INESC TEC

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Retrospective and Lessons from a blackout

Position Paper

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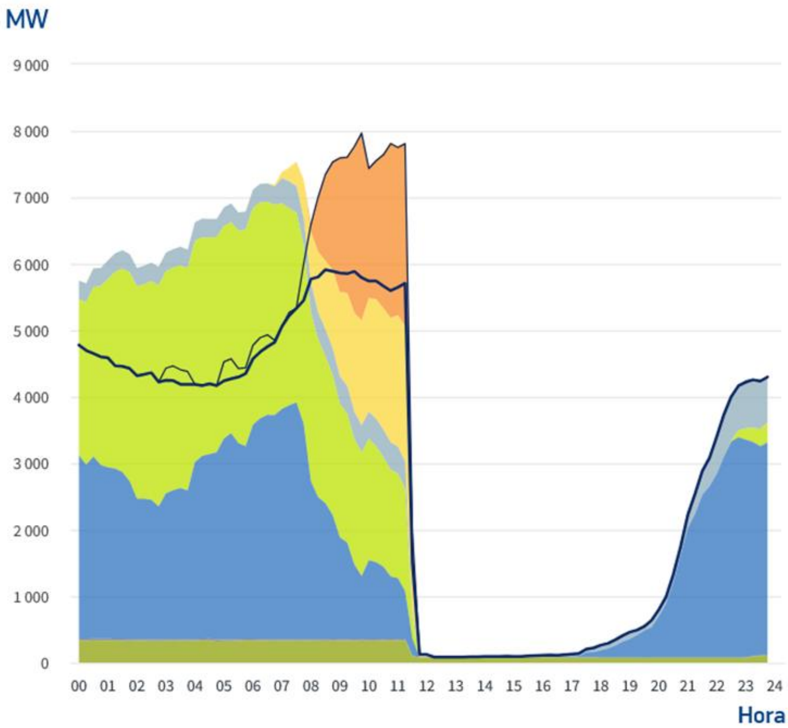
Monday, April 28, 11:33 a.m. (Portugal time).

The Spanish power system had a total load of nearly 33 GW, exporting electricity to Portugal, France, and Morocco, mostly powered by 23 GW of solar PV and around 3 GW of wind generation. Synchronous generation was limited to approximately 3.5 GW from nuclear, 1.5 GW from combined cycle gas units, 1 GW from biomass, and 1 GW from solar thermal plants. There was virtually no hydro generation.

In Portugal, the system had a load of 5,800 MW, plus over 2,100 MW for pumping (see figure), and was importing more than 2,500 MW from Spain, taking advantage of favourable solar PV generation prices. Most of this imported power was used for reversible hydro pumping storage. Synchronous generation was also low: about 185 MW from run-of-river hydro, 270 MW from combined cycle gas, 90 MW from biomass, and 20 MW from cogeneration.



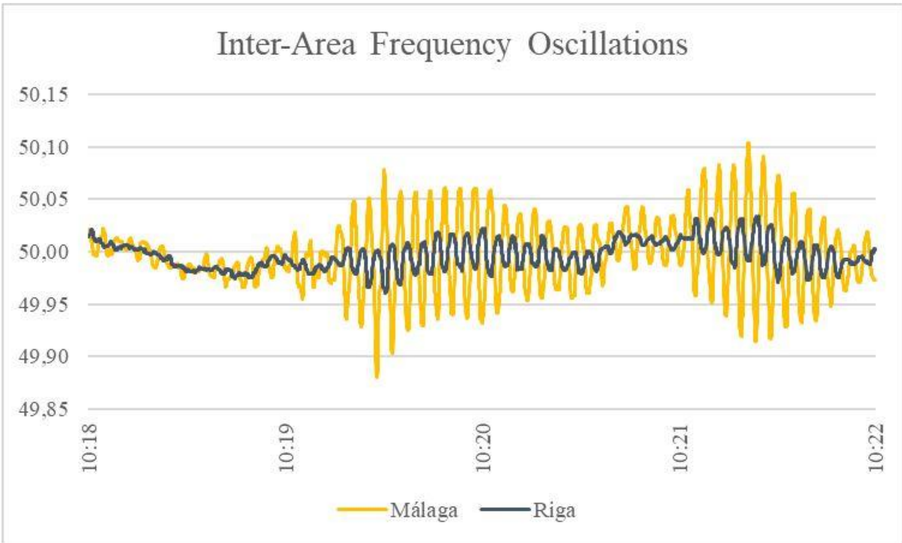
Source: REN

The electric grid must continuously balance supply and demand, monitored through frequency, a key parameter measured in Hertz (Hz). In Europe, this nominal frequency is 50 Hz. If consumption exceeds production, frequency drops; if production exceeds consumption, frequency rises. This frequency deviation is a critical indicator for grid operators.

Frequency Oscillations and Evolution

At around 11:20 a.m. that day, anomalous frequency fluctuations were detected in the Iberian electricity grid by Phasor Measurement Units (PMUs), devices used to precisely measure the amplitude and phase angle of voltage and current in electrical systems. These PMUs, installed in Málaga and Porto (INESC TEC), were found to be out of phase with the frequency oscillations recorded by the PMU in Riga, with the oscillations being poorly damped. These oscillations in frequency, between 0.7 Hz and 0.2 Hz, remained in the system until the occurrence of the main incident, although with a smaller amplitude.

The following figure shows the evolution of frequencies in Málaga and Riga, as recorded by [Grid Radar].

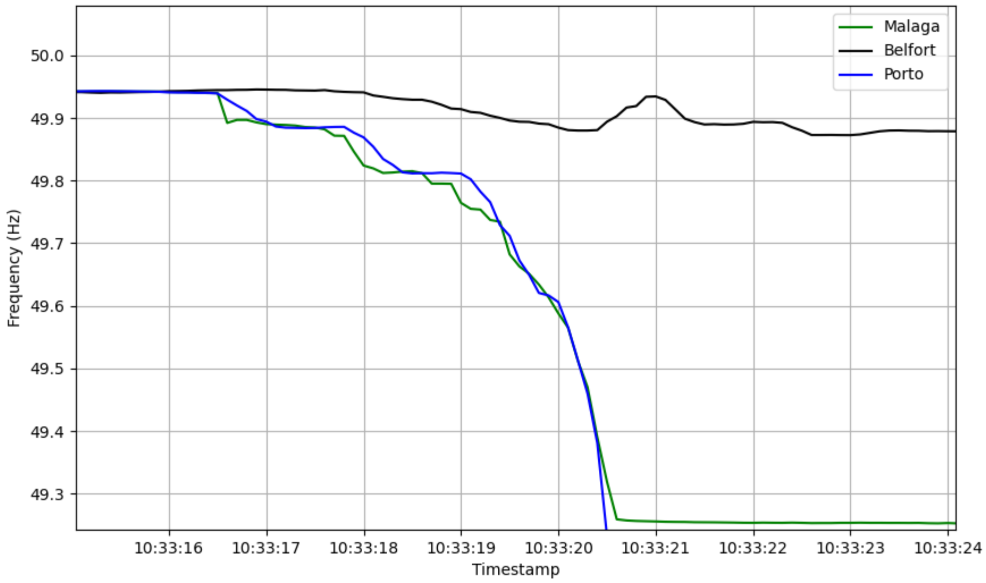


Source: Grid Radar

At 12:33:16, the first generation loss occurred in southeastern Spain, followed by a second loss at 12:33:18. This constituted an n-2 generation contingency, an extremely rare event. Following this, the frequency began to drop significantly from 12:33:18, and several photovoltaic generation plants automatically disconnected from the grid according to their protection protocols, to safeguard their equipment.

In the first five seconds, approximately 15 GW of generation capacity was lost in Spain. The frequency of the Iberian system took a dramatic plunge, leading to the shutdown of all remaining generation units in both Portugal and Spain. The rate of frequency change in Portugal exceeded 1.5 Hz per second, highlighting the speed at which the system was loosing stability.

Protection systems responded as designed, resulting in further generation loss and the disconnection of the interconnection with France. The nine-second temporal evolution of frequency in various European system nodes (Porto, Málaga, and Belfort) is shown in the following figure.



Source: x-Energy lab (INESC TEC) + Grid Radar

Given the massive generation shortfall in the Iberian system, the system frequency dropped rapidly, triggering emergency control measures via frequency-based load shedding. Loads were disconnected in the following order: pumping stations, interruptible consumer loads participating in frequency control, and some non-priority loads on distribution networks. However, the production shortfall was so large that the frequency continued to fall, and all remaining generation units were progressively disconnected by their frequency protection systems, which are designed to preserve equipment integrity. This resulted in a total system collapse.

The operational response to the disturbance included the activation of primary frequency control and the mobilisation of secondary and tertiary reserves in the early moments of the event.

Service Restoration

Following the blackout, black-start procedures were implemented. In Portugal, black-start capable plants (Castelo de Bode and Tapada do Outeiro) were activated, creating electrical islands around them and gradually reconnecting small loads step by step (initially around 5 MW, then 10 MW and 30 MW). This process naturally took time, as reconnecting too quickly could cause large frequency and voltage fluctuations, potentially leading to new system collapses, which indeed did occur.

By 10:00 p.m., REE had restored 43.3% of demand and re-energised 421 out of 680 substations (62%), with supply exceeding 90% by early Tuesday morning. In Portugal, REN had restored power to 85 out of its 89 substations and switching stations by the same time, with only Trafaria, Divor, Estremoz, and Portimão still without electricity. At that point, around 2.5 million Portuguese consumers had power again, the interconnection with the European grid had been re-established, and by the end of the night, nearly all consumption in Portugal had been restored. Despite everything, service restoration in Portugal went well and was carried out with high proficiency, thanks to excellent coordination between transmission and distribution network operators.

Incident Analysis

As with all blackouts, it is important to understand what happened—particularly what triggered the generator shutdowns in Spain that led to the described sequence of events. Post-mortem analysis of the time-based records of different protection activations, and the time evolution of voltages and frequencies, will help clarify the incident. Additional studies may also be required to simulate pre-disturbance operating conditions and determine the root cause of the event.

Although the exact causes remain under investigation, past evaluations of similar events suggest three potential contributing factors: the sudden generation loss (n-2 contingency), low system inertia due to high renewable penetration (which makes system frequency more sensitive to imbalances), and issues with voltage excursions and their control.

The frequency oscillations observed between areas in the Iberian system and the Baltic countries are associated with a problem known in the literature as "small-signal stability." This refers to power oscillations that induce significant frequency and voltage fluctuations. In weak systems with low short-circuit power, even small angle disturbances can cause considerable voltage oscillations.

These oscillations, also known as Low Frequency Oscillations (LFOs), are typically in the range between 0.1 and 2.0 Hz, involving groups of synchronous machines in different regions oscillating against each other. They result from electromechanical interactions between the rotating masses of synchronous generators, excitation systems, power system stabilisers (PSS), and the controllers of power electronic converters. If not properly damped, such oscillations can damage equipment, lead to generator disconnections, and—at worst—trigger cascading failures that result in total power loss. It is therefore plausible that phenomena of this nature contributed to the blackout.

Instability related to the behaviour of power electronic converters in wind and solar PV generators, which can oscillate among themselves, should also not be ruled out.

It is important to note that this incident was not the first major stability event in the Iberian grid. On 24 July 2021, the Iberian Peninsula (Portugal and Spain) was separated from the rest of the continental European power system due to a cascading series of events initiated by a wildfire in Moux, southern France. This fire caused failures on the Baixas-Gaudière transmission lines, overloading the remaining interconnections between France and Spain, leading to system separation. The peninsula experienced a significant frequency drop (down to 48.65 Hz), which triggered frequency-based load shedding of pumping and other loads, as well as some distributed renewable generation. On that occasion, a blackout was avoided. The frequency degradation rate during that event was slower—0.7 Hz/s.

Lessons Learned

From this entire process, important conclusions must be drawn about how to operate a system with such a high proportion of electricity generated through power electronic converters, commonly referred to as "grid-following" in Anglo-Saxon terminology (around 80% in Spain).

Several European transmission system operators, including REE, have been installing systems known as Wide Area Monitoring (WAM), which use PMUs to monitor system stability conditions and detect disturbances like those seen on 28 April, generating alerts for system operators. The widespread deployment of these devices is essential for today's power systems, allowing for detailed event analysis and definition of corrective actions.

These systems are evolving to support real-time operations by integrating protection and control functions, forming WAMPAC (Wide Area Monitoring, Protection, and Control) systems. These combine monitoring with automatic control actions, such as generator dispatch or disconnecting interconnection lines (e.g., between France and Spain), helping to preserve system integrity and prevent cascading failures. Such systems will simplify the analysis, detection, and mitigation of complex events using observable stability characteristics, without needing to predefine combinations or sequences of events.

System operators should therefore deploy dynamic security monitoring tools to detect critical operating conditions and identify timely preventive and corrective control procedures. Using simulation and machine learning during the system's operational planning phase (e.g., day-ahead), operators can define corrective actions for severe contingencies.

These tools can function as digital twins of the electrical system, replicating the expected behaviour of the system in response to disturbances. Artificial Intelligence (AI) has often been highlighted as a promising solution to address such events. However, these are characterised by an extremely low probability — and therefore lack sufficient historical records for machine learning — and also unfold on time scales ranging from milliseconds to seconds, which sometimes makes them faster than the inference time of modern AI algorithms and even faster than human reaction time.

Therefore, only by hybridising AI with the physical equations governing power system operation, ensuring interoperability with existing control room tools, and maintaining an appropriate interface with human operators, can AI have a truly positive impact on decision-making.

Ultimately, the software must accelerate simulation capabilities and provide prior impact analysis of events on the grid, supporting operators with virtual assistants. These solutions must account for both internal infrastructure factors (such as inertia levels or asset ageing) and external threats, including extreme weather and cyberattacks. Such events often propagate across time and space, not always affecting geographically close areas.

It is also important to adopt probabilistic rather than deterministic methodologies, capable of quantifying the likelihood and impact of specific events, thereby enabling risk quantification and assessing the effectiveness of preventive actions.

Most importantly, the need to install and fine-tune stabilisation systems (PSS – Power System Stabilisers) or recalibrate existing ones must be assessed. These can be linked to synchronous machines, FACTS devices, or power electronic converters operating in grid-forming mode. Grid-forming converters are central to future stable system operation, as they emulate synchronous machine behaviour and participate in voltage and frequency control. They may be combined with batteries and should be strategically placed and robustly sized in the transmission grid to ensure effectiveness under various operating configurations and stability challenges (transient, frequency, voltage, small-signal, and converter-related stability). Grid-forming converters can also help mitigate the system's declining synchronous inertia by providing synthetic inertia.

It is essential that future ancillary services markets in Iberia include new services like Frequency Containment Reserves (FCR), in addition to automatic and manual Frequency Restoration Reserves (aFRR and mFRR), which may be provided by energy storage systems. REN announced a pilot project in January for FCR participation from renewable sources. More advanced services like Fast Frequency Response (FFR), delivered by battery-based or even renewable generators' converters, should also be considered, as they provide rapid responses to frequency variations and enhance system stability.

In parallel, the potential use of synchronous machines as synchronous condensers should also be assessed. These act as motor-type loads operating at low power (just enough to cover their losses), supporting voltage control while also supplying synchronous inertia to the grid, helping to manage frequency oscillations.

Adjusting protection system parameters is also crucial to improve network resilience, as recommended by ENTSO-E in the "Limited Frequency Sensitive Mode" (2018) document. This calls for widening frequency operating ranges for generation modules, which should remain connected between 47.5 Hz and 51.5 Hz for at least 30 minutes. Additionally, coordinated frequency response systems should be implemented: overfrequency (LFSM-O, triggered at 50.2 Hz) and underfrequency (LFSM-U, triggered at 49.8 Hz), with response times suited to each technology. These measures aim to avoid unnecessary generation disconnections during severe disturbances, such as system separations, giving operators time to apply corrective measures and maintain stability.

In conclusion, there are technical solutions that allow for the safe operation of power systems with large volumes of renewable generation connected through power electronic converters. The islands of Madeira and the Azores serve as success stories, having integrated high shares of renewable generation and operating their networks with grid-forming converters capable of emulating synthetic inertia and controlling voltage and frequency effectively, thus stabilising transient disturbances swiftly. Lessons from these island systems should be adapted and applied to continental grids.

Critical Infrastructure – Risk Identification and Mitigation

The event of 28 April served as a reminder of the critical importance of the electricity grid in today's society, as well as its role in ensuring the reliability and resilience of other critical infrastructures, such as telecommunications networks and water supply systems.

Decree-Law No. 22/2025, dated 19 March, sets out the procedures for identifying, protecting, and ensuring the resilience of national critical infrastructures. It mandates the definition of resilience plans for each critical infrastructure and establishes penalties for non-compliance. It also outlines the national risk identification procedure and the development of a national resilience strategy.

In the context of the electricity system, critical infrastructures include the transmission and distribution networks, substations, electricity generation facilities, energy storage systems, and aggregators.

Risk identification and the development of security plans are of vital importance. However, it is equally crucial that critical infrastructure operators are provided with a suitable regulatory framework that allows for investment planning incorporating system resilience criteria. This planning must also be integrated, considering the interdependencies between different infrastructures and considering the role of new digital technologies and the flexibility of distributed energy resources (i.e., renewable generation, energy storage systems, and flexible loads) as part of the solution.