Assessment of Stability, Voltage-Source Behavior, and Passivity of Grid Forming Inverters

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1. Introduction

- Conventional small-signal modeling approaches lack the modularity needed to represent inverter-based resources (IBRs) with diverse control architectures.
- The Component Connection Method (CCM) provides a modular framework for unified small-signal modeling and stability analysis of grid-forming inverters.
- While CCM enables detailed white-box analysis, differences in voltage-control (VC) implementations lead to varying stability and grid-support characteristics that are difficult to quantify from a black-box perspective.

When improvements in one objective compromise another,
How should GFM technologies be quantitatively assessed and compared?

2. Small-Signal Modeling using Component Connection Method

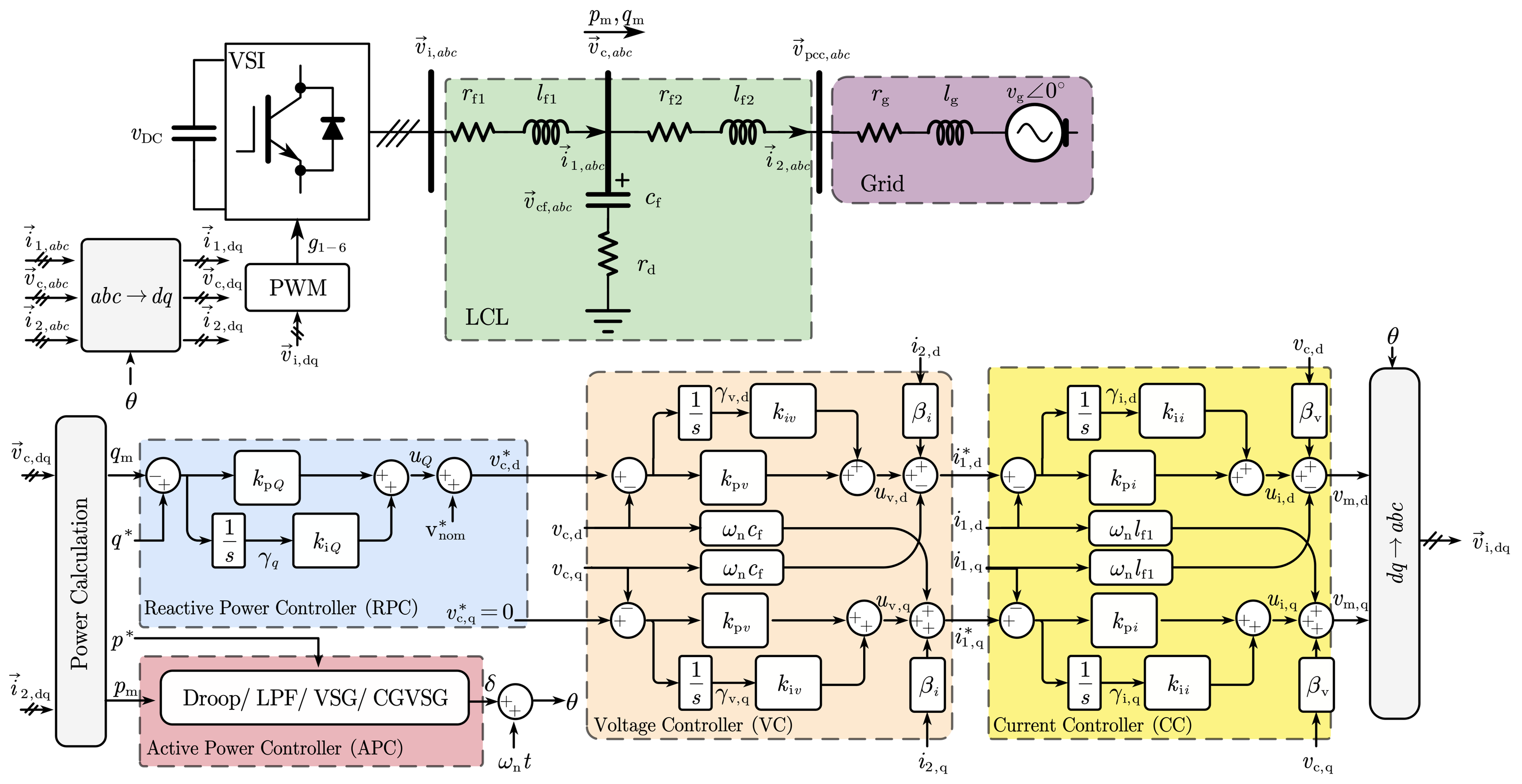

Fig. 1: Circuit and control diagram of a GFM in a SMIB network.

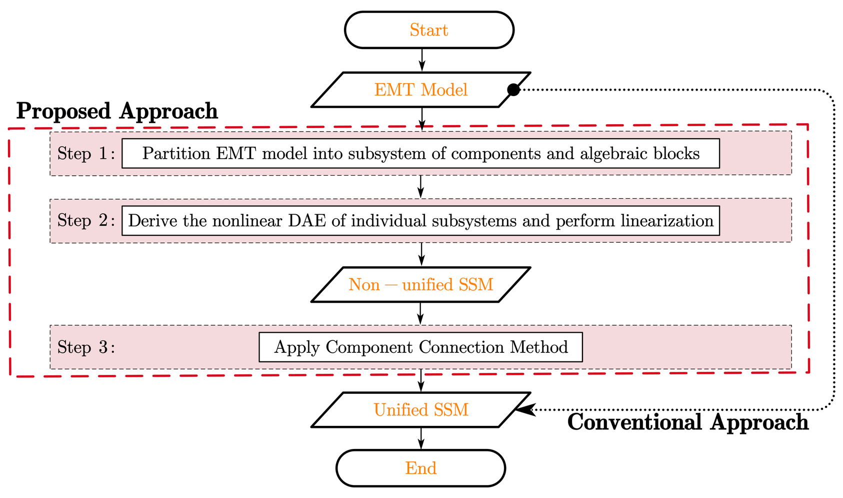

Fig. 2: Flowchart for CCM-based modeling.

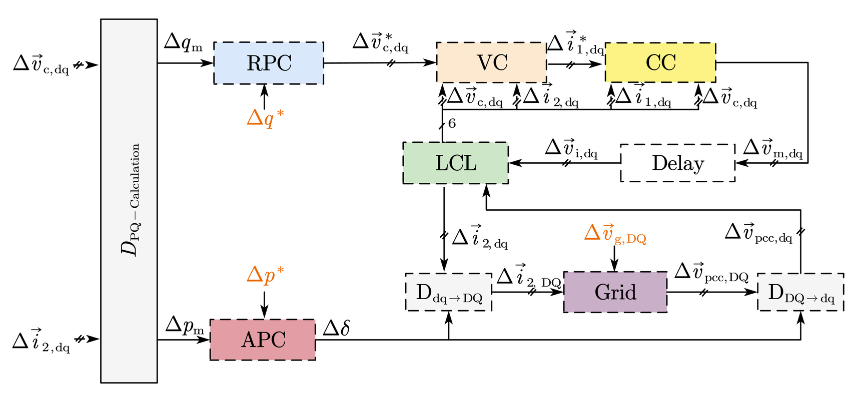

Fig. 3: Non-unified model.

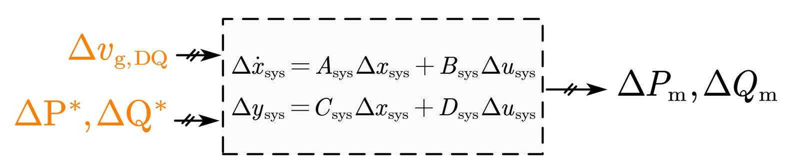

Fig. 4: Unified model using CCM.

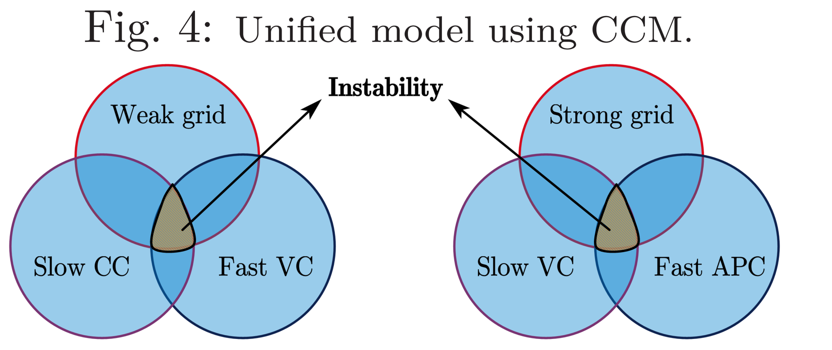

Fig. 5: Instability arising from control interaction.

PI-based voltage control is a dominant contributor to small-signal instability in strong grids.

3. Mitigation Strategies for Instability in Strong Grids

- GFM behavior is commonly defined by the ability to "maintain a **nearly constant internal voltage phasor** over sub-transient to transient time scales".
- However, ambiguity in defining the location of the **internal voltage** has resulted in diverse VC implementations across manufacturers.

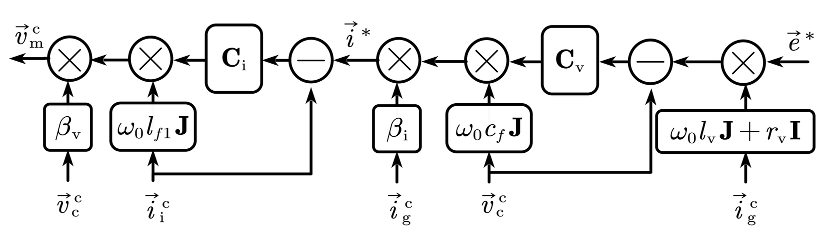

Fig. 6: Virtual Impedance (VI-VC).

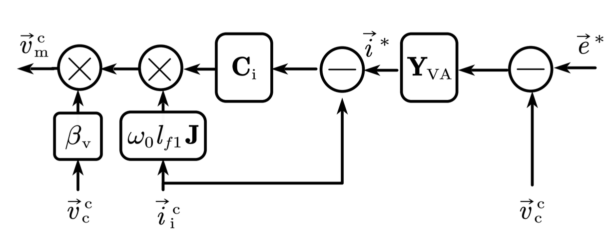

Fig. 7: Virtual Admittance (VA-VC).

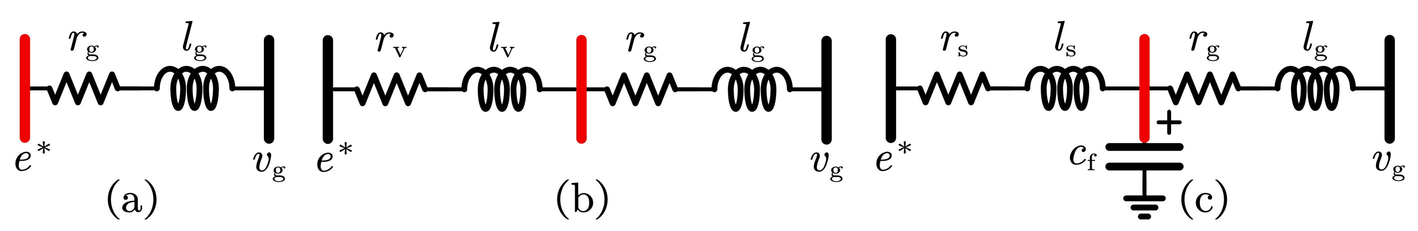

Fig. 8: Equivalent steady-state circuit model of (a) PI, (b) VI, and (c) VA-based GFM.

4. Comparative Analysis

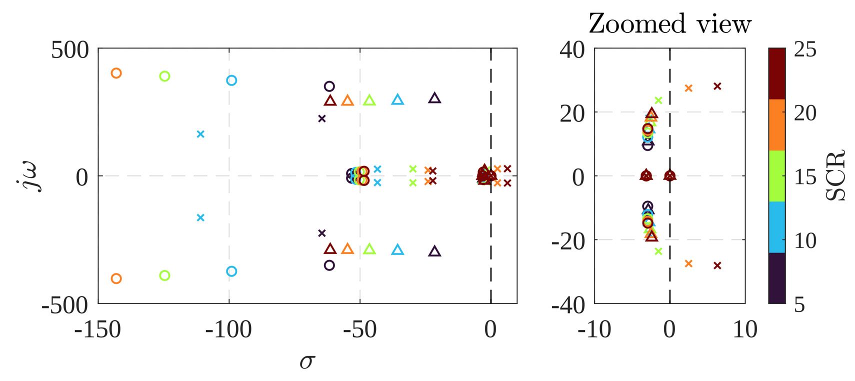

Fig. 9: Eigenvalue trajectories for SCR = [525]. Markers: × (PI), ∘ (VI), △ (VA) based GFM.

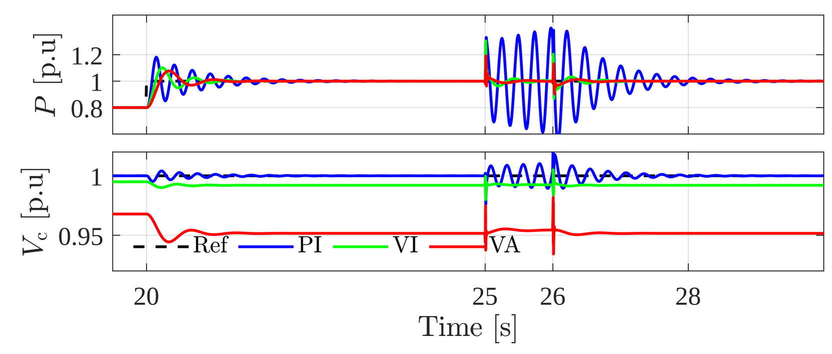

Fig. 10: SCR induced instability in the time domain. Δ SCR: 15 → 20 at $t = 25s$.

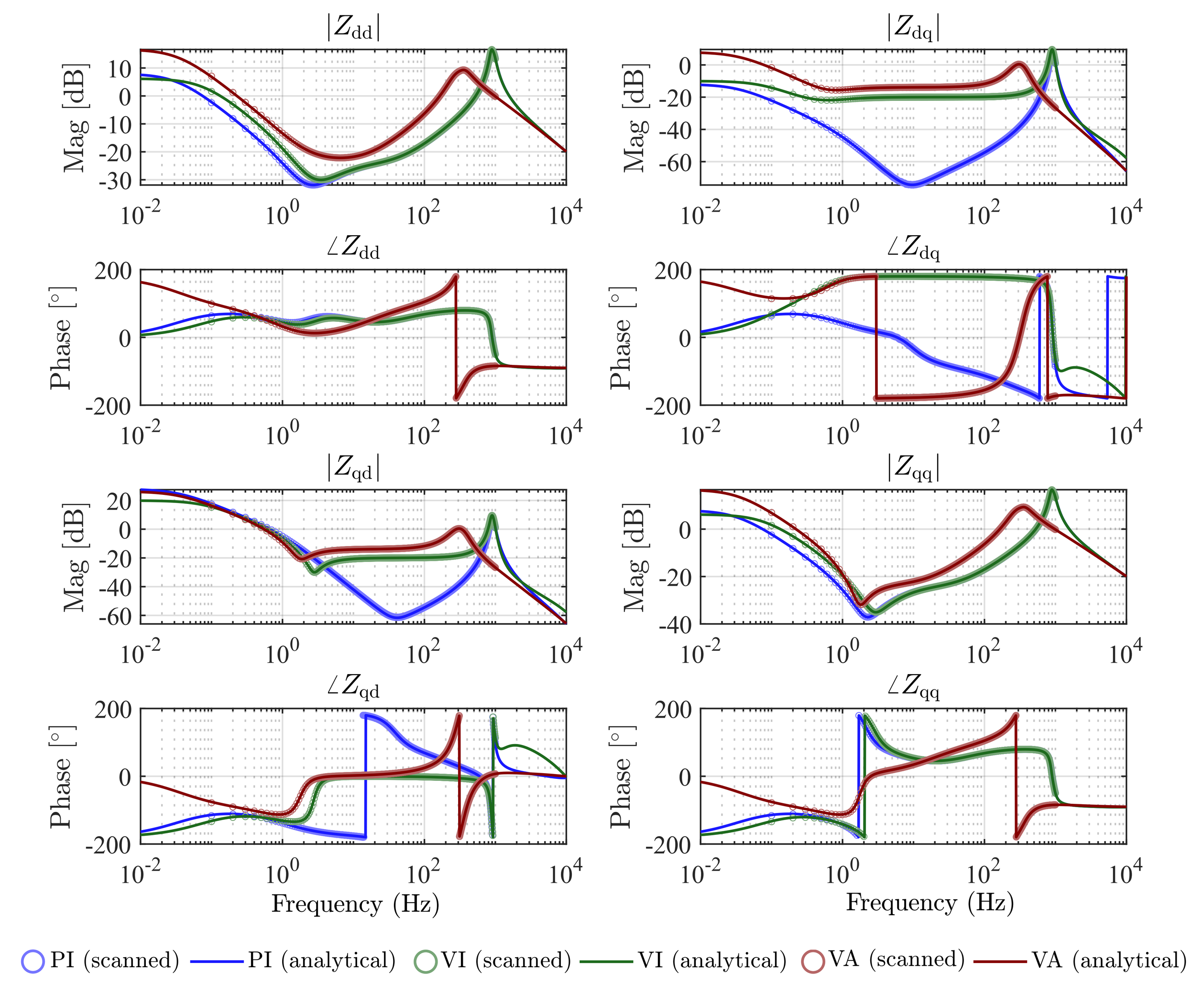

Fig. 11: Terminal impedance $\mathbf{Z}_{\mathrm{GFM}}(j\omega)$ of VC-based GFM: analytical models vs measured responses.

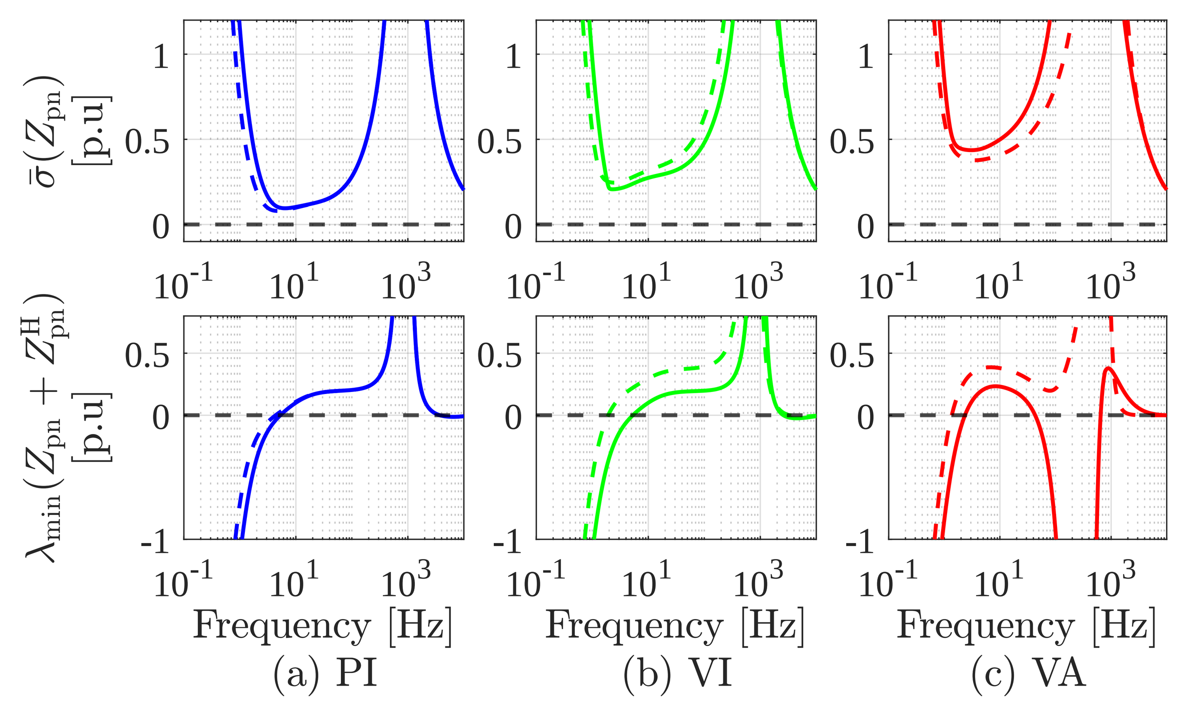

Fig. 12: Compromise between passivity and VSB. (a) PI: $h_v(5s \to 10s)$, (b) VI: $r_v(0 \to 0.05$ p.u.), and (c) VA: $\beta_v(1 \to 0)$.

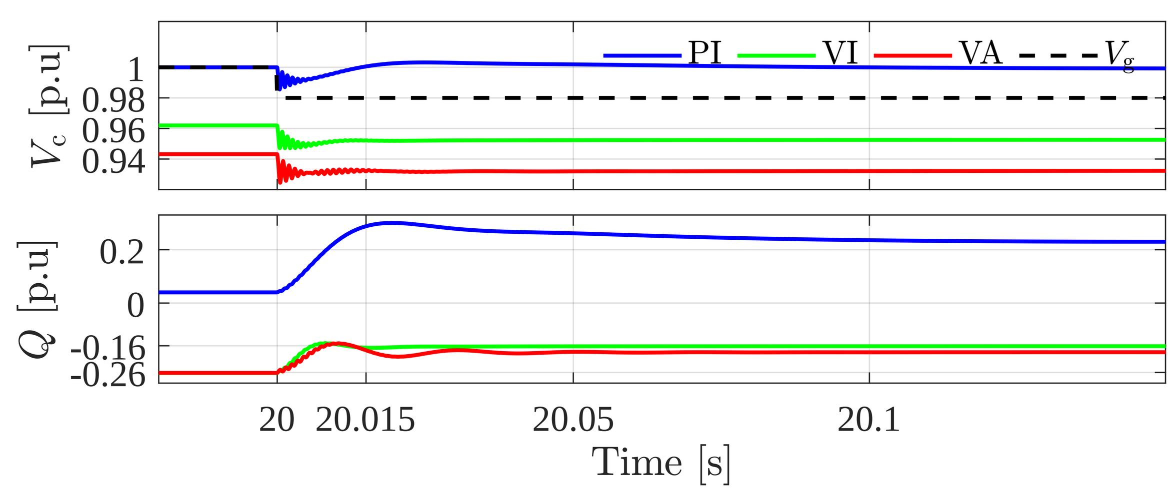

Fig. 13: PoC voltage support in response to a 2 % grid-voltage sag.

Virtual Impedance-based voltage control enhances stability at the expense of voltage stiffness.

5. Conclusions

1. A unified CCM-based small-signal framework enables systematic **comparison of GFM control structures**.
2. Stiff voltage-source behavior (VSB) can trigger **instabilities near synchronous frequency** in strong-grid conditions.
3. **Virtual impedance** improves stability but **degrades VSB** and closed-loop performance.
4. **Frequency-domain impedance** analysis provides a **quantitative basis for assessing** stability margins, VSB, and passivity.
5. Balancing these **competing objectives** requires **flexible control architectures** and impedance-based performance criteria.

References

1. S. A. Ali, P. Serna-Torre, P. Hidalgo-Gonzalez, M. G. Dozein, and B. Bahrani, Modularized small-signal modeling of grid-forming inverters, IEEE Access, vol. 13, pp. 97 01197 037, 2025.
2. A. Gupta, B. Chaudhuri, and M. OMally, Revisiting the Definition of Grid-Forming Inverter-Based Resources, TechRxiv, pp. 1180, 2025.