Reliability Challenges in IBR-Rich Power Grids

JOHNS HOPKINS UNIVERSITY

Sijia Geng and Enrique Mallada

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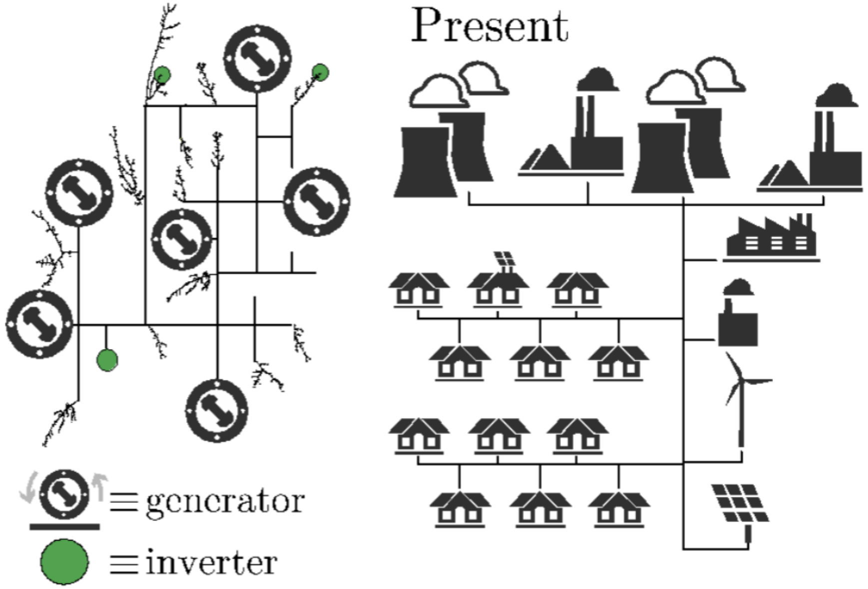
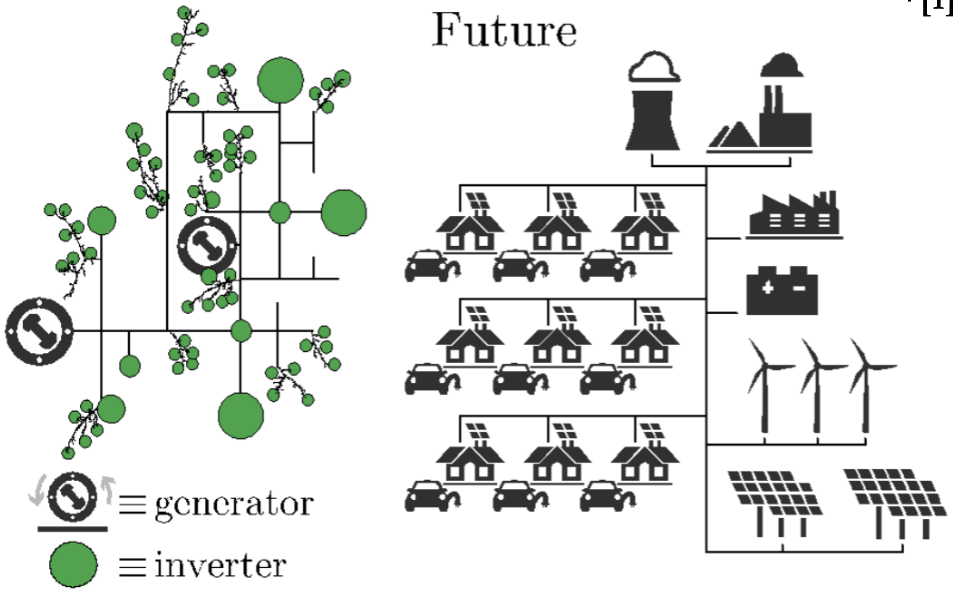
The Future Grid

*[1]





Present grid

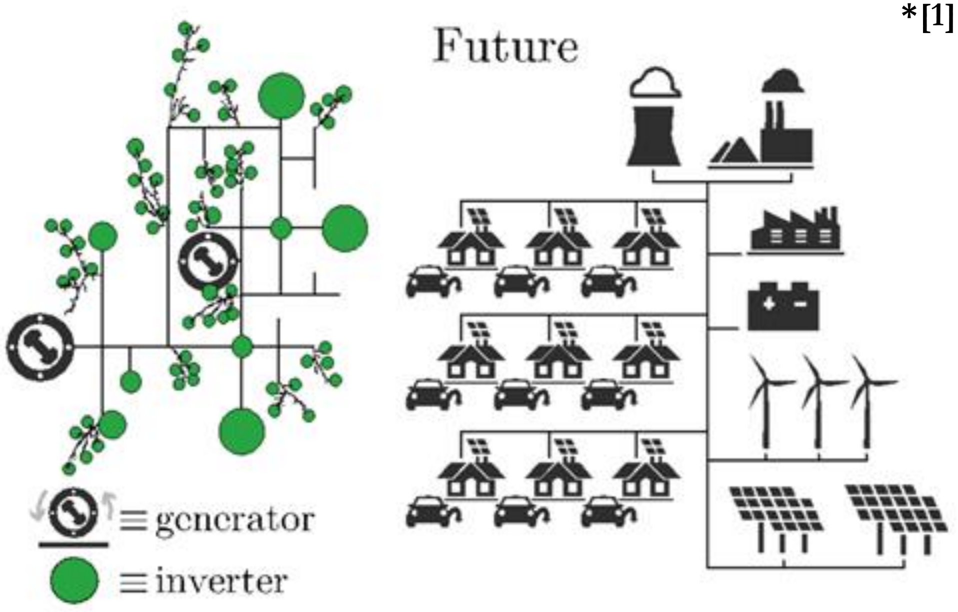
- dispatchable generation
- high inertial response
- strong voltage support
- well known physics

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)

Selected 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

Two Core Challenges

- **Mitigation of IBR-induced small-signal instabilities**
  - Decentralized Stability Analysis
  - Efficiency-Robustness Trade-offs

- **Reliable operation during large-signal disturbance**
  - Safety-critical nonlinear control design

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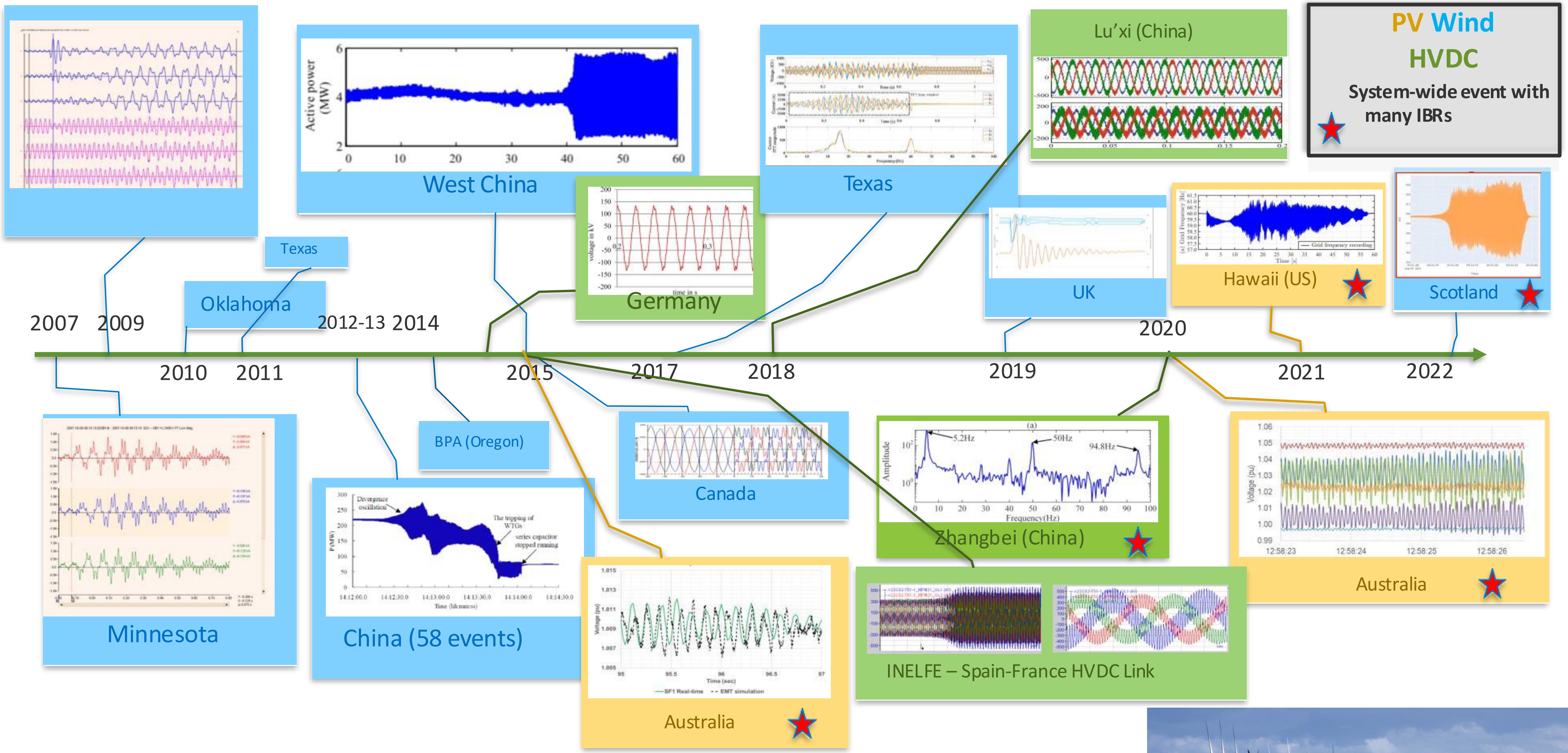
Oscillation Events Involving IBRs



Source: NREL, Shahil Shah

IBR-induced Sub Synchronous Oscillations

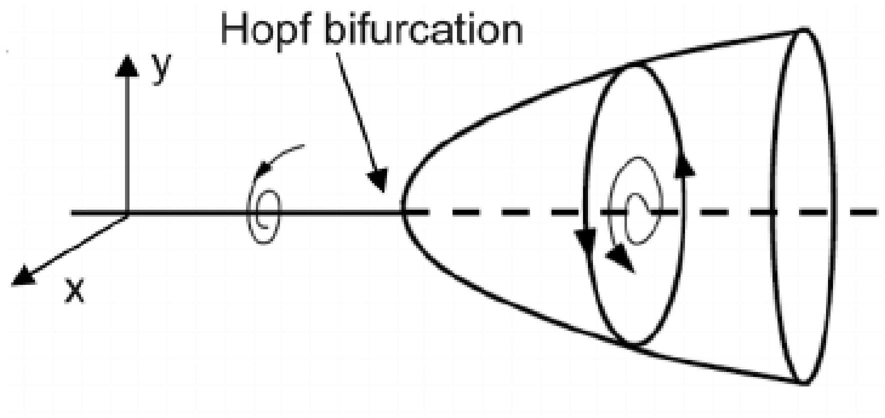
- **When do SSOs occur?**
  - **Series-compensated corridors** (SSCI)
  - **Weak grids** (low SCR, high impedance)
  - Clusters of **IBRs in remote areas**

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

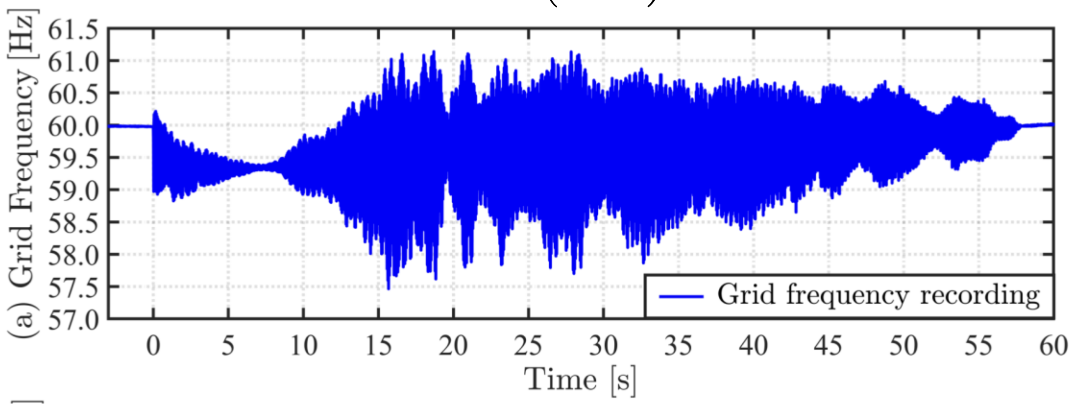
- **What do SSOs depend on?**
  - **Network state:** impedance, SCR, topology, compensation level
  - **Control configuration:** PLL dynamics, outer/plant controllers, GFL vs GFM
  - **Operating point:** power flow direction, voltage setpoints, dispatch

Understanding SSOs: What we know

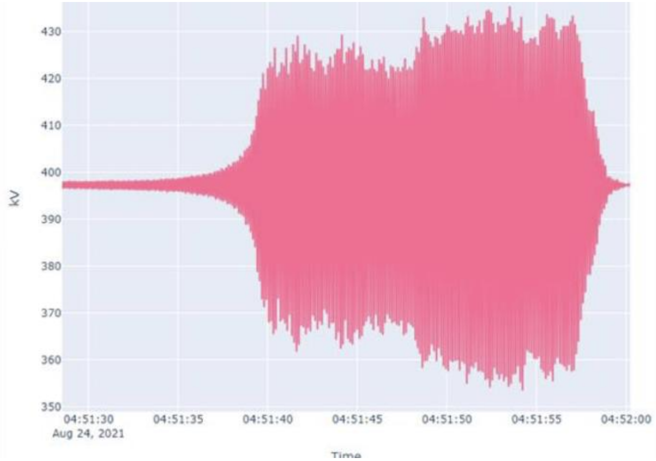
- **Hopf bifurcation** as the onset mechanism
  - SSOs emerge through Hopf bifurcations.
  - This means **linearized small-signal models are sufficient** to capture the transition to instability.

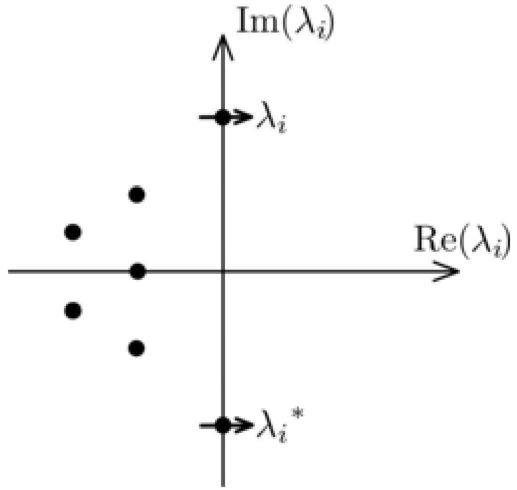


Hawaii (2021)



Scotland (2021)





Understanding SSOs: What we know and can do

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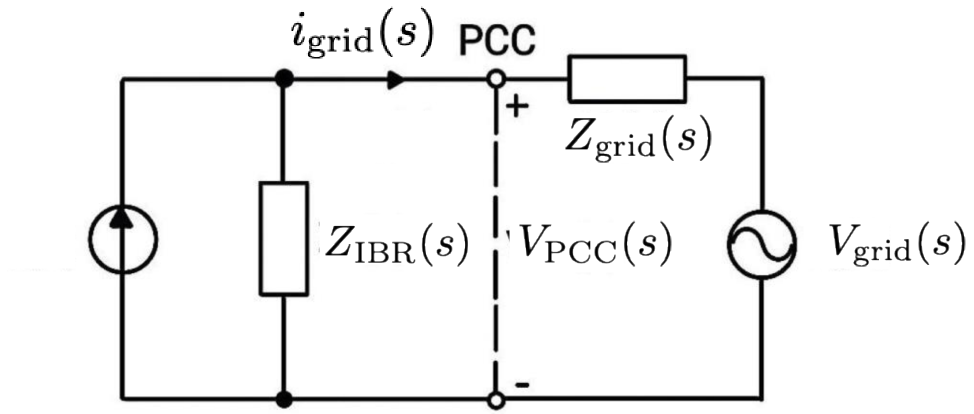
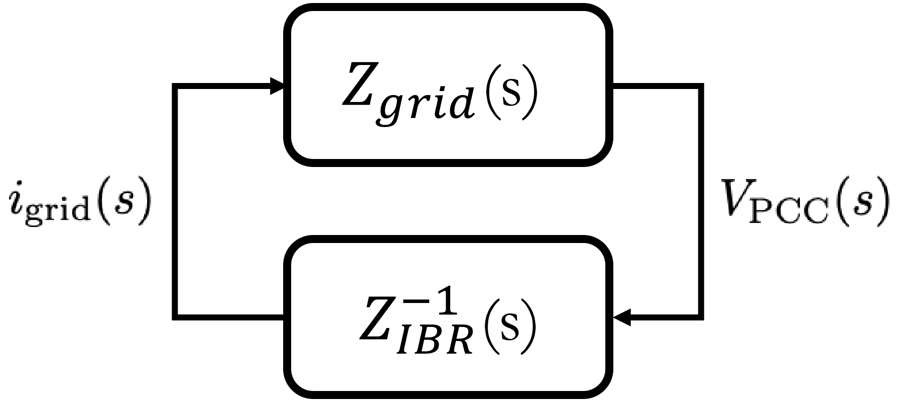


- Impedance models **can capture SSOs**
  - At the Point of Interconnection, stability can be analyzed by comparing inverter and grid impedances.



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

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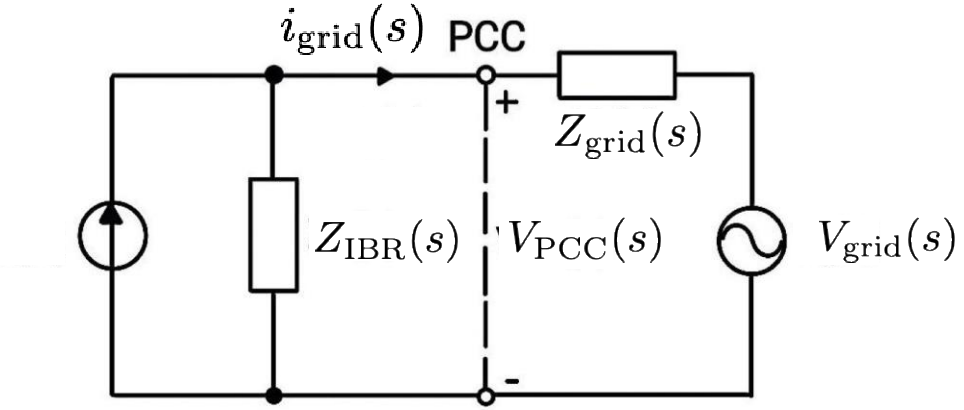
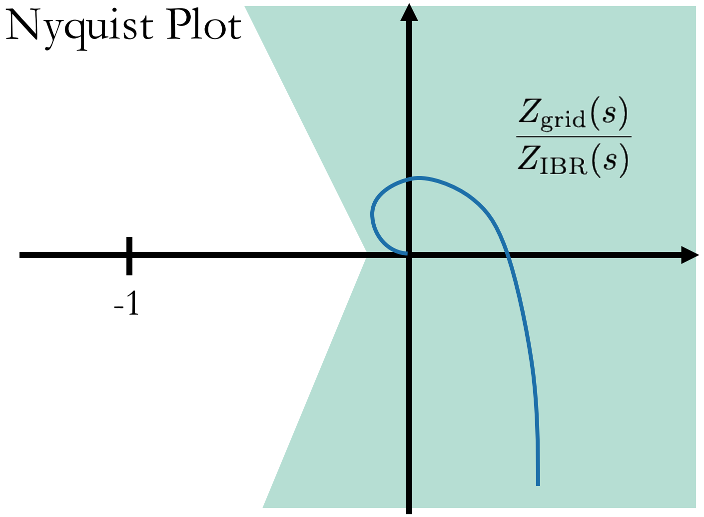


- Impedance models **can capture SSOs**
  - At the Point of Interconnection, stability can be analyzed by comparing inverter and grid impedances.
  - **Nyquist loop-gain criterion** $L(s) = \frac{Z_{grid}(s)}{Z_{IBR}(s)}$ explains why weak grids (high Z_{grid}) are more prone to instability.



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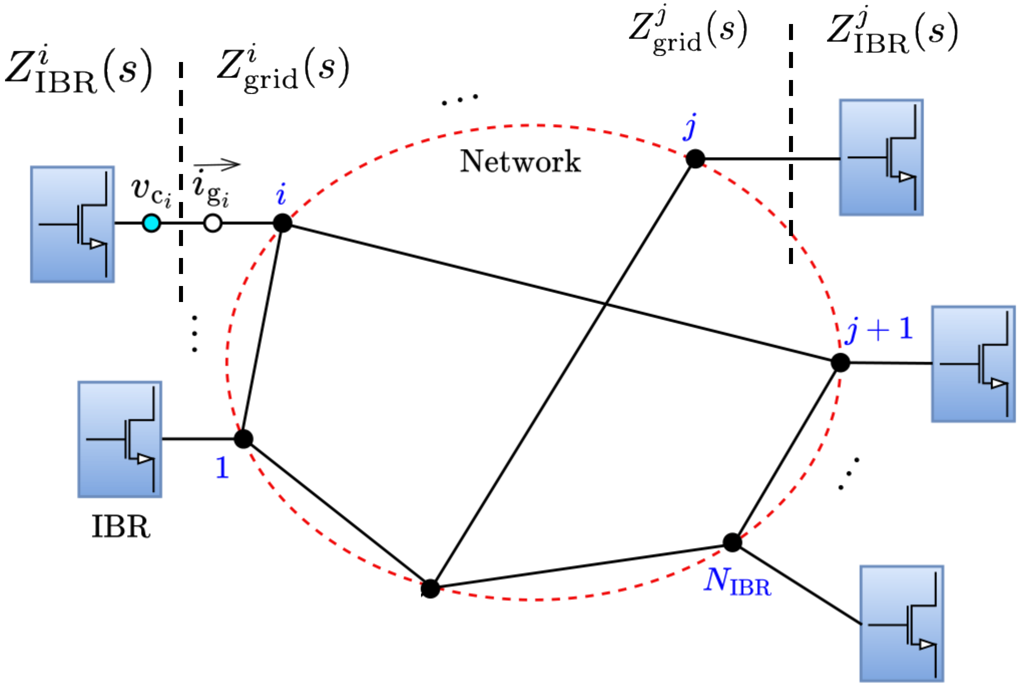
Challenges of Impedance Stability Analysis

- Z^{i}_{IBR} depends on:
  - Vendor Technology
  - Setpoints $(P_i\ , Q_i)$

- Z^{i}_{grid} depends on:
  - Location where it is measured
  - Network Topology
  - Power Flows (P_{net}, Q_{net})
  - Other connected devices

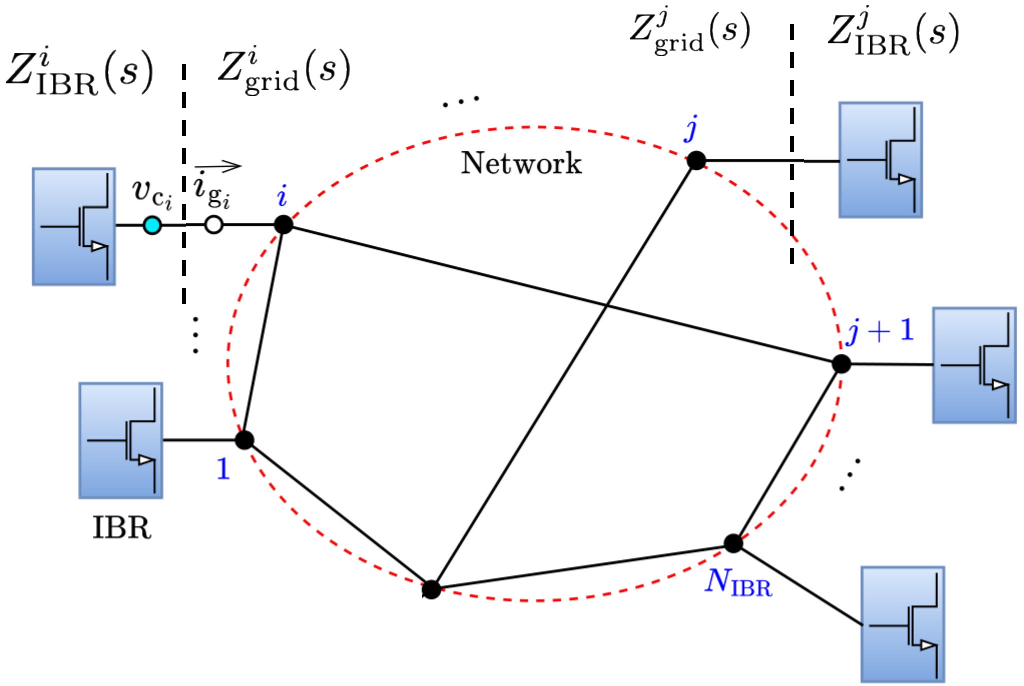


$$Z^{i}_{\mathrm{grid}}(s) \neq Z^{j}_{\mathrm{grid}}(s)$$

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_{IBR}^{i}
  - Handles variation of Z_{IBR}^{i}
  - 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**
PESGM 24] Siahaan, M, Geng, Decentralized Stability Criteria for Grid-Forming Control in Inverter-Based Power Systems **PES-GM 2024**

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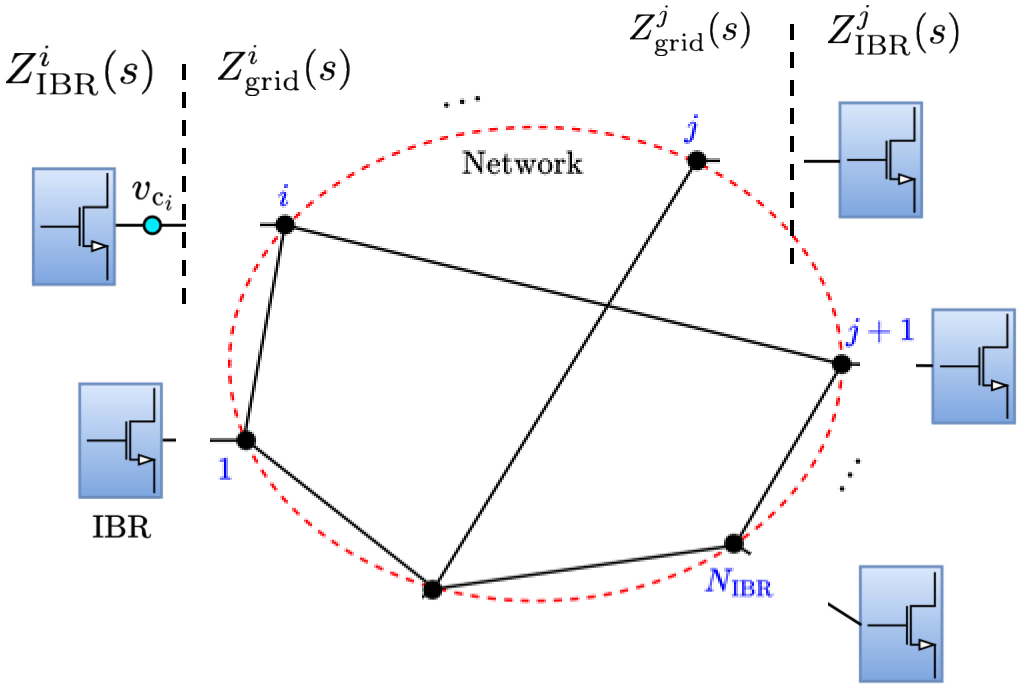

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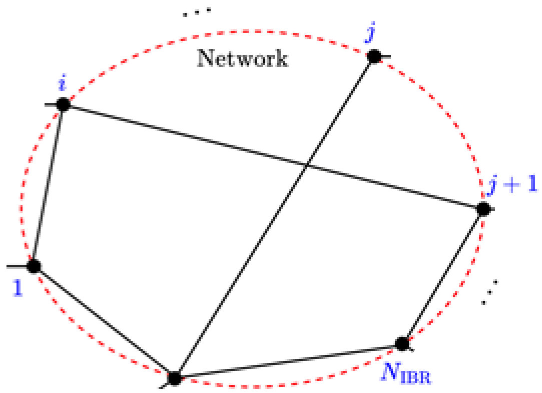
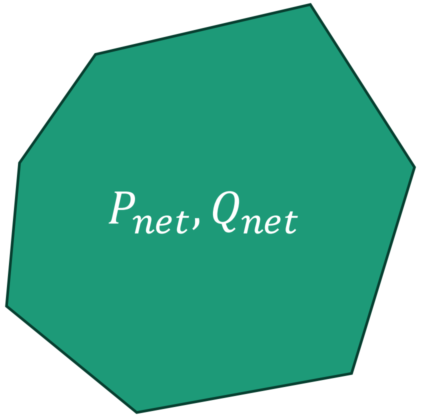
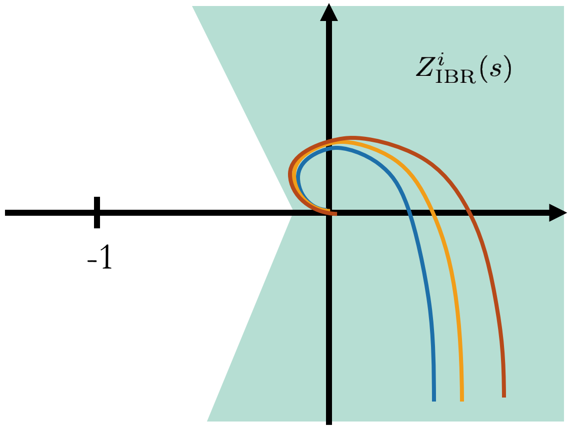
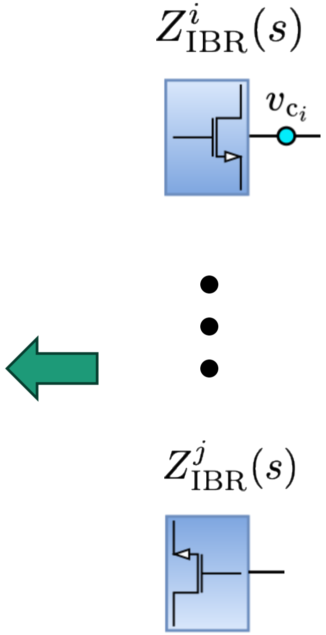


Stable Operating Points



Stable IBR Region





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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.

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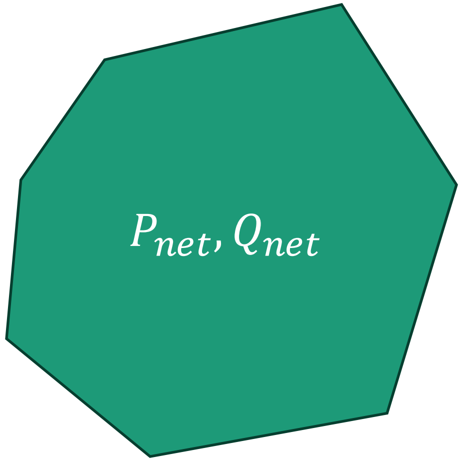

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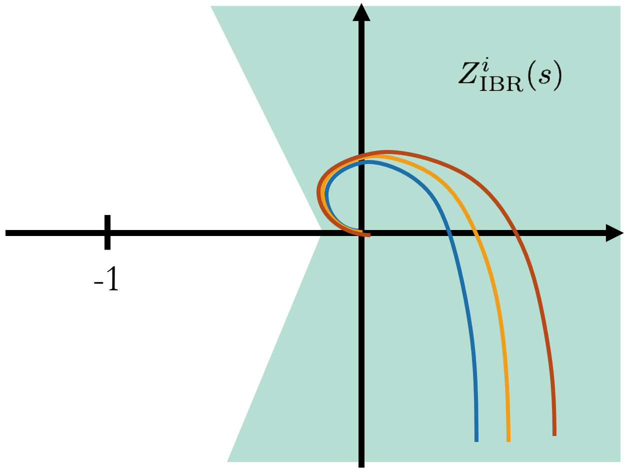

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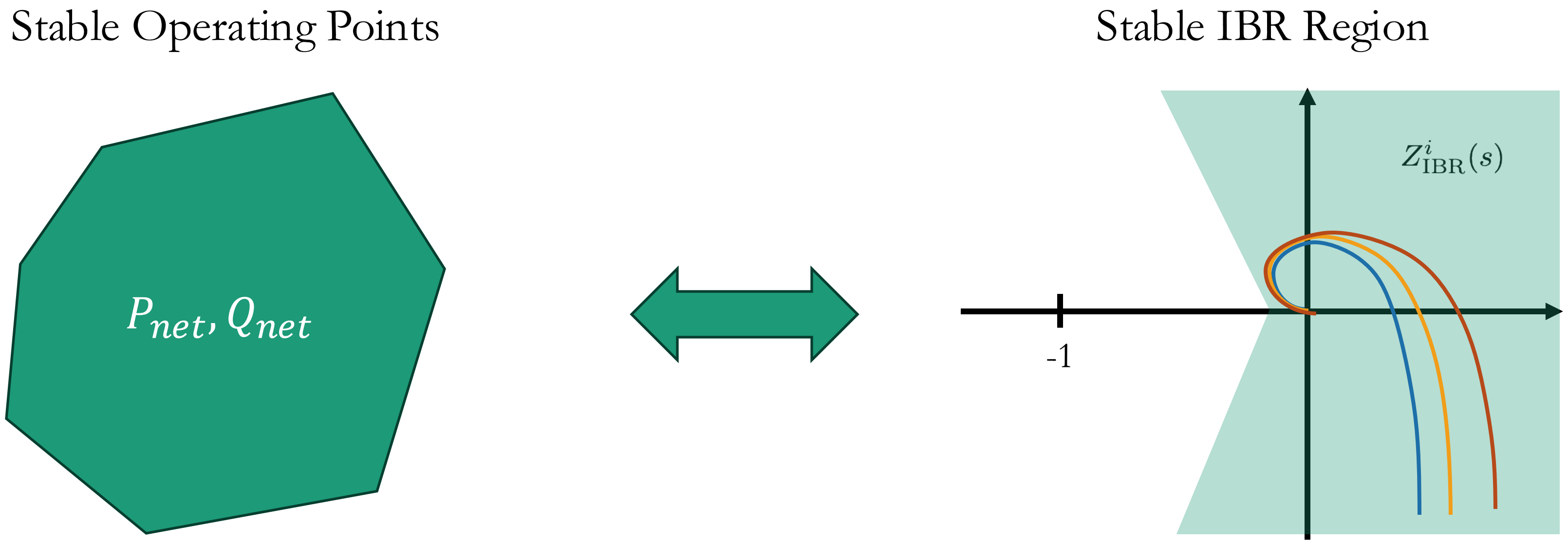

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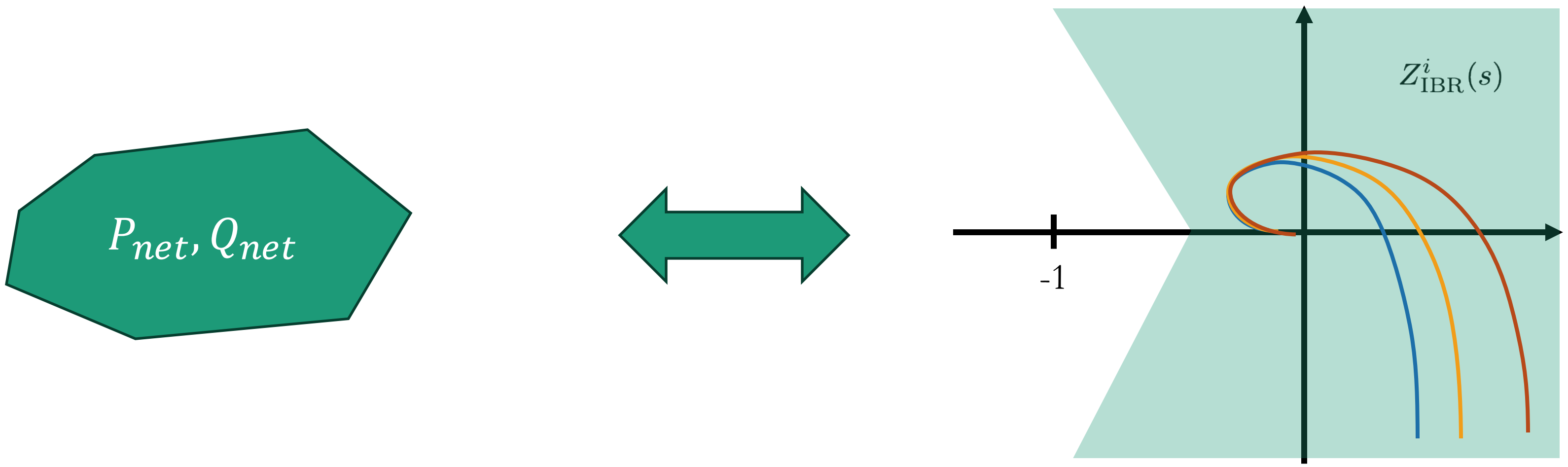

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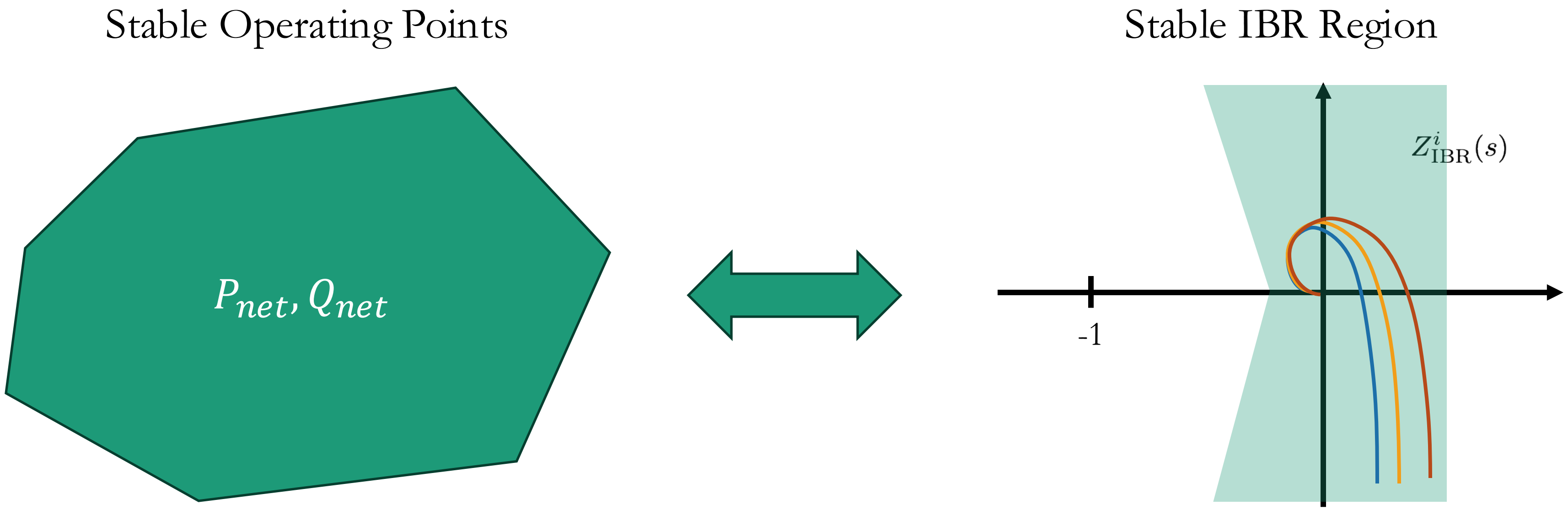

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What We Know — and What's Still Open

✅ What's Known

- **Linear small-signal models are sufficient**
  - SSOs emerge via Hopf bifurcations → linearized models around operating points capture instability onset.
- **Accuracy over dynamic frequencies is sufficient**
  - Models only need to capture inverter behavior around sub-synchronous frequency ranges of interest.
- **Impedance-based margins are valid and certifiable**
  - Frequency-domain criteria define meaningful stability margins and can be applied using **black-box models**, preserving vendor IP.

❓ Many Questions Remain Open

- **Generalizing analysis for more realistic models**
  - Current analysis introduces simplifying assumptions that need to be removed.
- **How should dynamic testing be standardized?**
  - What scan conditions (frequency range, injection size, operating points) should be required?
- **How do we account for dispatch and operating point variability?**
  - Do we need impedance envelopes? Adaptive margins? Parametric certificates?
- **Should compliance be static or operationally adaptive?**
  - Should dispatch constraints or tuning flexibility be part of certification?
- **How do we balance robustness and flexibility?**
  - What is the minimal stability margin that still allows meaningful operational freedom?

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Two Core Challenges

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- **Reliable operation during large-signal disturbance**
  - Safety-critical nonlinear control design

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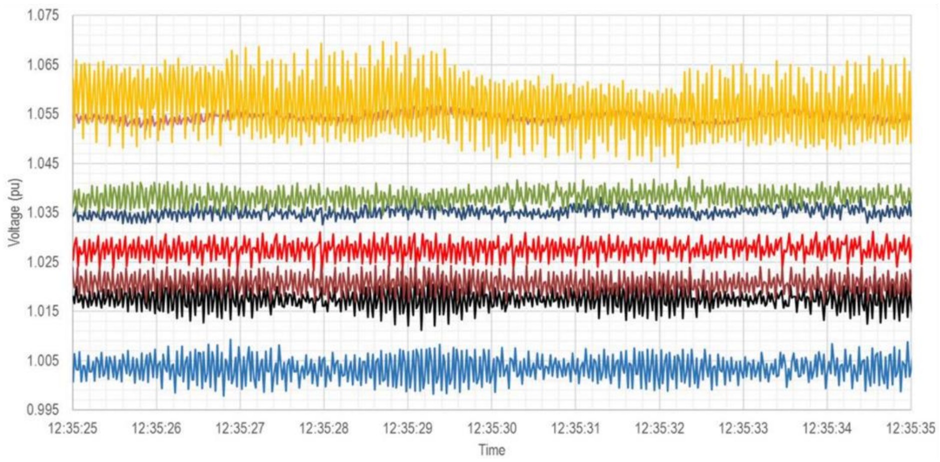
Why large-signal dynamics matter?



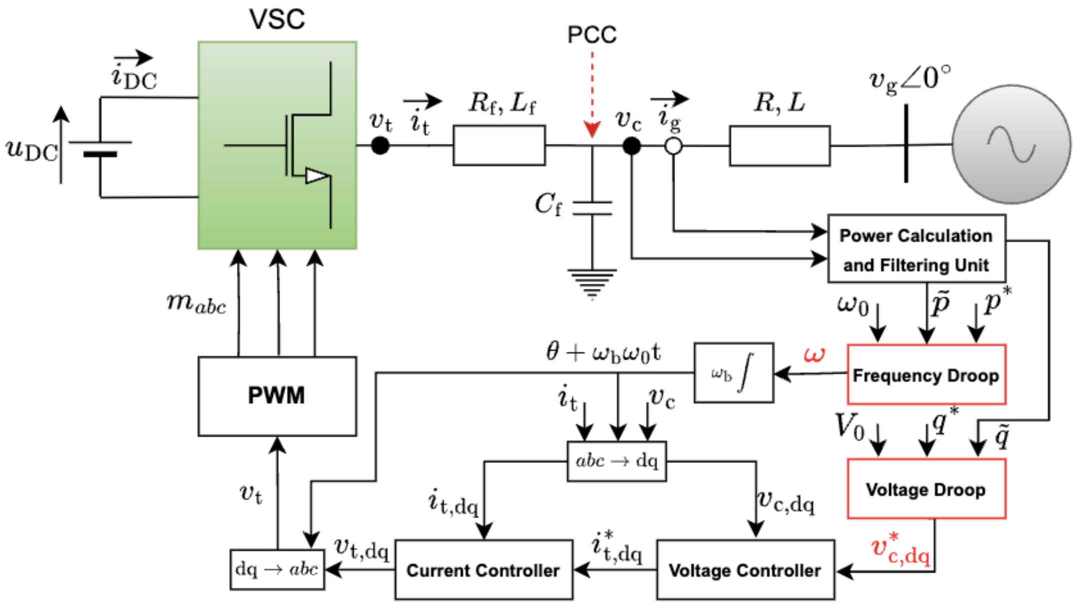
- Nonlinearity and discrete events are ubiquitous in power systems. Accurate handling of them is vital to have any chance of replicating complex power system behavior.
- Large-signal dynamics is essential for reliable operation of inverter-dominated power systems.
    - Higher complexity, nonlinearity, and variability.
    - Enables stability and safety under **faults, grid disturbances, and transients**.

Control Objectives versus Safety?

- A framework to combine "control objectives" and "safety"[1][2]:
  - Design a **nominal controller** to meet control objectives (GFM).
  - How can we encode "safety" into that controller?
  - Design a **safety filter** to ensure safety.

[1] Ames et. al. (2014), Control Barrier Function based Quadratic Programs with Application to Adaptive Cruise Control (CDC 2014)
[2] Kundu, **Geng**, et. al. (2019), Distributed barrier certificates for safe operation of inverter-based microgrids (ACC 2019)

Droop-Based Grid-Forming Inverter Model



d-q component dynamics

$$\dot{v}_{c,d}(t) = \omega_b\omega(t)v_{c,q}(t) + \frac{\omega_b}{C_f}\left(i_{t,d}(t) - i_{g,d}(t)\right)$$

$$\dot{v}_{c,q}(t) = -\omega_b\omega(t)v_{c,d}(t) + \frac{\omega_b}{C_f}\left(i_{t,q}(t) - i_{g,q}(t)\right)$$

$$\dot{i}_{t,d}(t) = \omega_b\omega(t)i_{t,q}(t) + \frac{\omega_b}{L_f}\left(v_{t,d}(t) - v_{c,d}(t)\right) - \frac{R_f}{L_f}\omega_b i_{t,d}(t)$$

$$\dot{i}_{t,q}(t) = -\omega_b\omega(t)i_{t,d}(t) + \frac{\omega_b}{L_f}\left(v_{t,q}(t) - v_{c,q}(t)\right) - \frac{R_f}{L_f}\omega_b i_{t,q}(t)$$

$$\dot{i}_{g,d}(t) = \omega_b\omega(t)i_{g,q}(t) + \frac{\omega_b}{L}\left(v_{c,d}(t) - v_{g,d}(t)\right) - \frac{R}{L}\omega_b i_{g,d}(t)$$

$$\dot{i}_{g,q}(t) = -\omega_b\omega(t)i_{g,d}(t) + \frac{\omega_b}{L}\left(v_{c,q}(t) - v_{g,q}(t)\right) - \frac{R}{L}\omega_b i_{g,q}(t)$$

- $v_{c,d}$ and $v_{c,q}$ are controlled variables (voltage at the PCC)
- $v_{t,d}$ and $v_{t,q}$ are control inputs (terminal voltage of the VSC)
- $v_{g,d}$ and $v_{g,q}$ are grid voltage components treated as **exogenous** disturbances
- R, L are **unknown** network elements

Safety-Critical Nonlinear GFM Control

- **Nonlinear backstepping-based** GFM controller that guarantees performance during transients and steady-state:
  - Ensures robust voltage regulation even under **faults**.
  - **Agnostic to grid disturbances** and ensures practical regulation.

Transient Behavior

$$\left(v_{c,d}-v^{\star}_{c,d}\right)^2+\left(i_{t,d}-i^{\star}_{t,d}\right)^2 \leq e^{-2kt}\left(\left(v_{c,d}(0)-v^{\star}_{c,d}(0)\right)^2+\left(i_{t,d}(0)-i^{\star}_{t,d}(0)\right)^2\right)+\frac{\mu_d\left(1+R^2+\|v_{g,d}\|^2_\infty\right)}{kL^2\left(1+e^{z_d(0)}\right)}$$

$$\left(v_{c,q}-v^{\star}_{c,q}\right)^2+\left(i_{t,q}-i^{\star}_{t,q}\right)^2 \leq e^{-2kt}\left(\left(v_{c,q}(0)-v^{\star}_{c,q}(0)\right)^2+\left(i_{t,q}(0)-i^{\star}_{t,q}(0)\right)^2\right)+\frac{\mu_q\left(1+R^2+\|v_{g,q}\|^2_\infty\right)}{kL^2\left(1+e^{z_q(0)}\right)}$$

Steady-state Convergence:

$$\limsup_{t\to+\infty}\left(|i_{t,d}-i^{\star}_{t,d}|\right) \leq \sqrt{2\varepsilon}$$

$$\limsup_{t\to+\infty}\left(|i_{t,q}-i^{\star}_{t,q}|\right) \leq \sqrt{2\varepsilon}$$

$$\limsup_{t\to+\infty}\left(|v_{c,d}-v^{\star}_{c,d}|\right) \leq \sqrt{2\varepsilon}$$

$$\limsup_{t\to+\infty}\left(|v_{c,q}-v^{\star}_{c,q}|\right) \leq \sqrt{2\varepsilon}$$

$\epsilon > 0$ is arbitrary

Convergence inside an **assignable ball** $\sqrt{2\epsilon}$

Safety-Critical Nonlinear GFM Control

- **Control Barrier Function (CBF)–based safety filter** to enforce strict current safety.

Consider

$$\dot{x} = f(x) + g(x)u$$

Safety set

$$\mathcal{C} = \{x \in \mathbb{R}^n \mid h(x) \geq 0\}, \quad h : \mathbb{R}^n \to \mathbb{R}$$

Safety > Control Objectives

$$u^*(x) = \underset{u \in \mathbb{R}^m}{\operatorname{argmin}} \quad \|u - u_{\text{nom}}(x)\|^2$$

$$\text{subject to} \quad L_f h(x) + L_g h(x) u + \gamma h(x) \;\geq\; 0.$$

Simulation Results with Current Limiting

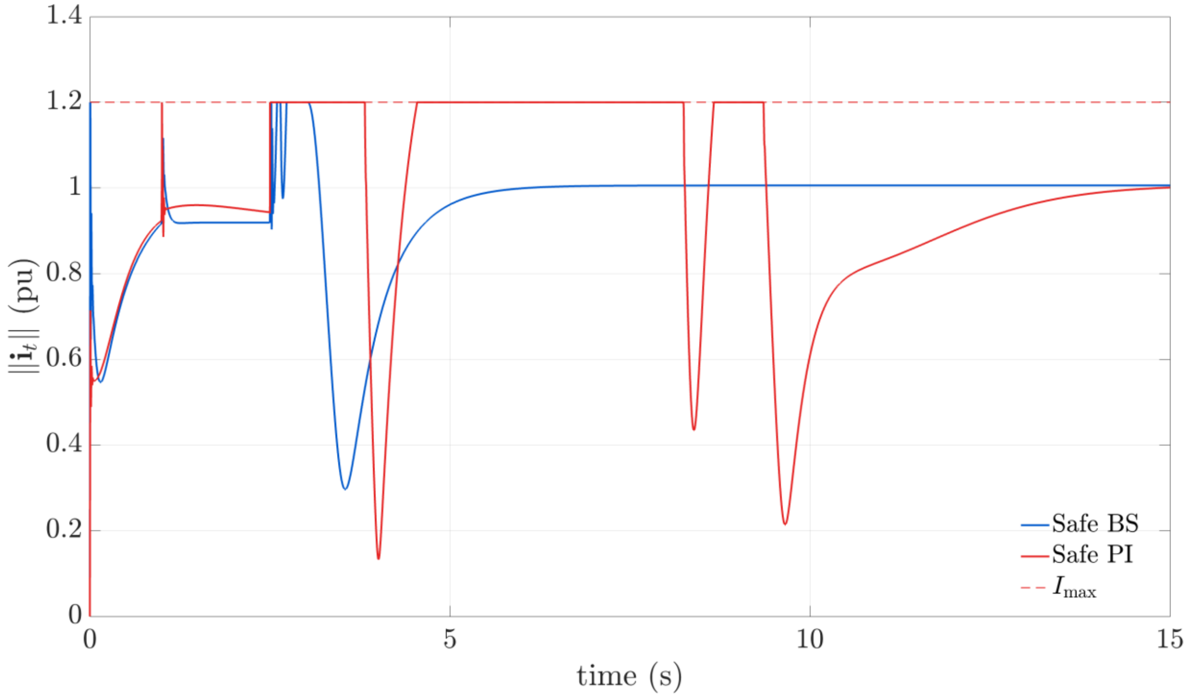


Fig. Magnitude of terminal current $\boldsymbol{i}_t$ of VSC

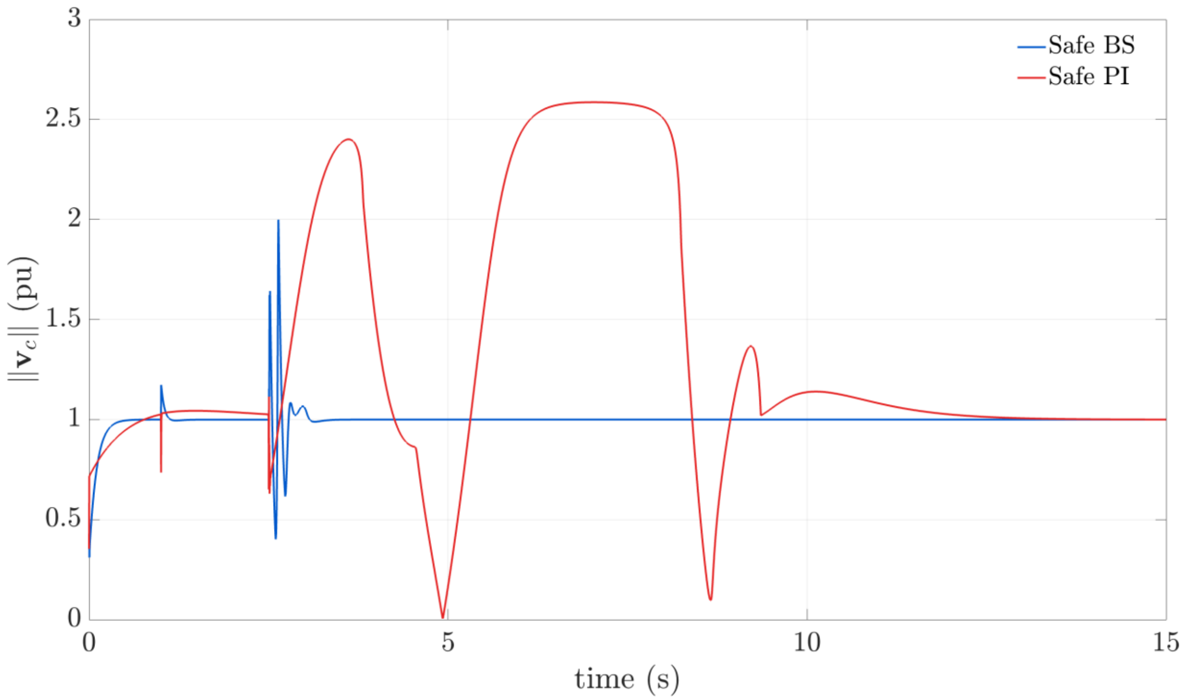
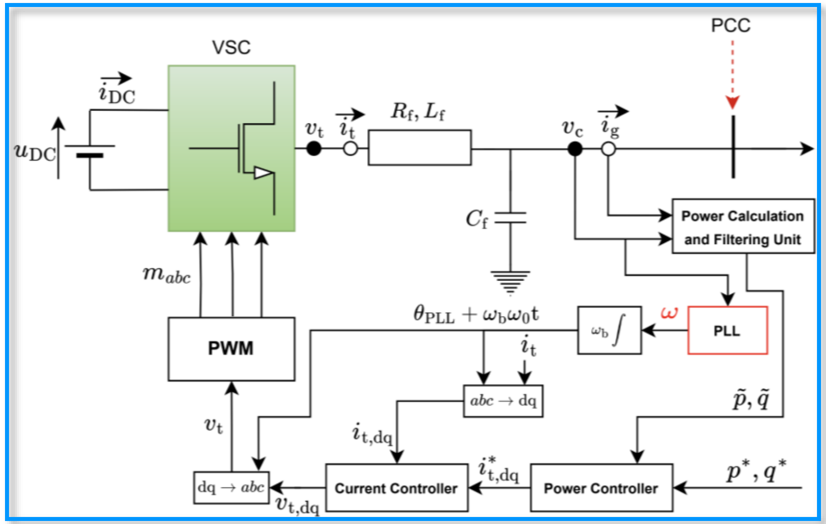


Fig. Voltage $\boldsymbol{v}_c$ at PCC.

Grid-following

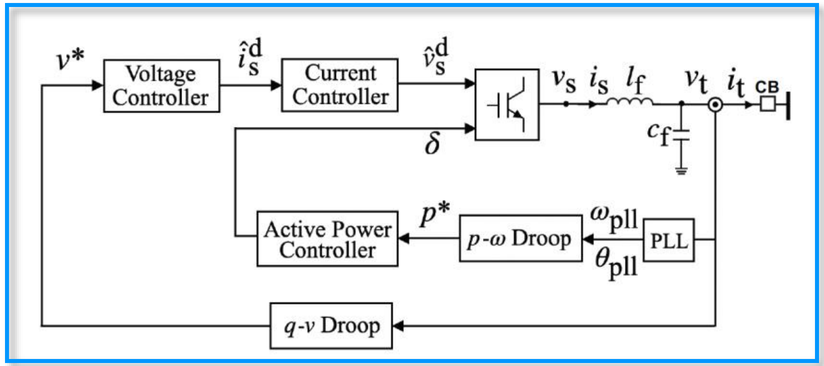
Source: Sushobhan Chatterjee and Sijia Geng. "Voltage Stability of Inverter-Based Systems: Impact of Parameters and Irrelevance of Line Dynamics." *IEEE PowerTech*, 2025.

- 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.

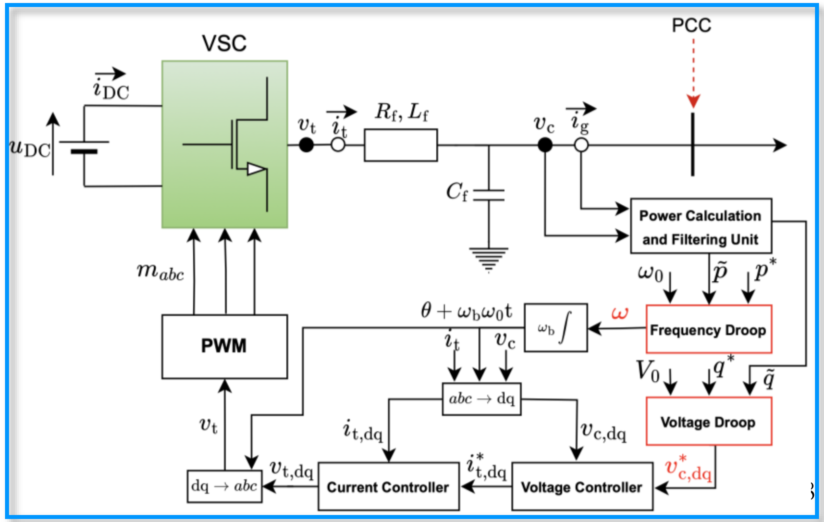


- Unified control: Incorporates both PLL and droop.
- Regulate: Voltage magnitude and active power.

Grid-forming

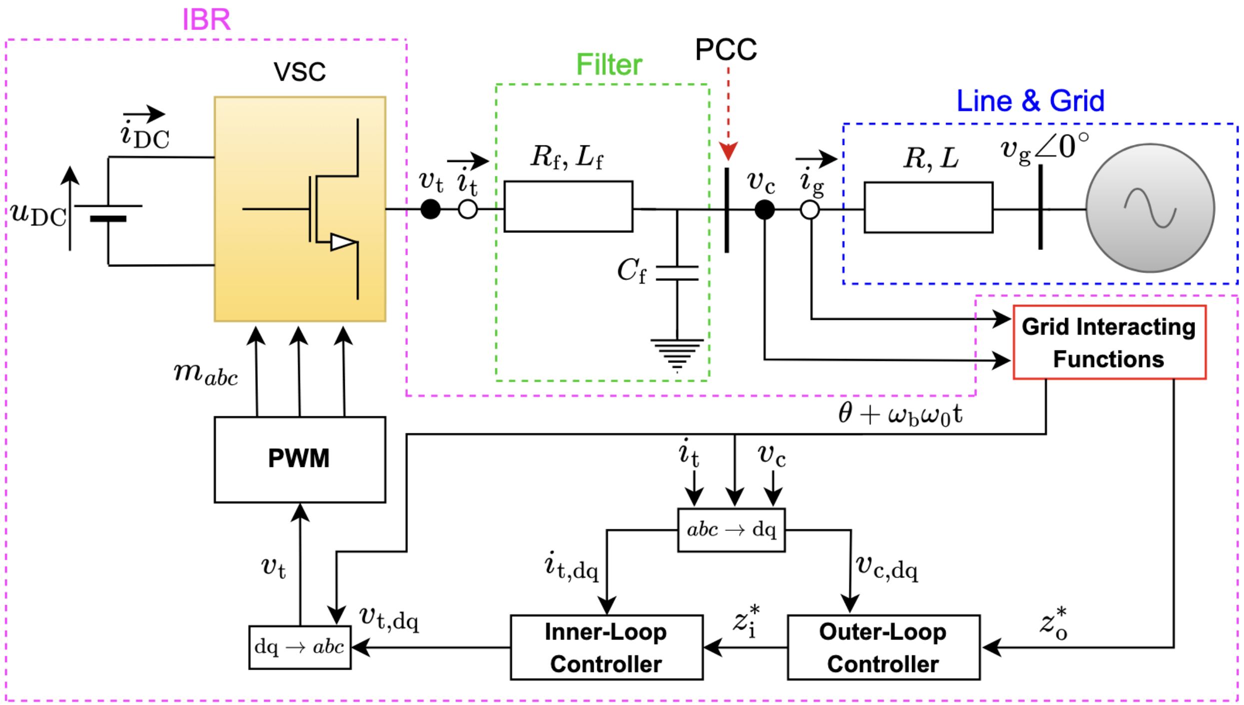
Source: Sushobhan Chatterjee and Sijia Geng. "Effects of Line Dynamics on the Stability Margin to Hopf Bifurcation in Grid-Forming Inverters." *IREP 2025 and Sustainable Energy, Grids and Networks (SEGAN)*, 2025.

- 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.



[PowerTech2025] Chatterjee, Geng, "Voltage Stability of Inverter-Based Systems: Impact of Parameters and Irrelevance of Line Dynamics." IEEE PowerTech, 2025.

What We Know — and What's Still Open

✅ What's Known

- **Ensures safety for individual GFM inverter connected to the grid.**
- **Tradeoff between performance and safety during transients and steady-state.**
    - Safety is critical and performance becomes secondary.

❓ Many Questions Remain Open

- **Generalizing analysis for a network with heterogenous IBRs.**
    - How to generalize the framework to handle arbitrary IBR control schemes? Often time without detailed model? Interoperability among heterogeneous IBR controls.
- **Provides theoretical certificates which can be used to tune controllable parameters to comply with/inform grid codes.**
- **How do we account for nonlinear and hybrid dynamics into operation problem?**
    - Do we need to consider stability in the operation problem?

[ACC 19] Kundu, **Geng**, et. al. Distributed barrier certificates for safe operation of inverter-based microgrids (ACC 2019).

[OAJPE 22] **Geng**, Hiskens. "Unified grid-forming/following inverter control." IEEE Open Access Journal of Power and Energy, 2022.

Thanks!