TESLA

Grid-Forming:
The Path to a Stable and Sustainable Future

Why Grid-Forming Inverters are Key to Future-Proofing the Power Grid

May 2025

Executive Summary

The integration of renewable energy sources into the global power grid is shifting the landscape of grid stability and reliability. As traditional synchronous machines that have long stabilized the grid are phased out, new technologies must be adopted to fill this crucial role. This whitepaper explores the importance of grid-forming technology for grid stability, and why Independent System Operators (ISOs) should incentivize adoption of grid-forming inverters to ensure a reliable and resilient grid.

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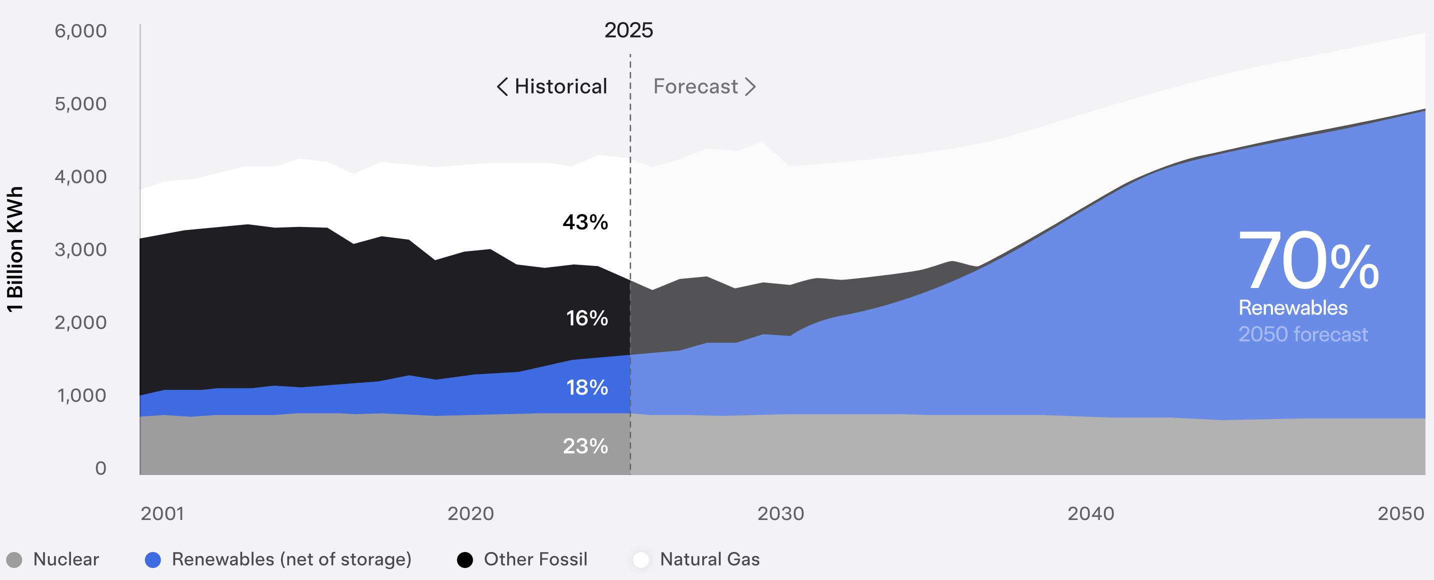
Introduction

As inverter-based renewable energy sources, like solar, wind and batteries, become a larger proportion of the overall energy mix, solutions are needed to manage increased intermittency and maintain grid stability. Historically[1], stability has been supplied by large, spinning synchronous generators that provide critical grid-forming functions, including inertia, voltage regulation, frequency support, and fault ride-through. As these synchronous generators are phased out, renewable energy systems need to provide the same stability features. Grid-forming inverters offer a clean alternative to traditional rotating machinery and provide a solution to the challenges of grid stability. This paper advocates for Independent System Operators (ISOs) to accelerate the adoption of grid-forming systems through markets incentives, updated interconnection standards, and regulatory frameworks that prioritize this advanced technology.

U.S. Electricity Generation from Selected Fuels
Annual Energy Outlook 2025 Reference case

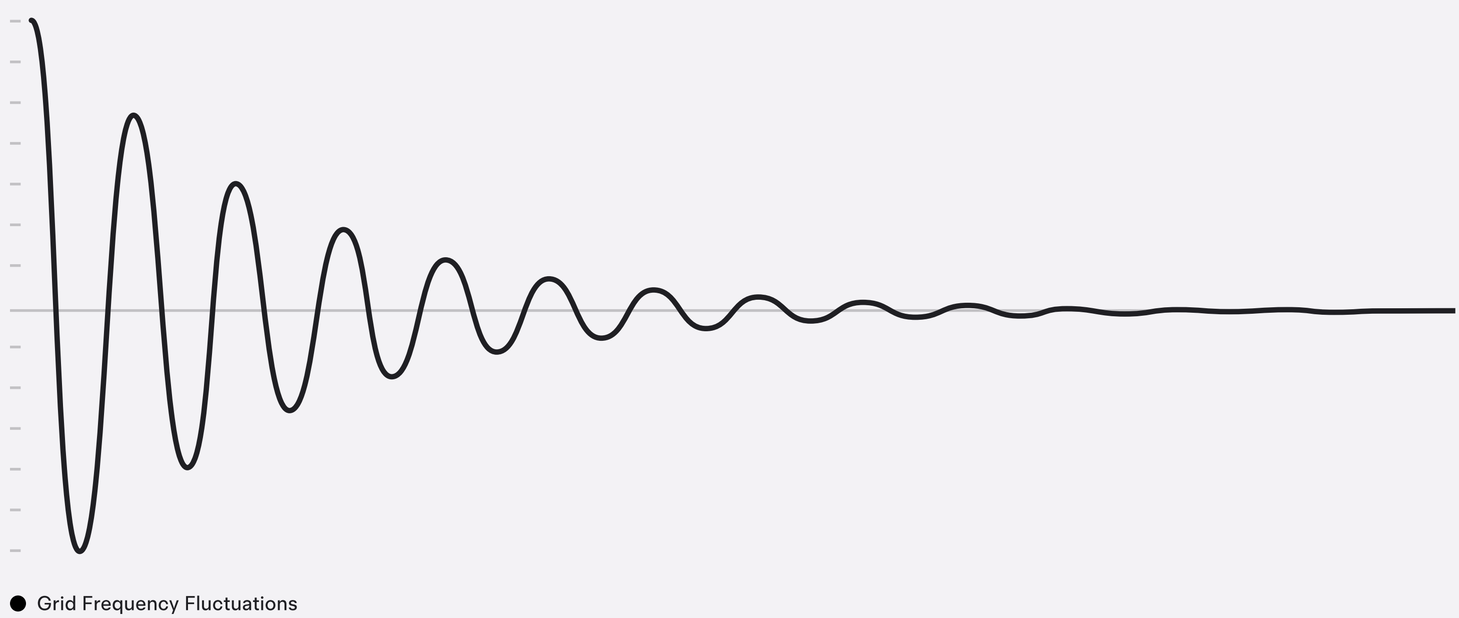


Source: www.eia.gov/outlooks/aeo/index.php

1 Y. Cheng et al., "Real-World Subsynchronous Oscillation Events in Power Grids With High Penetrations of Inverter-Based Resources," in IEEE Transactions on Power Systems, vol. 38, no. 1, pp. 316-330, Jan. 2023, doi: 10.1109/TPWRS.2022.3161418.

What is Grid-Forming?

Grid-forming contributes to grid stability much like a car's shock absorbers—it dampens fluctuations and maintains smooth operation, even during disturbances. Just as a vehicle without shock absorbers could lose control, a grid without proper damping could experience a blackout. Traditionally, fossil fuel-based synchronous generators have performed this grid-forming function by using mechanical inertia and rotational energy to stabilize voltage and frequency. Grid-forming inverters can achieve this same stabilizing function by independently establishing and regulating grid voltage and frequency and responding sub-cycle to counteract grid disturbances.



Why is Grid-Forming Technology Essential?

The ongoing shift from fossil fuel-based synchronous generation to inverter-based renewable energy systems, such as solar and wind, has created new opportunities for innovation and advancement in grid operation. Most renewable energy systems use grid-following inverters, which work with an external grid voltage and frequency as a reference to produce power. As power grids incorporate more of these grid-following renewables to replace traditional sources, grid stability will decrease if not managed. In these weak grid conditions, maintaining the stable voltage and frequency required by grid-following inverters becomes challenging. This creates a need to introduce grid-forming inverters that can independently maintain voltage and frequency without relying on external sources.

Grid-forming inverters aren't dedicated solely to performing grid-forming functions—they can be commanded just like grid-following inverters and therefore perform similar power and energy services. However, adding grid-forming inverters ensures existing and future grid-following renewable energy sources can operate effectively and continue to supply power during disturbances. This enables greater integration of renewables while preserving grid resilience.

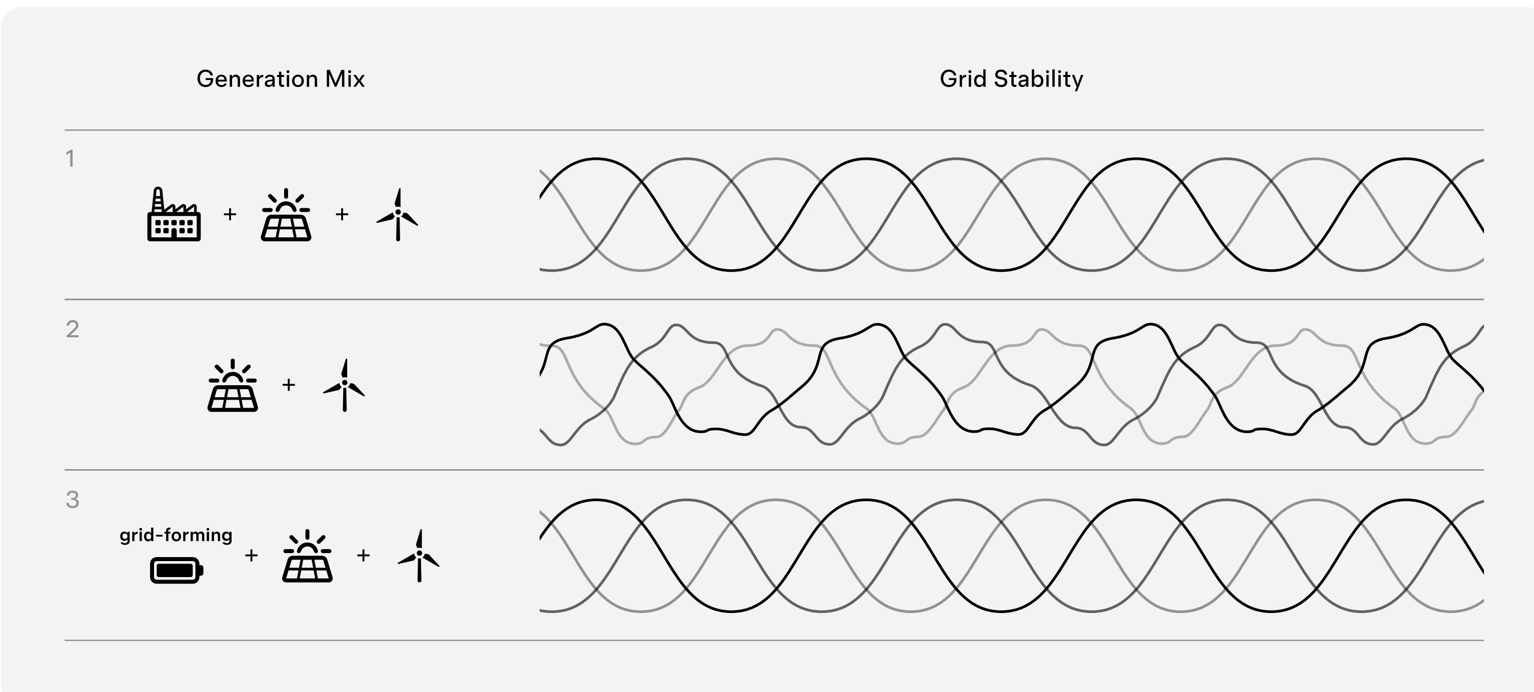


Figure 1. Grid Voltage Stability with 1) synchronous machine, 2) grid-following only and 3) grid-forming

Grid-Forming Inverter Capabilities and Benefits

Grid-forming inverters function as stable voltage sources that can respond to grid disturbances on a millisecond basis, like a synchronous machine would. Grid disturbances are common and can be caused by various issues including equipment failures, severe weather or even cyberattacks.

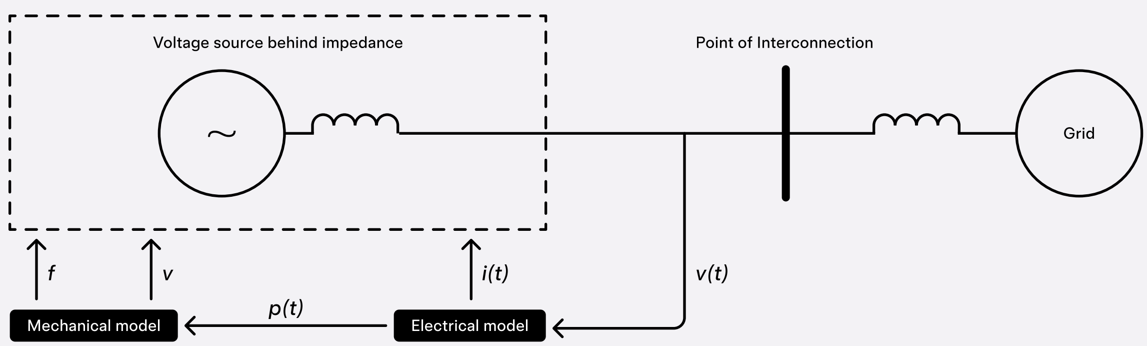


Figure 2. Grid-Forming Inverter Controls

These grid-forming inverters offer several key benefits over traditional grid-following systems when responding to grid disturbances:

Voltage Regulation
They can respond to sub-cycle voltage deviations and provide or absorb reactive power as needed, supporting voltage stability.

Fault Current Capability
They have the capability to provide fault current and continue operating during and after a grid fault (e.g., short circuits or other disturbances), without disconnecting or tripping offline.

Frequency Regulation
They offer droop-based frequency support and synthetic inertia, helping manage grid frequency during disturbances.

Blackstart Capability
They can initiate grid restoration during outages without requiring an external power source.

Grid-forming inverters provide voltage regulation, frequency regulation and fault ride-through capabilities under extreme grid conditions including when the grid is weak and less stable. These benefits are essential as the grid moves towards higher levels of renewable energy penetration. In contrast, grid-following inverters only offer these advantages when the grid is strong and stable.

Voltage Regulation

Grid-forming inverters regulate voltage by rapidly responding to instantaneous voltage deviations, supplying or absorbing current to counteract change. This is particularly useful in weak grids or islanded microgrids where traditional synchronous generators may be absent.

At the inverter-level, there are two main benefits to operating in grid-forming mode:

1. The inverter maintains its own voltage reference, eliminating reliance on the grid to provide a clean, harmonic-free voltage waveform - a common challenge in weaker grids. Similar to a synchronous generator, this self-reliance not only enables the grid-forming inverter to operate but also creates a stronger, more stable grid for nearby grid-following resources.
2. Some grid-forming inverters can respond to voltage disturbances with remarkable speed to counteract them. Similar to synchronous generators but unlike grid-following inverters, they can react sub-cycle to grid disturbances. This is illustrated in the figure below, where a grid fault depresses two phases of the voltage (VB and VC), and the grid-forming inverter immediately provides corrective current to counteract the voltage drop.

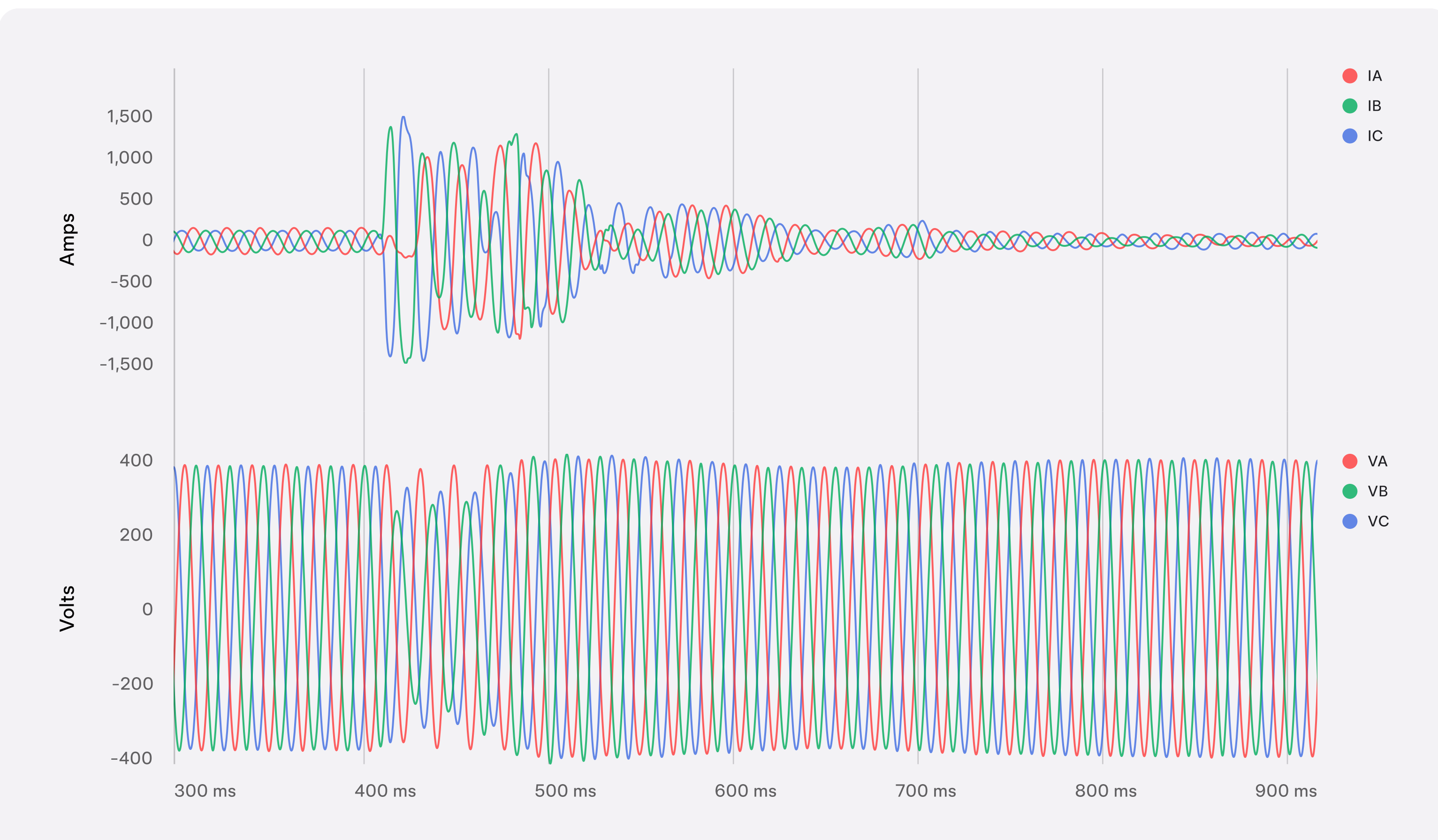


Figure 3. Grid-Forming Inverter Sub-Cycle Reaction to Voltage Disturbance

Fault Current Capability

Modern inverters are designed with fault ride-through capability, allowing them to continue operating and support voltage recovery during grid disturbances. While both grid-following and grid-forming inverters offer this capability, their approaches differ significantly. This section discusses the references used to produce fault current and the type of current produced.

During grid faults, voltage drops and becomes unstable. Grid-following inverters often struggle in these conditions because the grid voltage is not stable enough to “follow”. They may enter a “tail-chasing” pattern as they continually search for synchronization with the grid, which can worsen the instability through incorrect measurements and power output. Grid-forming inverters handle these situations more effectively. Like traditional synchronous generators, they act as voltage sources behind an impedance, providing a stable response without “tail-chasing” behavior seen in grid-following inverters.

In addition to the reference used to produce the fault current, the type of fault current produced is also important. The transmission grid relies on protection relays to detect short circuits and other grid anomalies and isolate them from the grid. These protection relays analyze voltage and current measurements and identify known event patterns. These patterns often are based on a symmetrical component, a mathematical method that converts per-phase voltage and current measurements to positive, negative and zero components.

When faults occur near a grid-forming inverter, its response mirrors the current components produced by synchronous generators. When an unbalanced fault occurs near a grid-forming inverter, the fault current sequence contribution follows the impedance characteristics between the source and the fault. This fault behavior closely resembles that of traditional synchronous generators, maintaining compatibility with established protection techniques, such as distance and directional protection. As a result, grid-forming inverters may not require significant, costly updates to the grid's existing protection systems.

Frequency Regulation

Grid-forming inverters can provide frequency support through droop-based control and synthetic inertia. These behaviors are crucial in systems with low mechanical inertia due to the reduction of synchronous generators. For frequency support with synthetic inertia, grid-forming inverters adjust their power output in response to changes in frequency—reacting near instantaneously and proportionally to the rate-of-change-of-frequency, reducing changes in power system frequency and helping stabilize the grid during disturbances. Grid-following inverters can also provide frequency support, but not with the sub-cycle response that is achieved by grid-forming inverters and synchronous generators.

For example, when a power source unexpectedly disconnects, the grid frequency decreases as there is no longer enough generation to supply the load.
A synchronous machine's rotor—which must spin at the grid's frequency—slows down with the grid. As it slows, it naturally dissipates power, which counteracts the frequency drop. Grid-forming inverters mimic this behavior to support frequency, but with the added benefit that their response can be tuned to meet specific grid needs and adjusted over time. In contrast, a synchronous generator's response is dictated by its physical characteristics and cannot be changed.

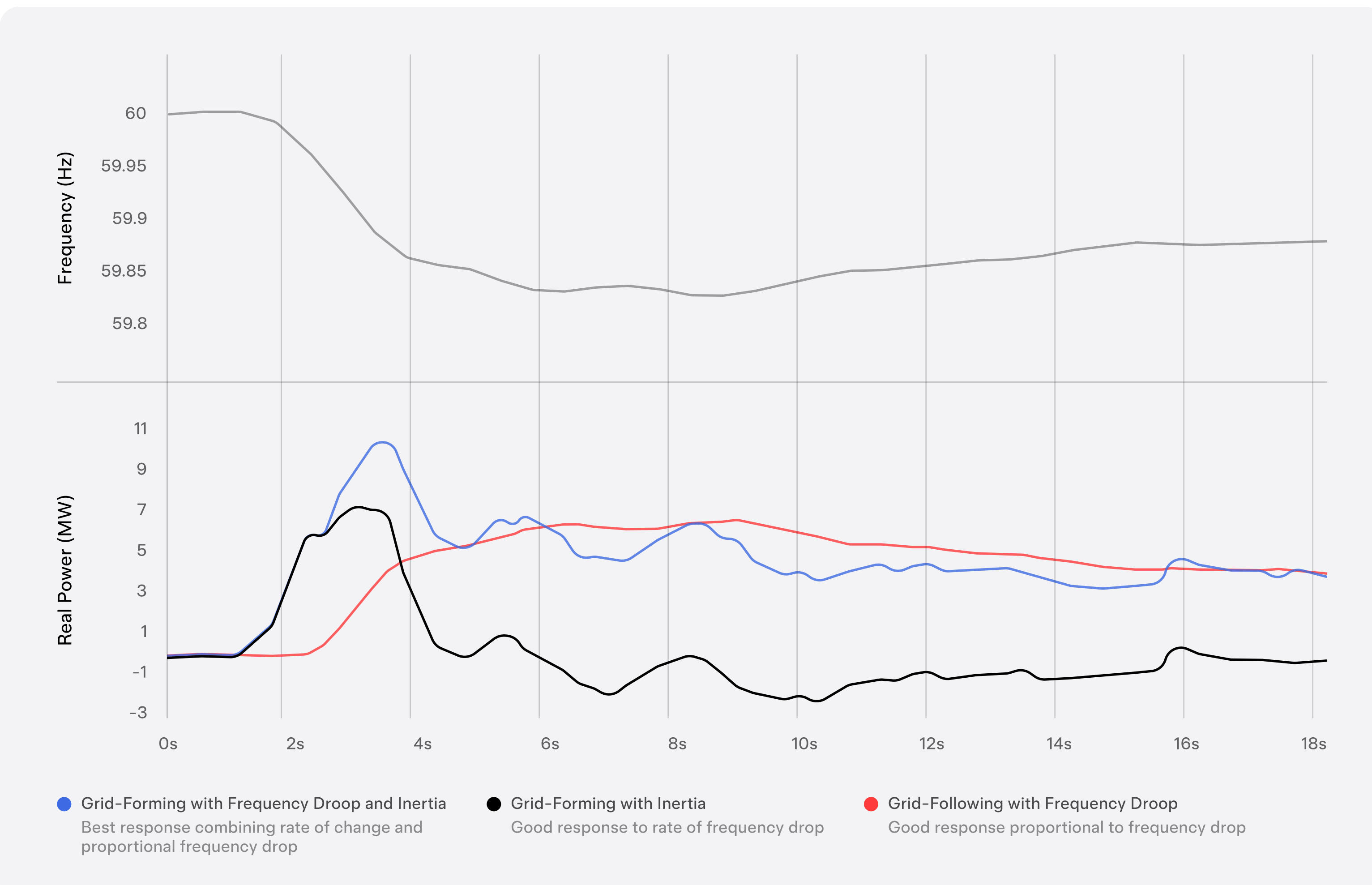


Figure 4. Example Responses from Grid-Forming and Grid-Following Inverters to a Frequency Disturbance

Blackstart Capability

In the event of a blackout or system-wide power outage, system restoration relies on energy sources that can establish a stable voltage and frequency independently—also known as blackstart. Grid-forming inverters can provide blackstart capabilities by acting as a stable power source, enabling the grid to restore without depending on external voltage or power sources.

Traditional synchronous generators require external power to start their pumps and compressors. To provide grid blackstart capability, these generators need additional on-site power sources. As a result, grid operators rely on pre-designated blackstart-capable plants equipped with this extra equipment, allowing them to restart without grid power.

Grid-forming energy storage systems (ESS) are ideal for blackstart operations because of their stored energy and minimal auxiliary load requirements. Unlike grid-following inverters, which require an external voltage reference, grid-forming batteries can independently establish a voltage waveform, energizing a local area without needing a nearby synchronous generator. Once operational, these inverters can enable startup of grid-following renewable energy sources, such as solar and wind, by providing the stable voltage and frequency needed for their operation.

The blackstart process begins by isolating key grid sections and selectively energizing loads and transmission lines. Each grid-forming battery plant provides a stable voltage reference in its assigned section. Once voltage is stable, the battery can power auxiliary load to recover traditional plants or bootstrap grid following renewables online. As sections stabilize, they are gradually synchronized and reconnected, with load introduced in stages. This process is illustrated in Figure 5.

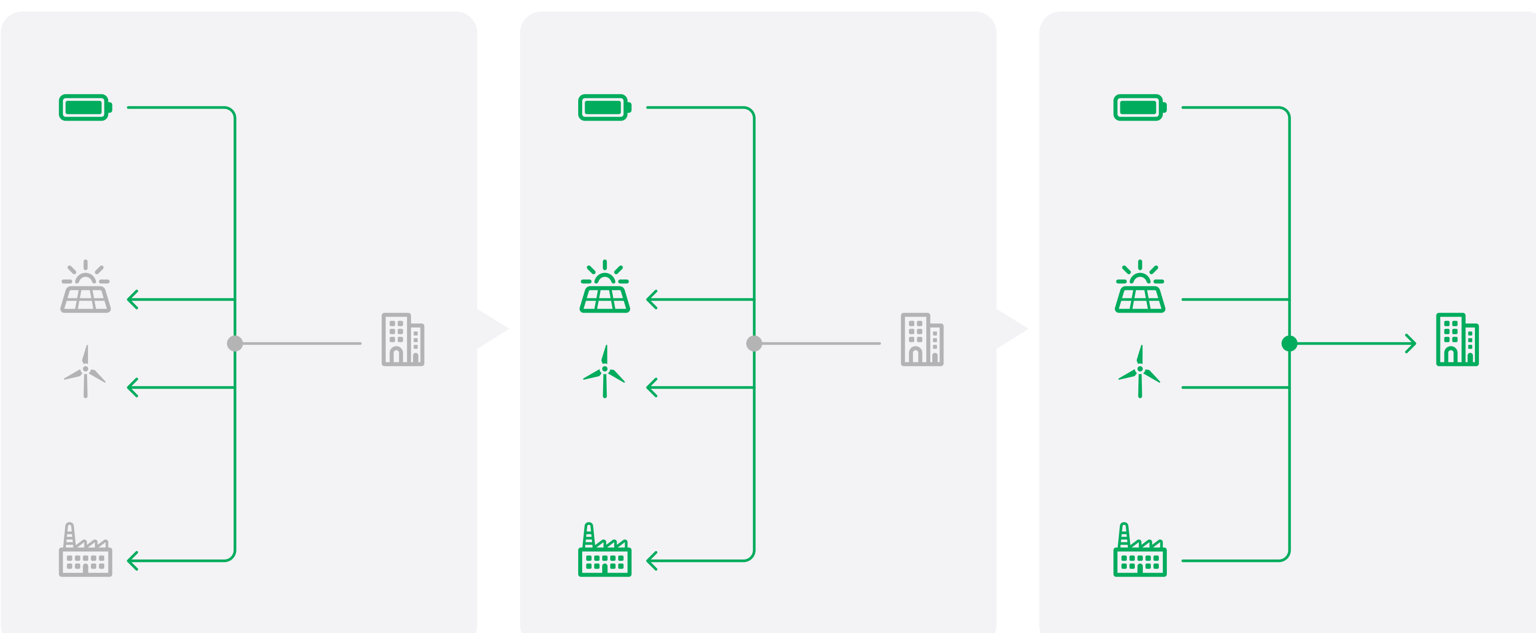


Figure 5. Blackstart with Grid-Forming Inverters on a Simplified Grid

Common Misconceptions About Grid-Forming Inverters

This section addresses some of the common misconceptions surrounding grid-forming inverters including short circuit current and use of phase-locked loops

Short-Circuit Current

“Short-circuit current is the best indicator for grid-strength.”

A common misconception is that a higher short-circuit current indicates greater grid strength[*]. Traditionally, synchronous machines provided both short-circuit current and a grid-forming voltage source, making short-circuit measures a rough proxy for electrical distance to a grid-forming source. However, grid-forming inverters can support voltage without significantly contributing to the short-circuit current[2], so these measures may no longer be reliable indicators of grid strength.

“Inverters cannot provide enough short-circuit current for protection to operate properly.”

Typically, grid-forming inverters supply short circuit current up to approximately 120% of their rated capacity. However, if a system needs to provide more fault current relative to the inverter’s rating, additional inverters can be deployed to increase the short circuit current.

Protection relaying schemes and fault detection at the transmission level do not rely heavily on high levels of fault current. However, at the distribution level, protection schemes typically depend on high levels of current and will likely require a source of higher fault current to operate as-is.

[*] Grid strength refers to how well the electricity grid can maintain stable voltage and power quality, both during normal operations and in response to unexpected events—such as a generator shutting down or a fault on a power line. A strong grid can quickly recover from these disturbances and continue operating smoothly. In contrast, a weak grid is more vulnerable to voltage instability and even power outages. Maintaining sufficient grid strength is increasingly important as more renewable sources like wind and solar are added.

2 T. Ackermann, T. Prevost, V. Vittal, A. J. Roscoe, J. Matevosyan and N. Miller, "Paving the Way: A Future Without Inertia Is Closer Than You Think," in IEEE Power and Energy Magazine, vol. 15, no. 6, pp. 61-69, Nov.-Dec. 2017, doi: 10.1109/MPE.2017.2729138.

Common Misconceptions About Grid-Forming Inverters

Phase-Locked Loop (PLL) Reliability

"Phase-Locked Loops are inherently unreliable."

PLLs are measurement algorithms in inverters that determine the grid voltage frequency or phasor. They adjust the inverter's internal frequency and phase to match the grid and are commonly used in grid-following inverters to synchronize their output with an external grid reference for power delivery.

A common misconception is that PLLs are inherently unreliable on weak grids, and therefore any use of them is frowned upon. First, modern PLLs have become more stable and are better at maintaining grid stability than older PLLs. Second, grid-forming inverters establish a strong voltage and frequency reference independent of external signals. This reference enables reliable operation of PLLs. As a result, PLLs can operate effectively alongside grid-forming sources, enabling fast power dispatch without compromising system stability[3].

Refer to the new EPRI paper:
"GFM inverter control architecture may also have the presence of high bandwidth current control within the first, fastest level of control."

Voltage Sags During Frequency Events

"Grid-forming can prevent voltage sags during frequency events."

Voltage sags are a natural consequence of increased power transfer during frequency disturbances, regardless of the type of generation or control method employed. Grid-forming inverters and synchronous generators cannot prevent these sags; this is a necessary trade-off, as their primary role is to counteract disturbances and prevent rapid shifts in the local phase angle. The primary goal during such events is to maintain synchronization and stabilize the grid frequency. The network voltage will recover once the grid is resynchronized and phase-angle separation across different areas diminishes.

3 Miller, Nicholas & Pourbeik, Pouyan & Ramasubramanian, Deepak & Walling, Reigh. (2024). An Overview of Grid-Forming Inverter Technologies and the Readiness of Power Systems Worldwide to Deploy the Technology. Epri.com, www.epri.com/research/products/000000003002031346.

Conclusion

As the energy landscape shifts towards renewable sources, the integration of grid-forming inverters is essential for ensuring a stable, resilient, and reliable grid. To facilitate this transition, grid-forming inverters must become a standard requirement for all inverter-based systems. Incentivizing the adoption of grid-forming inverters through market incentives and ISO standards ensures a future grid that can support high levels of renewable energy while maintaining stability and reliability.

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