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The 2025 Iberian Blackout: Why It Happened and Will There Be Another One?

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The blackout of **28 April 2025** was the largest power-system blackout in Europe since the 2003 Italian blackout, interrupting electricity supplies to approximately **55 million people in Spain, Portugal and parts of France**. Because wind and solar generation accounted for a very large share of Spanish generation at the time, the event immediately raised the question of whether high renewable penetration was itself responsible. The evidence presented in this paper points to a more nuanced conclusion: **renewable generation was not, in itself, the cause of the blackout. Rather, the blackout resulted from the interaction of a number of technical weaknesses in a power system whose operation and control had not been sufficiently adapted to a rapidly changing generation mix**.

The paper starts with a quick tutorial explaining fundamentals of voltage control, reactive power compensation and power system oscillations. Understanding those technical issues is essential for understanding how the blackout progressed.

What happened?

On the day of the blackout, around **70% of Spanish generation was supplied by wind and solar PV**, concentrated largely in the south-west of the country. System inertia, often identified as a major concern in systems with high renewable penetration, was adequate and **played no significant role in this event**. Transmission voltages were initially within their permitted limits. However, only ten conventional power stations were providing dynamic voltage support, fewer than usual, and relatively few of these plants were located close to the major concentration of renewable generation in south-west Spain. This was important because **voltage control is fundamentally local**: reactive power cannot readily be transferred over long distances.

The system then experienced two periods of oscillation. The first, at **0.63 Hz**, began at 12:03 and was subsequently identified as a forced oscillation associated with the controls of a renewable plant. A second, at **0.21 Hz**, began at 12:19 and was a well- known East-West inter-area oscillation. These oscillations did not directly cause the blackout, but they played an important role in the subsequent chain of events.

To damp the oscillations, the Spanish system operator, REE, took several actions, including reconnecting ten transmission lines, reducing exports to France, disconnecting some reactors and changing the operating mode of the France-Spain HVDC link. These measures helped

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address the oscillations but had **an inadvertent side effect: they increased voltages in the Spanish network**. In particular, reconnecting lines and reducing power flows reduced the inductive reactive-power consumption of the transmission network.

The critical cascade

The resulting rise in voltage triggered a sequence of generation trips, predominantly involving renewable plants. This produced a **positive-feedback—or "vicious circle"—mechanism**. When a plant tripped, power flows on the transmission network fell, reducing the network's inductive effect and causing voltage to rise further. Moreover, Spanish renewable plants were generally required to operate at a constant power factor and therefore could not provide flexible reactive-power support. When they disconnected, their reactive-power consumption was also lost, further increasing voltage.

The cascade accelerated rapidly. Between 12:32 and 12:33, about 800 MW of generation, mainly wind and solar, was lost. A 400/220 kV transformer in the Granada area then tripped on overvoltage, disconnecting another 355 MW. This was followed by the loss of a further 727 MW of PV and thermo-solar generation and the disconnection of **928 MW of wind and solar generation**. Importantly, transmission voltages were still below Spain's nominal maximum limit of 435 kV when many of these plants tripped; subsequent investigation found that some generation protection settings were below the applicable voltage limits.

Between 12:33:18 and 12:33:24 the system collapsed. The rapidly increasing voltage caused further generation losses, frequency declined, and Spain and Portugal began to lose synchronism with continental Europe. Automatic load shedding was activated but could not prevent the collapse; indeed, disconnecting loads further reduced reactive-power absorption and line loading and therefore tended to increase voltage. The interconnections with France and Marocco were tripped and the Iberian system became electrically separated from the rest of Europe. The blackout was complete **less than 1½ minutes after the first generation trips**.

Why was voltage control inadequate?

The paper identifies a combination of shortcomings. Conventional generators did not always provide the reactive-power absorption requested by the system operator; some supplied less than 75% of the required amount. Spanish wind and solar PV plants were not being used for flexible voltage control, unlike plants in Portugal and several other high-renewable systems. Shunt reactors were manually operated and therefore could not respond rapidly. Local voltage-control arrangements behind generation connection points were inadequate, some protection settings were inappropriate, and tap-changing transformers were too slow to respond to the rapid voltage rise.

The central lesson is therefore **not that Spain had too much renewable generation**, but that it was attempting to operate a high-renewable system using control arrangements that had evolved for a conventional power system. The paper argues that Spain had concentrated strongly on increasing the share of variable renewable energy while paying insufficient attention to adapting system operation and control to the new conditions. In particular, it failed to exploit the reactive-power and voltage-control capabilities of Inverter-Based Resources (IBRs), i.e. wind and solar PV.

Could another blackout happen?

The Iberian event should not be regarded simply as an isolated Spanish failure. The rapid replacement of synchronous generation by **IBRs** is changing the fundamental behaviour of power systems. Although the behaviour of individual inverters is generally well understood, the behaviour that emerges when thousands of electronically controlled devices interact with each other and with the network is still not fully understood. The 0.63 Hz forced oscillation preceding the Iberian blackout is one example of this problem.

This challenge is particularly important because the pace of change is unprecedented. The paper notes that renewable penetration levels once considered potentially problematic have risen dramatically—for example, reaching potentially around 80% in the Irish power system. System planning, operation and control therefore need to evolve much faster than they did during the century-long development of conventional power systems.

The way forward

The blackout demonstrates that the energy transition requires more than installing renewable generation and replacing conventional plants. **System operation, voltage control, protection, inverter controls and network planning must evolve together with the generation mix**. Spain has already begun introducing changes allowing renewable plants to participate in voltage control and has adopted additional measures to strengthen grid stability.

More broadly, the paper calls for a **substantial interdisciplinary research effort involving power-system engineers, power-electronics and control experts, data scientists and economists**, working jointly with industry. Many of the challenges are not necessarily problems requiring large hardware investments; they are problems of understanding, modelling, controlling and regulating a rapidly changing power system.

The principal message is therefore clear: the Iberian blackout was not a failure of renewable energy technology as such. It was a failure to adapt the operation and control of the power system rapidly enough to the new technical characteristics created by high penetration of inverter-based renewable generation. The same underlying challenge now faces power systems worldwide.

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