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Editorial

Challenges of variable energy resource integration and power system security: Lessons from the 2025 Iberian system blackout

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Abstract: This editorial explores the challenge posed by the growing integration of variable energy resources (VERs) into power systems, referencing the April 28, 2025 blackout in the Iberian grid as a case study. Despite robust grid infrastructure and dispatchable generation capacity, a sharp solar ramp, low demand, and limited voltage control led to system collapse. The event underscores the need for improved ancillary services, real-time visibility of distributed generation, and greater demand-side flexibility to ensure reliable operation under high VER penetration.

1. Introduction

On 28 April 2025, a sharp solar ramp, low spring demand, and insufficient reactive support triggered a blackout that split Spain and Portugal from the European grid. This event highlights the vulnerability of inverter-based systems—and the urgent need for new planning and control strategies.

This editorial examines the technical factors behind the event and proposes key lessons for enhancing system reliability in power systems with high shares of Variable Energy Resources (VERs). As countries accelerate the deployment of VERs to meet international climate targets, understanding their operational impact becomes increasingly critical.

2. Context: The Global Transition to VERs

Around the world, power systems are undergoing a profound transformation driven by the growing penetration of VERs, particularly wind and solar generation. Many countries have adopted these technologies as their main strategy to achieve the CO reduction targets set in the COP21 agreement [1]. While VERs are a viable and essential solution for decarbonizing the electricity sector, their integration poses new and complex challenges for power system operators, particularly in terms of system stability and controllability.

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3. Technical Background: Frequency, Voltage, and Inertia

At the core of power system operation lies a continuous and delicate balance between electricity consumption and generation [2–4]. This balance is expressed through two key physical variables: frequency, determined by the real-time equilibrium of active power, and voltage, governed by the management of reactive power. Frequency is a global parameter that reflects system-wide imbalances and can be regulated from any part of the grid. Voltage, by contrast, is a local phenomenon that must be controlled near its point of deviation. Traditional dispatchable generators—such as hydro and thermal plants—not only provide controlled active power, but also contribute inertia and reactive power support, helping to stabilize both frequency and voltage.

In contrast, inverter-based VERs lack physical inertia and offer limited reactive power capabilities. Their output depends on intermittent resources, making them non-dispatchable and challenging for frequency control. Moreover, their response to voltage disturbances is often constrained, especially in weak grid conditions. As their penetration increases, the reduction in system inertia and controllability narrows the operator's range of available actions, increasing the risk of instability during sudden changes in generation or demand. This context sets the stage for understanding the dynamics behind the Iberian system blackout—and the urgent need to adapt operational strategies, grid infrastructure, and planning tools accordingly [5].

4. Case Study: The 2025 Iberian Blackout

4.1. System Characteristics

Before discussing the details of the event, it is important to highlight the main characteristics of the Iberian system, which stands out for having more than 50% of its installed capacity concentrated in solar and wind power sources, totaling 65 GW. This is followed by combined cycle thermal generation, which accounts for 20% of the mix with an installed capacity of 24.5 GW. Table 1 describes the share and installed capacity of each technology.

Table 1. Installed capacity December 2024 (source: [6]).

Source	**GW**	**%**
Hydro	17.1	13.9
Nuclear	7.1	5.8
Coal	1.8	1.5
Fuel + Gas	0.0	0.0
Combined cycle	24.6	19.9
Wind	31.5	25.5
Solar photovoltaic	31.8	25.8
Solar thermal	2.3	1.9
Other renewables	1.1	0.9
Cogeneration	5.5	4.5
Non-renewable waste	0.4	0.3
Renewable waste	0.1	0.1
Total capacity	**123.4**	**100**

It should be noted that the Iberian system has a robust capacity of conventional or dispatchable sources, such as combined cycle, fuel + gas, coal, and hydroelectric plants. Additionally, there is a nuclear generation base in the dispatch that also has the ability to contribute inertia to the system. In addition to having a diversified energy mix, the Iberian system also has a robust electrical grid that covers most of the demand from a geographical perspective.

If the installed capacity and electrical grid of the Iberian system are sufficiently robust, what then led to the recent blackout on April 28, 2025? Perhaps this is still a question without a concrete answer regarding the root cause of the event, but here we can explore a bit of what happened before and during the incident.

4.2. Analysis of the Blackout Event

During the spring season—such as on April 28, 2025—active power consumption tends to be relatively low. Under such conditions, high-voltage transmission lines operating under light load can generate excess reactive power, which in turn causes voltage to rise across different parts of the grid. This phenomenon was particularly critical on the day of the event due to the combination of low demand and increasing solar generation, leading to voltage stress in several areas of the system.

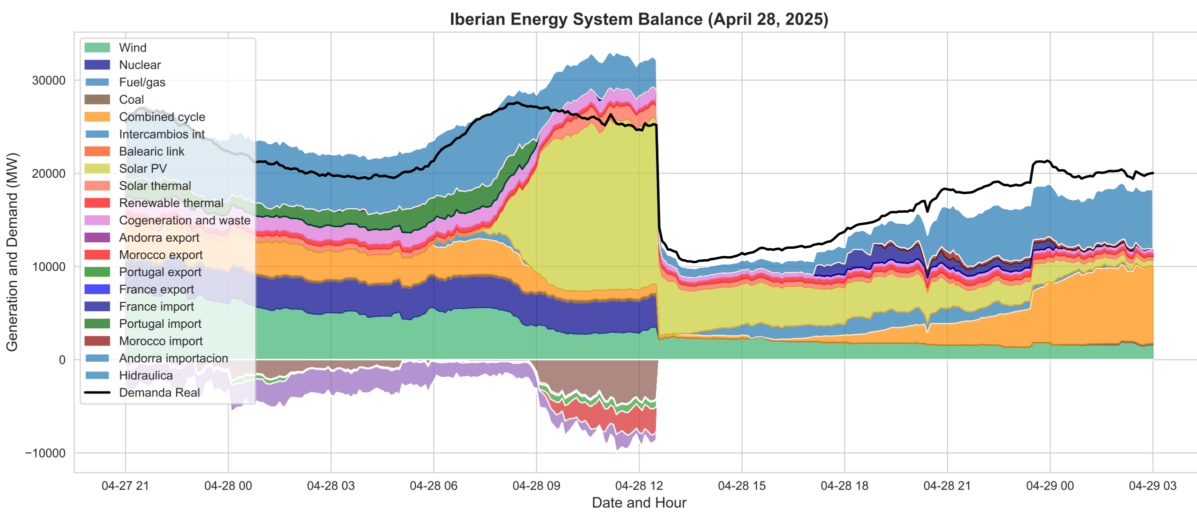

Figure 1. Iberian Energy Balance April 28, 2025 (source: [6])

As shown in Figure 1, one hour before the blackout, system demand hovered around 25 GW while solar generation increased rapidly, with a ramp-up exceeding 4 GW/h. To balance the system in response to this increase in renewable energy, the system operator reduced dispatchable combined cycle thermal generation from 3.5 GW at 8:00 am to just 1 GW by 9:00 am. This shift resulted in a loss of system inertia and reactive power support from conventional plants. Around noon, voltage measurements from cities such as Porto, Faro, and Milan began to exhibit oscillatory behavior (Figure 2), coinciding with the growing share of solar generation and the further reduction in synchronous generation.

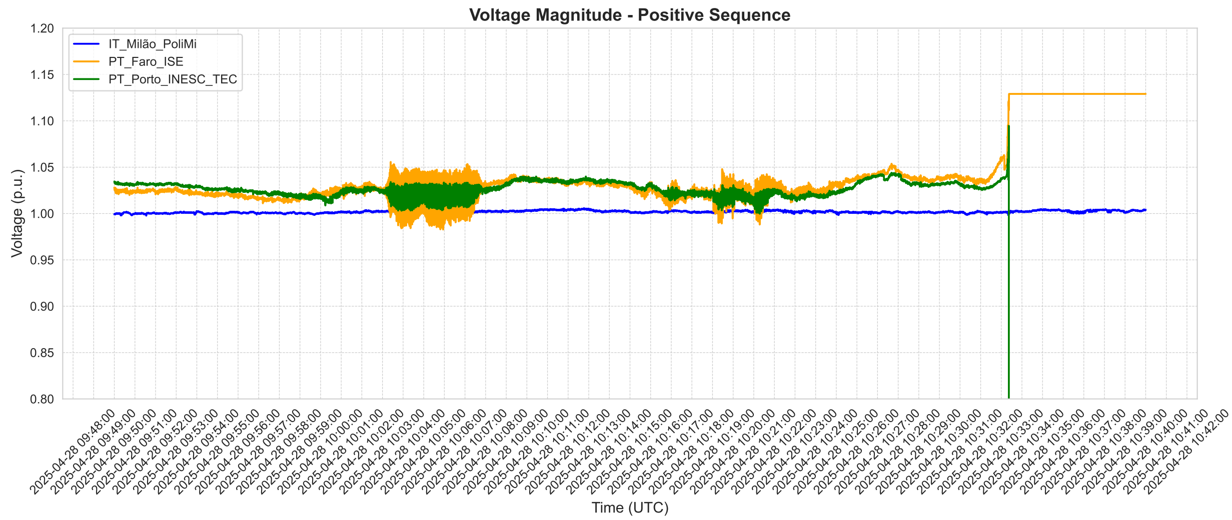

Figure 2. Voltage During the Event

Following the onset of voltage oscillations, a frequency collapse was observed in the Iberian system, as depicted in Figure 3. This frequency drop was likely due to the system's diminished capacity to regulate frequency, stemming from low inertia conditions—over 70% of the generation at the time came from inverter-based sources, which do not contribute physical inertia. In parallel, the overvoltage condition may have resulted from a combination of sudden load disconnection—visible in the system load curve—and possible reactive power injection from inverters. However, a more detailed investigation using synchronized phasor data and event recorders would be necessary to confirm this hypothesis.

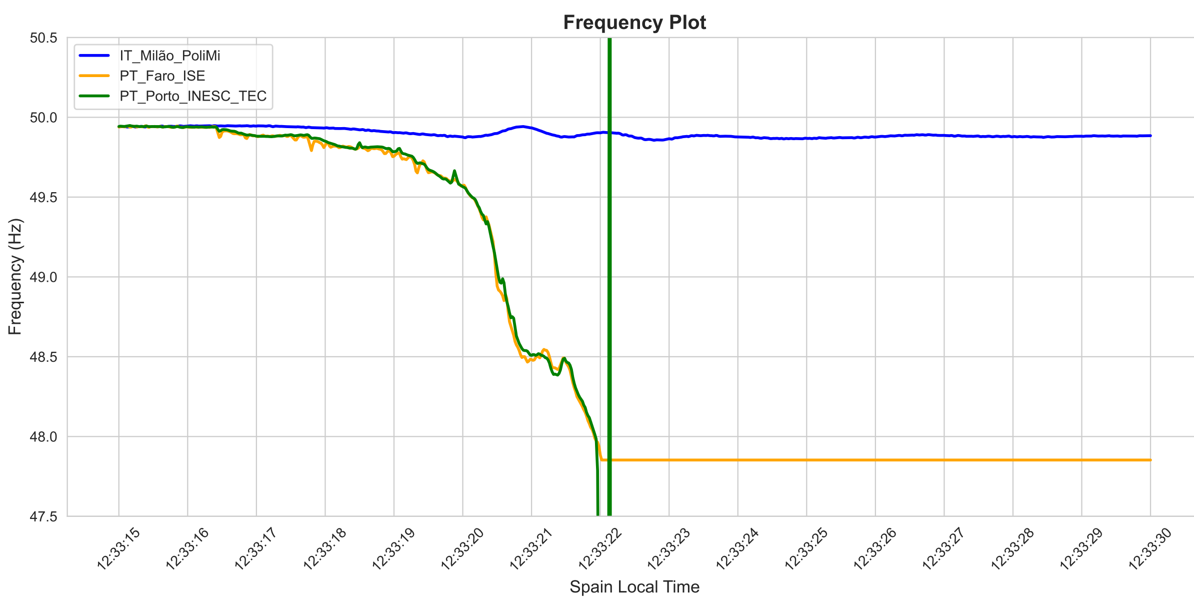

Figure 3. Frequency During the Event

The frequency data recorded in the Iberian Peninsula shows a clear collapse, while measurements in Milan, Italy demonstrate a successful recovery. This contrast strongly suggests that the Iberian system became electrically decoupled from the rest of the European grid. Such decoupling typically occurs when local instability grows beyond what can be supported by interconnections, isolating the affected region to prevent wider cascading effects.

Finally, it can be inferred that the reactive power control capacity contracted by the system operator for that day was insufficient to contain the voltage oscillations. As previously explained, voltage issues are highly localized and require reactive support to be available near the affected buses. Without sufficient voltage control distributed broadly across the power grid, the operator had limited means to respond effectively, further exacerbating the instability.

5. Conclusions and Recommendations

The blackout of April 28, 2025 in the Iberian system leaves several open questions that remain unanswered due to the limited availability of detailed operational data. Why did the operator decide to reduce conventional generation during the hours of highest solar output? Were all plausible risk scenarios properly evaluated in the lead-up to the event? Did the system operator have sufficient tools to guarantee the security of grid operation under such conditions? These and other questions highlight the complexity of managing increasingly inverter-dominated power systems, where traditional assumptions may no longer hold. What is clear, however, is that we are still in a learning phase in this transition. Each event like this offers an opportunity to refine our tools, methods, and understanding of the new dynamics introduced by modern renewable technologies.

To ensure the safe, reliable, and economical operation of power systems under high VER penetration, the following tools and operational strategies are recommended for system operators:

- **Greater dispatch of conventional generation:** Although dispatching conventional sources such as combined cycle thermal, hydroelectric, nuclear, coal, or fuel oil plants can be more expensive, they provide essential system services—such as inertia and reactive power—that are limited in inverter-based generation. The downside is potential curtailment of cheaper, cleaner energy.
- **Integration of ancillary service equipment beyond conventional generation:** Devices such as synchronous compensators, capacitor and reactor banks, and power electronics-based technologies like SVCs or DFACTS can provide local voltage support and reactive reserves, enabling operators to respond more effectively to disturbances and maintain system stability.
- **Improved access to information on distributed solar generation:** With approximately 7 GW of distributed solar installed in the Iberian system, real-time visibility is essential. Accurate data on installed capacity, expected behavior, and monitoring tools would allow operators to anticipate impacts and take preventive actions.
- **Demand-side response:** As consumers gain access to data and flexibility tools, demand can shift from a passive to an active role. Market designs can incentivize large consumers to participate in system balancing, particularly during periods of high VER variability.
- **Real-time stability validation tools:** While current grid operation relies on load flow and contingency analysis tools, there is still a gap in real-time decision-making capabilities based on dynamic system stability. Advanced tools based on state estimation and synchrophasor measurements could enable operators to detect and predict transitions toward insecure operating conditions, providing a foundation for timely corrective actions.
- **Stronger regulation for VER integration:** Although VER developers are increasingly developing more robust technologies, most of the units deployed today are still based on grid-following inverters—devices that track the voltage waveform of the grid rather than form it. Unlike conventional generation, they cannot sustain frequency and voltage on their own. Requiring future VERs to adopt

grid-forming capabilities would strengthen system resilience, enabling these sources to contribute to grid stability during disturbances.

It is important to emphasize that the effectiveness of these strategies depends on a robust regulatory framework—one that supports their implementation through appropriate economic incentives, coordination mechanisms, and alignment with existing grid codes and planning tools.

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