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Department of Electrical and Electronic Engineering

Robust IBR Control Design for Enhanced Grid Stability: A Multi-Input-Multi-Output (MIMO) Approach

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Introduction & Motivation

The rapid transition to renewable energy and the increasing penetration of Inverter-Based Resources (IBRs) significantly alters power system dynamics. A critical modern challenge is maintaining small-signal stability and addressing Sub-Synchronous Oscillations (SSO) across varying grid strengths.

- **Grid-Forming (GFM) Inverters in Strong Grids:** GFMs actively regulate voltage but often experience instability when operating in strong grids. Classical tuning methods rely on SISO decoupling assumptions, neglecting critical cross-coupling and network dynamics.
- **Grid-Following (GFL) Inverters in Weak Grids:** GFLs are highly susceptible to instability in weak grids due to complex multi-timescale interactions between current, voltage, and synchronisation loops.

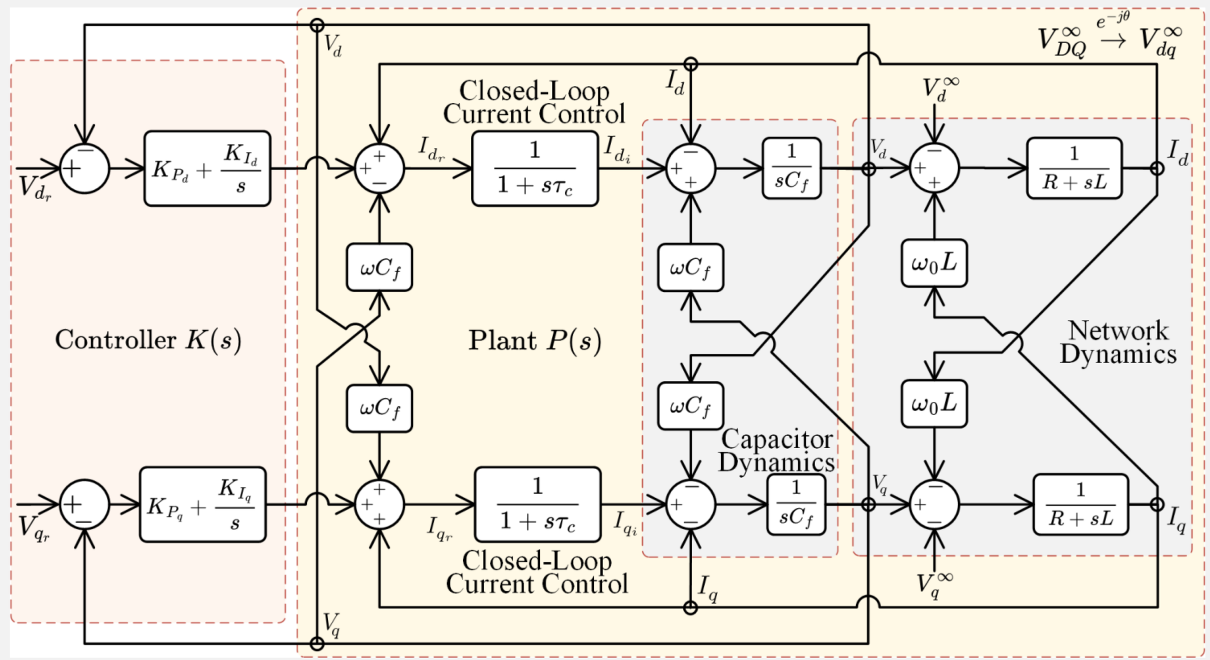
- **Classical Limitation:** Conventional Single-Input-Single-Output (SISO) PI controllers are tuned while ignoring crucial cross-dq and cross-loop coupling, and dynamic network interactions. This paradigm urgently requires a shift towards Multi-Input-Multi-Output (MIMO) optimization.
- **Unified Goal:** Overcome the limitations of typical PI-based SISO designs by leveraging robust MIMO H_∞ control to systematically shape input-output bandwidths, explicitly handle loop interactions, and guarantee stability across all grid conditions.

GFM: Methodology

Objective: Prevent voltage control interference and instability in strong grids.

H_∞-based Optimal Tuning

- **MIMO Concurrent Design:** Tunes the d-axis and q-axis voltage control loops simultaneously, without independent loop assumptions.
- **Disk Margin:** Uses Disk Margin $\alpha_{max} = 1/\mu_\Sigma(\mathcal{M})$ to evaluate robustness, optimizing the H_∞ norm of weighted sensitivity and complementary sensitivity.

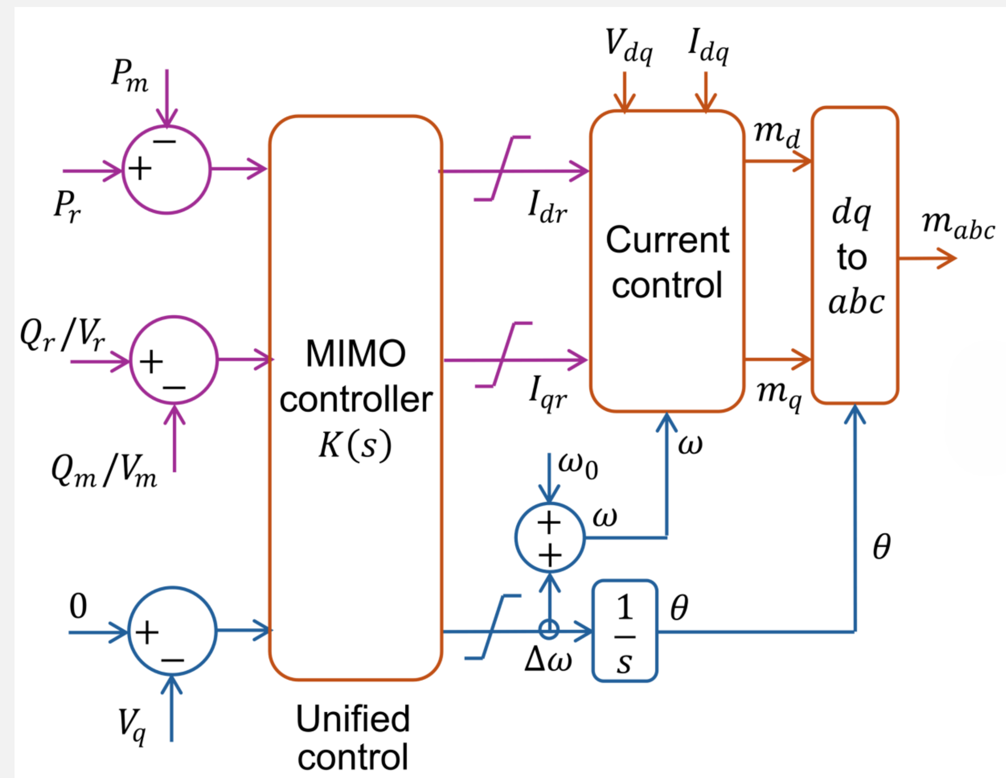


GFL: Methodology

Objective: Enhance weak-grid stability and suppress SSO without compromising bandwidth.

Polytopic LMI H_∞ Optimisation

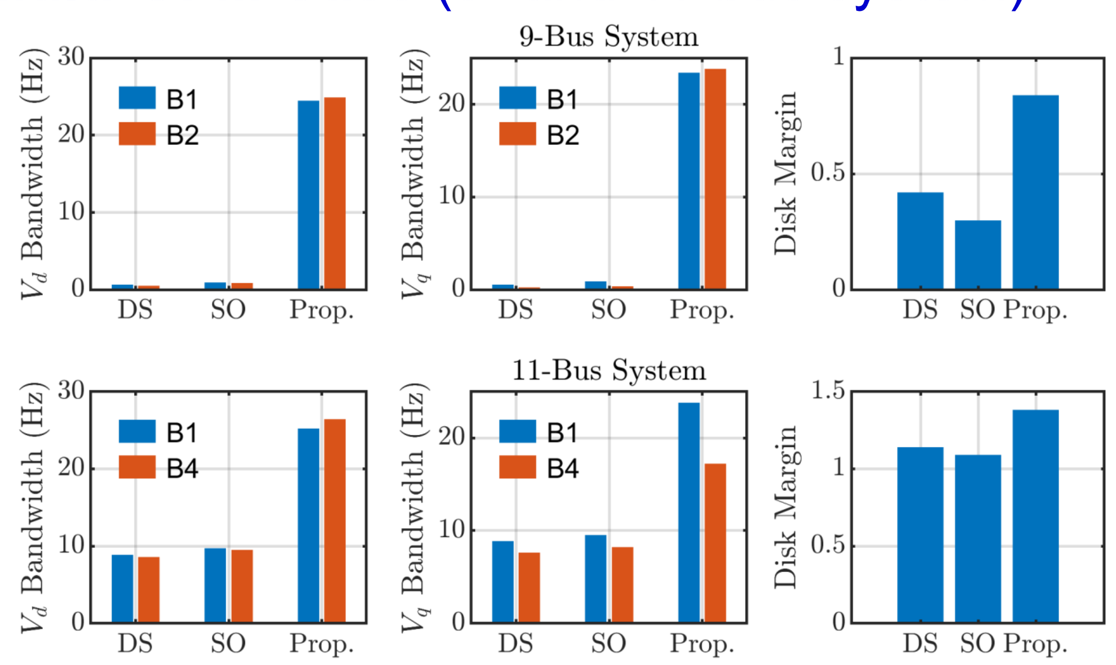
- **MIMO Control Structure:** Integrates voltage, and PLL dynamics into a robust H_∞ formulation, utilising a dynamic output-feedback controller.
- **LMI Synthesis:** Formulates the H_∞ minimization as a set of LMIs to achieve coordinated input-output shaping and regional pole placement.



Result

- **Strong Grid Stability:** In single GFM case, Direct Synthesis (DS) and Symmetrical Optimum (SO) become unstable at higher SCRs, MIMO remains stable
- **Better Bandwidth and Stability Margin:** In 9- and 11- bus systems, with the proposed controller, GFM voltage bandwidth and disk margin are higher than DS and SO, hence it outperforms the conventional designs.

Multi-GFM Case (9- and 11-bus system)



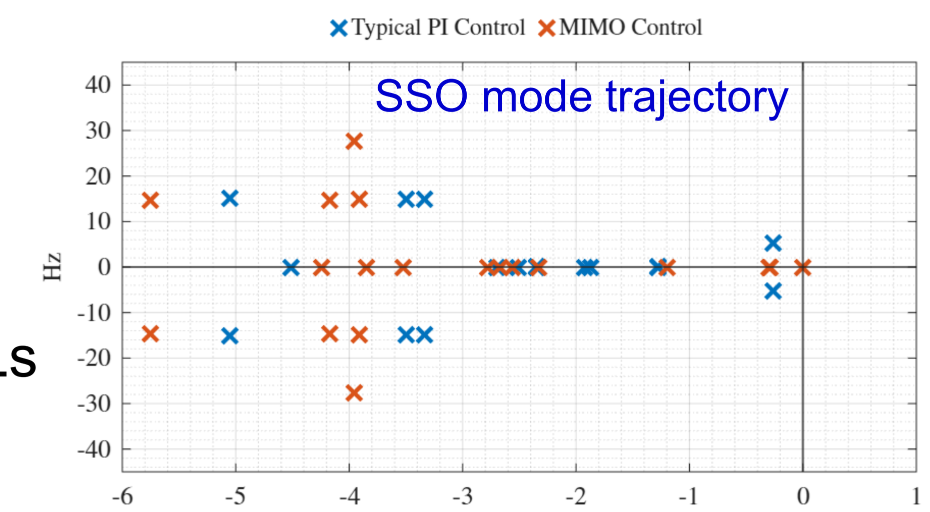
Voltage control bandwidth and disk margin

Acknowledgement: M. S. Javaid, B. Chaudhuri, F. Teng, and Z. Akhtar, "A novel tuning method of grid-forming inverter voltage control," IEEE PowerTech, Kiel, Germany, 2025

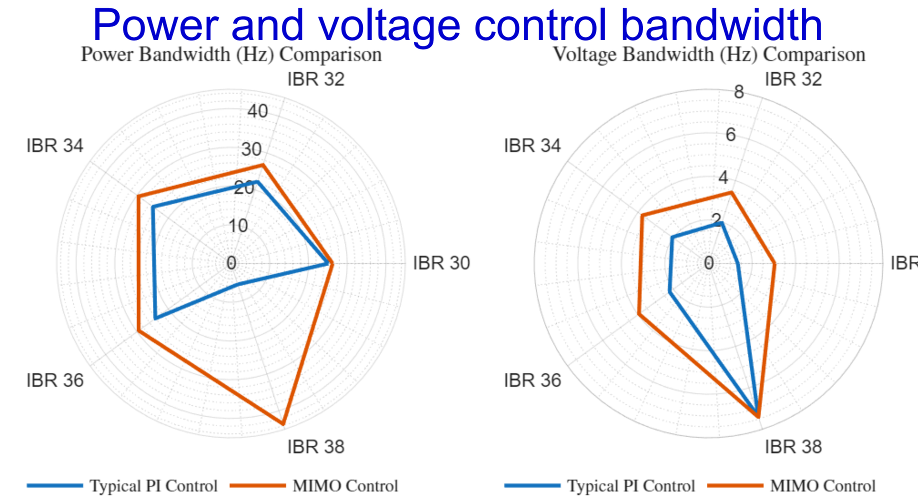
Result

Multi-GFL Case (39-bus system)

5 GFMs and 5 GFLs



Power and voltage control bandwidth



- **Weak Grid Stability:** Stable operation with all poles in the left-half plane across $1 \le SCR \le 10$. Standard PI controls failed at low SCRs.
- **Better Bandwidth and Damped Interaction:** In 39-bus system, MIMO design has better damping performance, and GFL closed-loop bandwidth are higher.

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