Statistical inference and superstatistics for power grid modeling

Uninterrupted power grid operation is central to a sustainable future. Yet surprisingly little is understood about power grids' collective behavior. In particular, what do the statistical signatures of grid frequency and phase-angle fluctuations between generators across the grid look like, and can we model them? Existing models either capture these features of real data only partially, rely on numerical simulations that do not allow for principled parameter inference, or focus on synthetic data. In this talk, I will: (i) introduce a model for grid frequency modeling grounded in non-equilibrium statistical physics, together with a dedicated statistical inference algorithm; and (ii) present a simple "tilted-washboard" model describing phase-angle differences. Both models closely match real-world measurements from a newly collected, high-resolution dataset measured in Great Britain and South Africa. Together, these results clarify how socio-technical factors influence power grid observables.

Reference 1:
Paper: https://journals.aps.org/prxenergy/accepted/10.1103/w42m-gb7l (arXiv: https://arxiv.org/abs/2604.03133)
Code: https://github.com/aleable/power-grid-complexity
Data: https://zenodo.org/records/19397526

Reference 2:
Paper: https://arxiv.org/abs/2607.28232
Code: https://github.com/aleable/power-grid-inference
Data: https://zenodo.org/records/21461024

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1 Introduction

Power grids are among the largest man-made networks ever built, and modern societies, as well as a sustainable future, depend on their uninterrupted operation [1].

In a grid, generators at the network nodes rotate in synchrony, all sharing a common frequency, and energy supply and demand are matched by adjusting the frequency: whenever there is an excess of energy supplied to the grid, the generators rotate faster; conversely, when supply falls short, generators rotate slower [2]. The grid frequency is therefore an important indicator of the grid's operational state, and fluctuations around its constant nominal value depend on many factors, such as consumer demand [3], intermittent renewable generation [4], and electricity market trading [5].

Measured frequency distributions in power grids worldwide are conspicuously not Gaussian, as they exhibit heavy tails and multimodality [6] (see also Fig. 1A). Capturing both features at once in a model has proven difficult. Established approaches tend to focus on only one of the two features, say heavy-tailedness, in favor of analytical tractability [7]. More recent models can reproduce both features through numerical simulation [8], but do not allow for principled statistical modeling. That is, the agreement between data and numerical simulations is checked *a posteriori*, rather than being enforced *a priori* for parameter identification. This opens a first research gap.

Beyond frequency, each generator's state is also captured by its phase angle. This raises a second important question, relatively overlooked in the study of power grids: what can the coupled fluctuations of angles between pairs of generators across the grid tell us about the network's spatial structure?

2 Results

In my talk, I will present two research works addressing the questions above [9, 10].

I will make a case in point by comparing theoretical predictions with high-resolution datasets of grid frequency and phase angles we collected from London and Glasgow, Great Britain, and Bloemfontein and Stellenbosch, South Africa. These two grids are central to their respective energy markets [11, 12], but operate under markedly distinct conditions and yield substantially different measurements.

Turning to methodology, I will first discuss a model for frequency dynamics built on superstatistics [13], a concept borrowed from non-equilibrium statistical physics. The idea is to model the frequency $\omega(t)$ with a stochastic differential equation governed by three factors: a nonlinear damping term $H(\omega)$, reflecting the control action engineered into generators to damp excessive frequency fluctuations; Gaussian white noise, $\varepsilon\xi(t)$, capturing fast fluctuations; and, crucially, a slowly varying driver $P(t)$, representing the fluctuating power imbalance between generation and load, namely, the environment in which the grid operates. These variables are combined as

$$\frac{\mathrm{d}\omega}{\mathrm{d}t} = H(\omega) + P(t) + \varepsilon\,\xi(t)\,. \tag{1}$$

Such a minimal model is remarkably effective when combined with statistical inference. In particular, I will show how Eq. (1) can be cast into an optimization problem that jointly infers the latent power imbalance $P(t)$, the control function $H(\omega)$, and the noise amplitude ε that best describe the data, using only frequency time series as input. Remarkably, the inferred quantities allow fitting measured frequency distributions with unprecedented detail compared to previous work (see Fig. 1A).

Second, I will discuss a reduced, two-node grid model that recasts the problem of modeling differences in the phase angles of grid generators as motion in a stochastically driven tilted washboard potential [14]. Such a model is analytically tractable but had never before been tested against large-scale measurements. Surprisingly, theoretical predictions match measurements from South Africa in close agreement (see Fig. 1B), despite the underlying physical grid's complexity (see Fig. 1C). I will discuss potential explanations for why this agreement holds so closely, as well as the limitations that prevent the same model from working in Great Britain, and link these open questions to future work.

Summary. Combining statistical inference with statistical physics, we obtained a physically interpretable model that fits measured grid frequency data with unprecedented fidelity. The same data show that a two-node grid model describes generator phase angles in South Africa well. Taken together, these results advance our understanding of how grid codes, energy markets, and network topology shape power grid observables, and propose quantitative characterizations of large-scale empirical data that had so far escaped detailed analysis.

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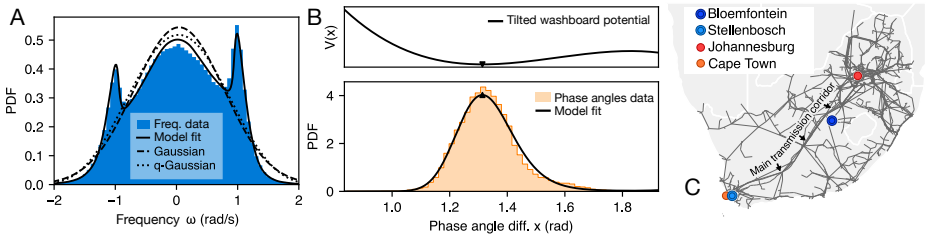


Fig. 1. (A) Grid frequency distribution measured in South Africa in 2025, fitted with our model (solid line) and compared against baselines (dashed and dotted lines). (B) Generator phase angle difference between measurements in Stellenbosch and Bloemfontein. The model fit and the tilted washboard potential are shown as solid lines. (C) The power grid of South Africa, with the main transmission corridor connecting the areas around Cape Town and Johannesburg highlighted.

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