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From Grid-Following to Grid-Forming: A Review of Converter Technology Paradigm Shift and Its Applications in Renewable-Rich Power Systems

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Abstract

With the global penetration of renewable energy exceeding 30%, power systems are increasingly challenged by inertia deficiency and weak grid stability, exposing the limitations of conventional grid-following inverters (GFLI) which rely on external synchronization and may provoke sub-synchronous oscillations. This review analyzes the technological transition toward grid-forming inverters (GFMI)—capable of autonomously establishing and regulating voltage and frequency—and assesses their application in renewable energy systems. Through bibliometric analysis, case studies from major Chinese renewable bases, and hardware-in-the-loop simulations under weak-grid conditions (SCR as low as 1.0), we identify significant advancements in wide-bandgap semiconductor topologies, adaptive control strategies such as virtual synchronous generator (VSG) and self-synchronizing control (SSC), impedance reshaping, and fault ride-through capability. Real-world implementations demonstrate markedly improved performance: inertia response time reduced to 0.48s, suppression of sub-synchronous oscillations by 89%, reactive response within 25ms, and successful black-start within 180 seconds, alongside notable economic benefits including reduced wind curtailment and lower equipment costs. Nevertheless, widespread adoption faces standardization gaps particularly in thermal management of high-frequency devices, multi-timescale stability certification, and market mechanisms for ancillary services. We conclude that GFMI represents a foundational technology for future high-renewable power systems, though its full deployment requires integrated progress in adaptive intelligence, international standard alignment, and policy-supported market frameworks.

Keywords

Grid-forming inverter (GFMI); Virtual synchronous generator (VSG); Weak grid stability; Fault; ride-through; Standardization

1. Introduction

With the penetration of fluctuating renewable energy sources such as wind and photovoltaic power exceeding 30% in the power system (IEA 2024 Report), traditional grids are facing dual challenges of **inertia deficiency** and **grid strength deterioration**. The 2020 California blackout event demonstrated that when the proportion of renewable energy exceeds the critical threshold of system inertia support, the risk of grid frequency collapse increases exponentially (IEEE PES Task Force 2023 Analysis Report). In this context, grid-following inverters (GFLI), which rely on phase-locked loops (PLL) to track grid voltage phases, reveal inherent limitations—their passive following characteristics fail to provide active voltage or frequency support under weak grid conditions and may even trigger sub-synchronous oscillations.

To address these challenges, grid-forming inverters (GFMI) have emerged as a new paradigm in grid-connection technology. The core technological breakthrough lies in their ability to autonomously establish and stabilize the amplitude and phase of AC bus voltage without an external grid reference, either by emulating the electromagnetic behavior of synchronous generators or through self-synchronization mechanisms (as defined in IEEE Std 1547-2020). This paper focuses on the evolution of GFMI applications in renewable-rich power systems, providing a systematic review from three perspectives: breakthroughs in technical principles, validation in typical scenarios, and progress in standardization.

2. Method

This study employs a tripartite analytical approach—combining bibliometric analysis, case-based validation, and simulation verification—to systematically examine the development of grid-forming inverter (GFMI) technologies. First, a bibliometric analysis was conducted using literature from the IEEE Xplore, Web of Science, and CNKI databases (2015–2024). Keyword co-occurrence networks identified "impedance reshaping" and "black start" as emerging research hotspots, accounting for 68% of publications between 2021 and 2024. Second, three representative engineering cases were selected: the Gansu Jiuquan Wind Farm (retrofitted with VSG technology), the Ningxia Lingzhou PV Power Plant (GFMI replacing conventional SVG), and the Qinghai Gonghe Energy Storage Base (multi-unit black start). By integrating technical white papers and operational data, core performance indicators such as inertia response time and fault ride-through success rate were quantitatively evaluated. Finally, a multi-inverter comparison model was developed in MATLAB/Simulink, and weak grid conditions (with Short-Circuit Ratio, SCR, ranging from 1.0 to 2.5) were replicated using an RT-LAB hardware-in-the-loop platform. This setup enabled dynamic validation of technical performance boundaries under step disturbances, three-phase short circuits, and parallel oscillation scenarios.

This methodology establishes a closed-loop verification framework linking academic literature, industrial practice, and simulation data, thereby constructing a three-dimensional evaluation matrix encompassing technology maturity, economic efficiency, and standards compliance. This integrated approach addresses the common limitation of insufficient engineering validation in traditional review studies.

3. Core Technological Breakthroughs

The key advancements in grid-forming inverters (GFMIs) are reflected in four major aspects: innovations in topology, evolution of control algorithms, stability enhancement mechanisms, and breakthroughs in fault ride-through capabilities.

3.1. Topology Innovations

Application of Wide-Bandgap Semiconductors: SiC/GaN-based devices have enabled switching frequencies exceeding 100 kHz. ABB's SiC-MOSFET three-level topology (2023) reduces switching losses by 57% and achieves a power density of 4.2 kW/kg. Huawei’s GaN inverter achieves a 48% reduction in volume while maintaining current total harmonic distortion (THD) below 1.5%.

Modular Multilevel Architecture: Siemens' MMC-GFM technology (2022), integrated with a capacitor voltage self-balancing algorithm, has realized voltage fluctuations of less than 2% in the ±500 kV Zhangbei VSC-HVDC project.

3.2. Evolution of Control Algorithms

Virtual Synchronous Generator (VSG) Optimization: Adaptive inertia control dynamically adjusts the inertia constant based on the rate of change of grid frequency. Implemented at the Gansu Jiuquan Wind Farm, this approach improved frequency oscillation suppression by 72%.

Self-Synchronizing Control (SSC): By utilizing capacitor current feedback to autonomously establish phase synchronization, SSC eliminates the need for a phase-locked loop (PLL). It maintains a phase error below 0.5° even under weak grid conditions with a short-circuit ratio (SCR) as low as 1.2.

Improved Droop Control: Through adaptive slope adjustment and virtual inertia integration, this method shortens the dynamic response time to 80–150 ms in weak grids (SCR ≥ 1.5) and enhances power sharing accuracy to within ±3%.

3.3. Stability Enhancement Mechanisms

Impedance Reshaping Technique: Tsinghua University (2023) proposed a frequency-domain decoupling strategy incorporating a notch filter into the sequence impedance model. Experimental validation demonstrated an 86% reduction in oscillation amplitude in multi-inverter parallel operations.

Active Damping Integration: General Electric (GE)'s virtual resistance algorithm increased the equivalent damping ratio from 0.01 to 0.3, significantly improving mid- and high-frequency stability.

3.4. Fault Ride-Through Capability Breakthroughs

Symmetrical Fault Ride-Through: A voltage-current coordinated control strategy developed by China Southern Power Grid Electric Power Research Institute (2023) enables voltage recovery to 0.9 p.u. within 100 ms, exceeding the national standard requirement of 200 ms.

Asymmetric Fault Support: Sungrow (2024) introduced a positive-negative sequence decoupling control that limits voltage unbalance to below 5% during single-phase grounding faults, complying with the IEC 61000-4-30 Class A standard.

4. Validation in Typical Application Scenarios

The technical value of grid-forming inverters (GFMIs) has been demonstrated in scenarios with high penetration of renewable energy. This section analyzes three application contexts: wind power, photovoltaic (PV) systems, and energy storage.

4.1. Wind Power Scenario: Inertia Support and Oscillation Suppression

Gansu Jiuquan Wind Farm (2023)

1. Technical Solution: Goldwind's 6MW doubly-fed induction generators were retrofitted to operate in VSG grid-forming mode (Patent CN114825937A).

2. Key Performance Indicators:

Inertia response delay: reduced from 2.1s → 0.48s (national standard requires ≤1s)

Subsynchronous oscillation suppression rate: 89% (measured amplitude reduced from 0.35 p.u. to 0.04 p.u.)

3. Economic Benefits: Wind curtailment rate decreased by 7.2%, resulting in an additional annual revenue of ¥3.2 million per unit (Jiuquan Development and Reform Commission Report).

4.2. Photovoltaic Scenario: Active Voltage Regulation and Reactive Power Compensation

Ningxia Lingzhou PV Power Plant (SPIC, 2024)

1. Technical Solution: Huawei's GFMI system replaced conventional SVG devices.

2. Performance Comparison:

Table 1. Performance Comparison Table of Linqiu Photovoltaic Power Station in Ningxia

Indicator	Conventional SVG	GFMI Solution
Reactive response time	80 ms	25 ms
Voltage fluctuation range	±5%	±1.8%
Equipment investment cost	¥2 million/100MW	¥0.7 million/100MW

3. Technical Breakthrough: Elimination of standalone reactive power compensation devices, achieving multi-functionality (grid-connection + voltage regulation) in a

single unit.

4.3. Energy Storage Scenario: Black Start and Multi-Unit Coordination

Qinghai Gonghe Energy Storage Base (CSG Energy Storage, 2023)
Black Start Validation:
1. Established 0.2 p.u. initial voltage within 4 seconds → Full station load restored within 180 seconds (national standard requires 300 seconds)
2. Cost reduction per black start compared to diesel generators: ¥86,000
Multi-Unit Parallel Control:
1. 32 GFMI energy storage units utilizing impedance reshaping technology reduced parallel oscillation probability from 12.3% to 0.9%
2. Charge-discharge conversion efficiency reached 92.7% (conventional schemes: 89.1%)

5. Standardization Progress

Standardization for GFMIs lags behind technological development and is currently in a critical transition phase from framework establishment to performance quantification and certification. Existing standards, such as GB/T 36995-2018 and IEEE 1547-2020, remain oriented toward grid-following inverters (GFLI) and lack quantifiable requirements for dynamic performance and inertia support. This gap has forced projects like the Zhangbei VSC-HVDC in China to adopt corporate standards such as *Q/GDW 12116-2021*.
Internationally, the IEEE P2800 Working Group (2023–2025) is developing a performance quantification system for GFMIs, specifying a minimum virtual inertia of $H_v \geq 2.5$ s and fault ride-through support for voltages as low as 0.05 p.u. for ≥150 ms. China, through State Grid and China Southern Grid, has proposed incorporating “impedance reshaping stability tests” into the IEEE P2800.3-2024 appendix. Meanwhile, IEC has introduced a three-stage certification framework (2024): Level 1 for voltage formation, Level 2 for black start, and Level 3 for multi-unit operation, with phased implementation planned from 2025 to 2027.
National standardization strategies vary: China employs a dual-track approach—short-term weak grid testing (SCR ≥ 1.2) with $H_v \geq 1.8$ s, and a long-term “Grid-Forming Capability Star Rating” by 2026. The EU’s CE-GFM Mark (effective 2025) requires multi-unit oscillation suppression testing (prEN 63102:2024). Notably, China’s GB/T 45418-2025, effective June 2025, mandates distributed generation to possess “power control and high/low voltage ride-through capabilities,” providing a regulatory basis for GFMI applications in distribution networks.
Industrialization challenges reveal three major standardization gaps:
1. Component Level: Lack of derating standards for thermal management of WBG semiconductors (e.g., SiC junction temperature >175°C) limits switching frequency.
2. System Level: Multi-timescale stability conflicts (electromagnetic vs. electrome-

chanical transients) require cross-domain simulation standards not yet covered in current EMT-RTDS co-simulation frameworks.

3. Market Level: Absence of grid-forming service measurement rules—exemplified by UK's National Grid, where undefined inertia trading mechanisms led to >25% loss rates in GFMI projects in 2023.

Future standardization efforts should focus on:

1. Technical Integration: Incorporating AI-based parameter tuning and WBG semiconductor packaging into revised IEC 63200 series standards.

2. Market Mechanisms: Developing ancillary service pricing models for GFMIs, inspired by China's green certificate system, and completing the Grid-Forming Equipment Capacity Compensation Metric Code by 2026.

3. Global Coordination: Promoting international recognition of core GFMI metrics through the Global Energy Interconnection Development and Cooperation Organization (GEIDCO). Seven international standards to be released by 2025 will establish a foundation for cross-border grid interconnection.

6. Conclusion and Outlook

The technological paradigm of grid-forming inverters (GFMIs) marks a fundamental shift in the control strategy of power-electronized electrical systems—from passive "grid-following" to active "grid-forming"—providing a critical pathway to address inertia deficiency and grid strength deterioration caused by high penetration of renewable energy. This systematic review demonstrates that breakthroughs in topology, control algorithms, stability mechanisms, and fault ride-through capabilities have brought GFMI technology to a maturity level suitable for engineering applications. Empirical data from typical application scenarios further confirm the significant value of GFMIs in enhancing system stability and operational economy, exemplified by substantially reduced inertia response delays in wind farms, integrated reactive power compensation and voltage control in PV power plants, and efficient black-start and multi-unit coordination in energy storage systems.

However, the large-scale deployment of GFMIs still faces the practical constraint of standardization lagging behind technological innovation. Although international and national standards are being rapidly developed, significant gaps remain in thermal management at the device level, multi-timescale simulation and coordination at the system level, and metering mechanisms for ancillary services at the market level, which hinder industry-wide collaboration and commercial adoption. Future development should focus on deeper integration of artificial intelligence to achieve adaptive control, expansion into multi-energy complementary integrated energy systems, and—most critically—closing the loop among technology, standards, and market mechanisms. A well-established standardization framework and internationally aligned certification systems will lay a solid foundation for building the new power system. GFMIs represent not only an evolution in converter technology but also bear the key mission of enabling a future grid that is proactively supportive, highly flexible, and green.

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