Power Blackouts and the Domino Effect: Real-Life examples and Modeling

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Acknowledgments

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- Rafal Weron, Wroclaw

Financial Support
- EU project IRRIIS
  - IRRIIS: “Integrated Risk Reduction of Information-based Infrastructure Systems”
- ERC
  - COST P10, “Physics of Risk”
Motivation

New York, August 14, 2003

Rome, September 28, 2003
Motivation

Blackout Northern America, 2003: total loss of 6.7 billion USD, 50 Mio. people without electric power for about 24 hours.

Blackout Italy, 2003: total loss of 151 Mio. USD.

Blackout in parts of the USA and Canada (2003), an impressive example of the long-reaching accompaniments of supply network failures.
Power Blackouts: How frequent are they?

- North American Electricity Reliability Council (NERC) data
  - Analyzed by Carreras, Dobson, Newman & Poole
  - 15 years of data (1984-1998)
  - 427 blackouts
  - On average 28.5 per year, waiting time of 12 days

- Three measures of blackout size
  - Energy unserved (MWh)
  - Amount of power lost (MW)
  - Number of customers affected

Source: Weron and Simonsen (2005)
Risk of Power Blackouts

- There are rather few large blackouts
  - So why should we care at all?

- Risk = Probability * Cost
- Large Power Blackouts are the most RISKY!

Source: Weron and Simonsen (2005)
Power Blackouts: Real-Life examples

Europe Nov. 2006: What happened…?

State of the power grid shortly before the incident

Sequence of events on November 4, 2006

1, 3, 4, 5 – lines switched off for construction work
2 – line switched off for the transfer of a ship by Meyer-Werft

Source: Report on the system incident of November 4, 2006, E.ON Netz GmbH

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Power Blackouts and the Domino Effect
Power Blackouts: Real-Life examples

Failure in the continental European electricity grid on November 4, 2006

Power Blackouts:
The Domino Effect (Cascading Failure)

“Under certain conditions, a network component shutting down can cause current fluctuations in neighboring segments of the network, though this is unlikely, leading to a cascading failure of a larger section of the network. This may range from a building, to a block, to an entire city, to the entire electrical grid.”

Power Blackouts: Real-Life examples


See: Wikipedia for sequence of events
Power Blackouts: Summary

- Cascading failures do exist in real life systems.
  - Examples
    - The power grid
    - Telecommunication networks
    - Transportation systems
    - Computer networks/the Internet
    - Pipe line systems (water/gas/oil)

- They can be very costly.
- They typically affect many people.

**Question**: How can one protect (supply) network systems against cascading failures?
A Short Primer on Complex Networks

- A network is a collection of
  - Nodes connected by links
- Adjacency matrix $W_{ij}$
- Degree (#links) distribution
  - Scale-free (e.g. the Internet)
  - Exponential (e.g. power networks)
- Betweenness centrality of a node
  - Total # shortest paths passing through that node for any pair of nodes
A few words on System Design

- The systems are designed with a *given load* in mind
- To ensure stability, the engineering approach, is to introduce some *overcapacity* into the system (security margins)
- …but overcapacity is *costly*!
- System robustness is often ONLY evaluated locally

- **Cascading failure**: When an initial perturbation occurs, loads have to redistribute. If the resulting loads exceed the capacities of link/nodes, new failures can result…. “the Domino effect”
Why do we have blackouts…..?

- System load (throughput)
  - optimized to get the maximum out of the system
  - high load means small operating margins
  - has impact on interactions and component failures

- Tradeoff between load and risk of failure
  - at system level
  - for system components

- What is the role of the deregulation?
Power Blackouts and the Domino Effect

Previous physics works: Cascading Failures


- No sinks/sources
- Initial load of a node, $L_i$, is its betweenness centrality
- Node Capacity: $C_i = (1+\alpha)L_i$
- One probes only the stationary state of the system ..... 
- The system is perturbed, and the fraction of nodes remaining in the largest component, $G$, is recorded after the cascade has stopped.

![Graph showing the fraction of nodes remaining in the largest component as a function of the perturbation parameter $\alpha$. The graph compares the effect of removing random nodes, high degree nodes, and high load nodes in the Northwest US power grid.](image)
Previous works: Cascading Failures


- More physically realistic model for the current flow (the Kirchoff laws)
- "The price to pay": one has to solve a large system of linear eq.

- NOTE: Also here one probes only the stationary state of the system .....
Previous works: Summary/Open Questions

- Previous works of cascading failures exclusively considered the stationary state.

- We asked ourselves: Why should the system *not* experience additional failure due to overloading during the transient period?

- Question to address:
  - What is the role played by dynamics in cascading failures in complex networks?

- A dynamical model is needed for such a study.
  - .... But which one to choose?
Expected difference between a static and a dynamic model for flow redistribution

Initial failure

Stationary model

Dynamic model

t = 1

t = 2
Model: Requirements

- It should be:
  - Generic: no particular physical process is addressed
  - As simple as possible, but not simpler…

- Important ingredient (in our opinion)
  - The flowing quantity should be \textit{CONSERVED}

\textbf{Our solution}: A Random Walk (or Diffusion type) model!
The Dynamical Model: Basic Principle (Flow/Diffusion Model)

- Random walkers (i.e. particles) “live” on the nodes
- They are moving (flowing) around on the network!
- In each time step, a walker moves one step forward towards one of the neighboring nodes chosen by random
- This process is repeated over and over again…….

- Note: The number of walkers is constant in time
The Dynamical Model: The Master Equation

- **Convention**: $W_{ij}$ refers to the link from node $j$ to $i$;
- Define the outgoing link weight from node $j$: $w_j = \sum_i W_{ij}$
- The change in no. of particle at node $i$ from $t$ to $t+1$

$$n_i(t+1) - n_i(t) = \sum_j W_{ij} \frac{n_j(t)}{w_j} - \sum_j W_{ji} \frac{n_i(t)}{w_i} + n^\pm_i(t),$$

- The “outgoing-term” is simple, and one gets

$$n_i(t+1) = \sum_j W_{ij} \frac{n_j(t)}{w_j} + n^\pm_i(t)$$
The Dynamical Model: The Master Equation

- Define the relative fraction of walkers (total N) at node $i$:
  \[ \rho_i(t) = \frac{n_i(t)}{N} \]

- The outgoing current per weight unit from node $i$ is:
  \[ c_i(t) = \frac{\rho_i(t)}{w_i} = \frac{n_i(t)}{w_iN} \]

- Hence, it follows
  \[ c(t + 1) = Tc(t) + j^\pm(t); \quad T_{ij} = \frac{W_{ij}}{w_i} \]
The Dynamical Model : Summary

Our simple dynamical model incorporates:

- Flow conservation
- Network topology
- Load redistribution

$c_i(t) : \text{The \textbf{outgoing} current from node } i \text{ per link weight unit}$

\[ c(t + 1) = Tc(t) + j^\pm(t); \quad T_{ij} = \frac{W_{ij}}{w_i} \]
The Dynamic Model

Network:

- $\mathcal{N}$ set of nodes
- $\mathcal{L}$ set of links
- $W$ adjacency matrix ($W_{ij} \geq 0$, link weight)

Model dynamics:

$n_i(t + 1) = \sum_{j=1}^{\mathcal{N}} T_{ij} n_j(t) + n_i^{\pm}$

$n_i(t)$ number of particles hosted by node $i$ at the time $t$

$T_{ij} = W_{ij}/w_j$, \quad $w_j = \sum_{\ell=1}^{\mathcal{N}} W_{\ell j}$

$n_i^{\pm} > 0$ node is source, \quad $n_i^{\pm} < 0$ node is sink

Stationary and Dynamic Models of Cascading Failures

Model normalization:

\[ \rho_i(t) = \frac{n_i(t)}{N} \quad \text{nodal particle density} \]
\[ c_i(t) = \frac{\rho_i(t)}{w_i} \quad \text{utilization of outflow current} \]
\[ j_i^\pm = \frac{n_i^\pm}{(N w_i)} \quad \text{sinks and sources terms} \]

Dynamic model

\[ c(t + 1) = T c(t) + j^\pm, \]

Stationary model

\[ c(\infty) = c^{(0)}(\infty) + (1 - T)^+ j^\pm \]

\( (1 - T)^+ \) generalized inverse of matrix \( 1 - T \)

Link flow:

\[ C_{ij}(t) = W_{ij} c_j(t) \quad \text{current on link from } j \text{ to } i \]
\[ L_{ij}(t) = C_{ij}(t) + C_{ji}(t) \]
Model Dynamics: Is it realistic?

Source: R. Sadikovic, Power flow control with UPFC, (internal report)

EUROSTAG power simulator: www.aurostag.epfl.ch
Model Dynamics: UK high voltage power grid (300-400kV)

At t=0, link 0 is broken!

Green source nodes
Red sink nodes
When does a link/node fail?

- Link/node capacities relative to the undisturbed state ($L_{ij}$) via a tolerance parameter $\alpha$
  \[ C_{ij} = (1 + \alpha) L_{ij}, \]

- A link/node fails whenever its current load, $C_{ij}(t)$ exceeds the capacity of that link/node

\[ C_{ij}(t) > (1 + \alpha) L_{ij} \]
Main steps of the simulations

The simulations consist of the following steps:

1. A *triggering event* \((t=0)\) [remove a random link]
2. Calculate the [new] link loads \(C_{ij}(t)\)
3. Check if any links are *overloaded* via \(C_{ij}(t) > (1 + \alpha)L_{ij}\)
   1. If so remove such overloaded links
4. Repeat step 2 and 3 till no more links are overloaded
5. Average the results over the triggering event of pnt. 1 (and source and slinks locations)
Stationary Model vs. Dynamic Model:
The northwestern US power transmission grid

- $|N|$ number of nodes (5000)
- $|L|$ number of links
- $|N_R|$ number of remaining nodes
- $|L_R|$ number of remaining links

The stationary model can overestimate robustness by more than 80% (in this case)

Overload exposure times may be relevant and will increase the robustness.

$$G_L(\alpha) = \frac{|L_R|}{|L|} \approx G_N(\alpha) = \frac{|N_R|}{|N|} = G(\alpha)$$
Stationary Model vs. Dynamic Model: The role of the two time-scales

- There are two characteristic time-scales in the problem:
  - Overload exposure time (protection system response time): \( \tau \)
  - Typical transient time for the dynamics: \( \tau_0 \)
- Control parameter: \( \chi = \frac{\tau}{\tau_0} \)
  - Static cascading failure model: \( \chi \gg 1 \)
  - Dynamical (\( \tau = 0 \)) cascading failure model: \( \chi = 0 \)
- The real situation is probably somewhere in between....
Conclusions

- The dynamical process on the network is important to consider when evaluating network robustness (cascading)
  - Using a stationary model may dramatically overestimate (by 80-95%) the robustness of the underlying network
  - The actual overestimation do depend on the actual overload exposure time

- In a dynamical model:
  - links may fail that otherwise would not have done so (overshooting)
  - The proximity to a disturbance is more important in a dynamical model

Thank you for your attention!
References

- Dynamical model:
  - See also:

- Stationary models: