

## MarSum Solutions: Grid-Forming Inverters for High-Renewable Power Systems

Renewable energy projects are moving from supplemental generation toward becoming the dominant source of electricity on many power systems. As solar, wind, battery storage, and high-voltage power electronic interfaces replace synchronous generation, the grid loses some of the natural voltage and frequency support historically provided by rotating machines. Grid-forming inverters are emerging as a practical answer to that transition. Instead of simply following an existing grid waveform, a grid-forming inverter can establish and regulate voltage and frequency, allowing inverter-based resources to help stabilize low-inertia grids, support islanded operation, and participate in restoration after outages.

This paper explains the engineering difference between grid-following and grid-forming inverter controls, the capabilities that matter in high-renewable grids, and the project environments where these technologies are becoming most valuable. It also highlights the integration challenges that developers, utilities, and equipment suppliers must address before grid-forming capability becomes a reliable part of project delivery rather than a feature listed on a datasheet.

### Why high-renewable grids need a new stability model

Traditional grids were built around synchronous generators. Their spinning mass provides stored kinetic energy, their excitation systems regulate voltage, and their short-circuit behavior helps protection systems detect and isolate faults. High-renewable grids behave differently. Solar photovoltaic plants, wind turbines, battery energy storage systems, and many high-voltage direct current (HVDC) links connect through power electronic converters. These inverter-based resources can respond very quickly, but their behavior is determined by controls, current limits, protection logic, and plant-level coordination rather than by electromechanical inertia alone.

At modest inverter penetration, many projects can rely on the broader grid to provide voltage and frequency references. At very high inverter penetration, that assumption becomes weaker. The system still needs a stable voltage waveform, frequency reference, reactive power support, fault behavior, damping, and restoration strategy. Grid-forming technology matters because it moves some of those stabilizing functions into the inverter controls themselves.

### Grid-following vs. grid-forming inverters

The distinction is not simply a hardware difference. In many cases, the power stage may look similar. The important difference is the control philosophy and how the inverter behaves when the grid is weak, disturbed, or absent.

#### Grid-following inverter behavior

A grid-following inverter synchronizes to an existing voltage waveform, typically using a phase-locked loop (PLL) or related synchronization method. Once synchronized, it injects controlled current to deliver active and reactive power according to its command set. This approach works well when the grid is strong enough to provide a stable voltage and frequency reference. Grid-following controls are common in today's solar, wind, and battery systems because they are mature, efficient, and well understood. However, they generally assume that something else is already forming the grid.

#### Grid-forming inverter behavior

A grid-forming inverter behaves more like a controlled voltage source. It maintains an internal voltage angle and magnitude reference and regulates its terminal voltage and frequency within defined current and energy limits. Instead of asking, "What waveform should I follow?" the control objective is closer to, "What waveform should I establish while sharing power with the rest of the system?" This enables support for weak grids, islanded systems, black-start sequences, and high-renewable networks where synchronous generators are reduced or absent.

### Core capabilities that matter in low-inertia systems

Grid-forming performance is not a single checkbox. A useful specification must describe what the inverter can do, how it behaves during faults and transients, and how the plant controller coordinates multiple devices under real operating constraints.

**Voltage and frequency regulation:** The inverter must establish and regulate a usable AC waveform while sharing active and reactive power with other resources. Droop control, virtual synchronous machine behavior, virtual oscillator control, and related approaches can all be used, but the project requirement is the same: stable voltage and frequency behavior across normal operation and credible disturbances.

**Low-inertia grid support:** As synchronous inertia falls, the grid has less natural buffering against sudden generation or load changes. Grid-forming controls can provide fast frequency response and damping, helping reduce the severity of frequency excursions. This support must be coordinated with energy limits, inverter current limits, plant controllers, and system protection settings.

**Black-start and islanded operation:** A grid-forming resource can help energize a dead or isolated system when supported by appropriate controls, stored energy, auxiliary power, and protection coordination. Black start is not just an inverter mode. It requires transformer energization planning, inrush-current management, load pickup sequencing, communications, and clear restoration procedures.

**Fault response and current limiting:** Inverters do not naturally provide the same short-circuit current profile as synchronous machines. Their current is tightly limited to protect power semiconductors and DC-link hardware. Grid-forming projects therefore need intentional fault ride-through behavior, protection coordination, and clear expectations for voltage support during abnormal conditions.

**Reactive power and voltage support:** Voltage stability depends heavily on reactive power response, especially in weak-grid and long-collector-system applications. Grid-forming inverters can support local voltage, but plant-level coordination must prevent devices from fighting each other or saturating current capacity during disturbances.

**Modeling and validation:** Successful deployment depends on models that represent dynamic inverter behavior accurately enough for system studies. Positive-sequence models may be useful early, but electromagnetic transient (EMT) studies are often needed for weak-grid, islanding, black-start, and multi-inverter interaction analysis.

## High-value use cases

Grid-forming inverters are most valuable where renewable generation and storage are expected to do more than produce energy. They become especially important when inverter-based resources must help establish a stable electrical system, ride through disturbances, or maintain service when the main grid is unavailable.

### Microgrids and critical facilities

Microgrids for campuses, military bases, industrial sites, hospitals, and data centers often need to operate both grid-connected and islanded. Grid-forming battery systems or hybrid renewable-storage plants can provide the voltage and frequency reference needed during islanded operation while supporting seamless transitions back to the utility grid.

### Utility-scale battery energy storage

Battery energy storage is a natural platform for grid-forming capability because it can source or absorb power quickly. In high-renewable regions, grid-forming storage can provide stability services that are separate from energy arbitrage, capacity, or renewable smoothing functions.

### Offshore wind and HVDC-connected resources

Offshore wind farms and HVDC-connected generation areas can create grid-forming opportunities and challenges. Converter controls, collector-system resonances, long cable effects, and offshore platform constraints all require careful modeling. In some cases, grid-forming behavior can help stabilize offshore networks or strengthen onshore interconnection points.

### Islanded power systems

Islands and remote communities often rely on diesel generation for grid stability even when solar, wind, or storage is available. Grid-forming inverters can reduce dependence on rotating generators by allowing renewable and storage resources to form the local grid under the right operating conditions.

### Solar and hybrid renewable plants

Large solar plants increasingly include co-located storage, plant-level controls, and interconnection requirements that go beyond simple real-power export. Grid-forming capability can help hybrid plants support voltage and frequency behavior, particularly in weak areas of the network or at the edge of transmission systems.

### System restoration and resilience

As conventional black-start units retire or run less frequently, utilities need restoration strategies that include inverter-based resources. Grid-forming controls can support bottom-up restoration, but only when equipment ratings, auxiliary supplies, switching sequences, communications, and protection systems are designed for that role.

## Markets moving toward grid-forming requirements

Interest in grid-forming technology is rising because renewable targets, reliability requirements, and inverter-based resource growth are all moving in the same direction. Market forecasts point to continued growth in grid-forming inverter demand, with one projection estimating an increase from roughly \$788 million in 2025 to about \$1.3 billion by 2031. The practical driver is straightforward: high-renewable systems need stability services, and those services must increasingly come from power electronics.

**United States:** The U.S. market is shaped by utility-scale solar, battery storage, resilience-driven microgrids, island grids, and transmission-level reliability needs. Federal and state clean-energy goals increase the need for inverter-based resources that can provide more than energy production. Developers also face interconnection study requirements, weak-grid constraints, and utility expectations for validated models and predictable disturbance behavior.

**Europe:** Europe is moving aggressively toward higher renewable penetration, with significant wind, solar, storage, offshore wind, and HVDC deployment. Transmission operators are increasingly focused on grid-forming capability, system strength, dynamic voltage support, and harmonized technical requirements for converter-connected resources. These trends make grid-forming design and validation important for both new projects and future compliance planning.

**Island grids and remote systems:** Island systems often feel the low-inertia transition first because they are smaller, weaker, and less able to absorb large disturbances. Grid-forming resources can reduce fossil backup dependence, but the controls must be tuned for local load behavior, generator coordination, protection limits, and restoration procedures.

**Industrial and private-power systems:** Industrial facilities, data centers, ports, mining operations, and large campuses are increasingly evaluating renewable microgrids and storage-backed power systems. For these customers, grid-forming capability is tied directly to uptime, resilience, power quality, and the ability to operate through disturbances without depending entirely on the utility grid.

## Integration challenges that determine project success

The most difficult grid-forming problems are usually not isolated inside the inverter. They appear at the boundary between equipment controls, plant-level coordination, protection systems, utility models, and commissioning procedures. This is why grid-forming projects need a system-level engineering approach from the beginning.

### Controls coordination

Multiple grid-forming devices must share power without unstable interactions. Droop settings, virtual impedance, current limits, phase angle behavior, and plant controller objectives all need to be coordinated across operating modes.

### Model fidelity

Grid-forming behavior can be sensitive to fast control dynamics and network impedance. EMT modeling, hardware-in-the-loop testing, and validated vendor models may be needed to uncover oscillations or fault interactions that simpler studies miss.

### Equipment ratings and energy limits

Grid-forming support is constrained by semiconductor current limits, DC-link energy, battery state of charge, thermal limits, and available reactive power capacity. Specifications must define capability over time, not just instantaneous response.

### Protection and fault studies

Protection schemes designed around synchronous-machine fault current may not operate as expected with current-limited inverters. Projects may require revised relay settings, fault detection logic, ride-through requirements, and staged protection validation.

### Commissioning and mode transitions

A project may need to operate grid-connected, islanded, black-start, resynchronization, and fault recovery modes. Each transition should be defined, tested, and documented so the system behaves predictably under real field conditions.

### Compliance and stakeholder alignment

Utilities, developers, inverter suppliers, protection engineers, and commissioning teams need a shared understanding of what grid-forming performance means for the specific project. Ambiguous requirements can create late-stage test failures or costly redesign.

## How MarSum Supports grid-forming inverter programs

MarSum Solutions supports renewable energy, storage, and advanced power electronics programs with an engineering-first approach focused on performance, robustness, and manufacturability. Grid-forming inverter projects sit directly at the intersection of power conversion, controls, protection, modeling, and system integration, which is where early engineering decisions have the largest effect on project risk.

Our work can include architecture review, grid-following vs. grid-forming control strategy assessment, inverter and plant controller requirements, EMT-oriented modeling support, black-start and islanding concept development, protection coordination review, and validation planning. We also help teams translate broad requirements such as low-inertia support, voltage regulation, ride-through behavior, and restoration capability into testable engineering criteria.

For developers, equipment suppliers, and project teams moving into high-renewable or islanded systems, grid-forming capability should be treated as a core architecture decision rather than a late-stage controls option. A disciplined system-level approach can reduce commissioning risk, improve utility confidence, and support a faster path from concept to reliable operation.

## Engagement models

We support customer teams through focused technical consulting, design reviews, model and controls support, and deeper co-development efforts depending on program phase. Typical engagements range from early feasibility and requirements definition to prototype validation, field-debug support, and production-readiness planning for inverter-based power systems.

**Selected sources:** NREL grid-forming inverter publications; NREL black-start and EMT modeling materials; TechSci Research grid-forming inverter market forecast.

**Contact us today to scope your grid-forming inverter, renewable microgrid, or inverter-based power system project!**