The effects on power grid synchronization of increasing the level of refinement in distribution networks

Daniel Campos[1], Javier Cristín[1]

[1]Universitat Autonoma De Barcelona, Barcelona, Spain

The increasing penetration of energy communities, prosumers, and aggregators fundamentally transforms the operational dynamics of electric networks and can significantly affect synchronization in power grids, reinforcing the need for improved control strategies and regulatory frameworks to maintain their resilience and stability.

This context calls for understanding how heterogeneities and structures of low- and medium- voltage distribution networks can then affect such a global behavior, in analogy with recent studies (1-3). Studies on power-grid synchronization have demonstrated that increasing heterogeneity in generation sources, such as that introduced by decentralized prosumer generation, can modify phase-locking behavior and the thresholds for achieving coherent frequency synchronization across the network.(1). Furthermore, research on scenarios with high penetrations of inverter-based renewables—which characterize many prosumer installations—shows that synchronization becomes increasingly dependent on damping and control mechanisms rather than physical inertia, making the system more sensitive to rapid fluctuations in distributed production and consumption patterns (2,3).

As a further contribution on this area, in our presentation we will show results for the synchronization dynamics (both for the first-order and second-order Kuramoto model) emerging from block structures of oscillators (4,5), with each block representing a particular distribution/consumption region. Different plausible choices of the distribution network topology, as well as different sources of heterogeneity/noise, are explored. The corresponding changes in the dynamics and the stationary values of the order parameter are shown. From this, one can see that some nontrivial effects (like nonmonotonic behavior of the order parameter as a function of coupling strengths) emerge when introducing an increasing level of refinement in the distribution network. We interpret such effects in terms of local vs global (this is, intrablock vs interblock) synchronization dynamics, so underscoring the combined role that network topology and external variability/fluctuations may exert on the future stability of electricity systems.

References:
(1) H. Kim. (2021) New J. Phys. 23 063029
(2) G. Ódor and B. Hartmann. (2018) Phys. Rev. E 98, 022305
(3) B. Hartmann, G. Ódor, K. Benedek and I. Papp. (2025) Chaos 35, 013138.
(4) T.J Nguyen, D. Lee and B.J. Stolz (2025) J. Phys. Complex. 6 045009.
(5) S. Achterhof, J. M. Meylahn. (2021) Chaos, 31 (3): 033115.