Stability of AC power grids – Dynamic and static investigations

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Abstract

The inclusion of more and more renewable energy sources into modern power grids leads inevitably to drastic changes of the topology of power grids. Nevertheless it is not known to date what an optimal network topology for power transport and robustness could be [1]. Here we use the recently introduced novel criteria of redundant capacities to identify weak links in power grids [2]. We propose new strategies to cure these critical links and show their advantages over possible alternatives. Our results may serve as a step towards optimal network topologies in real-world power grids.

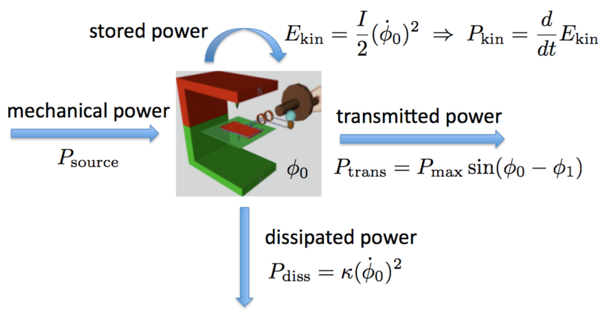
In an alternative approach, we investigate the long-range response to transmission line disturbances in DC and AC grids. Local changes in the topology of electricity grids can cause overloads far away from the disturbance [3], making the prediction of the robustness against power outages a challenging task. The impact of single-line additions on the long-range response of DC electricity grids has recently been studied [4]. In the future, we are going to extend the investigation to the case of alternating currents. To that end, we study electricity grids with a random distribution of complex impedances on the edges of a regular 2D grid. By determining the resonance frequencies of the circuit, we are able to forecast consequences for the conditions for stable grid operation. Further, we analyse the spatial distribution of the voltage amplitudes.

Oscillator model

Main features of the model [5]:

→ Derived from electric circuits of generators & motors

→ Two variables each generator or motor (phase ϕ and velocity $\dot\phi$)



The equation of motion for each unit is:

$$\ddot\phi_i = P_i - \alpha_i\dot\phi_i + K_{ij}\sum_{j\neq i} a_{i,j}\sin(\phi_j - \phi_i) \qquad (1)$$

→ loads of the power sources (P_i)

→ maximum transmission of lines (K_{ij})

→ time scale of phase changes (α_i^{-1})

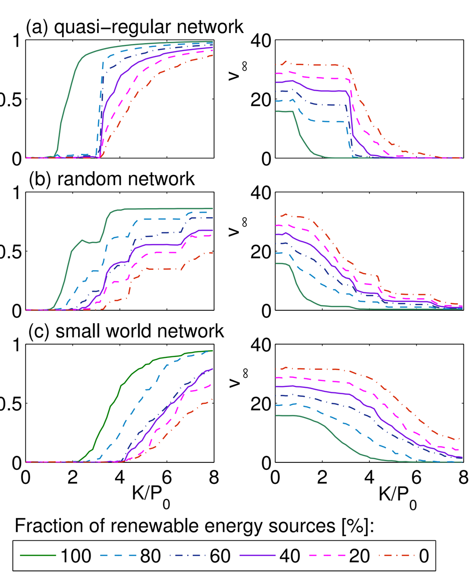
→ adjacency matrix (a_{ij})

Decentralization

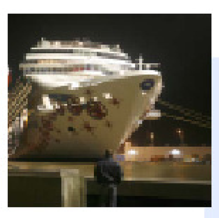
→ Synchronization transition for different fractions of renewable energies and different network topologies (regular, small-world, random)

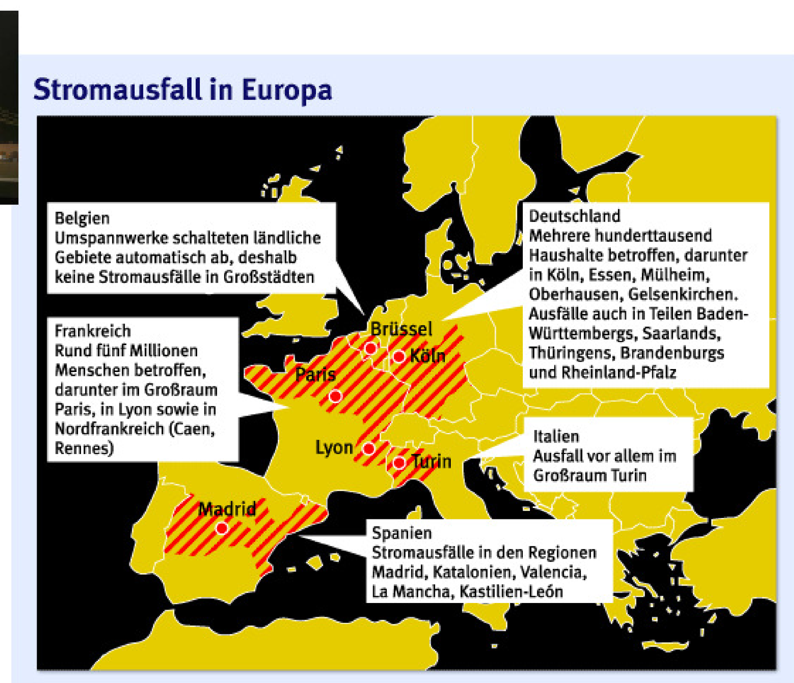
→ The results of the order parameters are averages over 100 realizations in the long time limit

→ Synchronization is faster in case of higher fraction of renewables [1]



Power outages





Power outage in Germany in 2006 after the intentional shutdown of a single transmission line [6].
P. Pourbeik: "Typically, the blackout can be traced back to the outage of a single transmission element." [7]

Breakdown of transmission lines

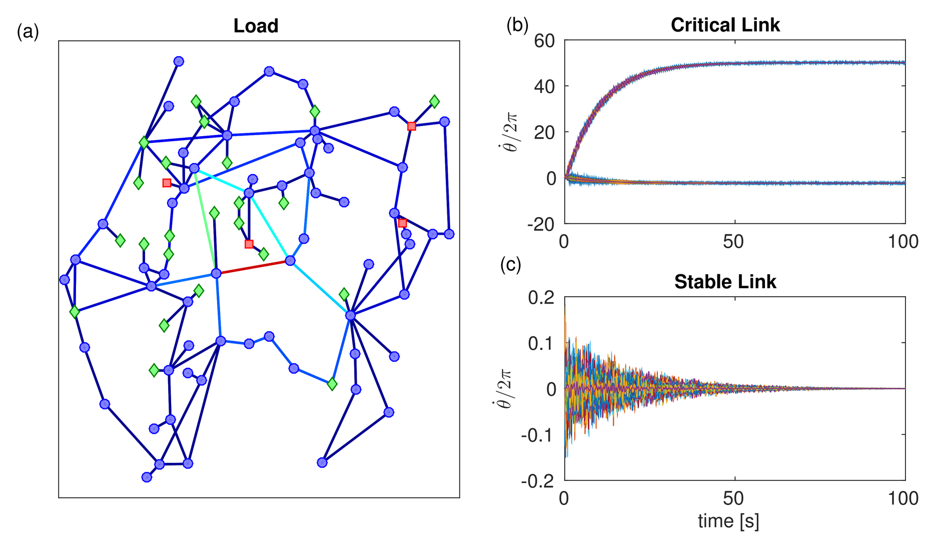


Figure 1: *Stable and critical links [8]. (a) Romanian high voltage power grid. (b) Failure of a critical transmission line. (c) Failure of a non-critical transmission line.*

Color Code of transmission lines: power flow
Red squares: conventional power sources
Green diamonds: renewable power sources
Blue circles: consumers

Strategies to prevent power outages

→ Building more transmission lines?

→ Identifying heavily loaded transmission lines and strengthen them?

→ Calculate redundant capacities, i.e., the difference between capacities and loads of transmission lines?

→ Consider alternative paths for the power flow of critical lines?

In preparation: Performance of different strategies

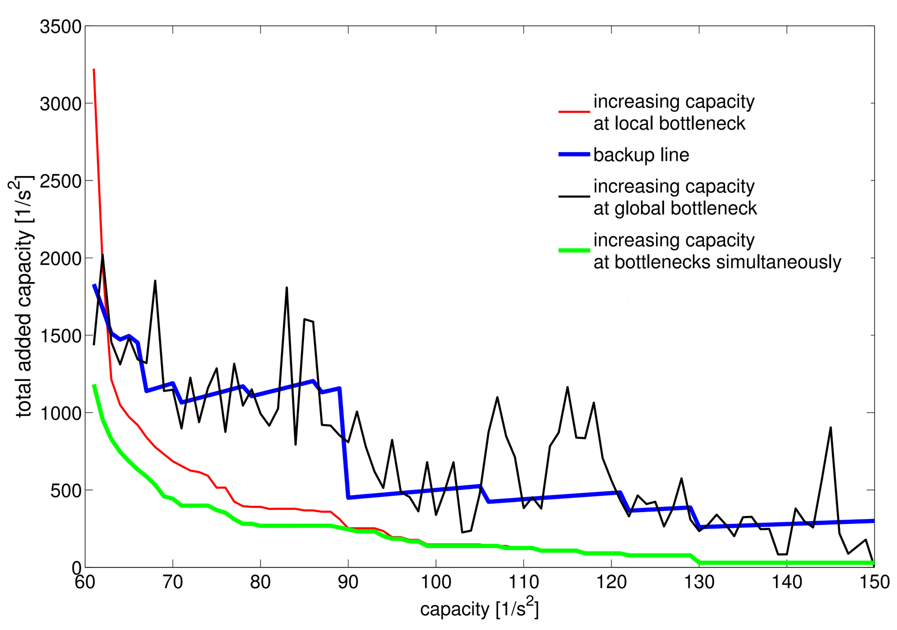


Figure 2: *Performance of four different strategies for the Romanian high voltage power grid [8].*

→ Blue curve: Additional backup transmission line as benchmark strategy.

→ Black curve: Increase capacity of transmission lines at the global minimum of the difference between capacity and power flow.

→ Red curve: Increase the capacity of transmission lines sequentially at the bottleneck of the alternative paths.

→ Green curve: Increase the capacity of transmission lines simultaneously at the bottleneck of the alternative paths.

Summary and Outlook

→ Identifying and strengthening of the capacity of bottlenecks of alternative paths seems to be a good strategy

→ Which are the limitations for this method?

→ Maximal length for the alternative path for the method in order to work more efficiently?

→ General topologies?

→ Optimal network structure?

Long-range response in DC electricity grids

What effect does the addition of a single transmission line have on the stability of the network?

Model

→ 2D grid with periodic boundary conditions, $L \times L$.

→ Constant link conductances $Y_{ij} \in \mathbb{R}$, i.e. *ohmic resistances* [4].

→ Consider Joule's heat dP^{Ω}_{ij}.

Combine *Ohm's law*

$$I_{ij} = Y_{ij}V_{ij} \qquad (2)$$

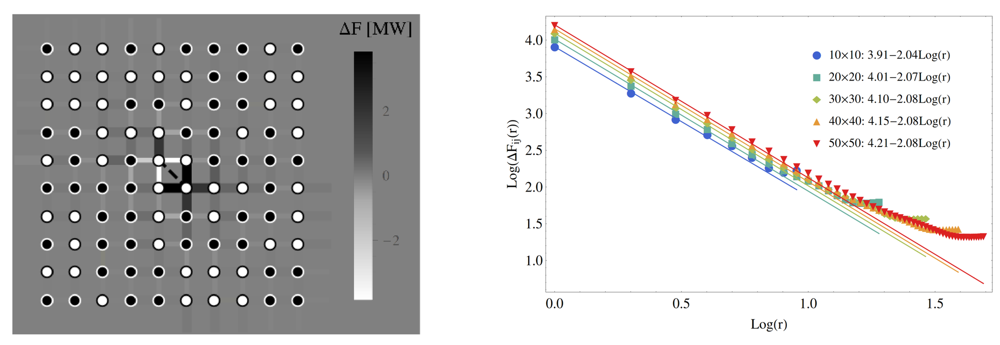
with *Kirchhoff's laws*

$$I_i = \sum_j I_{ij} \qquad V_{ij} = V_i - V_j \qquad (3)$$

and transmitted powers $F_{ij} = V_i I_{ij}$ to get *power flow equations*

$$P_i = V_i \sum_j Y_{ij}(V_i - V_j) \quad . \qquad (4)$$

Observe change ΔF_{ij} in the transmitted power as a function of the distance r from the disturbance after one line has been added.



(a) Change of power flow. (b) Distance dependence.

Figure 3: *Change of power flow ΔF_{ij} in dependence of the distance r to the added link [4].*

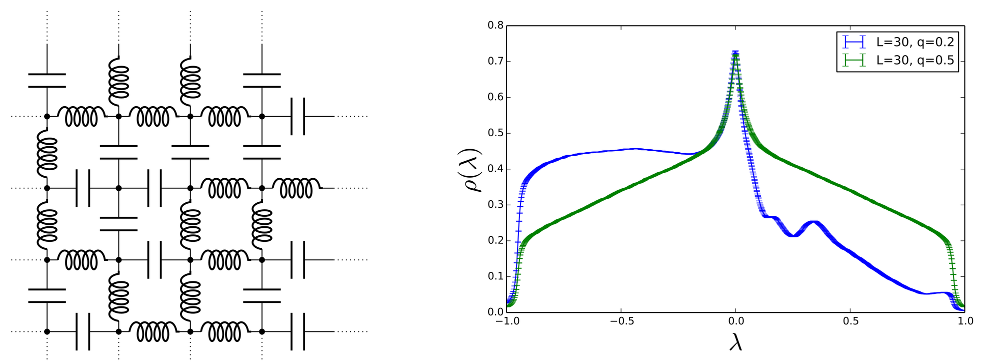
$$\Rightarrow \quad \langle|\Delta F_{ij}|\rangle \sim r^{-\beta} \qquad \beta \approx 1.3 \qquad (5)$$

In preparation: Long-range response in AC grids

→ Extend the method to AC power grids.

→ First consider only *current flow equations* and the *resonance case*, $I_i = 0\,\forall\, i$ [9].

→ Start with *binary distribution* for the link admittances $Y_{ij} \in \mathbb{C}$ with *composite ratio* q [9].



(a) 2D grid. (b) Resonance spectrum.

Figure 4: *Density of resonance frequencies $\rho(\lambda)$ of a regular 2D grid with a binary distribution of capacitances and inductances.*

Outlook

→ Simulate *power flow* (like in the DC case).

→ Consider realistic *network topologies*.

→ Consider realistic admittance distributions $\mathcal{P}(Y_{ij})$.

→ Consider realistic *power consumption and generation* distributions $\mathcal{P}(P_i)$.

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