Risk of Large Cascading Blackouts

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TOPICS

- Why worry about large blackouts?
  Risk of large blackouts and NERC data
- Where is the ‘edge’ for cascading failure?
  Critical loading in cascading failure models
- Can we quantify, manage, and monitor overall blackout risk?
- Reliability in an evolving system: complex systems aspects

Cascading failure; large blackouts

- Rare, unanticipated, dependent events
  + huge number of possibilities and combinations
  = hard to analyze or simulate
- Mechanisms include: hidden failures, overloads, oscillations, transients, control or operator error, ... but all depend on loading

Detailed postmortem analysis of a particular blackout

- arduous (months of simulation and analysis) but very useful
- a basis for strengthening weak parts of system
- motivates good practice in reliability: “Blackouts cause reliability”

General approach

- Instead of looking at the details of individual blackouts, look at overall risk of blackouts of all sizes
- Global top-down analysis of bulk system properties.
- Complementary to detailed analysis

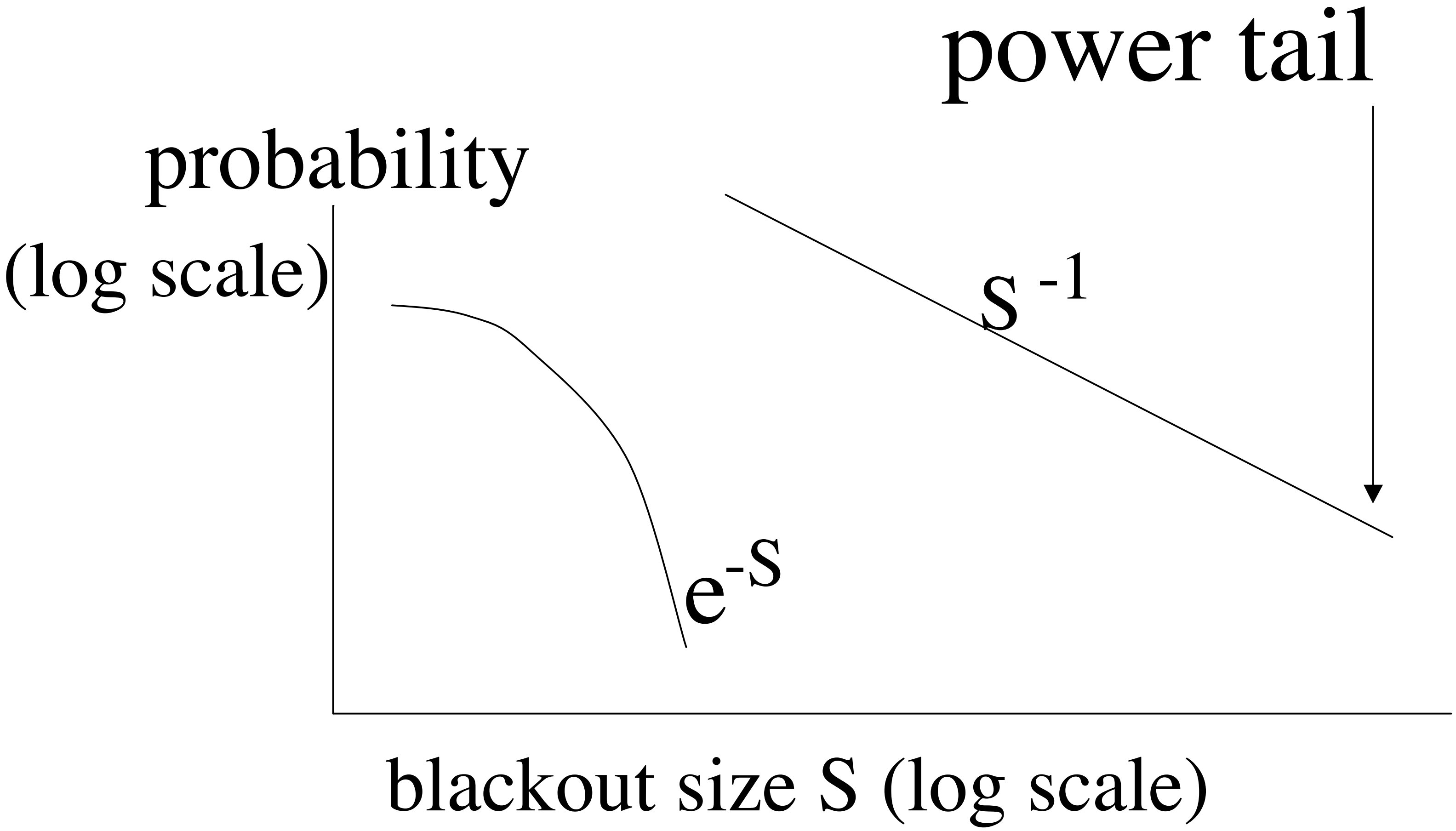
Who pays the blackout cost?

- Public and business. Halts the economy + indirect costs + harms other infrastructures
- Utilities. Reputational, legal, regulatory costs, cost of upgrade or personnel to avoid similar blackouts
- Government. Political risk

Blackout risk as size increases

risk = probability x cost

- Cost increases with blackout size.
  example: direct cost proportional to size
- How does blackout probability decrease as size increases? … a crucial consideration for blackout risk!



power tails have huge impact on large blackout risk.

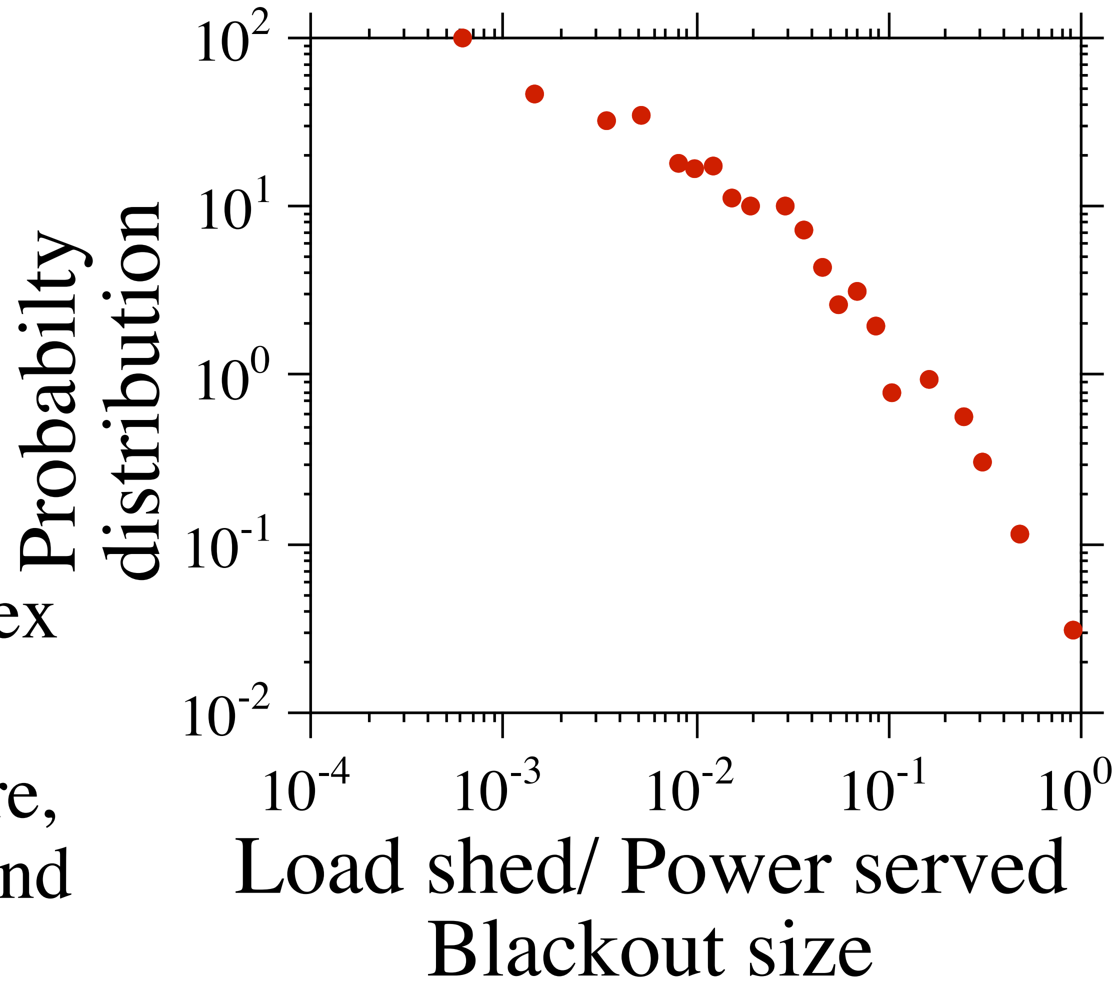
risk = probability x cost

NERC blackout data

- Major North American transmission outages over 15 years 1984-1998
- 427 blackouts
- Data includes MW shed, restoration time, number of customers
- Can process data to obtain frequency of blackouts in various size ranges and hence estimate probability distribution of blackout size

NERC blackout data shows power tail

- Large blackouts more likely than expected
- Conventional risk analysis tools do not apply; new approaches needed
- Consistent with complex system near criticality
- Large blackouts are rare, but have high impact and significant risk



NERC data shows that risk of large blackouts may be comparable to risk of small blackouts. To manage blackout risk we must consider risk of all sizes of blackouts.

Two complementary types of risk analysis calculations for cascading failure:

1) Compute high risk sequences of N-k events …
   very useful for fixing weakest parts and operator actions in likely situations.
2) Estimate overall blackout risk due to all sequences of events, including many or all of the vast number of unlikely sequences …
   opens up quantifying reliability and managing blackout risk.

How do we manage blackout risk?

- *Formulate* problem as jointly reducing small, medium, and large blackout frequency
(e.g., avoid suppressing small blackouts at the expense of greatly increasing large blackouts)

- Requires *quantifying* the risk for the blackouts of various sizes; particularly the blackout frequency and cost for the various sizes.

Where the overall blackout risk topic is now

- NERC historical blackout data; August 2003 data
- Some cascading failure simulations: CMU, OPA, Manchester, TRELSS
- Probabilistic models of cascading failure
- Efficiently predicting blackout size distribution from simulation data is being tested.

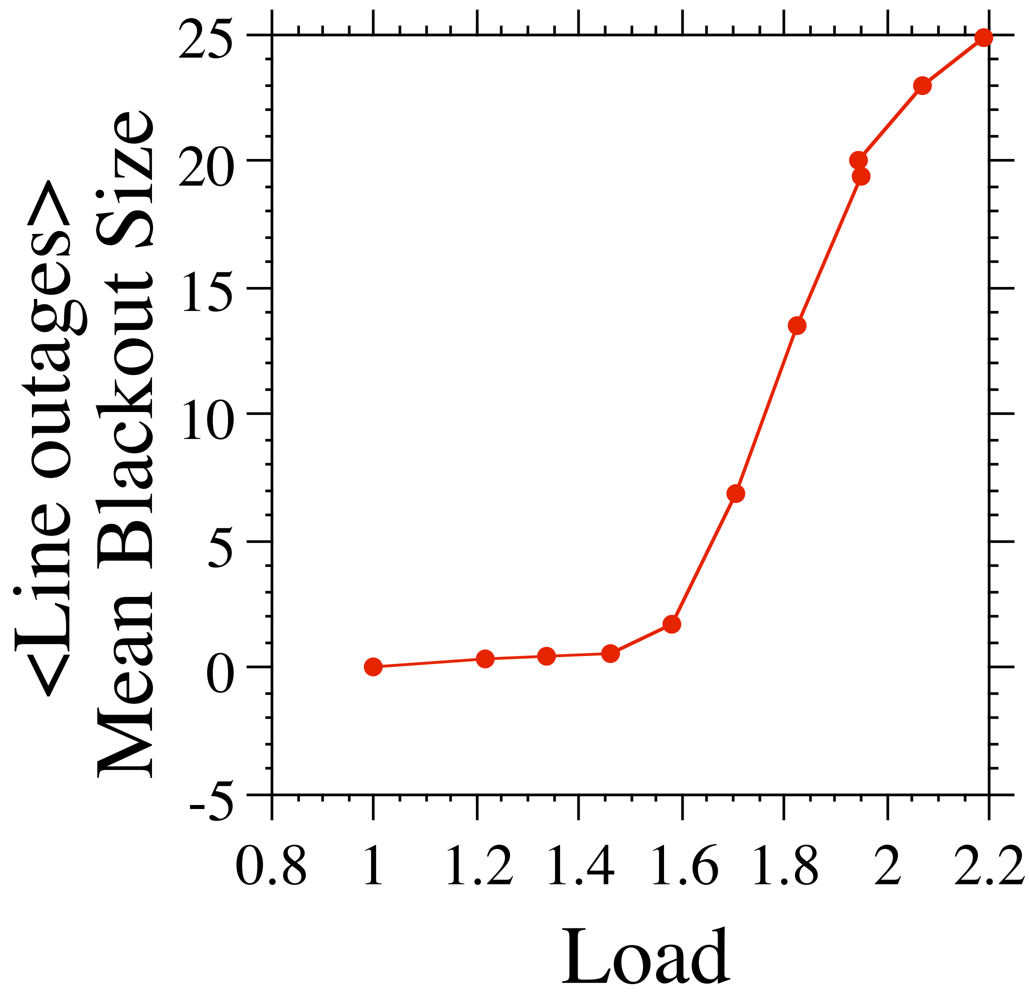
Key ideas emerging from research

- Critical loading.
  Where is the edge for cascading failure?
- λ = propagation of failures.
  How much on average do failures propagate after they start?
- Estimating λ and the overall risk

Blackout model summary

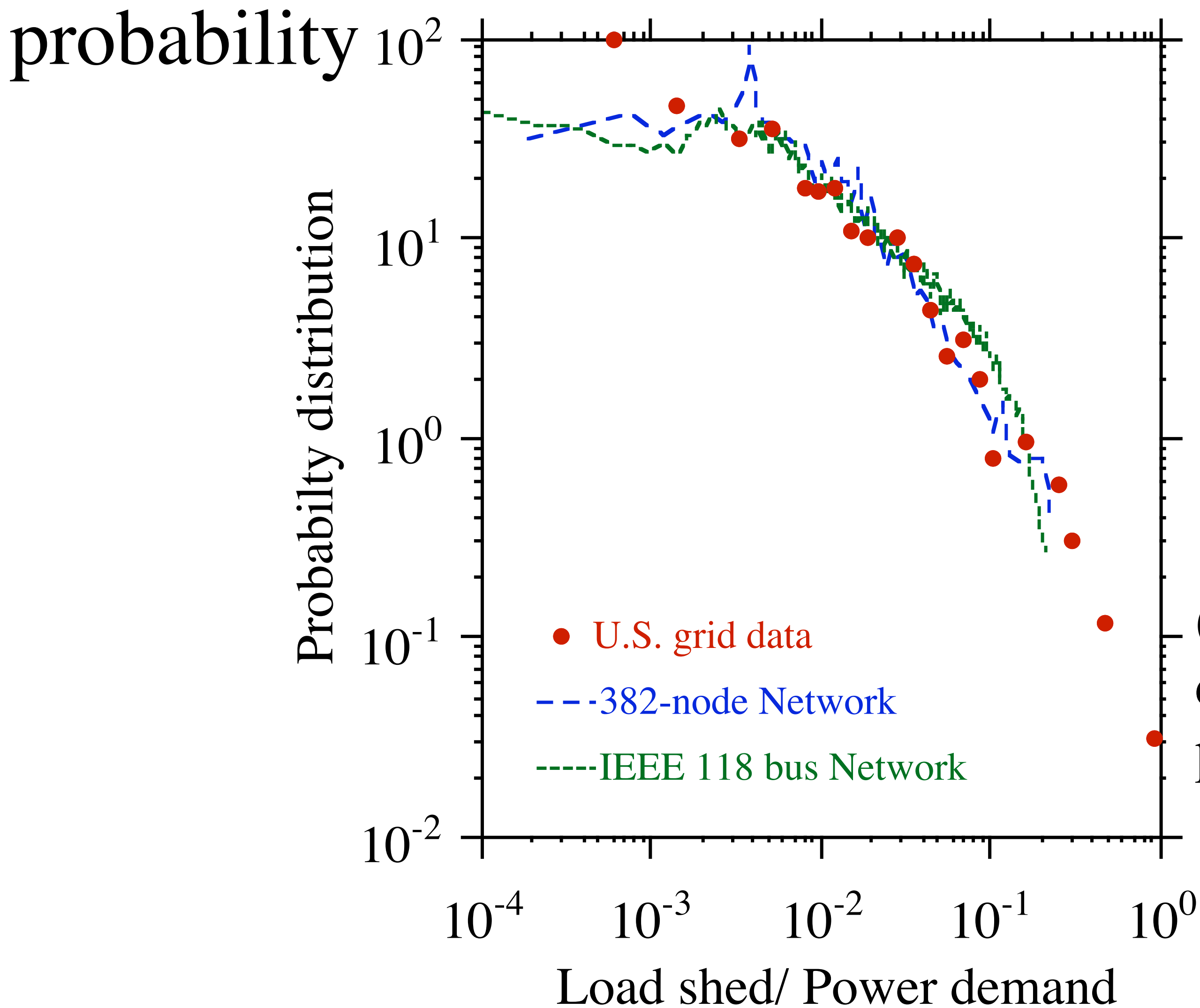
- transmission system modeled with DC load flow and LP dispatch
- random initial disturbances and probabilistic cascading line outages and overloads

Critical loading in blackout model



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

blackout model can match NERC data

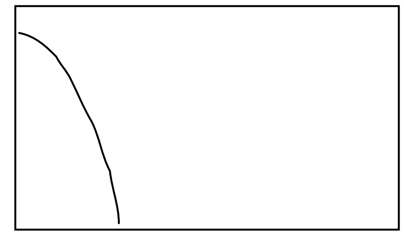


(August 14 blackout is consistent with this power tail)

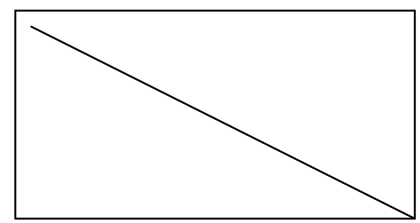
Critical Loading

log log plots

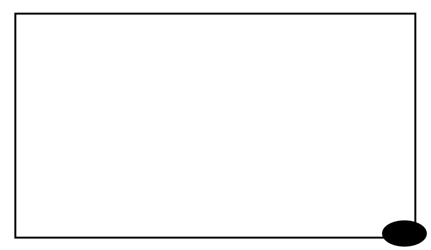
- VERY LOW LOAD
  - failures independent
  - exponential tails



- CRITICAL LOAD
  - power tails



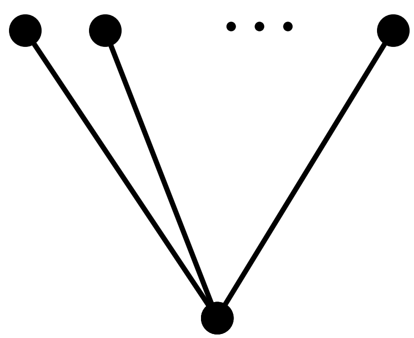
- VERY HIGH LOAD
  - total blackout likely



Significance of criticality

- At critical loading there is a power tail, sharp increase in mean blackout size, and an increased risk of cascading failure.
- Criticality gives a power system limit with respect to cascading failure.
- How do we practically monitor or measure margin to criticality?

Cascading as a branching process: Branching from one failure

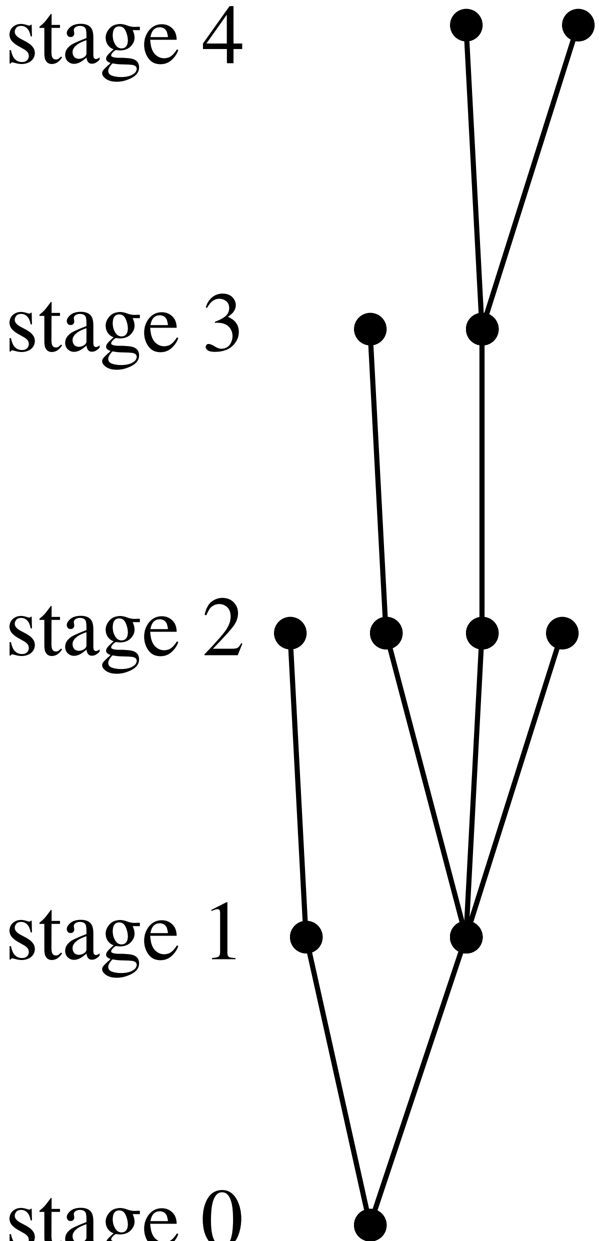


offspring failures

a failure

random number of offspring

mean number of offspring failures = λ



Branching Process

– each failure independently has random number of offspring in next stage

– **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 and blackout of limited size
- Critical case $\lambda=1$:
  probability distribution of total number of failures
  has power tail
- Supercritical case $\lambda>1$:
  failures can proceed to system size

Implication for managing risk of cascading failure:

design and operate system to limit propagation so that

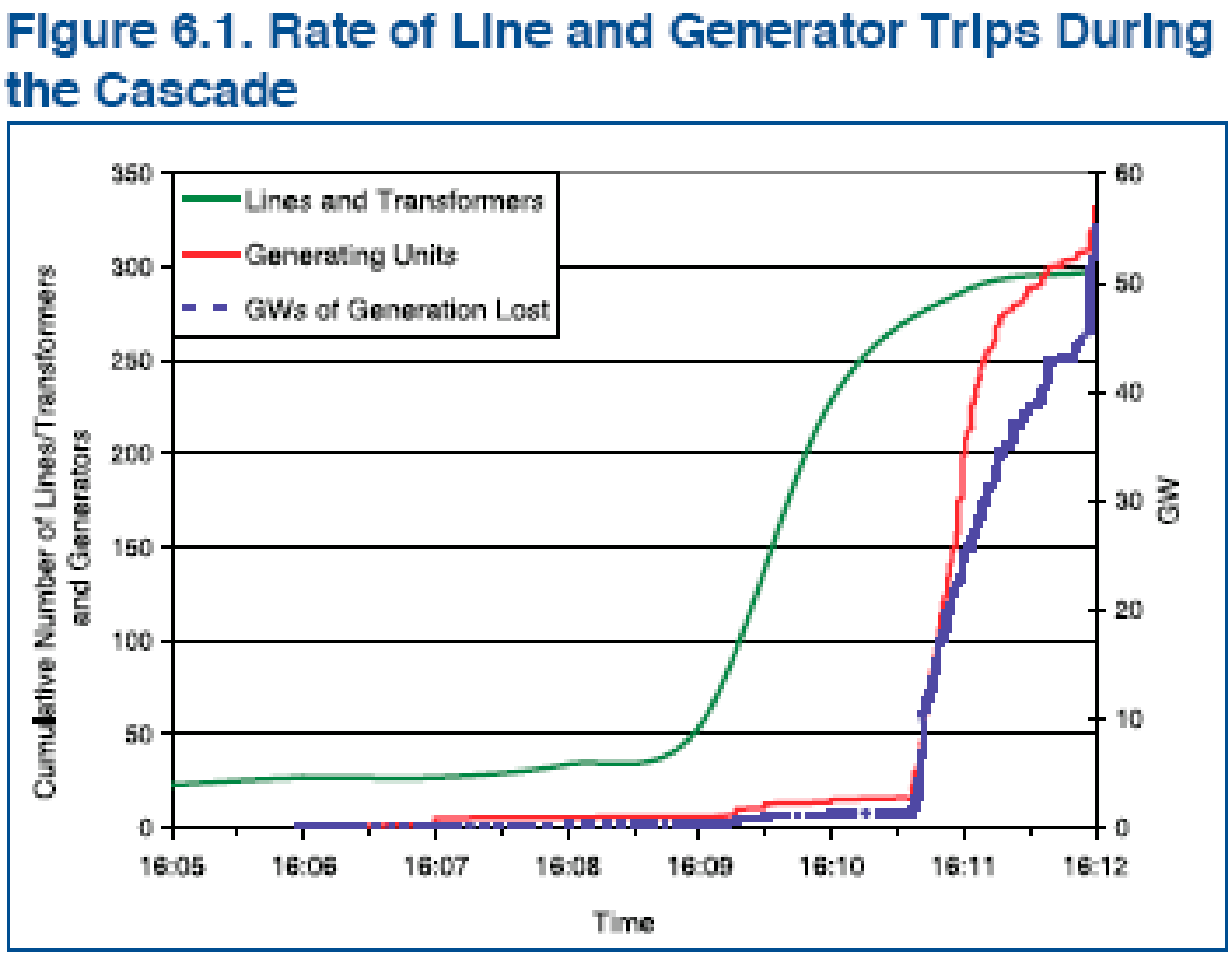
$$\lambda < \lambda_{max} < 1$$

can estimate risk of cascading failure from λ

Context

- We are suggesting adding an "increased risk of cascading failure" limit to usual power system operating limits such as thermal, voltage, transient stability etc.
- Cascading failure limit measures overall system stress in terms of how failures propagate once started; complementary to measures to limit cascading failure by inhibiting start of cascade such as n-1, n-2 criterion.

Cumulative Line Trips from August 2003 Blackout Final Report



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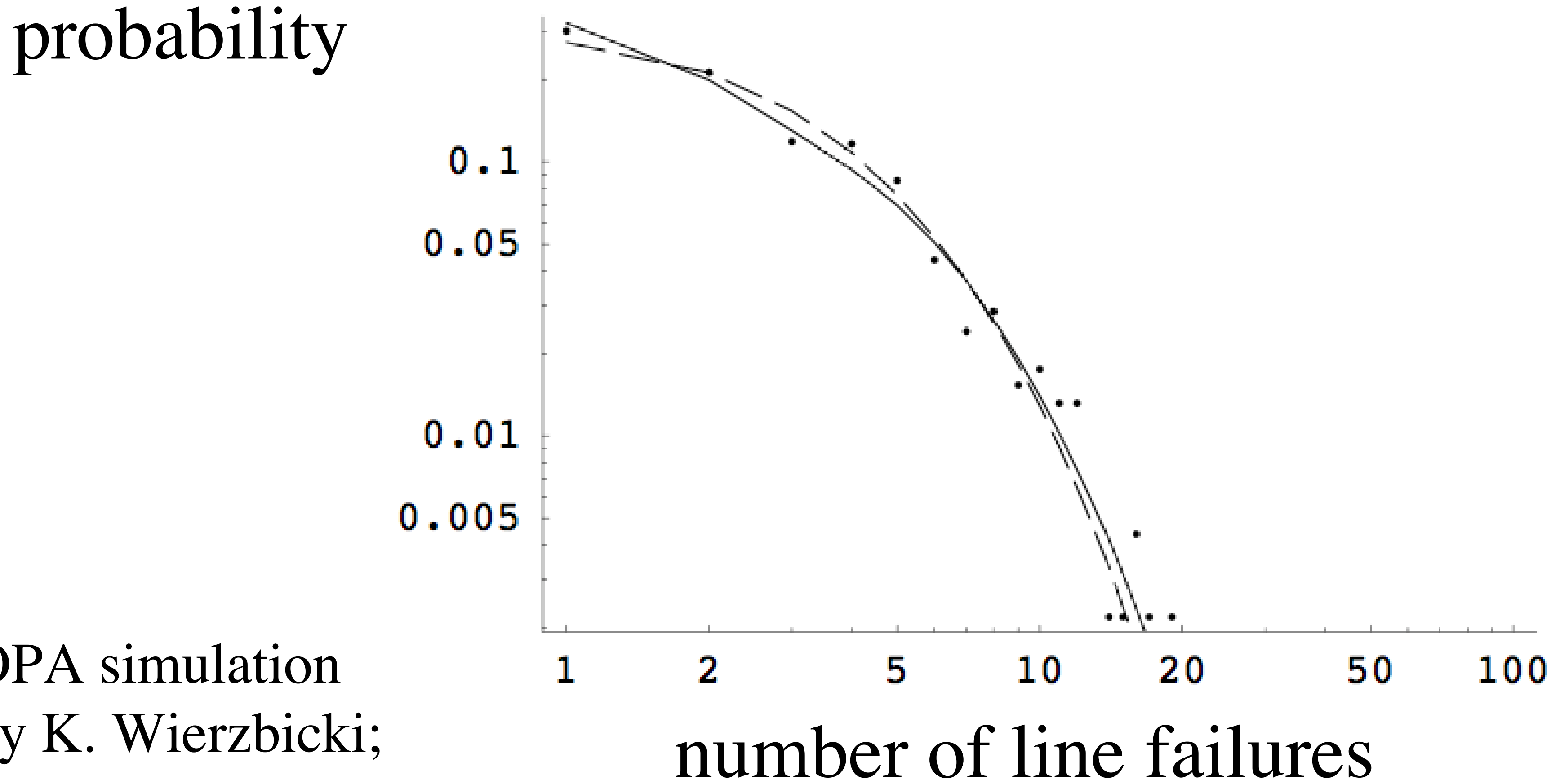
Estimating overall blackout risk

- Cascade characterized by initial failures and amount of propagation λ ; can estimate distribution of blackout size from these.
- Idea is to efficiently estimate distribution of blackout size by first estimating initial failures and parameters such as λ from data.
- Currently being tested on data from blackout simulations
- Opens possibility of extending this to real data-direct monitoring of system reliability

distribution of line failures

dots = empirical pdf

dashed line = predicted pdf; $\hat{\lambda}$= 0.4; $\hat{\theta}$=1.5



OPA simulation
by K. Wierzbicki;
IEEE 118 bus system

Can we directly monitor system reliability?

- Ongoing research, not yet established.
- Efficiency of predicting blackout size distribution important in practice.
- What would be the effect of being able to quantify overall reliability of power systems?

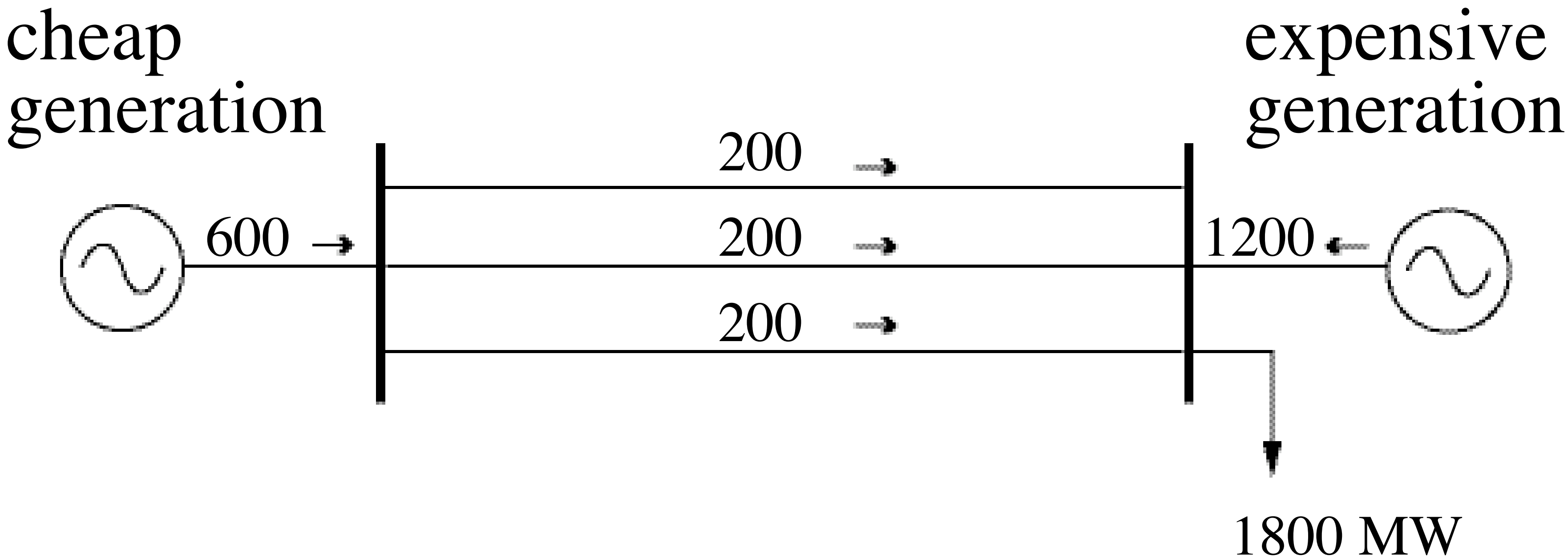
Complex systems aspects of blackout risk mitigation

- Upgrades do not necessarily increase reliability
- Power system may evolve to near criticality
- Implications for framing the problem of managing blackout risk

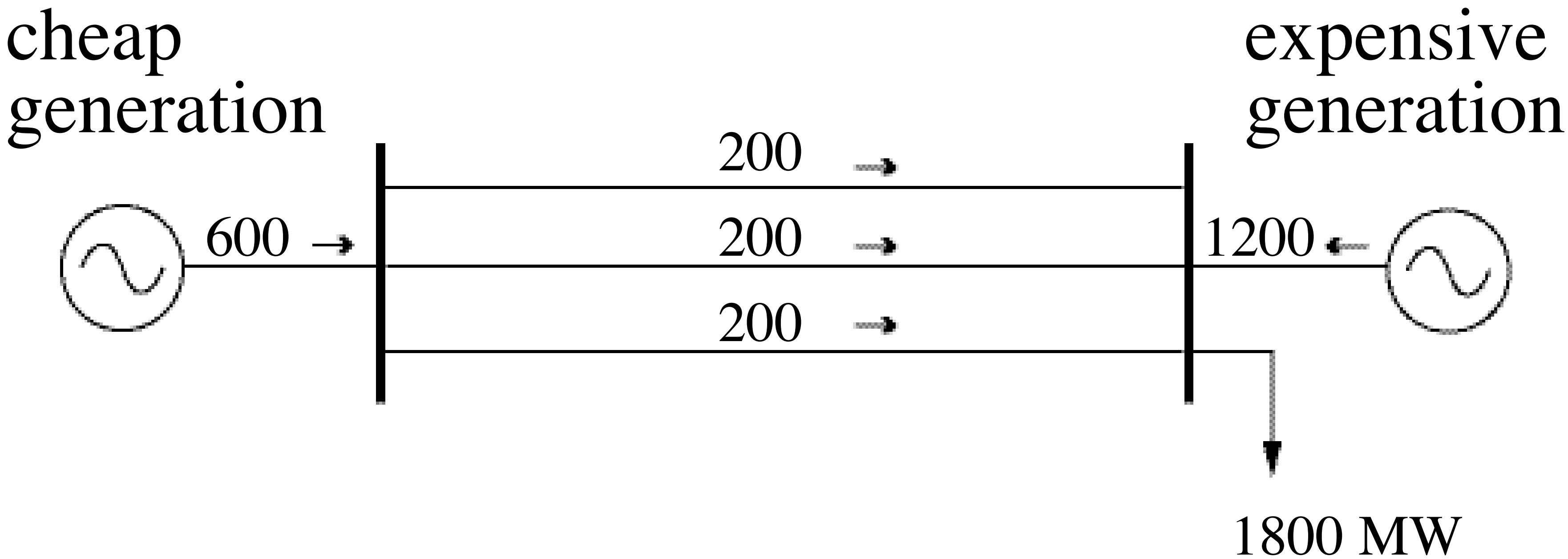
Upgrading transmission does not necessarily improve security

- The (eventual) changes in system loading are also important
- Example is based on
  D. Kirschen, G. Strbac, Why investments do not prevent blackouts, UMIST 2003
  www.ksg.harvard.edu/hepg/Standard_Mkt_dsgn/Blackout_Kirschen_Strbac_082703.pdf

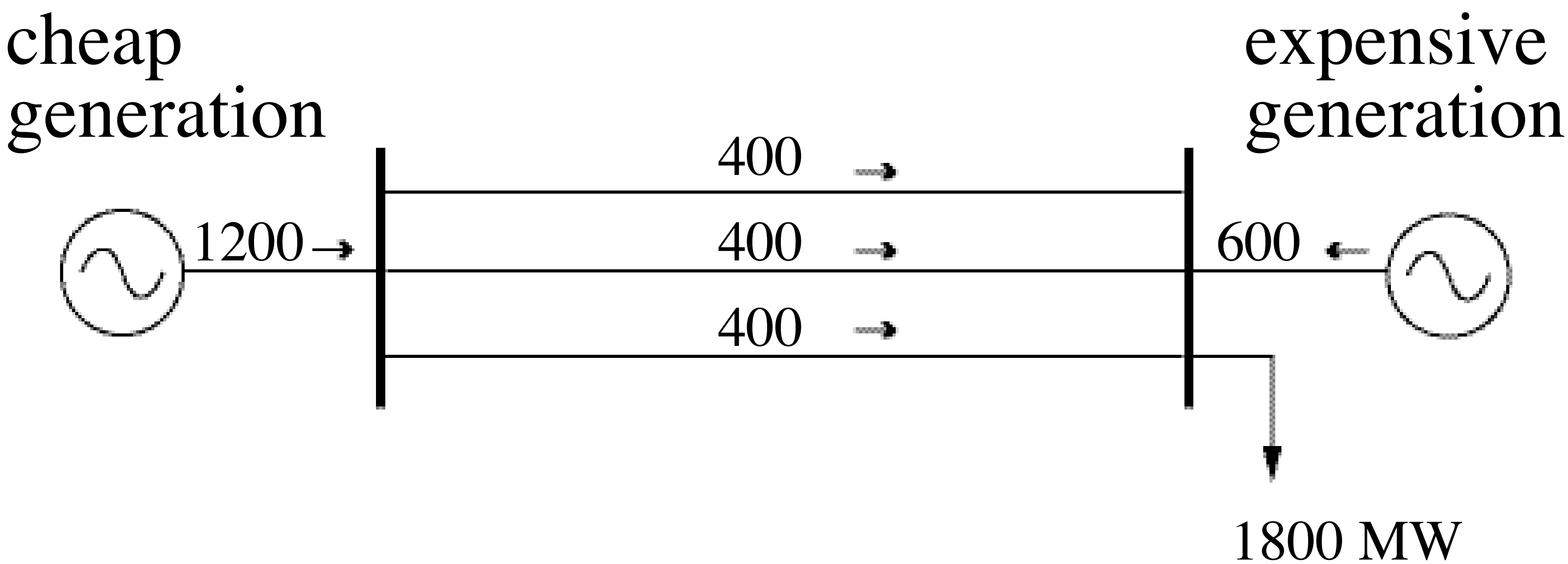
N-1 secure system; line limit 300 MW



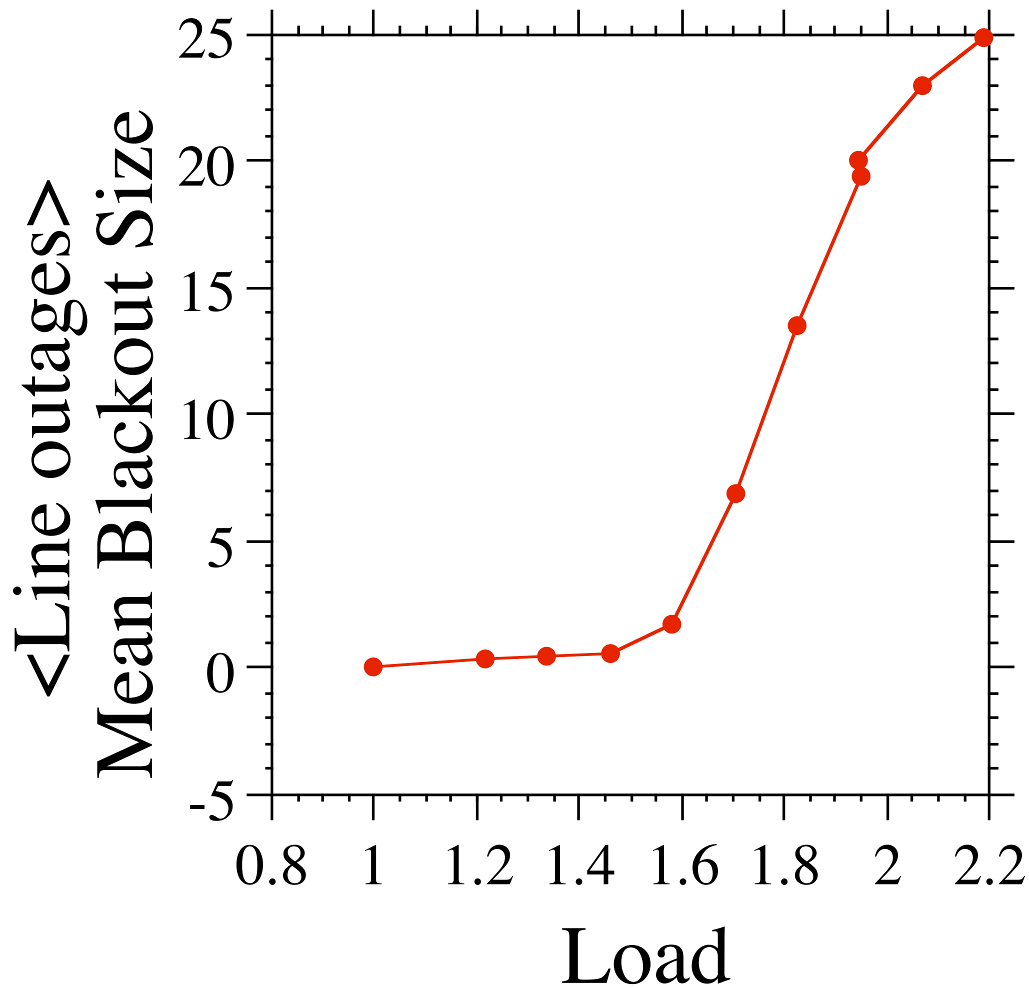
upgraded lines 600 MW; increased security?



Economics can drive the flows to again minimally satisfy N-1 criterion



An explanation of power system operating near criticality



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

Strong economic and engineering forces drive system to near critical loading

Effect of risk mitigation methods on probability distribution of failure size

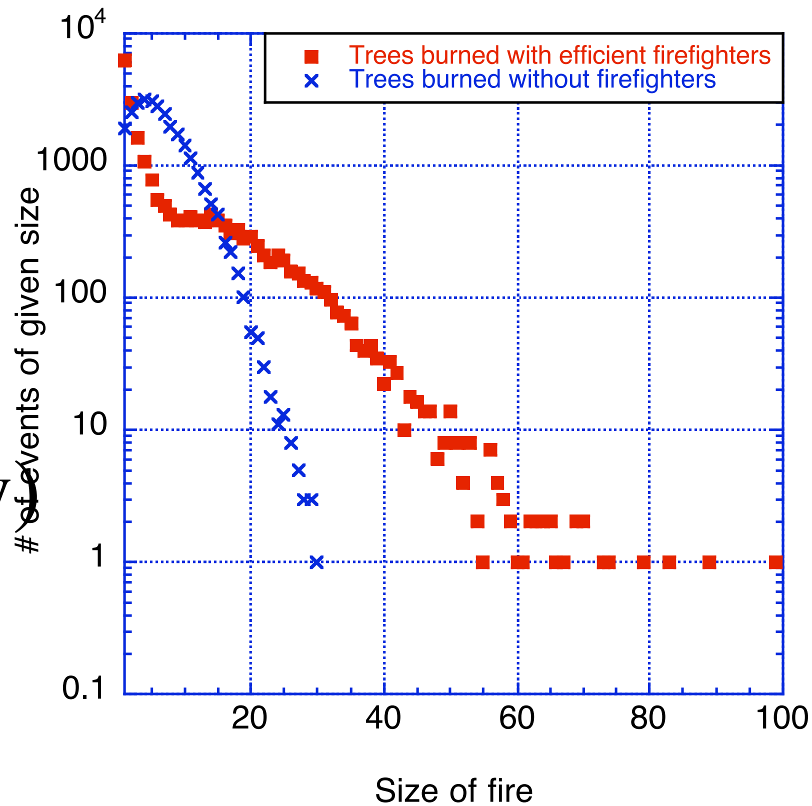
"obvious" methods can have
counterintuitive effects
in complex systems

Forest fire mitigation simulation

red = efficient fire fighting

blue = no fire fighting

number of fires of given size (proportional to probability)



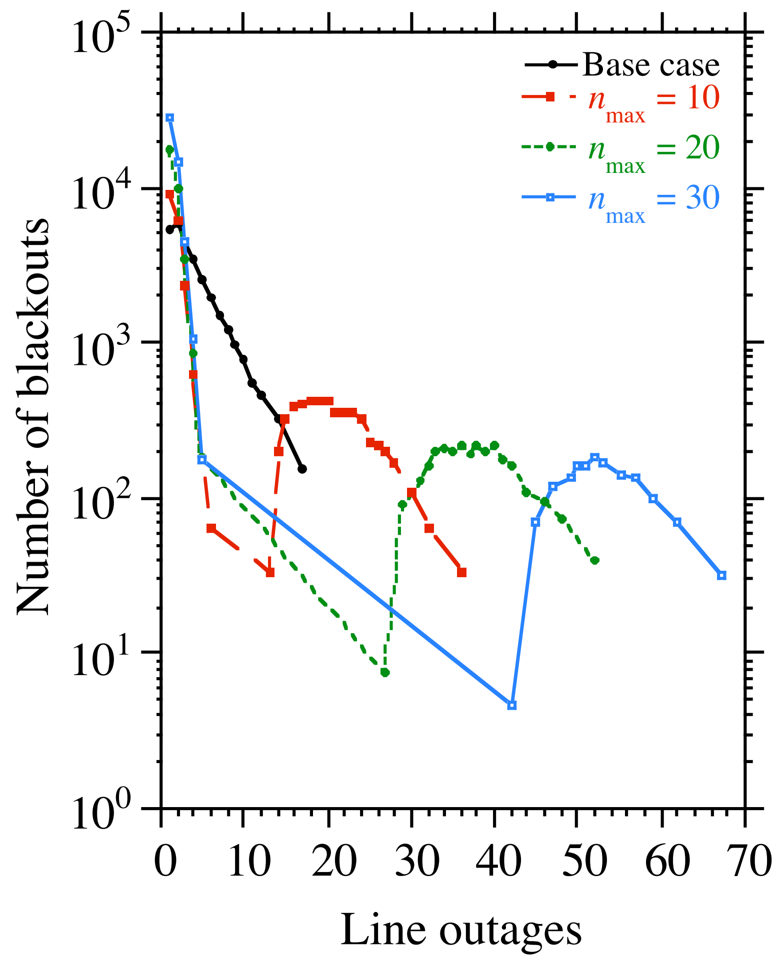
size of fire

Blackout mitigation example

- Require a certain minimum number of transmission lines to overload before any line outages can occur.

A minimum number of line overloads before any line outages

- With no mitigation, there are blackouts with line outages ranging from zero up to 20.
- When we suppress outages unless there are $n > n_{max}$ overloaded lines, there is an increase in the number of large blackouts.
- The overall result is only a reduction of 15% of the total number of blackouts.
- this reduction may not yield overall benefit to consumers.



KEY POINTS

- NERC data shows relatively high risk of large blackouts
- Cascading models show an “edge” or loading limit for cascading failure risk
- Current research goal is to develop practical tools to measure propagation of failures, margin to the edge and estimate overall blackout risk.
- Complex systems effects impact blackout risk and mitigation; system upgrade and loading increase processes should not be ignored!
- For more info, google ian dobson papers