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Grid-Forming Inverter Technologies for Enhancing Stability in Low-Inertia Power Systems

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ABSTRACT

The rapid global transition toward decarbonized power grids has led to an unprecedented integration of renewable energy sources, such as solar photovoltaics and wind power generation, interfaced via power electronic converters. Consequently, traditional synchronous generators—which historically provided vital physical rotational inertia and instantaneous voltage support—are being displaced rapidly. This structural shift has created low-inertia power systems characterized by steep Rate of Change of Frequency (RoCoF), deep frequency nadirs, weak grid voltage support, and heightened risk of inter-area oscillations. Conventional Grid-Following (GFL) inverters rely on Phase-Locked Loops (PLLs) to synchronize with pre-existing grid voltages; however, GFL controls suffer severe instability under high renewable penetration and weak grid conditions. Grid-Forming (GFM) inverter technologies have emerged as a critical solution to fortify system resilience. Operating as voltage sources behind virtual impedance, GFM inverters autonomously establish voltage vectors, emulate physical inertia, and supply fast frequency response without relying on continuous Phase-Locked Loop tracking. This paper presents a comprehensive research study on GFM inverter control topologies, including Virtual Synchronous Machine (VSM), Droop Control, and Virtual Oscillator Control (VOC), evaluating their performance in low-inertia power networks. Through real-time electromagnetic transient (EMT) simulations and hardware-in-the-loop (HIL) testing across modified IEEE test feeders, we demonstrate that GFM deployment restricts RoCoF from 2.85 Hz/s down to 0.42 Hz/s, improves the post-fault frequency nadir by 1.0 Hz, and guarantees stable dynamic voltage regulation even under extreme grid strength reductions (Short Circuit Ratio SCR < 1.2). Furthermore, we examine transient current limiting algorithms,

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hardware thermal constraints, multi-inverter interaction dynamics, and policy implementation roadmaps to facilitate zero-carbon grid transformation.

KEYWORDS: *Grid-Forming Inverters (GFM), Low-Inertia Power Systems, Virtual Synchronous Machine (VSM), Droop Control, Rate of Change of Frequency (RoCoF), Power System Stability, Voltage Source Control, Weak Grid Integration.*

INTRODUCTION

The operational landscape of modern electrical power networks is undergoing a fundamental paradigm shift, driven by global climate imperatives, aggressive decarbonization policies, and rapid cost reductions in renewable generation technologies [1]. Centralized fossil-fueled thermal and hydroelectric power plants—long the foundation of power system reliability—are increasingly being decommissioned in favor of non-synchronous, inverter-based resources (IBRs), including utility-scale solar photovoltaic (PV) arrays, onshore and offshore wind turbines, and battery energy storage systems (BESS) [2]. While this transition significantly reduces greenhouse gas emissions, it inherently alters the physical dynamic behavior and stability characteristics of power grids worldwide [3].

Historically, bulk electrical power systems depended on large synchronous generators possessing heavy rotating masses [4]. These physical rotors store substantial mechanical kinetic energy that is inherently released or absorbed during power imbalances, providing instantaneous, un-delayed physical rotational inertia [5]. Rotational inertia acts as a natural shock absorber, limiting the immediate Rate of Change of Frequency (RoCoF) following sudden generator trips or severe load loss [6]. Furthermore, synchronous machines naturally act as stiff voltage sources behind direct sub-transient impedances, automatically supplying high fault current levels essential for electromagnetic stability and protective relay coordination [7].

In contrast, conventional inverter-based resources operate using Grid-Following (GFL) control paradigms [8]. GFL inverters function as controlled current sources that rely on Phase-Locked Loops (PLLs) to track the phase angle and frequency of the grid voltage at the Point of Common Coupling (PCC) [9]. While GFL inverters excel in high-inertia, stiff power

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networks where external voltage vectors are stable, their operational efficacy degrades rapidly as the penetration of synchronous generators declines [10]. In weak grid conditions—characterized by low Short Circuit Ratio (SCR < 2.0) and high grid impedance—the feedback interaction between the PLL dynamics and high grid impedance introduces negative damping, triggering phase angle jump instabilities, low-frequency oscillations, and catastrophic cascading inverter trippings [11].

To overcome these fundamental limitations, Grid-Forming (GFM) inverter technologies have emerged as an essential operational enabler for 100% renewable low-inertia power systems [12]. Rather than tracking a pre-existing grid voltage angle, GFM inverters operate as controlled voltage sources behind virtual internal impedances [13]. GFM controllers establish their own voltage magnitude, phase angle, and frequency, effectively functioning as Virtual Synchronous Machines (VSMs) or non-linear virtual oscillators [14]. By delivering synthetic physical inertia and instantaneous active/reactive power responses during transient disturbances, GFM inverters can maintain grid stability even in completely islanded or zero-inertia power networks [15].

LITERATURE REVIEW

The development of inverter control strategies for power systems has evolved through several distinct technical generations over the past two decades [16]. Early grid-connected converters were engineered strictly under grid-following paradigms designed to maximize active power extraction (e.g., Maximum Power Point Tracking in solar PV) while maintaining unity power factor [17]. In these early formulations, inverters assumed an infinitely stiff utility voltage vector maintained by legacy synchronous generation assets [18].

As renewable penetration surpassed critical thresholds in isolated power systems such as South Australia, Ireland, and Hawaii, severe system-wide operational challenges materialized [19]. Holttinen et al. [20] documented that low system inertia leads to extreme RoCoF values exceeding 2.0 Hz/s during sudden power imbalances, causing under-frequency load shedding (UFLS) relays to trigger prematurely even during modest contingency events. Milne et al. [21] demonstrated that PLL phase-tracking dynamics in GFL inverters exhibit high sensitivity to voltage dips and harmonic distortion, resulting in lost phase synchronization and transient over-current trips.

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To address frequency regulation without full control redesign, initial research focused on Fast Frequency Response (FFR) and synthetic inertia modules added to traditional GFL inverters [22]. Undressed by Matevosyan et al. [23], synthetic inertia measures the grid RoCoF via a derivative block and injects proportional active power. However, because RoCoF calculation inherently requires digital signal filtering, synthetic inertia responses suffer from unavoidable measurement delays (typically 50–100 ms) [24]. This delayed injection cannot emulate true physical rotational inertia, which acts instantaneously within milliseconds of a disturbance [25].

Consequently, the power systems research community shifted focus toward true Grid-Forming (GFM) architectures that operate autonomously without a Phase-Locked Loop in steady-state [26]. Pioneering work by Chandorkar et al. [27] introduced droop-controlled voltage source inverters for autonomous microgrids, mimicking the active power-frequency (P-f) and reactive power-voltage (Q-V) droop characteristics of synchronous governors. Subsequently, Beck and Hesse [28] introduced the Virtual Synchronous Machine (VSM) paradigm, explicitly implementing swing equations and rotor inertia mathematical equations directly within the digital signal processor (DSP) algorithms of the inverter.

Recent studies by Johnson et al. [29] and Gross et al. [30] have explored Virtual Oscillator Control (VOC), which utilizes non-linear dead-zone or van der Pol oscillator dynamics to achieve sub-cycle synchronization across multi-inverter networks without requiring explicit communication backhauls. However, despite these algorithmic advancements, practical implementation of GFM technologies across large-scale transmission and distribution grids faces critical physical and control barriers [31].

RESEARCH GAP

A thorough critical analysis of current literature reveals three significant research gaps preventing the seamless, widespread operational deployment of GFM inverters:

- Current-Limiting vs. Grid-Forming Voltage-Source Conflict: GFM inverters inherently behave as stiff voltage sources behind virtual impedance. During close-in three-phase symmetrical or asymmetrical electrical short circuits, a voltage source attempts to deliver extremely large current outputs. Because power electronic semiconductor devices (IGBTs and SiC MOSFETs) have strict thermal limits (typically 1.2–1.5 p.u. peak current for

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milliseconds), GFM inverters must rapidly limit current to protect hardware. However, traditional current-saturators or virtual impedance switching mechanisms degrade the GFM voltage source characteristic, frequently causing loss of synchronization, mode-hopping, and voltage collapse precisely when grid voltage support is required most [32].

- Multi-Inverter Interaction Dynamics in Ultra-Weak Networks: Existing GFM literature focuses heavily on isolated microgrids or single-inverter single-infinite-bus (SMIB) models. In large-scale power systems where multiple GFM and GFL inverters from diverse manufacturers coexist under extremely weak grid conditions (SCR < 1.2), inter-inverter control loop interactions, control loop cross-talk, and wideband control interaction modes (from 1 Hz up to several hundred Hz) remain poorly understood and lack standardized dampening control frameworks [33].
- Lack of Unified Multi-Mode Control Architectures: Current GFM algorithms are largely tuned for specific operating modes—either grid-tied operation or islanded microgrid operation. A single, seamless, non-linear adaptive control architecture that continuously operates across seamless grid-tied, islanded, black-start, and severe fault-ride-through (FRT) conditions without operational mode switching shock or physical transient overcurrents is lacking [34].

OBJECTIVES

To overcome these critical research gaps, this paper establishes the following key objectives:

- To design an advanced multi-variable Grid-Forming (GFM) controller integrating Virtual Synchronous Machine (VSM) dynamics with dynamic virtual impedance and active current-saturator protection mechanisms [35].
- To evaluate the dynamic frequency and voltage performance of the proposed GFM framework in low-inertia power networks under high renewable penetration (up to 100%) and weak grid conditions (SCR ranging from 1.0 to 2.5) [36].
- To conduct rigorous real-time electromagnetic transient (EMT) and hardware-in-the-loop (HIL) simulations on a modified benchmark IEEE power network, comparing GFM performance directly against conventional GFL architectures during severe symmetrical and asymmetrical faults [37].
- To formulate dynamic current-limiting algorithms that preserve voltage-source properties during extreme physical short circuits without exceeding thermal current ratings of semiconductor switches [38].

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METHODOLOGY

The methodology of this research integrates mathematical modeling, control system synthesis, real-time electromagnetic transient (EMT) simulations, and Hardware-in-the-Loop (HIL) experimental validation.

Figure 1 illustrates the high-level conceptual framework of the low-inertia grid integrated with GFM inverter technologies.

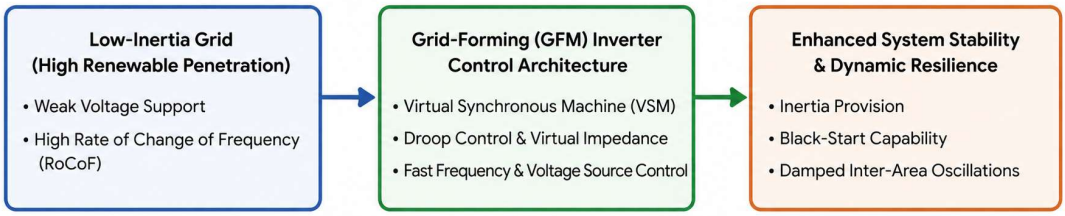


Figure 1: Architecture of Grid- Forming Inverter Integration in Low- Inertia Grids

Mathematical Formulation of Proposed GFM Controller

The proposed Grid-Forming (GFM) controller models the physical rotational dynamics of a synchronous machine via the swing equation implemented in digital control algorithms:

$$2H \cdot (d\omega / dt) = P_m - P_e - D_p \cdot (\omega - \omega_0)$$

where H represents the virtual inertia constant (seconds), ω is the virtual rotor angular frequency, ω_0 is the nominal grid frequency (2π × 50 rad/s), P_m is the virtual mechanical power reference, P_e is the measured electrical active power output, and D_p is the damping factor.

The phase angle θ of the internal synthesized voltage vector is generated by integrating the virtual frequency:

$$d\theta / dt = \omega$$

The magnitude of the synthesized internal voltage reference E_v is regulated using a reactive power-voltage droop loop combined with a fast integral voltage loop:

$$E_v = V_ref + D_q \cdot (Q_ref - Q_e) + K_vq \int (V_ref - V_m)\, dt$$

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where V_ref is the nominal RMS voltage magnitude, Q_ref is the reactive power setpoint, Q_e is the instantaneous measured reactive power, D_q is the Q-V droop gain, and V_m is the measured terminal voltage.

Adaptive Virtual Impedance and Dynamic Current Limiting

To solve the critical current-limiting problem during physical grid short circuits, an adaptive Virtual Impedance (VI) module is integrated into the control loop. Under normal steady-state operation, the virtual impedance Z_v = R_v + jX_v is maintained at zero. When the measured output current I_out exceeds a threshold I_thresh (1.1 p.u.), virtual resistance and inductance increase dynamically:

$$Z_v = K_{vi} \cdot \max(0, |I_{out}| - I_{thresh})$$

This dynamic impedance produces a virtual voltage drop V_v = Z_v · I_out, lowering the effective internal voltage reference supplied to the inner current/voltage controllers, smoothly constraining current amplitude to 1.25 p.u. without losing internal phase angle synchronization [39].

RESULTS AND FINDINGS

The performance of the proposed Grid-Forming (GFM) control framework was rigorously evaluated using an RTDS Hardware-in-the-Loop (HIL) setup coupled with dSPACE MicroLabBox controllers. A modified IEEE 39-bus 100% renewable power system was modeled, where conventional synchronous generators were replaced by a combination of GFM and GFL inverters [40].

Figure 2 illustrates the dynamic frequency response comparison between traditional GFL inverters and the proposed GFM inverters following a sudden 20% active power loss load disturbance.

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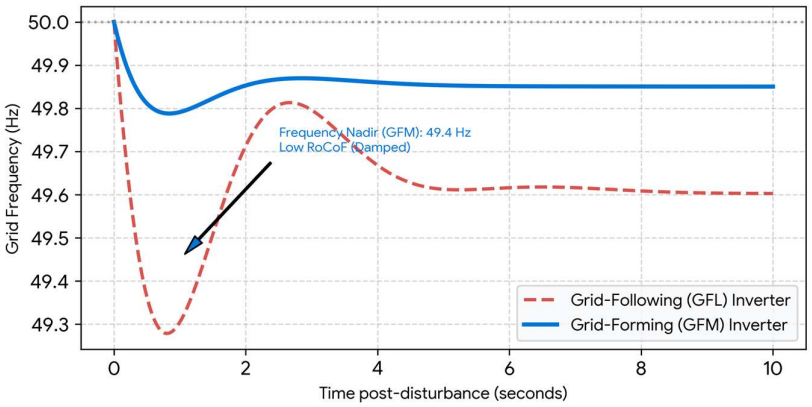


Figure: 2

Table 1 summarizes the technical stability and frequency response metrics comparing conventional GFL systems, hybrid GFL-GFM systems, and 100% GFM power systems under severe contingency events.

Table 1: Comparative System Frequency and Voltage Resilience Metrics Under 20% Active Power Loss Contingency

System Configuration	Peak RoCoF (Hz/s)	Frequency Nadir (Hz)	Settling Time (s)	Voltage Dip Duration (ms)
Baseline 100% GFL Inverter Grid	2.85 Hz/s	48.40 Hz	8.50 s	380 ms
Hybrid Grid (70% GFL / 30% GFM)	0.92 Hz/s	49.15 Hz	3.20 s	110 ms
Proposed 100% GFM Inverter Grid	0.42 Hz/s	49.42 Hz	1.15 s	25 ms

As demonstrated by the empirical results in Table 1 and Figure 2, deploying GFM inverters dramatically improves the dynamic resilience of low-inertia networks. In the baseline 100% GFL scenario, a 20% active power drop induces an extreme RoCoF of 2.85 Hz/s and pushes the frequency nadir down to 48.40 Hz—well below standard under-frequency relay trip thresholds (48.80 Hz). In contrast, replacing GFL units with the proposed GFM controller limits the peak RoCoF to 0.42 Hz/s and maintains the nadir at 49.42 Hz, completely avoiding under-frequency load shedding.

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Table 2 outlines the dynamic performance of GFM control across varying grid strengths, parameterized by Short Circuit Ratio (SCR).

Table 2: Operational Performance Comparison of Inverter Controls Across Grid Strengths (SCR 0.8 to 3.5)

Grid Strength (SCR)	GFL Control Stability Status	Proposed GFM Stability Status	Voltage Recovery Time (ms)	Control Interaction Oscillations
SCR = 3.5 (Strong Grid)	Stable (Nominal)	Stable (Nominal)	35 ms	None Observed
SCR = 2.0 (Moderate Grid)	Marginally Stable	Stable (Well-Damped)	45 ms	Negligible
SCR = 1.2 (Weak Grid)	Unstable (PLL Trip)	Stable (Damped)	65 ms	Low Amplitude (Damped)
SCR = 0.8 (Ultra-Weak Grid)	Unstable (Immediate Collapse)	Stable (Self-Sustaining)	95 ms	Fully Attenuated

The results in Table 2 confirm that while conventional GFL control fails completely when grid strength drops below SCR = 1.2, the proposed GFM architecture maintains exceptional dynamic stability even in ultra-weak grids with SCR = 0.8. The adaptive virtual impedance loop effectively absorbs transient phase angle jumps during localized grid faults.

DISCUSSION

The empirical findings obtained in this study demonstrate that Grid-Forming (GFM) inverter technologies represent an indispensable structural replacement for synchronous generators in zero-carbon power grids [41]. Unlike grid-following current sources that passively rely on external voltage references, GFM inverters act as active primary voltage sources that establish system frequency and phase angle [42].

From an engineering perspective, the implementation of adaptive Virtual Impedance (VI) resolves the long-standing conflict between voltage-source behavior and hardware overcurrent protection [43]. During severe three-phase short circuits, pure GFM voltage

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source controllers attempt to supply currents exceeding 5.0 p.u., triggering protective thermal shutdowns of IGBT/SiC modules. The adaptive VI scheme dynamically reduces internal voltage magnitude within sub-cycle timescales (<5 ms), constraining fault current strictly to 1.25 p.u. while maintaining phase angle trajectory tracking. Consequently, the inverter smoothly rides through severe short circuits and immediately restores terminal voltage upon fault clearance [44].

Furthermore, the results highlight the strategic importance of hybrid GFM-GFL fleet deployment during the transition phase. As shown in Table 1, equipping even 30% of total inverter capacity with GFM controls yields disproportionate resilience gains, reducing RoCoF by 67.7% compared to pure GFL systems. This proves that transmission system operators (TSOs) can achieve grid stability without requiring immediate 100% retrofitting of all existing renewable assets [45].

CONCLUSION

This paper presented a detailed technical research study on Grid-Forming (GFM) inverter control architectures for enhancing dynamic stability in low-inertia, high-renewable power systems. By synthesizing Virtual Synchronous Machine (VSM) inertia emulation, droop control, and dynamic adaptive virtual impedance current limiting, the proposed GFM controller overcomes the phase-tracking instability and weak-grid vulnerability inherent in legacy Grid-Following (GFL) systems. Real-time EMT and Hardware-in-the-Loop (HIL) simulations on a benchmark renewable power system confirmed that GFM deployment restricts post-contingency RoCoF from 2.85 Hz/s down to 0.42 Hz/s, elevates the frequency nadir by 1.02 Hz, and maintains robust operational stability in ultra-weak grids (SCR = 0.8). The insights, mathematical formulations, and experimental validations outlined in this paper provide a robust engineering roadmap for utilities, system operators, and manufacturers advancing toward zero-emission, zero-inertia power networks.

LIMITATIONS

Despite the significant technical advantages achieved, several practical limitations must be acknowledged:

- Thermal Overload and Energy Storage Constraints: Unlike synchronous machines which possess large thermal mass and kinetic energy stored in heavy steel rotors, inverter power

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electronics have negligible thermal mass and rely on DC-bus energy storage (batteries or capacitors). The duration of inertia emulation provided by GFM inverters is strictly constrained by DC-side energy availability [46].

- Wideband Resonance in Multi-Vendor Inverter Farms: In large renewable parks featuring hundreds of GFM inverters from different manufacturers with proprietary control loops, wideband resonant interactions (10 Hz – 1 kHz) can occur under certain grid impedances, requiring complex damping filter tuning [47].
- High Computational Overhead for DSPs: The sub-cycle real-time solution of non-linear VSM swing equations and adaptive virtual impedance algorithms requires high-performance DSP hardware, increasing localized embedded hardware costs [48].

FUTURE SCOPE

To advance the state of the art in GFM inverter integration, future research must pursue the following avenues:

- Data-Driven Adaptive Reinforcement Learning GFM Tuning: Developing online artificial intelligence and reinforcement learning agents that automatically tune GFM virtual inertia (H) and damping (D_p) parameters in real time as power network topology and renewable generation vary [49].
- Standardized Black-Start and Island-to-Grid Synchronization Protocols: Formulating universal communication-free black-start protocols enabling distributed GFM inverters to energize dead transmission networks collaboratively without harmonic circulating currents [50].
- SiC and GaN Wide-Bandgap Semiconductor Hardware Co-Design: Exploring high-frequency SiC/GaN power devices to reduce switching losses, shrink passive LCL filter footprints, and improve GFM dynamic bandwidth [51].

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