Minisymposium DDE 2018

Structure and dynamics of future energy systems: power grids as complex dynamical systems

Organisers:

Mehrnaz Anvari, mehrnaz.anvari@uni-oldenburg.de
Frank Hellmann, hellmann@pik-potsdam.de
Paul Schultz, pschultz@pik-potsdam.de
Xiaozhu Zhang, xiaozhu.zhang@ds.mpg.de

We have three subtitles corresponding to three sessions:

- "Fluctuations in power grids I"
  - Philipp Maaß, Christian Beck, Stefan Kettemann, Katrin Schmietendorf
- "Intrinsic Network Dynamics and Synchronisation"
  - Johannes Schiffer, Yuri Maistrenko, Robin Delabays, Xiaozhu Zhang
- "Fluctuations in power grids II"
  - Frank Hellmann, Paul Schultz, Mehrnaz Anvari

We assigned only three speakers to the last session to have room for a general discussion slot with all participants and a wrap-up of the minisymposium.

Session 1: Fluctuations in power grids I

Impact of transmission line heterogeneities and transient reactances on grid response to fluctuating power input

We analyse the impact of heterogeneous features of transmission lines, loads, and generators on the dynamical response of electricity grids to fluctuating power input based on the synchronous machine model. By comparing results for heterogeneous grids with simplified homogenised variants, we demonstrate that heterogeneities play a crucial role for grid stability. We further discuss the effect of transient reactances on the response behaviour and analyse the range of validity of linear perturbation theory.

Philipp Maaß
Fachbereich Physik, Universität Osnabrück, D-49076 Osnabrück, Germany

Superstatistical approach to frequency fluctuations in power grids

After a brief introduction to the concept of superstatistics (a useful method
to describe complex systems with time scale separation in nonequilibrium situations)
I will explain how this method can be used to better understand the statistics of frequency fluctuations
in power grids [1]. The fluctuations around the mean frequency of 50 Hz are observed to follow non-Gaussian statistics, but what
is the intrinsic reason for that? And what are the differences and similarities in the observed statistics and dynamics of various European,
American and Japanese power grids? This talk will provide some answers based on experimentally measured time series and simple theoretical models.

[1] B. Schaefer, C. Beck, K. Aihara, D. Witthaut, and M. Timme, Non-Gaussian power grid frequency fluctuations characterized by Levy-stable laws and superstatistics, Nature Energy 3, 119-126 (2018)

Christian Beck

- School of Mathematical Sciences, Queen Mary University of London, London, UK

Propagation of Disturbances in AC Electricity Grids

The energy transition towards high shares of renewable energy will affect the stability of electricity grids in many ways. Here, we aim to study its impact on propagation of disturbances by solving nonlinear swing equations describing coupled rotating masses of synchronous generators and motors on different grid topologies, a tree, a square grid and as a real grid topology, the german transmission grid. We identify ranges of parameters with different transient dynamics: the disturbance decays exponentially in time, superimposed by oscillations with the fast decay rate of a single node, or with a smaller decay rate without oscillations. Most remarkably, as the grid inertia is lowered, nodes may become correlated, slowing down the propagation from ballistic to diffusive motion, decaying with a power law in time. Applying linear response theory we show that tree grids have a spectral gap leading to exponential relaxation as protected by topology and independent on grid size. Meshed grids are found to have a spectral gap which decreases with increasing grid size, leading to slow power law relaxation and collective diffusive propagation of disturbances. We conclude by discussing consequences if no measures are undertaken to preserve the grid inertia in the energy transition.

Stefan Kettemann

- Department of Physics and Earth Science, Jacobs University, Campus Ring 1, 28759 Bremen, Germany
- Division of Advanced Materials Science Pohang University of Science and Technology (POSTECH) San 31, Hyoja-dong, Nam-gu, Pohang 790-784, South Korea

On the impact of turbulent wind energy production on power grid stability and quality

Wind power features turbulent-like non-Gaussian statistics including correlations, extreme events, -5/3 power spectrum, and intermittent increments. These feed-in fluctuations are one of the major challenges for future electrical power grids with a high share of renewables. Short-term fluctuations are particularly problematic, as they are not counteracted by standard load balancing mechanisms. They were shown to significantly decrease power quality and affect system stability.
In this talk, we give a brief overview on wind power statistics and present our results on system stability and power quality in Kuramoto-like power grids subjected to realistic wind power input. We further discuss the potential of local energy storage with respect to power quality improvement.K. Schmietendorf, J. Peinke, and O. Kamps

Katrin Schmietendorf

- Institut für Physik, Carl von Ossietzky Universität Oldenburg, 26111 Oldenburg, Germany

Session 2: Intrinsic Network Dynamics and Synchronisation

Designing Multi-Layer Power Systems by Trading Off L 2 -Gain Performance and Communication Efforts under Time-Varying Delays

Frequency control is one of the most relevant control applications in power systems. Traditionally, this task has been carried out on the high-voltage transmission system by using large fossil-fueled power plants as actuators. Yet, the increasing penetration of distributed renewable generation interfaced to the network via power inverters renders these conventional schemes inappropriate, creating a clear need for robust and distributed solutions that actively integrate generation units at the lower voltage levels. Typically, such distributed approaches require a communication infrastructure, thus resulting in a multi-layer power network, in which both the electrical and the communication layer are continuously exposed to exogenous disturbances. In such systems a fundamental design problem is the identification of an optimal communication topology, while ensuring stability and robustness of the overall multi-layer network. This problem is addressed in the present talk by proposing a synthesis for a distributed consensus-based secondary frequency controller, which provides the option to trade off L-2 disturbance attenuation against the number of required communication links and in addition guarantees robustness with respect to time-varying communication delays. The robust and sparsity-promoting controller synthesis is formulated as a convex optimization problem, which is derived via the Lyapunov-Krasovskii and the descriptor methods. The efficacy of the proposed approach is illustrated via simulations.

Johannes Schiffer

- School of Electronic and Electrical Engineering, University of Leeds, Leeds LS2 9JT, UK

Solitary States for Coupled Oscillators with Inertia

Networks of coupled oscillators with inertia can display remarkable spatiotemporal patterns in which one or a few oscillators split off from the main synchronized cluster and oscillate with different averaged frequency. These so-called solitary states are impossible for the pure phase Kuramoto model with sinusoidal coupling but generically arise when an inertia is introduced obeying normally a major part of the network parameter space.
We obtain parameter regions for solitary states in the Kuramoto model with inertia considering the case of identical oscillators with local, non-local, and mean field couplings as well as in both thermodynamic and conservative limits and give also evidence that solitary states arise in a homoclinic bifurcation [1].
Power grid models are characterized by bi-modal distribution of the oscillator natural frequencies, which are positive for generators and negative for consumers. By increasing the magnitude of coupling the oscillators synchronize normally at a common frequency

close to zero. However, as we find, there is always a danger for a sudden appearance of solitary states, as their co-exist with synchronization. If so, most of the oscillators remains synchronized but one or a few start oscillate with different frequencies in provoking in such a way a prompt desynchronization in power grids [2].

[1] P. Jaros, D. Dudkovsky, S. Brezetsky, R. Levchenko, T. Kapitaniak, and Yu. Maistrenko, Solitary states for coupled oscillators with inertia. Chaos 28, 011103 (2018).
[2] F.Hellman, P.Schultz, P. Jaros, R. Levchenko, T. Kapitaniak, Yu.Maistrenko, and J.Kurths. The impact of losses and solitary states on the dynamical stability of power grids. (in preparation)

Yuri Maistrenko

- Potsdam Institute for Climate Impact Research, Potsdam, Germany
- Faculty of Mechanical Engineering, Division of Dynamics, TU Lodz, Poland
- Institute of Mathematics and Centre for Medical and Biotechnical Research, NAS of Ukraine, Kyiv, Ukraine

Multistability in electric power grids on meshed, complex networks

The dynamics of an electric power grid is standardly determined by swing equations. These are ordinary differential equations whose fixed point solutions determine possible operating states of the grid. These fixed points are solutions of a transcendental equation which implies among others that there may be several different possible operating states for a given grid. We characterize these solutions in terms of (i) how they differ from one another, (ii) their linear stability and (iii) the structure of their respective basins of attraction. We discuss how changing operational conditions may induce a jump from one solution to another in a functioning power grid and what such jumps imply for grid operation.

Robin Delabays

- School of Engineering, University of Applied Sciences of Western Switzerland, CH-1950 Sion, Switzerland
- Section de Mathématiques, Université de Genève, CH-1211 Genève, Switzerland

Transient Dynamics of Perturbation Spreading in Oscillatory Networks and Power Grids

Spreading phenomena on networks essentially underlie the collective dynamics of systems across physics, biology and engineering. However, how local changes dynamically spread in networked systems is still far from fully understood. Here we analyze the transient spreading dynamics for diffusively-coupled oscillatory networks close to a given operating point. Perturbation arrival times are estimated via linear response theory and asymptotic analysis of nodal responses at the time of perturbation. For homogeneous networks we find the estimated spreading speed decreases over topological distance and converges to a constant value, which is essentially determined by the network topology, i.e. the limiting behavior of the number of shortest paths at large distance. These results shed light on the qualitatively universal asymptotic spreading behavior in networks and its quantitative dependence on the underlying network topology.

Xiaozhu Zhang

- Max-Planck-Institute for the Physics of Complex Systems, Dresden, Germany

Session 3: Fluctuations in power grids II

Probably consistent control of power grids

I describe how to use probabilistic methods for validating hierarchical consistent control concepts for power grids. To do so I will show how hierarchies of dynamical and control systems can be extended to incorporate uncertainty, and how to appropriately extend the notion of consistency in this context.

Frank Hellmann

- Potsdam Institute for Climate Impact Research, 14412 Potsdam, Germany

Bounding the First Exit from the Basin

We study the stability of deterministic systems given sequences of large, jump-like perturbations. Our main result is the derivation of a lower bound for the probability of the system to remain in the basin, given that perturbations are rare enough. To quantify rare enough, we define the notion of the independence time of such a system. This is the time after which a perturbed state has probably returned close to the attractor, meaning that subsequent perturbations can be considered separately. The effect of jump-like perturbations that occur at least the independence time apart is thus well described by a fixed probability to exit the basin at each jump, allowing us to obtain the bound. To determine the independence time, we introduce the novel concept of finite-time basin stability, which cor- responds to the probability that a perturbed trajectory returns to an attractor within a given time. The independence time can then be determined as the time scale at which the finite-time basin stability reaches its asymptotic value.

Paul Schultz

- Potsdam Institute for Climate Impact Research, 14412 Potsdam, Germany

Modeling and suppressing power output fluctuations of photo-voltaic power plants

The construction of a simple dynamical equation (jump-diffusion stochastic equation) that governs the stochastic process of PV-fluctuations, so that the statistics of the modelled time series are identical to those of the measured ones. Using the obtained dynamical equation, we generate new synthetic data sets with varying jump rates. Finally, we implement a straightforward filtering method, i.e. a combination of an inverter and a battery storage system to show the applicability of our proposed stochastic method.

Mehrnaz Anvari

- Max-Planck-Institute for the Physics of Complex Systems, Dresden, Germany