Distinct Synchronization Profile of the Gate Node in a Modular Power Grid

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Extended Abstract

The stability of power grids is critical to ensure reliable electricity supply [1]. In AC power grids, particularly, maintaining frequency synchronization among the power grid nodes is important for system stability. From this synchronization perspective, stability is generally analyzed in two perspectives: local and global. Local stability refers to the rate of return to the synchronized state after small perturbations, while global stability measures the size of the basin of attraction that leads the system to the synchronized state. [2]. Recent studies report that these two stability characteristics exhibit opposite trends, yet these findings focus on either a microscopic(node-level) or a macroscopic(system-level) point of view [2, 3]. In this study, we analyze the dynamics of synchronization in modular networks to understand the local and global stability at the mesoscale scale. In terms of dynamics, the synchronization dynamics of power grids is described by the second-order Kuramoto model, given in Eq. 1 [4].

$$m_i \ddot{\theta}_i(t) = P_i - \gamma_i \dot{\theta}_i(t) - \sum_j K_{ij} \sin(\theta_i(t) - \theta_j(t)), \tag{1}$$

where m_i, P_i, and γ_i denote inertia, power input or output, and damping coefficient of node i, respectively. The variable θ_i is the phase of node i at time t, and K_{ij} is the coupling strength between nodes i and j. Structurally, each network consists of two ring-based modules connected by a single intermodule link. We systematically vary intramodule connectivity k_{in}, homogeneity of each module for power h, and rewiring probability p to generate ensembles of network configurations (Fig. 1). We quantify homogeneity by the absolute difference in total power between the two modules. Across this design, gate nodes that connect the two modules and non-gate nodes within modules display different stability patterns. For gate nodes, increasing k_{in} improves local stability but undermines global stability (see Fig. 2(a)). However, increasing homogeneity strengthens both stabilities when the system is not fully heterogeneous($h > 0$). These patterns persist under rewiring probability p. For nongate nodes, the change in global stability is negligible, whereas local stability grows with k_{in}(Fig. 2(b)), homogeneity h, and intra-rewiring probability p. Importantly, gate and nongate nodes, despite belonging to the same module, display distinct stability behaviors, and the observed dynamics depends on parameter types. These findings highlight that modular structure inherently differentiates gate and non-gate nodes, leading to distinct structural characteristics and dynamical behavior. By providing a mesoscopic perspective, our work offers deeper insights into synchronization stability in complex oscillator networks in the real world, such as power grids.

References

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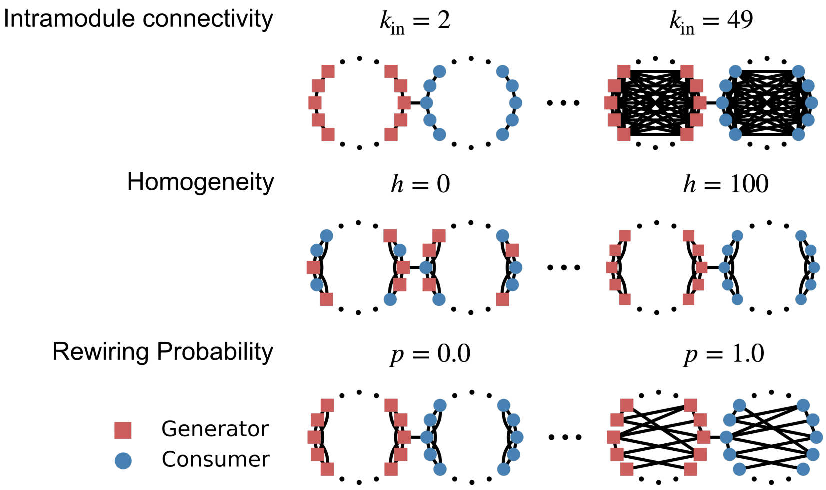

Figure 1: **Models.** We analyze synchronization dynamics in modular networks by systematically varying intramodule connectivity (k_{in}), node-attribute homogeneity (h), and intramodule rewiring probability (p) within two ring-based modules.

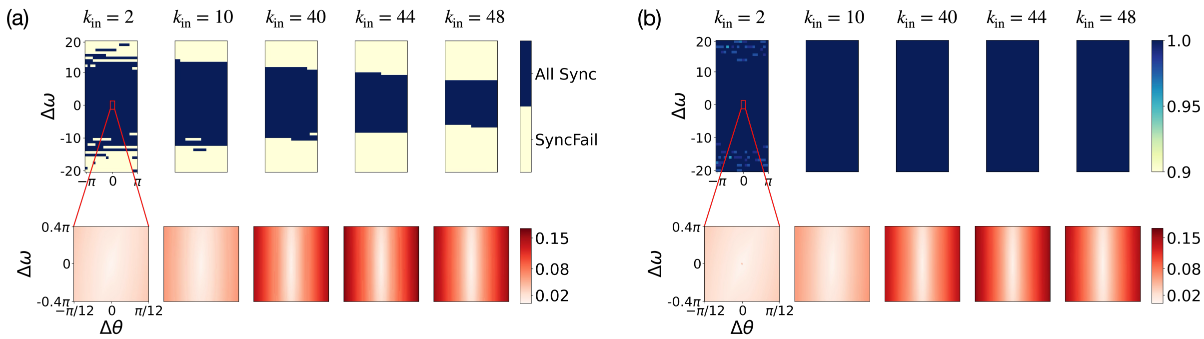

Figure 2: **Stability profile for gate and non-gate nodes.** (a) Gate nodes: Increasing intramodule connectivity k_{in} decreases global stability (top) and increases local stability (bottom). (b) Nongate nodes (averages): Global stability changes negligibly, while local stability increases with k_{in}.