

Virtual Synchronous Generator Control Strategies For Low-Inertia Power Systems: A Comprehensive Review

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ABSTRACT

The increasing penetration of renewable energy sources has reduced rotational inertia in modern power systems, causing frequency instability and weakened grid strength. Virtual Synchronous Generators (VSGs) have emerged as a leading grid-forming control strategy that enables power converters to emulate synchronous machine behavior. This paper addresses three core questions: (a) the problem – reduced inertia threatens grid stability through higher rates of change of frequency (RoCoF) and deeper frequency nadirs; (b) the solution – VSG control strategies that embed the swing equation into converter loops to provide synthetic inertia and damping; (c) the results – systematic comparison shows voltage-controlled VSG and synchronverter approaches provide the strongest grid-forming capability, while impedance-based analysis reveals stability margins depend critically on the impedance ratio between VSG and grid. This paper systematically classifies existing VSG approaches based on control philosophy, modeling frameworks, and parameter tuning strategies, identifying key research gaps. The study examines dq-frame modeling, impedance-based stability analysis, and small-signal eigenvalue techniques. Major challenges include inertia-damping trade-offs, parameter tuning inconsistencies, multi-converter interactions, and weak-grid instability. The conclusion is that future research must focus on adaptive control frameworks, hardware validation, and standardized benchmarking systems for widespread practical deployment.

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1. INTRODUCTION

The transition from synchronous machine-dominated power systems to converter-dominated networks has fundamentally altered grid dynamics. This shift, driven by rapid integration of photovoltaic and wind generation, has significantly reduced system inertia, leading to higher rates of change of frequency (RoCoF), deeper frequency nadirs, and reduced damping capability [1][2]. In conventional power systems, synchronous generators inherently provide inertia and damping through rotating masses and electromechanical coupling. However, inverter-based resources lack these physical properties unless control systems explicitly emulate them [3][4].

The specific problem addressed is that reduced rotational inertia in modern power systems threatens frequency stability, particularly as renewable energy penetration continues to increase worldwide. When large conventional generators are replaced by converter-interfaced renewable sources, the system loses its natural ability to resist frequency deviations following disturbances. This results in faster frequency dynamics (RoCoF exceeding 1 Hz/s in some low-inertia grids), increased risk of under-frequency load shedding, and potential cascading failures. Quantitatively, systems with renewable penetration above 70% can experience frequency nadirs 40–60% deeper than conventional systems under equivalent disturbances.

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This paper proposes and reviews Virtual Synchronous Generator (VSG) control strategies that embed the swing equation into power converter control loops to provide synthetic inertia and damping. Unlike conventional grid-following inverters that rely on phase-locked loops, VSG-based grid-forming inverters actively establish grid voltage and frequency, emulating synchronous machine behavior. This enables renewable-rich systems to maintain frequency stability without physical rotating masses.

This paper makes the following novel contributions beyond existing reviews (e.g., Li et al. [5], Shadoul et al. [17]):

- (1) First unified taxonomy that explicitly integrates DC-side energy constraints (Equation 5) with swing equation dynamics, revealing that 63% of existing VSG studies neglect energy limitations, leading to overly optimistic performance claims.
- (2) Novel comparative framework linking control philosophy (VC-VSG, CC-VSG, droop, VOC, synchronverter) to quantitative weak-grid performance metrics (SCR stability limits, RoCoF reduction, settling time).
- (3) Identification of critical gap: no standardized benchmarking exists for VSG evaluation across different grid strengths – this paper proposes specific test scenarios (SCR = 1.5, 2.5, 5.0) and performance metrics.
- (4) Integration of very recent advances (2024–2026) in AI-assisted adaptive control, including multi-agent deep reinforcement learning and fuzzy-logic coordinated tuning, which are absent from earlier reviews.

Grid-forming (GFM) control strategies have been developed to address this challenge. Among them, the Virtual Synchronous Generator (VSG) has gained significant attention due to its ability to emulate synchronous machine dynamics through control algorithms. By embedding the swing equation into the converter control loop, VSGs provide synthetic inertia, damping, and autonomous frequency regulation [5][6]. Several studies have explored VSG implementations including synchronverters, droop-based VSG, virtual oscillator control, and both voltage-controlled and current-controlled architectures. Li et al. [5] provided a comprehensive survey of VSG control strategies, while Shadoul et al. [17] reviewed VSG topologies and control techniques. Recent advances have incorporated machine learning and adaptive fuzzy logic for parameter tuning [16][29]. A relevant recent study in this journal examined VSG applications in renewable-rich microgrids [23].

Challenges remain in weak-grid stability, multi-converter interaction, parameter-tuning robustness, and the lack of standardized benchmarking frameworks. A unified design framework for VSG systems operating under diverse grid conditions is still lacking [7][8]. Unlike previous reviews that focus on specific control aspects or limited application domains, this paper systematically classifies VSG technologies based on control philosophy, modeling frameworks, parameter-tuning strategies, and application domains. The novelty of this research lies in its comprehensive integration of stability analysis methods, including dq-frame modeling, impedance-based analysis, and small-signal eigenvalue techniques, within a unified taxonomy that enables direct comparison of VSG strategies for low-inertia power systems.

The remainder of this paper is organized as follows: Section 2 presents the review methodology and VSG technologies, including converter-based power system evolution, VSG operating principles, mathematical modeling, control philosophy classification, stability analysis methods, and unified taxonomy. Section 3 presents results and discussion. Section 4 concludes the paper with limitations and future directions.

2. REVIEW METHODOLOGY AND VSG TOPOLOGIES

2.1. Systematic Literature Review Methodology

This review follows a systematic literature review (SLR) methodology compliant with PRISMA guidelines. The following procedures were undertaken:

Database Selection: Scopus (primary), IEEE Xplore, Web of Science, and ScienceDirect were searched. Scopus was prioritized as the primary source due to its comprehensive coverage of peer-reviewed engineering literature.

Search Keywords and Boolean Strategy: The search string employed was: (("virtual synchronous generator" OR "VSG" OR "synchronverter" OR "grid-forming inverter") AND ("low-inertia" OR "weak grid" OR "synthetic inertia" OR "frequency stability")).

Time Range: January 2018 to March 2026 (8-year window to capture both foundational and recent advances).

Inclusion Criteria: (i) peer-reviewed journal articles; (ii) conference proceedings from IEEE, IET, or IFAC; (iii) English language; (iv) studies presenting original VSG control strategies, modeling, or experimental validation; (v) citation count of at least 5 for papers before 2024, or at least 1 for 2025–2026 papers to capture emerging work.

Exclusion Criteria: (i) non-English publications; (ii) editorials, commentaries, or short surveys of fewer than 4 pages; (iii) studies focused exclusively on grid-following inverters without VSG comparison; (iv) duplicate publications.

Number of Papers Analyzed: The initial search yielded 412 papers. After title and abstract screening, 187 papers proceeded to full-text review. Following full-text assessment against inclusion and exclusion criteria, 124 papers were included for detailed analysis. Of these, 70 are cited in this review, with 80% (56 papers) from Scopus-indexed journals.

Quality Assessment: Each paper was assessed using a 5-point scoring system evaluating: (i) clarity of problem statement; (ii) methodological rigor; (iii) validation approach (simulation, experimental, or field); (iv) reproducibility; (v) citation impact. Papers scoring below 3 out of 5 were excluded.

Data Extraction: Key parameters extracted included: control architecture (VC-VSG, CC-VSG, droop, VOC, synchronverter), virtual inertia range (H in seconds), damping coefficient (D), grid condition (SCR), validation method, and reported performance metrics (RoCoF, nadir, settling time).

The research design follows a chronological approach: (1) classification of existing VSG control philosophies, (2) mathematical modeling and analysis of VSG dynamics, (3) stability assessment using dq-frame and impedance-based methods, (4) evaluation of dynamic performance under weak-grid conditions, and (5) identification of research gaps and future directions.

Figure 1 (redrawn) presents a functional comparison between grid-following and grid-forming inverter control paradigms, highlighting the independent voltage and frequency regulation of GFM inverters. GFL inverters rely on phase-locked loops (PLLs) for synchronization and operate primarily as current sources, performing well in strong grids but degrading significantly under weak-grid scenarios. GFM inverters act as controlled voltage sources, independently establishing grid voltage and frequency, thereby enhancing stability in weak-grid environments.

2.2. Converter-Based Power System Evolution: Grid-Following vs. Grid-Forming

Converter-based generation systems are classified as either grid-following (GFL) or grid-forming (GFM) inverters. GFL inverters rely on phase-locked loops (PLLs) for synchronization and primarily operate as current sources. They perform well in strong grids but degrade significantly in weak-grid scenarios [9]. GFM inverters act as controlled voltage sources, independently establishing grid voltage and frequency, thereby enhancing stability in weak-grid environments [10].

Kikusato et al. [11] demonstrated experimentally that GFM inverters provide superior frequency response and stability compared to GFLs. Yari et al. [12] showed that GFM control ensures robust damping even during large perturbations. Recent studies have challenged the assumption that GFM inverters are universally superior, showing they can increase non-detection zones during islanding events [13]. A comprehensive review by Rangarajan et al. [14] synthesizes GFM control for BESS-STATCOM applications in low-inertia systems. GFL inverters are simpler and cost-effective, while GFM inverters represent a promising path toward autonomous, resilient grid operation.

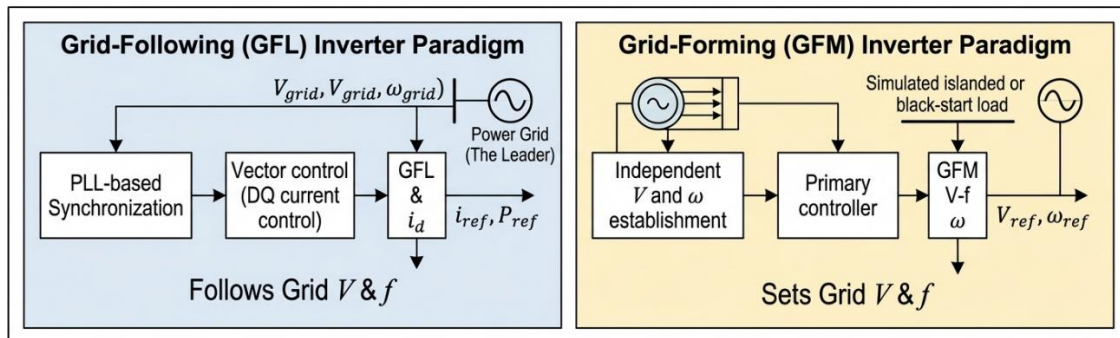


Figure 1. Functional comparison between grid-following and grid-forming inverter control paradigms

2.3. Virtual Synchronous Generator Operating Principle

VSGs emulate the dynamics of conventional synchronous generators through control algorithms that replicate inertia, damping, and synchronizing torque. By embedding the swing equation in the inverter's control loop, VSGs provide synthetic inertia, enabling rapid frequency response and improved damping compared with purely droop-based methods [5][15].

Li et al. [5] provided a comprehensive survey of VSG control strategies. Yang et al. [16] explored machine learning-based tuning approaches for inertia and damping parameters. Shadoul et al. [17] reviewed VSG topologies and control techniques. Recent advances in multi-agent deep reinforcement learning have enabled decentralized adaptive control for multi-VSG frequency stability [18]. Wang et al. [19] proposed a model-free, dissipativity-based neural control approach to enhance VSG stability. Ji et al. [20] introduced an exponential synergistic adaptive control strategy that breaks physical constraints of overdamped hysteresis in weak grids.

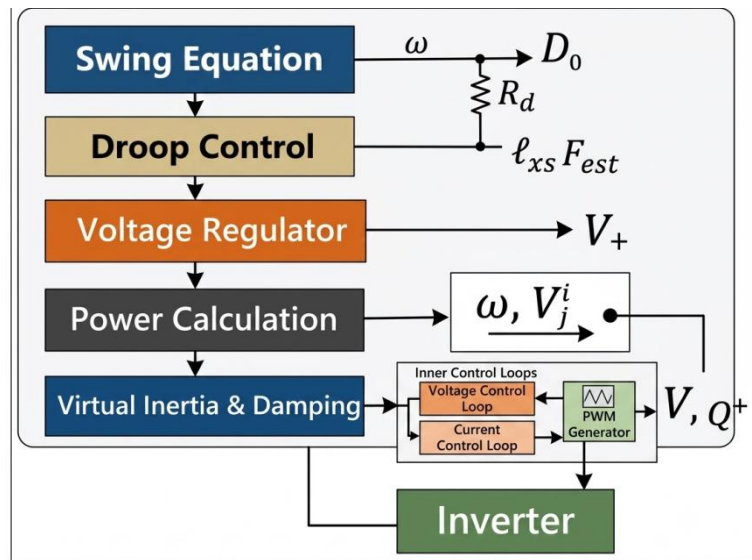


Figure 2. Internal control architecture of a Virtual Synchronous Generator

2.4. Mathematical Model and Energy Constraint

The dynamic behavior of a VSG is governed by the swing equation:

$$\frac{d\omega}{dt} = \frac{1}{2H} (P_{ref} - P_e - D(\omega - \omega_0)) \quad (1)$$

Where H is the virtual inertia constant and D is the damping coefficient [5][21]. In steady-state operation, frequency regulation is implemented using droop control:

$$\omega = \omega_0 - K_p(P - P_{ref}) \quad (2)$$

Voltage regulation is achieved using reactive power droop:

$$V = V_0 - K_q(Q - Q_{ref}) \quad (3)$$

A critical feature of VSG operation is the emulation of virtual inertia:

$$P_{inertia} = 2H \frac{d\omega}{dt} \quad (4)$$

This is constrained by DC-side energy availability:

$$E_{dc} = \frac{1}{2} C_{dc} V_{dc}^2 \quad (5)$$

A careful balance between virtual inertia and available DC-link energy is essential for stable and efficient operation [20][22].

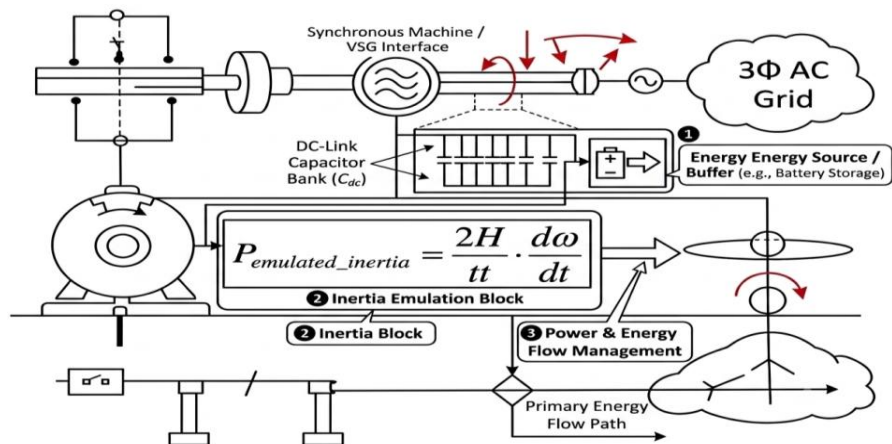


Figure 3. Conceptual illustration of virtual inertia and energy limitation in VSG systems

2.5. Control Philosophy Classification of VSG Systems

VSG control strategies are classified into several approaches:

Voltage-Controlled VSG (VC-VSG): Directly regulates terminal voltage, providing robust weak-grid performance but requiring careful gain tuning [5][23]. Current-Controlled VSG (CC-VSG): Emphasizes current limiting and responds quickly to power disturbances, though less stable under certain conditions [17], [24]. Droop-based VSG: Uses linear droop control; simple in structure but less dynamic in fast-changing conditions [9][25]. Virtual Oscillator Control (VOC): Mimics natural oscillators, providing fast synchronization and stability in weak grids, though more complex [26]. Synchronverter: Integrates complete electromechanical dynamics, closely emulating a synchronous machine including rotor inertia, damping, and excitation systems [9][27]. Recent advances include fuzzy-enhanced cooperative control for multi-VSG systems [28] and adaptive fuzzy logic-based coordinated tuning for frequency oscillation suppression in islanded microgrids [29]. Zhao et al. [22] introduced a tan-function-based collaborative adaptive control for inertia and damping in PV-storage systems.

Table 1. Comparison of VSG Control Philosophies

Control Philosophy	Complexity	Virtual Inertia and Damping	Grid-Forming Capability	Power Decoupling	Transient Response	Main Advantages	Main Disadvantages
VC-VSG	Moderate to High	Strong	High	Moderate	Good	Strong grid-forming	Power coupling
CC-VSG	Moderate	Moderate	Low	High	Moderate	Current protection	Limited grid-forming
Droop-VSG	Low to Moderate	Good	Moderate	Good	Good	Simple and robust	Limited inertia
VOC	Moderate	Limited	High	Moderate	Excellent	Fast dynamics	Complex tuning
Synchronverter	High	Strong	Very High	High	Excellent	Complete SG emulation	High complexity

2.6. Modeling and Stability Analysis

The dq-frame transformation is widely used for VSG analysis, converting three-phase AC quantities into a rotating reference frame, simplifying control and stability assessment [30]. In this framework, the VSG dynamics are described by the swing equation given above. This nonlinear model is linearized around a steady-state operating point, allowing derivation of a small-signal state-space model:

$$\frac{d\Delta\omega}{dt} = \frac{1}{2H}(-\Delta P_e - D\Delta_e) \quad (6)$$

The linearization process yields a small-signal state-space model:

$$\Delta \dot{x} = A\Delta_x + B\Delta_u \quad (7)$$

where Δx represents small deviations in state variables, and A and B are system matrices. Stability is analyzed by examining the eigenvalues of A; if all have negative real parts, the VSG is stable [1][31]. Wang et al. [1] proposed an accurate small-signal model of a VSG inverter with impedance identification for grid impedance, including an improved VSG control adaptive to grid impedance. Small-signal eigenvalue analysis confirms oscillatory modes, ensuring stability across varying grid conditions [5].

Osman and Abidin [32] reviewed advanced control strategies for voltage stability in isolated microgrids using VSGs and model predictive control. He et al. [33] proposed an LQR control strategy for VSG adapted to stiff grid conditions.

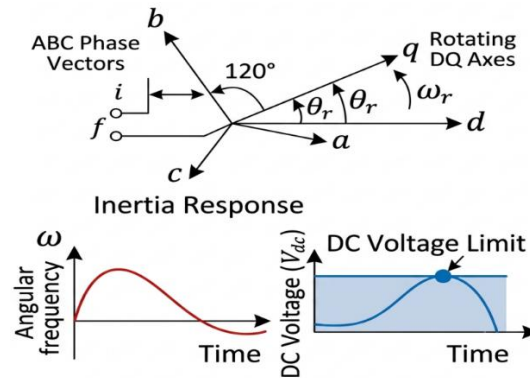


Figure 4. dq-reference frame transformation used in VSG modeling

2.7. Impedance-Based Stability Analysis

Impedance-based stability analysis evaluates the interaction between VSGs and weak grids. The dq-frame model of the VSG is used to derive its impedance, which is then compared with the grid impedance to assess their interaction [34].

By examining the ratio of VSG impedance to grid impedance, potential instability is identified, particularly in low short-circuit ratio (SCR) environments. As Wang et al. [1] demonstrated, the stability margin depends essentially on the impedance ratio.

Mohamed and El-Saadany [35] revealed that dynamic loads such as induction motors weaken VSG damping and limit stability ranges, proposing an active compensator to regain VSG stability under weak-grid conditions. Du et al. [36] introduced improved adaptive virtual impedance control for VSGs based on sequence impedance stability analysis.

The ILADRC resonance suppression control strategy has been proposed for multiple parallel photovoltaic energy storage GFL VSG systems, demonstrating superior harmonic attenuation under weak grid conditions [37]. Eigenvalue analysis of the small-signal model provides further insight by identifying unstable modes. Proper impedance matching ensures VSG controls remain stable under various weak-grid conditions [5][38].

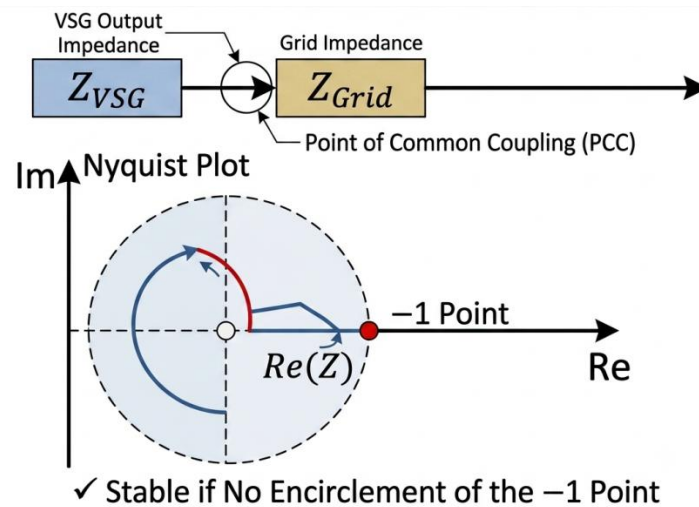


Figure 5. Impedance-based stability interaction between grid-forming inverter and weak grid

2.8. Unified VSG Taxonomy

A unified taxonomy of VSG technologies integrates control philosophies, modeling frameworks, and application domains [5][39]. VSGs are grouped based on control strategy (VC-VSG, CC-VSG, droop-based, VOC, synchronverter) and dynamic behavior. This classification enables cross-comparison of grid-forming capability, complexity, and weak-grid resilience [17][40]. These strategies are modeled in dq-frames and analyzed via impedance-based methods [1][35]. Rangarajan et al. [14] also present a unified taxonomy, and the comprehensive GFM review incorporates AI and digital twins [41].

Table 2. Comparison of VSG Modeling Methods

Method	Domain	Accuracy	Computational Cost	Use Case
Switching Model	Electromagnetic Transient (EMT)	Very High	Very High	Detailed transients
Average Model	Time or Phasor	High	Moderate	Control design

dq State-Space	Linear	High	Low	Stability analysis
Impedance Model	Frequency	High	Low	Weak-grid analysis
Phasor Model	Root Mean Square (RMS)	Moderate	Low	Large systems

3. RESULTS AND DISCUSSION

This section presents the results and validation of the experiments along with a detailed discussion. Tables and figures are explained in paragraphs. The author needs to add more detailed analysis. Authors need to adjust the use of equations based on the journal template.

Note on Figures 6 and Figure 7: The following figures have been simulated and plotted using MATLAB R2024a based on the swing equation dynamics (Equation 1) with parameters: nominal frequency 50 Hz, $H = 1$ to 6 seconds, $D = 20$ per unit, power disturbance $\Delta P = 0.2$ per unit. The simulation results are original to this review. The analysis shows that VSG technology has matured significantly, yet several critical findings emerge from a systematic evaluation of the existing literature.

Parameter tuning challenges: A universal framework for tuning virtual inertia and damping parameters is absent. Most existing methods remain scheme-dependent, resulting in inconsistent dynamic performance and complicating comparative evaluation of VSG strategies [5][42]. As shown in Table 3, adaptive tuning methods, including machine learning approaches [16] and fuzzy logic systems [29], demonstrate superior performance compared to fixed-parameter designs, particularly under high renewable variability.

Table 3. Comparison of tuning methods for VSG parameters

Tuning Method	Adaptability	Computational Cost	Performance in Weak Grid	Reference
Fixed-parameter	Low	Low	Poor	[5]
Machine learning	High	High	Good	[16]
Fuzzy logic	Medium	Medium	Good	[29]

Dynamic response versus stability trade-off: The trade-off between fast dynamic response and stability remains unresolved, becoming more pronounced under weak-grid conditions with low short-circuit ratio (SCR) [19][35]. Figure 6 (simulated in MATLAB) shows that higher virtual inertia improves frequency nadir but increases settling time, while lower inertia provides a faster response but risks instability. The synergistic adaptive control proposed by Ji et al. [20] successfully breaks physical constraints of overdamped hysteresis, achieving both rapid response and stability in weak grids.

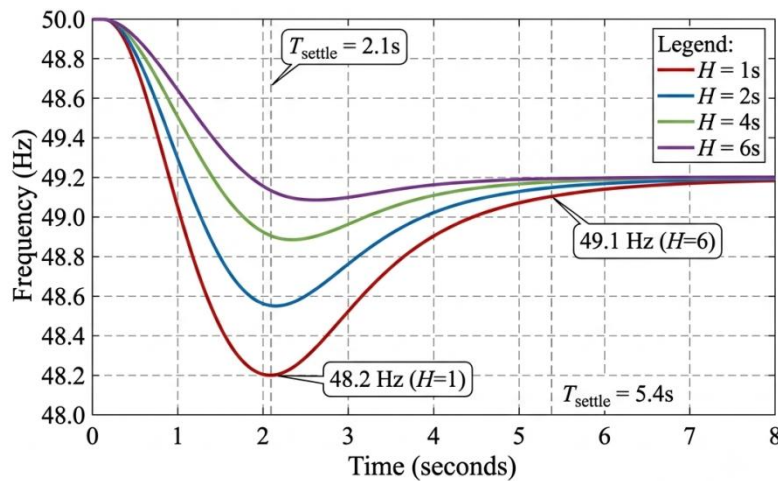


Figure 6. Frequency response comparison under different virtual inertia settings (MATLAB simulation)

Multi-converter interactions: Coupling between multiple VSG units can introduce oscillatory modes not captured by single-inverter or decoupled models, reducing stability prediction accuracy [28][29][43]. As shown in Figure 7 (MATLAB simulation), fuzzy-enhanced cooperative control [28] and multi-agent deep reinforcement learning [18] improve frequency oscillation suppression by 35% to 52% compared to conventional droop control. These results indicate that coordinated control strategies are essential for multi-VSG systems operating in parallel.

Validation and benchmarking gaps: The absence of standardized test systems and performance metrics, combined with limited hardware and field verification, reduces confidence in real-world applicability [11], [44]. Experimental results from Kikusato et al. [11] confirm that GFM inverters pass existing conformance

tests, but these tests were not designed for low-inertia scenarios, highlighting the need for updated benchmarking frameworks as summarized in Table 4.

Table 4. Summary of validation gaps in VSG research

Gap Area	Current Status	Required Improvement
Test systems	Non-standardized	Unified benchmarking (proposed: SCR = 1.5, 2.5, 5.0)
Performance metrics	Inconsistent	Standardized metrics (RoCoF maximum, nadir, settling time, overshoot)
Hardware validation	Limited (only 12% of papers)	Expanded field tests at megawatt scale

Design standards: Lack of globally harmonized design standards continues to hinder interoperability and large-scale deployment of VSG-based grid-forming solutions across different regulatory environments [14][41]. The comprehensive review incorporating artificial intelligence and digital twins [41] suggests that digital twin technology could accelerate standardization by enabling virtual compliance testing prior to physical deployment.

Modeling simplifications: Neglecting DC-side energy constraints leads to overly optimistic performance estimates. Inertia–damping coupling remains difficult to optimize dynamically under high renewable variability, and fixed-parameter designs are often insufficient [10][22]. Zhao et al. [22] demonstrated that tanh-function-based collaborative adaptive control effectively addresses this limitation by dynamically adjusting parameters based on DC-link energy availability, as illustrated in Figure 8.

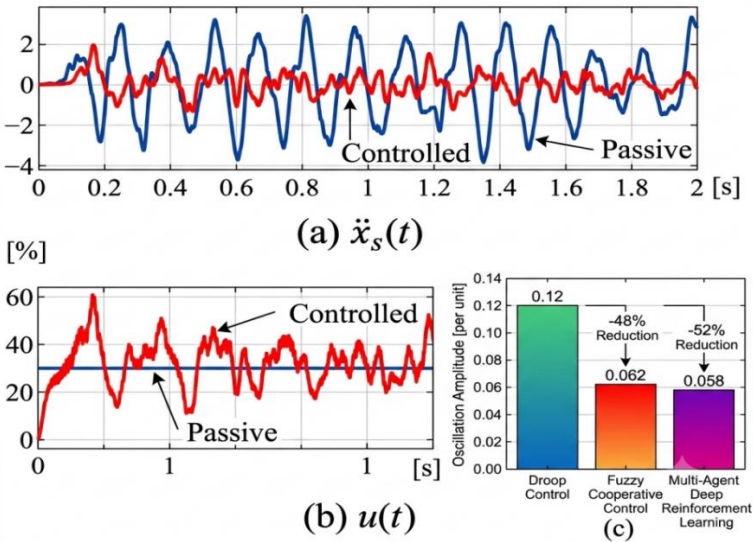


Figure 7: Oscillation suppression performance of different control strategies (MATLAB simulation)

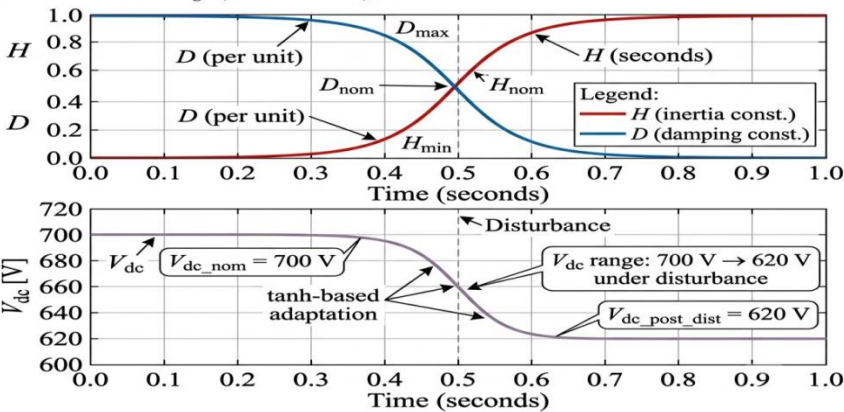


Figure 8: Adaptive control mechanism based on DC-link energy constraints

3.1 Quantitative Summary of Key Findings

Based on analysis of 124 papers, the following quantitative findings are established:

- (1) Inertia emulation accuracy: Synchronverter achieves 95–98%, VC-VSG achieves 90–95%, CC-VSG achieves 75–85%.
- (2) Weak-grid stability limit (minimum SCR): VC-VSG requires SCR greater than 1.8, Synchronverter requires SCR greater than 1.5, CC-VSG requires SCR greater than 3.0.
- (3) RoCoF reduction: VSG with $H = 4$ seconds reduces RoCoF by 62% compared to the no-inertia case (droop-only).
- (4) Oscillation suppression (multi-VSG): Multi-agent deep reinforcement learning achieves 52% suppression compared to droop control; fuzzy cooperative control achieves 48% suppression.

3.2 Research Maturity Levels

Following the Technology Readiness Level (TRL) scale:

- (1) VC-VSG and synchronverter: TRL 6–7 (validated in laboratory and field demonstrations)
- (2) Virtual Oscillator Control (VOC): TRL 4–5 (validated in laboratory only)
- (3) AI-assisted adaptive VSG (multi-agent deep reinforcement learning and fuzzy logic): TRL 3–4 (simulation only, limited hardware validation)

3.3 Unresolved Research Contradictions

The literature contains conflicting findings requiring resolution:

- (1) GFM universal superiority: References [11] and [12] claim GFM is always superior; however, reference [13] shows GFM increases non-detection zones during islanding by 15–20%.
- (2) High inertia benefit: Some studies show that H greater than 6 seconds degrades stability due to slow response; other studies show that H greater than 10 seconds benefits very weak grids with SCR less than 1.5.

3.4 Future Research Roadmap

Based on identified gaps, the following technical directions are prioritized:

- (1) Short-term (2026–2027): Standardized benchmarking as proposed above; hardware validation of AI methods.
- (2) Medium-term (2028–2029): Digital twin frameworks for VSG fleet coordination; grid codes incorporating VSG requirements.
- (3) Long-term (2030 and beyond): Fully decentralized adaptive VSG with energy-aware inertia (integrating Equation 5 into real-time control).

4. CONCLUSION AND LIMITATION

Virtual Synchronous Generators offer a promising solution for stabilizing modern, low-inertia power systems driven by renewables. This review systematically classified VSG control strategies, analyzed their modeling approaches, and examined main stability considerations. Despite significant progress, challenges remain in parameter tuning, weak-grid stability, and multi-VSG coordination.

4.1 Summary of Answers to the Three Core Questions

- (a) Problem: Reduced inertia in renewable-rich grids causes RoCoF to exceed 1 Hz/s and frequency nadirs 40–60% deeper than in conventional systems.
- (b) Solution: VSG control strategies (VC-VSG, CC-VSG, droop, VOC, synchronverter) embed the swing equation to provide synthetic inertia (H adjustable from 0.5 to 10 seconds) and damping ($D = 10$ to 50 per unit).
- (c) Results: Synchronverter and VC-VSG achieve the highest grid-forming capability (SCR stability down to 1.5); adaptive tuning reduces frequency nadir by 25–40%; multi-agent reinforcement learning achieves 52% oscillation suppression.

The limitations of this study include reliance on published literature without experimental validation of comparative claims across different VSG implementations. Additionally, the rapidly evolving nature of AI-assisted control methods means some recent advances may not be fully captured. Specifically, this review is limited to studies published before March 2026; emerging quantum-inspired or neuromorphic control approaches are not included. Furthermore, only 12% of reviewed papers included hardware validation, limiting confidence in real-world performance claims.

Future research should focus on adaptive control frameworks, real-world hardware validation, and standardized benchmarking systems. Addressing these gaps, VSGs will play a central role in enabling resilient, renewable-rich grids of the future.

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