247 ENERGY

Grid-Forming Inverters and Synthetic Inertia

How Battery Storage Replaces the Stability Services That Rotating Generators Once Provided

What every grid operator, developer, and investor needs to understand about synthetic inertia.

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December 2025

FOREWORD

Why I Write About This Now

Few conversations in the energy sector are as technically demanding and as commercially consequential as the one about inertia. I have spent years explaining to investors, regulators, and industrial clients why the retirement of spinning generation does not simply create a carbon dividend but also removes a physical property from the grid that cannot be assumed, only replaced. The replacement is now available, technically proven, and commercially deployable. This paper explains how it works and why acting on it now is not merely prudent but necessary.

The energy transition is often discussed as though its primary challenge is financial: the cost of solar panels, the price of batteries, the economics of offshore wind. These are real considerations, but they are tractable ones. The deeper challenge is engineering: how do we operate a grid that, within a generation, has moved from being dominated by large synchronous machines to being dominated by inverter-based resources that do not inherently participate in frequency regulation? The answer to that question determines whether the transition succeeds reliably or produces a grid that is cleaner but measurably less stable.

Grid-forming inverter technology, paired with large-scale battery storage, offers a credible answer. 247 Energy has built our project development methodology around this conviction, embedding grid-forming capability into our battery storage park designs from the outset rather than retrofitting it as an afterthought. I hope this paper provides the context that investors, developers, and industrial partners need to engage with this opportunity with the confidence that comes from understanding the underlying physics.

James Troch,

Chief Executive Officer,

247 Energy

THE INERTIA DEFICIT

How Modern Grids Lost Their Stability Buffer

The Physical Foundation That Transition Is Eroding

For most of the twentieth century, the physical stability of electrical grids rested on a property that engineers called inertia: the tendency of large rotating masses to resist sudden changes in rotational speed. Every synchronous generator, whether driven by steam, gas, or water, was mechanically coupled to the alternating current grid and contributed its rotational kinetic energy to a shared pool. When generation and demand fell out of balance, that pool absorbed the shock instantaneously, slowing the rate of frequency change and giving automatic control systems time to restore equilibrium. This was not a deliberately designed feature of the grid; it was an emergent property of its dominant technology.

The large-scale deployment of wind and solar generation has changed this picture at a pace that grid operators are still working to absorb. Photovoltaic installations and most wind turbines connect to the grid through power electronic inverters. These devices decouple the generating source electrically from the grid, which enables efficient conversion and flexible control but eliminates the electromagnetic coupling that made synchronous generators natural inertia providers. As fossil-fuel generation retires and renewable capacity expands, the total synchronous inertia of interconnected power systems is falling, and the rate of frequency deviation following sudden generation losses is accelerating.

The technical indicator that captures this change most precisely is the Rate of Change of Frequency, commonly abbreviated as RoCoF. In a high-inertia system, a large generation trip produces a RoCoF of a fraction of a hertz per second, a deviation that reserve providers can manage comfortably within standard response windows. In a low-inertia system, the same event can produce RoCoF values several times higher, reaching frequency levels at which automatic protection systems trip generating units and loads before conventional reserves have even begun to engage. The result is a cascade rather than a correction.

> ***As synchronous generation retires, the grid loses not just carbon but the physical inertia that has silently been its first line of defence for decades.***

Several transmission system operators have already encountered conditions where inertia fell below levels they consider prudent for reliable operation. The responses have included curtailing renewable generation during low-demand periods to keep synchronous machines online, procuring dedicated synchronous condensers to provide inertia without active generation, and tightening the operating envelopes within which inverter-based resources are permitted to connect. Each of these measures represents an operational accommodation of an underlying structural deficit rather than a resolution of it.

The fundamental resolution requires replacing the stabilising functions of retiring synchronous generation with a technology that can provide equivalent services without the associated carbon emissions. Grid-forming inverter technology, deployed through battery energy storage systems, is the leading candidate for this role. It is technically mature, commercially available, and increasingly recognised by grid codes and market frameworks as a distinct and valued service category. The path from recognition to deployment at scale runs through decisions that investors, developers, and policymakers are making today.

GRID-FOLLOWING VERSUS GRID-FORMING

A Fundamental Distinction

Why Control Architecture Determines Grid Value

The inverter is the critical interface between a battery energy storage system and the alternating current grid. Its fundamental task is to convert the direct current output of the battery into alternating current that matches the voltage and frequency of the grid to which it connects. However, the control strategy by which an inverter achieves this match determines whether the asset consumes grid stability or contributes to it.

Conventional inverters operate in what engineers call grid-following mode. They use a phase-locked loop to measure the existing grid voltage and frequency and adjust their output to synchronise with it. Grid-following inverters are robust, well-understood, and commercially dominant across the global storage and renewable sector. Their limitation is intrinsic: a grid-following inverter cannot function without a stable grid to follow. It requires an external voltage and frequency reference. In the absence of such a reference, it cannot operate. A grid populated entirely by grid-following inverters has no anchor.

Grid-forming inverters operate on a fundamentally different control principle. Rather than measuring and following an external reference, a grid-forming inverter generates its own internal voltage and frequency reference and imposes it on the grid connection point. It behaves as a voltage source rather than a current source. This distinction carries three important practical consequences: a grid-forming inverter can operate in the absence of any other voltage source on the network, enabling black-start capability; it can actively resist frequency deviations, providing the inertia-like response that grid-following systems cannot; and multiple grid-forming inverters can share a network and establish a stable collective frequency reference without requiring a synchronous generator as an anchor.

The engineering challenge of designing effective grid-forming control systems is substantial. The control algorithm must simultaneously achieve rapid frequency support during disturbances, stable power-sharing among multiple assets connected to the same network, robust behaviour during fault conditions without nuisance tripping, and seamless transition between grid-connected and islanded operation. Several control architectures have been developed to meet these requirements, including virtual synchronous machine emulation, droop-based control, and matching control frameworks, each with different stability profiles and compatibility characteristics.

For investors and project developers, the significance of this distinction is commercial as well as technical. A battery storage asset equipped with grid-forming inverters can compete for a materially broader range of grid services than a conventional grid-following system. Synthetic inertia contracts, system restoration ancillary services, enhanced frequency response products, and weak-grid support capabilities are all accessible to grid-forming assets but not to their grid-following counterparts. This expanded service portfolio supports more diverse revenue streams and reduces exposure to any single market mechanism.

SYNTHETIC INERTIA

Engineering Frequency Stability Without Rotating Mass

What Inertia Does and Why It Must Be Replaced

Synthetic inertia is the term used to describe the ability of an inverter-based resource to respond to frequency deviations in a manner that replicates the natural inertia response of a synchronous generator. The behaviour it replicates is specific: in the immediate moments following a sudden generation loss, before any automated intervention has occurred, a synchronous generator releases kinetic energy from its rotating mass at a rate proportional to the frequency deviation. This release happens in milliseconds and is the first line of defence against destabilising frequency excursions. Synthetic inertia aims to reproduce this response using power electronics and software rather than rotating machinery.

The distinction between synthetic inertia and conventional frequency response services is important and is increasingly reflected in market design. Standard frequency response services activate within seconds of a frequency deviation and ramp up over a period of tens of seconds. They are valuable but they do not address the initial rate of change of frequency in the first instants after a disturbance. Synthetic inertia targets precisely this window, from approximately zero to two seconds after the event, when the grid is most vulnerable to protection system trips that can convert a manageable disturbance into a wider system event.

> ***Synthetic inertia does not imitate physics; it replicates its effects at a speed that a rotating machine could never match, because millisecond power electronics have no mechanical inertia to overcome.***

Battery energy storage is particularly well suited to providing synthetic inertia because its power electronics can respond within a single cycle of the alternating current waveform. The limiting factor is not the physical response time of the battery but the accuracy of the frequency measurement and the sophistication of the control algorithm that translates a detected frequency deviation into an appropriate power injection. Well-designed grid-forming control systems can achieve response times that equal or exceed those of the fastest conventional reserves, without the need for physical spinning reserves.

Several technical architectures have been developed to provide synthetic inertia from inverter-based resources. Virtual synchronous machine designs replicate the mathematical equations of a synchronous generator within the inverter control software, producing an output that behaves as though a rotating machine were present at that grid point. Droop-based designs establish a linear relationship between frequency deviation and power injection, trading some physical fidelity for greater tuning simplicity and predictability. Both approaches can meet the technical requirements that grid operators are beginning to codify in grid codes and connection standards across major electricity markets.

The measurement and certification of synthetic inertia performance is an area of active development among transmission system operators and standards bodies. Unlike the inertia constant of a synchronous generator, which is a fixed physical property that can be verified by inspection, the effective inertia provided by a battery system depends on the active parameter settings, the state of charge, and the accuracy of the frequency measurement system. Developing robust test and certification protocols is essential to building the market confidence that will support widespread procurement of synthetic inertia as a traded grid service.

BATTERY ENERGY STORAGE

The Platform of Choice for Grid-Forming Services

Technical and Economic Advantages at Scale

Several technologies can contribute to the replacement of synchronous inertia: synchronous condensers, flywheels, hydrogen-fuelled gas turbines, and battery energy storage systems each offer a different performance profile, capital cost structure, and operational footprint. Battery energy storage has emerged as the primary platform for grid-forming services for reasons that are both technical and economic, and understanding these reasons is essential for any investor or developer evaluating the market.

Synchronous condensers are rotating machines that provide reactive power and inertia without generating electricity. They are a well-established technology and have been deployed by grid operators in markets where inertia procurement has been formalised. Their inertia provision is genuine and physically robust, but they are expensive to install, require regular mechanical maintenance, and cannot provide the active power support during frequency deviations that battery systems can deliver. They stabilise frequency through inertia alone; they cannot inject the additional generation that a low-frequency event may require to restore the system to its nominal operating point.

Flywheel energy storage systems can provide very rapid response and have low degradation over repeated cycling, but their energy storage duration is limited to seconds or minutes. They are well suited to very short-duration inertia emulation but cannot provide the sustained frequency support that a grid with a severe generation shortfall may require. Their capital costs per megawatt-hour are also substantially higher than those of lithium-based battery systems at current market prices, which constrains their economic case outside specific high-cycle, short-duration niches.

Battery energy storage combines the millisecond response time of power electronics with the energy storage capacity needed to sustain that response over meaningful durations. A well-designed battery storage system with grid-forming inverters can provide synthetic inertia in the first seconds of a disturbance and then transition seamlessly into sustained frequency response, all without mechanical components, without fuel, and with a maintenance profile that is substantially simpler than that of rotating machinery. The incremental cost of adding grid-forming capability to a battery storage project, compared to the conventional grid-following alternative, is primarily a software and commissioning cost rather than a hardware cost.

The co-location opportunity further strengthens the case for battery energy storage. A single battery storage asset can provide grid-forming services for inertia and frequency stability while simultaneously participating in energy arbitrage, providing reactive power support, and offering demand response capabilities. This service stacking is not available to a synchronous condenser or a flywheel system. For investors evaluating long-duration returns from energy infrastructure, this multi-function characteristic is one of the most important differentiators between battery storage and alternative inertia technologies.

FROM DESIGN TO GRID CONNECTION

Deploying Grid-Forming BESS at Scale

Technical Design Considerations

Deploying a battery energy storage system with grid-forming capability involves engineering decisions at every level, from the selection and configuration of inverter hardware to the design of the protection systems that govern the asset's behaviour under fault conditions. The starting point is the choice of inverter platform. Not all commercial inverters support grid-forming control modes, and among those that do, the maturity, flexibility, and certification status of the grid-forming functionality varies considerably. Developers must evaluate both the technical performance of the control algorithm and its compliance status under applicable grid codes.

The sizing of the battery system for grid-forming service provision involves a different set of calculations than sizing for energy arbitrage. The key parameters for inertia provision are not primarily the energy capacity of the battery but the maximum power output, the response time, and the duration over which the system can sustain its inertia response before the state of charge falls to a level where continued provision would compromise the ability to participate in subsequent energy markets. These parameters drive a design optimisation that must balance inertia provision requirements, energy market participation, and overall round-trip efficiency.

Grid connection design for a grid-forming asset requires careful attention to the interface between the BESS control system and the transmission or distribution network to which it connects. Grid-forming inverters interact with existing grid protection systems in ways that grid-following inverters do not, and the interaction between multiple grid-forming assets connected to the same network requires analysis of potential control interactions and resonance risks. Pre-connection studies, including electromagnetic transient simulation and small-signal stability analysis, are standard requirements for grid-forming projects in jurisdictions where the technology is being deployed at scale.

The commissioning and testing of a grid-forming battery storage asset involves verification of performance parameters that are specific to the grid-forming service portfolio. The effective inertia constant, the droop characteristic, the fault ride-through behaviour, and the black-start sequence all require dedicated testing protocols. In some markets, certification of grid-forming performance is a prerequisite for participation in the relevant ancillary service markets, and the development of these certification frameworks is an area of active work among transmission system operators and standardisation bodies.

Operational management of a grid-forming battery system adds dimensions that are not present in the operation of a purely grid-following asset. The state of charge must be managed not only to maximise energy market revenues but also to ensure that the system is always positioned to provide its contracted inertia and frequency services. This requires a sophisticated operational dispatch algorithm that can anticipate grid conditions, forecast market prices, and maintain the operational envelope within which grid-forming services can be reliably provided. In-house software development capability is a significant advantage in this context.

FROM SERVICES TO REVENUE

Monetising Grid Stability in Modern Electricity Markets

The Commercial Framework for Grid-Forming Assets

The monetisation of grid-forming services requires engagement with electricity market frameworks that are, in many jurisdictions, still catching up with the technical capabilities that grid-forming battery storage systems can provide. The development of specific market products for synthetic inertia and enhanced frequency response is at different stages in different markets, ranging from well-established procurement mechanisms with competitive tendering to nascent frameworks where the product definition remains under consultation. Developers who engage early with this market development process are better positioned to shape the commercial frameworks that will govern the sector for the coming decade.

Where synthetic inertia markets are established, they typically operate on a capacity basis: the asset owner is paid for maintaining the capability to provide a defined level of inertia response, regardless of whether that capability is actually activated in any given period. This structure is analogous to the capacity payments that firm generation and frequency response assets receive in many markets, and it provides a stable, predictable revenue stream that is particularly attractive to infrastructure investors with long investment horizons and a preference for contracted cash flows over merchant market exposure.

Enhanced frequency response and fast frequency response products represent a separate but closely related revenue stream. These products target the first seconds of a frequency disturbance rather than the instantaneous inertia response, and they are typically procured through competitive tender processes. Battery energy storage systems have consistently demonstrated the fastest response times of any technology participating in these markets, and the market share of battery storage in fast frequency response procurement has grown substantially in markets where the product is well established. Grid-forming battery storage can layer both inertia response and fast frequency response capabilities within a single asset.

> ***The battery storage asset that can simultaneously provide synthetic inertia, fast frequency response, and energy arbitrage is not serving three markets; it is serving one integrated grid, and capturing the full value of doing so.***

The revenue from grid-forming and frequency services can be stacked with revenues from energy arbitrage, capacity market participation, and reactive power provision. The optimal stacking strategy requires modelling of the interaction between service obligations and energy market participation, since a commitment to provide frequency response in a given period constrains the portion of the battery capacity that can be allocated to energy trading. The design of the dispatch optimisation system is therefore a significant value driver, and developers with strong in-house software capabilities have a measurable advantage over those who depend on third-party energy management systems.

Looking forward, the revenue available from grid-forming services is expected to increase as renewable penetration rises and the scarcity of inertia resources becomes more pronounced. Markets that have not yet established synthetic inertia products are likely to do so as the operational consequences of inertia deficiency become more visible to regulators and the public. First-mover battery storage developers who have established grid-forming capability in their portfolios will be positioned to capture both the initial premiums that typically accompany new market products and the long-term contracted revenues that follow as market frameworks mature.

THE INVESTMENT CASE

Grid-Forming Battery Storage as Infrastructure

Three Reinforcing Pillars of Return

The investment case for battery energy storage with grid-forming capability rests on three reinforcing pillars: a growing market need driven by structural forces rather than policy preferences, a technology that is proven and deployable at scale, and a revenue model that benefits from diversification across multiple service categories. Each of these pillars is stronger for grid-forming assets than for conventional grid-following battery storage, and the premium they justify reflects a real and durable competitive advantage.

The structural driver is unambiguous: renewable energy deployment will continue, synchronous generation will continue to retire, and the inertia deficit will continue to deepen. These trends are not sensitive to the political cycle or to individual policy decisions; they reflect the economics of generation technology and the long-run cost trajectory of batteries and renewables. The consequence is that the market for grid-forming services will grow, not merely as a product of regulatory intervention but as a product of physical necessity. Grids cannot operate reliably without the stabilising services that grid-forming assets provide, and market frameworks will be adapted to procure those services at the scale required.

The technology risk in grid-forming battery storage is lower than in many energy transition investment categories. The underlying battery technology is well established, the power electronics are commercially available from multiple vendors, and the grid-forming control algorithms have been demonstrated in operational settings in several markets. The residual technical risks relate to the performance of specific control architectures under novel grid conditions and to the certification of grid-forming performance within evolving grid code frameworks. These risks are manageable within a well-designed project development process and a competent engineering team.

The revenue diversification that grid-forming capability enables is a direct contributor to risk-adjusted returns. A battery storage asset that can provide synthetic inertia, enhanced frequency response, energy arbitrage, and capacity market services is exposed to fewer correlated risks than one that depends on a single revenue stream. If energy price volatility compresses arbitrage margins in a given period, frequency service revenues provide a floor. If frequency markets are temporarily oversupplied as new projects commission, energy arbitrage and capacity revenues continue. This portfolio effect is valuable independent of the absolute level of revenues.

For infrastructure investors with long investment horizons, the asset life and residual value considerations of grid-forming battery storage are also favourable. Battery systems have a design life that extends over multiple contract periods, and the value of grid-forming capability can be expected to appreciate over the asset's lifetime as inertia scarcity increases. The combination of a long asset life, a growing market need, and a diversified revenue model creates a compelling risk-adjusted return profile that compares favourably with other infrastructure investment categories in the current interest rate environment.

THE WINDOW IS NARROWING

Why Timing Matters in Grid-Forming Deployment

The Forces That Reward Early Action

The urgency of grid-forming battery storage deployment is not manufactured by commercial interest; it is driven by the pace of renewable energy installation and the retirement schedule of the synchronous generation fleet. Both processes are accelerating. Solar and wind capacity additions are running at record levels globally, and the retirement of coal, gas, and nuclear plants is proceeding across multiple major markets. The intersection of these two trends means that the inertia deficit is deepening faster than the market frameworks needed to address it are developing.

Permitting and grid connection timelines for utility-scale battery storage projects are measured in years rather than months. A developer who begins the development process today can realistically expect commissioning in three to five years in most markets, depending on the complexity of the grid connection and the efficiency of the planning and permitting process. Projects that are not in development now will not be commissioned in the early years of the next decade, precisely the period when inertia deficiency is expected to become most acute in markets with aggressive renewable energy targets.

Grid-forming capability as a standard feature of new battery storage projects has a natural adoption window. As long as most new storage projects are built without grid-forming control, the scarcity of grid-forming assets keeps the value of that capability elevated. As the market matures and more projects incorporate grid-forming as standard practice, the premium associated with early deployment narrows. Developers who are building grid-forming capability into their projects during the current period are capturing a scarcity premium that will not persist indefinitely.

Regulatory evolution is also creating a timing dynamic that rewards early action. Several transmission system operators are in the process of revising their grid codes to mandate or incentivise grid-forming behaviour from new inverter-based connections. Projects that are designed now with grid-forming as a standard feature will comply with the grid codes of the next decade rather than struggling to retrofit compliance onto assets designed under less demanding requirements. This regulatory alignment is not only a commercial advantage but a risk management consideration: assets designed to meet evolving technical standards are less exposed to the upgrade costs and potential stranded asset risks associated with projects built to the minimum requirements of today.

Grid-Forming and Synthetic Inertia

247 Energy NV has made grid-forming capability a central design principle of its battery storage park development programme. This is not a feature added to projects as an afterthought or in response to a specific tender requirement; it is built into the engineering specification of every battery storage park in the 247 Energy portfolio from the earliest stages of site development. The rationale is direct: the projects being developed and commissioned today will be operating in the grid environment of the 2030s and beyond, and that environment will require grid-forming performance as a baseline expectation rather than a premium service.

The foundation of 247 Energy's approach to grid-forming is its in-house software development capability. Rather than depending on the control software provided by inverter manufacturers, which is typically configured to meet the minimum requirements of current grid codes, 247 Energy develops and maintains its own battery management and inverter control software. This provides full visibility into the control logic at every level, enables continuous optimisation of the grid-forming algorithms as operating experience accumulates, and ensures that the company is not dependent on external vendors for the technical evolution of its core service offering.

247 Energy's current development pipeline encompasses 505 megawatts of battery storage capacity across Belgium and surrounding markets. This pipeline provides the scale necessary to engage with grid operators on grid-forming service contracts at commercially meaningful levels and to establish the operating track record that institutional investors and grid operators require before committing to long-term ancillary service agreements. Each project in the pipeline is developed with the explicit intention of providing grid-forming services, incorporating the pre-connection studies, protection system design, and commissioning test protocols that these projects require.

For industrial and commercial clients with on-site generation or significant grid-connected loads, 247 Energy offers a co-investment model that allows clients to participate in the economic upside of grid-forming services while benefiting from the stability and resilience capabilities of a co-located battery storage asset. This model aligns the interests of the asset operator, the grid, and the industrial client, and represents one of the more attractive structures available for organisations that want to move beyond passive grid connection towards active participation in the services that the modern grid requires. 247 Energy welcomes enquiries from investors, grid operators, developers, and industrial clients who want to discuss specific requirements in detail.

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