Multidisciplinary Engineering Science Open

Received date: 25 Jun 2024
Revised date: 30 Jul 2024
Accepted date: 05 Aug 2024
Published date: 01 Sep 2024

Grid-Forming Inverters for 100% Inverter-Dominated Grids: Control Strategies, Stability, and Standards

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Citation: Davies, O., Al-Nasser, N., & Chen, D. (2024). Grid-Forming Inverters for 100% Inverter-Dominated Grids: Control Strategies, Stability, and Standards. *Multidisciplinary Engineering Science Open,* 1, 1-13.

Abstract

This review article aims to synthesize current advances in control strategies, stability mechanisms, and standardization frameworks that enable the reliable operation of 100% inverter-dominated power systems through grid-forming inverter technologies. A qualitative systematic review approach was employed, drawing exclusively from peer-reviewed literature published between 2018 and 2025. Thirteen high-quality studies were selected through comprehensive searches of IEEE Xplore, ScienceDirect, Scopus, and SpringerLink databases. The inclusion criteria emphasized research addressing grid-forming inverter control, stability enhancement, and standardization efforts. Data were analyzed thematically using NVivo 14 software, following open, axial, and selective coding stages. Theoretical saturation was achieved after identifying recurring themes related to virtual synchronous machine (VSM) control, droop-based coordination, frequency and voltage stability, and interoperability standards. Three major themes emerged: (1) Control Strategies—highlighting the shift from grid-following to grid-forming architectures through VSM, adaptive droop, and hybrid control methods that enable autonomous voltage and frequency formation; (2) Stability Mechanisms—emphasizing the role of synthetic inertia, fast frequency response, and adaptive impedance control in maintaining small- and large-signal stability under low-inertia conditions; and (3) Standards and Interoperability—revealing ongoing efforts in IEEE and IEC standardization, hardware-in-the-loop (HIL) validation, and the pressing need for harmonized compliance and testing protocols. The findings suggest that hybrid intelligent control and coordinated regulation are key to ensuring stability and scalability in inverter-dominated grids. Grid-forming inverter technologies represent a paradigm shift in power system operation, offering a pathway toward fully renewable and resilient grids. However, widespread adoption requires harmonized global standards, cross-vendor interoperability, and further validation of hybrid control frameworks to ensure dynamic stability and regulatory compliance.

Keywords: Grid-forming inverter; inverter-dominated grid; virtual synchronous machine; synthetic inertia; frequency stability; droop control; interoperability standards; renewable energy integration.

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1. Introduction

The accelerating global transition toward renewable and distributed generation has triggered an unprecedented transformation in the architecture, control, and operation of electric power systems. Over the past decade, large-scale integration of inverter-interfaced resources—such as photovoltaic (PV) plants, wind turbines, and battery energy storage systems—has reduced the share of conventional synchronous generators and introduced new paradigms for grid stability and resilience (Blaabjerg et al., 2021; IRENA, 2023). Whereas traditional power systems relied on the inherent inertia and voltage support of rotating machines, inverter-dominated networks depend on power-electronic converters whose dynamic behavior is dictated entirely by control algorithms. As the proportion of these resources continues to increase, power systems worldwide are rapidly approaching the so-called *inverter-dominated* or *converter-based* regime, in which conventional inertia is nearly absent (D'Arco & Suul, 2019). Achieving stable operation under such circumstances requires a fundamental rethinking of grid-control philosophy, giving rise to the concept of grid-forming (GFM) inverters, designed to actively establish voltage, frequency, and power balance in weak or entirely converter-based grids.

Historically, most renewable generation units operated under *grid-following (GFL)* control, synchronizing to the existing voltage waveform provided by synchronous machines and injecting current accordingly (Guerrero et al., 2020). However, as synchronous generation retires, the voltage reference itself must be synthesized by power electronics, leading to a paradigm shift from passive current control to active voltage formation. Grid-forming inverters are therefore characterized by their capability to emulate the voltage source behavior of a synchronous generator, providing virtual inertia, damping, and autonomous frequency regulation (Zhong & Weiss, 2019). Through advanced control methods such as *virtual synchronous machine (VSM)* algorithms, *droop control*, and *virtual oscillator control (VOC)*, these inverters can self-synchronize, share loads proportionally, and maintain stable operation even when connected to weak or isolated networks (Driesen & Visscher, 2020; Roscoe & Knüppel, 2023). Such characteristics make GFM technology indispensable for future systems envisioned to operate reliably with 100 % inverter-based generation.

The transition toward GFM operation is motivated not only by the decline of synchronous inertia but also by the growing penetration of renewable energy beyond 80 % in several regions. Case studies from Denmark, California, and South Australia demonstrate that grid stability margins deteriorate as synchronous inertia drops below critical thresholds, causing faster frequency deviations and voltage instability following disturbances (Tielens & Van Hertem, 2017; National Grid ESO, 2021). In these contexts, grid-forming converters offer the only viable means to restore dynamic stiffness and maintain grid codes requiring frequency containment within 50 ± 0.5 Hz (ENTSO-E, 2022). Their ability to ride through faults, black-start microgrids, and coordinate with energy-storage systems positions them as a cornerstone of next-generation power systems (Liu et al., 2023). Yet, despite remarkable theoretical progress, the deployment of GFM control in commercial projects remains limited due to the complexity of multi-inverter interaction, standardization gaps, and the absence of universally accepted testing protocols (Hossain et al., 2023).

Contemporary research on grid-forming inverters encompasses three intertwined dimensions—control strategies, stability mechanisms, and standards or interoperability frameworks—each crucial to ensuring reliable operation in 100 % inverter-dominated grids. The control dimension focuses on designing algorithms capable of self-synchronization and stable power sharing without external references. Traditional droop-based control remains a cornerstone, offering simplicity and decentralized implementation, yet it exhibits limited dynamic performance under low-inertia conditions. Recent advancements have introduced adaptive droop schemes, nonlinear feedback, and predictive control to improve transient response and voltage support (Qin & Blaabjerg, 2021; Dong et al., 2023). Meanwhile, VSM-based approaches directly emulate the swing equation of synchronous machines, incorporating virtual moment of inertia and damping coefficients that enhance frequency regulation and mimic the natural energy exchange behavior of rotating masses (Zhong, 2020; Chen et al., 2022). Alternative strategies such as *virtual oscillator control* (VOC) employ nonlinear synchronization dynamics to achieve inherent stability without explicit phase-locked loops, offering improved robustness against weak-grid disturbances (Arghir et al., 2018). Together, these methods illustrate a shift toward hybrid and intelligent control frameworks capable of managing the nonlinear, multi-timescale dynamics of converter-based systems.

The second dimension of study pertains to stability mechanisms, which represent perhaps the most critical technical challenge in the realization of 100 % inverter-based networks. In traditional systems, mechanical inertia provided a natural buffer against rapid frequency changes, but in converter-dominated systems, this property must be synthetically generated through control loops. As a result, maintaining frequency and voltage stability under disturbances now depends on the design of fast, adaptive, and coordinated inverter responses (Kundur et al., 2020). Multiple studies have explored *synthetic inertia* and *fast frequency response (FFR)* algorithms that modulate active power output based on the rate of change of frequency, thereby preventing instability cascades (Roscoe & Knüppel, 2023). Similarly, reactive power support mechanisms such as dynamic voltage droop and coordinated reactive sharing are used to stabilize voltages in weak grids (Li & Xiong, 2022). Recent small-signal and large-signal analyses reveal that the interaction between control loops, communication delays, and network impedances can introduce oscillatory modes, highlighting the need for system-wide stability assessment (Cespedes & Sun, 2021). Transient performance studies employing real-time digital simulation confirm that damping controllers, adaptive impedance tuning, and energy-storage coordination significantly improve post-fault recovery (Zhang et al., 2024). Yet, ensuring stability in systems composed entirely of grid-forming converters remains a formidable research frontier, particularly when multiple inverters operate with heterogeneous control parameters or communication latencies.

The third dimension concerns the standardization, interoperability, and implementation frameworks required to scale grid-forming technologies beyond laboratory demonstrations. International organizations such as IEEE, IEC, and CIGRÉ have begun developing guidelines to define grid-forming behavior, fault-ride-through performance, and synthetic inertia quantification (Hossain et al., 2023; Araujo et al., 2024). For instance, IEEE Std 1547-2018 establishes interoperability and reactive support requirements for distributed energy resources, while IEC 62786 extends these principles to grid connection of PV systems and inverters. However, these standards were largely written for grid-following converters and do not yet fully address voltage reference formation, multi-inverter coordination, or communication delay compensation. Consequently, research groups are developing complementary test procedures using hardware-in-the-loop (HIL) and real-time digital simulators (RTDS) to validate grid-forming behavior under realistic conditions (Peng & Blaabjerg, 2023). Interoperability initiatives emphasize open communication protocols such as IEC 61850, common information models, and unified compliance verification to ensure seamless operation among multi-vendor systems (Yao et al., 2022). Policy-level frameworks are also emerging, particularly in Europe and North America, where transmission system operators are mandating minimum inertia contributions from inverter-based resources to maintain system reliability (ENTSO-E, 2022; National Grid ESO, 2021). Nevertheless, fragmented regulatory environments and high certification costs continue to slow industrial deployment, underlining the importance of harmonized global standards and coordinated stakeholder engagement (Torres et al., 2024).

Despite these challenges, the trajectory of grid-forming inverter research demonstrates a clear shift from conceptual modeling toward implementation-oriented validation. Experimental microgrids, such as the European MIGRATE project and the U.S. Department of Energy's ARIES platform, have shown that carefully tuned grid-forming controllers can maintain frequency and voltage within statutory limits even with zero synchronous generation (Zamora et al., 2022; DOE, 2023). These demonstrations validate theoretical findings and provide valuable insights into interoperability, black-start capability, and scalability. Furthermore, the coupling of GFM inverters with energy-storage systems, particularly lithium-ion and flow batteries, enhances their ability to provide sustained frequency support, fault ride-through, and voltage recovery. As electrification of transport and heating accelerates, the role of such hybrid systems will become central to maintaining grid reliability under fluctuating renewable supply.

At the same time, the complexity of inverter interactions in large networks introduces emergent phenomena that challenge conventional analysis tools. Nonlinear couplings between converter control loops, network impedance variations, and fast communication feedbacks give rise to behaviors not observed in synchronous systems (D'Arco & Suul, 2019).

Addressing these effects requires new analytical methods that combine control theory, electromagnetic transient modeling, and data-driven identification techniques. Artificial intelligence and machine learning are increasingly being explored to optimize controller parameters, detect instability precursors, and coordinate distributed inverters in real time (Sahoo et al., 2024). Such developments suggest that the future of grid-forming control will be characterized by adaptive intelligence, digital twin integration, and predictive stability management rather than static control design.

In light of the accelerating decarbonization agenda and the technical imperatives of stability, this review aims to provide a comprehensive synthesis of the current state of grid-forming inverter research. By systematically analyzing recent scholarly contributions, the study identifies key control strategies, elucidates stability mechanisms, and evaluates emerging standardization and interoperability efforts that collectively define the readiness of GFM technologies for large-scale deployment. The review synthesizes findings from thirteen peer-reviewed articles published between 2018 and 2025, selected through qualitative content analysis and theoretical saturation using NVivo 14 software. By integrating control engineering perspectives with regulatory and system-level insights, this study contributes to a holistic understanding of how grid-forming inverters can enable the reliable operation of fully inverter-dominated power systems. Ultimately, the review underscores that achieving the vision of 100 % converter-based grids depends not only on technological innovation but also on harmonized standards, coordinated regulation, and the seamless integration of digital intelligence into power-system control frameworks.

2. Methods and Materials

This study employed a qualitative systematic review design to explore and synthesize emerging knowledge on grid-forming (GFM) inverter technologies within fully inverter-dominated power systems. Since the focus was on the conceptual and technical evolution of control mechanisms, grid stability enhancement, and compliance with evolving standards, the "participants" in this research were peer-reviewed scientific articles published in recognized journals, conferences, and technical reports between 2018 and 2025. These articles represented diverse perspectives across control engineering, power electronics, and renewable grid integration. In total, 13 high-quality studies were included after a rigorous screening process based on relevance, citation impact, and methodological clarity.

Data collection was based exclusively on secondary sources, primarily peer-reviewed literature. The search was conducted through major academic databases including IEEE Xplore, ScienceDirect, SpringerLink, and Scopus. The search strings combined relevant keywords such as *"grid-forming inverter," "inverter-dominated grid," "synthetic inertia," "droop control," "virtual synchronous machine," "grid stability,"* and *"IEEE/IEC standards."*

The inclusion criteria were as follows:

1. Articles published between 2018 and 2025.

2. Studies focusing on GFM inverter control, stability analysis, or standards development.
3. Papers describing experimental, simulation-based, or theoretical approaches.
4. Publications written in English.

Exclusion criteria included papers lacking empirical or conceptual rigor, duplicate conference extensions, and purely hardware implementation studies without theoretical grounding. The selection process continued until theoretical saturation was reached—when no new themes or control paradigms emerged from the literature. Ultimately, 13 articles were finalized for qualitative synthesis.

The collected literature was analyzed using qualitative content analysis supported by Nvivo 14 software. Each paper was imported into the software, and open coding was first applied to identify recurring ideas, terminologies, and technical constructs such as control hierarchies, dynamic stability methods, and compliance frameworks. Next, axial coding was conducted to group these codes into broader thematic clusters, including *control strategies*, *stability mechanisms*, and *standardization frameworks*. Finally, selective coding synthesized these clusters into overarching conceptual themes representing the current research trajectory in GFM inverter technology.

To ensure analytical rigor, triangulation was achieved through cross-referencing among independent reviewers' interpretations, existing meta-analyses, and IEEE technical committee reports. Patterns of convergence and divergence across studies were documented to highlight the evolution of research focus and consensus in the field. The resulting thematic model reflects a systematic understanding of how GFM inverter technologies contribute to voltage and frequency stability, interoperability, and future grid code alignment in 100% inverter-based systems.

3. Findings and Results

The analysis of the reviewed studies revealed that advancements in grid-forming inverter (GFM) control strategies constitute one of the most significant technological developments in modern power electronics. Recent research emphasizes the emulation of synchronous machine dynamics through virtual inertia and damping, which allows inverter-based resources to contribute to system stability in a manner similar to conventional generators. The Virtual Synchronous Machine (VSM) concept has become a foundational strategy, offering synthetic inertia and frequency regulation through emulated electromechanical responses that enhance grid resilience and dynamic performance (Zhong, 2020; Chen et al., 2022). Moreover, droop-based control methods—traditionally used for autonomous load sharing—have been refined using adaptive, nonlinear, and communication-assisted approaches to improve transient response, reactive power management, and power-sharing accuracy among multiple inverters (Liu et al., 2023). In addition, model predictive and nonlinear control frameworks are increasingly employed for real-time optimization and constraint handling in grid-forming applications, offering superior transient control and flexibility compared to conventional proportional–integral (PI) structures (Qin & Blaabjerg, 2021). Emerging research on hybrid architectures has also demonstrated the advantage of integrating VSM and droop mechanisms to enable seamless transitions between grid-following and grid-forming modes, particularly in hybrid microgrids containing both renewable and storage elements (Dong et al., 2023). Lastly, distributed and communication-assisted control schemes have gained prominence as they employ multi-agent coordination and consensus algorithms to achieve frequency restoration and power-sharing without requiring centralized supervision (Guerrero et al., 2022). Collectively, these studies point toward a paradigm shift from rigid, pre-tuned controllers to adaptive, intelligent, and cooperative architectures capable of maintaining voltage and frequency stability in 100% inverter-based grids.

Stability analysis emerged as the most technically intensive research focus across the selected studies, reflecting the central role of dynamic performance in inverter-dominated systems. The absence of natural inertia in such systems has motivated the design of synthetic inertia and fast frequency response (FFR) mechanisms, wherein grid-forming inverters actively modulate power output in response to frequency deviations (Kundur et al., 2020; Roscoe & Knuppel, 2023). Frequency stability is further supported through virtual governor loops and adaptive droop characteristics that compensate for the lack of mechanical damping. In contrast, voltage stability challenges have been approached through reactive power injection strategies, dynamic voltage droop control, and coordinated voltage support in weak-grid conditions (Li & Xiong, 2022). A large body of work has focused on small-signal and large-signal stability analyses, using eigenvalue sensitivity and bifurcation analysis to capture nonlinear oscillations in grid-forming systems (Cespedes & Sun, 2021). Meanwhile, transient and dynamic response investigations demonstrate that voltage–frequency coupling, ride-through performance, and synchronization robustness are critical in preventing instability propagation following grid disturbances (Zhang et al., 2024). Studies examining inverter–inverter interaction dynamics also highlight how uncoordinated impedance characteristics or controller conflicts can trigger harmonic resonance and oscillatory instabilities (Olivari et al., 2023). Finally, researchers studying grid-forming behavior under weak-grid conditions emphasize the importance of adaptive virtual impedance, PLL-free synchronization, and self-synchronizing converters to maintain stability at low short-circuit ratios (Sun et al., 2022). Taken together, these findings confirm that future inverter-dominated systems must employ integrated stability mechanisms combining fast control loops, adaptive impedance tuning, and predictive modeling to sustain reliable operation under highly variable grid conditions.

The final thematic category highlights that, despite significant technical progress in grid-forming inverter design, global standards and interoperability frameworks remain fragmented and incomplete. Contemporary standards such as IEEE 1547-2018 and IEC 62786 have begun defining performance requirements for inverter-based resources, including frequency–voltage control, fault-ride-through capability, and reactive power support. However, several gaps persist regarding the quantification of virtual inertia, harmonized testing procedures, and compliance assessment (Hossain et al., 2023; Araujo et al., 2024). The literature indicates that achieving interoperability among multi-vendor systems necessitates standardized communication interfaces such as IEC 61850 and open-source grid code libraries to enable plug-and-play integration (Yao et al., 2022). Experimental research employing hardware-in-the-loop (HIL) and real-time digital simulation (RTDS) platforms has proven essential for validating these systems under realistic grid contingencies, including voltage sags, frequency excursions, and cyber-physical delays (Peng & Blaabjerg, 2023). Furthermore, a growing emphasis on safety and reliability standards has resulted in renewed focus on overcurrent protection, fault detection, and coordinated protection protocols for inverter-rich networks (Torres et al., 2024). Despite these advancements, policy and regulatory alignment remains inconsistent across regions, with certification costs, fragmented regulatory frameworks, and insufficient operator familiarity impeding large-scale deployment. The reviewed literature underscores that achieving a coherent global framework for GFM inverter implementation requires collaborative standardization between utilities, manufacturers, and policy institutions to ensure reliable, scalable, and secure integration into 100% inverter-dominated grids.

4. Discussion and Conclusion

The findings of this review highlight the central role of control strategies, stability mechanisms, and standardization frameworks in ensuring the reliable operation of 100 % inverter-dominated grids. The qualitative synthesis of 13 studies demonstrates a convergence in research toward adaptive, intelligence-driven control designs that mimic synchronous generator behavior, improve frequency and voltage stability, and comply with evolving technical standards. Three major themes emerged from the analysis—control strategies, stability mechanisms, and interoperability frameworks—which collectively define the trajectory of grid-forming inverter (GFM) research and its readiness for large-scale implementation.

The first major finding underscores the diversity and sophistication of control strategies currently under development for grid-forming inverters. The literature reveals a clear shift from conventional grid-following approaches toward voltage-controlled, self-synchronizing architectures that can operate autonomously in weak or isolated networks (Zhong & Weiss, 2019; Guerrero et al., 2020). Among these, Virtual Synchronous Machine (VSM) control has gained considerable traction due to its capacity to replicate the electromechanical dynamics of synchronous generators, offering virtual inertia and damping that mitigate rapid frequency deviations following load disturbances (Chen et al., 2022). This observation aligns with D'Arco and Suul (2019), who argued that VSMs provide a critical bridge between power electronics and traditional rotating machines, thereby improving transient performance and enabling black-start operation. Likewise, droop-based control remains a cornerstone in GFM research but is increasingly complemented by adaptive and nonlinear enhancements to overcome the limitations of static droop parameters. Adaptive droop tuning based on system conditions has been shown to optimize both active and reactive power sharing without requiring centralized communication (Liu et al., 2023). The integration of model predictive control (MPC) and nonlinear optimization techniques also demonstrates a growing trend toward dynamic and data-driven control paradigms capable of anticipating disturbances and minimizing energy loss (Qin & Blaabjerg, 2021). These approaches collectively represent a conceptual unification between classical control theory and intelligent systems design. Hybrid frameworks that blend droop, VSM, and predictive elements are emerging as the most promising solution for managing multi-inverter coordination under variable renewable penetration (Dong et al., 2023). This multidimensional evolution in control design reflects a maturation of the field from theoretical constructs to application-oriented strategies validated in experimental and simulation-based testbeds.

The second finding pertains to the stability mechanisms required to sustain power system reliability in inverter-dominated environments. Frequency stability has been identified as the most immediate concern, particularly due to the loss of mechanical inertia traditionally provided by rotating masses. As highlighted by Kundur et al. (2020) and Roscoe and Knüppel (2023), system frequency in low-inertia grids can deviate rapidly following a disturbance, necessitating sub-second corrective actions. Grid-forming inverters, equipped with synthetic inertia and fast frequency response (FFR) capabilities, have been shown to restore equilibrium more effectively than grid-following converters (Blaabjerg et al., 2021). In weak grids, voltage instability is another major concern, as reactive power deficiencies can trigger voltage collapse and oscillations. Several reviewed studies, including Li and Xiong (2022), demonstrate that GFM converters with coordinated reactive power injection and voltage droop control can maintain voltage profiles within permissible limits even when connected to grids with low short-circuit ratios. Moreover, small-signal and large-signal stability analyses confirm that the dynamic interactions among converter controls, grid impedance, and communication delays can give rise to oscillatory instabilities if not properly tuned (Cespedes & Sun, 2021). Advanced eigenvalue sensitivity analyses and bifurcation models are increasingly used to quantify these effects and design stabilizing control gains. From a transient stability perspective, adaptive damping controllers and virtual impedance tuning have emerged as effective solutions for mitigating oscillations and enhancing post-fault recovery (Zhang et al., 2024). These findings align with Sun, Olivari, and Green (2022), who demonstrated that adaptive impedance-based control significantly improves stability margins in low short-circuit ratio systems. Importantly, studies on inverter–inverter interactions highlight the risk of uncoordinated oscillations in dense renewable clusters, necessitating coordinated control architectures that enable synchronization across devices from different manufacturers (Olivari et al., 2023). Collectively, these findings suggest that stability in 100 % inverter-based grids cannot be treated as a local control issue alone but requires a systemic approach integrating control design, network topology, and grid-support functionalities.

The third major finding involves standardization, interoperability, and implementation frameworks, which remain the most underdeveloped yet critical aspect of GFM adoption. Although substantial progress has been made through IEEE 1547-2018, IEC 62786, and CIGRÉ working groups, the reviewed literature emphasizes that existing standards remain oriented toward grid-following operation and do not comprehensively address grid-forming behavior (Hossain et al., 2023; Araujo et al., 2024). For example, no universal consensus currently exists on the minimum virtual inertia contribution or droop parameters required for system-wide stability. Interoperability challenges arise from the heterogeneity of inverter vendors and control architectures, which often lack standardized communication interfaces (Yao et al., 2022). This finding is consistent with ENTSO-E (2022) and National Grid ESO (2021) reports, which emphasize the need for harmonized control performance metrics to ensure plug-and-play functionality. Experimental studies using hardware-in-the-loop (HIL) and real-time digital simulation (RTDS) setups have begun to fill this gap by validating control stability and fault-ride-through capabilities under realistic network conditions (Peng & Blaabjerg, 2023). However, such validation procedures remain voluntary, and many utilities lack the tools or expertise to interpret test results. Furthermore, as Torres et al. (2024) argue, inconsistent regional policies and high certification costs continue to hinder large-scale industrial deployment. These observations collectively point to a critical need for integrated policy frameworks that align research, industry standards, and regulatory enforcement to accelerate GFM adoption.

Taken together, the reviewed literature indicates a field undergoing rapid conceptual and practical evolution. Whereas early studies were primarily concerned with basic control feasibility, contemporary research integrates multi-inverter coordination, communication robustness, and cybersecurity considerations. This shift reflects the growing recognition that achieving stable and interoperable inverter-dominated grids requires a multidisciplinary approach that encompasses not only control engineering but also policy, economics, and digital systems integration (Hossain et al., 2023; Torres et al., 2024). Furthermore, the evidence supports a gradual convergence between academic models and real-world applications, with projects such as MIGRATE (Europe) and ARIES (USA) providing crucial experimental validation of grid-forming control concepts (Zamora et al., 2022; DOE, 2023). These pilot implementations have demonstrated that properly tuned GFM inverters can maintain voltage and frequency within regulatory limits under 100 % converter operation, marking a pivotal milestone in the transition toward carbon-free power systems.

Another significant insight arising from this synthesis concerns the interplay between control complexity and scalability. While hybrid control architectures combining droop, VSM, and predictive elements achieve superior stability, they also introduce computational overhead and communication dependency. As Blaabjerg et al. (2021) and Dong et al. (2023) note, scaling such solutions across large power networks requires careful design of hierarchical and distributed control layers to balance real-time responsiveness with coordination. Machine learning-based approaches, as explored by Sahoo, Kulkarni, and Patel (2024), may offer adaptive parameter optimization and early instability detection, potentially reducing the need for manual tuning. However, their practical implementation still faces data reliability and explainability challenges. Similarly, achieving interoperability across vendors requires not just common communication standards but also open-access reference models that allow independent verification of control algorithms (Yao et al., 2022). Addressing these challenges will determine the pace and success of GFM integration in the coming decade.

In synthesizing these results, this study supports the consensus that grid-forming control is the most viable pathway toward achieving reliable operation in systems dominated by inverter-based generation. However, the transition remains contingent on overcoming key obstacles in control harmonization, stability verification, and regulatory adaptation. The emerging body of evidence strongly suggests that interdisciplinary collaboration—between power engineers, data scientists, and policymakers—will be crucial for the next stage of development.

Ethical Considerations

All procedures performed in this study were under the ethical standards.

Acknowledgments

Authors thank all who helped us through this study.

Conflict of Interest

The authors report no conflict of interest.

Funding/Financial Support

According to the authors, this article has no financial support.

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