A Mean Field Game approach for balancing intermittent power generation and consumption in electrical networks.

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The integration of renewable energy sources poses a major challenge for the stability of electrical grids.

While grid stability has historically been studied through the Kuramoto mean-field model [1, 2, 3], where nodes are treated as passive coupled oscillators governed by a Fokker–Planck equation this framework fails to capture the strategic behavior of modern energy actors. Indeed, producers and consumers are no longer simple machines, but active agents who optimize their energy strategy in response to market signals.

The present work proposes to extend the mean-field Kuramoto model by incorporating this strategic dimension through the formalism of Mean Field Games (MFG) [4, 5]. This approach replaces passive agents with strategic ones who, by virtue of their anticipatory capacity, optimize their decisions. At the microscopic level, each agent still follows a Langevin dynamics, but now controls its drift term, which corresponds to the power it injects or consumes. Each agent continuously adjusts this variable by anticipating the collective evolution of the grid. Its primary objective is not global stability, but rather the minimization of an individual cost functional that penalizes simultaneously its misalignment with the physical mean field, its economic expenditure (modulated by a dynamic price signal [6]), and user discomfort (social cost).

By adopting this formalism, we are able to investigate, through numerical simulations, what strategies agents adopt in response to market conditions and the overall state of the grid, and how these strategies in turn affect stability. Our numerical resolution of the MFG system reveals a phase transition between a coherent regime, in which all agents synchronize, and an incoherent regime, in which synchronization breaks down. Furthermore, we develop a variational approach to characterize the collective behavior of the system locally around the global phase in the coherent regime.

References:

[1] Kuramoto, Y.Self-entrainment of a population of coupled non-linear oscillators. In International symposium on mathematical problems in theoretical physics (1975) Springer (pp. 420-422).

[2] Filatrella G, Nielsen A.H and Pedersen N.F Analysis of a power grid using a Kuramoto-like model (2008) Eur. Phys. J. B 61 485–91

[3] Francisco A. Rodrigues, Thomas K. DM. Peron, Peng Ji, Jürgen Kurths. The Kuramoto model in complex networks, Physics Reports 610 (2016) 1–98.

[4] Jean-Michel Lasry, Pierre-Louis Lions. Mean field games. Japanese journal of mathematics, (2007) 2(1), 229-260.

[5] D.Ullmo, I.Swiecicki, T. Gobron, Quadratic Mean Field Games., Physics Reports 799 (2019) 1–35.

[6] Benjamin Schäfer et al. Decentral Smart Grid Control, New J. Phys. 17 015002 (2015).