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Assessing the robustness of the U.S. power grid under extreme wind events

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In this work we address the problem of assessing the network robustness of transportation networks due to external stressors, such as natural events. Here we focus on US power grid, but the same framework can be applied in a system where there is a physical quantity flowing through the nodes, as current in the power lines. As a stressor, we consider daily wind gust data at 10 meters above ground level, spanning from 2014 to 2023, as an external field that drives node failures as in Fig. 1 (left), according to the probability function proposed in [1].

For the dynamical model, we adopt a non-Markovian spreading mechanism introduced in [2], which we simulate over the U.S. power grid topology, denoted as W_{ij} :

$$c_i(t+1) = \sum_j T_{ij} c_j(t) + j_i^{\pm}$$

where $T_{ij} = W_{ij} / c_i$ is the transfer matrix, $c_i(t)$ represents the outflow current per unit weight from node i and the last term account for possible source j^+ or sink j^- contributions.

At each time step, the directed current from i to j is computed as $L_{ij} = c_i W_{ij}$, with the total load on the line is given by $C_{ij} = L_{ij} + L_{ji}$, following the mechanism proposed in [2]. In power grids, the redistribution of load following an initial failure can trigger secondary failures, potentially leading to cascading failures. To model this, we impose that each line has a maximum capacity $C_{ij}^{\max} = (1+\alpha) C_{ij}^0$, which is proportional to the initial load on the line C_{ij}^0 and to a tolerance parameter α . If a power line fails due to strong wind, the transfer matrix in Eq. (1) is updated accordingly, and the dynamics evolve until equilibrium is reached.

Finally, we validate our approach using a dataset of historical power outages in the U.S. We apply our framework to predict the number of people affected by outages during extreme weather events, as shown in Fig. 1 (right). Our model achieves a significant Spearman correlation of 0.37, demonstrating that, despite its simplicity, it aligns with real-world observations. This framework has potential applications in real-time network control and optimization, particularly for large-scale systems where using more detailed models would be computationally unfeasible.

References

- [1] Mathaios Panteli, Cassandra Pickering, Sean Wilkinson, Richard Dawson, and Pierluigi Mancarella. Power System Resilience to Extreme Weather: Fragility Modeling, Probabilistic Impact Assessment, and Adaptation Measures. *IEEE Transactions on Power Systems*, 32(5):3747–3757, September 2017.
- [2] Ingve Simonsen, Lubos Buzna, Karsten Peters, Stefan Bornholdt, and Dirk Helbing. Transient Dynamics Increasing Network Vulnerability to Cascading Failures. *Physical Review Letters*, 100(21):218701, May 2008.

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