

Decentralized Stability Certificates in IBR-Dominated Grids

The Role of the Network State

Enrique Mallada



JOHNS HOPKINS
UNIVERSITY

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February 10, 2026

Acknowledgements



Zhimeng Wang



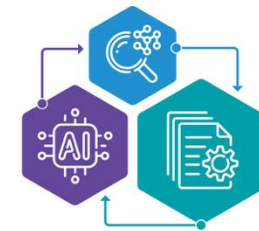
Sushobhan Chatterjee



Sijia Geng

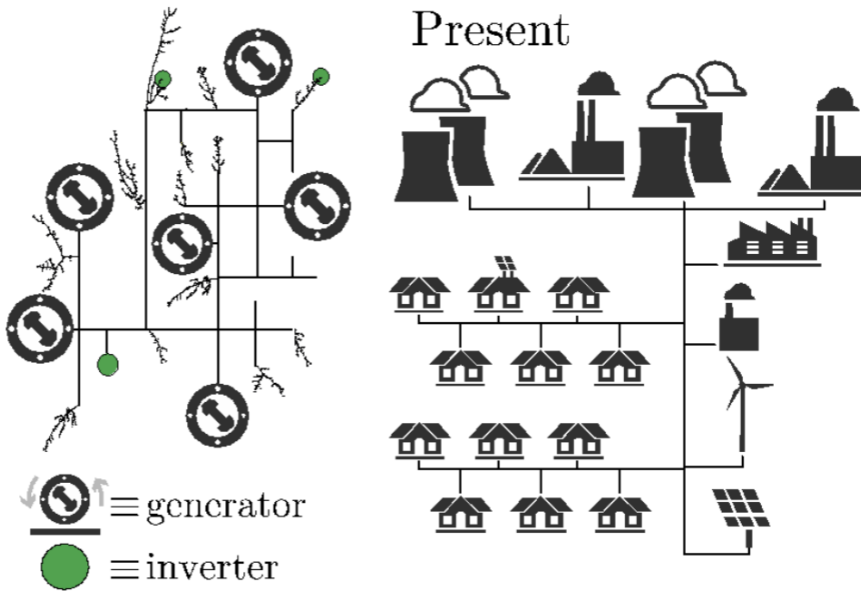


Richard Pates



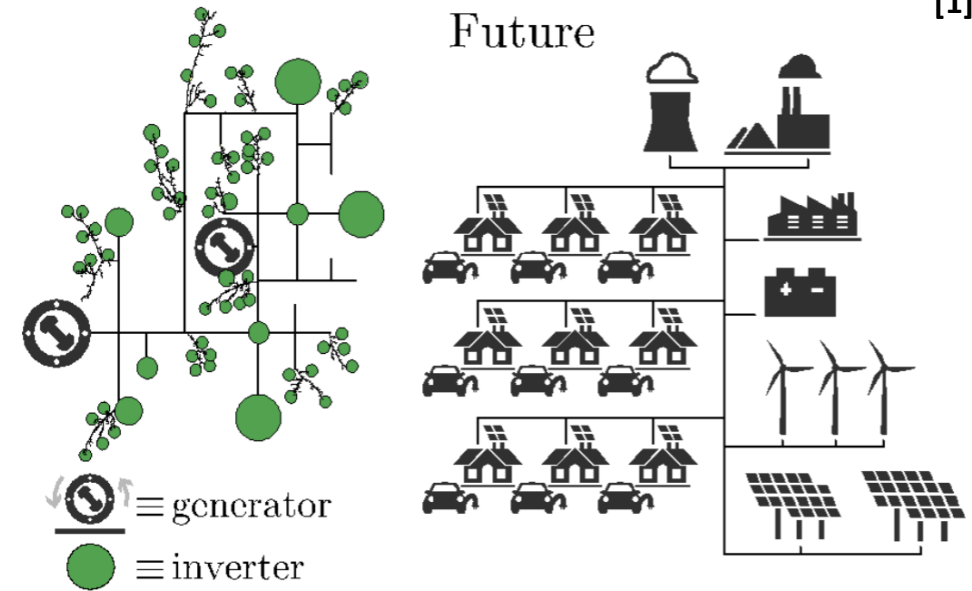
**LEARNING-ACCELERATED
DOMAIN SCIENCE (LEADS)**
SciDAC institute

Why we are here*



Present grid

- dispatchable generation
- high inertial response
- strong voltage support
- well known physics



Future

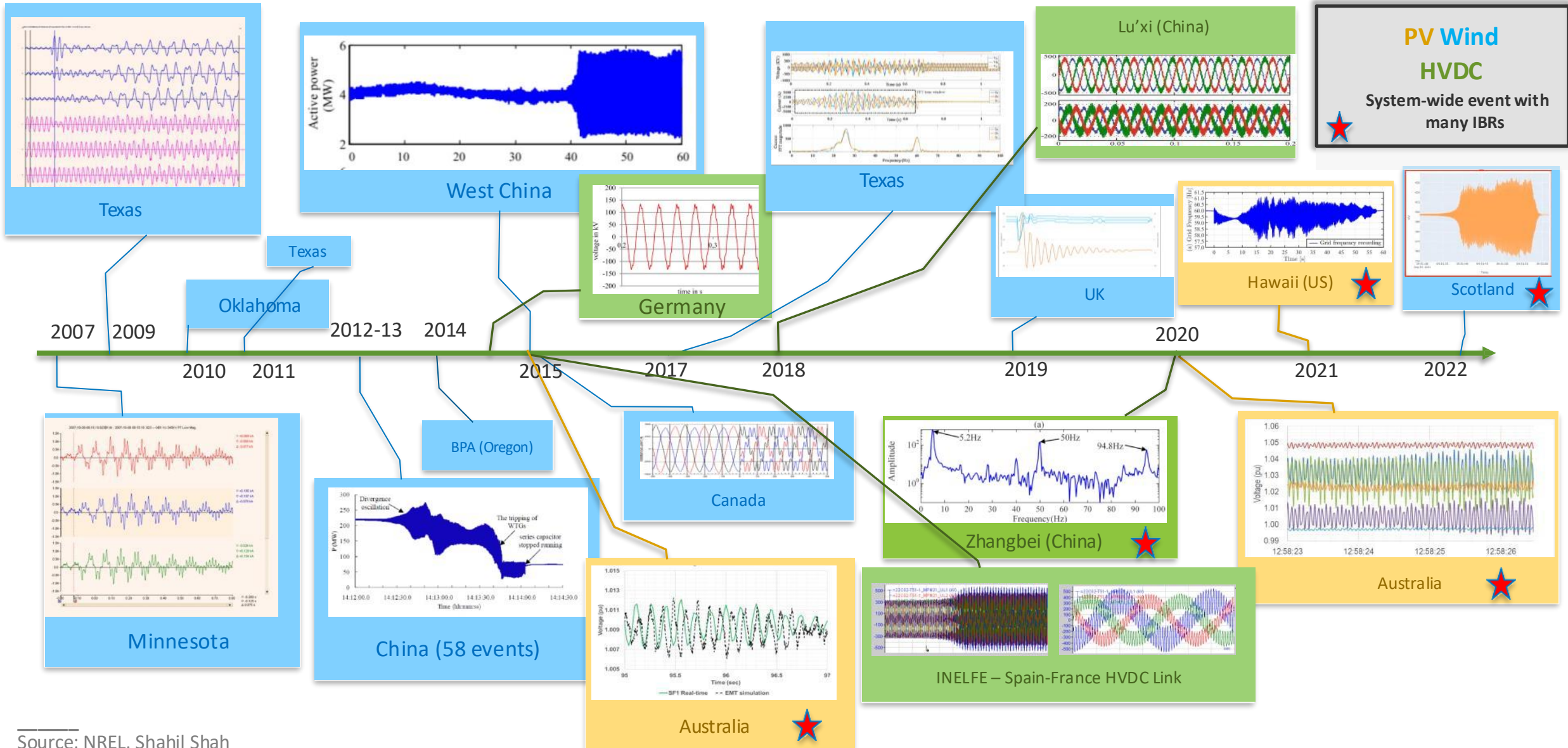
- variable and distributed generation
- limited inertia levels
- weak voltage support
- proprietary control laws (black box)

*besides slopes and powder

[1] Lin et al. Research roadmap on grid-forming inverters. Technical report, National Renewable Energy Lab.(NREL), Golden CO, 2020

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Oscillation Events Involving IBRs



Source: NREL, Shahil Shah [TPWRS 23] Cheng et al., "Real-World Sub-synchronous Oscillation Events in Power Grids With High Penetrations of Inverter-Based Resources," IEEE TPWRS 2023

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IBR-induced Sub Synchronous Oscillations

- **When do SSOs occur?**
 - **Series-compensated corridors (SSCI)**
 - **Weak grids** (low SCR, high impedance)
 - **Clusters of IBRs in remote areas**
 - **After contingencies/topology changes** (radialization)
 - **During commissioning** or controller retuning
- **What do SSOs depend on?**
 - **Network state:** impedance, SCR, topology, compensation level
 - **Control configuration:** PLL dynamics, outer/plant controllers, GFL vs GFM
 - **Operating point:** power flow direction, voltage setpoints, dispatch

IBR-induced Sub Synchronous Oscillations

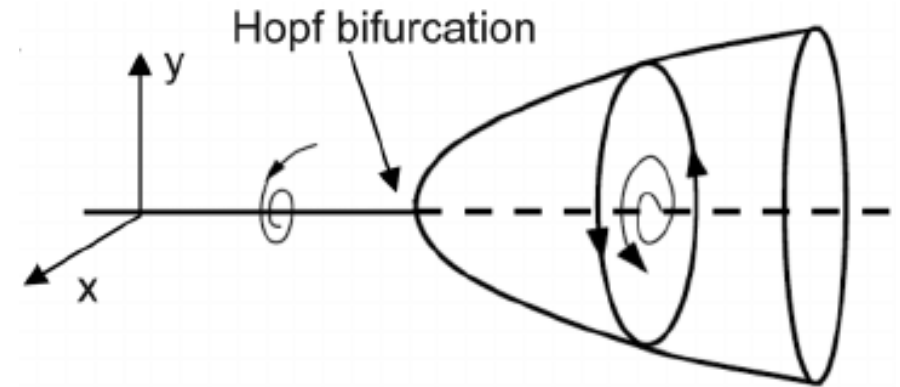
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Goal: To develop a framework to predict, prevent, and manage SSOs across grid planning, real-time operation, and compliance testing

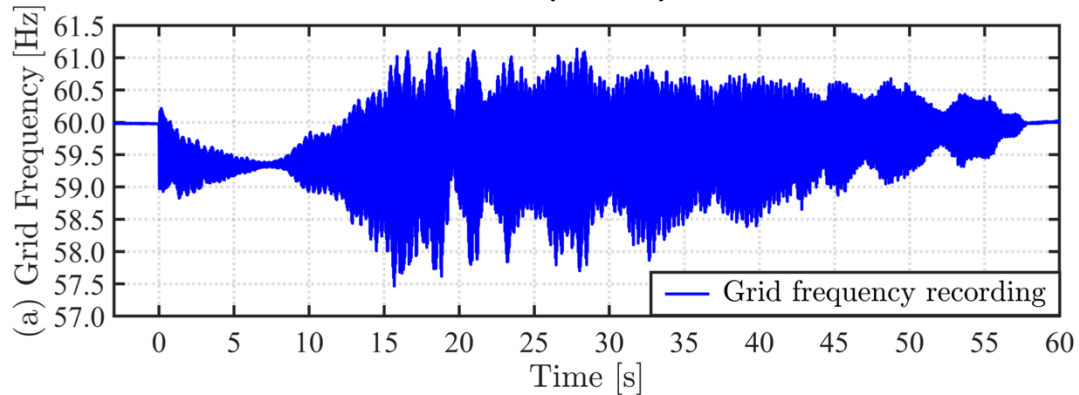
- **Network state:** impedance, SCR, topology, compensation level
- **Control configuration:** PLL dynamics, outer/plant controllers, GFL vs GFM
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Understanding SSOs: What we know

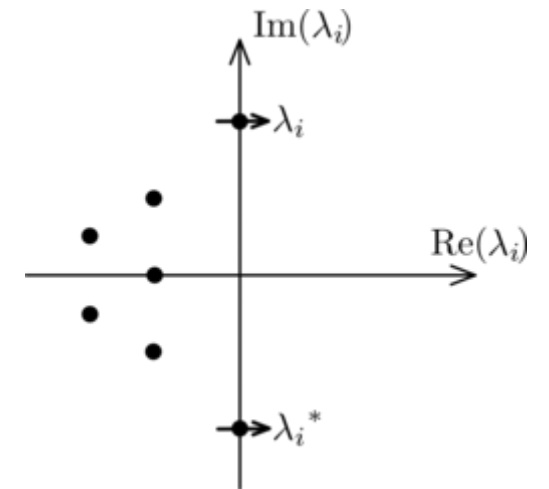
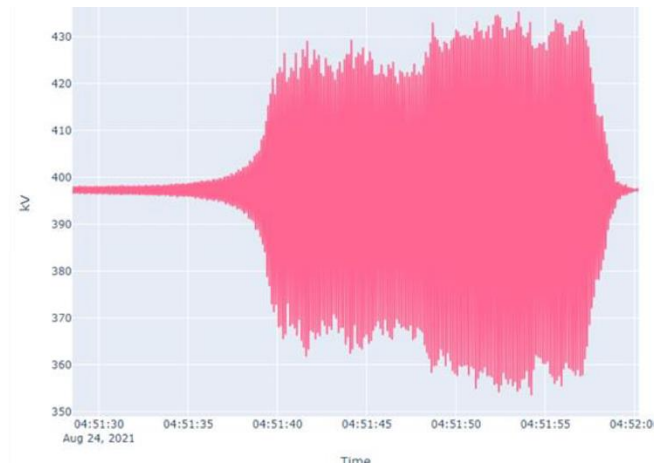
- **Hopf bifurcation** as the onset mechanism
 - SSOs emerge through **supercritical Hopf** bifurcations.
 - This means **linearized small-signal models are sufficient** to capture the transition to instability.



Hawaii (2021)

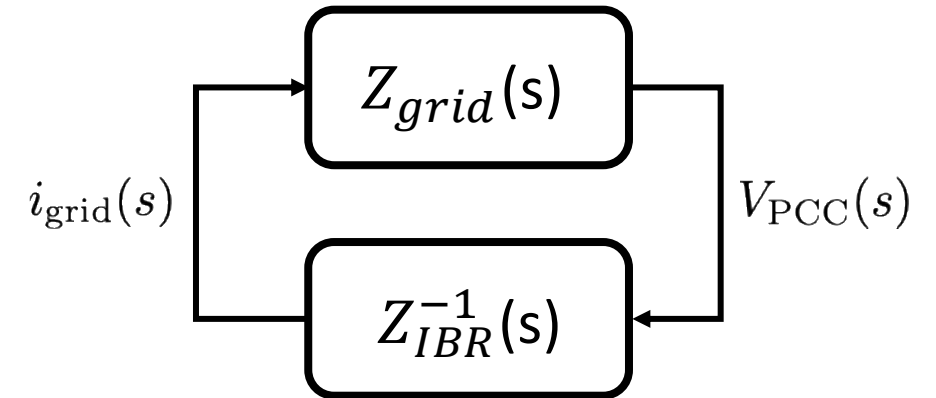
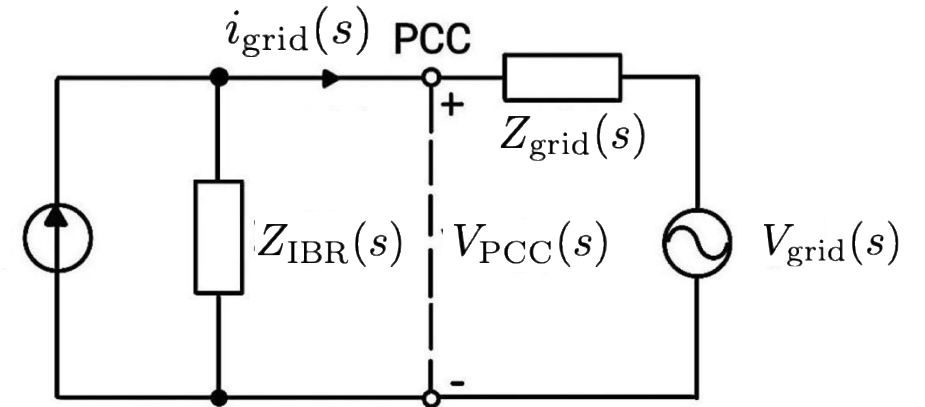


Scotland (2021)



Understanding SSOs: What we can naively do

- **Hopf bifurcation** as the onset mechanism
 - SSOs emerge through **supercritical Hopf** bifurcations.
 - This means **linearized small-signal models are sufficient** to capture the transition to instability.
- Impedance models **can capture SSOs**
 - At the Point of Interconnection, stability can be analyzed by comparing inverter and grid impedances.

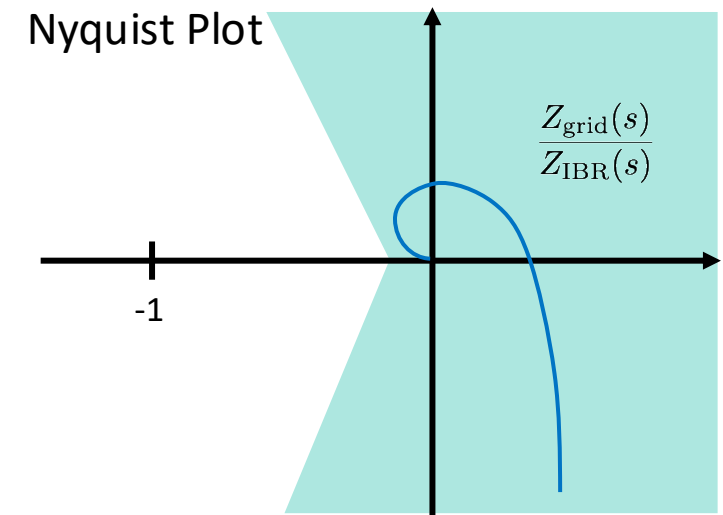
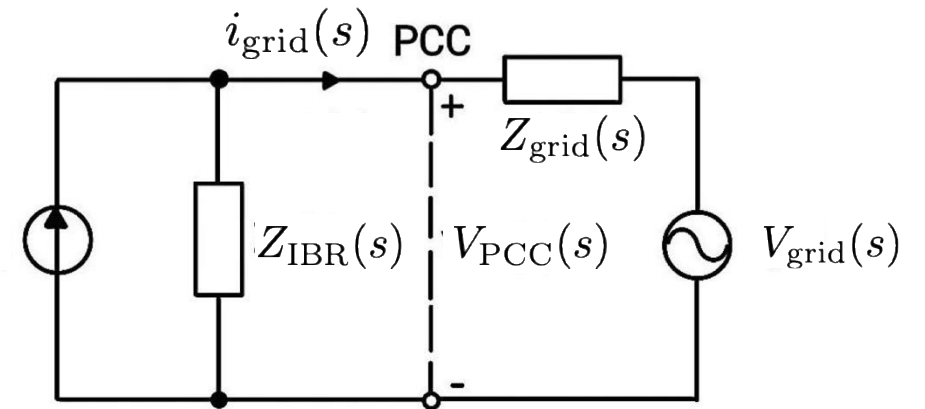


$$V_{\text{PCC}}(s) = \frac{1}{1 + \frac{Z_{\text{grid}}(s)}{Z_{\text{IBR}}(s)}} V_{\text{grid}}(s).$$

Understanding SSOs: What we can naively do

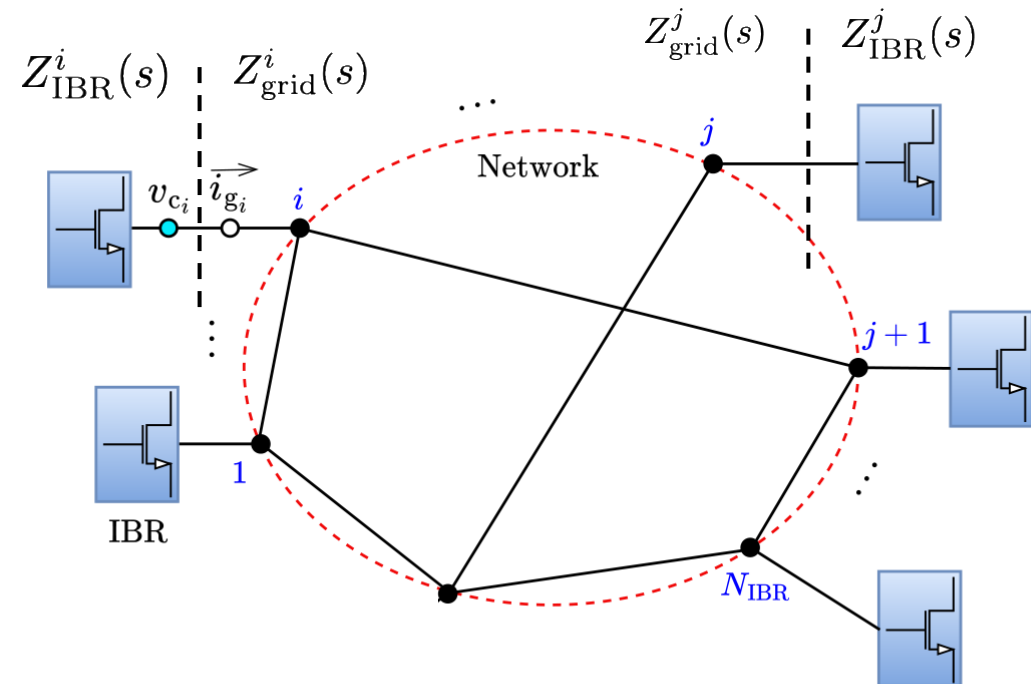
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 - SSOs emerge through **supercritical Hopf** bifurcations.
 - This means **linearized small-signal models are sufficient** to capture the transition to instability.
- Impedance models **can capture SSOs**
 - At the Point of Interconnection, stability can be analyzed by comparing inverter and grid impedances.
 - **Nyquist loop-gain criterion** $L(s) = \frac{Z_{grid}(s)}{Z_{IBR}(s)}$ explains why weak grids (high Z_{grid}) are more prone to instability.

$$V_{PCC}(s) = \frac{1}{1 + \frac{Z_{grid}(s)}{Z_{IBR}(s)}} V_{grid}(s).$$



Challenges of Impedance Stability Analysis

- Z_{IBR}^i depends on:
 - Vendor Technology
 - Setpoints (P_i, Q_i)
- Z_{grid}^i depends on:
 - Location where it is measured
 - Network Topology
 - Power Flows (P_{net}, Q_{net})
 - Other connected devices



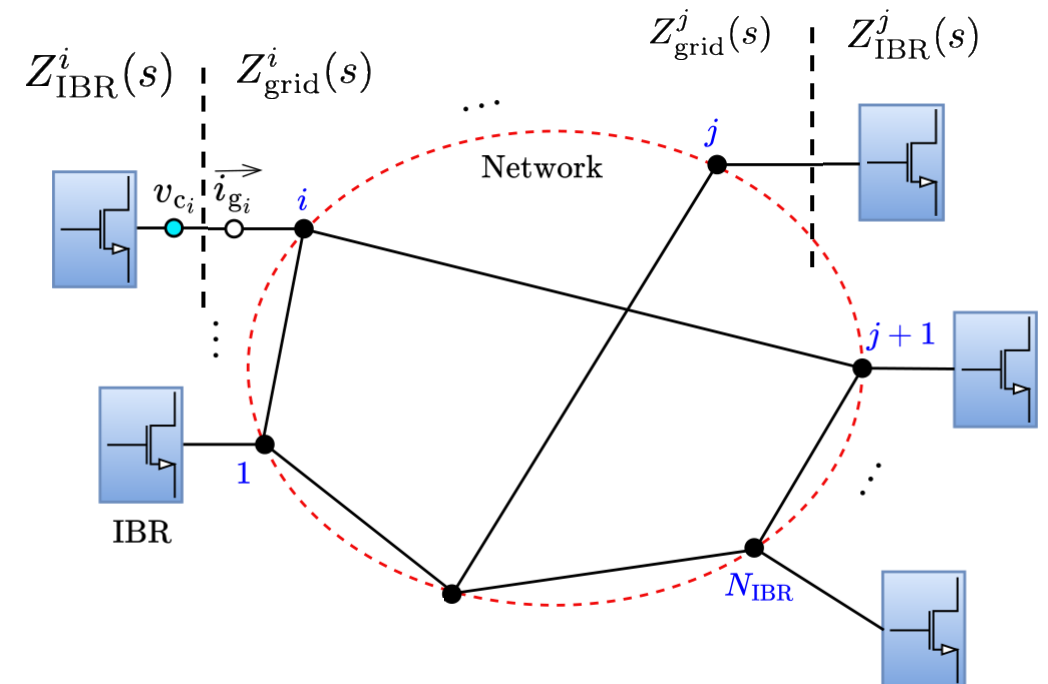
$$Z_{grid}^i(s) \neq Z_{grid}^j(s)$$

Robust, Decentralized, Small-Signal Analysis

- **Goal:** Develop small-signal stability analysis methods that account for **IBR's dynamics & network operating conditions**.

- **Key properties:**

- Requires *individual tests* on IBRs, using *local information*
- Account for *variations* in network components, topology, scheduling
- Characterizes *valid grid operating conditions* (P_{net}, Q_{net})
- *Trade-off* conservativeness between operating conditions and IBR dynamic constraints

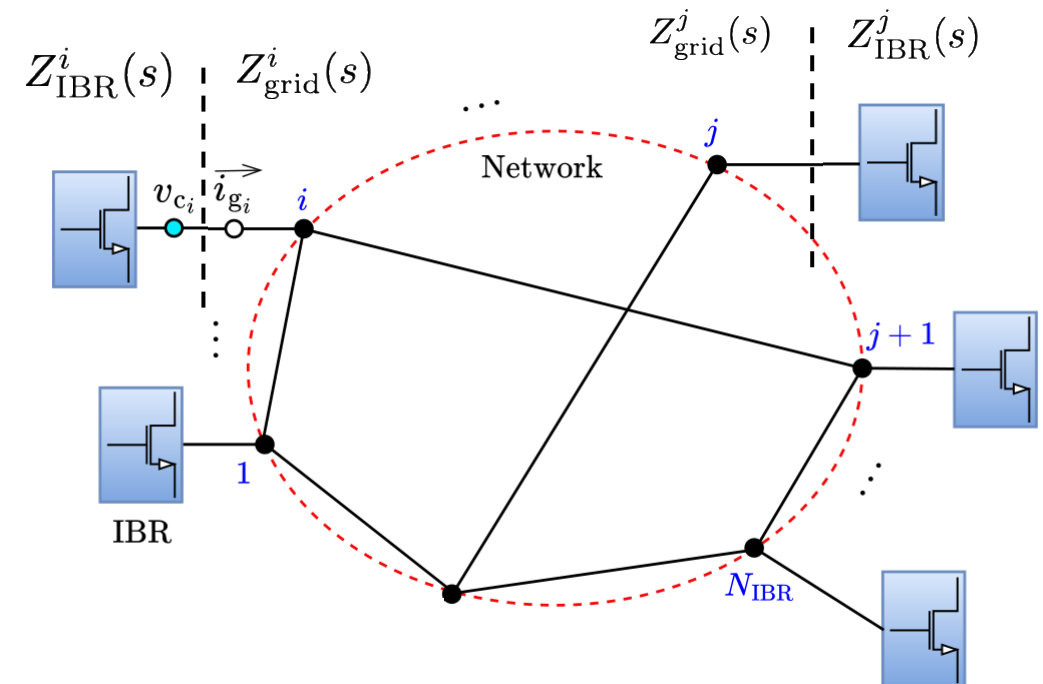


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[TCNS 19] Pates, M, Robust Scale Free Synthesis for Frequency Regulation in Power Systems **IEEE TCNS 2019**

[GM 24] Siahann, M, Geng, Decentralized Stability Criteria for Grid-Forming Control in Inverter-Based Power Systems **PES-GM 2024**

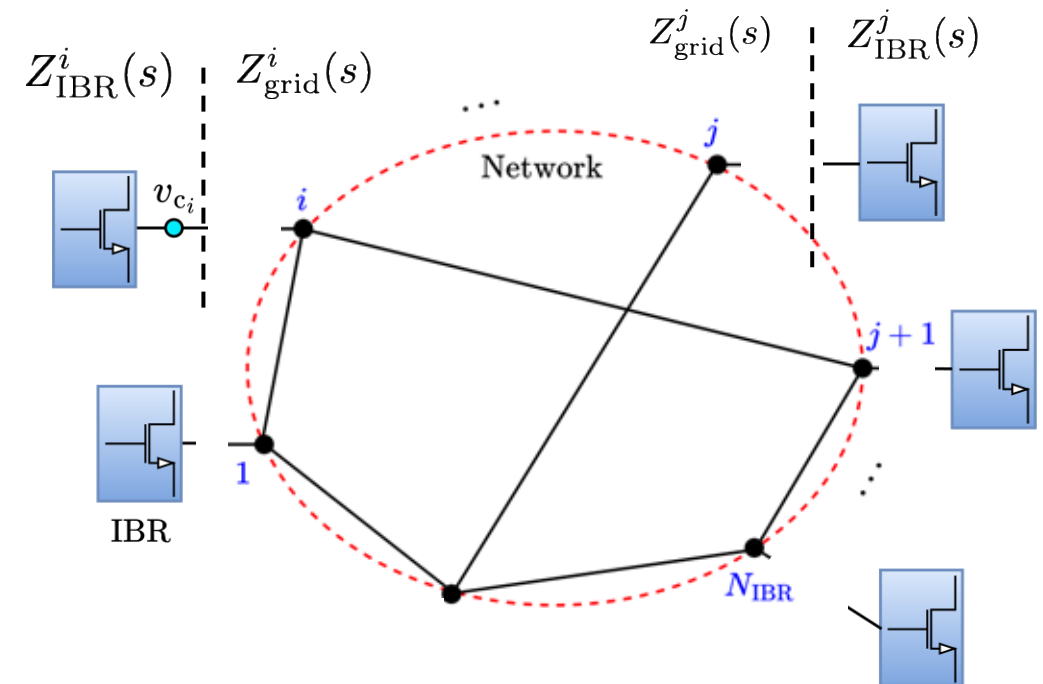
[Preprint 26] Wang, Chatterjee, Geng, Pates, M, Decentralized Stability Certificates for Small-Signal Stability in IBR-Dominated Grids: The Role of the Network State **submitted**

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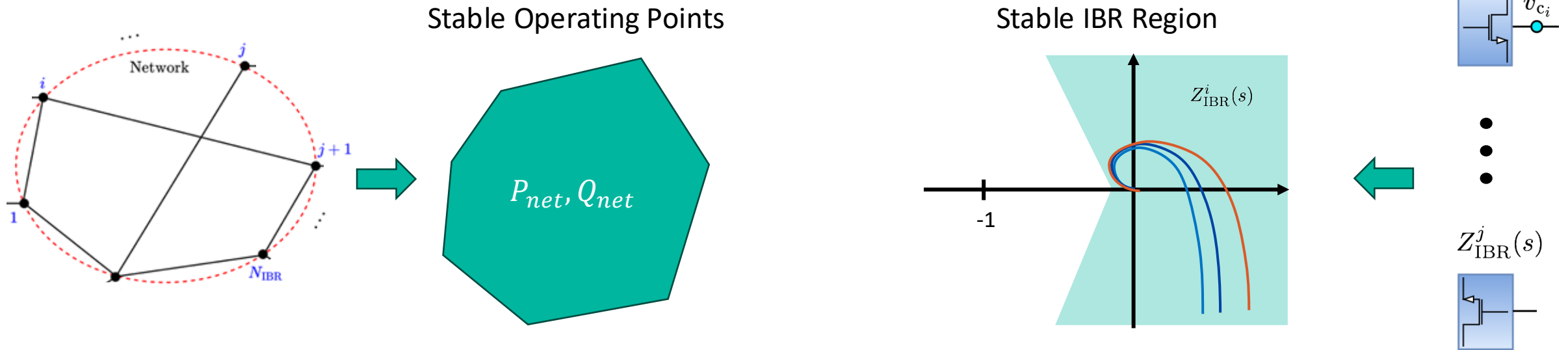
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Robust, Decentralized, Small-Signal Analysis

- **Goal:** Develop small-signal stability analysis methods that account for **IBR's impedance variations & network operating conditions.**



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Related Literature

Work	Coordinates	Operating Conditions	Info Requirements	Other Properties
[1]	dq-voltage and current: $v^{d/q}, i^{d/q}$	$\theta_i \approx \theta_j, v_i \approx v_j $, or implicit	local	IQC based
[2]	real power and freq: P, ω	decoupled power flows	local	IQC adjacent, exploits model structure
[3], [4]	dq-voltage and current $v^{d/q}, i^{d/q}$	implicit	distributed	passivity, Port Hamiltonian, microgrids
[5]	dq-voltage and current $v^{d/q}, i^{d/q}$	implicit	distributed	general IBR models, line dynamics
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[7]	real power and phases: P, θ	$\theta_i \approx \theta_j, v_i \approx v_j $	local	diagonalization, line dynamics
[8]	power and polar voltages: P, Q, v , θ	decoupled power flows	local	IQC adjacent, exploits model structure
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[10]	power and polar voltages: P, Q, v , θ	$\theta_i \approx \theta_j$	local	passivity + FVT, line dynamics
[11]	dq-voltage and current: $v^{d/q}, i^{d/q}$	implicit	distributed	DW Shells

[1] Vorobev, P., Chevalier, S., and Turitsyn, K., *Decentralized Stability Rules for Microgrids*, IEEE ACC, 2019.

[2] Pates, R., and Mallada, E., *Robust Scale-Free Synthesis for Frequency Control in Power Systems*, IEEE Transactions on Control of Network Systems, 2019.

[3] Farokhian Firuzi, M., Roosta, A., and Gitizadeh, M., *Stability Analysis and Decentralized Control of Inverter-Based AC Microgrids*, Protection and Control of Modern Power Systems, 2019.

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[10] Häberle, V., et al., *Decentralized Parametric Stability Certificates for Grid-Forming Converter Control*, arXiv:2503.05403, 2025.

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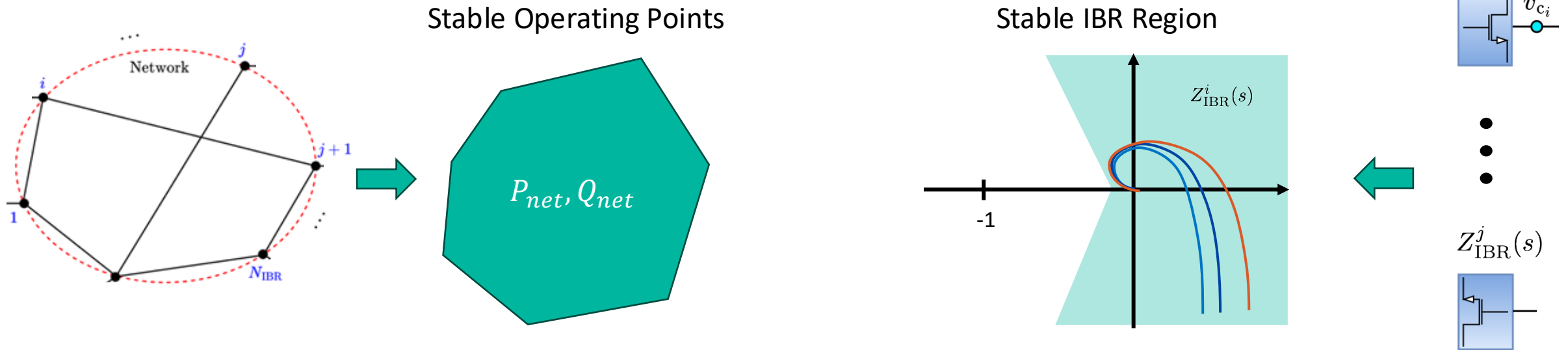
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[12] J. Niehues, R. Delabays, A. Büttner, and F. Hellmann, *Small-signal stability of power systems with voltage droop*, IEEE Trans. Power Systems, 2025.

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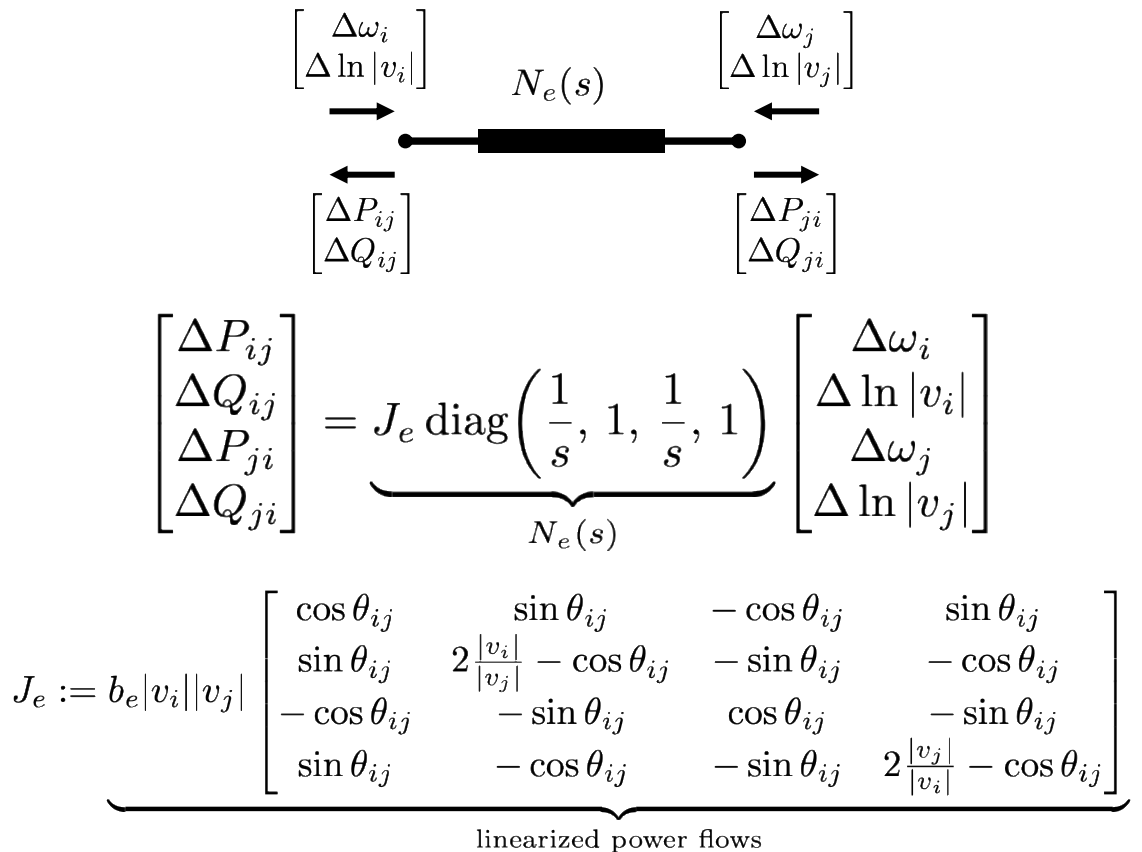
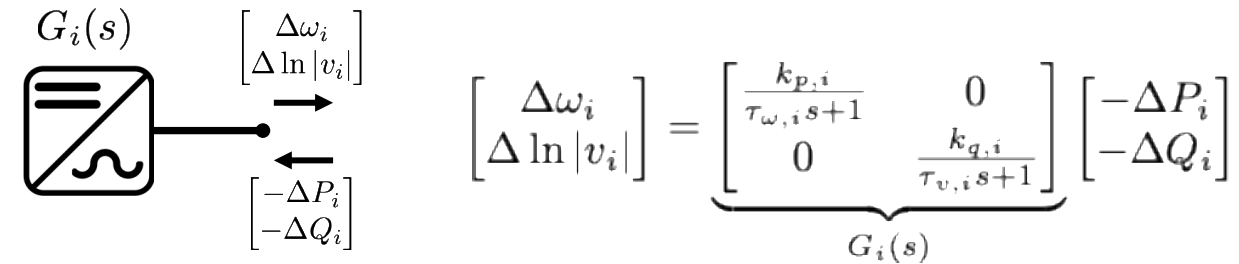
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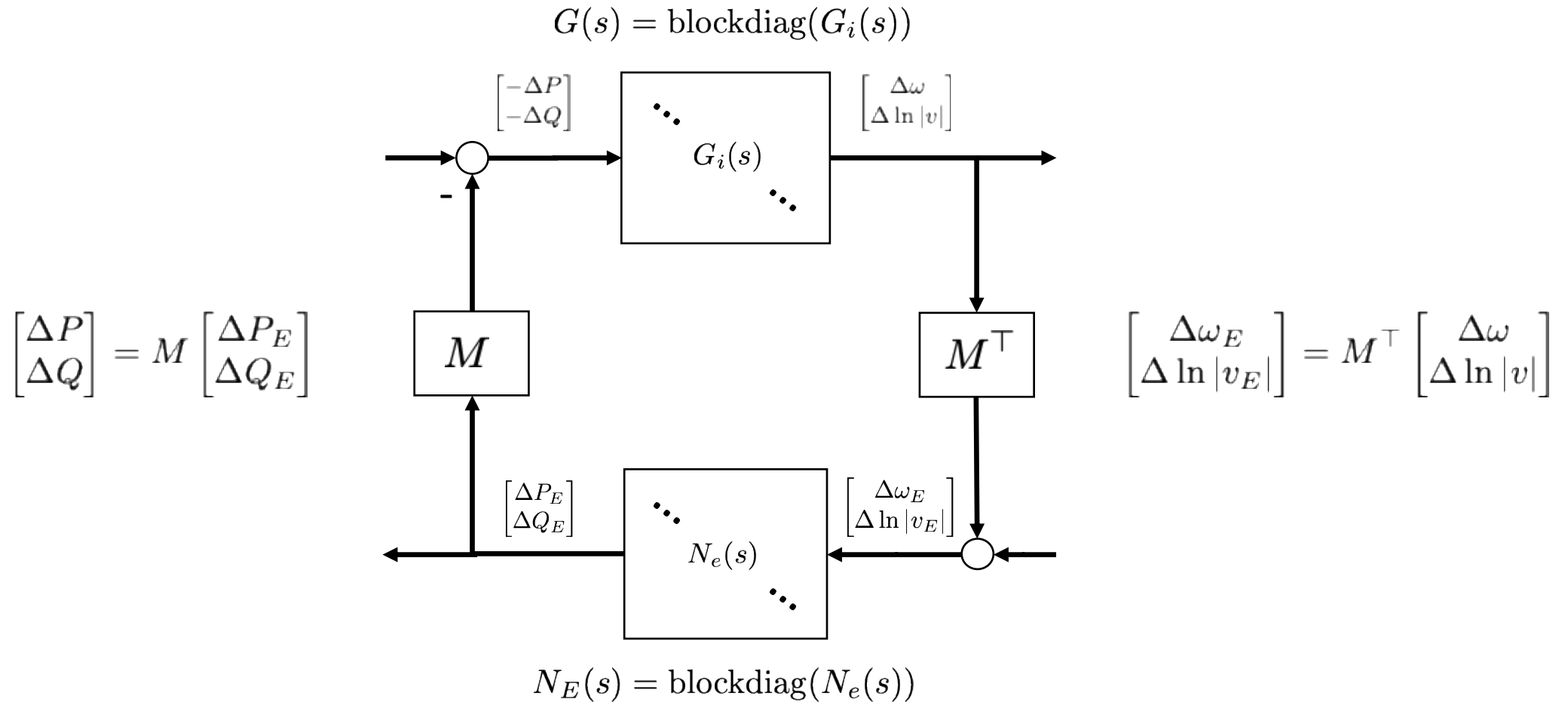
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Port-based Network Model

- **IBRs Model:** $G_i(s)$
 - GFM converter with filtered droop control
 - Internal converter dynamics are neglected
 - Linearized power and log-polar voltage coordinates: $\Delta P_i, \Delta Q_i, \Delta \ln|v_i|, \Delta \theta_i$
- **Transmission System:** $N_e(s)$, $e := \{i, j\}$
 - Lossless inductive lines $b_e = 1/L_e\omega_0$
 - Linearized power and log-polar voltage coordinates: $\Delta P_{ij/ji}, \Delta Q_{ij/ji}, \Delta \ln|v_{i/j}|, \Delta \theta_{i/j}$
 - Quasi-steady state assumptions



Network Interconnection: $G(s) \#_M N_E(s)$



State-aware Decentralized Stability Certificate

Theorem (Main result)

The feedback interconnection $G(s) \#_M N_E(s)$ is internally stable if there exist **nonnegative scalars** $\{d_e\}_{e \in E}$ such that the following holds:

(i) IBR gain condition:

For each device $i = 1, 2, \dots, n$,

$$\sum_{e \in E: i \in e} d_e < \frac{1}{k_{q,i}}$$

where sum is over lines e adjacent to i

(local to each bus)

(ii) Network state condition:

For each line $e = \{i, j\} \in E$,

$$\left(2 \frac{d_e}{b_e |v_i| |v_j|} - \frac{2}{\cos \theta_{ij}}\right) \sqrt{\left(\frac{Q_{ij} - Q_{ji}}{b_e |v_i| |v_j|}\right)^2 + 4} + \left(\frac{d_e}{b_e |v_i| |v_j|}\right)^2 - \frac{2}{\cos \theta_{ij}} \frac{d_e}{b_e |v_i| |v_j|} + 4 \geq 0.$$

(local to each line)

Understanding Stability Certificates

- Main theorem requires nonnegative $\{d_e\}_{e \in E}$ s.t.

$$(i) \quad \sum_{e \in E: i \in e} d_e < \frac{1}{k_{q,i}}, \quad \forall i \in \{1, \dots, n\}$$

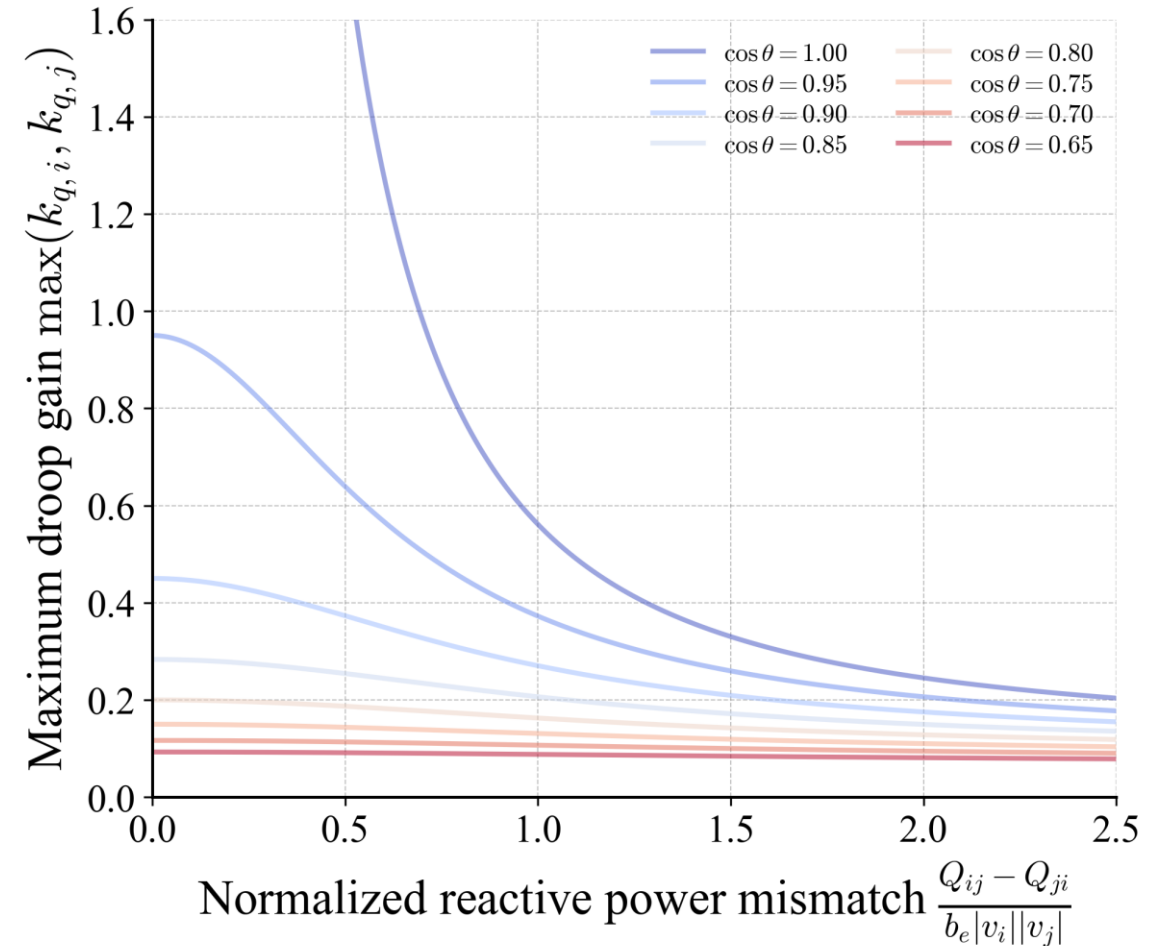
$$(ii) \quad \left(2 \frac{d_e}{b_e |v_i| |v_j|} - \frac{2}{\cos \theta_{ij}} \right) \sqrt{\left(\frac{Q_{ij} - Q_{ji}}{b_e |v_i| |v_j|} \right)^2 + 4} + \left(\frac{d_e}{b_e |v_i| |v_j|} \right)^2 - \frac{2}{\cos \theta_{ij}} \frac{d_e}{b_e |v_i| |v_j|} + 4 \geq 0, \quad \forall e \in E$$

- Two key *detrimental* quantities
 - Normalized *reactive power imbalance*

$$\frac{Q_{ij} - Q_{ji}}{b_e |v_i| |v_j|} = \frac{|v_i|}{|v_j|} - \frac{|v_j|}{|v_i|}$$

- Line loading*

$$\cos \theta_{ij} = \sqrt{1 - \left(\frac{P_{ij}}{b_e |v_i| |v_j|} \right)^2}$$



Understanding Stability Certificates

- Two key *detrimental* quantities
 - Normalized *reactive power imbalance*

$$\frac{Q_{ij} - Q_{ji}}{b_c |v_i| |v_j|} = \frac{|v_i|}{|v_j|} - \frac{|v_j|}{|v_i|}$$

- Line loading*

$$\cos \theta_{ij} = \sqrt{1 - \left(\frac{P_{ij}}{b_c |v_i| |v_j|} \right)^2}$$

- Simplifying assumptions:

- a. **Equal terminal voltages**

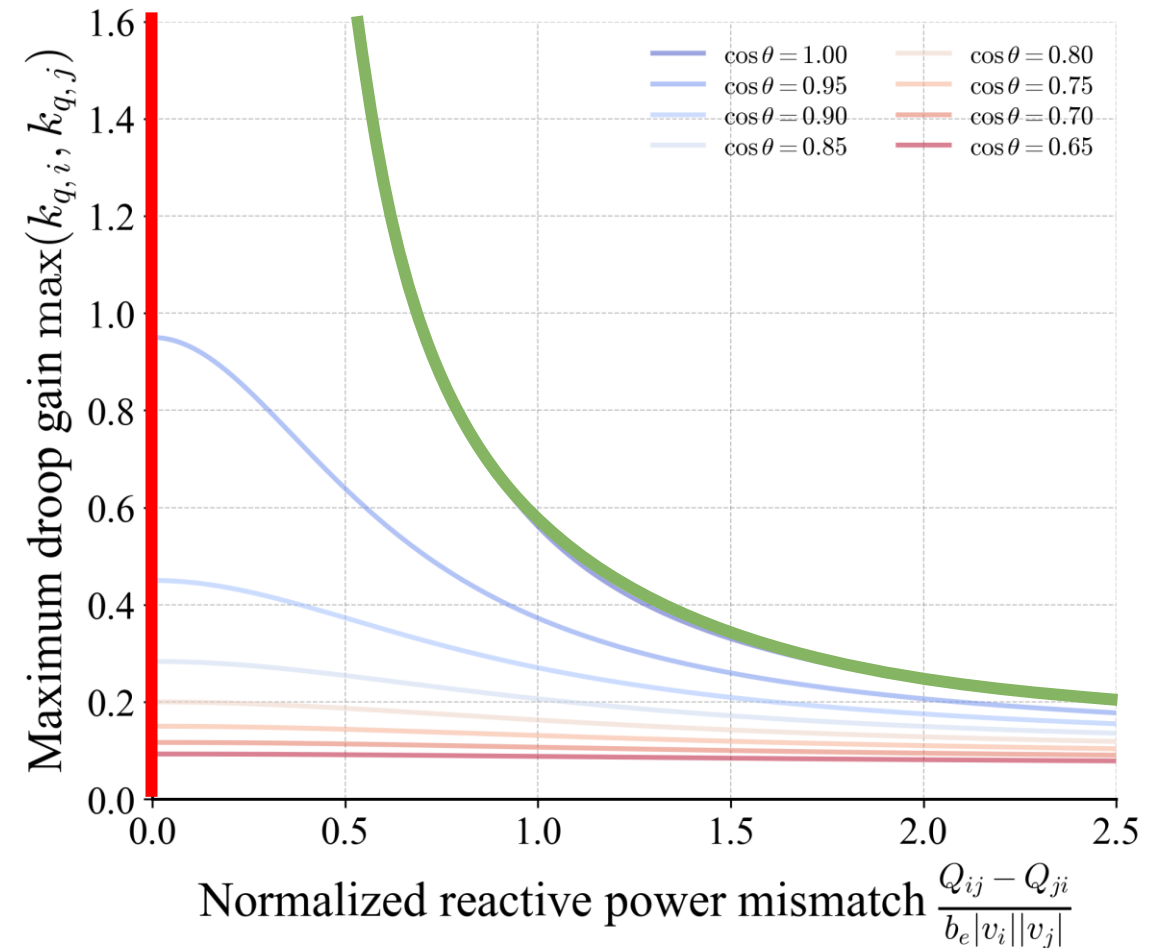
$$|v_i| = |v_j| \implies \max(k_{q,i}, k_{q,j}) < \frac{\cos \theta_{ij}}{Q_{ij} + Q_{ji}}$$

- b. **Small phase differences**

$$\cos \theta_{ij} = 1 \implies \max(k_{q,i}, k_{q,j}) < \frac{1}{|Q_{ij} - Q_{ji}|}$$

- a. + b. **Zero power flows**

$$\max(k_{q,i}, k_{q,j}) < \infty$$



Proof Sketch of Main Result

- **Step 1:** Change voltage coordinates

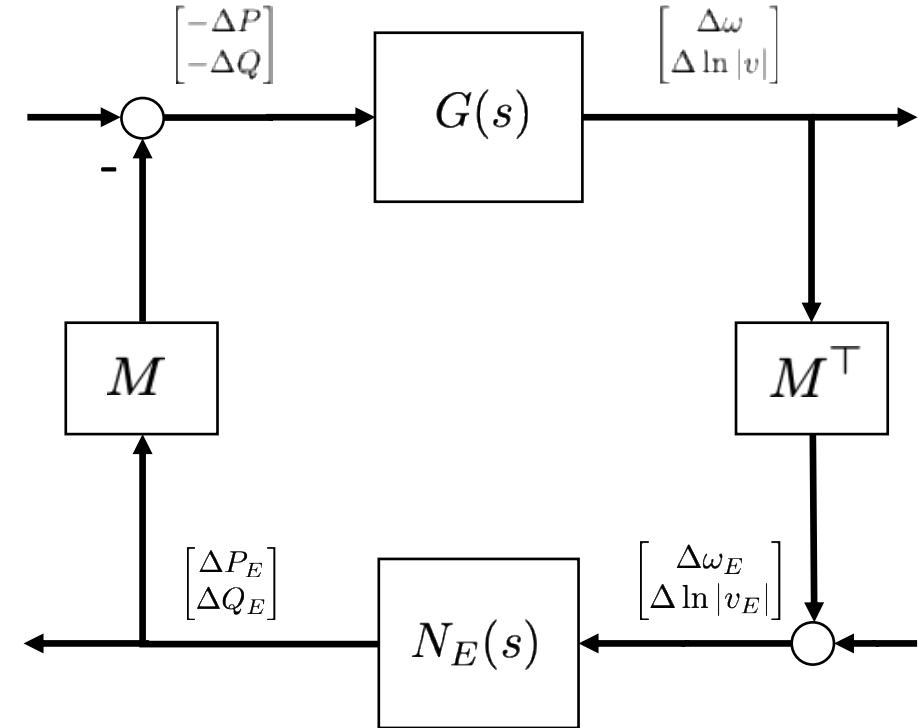
$$\Delta \ln |v| \rightarrow \Delta \ln \dot{|v|}$$

leading to loop transformation:

$$(i) \quad G(s) \#_M N_E(s) \rightarrow G'(s) \#_M \frac{1}{s} J_E$$

$$G_i(s) = \begin{bmatrix} \frac{k_{p,i}}{\tau_{\omega,i}s+1} & 0 \\ 0 & \frac{k_{q,i}}{\tau_{v,i}s+1} \end{bmatrix}$$

$$G(s) = \text{blockdiag}(G_i(s))$$



$$N_E(s) = \text{blockdiag}(N_e(s))$$

$$N_e(s) = J_e \text{diag}\left(\frac{1}{s}, 1, \frac{1}{s}, 1\right)$$

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- **Step 2:** Loop transform to compensate lack of passivity of J_e s.t.

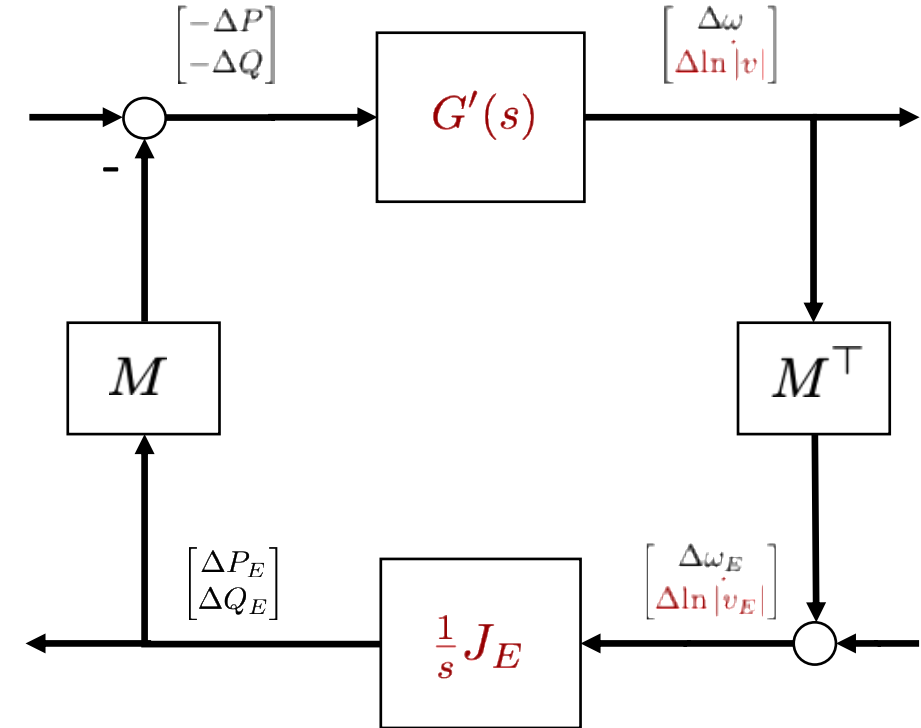
$$J_e + D_e \succeq 0$$

leading leading to loop transformation:

$$(ii) \quad G'(s) \#_M \frac{1}{s} J_E \rightarrow \hat{G}(s) \#_E \hat{N}_E(s)$$

$$G'_i(s) = \begin{bmatrix} \frac{k_{p,i}}{\tau_{\omega,i}s+1} & 0 \\ 0 & \frac{k_{q,i}s}{\tau_{v,i}s+1} \end{bmatrix}$$

$$G'(s) = \text{blockdiag}(G'_i(s))$$



$$J_E = \text{blockdiag}(J_e)$$

$$J_e := b_e |v_i| |v_j| \begin{bmatrix} \cos \theta_{ij} & \sin \theta_{ij} & -\cos \theta_{ij} & \sin \theta_{ij} \\ \sin \theta_{ij} & 2 \frac{|v_i|}{|v_j|} - \cos \theta_{ij} & -\sin \theta_{ij} & -\cos \theta_{ij} \\ -\cos \theta_{ij} & -\sin \theta_{ij} & \cos \theta_{ij} & -\sin \theta_{ij} \\ \sin \theta_{ij} & -\cos \theta_{ij} & -\sin \theta_{ij} & 2 \frac{|v_j|}{|v_i|} - \cos \theta_{ij} \end{bmatrix}$$

Proof Sketch of Main Result

- **Step 1:** Change voltage coordinates

$$\Delta \ln |v| \rightarrow \Delta \ln \dot{|v|}$$

leading to loop transformation:

$$(i) \quad G(s) \#_M N_E(s) \rightarrow G'(s) \#_M \frac{1}{s} J_E$$

- **Step 2:** Loop transform to compensate lack of passivity of J_e s.t.

$$J_e + D_e \succeq 0$$

leading leading to loop transformation:

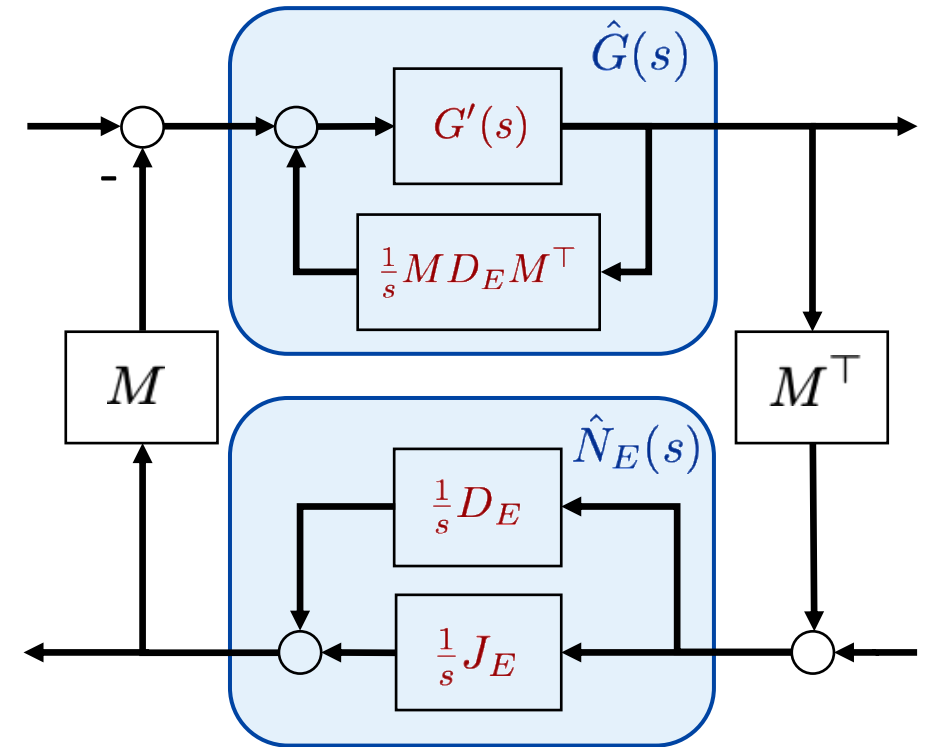
$$(ii) \quad G'(s) \#_M \frac{1}{s} J_E \rightarrow \hat{G}(s) \#_E \hat{N}_E(s)$$

- **Step 3:** Int. Stab. of $\hat{G}(s) \#_E \hat{N}_E(s)$

- **Step 4:** Connect back to original system

$$\hat{G}(s) \#_M \hat{N}(s) \xrightarrow{\text{I.S.}} G'(s) \#_M \frac{1}{s} J_E \xrightarrow{\text{I.S.}} G(s) \#_M N_E(s)$$

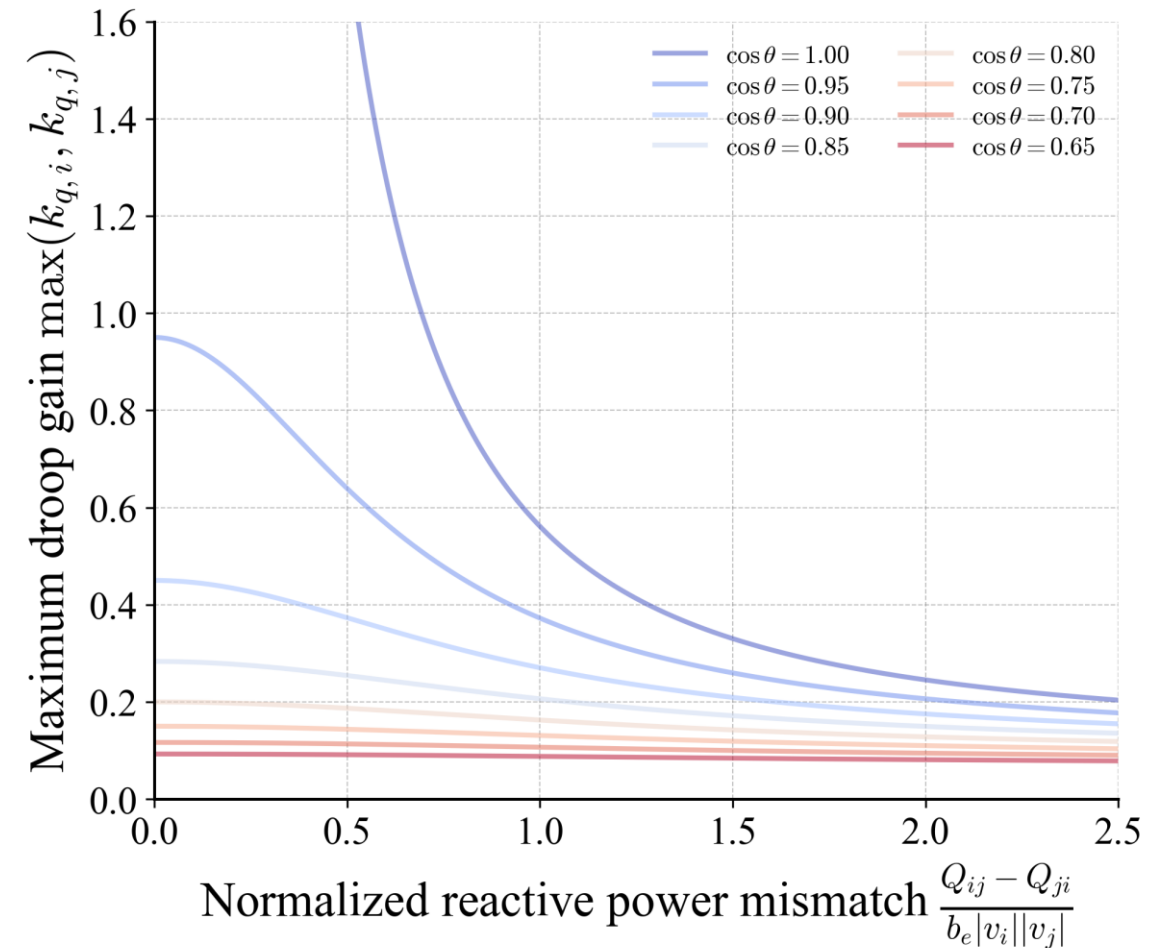
$$G'_i(s) = \begin{bmatrix} \frac{k_{p,i}}{\tau_{\omega,i}s+1} & 0 \\ 0 & \frac{k_{q,i}s}{\tau_{v,i}s+1} \end{bmatrix}$$



$$D_E = \text{blockdiag}(D_e) \quad D_e = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & d_e & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & d_e \end{bmatrix}$$

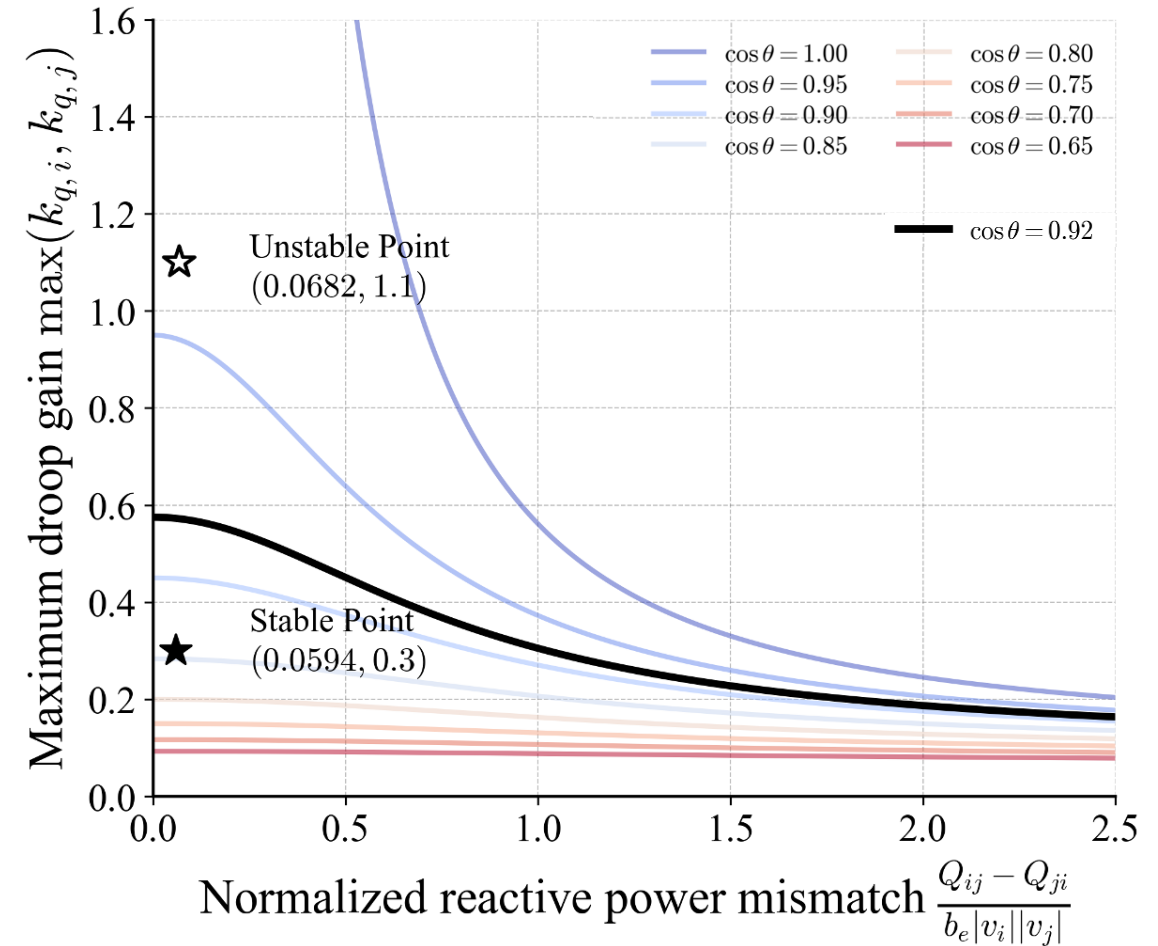
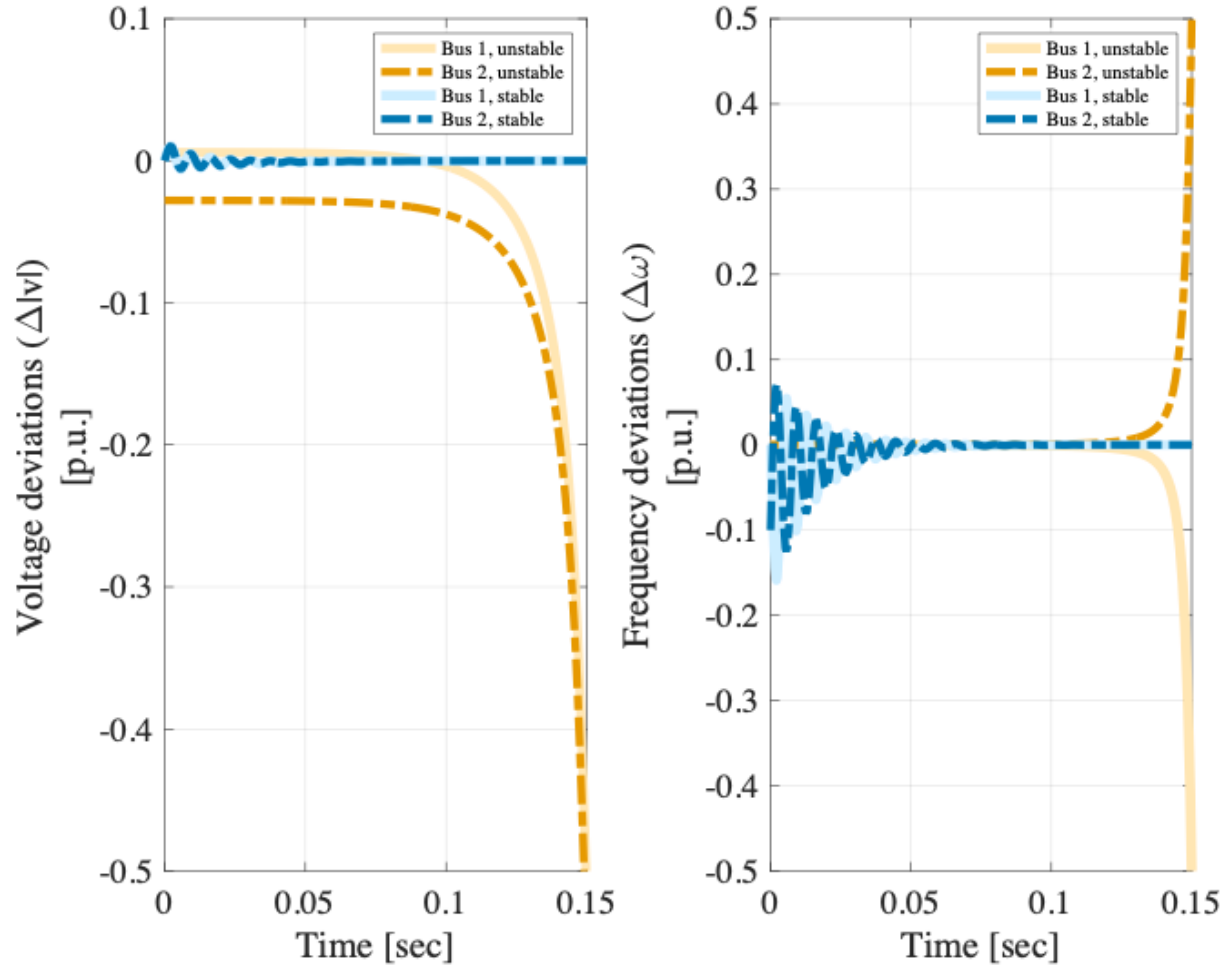
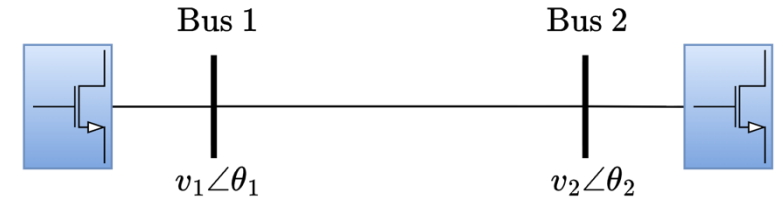
Numerical Illustration

- Operating point: $\cos \theta_{ij} = 0.92$, $\frac{Q_{ij} - Q_{ji}}{b_e |v_i| |v_j|} = 0.059$.
- Control gains: ★ $(k_{q,i}, k_{q,j}) = (0.3, 0.3)$ ☆ $(k_{q,i}, k_{q,j}) = (1.1, 1.0)$



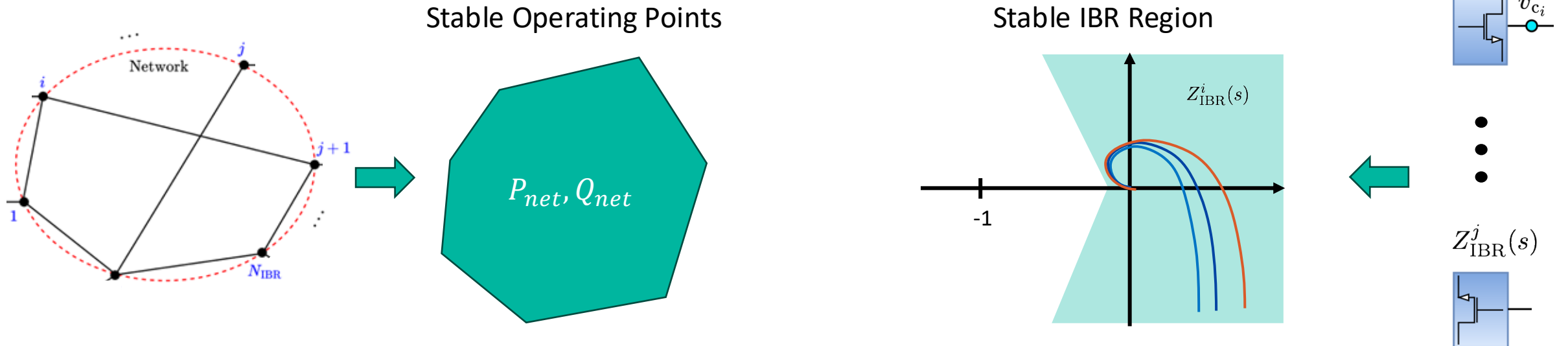
Numerical Illustration

- Operating point: $\cos \theta_{ij} = 0.92$, $\frac{Q_{ij} - Q_{ji}}{b_e |v_1| |v_2|} = 0.059$.
- Control gains: $\star (k_{q,i}, k_{q,j}) = (0.3, 0.3)$ $\star (k_{q,i}, k_{q,j}) = (1.1, 1.1)$



Robust, Decentralized, Small-Signal Analysis

- **Goal:** Develop small-signal stability analysis methods that account for **IBR's impedance variations & network operating conditions.**



[TCNS 19] Pates, M. Robust Scale Free Synthesis for Frequency Regulation in Power Systems. **IEEE TCNS 2019**

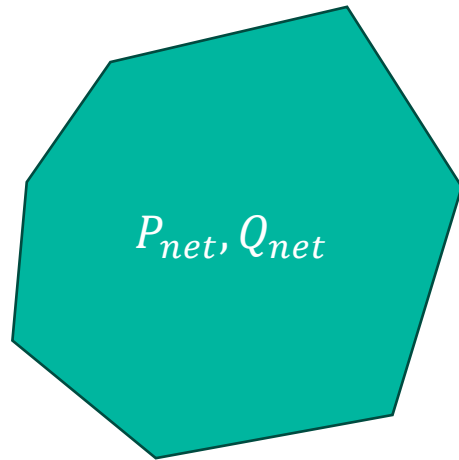
[GM 24] Siahhaan, M, Geng, Decentralized Stability Criteria for Grid-Forming Control in Inverter-Based Power Systems **PES-GM 2024**

[Preprint 26] Wang, Chatterjee, Geng, Pates, M "Decentralized Stability Certificates for Small-Signal Stability in IBR-Dominated Grids: The Role of the Network State **submitted**

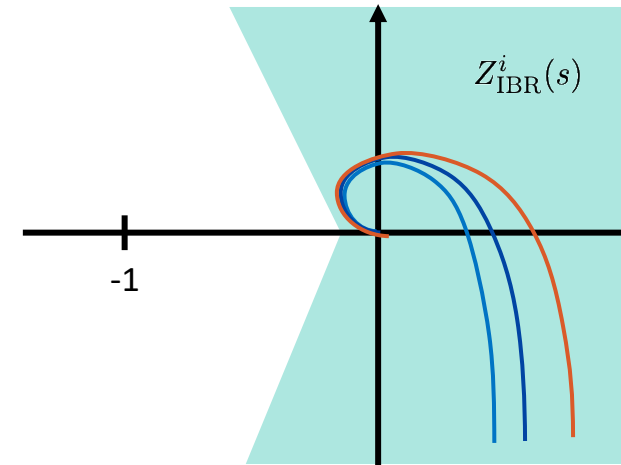
Trade-off: Robustness vs Efficiency

- **Analysis unveils a fundamental trade-off:** expanding the dispatch region demands stricter limits on inverter frequency-domain behavior.

Stable Operating Points



Stable IBR Region



Network State Condition: For all transmission lines

$$\left(2 \frac{d_e}{b_e |v_i| |v_j|} - \frac{2}{\cos \theta_{ij}}\right) \sqrt{\left(\frac{Q_{ij} - Q_{ji}}{b_e |v_i| |v_j|}\right)^2 + 4} + \left(\frac{d_e}{b_e |v_i| |v_j|}\right)^2 - \frac{2}{\cos \theta_{ij}} \frac{d_e}{b_e |v_i| |v_j|} + 4 \geq 0$$

IBR Constraint: For all IBRs

$$\sum_{e \in E: i \in e} d_e < \frac{1}{k_{q,i}}$$

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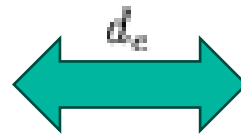
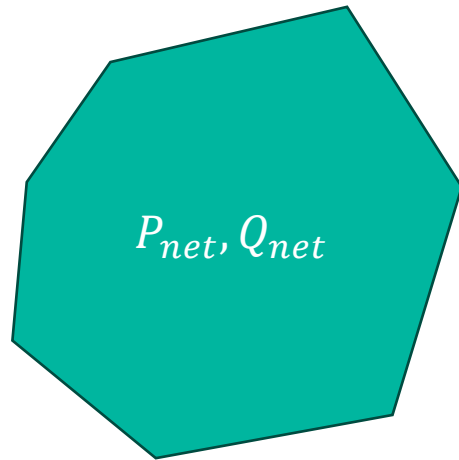
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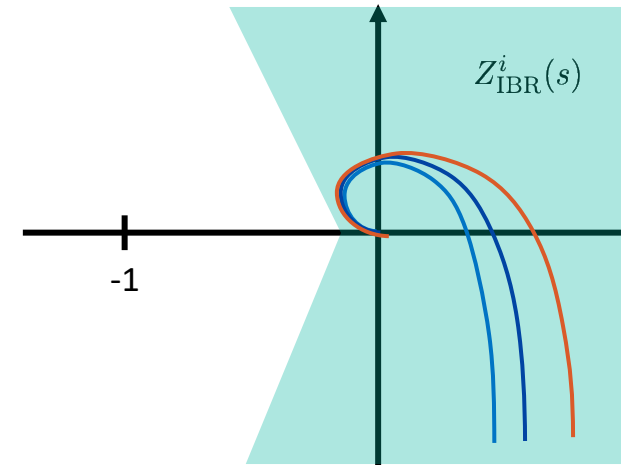
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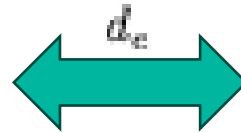
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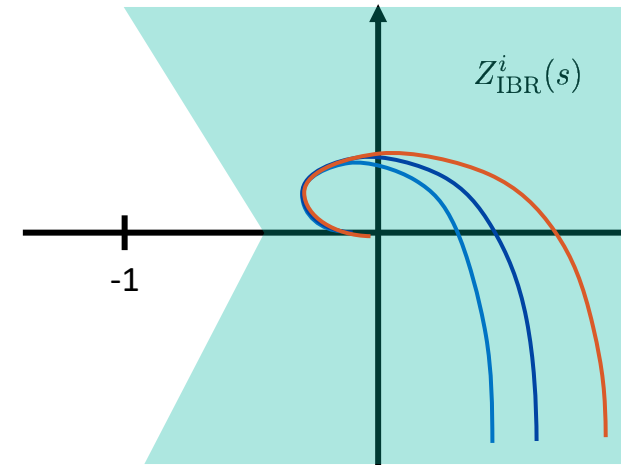
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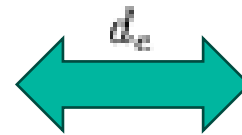
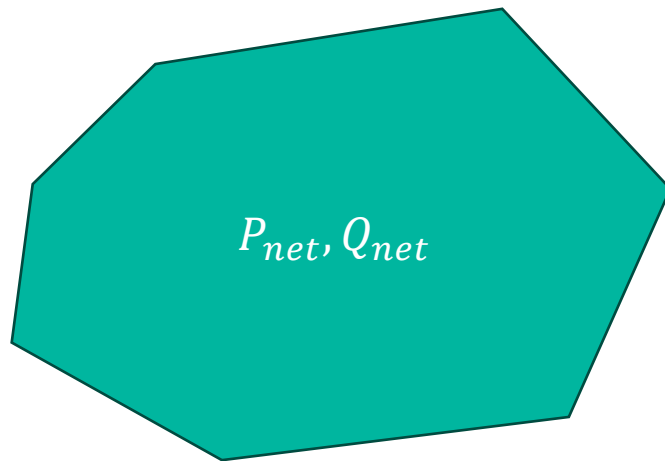
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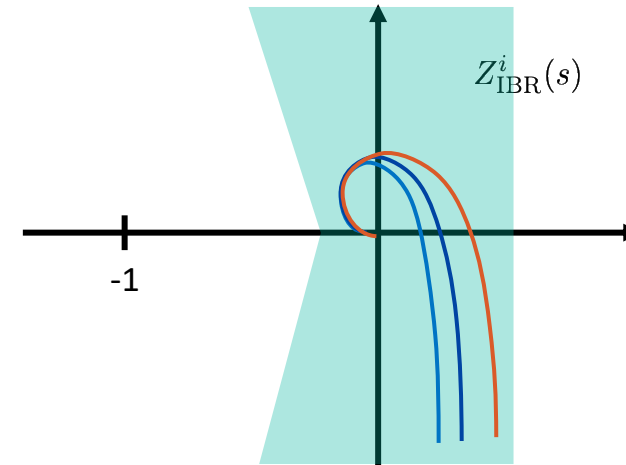
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Summary

Conclusions

- We derived **decentralized stability conditions** that account for the **role of the network state** in small signal stability.
- The resulting stability certificates are **local and interpretable**, linking controller tuning directly to measurable network quantities.
- Analysis makes explicit the **importance of line loading** and **reactive power mismatch** on stability conditions and tighten admissible voltage-droop gains.
- Stability certificates can be **readily integrated in dispatch** and enable **state-aware IBR tuning**.

Future Work

- Extensions line dynamics and generalized IBR models
- Integration with operations and dispatch

Thanks!

Related Publications:

1. Pates, M. *Robust Scale Free Synthesis for Frequency Regulation in Power Systems*, **IEEE TCNS 2019**
2. Siahaan, M, Geng, *Decentralized Stability Criteria for Grid-Forming Control in Inverter-Based Power Systems*, **PES-GM 2024**
3. Wang, Chatterjee, Geng, Pates, M, *Decentralized Stability Certificates for Small-Signal Stability in IBR-Dominated Grids: The Role of the Network State*, **submitted**

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