Interconnection Compliance in High-IBR Grids

Robust + Decentralized Stability Analysis

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Interconnection Compliance in High-IBR Grids

- Recap: What We Know About IBR-Induced SSOs
- Compliance Challenges in Preventing SSOs
- Understanding SSOs: What We Know
- Impedance-Based Stability Analysis and Challenges
- New Methodology: Robust and Decentralized Stability Analysis
- Robustness vs Efficiency Trade-offs

Recap: 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

Compliance Challenges in Preventing SSOs

- **Proprietary vendor models:** limited transparency in control details
  - What level of model detail should be mandatory for interconnection studies?
  - Can we certify "black-box" models without exposing sensitive IP?

- **Model fidelity:** dynamic scans sensitive to injection size, operating point, and sequence type
  - Should scans be standardized (e.g., fixed injection magnitudes, sequences)?
  - How do we account for nonlinearities and operating-point dependence in compliance tests?

- **Heterogeneity:** each IBR model/implementation behaves differently
  - Need for compliance requirements that's technology-agnostic.
  - Should there be a universal format for reporting impedance/admittance?

- **Limited standardization:** SCR screening common, but no universal SSO margin tests
  - Should interconnection rules require explicit SSO stability margins (like they do for SCR)? How to define SSO stability margin?!
  - How do we define "pass/fail" for impedance-based stability checks?

- **Trade-off:** conservative criteria risk blocking projects; permissive criteria risk instability
  - Should compliance include operational flexibility (adaptive tuning) rather than fixed thresholds only?
  - How do we set stability margins without making interconnection overly restrictive?

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> *“Without a **clear methodology** to assess and prevent SSOs, these questions will remain unanswered — or worse, misanswered.”*

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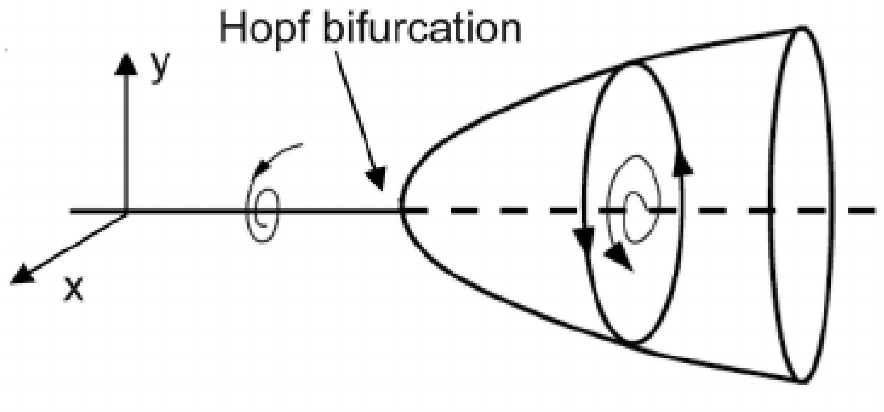
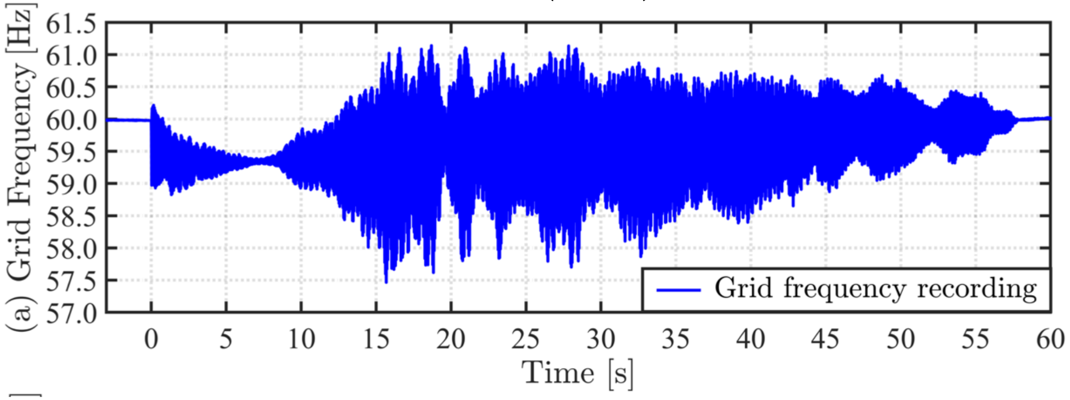
Understanding SSOs: What we know

- **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)



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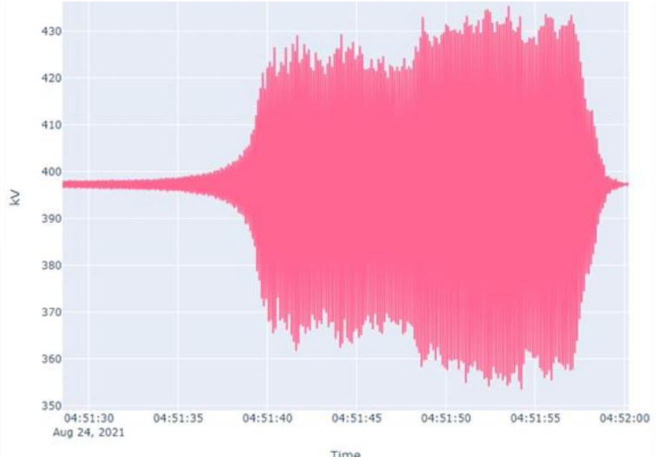

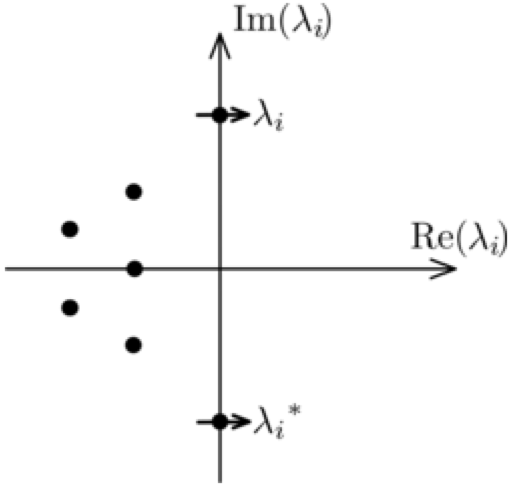

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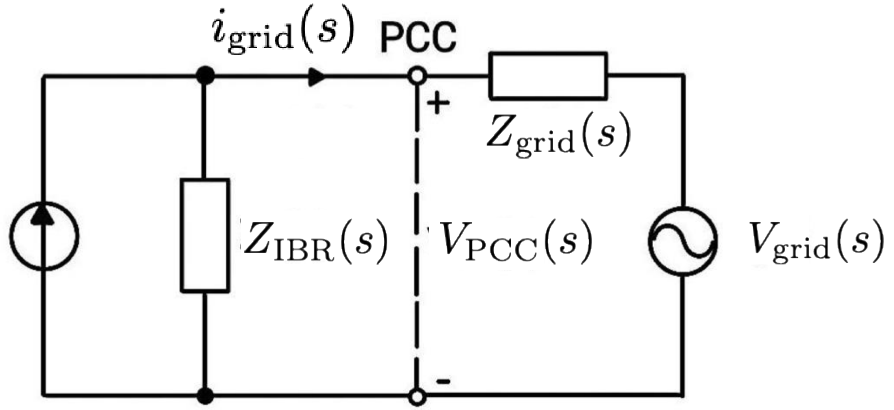
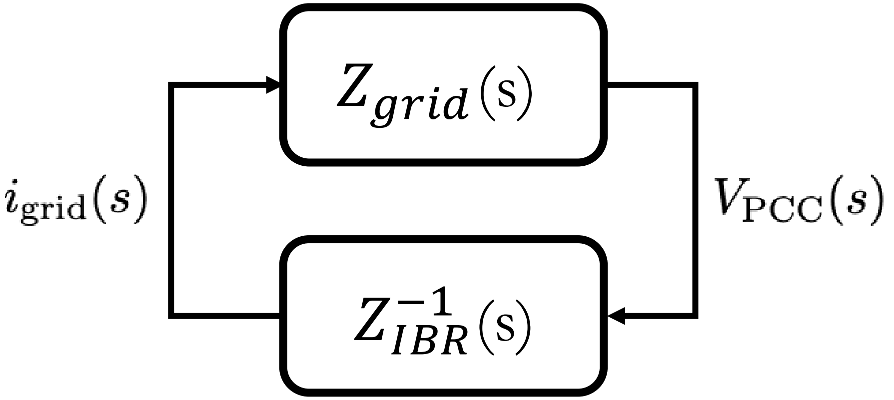


- Impedance models **can capture SSOs**
  - At the Point of Interconnection, stability can be analyzed by comparing inverter and grid impedances.



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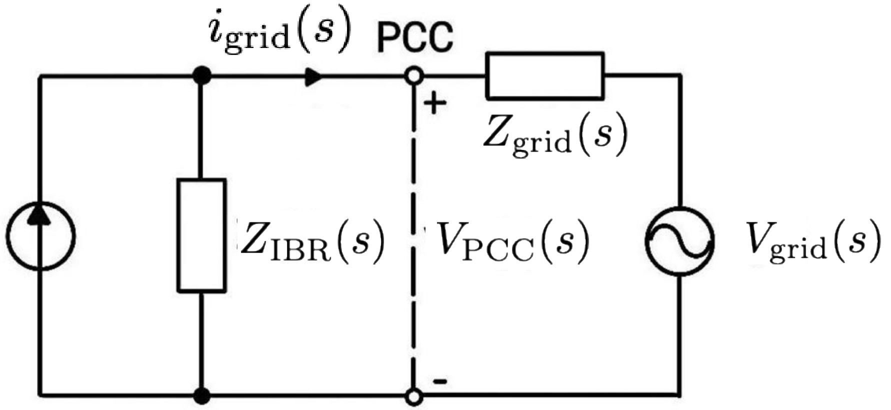
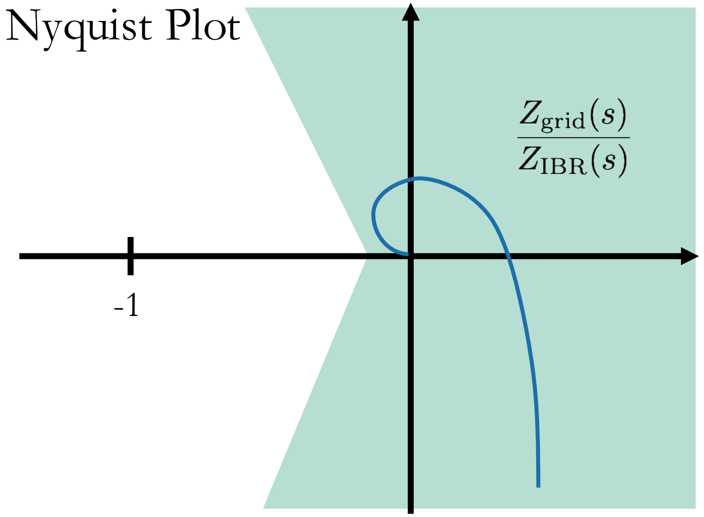


- Impedance models **can capture SSOs**
  - At the Point of Interconnection, stability can be analyzed by comparing inverter and grid impedances.
  - **Nyquist loop-gain criterion** $L(s) = \frac{Z_{grid}(s)}{Z_{IBR}(s)}$ explains why weak grids (high Z_{grid}) are more prone to instability.



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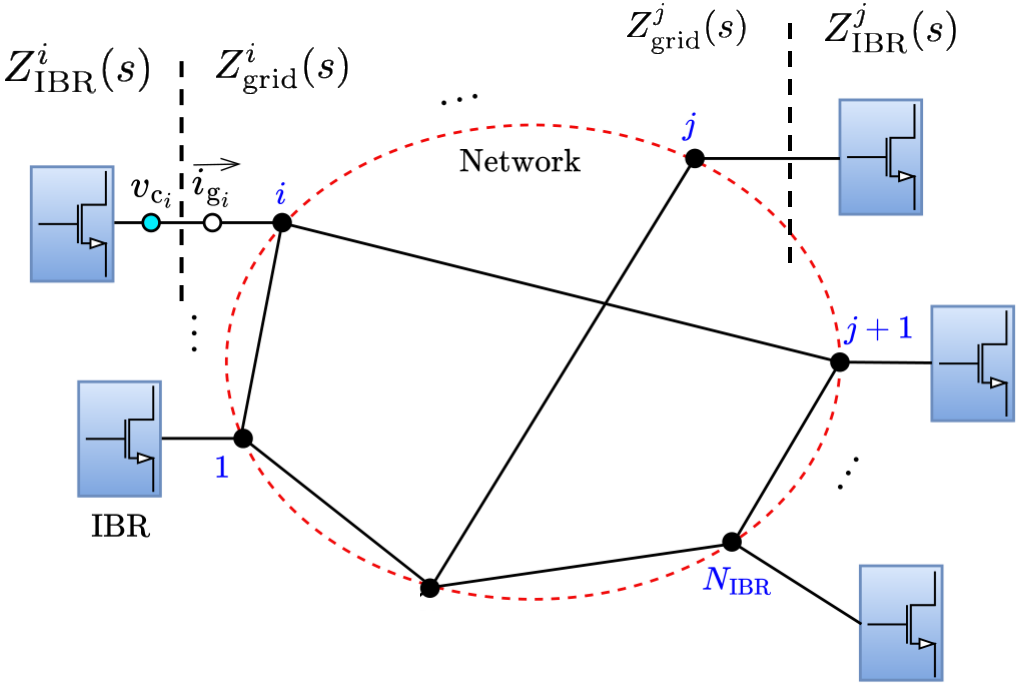
Challenges of Impedance Stability Analysis

- 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

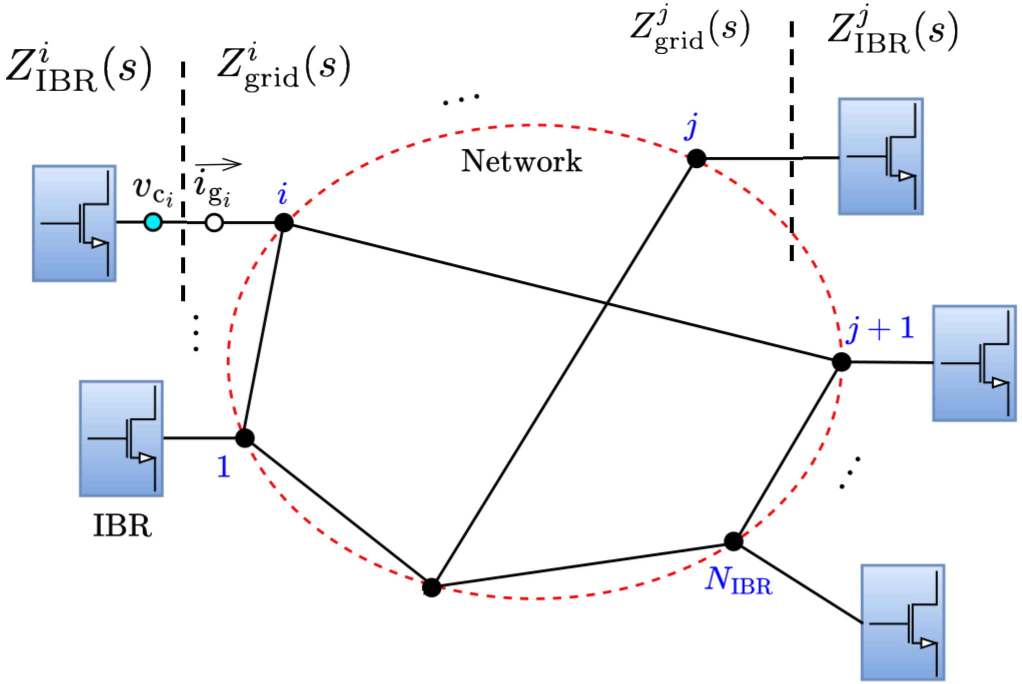


$$Z^i_{\text{grid}}(s) \neq Z^j_{\text{grid}}(s)$$

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



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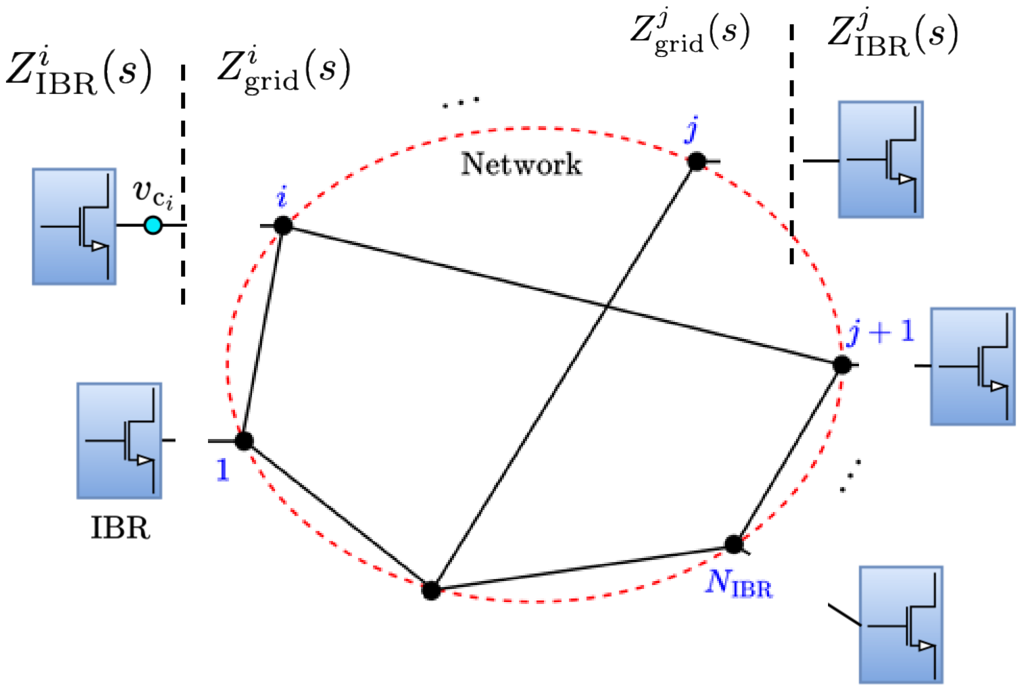
  - Can trade-off conservativeness between network and IBRs



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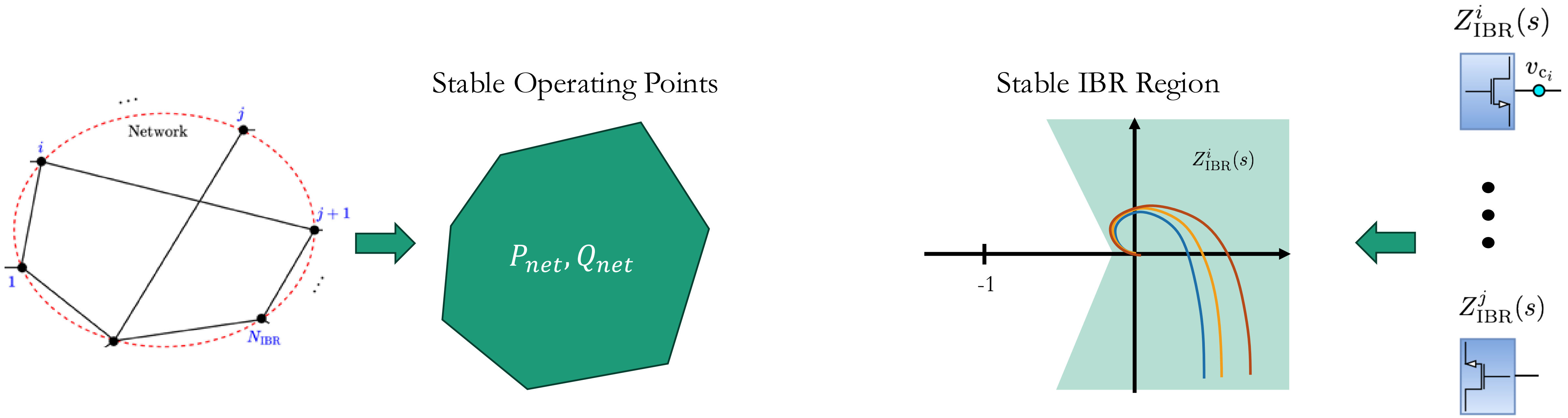

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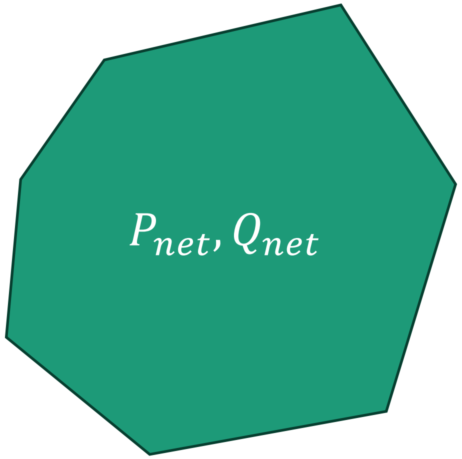
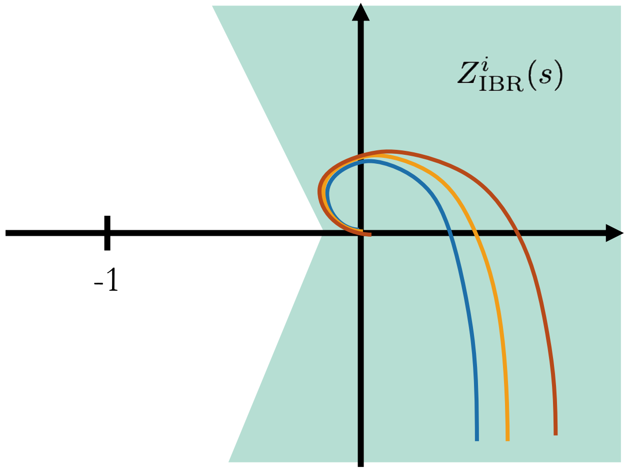
Trade-off: Robustness vs Efficiency

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

Stable Operating Points



Stable IBR Region



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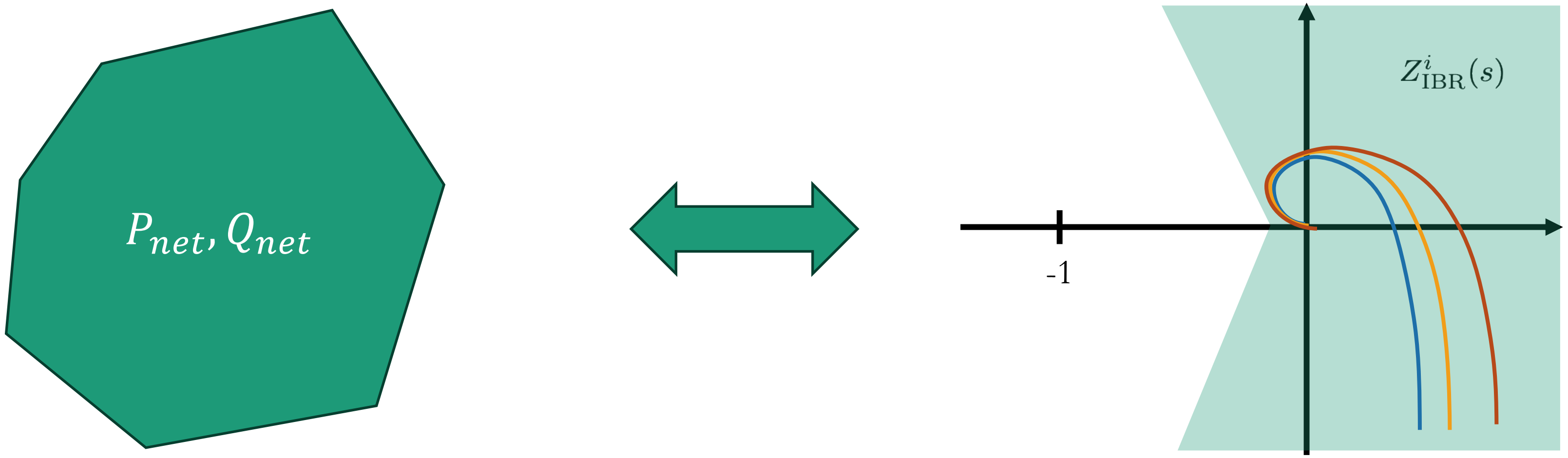

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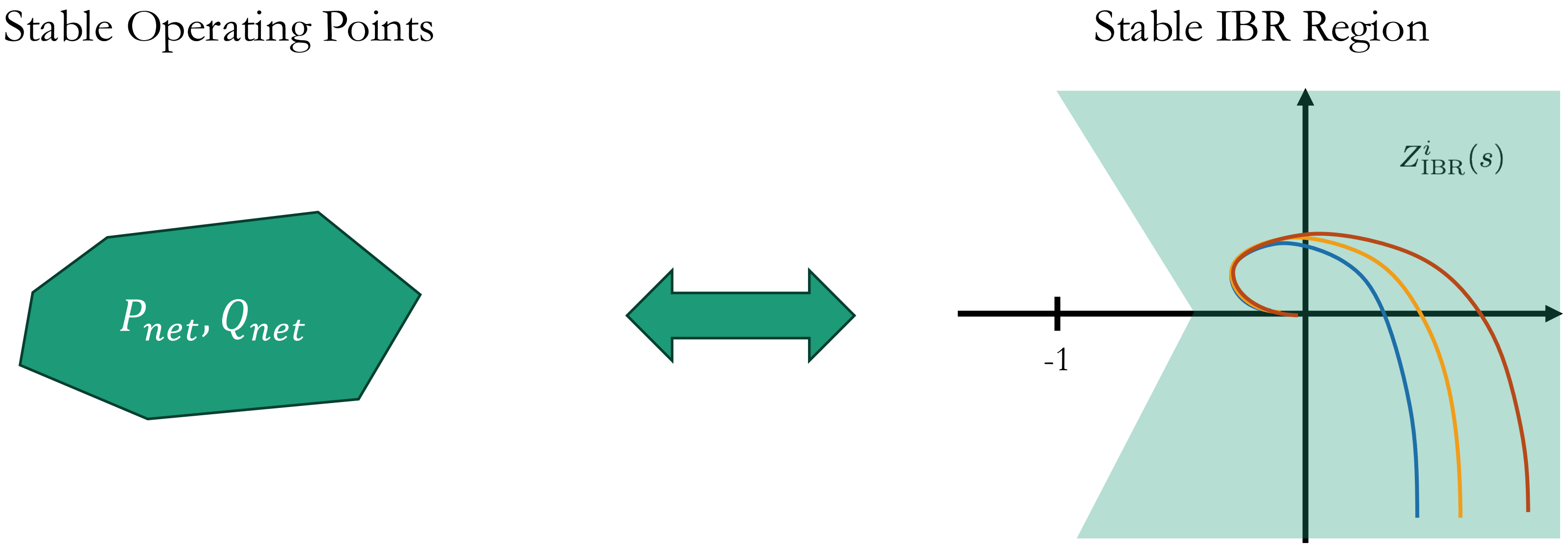

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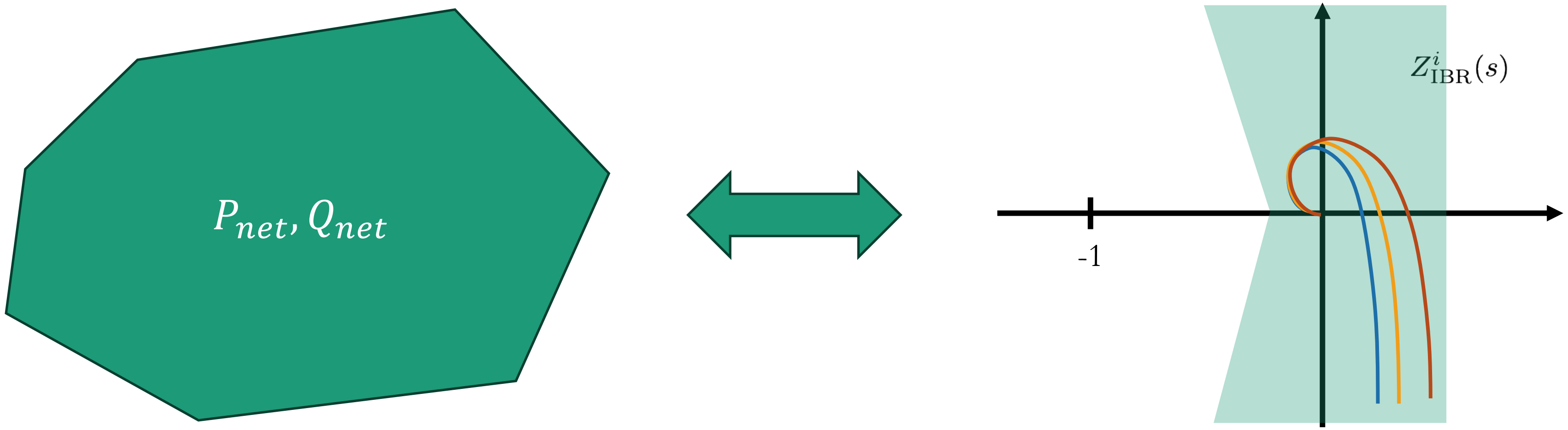

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What We Know — and What's Still Open

✅ 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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