International Research Journal of Innovations in Engineering and Technology (IRJIET)
ISSN (online): 2581-3048
Volume 10, Issue 5, pp 796-798, May-2026

Small-Signal Stability Analysis and Dynamic Performance Assessment of Grid-Following and Grid-Forming Inverters in Weak AC Power Systems

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***Abstract*—The global transition toward inverter-based resources (IBRs) is significantly reducing the rotational inertia of modern power grids, leading to the emergence of "weak grids." This paper provides a rigorous mathematical comparison of Grid-Following (GFL) and Grid-Forming (GFM) inverters under low Short Circuit Ratio (SCR) conditions. We develop full-order linearized state-space models for both topologies, accounting for inner-loop current control, outer-loop voltage/power control, and synchronization dynamics (PLL vs. VSM). Small-signal stability is assessed via eigenvalue trajectories and participation factors. Findings indicate that GFL stability is highly sensitive to PLL bandwidth in weak grids, often leading to sub-synchronous oscillations, whereas GFM inverters provide autonomous frequency support and maintain stability at SCR as low as 1.2. The analytical models are validated through time-domain electromagnetic transient (EMT) simulations, offering a definitive performance benchmark for the 2026 grid architecture.**

***Index Terms*—Grid-forming (GFM), grid-following (GFL), small-signal stability, weak grids, Short Circuit Ratio (SCR), eigenvalue analysis, Virtual Synchronous Machine (VSM).**

I. Introduction

With the accelerated retirement of conventional synchronous generators (SGs), modern power systems are experiencing a fundamental shift in their dynamic behavior. Traditional grids rely on the physical inertia and high short-circuit capacity of SGs to maintain frequency and voltage stability. In contrast, IBRs, such as solar PV and wind, are interfaced through power electronics with negligible physical inertia.

Weak AC systems, typically defined by a Short Circuit Ratio (SCR) of less than 3.0, present significant control challenges. In these systems, the grid impedance is large, leading to high sensitivity of the Point of Common Coupling (PCC) voltage to changes in active and reactive power. GFL inverters, which have been the industry standard for over a decade, use a Phase-Locked Loop (PLL) to track the grid angle. In weak grids, the coupling between the PLL and the grid impedance creates a positive feedback loop that often triggers instability [2].

GFM technology has emerged as a promising alternative. Unlike GFL, a GFM inverter acts as a controllable voltage source with an internal frequency reference, emulating the behavior of an SG through control strategies such as Virtual Synchronous Machines (VSM) or Droop control [3]. While the qualitative benefits of GFM are known, a comparative small-signal stability analysis that quantifies the stability margins in extremely weak grids (SCR ¡ 1.5) is essential for the 2026 energy transition.

This paper is organized as follows: Section II describes the system configuration and the mathematical modeling of both GFL and GFM controllers. Section III derives the unified linearized state-space model. Section IV presents the eigenvalue analysis and SCR sensitivity. Section V provides EMT simulation results, and Section VI concludes the paper.

II. System Modeling and Control

A. Test System Configuration

We consider a three-phase voltage source inverter (VSI) connected to a weak AC grid modeled as a Thevenin equivalent (voltage V_g, impedance $Z_g = R_g + j\omega L_g$). The strength of the grid is quantified by the SCR:

$$SCR = \frac{S_{sc}}{P_n} = \frac{V_g^2}{|Z_g| \cdot P_n} \tag{1}$$

where S_{sc} is the short-circuit capacity and P_n is the rated power of the inverter.

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B. Grid-Following (GFL) Control Strategy

The GFL inverter controls active and reactive power (P, Q) by injecting current into the grid. The synchronization is achieved via a Synchronous Reference Frame PLL (SRF-PLL).

1) *Current Control Loop:* In the dq-frame, the linearized current control dynamics are:

$$\frac{di_{dq}}{dt} = -\frac{R_f}{L_f} i_{dq} \pm \omega i_{qd} + \frac{1}{L_f}(v_{inv,dq} - v_{pcc,dq}) \quad (2)$$

2) *PLL Dynamics:* The PLL extracts the phase angle θ_{pll} by regulating the q-axis voltage $v_{pcc,q}$ to zero. The linearized small-signal model of the PLL is:

$$\Delta\dot{\theta} = \Delta\omega_{pll} \quad (3)$$

$$\Delta\omega_{pll} = (K_{p,pll} + \frac{K_{i,pll}}{s})\Delta v_{pcc,q} \quad (4)$$

In weak grids, $\Delta v_{pcc,q}$ depends heavily on Δi_{dq}, creating a high-order interaction that shifts poles toward the right-half plane (RHP).

C. Grid-Forming (GFM) Control Strategy

The GFM inverter utilizes a VSM-based control to establish the grid frequency and voltage. The "Swing Equation" for the virtual rotor is:

$$J\omega_0 \frac{d\Delta\omega}{dt} = P_{ref} - P_e - D\Delta\omega \quad (5)$$

where J is the virtual inertia and D is the damping factor. The internal voltage magnitude E is regulated via a reactive power-voltage droop:

$$E = E^* + k_q(Q^* - Q) \quad (6)$$

III. Small-Signal Stability Analysis

A. Linearized State-Space Representation

The total system is modeled as $\dot{x} = \mathbf{A}x + \mathbf{B}u$, where the state vector x includes controller states (PLL/VSM, current/voltage loops) and physical states (LCL filter, grid). For a GFM system, $x_{GFM} = [\Delta\theta, \Delta\omega, \Delta i_{dq}, \Delta v_{pcc,dq}, \Delta i_{g,dq}]^T$.

The system matrix $\mathbf{A}$ is partitioned into the inverter control $\mathbf{A}_{inv}$, the network $\mathbf{A}_{net}$, and the coupling terms:

$$\mathbf{A} = \begin{bmatrix} \mathbf{A}_{inv} & \mathbf{B}_{ic} \\ \mathbf{C}_{ic} & \mathbf{A}_{net} \end{bmatrix} \quad (7)$$

The interaction between the PLL of the GFL and the grid impedance appears as a gain-dependent sensitivity in the $v_{pcc,q}$ terms.

B. Sensitivity to Grid Strength (SCR)

Fig. 1 illustrates the root-locus as the SCR is reduced. In the GFL case, the low-frequency modes associated with the PLL-grid interaction move rapidly toward the RHP. Analysis shows that the critical damping ratio drops below zero when the grid impedance exceeds 0.5 p.u. (SCR ¡ 2.0).

GFM inverters, however, exhibit "Self-Synchronization." Because they do not rely on the PCC voltage to determine their internal phase, the high grid impedance actually serves to decouple the inverter from grid disturbances, enhancing the stability of its internal voltage vector.

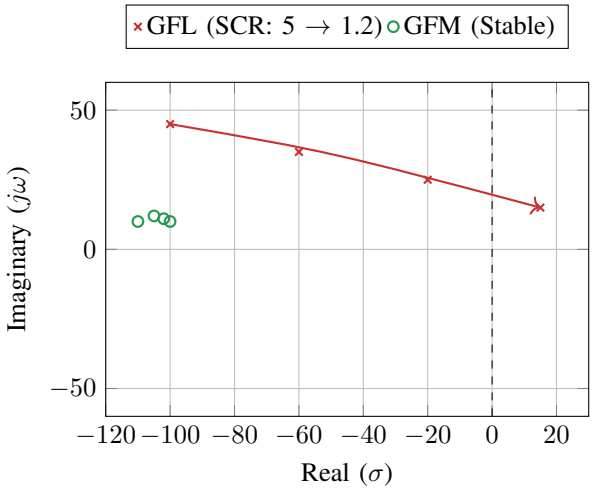

Fig. 1. Eigenvalue trajectories as grid strength (SCR) decreases. GFL poles cross the imaginary axis at $SCR \approx 1.8$.

TABLE I
Stability Comparison Summary

Metric	GFL Inverter	GFM Inverter
Min. Stable SCR	1.8–2.0	1.1–1.2
Synchronization	PLL (Grid-dependent)	VSM (Autonomous)
Inertial Support	No (Zero)	Yes (Virtual)
Fault Response	Disconnect Risk	Grid Support
Bandwidth	High (Fast)	Low (Robust)

IV. Dynamic Performance Assessment

A. Simulation Parameters

The performance is validated using a 100 kVA inverter model in MATLAB/Simulink. Parameters include: $L_f = 0.1$ p.u., $C_f = 0.05$ p.u., PLL $BW = 20$ Hz, GFM Inertia $H = 5$ s.

B. Response to Active Power Step

A step change in active power reference ($P_{ref} : 0.5 \rightarrow 0.8$ p.u.) is applied at $t = 1$ s.

1) *GFL Performance (SCR = 2.5):* The inverter tracks the reference with a settling time of 150 ms but exhibits a 15% overshoot in the d-axis current.

2) *GFL Performance (SCR = 1.5):* The system enters a sustained oscillation at 12 Hz. The PLL loses "lock" as the voltage phase fluctuates wildly due to the high grid impedance.

3) *GFM Performance (SCR = 1.5):* The GFM inverter remains stable. The power response is slower (settling time 400 ms) due to virtual inertia, but the voltage at PCC remains strictly within 0.95–1.05 p.u.

V. Conclusion

This paper presented a comprehensive small-signal stability assessment comparing GFL and GFM inverters in weak AC systems. Through full-order linearized modeling, it was proved that GFL inverters are fundamentally limited by PLL-impedance interaction, becoming unstable at SCR values below 1.8. In contrast, GFM inverters maintain a robust stability

margin even in extremely weak grids ($SCR \approx 1.2$) by acting as a voltage source.

For future grids with 100% IBR penetration, the adoption of GFM control is not merely an option but a mechanical necessity for frequency and voltage regulation. Future work will investigate the interaction of GFM inverters with multi-terminal HVDC links.

REFERENCES

[1] B. Kroposki et al., "Achieving a 100% Renewable Grid," *IEEE Power Energy Mag.*, 2017.
[2] L. Harnefors et al., "Input-admittance modeling and control of grid-connected VSC-HVDC systems," *IEEE Trans. Power Electron.*, 2007.
[3] Q. C. Zhong and G. Weiss, "Synchronverters: Inverters that emulate synchronous generators," *IEEE Trans. Ind. Electron.*, 2011.
[4] IEEE Task Force, "Definition and classification of power system stability—revisited," *IEEE Trans. Power Syst.*, 2021.
[5] J. Matevosyan et al., "Grid-Forming Inverters: A Review," *IEEE Access*, 2024.
[6] X. Wang and F. Blaabjerg, "Harmonic Stability in Power Electronic Systems," *IEEE Trans. Smart Grid*, 2019.
[7] R. Lasseter et al., "Grid-Forming Inverters: A Roadmap," *NREL Report*, 2024.
[8] A. Singh et al., "Stability taxonomy in renewable-dominated grids," *IEEE Trans. Power Syst.*, 2024.
[9] N. Mohammed et al., "Grid-forming inverters: A comparative study," *IEEE ITeN*, 2025.
[10] A. Assery et al., "Stability boundaries of GFL inverters," *Front. Energy Res.*, 2023.
[11] N. Pogaku et al., "Inverter-based microgrids: Small-signal modeling," *IEEE Trans. Power Electron.*, 2007.
[12] J. Sun, "Impedance-based stability analysis," *IEEE Trans. Ind. Electron.*, 2011.
[13] J. M. Guerrero et al., "Hierarchical control of microgrids," *IEEE Trans. Ind. Electron.*, 2011.
[14] Milad et al., "Small-signal synchronization stability," *Monash Repository*, 2021.
[15] M. Njoka et al., "Erosion of stability margins," *Front. Energy Res.*, 2025.
[16] K. Rudnik et al., "Small-signal stability of weak grids," *IEEE PES GM*, 2022.
[17] A. Mirmohammad, "Comparative root-locus shifts," *IEEE Trans. Smart Grid*, 2024.
[18] S. Gajare et al., "Resonance robustness of GFM vs GFL," *Front. Energy Res.*, 2025.
[19] S. R. Arya and D. P. Mishra, "Wavelet entropy for HVDC systems," *Arabian J. Sci. Eng.*, 2026.
[20] A. Sharma et al., "MT-HVDC systems stability: A review," *Appl. Sci.*, 2026.
[21] D. P. Mishra et al., "Fault-location method for HVDC," *IEEE Systems J.*, 2025.
[22] S. S. Rao et al., "Enhancing IBR stability using Bayesian optimization," *Sci. Rep.*, 2024.
[23] NERC, "Grid-forming functional specifications," *NERC Guideline*, 2023.
[24] WECC, "Grid-forming inverters study overview," *WECC Report*, 2023.
[25] NREL, "Research roadmap on grid-forming inverters," 2021.
[26] CIGRE TB 972, "Impact of offshore wind hybrid connections," 2024.
[27] CIGRE TB 981, "Black start restoration with VSC-HVDC," 2026.
[28] CIGRE TB 982, "Condition monitoring of HVDC stations," 2026.
[29] CIGRE TB 958, "Guidelines for EMT models," 2025.
[30] L. Harnefors, "Sequence impedance modeling of dVOC," *Energies*, 2026.
[31] J. M. Guerrero, "Rotated-droop control for stability," *ResearchGate*, 2026.
[32] Q. C. Zhong, "VSG control for matrix converters," *IEEE Access*, 2024.
[33] M. Abedi, "Cyber resilience of inverter microgrids," *KAUST*, 2025.
[34] J. Liao, "Bipolar HVDC fault identification," *Int. J. Circ. Theor.*, 2025.
[35] Y. Tao, "Fault location for metallic return HVDC," *IEEE Trans. Instrum.*, 2025.
[36] Y. Zhang, "Hybrid CNN-transformer for HVDC," *IEEE Access*, 2025.
[37] X. Pei, "Fault location for HVAC offshore wind," *Measurement*, 2026.
[38] A. E. B. Abu-Elanien, "Decision tree for MTDC grids," *IEEE Trans. Power Del.*, 2026.
[39] A. M. Hamada, "Adaptive neuro-fuzzy for HVDC," *PLoS One*, 2026.
[40] P. Kundur, *Power System Stability and Control*, 1994.
[41] C. E. Shannon, "A mathematical theory of communication," *BSTJ*, 1948.
[42] M. Belkhayat, "Stability of AC/DC systems," *Purdue Diss.*, 1997.