Modelling Dynamics of Power Grids (MoDyPoG)

Special Track along with the 11th Int. Conf. on Smart Grids, Green Communications and IT Energy-aware Technologies
ENERGY 2021, May 30 - June 3, 2021 Valencia, Spain

Eckehard Schöll
Institut für Theoretische Physik
Technische Universität Berlin
Berlin, Germany
Potsdam Institute for Climate Impact Research
Potsdam, Germany
email: schoell@physik.tu-berlin.de
ORCID 0000-0002-7318-2672

***Abstract*—The transition to renewable and sustainable energy sources poses special challenges in order to secure stable and efficient operation of the power grid. This Editorial summarizes the state of the art presented in a special track on modelling the dynamics of power grids. It focusses on the following key issues of this track: Modelling approaches based on the interplay of complex and realistic network topologies and dynamics of generators and loads described by simple phase oscillator models; control of synchronization and stability of the power grid; analysis of cascading failure; influence of stochastic fluctuations of energy generation and consumption. The contributions in this track address vital current research directions that are of great importance for our future energy systems which are bound to limit the carbon dioxide emissions and hence the climate change.**

***Index Terms*—power grids, sychronization, stability, control, frequency fluctuations**

I. INTRODUCTION

To reach the goal of limiting the climate change below two degrees, integrating renewable and sustainable energy sources into the electrical power grid is essential. Wind and solar power are the most promising contributors to reach a sustainable energy supply but their integration into the existing electric power system remains an enormous challenge. To ensure stable operation of the grid, a complex systems approach is needed, gathering a multidisciplinary scientific community. The first steps towards applying the methods of statistical physics and nonlinear dynamics of complex networks to characterize the collective evolution emergent in power grids have been taken, and active research is ongoing.

The central observable in power grid monitoring, operation, and control is the grid frequency: primary control on short time scales to stabilize the grid frequency and secondary control on longer time scales to restore the nominal grid frequency are both fundamental. The increase of renewable energy challenges this central control paradigm, as generation becomes more volatile and the spinning reserve decreases. In addition, fluctuating demand and fixed trading intervals already contribute to frequency deviations.

In this Special Track we focus on recent developments in modelling from a complex systems and networks perspective. Promising directions of research are, e.g., how the collective grid dynamics is driven by fluctuations originating from varying power demands, fluctuating power input, and trading; how the dynamics changes according to decentralization and modification of the network topology; how power quality and grid stability can be improved by novel control concepts.

II. OVERVIEW OF CONTRIBUTIONS

The first contribution to this special track by Olmi et al. [1], [2] on ”Control of Synchronization in two-layer power grids” presents a novel highly efficient method of control of synchronization in a dynamic two-layer network model. The first layer represents the power grid consisting of generators and consumers, while the second layer represents a dynamic communication network that serves as a controller of the first layer and provides a dynamic control signal. In particular, the dynamics of the power grid is modelled by the Kuramoto model with inertia, while the communication layer provides a control signal for each generator to improve frequency synchronization within the power grid. The Italian high voltage power grid is used as a proof-of-principle example. Different realizations of the communication layer topology and different ways to calculate the control signal are proposed. A systematic survey of the two-layer system is conducted against a multitude of different realistic perturbation scenarios, such as disconnecting generators, increasing demand of consumers, or generators with stochastic power output. When using a control topology that allows all generators to exchange information, the authors find a control scheme aimed to minimize the frequency difference between adjacent nodes operates very efficiently even against the worst scenarios with the strongest perturbations.

The contribution by Frasca on ”Analysis of cascading failures in power grids via network based structure preserving models” [3] deals with desynchronization of power grids where the failure of one line results in successive switching-off grid components, which can in turn desynchronize other components, possibly provoking a cascade of further shutdowns and ending in large area outages of electric supply networks [4]. The propagation of an initial failure of any line is investigated within a network-based description of the power grid. The Italian high-voltage power grid is used as an example [5], and the role of renewable energy resources and their geographic position is illuminated, in particular whether the nodes with renewable energy production systems are randomly placed in the territory, or whether their positions are correlated due to social effects or territory characteristics [6].

The paper by Tumash et al. on ”Stability and control of power grids with diluted network topology” considers sparse random networks of Kuramoto phase oscillators with inertia, and investigates the dynamics emerging in high-voltage power grids [7]. The corresponding natural frequencies are assumed to be bimodally Gaussian distributed, thus modeling the distribution of both power generators and consumers, which must be in balance. The main focus is on the theoretical analysis of the linear stability of the frequency-synchronized state, which is necessary for the stable operation of power grids, and the control of unstable synchronous states. It is demonstrated by numerical simulations that unstable frequency-synchronized states can be stabilized by feedback control. Further, stochastic temporal power fluctuations are included, and the interplay of topological disorder and Gaussian white noise for various model configurations is discussed.

In the paper by Nnoli and Kettemann on ”Dynamics of Momentary Reserves under Contingency: Observations from Numerical Experiments” the spreading of disturbances is investigated under the conditions of different levels of grid inertia [8], [9]. With the introduction of renewable energy resources like wind and solar the grid inertia is reduced, which makes the electromechanical grid stability more vulnerable. Using reserves of synchronous machines’ inertia can serve the purpose of primary frequency control, preventing voltage collapse in the case of reactive power reserves. A numerical simulation is performed on a realistic Nigerian 330 kV transmission network with the swing equation to study and investigate the mechanism of these reserve functions on the network as an inertia active power control method. The issue is of great practical relevance, and the paper gives concrete recommendations to make the grid more stable and resilient with respect to power outages.

The contribution by Tyloo on ”Power grids: Small Signal Stability vs. Dynamical Parameters” [10] discusses how grid parameters like inertia and damping, and time-correlated fluctuations of renewable power sources affect the performance and stability. A robustness assessment based on linear response to perturbations is made. Numerical simulations of the swing equation in the lossless line approximation, and colored noise representing power fluctuations are performed, and the results are illustrated with a model of the synchronous grid of continental Europe. Of particular interest are inhomogeneous power grids in cases where disturbances occur on time scales that are long compared to the intrinsic time scales of the grid [11]. Interestingly, the magnitude of the transient excursion generated by disturbances with long characteristic times does not depend on inertia. For continental-size, high-voltage power grids, this corresponds to power fluctuations that are correlated on timescales of few seconds or more. Thus it is concluded that power fluctuations arising from renewable energy generation will not require per se the deployment of additional rotational inertia.

The paper by Martinez-Barbeito, Gomila, and Colet on ”Data analysis of frequency fluctuations in the Balearic grid before and after coal closure” [12] focusses on frequency fluctuations in a case study of the Balearic islands where in 2019, the most polluting power station was partially closed down, marking the end of coal as the main energy source in the territory. In this work the differences in the statistics of fluctuations of the electrical frequency before and after the closure is analyzed. This issue is of great importance for the transition to renewable energies and decarbonization of our economy. In this context the statistics of frequency fluctuations is highly relevant, but it has not been looked into before in such a thorough way, using empirical data from a real power grid, and taking a statistical physics perspective. The situation with coal and without coal power station is contrasted.

Stürmer, Plietzsch and Anvari in their paper on ”The risk of cascading failures in electrical grids triggered by extreme weather events” [13] study the risk of cascading failures in electrical grids triggered by extreme weather events like hurricanes. They use synthetic electrical grid data generated on the footprint of Texas. They investigate the re-routing of power flows following line destruction in a quasi-static approximation and probabilistic description of the damage. One of the serious threats related to climate change is an increase in the number and severity of extreme weather events. A prominent example are hurricanes which result from rising coastal temperatures. Such extreme weather events can cause extensive damages in infrastructure systems and, potentially, destroy components in electricity transmission networks, which in turn can lead to major blackouts. For this purpose, the destruction of overhead transmission lines during hurricanes is modelled, where each failing line causes a re-routing of power flow in the system. New power flows can overload additional lines, which are then automatically deactivated and thereby cause another rerouting of power flow and so on. Ultimately, a cascade of failures can unfold that can black out large parts of the power system. This issue is of great practical relevance.

The contribution by Meyer-Ortmanns on ”Arbitrage on the energy market and its impact on the physical grid stability” [14], [15] deals with the interaction of market demand, pricing, and energy fluctuations. This issue is of great importance for the grid stability with renewable energies. The paper draws an interesting analogy with spin glasses in physics and the associated phase transition, and uses game theory. Collective effects, due to the interplay of nonlinear price functions with stochastic fluctuations are manifested in a phase transition. As a consequence of the energy transition to renewables, the energy market is reorganized towards more decentralized structures. Retailers on local markets try to optimize their own profit while possibly losing track of the physical grid stability. The physical stability of the German grid was actually endangered in 2019, when the reserve energy was almost completely exhausted due to strong fluctuations in renewable energy, so that drastic changes in the price for reserve energy were very likely abused by arbitrageurs. Afterwards a careful analysis tried to identify the main responsible parties for these events, without an analysis of the mechanisms behind them. The present paper models a situation where arbitrageurs may buy reserve energy at a lower price than they can sell energy on the intraday market; this way they exploit the option for arbitrage by short selling reserve energy. Arbitrage is in general not appreciated and illegal on the reserve energy market. It refers to the simultaneous purchase and sale of the same asset, here energy, in different markets in order to profit from price differences without taking a risk. The action of arbitrageurs is modelled as a minority game with strategies depending on the success of their actions in hindsight, chosen out of a repertoire that is parametrized by the length of the memory of retailers. The players or agents of the game are the retailers. Based on these results, economic measures are proposed to reduce the amount of arbitrage below a tolerable low threshold. The model suggests that it is sufficient to control the few big parties on the market via small penalties, since a small amount of risk-aversion has a disproportionally large effect.

Rydin Gorjao in his contribution on ”Scaling and spatio-temporal properties of power grid frequencies: An open database” [16], [17] performs a frequency fluctuation analysis of a large number of real-world recorded data on power grids, using sophisticated tools of statistical scaling analysis. This issue is of great relevance for a better understanding of the nature of frequency fluctuations. The stochastic modeling approach employs uncorrelated Gaussian white noise and a Fokker-Planck equation. In order to validate theoretical predictions from scaling laws of fluctuations to propagation velocities of disturbances, here an open database of measurements of electric power grid frequencies across 17 locations in 12 synchronous areas on three continents is analyzed. The power grid frequency is of particular interest, as it indicates the balance of supply and demand and carries information on deterministic, stochastic, and control influences. From the recorded data, different synchronous areas are compared, and a previously conjectured scaling law is validated. Furthermore, it is shown how fluctuations change from local independent oscillations to a homogeneous bulk behaviour. Overall, the presented open database and analyses constitute a step towards more shared, collaborative energy research.

Finally, the paper by Berner et al. [18], [19] on ”Modelling power grids as pseudoadaptive networks” provides a new perspective on power grids by demonstrating that they can be viewed as a special class of adaptive networks, where the coupling weights are continuously adapted by feedback of the dynamics, and both the local dynamics and the coupling weights evolve in time as co-evolutionary processes. Such adaptive networks are very common in neural networks with synaptic plasticity. In terms of power grids, the power flow into the network nodes from other nodes represent pseudo coupling weights. This modelling approach allows one to transfer methods and results from neural networks, in particular the emergence of multifrequency clusters [20], which may form in a hierarchical way and destabilize the desirable completely synchronized operating state of the power grid. In this work, the relation between these two types of networks, in particular the model of Kuramoto-Sakaguchi phase oscillators with inertia (swing equation for power grids) and the model of phase oscillators with adaptivity, is used to gain insights into the dynamical properties of multifrequency clusters in power grid networks. Building on this, a new perspective on solitary states in power grid networks [21], [22] and their influence on network stability is provided and illustrated by the ultrahigh-voltage power grid of Germany.

III. CONCLUSIONS

The perspective of complex networks is a promising approach to describe various processes in nature and technology, ranging from physics and neuroscience to engineering and socioeconomic systems, and in particular power grid systems. It has been shown that simple low-dimensional models capture certain aspects of the dynamics of power grids very well [23]–[26]. In particular, the model of phase oscillators with inertia [27], [28], also known as swing equation, has been widely used as a paradigm for the dynamics of modern power grids [2], [4], [7], [21], [22], [29]–[43]; it has recently been generalized to allow for voltage dynamics in addition to the phase dynamics [44].

An important issue is connected with stability and control of frequency synchronization, and several novel control concepts, including secondary control, feedback control, and dynamic control via an extra dynamic communication network layer have been developed and presented in this Special Track. Another important research direction is the role of random fluctuations, introduced, e.g., by renewable energy sources like wind and solar, where non-Gaussian intermittent fluctuations typically occur [2], [45]–[47], and by fluctuating demand, and by market forces reacting to pricing policies. Great progress has been made in modelling real-world networks from available open-source data, which has greatly enhanced the predictive power of dynamic grid modelling.

The dynamical systems approach opens up novel insights and directions of research since it not only focusses on the desirable state of complete frequency synchronization of the whole grid, but also on possible instabilities, bifurcations, and multistabilities. Although such desynchronized states are generally undesirable in a properly functioning real-world power grid, it is important to study when they occur, in order to be able to take control measures to prevent them. For instance, recent works [21], [22] have shown that the solitary states, which are a subclass of multicluster states, arise naturally in the desynchronization transition of real-world power grid networks (with the examples of the German and the Scandinavian power grid), and that this knowledge is essential for an efficient power grid control, and for the design of future power grids.

ACKNOWLEDGMENT

I am grateful to the organizers for the invitation to set up this special track in the conference. Special thanks go the authors of the contributions for presenting their cutting-edge work. I am also obliged to Deutsche Forschungsgemeinschaft (DFG) for funding several projects (Project Nos. 429685422, 440145547, and 163436311-SFB 910), and I thank Jürgen Kurths for his hospitality at the Potsdam Institute for Climate Impact Research.

REFERENCES

[1] S. Olmi, C. H. Totz, and E. Schöll: *Control of synchronization in two-layer power grids*, in Special Track: Modelling Dynamics of Power Grids (MoDyPoG), along with Energy 2021, IARIA XPS Press (2021).

[2] C. H. Totz, S. Olmi, and E. Schöll: *Control of synchronization in two-layer power grids*, Phys. Rev. E **102**, 022311 (2020).

[3] M. Frasca: *Analysis of cascading failures in power grids via network based structure preserving models*, in Special Track: Modelling Dynamics of Power Grids (MoDyPoG), along with Energy 2021, IARIA XPS Press (2021).

[4] B. Schäfer, D. Witthaut, M. Timme, and V. Latora: *Dynamically induced cascading failures in power grids*, Nat. Commun. **9**, 1975 (2018).

[5] L. Fortuna, M. Frasca, and A. Fiore: *Network of oscillators emulating the Italian high-voltage power grid*, Int. J. Mod. Phys. B **26** (2012).

[6] R. Volpe, M. Frasca, A. Fichera, and L. Fortuna: *The role of autonomous energy production systems in urban energy networks*, J. Complex Netw. **5**, 461 (2017).

[7] L. Tumash, S. Olmi, and E. Schöll: *Stability and control of power grids with diluted network topology*, in Special Track: Modelling Dynamics of Power Grids (MoDyPoG), along with Energy 2021, IARIA XPS Press (2021); Chaos **29**, 123105 (2019).

[8] K. P. Nnoli and S. Kettemann: *Dynamics of Momentary Reserves under Contingency: Observations from Numerical Experiments*, in Special Track: Modelling Dynamics of Power Grids (MoDyPoG), along with Energy 2021, IARIA XPS Press (2021).

[9] K. P. Nnoli and S. Kettemann: *Spreading of disturbances in realistic models of transmission grids: Dependence on topology, inertia and heterogeneity*, engrXiv (2021).

[10] M. Tyloo: *Power grids: Small Signal Stability vs. Dynamical Parameters*, in Special Track: Modelling Dynamics of Power Grids (MoDyPoG), along with Energy 2021, IARIA XPS Press (2021).

[11] M. Tyloo and P. Jacquod: *Primary control effort under fluctuating power generation in realistic high-voltage power networks*, IEEE Contr. Syst. Lett. **5**, 929 (2021).

[12] M. Martinez-Barbeito, D. Gomila, and P. Colet: *Data analysis of frequency fluctuations in the Balearic grid before and after coal closure*, in Special Track: Modelling Dynamics of Power Grids (MoDyPoG), along with Energy 2021, IARIA XPS Press (2021).

[13] J. M. Stürmer, A. Plietzsch, and M. Anvari: *The risk of cascading failures in electrical grids triggered by extreme weather events*, in Special Track: Modelling Dynamics of Power Grids (MoDyPoG), along with Energy 2021, IARIA XPS Press (2021).

[14] T. Ritmeester and H. Meyer-Ortmanns: *Arbitrage on the energy market and its impact on the physical grid stability*, in Special Track: Modelling Dynamics of Power Grids (MoDyPoG), along with Energy 2021, IARIA XPS Press (2021).

[15] T. Ritmeester and H. Meyer-Ortmanns: *Minority games played by arbitrageurs on the energy market*, Physica A **573**, 125927 (2021).

[16] L. Rydin Gorjão: *Scaling and spatio-temporal properties of power grid frequencies: An open database*, in Special Track: Modelling Dynamics of Power Grids (MoDyPoG), along with Energy 2021, IARIA XPS Press (2021).

[17] L. Rydin Gorjão, R. Jumar, H. Maass, V. Hagenmeyer, C. Cigdem Yalcin, J. Kruse, M. Timme, C. Beck, D. Witthaut, and B. Schäfer: *Open database analysis of scaling and spatio-temporal properties of power grid frequencies*, Nat. Commun. **11**, 6362 (2020).

[18] R. Berner, S. Yanchuk, and E. Schöll: *Modelling power grids as pseudo adaptive networks*, in Special Track: Modelling Dynamics of Power Grids (MoDyPoG), along with Energy 2021, IARIA XPS Press (2021), arXiv:2104.06128.

[19] R. Berner, S. Yanchuk, and E. Schöll: *What adaptive neuronal networks teach us about power grids*, Phys. Rev. E **103**, 042315 (2021).

[20] R. Berner, S. Vock, E. Schöll, and S. Yanchuk: *Desynchronization transitions in adaptive networks*, Phys. Rev. Lett. **126**, 028301 (2021).

[21] H. Taher, S. Olmi, and E. Schöll: *Enhancing power grid synchronization and stability through time delayed feedback control*, Phys. Rev. E **100**, 062306 (2019).

[22] F. Hellmann, P. Schultz, P. Jaros, R. Levchenko, T. Kapitaniak, J. Kurths, and Y. Maistrenko: *Network-induced multistability through lossy coupling and exotic solitary states*, Nat. Commun. **11**, 592 (2020).

[23] F. Dörfler, M. Chertkov, and F. Bullo: *Synchronization in complex oscillator networks and smart grids*, Proc. Natl. Acad. Sci. U.S.A. **110**, 2005 (2013).

[24] T. Nishikawa and A. E. Motter: *Comparative analysis of existing models for power-grid synchronization*, New J. Phys. **17**, 015012 (2015).

[25] S. Auer, K. Kleis, P. Schultz, J. Kurths, and F. Hellmann: *The impact of model detail on power grid resilience measures*, Eur. Phys. J. Spec. Top. **225**, 609 (2016).

[26] M. Anvari, F. Hellmann, and X. Zhang: *Introduction to focus issue: Dynamics of modern power grids*, Chaos **30**, 063140 (2020).

[27] F. Dörfler and F. Bullo: *Synchronization in complex networks of phase oscillators: A survey*, Automatica **50**, 1539 (2014).

[28] F. A. Rodrigues, T. K. D. M. Peron, P. Ji, and J. Kurths: *The Kuramoto model in complex networks*, Phys. Rep. **610**, 1 (2016).

[29] A. E. Filatova, A. E. Hramov, A. A. Koronovskii, and S. Boccaletti: *Synchronization in networks of spatially extended systems*, Chaos **18**, 023133 (2008).

[30] M. Rohden, A. Sorge, M. Timme, and D. Witthaut: *Self-organized synchronization in decentralized power grids*, Phys. Rev. Lett. **109**, 064101 (2012).

[31] S. P. Cornelius, W. L. Kath, and A. E. Motter: *Realistic control of network dynamics*, Nat. Commun. **4**, 1942 (2013).

[32] A. E. Motter, S. A. Myers, M. Anghel, and T. Nishikawa: *Spontaneous synchrony in power-grid networks*, Nat. Phys. **9**, 191 (2013).

[33] P. J. Menck, J. Heitzig, J. Kurths, and H. J. Schellnhuber: *How dead ends undermine power grid stability*, Nat. Commun. **5**, 3969 (2014).

[34] S. Olmi, A. Navas, S. Boccaletti, and A. Torcini: *Hysteretic transitions in the Kuramoto model with inertia*, Phys. Rev. E **90**, 042905 (2014).

[35] D. Witthaut, M. Rohden, X. Zhang, S. Hallerberg, and M. Timme: *Critical links and nonlocal rerouting in complex supply networks*, Phys. Rev. Lett. **116**, 138701 (2016).

[36] S. Auer, F. Hellmann, M. Krause, and J. Kurths: *Stability of synchrony against local intermittent fluctuations in tree-like power grids*, Chaos **27**, 127003 (2017).

[37] E. B. T. Tchuisseu, D. Gomila, P. Colet, D. Witthaut, M. Timme, and B. Schäfer: *Curing Braess' paradox by secondary control in power grids*, New J. Phys. **20**, 083005 (2018).

[38] V. Mehrmann, R. Morandin, S. Olmi, and E. Schöll: *Qualitative stability and synchronicity analysis of power network models in port-Hamiltonian form*, Chaos **28**, 101102 (2018).

[39] P. Jaros, S. Brezetsky, R. Levchenko, D. Dudkowski, T. Kapitaniak, and Y. Maistrenko: *Solitary states for coupled oscillators with inertia*, Chaos **28**, 011103 (2018).

[40] B. Schäfer, 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 (2018).

[41] L. Tumash, S. Olmi, and E. Schöll: *Effect of disorder and noise in shaping the dynamics of power grids*, Europhys. Lett. **123**, 20001 (2018).

[42] C. Kuehn and S. Throm: *Power network dynamics on graphons*, SIAM J. Appl. Dyn. Syst. **79**, 1271 (2019).

[43] F. Molnar, T. Nishikawa, and A. E. Motter: *Asymmetry underlies stability in power grids*, Nat. Commun. **12**, 1457 (2021).

[44] K. Schmietendorf, J. Peinke, R. Friedrich, and O. Kamps: *Self-organized synchronization and voltage stability in networks of synchronous machines*, Eur. Phys. J. Spec. Top. **223**, 2577 (2014).

[45] M. Anvari, G. Lohmann, M. Waechter, P. Milan, E. Lorenz, D. Heinemann, M. Reza Rahimi Tabar, and J. Peinke: *Short term fluctuations of wind and solar power systems*, New J. Phys. **18**, 063027 (2016).

[46] M. Anvari, M. Waechter, and J. Peinke: *Phase locking of wind turbines leads to intermittent power production*, Europhys. Lett. **116** (2017).

[47] K. Schmietendorf, J. Peinke, and O. Kamps: *The impact of turbulent renewable energy production on power grid stability and quality*, Eur. Phys. J. B **90**, 222 (2017).