DY 38: The Physics of Power-Grids – Fluctuations, Synchronization and Network Structures (Focus session, joint DY/SOE)

The resilient and sustainable energy supply via power grids is one of the main future challenges for science and technology. Since the dynamics of power grids can be described by models that resemble the structure of Kuramoto's famous model for synchronization, power grid modeling is a topic where nonlinear dynamics, statistical physics and network science meet an important topic from engineering. Especially the integration of renewable energy sources accompanied by grid decentralization and fluctuating power feed-in from wind and solar power generation raises novel challenges for power system stability and design which can be addressed from the viewpoint of physics. In this focus session we will cover different aspects of the question how fluctuations and network structure influence the stability of the power grid.

Organized by Oliver Kamps, Joachim Peinke, Philipp Maass

Time: Wednesday 15:00–19:15 Location: ZEU 160

Invited Talk DY 38.1 Wed 15:00 ZEU 160

Asymmetry-Induced Synchronization Stability in Power-Grid Networks — •Adilson Motter — Northwestern University, Evanston, IL, USA

Synchronization is a paradigm for behavioral uniformity that can emerge from interactions and a necessary condition for the operation of coupled generators in power-grid networks. When the interacting entities are identical and their coupling patterns are also identical, the complete synchronization of the entire network is the state inheriting the system symmetry. As in other systems subject to symmetry breaking, such symmetric states are not always stable. Here, I will discuss the discovery of the converse of symmetry breaking—the scenario in which complete synchronization is not stable for identically coupled identical oscillators but becomes stable when, and only when, the oscillator parameters are judiciously tuned to nonidentical values. This corresponds to breaking the symmetry of the system to preserve the symmetry of the state. I will discuss how this implies that heterogeneity of dynamical units can facilitate and even be required for the stability of synchronous states in power grids and other oscillator networks. (Joint work with Takashi Nishikawa and Ferenc Molnar.)

DY 38.2 Wed 15:30 ZEU 160

The benefit of cooperation in a simplified highly renewable European electricity infrastructure — Leon Schwenk-Nebbe[1], Jonas Hörsch[2], Mirko Schäfer[1], and •Martin Greiner[1] — [1]Department of Engineering, Aarhus University, Denmark — [2]Frankfurt Institute for Advanced Studies, Germany

We consider a simplified model of a future European electricity network with a high share of renewable generation. In a cost optimal design of such a system, most of the renewable generation capacity is placed at locations with favorable weather conditions, that is for instance onshore wind in countries bordering the North Sea and solar PV in South European countries. Countries with less favorable renewable generation conditions benefit from this capacity by importing the respective electricity as power flows through the transmission grid. Using flow tracing techniques, which are related to directed diffusion processes on networks, we disentangle the emerging pattern of imports and exports and assign shares of the distributed generation capacity in the European system to the countries which actually make use of them. This procedures yields nodal levelized costs, which incorporate both internal and external generation as well as transmission costs associated with the electricity consumption in a country. Compared to a scenario without transmission, these nodal levelized costs are reduced by about 15% and represent the benefit of cooperation.

DY 38.3 Wed 15:45 ZEU 160

Scaling of transmission capacities in aggregated renewable electricity networks — Simon Bugge Siggaard[1], Chris Risager Poulsen[1], Jonas Hörsch[2], Mirko Schäfer[1], and •Martin Greiner[1] — [1]Department of Engineering, Aarhus University, Denmark — [2]Frankfurt Institute for Advanced Studies, Germany

Models of the electricity system often feature only a reduced spatial resolution, either due to lack of data or in order to reduce the complexity of the problem with respect to numerical calculations. For the determination of power flows in the respective electricity grid model, this reduced spatial resolution is connected to an aggregation procedure, which concerns both the network topology as well as the pattern of power imports and exports at the network nodes. The resulting flow patterns and transmission capacities of the system thus depend on the spatial resolution of the aggregated network. In this contribution, we investigate the scaling properties of aggregated power flows and transmission capacities on synthetic complex networks and a model of the European power grid, both including a high share of fluctuating renewable generation. The numerical findings are supported by analytical results for the scaling of power flows on aggregated two-dimensional lattices.

DY 38.4 Wed 16:00 ZEU 160

Probabilistic methods for deterministic systems (on networks) — •Frank Hellmann — Potsdam-Institut für Klimafolgenforschung (PIK), Potsdam, Detuschland

I discuss how we use probabilistic, sampling based methods to understand and uncover dynamic properties of complex systems on networks. The motivating example are Kuramoto oscillators with inertia, which we interpret as a simple example of power grids.

Concretely I show how the underlying network topology leaves a quantifiable imprint on the dynamical properties of the overall system, in particular its ability to return to or stay close to synchronization, and how we can identify novel asymptotic states that are only accessible by perturbations at specific nodes.

DY 38.5 Wed 16:15 ZEU 160

From conventional to renewable power: the role of grid heterogeneities — •Pedro Lind, Philipp Maass, Christoph Schiel, and Matthias Wolff — Universität Osnabrück, Fachbereich Physik, Barbarastraße 7, 49076 Osnabrück, Germany

The influence of heterogeneities characterizing transmission lines and generators on the functioning of power grids is investigated, focusing on the situation where conventional power plants are replaced by renewable power sources.Two problems are addressed.

First, we study the probability of single line failure [1], showing that it is necessary to consider the maximum power at the generator where renewable power is injected into the grid, the mean injected power and operating time scales of human intervention. We derive a formula for the failure probability that incorporates all these three aspects as well as simple parameters characterizing the wind statistics at the envisaged injection node. Our derivation is based on empirical sets taken at the North Sea.

Secondly, we report on simulations of the time-dependent power flow in grids [2], where power input from a fraction of the generator nodes is fluctuating and follows stochastic dynamics mimicking statistical features of wind and solar power injection. Different measures of the grid stability are discussed, as, for example, frequency stability and phase synchronization.

[1] S. Backhaus and M. Chertkov, Phys. Today 66, 42-48 (2013).
[2] T. Nishikawa and A. E. Motter, New J. Phys. 17, 015012 (2015).

DY 38.6 Wed 16:30 ZEU 160

Complex statistics of regenerative power feed-in — •Matthias Wächter, Mehrnaz Anvari, Patrick Milan, and Joachim Peinke — Instute of Physics and ForWind, Carl von Ossietzky University, 26111 Oldenburg, Germany

Future power grids are expected to experience a high share of renewable power generation. These renewable sources present pronounced statistical features stemming from the turbulent and intermittent nature of the wind and solar resources. Such features include strongly intermittent power fluctuations as well as long-range and higher-order correlations in time and space. Moreover, photovoltaic power feed-in is characterized by jump-like behavior due to cloud borders. We will give an overview on the current knowledge of these complex statistics specific for renewable power, which will pose significant challenges for future power grids.

15 min. break

Invited Talk DY 38.7 Wed 17:00 ZEU 160

Nonlinear Rerouting and Response in Electric Power Networks — •Marc Timme[1,2], Dirk Witthaut[3], and Xiaozhu Zhang[1,2] — [1]Network Dynamics, Max Planck Institute for Dynamics and Self-Organization and Technical University of Darmstadt — [2]http://networkdynamics.info — [3]FZ Julich

Networks dominate our daily life – and most of them are dynamic. For instance, almost all of the infrastructure we use today, from simple lights to hospital treatment, from communication to transport systems, crucially depend on electric energy reliably supplied via power grids. The ongoing integration of renewable energy sources, being smaller, more heterogeneous, decentralized and more fluctuating, implies more strongly networked systems with more distributed operation states. In our research group we aim to understand fundamental principles underlying the collective nonlinear dynamics of networked systems in general. This talk highlights recent developments and provide two examples of collective phenomena in decentrally organized power grids. First, we offer a theory of non-local rerouting of electricity upon line failure, providing an accurate prediction of flow redistribution that goes beyond local predictors. Second, we analyze patterns of dynamic responses to distributed fluctations across time scales and demonstrate under which conditions the notion of a "variation in the grid frequency" breaks down.

See also: Phys. Rev. Lett. 109:064101 (2012); Phys. Rev. Lett. 116:138701 (2016); Zhang et al., DPG talk (2017); New J. Phys. 14:083036 (2012); Nature Comm. 7:11061 (2016).

DY 38.8 Wed 17:30 ZEU 160

Impact of Wind Feed-in on Power System Stability and Quality — •Katrin Schmietendorf[1], Joachim Peinke[1], and Oliver Kamps[2] — [1]Universität Oldenburg, ForWind — [2]Universität Münster, Center for Nonlinear Science

Feed-in fluctuations are one of the major challenges for future electrical power grids. Short-term fluctuations on the second and sub-second scale are not counteracted by standard load balancing mechanisms. Moreover, on these time scales feed-in fluctuations are strongly non-Gaussian with intermittent increment statistics. We focus on short-term wind power fluctuations with realistic properties: temporal correlation, power spectrum, and intermittent increments. We discuss the implications on power system stability in terms of noise-induced desynchronization. Furthermore, we show that the turbulent nature of wind significantly reduces power quality as it is directly transferred into the fluctuations of frequency and voltage.

DY 38.9 Wed 17:45 ZEU 160

Collective Network Dynamics of Electric Power Grids — Xiaozhu Zhang[1,2], Dirk Witthaut[3], and •Marc Timme[1,2] — [1]Network Dynamics, Max Planck Institute for Dynamics and Self-Organization and Technical University of Darmstadt — [2]http://networkdynamics.info — [3]FZ Julich

Networks dominate our daily life – and most of them are dynamic. For instance, almost all of the infrastructure we use today, from simple lights to hospital treatment, from communication to transport systems, crucially depend on electric energy reliably supplied via power grids. The ongoing integration of renewable energy sources, being smaller, more heterogeneous, decentralized and more fluctuating, implies more strongly networked systems with more distributed operation states. In our research group we aim to understand fundamental principles underlying the collective nonlinear dynamics of networked systems in general. This talk highlights recent developments and provide two examples of collective phenomena in decentrally organized power grids. First, we offer a theory of non-local rerouting of electricity upon line failure, providing an accurate prediction of flow redistribution that goes beyond local predictors. Second, we analyze patterns of dynamic responses to distributed fluctations across time scales and demonstrate under which conditions the notion of a "variation in the grid frequency" breaks down.

This is work with various other colleagues. see also: Phys. Rev. Lett. 109:064101 (2012); Phys. Rev. Lett. 116:138701 (2016); New J. Phys. 14:083036 (2012); Nature Comm. 7:11061 (2016).

DY 38.10 Wed 18:00 ZEU 160

Topology related Instabilities driven by Intermittent Fluctuations in Distribution Grids — •Sabine Auer[1,2], Frank Hellmann[1], and Jürgen Kurths[1,2,3,4] — [1]Potsdam Institute for Climate Impact Research, 14412 Potsdam, Germany — [2]Department of Physics, Humboldt University Berlin, 12489 Berlin, Germany — [3]Institute of Complex Systems and Mathematical Biology, University of Aberdeen, Aberdeen AB24 3FX, UK — [4]Department of Control Theory, Nizhny Novgorod State University, 606950 Nizhny Novgorod, Russia

The impact of increased shares in variable renewable energy sources on the power system is subject to a controversial public debate. The question to what extent grid stability is influenced, especially the effect on distribution grids, is not well-understood but has come into focus, recently.

Thus, we investigated the influence of intermittent fluctuations from renewables on frequency stability with respect to network topology. Here, single node fluctuations are exerted onto each node of a typical distribution grid and the reaction in network frequency is quantified studying the frequency tail distributions.

We chose two prominent model cases which stand for today's Mid-Voltage distribution and potential future micro grids. Results and potential balancing measures as decentral smart grid control with the help from electric vehicles will be discussed.

DY 38.11 Wed 18:15 ZEU 160

Power Grid Resilience: Short-term Fluctuations and Intermittency — •Hauke Haehne, Matthias Waechter, and Joachim Peinke — Carl von Ossietzky University Oldenburg, Institute of Physics and ForWind, 26111 Oldenburg, Germany

Future power grids will be fed by a high share of renewable generation with strongly intermittent fluctuation patterns of produced power. This poses new challenges for resilient grid operation. From a physical perspective, the frequency of the alternating current in a power grid provides information on the instantaneous ratio of demand to production. We use high-resolution frequency measurements of the continental European power grid to analyze resilience regimes of the electric transport and actor system. We characterize fluctuations on different time scales and compare our findings to prior results from renewable power systems analysis. We combine stochastic methods and network dynamics, data analysis and simulations.

DY 38.12 Wed 18:30 ZEU 160

Frequency Fluctuations in Power Grids: From Observed Data to Lévy-stable Laws — •Benjamin Schäfer[1], Kazuyuki Aihara[2], Dirk Witthaut[3,4], and Marc Timme[1,5] — [1]Network Dynamics, Max Planck Institute for Dynamics and Selforganization (MPIDS), Göttingen — [2]Institute of Industrial Science, The University of Tokyo, Komaba, Meguro-ku, Tokyo, Japan — [3]Forschungszentrum Jülich, Institute for Energy and Climate Research - Systems Analysis and Technology Evaluation (IEK-STE), Jülich — [4]Institute for Theoretical Physics, University of Cologne, Köln — [5]Department of Physics, Technical University of Darmstadt, Darmstadt

The ongoing energy transition (*Energiewende*) to replace fossil by renewable energy sources raises new challenges for power grid design and control, because renewables do not supply a constant power but introduce fluctuations to the grid. Here, we analyze fundamental dynamics of power grid frequency fluctuations. We analyze specific frequency data for the continental European grid, the British grid, the Japanese power grids as well as for the Eastern Interconnection in North America. We model the underlying stochastic process using (generalized) Fokker-Planck equations and validate our analytical predictions by Monte-Carlo simulations. We conclude that dominant contributions to the frequency fluctuations in a grid may be approximated by a single variable, the average frequency deviation, modeled as a random variable following a Lévy-stable distribution.

DY 38.13 Wed 18:45 ZEU 160

Mathematical models for the transient stability of conventional power generating stations connected to low inertia

systems — •Marios Zarifakis[1], William T Coffey[2], Yuri P Kalmykov[3], and Sergei V Titov[4] — [1]Electricity Supply Board, Generation, Asset Management, Dublin 2, Ireland — [2]Department of Electronic and Electrical Engineering, Trinity College, Dublin 2, Ireland — [3]Laboratoire de Mathématiques et Physique (EA 4217), Université de Perpignan Via Domitia, F-66860, Perpignan, France — [4]Kotelnikov Institute of Radio Engineering and Electronics of the Russian Academy of Sciences, Vvedenskii Square 1, Fryazino 141120, Russia

Recent experience shows that this increase of power generation sources influences the behaviour of grid connected generating units. One observation is the change in the generated power after a transient disturbance especially its oscillatory behaviour accompanied by similar oscillatory behaviour of the grid frequency. An understanding of such behaviour of generators under various disturbances requires a new modelling technique. Therefore, a mathematical model of a generating station based on a system of coupled nonlinear differential equations and suitable for analysis of its stability is presented. The mathematical model will allow one to highlight limitations to the operational range of synchronous generators and could also be used to identify limits to the amount of total inertia necessary to maximise the usage of grid connected non-synchronous generators such as wind turbines and solar photo-voltaic installations.

DY 38.14 Wed 19:00 ZEU 160

Langevin analysis of large scale power outages - A case study

— •Frank Ehebrecht[1] and Oliver Kamps[2] — [1]Institut für Theoretische Physik, WWU Münster, Germany — [2]Center for Nonlinear Science, WWU Münster, Germany

The anticipation of critical transitions in complex systems is a field of active research in such diverse disciplines as ecology, climate research or engineering [1]. In [2] large scale power outages are considered as critical transitions in the operation of power grids. It was shown for the large scale power outage on August 10 in 1996 in the USA that the event could be anticipated from critical fluctuations of the system frequency.

In this talk we present results from the analysis of two different data sets of the system frequency from the same event that have been measured at two different positions in the grid. We show that critical fluctuations seem not to be a reliable indicator for a critical transition in the power grid. In contrast to that, analyzing the data from the viewpoint of Langevin equations by estimating the drift and diffusion coefficients shows to be more reliable to anticipate the outage.

[1] M. Scheffer et. al., Nature, 461, 2009

[2] E. Cotilla-Sanchez et. al., IEEE Transactions on Smart Grid, 3, 2012