GE Vernova's
Electrification Business

ENSURING POWER SYSTEM STABILITY IN AN EVOLVING ELECTRICAL GRID

Whitepaper

GE VERNOVA

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EXECUTIVE SUMMARY

Grid stability is an increasingly challenging topic given the many structural changes occurring across the power system. Therefore, stability challenges need to be solved with a system view where generation, transmission, distribution, and loads interact and are considered at the aggregate level. To ensure future system stability and deployment of solutions, additional foundational enablers such as revision of grid codes, operating rules and regulatory updates, market instruments, and investment allocation need to be ready now.

Many grids are experiencing significant changes including increased penetration of inverter-based resources (IBRs), aging assets, congested grids, and the increasing appearance of large and complex loads such as AI factories. Ensuring grid stability in this new context will require system planning, as in most cases widespread events are linked to a lack of anticipation, investment, and deployment of already available solutions.

The solution requires a multilayered approach that incorporates, not only system planning, but also orchestration (situation awareness), and technical stability contributors (interconnections, rotating machines, power electronics, and loads). It may also require different time horizons for actions than were historically acceptable.

While a "one-size-fits-all" technical stability solution does not exist, it is also not required, as each system has its own scarcities and challenges. Technical solutions to support grid stability exist with different levels of maturity, complexity, cost, and range of capabilities. From well-known STATCOMs and synchronous condensers to grid-forming power electronics with storage and new flow controlling devices like Static Synchronous Series Compensator (SSSC), the best technical solutions will come through rightsizing, strategic placement, and hybridized options based on existing building blocks.

As technology has advanced, grid operators now rely heavily on comprehensive network views and applications to operate grids within physical limits. Modern systems, such as Advanced Energy Management Systems (AEMS) and Advanced Distribution Management Systems (ADMS), leveraging Wide-Area Monitoring Systems (WAMS), integrate real-time data, forecasting, market management, and operational planning to maintain grid stability. Advanced grid orchestration employs Wide-Area Monitoring, Protection, and Control (WAMPAC) and Zonal Autonomous Control (ZAC) solutions for autonomous decision-making during grid instability events.

Grids are the backbone of the energy transition and need combined action from operators, regulators & technology providers for our future energy system.

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THE CURRENT GRID: CONTEXT AND CHALLENGES

Power grids are the critical infrastructure underpinning modern economies and ways of life. We are immersed in an important transition: electrifying more of our energy use while decarbonizing the electricity that powers it. This creates new and emerging challenges that we must navigate together to maintain the integrity of the power system that is so central to us all.

In this context, electricity system stakeholders – regulators, generators, grid operators, and end users – must reassess their approach to maintaining stability and resilience, particularly as grid planning and operation are changing, putting grid stability at risk. The IEEE/CIGRE stability group[1] defines stability of a power system as the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that essentially the entire system remains intact. This requires a coordinated system response to stabilize both frequency and voltage, preventing the loss of synchronism and system separation. When full system integrity cannot be maintained, the grid must demonstrate system stability by containing the disturbance, avoiding cascading widespread blackouts, protecting generation and transmission, and enabling rapid restoration.

For the past century, power system stability has been anchored by synchronous rotating machines – such as gas turbines or nuclear and coal-powered generators - that inherently act as a kinetic energy buffer for the grid to help regulate frequency and voltage. Synchronous plants also have characteristics of voltage regulation and fault performance that are embedded in established assumptions of grid stability. However, wind turbines, solar panels, batteries, and HVDC interconnectors are all inverter-based electrical assets with fundamentally different characteristics. Furthermore, there is an increasing volume of new loads (e.g., data centers, heat pumps, electric vehicles (EVs), etc.) that affect grid frequency and voltage fluctuations. Attempting to continue applying the historic methods and assumptions leads to much greater risks to grid stability as well as impeding progress to a sustainable electricity system. By contrast, a coordinated approach that accounts for different physical characteristics of the grid and harnesses the new control capabilities and flexibility of modern IBRs is valuable for managing stability risks.

1 "Definition and classification of power system stability IEEE/CIGRE joint task force on stability terms and definitions", P. Kundur; J. Paserba; V. Ajjarapu; G. Andersson; A. Bose; C. Canizares 2021, LINK

As reinforced by ENTSO-E in Figure 1[2] "inverter-based generation is only one element of a complex mosaic." Stability is being challenged by grid expansion, load behavior, weather events, and market regulations all bringing challenges and implications into operations. The key takeaway is that those responsible for ensuring grid security acknowledge the growing complexity and challenges of the evolving power system.

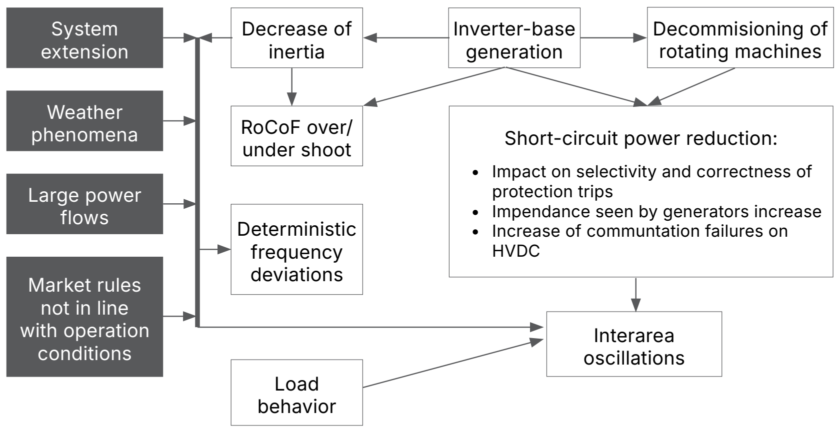

Figure 1: Map of interactions affecting grid stability

Some of the underlying drivers of these structural changes include:

- Grids are moving **from dispatchable on demand sources to an increased percentage of variable generation sources.** As shown in Figure 2[3], by 2030 many large grids will see variable renewable energy (VRE) meet almost all demand at times and experience surplus VRE generation.
- As the power mix transitions to solar photovoltaic (PV) and wind IBRs, **rotating machines are displaced by power electronics** grid-interfaced variable renewable plants reducing system inertia, voltage support, and short-circuit currents. IBR characteristics change the dynamics of the system, exacerbating and introducing new instability phenomena, whilst also offering new ways of mitigating them. Additionally, understanding dynamic IBR behavior requires analysis techniques (modeling and simulation) that are different from the conventional methods used today.
- The grid is seeing an **increase in grid congestion**. Renewable generation hubs are located based on availability of resources and these sites are typically located far from main consumption centers. Figure 3 shows ideal solar and wind locations in the United States are not necessarily close to consumption.[4] Power flows are now transmitted over longer distances and can become bidirectional. This mismatch, coupled with the fact that the increase in renewable energy generation has outpaced the reinforcement of the transmission grid and the loads, has resulted in congestion challenges in certain grid zones.

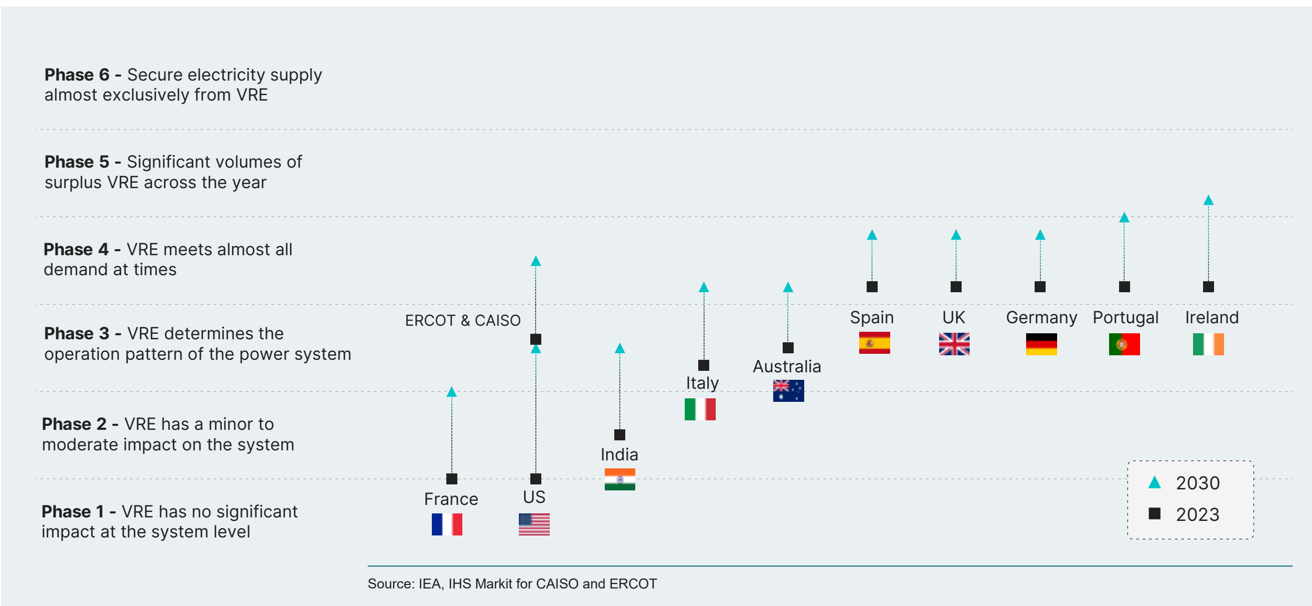

Figure 2: Variable Renewable Energy integration phase for selected countries (IEA)

2 "Inertia and Rate of Change of Frequency (RoCoF)", ENTSO-E, December 2020, LINK

3 "Integrating Solar and Wind", International Energy Agency, September 2024, LINK

4 Interconnections Seam Study, National Renewable Energy Laboratory (NREL), April 2025 LINK

Enhancing transmission efficiency, meaning transmitting more power using the current infrastructure, presents a significant challenge. Since building new transmission implies long lead times and important capital expenditures (CAPEX), operators must maximize the existing system's capacity. Achieving this involves addressing two key issues: reducing transmission impedance and managing congestion.

- In advanced economies, more than 50% of grid infrastructure is more than 20 years old (see Figure 4[5]). **Aging grid infrastructure** poses additional failure risks.
- Grid operators are seeing **increasing demand from GW-scale electro-intensive industries**. AI factories, steel electric arc furnaces, and rail networks are bringing additional stability challenges given the specificities of their operational consumption and variability.

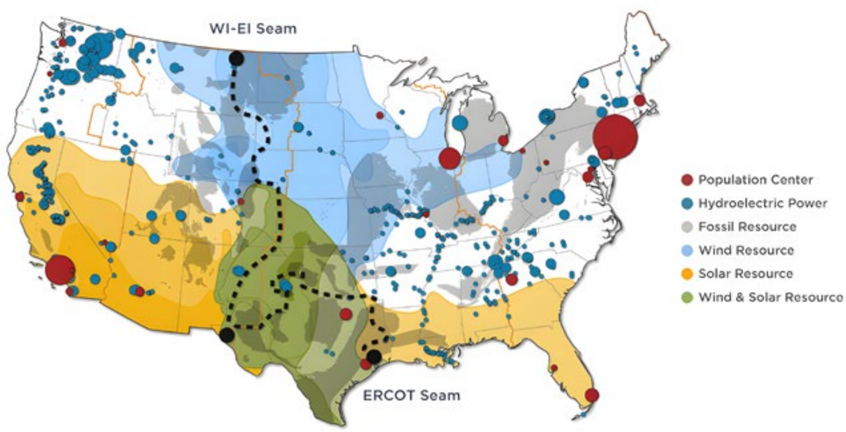

Figure 3: Interconnections Seam Study (NECR)

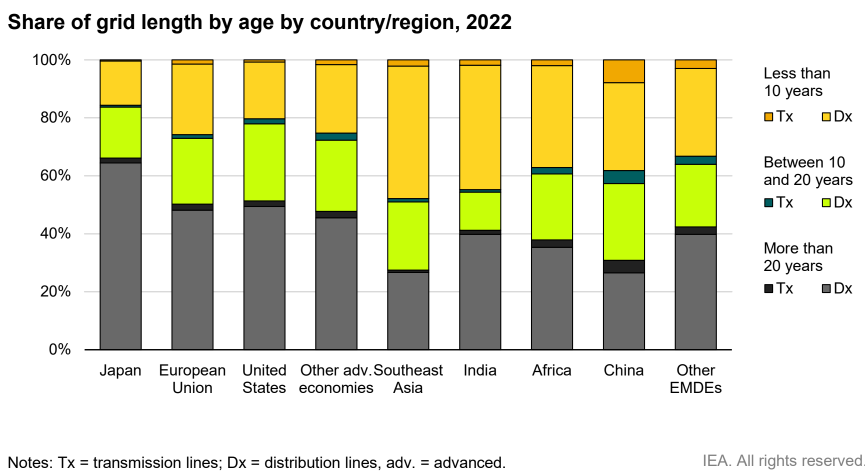

Figure 4: Share of grid length by age by country/region, 2022

System planning and development processes have consequently become increasingly complex, subjected to increased uncertainty from load and generation growth rates, energy market conditions, and extreme weather phenomena. Coherent modeling assumptions, analysis methods, and simulation tools across planning steps and models are critical to effectively plan for and operate a reliable and secure grid:

- **Need for analysis beyond typical system conditions**: Traditional planning methods focus on the grid's high-risk periods, such as peak demand. However, as the system shifts towards greater reliance on weather-dependent generation – whose output can fluctuate significantly over short timeframes – the most critical risk periods will no longer include only peak demand times. As a result, the planning approach must ideally model uncertainty, include multi-temporal and multi-period models, and include the impact of extreme weather events on infrastructure, load, and generation profiles.
- **Need for integrated system planning**: One of the most significant benefits to the integrated system planning approach is to identify high-risk system periods via adequacy and/or production cost analysis and simulate such conditions in the power flow models to assess system stability risks under a range of operational situations.
- **IBR modeling considerations**: There is a significant amount of standardization in the generator, exciter, and turbine control models for conventional generation used for power system stability analysis. Furthermore, these are designed to respond to slower phenomena due to the system inertia. With IBR models being typically vendor proprietary black-boxed, identifying root cause(s) for system stability from the models will become inherently more challenging.
- **Financial modeling** is crucial for grid operations as it helps forecast and manage the economic aspects of energy distribution. With the evolving generation mix, including a significant increase in renewable sources, financial models must account for the inherent variability and intermittency of renewables. This ensures that grid operators can optimize investments, manage costs, and maintain reliability in power delivery. By integrating these dynamic elements into financial projections, operators can make informed decisions that balance economic efficiency with the stability of the energy supply.

5 "Electricity Grids and Secure Energy Transitions", International Energy Agency, November 2023, LINK

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NAVIGATING THE SHIFT: OPERATIONAL EXAMPLES

As previously indicated, the increase in new large and complex loads and higher penetration of renewables generation is presenting new stability challenges. Utility planners must understand and anticipate those challenges considering their system characteristics and leverage all assets to ensure grid security.

Here is a summary of key stability challenges and the capabilities required in today's grid:

Challenge to solve	Capability	Details
Frequency stability and regulation	Synchronous inertia	Inertia inherent to rotating generators
	Inertial/Fast frequency response	Power/energy injection <2s to maintain frequency
	Primary/Secondary frequency control	Generation and demand matching with decentralized control and centralized governance
Voltage stability and regulation	Slow/steady control	Maintain voltage within a limit while reactive power changes
	Dynamic changes/flicker control	
Short-circuit strength	Provide high current for a limited time to allow networks to recover from faults and ensure operation of protection equipment	
Transient / rapid phase angle jump stability	Ability to keep system synchronism during sudden shifts in voltage phase angle caused by grid faults or disturbances	
Power oscillations/rotor angle stability	Power oscillation damping (POD)	Dampen electromechanical oscillations in power flows under small perturbations (i.e., small signal stability including local area and inter-area modes and slow, new converter-driven instability interactions)
Harmonics filtering	Super synchronous filtering	Filter oscillations above fundamental frequency that create increase current reducing transmission capacity
	Sub-synchronous resonance filtering	Filter oscillations bellow fundamental frequency that can damage IBRs and rotating equipment
Power flow control	Balancing	Ability to control how power flows between two points through parallel paths
Black start	Black start/restoration	Restoring the grid in case of blackout

However, these stability challenges will not look alike, occur simultaneously, or have the same impact in all grid networks. Depending on the topology and characteristics of the local power system, some will be more relevant and frequent than others.

Grid Topology Segmentation

ELECTRIC ISLANDS

Grids with limited interconnections to other grids (physical islands or electric islands)

Main Challenges

- Limited AC interconnections
- Lower inertia
- Need for self-sufficient power, stability and blackstart capabilities

Examples

UK, Ireland, Iberia, Australia, US (ERCOT) & small islands

LONG TRANSMISSION GRIDS

Grids with very long transmission networks (200 km+) driven by generation hubs far from consumption & country length/distribution of population

Main Challenges

- Transmission efficiency
- Power flow/congestion
- Inter-area oscillations

Examples

US, Nordics, Australia, Turkey, South America

DISTRIBUTED GENERATION

Grids with important volumes of generation connected to distribution networks

Main Challenges

- Scattered points of consumption/generation
- Access to distributed flexibility and ancillary services (ie. Voltage regulation, Protection and Blackstart)

Examples

Europe, US, & India

HIGH PENETRATION OF IBR

Grids with high penetration of IBR renewable energy

Main Challenges

- Low frequency and voltage stability
- Lack of short-circuit strength
- Small-signal stability/controls interaction

Examples

Spain, UK, Ireland, Germany, Australia, US (ERCOT & CAISO)

The challenges and impact on grid stability are becoming more visible with concrete incidents and degradation of key reliability and resiliency indicators today.

Frequency Stability Challenges in Continental Europe[6]

As reflected in Figure 5, the number of minutes outside standard frequency ranges has been rising in recent years in Continental Europe. One example of this was EirGrid[7], in collaboration with SONI (Northern Ireland's Transmission System Operator (TSO)) undertook a multi-year program to increase the maximum allowable Rate of Change of Frequency (RoCoF) of Ireland's power system from 0.5 Hz/s to 1 Hz/s. This allowed the system to tolerate faster frequency changes without automatic disconnections, enabling higher levels of renewable penetration.

Voltage Stability Challenges in France[8] & Iberia[9]

In 2023, RTE reported an increase of voltage limit breaches, specifically in the 225 kV network, highlighting the lower availability of voltage regulation resources during the year, against a background of falling consumption (see Figure 6).

Additionally, overvoltage in the grid has been one of the major stability challenges leading to recent blackout in Iberia. (Refer to the Case Study on page 18.)

Grid Congestion Costs

As the penetration of renewables increases, constraints and inefficiencies are manifesting in congestion and balancing charges:

- The cost of grid congestion in the EU was €4.2B in 2023[10]
- In the United States, it has been estimated at $11.5B in 2023[11]

Short-Circuit Strength (SCS)

Short-circuit strength is a well-known and measured feature driving grid stability management decisions by TSOs. Figure 7 reflects short-circuit strength analysis of the Italian grid, highlighting weak areas to be reinforced in Italy made by Terna.[12]

The United Kingdom and Ireland developed the innovative Stability Pathfinder programs remunerating inertia and SCS solutions. Synchronous condensers and some Battery Energy Storage Systems (BESS) were the main technologies selected.[13]

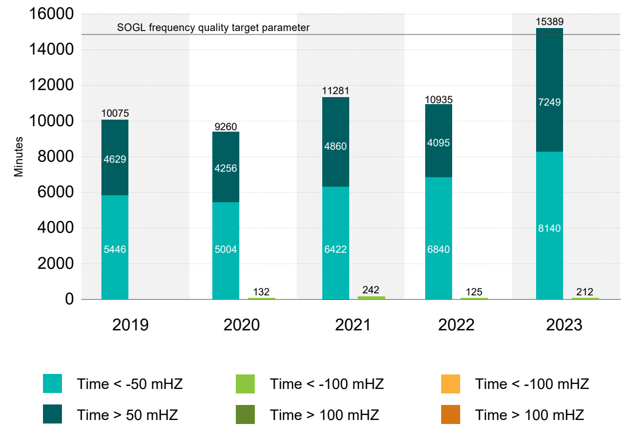


Figure 5: Number of minutes outside standard frequency ranges in Continental Europe, 2019-2023

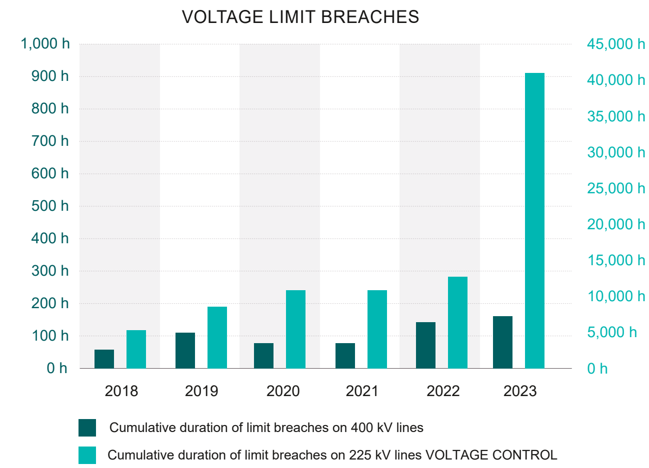


Figure 6: Voltage limit breaches in France's network, 2018-2023

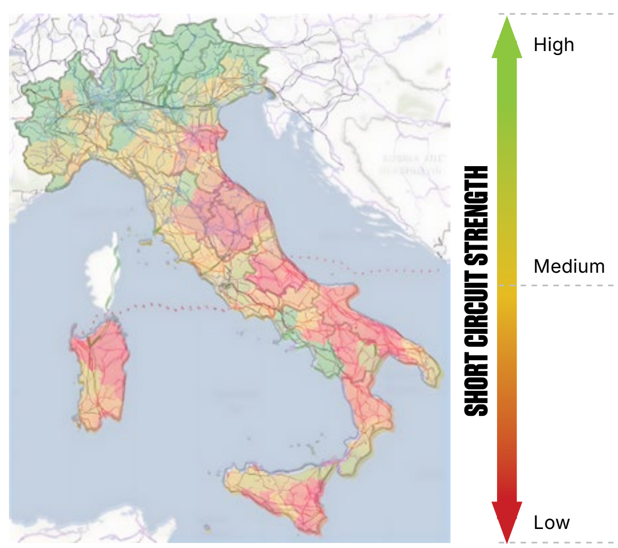


Figure 7: Analysis of short-circuit strength in Italy

6 "2023 ALFC Report", ENTSO-E, September 2024, LINK

7 "Evolution of Shaping Our Electricity Future", EirGrid, 2025, LINK

8 "Bilan Surete", RTE, October 2024, LINK

9 "28 April 2025 Blackout", ENTSO-E Summary, July 2025, LINK

10 "EU Electricity Grids", European Parliamentary Research Service, May 2025, LINK

11 "2023 Transmission Congestion Report", Grid Strategies, September 2024, LINK

12 "Benefici di sistema e analisi robustezza rete", Terna, March 2025, LINK

13 "Stability Pathfinders: what they mean for battery energy storage", Modoenergy, September 2023, LINK

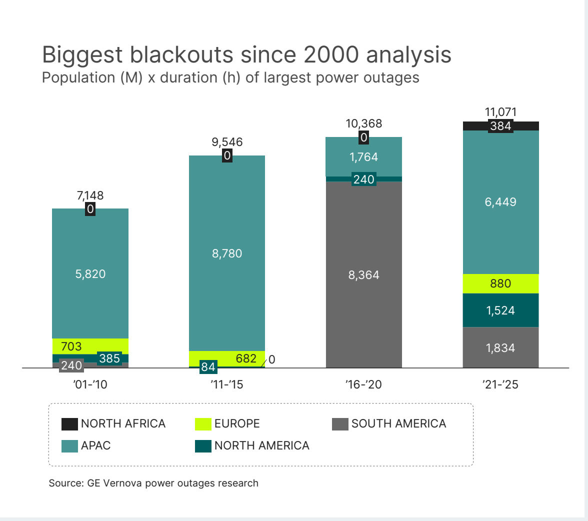


Figure 8: World's 20 biggest blackouts between 2000-2025

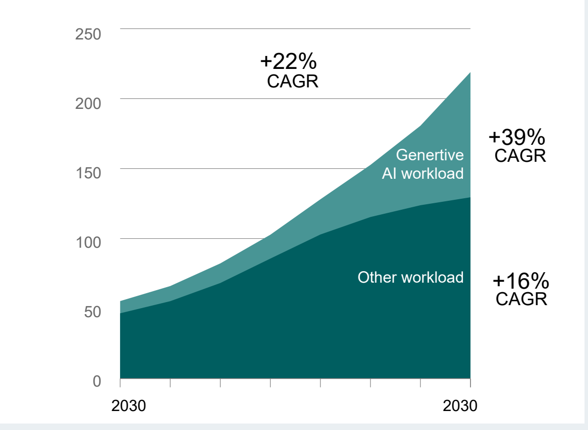


Figure 9: Estimated global data center capacity demand in gigawatts

System Strength[14]

AEMO has been leading the efforts on extending the short-circuit strength to a concept termed "system strength". They are in the process of defining methodologies for undertaking system strength impact assessments, calculating a system strength locational factor (SSLF), available fault levels (AFLs), and system strength quantity (SSQ). These, as well as requirements to ensure voltage waveform quality at the point of interconnection, reflect the potential concerns on IBR controls degrading the system response during and after disturbances.

Consequently, power outages and blackout events are becoming more common in most developed grids, as shown in Figure 8[15].

Loads Impact

System stability is an entire system problem involving generation, the network, loads, and storage. These variables all constantly interact to maintain system stability. Specifically, rising demand is driven partly by the transition in energy-intensive sectors like steel manufacturing (electric arc furnaces) and in transportation modes (rail and EVs). Additionally, AI factory demand for energy capacity is estimated to grow by +39% until 2030, as shown in Figure 9[16]. AI data centers introduce a new stability challenge due to rapid load shifts. Although all electrical loads can vary, AI factories cause exceptionally large, synchronized load swings, which are unprecedented in scale. This shift will alter demand behavior, affect system stability, and require tailored grid connection codes. On one hand, these loads require a high-quality power supply characterized by cleanliness, stability, and uninterrupted delivery. On the other hand, due to their non-linear nature and integration via power electronics, these loads introduce new challenges to the grid regarding power stability (as shown in Table 2) such as harmonic currents, voltage distortion, and negative incremental impedance behavior. The latter is a growing concern, as many electronic loads are controlled to maintain constant power output despite variations in voltage and current. For instance, a voltage drop may lead to an increase in current, further destabilizing voltage. This phenomenon can be modeled as a negative incremental impedance, posing a risk to the stability of power systems.

14 "AEMO System strength Impact Assessment Guidelines", AEMO, June 2024, LINK

15 GE Vernova analysis based on World Bank data and various sources

16 "AI power: Expanding data center capacity to meet growing demand", McKinsey & Company, October 2024, LINK

Industry	Challenges	Details
Steel – Electric Arc Furnaces (EAFs)	Flickers/dynamic voltage change	Voltage fluctuations can lead to inefficient melting processes, increased wear on components, and potential safety hazards
	Current stability	Variations in the current can affect arc stability, leading to inconsistent heating and increased energy consumption
	Power factor	EAFs require significant reactive power supply and control, which must be managed to prevent disturbances in the power grid
	Harmonics	EAFs can introduce harmonics into the electrical system, affecting operations of other equipment connected to the same network
Electrified Rail	Frequency conversion	Frequency conversion to the rail network but ultimately can also support stability by decoupling the grid and rail network frequencies
	Dynamic load	Transient inrush power requirements from trains at local substations are more likely to disrupt the network
AI Factories	High load variability	Graphic Processing Units (GPUs) synchronously working and idling in high frequency cycles generating multi-MW load swings several times per second
	Microgrids/grid integration	Uninterruptible power supply (UPS) system disconnection/reconnection to the grid when some disturbances appear could amplify grid instability. Additionally, harmonics can generate torsional stress on surrounding conventional generation or collocated gas turbines (in islanded mode).

Table 2: Load-Driven Stability Considerations

While meeting electro-intensive industry demand is an evident challenge, it is worth noting that these same loads can also be part of the solution, providing flexibility with specific compensation schemes. For example, in France, the industry provides ~60% of load disconnection flexibility to the system as of 2020[17] (see Figure 10).

As the size and complexity of modern loads continue to grow, it is imperative to address and anticipate their impact to ensure future grid stability. Furthermore, grid connection codes must account for this, enabling large and complex loads to incorporate appropriate technologies for effective grid integration.

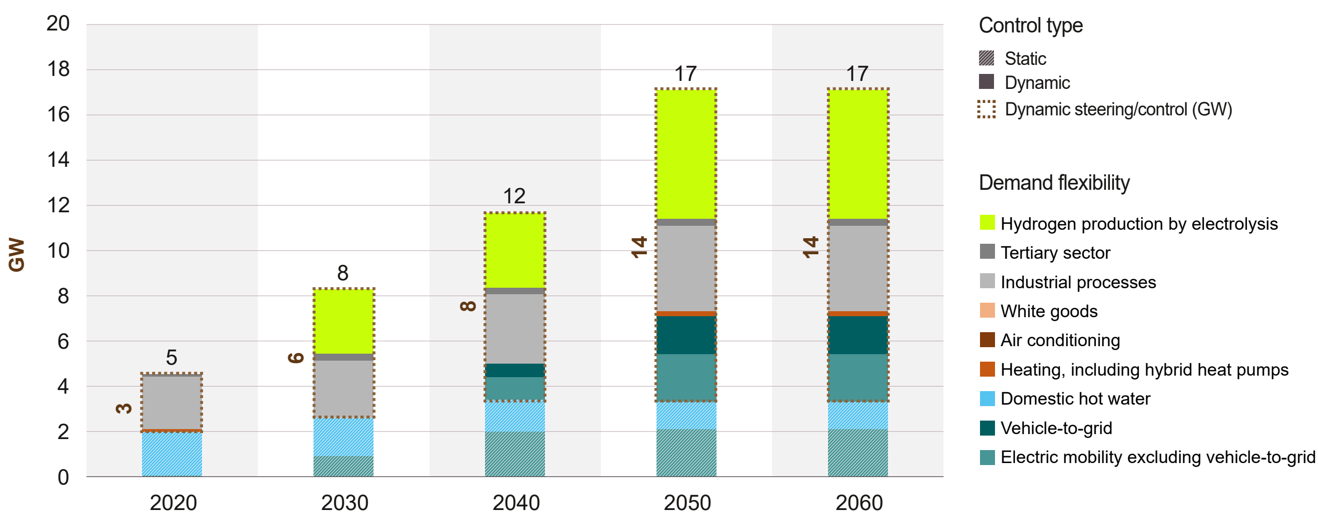


Figure 10: Forecasted size of demand providing flexibility support from 2020 to 2060

17 "Futurs Energetiques 2050", RTE, February 2022, LINK

4

INNOVATING FOR A RESILIENT FUTURE

Today's grid challenges are complex and demand significant engineering analysis and smart intervention to ensure system-wide stability and support informed, system-level decision-making. An Integrated System Planning (ISP) approach can offer a clear vision of future grid stability challenges and guide effective strategies for building a resilient grid. Additionally, stability will not be accomplished through a single piece of technology, but rather through a combination of technologies including equipment solutions strategically deployed across the grid and orchestration controls and software enabling near real-time monitoring, protection, and control.

An ISP approach allows for an iterative assessment where the output of each planning step (i.e., adequacy, capacity expansion, production cost, power flows) is considered as an input to the next. By using this integrated approach, system risks can be quantified, and solutions for these risks can consequently be developed and deployed. Benefits are as follows:

One Source of Data

With an ISP approach, each simulation step pulls from a common source of data. Generator names and system assumptions are consistent, saving time on data clean-up.

Cross-Functional Improvement

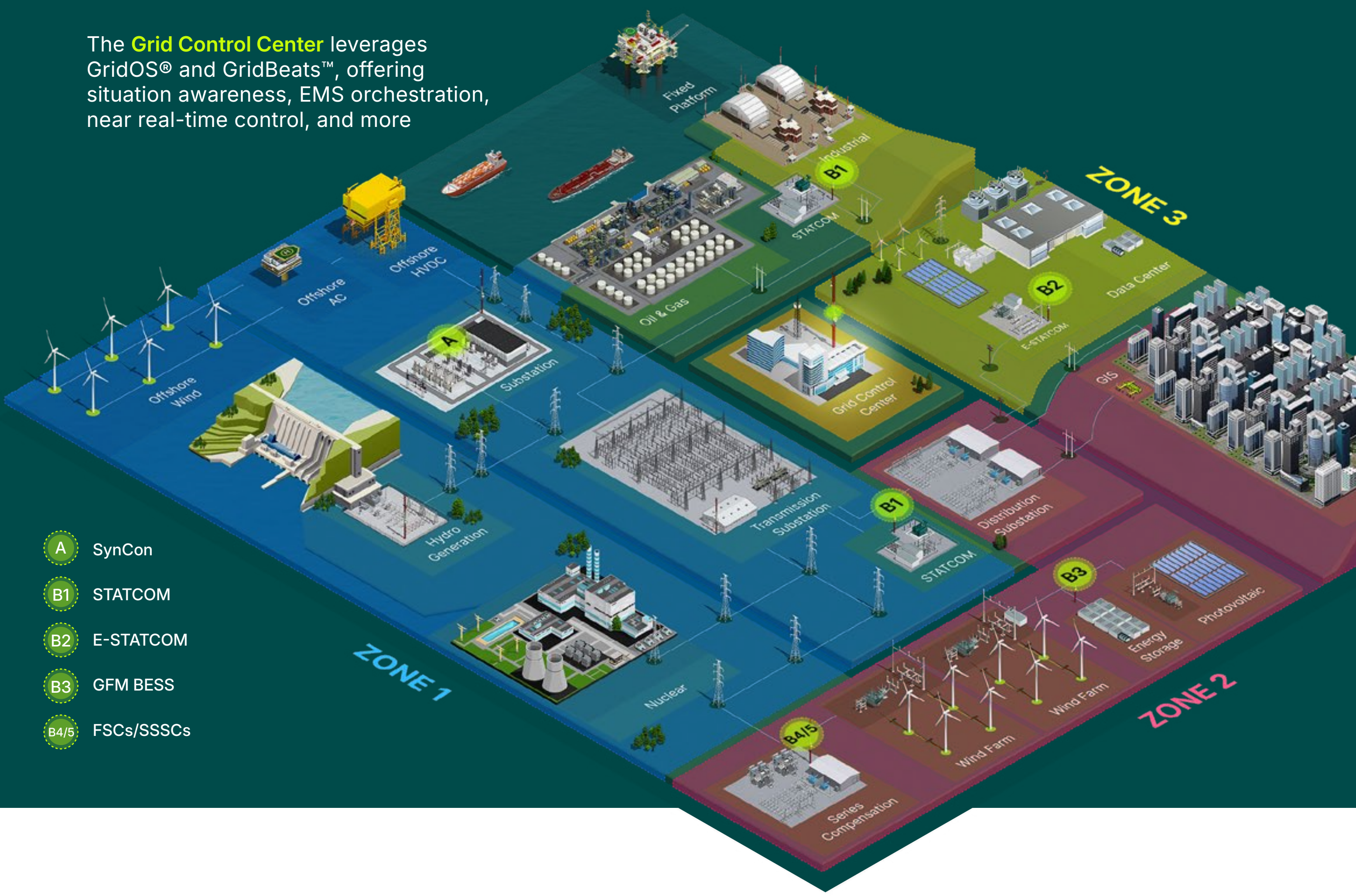
In this way, the impact of grid transformations can be evaluated together and upgrades to system performance can be defined holistically. For example, a generation plan may now reflect benefits to network stability. At the same time, network planners may consider resource expansion alternatives to meet system needs.

Time-Series Risk Analysis

One of the most significant benefits to the ISP approach is the focus on time-series analysis (i.e., hourly) to identify the conditions of greatest risk.

GRID STABILITY AND FLEXIBILITY IS AN END-TO-END CHALLENGE

The **Grid Control Center** leverages GridOS® and GridBeats™, offering situation awareness, EMS orchestration, near real-time control, and more



The "Perfect" Stability Solution

A "perfect" stability solution, addressing all needs simultaneously and across the entire network, does not exist; however, in most cases it is not needed, as each grid/zone has its own specific challenges to be solved. Today, several solutions to respond effectively to different system needs already exist, including interconnections among systems and technologies integrated into a system, or at the electro-intensive load's grid connection.

Interconnections enhance grid stability by providing a pathway for electricity to flow between different systems, allowing for a more reliable and resilient power supply. Interconnections between large synchronous grids enable sharing inertia and frequency regulation (e.g., in Continental Europe) and thus improve stability. High-voltage direct current (HVDC) transmission technology between asynchronous grids enables better control of power flows and contribute to overcome some grid stability challenges including:

- Dynamic voltage control
- Fault recovery
- Oscillation dampening, grid harmonics filtering, and phase balancing
- Frequency regulation, brown start, and system restoration when associated with energy resources

HVDC technology with grid-forming (GFM) controls additionally provides inertial response to support grid stability even further.

As an example, the primary objective of the NEMO link between Great Britain and Belgium (2019) was increasing emergency power from the United Kingdom and sharing of ancillary services (frequency coupling, frequency reserves, black start, and reactive power).

Flexible Alternating Current Transmission Systems (FACTS) and other technologies support stability by being deployed either close to generation assets, within the transmission and distribution networks and behind-the-meter in large complex loads such as industrial, rail, and AI factories that can have a big impact on system stability and can play an active role on stabilizing the grid.

A. Rotating Machines and Synchronous Condensers

Synchronous condensers are freely spinning synchronous machines connected to a high-voltage (HV) network. They control reactive power and voltage by adjusting their field current, actively supplying or absorbing reactive power to regulate voltage as needed. As rotating machines with mass, they inherently have synchronous inertia, through magnetic field energy in their windings and the kinetic energy stored in their rotating mass, and they provide support in voltage and frequency regulation during power imbalances. Additionally, synchronous condensers provide significant short-circuit strength to the grid which is critical for the activation of conventional over-current based protection systems.

B. Power Electronic Systems and Controls

We differentiate between equipment connected in parallel (shunt) or in series, each of which has different capabilities and use cases.

Shunt-Connected Devices

Are primarily used to control voltage, support reactive power needs, strengthen the frequency response and provide phase angle control in electrical transmission systems.

B1. Static Synchronous Compensator (STATCOM) is a fast-acting device capable of providing or absorbing reactive current and thereby regulating the voltage at the point of connection to a power grid. From the load power stability side, STATCOMs can be adapted to provide a wide range of applications to solve the industry-specific challenges mentioned above (e.g., improve power factor, active harmonic filtering, flicker reduction, POD, network voltage asymmetry mitigation, etc.). Unlike synchronous condensers whose fault response is guided by physical properties of rotor size and winding design, the STATCOM fault response is programmed. This means they can be more difficult to model in a system, but they can also be more flexible by the ability to have a specific response to a predetermined set of fault conditions. The technology started commercial development in the mid-1990s and as of 2024, more than 1,200 STATCOM units are in operation globally.

B2. E-STATCOM is an enhancement of STATCOMs incorporating grid-forming algorithms combined with real energy storage. Using short-term energy storage devices such as supercapacitors, lithium capacitors, and lithium-titanium-oxide (LTO) to inject energy quickly in response to system fault conditions, they can provide inertial/fast frequency response for grid stability. Grid-forming controls further enhance the capabilities of E-STATCOMs by improving stability response to dynamic and transient grid changes. This new technology has started to gain popularity more recently, representing 15% of installations in 2023[18].

AI factories can benefit from these solutions, leveraging storage technologies that filter very dynamic power fluctuation loads (grid and islanded microgrid integration) and at the same time ensure very high availability requirements.

B3. Grid-Forming Battery Energy Storage Systems (GFM BESS): Many of today's grid-connected IBRs like wind, solar, and batteries use grid-following (GFL) controls. These inverters operate by "following" the existing grid's voltage and frequency, assuming a strong and stable grid supported by traditional synchronous generators. However, if the grid lacks strong synchronous generation, its voltage becomes more susceptible to changes from IBR current, making it difficult for GFL controls to maintain stable power. This is problematic because a grid or an area with only "followers" can become unstable.

In contrast, GFM controls are fundamentally different. Immediately following a grid disturbance, GFM inverters aim to maintain a constant voltage, mimicking how synchronous machines operate. This allows GFM technology to "form" grid voltages rather than just "following" them, replicating one of the crucial grid-stabilizing features of synchronous generators.

Today, grid-forming inverters are being deployed in the United Kingdom, the United States (particularly in Texas with ERCOT and California through CAISO), Australia, and Germany[19].

Series-Connected Devices

High-voltage transmission lines are limited by thermal capacity due to resistive losses and by voltage and stability limits due to reactive impedance of transmission lines. To maximize the utilization of transmission assets, adjusting reactive series impedance is a critical tool. The most cost-effective way to achieve this is by installing series compensation solutions.

B4. Fixed-Series Compensators (FSCs) are installed in series to reduce transfer reactance of transmission lines, although they introduce stability issues, most notably sub-synchronous resonance (SSR). Typically, custom-designed systems include power capacitors arranged in series and parallel. It is a well-established technology with >860 systems worldwide as of 2023[20].

18 "Static Synchronous Compensator (STATCOM) Market Overview", Market Growth Reports, June 20'25, LINK

19 "Grid-forming inverter technology to boost greener power systems", S&P Global Commodity Insights, April 2024, LINK

20 "FACTS Market Overview", Markets Reports World, June 2025, LINK

B5. Static Synchronous Series Compensators (SSSCs) use insulated-gate bipolar transistor-based power electronics connected in series with a transmission line to act like a controllable series capacitor or series inductor. The device is used primarily to adjust transmission line impedance dynamically, allowing power flow across networks. The most innovative models do not require HV transformers, and some references exist in the United States, the United Kingdom, and Colombia.

Additionally, the market will see innovative technologies enhancing the capabilities of installed transformers. The connection of a power electronics solution to the primary or secondary of the main transformer (when the three neutrals are accessible) can provide additional support to grid stability issues such as steady-state and dynamic control of power flow, voltage, impedance, and oscillations damping. Such solutions only require a power electronics rated at a fraction (6%-10%) of the transformer power rating.

		Power Electronics									
		Shunt			Series		Rotating	Hybrid Solutions			UPFC
CHALLENGE	**CAPABILITY**	STATCOM GFM	E-STATCOM	GFM IBR w/BESS	FSC	SSSC	Synchro. Condenser	BESS + E-STATCOM	SynCon + E-STATCOM	GFM BESS + SynCon	UPFC
Frequency Variations	Synchronous Inertia						High		High	High	
	Inertial/Fast Frequency Response	Low	High	Medium				High	High	Medium	High
	Primary/Secondary Frequency Control			High				High	Medium	High	Medium
Voltage Fluctuations	Slow/Steady Control	High	High	Medium	Low		High	High	High	High	High
	Dynamic/Flickers Control	High	High	Medium			Low	High	High	Medium	High
Short-Circuit Current			Low	Low	Medium		High		High	High	Medium
Transient/Rapid Phase Angle Jump Stability		Low	High	Medium			High	High	High	High	High
Power Oscillations/ Small-Signal Stab.	Power Oscillations Damping	Medium	Medium	Medium	Low	Medium	Medium	Medium	Medium	Medium	Medium
Harmonics	Super Synchronous Filter	Medium	Medium	Low			Medium	Medium	Medium	Medium	Medium
	Sub-Synchronous Reso.	Low	Low		Medium	High	Low	Low	Low	Low	High
Power Flow	Balancing	Low	Low	Low		High	Low	Low	Low	Low	High
Blackstart	Blackstart/Restoration			High				High		High	

Figure 11: FACTS equipment capabilities benchmarked against stability challenges ● High ○ Medium ◌ Low

C. Hybrid FACTS Solutions

As Figure 11 reflects, each piece of equipment has its own capability, and the complementarity of these solutions offers opportunities to hybridize products, forming more capable solutions. The rationale for the technology selection will be based on solution capability, flexibility for future changes, and total cost of ownership (including CAPEX and OPEX).

In addition, to determine which technology is best suited to solve current and future problems, a key element is to define the most effective location of those solutions through grid studies.

In Spain, Red Electrica de Espana (REE) analyzed the best locations for STATCOMs to dampen inter-area oscillations: "the results show the effectiveness in damping oscillations for a ±150 MVAr STATCOM, depending on the location. In general, it can be stated that the effectiveness is determined by the distance of the device from the center of the oscillation"[21] (see Figure 12).

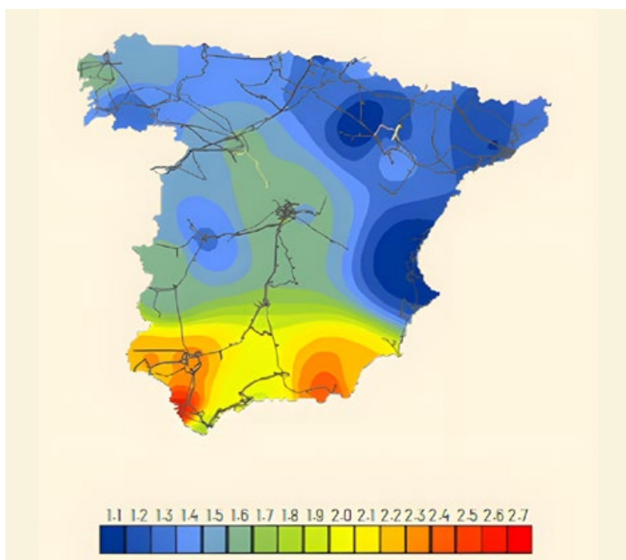


Figure 12: STATCOM damping improvement map

21 "Transmission network development plan 2021-2026", REE, 2024, LINK

INESC TEC also proposed a methodology to site and size STATCOMs to improve fault Ride Through (FRT) by injecting reactive current to mitigate the disconnection of large amounts of wind farms in case of severe grid faults. The proposed strategy minimizes the number of required STATCOMS and their capacity, while keeping system stability and security[22].

A more recent study presented by INESC TEC shows that both right-sizing and location of grid-forming power electronics have a significant impact on maintaining stability for multi-class stability problems[23].

Orchestration and Coordination Solutions

Orchestration and coordination are required to ensure that resources are controlled appropriately for the operating state of the wider grid.

Transmission systems have been supervised using SCADA/ Energy Management Systems (EMS) and Distribution Management Systems (DMS) since the 1970s. As monitoring, communication, and computational power have intensified, grid operators increasingly depend on a view of the state of the overall network and applications to maintain operation of the grid within its physical limits.

While the core concept of a centrally orchestrated grid coordinating local controls is well established, there is now a much greater need to structure the control and management of the power system with much greater diversity of the devices and sub-systems connected to the grid. Furthermore, in contrast to traditional control of a small number of large devices, there is a much larger number of units of renewable and distributed generators, fast-response storage and demand-side flexibility to be controlled. Present-day advanced transmission and distribution systems (AEMS and ADMS) include a large and expanding range of real-time, forecasting, market management, and operational planning features that assist grid system operators in maintaining the stability of the power system.

Grid orchestration typically incorporates the following characteristics:

1. Diverse information sources made accessible to applications in a unified way, breaking down the traditional silos.
2. Near real-time observability of high-resolution dynamic data through WAMS providing resources for stability monitoring and control.
3. Forecasting functionality with load flow and contingency analysis to navigate future grid situations.
4. Secure communication of automated and human controls to the relevant resources and subsystems.
5. Complexity of overall grid operation being managed by central systems providing high-level requirements applied to intelligence in the field that manages a local or network zone level of control.

Taking a zonal approach to grid control facilitates operational improvement in which the central orchestration defines the targets for the zone's participation in wider grid services. The zonal level of control maintains the stability and integrity within the zone, while also dispatching the zone's resources to achieve the outcomes that are required by the orchestrator. During critical events on the grid, the EMS needs fast response and awareness of adjacent zones to ensure resiliency of the complete network. Centralized orchestration can then take appropriate action after the fast response of the decentralized zones to get the system back to a non-critical stage while considering the global network state.

In this way, a zone of the network can use various resources with diverse characteristics of response time, variability, duration of response, etc. to deliver a reliable and predictable service. ZAC aims to improve network monitoring and predictive control at a zonal level, to prevent congestion and minimize renewable generation curtailment, while improving near real-time response to local disturbances. As shown in Figure 13, ZAC can ensure zonal management of RES generation limits according to Dynamic Line Rating information, conventional generation dispatch, and network technical limits.

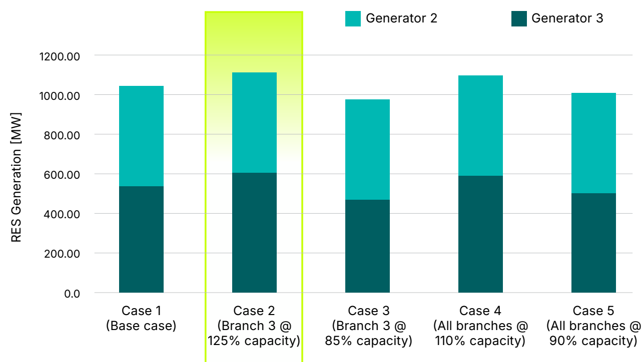


Figure 13: Dynamic management of RES limits with ZAC

An important enabling technology for this approach is WAMS and WAMPAC, which facilitate fast-response capability to use many distributed resources to participate in system stability services.

Using Phasor Measurement Units (PMUs), WAMS offers near real-time visibility across large sections of the grid, enabling operators to monitor system stability involving multiple interconnected elements. WAMS significantly transforms power system operations from a predominantly reactive stance to a more proactive approach. Complementing WAMS with network Digital Twins can provide a more accurate classification of the system's stability and robustness (such as the RoCoF or frequency nadir values) and recommend preventive and remedial control advice actions to human operators.

22 "Sizing and siting static synchronous compensator devices in the Portuguese transmission system for improving system security", Pedro Barbeiro, Carlos Moreira, et. al, 2015, LINK

23 "Location of grid-forming converters when dealing with multi-class stability problems", João Peças Lopes, Francisco Fernandes, Carlos Moreira, January 2025, LINK

Advanced grid orchestration through WAMPAC and ZAC solutions uses this data to make sub-second autonomous decisions, where human decision-making is not possible or slower during instability events. Those solutions are designed not only to assess the current network state but also to incorporate asset capabilities, thus providing dynamic, coordinated orchestration mechanisms – a feature not achievable through local observability alone.

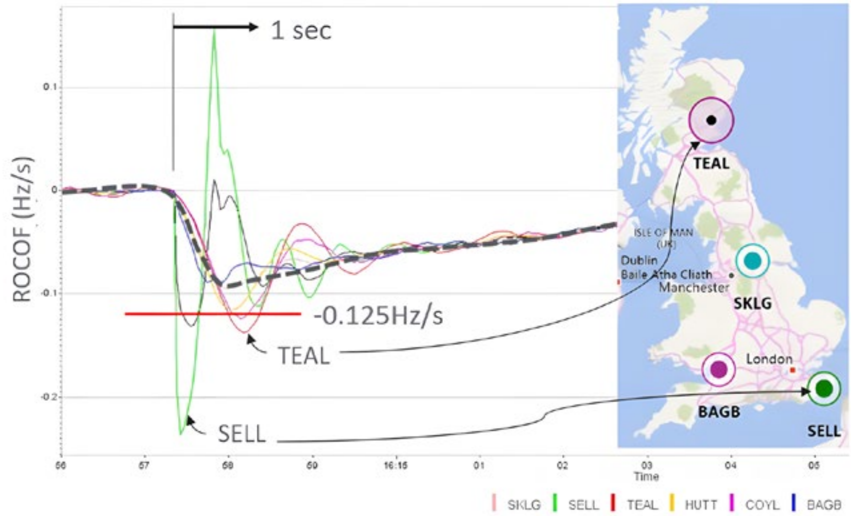


Figure 14: Wide-area frequency/RoCoF during a disturbance

Multiple assets can be included in this orchestration, such as FACTS, IBRs, conventional generation, load shedding, and more, to damp oscillatory behaviors, and provide fast frequency response and control voltage or angular stability challenges (more regional). Supported by modern data-driven techniques, ZAC will complement WAMPAC and central dispatch and operation, ensuring an effective response to the system's operation and improved participation of flexible resources.

The benefit of wide-area observability is evidenced in a generation loss event (see Figure 14), which shows significant dispersion in frequency and RoCoF between locations in the first few seconds of the event. During large events, the impact experienced by the grid in the initial seconds is also when control actions can be most effective in arresting further stability issues. Therefore, the response must be carefully coordinated to prevent aggravating the impact to the system.

Wide-area observability is vital for event responses, as localized measurements may delay response or provide inaccurate assessment. For instance, Figure 15 shows a large RoCoF during a line-trip event without net power loss, necessitating no response. Comparing frequency measurements from neighboring areas helps determine event types and responses quickly, preventing unnecessary actions that could destabilize the grid.

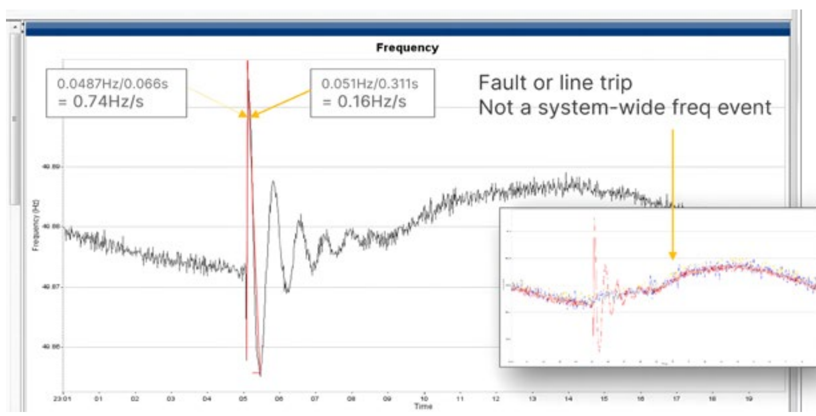


Figure 15: Utilizing local measurements alone vs. wide-area

Protection devices are a fundamental line of defense against grid instability. However, as network conditions change more frequently, the demand for adaptive protection schemes is growing. These schemes dynamically adjust settings in response to near real-time system conditions – to improve the responsiveness and resilience of power systems. The area of protection is changing significantly in response to these new trends including virtualization of protection and control, advanced System Integrity Protection Schemes (SIPS), and increased observability at the grid edge through distribution automation which is greatly improving the ability to identify, and react to, faults within networks and improve system restoration times.

Apart from the electrical measurements, an understanding of the non-electrical parameters, such as asset health and impact of overloading, communication status of various assets/controllers, and system security considerations would be needed to achieve a holistic solution to the grid stability challenge. Improved distributed electrical sensing solutions would further improve the observability of the system and may have to extend beyond the fundamental phasors, due to the controller interactions that would result in sub/super-harmonic oscillations in the network.

5

CASE STUDY: SPAIN AND PORTUGAL BLACKOUT SUMMARY

On April 28, 2025, at 12:33 PM CEST, the power systems of Spain and Portugal suffered a total blackout. A small area in France, close to the border with Spain, was also affected for a limited time by the incident. The rest of Continental Europe did not experience any disturbance.

Following the blackout incident, the European Network of Transmission System Operators for Electricity (ENTSO-E) and its member TSOs set up a joint expert panel to investigate root causes and propose recommendations.

Red Electrica de España (REE) on June 18, 2025 published an initial report on the analysis of the blackout.

In tandem, the Spanish government also has issued three key documents:

- July 17, 2025 – Non-confidential report detailing the analysis of the blackout and initial actions[24].
- June 26, 2025 – Royal Decree Law (Real Decreto Ley): "On the modification of operating procedures for the development of a voltage control service in the Spanish mainland electricity system"[25]
- July 8, 2025 – A list of 65 specific actions to be incorporated as a new specific "Modification to the Development Plan of the Electricity Transmission Network 2021-2026"[26].

The published reports point to different events and system disturbances before and during the blackout cascade. Data shows power system oscillations at two different instances before 12:33 PM, overvoltage and lack of coordination/ response in the actions to control system voltage, and large-scale generation disconnection at the inception of the blackout. More clarifications are expected from ENTSO-E and relevant stakeholders in Spain and Portugal.

24 Non-confidential version of the report of the committee for the analysis of the circumstances surrounding the electricity crisis of the 28th of April 2025, Government of Spain, June 2025, LINK

25 "Blackout in Spanish Peninsular Electrical System the 28th of April 2025", Red Electrica, June 2025, LINK

26 "Modification to the Development Plan of the Electricity Transmission Network 2021-2026", Strategic Energy Europe, June 2025, LINK

Blackout Chronology[27]

Before the Blackout

Just before the incident, Spain's generation mix was 55% solar, 11% wind, 10% hydro, and 10% nuclear (Figure 16). Spain was exporting 1,000 MW to France, 2,000 MW to Portugal, and 800 MW to Morocco. Portugal's mix was also renewables-heavy, dominated by solar, wind, hydro, and biomass, with minimal gas generation (Figure 17).

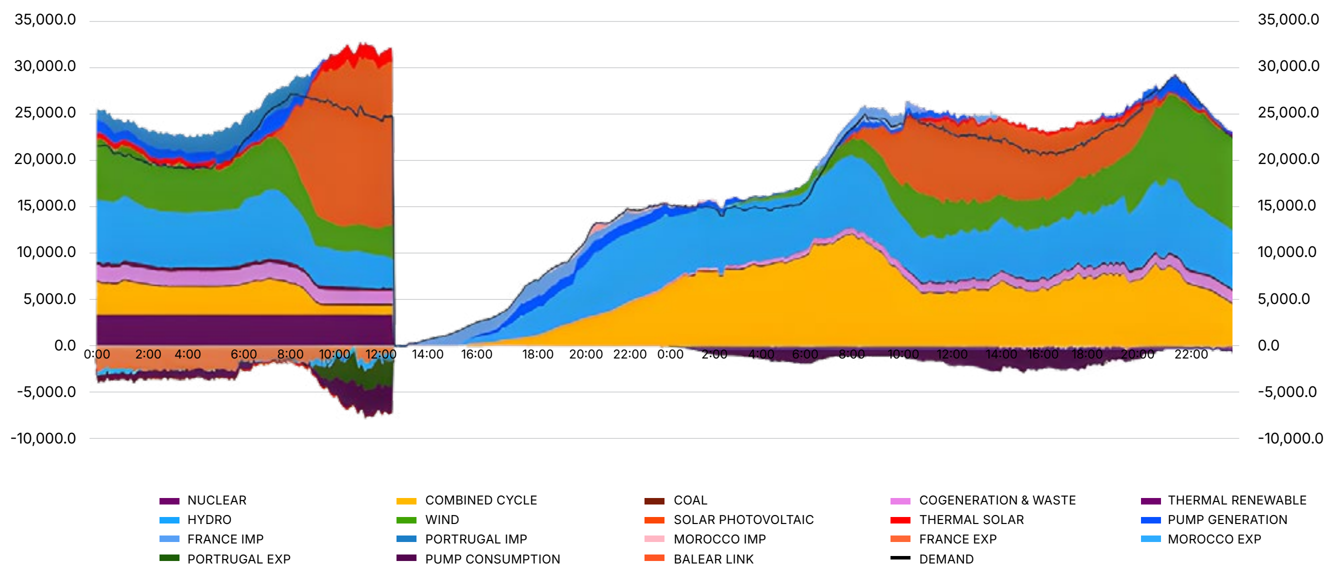


Figure 16: Spain's power generation mix on April 28, 2025

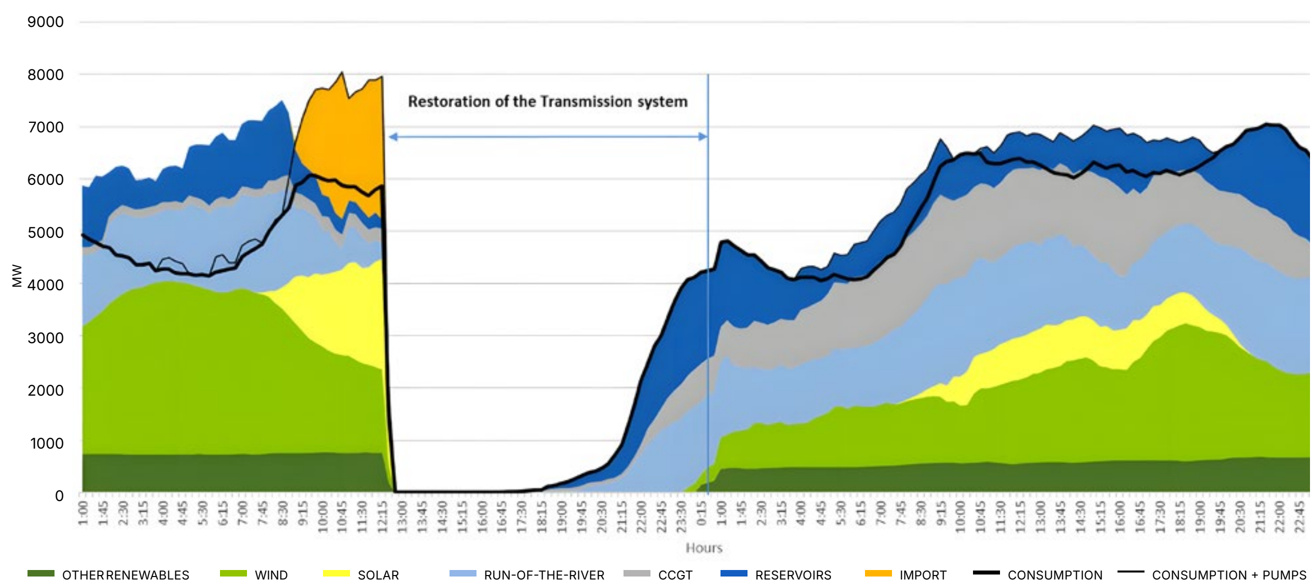
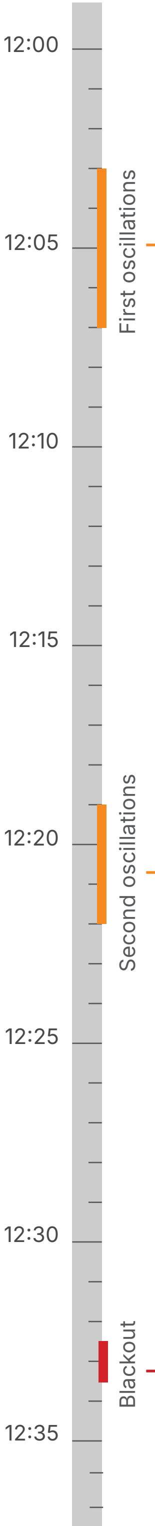


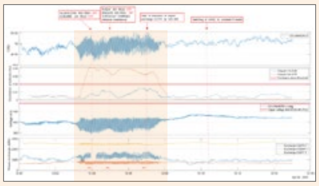
Figure 17: Portugal's power generation mix on April 28, 2025

27 "28 April 2025 Blackout", ENTSO-E, April 2025, LINK

The official sequence of events



12:03-12:07 - First oscillations

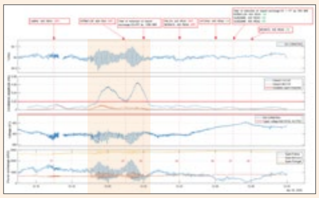


A 0.6 Hz local oscillation combined with a 0.2 Hz inter-area mode oscillation observed.

Voltage fluctuations reached 30 kV.

- Spain-France HVDC link to reduced by 800 MW and in fixed power mode (stabilize system)
- Additional measures were also applied to further improve the system damping. Voltage levels were affected but remained within operational limits.

12:19-12:22 - Second oscillations

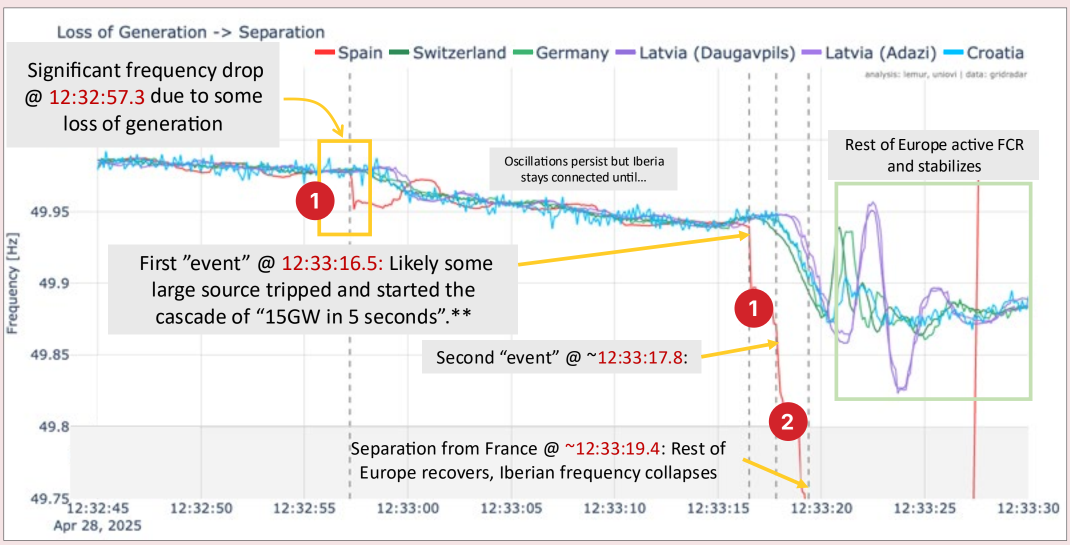


A new 0.6 Hz local oscillation combined with a 0.2 Hz inter-area mode oscillation observed.

Voltage fluctuations reached 28 kV

- Countertrading measures reducing power flows between France and Spain
- Coupling of the internal power lines in the South of Spain. Actions resulted in further voltage increase across the country (within operational limits).

12:33- Blackout



Iberia April 28 Blackout analysis, LEMUR-Universidad de Oviedo, May 2025

Voltage impact

1. Generation trips at 12:32:57, 12:33:16 and 12:33:17, and this creates voltage increases in the grid.
2. Between 12:33:18 and 12:33:21, the voltage of the South area of Spain increased sharply; the over-voltage triggered a cascade of generation losses that caused the frequency of the Spanish and Portuguese power system to drop

System Restoration

- As soon as the disruption of the electricity supply occurred and in the following hours, the TSOs worked together to restore power in the affected regions:
  - Interconnection between France and Morocco was brought back.
  - Generation plants in both Spain and Portugal started their process to initiate system restoration.
  - Interconnection between Portugal and Spain was brought back at 21:35 CEST.
- Power was restored in Spain over a period of several hours. By the evening of April 28, most of the Iberian Peninsula had power again. By 07:00 CEST on April 29, electricity had been restored to 99% of Spain's energy demand. In Portugal, half of the population regained power by 21:30 CEST and 80% by midnight. Full supply was reported early next day.

Key Takeaways

- This was not a cyberattack.
- The Iberian power system had enough generation, and low inertia was not the cause of the blackout.
- Low inertia and in general fast controls associated with converter-interfaced renewable generation may have had a role in the acceleration of the cascading system failure.
- The blackout was not triggered by frequency collapse, but a drop in frequency caused by generation disconnection resulted in the final cascading system failure.
- System voltage and its control (both technical and market driven) had a central role in the blackout.
- Local power oscillations and inter-area mode oscillations had an important role in the blackout with further analysis needed to understand what caused the local modes and potentially misalignment of power plant controllers.
- System actions to address power oscillations contributed to additional voltage instability.
- Load shedding reduced demand (thus addressing frequency drops) but then resulted in further voltage increase.
- Embedded generation disconnection further contributed to system collapse.
- Conventional protection focusing on frequency needs to be revised in the light of voltage instability and increasing penetration of converter-interfaced generation.
- Higher penetration of converter-interfaced generation has introduced new stability phenomena in the power system.

Identified Recommendations of the Spanish Government

The Royal Decree Law 7/2025 published on June 26, 2025, and the following additional list of actions published on July 8, 2025, contain several specific recommendations that would significantly bolster the resilience, robustness, and stability of the Spanish electricity system while increasing electrification and the integration of a growing share of renewable energy sources. Key recommendations include:

- Enforce stricter compliance and review relevant grid codes (including protection settings)
- Participation of renewable energy generators in voltage control
- Enhance dynamic voltage control system capabilities (e.g., through synchronous condensers and STATCOMs)
- Increase the demand and flexibility of the electricity system including storage capacity
- Increase level of interconnection with neighboring countries
- Increase industrial demand

6

CONCLUSION

As has been detailed, grid stability is becoming an increasingly complex challenge. The power system is undergoing significant structural changes, including a greater reliance on IBRs, aging infrastructure, congested grids with long-distance power flows, and the emergence of more complex electrical loads.

Addressing new stability challenges requires an integrated system planning approach, system-wide perspective (aggregating interactions of **generation, transmission, and loads), the appropriate deployment of innovative technologies such as HVDC, hybrid FACTS solutions, and advanced EMS/near real-time orchestration**.

As power systems continue to evolve, ensuring stability will require an adaptive and technology-drive approach. Stronger ties between system operators & integration solution providers will be critical to build the most capable and cost-optimized solutions required in each system and zone.

At GE Vernova, we're committed to delivering innovative solutions that help utilities navigate complexity, strengthen resilience, and build a more reliable grid for the future. GE Vernova offers a portfolio of advanced solutions that support grid stability including HVDC systems, FACTS technologies such as STATCOMs and synchronous condensers, as well as wide-area monitoring systems and digital protection platforms designed for near real-time situational awareness and adaptive control.

Acknowledgement

GE Vernova gratefully acknowledges the contribution from INESC TEC team to this white paper

7

ABBREVIATIONS/ GLOSSARY

AI	Artificial Intelligence
CPL	Constant Power Load
EAF	Electric Arc Furnace
FACTS	Flexible Alternating Current Transmission System
GFM	Grid-Forming
GFL	Grid-Following
IBR	Inverter-Based Resource
LFP	Lithium Ferro-Phosphate
LTO	Lithium-Titanium-Oxide
MVAr	Mega-Volt Ampere Reactive
NMC	Nickel-Manganese-Cobalt
POD	Power Oscillations Damping
PV	Photovoltaic Solar
RoCoF	Rate of Change of Frequency
STATCOM	Static Synchronous Compensator
SSSC	Static Synchronous Series Compensator
TSO	Transmission System Operator
UPFC	Universal Power Flow Controller
WAMS	Wide-Area Monitoring Systems
WAMPAC	Wide-Area Monitoring, Protection, and Control
ZAC	Zonal Autonomous Control

For more information, visit
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