Energy at Hopkins

JOHNS HOPKINS
RALPH O'CONNOR SUSTAINABLE
ENERGY INSTITUTE

IBR-Based Power Systems: Stability, Control, Operation and Planning

Dr. Sijia Geng
Assistant Professor
Department of Electrical and Computer Engineering
Johns Hopkins University

January 28, 2026

CSIRO, Newcastle, Australia

JOHNS HOPKINS
UNIVERSITY

Outline

1. Challenges in inverter-dominated power systems
2. Systematic modeling, control, and planning
3. Decentralized stability and operation

➢ Scale-free decentralized stability guarantee

➢ Stability-constrained OPF

➢ Economic value of stability service

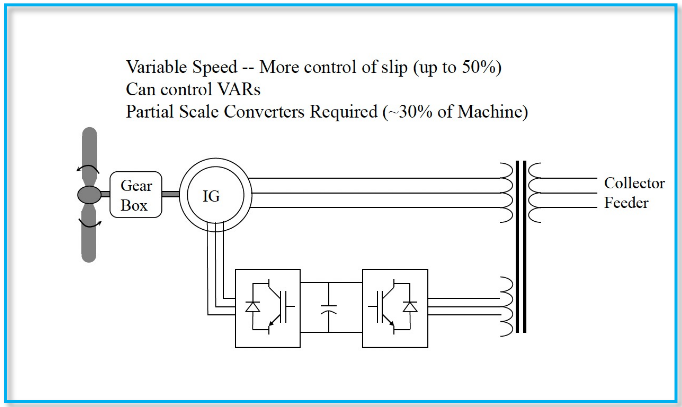
4. Future directions

1. Introduction

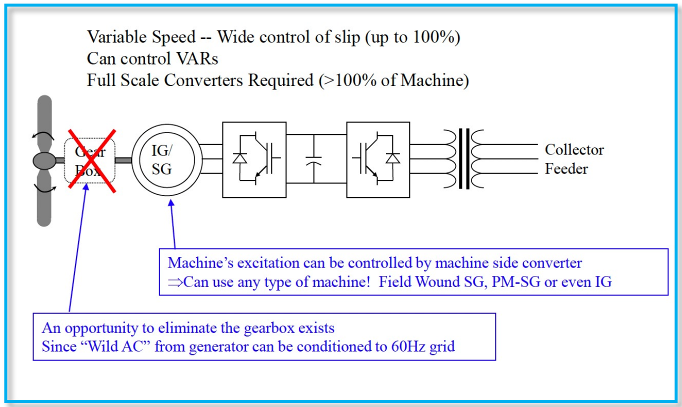
Challenges in inverter-dominated power systems

Inverter-based resources

- Electrical generator
  - ➢ Synchronous machines: Rotor spins at synchronous speed. Large generators for example: pumped hydro, nuclear plant.
  - ➢ IBRs: The dynamic behavior (as seen from the grid) is dominated by control loops, not the physics of the machines. PE-based characteristics and limits.



Variable Speed -- More control of slip (up to 50%)
Can control VARs
Partial Scale Converters Required (~30% of Machine)



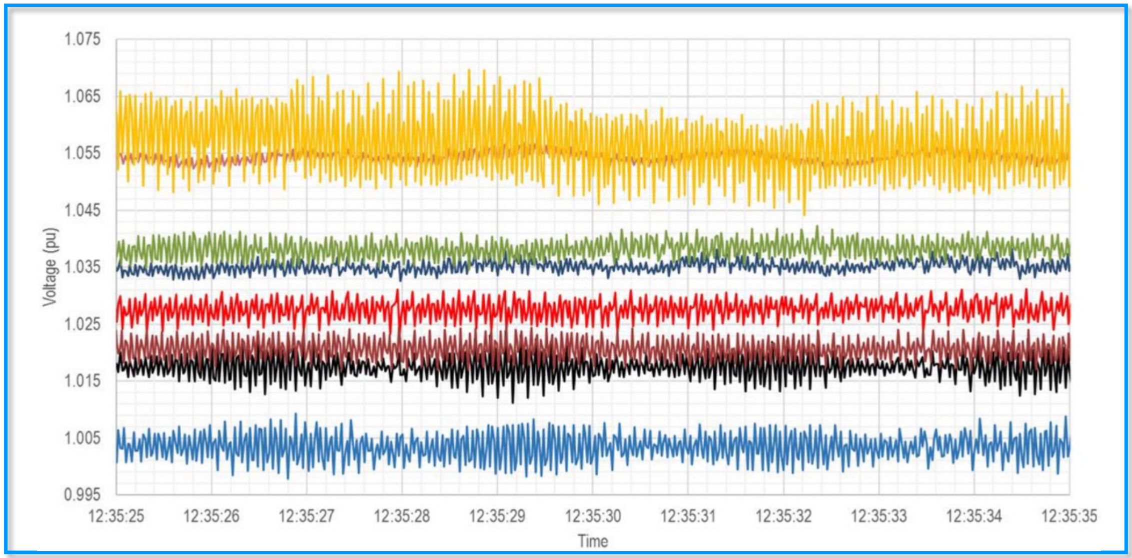
Variable Speed -- Wide control of slip (up to 100%)
Can control VARs
Full Scale Converters Required (>100% of Machine)

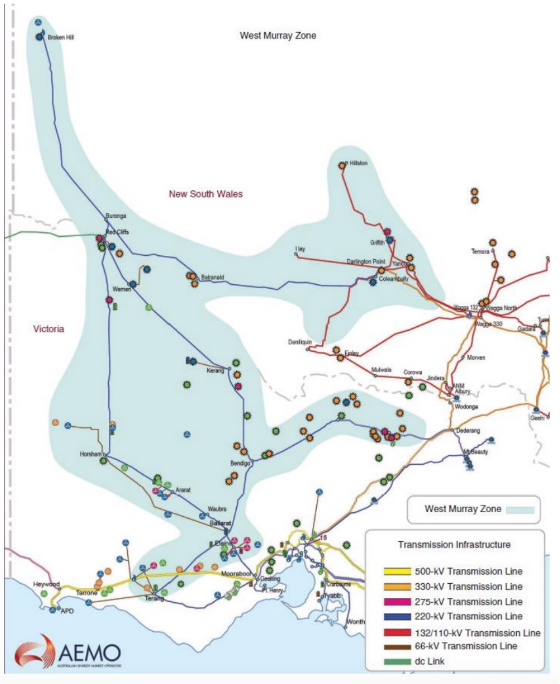
Machine's excitation can be controlled by machine side converter
⇒Can use any type of machine! Field Wound SG, PM-SG or even IG

An opportunity to eliminate the gearbox exists
Since "Wild AC" from generator can be conditioned to 60Hz grid

Sub-synchronous oscillations (SSO)

- SSO of 16-19 Hz observed by AEMO on various occasions from 2020-2021 in the West Murray Zone.





Source: National Electricity Market, "West Murray Zone Power System Oscillations 2020-2021", February 2023.

Challenges in IBR-dominated power systems

- New forms of dynamics and instability (v.s. swing equation)
  - Control-dominated nature: Grid-following (PLL), grid-supporting (unified), grid-forming (droop, VSM, VOC), etc.
  - Loss of time-scale separation: IBR operating times in milliseconds ⟹ may interact with filter & line dynamics.
  - Operational limits and characteristics due to power electronics.

- Outdated tools for stability assessment, control, operation, planning:
  - Highly variable generation/load, and hence, operating points.
  - Increased system complexity and nonlinearity.
  - Model uncertainty (OEM-specific proprietary models) and heterogeneity.

JOHNS HOPKINS
UNIVERSITY

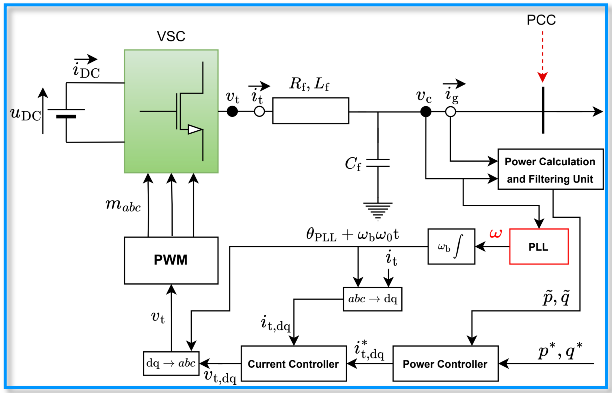
2. Systematic modeling, control, planning

- Nonlinear and hybrid dynamics
- Network modeling: Impacts of line dynamics
- Optimal allocation of GFM and GFL inverters

Grid-following

Source: Sushobhan Chatterjee and Sijia Geng. ”Voltage Stability of Inverter-Based Systems: Impact of Parameters and Irrelevance of Line Dynamics." *IEEE PowerTech*, 2025.

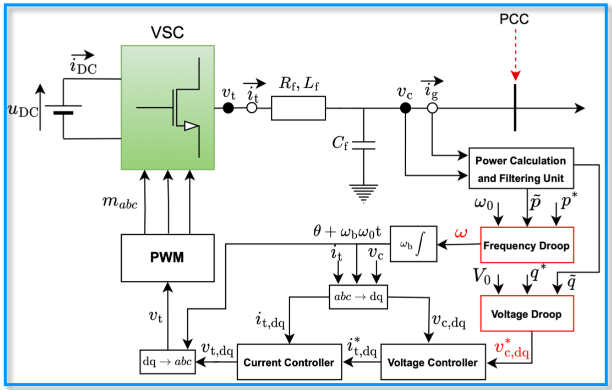
- Current source: Injects active & reactive power to the grid.
- “Follow”: Frequency is set to be synchronized with the existing grid voltage waveform using a phase-locked loop.
- Drawbacks: No black-start capability; Poorly damped oscillations in weak network.



Grid-forming

Source: Sushobhan Chatterjee and Sijia Geng. "Effects of Line Dynamics on the Stability Margin to Hopf Bifurcation in Grid-Forming Inverters.” *IREP 2025 and Sustainable Energy, Grids and Networks (SEGAN)*, 2025.

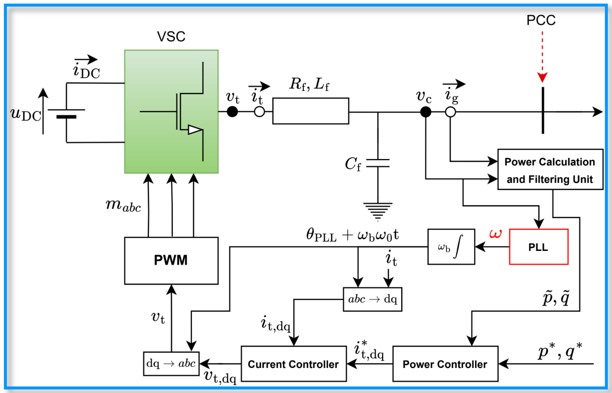
- Voltage source: Set voltage magnitude and angle.
- “Forming”: Frequency is set by droop function of exported power.
- Advantages: Black-start capability; Support weak network.



Grid-following

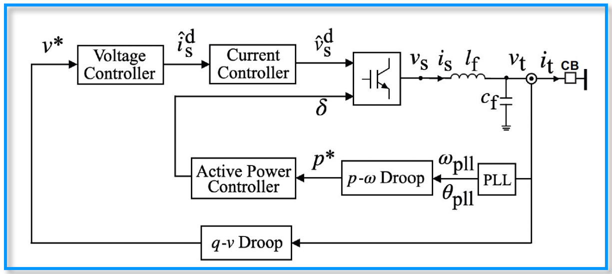
Source: Sushobhan Chatterjee and Sijia Geng. ”Voltage Stability of Inverter-Based Systems: Impact of Parameters and Irrelevance of Line Dynamics." *IEEE PowerTech*, 2025.

- Current source: Injects active & reactive power to the grid.
- “Follow”: Frequency is set to be synchronized with the existing grid voltage waveform using a phase-locked loop.
- Drawbacks: No black-start capability; Poorly damped oscillations in weak network.



Unified

Source: Sijia Geng, and Ian A. Hiskens. "Unified grid-forming/ following inverter control." *IEEE Open Access Journal of Power and Energy*, 2022.

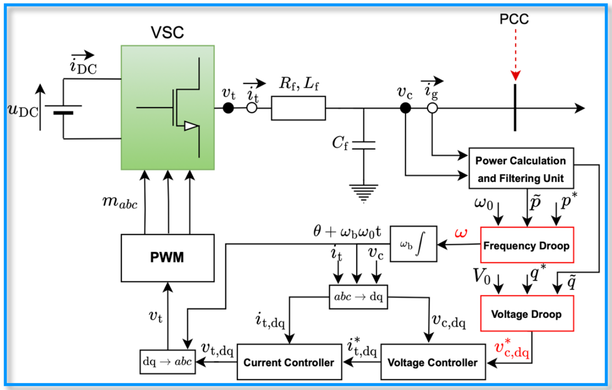


- Unified control: Incorporates both PLL and droop.
- Regulate: Voltage magnitude and active power.

Grid-forming

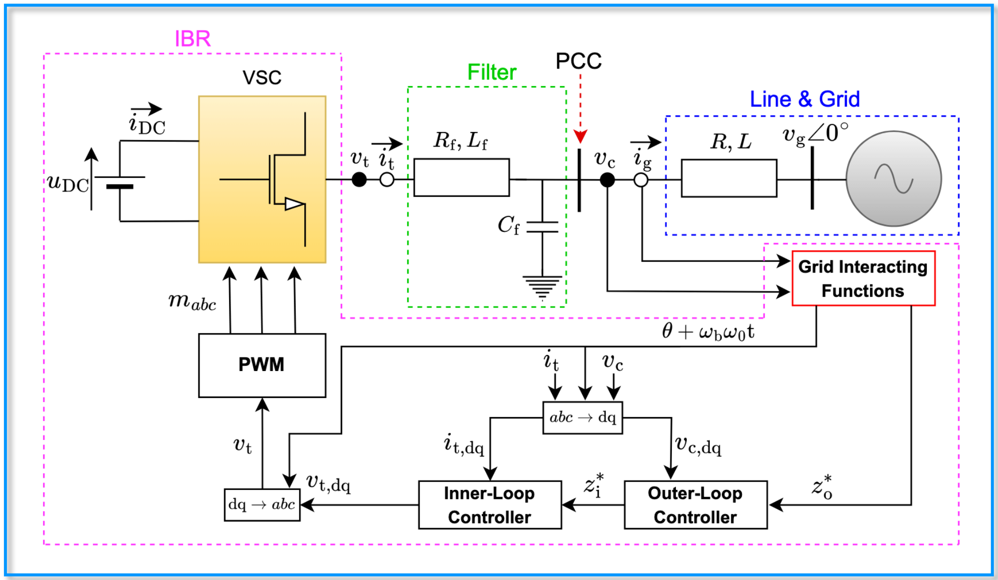
Source: Sushobhan Chatterjee and Sijia Geng. "Effects of Line Dynamics on the Stability Margin to Hopf Bifurcation in Grid-Forming Inverters.” *IREP 2025 and Sustainable Energy, Grids and Networks (SEGAN)*, 2025.

- Voltage source: Set voltage magnitude and angle.
- “Forming”: Frequency is set by droop function of exported power.
- Advantages: Black-start capability; Support weak network.



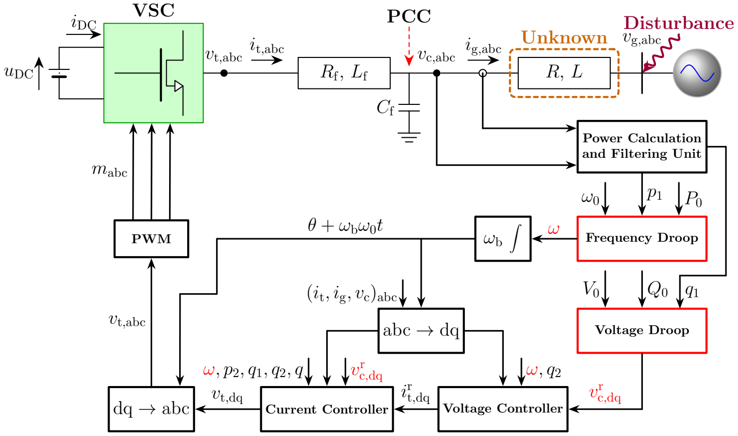
General IBR structure

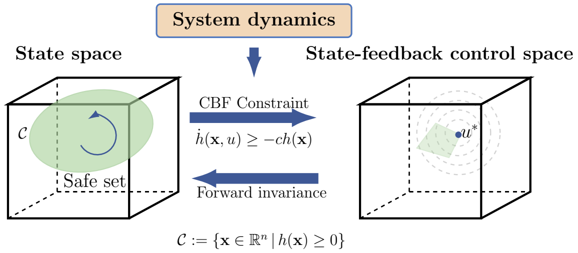
- IBR architecture can generally be represented using a unified schematic given here (dq-frame).
- Grid interacting functions: PLL (for GFL), droops (for GFM), etc.
- Outer-loop controller: Power/DC-side voltage (for GFL), DC-side/AC-side voltage (for GFM), etc.
- Inner-loop controller: Usually current.



Source: Sushobhan Chatterjee and **Sijia Geng**. "Voltage Stability of Inverter-Based Systems: Impact of Parameters and Irrelevance of Line Dynamics." IEEE PowerTech, 2025.

Safety-critical GFM control with rigorous current limiting





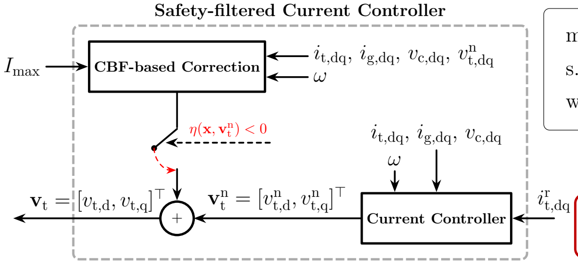
Let's consider the d-loop voltage-current relationship:

$$\dot{v}_{cdj} = \omega_b \omega_j v_{cqj} + \frac{\omega_b}{C_{fj}}\left(i_{tdj} - i_{gdj}\right)$$

$$\dot{i}_{tdj} = \omega_b \omega_j i_{tqj} + \frac{\omega_b}{L_{fj}}\left(v_{tdj} - v_{cdj}\right) - \frac{R_{fj}}{L_{fj}}\omega_b i_{tdj}$$

- i_{tdj} acts as a control input to the dynamics of v_{cdj}
- v_{tdj} acts as a control input the the dynamics of i_{tdj}

1. Design $i^{\star}_{tdj}$ that achieves $v_{cdj} \to v^{\star}_{cdj}$
2. Design v_{tdj} that achieves $i_{tdj} \to i^{\star}_{tdj}$
3. Use barrier function to ensure current limit.



$$\begin{array}{ll} \text{minimize} & \|\mathbf{v}_{\mathrm{t}} - \mathbf{v}^{\mathrm{n}}_{\mathrm{t}}\|^2 \\ \text{s.t.} & \dot{h}(\mathbf{x}, \mathbf{v}_{\mathrm{t}}) \geq -c\,h(\mathbf{x}) \\ \text{where} & h(\mathbf{x}) := I_{\max} - \mathbf{i}_{\mathrm{t}}^\top \mathbf{i}_{\mathrm{t}} \quad \text{(CBF)} \end{array}$$

SAFETY GUARANTY

$$\sqrt{i^2_{\mathrm{t,d}}(t) + i^2_{\mathrm{t,q}}(t)} = \sqrt{\mathbf{i}_{\mathrm{t}}(t)^\top \mathbf{i}(t)_{\mathrm{t}}} \ \leq \ I_{\max},$$

Source: Bhathiya Rathnayake and **Sijia Geng**. "Grid-Forming Control with Assignable Voltage Regulation Guarantees and Safety-Critical Current Limiting." *arXiv preprint arXiv:2603.02975,* 2026.

Optimal allocation of GFM and GFL IBRs

- Determine how much “grid-forming” vs. “grid-following” behavior is needed across the network.
- Combinatorial challenges.
- Use the unified inverter to find optimal droop gain profile $\mathrm{m_P}$ that jointly ensures:
  a. Small-signal stability of the system;
  b. Good transient performance via maximum energy dissipation.

$$
\begin{aligned}
\underset{\boldsymbol{m}_\mathrm{P},\mathrm{P},\mathrm{x}^*,\mathrm{y}^*}{\text{minimize}} \quad & \mathrm{trace(PS)} \\
& \tilde{\mathrm{A}}_\mathrm{eff}{}^\mathrm{T}\mathrm{P}+\mathrm{P}\tilde{\mathrm{A}}_\mathrm{eff}=-\mathrm{Q} \\
& \mathrm{P}\succ 0 \\
& \underline{\boldsymbol{m}}_\mathrm{P}\preccurlyeq \boldsymbol{m}_\mathrm{P}\preccurlyeq \overline{\boldsymbol{m}}_\mathrm{P} \\
& \tilde{\mathrm{A}}_\mathrm{eff}=\mathrm{A}_\mathrm{eff}(\mathrm{x}^*,\mathrm{y}^*,\alpha^0,\boldsymbol{m}_\mathrm{P}) \\
& \mathrm{f}(\mathrm{x}^*,\mathrm{y}^*,\alpha^0,\boldsymbol{m}_\mathrm{P})=0 \\
& \mathrm{g}(\mathrm{x}^*,\mathrm{y}^*,\alpha^0,\boldsymbol{m}_\mathrm{P})=0
\end{aligned}
$$

Source: **Geng, Sijia** and Sushobhan Chatterjee. "Unified Control Scheme for Optimal Allocation of GFM and GFL Inverters in Power Networks." *2025 IEEE 64th Conference on Decision and Control (CDC)*. IEEE, 2025.
Source: **Sijia Geng** and Ian A. Hiskens. "Unified grid-forming/ following inverter control." *IEEE Open Access Journal of Power and Energy*. 2022.

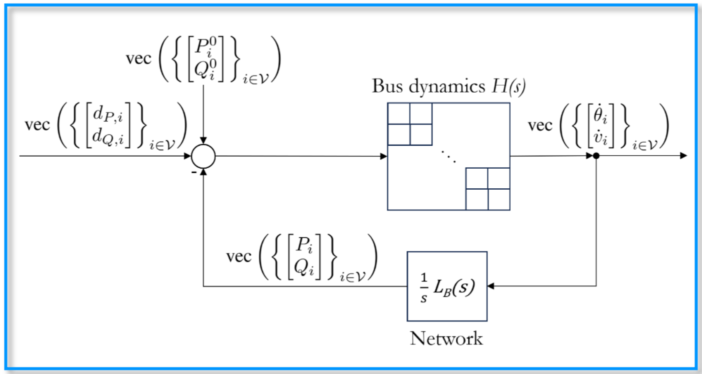
3. Decentralized stability and operation

- Scale-free decentralized stability guarantee.
- Stability-constrained OPF.
- Economic value of stability service.

Decentralized stability criteria: grid-code

JOHNS HOPKINS
RALPH O'CONNOR SUSTAINABLE ENERGY INSTITUTE

➢ Power system model:



Bus dynamics: Droop-based GFM IBR

$$\begin{cases}\dot\theta_i &= \omega_i\\ \omega_i &= \omega_i^0 + m_i^p f_i^p(s)(P_i^0 - P_i),\\ v_i &= V_i^0 + m_i^q f_i^q(s)(Q_i^0 - Q_i).\end{cases}$$

$$h_i^\theta = \frac{m_i^p\beta_i^p/\tau_i^p}{s+1/\tau_i^p} \qquad h_i^v = \frac{s m_i^q\beta_i^q/\tau_i^q}{s+1/\tau_i^q}$$

Theorem

Given the feedback interconnection on the left consisting of synchronous machines and droop-controlled GFM IBRs, with the droop constants $m_i^p, m_i^q \in \mathbb{R}_{\geq 0}$ and the filter's time constants $\tau_i^p, \tau_i^q \in \mathbb{R}_{>0}$. Then the system is stable whenever each controller gain satisfies,

$$\left(\max_{j\in\mathcal{N}_i}\{V_{0j}\} - V_{0i}\right)\beta_i^q m_i^q \leq \frac{1}{2|b_{ii}|}, \quad \forall i \in \mathcal{V}.$$

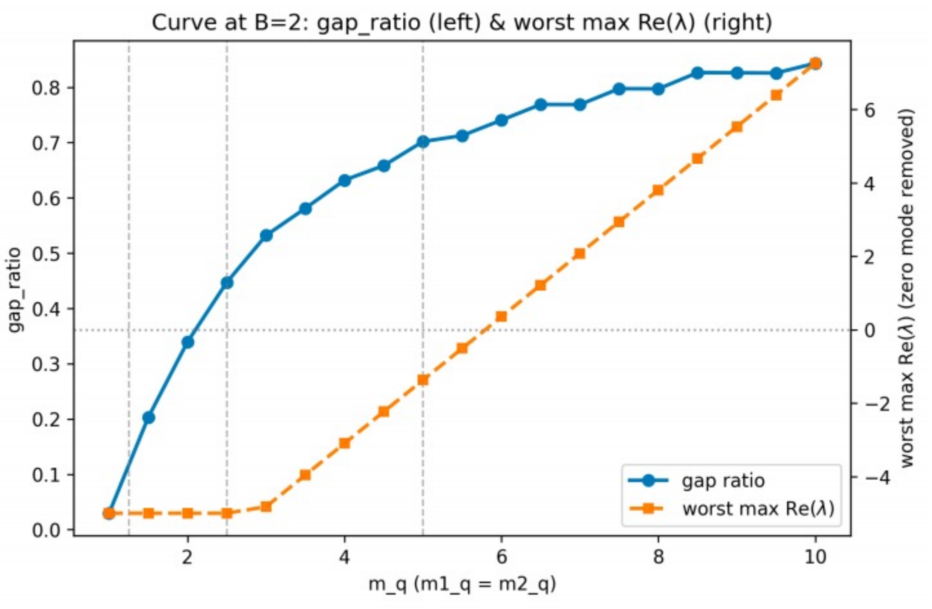
(+) Condition relies solely on local information
(+) Employ the least conservative decentralized framework
(+) Apply MIMO transfer functions
(-) Implement homogeneous model of GFM control
(-) Based on static lossless decoupled network model

GFM inverter is vulnerable to strong grids. (high $|b_{ii}|$)

Source: Zudika Siahaan, Enrique Mallada, and **Sijia Geng**. "Decentralized stability criteria for grid-forming control in inverter-based power systems." *The Proceedings of 2024 IEEE PES General Meeting*.

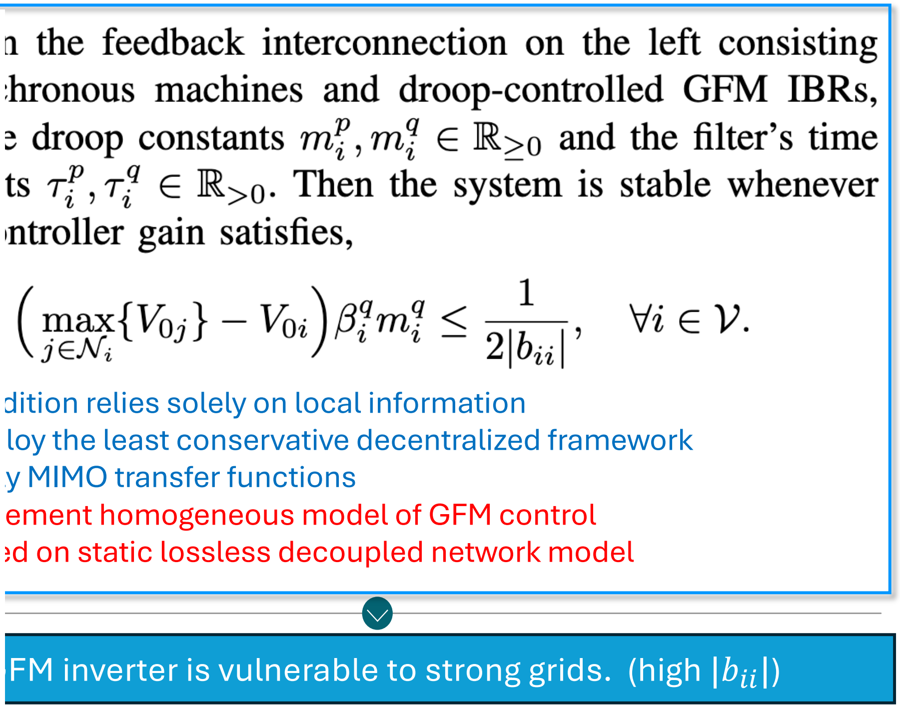
Decentralized stability criteria: grid-code

- Power system model:



(a) $B = 2$

Theorem



n the feedback interconnection on the left consisting hronous machines and droop-controlled GFM IBRs, e droop constants $m_i^p, m_i^q \in \mathbb{R}_{\geq 0}$ and the filter's time ts $\tau_i^p, \tau_i^q \in \mathbb{R}_{>0}$. Then the system is stable whenever ntroller gain satisfies,

$$\left(\max_{j\in\mathcal{N}_i}\{V_{0j}\} - V_{0i}\right)\beta_i^q m_i^q \leq \frac{1}{2|b_{ii}|}, \quad \forall i \in \mathcal{V}.$$

dition relies solely on local information

loy the least conservative decentralized framework

y MIMO transfer functions

ement homogeneous model of GFM control

ed on static lossless decoupled network model

FM inverter is vulnerable to strong grids. (high $|b_{ii}|$)

Source: Zudika Siahaan, Enrique Mallada, and **Sijia Geng**. "Decentralized stability criteria for grid-forming control in inverter-based power systems." *The Proceedings of 2024 IEEE PES General Meeting*.

Stability-constrained operation: Stability service and its value

- Operation model: Feasibility and optimality.

$$\begin{aligned} &min\, J(y) \\ &s.t.\ 0 = g(y), \\ &\quad 0 > h(y). \end{aligned}$$

- Dynamical model: Stability and control.

$$\begin{aligned} \dot{x} &= f(x, y), \\ 0 &= g(x, y). \end{aligned}$$

Higher-level operation (5mins)
[subspace of full state-space]

Determines the operating point.

Lower-level dynamics and control
(milisecs, secs and mins)

Gaps: the OPF solution may not be a stable operating point.

Stability-constrained OPF

- Existing approaches:

➢ Performance metrics: such as ROCOF, Nadir, etc.

➢ Abstracted metrics: SCR, etc.

➢ Eigenvalue-based stability: global model, no analytical expression.

➢ Hierarchical numerical evaluations: time-consuming.

- Challenges:

➢ Approximated stability characterization.

➢ Numerical complexity.

➢ Lack of interpretation of the economic value of stability service.

Decentralized stability-constrained OPF

- Key formulation: individual stability constraint for each IBRs to ensure system-level (small-signal) stability.

Advantages:

➢ Analytical form and easy to interpret its individual value of stability service provision;

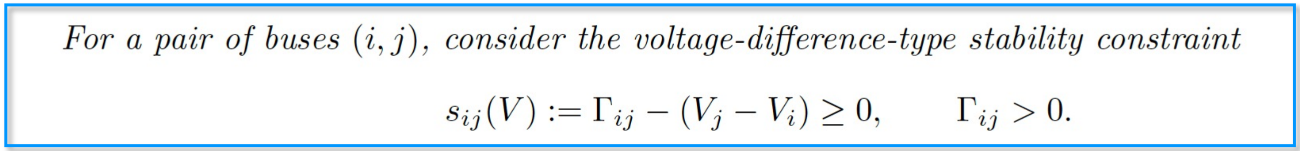
➢ Sufficient condition;

$$
\begin{aligned}
\min_{x} \quad & J_{obj} = \sum_{i=1}^{2} \left(c_i P_i^2 + b_i P_i + a_i \right) \\
s.t. \quad & \theta_1 = 0, \\
& P_1 = -V_1 V_2 B \sin\theta_2, \\
& P_2 = V_1 V_2 B \sin\theta_2, \\
& Q_1 = V_1^2 B - V_1 V_2 B \cos\theta_2, \\
& Q_2 = V_2^2 B - V_1 V_2 B \cos\theta_2, \\
& \textit{(line-flow and box constraints on } P_i, Q_i, V_i\textit{)}, \\
& V_2 - V_1 \le \Gamma_1, \\
& V_1 - V_2 \le \Gamma_2.
\end{aligned}
$$

Source: Shigeng Wang and **Sijia Geng**. "Decentralized stability constrained OPF and free stability provision for inverter-based power systems" under preparation.

Theoretical results and its interpretation

- Theorem 1: Free stability service (The decentralized stability constraint has zero shadow price).
  - Lossless network with GFM inverters
  - P-only objective function: $J(P_G) = \sum_{i=1}^{n} (c_i P_{Gi}^2 + b_i P_{Gi} + a_i)$
  - A class of voltage-difference inequality criteria:



For a pair of buses (i, j)*, consider the voltage-difference-type stability constraint*

$$s_{ij}(V) := \Gamma_{ij} - (V_j - V_i) \geq 0, \qquad \Gamma_{ij} > 0.$$

- Theorem 2 & 3: Existence and sufficiency condition: When stability starts to matter, and complete characterization of when stability induces an economic trade-off.
  - Cost associated with reactive power.

Future directions

- Increased system complexity and nonlinearity:
  - Scalable to detailed modeling of numerous IBRs.
- Significant fluctuations in operating conditions:
  - Robust to operating point variation.
- Adding and removing devices to the grid:
  - Adaptive to plug-and-play.
- Lack of transparency in control implementations:
  - Decentralized approach that only needs local information, to be checked by individual devices, yet ensure system-level stability.
  - Data-driven approach that doesn't need complete model.

Energy at Hopkins

JOHNS HOPKINS
RALPH O'CONNOR SUSTAINABLE
ENERGY INSTITUTE

Thank You

Sijia Geng, Johns Hopkins University

sgeng@jhu.edu

JOHNS HOPKINS
UNIVERSITY