A criticality approach to monitoring cascading failure risk and failure propagation in transmission systems

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Levels of modeling for cascading blackouts

ANALYTIC MODELS

(branching process, CASCADE)

SIMULATIONS

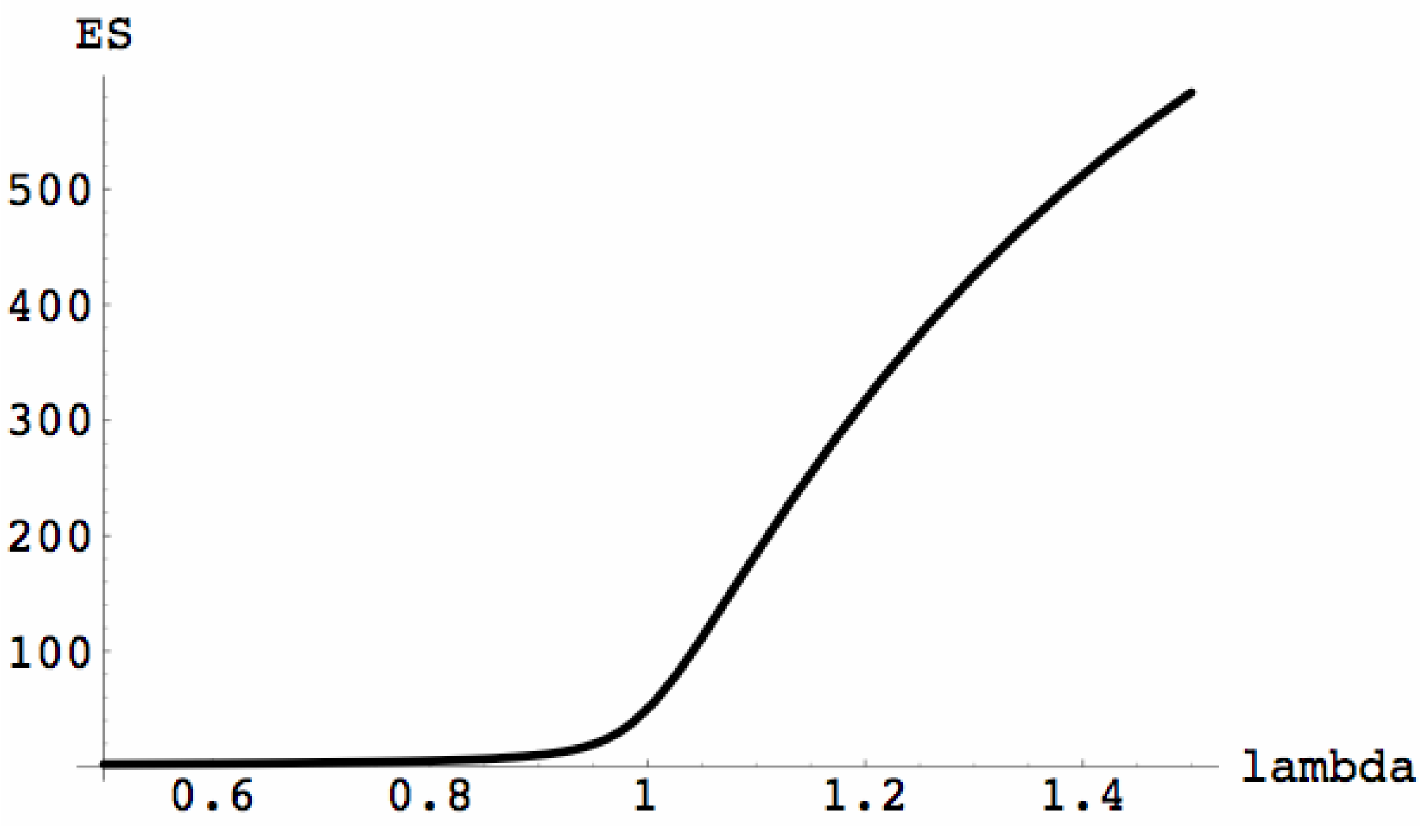
(OPA, hidden failure, Kirschen, CMU, TRELSS)

REAL BLACKOUTS

The probability of cascading failure blackout increases with system loading

Exactly how does it increase?

Mean number of failures

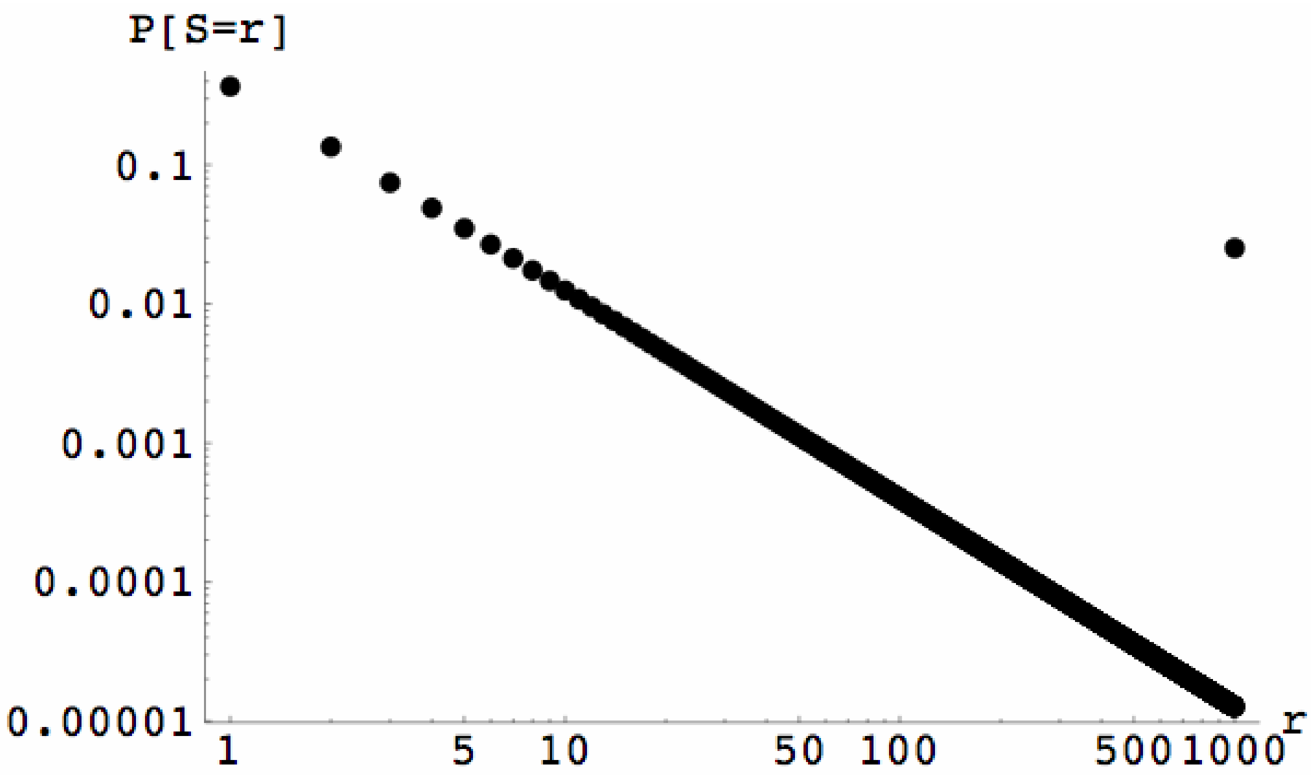


criticality

λ; system stress

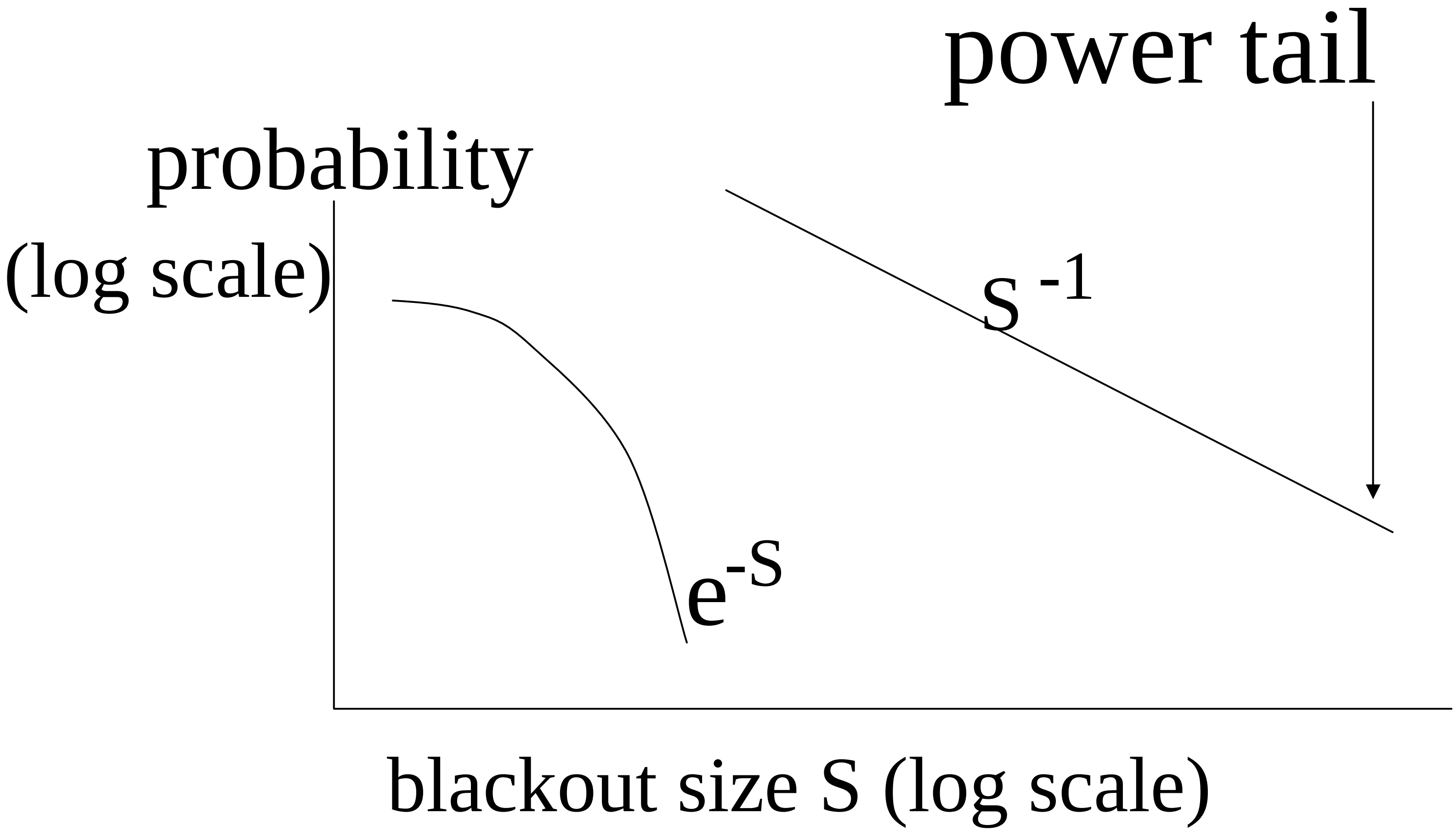
Branching model with 1000 components

probability



number of failures

Branching model with 1000 components at criticality



power tails have huge impact on large blackout risk.

risk = probability x cost

a working definition of critical loading

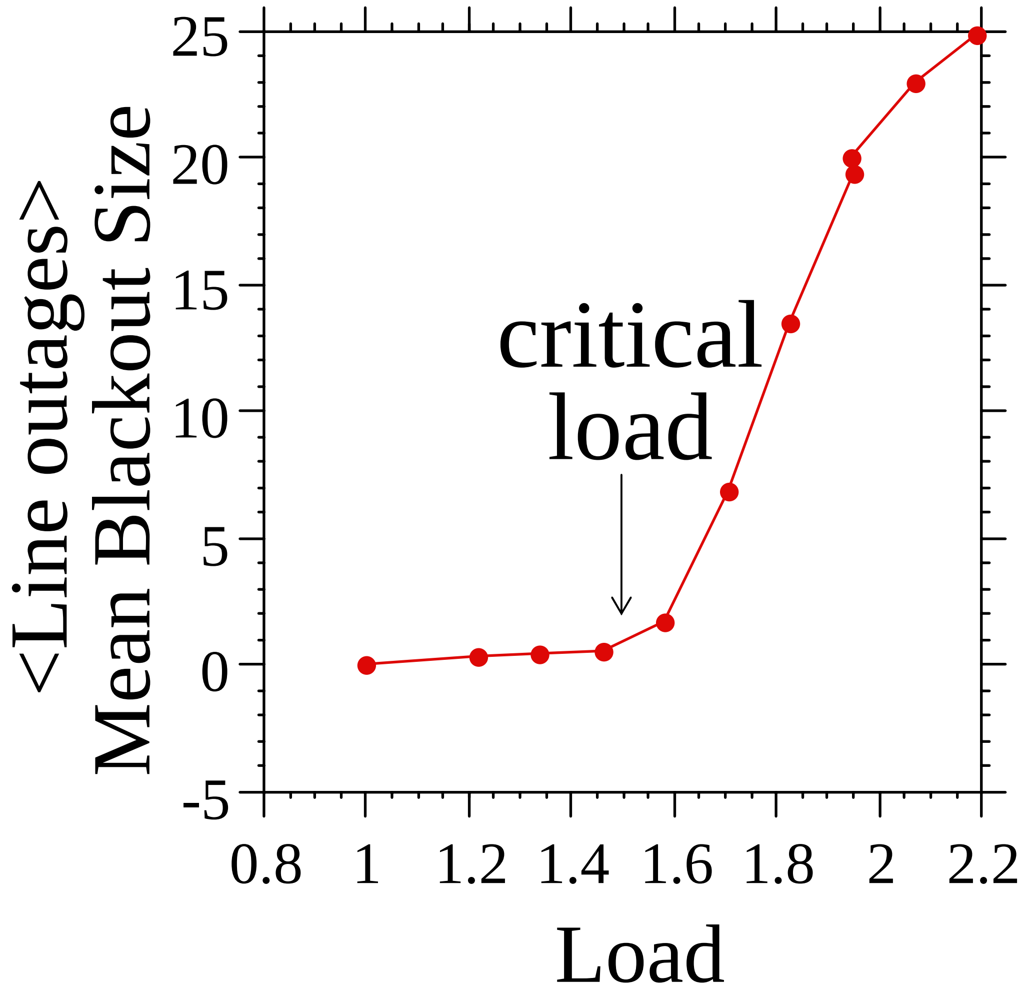
at criticality:

- there is a power law in the distribution of blackout size
- there is a kink or jump in mean blackout size

Summary of OPA blackout model

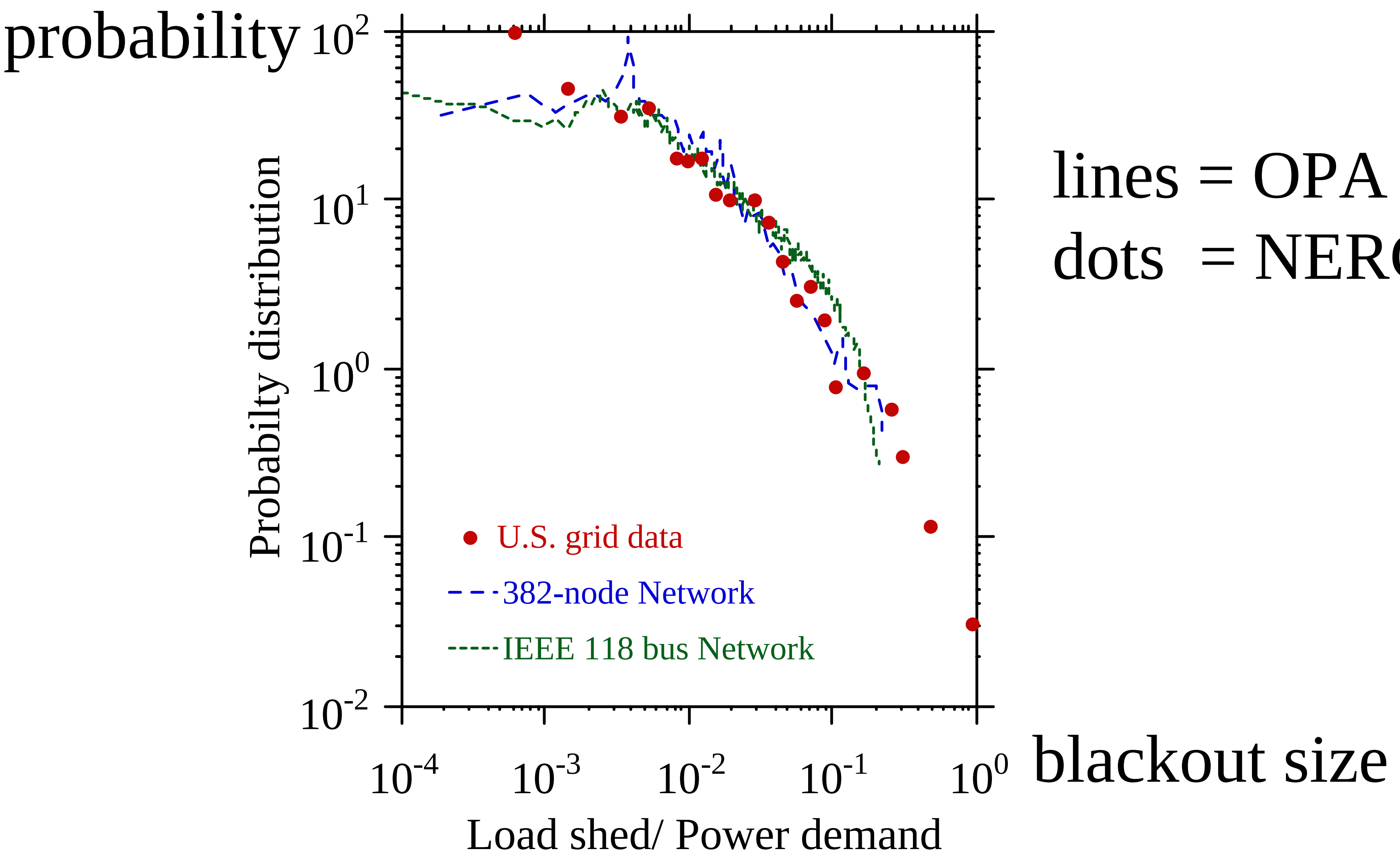
- transmission system network modeled with DC load flow and LP dispatch
- random initial disturbances and probabilistic cascading line outages and overloads

Critical loading in OPA blackout model



Mean blackout size sharply increases at critical loading; increasing risk of cascading failure.

power laws in OPA model & NERC data



lines = OPA

dots = NERC

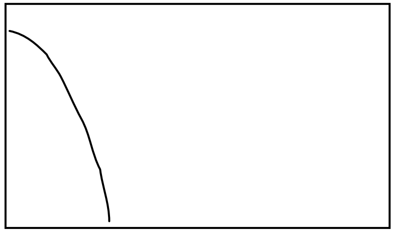
How does the probability distribution of blackout size change as system is loaded?

Don’t think about avoiding all blackouts; think about managing the probabilities of small, medium and large blackouts

Effect of Loading

log log plots

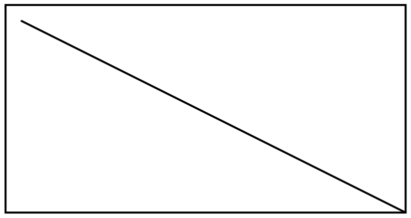
probability



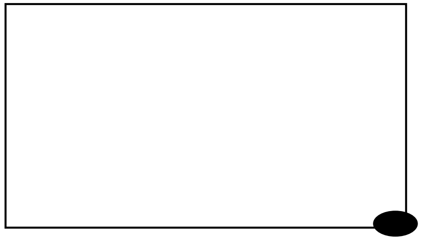
blackout size

- VERY LOW LOAD
  - failures independent
  - exponential tails

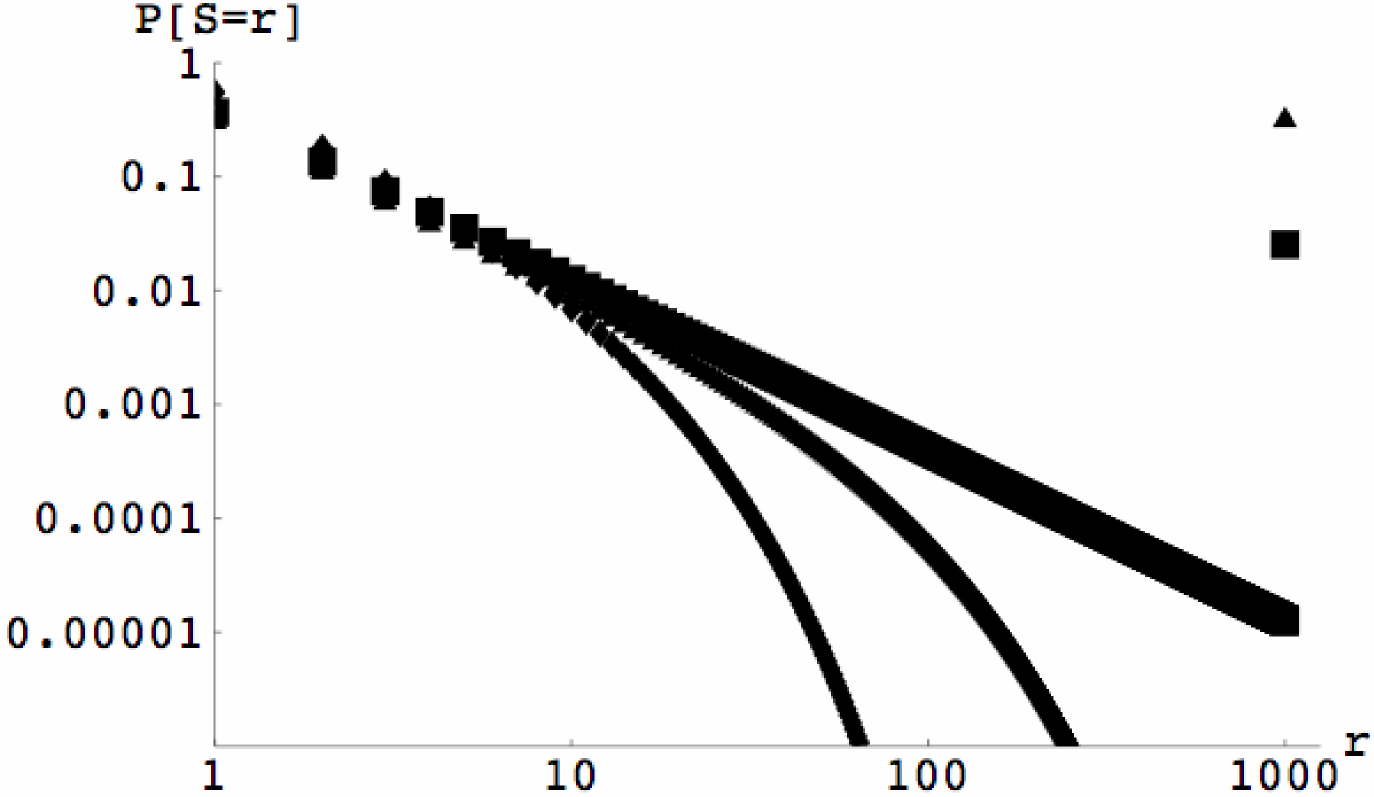
- CRITICAL LOAD
  - power tails



- VERY HIGH LOAD
  - total blackout likely



probability

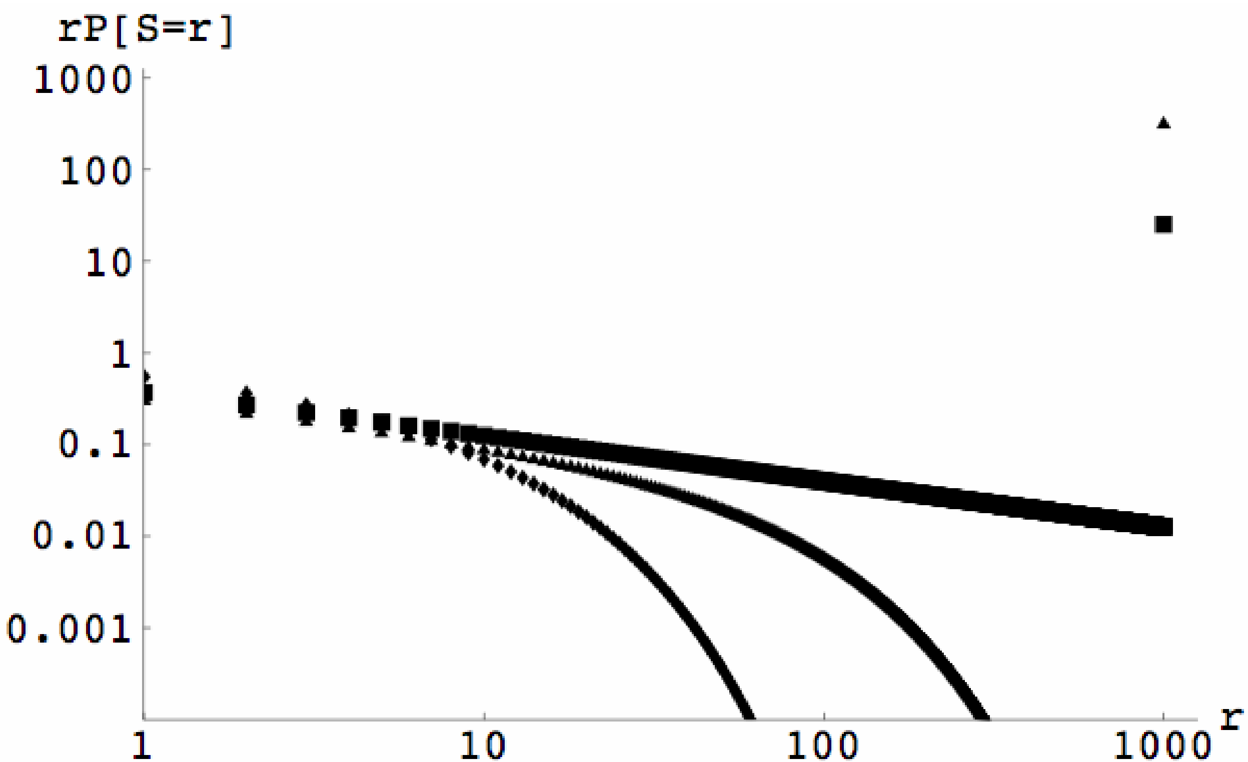


number of failures

Branching model with 1000 components
below, at, and above criticality

By assuming cost proportional to size, can obtain risk distribution from pdf

RISK



number of failures

Branching model with 1000 components below, at, and above criticality

Significance of criticality

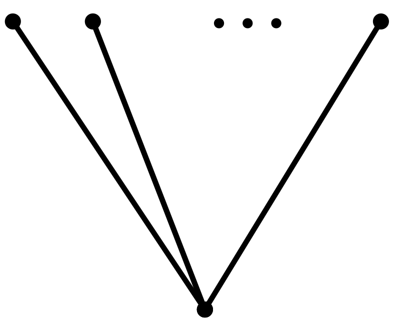
- At criticality there is a power tail, sharp increase in mean blackout size, and an increasing risk of cascading failure -- signatures of a phase transition in statistical physics.
- Criticality gives a power system limit or reference point with respect to cascading failure.
- Margin to criticality can be related to blackout risk
- How do we practically monitor or measure margin to criticality?

approaches to margin to criticality

1) Increase loading in blackout simulation until average blackout size increases.
2) Monitor or measure how much failures propagate (λ) from real or simulated data.

Summary of branching process model

Branching from one failure:

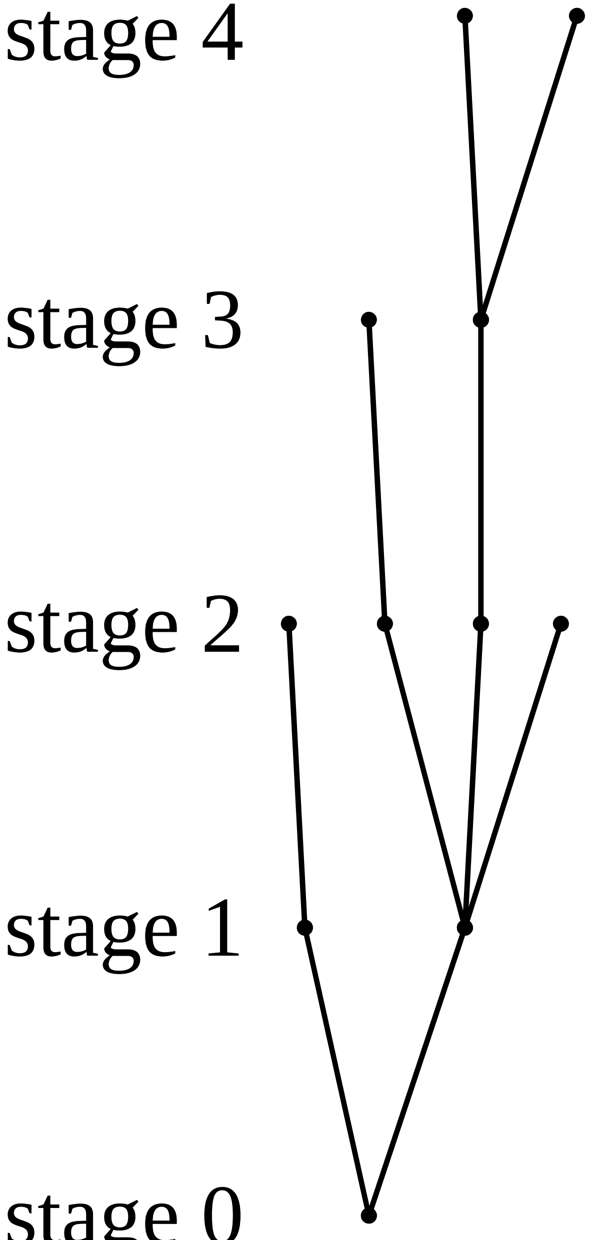


offspring failures

a failure

number of offspring ~ Poisson(λ)

mean number of failures = λ



Branching Process

– each failure independently has random number of offspring in next stage according to Poisson(λ)

– **λ = mean number failures per previous stage failure**

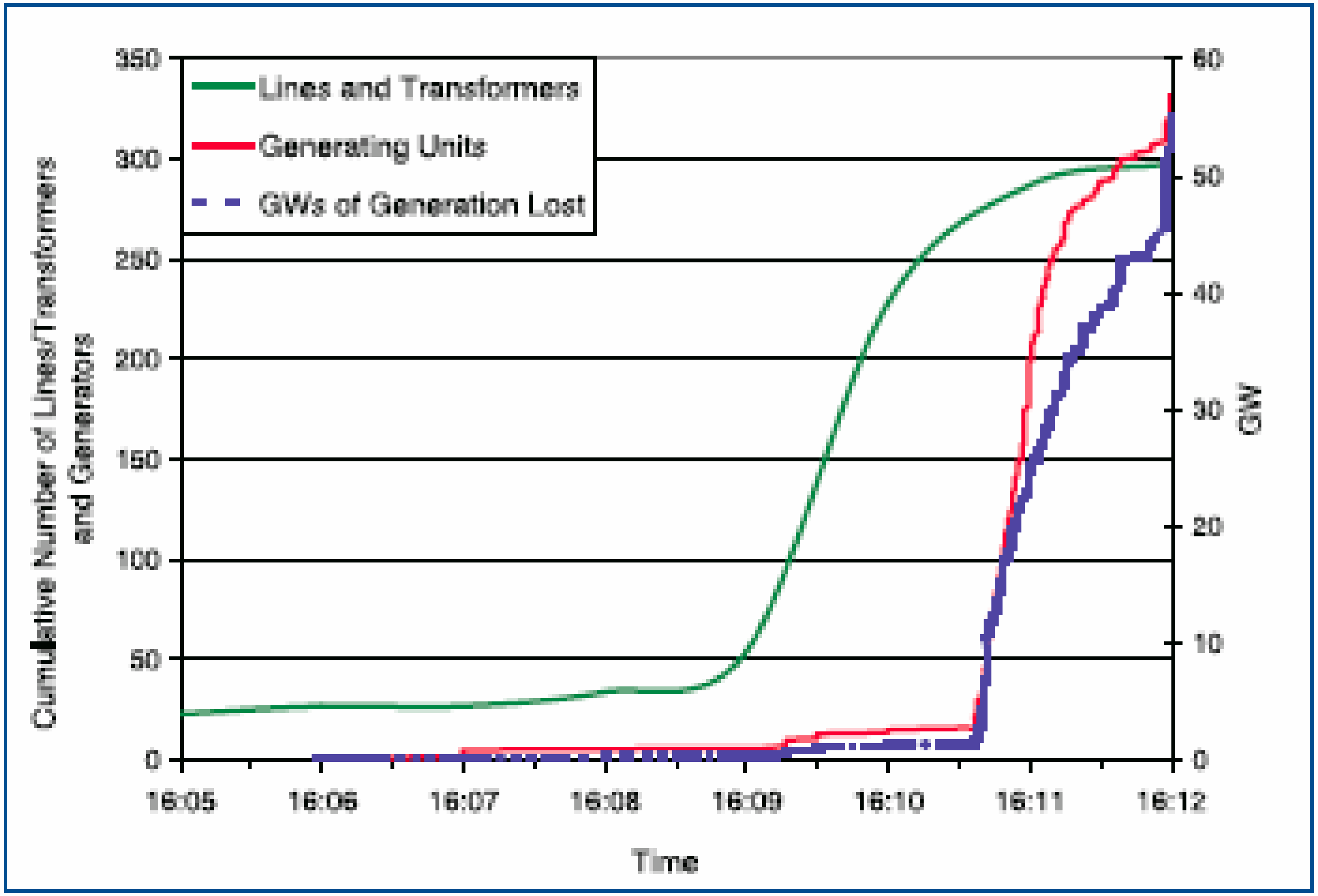
– λ^k = mean number of failures in stage k

λ controls failure propagation

- Subcritical case $\lambda<1$:
  failures die out
- Critical case $\lambda=1$:
  probability distribution of total number of failures has power tail
- Supercritical case $\lambda>1$:
  failures can proceed to system size

Cumulative Line Trips from August 2003 Blackout Final Report

Figure 6.1. Rate of Line and Generator Trips During the Cascade



Estimates of λ

- (number of failures in stage k)$^{1/k}$
- (number of offspring)/(number of parents)
- slope of log(cumulative failures)

We are starting to explore the use of these statistical estimates in this and other papers

Conclusions

- Criticality gives a reference point or system limit with respect to increasing risk of cascading failure.
- Margin to criticality and failure propagation λ can be related to distribution of risk of blackouts of all sizes. Goal: risk analysis for blackouts
- Analytic and simulation models and monitoring methods for cascading failure are emerging. One Goal: understand and quantify criticality and blackout risk from real and simulated data.

Our general approach

- Instead of only looking at postmortem details of particular blackouts, also look at bulk system statistical properties (global, top-down).
- Instead of avoiding all blackouts, shape the pdf of blackout size to manage risk of all blackout sizes.
- Design and operate system to limit propagation of failures after they are initiated; complementary to limiting likely and foreseeable combinations of initial failures.
- Add an explicit operating limit for increased risk of cascading failure.
- For detail see papers at http://eceserv0.ece.wisc.edu/~dobson/home.html

Research directions

- Gain research access to blackout data
- Estimate costs of large blackouts
- Confirm and study criticality
- Further develop power system and abstract models of cascading failure
- Develop practical methods of monitoring margin to criticality from real or simulated data