A System Divided: Stability and Size Dependence of Segmented Power Grids

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Traditionally, large interconnected power systems with extensive synchronous zones have been assumed to provide higher reliability. However, in large grids perturbations can propagate across the whole system following to the underlying topological connectivity leading to unexpected and potentially catastrophic outcomes.

Motivated by the 2025 Iberian blackout [1] and recent advances in the study of transmission grid stability under large interregional power flows [2], we investigate the dynamical consequences of intentional or accidental grid segmentation. In particular, we ask whether the sudden removal of a geographically coherent region can destabilize not only the disconnected part, but also the remaining system, and which eigenmodes become dominant after the split.

Furthermore, considering both the original and segmented systems, we systematically approach the stability boundary by gradually reducing transmission line capacities. This allows us to compare the resilience of the intact large-scale grid and its smaller, partitioned counterparts with respect to bifurcation-induced instabilities.

We analyze this problem within a dynamical systems framework, combining fixed-point analysis with time-dependent simulations. Starting from a steady-state operating point, we partition a pan-European transmission grid model into subnetworks along realistic geographical boundaries (e.g., Iberian, Balkan, and Baltic regions). For each resulting subsystem, we assess the existence and stability of new operating points and track the evolution of the leading complex eigenvalue pair, which governs the onset of instability.

Our results are obtained using two complementary approaches: (i) solving the nonlinear power balance equations with Newton, Krylov, and Levenberg-Marquardt methods, and (ii) simulating the dynamics via the second-order Kuramoto model. The analysis is performed on the PanTaGruEl dataset [3], enabling a detailed and realistic representation of the European grid.

This work extends and complements previous studies on interregional power flows by explicitly addressing post-segmentation stability and highlighting how large-scale connectivity shapes the resilience of power systems.

References:

[1] ENTSOE. 28 April 2025 Blackout. 2026. URL: https://www.entsoe.eu/publications/blackout/28-april-2025-iberian-blackout/.

[2] María Martínez-Barbeito, Damià Gomila, Pere Colet, Julian Fritzsch, and Philippe Jacquod. "Transmission grid stability with large interregional power flows". In: Phys. Rev. Res. 7 (1 2025), p. 013137. DOI: 10.1103/PhysRevResearch.7.013137.

[3] Laurent Pagnier and Philippe Jacquod. PanTaGruEl - a pan-European transmission grid and electricity generation model. Version 0.1. Dec. 2019. DOI: 10.5281/zenodo.2642175.