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The 2025 Iberian Blackout: Why it Happened, Will There Be Another

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Abstract : This paper provides a high-level analysis of the Iberian blackout and is aimed at a non-technical audience. It starts with quick tutorials on the relationship between reactive power and voltage and on power system oscillations as they are key to understanding the blackout. Then it proceeds with overviewing how the blackout evolved. The direct cause of the blackout was an unexpected interaction between oscillations and voltage stability compounded by inadequate voltage control arrangements in Spain. However the underlying cause is that Spain has concentrated in recent years on increasing the share of renewables but seems to have paid less attention to adapting power system operation and control to the changing needs.

The rapidly increasing share of renewables in many power systems causes a profound change in the way power systems behave which we do not yet fully understand. Hence a significant interdisciplinary research effort of the academia and industry is required to overcome the challenges and prevent future blackouts.

Keywords : power system blackouts, security of supply, Iberian blackout 2025

JEL Classification : L94, L98, Q40, Q48, Q42

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I. Introduction

Iberian blackout of 28 April 2025 was the largest blackout in Europe since the 2003 Italian blackout. 55 million of people in Spain and Portugal, and a little bit of France, lost supply. As Variable Renewable Energy (VRE), i.e., solar and wind plants, in Spain and Portugal form a significant part of overall generation, people were asking questions. Are renewables to blame? Are other systems with high VRE penetration in danger of a blackout? This article will attempt to answer those questions by providing a high-level analysis of the Iberian blackout. The article is aimed at a non-technical audience.

II. Fundamentals

We start with quick tutorials on the relationship between reactive power and voltage and on power system oscillations as they are key to understanding the blackout.

II.1 Voltages and reactive power

First let us explain what reactive power is as it is an elusive and not well-understood concept. Reactive power (usually denoted by Q) is a phenomenon connected with existence of inductors and capacitors in AC circuits. There is no reactive power in DC circuits. It is important to appreciate that inductors (coils) and capacitors (condensers) store energy: an inductor stores magnetic energy proportionally to the square of the current flowing through it while a capacitor stores electric energy proportionally to the square of the voltage across it.

Now let us consider an inductor supplied by an AC source. When the current increases, the inductor is magnetised. When the current decreases, the inductor is demagnetised. Hence the AC current magnetises and demagnetises the inductor twice in every AC cycle[1] so energy flows back and forth with double the fundamental frequency (100 Hz = 2x50 Hz in Europe). Reactive power quantifies this oscillating energy. On average (i.e. over the cycle) the reactive energy flow is zero (which means that it cannot be used to do any useful work) –but by convention we say that reactors “consume” reactive power.

The situation is similar but opposite with the capacitors. The AC voltage oscillates across the capacitor which means it is charged/discharged twice in every cycle. Hence the energy again flows back and forth with 100 Hz frequency, but the exchanges are 180^0 out of phase (i.e. in anti-phase) with respect to those in an inductor. This means that inductor and capacitor perfectly compensate each other: when one needs energy, the other gets rid of it. By convention, we say that capacitors “produce” reactive power.

II.2 The effects of reactive power

The most important effect of reactive power is its influence on network voltages. It takes some circuit theory, which we will skip, to prove that *inductive reactive power causes voltages to drop* while *capacitive reactive power causes voltages to rise*. Hence controlling reactive power production/consumption is essential for voltage control.

Next, it can be shown that the flow of reactive power between two points in a transmission network is roughly proportional to the voltage difference between those points and inversely proportional to the distance[2]. This means that for a given distance, a large reactive power

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[1] Also in the negative half-cycle as magnetic energy is proportional to the square of the current.

[2] If we neglect the resistance R of a transmission line, as it is much smaller than the reactance X, then a reactive power transfer Q along the line can be expressed as $Q = V_r(V_s \cos\theta - V_r)/X$ where V_s is the voltage at the sending end, V_r is the voltage at the receiving and ϑ is the voltage angle difference between the sending and the receiving end. As voltage angle differences tend to be small, we can approximately assume that cos ϑ =1.

transfer would cause large voltage differences which is unacceptable due to the voltage limits discussed above. On the other hand, for a given maximum allowable voltage difference, an increase in the transmission distance reduces the amount of reactive power transfer. Hence *reactive power has to be controlled locally* as it cannot be allowed to travel over long distances. The overall conclusion is that, as voltage control is closely linked to reactive power control, *voltage control has to be local*.

And finally, the flow of reactive power causes transmission I^2R heating losses[3]. This is another argument for reactive power compensation and avoiding long transfers of reactive power.

II.3 Producers and consumers of reactive power

Loads are typically inductive as they contain many electrical machines with their coils. This means that voltage (on per-unit basis[4]) is lower at the distribution level than transmission one. Figure 1 shows a typical transmission line[5] while Figure 2 shows the single-phase equivalent circuit of a transmission line. Transmission lines can be net inductive or capacitive as the equivalent circuit of a transmission line consists of inductances (due to self-inductances of conductors and mutual inductances between conductors) and capacitances (due to capacitances between conductors and between conductors and earth). Reactive power produced by the line's capacitance C is proportional to the square of line voltage V, which is relatively constant, while reactive power consumed by the line's inductance L is proportional to the square of the current I flowing through it, which depends on the operating conditions. Hence *a transmission line can be net inductive or capacitive depending on the operating conditions*. When the line current is high (i.e. during a day) the line is net inductive as the inductive effect of L prevails causing voltages to drop. When the line current is low (i.e. at night), line inductances consume less reactive power so the lines may be net capacitive causing voltages to rise. Hence system operators often switch off some lines at night to increase the load on the remaining lines so that they consume more inductive reactive power and prevent undesirable voltage rises.

Also the reactance is proportional to the line's length. Under those assumptions Q becomes proportional to the voltage difference $(V_s - V_r)$ and inversely proportional to the line's length.

[3] The average of reactive power flows over a cycle is zero but at any time there is a pulsating flow of power causing heating losses.

[4] Per-unit voltage is equal to the actual voltage divided by the nominal voltage in a given part of the network. As voltage levels in a network vary, per-unit voltage makes it possible to compare directly voltages in different parts of the network. For example 0.9 pu voltage would mean 360 kV in a 400 kV transmission line, but 9.9 kV in 11 kV distribution line.

[5] The line in the photo carries two parallel circuits, one on each side of the tower. Transmission and distribution lines are three-phase (for reasons not discussed here for brevity) hence each circuit consists of three phases. Each phase usually consists of a *bundle* of parallel conductors (two in the line shown in the photo) spaced apart to suppress corona discharge, reduce power loss, and lower the line's inductance. Hence the photo shows two parallel three-phase lines, with each phase consisting of two conductors.

Figure 1 A typical high-voltage transmission line.

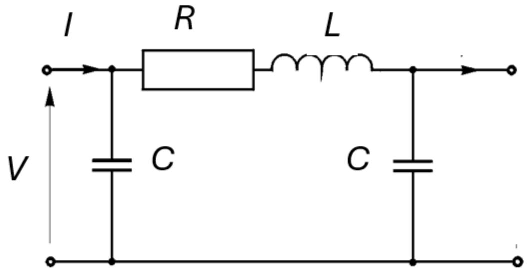

Figure 2 Equivalent circuit of a transmission line. R: resistance, L: inductance, C: capacitance, V: voltage, I: current.

II.4 How to control voltages in a network

Voltages in a grid have to be kept within tight limits, usually less than 10% of their nominal values[6]. In Spain, the upper voltage limit on the 400 kV grid is 435 kV which means that a power plant should not be disconnected by protection when the voltage is below 435 kV. At the 220 kV network, the upper voltage limit is 245 kV. In Portugal the limits are tighter. At the 400 kV level, the upper voltage limit is 420 kV.

Generally, voltage control is achieved by controlling the amount of reactive power in the power system in different parts of the grid. Recall that voltage control is local so the voltage controlling devices have to spread around the grid.

The main means of controlling voltages, and reactive power balance, in power systems are *synchronous generators* in traditional plants – see Figure 3. Depending on the excitation (rotor) current controlled by the Automatic Voltage Regulator (AVR), a generator may produce or

[6] Nominal voltages in a grid vary from hundreds of kV at the transmission level (to limit the heating losses which are proportional to the transmission distance and the square of the current which, in turn, is inversely proportional to the voltage) to tens of kV and lower at the distribution level (as the distances are smaller so the heating losses are less important).

consume reactive power, i.e. may appear as a capacitor or reactor from the network point of view[7]. This means that reactive power, and therefore also voltage, can be controlled smoothly and dynamically by the AVR.

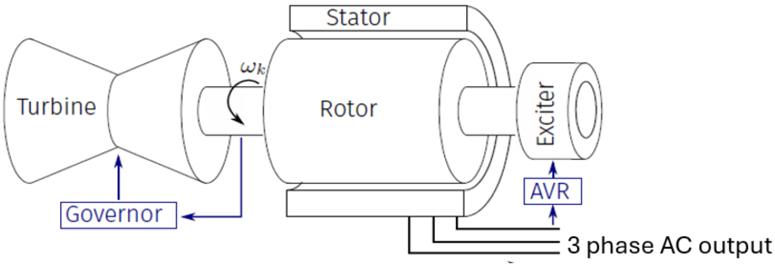

Figure 3 Schematic diagram of a synchronous generator

Reactive power can also be controlled by *static* (i.e. not rotating) *compensators*, i.e. *reactors* (coils) - see Figure 4, *capacitors* (*condensers*) (see Figure 5) and *Static Var Compensators (SVC)***[8]**. SVC consists of reactors and capacitors connected in parallel and switched on and off as required. The main disadvantage of static compensators is that they can change the output only in steps hence a smooth, continuous control of reactive power is not possible. Another type of static compensator is Static Synchronous Compensator (STATCOM) which is a fast-acting power electronic device capable of injecting or absorbing reactive power.

Figure 4 A grid reactor

[7] This explains why a synchronous machine which is freely-rotating (i.e. not connected to a turbine) is called a *synchronous condenser* **(**syncon**)** as it can be used for reactive power compensation. Syncons are nowadays often used also to provide inertia.

[8] Called so as the unit of reactive power is var.

Figure 5 A grid condenser (capacitor).

Additional means of voltage control are tap-changing transformers connecting transmission and distribution networks – see Figure 6. When voltage at the distribution (secondary) level is say too low, the tap changer moves its arm up changing the transformation ratio hence increasing the secondary voltage. Tap changers are mechanical devices which means that they are slow and cannot be used too often to prevent wear and tear.

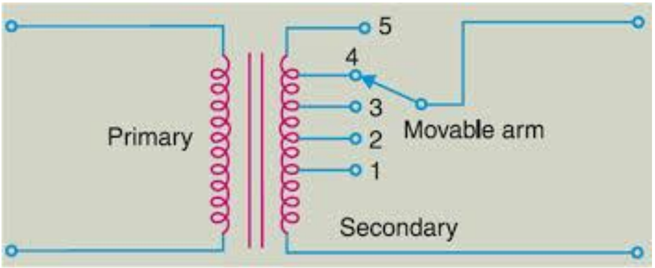

Figure 6 Schematic of a tap-changing transformer

Solar PV and wind plants produce DC electricity[9] and therefore have to be connected to the AC grid using power electronic devices called *inverters (*or *converters)*[10]. Inverters themselves can produce or absorb reactive power so they can be utilised for voltage control[11]. Hence many power systems with high penetration of VRE, such as e.g. Great Britain (GB) or Portugal, utilise VRE for voltage control but, crucially, not Spain which was one of the major contributing factors

[9] Strictly speaking wind turbines produce AC electricity, rather than DC, but it is usually passed through converters for better controllability and to allow wind turbine speed to vary.

[10] Hence wind and solar PV plants are often referred to as Inverter Based Resources (IBR). The term IBR also include other DC devices that require to be connected by inverters to the grid such electric vehicles, data centres, HVDC converter stations, STATCOM etc.

[11] If a wind of solar PV plant operates at its maximum real power output, reactive power cannot be provided as it would overload inverter circuits (recall that the flow of reactive power causes heating losses). However most of VRE plants usually operate below their maximum output, as wind or sun radiation are rarely at maximum, leaving some headroom for reactive power.

to the blackout. In Spain, VRE were asked to operate at a *constant power factor*, i.e. with reactive power output (usually inductive) as a function of the real power output.

The Iberian blackout was the first major blackout which was caused by overvoltage. Usually voltage stability is analysed from the point of view of undervoltage which tended to be seen as the main danger to system security. For example VRE plants are required to follow *Fault Ride Through (FRT)* characteristics which ensure that they remain connected for certain time to the grid when voltages drop suddenly due to faults (short-circuits). Problems with overvoltages did not attract a similar research attention so far as undervoltage. This is likely to change following the Iberian blackout.

II.5 Electromechanical oscillations

Oscillations are a routine occurrence in power systems and are usually caused by an event, e.g., disconnection of a line or tripping of a large power station. They may also occur spontaneously, i.e., without any apparent reason, under certain grid conditions, especially when there are high power transfers over weak network connections. They are referred to as *electromechanical oscillations* as they are caused by rotors of synchronous machines swinging against each other in a spring-like manner causing their speeds to oscillate slightly around the synchronous speed (50 Hz in Europe). The speed and frequency oscillations may cause large power transfer oscillations due to large masses of generators involved so they have to be quickly damped.

A useful mechanical analogy of electromechanical oscillations is shown in Figure 7. In the steady-state, the generator rotors (represented by the balls) rotate at the same synchronous speed (corresponding to 50 Hz in Europe) so they are stationary with respect to each other. After a disturbance, such as e.g. a generator trip (represented by cutting a string connecting one of the balls), the remaining balls start to bounce up and down corresponding to generator rotors oscillating against each other. This means that the rotor speeds (and therefore local grid frequencies) oscillate around the synchronous speed.

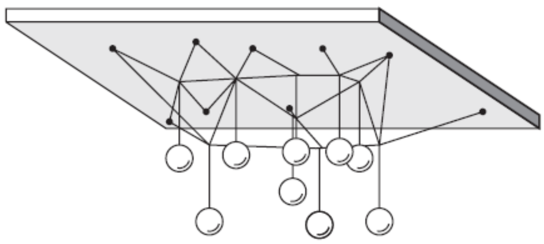

Figure 7 A mechanical analogue of swings in a multimachine system. The balls represent rotors of synchronous generators while the elastic strings linking them represent electromagnetic forces acting on the generators.

There are several well-known modes of oscillation in Europe, see Figure 8, whereby rotors of synchronous machines in a country, or a group of countries, start to swing spontaneously against another group – they are referred to as inter-area oscillations. Hence many synchronous generators at strategic locations are equipped with *power system stabilisers* (PSS) which are additional controls increasing damping of power swings. Similarly HVDC converter stations are equipped with *power oscillation dampers* (PODs). Post-mortem analysis showed that PSS on some of large units in Spain were missing and insufficient actions was undertaken by the existing ones.

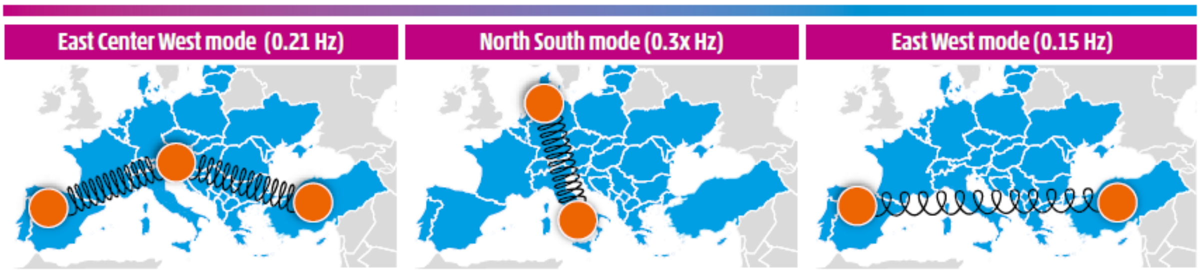

Figure 8 Modes of electromechanical inter-area oscillations in Europe.

The mechanism of inter-area oscillations is well-known, and System Operators know how to deal with them. The measures include reducing inter-area power flows, strengthening the network by re-connecting previously disconnected transmission lines and increasing the network voltage.

II.6 Subsynchronous oscillations (SSO)

Over the last 10 years or so a new type of oscillations, dubbed *Sub Synchronous Oscillations* (SSOs), has been observed in many grids with a high penetration of IBRs. Inverters are programmable devices and they have a high number of control loops ensuring their required behaviour. A behaviour of a grid with a high penetration of interacting IBRs is still not well understood and sometimes the controllers of inverters may misbehave causing SSO for no apparent reasons. Figure 9 shows an example of spontaneous SSO appearing and disappearing for no apparent reasons in 2021 in Northern Scotland which is dominated by wind farms with few traditional plants. The problem of SSO is the subject of intensive research as the IBR technology is relatively new. Note that the means of dealing with inter-area oscillations, described in the previous section, may not be effective in damping SSOs as their mechanism is completely different.

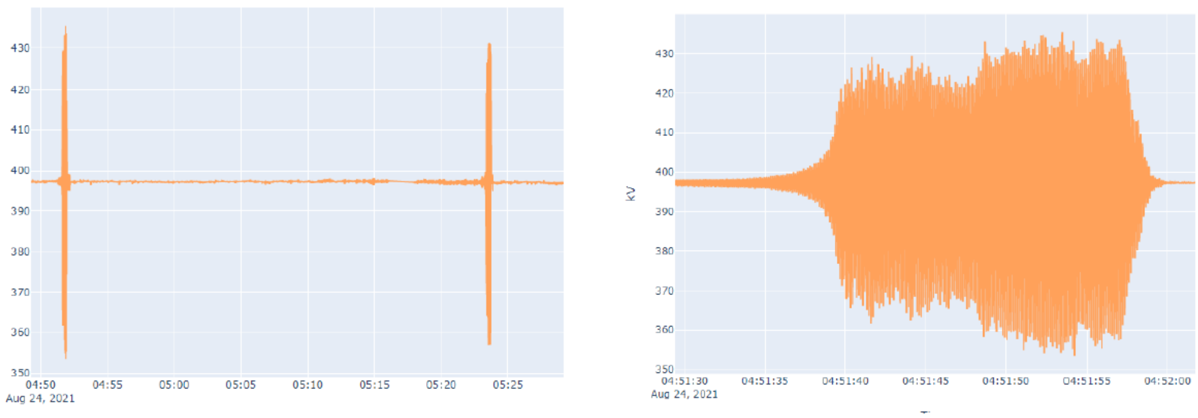

Figure 9 Voltage oscillations in Scotland in 2021.

III. Description of events

The description of how the blackout proceeded is based on the information provided by the Spanish Transmission System Operator Red Electrica de Espana (REE) [1], Spanish government report [2] and two reports by ENTSOE [3,4]. There are few publications analysing the blackout as the authoritative ENTSOE report [4] has been published only recently. [5] discusses lessons for modern power systems and policy implications while [6] presents technical analysis of voltage stability.

The day of the incident was a typical spring day in Spain, with mild temperatures and mostly sunny weather. The system's solar generation was similar to previous days, while wind generation was more variable but within the ranges observed in previous days. About 70% of generation in Spain was produced by wind and solar PV located mainly in south-west of the country, see Figure 10 and Figure 11, with exports to France, Portugal and Marocco. One of the main well-known possible problems in systems with high VRE penetration is low inertia[12], but in Spain inertia was adequate and played no role in the blackout. Voltages were within the limits. However only 10 traditional power stations provided voltage support, which was fewer than normal due to fire in one of the plants. An additional plant was instructed to connect but did not manage to do so in time before the blackout. Importantly, few traditional plants providing dynamic voltage support were located in the south-west of the country, where majority of VRE were installed. This was potentially a problem as voltage support is local in character meaning that reactive power has to be compensated locally – it cannot be sent over long distances.

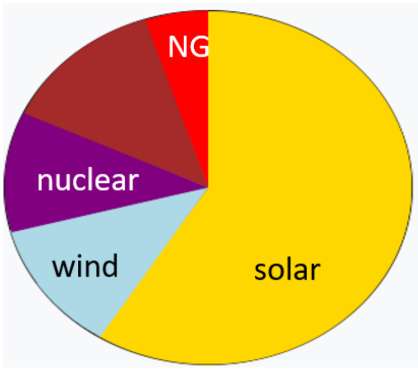

Figure 10 Generation in Spain before the blackout. NG means natural gas.

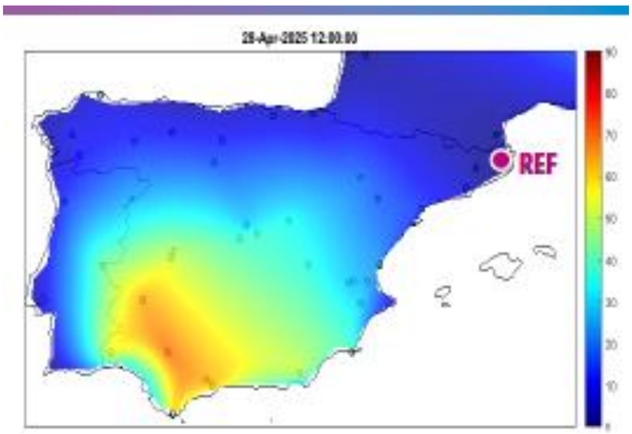

Figure 11 Heatmap of angular displacement at 12:00. Power flows from red coloured areas to blue-coloured ones.

III.1 Oscillations

The grid started to experience two periods of voltage, frequency and power oscillations about ½ hour before the blackout. Although the oscillations did not directly cause the blackout, they were a significant contributing factor.

The first period of oscillations in Iberia of frequency 0.63 Hz started at 12:03 and lasted about 5 minutes – see Figure 12. It was a local Iberian oscillation and did not propagate to the rest of

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[12] Inertia, which is provided by synchronous generators in traditional plants, helps maintain frequency stability of a power system, i.e. when there is a sudden trip of a large plant disturbing the power balance. VRE provide little inertia.

Europe. Subsequent analysis revealed that it was a forced mode of oscillations (i.e. SSO) caused by controls of a VRE plant (not named in the reports).

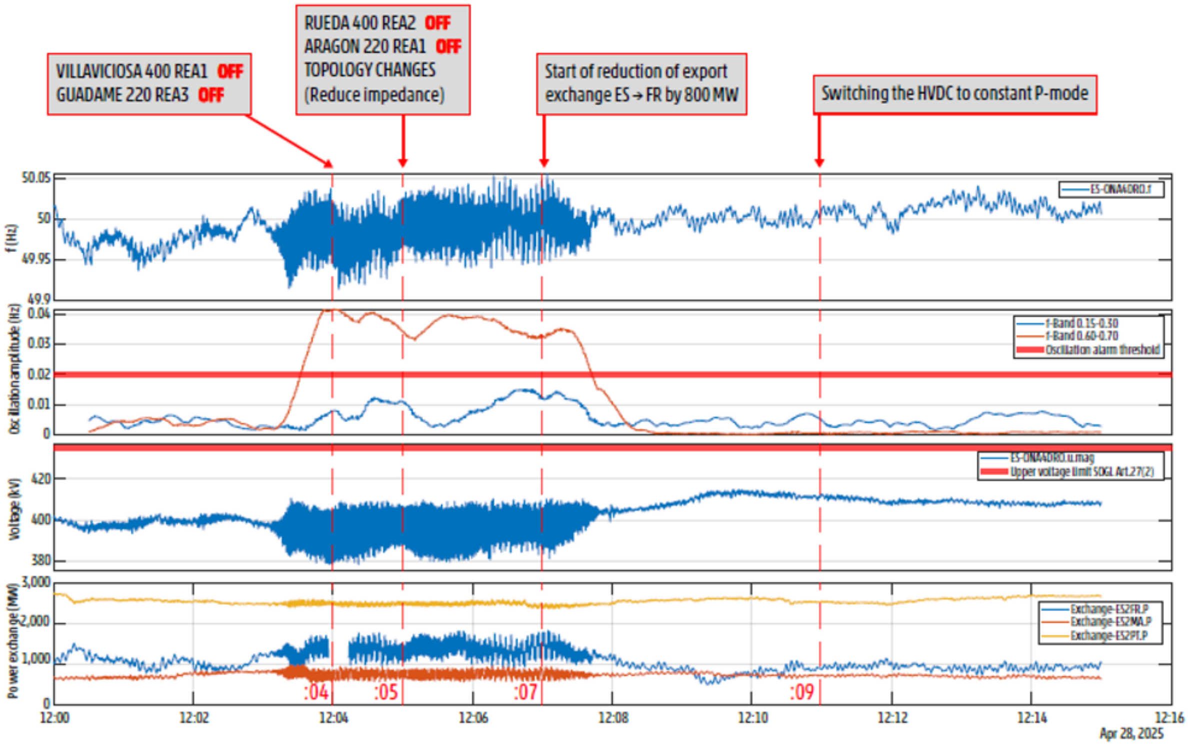

Figure 12 First period of oscillations showing also countermeasures applied.

The second period of oscillations of frequency 0.21 Hz started at 12:19 and lasted about 3 minutes – see Figure 13. This mode of oscillations was a well-known East-West inter-area mode whereby generators in Iberia swing against Eastern Europe (Baltics, Hungary, Poland, and Turkey), see Figure 14.

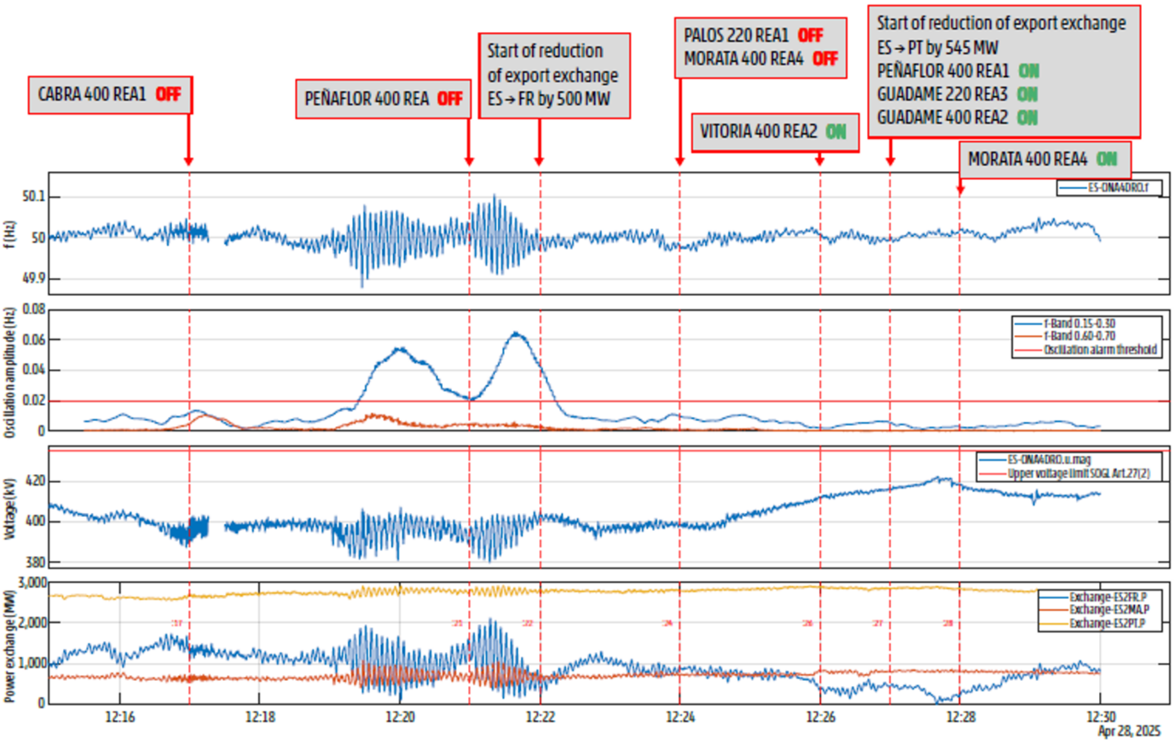

Figure 13 Second period of oscillations showing countermeasures applied.

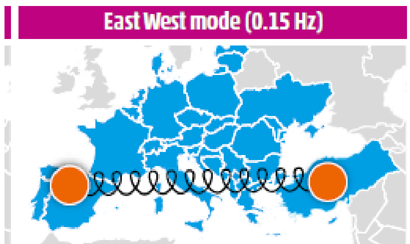

Figure 14 East-West model of oscillations.

To deal with the oscillations the Spanish System Operator, Red Eléctrica de España (REE), undertook the following actions (indicated in Figure 12 and Figure 13):

- 10 previously disconnected transmission lines have been reconnected to strengthen the network. This had a side-effect of reducing flows on other lines, as some of their load was carried now by the newly connected lines. This reduced their inductive effect, as discussed previously, and therefore caused increase in system voltages.
- Exports to France were reduced by reducing output of some of the southern plants. This had again a side-effect of reducing power flows across Spain and therefore increasing voltages as the inductive effect of lines was less.
- Some reactors have been disconnected to increase the voltages and improve damping of oscillations.
- The mode of operation of HVDC link to France was changed from AC emulation to constant power[13]. This means that power was still exported even after generation trips in Spain

[13] HVDC connection separates systems from frequency control point of view. Hence sometimes HVDC converters are programmed to behave as if they were AC lines hence allowing countries to help each other with frequency control.

started causing power deficit. Changing the mode of operation did not have a direct effect on the voltages.

III.2 Generation trips

The measures undertaken to damp oscillations caused a significant increase in system voltages and led to plants, mainly VRE, tripping on overvoltage as described in the rest of this section. This caused a vicious circle: tripping of a plant causes a reduction of power flows and therefore reduction of the inductive effect of transmission lines and an increase in voltage. Additionally, as those plants operated at a constant inductive power factor, their tripping removed reactive power absorbed by the plants. This led to further increase in voltage and subsequent trips.

Figure 15 shows the cumulative power imbalance (the sum of generation lost and demand increase) and the voltage at one of the transmission substations within the 12:32:00-12:33:18 time frame. Before the trips started, there were no oscillations and transmission voltages were within the limits.

First stage: 12:32:00-12:32:57

The first stage started with the power output of large VRE plants (higher than 5 MW) in Spain decreasing by approximately 500 MW between 12:32:00 and 12:32:48. Between 12:32:00 and 12:32:57, 208 MW of distributed wind and solar generating units in northern and southern Spain tripped 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 distribution-connected generators < 1 MW (mainly rooftop PV) and partly to an increase in voltage-dependent loads as a result of a voltage rise. The exact reasons for some of these events are not known.

Second stage: 12:32:57-12:33:17

From around 12:32:20, a particularly steep rise in local voltage occurred at a substation in the area of Granada. This initiated the second stage starting at 12:32:57 when a 400/220 kV transformer in that substation tripped due to the activation of an overvoltage protection disconnecting several PV, wind and thermo-solar plants, resulting in the loss of 355 MW, and an additional step change in voltage.

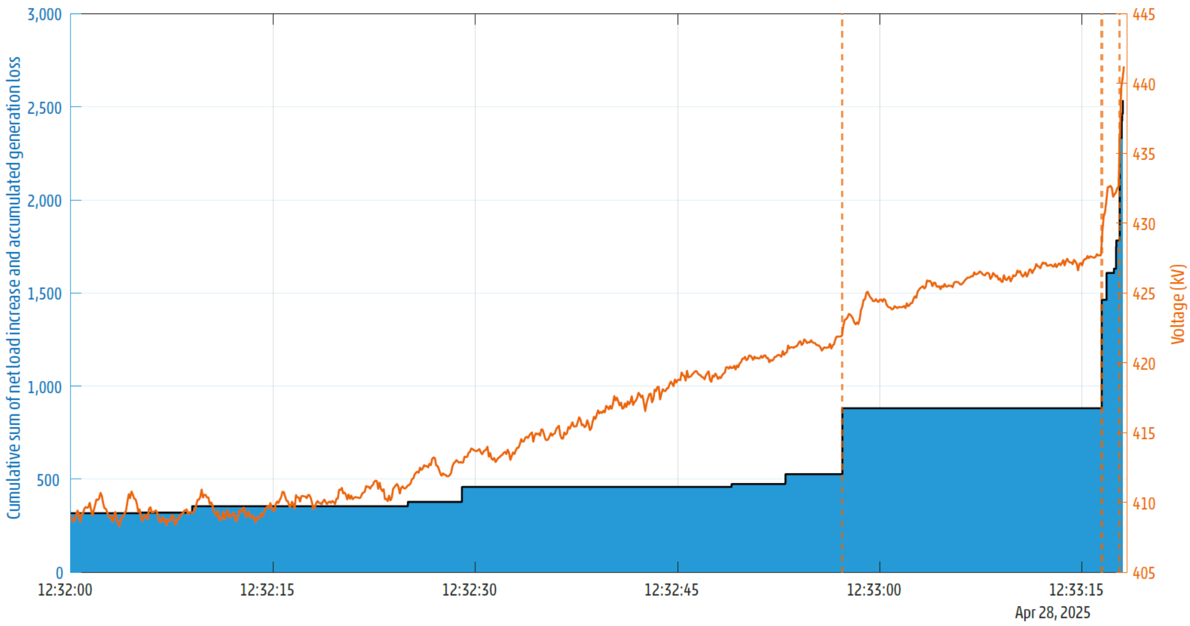

Figure 15 Cumulative power lost and load increase (in blue) and voltage (in orange) between 12:32:00-12:33:18 in the Iberian peninsula. The first three stages are shown by the vertical dotted lines.

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 which tripped on overvoltage.

Third stage: 12:33:17-12:33:18

The third stage lasted just one second when several trips occurred leading to the disconnection of wind and solar generation of 928 MW. Some of these trips occurred due to overvoltage protection, but the ENTSOE Expert Panel was not able to establish the cause of most of these trips. The post-mortem analysis indicated that the overvoltage protection settings at some generation units were set below the voltage limits established in accordance with the applicable requirements.

Note that transmission voltages until 12:33:18 in Spain were lower than the allowed maximum of 435 kV, yet power plants were tripping. No generation trips were observed in Portugal or France within the 12:32:00 – 12:33:18 timeframe.

The final phase of the blackout: 12: 33:18-12:33:24

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 - see Figure 16. Between 12:33:19 and 12:33:22, the automatic load shedding[14] of Spain and Portugal was activated, but was unable to prevent the collapse of the Iberian power system as the core reason was overvoltage rather than deficit of generation. Load shedding actually made the overvoltage worse as the reactive power-absorbing loads were disconnected and line loadings also decreased hence further increasing voltages. However the subsequent investigation revealed that blocking load shedding would not have prevented the blackout.

At 12:33:20.473, the AC interconnection to Morocco tripped due to underfrequency in Spain. 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 Europe.

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). The total blackout occurred less than 1.5 minutes after the first trips.

[14] Load shedding, technically referred to as Low-Frequency Demand Disconnection (LFDD), is a system defence action that, when frequency drops below certain level indicating a severe power imbalance, automatically disconnects some parts of distribution networks with their loads to reduce system load and improve power balance.

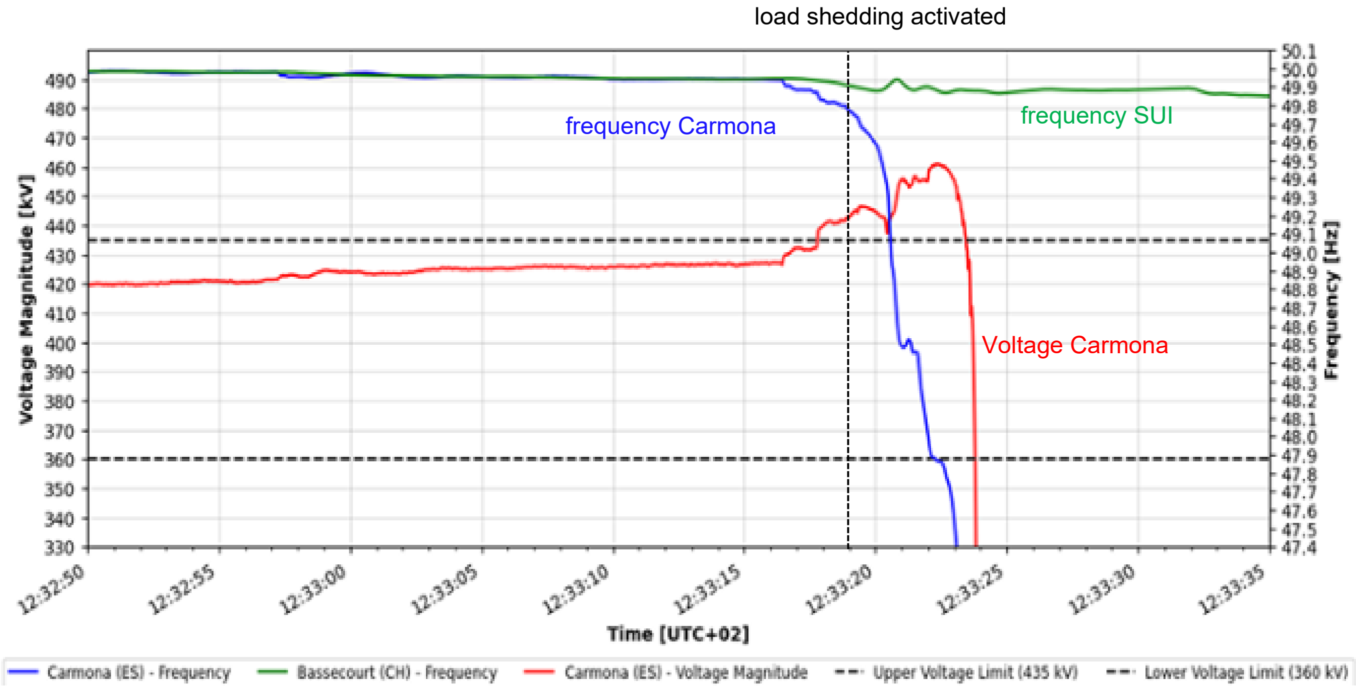

Figure 16 Frequency in Spain (blue), frequency Europe (green), voltage at Carmona substation in Span (red). Dashed horizontal lines show the upper and lower voltage limits at 400 kV networks in Spain.

Restoration of supplies was relatively quick. The Spanish system was fully restored within 16 hours, while the Portuguese system was back online within 12 hours after the blackout, with many parts regaining power much quicker, see Figure 17.

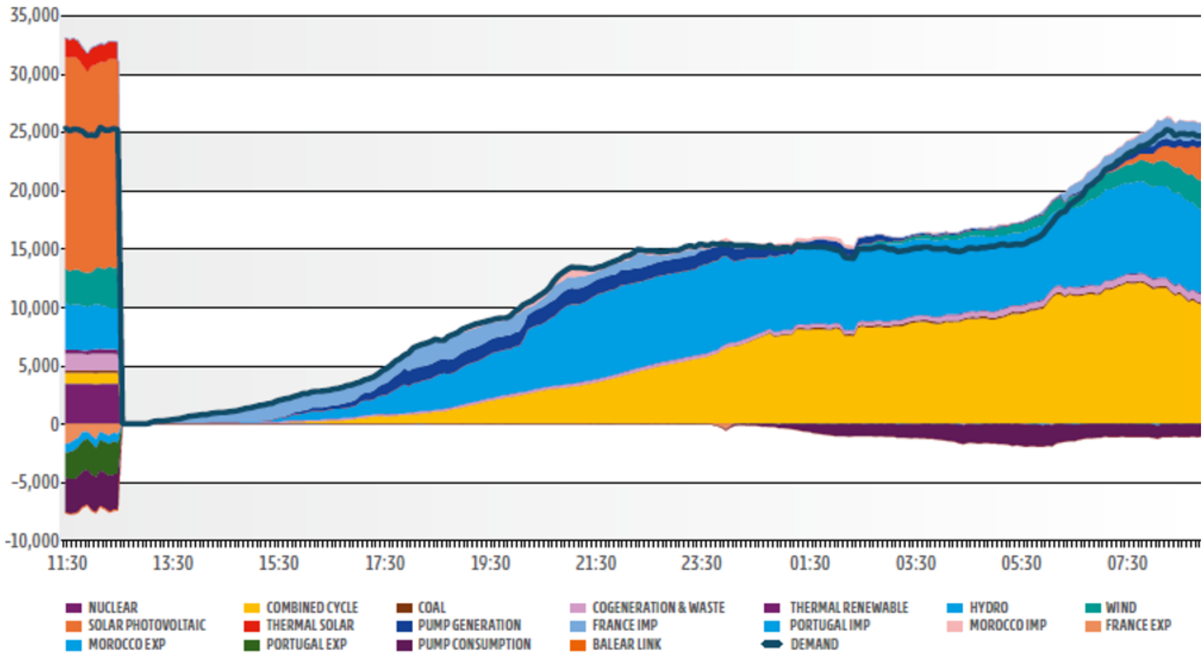

Figure 17 Evolution of load and generation in the Spanish system during restoration.

IV. Why voltage control was slow and ineffective

An obvious question arises why the Spanish System Operator, REE, was unable to contain the fast rise in voltages. The main reasons were [4]:

- REE had only 10 conventional plants under control for dynamic voltage control which was lower than usual due to fire at one of the plants. The replacement plant did not manage to connect before the blackout.
- Traditional plants with their synchronous machines are the main means of controlling voltage in a network, but a number of plants did not control voltage as effectively as planned. They delivered only less than 75% of reactive power absorption demanded, see Figure 18. One of the reasons for this non-compliance was that there were no penalties for non-delivery of reactive power in Spain.
- As mentioned earlier, VRE plants in Spain operate at a constant power factor so could not provide a flexible voltage support. In Portugal, VRE plants with output higher than 1 MW contribute to voltage control. Hence Portugal did not experience voltage problems but was brought down by Spain.
- Shunt reactors are manually operated in Spain so they could not be quickly reconnected. Note that in France about half of reactors can be automatically connected if voltage rises quickly.
- Design of voltage control of local generation networks (behind the connection point) was poor and not aligned with system needs. Hence they did not help with voltage control.
- Many overvoltage disconnection protection settings diverged from applicable requirements or were not aligned with system needs. Hence the plants tripped when they should not have had.
- Spanish 400 kV grid is operated at a wider voltage range than in other EU countries, enabled by specific provisions applicable to Spain. This means that voltage control in Spain is less tight than in Europe.
- Tap-changing transformers operate with dead-zones and delays to avoid unnecessary operation so they could not react quickly to voltages increasing quickly

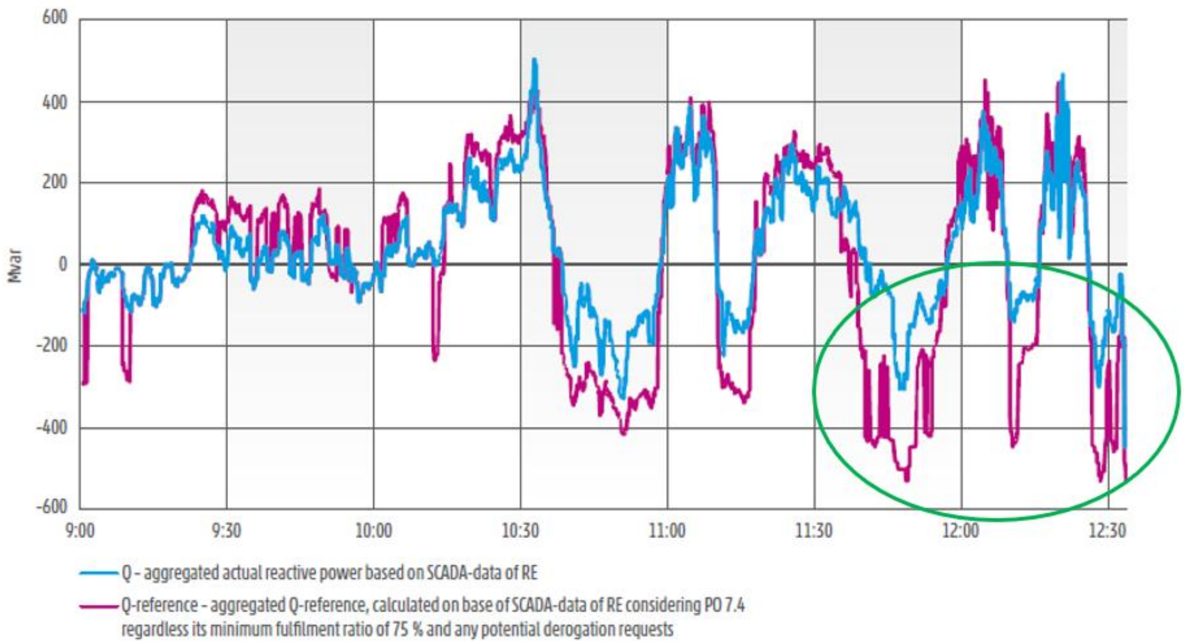

Figure 18 Reactive power provided (blue) and requested (red) in the centre and south-west of Spain. Green oval shows the period preceding blackout. Negative reactive power (i.e. consumption) lowers the voltage.

Due to the perceived shortcomings in voltage control, in April 2026 National Markets and Competition Commission (CNMC) opened a probe into REE and power companies [7]. The CNMC has identified various indications of non-compliance that may have affected the operation of the electricity system and could constitute administrative offences. CNMC was probing REE over “very serious” alleged breaches of Spain’s electricity law, pointing to sections on the scheduling of power generation, the balancing of the grid system, information sharing and the issuance of instructions to power suppliers. The CNMC opened five probes apiece into the big power generation companies, saying it had found indications of “serious” breaches of the law. At the time of writing, the results of the probes are not known yet.

V. The underlying institutional reasons for the blackout

While the direct reasons for the blackout were inadequate voltage control arrangements in Spain, the underlying institutional reason are much deeper. Spain has some of the most ambitious renewable energy targets in Europe so, in order to achieve them, the country has concentrated in recent years on increasing the share of VRE but, in the author’s view, seems to have paid less attention to adapting power system operation and control to the new conditions. Hence one cannot claim that the VRE per se caused the blackout. Rather it was the result of inadequate adjustment of power system control to a high penetration of VRE. One cannot run a system with a high penetration of VRE the same way as a conventional system. Most relevantly to the blackout, Spain did not take advantage of voltage-control abilities of IBRs, despite obvious benefits of that. Many other countries with a high penetration of VRE, e.g. GB, Ireland and Portugal, seem to have done a much better job in that respect - see for example [9]. Portugal was facing similar conditions as Spain but did not experience voltage problems until it was brought down by Spain.

After the blackout, REE warned about voltage instability linked to renewables and urged technical changes. In October 2025, the system operator began implementing the framework and authorising renewable plants to provide voltage control. By 2026, additional rules were adopted to further strengthen voltage control and grid stability [10].

VI. Are future similar blackouts inevitable?

Does it all mean that the Iberian blackout was a particular Spanish mishap and the rest of the world can sleep in peace? Unfortunately it does not seem to be the case. Fast replacement (in many parts of the world) of gas/coal power stations, which operate with synchronous machines, by IBRs changes fundamental characteristics of the system. They are no longer determined by the physics of synchronous machines (and physics never fails) but by software of inverters (which may cause unexpected and potentially harmful effects). While we understand well how individual inverters and their controls work, the system effects of connecting in parallel thousands or more of IBRs in a power system are still not well-understood. Sub synchronous oscillations (SSOs), of the type of the first pre-blackout oscillation in Iberia, is just one example of poorly understood phenomena, but there are more.

Note that it took about 100 years, from the end of the 19th Century, for traditional power systems to mature. Power systems did change during that period but the changes were slow so there was time to adapt. But now the pace of change is much faster. As an example, there was a consensus among power engineers around 2010 that the maximum penetration of VRE in power systems cannot exceed about 20-25% without causing serious problems. 15 years later that limit in e.g. Irish power system is 80%. System operation, control and planning has to be quickly adapted to the changed system profiles and characteristics. We must make quickly progress equivalent of the previous 100 years of progress in understanding power systems as more and more IBRs are commissioned. A significant research effort is needed as there are many problems, apart from SSO, which we simply do not know how the solve and also there are possibly many problems we do not know about yet –so-called “unknown unknowns”. The necessary research must be multi-disciplinary as it requires close cooperation between power system engineers, power electronics experts (to deal with the design of inverters), control theory experts (to design control systems of inverters), data scientists (as many problems are difficult to solve analytically) and economists (as new services need to be designed). It requires a combined effort of the industry and academia to overcome the challenges. An example of such efforts is the Power System Transformation Consortium which has published in 2025 a modified Research Agenda [8] with 48 IBR-related research questions which require urgent answers. It should be emphasised that the problems are not unsurmountable, they just require a significant research effort to solve. In most cases, no hardware investment is needed – just research. As we do not know yet the answers to many of the questions, do not be surprised if you hear about another blackout soon.

VII. Conclusions

The direct cause of the Iberian blackout was an unexpected interaction between oscillations and voltage stability compounded by inadequate voltage control arrangements in Spain. Actions taken to damp oscillations had a side effect of increasing suddenly the voltages in the Spanish network which caused some plants to trip. This caused a vicious circle: tripping of plants caused voltages to rise even more due to reduced line loading and lost reactive power consumption, which finally led to the full blackout.

However the underlying causes were much deeper and institutional in nature. Spain has concentrated in recent years on increasing the share of VRE but seems to have paid less attention to adapting power system operation and control to the changing needs. One cannot run a system with a high penetration of VRE the same way as a conventional system.

Power systems are changing quickly with rapidly increasing share of VRE in many parts of the world. This causes a profound change in the way power systems behave which we do not yet fully understand. Hence a significant interdisciplinary and combined research effort of the industry and academia is required to overcome the challenges and prevent future blackouts.

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