

CONDON

The Nordic Position on Grid-Forming

Enabling the Future Nordic Power System

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1. Introduction

The Nordic synchronous area Transmission System Operators (TSOs) – Fingrid, Energinet, Statnett, and Svenska kraftnät – have jointly identified the urgent need for advanced technical measures to ensure the reliable and secure operation of a future grid, dominated by power-electronic interfaced generation. Historically, the stability of the Nordic synchronous power system has relied on traditional synchronous generators, which inherently provide inertia and resist grid disturbances. However, new generation and consumption (particularly wind, solar and Power-to-X facilities), rapidly deployed across the Nordics, are connected through converters. Converters lack the inherent ability to provide system inertia, damp power oscillations, or automatically adjust to disturbances as synchronous generators do. This negatively impacts conventional system stability phenomena. Furthermore, the increasing integration of power-electronics-based generation introduces distinct stability issues that are specifically associated with inverter-based resources.

As the Nordic system transitions to a more complex power system dominated, at times, by converter-connected generation and converter connected loads, the very nature of the grid's technical performance is shifting. With wind and solar expected, at times, to form the backbone of the Nordic energy mix, the Nordic grid faces unprecedented challenges. In 2022, for the first time in Nordic history, more than half of the power fed into the grid during peak renewable penetration came through converters. By 2030, the capacity of converter-connected generation is expected to more than double, highlighting the increasing vulnerability of the entire system's stability in the absence of immediate action. As power-electronic generation continues to expand across multiple regions, its influence will extend beyond individual areas, potentially causing cross-border impacts and challenging the stability of the synchronous system at large.

To address this emerging challenge, grid-forming (GFM) converters serve as an important mitigation measure. Unlike conventional converters, grid-forming technology can emulate desirable behavior of synchronous machines by providing inertial response, stabilizing voltage, and supporting frequency during disturbances. This ensures that even as the Nordic grid relies more heavily on renewable energy sources, it can help maintain a comparable level of resilience and stability to that of the synchronous generation era. The implementation of grid-forming is not merely a precaution – it's a critical step in safeguarding the future of the Nordic grid.

2. The Nordic Position on Grid-Forming

2.1 General understanding of Grid-Forming behavior

Currently, most power electronic interfaced devices (PEIDs) operate in a grid-following (GFL) mode. In grid-following mode the voltage at the point of connection (PoC) is measured and a dedicated synchronization unit such as a Phase-Locked Loop (PLL) is used to track the voltage angle to ensure the appropriate injection of active and reactive power. Under this control strategy, PEIDs behave as a controlled current source. In scenarios where the grid is weak and during disturbances such as short-circuits, the PLL may struggle to accurately track the voltage angle, potentially compromising the stability of the source. Another control mode is the island mode, where the converter generates the voltage waveform for the islanded network. In this mode, the converter imposes the frequency and phase angle, effectively acting as a slack bus that balances the power within the islanded network. However, since the converter dictates the voltage angle to the network, it lacks synchronization capability and cannot self-synchronize with other voltage sources in parallel. Therefore, it must be the primary source driving the frequency of the islanded network.

Grid-forming is typically understood as a control strategy that enables PEIDs to function as a controlled voltage source (within current and energy limits) behind an impedance, equipped with the capability to self-synchronize with the grid. Grid-forming applications are relevant across various technologies, including High Voltage Direct Current (HVDC) systems, Flexible AC Transmission Systems (FACTS), and Power Park Modules (PPMs). This voltage-source behavior implies that the PEID should be capable of maintaining a constant, or nearly constant internal phasor, in the sub-transient or transient time frame following a disturbance, and subsequently synchronizing with other devices connected to the same synchronous network. This independence in synchronization differentiates grid-forming mode from island mode, where self-synchronization is not feasible.

In the event of a disturbance affecting the phase angle, frequency, or amplitude of the voltage at the PoC, the grid-forming converter is expected to sustain the magnitude and angle of its internal voltage phasor with minimal deviation during the initial

milliseconds post-disturbance. This results in a discrepancy between the internal voltage phasor of the grid-forming converter and the voltage phasor at the PoC, leading to the inherent injection or absorption of active or reactive power by the grid-forming converter without any additional control functions.

2.2 Overview of Fundamental Grid-Forming Behavior from International Efforts

The discussions and ongoing work with the European Network Codes (NC RfG and NC HVDC) have emphasized the necessity of a harmonized approach to defining and implementing grid-forming functionalities. These efforts are being coordinated through initiatives like InterOPERA and ACER/ENTSO-E, which aim to foster a common understanding among various stakeholders in the energy sector. The basic definitions largely align. To illustrate this, three examples follow below:

InterOPERA:

“GFM behavior is understood as the behavior of an HVDC system or DC-connected PPM as a **voltage source behind an impedance**. However, with the aim to further detail GFM functional requirements and more importantly to make it quantifiable and measurable, the **state-of-the-art literature largely agrees to break the voltage source behavior down to different distinguishable functionalities** in response to different types of grid disturbances, which can be measured quantitatively on a timescale.”

ACER/ENTSO-E:

“Within the power park module’s current and energy limits, the power park module shall be capable of behaving ... **as a voltage source behind an internal impedance** ... The Thevenin source is characterized by its internal voltage amplitude, voltage phase angle, frequency and internal impedance.”

Svenska kraftnät HVDC specification:

“The GFM control mode shall enable dynamic voltage magnitude and phase control similar to a **controllable voltage source behind an impedance**.”

Fingrid Requirements for Grid Energy Storage Systems:

“GFM shall provide autonomous, near-instantaneous frequency and voltage support by maintaining a **nearly constant internal voltage phasor** in the sub-transient time frame.”

Evidently, all of the above align with the general understanding of grid-forming behavior. However, these definitions are non-exhaustive and, while there are exhaustive versions underway, there will be a need for specification of parameters by the TSO.

Specifically, grid-forming requirements and validation are usually discussed based on the following:

Voltage-Source Behavior: Grid-forming converters may primarily be defined as controlled voltage sources. This definition implies that these systems should maintain a nearly constant internal voltage phasor immediately following a disturbance, demonstrating a robust ability to adapt slowly to post-disturbance conditions within their operational limits. As a consequence, any deviation between the converter's internal voltage phasor and the voltage at the PoC will naturally drive an exchange of active and/or reactive power, even in the absence of explicit control action.

Inertial response: A grid-forming converter has the inherent ability to deliver an immediate active power response, proportional to the Rate of Change of Frequency (RoCoF), without relying on frequency measurements.

Limits: Under normal conditions, grid-forming functionality involves maintaining the characteristics of a voltage source. Additional requirements are needed regarding contribution of active and reactive currents outside operational limits. These requirements may aim at maintaining the voltage source characteristics based on the angle or ratio of reactive and active currents.

Self-synchronization: Grid-forming converters have the ability to autonomously synchronize with the grid, regardless of grid conditions or the presence of synchronous generators. This capability ensures that the grid-forming converter can operate whether the grid has no synchronous generators or only a few remaining. Even after the disconnection of the last synchronous generator, the self-synchronization function allows the grid-forming converter to continue operating reliably, contributing to grid stability.

Positive damping power: Grid-forming converters have positive damping power as an intrinsic feature, enabling them to naturally mitigate power oscillations within the AC system. This damping effect arises from the dynamic interaction between the voltage at the PoC and the internal voltage of the grid-forming converter. As these voltages oscillate relative to each other, the grid-forming converter autonomously adjusts its active- and reactive power outputs, effectively damping the oscillations and enhancing system stability without the need for external control intervention. It is crucial to distinguish this intrinsic positive active power damping – resulting from the voltage-source behavior – from the broader concept of converter damping

characteristics for small-signal analysis. Converter damping behavior is frequency-dependent, and under certain conditions a converter may introduce negative damping, potentially exacerbating oscillations rather than mitigating them at a specific resonance frequency. Thus, ensuring converter stability is still necessary with converters implementing voltage source behavior and inherent active power damping.

The extent to which grid-forming capabilities can be sustained or utilized in practice will also depend on the availability of energy storage. Converters without dedicated storage can still exhibit certain grid-forming characteristics, particularly in voltage regulation and short-term dynamic response, but lack the ability to sustain active power exchange over time, limiting their capability to support frequency or maintain operation through prolonged imbalances.

3. Timelines for Grid-Forming Implementation Across Converter-Based Technologies

The implementation timelines for grid-forming capabilities vary significantly across different converter-based technologies due to their technical characteristics and procurement processes. For technologies like HVDC and FACTS, grid-forming functionality can already be specified and integrated into systems procured by TSOs. Such systems are typically custom-designed based on detailed specifications provided by the TSO, allowing grid-forming to be incorporated from the outset as part of the overall system design.

In contrast, technologies like wind and solar power generation often follow a more standardized, product-based approach. These are typically off-the-shelf solutions, which makes it more challenging to implement grid-forming without clear regulatory requirements or grid codes. The adoption of grid-forming in these systems will largely depend on the development of European network codes that mandate such capabilities. However, when the new network codes are released, the TSOs need to be prepared with requirements for these codes.

Battery energy storage systems (BESS) present a different case. Grid-forming functionality is technically feasible for BESS due to their inherent energy storage capability and ability to maintain a stiff DC voltage. This allows BESS to support grid-forming implementation more readily compared to wind and solar, enabling their use in stabilizing the grid even in the absence of synchronous generators.

This variation across different technologies leads to differing timelines for grid-forming adoption, with HVDC, FACTS and BESS capable of near-term integration,

while other technologies will follow as regulatory frameworks evolve. While the progress differs between the Nordic TSOs, grid-forming requirements are already being introduced for HVDC links, FACTS and BESS.

4. Standardized Testing Protocol for Grid-Forming

As grid-forming capabilities become essential for the Nordic power system, the Nordic TSOs must develop comprehensive testing protocols and define evaluation criteria to ensure successful grid-forming integration. By the time future network codes are introduced, test scenarios and parameters for wind and solar should be fully developed to ensure seamless integration. In contrast, for HVDC, FACTS, and BESS, grid-forming functionality can already be specified and integrated, and testing frameworks for these technologies are either complete or nearing completion. A key aspect of this preparation is designing standardized test frameworks, such as envelope curve methodologies, to evaluate how grid-forming systems respond to grid disturbances.

Developing test cases relies on engineering expertise and system-specific design parameters. However, to ensure consistency and drive industry-wide adoption of grid-forming technology, it is crucial to collaborate on defining these requirements within the Nordics. Harmonizing test benches and parameters within the Nordic countries will strengthen the position when negotiating with suppliers and manufacturers, enabling a more seamless and coordinated grid-forming implementation across regions, both for current systems like HVDC, FACTS, and BESS, and for future wind and solar applications once network codes come into effect. A harmonized definition along with Nordic requirements simultaneously benefits the suppliers and manufacturers by removing the need to adapt solutions for individual countries.

5. Summary and next steps

The Nordic view on grid-forming capabilities builds on European experiences and ongoing work but tailored to the specific operational needs of the Nordic power system. While the progress differs between the Nordic TSOs, grid-forming requirements are already being introduced for key technologies such as HVDC links, FACTS, and BESS.

The continued work within CONDON will focus on harmonizing requirements and developing common criteria for validation of performance, in close collaboration with external stakeholders. In this manner, we can ensure consistent performance requirements for grid-forming converters, provide clarity for developers and manufacturers in terms of expectations, and facilitate pilot projects and real-world validation of grid-forming behavior in the Nordic context.

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