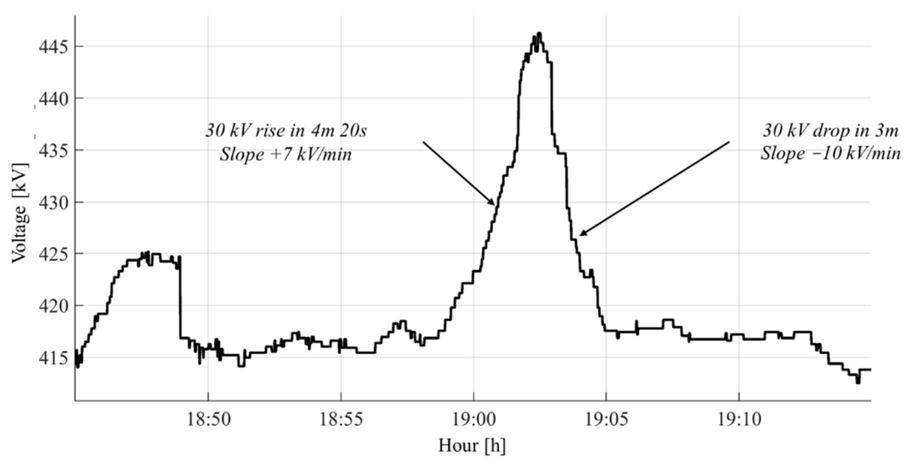

Figure 3-1: Voltages recorded at Núñez de Balboa 400 kV on 22nd April around 19:00.

First, we will show the evolution of the voltage at Núñez de Balboa 400 kV, specifically around 19:00 on 22nd April (see Figure 3-1) and around 18:00 on 24th April (see Figure 3-2). On 22nd April, there was an abrupt rise (4 minutes) in voltage from 415 kV to 445 kV, followed by an abrupt drop (3 minutes). On 24th April, there was an abrupt drop (2 minutes) from 415 kV to 395 kV, followed by an abrupt rise (less than 1 minute).

The above voltage variations highlight, from our point of view, the limitations of the voltage control system of the Spanish peninsular system, in which RCR generation, controlled with power factor, reached a very high penetration.

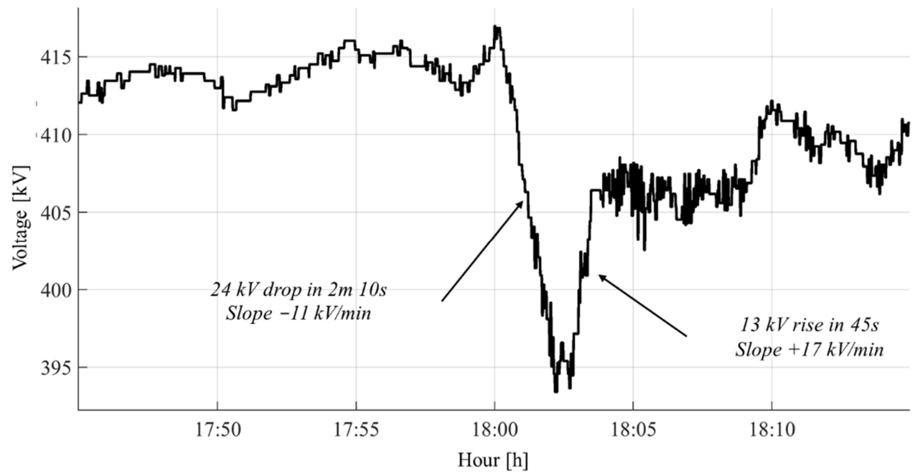

Figure 3-2: Voltages recorded at Núñez de Balboa 400 kV on 24th April at around 18:00.

We now turn to an analysis of the evolution of voltages throughout the day on the selected days.

Figure 3-3 shows the voltages at Núñez de Balboa 400 kV on 22nd, 24th, 28th April, and 5th May. It can be seen that the voltages show fewer oscillations on 5th May than on the previous days. On 28th April, the wide voltage oscillations in the hours preceding the blackout are clearly visible, reaching an amplitude of more than 50 kV. Finally, on 22nd and 24th April, significant oscillations are observed, concentrated between 10:00 and 20:00.

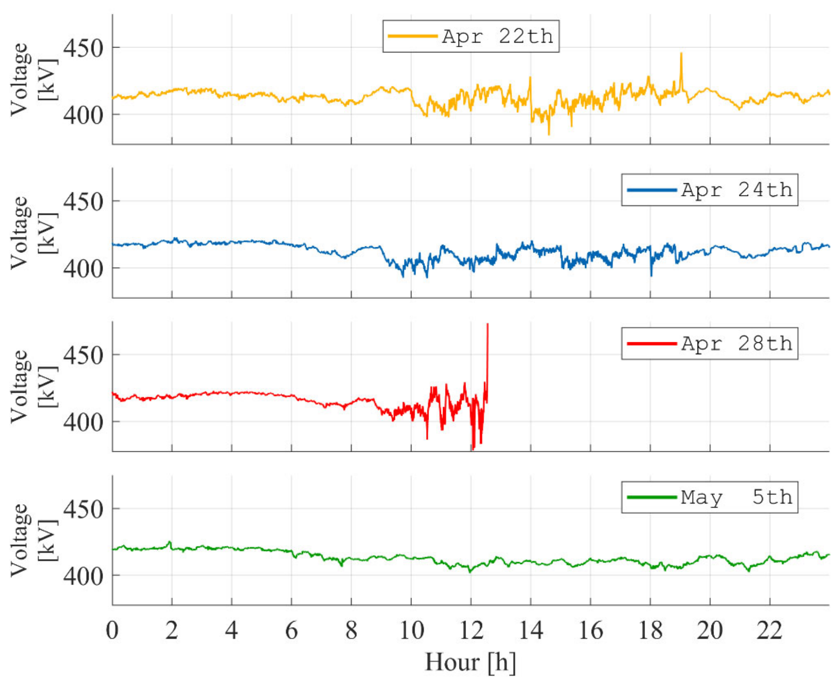

Figure 3-3: Voltages recorded at Núñez de Balboa 400 kV on 22nd, 24th, and 28th April, and 5th May.

Although the amplitude of voltage variations is an indicator of system safety, it is not a sufficient measure. To overcome the limitations of mere visual inspection of voltages, we propose to explore the Rate of Change of Voltage (RoCoV). The proposal to use RoCoV is taken from the use of the Rate of Change of Frequency (RoCoF) in frequency control. RoCoV measures the rate at which voltages vary over time. It is obtained by subtracting the voltage value at each instant from the voltage value at the previous instant. Figure -34 shows an example of a voltage signal and its corresponding RoCoV.

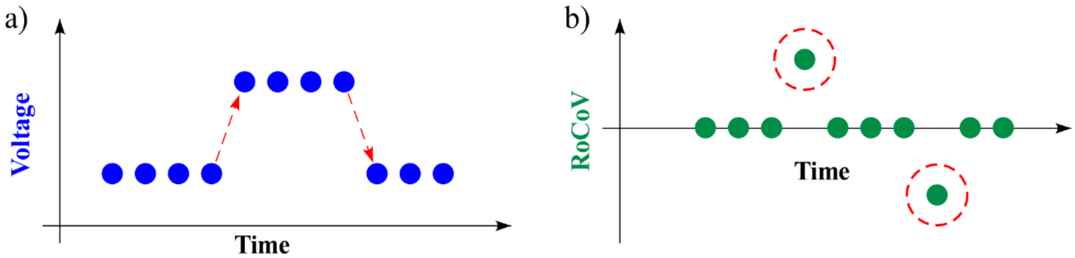

Figure 3-4: Example of a voltage signal (a) and its corresponding RoCoV (b)

Figure 3-4 (a) illustrates an example of voltage evolution over time, where, at one instant, there is a voltage rise and, at a later instant, a voltage drop. Figure -34 (b) shows the RoCoV of the signal, which remains zero until the instant when the voltage changes. In the first change, when the voltage increases, the value of the RoCoV is positive. At the second change, when the voltage decreases, the RoCoV is negative.

Figure 3-5 shows the RoCoV of Núñez de Balboa 400 kV voltage on 22nd, 24th, and 28th April, and 5th May.

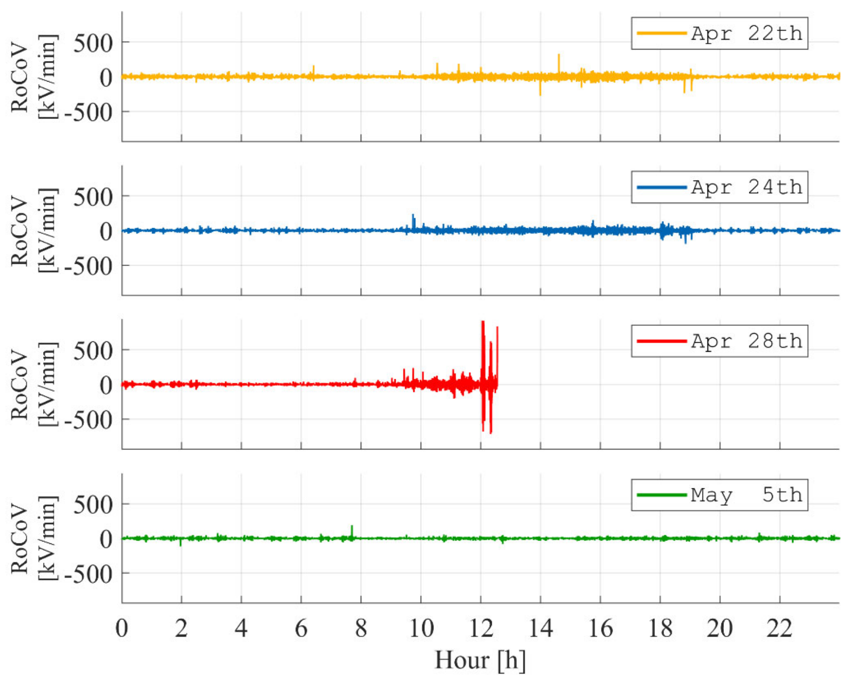

Figure 3-5: RoCoV of the voltages recorded at Núñez de Balboa 400 kV on 22nd, 24th, 28th April, and 5th May.

The RoCoV clearly shows an exceptional situation on 28th April from 9 onwards. Except for isolated peaks, the RoCoV on the rest of the dates barely reaches 50 kV/min, while on 28th April between 12 and 12:30, maximum values of over 400 kV/min are reached at the 400 kV nodes, and 200 kV/min at 220 kV. Compared to the other days, the voltages on 5th May show a RoCoV that hardly varies throughout the day. However, on 22nd and 24th April, RoCoV increases in amplitude during daylight hours, between 10:00 and 20:00.

As we have seen, the RoCoV provides valuable information in the analysis of voltage oscillations. However, more sophisticated metrics are needed to obtain more information about voltage swings. One of the problems with RoCoV is that it exhibits oscillations similar to those of the signal itself. In order to filter out these oscillations, the moving average is used. The moving average shows at each point the result of averaging a given set of previous values over time. For example, if the averaging window were one hour, the moving average of a signal at 12:00 would be the average value of the signal between 11:00 and 12:00. At the same time, since we are only interested in the magnitude of the RoCoV, this moving average is done on the RoCoV-squared signal.

Figure 3-6 shows an example of a voltage signal and how to obtain the proposed metric. Figure 3-6 (a) shows the starting signal. Figure 3-6 (b) shows the corresponding RoCoV. In Figure 3-6 (c), the RoCoV is squared to remove the sign ambiguity. Finally, to smooth the resulting curve, a moving average is applied, and then the square root is applied, resulting in the evolution of the metric in Figure 3-6 (d).

Physically, the proposed metric tells us the average value of the voltage derivatives (either rising or falling) over a time window. By using a moving time window, the proposed metric reports whether the voltage derivatives increase, persist or decrease over time.

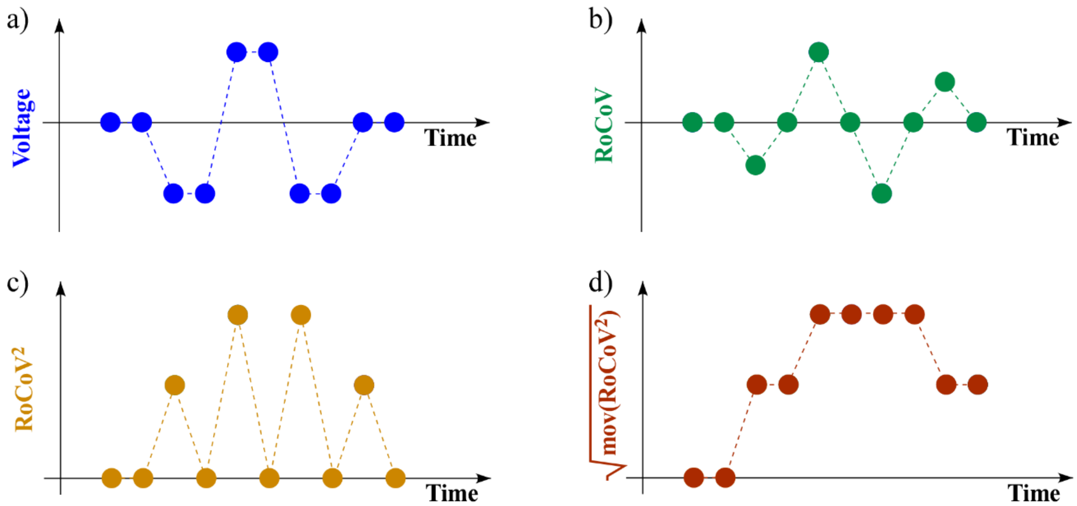

Figure 3-6: Example of voltage signal (a), RoCoV (b), RoCoV squared (c) and moving average of RoCoV squared (d).

Figure 3-7 shows the evolution throughout the day of the proposed metric at Núñez de Balboa 400 kV on 22nd, 24th, 28th April, and 5th May, assuming a one-hour moving average window. The evolution of the proposed metric shows the anomalous situation of the voltage control of the transmission grid in the Spanish peninsular system before 28th April, the extreme anomaly on 28th April, and the return to normality on 5th May. It should be noted that on 28th April, the metric is only plotted up to 11:30 as the window of the moving average is one hour. The evolution of the metric on 28th April shows that the problem of voltage instability was present from 9:00 and grew as the morning progressed.

In summary, the voltage instability phenomena were present before 28th April and from 9:00 on 28th April.

Figure 3-7 shows that on 22nd and 24th April, the proposed metric increases from onwards, is maintained throughout the day, and decreases from 19:00 onwards. Bearing in mind that this is the form of temporal variation of solar generation, we can reasonably say that the voltage variations are related to solar generation.

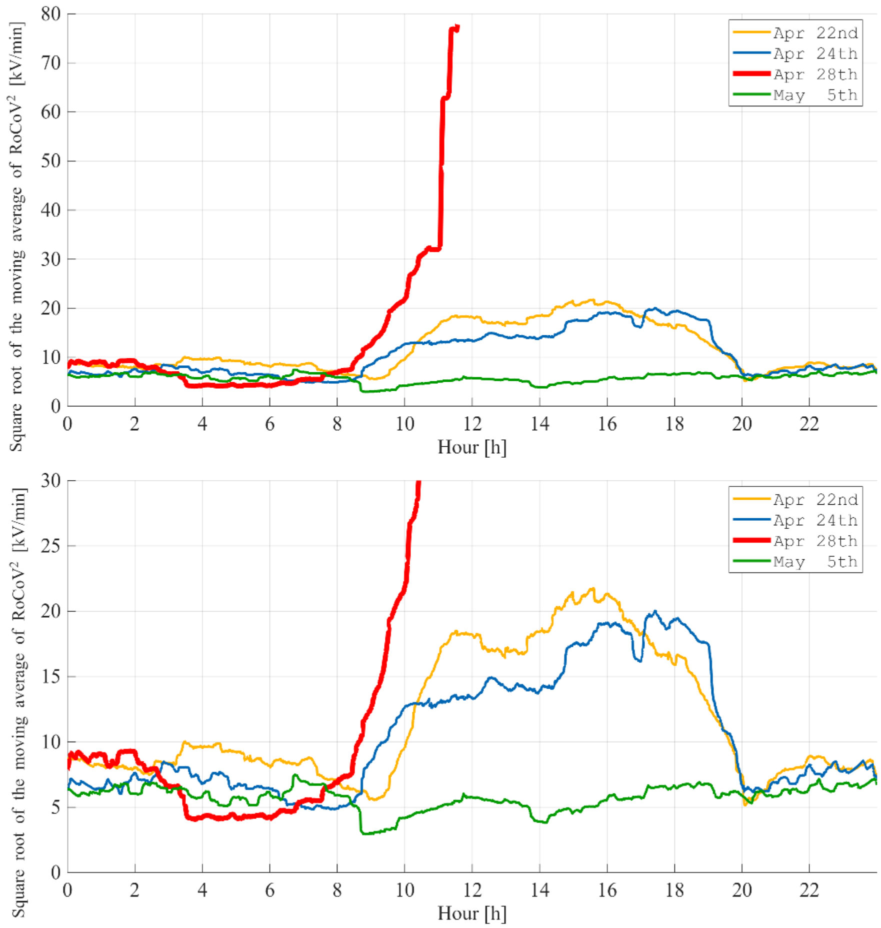

Figure 3-7: Evolution of the proposed metric at Núñez de Balboa 400 kV on 22nd, 24th and 28th April, and 5th May. The lower image is a vertical axis zoom of the upper one.

3.3 Partial conclusions

The stress instability phenomena referred to by the Analysis Committee cannot be assessed solely by inspecting the time variation of voltages and cannot be dismissed simply because the voltages are within the permissible ranges.

It is just as important that the voltages are within the permissible range as it is that they vary "little" and "slowly". If, for example, voltages are close to their upper limit and "fast" variations are experienced, these variations can lead to the tripping of overvoltage protections. Red Eléctrica has reported an increase in untimely tripping of overvoltage protections, justifying the need for a new OP 7.4 to enhance voltage control of the transmission grid [10].

An in-depth analysis of the time evolution of voltages on 22nd, 24th and 28th April and 5th May (one week after the blackout when Red Eléctrica was already applying the so-called reinforced operation of the electricity system) with a metric based on the voltage derivative reveals the anomalous situation of voltage control of the transmission grid before 28th April, the extreme anomaly on 28th April and the return to normality on 5th May. On 28th April, the voltage instability phenomena began at around 9:00 and increased as the morning progressed.

In summary, voltage instability phenomena were present before 28th April and from 9:00 on 28th April itself.

4 THE LOW SYNCHRONOUS GENERATION IN THE SOUTHERN AND CENTRAL AREAS AND THE WEAKNESS OF THE TRANSMISSION GRID IN THOSE AREAS

From our point of view, two circumstances characterize the situation of the peninsular electricity system at 9:00 on 28th April:

- The combination of low synchronous generation with dynamic voltage control in the south (only one combined cycle unit in Andalusia) and in the center (only one of the nuclear units).
- The weakness of the transmission grid.

The Analysis Committee notes in its report that

> *The final number of thermal units connected at 12:30, just before the event, was 11, a figure that has not been recorded on any other day of the year.*

This section examines the geographical distribution of synchronous generation. To do so, we will use inertia as a measure. It also contains an exhaustive analysis of the evolution of combined cycle generation in Andalusia between January 2024 and July 2025.

On the other hand, the line connection maneuvers carried out by Red Eléctrica between 9:00 and 12:30, especially those carried out between 12:00 and 12:30 to dampen oscillations, suggest the analysis of the state of the transmission grid (opened lines) at 9:00.

4.1 Low synchronous generation in southern and central areas

Red Eléctrica divides the Spanish peninsular system model into five areas: northwest (area no. 1), north (area no. 2), east (area no. 3), center (area no. 4), and south (area no. 5) as shown in Figure 4-1.

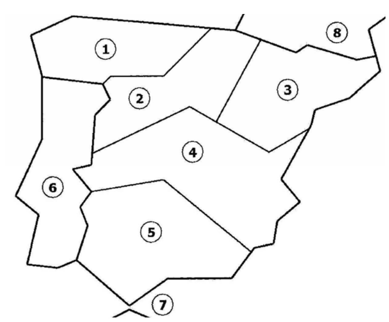

Figure 4-1: Areas of the Spanish peninsular system and external areas.

Table 4-1 contains the details of the calculation of the inertia by area of the Spanish peninsular system[1]. The values of rotational kinetic energy[2] are detailed by generation technology (nuclear,

[1] The inertia of an area, expressed in seconds, is calculated as the quotient between the rotational kinetic energy of the generators coupled in the area, expressed in MWs, divided by the demand, expressed in MWs [13] .

[2] The inertia constant of the generator and turbine assembly, expressed in seconds, is defined as the rotational kinetic energy at the nominal angular velocity, expressed in MWs, divided by the nominal apparent power of the generator expressed in MVA. Therefore, the rotational kinetic energy is calculated as the product of the inertia constant and the nominal apparent power of the generator.

combined cycle, coal, and hydro) and by area. The calculation of demand by area is also included.

Table 4-1: Inertia distribution at 12 noon on 28th April 2025.

Area	Kinetic Energy [MWs]					Demand			Inertia [s]
	Nuclear	CCGT	Coal	Hydro	Total	Raw file e-sios [MW]	Raw file e-sios [%]	Estimation [MW]	
NORTHWEST	0	3714	1746	6652	12111	3194	13%	3152	3,84
NORTH	0	2995	0	7843	10837	3633	15%	3585	3,02
EAST	9642	0	0	4105	13747	5988	24%	5909	2,33
CENTER	2906	8875	0	4204	15984	8780	35%	8664	1,84
SOUTH	0	2881	0	1535	4417	3443	14%	3398	1,30
TOTAL	12547	18465	1746	24339	57097	25038	100%	24708	2,31

The starting point for the calculation of the case study construction has been:

- Information collected in the CDTI-funded FLEXENER project on the inertia of generator units [14].
- The raw PSS/e load flow file of the hourly electricity system operating scenario at 12:00 before the solution of Red Eléctrica's operating restrictions available in the system operator's information system (e-sios).
- The technical restrictions solution report of 28th April.

Red Eléctrica provides to the agents the PSS/e load flow files in raw format of the hourly operation scenarios of the electricity system before the solution of operation restrictions. These load flow scenarios include the generation and demand per node resulting from market matching and the lines and transformers that are not in service due to scheduled maintenance. The technical constraints solution report informs about the actions taken by Red Eléctrica in this process.

Table 4-1 shows that the total inertia calculated by us is slightly higher than the one calculated and published by ENTSO-e. Table 4-1 and Figure 4-2 also show that the distribution of inertia is not uniform in the areas of the Spanish peninsular system: it falls from north to south. The inertia varies between 3.84 seconds in the north-west area and 1.3 seconds in the south area. In the center area, it is 1.84 seconds. The inertias in the south and center areas, where the generation disconnections occurred, are significantly lower than the ENTSO-e recommendations of a minimum inertia of 2 seconds [15].

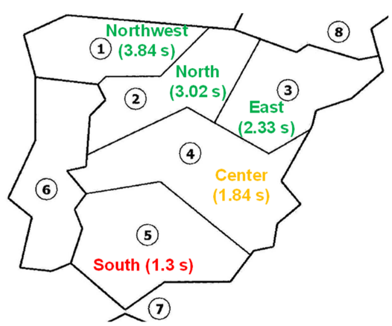

Figure 4-2: Inertia in the areas of the Spanish peninsular system.

4.2 Low synchronous generation in Andalusia on April 28th

Andalusia has a total of 13 combined cycle power plants. Out of the 13 plants, 11 have a 1+1 single-shaft configuration (with 1 single alternator integrating the gas and steam turbine on the same shaft), and two have a 2+1 multi-shaft configuration (3 different alternators for a steam turbine and 2 gas turbines with independent shafts). Out of the 13 plants, 8 were available to be scheduled in the technical constraint-solving process.

Red Eléctrica scheduled Arcos 1 and San Roque 2. The reasons were SOT (Transmission Network - Over Voltage) and COT (Voltage Control). San Roque 2 declared its unavailability on the night of 27th April. Red Eléctrica did not replace San Roque 2 with another unit.

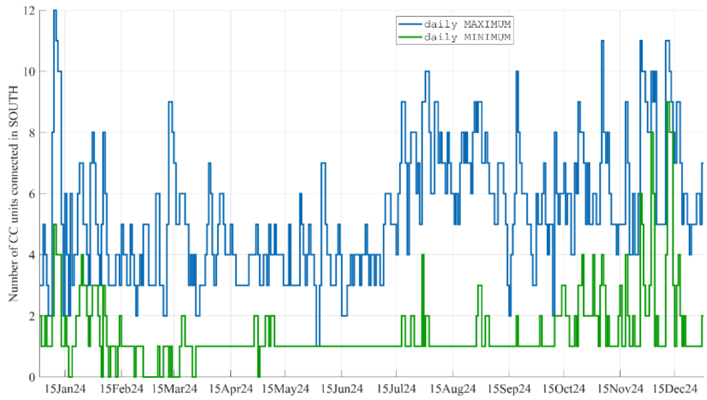

Figure 4-3: Maximum and minimum number of combined cycle power plant units coupled on each day in Andalusia during the year 2024.

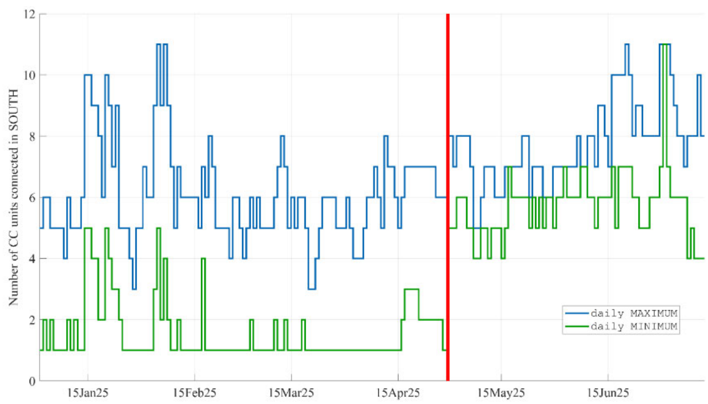

Figure 4-4: Maximum and minimum number of combined cycle power plant units coupled on each day in Andalusia during the year 2025. The red bar marks 28th April.

Let us examine the time evolution of the minimum and maximum daily numbers of connected combined-cycle power plant units in Andalusia. Figure 4-1 shows these numbers throughout 2024, and Figure 4-3 shows them until the end of June 2025. Until 28th April, the most frequent minimum number of units was one. From 28th April, the most frequent minimum number is six. The transformation of the electricity system, driven by the increasing incorporation of solar PV generation in Andalusia and Extremadura, has not led to changes in the solution of technical constraints, resulting in the connection of units from combined cycle power plants.

4.3 Weakness of the grid on 28th April

For years, the competent Ministry and Red Eléctrica had acknowledged in various documents that the transmission grid of the Spanish peninsular system suffered from an endemic problem of high voltages [15]. This problem, combined with the limitations of the voltage control system provided for in OP 7.4 and RD 413/2014, led to the daily opening of around 70 lines for voltage control, a very high number of hours with voltages higher than those normally admissible (420 kV/240 kV) and an increasing number of disconnections due to overvoltage protection tripping [10].

As shown in Table 4-2, at 9:00 on 28th April, a total of 49 lines were opened for voltage control (41 at 400 kV and 8 at 220 kV), and the total number of lines open for voltage control, unavailability, and planned work reached 86 lines. Even more relevant is the length of the lines opened compared to the total length of the transmission grid. A total of 18.4% of the 400 kV grid extension was open for voltage control, and 22.9% for voltage control, unavailability, and planned work. It should be noted that 35.8% and 34.3% of the 400 kV grid extension in the south and center areas, respectively, were disconnected.

Table 4-2: Number of lines open for voltage control, unavailability, and planned work by area and voltage level.

AREA	Number of opened lines due to voltage control at 9:00			Number of unavailable lines			Number of lines with planned works starting at 9:00		
	220 kV	400 kV	Total	220 kV	400 kV	Total	220 kV	400 kV	Total
NORTHWEST		7	7	3	1	4			
NORTH		4	4	1	1	2			
EAST	3	7	10	5	4	9	2	1	3
CENTER	5	13	18	10	4	14	1	1	2
SOUTH		10	10		3	3			
TOTAL	8	41	49	19	13	32	3	2	5

Table 4-3: % km of lines open for voltage control, unavailability, and planned work by area and voltage level.

AREA	% km of opened lines due to voltage control at 9:00		% km of unavailable lines		% km lines with planned works starting at 9:00	
	220 kV	400 kV	220 kV	400 kV	220 kV	400 kV
NORTHWEST		20,74%	2,5%	0,9%		
NORTH		14,4%	0,7%	1,6%		
EAST	1,5%	8,5%	2,8%	4,8%	0,3%	1,3%
CENTER	7,0%	26,7%	5,6%	2,2%	0,4%	5,4%
SOUTH		27,5%		8,3%		
TOTAL	1,8%	18,4%	2,3%	3,8%	0,2%	1,4%

4.4 Partial conclusions

This section has clearly shown the uniqueness of 28th April in terms of low synchronous generation with dynamic voltage control in the south and center areas. Inertia has been used as a measure of the geographical distribution of synchronous generation. The inertia in the south area was equal to 1.3 seconds, while in the center area it was 1.84 seconds. Both are lower than the ENTSO-e recommendations (2 seconds).

It can therefore be concluded that there is a shortage of means for dynamic voltage control. Up to that date, there had never been a single combined cycle unit in Andalusia and a single nuclear unit in the center.

It also showed the evolution of the number of combined cycle power plant units connected in Andalusia from 1st January 2024 to 30th June 2025. The change that has taken place since 28th April has been outlined.

The extent of the peninsular 400 kV network opened for various reasons (voltage control, unavailability, and programmed work), at 9:00, reached 22.9% on 28th April at 9:00. It should be noted that 35.8% and 34.3% of the 400 kV grid extension in the southern and central areas, respectively, were disconnected. With more than one-third of the 400 kV grid disconnected, it is evident that the transmission grid in the southern and central areas is weak.

The occurrence of weakly damped oscillations with a weak grid and low synchronous generation (combined cycle power plants) in Andalusia is therefore not surprising, as all combined cycle power plant units are equipped with Power System Stabilisers (PSSs). The importance of combined cycle power plant units in damping inter-area oscillations stems from their high observability. On the other hand, the damping effect of the maneuvers carried out by Red Eléctrica between 12:00 and 12:30 is also not surprising.

5 SYSTEM OSCILLATIONS

Between 12:00 and 12:30, two episodes of large-amplitude oscillations of 0.6 Hz and 0.2 Hz occurred. Before 12:00, oscillations of 0.2 and 0.6 Hz also occurred, which, although not of great amplitude, led Red Eléctrica to connect three 400 kV lines.

The system oscillations that occurred between 12:00 and 12:30 can be observed in different variables of the electrical system (frequency at a node, power per line, etc.). Although the system frequency is often mentioned, the frequency at each node of the electrical grid is different.

In the time evolution of frequency in Almaraz between 12:00 and 12:33 (see Figure 5-1), two periods can be observed in which the frequency exhibits variations of greater amplitude and frequency. The frequency in Almaraz was chosen because it is close to the rotational speed of the rotor of unit 2 of the Almaraz nuclear power plant, which was connected to the grid.

Between 12:02 and 12:08, there was a sustained oscillation (very low damping, around 1%) of 0.6 Hz, and between 12:10 and 12:23, there was another sustained oscillation (also with very low damping, around 1%) of 0.2 Hz. The damping of the oscillations was calculated using the Prony method ([17], [18]).

The occurrence of oscillations with damping as low as 1% is not in agreement with the provisions of both PO 13.1 on criteria for the development of the transmission grid [19] and the detailed specifications for calculating the access capacity of generation to transmission and distribution grids [20], which require that the damping of oscillations be greater than or equal to 5%.

Between 12:00 and 12:30, Red Eléctrica connects 11 lines at 400 kV and changes the control mode of the link to direct current. These maneuvers have a damping effect on oscillations.

First, we will discuss the 0.2 Hz oscillation and then the 0.6 Hz oscillation. We will use the 0.2 Hz oscillation as a reference, allowing us to compare the 0.6 Hz oscillation with it.

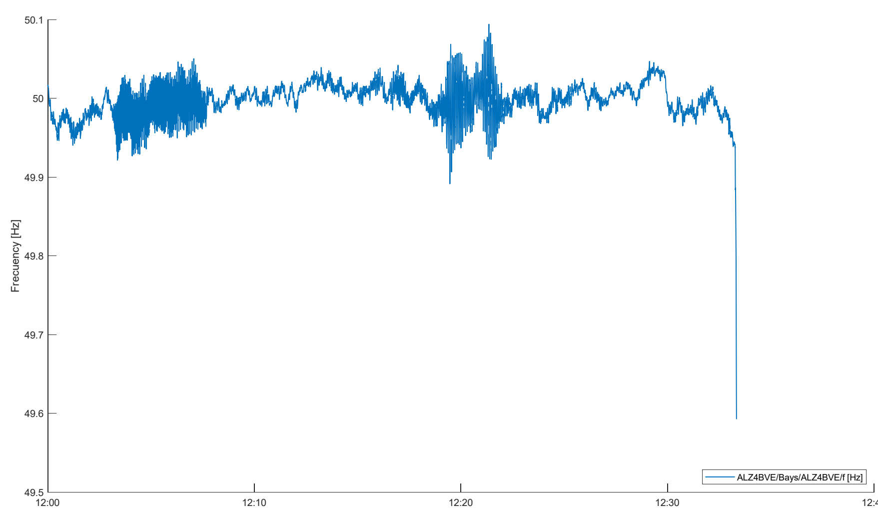

Figure 5-1: Frequency evolution in Almaraz between 12:00 and 12:33.

Between the occurrence of the 0.6 Hz oscillations and the occurrence of the 0.2 Hz oscillations, the control mode of the DC link was changed from AC line emulation to constant power, as shown in Figure 5-2. The change occurred when the 0.6 Hz oscillations had already been damped. When the control mode change occurred, the Vich-Baixas line began to have a power flow in the opposite direction to that of the Santa Llogaia-Baixas DC link, which is anomalous. The impact of the DC link control mode on the events that occurred can only be investigated using simulation models that are currently available only to Red Eléctrica.

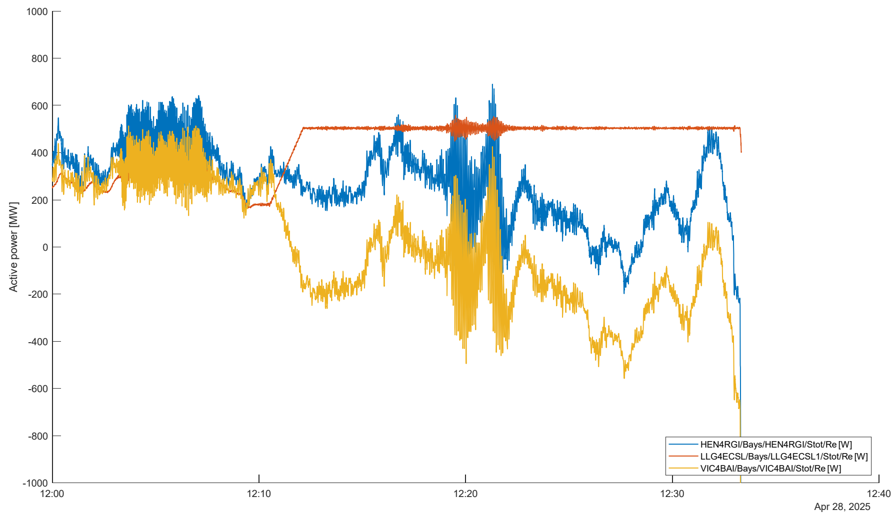

Figure 5-2: Evolution of power through the 400 kV interconnection lines and the DC link.

5.1 The 0.2 Hz oscillations

Figure 5-6 shows the details of the evolution of the frequency in Almaraz between 12:15 and 12:23 to better appreciate the beginning of the oscillations. Figure 5-7 shows the evolution of the frequency between 12:19 and 12:20 in Almaraz and Vandellós. These frequencies were chosen because they are close to the rotational speeds of the rotors of the Almaraz 2 and Vandellós 2 generators, which were connected to the grid. It can be observed that the oscillation period is approximately 5 seconds, corresponding to an oscillation frequency of 0.2 Hz. It can also be seen that the frequency oscillations at Almaraz and Vandellós are in phase.

The 0.2 Hz oscillation is a well-known oscillation in the European continental system. It is also well known to Red Eléctrica and RTE (the French transmission system operator) following the oscillations of December 1, 2016 ([21]-[23]).

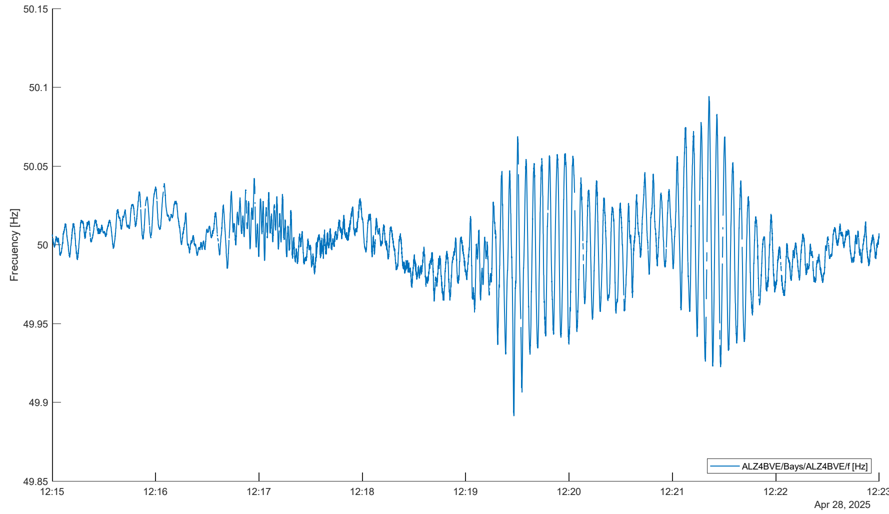

Figure 5-3: Detail of the frequency evolution in Almaraz between 12:15 and 12:23.

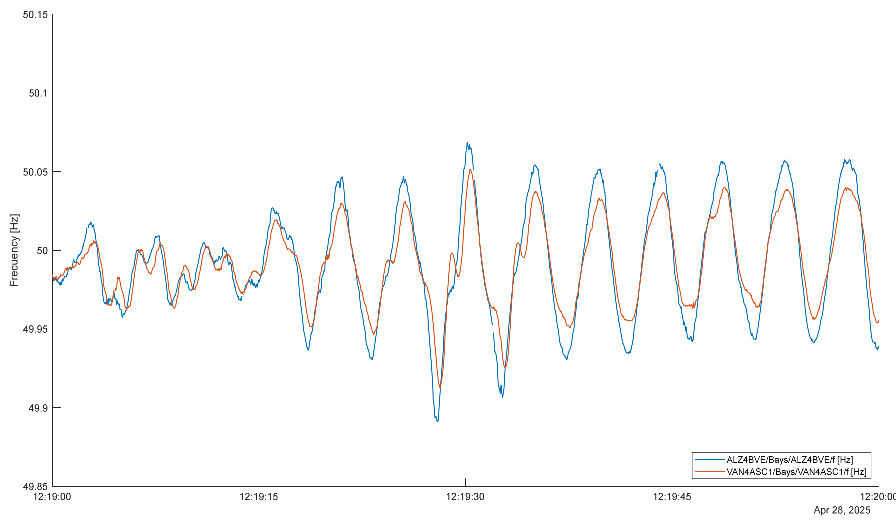

Figure 5-4: Detail of the evolution of the frequency at Almaraz between 12:19 and 12:20.

Figure 5-5 shows the evolution of active power exchange between Spain and France between 12:19 and 12:20. The amplitude of the 0.2 Hz oscillation is around 1480 MW peak to peak. Examining the exchange power between France and Spain helps us understand the nature of the 0.2 Hz oscillation. This is an oscillation in which generators on the Iberian Peninsula exchange power with generators in the rest of the European continental system.

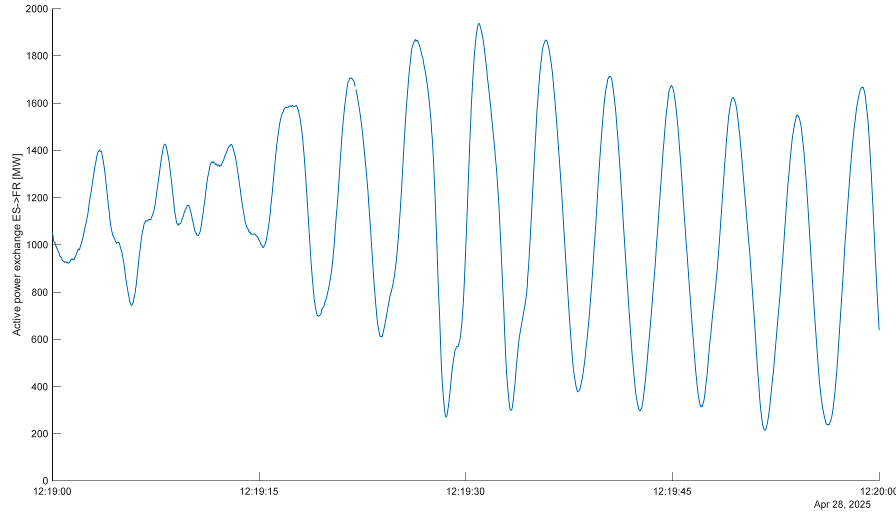

Figure 5-5: Detail of the evolution of the total active exchange power between France and Spain between 12:19 and 12:20.

5.2 The 0.6 Hz oscillations

Figure 5-6 shows the evolution of the frequency between 12:02 and 12:08.Figure 5-7 shows the evolution of the frequency between 12:03 and 12:04. At the beginning of the disturbance, only a 0.6 Hz oscillation can be seen. At the end of the period shown, superimposed oscillations of 0.6 and 0.2 Hz are visible. There is a slight phase shift between the frequencies of Almaraz and Vandellós, representing the southwest and northeast, respectively.

ENTSO-e points out, based on a representation of the geographical mode shape (in technical literature), that the 0.6 Hz oscillation is an oscillation between the southwest and northeast of the Iberian Peninsula. From our point of view, despite this difference between Almaraz and Vandellós, it cannot be said that this is an oscillation between the southwest and northeast of the Iberian Peninsula.

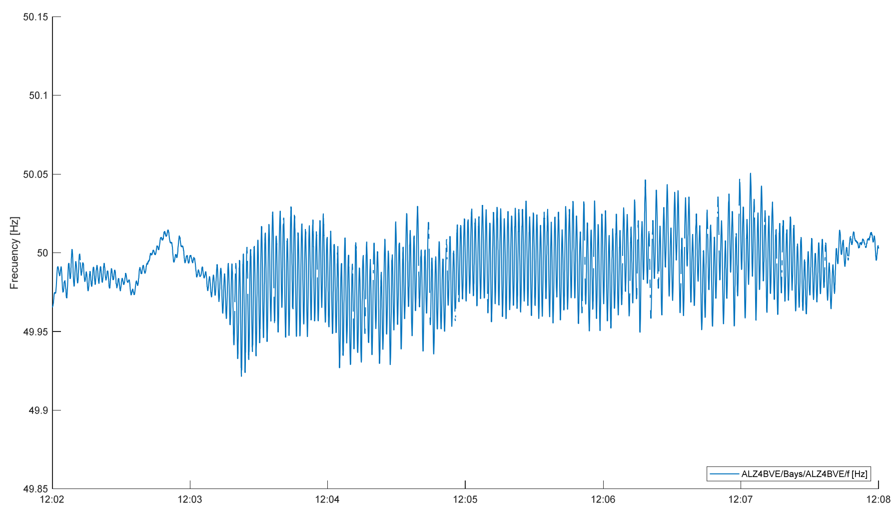

Figure 5-6: Detail of the evolution of the frequency between 12:02 and 12:08.

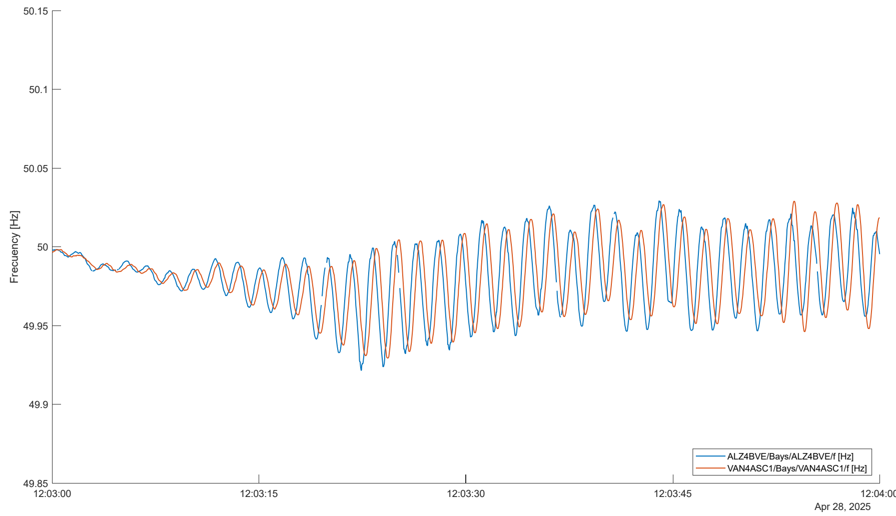

Figure 5-7: Detail of the evolution of frequency between 12:03 and 12:04 hours.

Figure 5-8 shows the evolution of active power exchange between Spain and France between 12:03 and 12:04. The amplitude of the 0.6 Hz oscillation is around 470 MW peak to peak. Examining the exchange power between France and Spain helps us understand the nature of the 0.6 Hz oscillation. This is an oscillation in which generators on the Iberian Peninsula exchange power with generators in the rest of the European continental system.

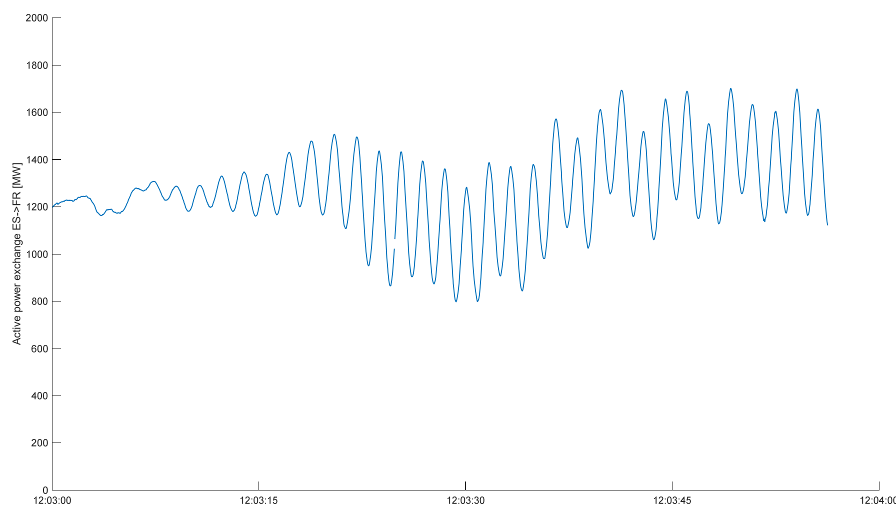

Figure 5-8: Detail of the evolution of active exchange power through the 400 kV AC and DC interconnection lines with France between 12:02 and 12:08.

In its report, Red Eléctrica attributes the 0.6 Hz oscillation that occurred between 12:03 and 12:08 to a forced oscillation originating in a photovoltaic (PV) plant located in southern Extremadura. ENTSO-e also points out that this was a forced oscillation.

The Analysis Committee's report indicates that the aforementioned 0.6 Hz oscillation had a large amplitude in Portugal. It was also observed in France (Tavel, Loony, and Albertville) and even in Germany (Freiburg). Although the source of this information included in the Analysis Committee's report is Red Eléctrica, Red Eléctrica does not mention it in its report.

The Red Eléctrica report does not contain evidence and/or analysis to support the nature of forced oscillation. Nor is the ENTSO-e statement supported by evidence and/or analysis.

The scientific literature on forced oscillations in electrical systems ([17], [24]) states that typical evidence of such oscillations is "non-linear waveforms" or "the presence of harmonic components," which are not apparent in the records. The scientific literature also offers methods for establishing the forced nature of an oscillation: the "Dissipating Energy Flow Method" or the "Cross Power Spectral Density Method."

The amplitude (in MW peak-to-peak) of the 0.6 Hz oscillation is comparable to the amplitude of the 0.2 Hz oscillation. This indicates that the generators involved in the 0.6 Hz oscillation are not only located on the Iberian Peninsula, but also beyond our border with France. The observations mentioned in the Analysis Committee's report confirm this.

Therefore, it can be stated that there is a natural 0.6 Hz oscillation in the European system in which generators on the Iberian Peninsula interact with generators in the rest of Europe. There is no basis for claiming that the periodic variation in the power delivered by the aforementioned PV plant is responsible for the natural 0.6 Hz oscillation of the European continental system.

Even if it were a forced oscillation due to a specific installation, it should not be forgotten that the amplitude of the oscillations caused by a forced oscillation depends on the proximity of the frequency of the forced oscillation to the frequency of one of the natural oscillations of the system and on the damping of the latter.

The natural oscillations of a dynamic system result from the interactions between its components. The stability of the natural oscillations of the system is the responsibility of the entity that integrates the components into a system. Transmission system operators and system operators in Europe are responsible for providing the control settings to damp oscillations, as they alone possess knowledge of all the components connected to their networks.

5.3 Oscillations and synchronous generation in Andalusia

The combined cycle power generating units in Andalusia play a crucial role in damping the 0.2 Hz oscillation, as they are located at one end of the European continental system. Remember that the 0.2 Hz oscillation corresponds to an oscillation in which the generators at the western (Spain) and eastern (Turkey) ends oscillate against the center.

The different amplitudes of the frequency oscillations at the southern end of the peninsula (Puerto de la Cruz 400 kV) and on the border between Spain and France (Hernani 400 kV and Santa Llogaia 400 kV), shown in Figure 5-8 confirm the greater observability of the 0.2 Hz oscillation at the southern end of the peninsula.

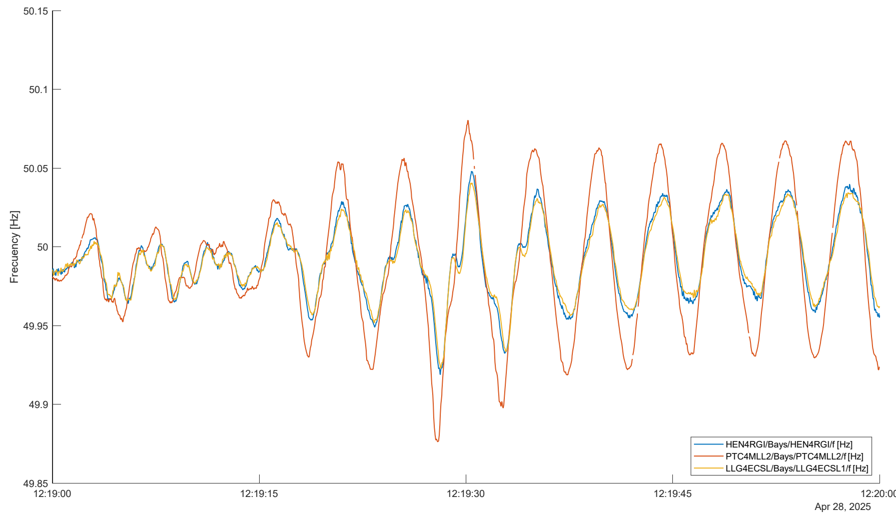

Figure 5-8: Detail of the frequency evolution in Hernani, Puerto de la Cruz, and Santa Llogaia between 12:19 and 12:20.

A simple example, such as the one shown in Figure 5-9 [25], suggests that it is at the extremes of an oscillation where an oscillation is most noticeable and where a device to dampen it can be most effective. In fact, if action is taken at the fulcrum of our simple example (the node of the oscillation), the oscillation cannot be modified. On the contrary, if action is taken at the extremes (bellies of the oscillation), it can be modified.

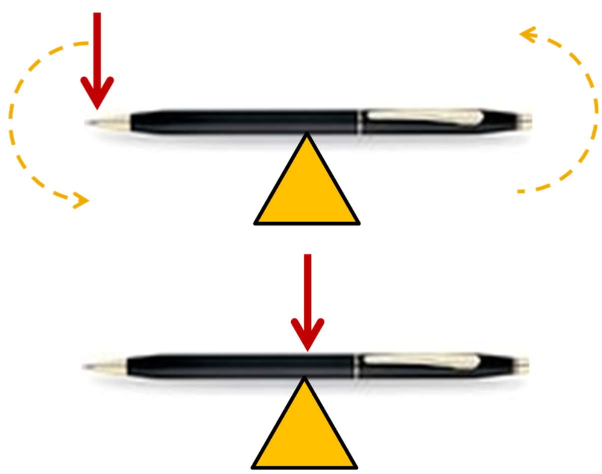

Figure 5-9: Simple example to explain the controllability and observability of oscillations depending on the location of the control action.

Therefore, it is not surprising that poorly damped oscillations occur with a weak grid and low synchronous generation (combined cycle power plants) in Andalusia, since all combined cycle power plant units are equipped with Power System Stabilizers (PSSs). The importance of combined cycle power plant units for damping interarea oscillations is due to their high observability. On the other hand, the damping effect of the maneuvers carried out by Red Eléctrica between 12:00 and 12:30 is also not surprising.

5.4 Partial conclusions

The results of the analysis of the oscillations that occurred between 12:00 and 12:30 can be summarized as follows:

- The dampening effect of the maneuvers carried out by Red Eléctrica would confirm the weakness of the grid.
- The combined cycle power plants in Andalusia are very important for dampening 0.2 Hz oscillations because they are located at the edge of the European continental system and are equipped with power system stabilizers.
- The 0.6 Hz oscillation is an inter-area oscillation between generators in the Iberian system and generators in the rest of the European continental system, as the amplitude of the active power exchange oscillation (470 MW peak to peak) is comparable to the amplitude of the 0.2 Hz oscillation (1480 MW peak to peak).
- The statements made by Red Eléctrica and ENTSO-e regarding the forced nature of this oscillation are not supported by evidence and/or analysis. Even if it were a forced oscillation due to a specific installation, it should not be forgotten that the amplitude of the oscillations caused by a forced oscillation depends on the proximity of the frequency of the forced oscillation to the frequency of one of the natural oscillations of the system and on the damping of the latter. The natural oscillations of a dynamic system result from the interactions between its components. The stability of the natural oscillations of the system is the responsibility of the entity that integrates the components into a system.

6 THE MARGIN TO OVERVOLTAGE COLLAPSE

A conceptual model has been developed to explain the primary phenomenon that occurred, which we have called *overvoltage collapse*. While the phenomenon of *voltage collapse*, or more precisely *undervoltage collapse*, is widely discussed in the scientific literature ([26], [27]), the phenomenon of overvoltage collapse is new. In undervoltage collapse, the voltage drops as the load on an electrical system increases. In an overvoltage collapse, voltage rises as the load on the power system decreases due to reduced generation. In both phenomena, the ability of generators to generate and consume reactive power, as well as the operation of power transmission lines at high and low loads, play key roles.

The value of the conceptual model lies not only in explaining what happened, but also in assessing the impact of decisions and measures taken.

This section will apply the conceptual model to the situation of the peninsular electricity system at 12:30 on 28th April. It also contains two sensitivity studies:

- The impact of the dispatch on 30th April
- The impact of the maneuvers carried out by Red Eléctrica between 12:00 and 12:30.

6.1 Conceptual model

In the voltage collapse phenomenon, the voltage drops as the load on an electrical system increases. Figure 5-1 shows the characteristic nose curve in the voltage-load plane of the system. The nose corresponds to the point at which the maximum power transportable by the power system is reached. In Figure 5-1, the solid line represents the voltage variation (ordinate axis) as a function of the system load (abscissa axis). If the system load increases, the voltage drops. In Figure 6-1, the dashed line represents the voltage evolution as a function of load when a generator reaches its reactive power generation limit. In Figure 6-1, the system trajectory has been highlighted when the system load increases. In the voltage collapse phenomenon, the collapse is caused by undervoltage.

On 17th December 2001, a situation occurred in the Spanish peninsular system that was close to collapse due to undervoltage, which was prevented by Red Eléctrica giving instructions for load shedding in Madrid and Levante ([28], [29]).

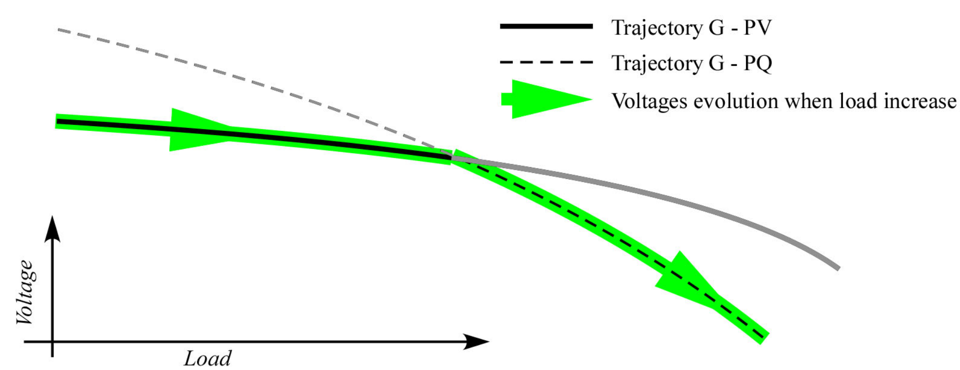

Figure 6-1: Voltage evolution upon load increase.

We have developed a conceptual model and a simulation model to explain what happened in the Iberian system on 28th April 2025, in which out-of-control overvoltages appeared when controlled generation with constant power factor (reactive power supplied is proportional to active power) was disconnected in Andalusia and Extremadura.

The phenomenon is abbreviated as *overvoltage collapse* or, more precisely, collapse due to exhaustion of the reactive power absorption capacity of the system elements. Figure 5-2 illustrates the system's trajectory in the voltage-load plane as the load decreases.

In Figure 6-2 , the trajectory of the voltage evolution has been highlighted when the system load is reduced, e.g. by generation disconnections due to overvoltage. It can be observed that when the reactive power absorption limit of the generators is reached, the slope of the voltage variation increases, which can act as an accelerator for overvoltage generation disconnections.

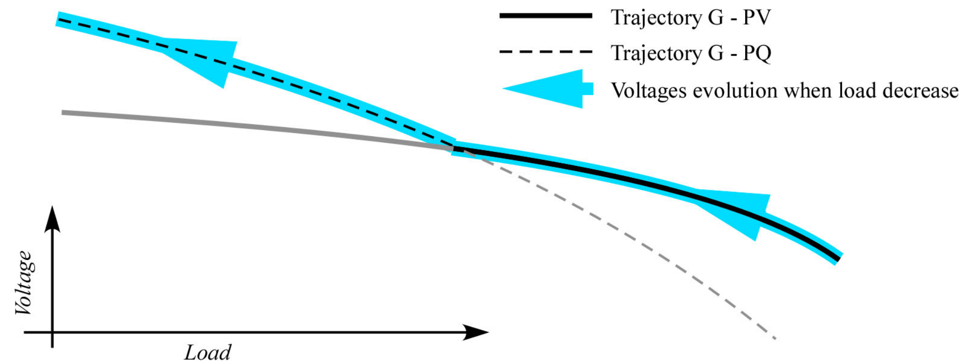

Figure 6-2: Voltage evolution with load shedding.

6.2 Application of the conceptual model to the situation of the peninsular electricity system at 12:30 on 28th April.

The conceptual model has been implemented as a simulation model that allows the evolution of voltages to be traced when controlled generation with constant power factor is progressively disconnected, starting from the instantaneous operation of the Iberian electricity system at 12:30 (load flow case).

The starting point for the construction of the case study has been:

- The raw PSS/e load flow file of the hourly electricity system operating scenario at 12 o'clock before the solution of Red Eléctrica's operating restrictions available in the system operator's information system (e-sios).
- The technical restrictions solution report of 28th April.
- Red Eléctrica's daily operation report of 28th April.

Red Eléctrica makes available to agents the raw load flow files of PSS/e for the hourly operation scenarios of the electricity system prior to solving operating restrictions. These load flow scenarios (without convergence) include the generation and demand per node resulting from market matching, as well as the lines and transformers that are not in service due to scheduled maintenance. The technical restrictions solution report informs on the actions taken by Red Eléctrica in this process. The daily operation report provides information about the actions on the grid (maneuvers of elements) carried out by Red Eléctrica throughout the day.

Figure 5-3 compares the evolution of voltages in the 400 kV grid with renewable generation in Andalusia and Extremadura in cases where this is represented as generation with dynamic voltage control (Gen Rnwble Ctrl V) or as generation with power factor control (Gen Rnwble Ctrl PFfix). It should be noted that generation disconnection is carried out homothetically in all nodes in Andalusia and Extremadura. This is certainly not what happened. However, it is the standard method considered in the literature for studying the margin that collapses due to undervoltage.

The evolution of the voltage at Carmona 400 kV is shown (with a thick line), and the intervals of maximum variation in the network voltages at 400 kV are indicated (with a thin line). The evolution should be viewed in the reverse direction (from right to left) in order to measure the effect of generation disconnections due to overvoltage.

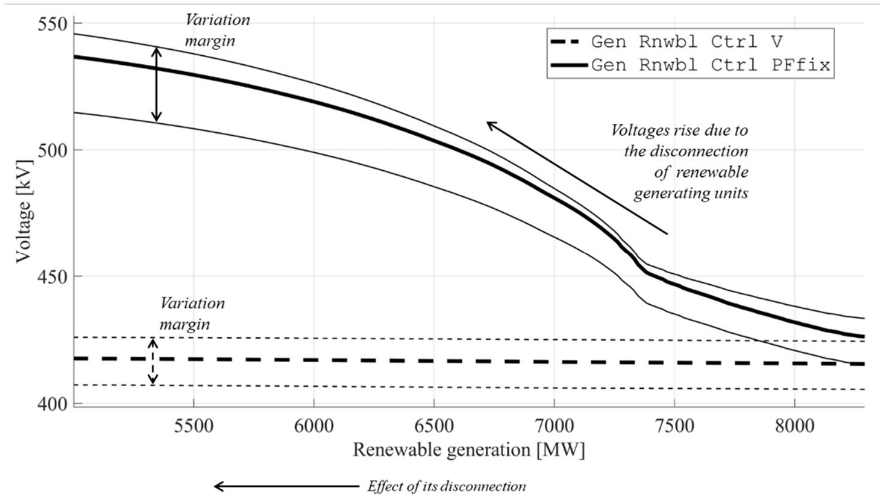

Figure 6-3: Effect on voltage at Carmona 400 kV of renewable generation and voltage variation margins at 400 kV.

First, there is a clear difference between generation with dynamic voltage control and generation controlled with constant power factor control (continuous line). When renewable generation is equipped with dynamic voltage control, the voltages do not change significantly when the generation is lost. The legal requirement on 28th April was for renewable generation to be controlled at a constant power factor. It should be noted that, if the generation is equipped with dynamic voltage control, the reactive power supplied/consumed is modified when there is a disconnection to maintain a constant voltage.

It can also be seen that when the generation is controlled with a constant power factor, from a generation disconnection of approximately 1000 MW, there is a change in the slope of the voltage evolution and a more pronounced increase in voltage.

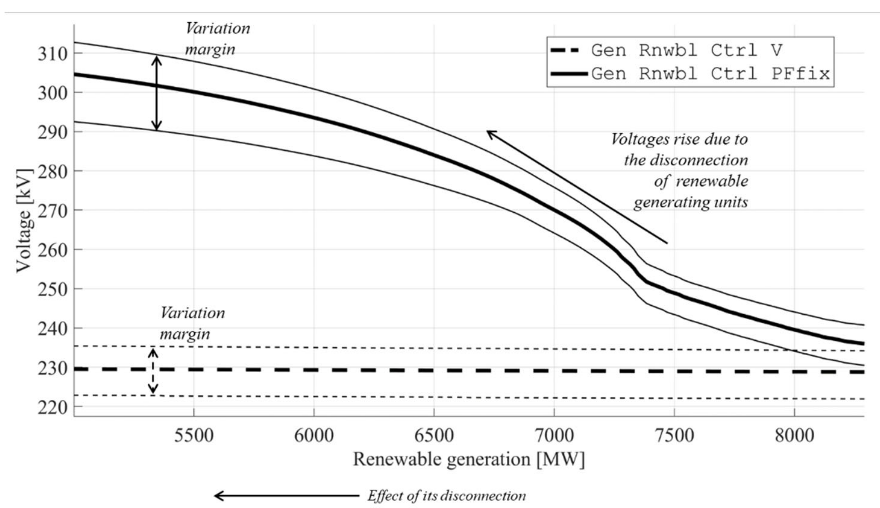

Figure 6-4: Effect on voltage at Guillena 220 kV of disconnection of renewable generation and voltage variation ranges at 220 kV.

Figure 5-4 compares the voltage evolution at Guillena 220 kV and the voltages in the 220 kV grid in the same way as Figure 5-3 compares the voltage evolution at Carmona 400 kV and the voltages in the 400 kV grid.

The shape of the voltage evolution in Figure 5-4 is very similar to the shape of the voltage evolution in Figure 5-3. However, the location of the voltage evolution at Guillena 220 kV, within the range of variation of voltages at 220 kV, differs from the location of the voltage evolution at Carmona 400 kV, within the range of variation of voltages at 400 kV.

The so-called voltage maps (see Figure 6-5) help to achieve a deeper understanding of the phenomenon. The geographical distribution of the voltages at the initial instants and after the three events identified by the Analysis Committee has been plotted. It should be emphasized that four points on the curves of Figures 5-3 and 6-- 4 have been represented geographically. It can be seen how the event spreads from its epicentre in Andalusia and Extremadura towards the rest of the peninsular system and how, after event 3, the overvoltages already reached almost the entire peninsula. It is worth highlighting the situation in Catalonia thanks to the coupling of its nuclear power plants and the DC link of the interconnection with France.

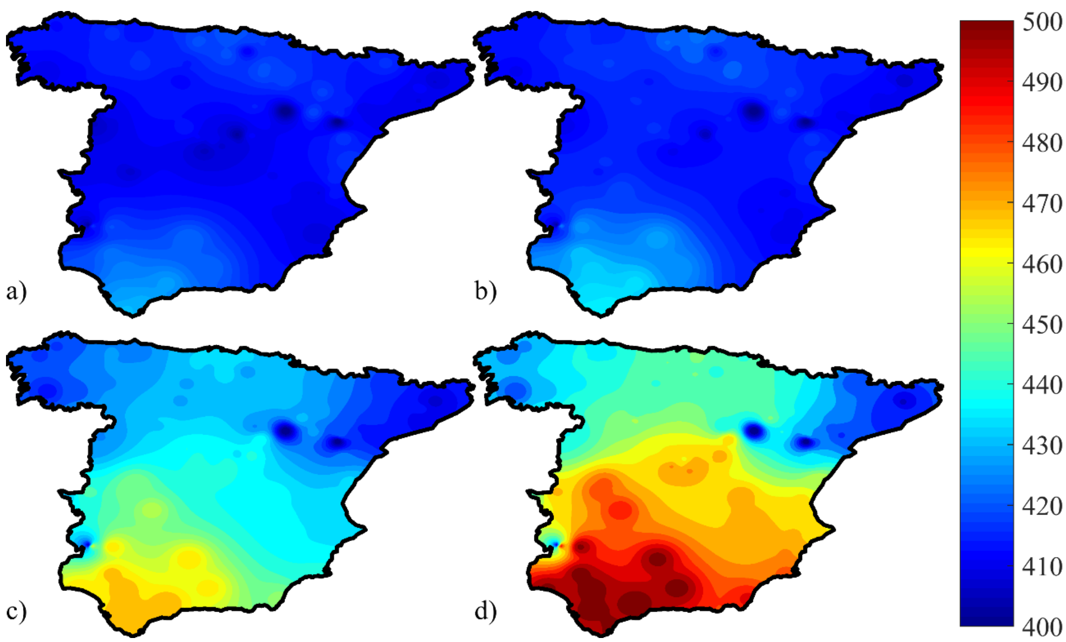

Figure 6-5: Voltage maps: a) initial situation, b) loss of 355 MW (event 1), c) loss of 1085 MW (event 1+event 2), and d) loss of 1635 MW (event 1+event 2+event 3).

6.3 Margin to overvoltage collapse

To quantify system security, the overvoltage collapse margin is proposed. The overvoltage collapse margin can be defined as the volume of generation that can be disconnected until the tripping threshold of the overvoltage protections is reached. According to the general protection criteria of the Spanish peninsular system, the overvoltage protection tripping threshold will be between 110 and 120% of the nominal voltage. For illustrative purposes, we will take 120% (1.2 pu). As there is a different voltage variation at each node of the network, we will give the maximum and minimum values of the margin for each voltage level.

Figure 6-6 shows the concepts of maximum and minimum margin to overvoltage collapse at 400 kV. Figure 6-7 does the same for 220 kV. It is clear that the overvoltage collapse margins at 220 kV are lower than at 400 kV.

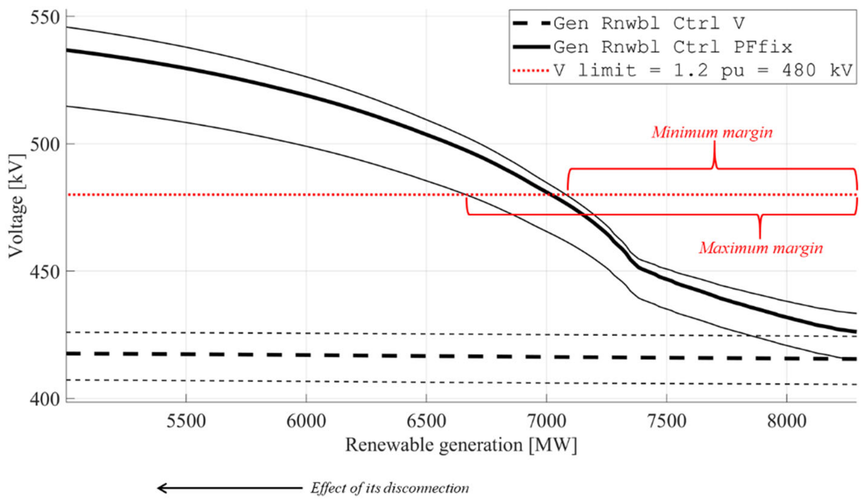

Figure 6-6: Overvoltage collapse margins at 400 kV.

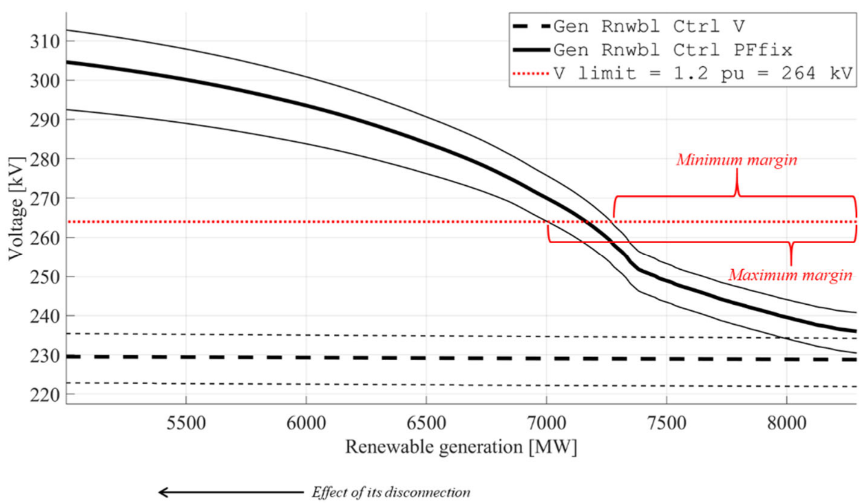

Figure 6-7: Overvoltage collapse margins at 220 kV.

Table 6-1 provides the numerical values derived from Figure 6-6 and Figure 6-7. The most restrictive network is the 220 kV network. The minimum safety margin was 1019 MW, while there were disconnections of at least 1615 MW, with the system having to withstand disconnections of 3000 MW as established in OP 13.1 on criteria for the development of the transmission grid [19] and in the detailed specifications for the calculation of the access capacity of generation to the transmission and distribution networks [20].

Table 6-1: Overvoltage collapse margins.

Level	Upper margin [MW]	Selected node margin [MW]	Lower margin [MW]
400	1625	1268	1213
220	1286	1199	1019

6.4 The impact of the 30th April dispatch

More relevant than the explanation of what happened, if possible, is the impact on the voltage variation of the disconnection of controlled generation with constant power factor in Andalusia and Extremadura of the application of the generation dispatch of 30th April, in which five units of combined cycle power plants were connected in Andalusia in the process of solving technical restrictions.

Figure 6-8 compares the voltage evolution with renewable generation in two cases: (1) starting case of the Figure 6-3 (Gen Rnwbl Ctrl PFfix) and (2) with the generation dispatch of 30th April (wed30Apr12h). The evolution must also be considered in the reduction direction (from right to left) to measure the effect of generation disconnections due to overvoltage. The effect of generation disconnection would have been much more attenuated if the 30th April dispatch had been applied, so that the safety margin at Carmona 400 kV would have gone from 1268 MW to 2758 MW.

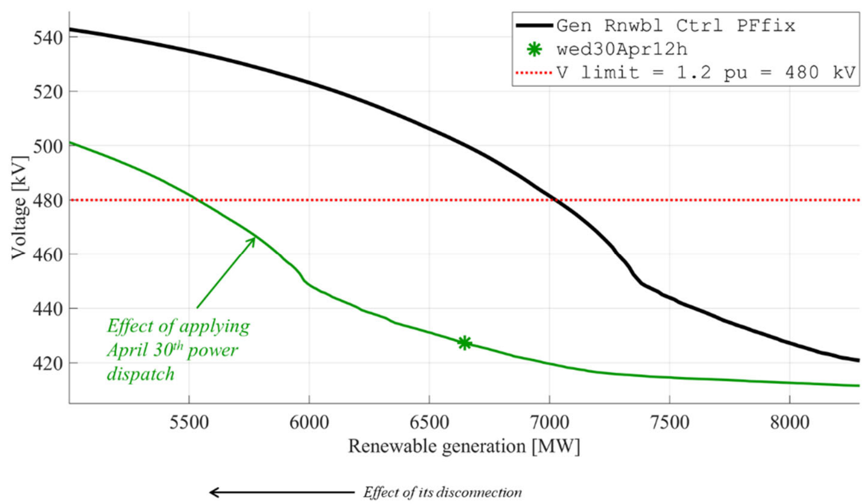

Figure 6-8: Effect on voltages of the application of the 30th April dispatch when renewable generation is disconnected.

6.5 The impact of the maneuvers carried out by Red Eléctrica between 12:00 and 12:30

To dampen the oscillations that occurred between 12:00 and 12:30, Red Eléctrica connected up to 11 lines. Given the effect of the aforementioned connections on the voltages, it also switched 13 reactors. The connection of the aforementioned lines contributed 650 Mvar, and the switching of the 13 reactors eliminated 400 Mvar of compensation. In total, 1050 Mvar were fed into the grid.

We have analyzed the impact of these maneuvers. Figure 5-9 compares the voltage evolution at Carmona 400 kV with renewable generation in four cases: (1) starting case of Figure 6-3 (Gen Rnwble Ctrl PFfix), (2) undoing line maneuvers (-Mnbrs LIN), (3) undoing reactor maneuvers (-Mnbrs SHN), and (5) undoing line and reactor maneuvers (-Mnbrs LIN&SHN).

Here, too, the evolution should be viewed in a reverse direction (from right to left) in order to measure the effect of generation disconnections due to overvoltage. The unfavorable effects of the maneuvers carried out by Red Eléctrica between 12:00 and 12:30 are evident. The effect of the maneuvers causes the safety margin at Carmona 400 kV to drop from 2964 MW to 1268 MW.

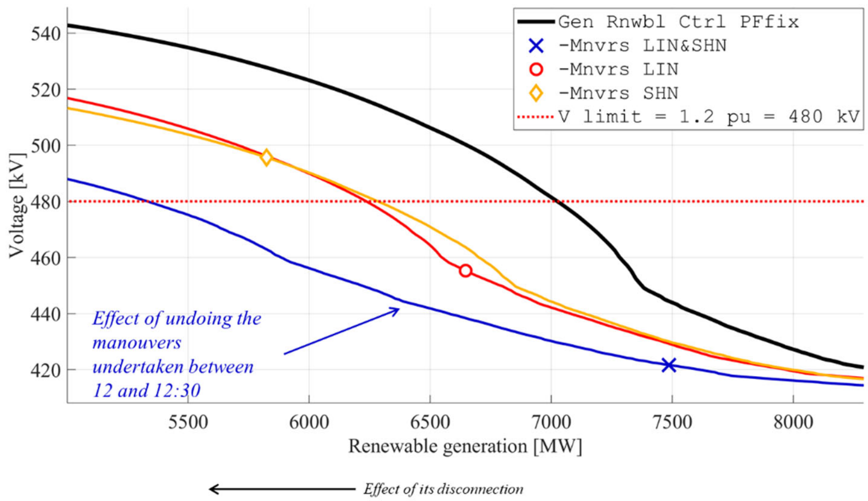

Figure 6-9: Effect on voltages of undoing the maneuvers carried out between 12:00 and 12:30 and the application of the dispatch of 30th April when renewable generation is disconnected.

6.6 Partial conclusions

A conceptual model of overvoltage collapse can explain the overvoltages reached on 28th April 2025 due to the disconnection of generation with constant power factor control in Andalusia and Extremadura.

The results of the simulation of the overvoltage collapse that occurred in the Iberian system at 12:30 on 28th April 2025 can be summarised as follows:

- The overvoltage collapse occurs due to the disconnection of controlled generation with a constant power factor in Andalusia and Extremadura.
- An overvoltage collapse margin has been proposed and calculated. The most restrictive network is the 220 kV network. The safety margin was 1019 MW, while there were disconnections of at least 1615 MW, with the system having to withstand disconnections of 3000 MW.
- The overvoltage collapse occurred due to low synchronous generation with dynamic voltage control in the south and in the center after the process of solving technical restrictions carried out by Red Eléctrica. The application of the 30th April dispatch would have significantly increased the margin for overvoltage collapse.
- The maneuvers carried out by Red Eléctrica between 12:00 and 12:30 had an adverse effect by significantly reducing the margin for overvoltage collapse.

While this model provides a very plausible explanation of the effect on voltages of the disconnection of constant power factor controlled generation in Andalusia and Extremadura, it must be pointed that the conclusions of this report should be taken with caution, as the load flow case constructed only approximately reflects the situation of the Iberian electricity system at 12:30. The caution could be dismissed if the Red Eléctrica state estimator output cases that provide the most likely state of the grid from remote measurements were available. Endesa and Iberdrola requested these cases from Red Eléctrica. Red Eléctrica has not provided them on the grounds of confidentiality.

7 CONCLUSIONS

This document contains a summary of the report carried out by Dr Luis Rouco Rodríguez, Dr Enrique Lobato Miguélez, and Dr Francisco M. Echavarren Cerezo, at the request of Endesa and Iberdrola, on the facts and circumstances that led to the blackout in the Iberian system on 28th April 2025. Although the report addresses all the facts and circumstances that led to the blackout, this summary aims to bring to the reader's attention novel analyses that offer well-founded answers to unresolved questions that arise from careful study of the reports issued.

The paper has analyzed three circumstances that, in our view, are key to explaining what happened:

1. The voltage instability phenomena occurred during the week before and in the morning of the event between 9:00 and 12:00.
2. The combination of low synchronous generation in the southern and central areas and a weak grid.
3. The insufficient safety margin against overvoltage collapse (caused by the disconnection of renewable generation with power factor control).

The report analyzes and quantitatively measures the generation situation in the southern and central areas of the Spanish peninsular system and its transmission grid on 28 April.

In addition, the document discusses the nature of the oscillations that occurred between 12:00 and 12:30 and their relationship to the synchronous generation situation in the south area and the transmission network.

The results of our analysis can be summarized as follows:

1. The voltage instability phenomena referred to by the Analysis Committee cannot be assessed simply by inspection of the time variation of voltages and dismissed because the voltages are within the admissible margins.

2. An in-depth quantitative analysis of the time evolution of voltages on 22nd, 24th and 28th April and 5th May (one week after the blackout) with a metric based on the voltage derivative shows the anomalous situation of the voltage control of the transmission grid in the Spanish peninsular system before 28th April, the extreme anomaly on 28th April and the recovery to normality on 5th May.

3. The singularity of 28th April in terms of low synchronous generation with dynamic voltage control in the southern (only one combined cycle unit in Andalusia was connected) and central areas (only one of the nuclear units was coupled) has been shown. Inertia has been used as a measure of the geographical distribution of synchronous generation. The inertia in the southern area was equal to 1.3 seconds, while in the centrer area it was 1.84 seconds. Both are lower than the ENTSO-e recommendations (2 seconds). These values indicate low synchronous generation in the south and center areas and, therefore, the scarcity of means to carry out dynamic voltage control.

4. The weakness of the transmission grid at 9:00 has also been shown. The extent of the peninsular 400 kV network open for various reasons (voltage control, unavailability, and programmed work) reached 22.9% on 28 April at 9:00. It should be noted that 35.8% and 34.3% of the 400 kV grid extension in the southern and central areas, respectively, were disconnected.

5. The occurrence of poorly damped oscillations with a weak network and low synchronous generation in the area of greatest observability of these oscillations is not surprising. Nor is the damping effect of the maneuvers carried out by Red Eléctrica between 12:00 and 12:30 surprising.

6. The 0.6 Hz oscillation is an inter-area oscillation between generators in the Iberian system and generators in the rest of the European continental system, since the amplitude of the active power exchange oscillation (470 MW peak-to-peak) is comparable to the amplitude of the 0.2 Hz oscillation (1480 MW peak-to-peak). The statements made by Red Eléctrica and ENTSO-e regarding the forced nature of this oscillation are not supported by evidence and/or analysis.

7. The overvoltage collapse occurs due to the disconnection of renewable generation, controlled with constant power factor, in Andalusia and Extremadura. An overvoltage collapse margin has been proposed and calculated. The most restrictive network is the 220 kV network. The overvoltage collapse margin is found to be 1019 MW. Lower than the disconnected generation. It can be concluded that the system did not have a sufficient safety margin to account for the lost generation.

8. The overvoltage collapse occurs due to the low synchronous generation with dynamic voltage control connected in the southern and central areas after the process of solving technical restrictions carried out by Red Eléctrica. The application of the 30th April dispatch would have significantly increased the margin for overvoltage collapse. The maneuvers carried out by Red Eléctrica between 12:00 and 12:30 significantly reduced the margin to overvoltage collapse.

8 BIBLIOGRAPHICAL REFERENCES

[1] ENTSO-E, Incident Classification Scale Subgroup, "INCIDENT CLASSIFICATION SCALE", 4 December 2019, available at https://eepublicdownloads.entsoe.eu/clean-documents/SOC%20documents/Incident_Classification_Scale/IN_USE_FROM_JANUARY_2020_191204_Incident_Classification_Scale.pdf.

[2] ABC, "Apagón en casi toda España por una rara avería técnica", Thursday 7nd July 1977, pages 18 and 19.

[3] ABC, "Una explosión fortuita en un transformador dejó sin luz a ocho millones de españoles", 15th October 1987, page 84.

[4] ABC, "Cataluña emuló ayer durante dos horas el gran apagón de Nueva York", Wednesday 25th August 1994, page 55.

[5] UCTE, "FINAL REPORT of the Investigation Committee on the 28 September 2003Blackout in Italy", available at https://eepublicdownloads.entsoe.eu/clean-documents/pre2015/publications/ce/otherreports/20040427_UCTE_IC_Final_report.pdf.

[6] Government of Spain, Consejo de Seguridad Nacional, Comité de Análisis de las circunstancias que concurrieron en la crisis de electricidad del 28 de abril de 2025, "Versión no confidencial del informe Comité de Análisis de las circunstancias que concurrieron en la crisis de electricidad del 28 de abril de 2025", available at https://www.lamoncloa.gob.es/consejodeministros/resumenes/Documents/2025/Informe-no-confidencial-Comite-de-analisis-28A.pdf.

[7] Red Eléctrica, "Informe del incidente acaecido en el sistema peninsular español el día 28 de abril de 2025", available at https://www.ree.es/sites/default/files/2025-06/NP_RedElectrica_InformeOS_180625.pdf.

[8] ENTSO-E, Iberian Black-out: ENTSO-E congratulates Red Electrica and REN for the rapid recovery of the electricity systems of Portugal and Spain, and establishes an Expert Panel to investigate the incident, https://www.entsoe.eu/news/2025/05/01/iberian-black-out-entso-e-congratulates-red-electrica-and-ren-for-the-rapid-recovery-of-the-electricity-systems-of-portugal-and-spain-and-establishes-an-expert-panel-to-investigate-the-incident/

[9] ENTSO-E, 28th April blackout, https://www.entsoe.eu/publications/blackout/28-april-2025-iberian-blackout/

[10] Red Eléctrica, "Webinar public consultation on new voltage control service", January 2024.

[11] Ministry of Industry, Energy and Tourism, Resolution of 5 April 2016, of the Secretary of State for Energy, approving the electricity system operation procedure 1.1 "Functioning and safety criteria for the operation of the electricity system". "BOE" no. 83, 6 April 2016, pages 24013 to 24018 (6 pages).

[12] Ministry of Industry and Energy, Resolution of 30 July 1998, of the Secretary of State for Energy and Mineral Resources, approving a set of technical and instrumental procedures necessary for the appropriate technical management of the electricity system. "BOE" no. 197, 18 August 1998, pages 28158 to 28183 (26 pages).

[13] ENTSO-e, Inertia and Rate of Change of Frequency (RoCoF), Version 17, SPD – Inertia TF, Dec. 16, 2020, Available at https://eepublicdownloads.entsoe.eu/clean-documents/SOC%20documents/Inertia%20and%20RoCoF_v17_clean.pdf

[14] PROJECT: [FLEXENER] - New 100% renewable, flexible and robust energy system for the integration of new technologies in generation, grids and demand, DELIVERABLE E5.1.2, EVALUATION OF THE SAFE OPERATION OF THE ELECTRICITY SYSTEM AT THE GLOBAL LEVEL: CONSTRUCTION OF SYSTEM MODELS.

[15] ENTSO-e Project Inertia, "PROJECT INERTIA - PHASE II, Reecovering power system resilience in case of system splits for a future-ready decarbonised system: Supporting", Technical report, 10 January 2025, available at https://eepublicdownloads.blob.core.windows.net/public-cdn-container/clean-documents/SOC%20documents/241220_Project_Inertia_II_milestone_3_support_technical_report_proofread_tracked_reviewed.pdf.

[16] Ministerio de Industria, Energía y Turismo, "Planificación Energética, Plan de desarrollo de la Red de Transporte de Energía Eléctrica 2015-2020", página 116, disponible en https://www.miteco.gob.es/content/dam/miteco/es/energia/files-1/planificacion/Planificacionelectricidadygas/desarrollo2015-2020/Documents/Planificaci%C3%B3n%202015_2020%20%202016_11_28%20VPublicaci%C3%B3n.pdf

[17] G. Rogers, R.T. Elliot, D. J. Trudnowski, F. Wilches-Bernal, D. Osipov, J. H. Chow, "Power System Oscillations: An Introduction to Oscillation Analysis and Control", Second Edition, Springer, 2025.

[18] J.F. Hauer, C.J. Demeure, L.L. Scharf, "Initial results in Prony analysis of power system response signals", IEEE Transactions on Power Systems, Vol. PWRS-5, No. 1, February 1990, pp. 80-89.

[19] Ministry of Industry, Tourism, and Trade, Resolution of March 22, 2005, of the General Secretariat of Energy, approving Operating Procedure 13.1. "Criteria for the Development of the Transmission Network," of a technical and instrumental nature necessary for the proper technical management of the Electric System. BOE No. 85, April 9, 2005, pages 12351 to 12358 (8 pages).

[20] National Commission for Markets and Competition, Resolution of June 27, 2024, of the National Commission for Markets and Competition, establishing the detailed specifications for determining the capacity of generation access to the transmission network and distribution networks. BOE No. 162, July 5, 2024, pages 84336 to 84356 (21 pages).

[21] ENTSO-E, "ANALYSIS OF CE INTER-AREA OSCILLATIONS OF 1ST DECEMBER 2016," available at https://www.entsoe.eu/Documents/SOC%20documents/Regional__Groups_Continental_Europe/2017/CE_inter-area_oscillations_Dec_1st_2016_PUBLIC_V7.pdf.

[22] A. Díaz, G. Torresan, A. Cordón, L. Coronado, S. Sanz, J. Peiró, A. Hernández, J. Pérez, F. Xavier, C. Cardozo, S. Akkari, "Improvement of the oscillatory behavior of the HVDC link between Spain and France." 47th Cigre Session, Paris, France, August 26-31, 2018, Article no. B4-130.

[23] J. Renedo, A. Díaz-García, G. Torresan, E. Lorenzo-Cabrera, A. Cordón, S. Sanz-Verdugo, J. Peiró, J. Pérez-Castro, G. Calvo, A. Hernández-Sautua, A. Petit, H. Oukhayi, S. Akkari, H. Saad, “Tests of the POD-P controller of INELFE Spain-France VSC-HVDC interconnector,” B4 SC Meeting and Colloquium, September 11-15, 2023, Vienna, Austria, Article No. B4-1145.

[24] Oscillation Source Location Task Force, Power System Stability Controls Subcommittee, Power System Dynamic Performance Committee, IEEE Power & Energy Society, “Forced Oscillations in Power Systems,” May 2023, TECHNICAL REPORT PES-TR110.

[25] L. Rouco, “Eigenvalue sensitivities for location and tuning of damping controllers of HVDC links and FACTS devices”, Farewell event Prof. Göran Andersson, ETH, Zürich, Switzerland, 9-10 June 2016.

[26] P. Kundur, "Power System Stability and Control", Mc Graw Hill, 1998.

[27] T. Van Cutsem, C. Vournas, "Voltage Stability of Electric Power Systems", Kluwer Academic Publishers, 1998.

[28] F.M. Echavarren, E. Lobato, L. Rouco, J.M. Rodríguez-García, "El colapso de tensión: Causas y soluciones (I/II)", Anales de Mecánica y Electricidad, Vol. LXXXIII, Fascículo. I, January 2006, pp. 54-62, available at www.icai.es.

[29] F.M. Echavarren, E. Lobato, L. Rouco, J.M. Rodríguez-García, "El colapso de tensión: Causas y soluciones (II/II)", Anales de Mecánica y Electricidad, Vol. LXXXIII, Fascículo II, March 2006, pp. 17-22, available at www.icai.es.

9 RATIFICATION

In Madrid, this 1st day of October 2025, we ratify and sign this report.

Dr. Luis Rouco Rodríguez
Professor of the
School of Engineering of
Comillas Pontifical University

Dr. Enrique Lobato Miguélez
Professor of the
School of Engineering of
Comillas Pontifical University

Dr. Francisco M. Echavarren Cerezo
Associate Professor of the
School of Engineering of
Comillas Pontifical University