# Modelling the Cascading Failure in Power Grid Network

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## Abstract

In this project, I have performed an analysis of the USWI (US Western Interconnection) power grid network and created a synthetic power grid network similar to the Degree and Distance Attachment (DADA) model. It has topology and resilience similar to the USWI power grid.

## 1 Introduction

### 1.1 Power Grid Operations and Impact of Blackouts:

The intricate nature of power grid operations often goes unnoticed in our daily lives when we perform simple actions like turning on lights. Electric power systems serve billions globally with remarkable dependability, typically achieving reliability rates exceeding 99.9%. However, this high reliability has led modern societies to become deeply dependent on an uninterrupted power supply. When power systems fail, the consequences ripple through every aspect of urban life: transportation networks cease operations, climate control systems fail, computing infrastructure becomes inoperable, and essential infrastructure including water supply, sewage systems, and telecommunications rapidly deteriorate. Power outages can also expose underlying social tensions, as demonstrated during the 1977 blackout in New York City, which triggered extensive civil unrest resulting in over 3,000 arrests.

### 1.2 What is a Cascading Failure?

Power grid failures typically initiate through the disruption of transmission lines, triggering a complex cascade of events that can culminate in widespread blackouts. When a transmission line fails, power flows redistribute automatically across the remaining network infrastructure, potentially overloading other components beyond their operational capacity. Multiple factors can initiate these cascading events:

- **Natural Causes:** Earthquakes, hurricanes, solar flares, and extreme weather events.
- **Human Factors:** Operational errors, equipment failures, and potential cyber attacks.
- **Combined Effects:** Natural growth of vegetation near power lines combined with inadequate maintenance.

Blackouts have a great impact on modern life as most of our activities are directly connected to the availability of electric power. There is a growing interest in research to study the power grid failure mechanism to measure power grid vulnerability and work towards power grid resilience.

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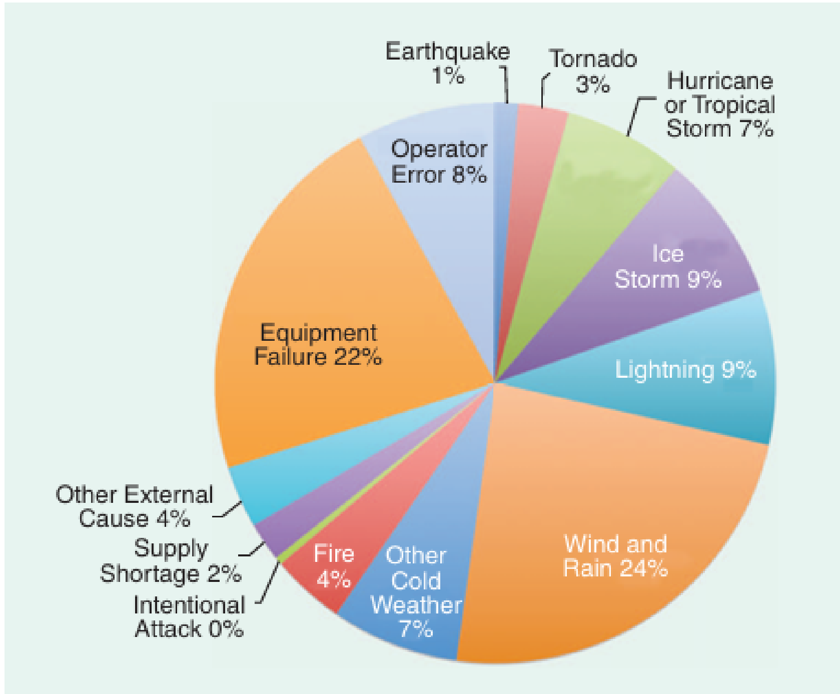



Figure 1: Initial causes of blackouts affecting at least 50,000 customers between 1984 and 2006.

Research on power grid failure mechanisms frequently employs the Direct Current (DC) power flow model as a primary analytical tool. This paper follows a model for cascading failures, which shows how small failures can lead to larger ones. Previous studies found that blackout occurrences in power grids often follow a "power law" pattern, meaning most blackouts are either very small or very large. Their main goal is to study these failures in depth and build a realistic model of a power grid.

To do this, we study failures in the US Western power grid and create a synthetic model called the Degree and Distance Attachment (DADA) model. We find that blackouts tend to follow universal patterns, but they are smaller in the real grid compared to the DADA model, which has a different layout.

We study how blackout size depends on three key factors that measure the grid's robustness:

1. Tolerance ($\alpha$), or how much load a line can handle compared to its initial load.
2. Minimum flow ($I_p$), the smallest amount of flow any line can carry.
3. Initial failure load ($I_u$), the load of the first line that fails.

These factors are represented by $p$ and $u$, which are percentages of lines carrying less than $I_p$ and $I_u$, respectively. Large blackouts are more likely in certain ranges of values for $\alpha$, $p$, and $u$. The yield (demand met after a failure) has a bimodal pattern, meaning outcomes are mostly either minor or major blackouts.

An important finding is the presence of a "latent period" at the start of large blackouts, where few lines are affected, and yield remains high. This period gives time for intervention to prevent a full blackout. The length of this latent period increases as tolerance $\alpha$ increases. Large blackouts end when the grid breaks into small, disconnected sections.

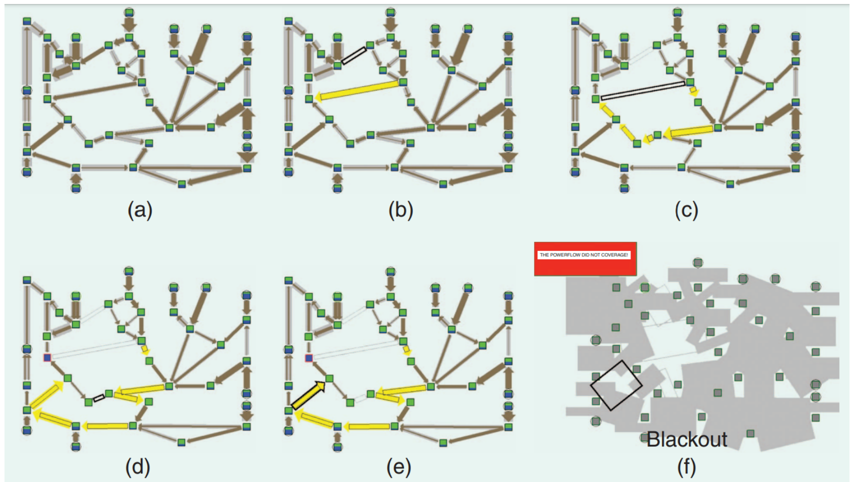



Figure 2: Illustration of a cascading failure in a small system. The thickness of the lines indicates current flow, and the blue-green threshold at the nodes indicates voltages.

## 2 Data and Metrics

The dataset for USWI used in this study has been obtained from [2]. . I have analyzed this data and found it to have similar topological properties to those mentioned in [3]. An exploratory data analysis of the power grid data reveals findings similar to the ones reported in the literature.

### 2.1 DC Power Flow Model

In this section, we analyze power flow using the DC power flow model, which is commonly used in electrical engineering. This model simulates how electricity flows through a grid by treating it similarly to a resistor network: power flow is treated like electrical current, transmission resistance as resistance, and power phase angles as voltages.

#### 2.1.1 Grid Representation

The power grid is represented by a graph $G = (N, E)$, where:

- $N$ is a set of nodes (representing power stations, substations, or demand points).
- $E$ is a set of edges (representing transmission lines between nodes).

There are three types of nodes:

- **Supply nodes** $(n^+)$: nodes providing power.
- **Demand nodes** $(n^-)$: nodes consuming power.
- **Transmission nodes** $(n^0)$: nodes that only help transmit power between supply and demand nodes.

#### 2.1.2 Power Flow Equations

For each line between nodes $i$ and $j$, the current flowing between nodes is given by:

$$I_{ij} = \frac{V_i - V_j}{R_{ij}}$$

where $V_i$ and $V_j$ are the voltages at nodes $i$ and $j$, and $R_{ij}$ is the resistance of the line.

### 2.2 Cascading Failures Model

The cascading failures model involves transmission capacity and how overloads propagate through the network. The model considers two key parameters:

- **Level of Protection** ($p$): Ensures most lines have a reasonable capacity even if they don't carry much current initially.
- **Tolerance** ($\alpha$): Represents the maximum safe load a line can carry compared to its starting load.

When a line carrying high current fails, it can lead to cascading failures as the load redistributes across other lines. The process continues until no more lines fail due to overloading.

## 3 Results

The USWI power grid data contains 8277 transmitting nodes, 3058 supply nodes, 3095 demand nodes, and 16786 transmission lines. To avoid exposing potential vulnerabilities of the actual USWI, the dataset does not include the geographic coordinates of the nodes but does include the length of each transmission line.

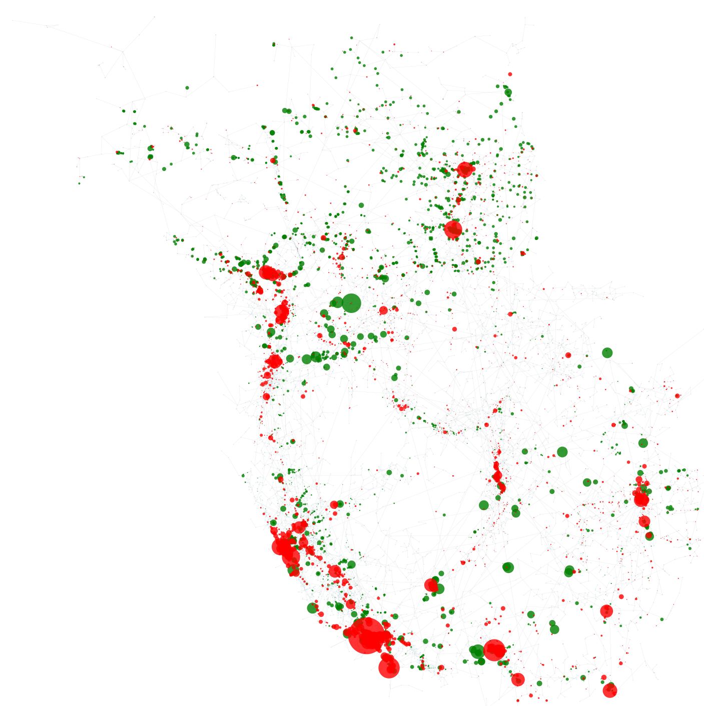


Figure 3: Visualization of nodes and transmission lines in the USWI power grid.

### 3.1 Degree Distribution

The degree distribution of the nodes in the USWI follows a fat-tail distribution, approximated by a power law $P(k) \approx k^{-3}$ with an exponential cutoff. The average degree $\langle k \rangle$ of nodes in the USWI is 2.32.

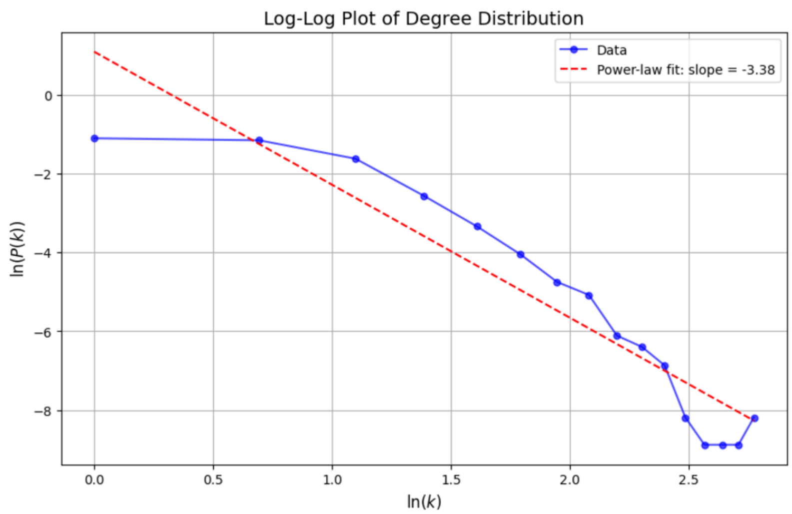
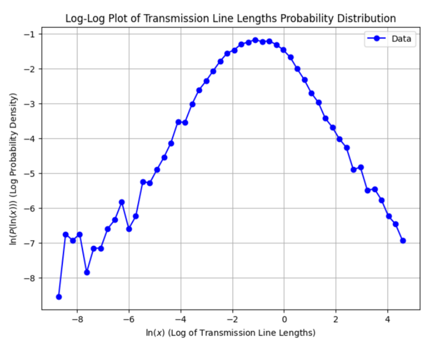


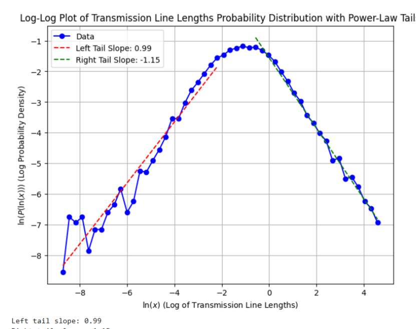

Figure 4: Degree Distributions of the nodes in the USWI power grid.

### 3.2 Length Distribution of the Lines

The length distribution of the transmission lines in the USWI follows a log-normal shape with power-law tails.




(a) Without power law fit




(b) With power law fit.

Figure 5: Length distribution of the lines, which are the same as the resistance values.

### 3.3 DADA Model Network

After understanding the topology of USWI grid network, I have constructed DADA network. The DADA model randomly generates nodes $j = 1, 2, \dots, n$ one by one on a plane with a uniform density. It connects each new node $j$ to an existing node $i$ based on $i$'s degree and distance with probability

$$P(\{i,j\}) \propto \frac{k_i}{r_{ij}^{\mu}},$$

where $k_i$ is the present degree of node $i$ and $r_{ij}$ is the distance between nodes $i$ and $j$. This rule mimics the way real networks evolve.

A real network such as the USWI is not planned all at once; rather, new stations are added to the grid as necessity dictates. The probability of connection

$$P(\{i,j\}) \propto \frac{k_i}{r_{ij}^{\mu}}$$

is assumed to be proportional to $k_i$, since connections to nodes of high degree are more reliable, but also inversely proportional to a power of $r_{ij}$, since construction of long transmission lines costs more. The distance penalty $\mu$ is a factor that seeks to optimize the balance between reliability and cost.

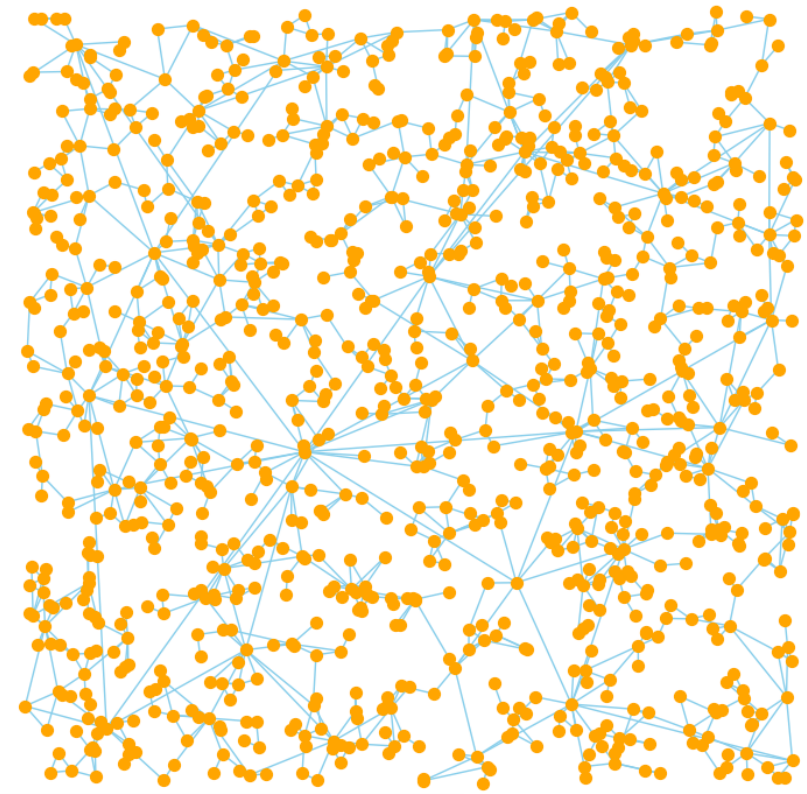


Figure 6: DADA Model Network.

### 3.4 Synthetic Grid Results

The synthetic DADA model closely follows the degree distribution found in the USWI grid. The transmission lines of the synthetic grid have an approximately log-normal length distribution. This consistency allows the synthetic model to serve as a useful proxy for real-world power grids.

## 4 Conclusions

This work explores cascading failures in the power grid by analyzing the USWI and using the DADA model to create a synthetic power grid. The model offers insight into the mechanisms driving grid failures and potential interventions to enhance grid resilience.

## 5 References

## References


[1] Paul Hines, Karthikeyan Balasubramaniam, and Eduardo Cotilla Sanchez, "Cascading Failures in Power Grids," *Cascading Failures in Power Grids*, 2011..

[2] Saleh Soltan, Alexander Loh, and Gil Zussman, "A learning-based method for generating synthetic power grids," *IEEE Systems Journal*, vol. 13, no. 1, pp. 625-634, 2018, doi: 10.1109/JSYST.2017.2696980.

[3] Russell Spiewak, Saleh Soltan, Yakir Forman, Sergey V. Buldyrev, and Gil Zussman, "A Study of Cascading Failures in Real and Synthetic Power Grid Topologies," *A Study of Cascading Failures in Real and Synthetic Power Grid Topologies*, 2019.