Transmission Grid Stability with Large Interregional Power Flows

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The urgent need to reduce CO_2 emissions requires the gradual phase-out of fossil fuel power plants, increasing the amount of generation from renewable sources such as sun and wind which are subject to weather variability and geographical constraints. However, areas with high solar irradiation or persistent wind are often located far from major consumption centers. This spatial mismatch leads to significant long-distance power flows and increases stress on transmission networks. This is particularly relevant for large networks formed by the addition of smaller ones, such as the continental Europe synchronous area, which are not specifically designed for large inter-area flows. Here we discuss a general methodology for identifying critical lines in the long-distance transmission of power across large electric grids [1].

For large power imbalances such as those generated by high penetration of variable renewable energy sources, the network gets destabilized and loses synchrony. As flows increase, we identify two different instability scenarios. In the first one, specific sets of lines reach their maximal load simultaneously, causing the grid to split into two desynchronized zones. In the second, more generic, instabilities occur well after one or several phase differences exceed $\pi/2$. Thus line capacity limits are not the immediate cause of the instability; rather it emerges from grid topology constraints. The mechanism behind this is a pair of complex eigenvalues, associated to a Jacobian eigenvector with nonzero components on nodes with generation, that become real (Belayakov–Devaney transition) and move apart, triggering a saddle-node bifurcation when one of them becomes zero.

To push the system beyond this limit, we have proposed a mathematical trick converting certain lines to DC. The critical lines identified in this way match those that triggered the separation of the synchronous grid of continental Europe in two instances in 2021. We further discuss how the modes of the system provide information on which areas are more susceptible to lose synchrony with each other. In particular, we find that, for a very broad range of scenarios, the Pyrenees and Balkans are particularly vulnerable areas.

Reference:

[1] M. Martínez-Barbeito et al, Physical Review Research, 7, 013137 (2025)