Cascading Failures on Power Grids

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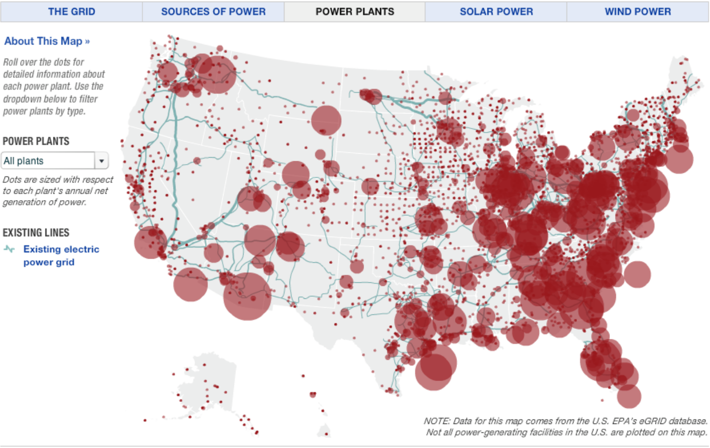
Outline

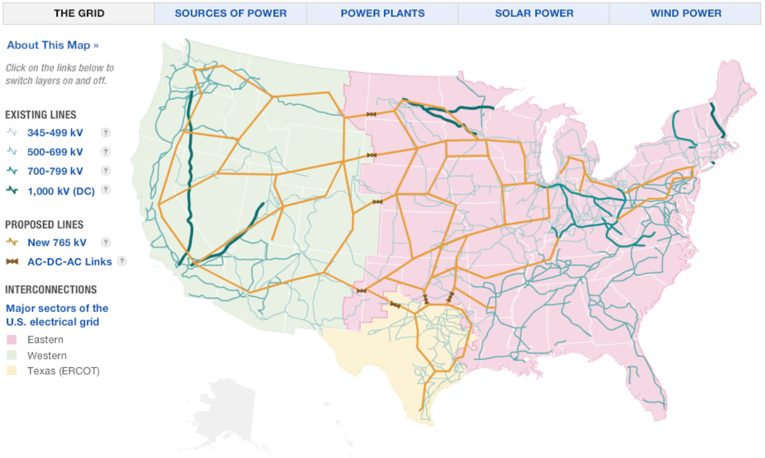
Background: US Electric Power Plants



Data: U.S. EPA's eGrid database

Visualization: www.npr.org/templates/story/story.php?storyId=110997398

Background: US Electric Transmission Grid



Data: Various sources

Visualization: www.npr.org/templates/story/story.php?storyId=110997398

Observations

- Power Grid has large number of interacting components
- Several failure mechanisms: hidden failures, operator error, shorting of lines due to lack of maintenance, relays misbehaving due to over-maintenance, erratic consumer demands, lightning, earthquakes etc
- Non local effects of failures

Observations

- Large blackouts are typically triggered by very few (one or two) primary events, which are followed by a cascading sequence of secondary failures
- Larger disruptions are less probable: probability is a decreasing power function of event size
- Larger blackouts though rarer, are <u>much more costlier</u>
- So it pays to study cascading failures

Cascading Failure Models in Literature

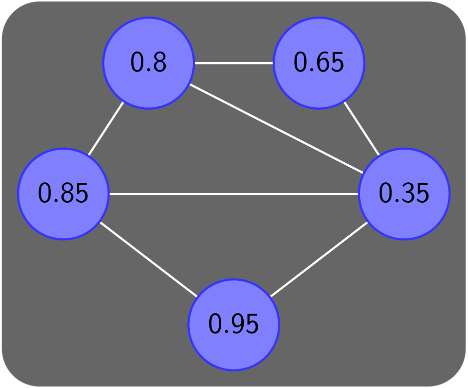
Grid Specific

- Each failing node increases the load on every other node uniformly (Dobson, 2004)
- Branching process: each failing node takes with it a random number of nodes (Dobson, 2004)

General Networks

- A node fails if a fraction of its neighbors fail (Watts, 2002)
- Drop in efficiency of a network because of an imbalance in flow distribution(Crucitti et al., 2004; Latora et al., 2001)

A Simple Initial System Model



High level abstraction of the grid

- Grid is modeled as an undirected graph
- Nodes are generators and weights are loads served
- All nodes have unit capacity
- Generator is online if load demand is less than capacity

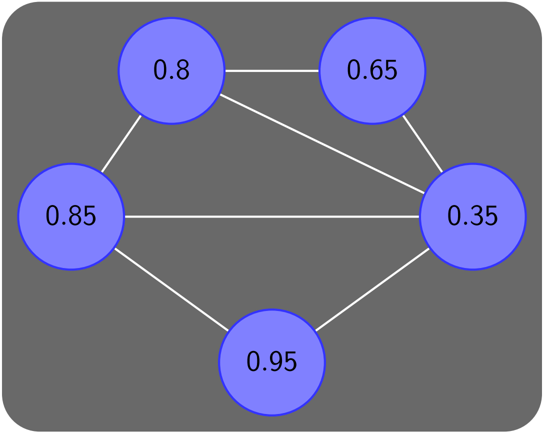
A Simple Initial System Model

- Edges are not power lines: they represent a load sharing arrangement
- Equal sharing of offline generator loads: all graph neighbors take up the offline generator's load
- Underlying electrical network is assumed to be capable of supporting the imposed redundancy

A Simple Failure Model

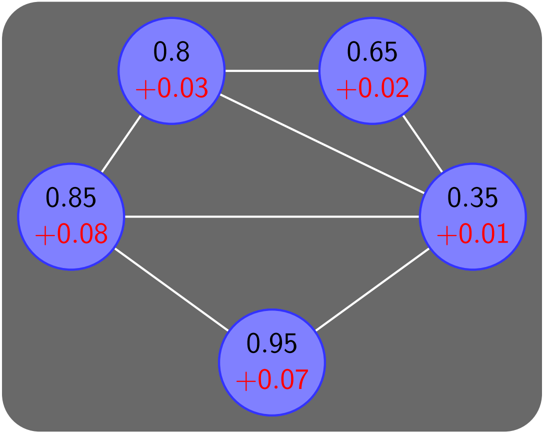
- In steady state, the load demand at each node is below rated capacity
- Initial load is modeled as independent random variables at each node
- Load disturbances increase load at nodes
- Disturbance is modeled as independent random variables at each node
- The load disturbances cause a few generators to go offline
- The offline generator loads get picked up by graph neighbors leading to a propagation of the disturbance and potentially more failures

A Simple Failure Model



An example of a blackout resulting from a cascade

A Simple Failure Model



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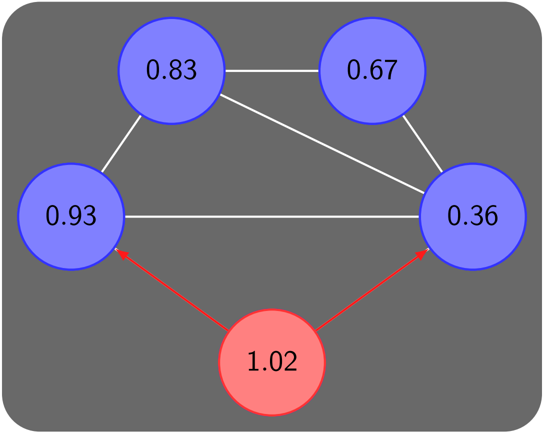

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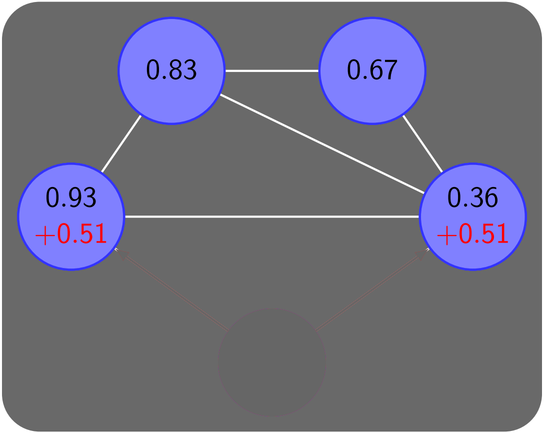

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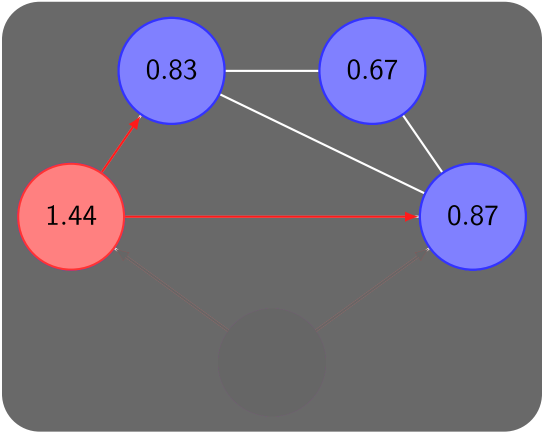

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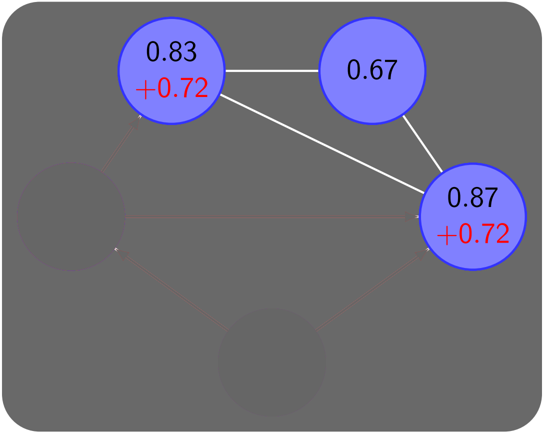

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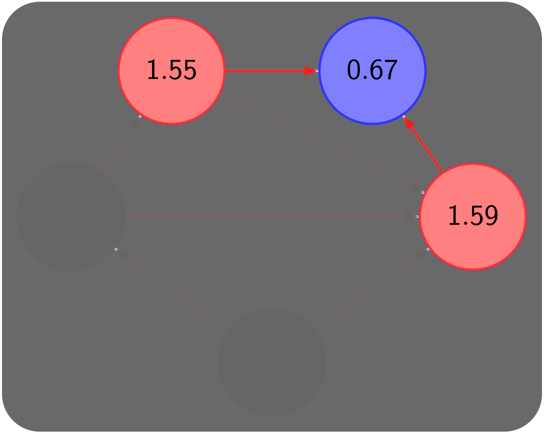

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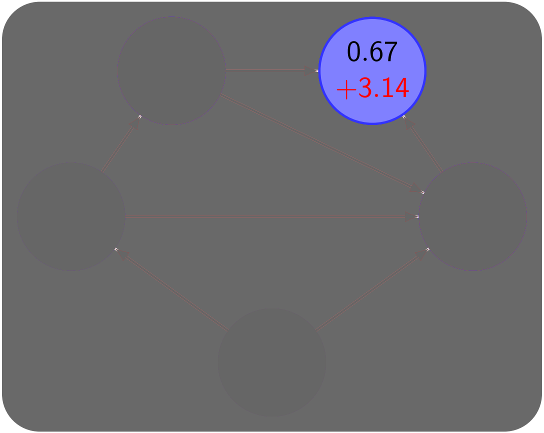
A Simple Failure Model



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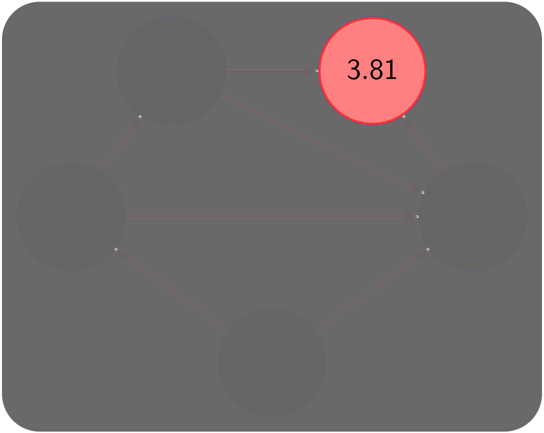

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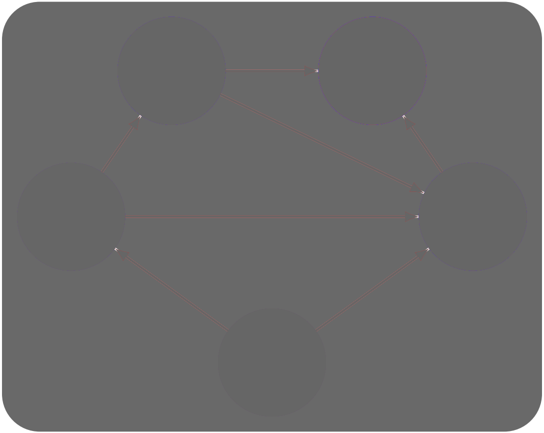
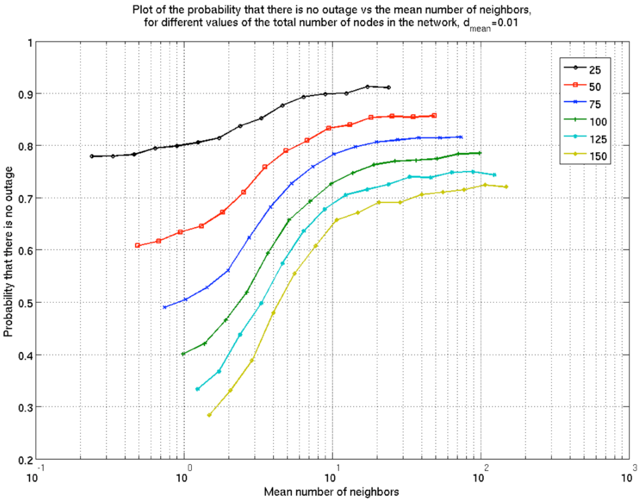
A Simple Failure Model



An example of a blackout resulting from a cascade

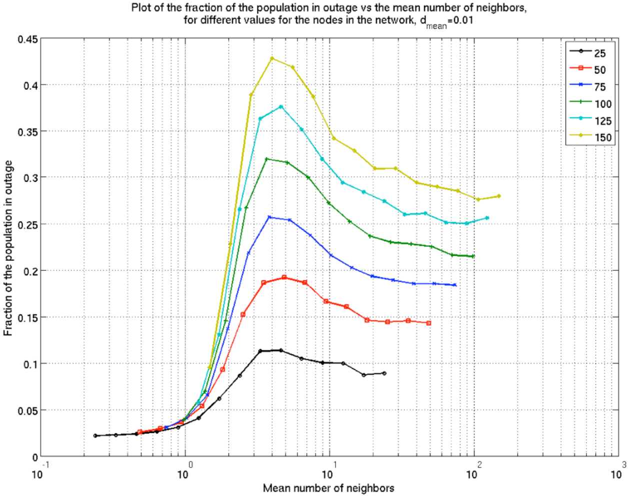
Fully Connected Redundancy Graph

- There is load sharing arrangement between every pair of nodes
- Intuitively - good for robustness
- Good for customers - *outage probability* is least:



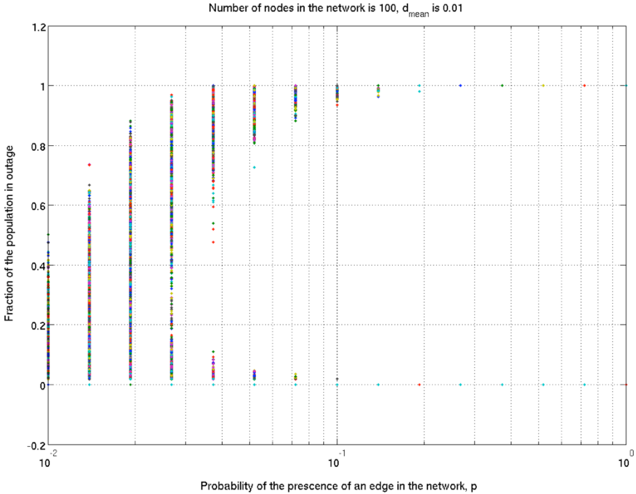
Fully Connected Redundancy Graph

- Not good under other metrics
- Sparse network - cascades subside easily
- Somewhat sparser redundancy graph is good for utilities - *Expected % of population in outage* is least:



Fully Connected Redundancy Graph

- Fully connected redundancy graph: either there is no outage or there is a total blackout:



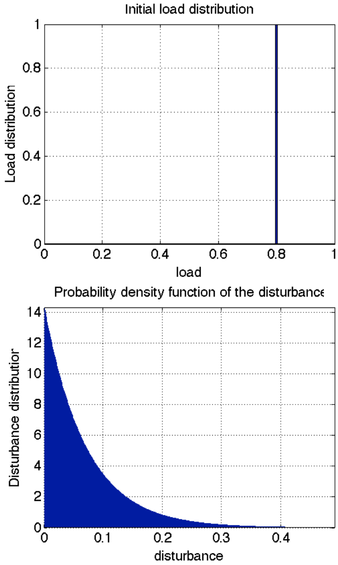
Analysis Result

- Fully connected redundancy graph
- Initial loads at each node is a constant
- Disturbance is exponential with mean d_m

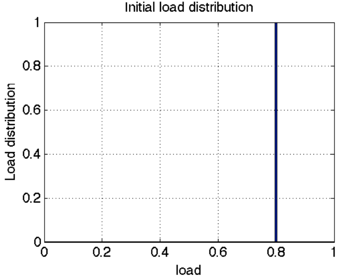
Result

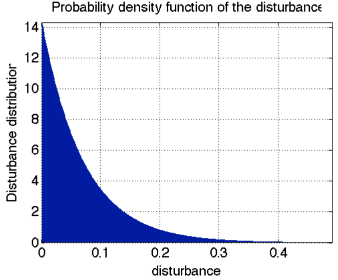
There is a $d_{critical}$ such that, when $d_m < d_{critical}$, cascading failures subside with probability 1, and when $d_m \geq d_{critical}$, all nodes fail with probability 1

Initial distributions

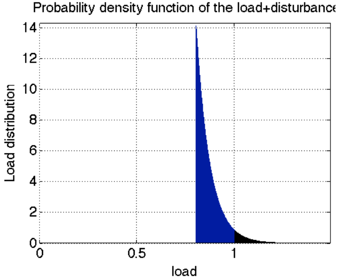


Initial distributions





Resulting convolution



Notation

- a_n = least possible load at the online nodes in stage n
- p_n = probability that a node which is alive at stage n goes offline at stage $(n+1)$
- $\mathcal{D}_n$ = prob. distribution of the re-distributed load at stage n
- $\mathcal{L}_n$ = prob. distribution of the total load at stage n
- N = total number of nodes
- N_{off} = number of nodes which go offline due to the added disturbance
- Load after re-distribution:

$$L_{j_i}(1) = L_{j_i}(0) + \frac{\sum_{i=0}^{N_{off}} L_{k_i}(0)}{(N - N_{off})}$$

Analysis

- $N_{off} \sim \text{Binomial}(N, p_0)$
- $\mathcal{L}_0 \sim \delta(a_0)$ and $\mathcal{D}_0 \sim \text{Exponential}(d_m)$
- $\mathcal{D}_n =$ prob. distribution of the re-distributed load at stage n
- $L_{j_i}(0) \;:\; f_{L_{j_i}(0)}(x) = f_{\mathcal{L}_0+\mathcal{D}_0}(x|\mathcal{L}_0 + \mathcal{D}_0 < 1)$
- $L_{k_i}(0) \;:\; f_{L_{k_i}(0)}(x) = f_{\mathcal{L}_0+\mathcal{D}_0}(x|\mathcal{L}_0 + \mathcal{D}_0 \geq 1)$

Analysis

Re-distributed load tends to a constant for large networks

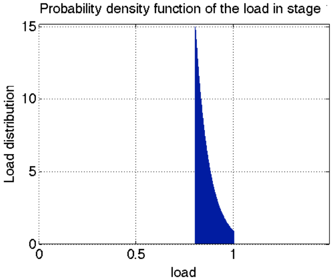
$$\begin{aligned}\lim_{N\to\infty} S_{N_{off}} &= \lim_{N\to\infty} \frac{N_{off}/N}{1-N_{off}/N} \cdot \frac{\sum_{i=0}^{N_{off}} L_{k_i}(0)}{N_{off}} \\ &\overset{p}{=} \frac{p_0}{1-p_0} \cdot \mu_0\end{aligned}$$

- $\mu_0 = E(L_{k_i}(0)) = \int_{x=1}^{\infty} x \cdot f_{\mathcal{L}_0+\mathcal{D}_0}(x|\mathcal{L}_0 + \mathcal{D}_0 \geq 1)\, dx$
- $p_0 = \Pr(\mathcal{L}_0 + \mathcal{D}_0 \geq 1) = \int_{x=1}^{\infty} f_{\mathcal{L}_0+\mathcal{D}_0}(x)\, dx$
- **Consequence:** *Loads at all online nodes at each stage are independent and identically distributed (iid)*

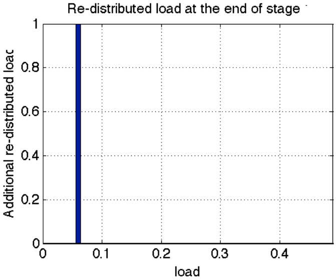
Analysis Proceeds in Stages

Stage 1:

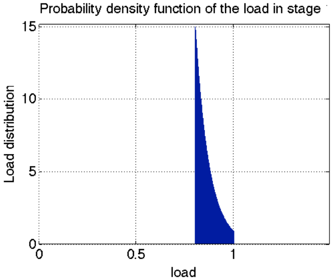
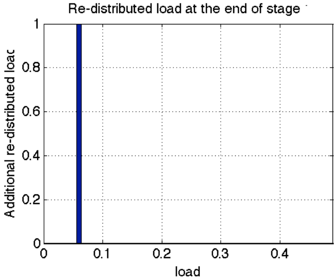
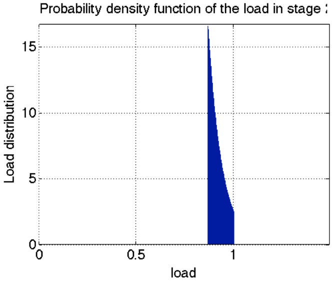
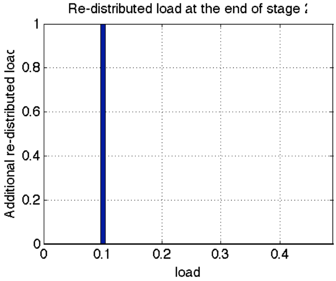
Load



Re-distributed load



Analysis Proceeds in Stages

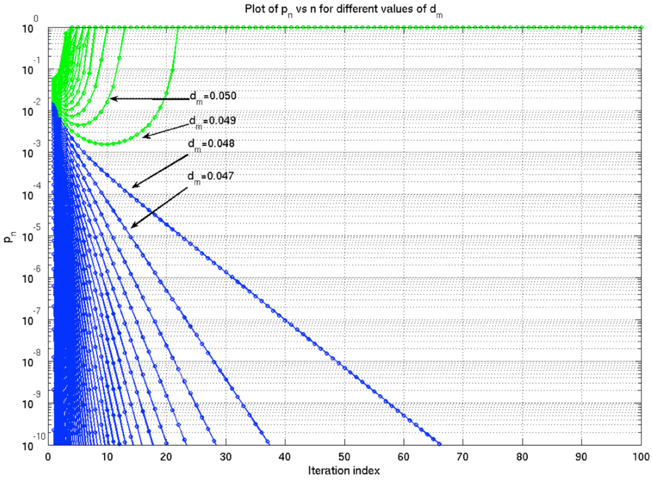
	Load	**Re-distributed load**
Stage 1:		
Stage 2:		

Recursive Equations Governing System Evolution

1. Initialize: $p_0 = e^{-\frac{1-a_0}{d_m}}$, $\mathcal{D}_1 = \frac{p_0}{1-p_0}(1+d_m)$, $a_1 = a_0$,
   $p_1 = \frac{e^{-\frac{1-a_1}{d_m}}}{1-e^{-\frac{1-a_1}{d_m}}}(e^{\frac{\mathcal{D}_1}{d_m}} - 1)$
2. For $n = (2, \ldots, N_{iterations})$, do:
   If $((a_{n-1} + \mathcal{D}_{n-1}) > 1)$ and $(a_{n-1} < 1)$, STOP
   else:
   (a) $a_n = a_{n-1} + \mathcal{D}_{n-1}$
   (b) $\mu_{n-1} = 1 + d_m - \frac{\mathcal{D}_{n-1}}{e^{\frac{\mathcal{D}_{n-1}}{d_m}} - 1}$
   (c) $\mathcal{D}_n = \frac{p_{n-1}}{1-p_{n-1}} \cdot \mu_{n-1}$
   (d) $p_n = \frac{e^{-\frac{1-a_n}{d_m}}}{1-e^{-\frac{1-a_n}{d_m}}}(e^{\frac{\mathcal{D}_n}{d_m}} - 1)$

Results: Evolution of p_n

- From the recursive system:



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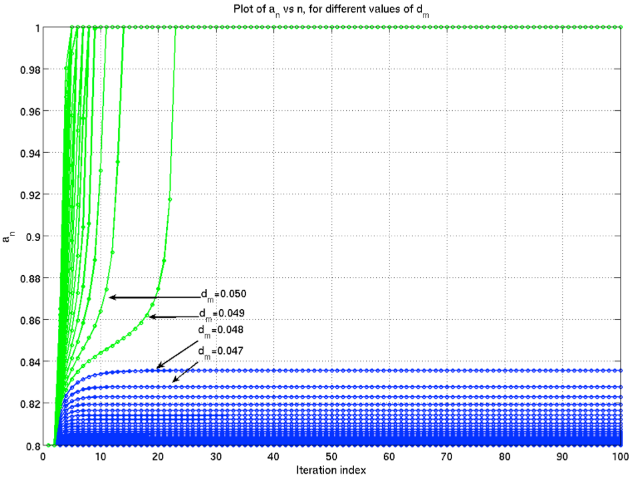
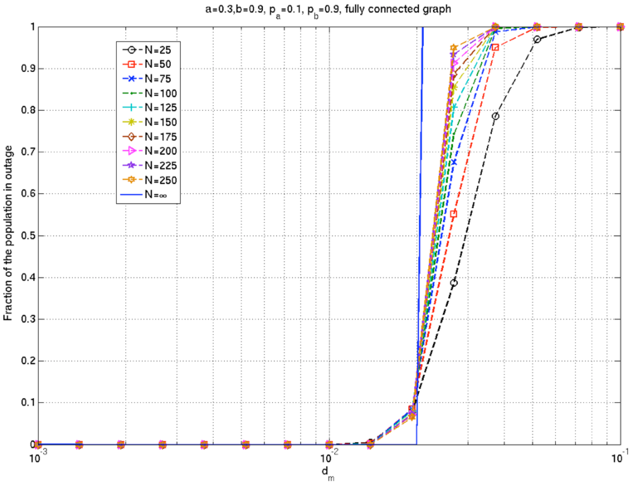
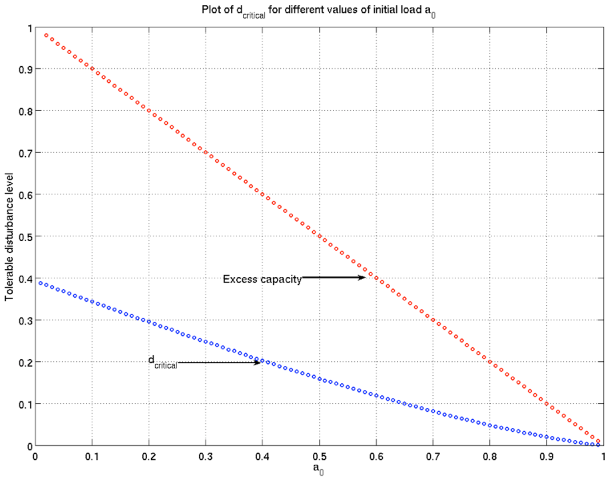


Results: Behavior of a Finite Fully Connected System

- $d_{critical}$ for some large enough finite size networks:



- $d_{critical}$ and required excess generation capacity:

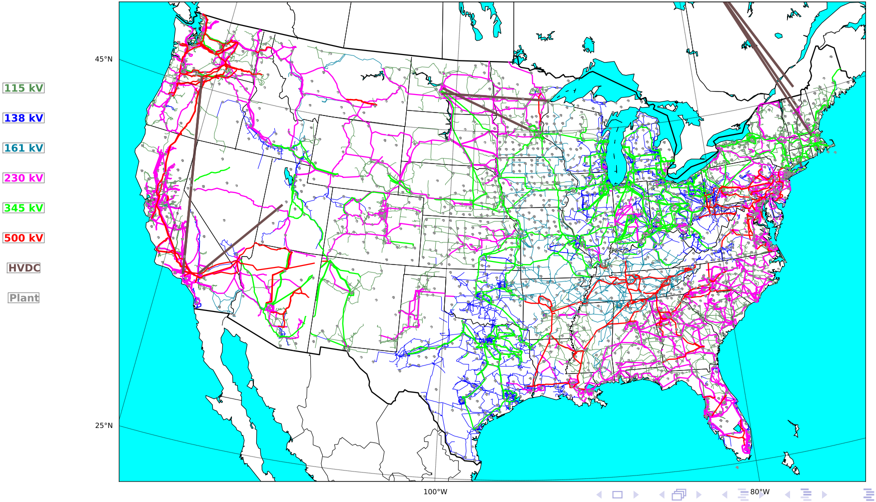


Improvements to the System/Failure Model

- **Generators rarely trip, they are protected using relays etc -** can be modeled using a probability of failure for the protective devices associated with each generator
- **The redundancy graph is never fully connected -** this assumption is used only for simplifying analysis. Simulations can be performed even without this assumption
- **Electricity flow does not behave like this -** when the exact topology of the electrical network is known, simulations can take into account the power flow equations and redistribute load accordingly
- **Load sharing arrangements could change dynamically with market prices -** a market based algorithm can be used to account for this during simulations

Transmission Grid Topology (FEMA, 1993)

- Used ESRI shape-files available from NREL (Originally from FEMA, 1993)
- Used generator data available from EIA, 2008

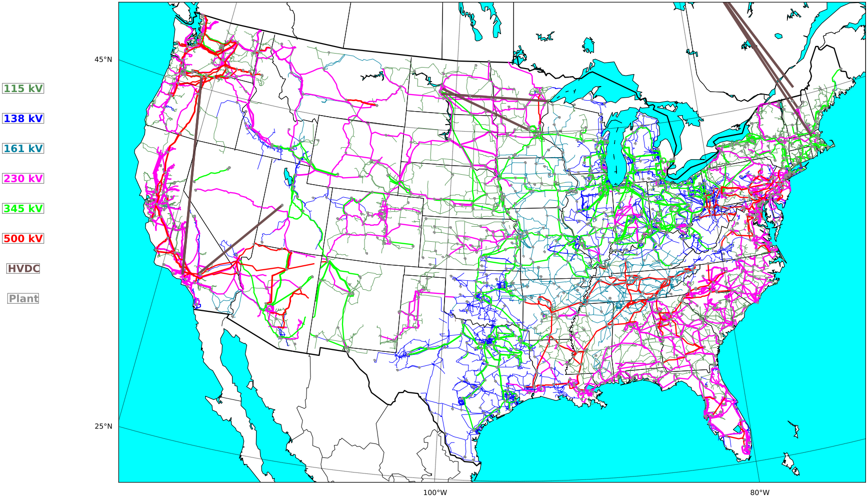


Limitations on Openly Available Data

- Grid topology is somewhat old, but probably not much has changed
- Electrical parameters are not available, but exact length and line voltage are known
- Unit length impedances and transformer parameters may be estimated from similar grids elsewhere
- Generator locations are sometimes available only upto the county level - then we use the county centroid

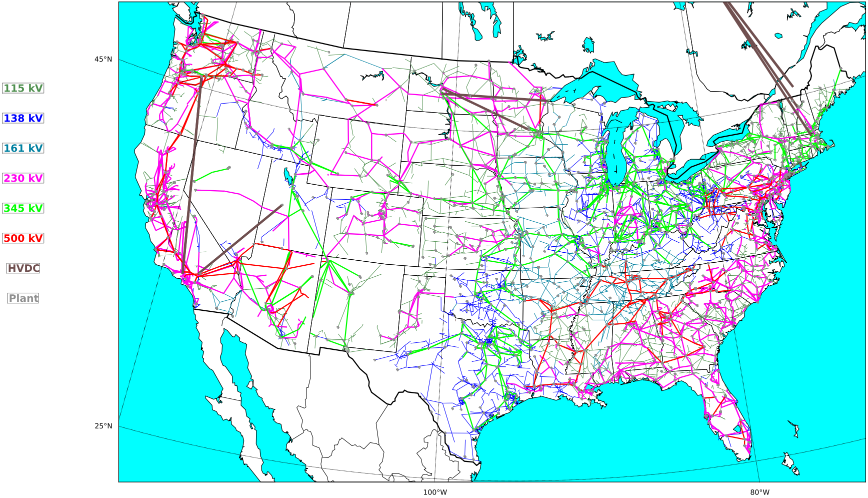
Grid + Generating Plants

- After fixing the generator locations to closest grid point



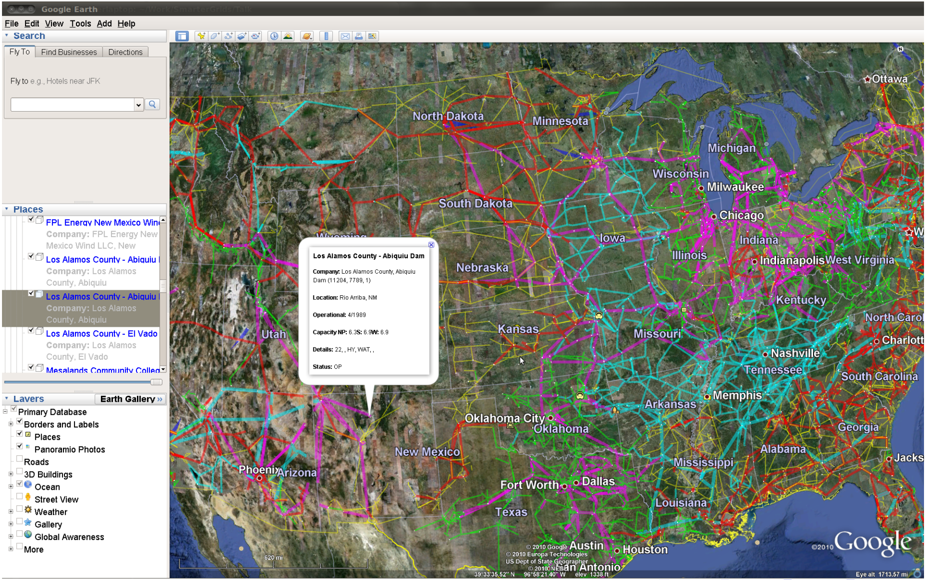
Grid + Generating Plants

- Topology after removing bends (electrically unimportant)



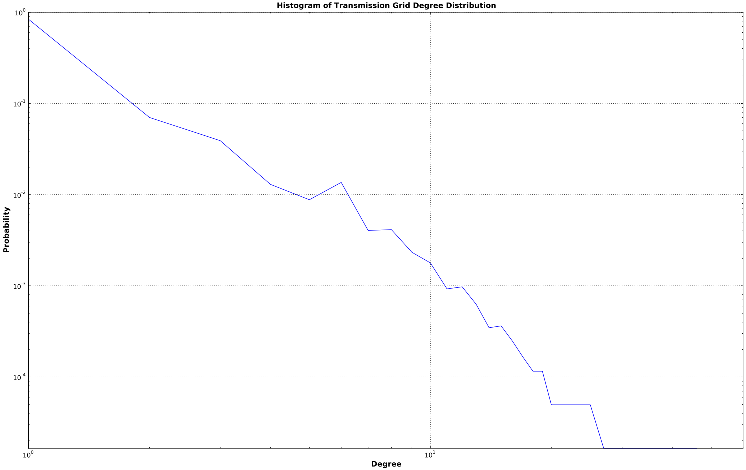
Detail View

- Abiquiu



Power Law in Grid Topology

- Transmission grid degree distribution
- Shows an approximate power law behavior:



Conclusions

- Studying cascading failures is important for understanding large scale blackouts
- Developed a simple system and failure model and rigorously analyzed it
- Several improvements are possible to the simple model - however these will make analysis difficult and necessitate simulations
- Further realism is possible only by considering the actual transmission network topology
- Gathered openly available US transmission grid data
- **For future:** simulate more realistic/complicated algorithms for load sharing and failure using the grid data