Towards full-network modeling of large power grids

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The renewable energy transition poses new challenges for existing power grids by introducing larger and more unpredictable fluctuation of energy production in both space and time. We model the the synchronization dynamics on large power grids using the second-order Kuramoto coupled oscillator model. Our goal is to predict both the behavior of synchronized networks as well as the resiliency of networks against perturbations such as line or node failures.

In a recent study [1], we simulate the model on real high-voltage grid data from the US and EU by direct numerical integration of the second-order Kuramoto equation. These networks, with 4194 and 13478 nodes, respectively, are highly modular with topological dimensions above two. We investigate the local synchronization in the steady state using the local Kuramoto order parameter and local power flows, revealing topological hot-spots in the networks. Considering a line failure model where links between neighboring nodes with a power flow exceeding a threshold T are cut dynamically, we investigate line failure cascades triggered by perturbations in the form of single line cuts introduced in the steady state. Near the critical value coupling parameter K the size distributions of these cascades follow power laws depending on T and an islanding effect leading to a new steady state is observed.

In the future we plan to study even model detailed representations of real power grids by including medium- and low-voltage levels into the networks to better capture topological effects present in real network, including rare regions. These studies are enabled by a GPU code, which we developed specifically to efficiently handle numerical integration on these sparse modular graphs. Here, we present the above-mentioned simulation results and the specific computational optimizations employed to obtain them on large-scale networks with an acceleration of up to two orders of magnitude over CPU. We also present our threshold extension to the Kuramoto model and the various observables computed on-the-fly.

References

[1] G. Ódor, S. Deng, B. Hartmann, J. Kelling, Synchronization dynamics on power grids in Europe and the United States, Phys. Rev. E 106, 034311 (2022).