

# The Impact of Various Upgrade Strategies on the Long-Term Dynamics and Robustness of the Transmission Grid

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Main points:

- 1) A global dynamic model of transmission grid - dynamics and heavy tails characteristic of real NERC data
- 2) Need probabilities of blackout as function of size to calculate risk
- 3) Upgrade strategies can have different (counter intuitive) effects on risk  
Redundancy can reduce frequency of large blackouts and line reliability can increase the frequency

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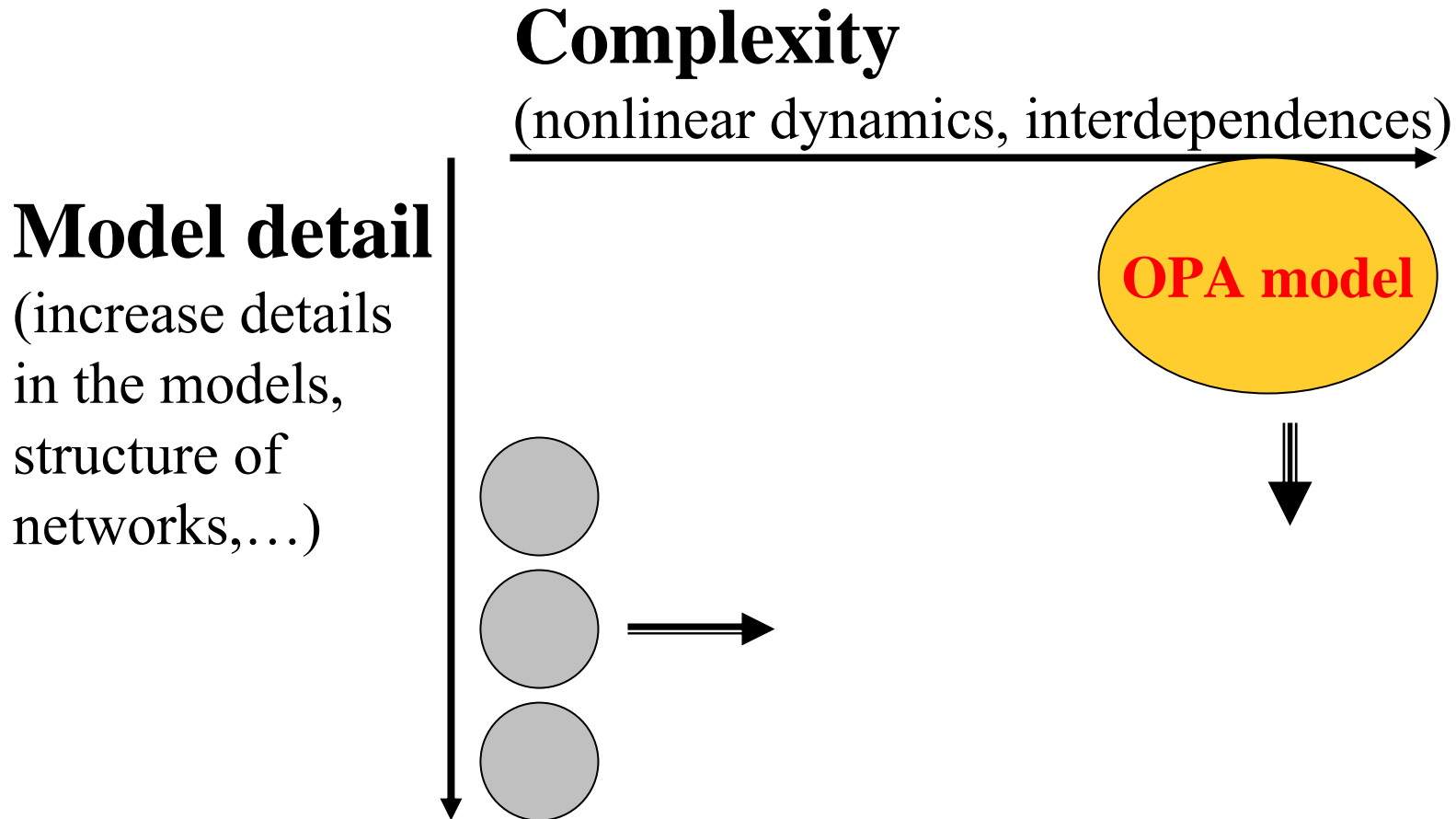
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- Basic motivation
  - General Dynamical model (OPA)
    - Motivation
    - Characteristics
    - Uses
  - Upgrade techniques and their effect
  - Future work/questions

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- Power law tails and long time correlations in (NERC) blackout data suggest need for dynamical model (sits near critical point)
  - Model which incorporates competing forces between increasing demand and the physics, engineering and economic responses. (very interdisciplinary)
  - Need model that capture characteristics to investigate impact of modifications to power transmission network
    - Operating rules
    - Mitigation techniques
    - Upgrade schemes
    - Network topology/structure
  - What is characteristic of a reliable/robust transmission network?
    - Smaller, fewer, both?

# Possible Approaches to Modeling Blackout Dynamics



By incorporating the complex behavior, the OPA approach aims to extract universal features (power tails,...).

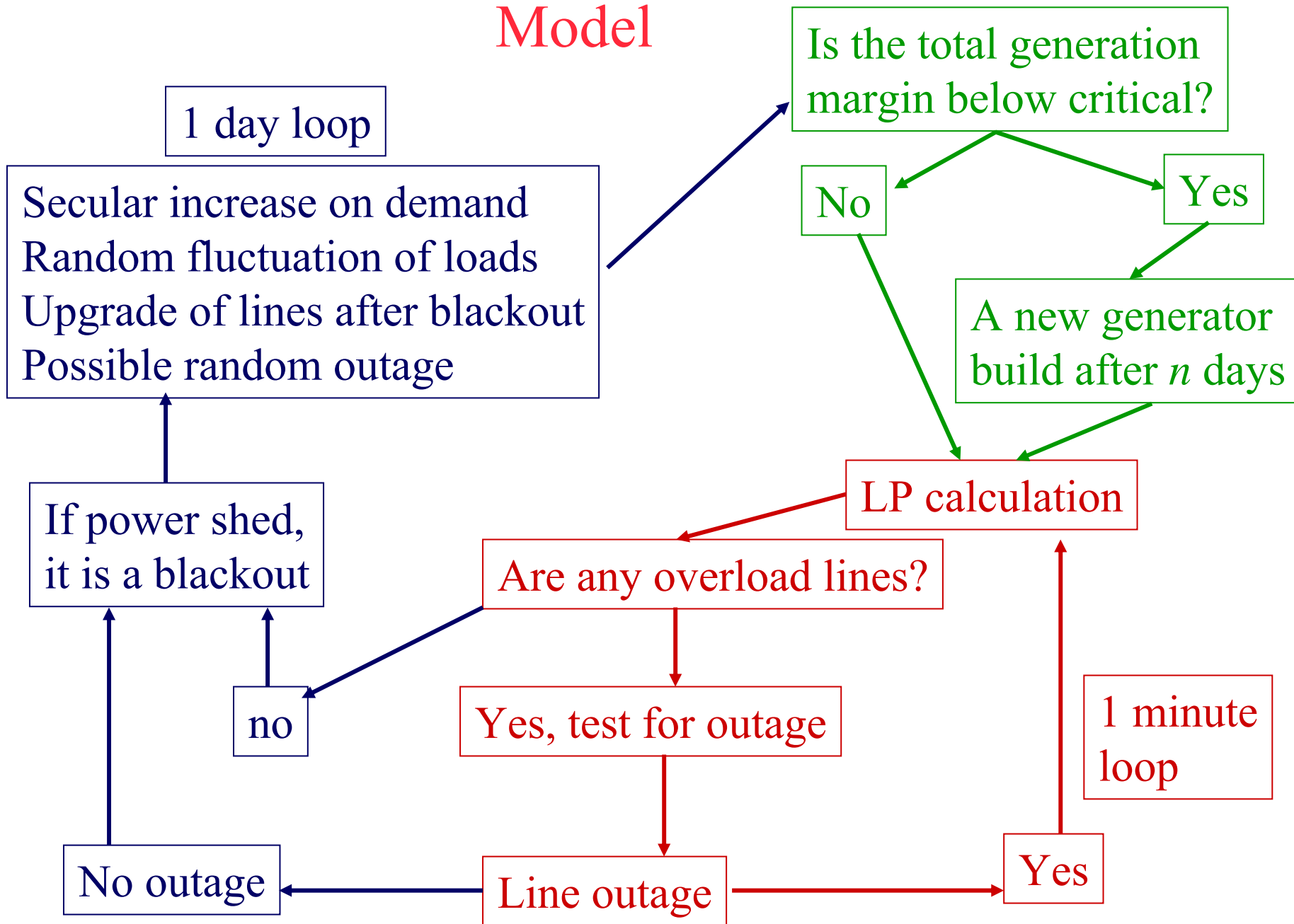
# A Dynamical Model (OPA)

- The OPA model consists of:
    - Transmission network model with DC load flow and LP dispatch
    - Random initial disturbances and probabilistic cascading line outages and overloads
    - Underlying load growth and load variations
    - Engineering/economic responses to blackouts: upgrade lines involved in blackouts
    - Upgrade generation in response to increase demand
  - The blackout dynamics are the result of opposing forces:
    - Increase demand (and/or economic pressure)  $\Rightarrow$  push toward critical point.
    - Engineering responses to failures
    - Upgrades of the transmission system
    - Investment in new power plants.

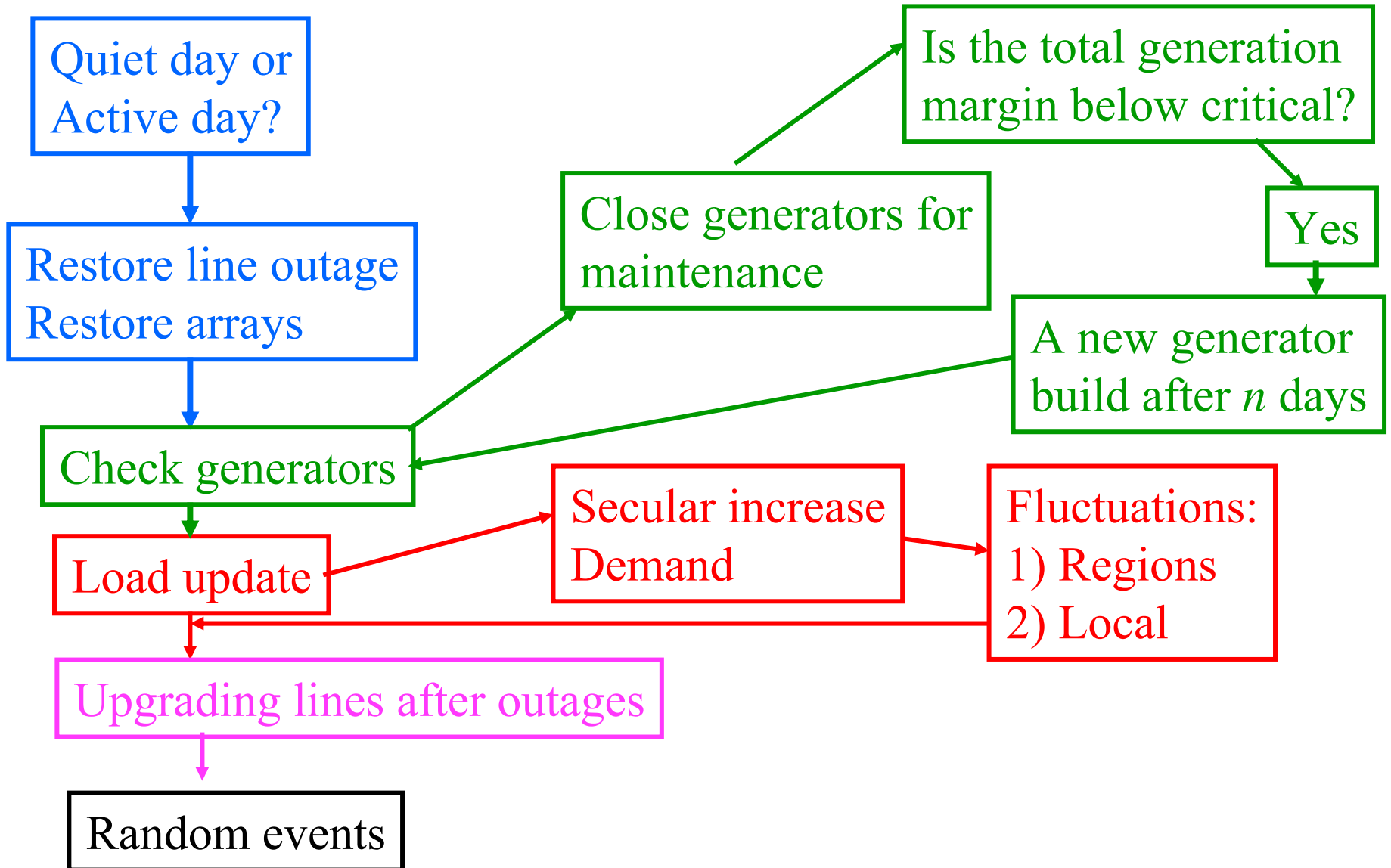
}  $\Rightarrow$  □□□□□□□□ the critical point

  - Regulatory measures may set constraints in this process
- The individual parts of the model can be modified to increase realism or to explore changes in rules or topology.

# Model

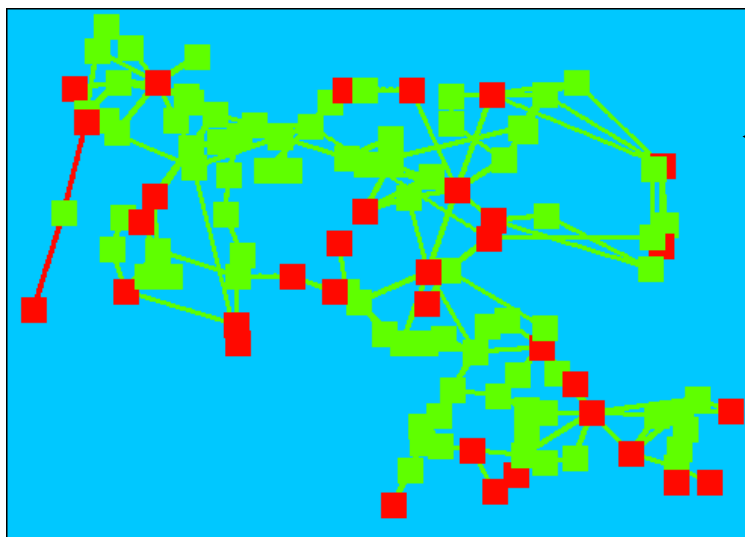


# Daily Loop



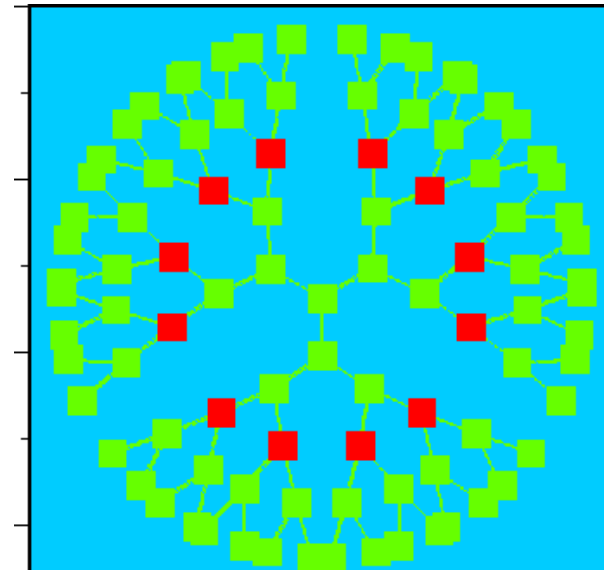
# A variety of network configurations are used

- We use both tree-like networks with up to 380 nodes and more realistic IEEE test networks. Each network is characterized by a number of nodes  $N_d$  and a number of connecting lines  $N_l$
- Nodes are either generators or loads. Each node is assigned a power  $P_i$ . Generators have a maximum operation power,  $P_i^{\max}$ .
- Lines are characterized by their impedance  $z_l$  and by a power flow,  $F_l$ , the maximum power flow that they can carry,  $F_l^{\max}$ .



← IEEE-118

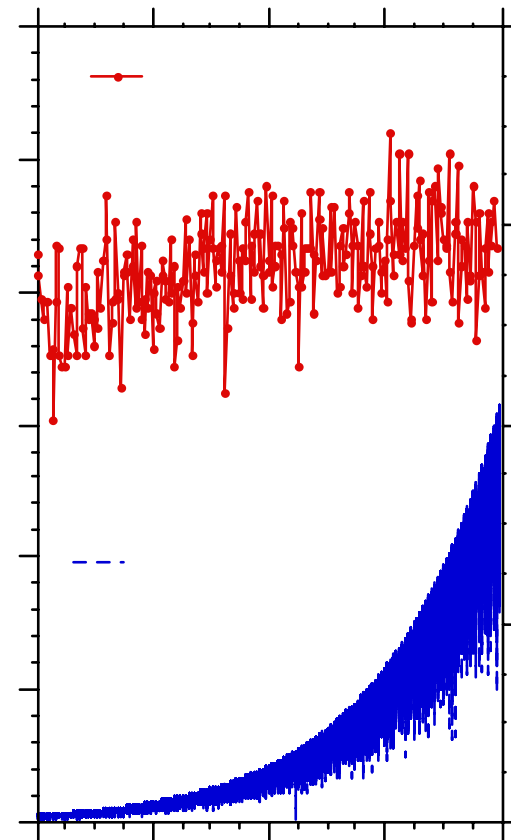
Tree →





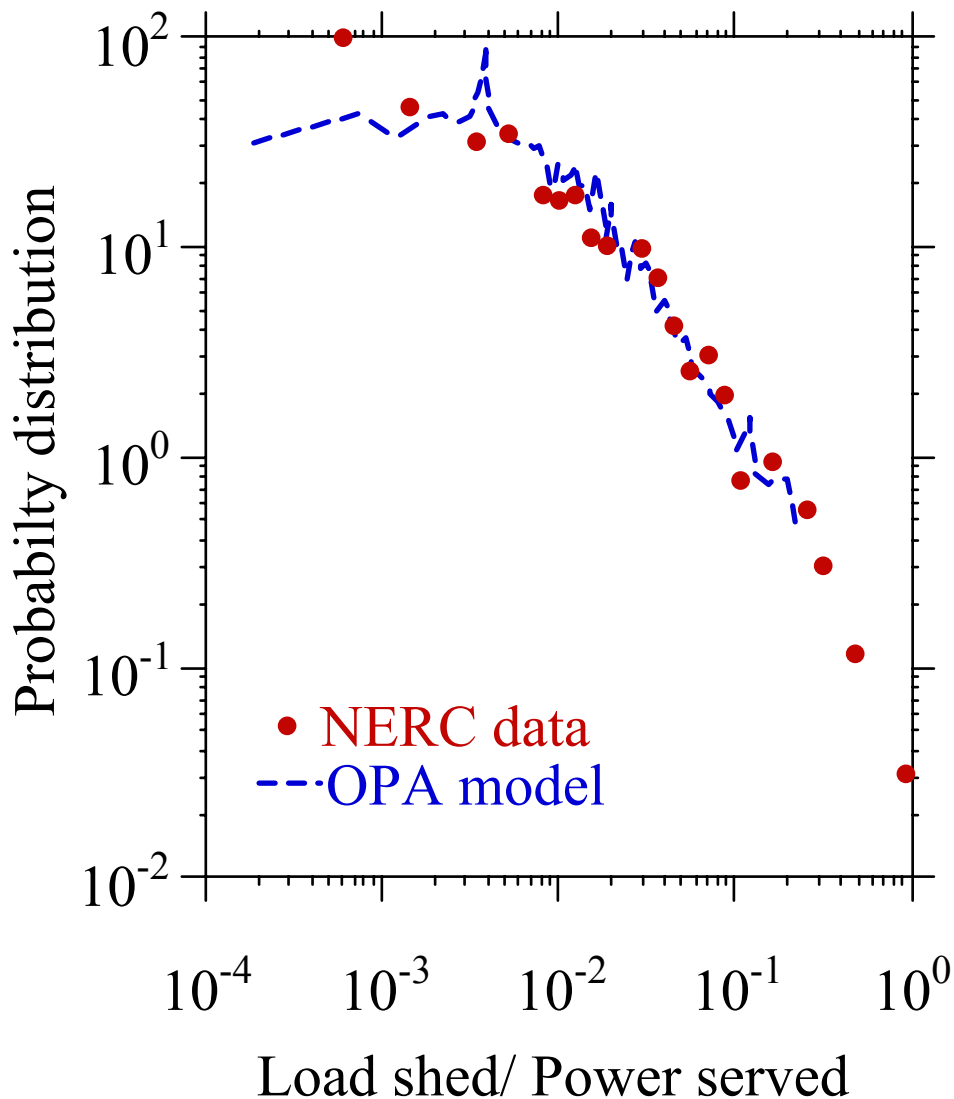
# Characteristic dynamics

- OPA - two intrinsic time scales.
- A slow time scale over which load power demand slowly increases and the network is upgraded in response to the increased demand.
- A fast time scale, of the order of minutes to hours, over which cascading overloads or outages may lead to blackout.
- Assessments done in steady state (takes a significant time to reach).
- Multiple critical points



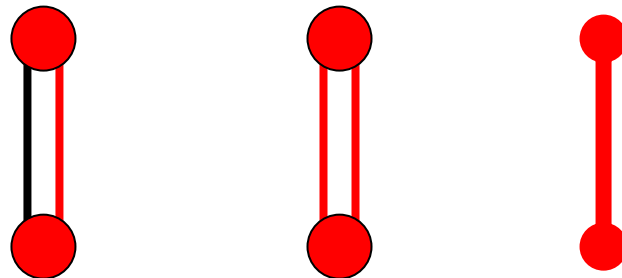
# Probability of large blackouts falls off as a power of their size instead of exponentially

- Probability distribution calculated from NERC blackout data 1984-1998:  
15 years, 427 blackouts
- The power tail in pdf of the NERC data is consistent with the power system being operated near criticality

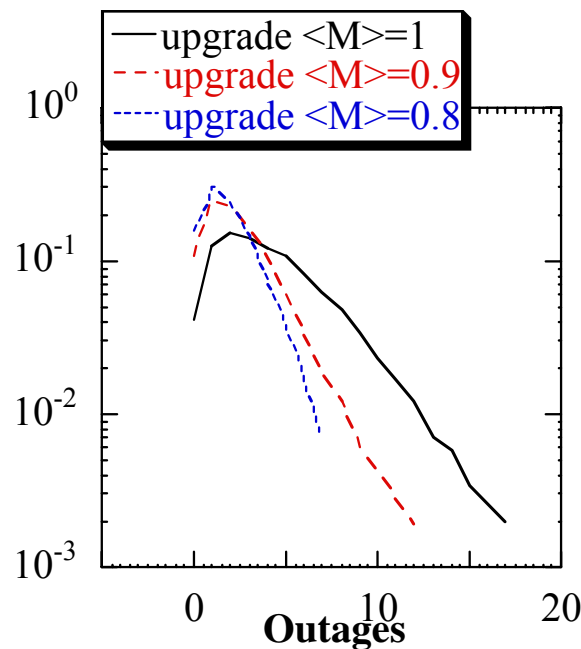
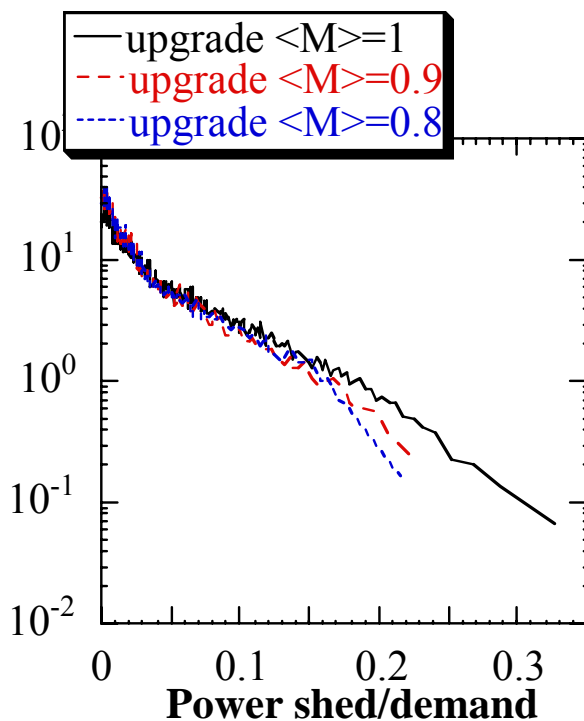


# Methods for improving transmission network robustness

- Reliability (line not network)
  - Component reliability is the complement of component operating margin [ $M_R$  vs  $(1-M_R)$ ] in this implementation
  - This is point at which new failure probability grows
- Redundancy
  - True redundancy (not used until needed)(like the old NASA)
  - True doubling but half load carried by each line (danger, pressure and aging)
  - Capacity redundancy (fatter pipe)(danger, pressure and random)

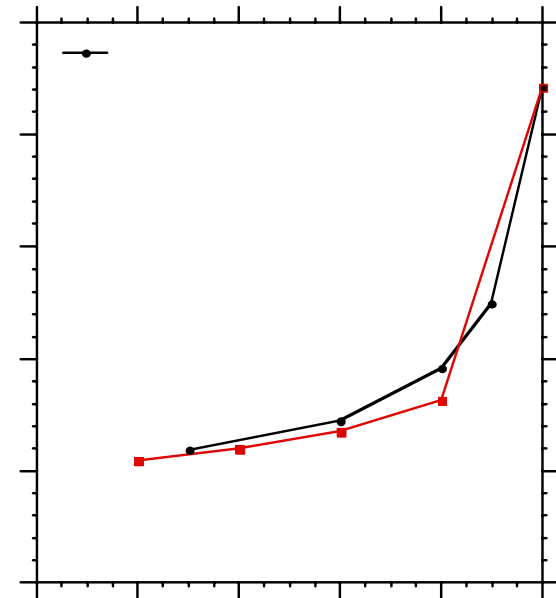
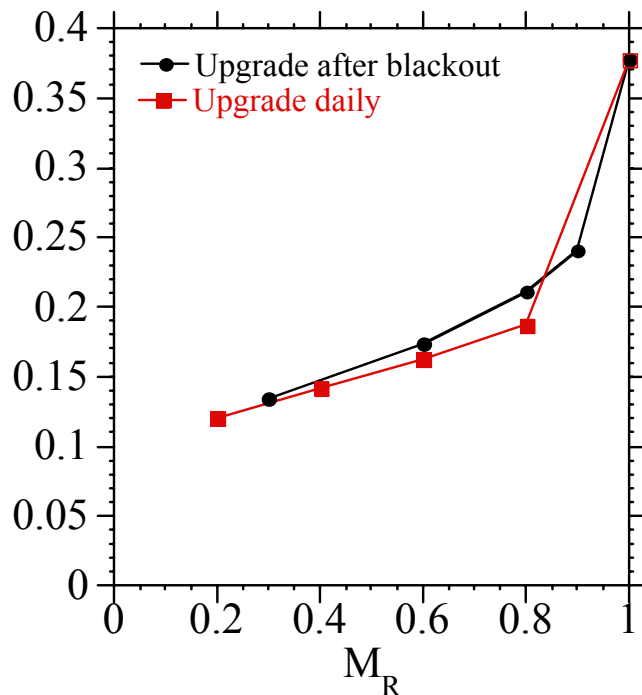


- Probability of larger blackouts/more outages increases as reliability increases (or margin decreases)
- Small outages can decrease



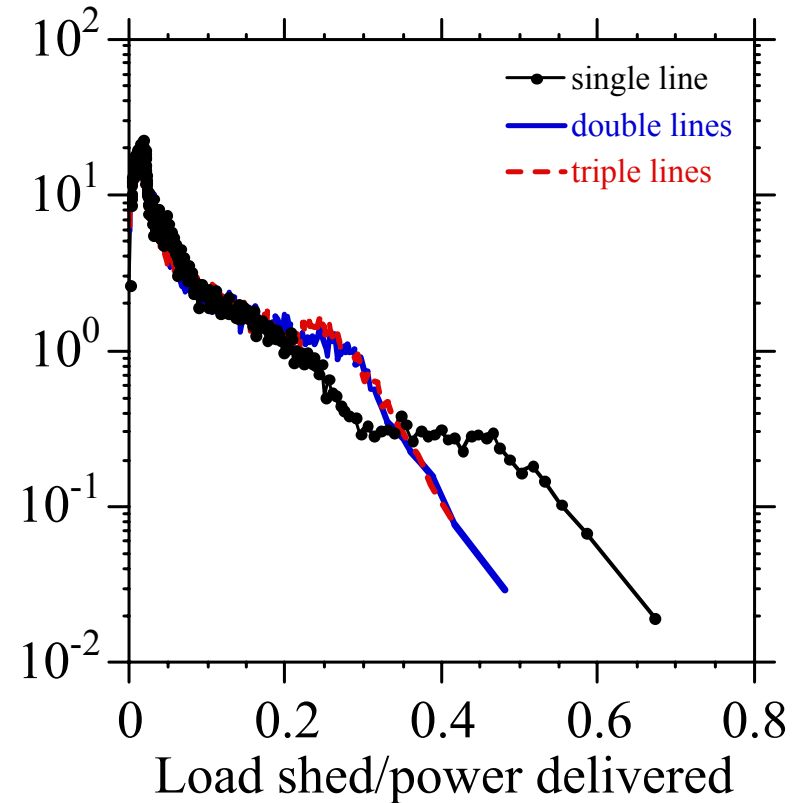
# Prophylactic and reactive improvement give same outcome

- Reliability/Margin “improvements” saturate at ~ reliability of 80%
- Upgrading when in margin region and upgrading after failure give qualitatively same result

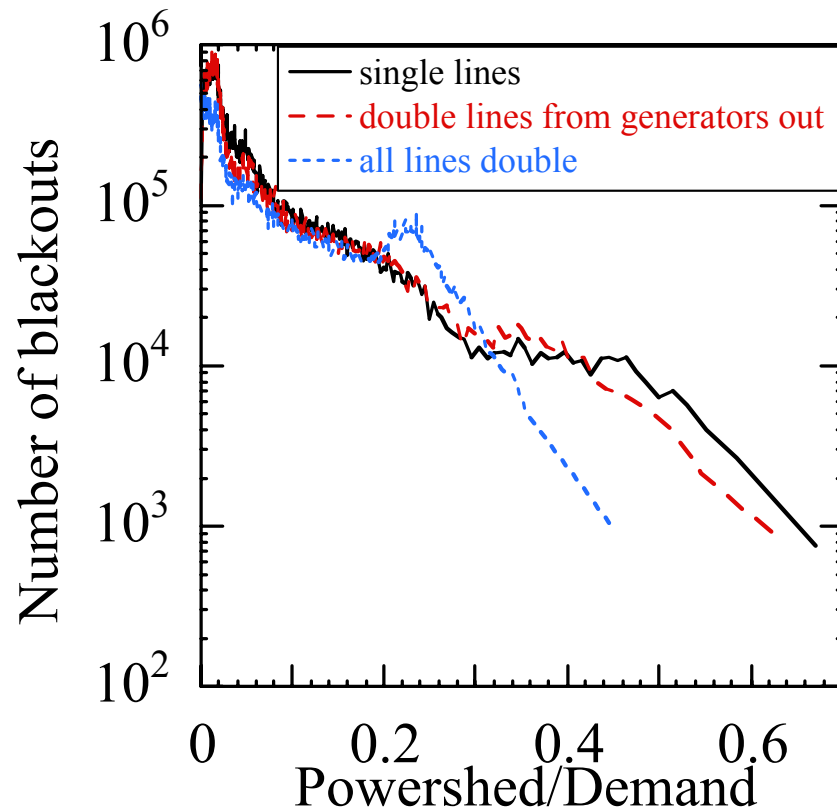


# Redundant lines can improve system robustness

- Redundant lines can reduce large blackouts
- Triple lines have little further effect (good thing!)
- Small blackouts are not increased (improved system reliability??)



- Depending on the limiting components, phasing in redundancy can have significant effect on tail.
- Start with critical/limiting lines and work down the system.
- Must maintain component and capacity redundancy otherwise the redundant line becomes another element in the cascade



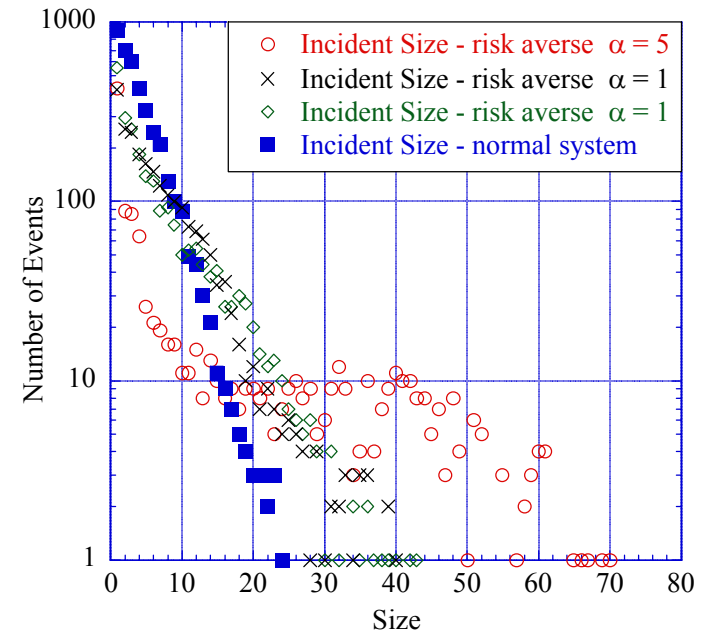
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- Need more data!!
    - To characterize the real network dynamics more data is needed
      - For comparison with models
      - To develop state metrics for “real time” evaluation
  - Explore different:
    - Topologies, connectivity/islanding, different redundancy models and implementations (phased in, etc)
    - More realistic models of reliability which should include at least 4 probabilities associated with component reliability; external random failure, defect failure, aging failure, and stress failure.
  - Develop better economic models (i.e add agent based market models)
  - Interacting/coupled infrastructure issues. **These interacting infrastructures include economic systems, IT systems and human decision making systems.** Incorporating these as separate interacting complex systems or as “agent based models” within the transmission network complex system model needs to be investigated to explore the effect on risk from the system interactions.



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- There is evidence that power systems behave as a complex dynamical system (perhaps with SOC characteristics). Strong but fragile - house of cards
  - Such dynamics imply the intrinsic unavailability of cascading events in such a system when driven(operated) near its operational limits
    - Understanding and avoiding a particular failure mode does not necessarily reduce the risk of disruption. (Control can be counter intuitive)
  - The characteristic power law PDF implies that blackouts up to the size of the full grid are possible and Gaussian statistics can not be used in risk analysis
  - Increasing reliability could decrease small events and increase larger events (push system closer to the edge)
    - Component Redundancy vs. Reliability?
  - Redundancy reduces large blackouts without increasing small...but costly!
  - Course grained models (while not accurately representing the details) are very useful in design, characterization and control studies.

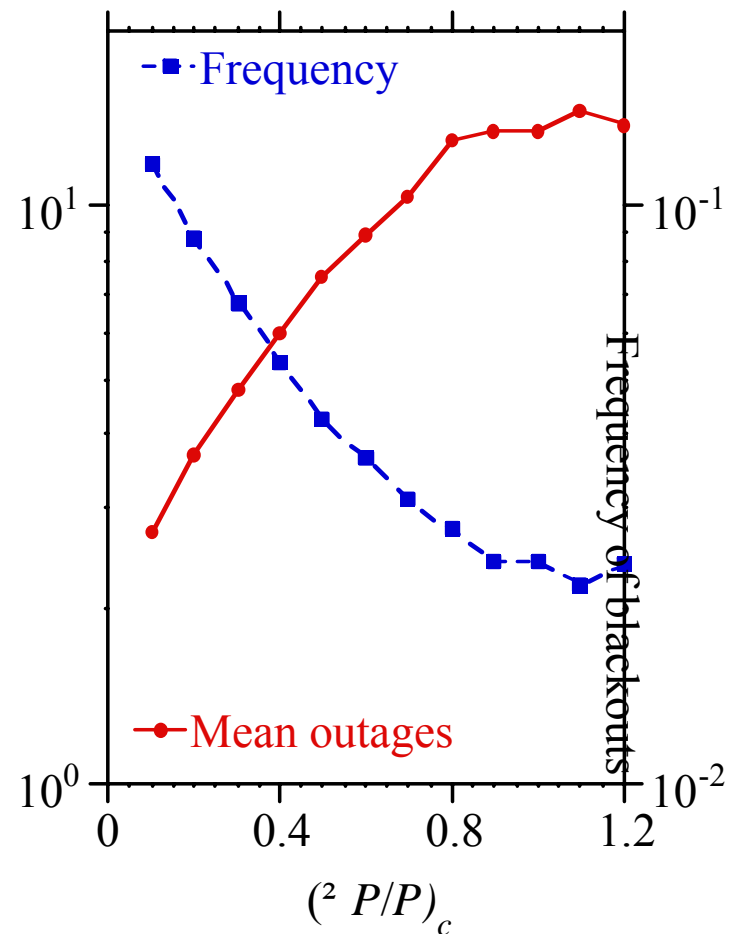
# Human interactions and risk aversion

- In order to progress, society has to recognize that accidents are unavoidable therefore an intelligent risk management program must be implemented in which major accidents can be avoided. It is not possible to avoid all risk but it is better to avoid the greater risk situations for society.
- The most important remediation to this problem is the ability to differentiate between large and small risks in planning and response.
- Without this, “We may wake up one morning and find the human race is in decline, undone by something as simple as being unable to take a risk.” [B. S. Burstyn]



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- Complex system dynamics in the power transmission system have important implications for mitigation efforts to reduce the risk of blackouts.
  - The OPA model shows that apparently sensible efforts to reduce the risk of smaller blackouts can sometimes increase the risk of large blackouts.
  - The possibility of an overall adverse effect on risk from apparently sensible mitigation efforts shows the importance of accounting for complex system dynamics when devising mitigation schemes.
  - The negative effects of some mitigation measures may not necessarily appear right away. They can cause a slow worsening of system performance over an extended period of time. That may increase the difficulties in assessing the effectiveness of a measure.

- The overall effect of the generation margin on the cost of the blackouts is rather subtle.
- As the frequency decreases, the average size of the blackout increases, there is compensation of the beneficial effects of this measure.
- For the tree 46 node network there is a reduction in the cost of the blackouts, but the reverse happens for larger tree networks.





# Time series of blackouts has statistical and dynamical signature

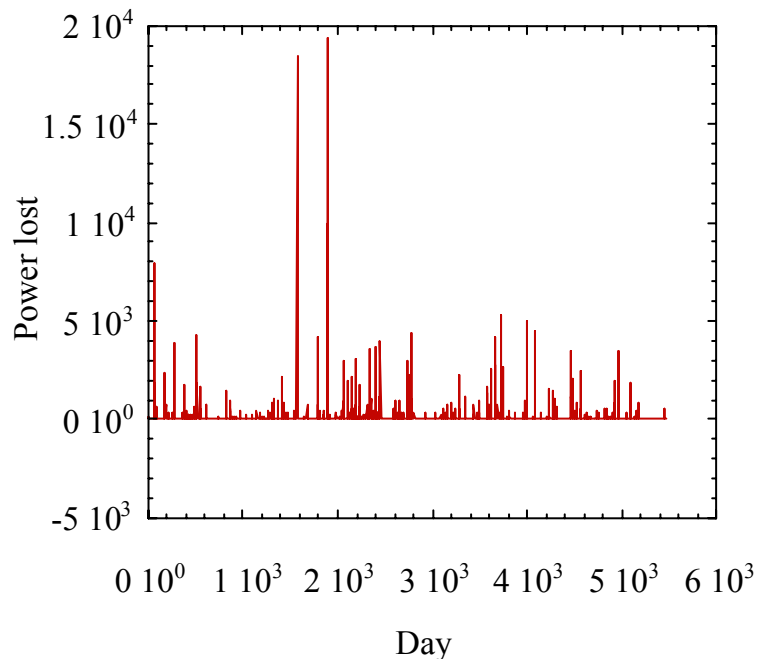


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- Events are disturbances of the grid that can cause loss of power to the customers. We used the North American Electrical Reliability Council documented list of such disturbances.
  - We constructed a time series with the resolution of a day for the number of disturbances reported between 1984 and 1998.
  - We have also constructed complementary time series for:
    - Amount of power lost
    - Number of customers affected
    - Time taken for recovery
    - Total number of MWh unserved
  - These four series are used as a measure of the size of the events.

# Not many events but interesting characteristics

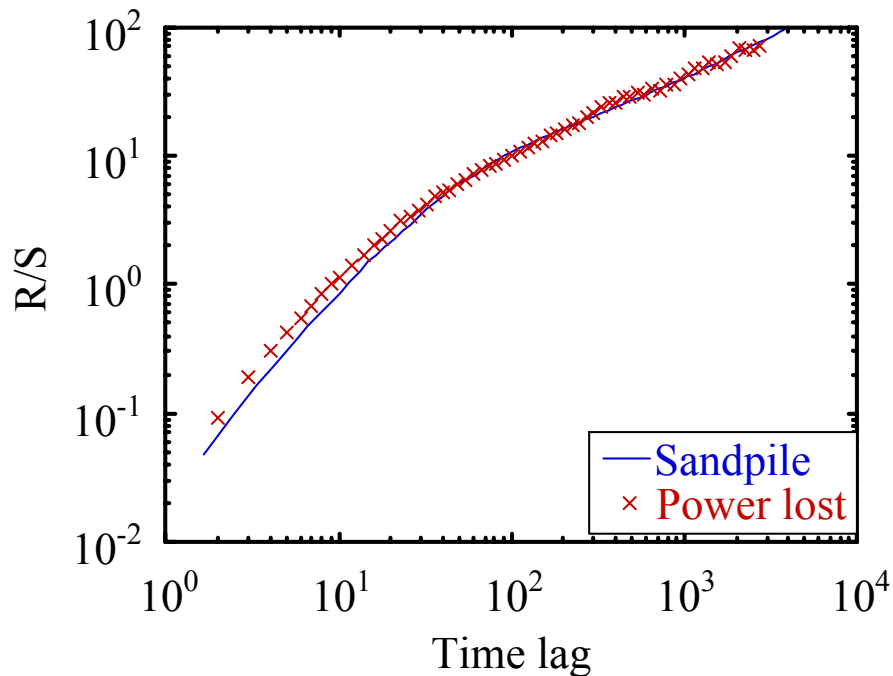
- Events are rare
  - 427 in 15 years
  - or less than 29 blackout events per year recorded
  - or more than 12 days between events on average



- Mean is non-zero but is much below peak.
- Large events up to system size occur but are less likely for increasing size
- Characteristic of complex system dynamics

# Long time correlations

- Comparison of R/S from analysis of the power grid disturbances with a time series of avalanches generated from a running sandpile model with the same frequency of events.



	H (total)	H (Non W)
Events	0.62	0.62
Power lost	0.59	0.64
Customers	0.57	0.58
MWh	0.53	0.57

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- To evaluate the risk of a blackout, we need to know both the frequency,  $F(S)$ , of the blackout and its costs,  $C(S)$ .

$C(S) \sim \text{Direct costs} = (\text{interrupted energy assessment rate}) * (\text{unserved energy}) \$$

$$\text{Risk} = F(S) C(S)$$

- The NERC data indicate a power law scaling of blackout frequency with blackout unserved energy as  $F(S) \sim S^\alpha$ , where  $\alpha \sim -1.2$ ,

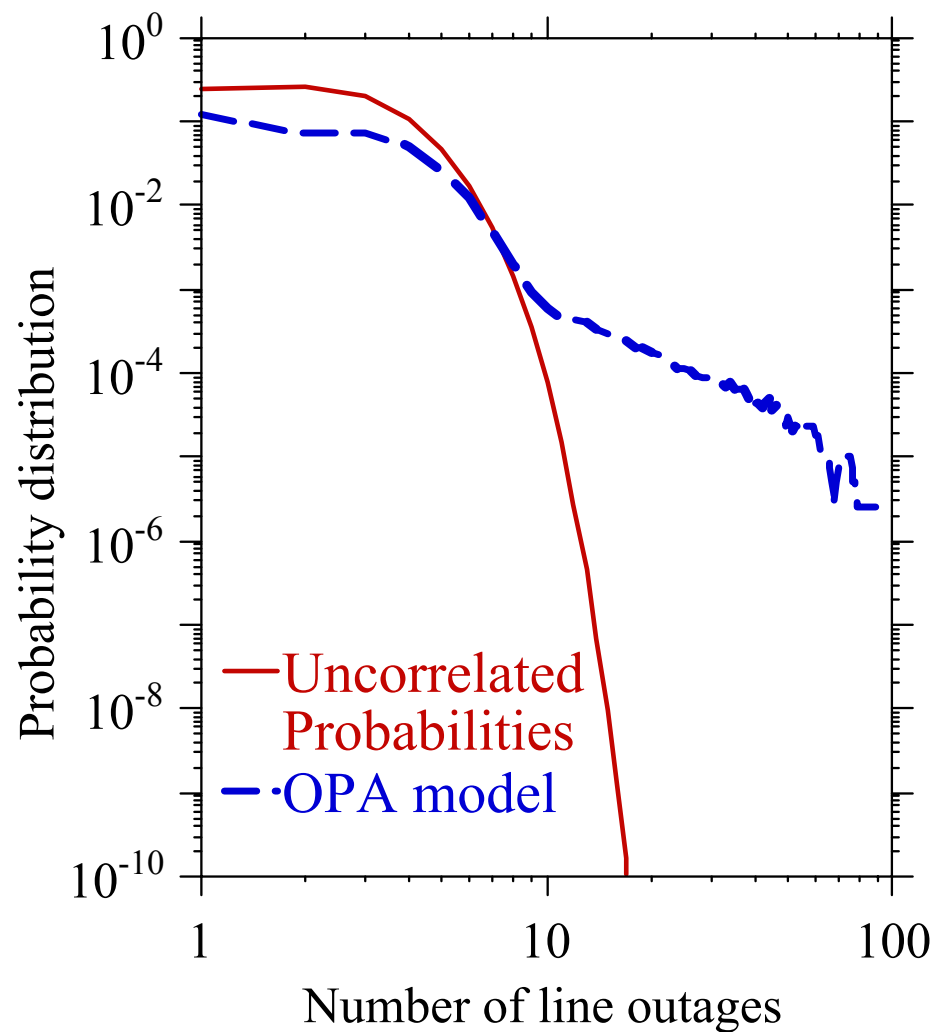
$$\text{Risk} \sim \tilde{S}^{0.2}$$

- High cost of large blackouts - large blackouts dominate the risk



# Probability of large blackouts falls off as a power of their size instead of exponentially

- Power tails imply:
  - long-range correlations
  - standard risk analysis does not apply
- We must:
  - Understand the cause of these correlations (criticality?)
  - Develop the bases for a risk evaluation
  - Be able to evaluate the impact of mitigation measures



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- Bottom line...there was a well defined cascading event...blame can be placed...But, the system worked!
    - Stressed system
    - Individual Failures (operator error, equipment failure, maintenance failure, interdependent infrastructure effects)
    - Then the system behaved as is should to protect itself...like the Spirit Lander perhaps...shutdown into safe mode
    - Note n-1 or 2 criteria
  - System comes back slowly...strong but fragile
  - <http://www.nerc.com>