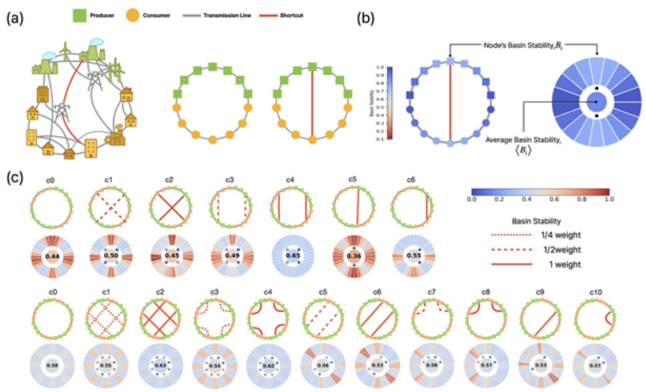
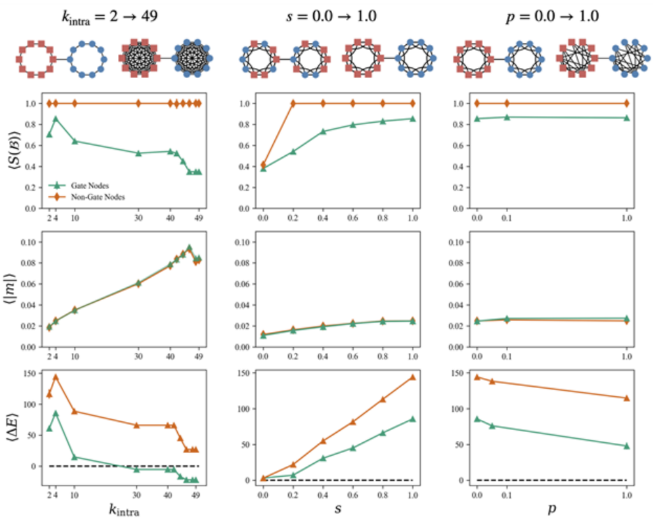
Stability of Modular Power Grids under Minimal Structural Interventions

Yunju Choi[1], Jonghoon Kim[1], Daekyung Lee[2], Cook Hyun Kim[1], **Heetae Kim**[1]

[1]Korea Institute Of Energy Technology, Naju, South Korea

The transition toward decentralized power systems, characterized by the proliferation of microgrids, is reshaping the topology and dynamics of modern power networks. Given the practical limitations of large-scale transmission expansion, understanding how minimal structural modifications influence stability has become increasingly important. In particular, as power grids evolve into modular systems composed of interconnected communities, it is essential to identify how both local connectivity changes and higher-level structures affect synchronization dynamics.





In this work, we present two complementary studies that investigate the stability of power-grid networks under minimal and structured connectivity changes.

First, we analyze a minimal motif-based model by introducing a single additional transmission line to a ring network composed of alternating generator and load nodes. This controlled setup allows us to systematically evaluate how the placement of the added link affects synchronization stability. We find that stability is maximized when the additional line connects nodes located near the center of mass of power injection and consumption. In contrast, connections formed away from this center can degrade stability, revealing a Braess paradox-like behavior where adding transmission capacity counterintuitively destabilizes the system. We further extend this analysis to other connection patterns and observe diverse stability responses depending on the relative positioning of nodes, highlighting the nontrivial role of spatial power distribution in determining optimal network modifications.

Second, we investigate networks with explicit community structures arranged in chain-like configurations, representing interconnected microgrids. By analyzing the impact of inter-community connections, we evaluate stability using two complementary measures: basin stability, capturing global robustness, and convergence tendency, reflecting local dynamical stability. Our results show that nodes exhibiting high basin stability do not necessarily possess high convergence tendency. This discrepancy indicates that global and local stability metrics can lead to fundamentally different interpretations of system resilience in modular networks.

Taken together, these results provide a unified perspective on stability in evolving power-grid architectures. While the motif-based analysis reveals how minimal interventions can induce both stabilizing and destabilizing effects depending on structural context, the community-level analysis demonstrates that different notions of stability may not align in modular systems. These findings suggest that designing future power grids requires a multi-scale and metric-aware approach, where both local structural features and global modular organization are carefully considered.