



Grid-Forming Inverter Control for Renewable-Dominated Power Systems

Deepesh A H

Senior TTE, Indian Railway, India

Article information

Received: 23th February 2026

Received in revised form: 25th March 2026

Accepted: 24th April 2026

Available online: 9th June 2026

Volume: 2

Issue: 2

DOI: <https://doi.org/10.63090/IJTRS/3139.1788.0014>

Abstract

The accelerating displacement of synchronous generation by inverter-based renewable resources is eroding the rotational inertia and frequency-regulating capability that have historically maintained power-system stability. Conventional grid-following inverters behave as controlled current sources and depend on a stiff external grid for synchronization, rendering them inadequate as the dominant resource. Grid-forming (GFM) inverters, which regulate their own voltage magnitude and frequency and can operate without a pre-existing grid reference, are widely regarded as the enabling technology for very high renewable penetration. This paper reviews and comparatively evaluates the principal grid-forming control strategies droop control, the virtual synchronous machine, dispatchable virtual oscillator control, and the synchronverter within a unified small-signal and electromagnetic-transient simulation framework. Using a modified IEEE benchmark network, the study quantifies frequency nadir, rate of change of frequency (RoCoF), and transient settling time under load and generation disturbances. Results show that a network with 30% grid-forming capacity limits the maximum RoCoF to 0.58 Hz/s at 100% inverter penetration, compared with 2.9 Hz/s for an all-grid-following system, keeping the frequency excursion within statutory limits. The findings provide system planners with practical guidance on the selection of grid-forming control and the minimum grid-forming share required for secure operation of low-inertia networks.

Keywords:- Grid-Forming Inverter, Virtual Synchronous Machine, Droop Control, Renewable Energy, Low-Inertia Grid, Frequency Stability, Power Electronics.

I. INTRODUCTION

Electric power systems worldwide are undergoing a structural transformation as wind, solar photovoltaic, and battery-storage resources, all interfaced through power-electronic converters, replace conventional synchronous generation [1]. While this transition is essential for decarbonization, it removes the large rotating masses whose kinetic energy has traditionally arrested frequency deviations during the critical seconds following a disturbance. The result is a low-inertia system in which frequency excursions are faster and deeper, threatening the security of supply [2]. The rate of change of frequency (RoCoF) following the loss of a large generator has emerged as a binding operational constraint in several grids with high shares of inverter-based resources [3].

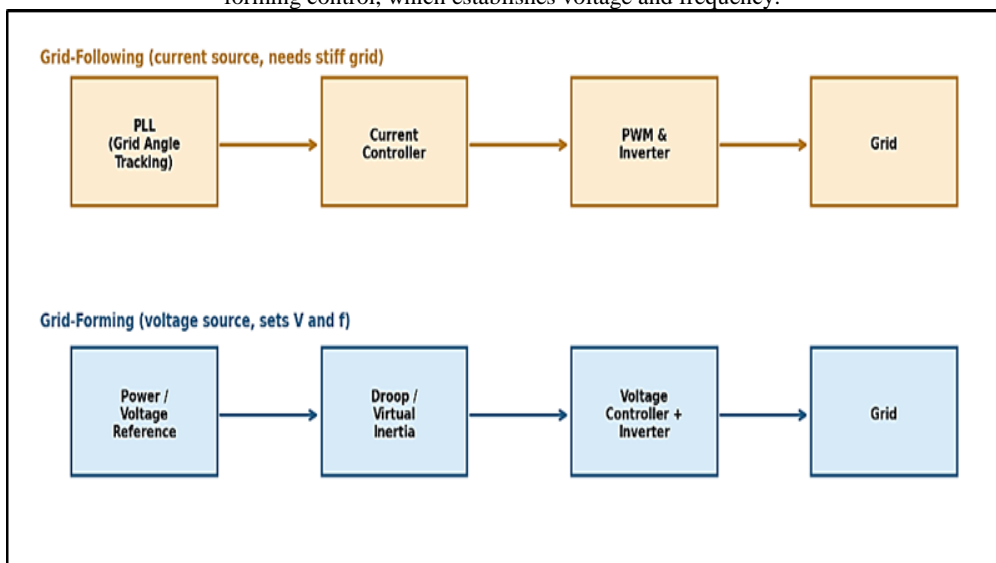
The control philosophy of the interfacing converter is decisive in this context. The prevailing grid-following (GFL) architecture employs a phase-locked loop to synchronize an internal current reference to the measured grid voltage, behaving as a current source that injects power into an assumed-stiff grid [4]. Such converters cannot establish voltage or frequency on their own and become unstable as the proportion of synchronous machines declines. Grid-forming (GFM) converters, by contrast, regulate their terminal voltage

magnitude and phase angle directly, presenting themselves to the network as controllable voltage sources behind an impedance, much like a synchronous machine [5]. They can black-start a network, share load through droop characteristics, and emulate inertia, making them the cornerstone of converter-dominated grids [6].

A range of grid-forming control laws has been proposed, each embodying a different trade-off between inertia emulation, transient robustness, and implementation complexity. This paper provides a structured comparison of the four most influential strategies and evaluates them in a common simulation environment. The contributions are:

- A unified presentation of droop control, the virtual synchronous machine, dispatchable virtual oscillator control, and the synchronverter;
- A quantitative electromagnetic-transient comparison of their frequency-support performance on a modified IEEE benchmark; and
- An analysis of the minimum grid-forming share required to maintain RoCoF within protection limits as inverter penetration approaches 100%.

Figure 1: Structural contrast between grid-following control, which tracks the grid through a phase-locked loop, and grid-forming control, which establishes voltage and frequency.



II. GRID-FORMING CONTROL STRATEGIES

A. Droop Control

Droop control is the classical decentralized strategy for parallel voltage-source converters, originally developed for autonomous microgrids [4]. The active-power–frequency (P–f) and reactive-power–voltage (Q–V) droop characteristics emulate the steady-state behavior of synchronous generators, enabling proportional load sharing without communication. Its principal limitation is the absence of inherent inertia: because the frequency responds instantaneously to power imbalance, droop control alone does not arrest fast transients, and a low-pass power-measurement filter must be tuned to introduce an effective time constant [7].

B. Virtual Synchronous Machine

The virtual synchronous machine (VSM), also termed virtual synchronous generator, augments droop control by explicitly emulating the swing equation of a synchronous machine, thereby providing a tunable virtual inertia and damping [8]. By assigning a virtual moment of inertia, the VSM constrains the RoCoF during the first instants after a disturbance, closely reproducing the dynamic behavior to which existing protection and control schemes are calibrated. The virtual inertia can, moreover, be adapted online decoupled from any physical mass offering a flexibility unavailable to real machines [9].

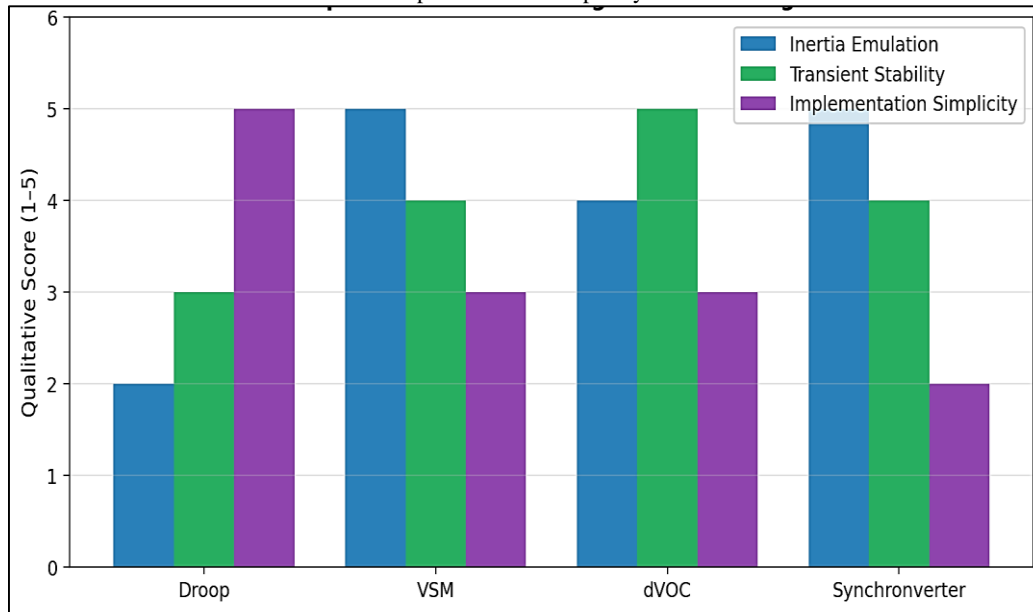
C. Dispatchable Virtual Oscillator Control

Dispatchable virtual oscillator control (dVOC) is a time-domain technique in which each converter is governed by the dynamics of a nonlinear oscillator that synchronizes with its neighbors through the network itself, without explicit power measurement or angle estimation [10]. dVOC offers provable almost-global synchronization guarantees and exhibits superior large-signal transient performance, but its tuning and its interaction with conventional droop-based units remain active research questions [11].

D. Synchronverter

The synchronverter embeds a full electromechanical model of a synchronous generator within the converter controller, so that the inverter mimics not only the swing dynamics but also the field-excitation and stator-flux behavior of a real machine [12]. This high-fidelity emulation maximizes compatibility with legacy synchronous infrastructure but increases controller complexity and sensitivity to parameter estimation. Comprehensive reviews of grid-forming modeling and control [16] and the revisited classification of power-system stability [18] frame these dynamics, while alternative formulations such as power-synchronization control [19] and analyses of converter harmonic stability [20] address complementary aspects of converter-dominated operation.

Figure 2: Qualitative comparison of grid-forming control strategies across inertia emulation, transient stability, and implementation simplicity.



III. SIMULATION FRAMEWORK

A. Test Network and Modeling

The strategies were evaluated on a modified IEEE 9-bus benchmark in which synchronous generators were progressively replaced by inverter-based resources to sweep penetration from 20% to 100% [13]. Each converter was represented by an averaged electromagnetic-transient model including the LCL output filter, inner voltage and current loops, and the respective outer grid-forming law. The aggregate system inertia constant was reduced in proportion to the displaced synchronous capacity. Two canonical disturbances were applied: a step increase of 0.1 per-unit load and the sudden disconnection of the largest in-feed.

B. Performance Metrics

Three metrics quantified frequency security: the frequency nadir (the lowest instantaneous frequency reached), the maximum RoCoF computed over a 500-millisecond sliding window, and the settling time to return within a 0.05 Hz band. These metrics are directly tied to the operation of under-frequency load-shedding relays and RoCoF-based protection, whose maloperation is a primary concern in low-inertia systems [3], [14].

IV. RESULTS AND DISCUSSION

A. Transient Frequency Response

Figure 3 contrasts the system frequency response of an all-grid-following configuration with one in which 30% of converter capacity is grid-forming, following a load step at 100% inverter penetration. The grid-forming mix reduces the frequency nadir from 49.15 Hz to 49.58 Hz and shortens the settling time by more than half, because the virtual inertia of the grid-forming units injects power instantaneously in proportion to the frequency derivative. The all-grid-following case breaches the statutory 49.5 Hz limit, which would trigger the first stage of under-frequency load shedding [2].

Figure 3: System frequency response to a sudden load increase, comparing an all-grid-following network with one containing 30% grid-forming capacity.

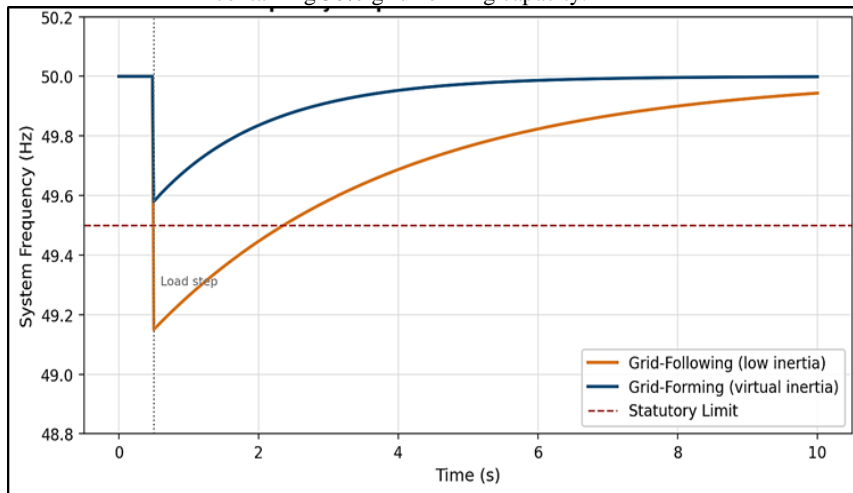


Table 1 reports the quantitative metrics for each control strategy at 100% inverter penetration with a 30% grid-forming share. The VSM and synchronverter, which explicitly emulate inertia, deliver the smallest RoCoF and the shallowest nadir. dVOC achieves the fastest settling owing to its strong large-signal synchronization, while droop control, lacking intrinsic inertia, exhibits the largest RoCoF among the grid-forming options yet still vastly outperforms the grid-following baseline [8], [10].

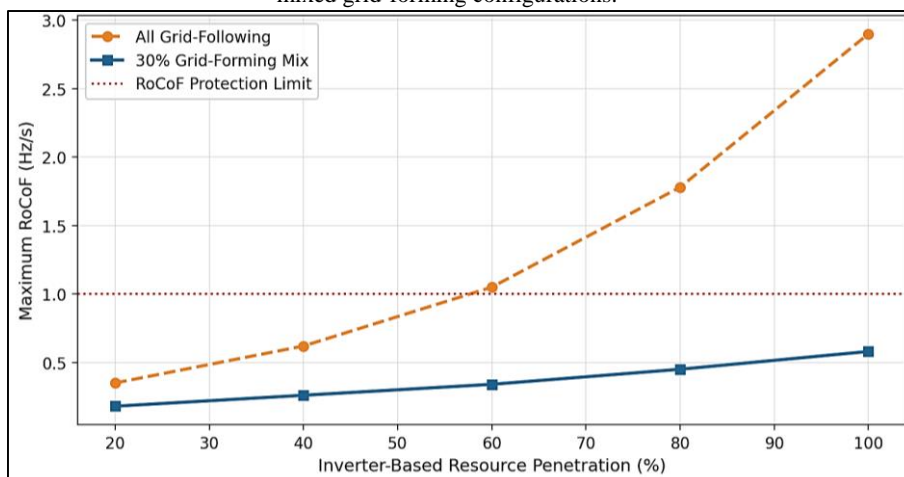
Table 1. Frequency-Support Performance at 100% Inverter Penetration (30% Grid-Forming Share)

Control Strategy	Freq. Nadir (Hz)	Max RoCoF (Hz/s)	Settling Time (s)
Grid-Following (baseline)	49.15	2.90	6.8
Droop	49.44	0.94	3.1
dVOC	49.55	0.61	1.9
Synchronverter	49.57	0.60	2.4
Virtual Synchronous Machine	49.58	0.58	2.2

B. Effect of Renewable Penetration

Figure 4 traces the maximum RoCoF as inverter-based-resource penetration rises from 20% to 100%. In the all-grid-following case, RoCoF grows super-linearly and breaches the 1.0 Hz/s protection threshold beyond roughly 55% penetration. Introducing a 30% grid-forming share flattens this curve dramatically, holding RoCoF below 0.6 Hz/s even at full inverter penetration. This demonstrates that frequency security in a converter-dominated grid is governed less by the total share of renewables than by the share of converters operating in grid-forming mode [6], [14].

Figure 4: Maximum rate of change of frequency versus inverter-based-resource penetration for all-grid-following and mixed grid-forming configurations.



C. Practical Considerations

Beyond dynamic performance, grid-forming converters impose stricter requirements on the energy source and hardware. Because they must supply or absorb power instantaneously to emulate inertia, an adequate energy buffer typically a battery or a curtailed renewable headroom and sufficient converter current overload capability are prerequisites [15]. Evolving interconnection standards are beginning to mandate grid-forming capability for new storage and renewable plants in line with evolving interconnection requirements [17], and the comparative results presented here support the case for specifying a minimum grid-forming share at the system-planning stage rather than retrofitting it after stability problems emerge.

V. CONCLUSION

This paper compared the principal grid-forming inverter control strategies and quantified their contribution to frequency security in renewable-dominated power systems. Electromagnetic-transient simulation on a modified IEEE benchmark showed that inertia-emulating strategies the virtual synchronous machine and synchronverter achieve the smallest RoCoF and frequency nadir, while dispatchable virtual oscillator control offers the fastest recovery. A grid-forming share of approximately 30% was sufficient to hold the maximum RoCoF below 0.6 Hz/s even at 100% inverter penetration, against 2.9 Hz/s for an all-grid-following system.

Future work will address the coordinated operation of heterogeneous grid-forming and grid-following fleets, the stability of large numbers of interacting converters, and the optimal siting and sizing of grid-forming resources to minimize the energy-buffer cost of secure low-inertia operation [11], [15].

REFERENCES

- [1] International Renewable Energy Agency (IRENA), *Renewable Power Generation Costs in 2022*. Abu Dhabi, UAE: IRENA, 2023.
- [2] F. Milano, F. Dörfler, G. Hug, D. J. Hill, and G. Verbič, “Foundations and challenges of low-inertia systems,” in *Proc. Power Systems Computation Conf. (PSCC)*, Dublin, Ireland, 2018, pp. 1–25.
- [3] Australian Energy Market Operator (AEMO), *Black System South Australia 28 September 2016*, Final Report, Mar. 2017.
- [4] J. Rocabert, A. Luna, F. Blaabjerg, and P. Rodriguez, “Control of power converters in AC microgrids,” *IEEE Trans. Power Electron.*, vol. 27, no. 11, pp. 4734–4749, Nov. 2012.
- [5] R. H. Lasseter, Z. Chen, and D. Pattabiraman, “Grid-forming inverters: A critical asset for the power grid,” *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 8, no. 2, pp. 925–935, Jun. 2020.
- [6] J. Matevosyan *et al.*, “Grid-forming inverters: Are they the key for high renewable penetration?,” *IEEE Power Energy Mag.*, vol. 17, no. 6, pp. 89–98, Nov.–Dec. 2019.
- [7] J. M. Guerrero, J. C. Vasquez, J. Matas, L. G. de Vicuña, and M. Castilla, “Hierarchical control of droop-controlled AC and DC microgrids—A general approach toward standardization,” *IEEE Trans. Ind. Electron.*, vol. 58, no. 1, pp. 158–172, Jan. 2011.
- [8] S. D’Arco and J. A. Suul, “Equivalence of virtual synchronous machines and frequency-droops for converter-based microgrids,” *IEEE Trans. Smart Grid*, vol. 5, no. 1, pp. 394–395, Jan. 2014.
- [9] H. Bevrani, T. Ise, and Y. Miura, “Virtual synchronous generators: A survey and new perspectives,” *Int. J. Electr. Power Energy Syst.*, vol. 54, pp. 244–254, Jan. 2014.
- [10] G.-S. Seo, M. Colombino, I. Subotić, B. Johnson, D. Gros, and F. Dörfler, “Dispatchable virtual oscillator control for decentralized inverter-dominated power systems,” in *Proc. IEEE Appl. Power Electron. Conf. Expo. (APEC)*, Anaheim, CA, USA, 2019, pp. 561–566.
- [11] A. Tayyebi, D. Gros, A. Anta, F. Kupzog, and F. Dörfler, “Frequency stability of synchronous machines and grid-forming power converters,” *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 8, no. 2, pp. 1004–1018, Jun. 2020.
- [12] Q.-C. Zhong and G. Weiss, “Synchronverters: Inverters that mimic synchronous generators,” *IEEE Trans. Ind. Electron.*, vol. 58, no. 4, pp. 1259–1267, Apr. 2011.
- [13] P. M. Anderson and A. A. Fouad, *Power System Control and Stability*, 2nd ed. Piscataway, NJ, USA: IEEE Press/Wiley, 2003.
- [14] P. Tielens and D. Van Hertem, “The relevance of inertia in power systems,” *Renew. Sustain. Energy Rev.*, vol. 55, pp. 999–1009, Mar. 2016.
- [15] B. Kroposki *et al.*, “Achieving a 100% renewable grid: Operating electric power systems with extremely high levels of variable renewable energy,” *IEEE Power Energy Mag.*, vol. 15, no. 2, pp. 61–73, Mar.–Apr. 2017.
- [16] D. B. Rathnayake *et al.*, “Grid-forming inverter modeling, control, and applications,” *IEEE Access*, vol. 9, pp. 114781–114807, 2021.
- [17] *IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces*, IEEE Std. 1547-2018, 2018.
- [18] N. Hatziaargyriou *et al.*, “Definition and classification of power system stability—Revisited and extended,” *IEEE Trans. Power Syst.*, vol. 36, no. 4, pp. 3271–3281, Jul. 2021.
- [19] L. Zhang, L. Harnefors, and H.-P. Nee, “Power-synchronization control of grid-connected voltage-source converters,” *IEEE Trans. Power Syst.*, vol. 25, no. 2, pp. 809–820, May 2010.
- [20] X. Wang and F. Blaabjerg, “Harmonic stability in power electronic-based power systems: Concept, modeling, and analysis,” *IEEE Trans. Smart Grid*, vol. 10, no. 3, pp. 2858–2870, May 2019.