Understanding the complexity of frequency and phase angle fluctuations in power grids

Power grids must modernize to meet climate goals and, at the same time, provide reliable and stable operating conditions. However, progress is hindered by a limited understanding of the stochastic processes underlying grid frequency fluctuations, which arise from increasing shares of renewables, consumer-induced fluctuations, and market trading. This issue is particularly acute in Africa, where grids often face limited investment and rapid demand growth. This talk presents results from a newly collected large-scale, high-resolution dataset of grid frequency and phase angles obtained in the United Kingdom and South Africa, containing close to one billion data points. Using superstatistical modeling, power fluctuations arising from market activity are treated as a slowly varying parameter that drives grid dynamics, thereby enabling the incorporation of nonlinear frequency control. This approach yields an analytical model that reproduces multimodal frequency distributions previously obtained through numerical simulations, along with heavy-tailed fluctuations and double-exponential decays of the frequency autocorrelation. Beyond frequency, the largely overlooked problem of characterizing spatial phase-angle fluctuations is addressed, and predictions are compared with measurements. A low-dimensional effective grid model is shown to accurately fit South African data despite the grid's complexity, highlighting significant differences relative to the United Kingdom grid. These results clarify how energy market activity and control policies shape grid dynamics in countries with contrasting levels of infrastructure maturity, offering a quantitative comparison between emerging and developed energy systems.

Paper: https://arxiv.org/abs/2604.03133
Open-source code: https://github.com/aleable/power-grid-complexity