Non-local synchronization and electric power-grid outages

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Dynamical simulation of the cascade failures on the EU, USA and Hungarian [1] high-voltage power grids has been done via solving thesecond-order Kuramoto equation. We show that synchronization transition happens by increasing the global coupling parameter K with meta-stable states depending on the initial conditions so that hysteresis loops occur. We provide analytic results for the time dependence of frequency spread in the large K approximation and by comparing it with numerics of d=2,3 lattices [2], we find agreement in the case of ordered initial conditions. However, different power-law (PL) tails occur, when the fluctuations are strong. After thermalizing the systems we allow a single line cut failure and follow the subsequent overloads with respect to threshold values T. The PDFs of the cascade failures exhibit PL tails near the synchronization transition point K_c. Below K_c we find signatures of T-dependent PL-s, caused by frustrated synchronization, reminiscent of Griffiths effects [3]. Here we also observe stability growth following blackout cascades, similar to intentional islanding, but for K > K_c this does not happen. For T < T_c, bumps appear in the PDFs with large mean values, known as ``dragon king'' blackout events. We also analyze the delaying/stabilizing effects of instantaneous feedback or increased dissipation and show how local synchronization behaves on geographic maps. We demonstrate the occurrence of non-local cascade failure events at the weak points of the networks.

The size distribution of planned and forced outages in power systems have been studied for almost two decades and has drawn great interest as they display heavy tails. Understanding of this phenomenon has been done by various threshold models, which are self-tuned at their critical points, but as many papers pointed out, explanations are intuitive, and more empirical data is needed to support hypotheses. We analyze outage data collected from various public sources to calculate the outage energy and outage duration exponents of possible power-law fits. Temporal thresholds are applied to identify crossovers from initial short-time behavior to power-law tails. We revisit and add to the possible explanations of the uniformness of these exponents. By performing power spectral analyses on the outage event time series and the outage duration time series, it is found that, on the one hand, while being overwhelmed by white noise, outage events show traits of self-organized criticality (SOC), which may be modeled by a crossover from random percolation to directed percolation branching process with dissipation. On the other hand, in responses to outages, the heavy tails in outage duration distributions could be a consequence of the highly optimized tolerance (HOT) mechanism, based on the optimized allocation of maintenance resources [4].

References

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