What Makes a *Good* Grid-Forming Inverter?:

Analytical assessment of Stability and Voltage-Source Behavior.

EPICS Workshop, CSIRO Energy Centre, Newcastle.

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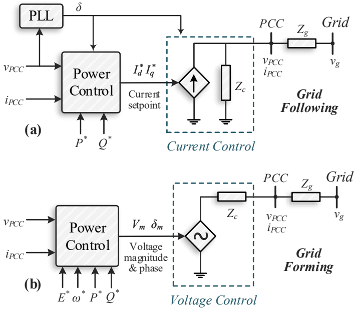
Introduction to Grid Forming Inverters

- GFLI/ GFMI inverters differ in their synchronization mechanism



Comparison of GFMI and GFLI

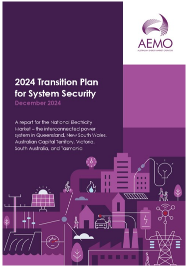
- Fundamentally, a GFM is a **Voltage-Source behind an Impedance**

- Market and regulatory incentives are accelerating GFM deployment


Stability Pathfinder Phase 2 FAQ

nationalgridESO

Economic: Inertia procurement (ESO, UK)


AEMO

2024 Transition Plan for System Security

December 2024

A report for the National Electricity Market – the interconnected power system in Queensland, New South Wales, Australian Capital Territory, Victoria, South Australia, and Tasmania

Technical: Grid strengthening (AEMO, AU)

- Yet, GFM capability is still assessed primarily through **qualitative time-domain simulations**.

GFM – Grid Forming Inverter, GFL – Grid Following Inverter, EMT – Electromagnetic Transient, ESO – Energy System Operator

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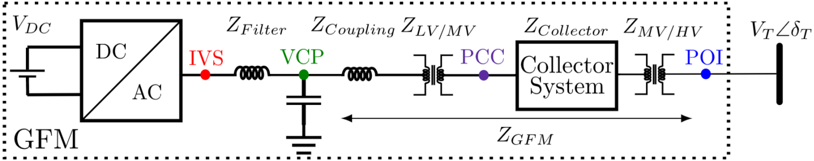
Voltage Source Behind an Impedance

Where is the internal voltage in a GFM?

- GFM are commonly defined as maintaining a **nearly constant internal voltage phasor (IVP)** over sub-transient to transient time scales (e.g., NESO, NERC, AEMO, UNIFI).
- Unlike Synchronous Machines, the IVP of IBRs is **not physically defined**, but instead realized through control.
- **Most** definitions do not explicitly specify the **location** of the IVP.
- Is the IVP at the **inverter terminal**, **PoC**, or a **virtual node**?



A generic GFM plant connected to POI [1].

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[1] A. Gupta, B. Chaudhuri, and M. O'Mally, "Revisiting the Definition of Grid-Forming Inverter-Based Resources," TechRxiv, pp. 1–180, 2025

Research Statement and Questions

Given that OEMs may implement distinct GFM devices under a common label, this fragmentation necessitates **objective**, **quantitative**, and **comparable** assessment methods.

This motivates the following research questions:

How can different GFM technologies be reliably compared using only black-box models?

Can frequency-domain impedance provide quantitative, technology-agnostic metrics for assessing stability and voltage-source behaviour (VSB)?

What are the system-level implications when a GFM performs well in one metric while degrading others?

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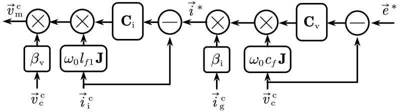
System Description

Three widely adopted voltage-control architectures

PI-Based Voltage Control (PI-VC)

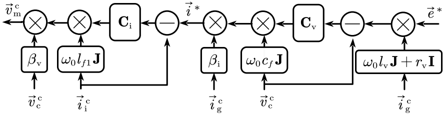
- Classical GFM implementation
- Widely used in research and early industrial designs
- Prone to oscillations in strong grids



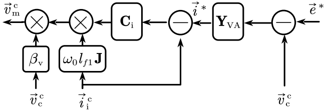
PI-VC — classical voltage control.

Virtual Impedance/ Virtual Admittance Control (VI-VC/ VA-VC)

- Mitigation for Instability in strong grids
- Introduces virtual impedance at the PoC



VI-VC — WECC/UNIFI (Tesla, SMA, GE Vernova).

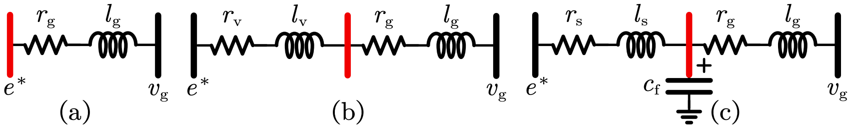


where, $\mathbf{Y}_{\mathrm{VA}} = \left[l_{\mathrm{s}}\left(s\mathbf{I} + \omega_{\mathrm{o}}\mathbf{J}\right) + r_{\mathrm{s}}\mathbf{I}\right]^{-1}$.

VA-VC — Siemens HVDC, Hitachi GFM- STATCOM.

Comparative Analysis of Voltage Control in GFM

Equivalent Steady-State Circuit Interpretation

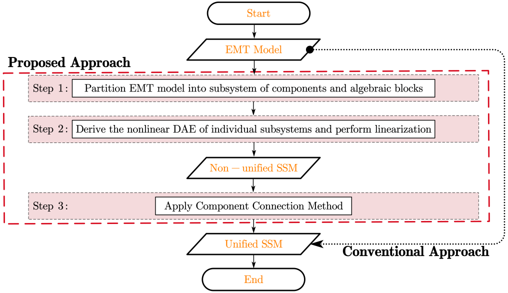


Equivalent steady-state circuit representations of (a) PI-, (b) VI-, and (c) VA-based GFM voltage control, illustrating their impact on **static power-transfer capability** under weak-grid conditions.

While these static differences can be compensated, how do the controllers differ in shaping the *dynamic* behaviour of a GFM?

Comparative analysis of Voltage Control in GFM

Small-signal modeling using Component Connection Method



Start

EMT Model

Proposed Approach

Step 1: Partition EMT model into subsystem of components and algebraic blocks

Step 2: Derive the nonlinear DAE of individual subsystems and perform linearization

Non − unified SSM

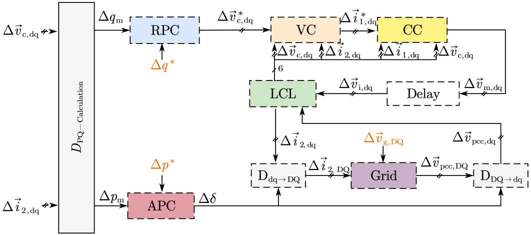
Step 3: Apply Component Connection Method

Unified SSM

Conventional Approach

End

Comparing process flowchart of Conventional vs CCM-based modeling.



Non-unified small-signal model

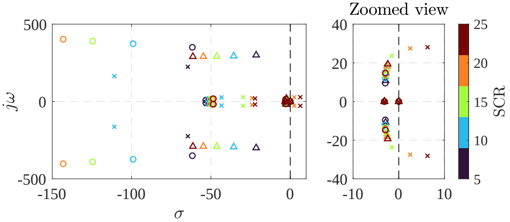
Apply the CCM algorithm:

Unified small-signal model using CCM

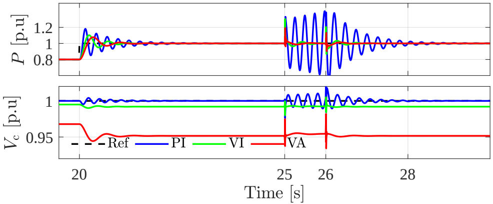
[2] S. A. Ali, P. Serna-Torre, P. Hidalgo-Gonzalez, M. G. Dozein, and B. Bahrani, "Modularized small-signal modeling of grid forming inverters," IEEE Access, vol. 13, pp. 97 011–97 037, 2025.

Comparative Analysis of Voltage Control in GFM

Stability under varying grid strength: Time Domain



Eigenvalue trajectories as grid strength varies (SCR = 5–25).
Markers: × PI, ∘ VI, △ VA.



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

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

Does the virtual impedance introduced for stability compromise the VSB of a GFM, and by how much?

Comparative Analysis of Voltage Control in GFM

Quantifying Voltage-Source Behaviour

An ideal voltage source will maintain a constant voltage $\vec{v}$ irrespective of current perturbations $\vec{i}$.

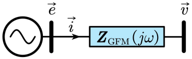
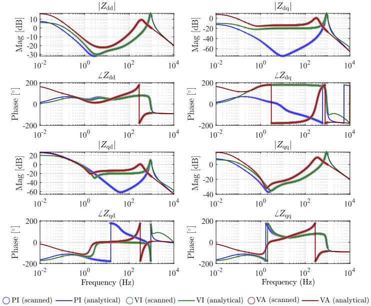


Figure 1. Thévenin Representation of a Voltage Source.

In small-signal form, $\Delta v = -Z_{\mathrm{GFM}}(j\omega)\,\Delta i$ indicating that **ideal VSB** corresponds to $Z_{\mathrm{GFM}}(j\omega) = 0$.

While **strong VSB** requires $Z_{\mathrm{GFM}}(j\omega)$ **to be small**.



The GFM terminal impedance $Z_{\mathrm{GFM}}(j\omega)$ is a **frequency-dependent** 2×2 **matrix in the** dq **frame**. (Validated between 0.1 to 1000 Hz)

How can "small" be quantified for a frequency-dependent impedance matrix $Z_{\mathrm{GFM}}(j\omega)$?

Comparative Analysis of Voltage Control in GFM

Quantifying VSB using Singular Value Decomposition

In [3], the singular values of the impedance matrix, $\sigma(Z(j\omega))$, are used to quantify VSB.

What does $\sigma(Z(j\omega))$ measure?

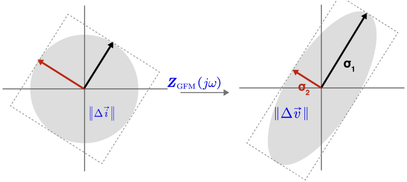


Figure 2. Geometric interpretation of SVD.

The **largest singular value** $\bar{\sigma}(Z_{\mathrm{GFM}}(j\omega))$ gives the *worst-case voltage deviation* due to a unit current perturbation, over **all** dq **directions**.

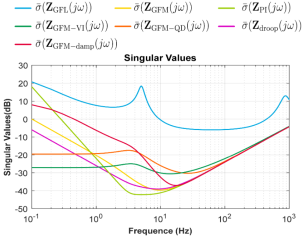


Figure 3. Largest singular value of $Z(j\omega)$: GFL vs GFM [3].

GFL and GFM with identical Q–V droop provide similar *steady-state* voltage support.

A **small** $\bar{\sigma}(Z(j\omega))$ in 5–150 Hz is required to improve strength at the PoC.

Weak grids require technologies (GFM/ Statcom) that lower impedance in the 5–150 Hz band.

H. Xin, et.al, "How many grid-forming converters do we need? a perspective from small signal stability and power grid strength," IEEE Transactions on Power Systems, 2025.

Comparative Analysis of Voltage Control in GFM

Quantifying Voltage-Source Behaviour of Voltage Control

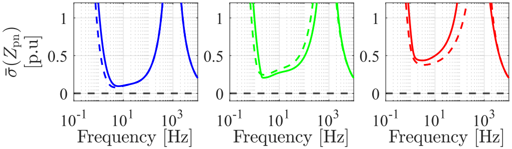
MONASH University

Power Engineering Advanced Research Laboratory [PEARL]

Design objective. Our objective is to maximise VSB, quantified by minimising the

$$\bar{\sigma}\left(Z_{\mathrm{GFM}}(j\omega)\right).$$

This requires tuning control parameters to **shape the terminal impedance**.

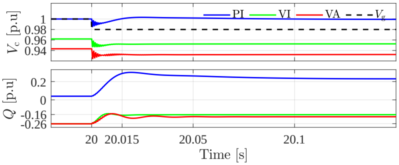


(a) PI (b) VI (c) VA

Analysing VSB of VC using the Singular Value Decomposition.

Key observations:

- PI-based VC achieves the **lowest** $\bar{\sigma}(Z_{\mathrm{GFM}})$, and thus the **strongest VSB**.
- VA-VC requires larger virtual impedance than VI-VC in order to stabalize therefore has lower VSB.



Time-domain comparison of PoC voltage and reactive power response to a 2% grid-voltage sag at t = 20 s.

Virtual-impedance-based voltage control enhances stability, but at the expense of voltage stiffness.

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Final Remarks

Conclusion, Limitation, and Future Work

Conclusion:

1. A unified CCM-based small-signal framework enables systematic **comparison of GFM control structures**.
2. Stiff VSB can trigger **instabilities near synchronous frequency** in strong-grid conditions.
3. **Frequency-domain impedance** analysis provides a **quantitative basis for assessing** stability and VSB.
4. **Virtual impedance** improves stability but **degrades VSB** and closed-loop performance.

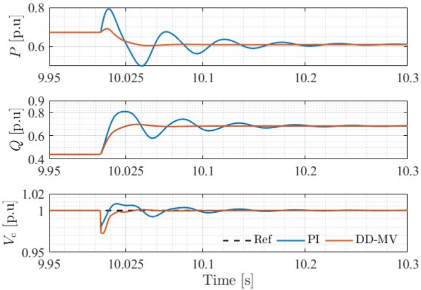
Limitation:

- The work establishes a **framework for comparing stability and VSB** trade-offs.
- It was unable to define a **universal threshold** for what constitutes a **good** grid-forming inverter.

Final Remarks

Conclusion, Limitation, and Future Work

- Ongoing work focuses on **voltage-control synthesis** to meet explicit **frequency-domain objectives** for stability and VSB.



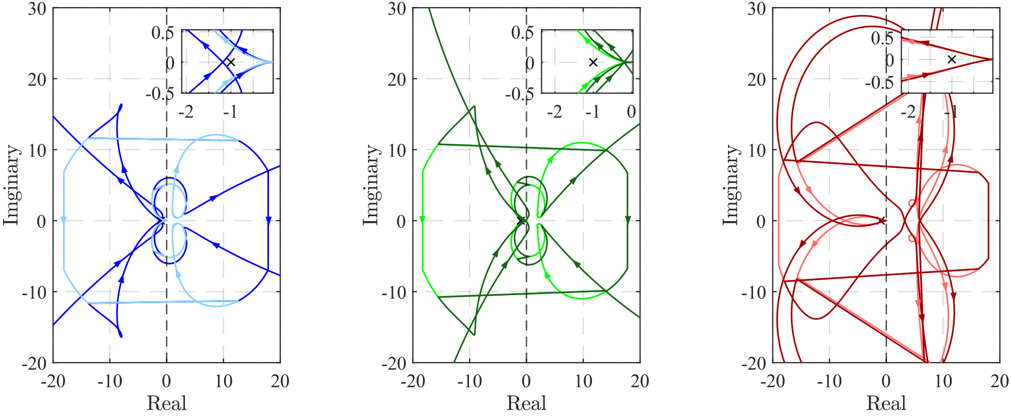
Time-domain comparison between PI-VC and the proposed control in a strong, multi-IBR system.

- The proposed framework preserves the **stability benefits of VA-VC** while achieving the **VSB of PI-VC**.

Thank you for your attention.

Appendix: Comparative Analysis of Voltage Control in GFM

Stability under Varying Grid Strength: Generalized Nyquist Criterion



(a) PI-based VC

(b) VI-based VC

(c) VA-based VC

Stability assessment using the generalized Nyquist criterion (GNC) at SCR = 20.