Stability Concepts of Networked Infrastructure Networks

Paul Schultz

The power system is currently undergoing a major transition, where coal-fired and nuclear power plants are being replaced by renewable energy producers and storage facilities. This transformation is enabled by appropriate modifications of the power grid's underlying structure. This network constitutes the complex interaction of numerous producers and consumers. Due to the intermittent nature of renewable production, the power grid is additionally subject to a distribution of disturbances that also includes large deviations. In conjunction, these aspects prompt methodological problems for (future) power grids in particular and complex systems in general. How can the stability of different operating points or scenarios be compared? What are the critical components of the network? To which extent is the stability of an operating point determined by the network structure?

This dissertation considers questions of this sort from the perspective of nonlinear dynamics and network theory. Here, the focus is on the emergent phenomenon of synchronisation in networks of coupled oscillators. In the context of power grids, this corresponds to all units working at the same rhythm – the rated grid frequency. The probability that a random perturbation strongly destroys this rhythm is given by basin stability, which is an example for so-called probabilistic stability measures that offer different approaches to quantify stability.

On the one hand, the following pages contain methodological advances to probabilistic stability measures, assessing important limitations but also developing novel approaches. In particular, the new measures consider sequences of repeated perturbations as well as operational bounds on transient deviations.

On the other hand, the influence of small network structures, so-called motifs, on the stability of synchronisation is investigated. For this purpose, the probabilistic stability measures are paired with network characteristics, using statistical approaches. To create a sufficient ensemble of diverse network topologies, a network model is created to provide synthetic power grids. On this basis, it turns out that while the abundance of special motifs enhances stability, others typically diminish it.

In conclusion, the development of analysis methods and their comparison with network characteristics uncovers relationships between network motifs and the stability of synchronisation. These results are general to a large class of complex systems and build a foundation to future research in this direction. In addition to that, the novel probabilistic stability measures extend the range of methods in nonlinear dynamics by important aspects, especially for high-dimensional complex systems.