Studying power-grid synchronization with incremental refinement of model heterogeneity

Bálint Hartmann, Géza Ódor, Kristóf Benedek and István Papp

Journal: Chaos 35, 013138 (2025)

The dynamics of electric power systems are widely studied through the phase synchronization of oscillators, typically with the use of the second-order Kuramoto equation. While there are numerous well-known order parameters to characterize these dynamics, shortcoming of these metrics are also recognized. To capture all transitions from phase disordered states over phase locking to fully synchronized systems, new metrics were proposed and demonstrated in the literature on homogeneous models.

In this paper, the aim is to address a gap in the literature, namely, to examine how gradual improvement of power grid models affects the goodness of certain metrics. To study how the details of models are perceived by the different metrics, 12 variations of a power grid models were created, introducing varying levels of heterogeneity through the coupling strength, the nodal powers, and the moment of inertia. The grid models were compared using the second-order Kuramoto equation and adaptive Runge-Kutta solver, measuring the values of the phase, the frequency, and the universal order parameters.

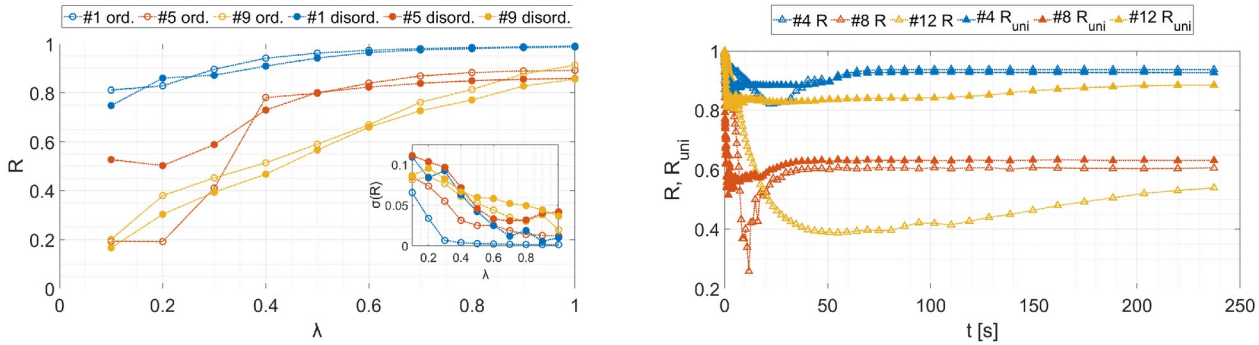

Figure. The left panel shows the Kuramoto order parameter R in the steady state in the function of different λ coupling values for modelling scenarios 1, 5, and 9. Inset: the corresponding standard deviations of the Kuramoto order parameter. The right panel displays the evolution of the Kuramoto and the universal order parameter for phase ordered initial condition at λ = 0.5. The general conclusion is that the Kuramoto order parameter captures the system in better detail when we study it in the function of the coupling, while from time evolution perspective, the universal order parameter shows a more noticeable separation between the curves corresponding to different model cases.

Finally, frequency results of the models were compared to grid measurements. It was found that the universal order parameter was able to capture more details of the grid models, especially in cases of decreasing moment of inertia. Even the most heterogeneous models showed notable synchronization, encouraging the use of such models.

References:

1. B. Hartmann, G. Ódor, K. Benedek, I. Papp; Studying power-grid synchronization with incremental refinement of model heterogeneity. *Chaos* 1 January 2025; 35 (1): 013138. https://doi.org/10.1063/5.0237050