Critical synchronization dynamics on power grids

Joint work with Géza Ódor, Bálint Hartmann and Jeffrey Kelling

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Wigner GPU Day 2022

June 21, 2022

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Energy Research

ELKH
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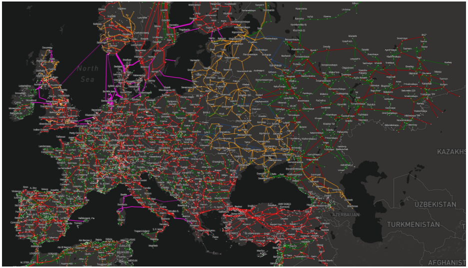
arxiv:2205.13472

Power-grid networks



- Power grids are critical for human civilization: generating, transmitting and distributing electric energy

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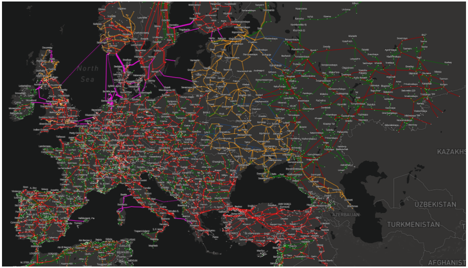

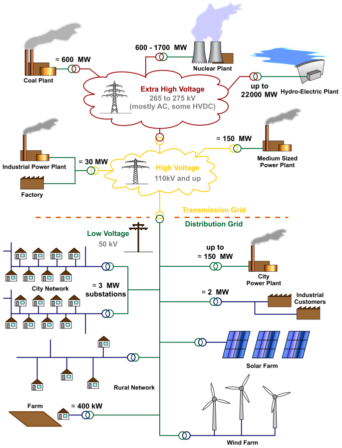

- Power grids are critical for human civilization: generating, transmitting and distributing electric energy
- Hierarchical: high – medium – low voltages, millions of nodes
- Crutial to maintain stability
  Challenges: nonlinear&complex system, multiple scales, growing number of renewables

Consequences of blackouts and their statistics

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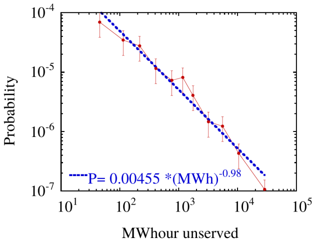

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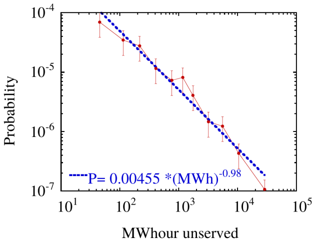

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- Blackout size dist. follow power laws
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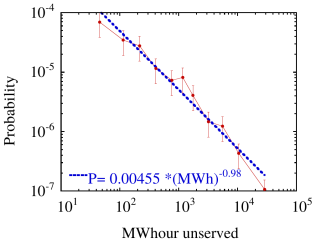

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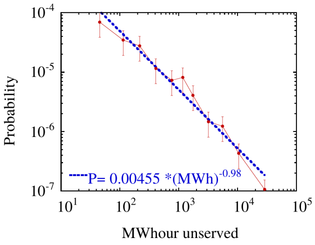

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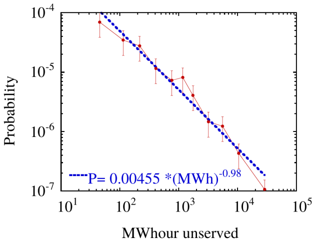

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blackout → AC desynchronization cascade ∼ DC threshold models

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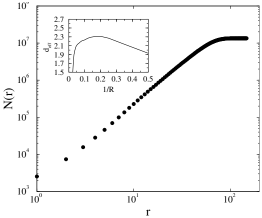
US and EU HV grids

	N	E	L	$\langle k \rangle$	C	σ	d
US	4194	6594	18.7	2.67	0.08	9.334	3.0(1)
EU	13478	33844	49.51	2.51	0.089	98.63	2.6(1)



N: Number of nodes

E: Number of edges

L: average shortest path length

C: Watts-Strogatz clustering coefficient

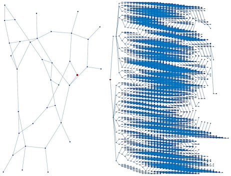
$$C = \frac{1}{N} \sum_i 2n_i/k_i(k_i - 1)$$

σ:

$$\sigma = \frac{C/C_r}{L/L_r}$$

$\Rightarrow$ EU HV is small world.

- This study will focus on HV nets.



HV: from operators

MV an LV: generated w.r.t. empirical electrical distributions [1].

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The synchronization model

- Blackouts can be modeled by desynchronization of AC power grids

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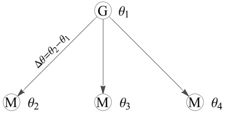

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The synchronization model

- Blackouts can be modeled by desynchronization of AC power grids
- Power transmission: a mismatch "$\Delta\theta$" in the phases between "G" and "M" ⇒ the Kuramoto model with **inertia** [1]:

$$
\begin{aligned}
P_{\text{source}} &= P_{\text{acc.kinetic}} + P_{\text{diss.}} + P_{\text{transmitted}} \\
&= \frac{1}{2} I \frac{d}{dt} \dot{\theta}_1^2 + P_{\text{diss.}} - P^{\text{MAX}} \sin(\Delta\theta) \\
\Rightarrow \ddot{\theta}_1 &= P - \alpha\dot{\theta}_1 + P^{\text{MAX}} \sin(\Delta\theta).
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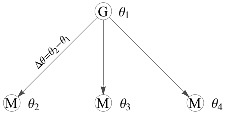
$$



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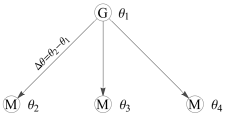

- For a network of N oscillators:

$$\begin{aligned} \dot{\theta}_i(t) &= \omega_i(t) \\ \dot{\omega}_i(t) &= \omega_i(0) - \alpha\dot{\theta}_i(t) + K \sum_{j=1}^{N} A_{ij} \sin\left[\theta_j(t) - \theta_i(t)\right] . \end{aligned} \quad (2)$$

α: damping factor; K: global coupling; $\omega_i(0) \sim N(0,1)$

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Method and measured quantities

- For large N, solved Eqs. (2) by numeric solvers: 4th-order Runge-Kutta, Bulirsch-Stoer

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- Measured quantities
  1. Phase order parameter

$$z(t_k) = \frac{1}{N}\left|\sum_j \exp\left[i\theta_j(t_k)\right]\right|$$
$$R(t_k) = \langle r(t_k)\rangle \,. \tag{3}$$

  2. Frequency variance: $\Omega(t_k) = \langle \mathrm{var}(\omega_i(t_k))\rangle$.

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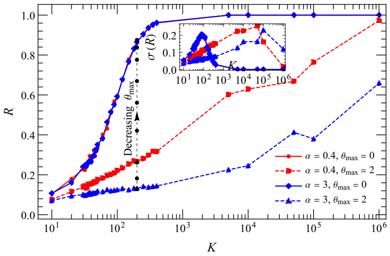

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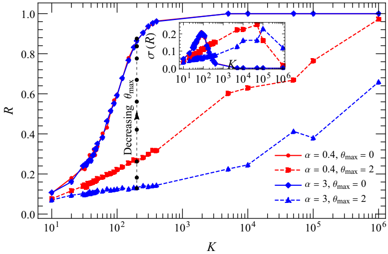

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- Thermalization followed by removing one link ⇒ cascade line failures.

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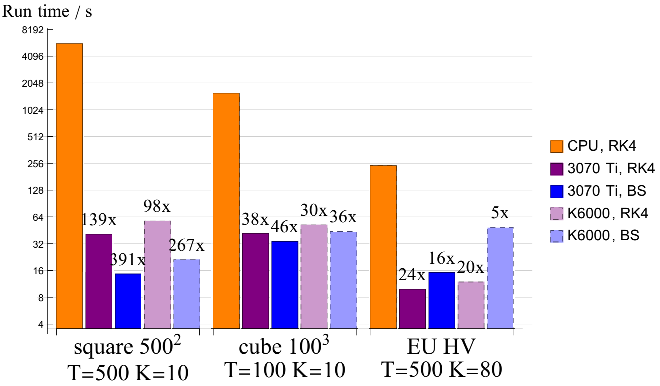
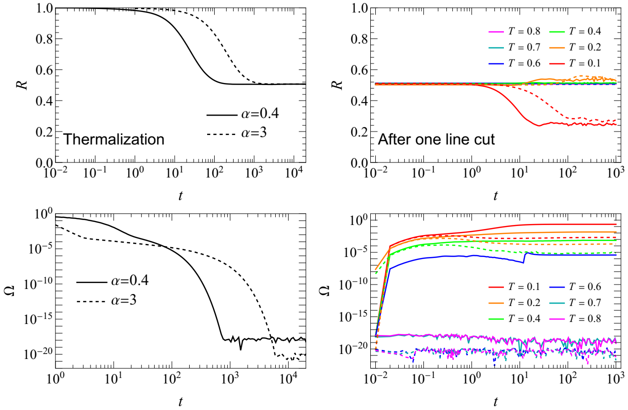
Benchmarks

- CPU: Intel Xeon X5650 @ 2.67GHz (debrecen)
- GPU:
  1. GeForce RTX 3070 Ti (local cluster)
  2. Quadro K6000 (debrecen2)



The effect of one line cut



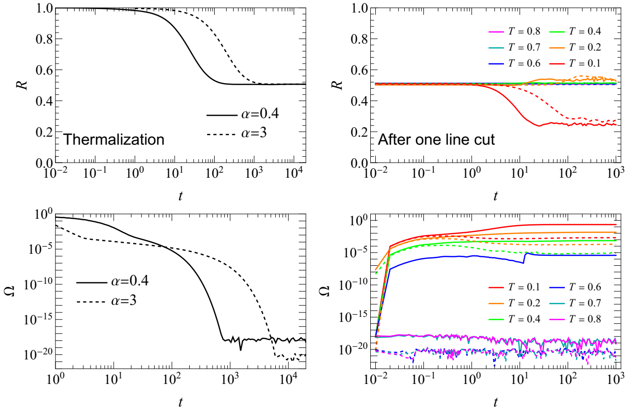
EU network $K = 80$

1. Stronger damping effect only slows down R, but leads to a smaller Ω.
2. For certain T, R may even increase: islanding effects?

The effect of one line cut

After thermalization, randomly **remove** a link w.r.t. the overload condition:

$$|\sin(\theta_j - \theta_i)| > T \Rightarrow A_{ij} := 0.$$



EU network $K = 80$

1. Stronger damping effect only slows down R, but leads to a smaller Ω.
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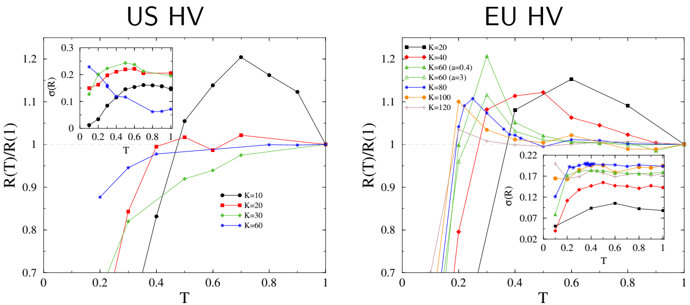
Relative change in R



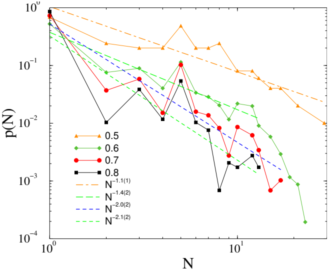
- Phase order may increase after an attack for not very strongly coupled systems; resemblance to the islanding effect [1,2].
- There may exist a critical line along (K_c, T_c) as indicated by $\sigma(R)$.

[1] R. Baldick *et al.*, 2008 IEEE Power and Energy Society General Meeting.

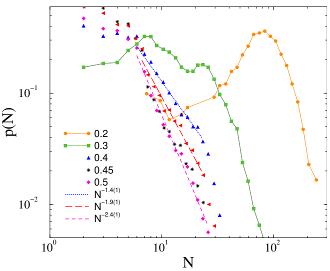
[1] A. Esmaeilian *et al.*, IEEE Trans. Ind. Appl. **53**, 622 (2016).

Cascade failure statistics

US HV $K = 30, \alpha = 0.4$



EU HV $K = 60, \alpha = 0.4$

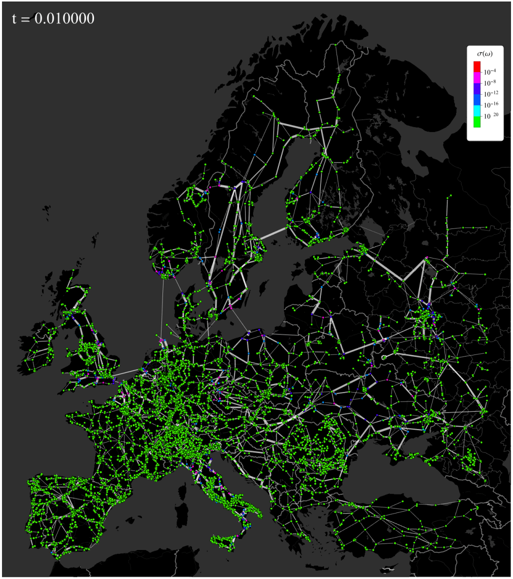


- The distribution of the total line failures N_f follows non-universal power laws in the vicinity of (K_c, T_c)

$$p(N_f) \sim N_f^{-\tau}. \tag{4}$$

- GPU support is quite crucial.
- "Dragon King" bumps for unexpected rare events may emerge for certain T.

Chimera state



Conclusion and outlook

1. The synchronization and desynchronization of AC power grids could be best modeled by the second-order Kuramoto equations;
2. The damping factor slows down the dynamics of the order parameter, but would be desirable for achieving better frequency entrainment;
3. One line cut after thermalization triggers cascade failures:
   1. For moderate K and T values, islanding effects;
   2. In the vicinity of (K_c, T_c), cascade sizes follow **non-universal power laws**.

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