Reliability Challenges in IBR-Rich Power Grids

Enrique Mallada

Johns Hopkins University

Australian EPICS Workshop

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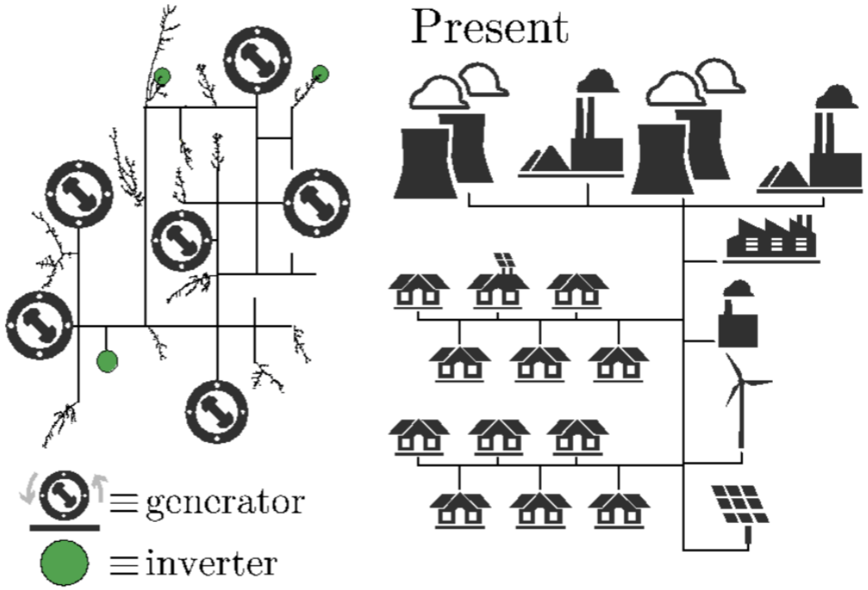
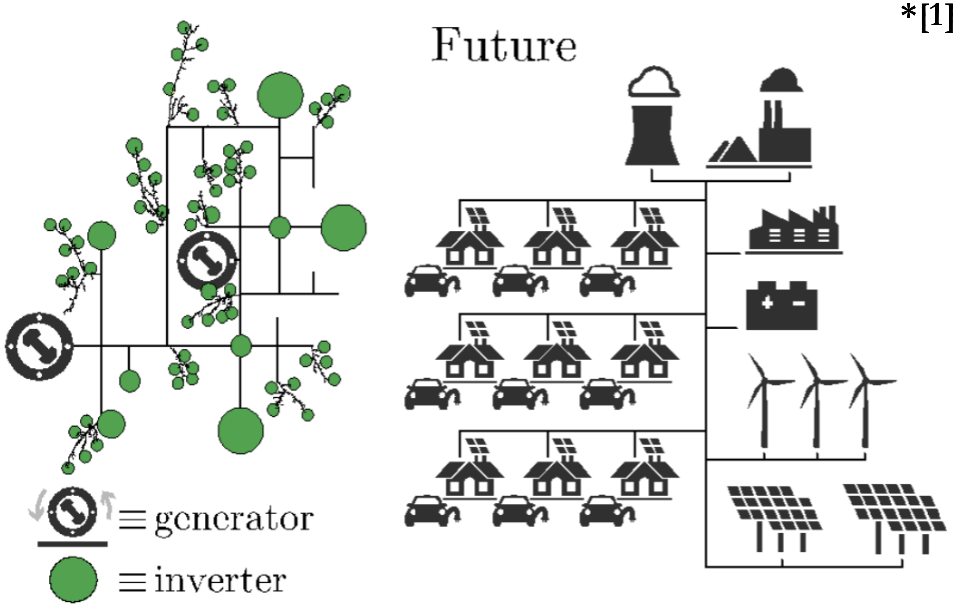
The Future Grid

*[1]





Present grid

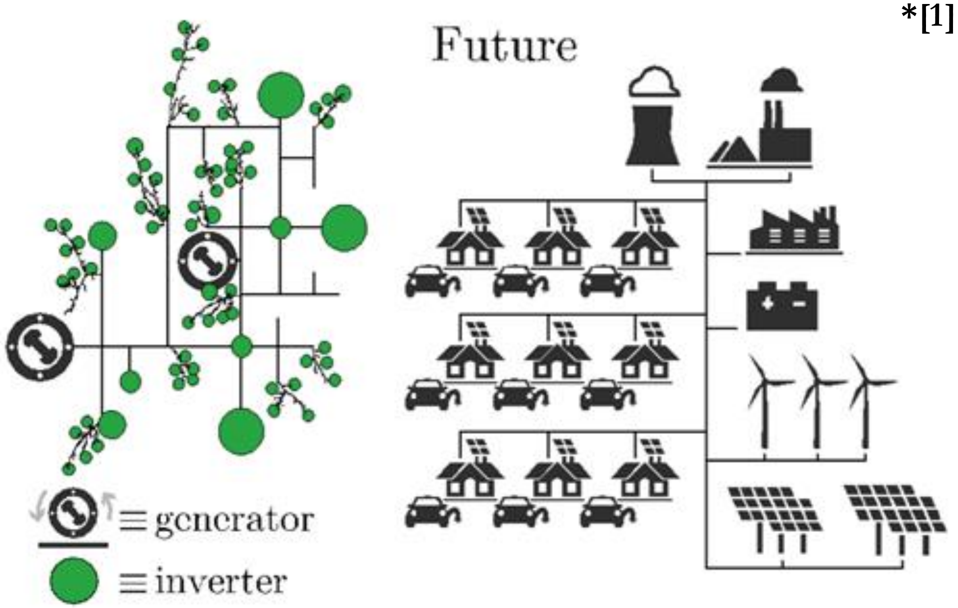
- dispatchable generation
- high inertial response
- strong voltage support
- well known physics

Future

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

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

The Future Grid



Future

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

Challenges

- increased system **uncertainty**
- **sensitivity** to disturbances
- new forms of **instabilities**, induced by inverter-based resources
- need to compensate for **reduced inertia grid strength**

Research questions:

- How should we control a grid with limited inertial/voltage support?
- How should we prevent the onset of IBR induced instabilities?

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

Thrust II – Model and Integration of IBRs

- Topic 2.1 – Modeling IBR-dominated systems
- Topic 2.2 – Stability analysis under uncertainty
- Topic 2.3 – IBR control design for grid shaping
- Topic 2.4 – Integrate stability with operations & services

Thrust goals: to make inverter-based resources predictable, certifiable, and dispatchable contributors to grid stability and ancillary services in future low-inertia power systems.

EPICS

For more info: https://energyinstitute.jhu.edu/epics/

United States *United Kingdom* *Australia*

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- Topic 2.2 – Stability analysis under uncertainty
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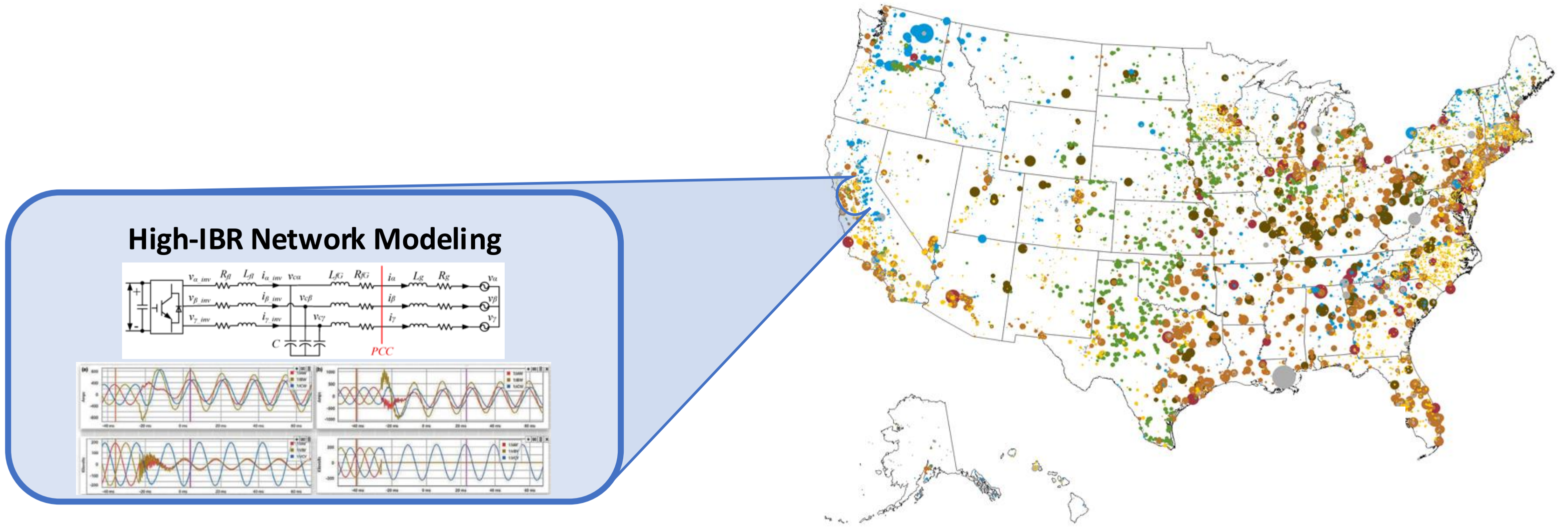
- Topic 2.4 – Integrate stability with operations & services

T2.1 Goal: Develop scalable dynamic models and identification methods that accurately capture IBR-driven instabilities and their operating-point dependence.



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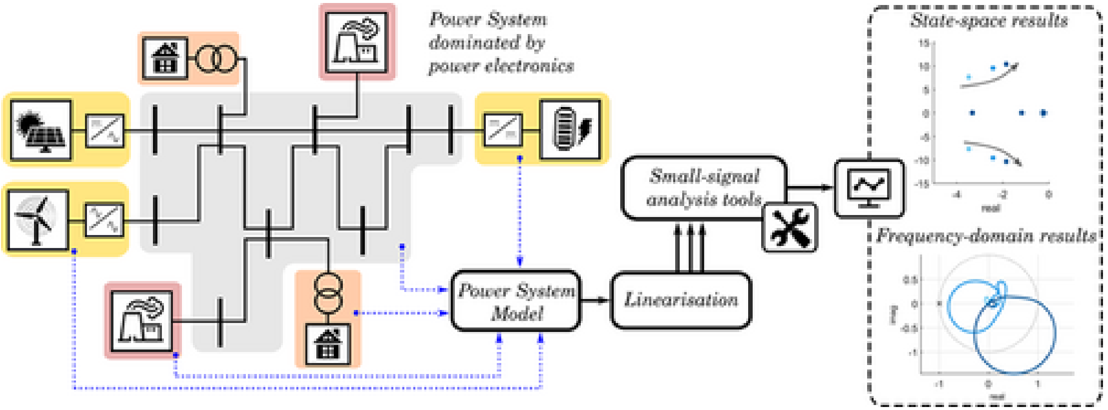
T2.2 Goal: Develop small-signal stability analysis methods that account for modeling uncertainty induced by IBR vendor heterogeneity & variable operating conditions.



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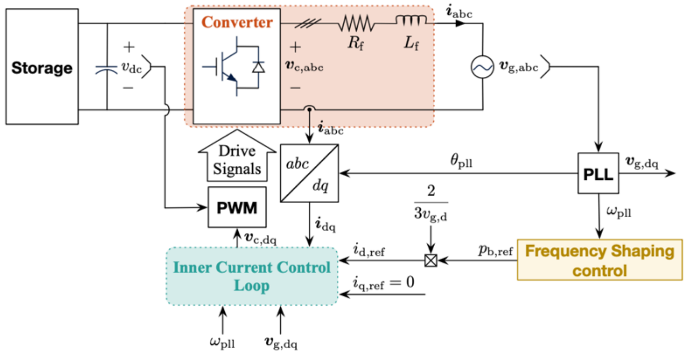
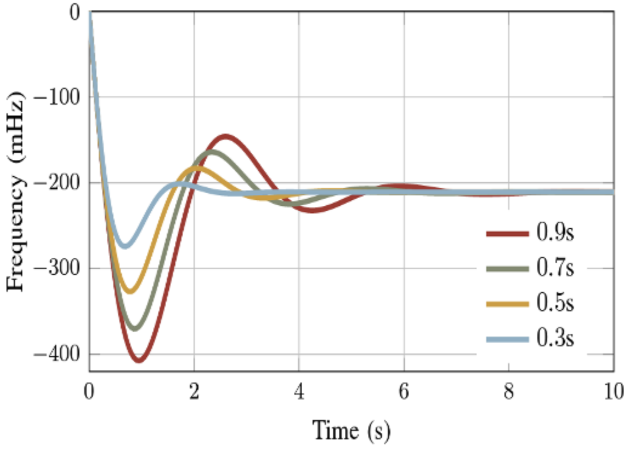
T2.3 Goal: Redesign IBR control loops for grid-following & -forming modes to leverage flexibility to mitigate IBR-driven instabilities/performance degradation.





Frequency response for a 1 p.u. load step

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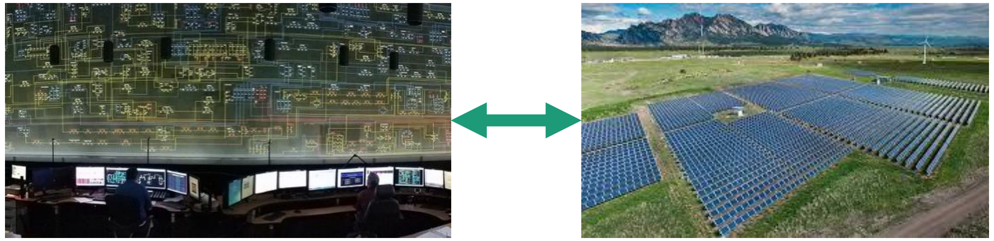
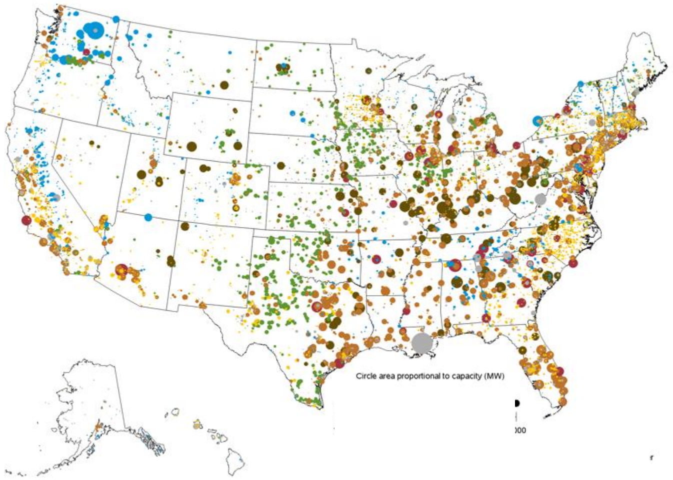
T2.4 Goal: Embed stability constraints and inverter-based services directly into grid dispatch and ancillary service design.

IBR Enabled Operations





Zhimeng Wang
Sushobhan Chatterjee
Sijia Geng
Richard Pates

JOHNS HOPKINS UNIVERSITY

LUND UNIVERSITY

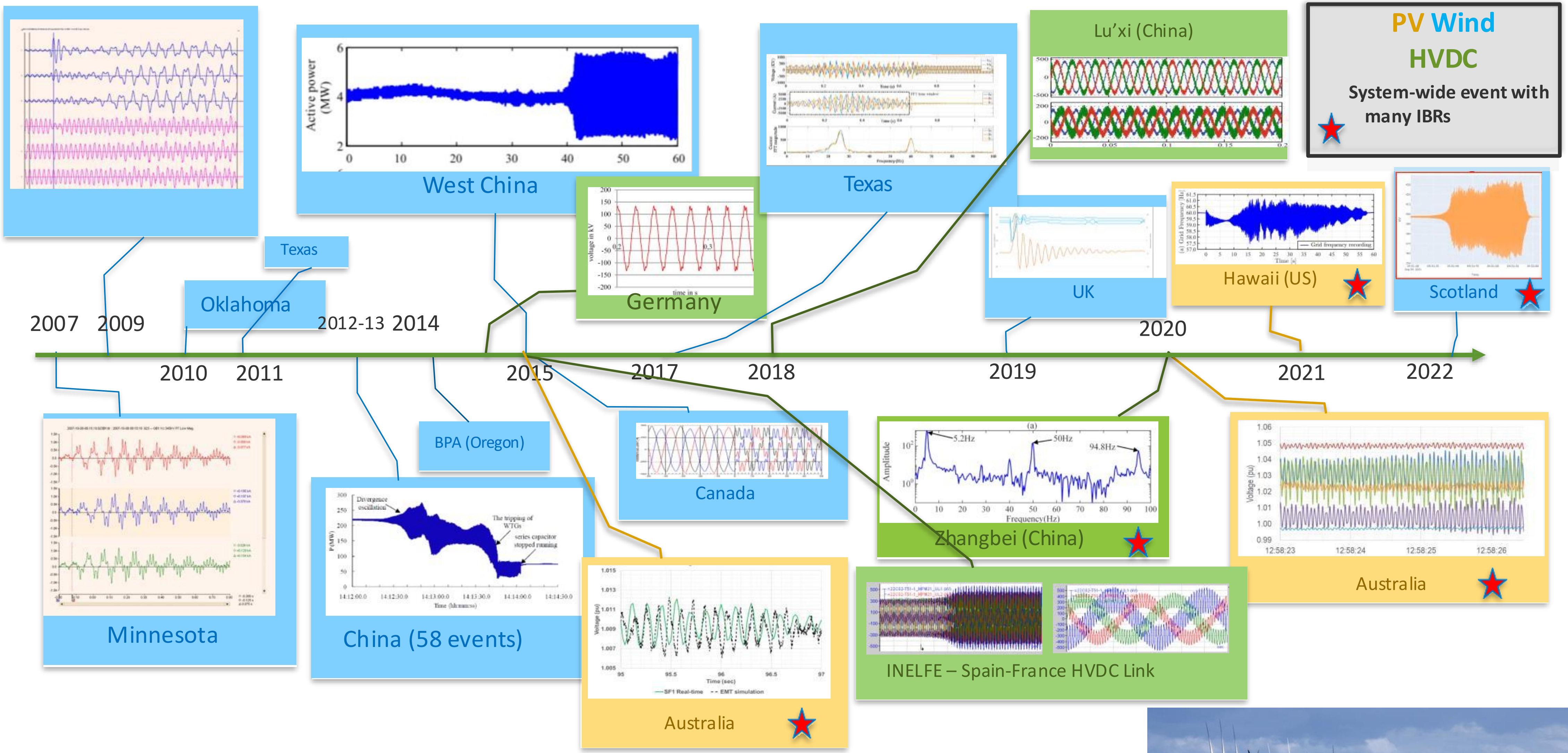
Decentralized Stability Analysis of IBR-Rich Power Systems

Richard Pates and Enrique Mallada, "Robust scale-free synthesis for frequency control in power systems," IEEE Transactions on Control of Network Systems, 2019

Zudika Siahaan, Enrique Mallada, and Sijia Geng. " Decentralized Stability Criteria for Grid-Forming Control in Inverter-Based Power Systems." IEEE PES General Meeting, 2024

Zhimeng Wang, Sushobhan Chatterjee, Sijia Geng, Richad Pates, "Decentralized Stability Certificates for Small-Signal Stability in IBR-Dominated Grids: The Role of Reactive Power." in preparation

Oscillation Events Involving IBRs



Source: NREL, Shahil Shah

IBR-induced Sub Synchronous Oscillations

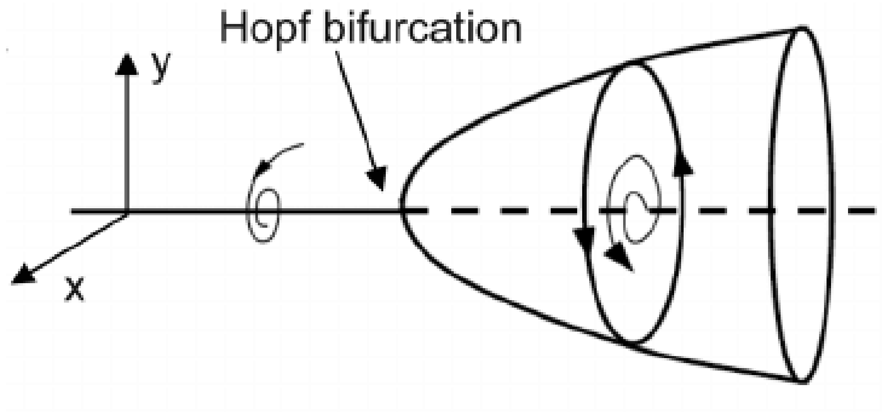
- **When do SSOs occur?**
  - **Series-compensated corridors** (SSCI)
  - **Weak grids** (low SCR, high impedance)
  - Clusters of **IBRs in remote areas**

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

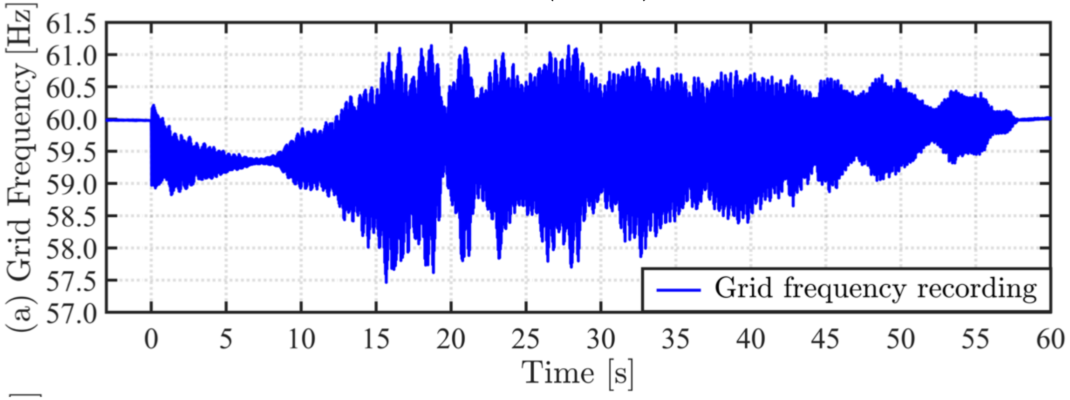
- **What do SSOs depend on?**
  - **Network state:** impedance, SCR, topology, compensation level
  - **Control configuration:** PLL dynamics, outer/plant controllers, GFL vs GFM
  - **Operating point:** power flow direction, voltage setpoints, dispatch

Understanding SSOs: What we know

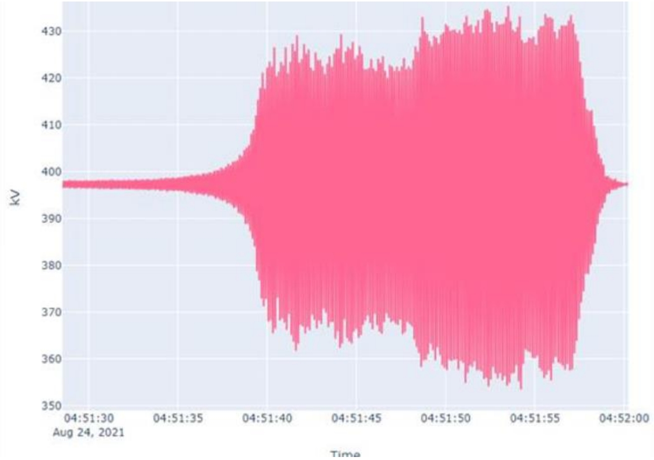
- **Hopf bifurcation** as the onset mechanism
  - SSOs emerge through Hopf bifurcations.
  - This means **linearized small-signal models are sufficient** to capture the transition to instability.

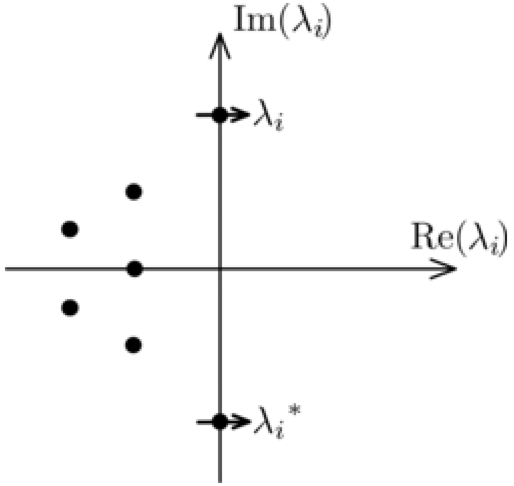


Hawaii (2021)



Scotland (2021)





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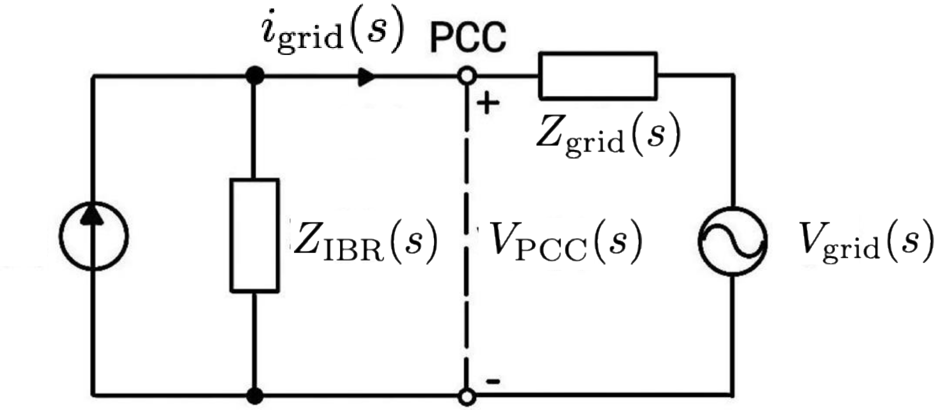
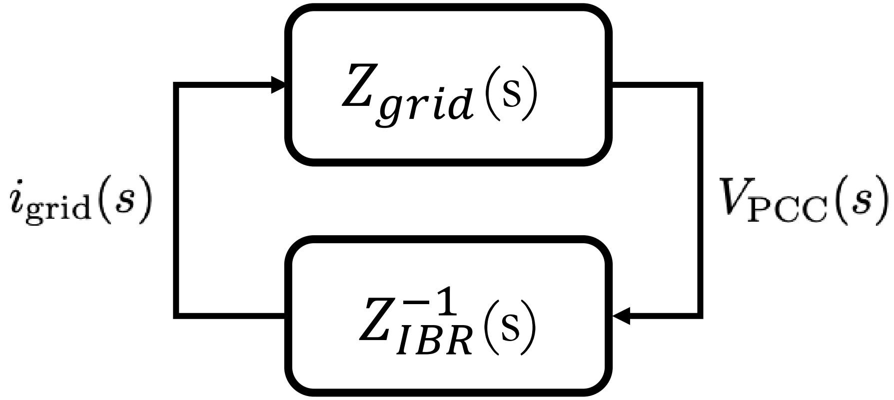


- Impedance models **can capture SSOs**
  - At the Point of Interconnection, stability can be analyzed by comparing inverter and grid impedances.



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

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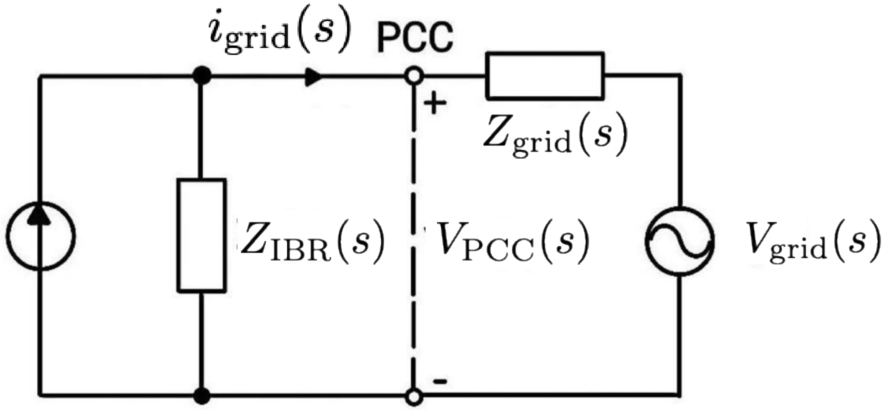
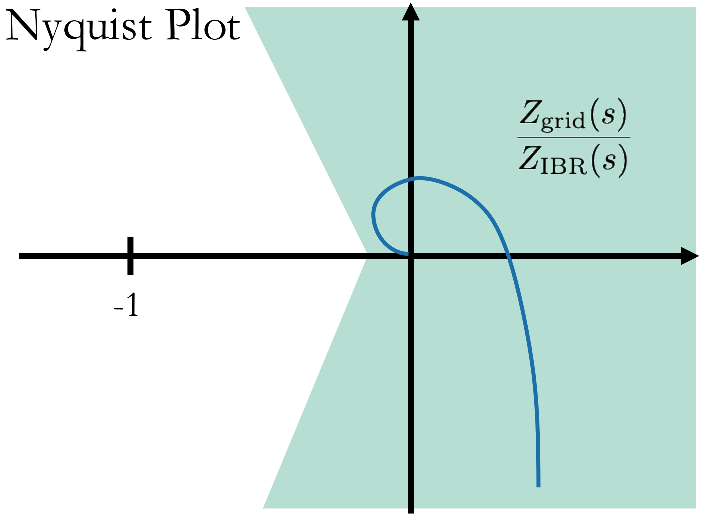


- Impedance models **can capture SSOs**
  - At the Point of Interconnection, stability can be analyzed by comparing inverter and grid impedances.
  - **Nyquist loop-gain criterion** $L(s) = \frac{Z_{grid}(s)}{Z_{IBR}(s)}$ explains why weak grids (high Z_{grid}) are more prone to instability.



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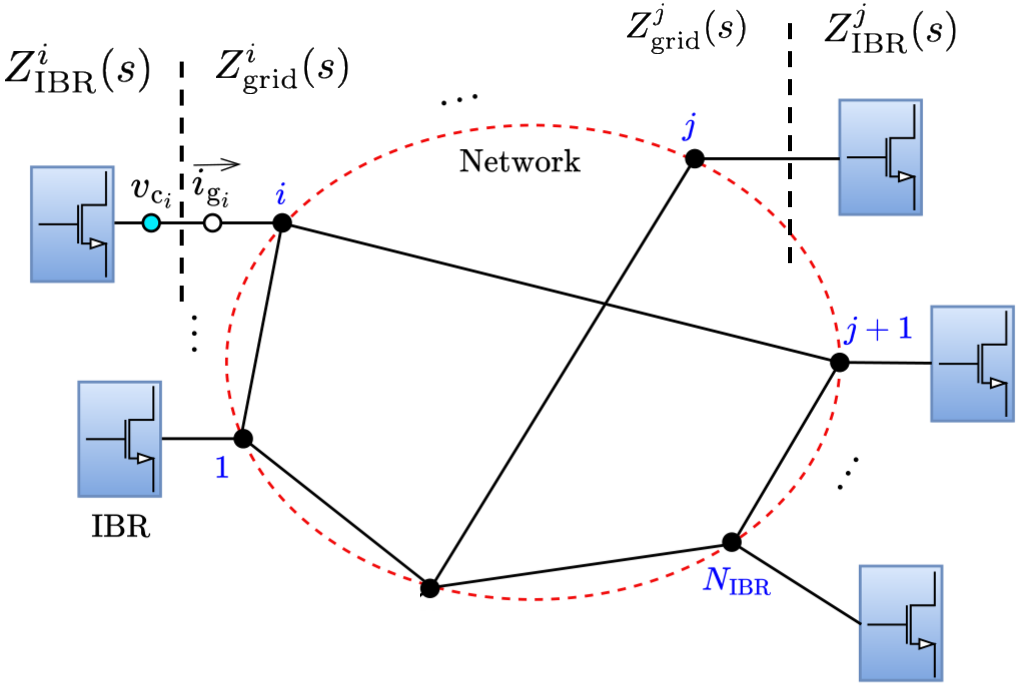
Challenges of Impedance Stability Analysis

- 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

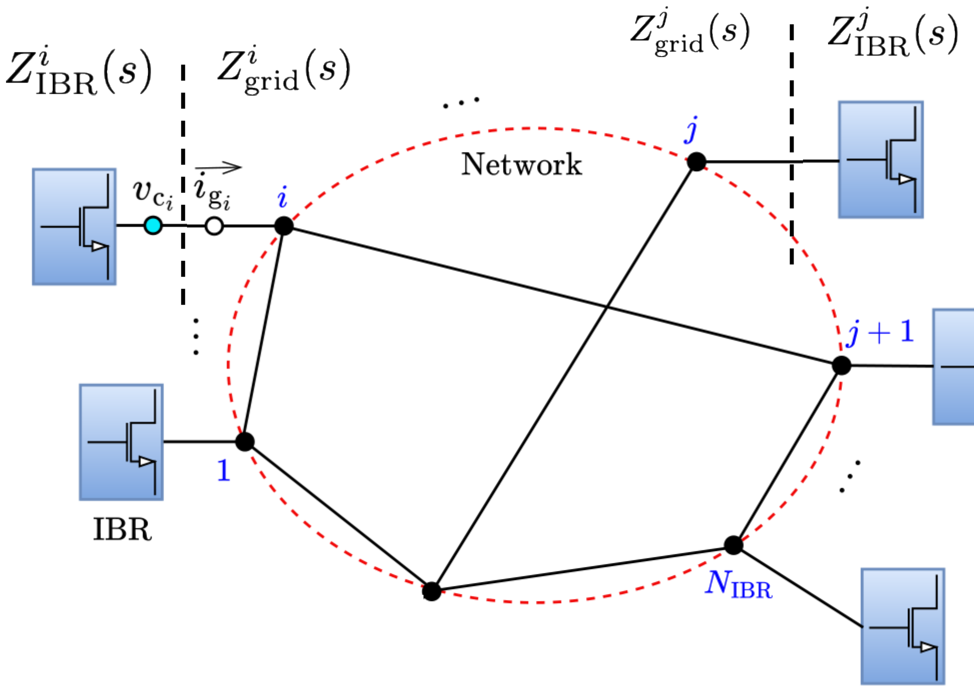


$$Z^i_{\mathrm{grid}}(s) \neq Z^j_{\mathrm{grid}}(s)$$

Robust, Decentralized Small-Signal Analysis

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

- **Key properties:**
  - Requires individual tests on Z^i_{IBR}
  - Handles variation of Z^i_{IBR}
  - Characterizes valid grid operating conditions (P_{net}, Q_{net})
  - Trade-off conservativeness between operating conditions and IBR dynamic constraints



[TCNS 19] Pates, M. Robust Scale Free Synthesis for Frequency Regulation in Power Systems. **IEEE TCNS 2019**
[GM 24] Siahaan, M, Geng, Decentralized Stability Criteria for Grid-Forming Control in Inverter-Based Power Systems **PES-GM 2024**
[PwrUP 26] Wang, Chatterjee, Geng, Pates, M "Decentralized Stability Certificates for Small-Signal Stability in IBR-Dominated Grids: The Role of Reactive Power." **in preparation**

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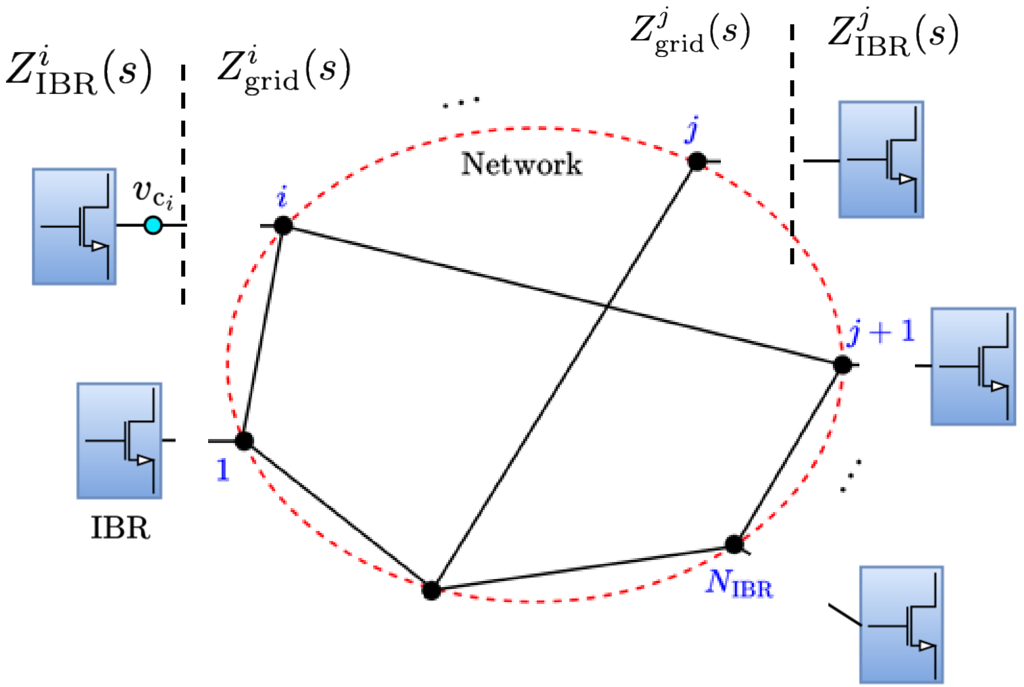

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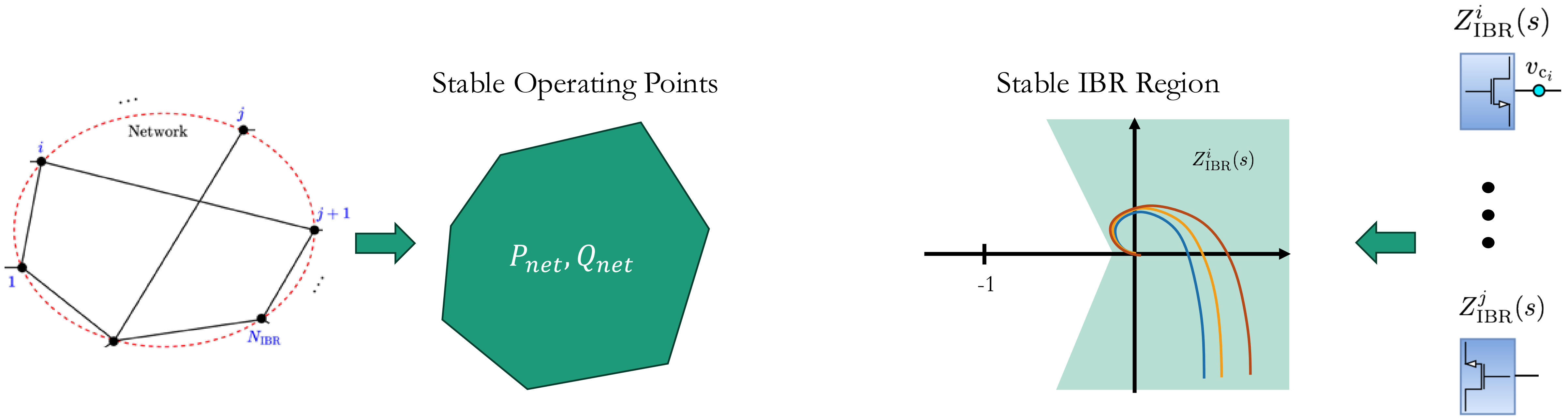

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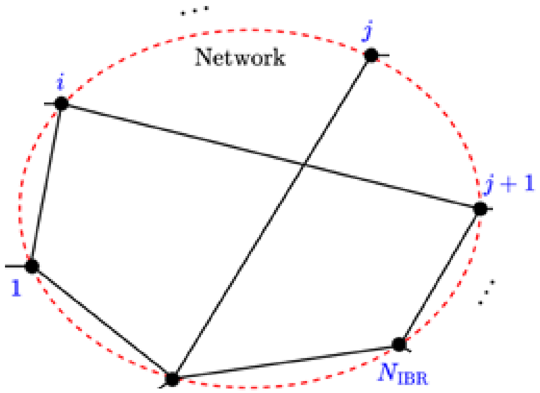
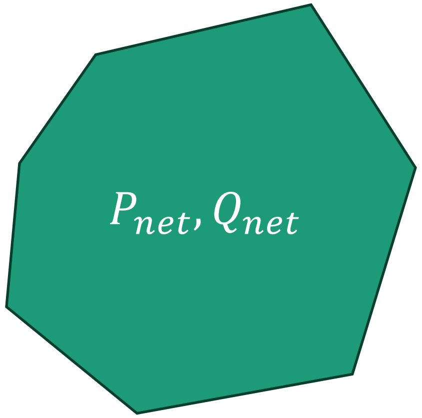
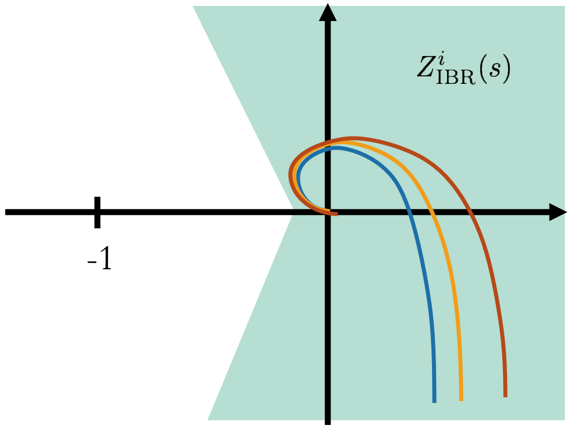
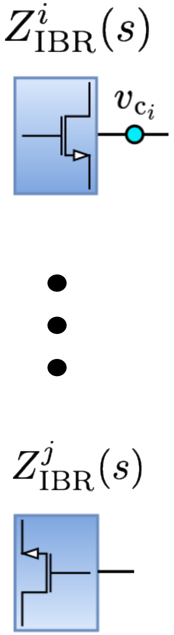


Stable Operating Points



Stable IBR Region





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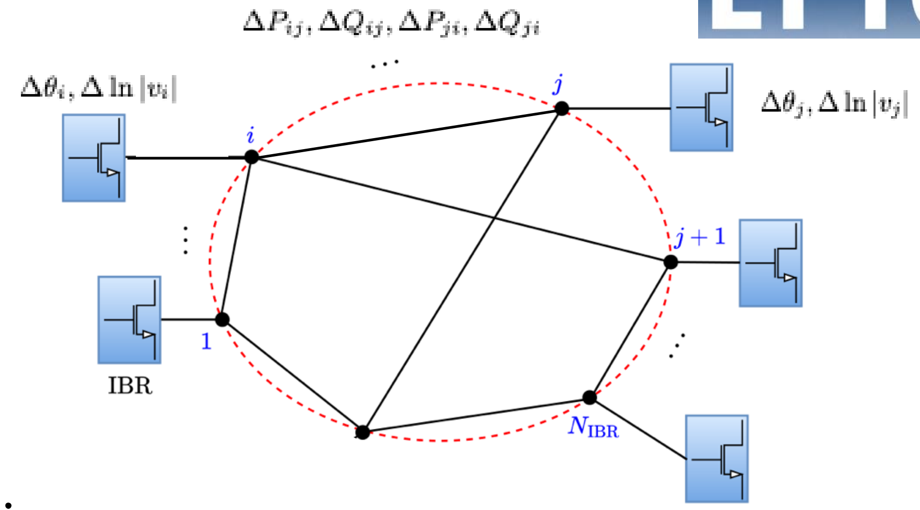
Power System Model

- **Multi-converter transmission system**
  - Lossless inductive lines $b_{ij} = \frac{1}{L_{ij}\omega_0}$
  - Linearized power and log-polar coordinates
    - $\Delta P_{ij}, \Delta Q_{ij}, \Delta \ln|v_i|, \Delta\theta_i, \Delta\ln|v_j|, \Delta\theta_j$
  - Static line model

- **IBR model:**
  - GFM converter with filtered droop control
  - Internal converter dynamics are neglected (time-scale separation)
  - Linearize power and log-polar coordinates
    - $\Delta P_i, \Delta Q_i, \Delta\ln|v_i|, \Delta\theta_i$



Static Line

$$\begin{bmatrix}\Delta P_{ij}\\ \Delta Q_{ij}\\ \Delta P_{ji}\\ \Delta Q_{ji}\end{bmatrix} = \begin{bmatrix} J_{ii} & J_{ij}\\ J_{ji} & J_{jj}\end{bmatrix}\begin{bmatrix}\Delta\theta_i\\ \Delta\ln|v_i|\\ \Delta\theta_j\\ \Delta\ln|v_j|\end{bmatrix}$$

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

$$J_{ij} := b_{ij}|v_i||v_j|\begin{bmatrix}-\cos\theta_{ij} & \sin\theta_{ij}\\ -\sin\theta_{ij} & -\cos\theta_{ij}\end{bmatrix}$$

GFM IBR

$$\begin{bmatrix}\Delta\theta_i\\ \Delta\ln|v_i|\end{bmatrix} = G_i(s)\begin{bmatrix}-\Delta P_i\\ -\Delta Q_i\end{bmatrix}$$

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

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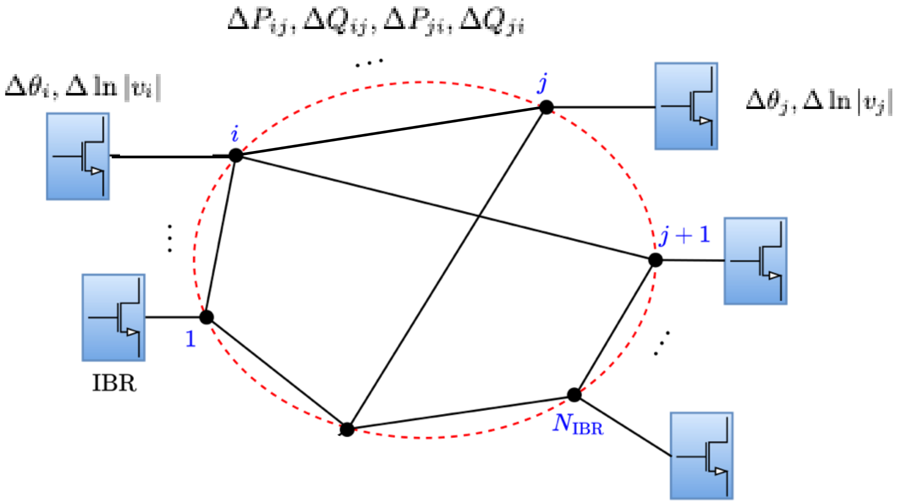
State Dependent Decentralized Certificate



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Theorem (informal):

The network interconnection is stable whenever one can find scalars $d_{ij} \geq 0$ satisfying:

Network State Condition: For all transmission lines

$$\left(\frac{Q_{ij}-Q_{ji}}{b_{ij}|v_i||v_j|}\right)^2 \leq \left(\sqrt{\left(\frac{Q_{ij}-Q_{ji}}{b_{ij}|v_i||v_j|}\right)^2+4}+\frac{d_{ij}}{b_{ij}|v_i||v_j|}\right)^2 - \frac{2}{\cos(\theta_{ij})}\left(\sqrt{\left(\frac{Q_{ij}-Q_{ji}}{b_{ij}|v_i||v_j|}\right)^2+4}+\frac{d_{ij}}{b_{ij}|v_i||v_j|}\right)$$

IBR Constraint: For all IBRs

$$\kappa_i k_{q,i} < 1, \qquad \kappa_i := \sum_{j:\, i\sim j} d_{ij}.$$

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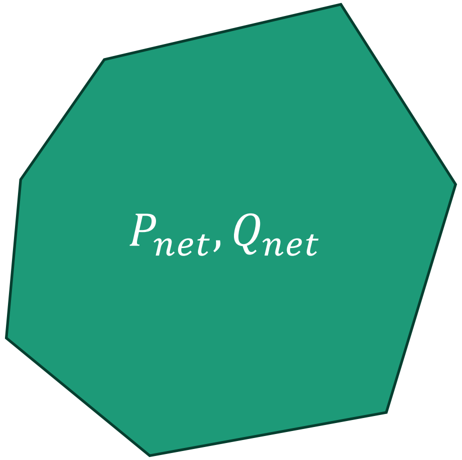
Trade-off: Robustness vs Efficiency

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

Stable Operating Points



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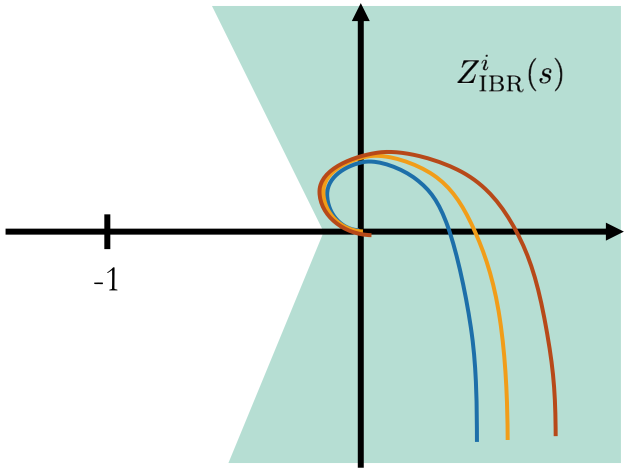

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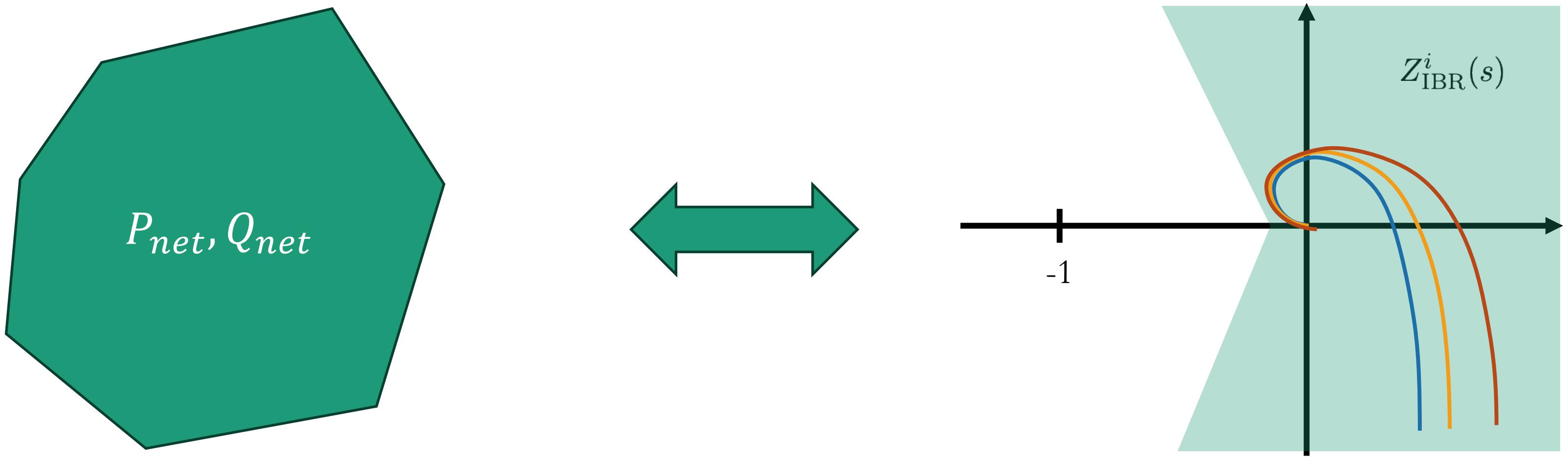
Stable Operating Points | Stable IBR Region



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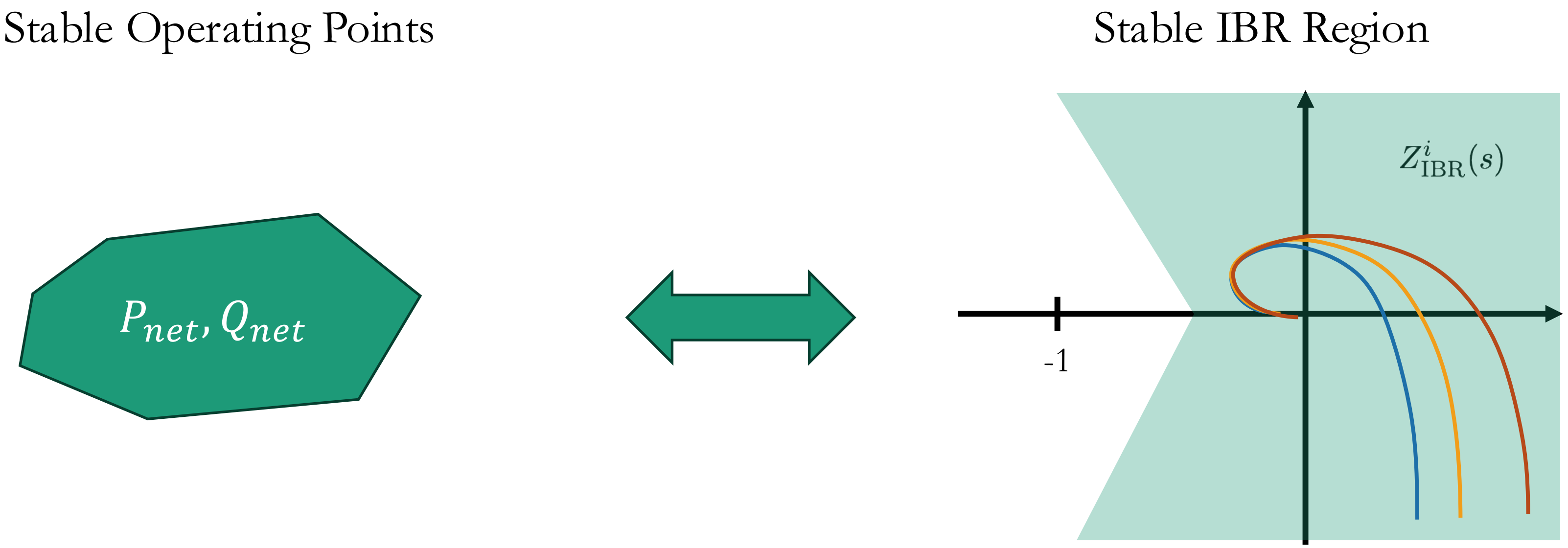

Network State Condition: For all transmission lines

$$\left(\frac{Q_{ij}-Q_{ji}}{b_{ij}|v_i||v_j|}\right)^2 \leq \left(\sqrt{\left(\frac{Q_{ij}-Q_{ji}}{b_{ij}|v_i||v_j|}\right)^2+4}+\frac{d_{ij}}{b_{ij}|v_i||v_j|}\right)^2 - \frac{2}{\cos(\theta_{ij})}\left(\sqrt{\left(\frac{Q_{ij}-Q_{ji}}{b_{ij}|v_i||v_j|}\right)^2+4}+\frac{d_{ij}}{b_{ij}|v_i||v_j|}\right)$$

IBR Constraint: For all IBRs

$$\kappa_i\, k_{q,i} < 1, \qquad \kappa_i := \sum_{j:\, i\sim j} d_{ij}.$$

[TCNS 19] Pates, M. Robust Scale Free Synthesis for Frequency Regulation in Power Systems. **IEEE TCNS 2019**
[GM 24] Siahaan, M, Geng, Decentralized Stability Criteria for Grid-Forming Control in Inverter-Based Power Systems **PES-GM 2024**
[PwrUP 26] Wang, Chatterjee, Geng, Pates, M "Decentralized Stability Certificates for Small-Signal Stability in IBR-Dominated Grids: The Role of Reactive Power." **in preparation**

Trade-off: Robustness vs Efficiency

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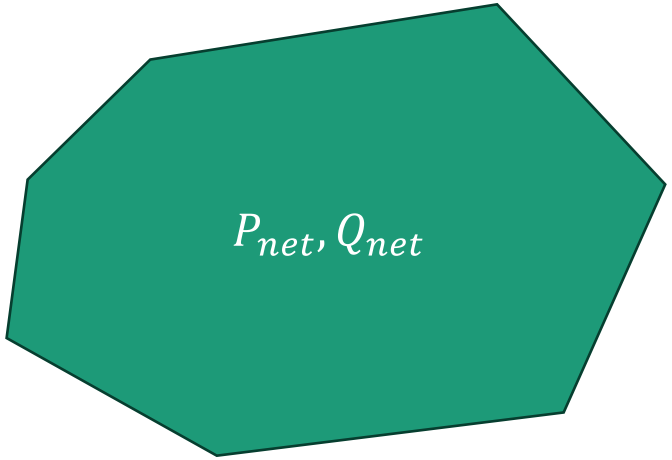
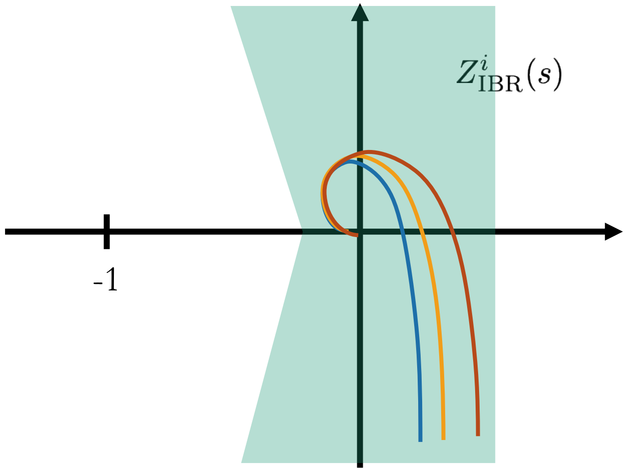
Stable Operating Points



Stable IBR Region



Network State Condition: For all transmission lines

$$\left(\frac{Q_{ij}-Q_{ji}}{b_{ij}|v_i||v_j|}\right)^2 \leq \left(\sqrt{\left(\frac{Q_{ij}-Q_{ji}}{b_{ij}|v_i||v_j|}\right)^2+4}+\frac{d_{ij}}{b_{ij}|v_i||v_j|}\right)^2-\frac{2}{\cos(\theta_{ij})}\left(\sqrt{\left(\frac{Q_{ij}-Q_{ji}}{b_{ij}|v_i||v_j|}\right)^2+4}+\frac{d_{ij}}{b_{ij}|v_i||v_j|}\right)$$

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Thanks!