Emergent failures and cascades in power grids: A large deviation approach

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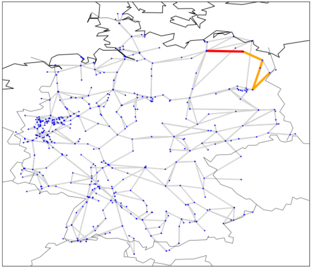
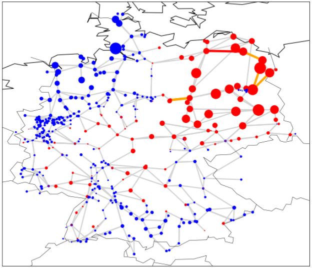
Emergent line failures

Intermittent renewable generation poses new challenges for power grid reliability, and questions the validity of classical cascading failure models.

- **Classical cascades:** initiated by an *external* event, which leads to the direct failure of the attacked network component
- **Emergent cascades:** initiated *endogenously* due to noisy weather-correlated power inputs and power flow physics





Research questions

- **Which lines are most vulnerable to noisy inputs?**
- **How do emergent failures most likely occur and propagate?**
- **How do they differ from classical cascades?**

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Setting:

$$\left.\begin{array}{l}\text{nominal operating point is safe}\\ \text{noise } \varepsilon \text{ is small}\end{array}\right\} \Longrightarrow \boxed{\text{Overloads due to large fluctuations}}$$

Large deviations theory:

$$\mathbb{P}(\text{line } \ell \text{ fails}) \approx \exp(-I_\ell/\varepsilon) \qquad \text{as } \varepsilon \to 0$$

$$I_\ell = \text{explicit function of nominal operating point and network structure}$$

Question 1: LD-based ranking of line failures

The **LD-based ranking** successfully predicts the most likely lines to fail, providing an accurate indicator of system vulnerabilitie.

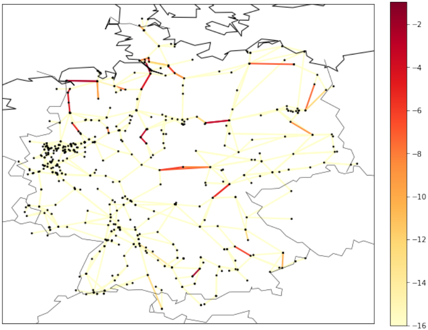


Figure: Exact overload probabilities $\log_{10} \mathbb{P}(\text{Line } \ell \text{ fails})$.

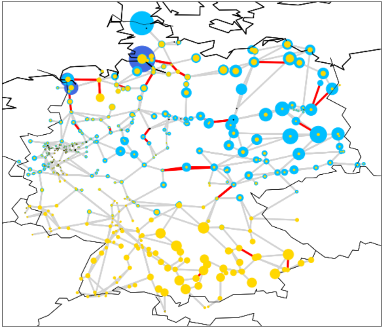
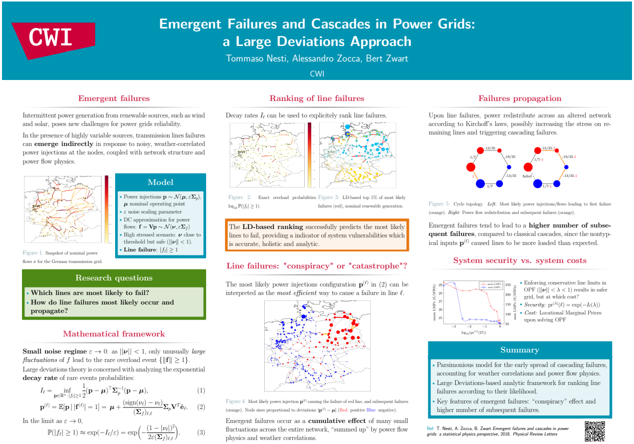


Figure: LD-based top 5% of most likely failures (in red), nominal renewable inputs

... Come see the poster for the full story!



Emergent Failures and Cascades in Power Grids: a Large Deviations Approach

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Emergent failures

Intermittent power generation from renewable sources, such as wind and solar, poses new challenges for power grids reliability.

In the presence of highly variable sources, transmission lines failures can **emerge indirectly** in response to noisy, weather-correlated power injections at the nodes, coupled with network structure and power flow physics.

Figure 1: Snapshot of nominal power flows ν for the German transmission grid.

Model

- Power injections $\mathbf{p} \sim \mathcal{N}(\boldsymbol{\mu}, \varepsilon \boldsymbol{\Sigma}_p)$, $\boldsymbol{\mu}$ nominal operating point
- ε noise scaling parameter
- DC approximation for power flows: $\mathbf{f} = \mathbf{V}\mathbf{p} \sim \mathcal{N}(\boldsymbol{\nu}, \varepsilon \boldsymbol{\Sigma}_f)$
- High stressed scenario: $\boldsymbol{\nu}$ close to threshold but safe ($\|\boldsymbol{\nu}\| < 1$).
- **Line failure**: $|f_\ell| \geq 1$

Research questions

- **Which lines are most likely to fail?**
- **How do line failures most likely occur and propagate?**

Mathematical framework

Small noise regime $\varepsilon \to 0$: as $||\boldsymbol{\nu}|| < 1$, only unusually *large fluctuations* of f lead to the rare overload event $\{\|\mathbf{f}\| \geq 1\}$.

Large deviations theory is concerned with analyzing the exponential **decay rate** of rare events probabilities:

$$I_\ell = \inf_{\mathbf{p} \in \mathbb{R}^n : |f_\ell| \geq 1} \frac{1}{2} (\mathbf{p} - \boldsymbol{\mu})^\top \boldsymbol{\Sigma}_p^{-1} (\mathbf{p} - \boldsymbol{\mu}), \tag{1}$$

$$\mathbf{p}^{(\ell)} = \mathbb{E}[\mathbf{p} \,|\, |\mathbf{f}^{(\ell)}| = 1] = \boldsymbol{\mu} + \frac{(\mathrm{sign}(\nu_\ell) - \nu_\ell)}{(\boldsymbol{\Sigma}_f)_{\ell,\ell}} \boldsymbol{\Sigma}_p \mathbf{V}^T \hat{\mathbf{e}}_\ell. \tag{2}$$

In the limit as $\varepsilon \to 0$,

$$\mathbb{P}(|f_\ell| \geq 1) \approx \exp(-I_\ell/\varepsilon) = \exp\left(-\frac{(1 - |\nu_\ell|)^2}{2\varepsilon (\boldsymbol{\Sigma}_f)_{\ell,\ell}}\right). \tag{3}$$

Ranking of line failures

Decay rates I_ℓ can be used to explicitely rank line failures.

Figure 2: Exact overload probabilities $\log_{10} \mathbb{P}(|f_\ell| \geq 1)$.

Figure 3: LD-based top 5% of most likely failures (red), nominal renewable generation.

The **LD-based ranking** successfully predicts the most likely lines to fail, providing a indicator of system vulnerabilities which is accurate, holistic and analytic.

Line failures: "conspiracy" or "catastrophe"?

The most likely power injections configuration $\mathbf{p}^{(\ell)}$ in (2) can be interpreted as the *most efficient* way to cause a failure in line ℓ.

Figure 4: Most likely power injection $\mathbf{p}^{(\ell)}$ causing the failure of red line, and subsequent failures (orange). Node sizes proportional to deviations $|\mathbf{p}^{(\ell)} - \boldsymbol{\mu}|$ (Red: positive Blue: negative).

Emergent failures occur as a **cumulative effect** of many small fluctuations across the entire network, "summed up" by power flow physics and weather correlations.

Failures propagation

Upon line failures, power redistribute across an altered network according to Kirchoff's laws, possibly increasing the stress on remaining lines and triggering cascading failures.

Figure 5: Cycle topology. *Left*: Most likely power injections/flows leading to first failure (orange). *Right*: Power flow redistribution and subsequent failures (orange).

Emergent failures tend to lead to a **higher number of subsequent failures**, compared to classical cascades, since the nontypical inputs $\mathbf{p}^{(\ell)}$ caused lines to be more loaded than expected.

System security vs. system costs

- Enforcing conservative line limits in OPF ($||\boldsymbol{\nu}|| < \lambda < 1$) results in safer grid, but at which cost?
- *Security:* $\mathrm{pr}^{(\lambda)}(\ell) = \exp(-I_\ell(\lambda))$
- *Cost:* Locational Marginal Prices upon solving OPF

Summary

- Parsimonious model for the early spread of cascading failures, accounting for weather correlations and power flow physics.
- Large Deviations-based analytic framework for ranking line failures according to their likelihood.
- Key features of emergent failures: "conspiracy" effect and higher number of subsequent failures.

Ref: T. Nesti, A. Zocca, B. Zwart *Emergent failures and cascades in power grids: a statistical physics perspective*, 2018. *Physical Review Letters*

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