Network Reliability and Cascading Blackouts

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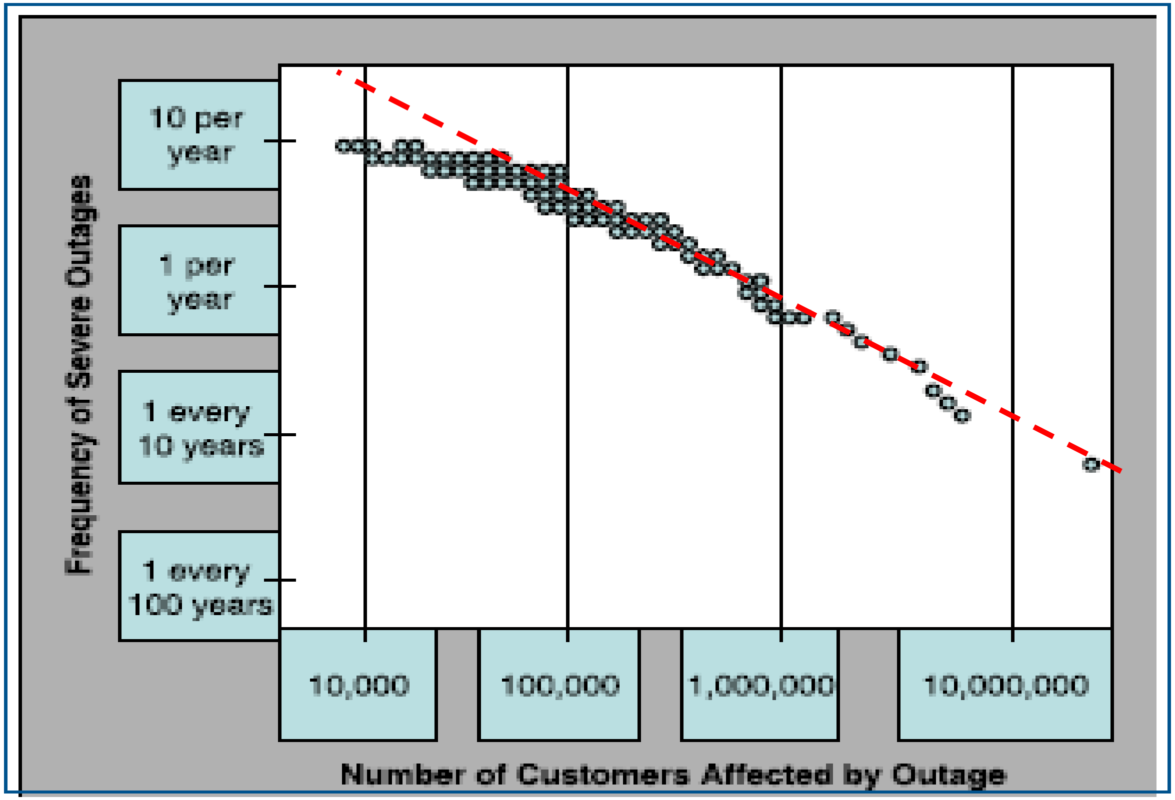
Rare Events in Power Grids

Individual Outages in North America, 1984-1997



Power-tailed Distribution

$$\Pr\{X > x\} \approx cx^{-a}$$

Source: U.S.-Canada Power System Outage Task Force. 2004. Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations. Adapted from John Doyle. 1999. Complexity and Robustness.

Related Research

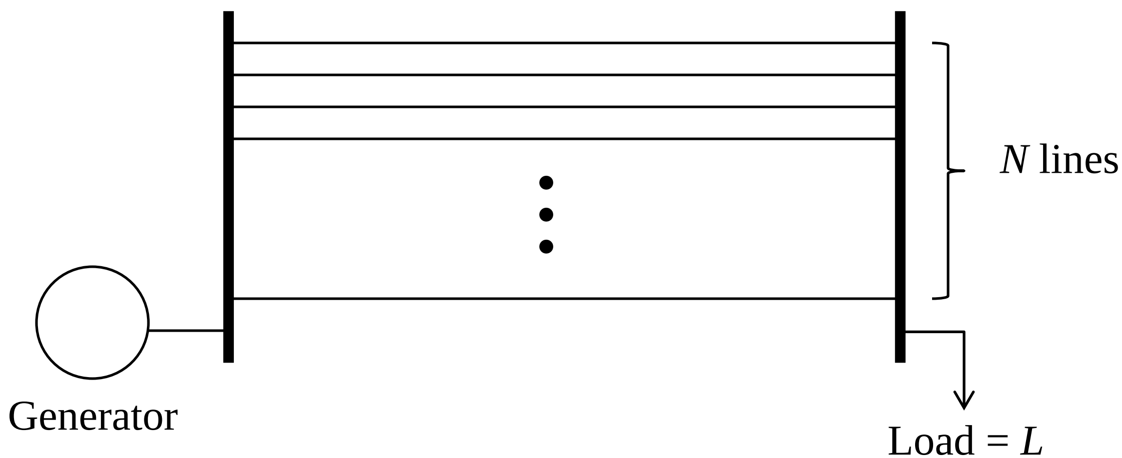
- Stochastic methods
  - Much work on rare-event stochastic reliability of *static* networks (assume line failures are independent)
- Cascading outages, detailed modeling methods
  - Cluster-based – identify network clusters and critical cut-sets
  - Enumeration of likely cascading paths
  - Monte-Carlo sampling – examination of random subset of cascading scenarios
    - Limited use of rare-event simulation methods

• Botev, Z., P. L'Ecuyer, G. Rubino, R. Simard, B. Tuffin. 2012. Static reliability estimation via generalized splitting. To appear in *INFORMS Journal on Computing*.

• Risk assessment of cascading outages: Part I – overview of methodologies. PES Task Force on Understanding, Prediction, Mitigation and Restoration of Cascading Failures, PES Annual Meeting, Detroit, MI, 2011.

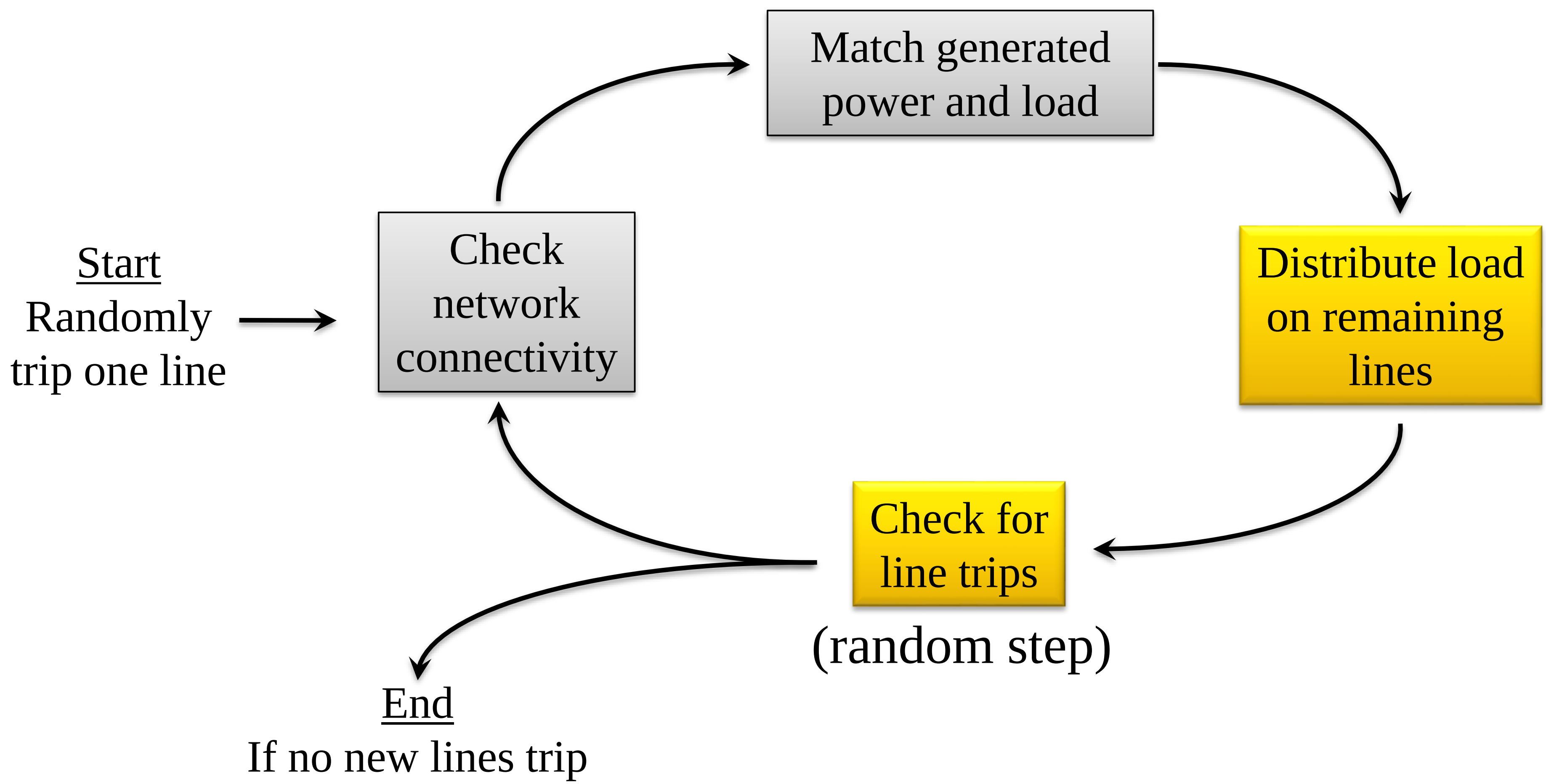
Example: Simple Cascading Model

- When a line fails, its load is equally distributed among the remaining lines
- Equivalent to *N* identical parallel lines connecting two buses



Similar to analytical model in Dobson, Carreras, Newman (2005)

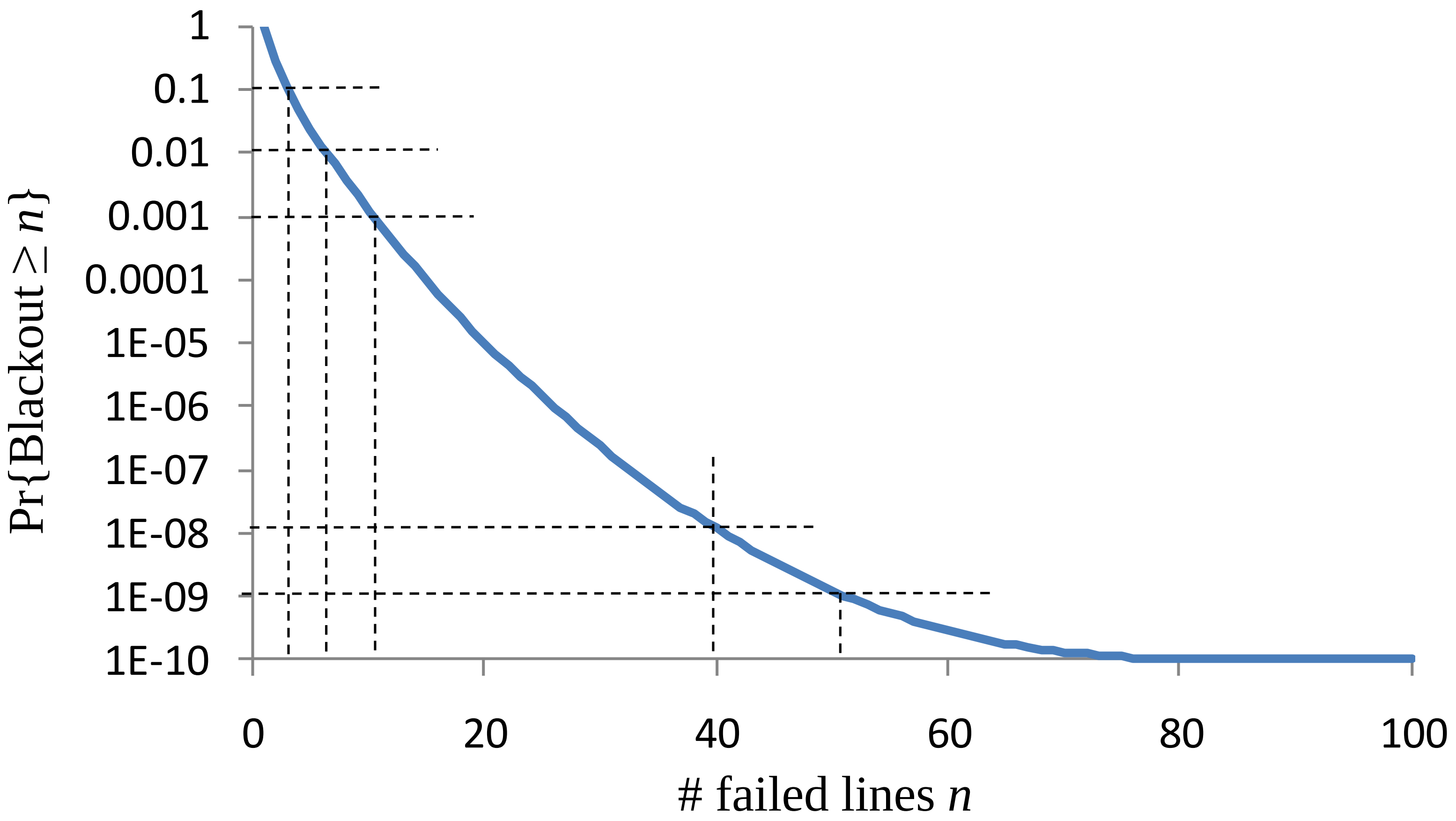
Cascading Blackout Model



Similar to some models in literature, for example:

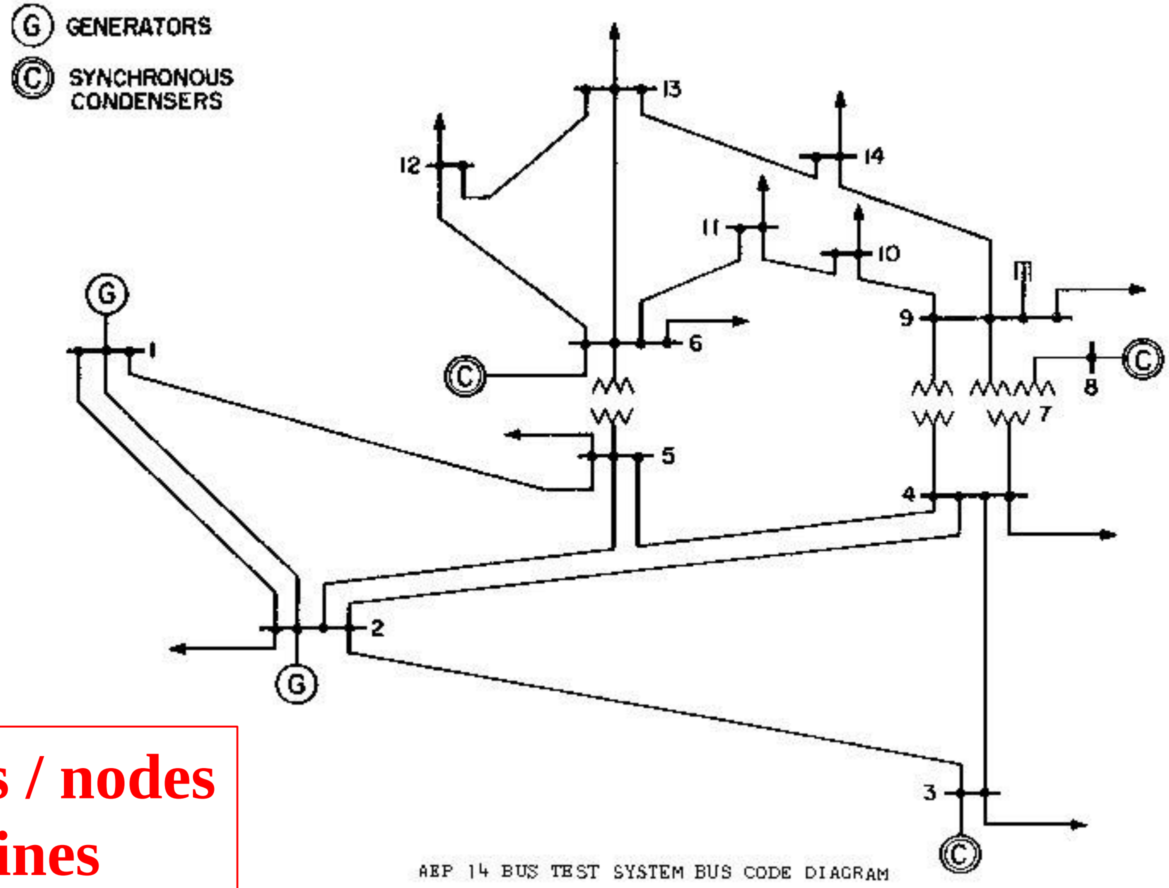
- Chen, J., J. Thorp, I. Dobson. 2005. Cascading dynamics and mitigation assessment in power system disturbances via a hidden failure model. *Electrical Power & Energy Systems*, 27, 318-326.
- Bae, K. J. Thorp. 1999. A stochastic study of hidden failures in power system protection. *Decision Support Systems*, 24, 259-268.

Blackout-size Distribution



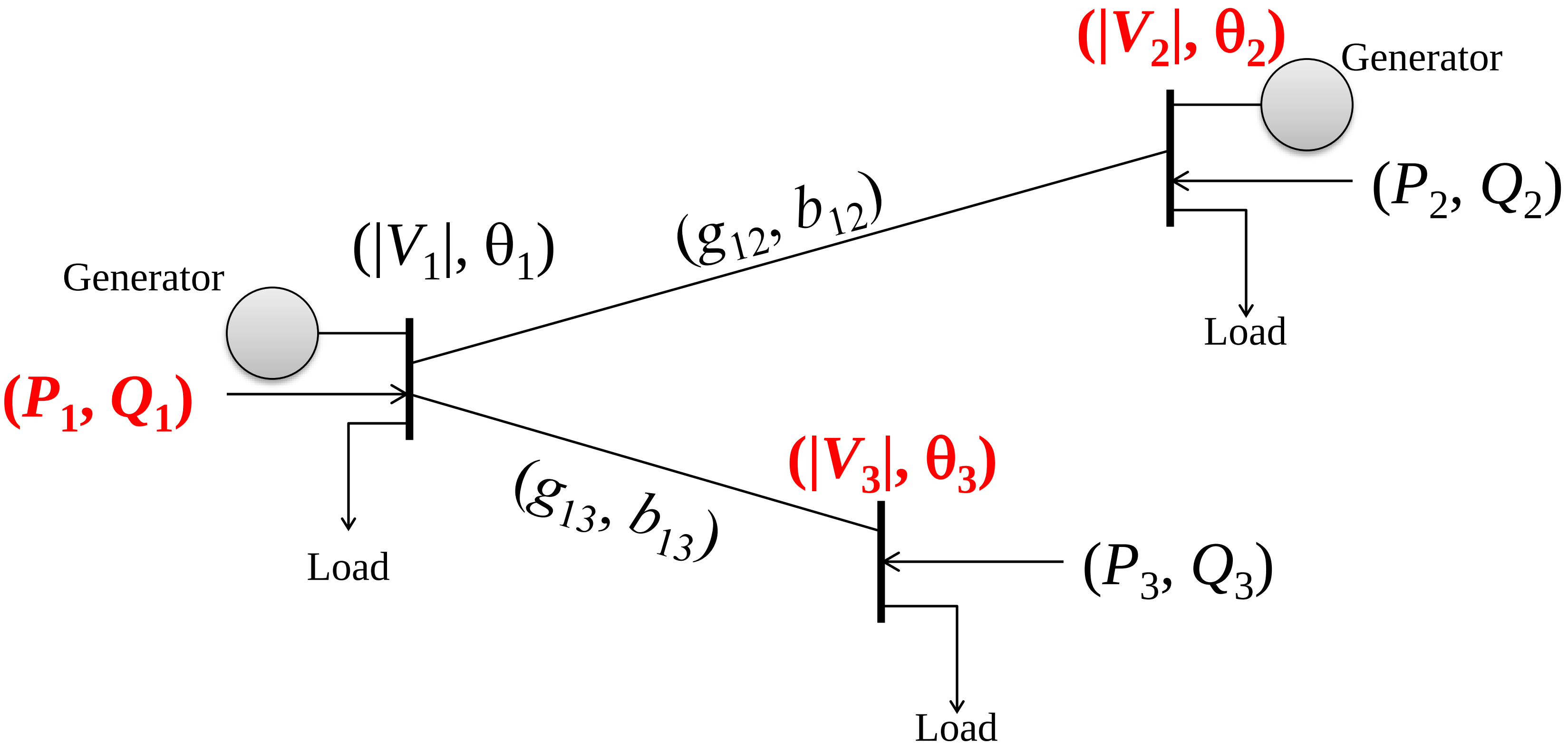
Network: 100 lines, load on each line = 1 MW, capacity of each line ~exp(mean = 3.034 MW)

IEEE 14-Bus Grid



14 buses / nodes
20 lines

Power-Flow Equations



<u>Notation</u>

- P_i, Q_i = *net* real, reactive power injected into bus i (negative for load bus)
- $|V_i|$ = root-mean-square voltage at bus i
- θ_i = phase angle of voltage at bus i
- g_{ik}, b_{ik} = conductance, susceptance for link i-k

Black = given

Red = unknown variable

Power Flow Equations

- Power-flow equations

$$P_i = \sum_{k=1}^{n} |V_i||V_k|[g_{ik}\cos(\theta_i - \theta_k) + b_{ik}\sin(\theta_i - \theta_k)] \qquad i = 1, \ldots, n$$

$$Q_i = \sum_{k=1}^{n} |V_i||V_k|[g_{ik}\sin(\theta_i - \theta_k) - b_{ik}\cos(\theta_i - \theta_k)] \qquad i = 1, \ldots, n$$

- Linear equations
  - Assume θ_i small, $|V_i| \approx 1$, $g_{ik} \approx 0$

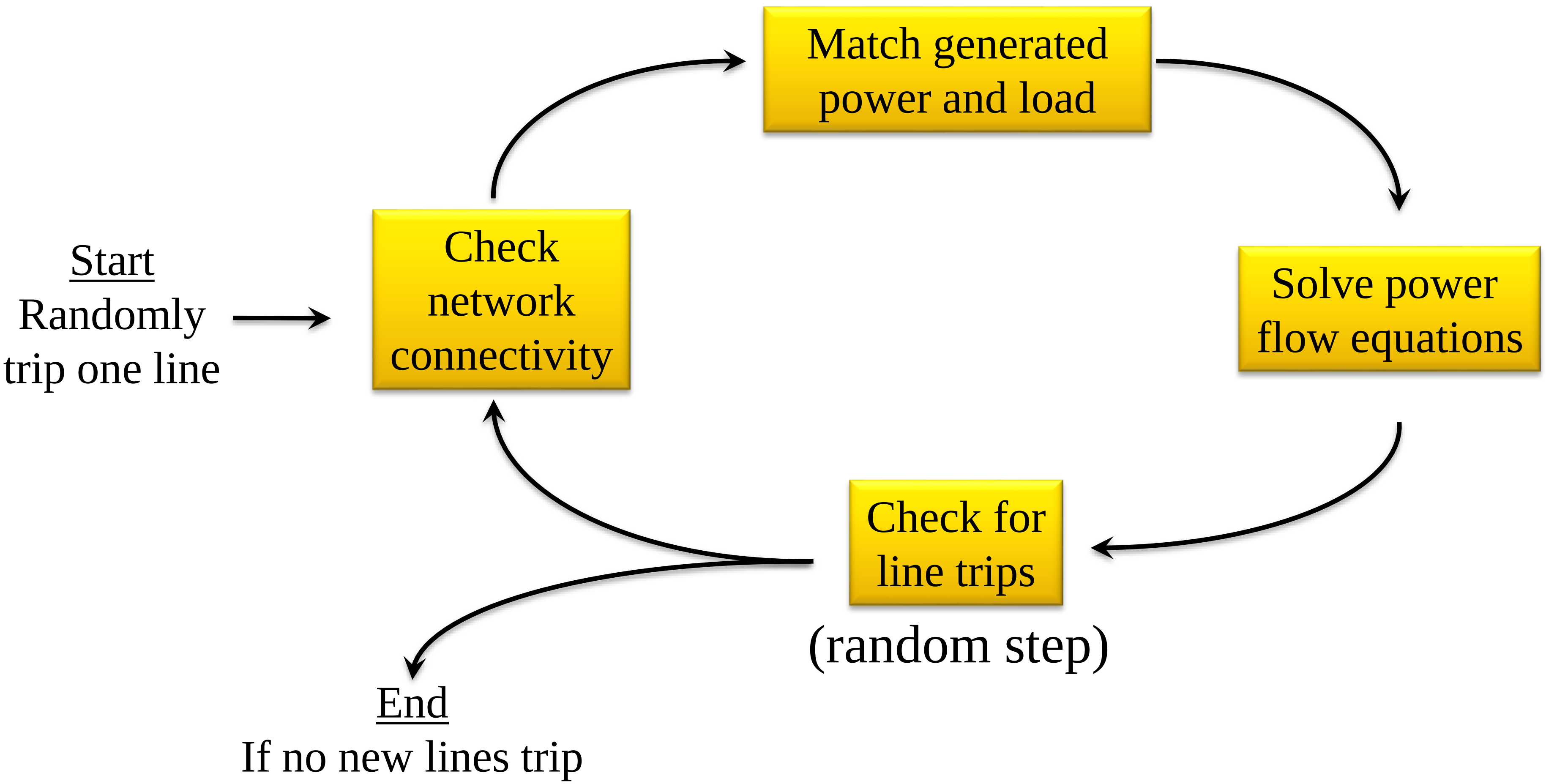
$$P_i = \sum_{k=1}^{n} b_{ik}(\theta_i - \theta_k)$$

  - Return: $P_1, \theta_2, \ldots, \theta_n$

<u>Notation</u>
- P_i, Q_i = *net* real, reactive power injected into bus i (negative for load bus)
- $|V_i|$ = RMS of voltage at bus i
- θ_i = phase angle of voltage at bus i
- g_{ik}, b_{ik} = conductance, susceptance for link ik

E.g., von Meier, A. 2006. *Electric Power Systems*. Wiley.

Cascading Blackout Model



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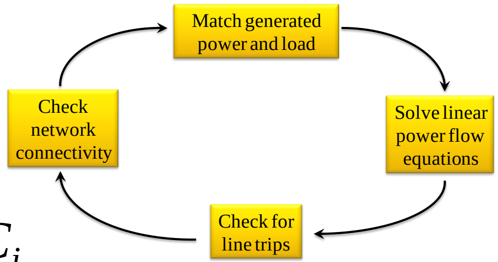
Stochastic Line Trip



- Definitions
  - C_j = capacity of line j (random)
  - $F_j(x)$ = cumulative distribution function of C_j
  - x_j = power flow on line j
  - x_j' = largest previously observed power flow on line j
  - $[x]^+$ = max(x, 0)
- Probability of line trip

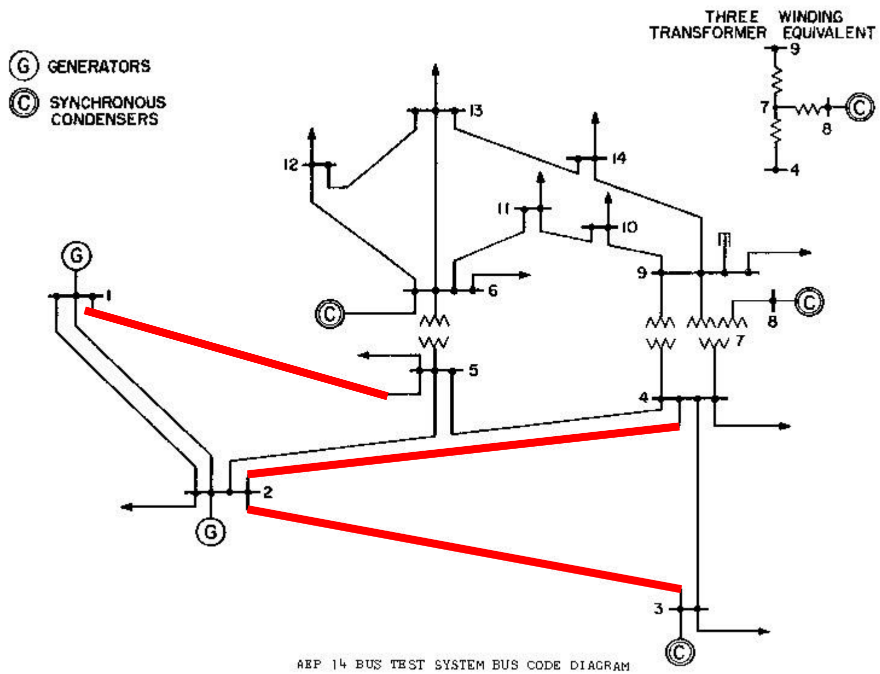
$$\Pr\{C_j \le x_j \mid C_j > x_j'\} = \frac{[F_j(x_j) - F_j(x_j')]^+}{1 - F_j(x_j')}$$

- Notes
  - Possible to have more than one line trip in each step
  - Distinctive feature: Model accounts for additional load above largest previously observed load

Cascading Blackout Model

Factors modeled

- Network structure
- Physics of power flows
- Dependent nature of cascade
- Stochastic failures, demand



Factors **not** modeled

- Timing of events
- Transient effects
- Generator failures
- Human factors
- ...

Problems Simulating Rare Events

$$\gamma \equiv \text{Probability of rare event}$$

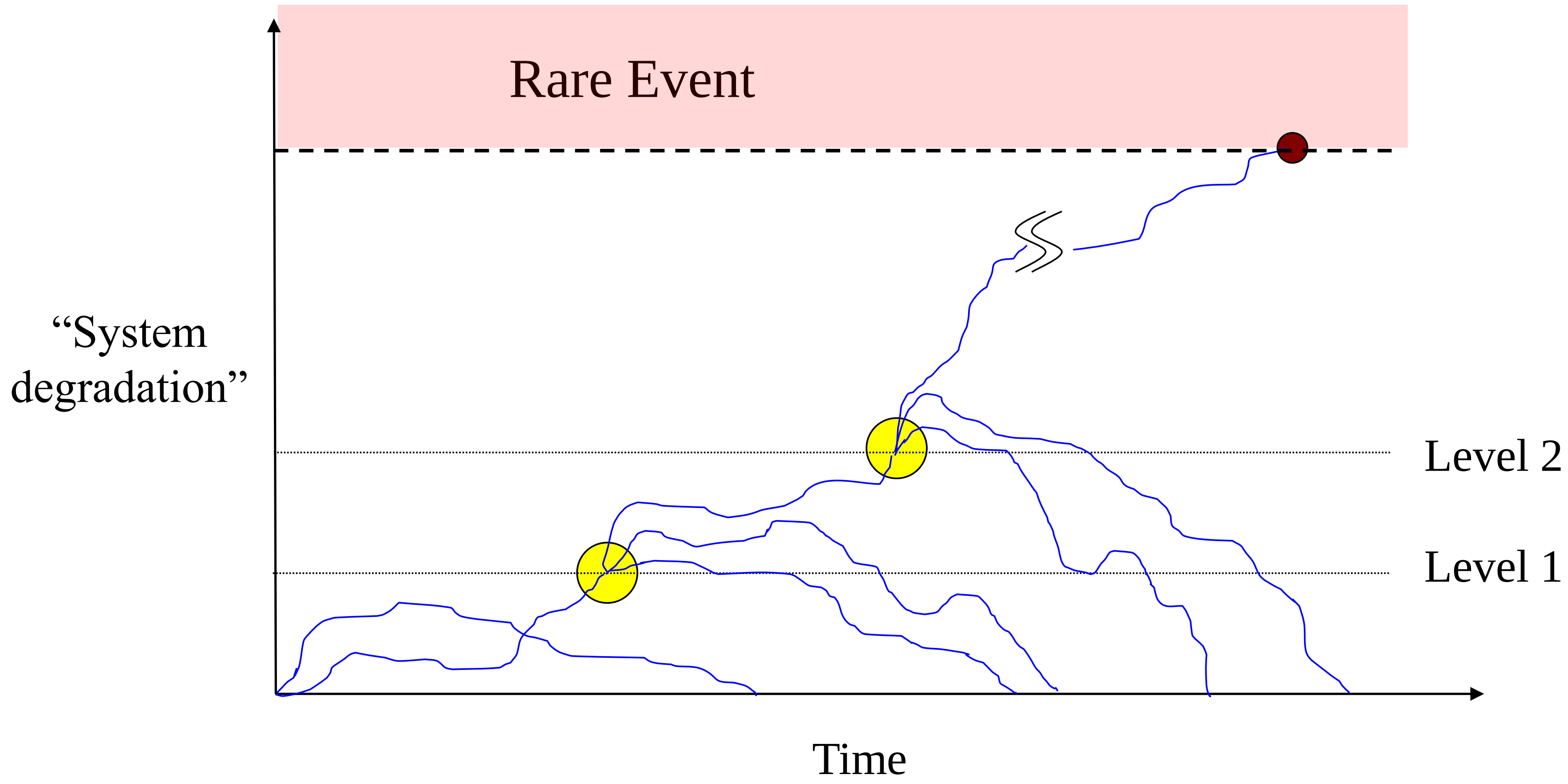
$$\hat{\gamma}_n \equiv \frac{\#\text{ replications in which rare event occurs}}{n}$$

$$\text{Relative Error}[\hat{\gamma}_n] \equiv \frac{\sqrt{\text{var}[\hat{\gamma}_n]}}{E[\hat{\gamma}_n]} = \frac{\sqrt{\gamma(1-\gamma)/n}}{\gamma} \approx \frac{1}{\sqrt{n\gamma}}$$

Time Required to Achieve 1% Relative Error
(Assumes 1,000 replications per second)

Rare Event Probability γ	**Simulation Runs** n	**Required Time**
10^{-3}	10^{7}	16.7 minutes
10^{-5}	10^{9}	1.2 days
10^{-7}	10^{11}	116 days
10^{-9}	10^{13}	31.7 years

Splitting

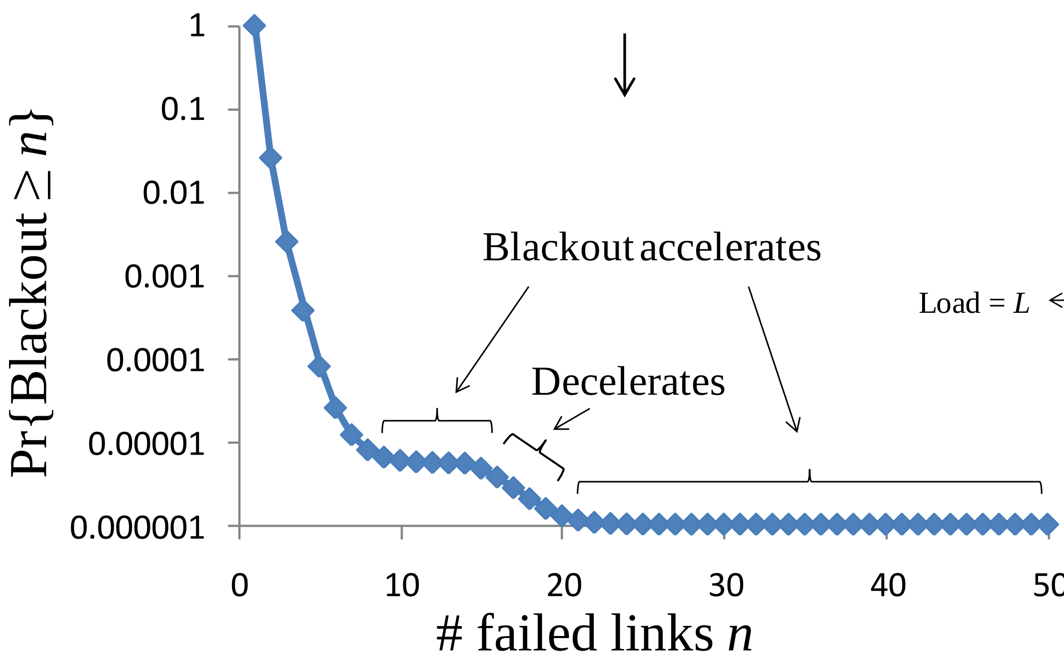


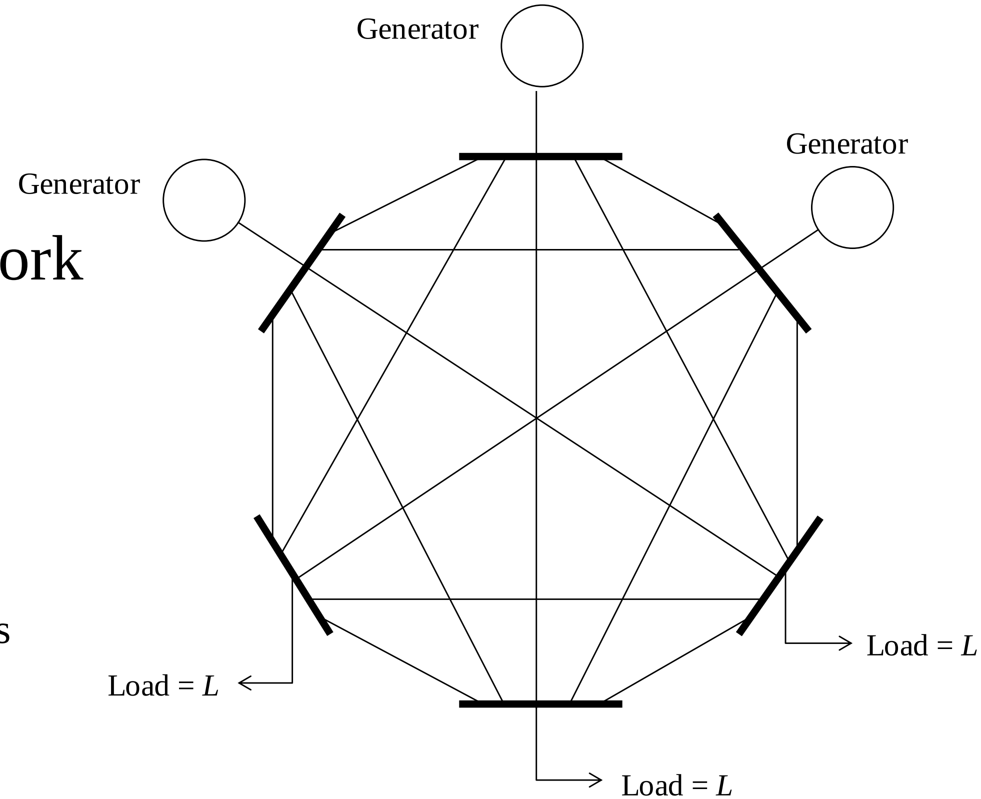
E.g.: Garvels, M. 2000 The splitting method in rare event simulation. Ph.D. thesis University of Twente, The Netherlands.

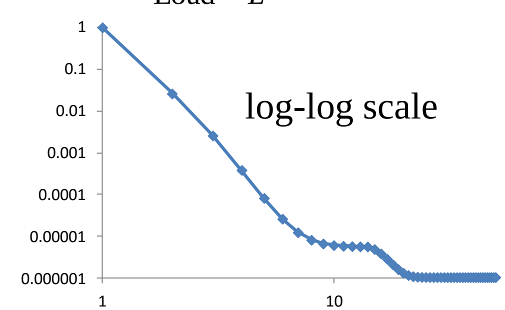
Example: Mesh Network

Example: 15-bus mesh network

5 generators, 10 loads



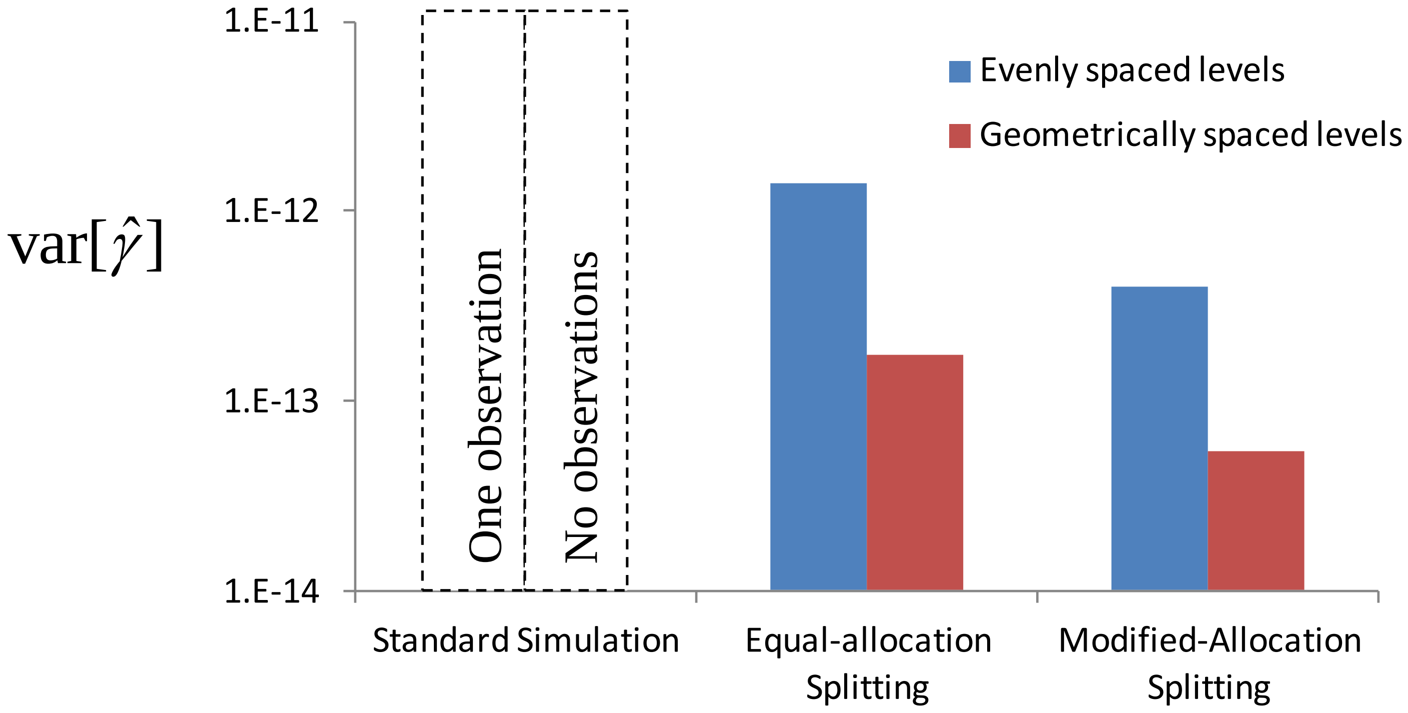




Line capacities follow normal distribution with mean = twice flow of maximum flow on any line when all lines are working. Std. dev = 0.2 x mean.

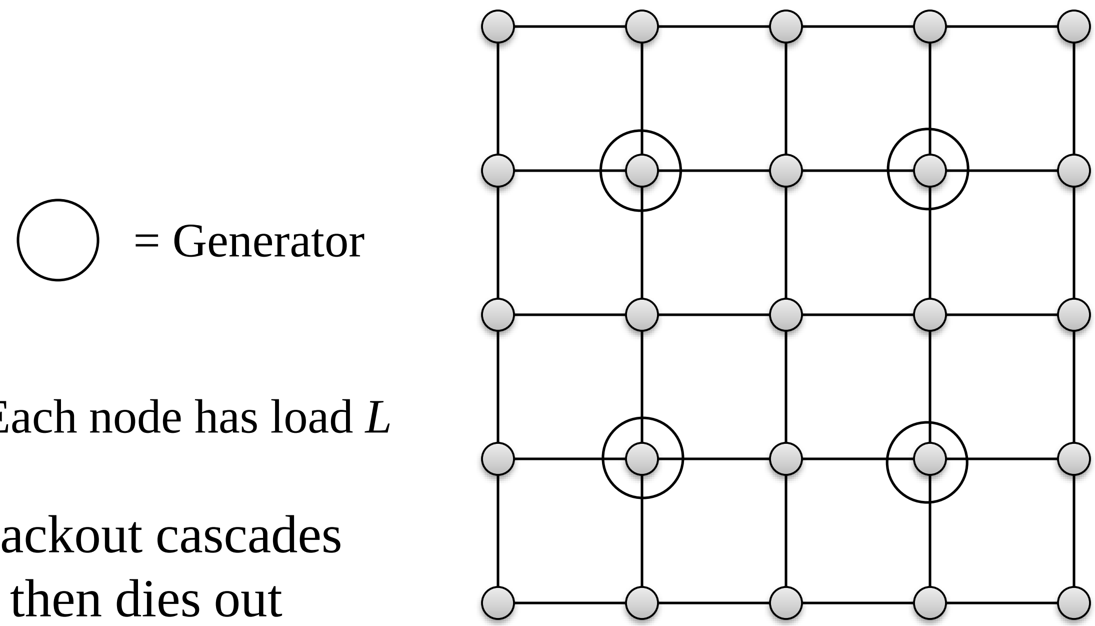
Simulation Efficiency

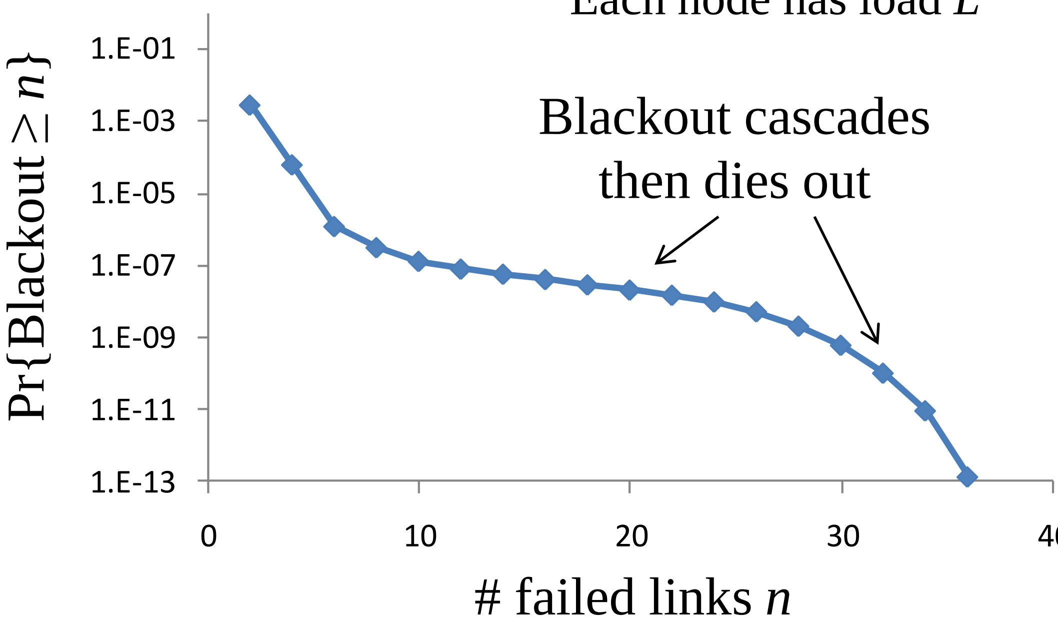
Objective: Estimate γ = Pr{50 lines fail}

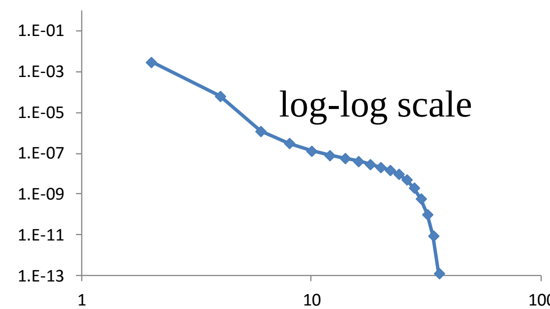


Computing budget = 8 minutes per replication, x 60 replications

Example: Grid Network



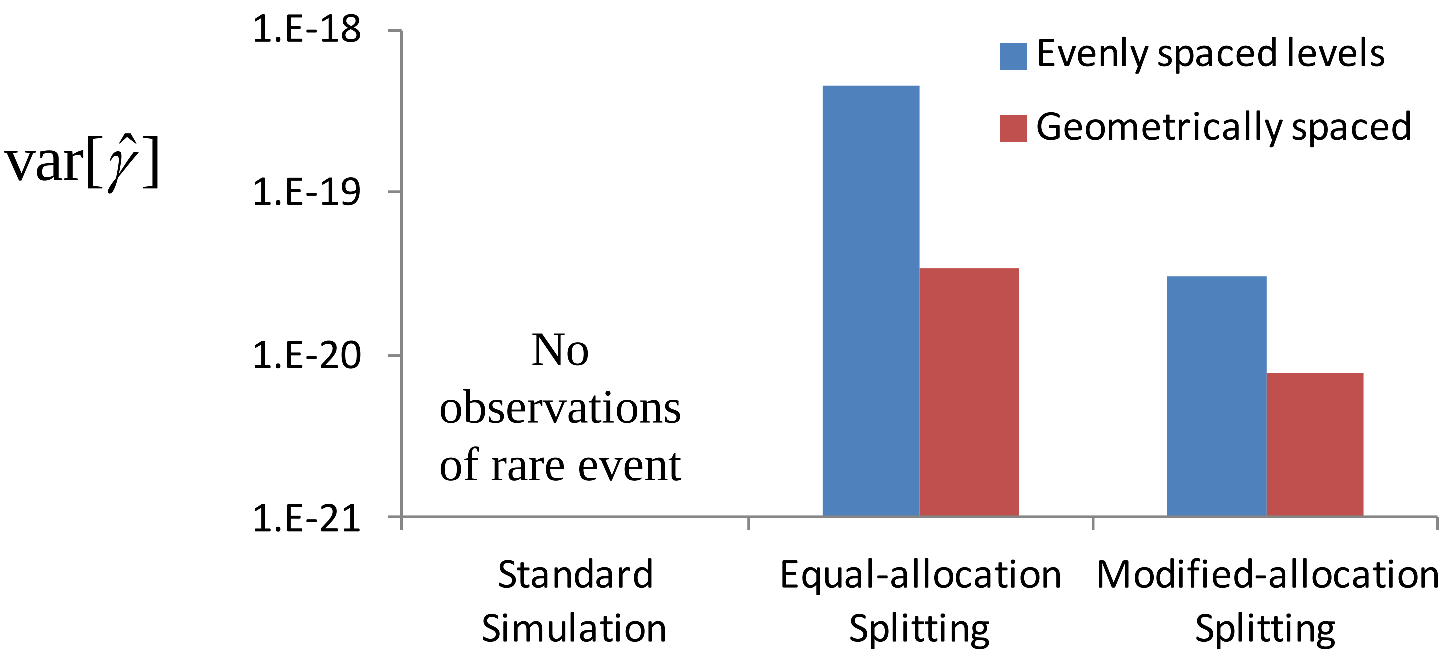




Line capacities follow normal distribution with mean = twice flow on any line after considering all single line failures. Std. dev = 0.2 x mean.

Simulation Efficiency

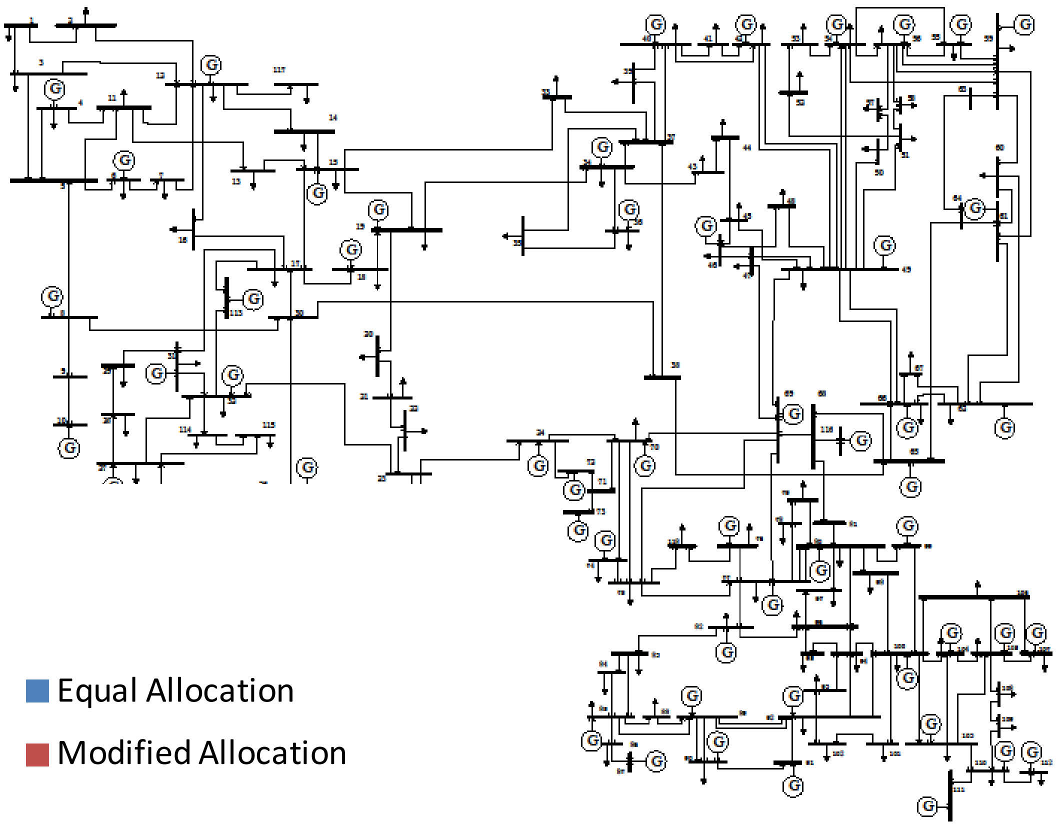
Objective: Estimate γ = Pr{32 lines fail (out of 40)}

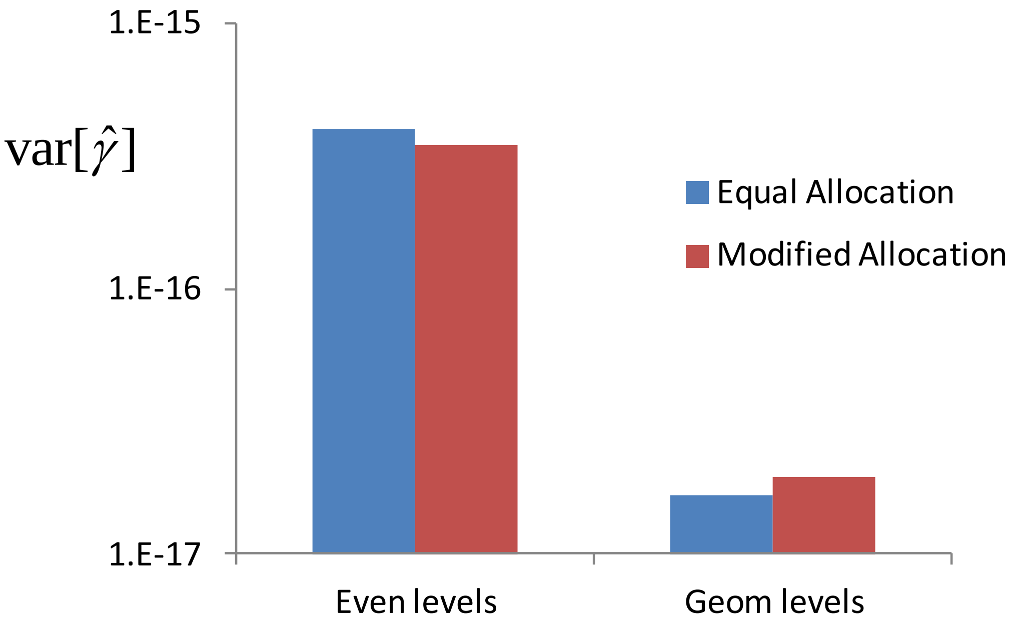


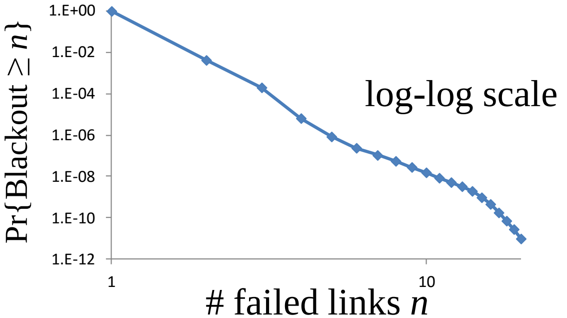
Computing budget = 5 minutes per replication, x20 replications

Example: 118-bus System

Line capacities follow normal distribution with mean = 1.25 times flow on any line after considering all single line failures. Std. dev = 0.2 x mean. Computing budget = 8 minutes per replication, x35 replications

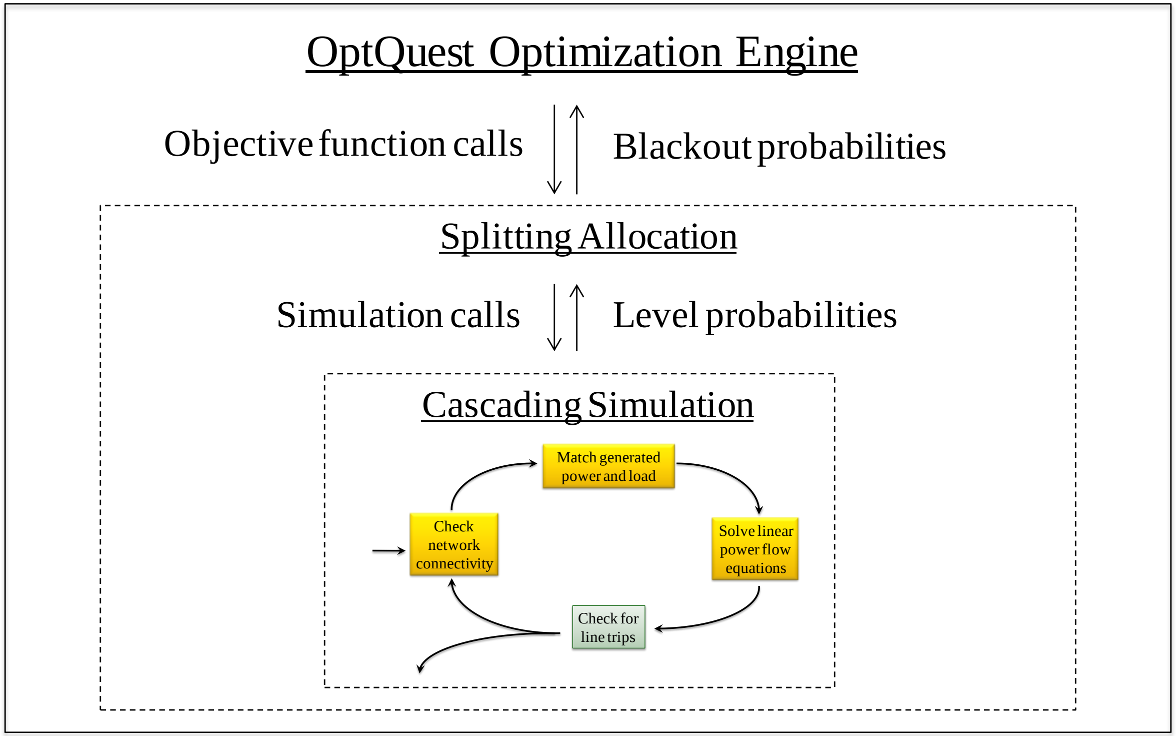






Optimal Capacity Expansion

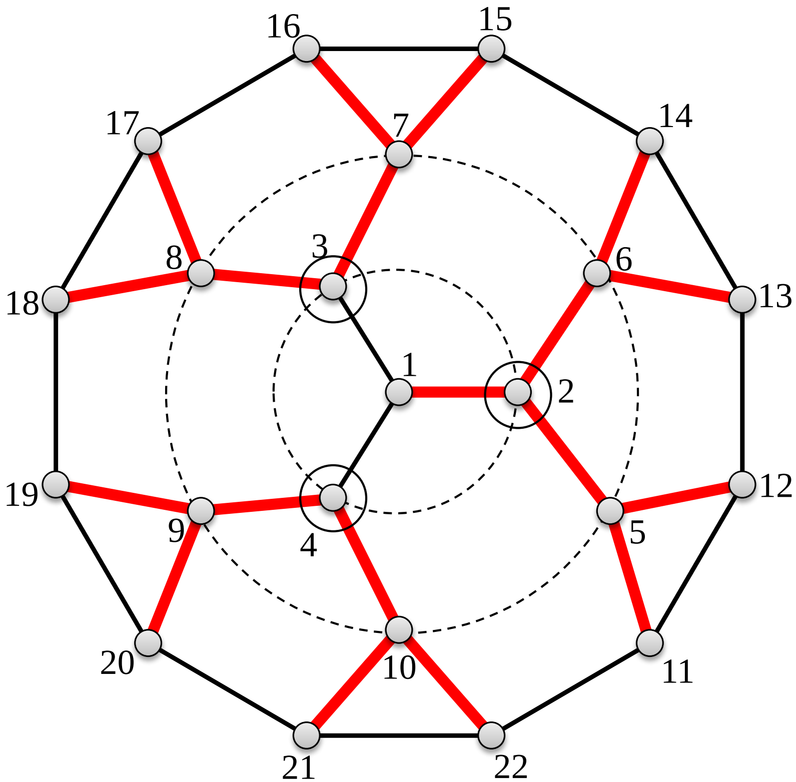
Minimize:	Pr{blackout size $\geq$ threshold}
Such that:	expansion cost $\leq$ budget



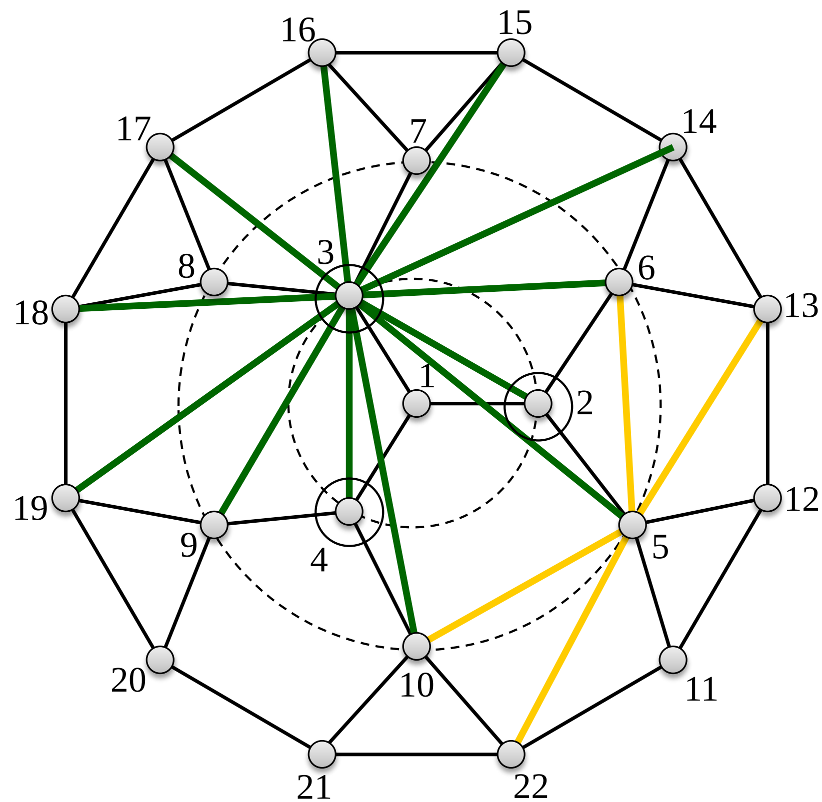
Shortle, J., S. Rebennack, F. Glover. 2014. Transmission-capacity expansion for minimizing blackout probabilities. *IEEE Transactions on Power Systems*, 29(1), 43-52.

Expansion: Tree Network

Large-scale Blackout



Medium-scale Blackout



Summary

- Dependent nature of cascade. Line failures change failure probabilities of other lines
- Standard simulation may not be computationally tractable for estimating rare-event probabilities
  - Splitting is a technique that can make problem tractable
- Other work
  - Evaluation of splitting parameters
  - Capacity optimization favors expanding a single path to each node for high utilization
- Current work in stochastic “N-k” problem