How can we model power systems for cascading blackouts?…considerable complications, cutting corners, and validation with data

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CASCADING BLACKOUTS

Transmission systems: continental scale bulk power electric grid > 30 kV

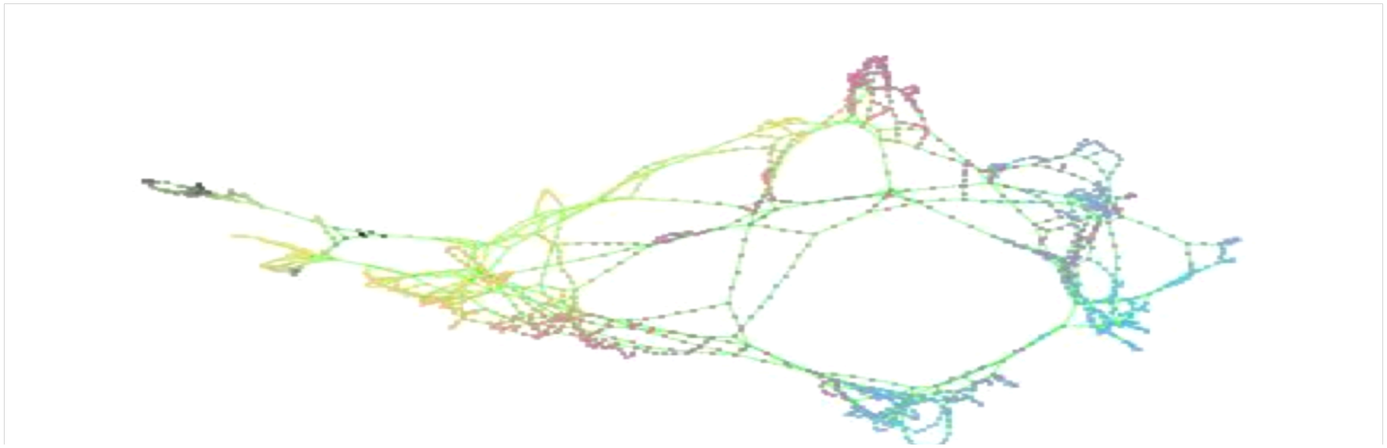
Large blackouts often happen by cascading outages and are long, complicated sequences of component outages and other events.

Outage usually disconnects the component, not necessarily damaged

Cascading outages is a sequence of dependent failures of individual components that successively weakens the system

CONSIDERABLE COMPLICATIONS

- cascading outages in large, heterogeneous, networks
- rare, unanticipated, dependent events
- huge number of possibilities and combinations
- physics + controls/protection + rules/operators
  + engineering upgrade + economics + policy
- varying conditions: loading, configuration, triggers
- models are hybrid, stochastic, nonlinear, dynamic



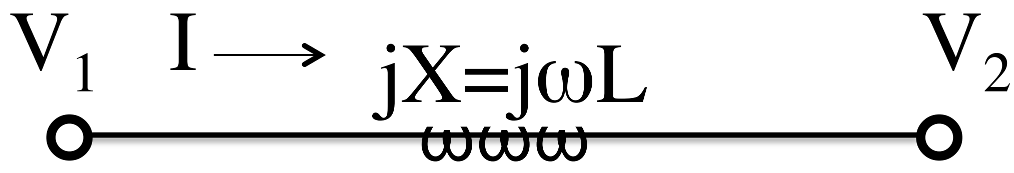
MODELS

- DC load flow
- AC load flow
- Differential-algebraic equations
- Markets, economics, investment, engineering upgrades, socio-technical

statics → dynamics → money and people
physics→engineering→social sciences

Key factors sometimes considered: hybrid system, operational or planning procedures and rules, stochastic

real power flow in inductive line



complex phasors $V_{1,}V_2$, I; line reactance X

$v_1(t) = \mathrm{Re}\{\sqrt{2}\,|V_1|\exp(j\theta_1)\exp(j\omega t)\}$

$\quad = \sqrt{2}\,|V_1|\cos(\theta_1 + j\omega t)$

$v_1^R(t)$ = component of $v_1(t)$ in phase with I

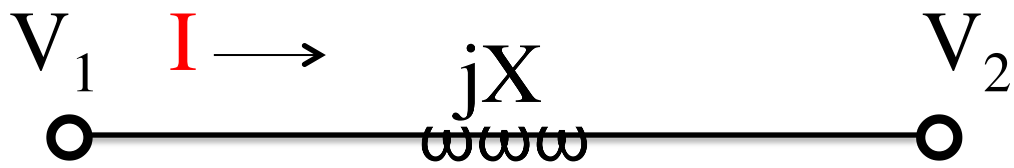
real power P from node 1 to node 2

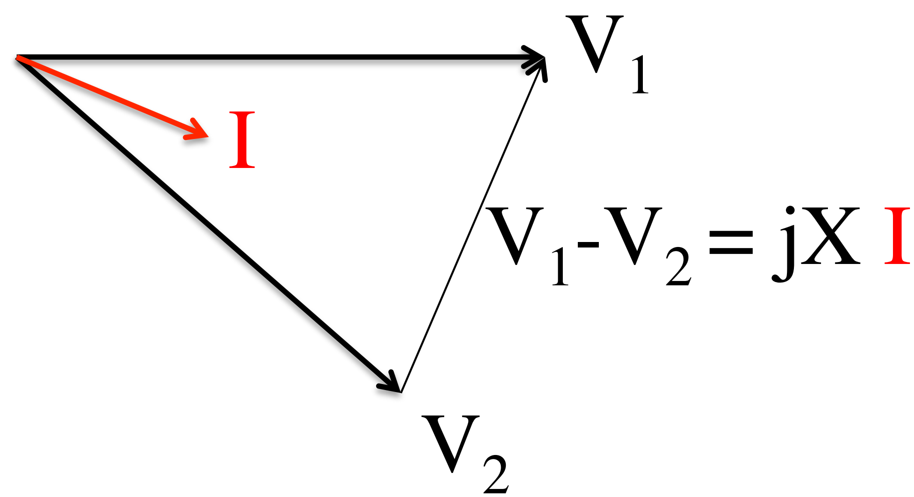
$v_1^R(t)\,i(t) = 2\,|V_1^R|\,|I|\cos^2(\omega t)$

$\quad = P + P\cos(2\omega t)$

$P = |V_1^R|\,|I|$

real power flow in inductive line

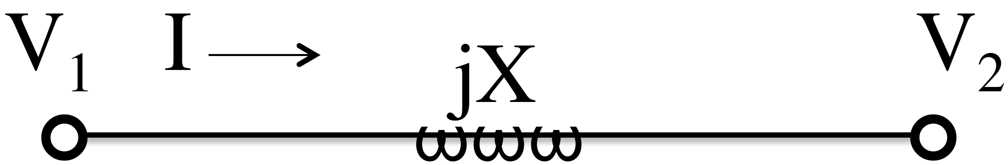




$$P = |V_1^R|\,|I| = \frac{2\Delta}{X} = \frac{|V_1||V_2|}{X}\sin(\theta_1 - \theta_2)$$

Δ = area of triangle

reactive power flow in inductive line

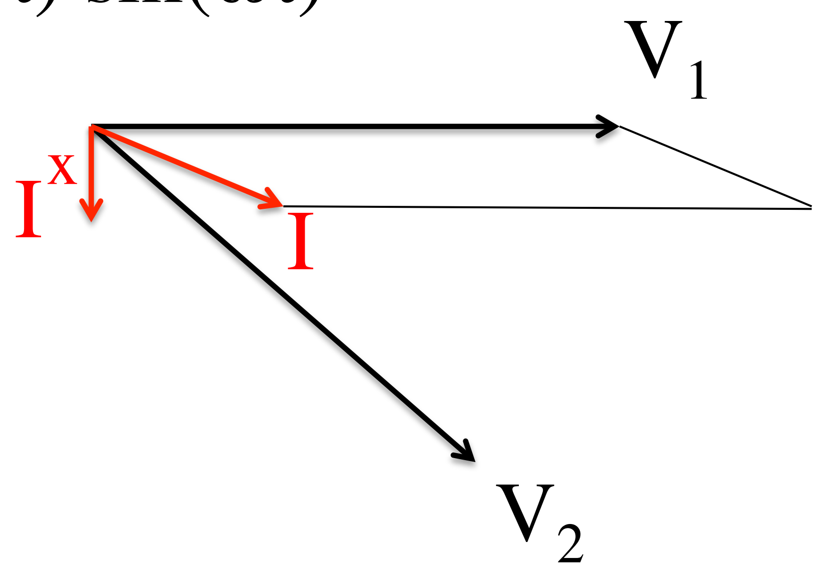


$i^x(t)$ = component of $i(t)$ out of phase with V_1

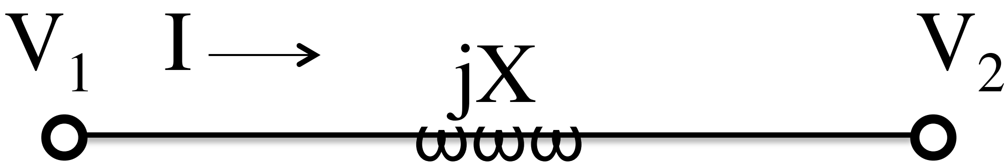
reactive power Q leaving node 1

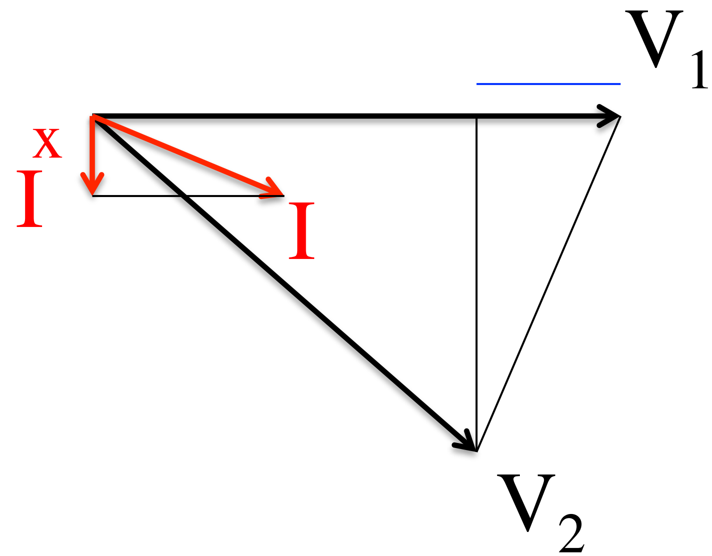
$$v_1(t)\, i^x(t) = 2\, |V_1|\, |I^x|\, \cos(\omega t)\, \sin(\omega t)$$
$$= Q \sin(2\omega t)$$

$$Q = |V_1|\, |I^x|$$
$$= \text{area of parallelogram}$$

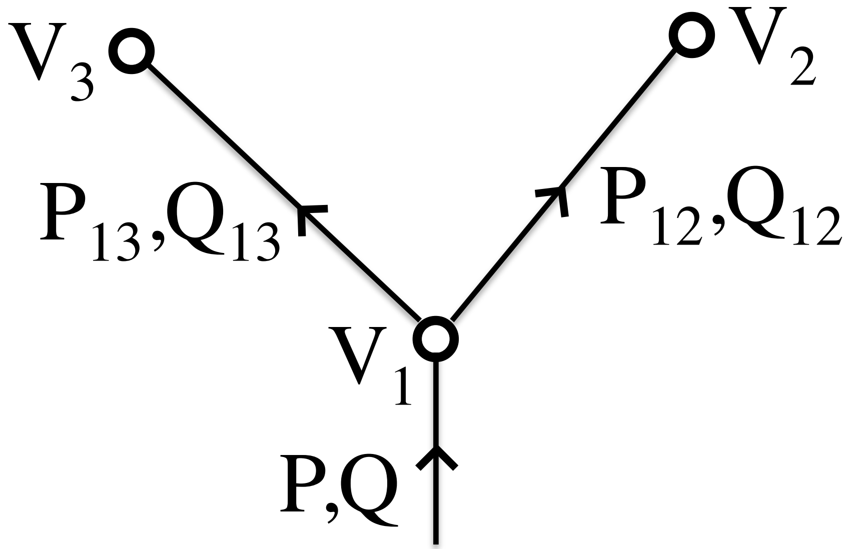


reactive power flow in inductive line





$$Q = |V_1|\ |I^x| = |V_1|\ \frac{|V_1| - |V_2| \cos(\theta_1 - \theta_2)}{X}$$



CONSERVATION
OF POWER

$$P = P_{12} + P_{13}$$
$$Q = Q_{12} + Q_{13}$$

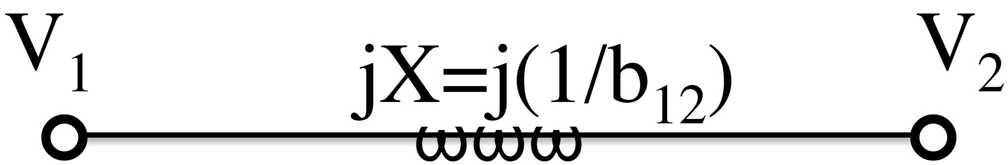
PQ LOAD	PV GENERATOR	OTHER NODE
fix P, Q	fix P, $\lvert V \rvert$	$P=0$, $Q=0$
variable $\lvert V_1 \rvert$, θ_1	variable θ_1, Q	variable $\lvert V_1 \rvert$, θ_1

AC load flow (nonlinear)

- conservation of power at each node
- each node has P, Q, |V|, θ
- fix 2 at each node;
  other 2 are variables to be solved

Main Theorem: no reasonable assertion about the AC load flow equations is always true

small angle approximations



$$P_{12} = |V_1||V_2|\, b_{12} \sin(\theta_1 - \theta_2)$$
$$\approx |V_1||V_2|\, b_{12} (\theta_1 - \theta_2)$$

$$P \longleftrightarrow \theta$$

$$Q_{12} = |V_1|(|V_1| - |V_2|)\, b_{12} \cos(\theta_1 - \theta_2)$$
$$\approx |V_1|(|V_1| - |V_2|)\, b_{12}$$

$$Q \longleftrightarrow |V|$$

For $|V_1|$, $|V_2|$ near 1 in nominal units, we get DC load flow approximation:

$$P_{12} = b_{12} (\theta_1 - \theta_2)$$

DC load flow

θ = node voltage vector

P = real power injected at each node

A = node-branch incidence matrix(with ± 1, 0)

Λ = diagonal matrix of line susceptances b

$$P = A\ \Lambda\ A^T \theta = B\ \theta$$

DC load flow on a transmission network

- power flows from generators to loads
  [nodes are not uniform]
- flows distributed by Kirchhoff laws
  [no unique path in meshed network]
- lines have flow limits and generators have capacity limits; all engineered, coordinated
- generators must supply demanded load; system is controlled mostly by gen. dispatch
- robust to variations in load and outages
- for reliability, need excess generation. Dispatch policy is important

Many mechanisms in cascading

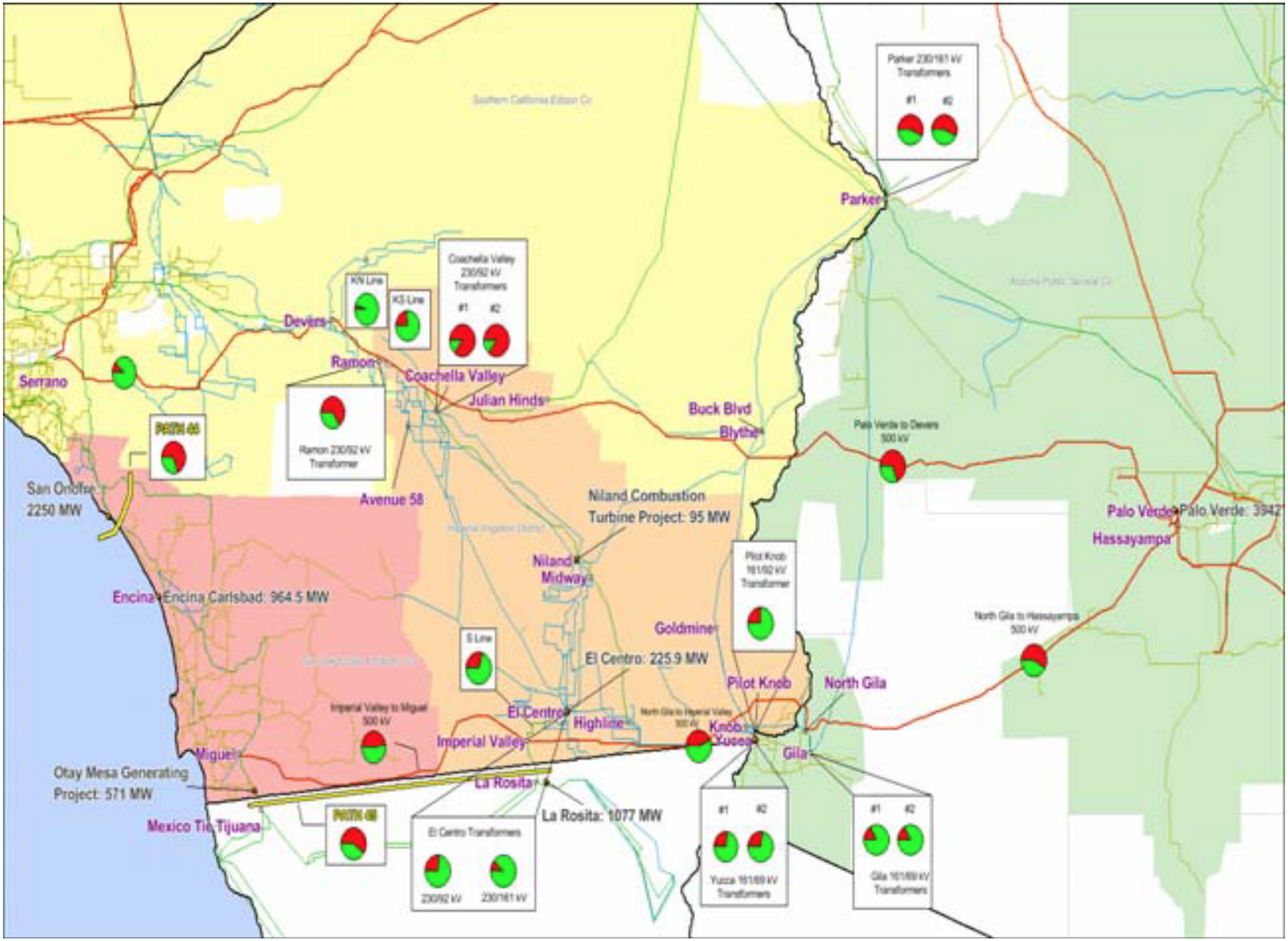
- wide variety of initial outages (triggers)
- power flow redistributions and static overloads
- control or protection malfunction or function not suited to conditions
- oscillations (Hopf bifurcation; timescale seconds or less)
- voltage collapse (load + AC; saddle-node bifurcation)
- transient instability (gen dynamics+AC; transient leaves basin of attraction; timescale subsecond)
- transients
- operational or planning errors, no situational awareness
- unusual or poorly understood interactions

How do outages propagate in blackouts?

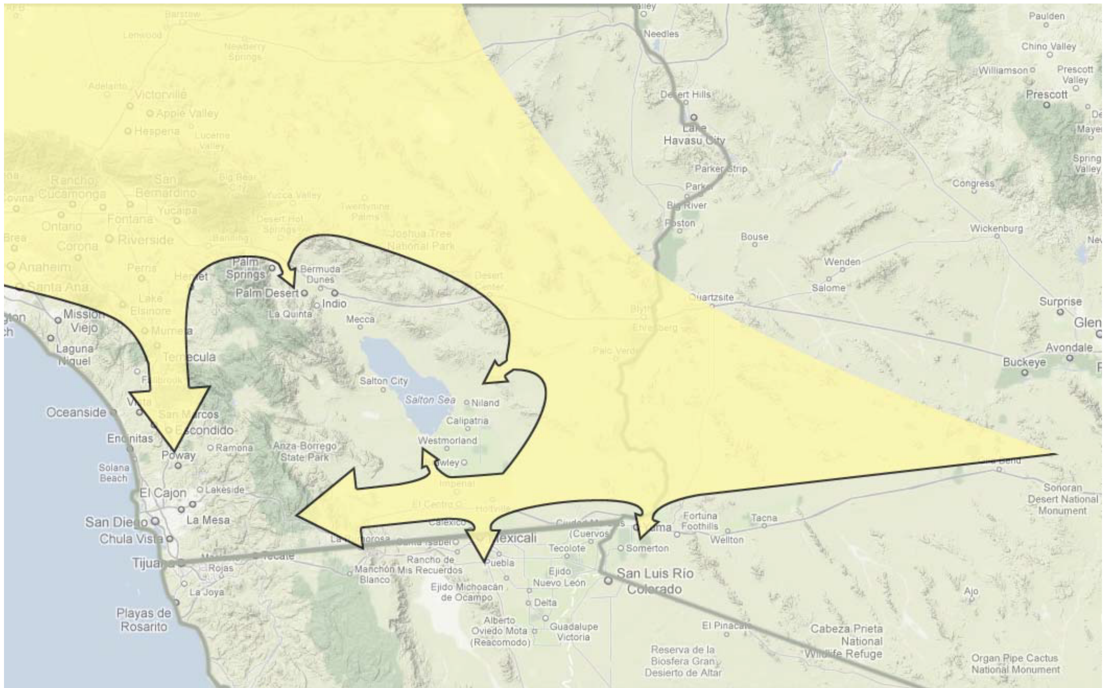
- many mechanisms
- both local and global effects
- let us look more closely at line overloads, outages, and power redistributions

Before 2011 Arizona-Southern California Blackout

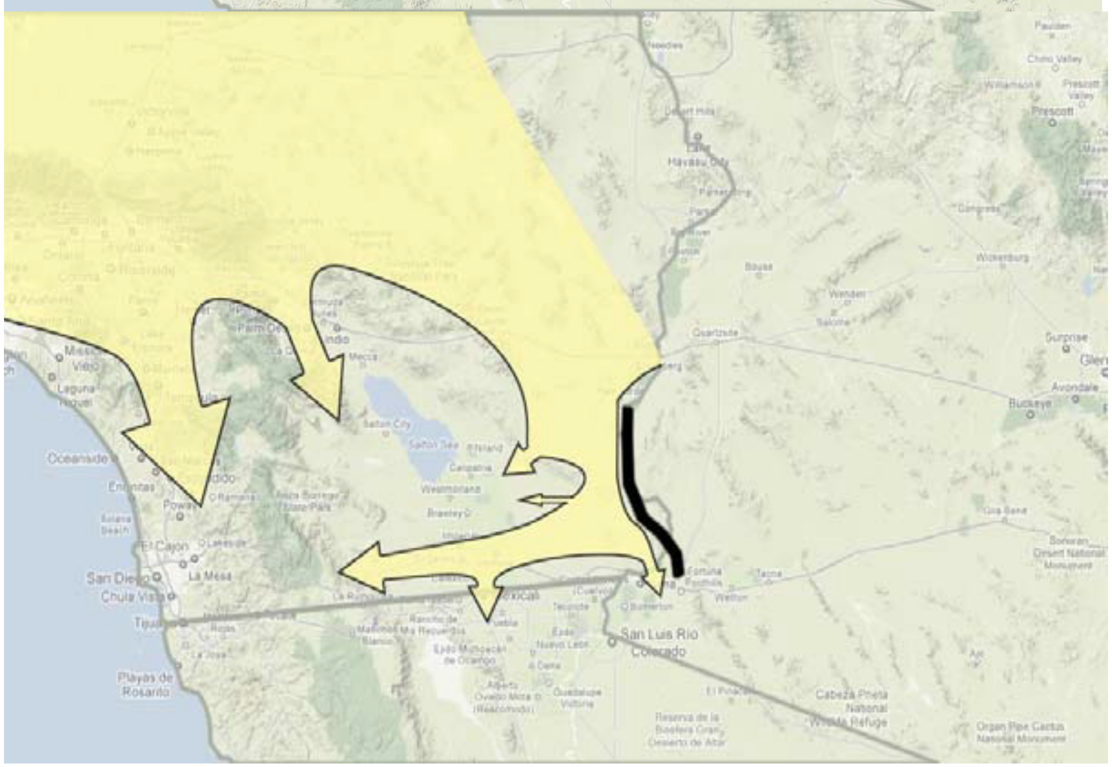
FERC/NERC Staff Report



Hassayampa-N. Gila line trip



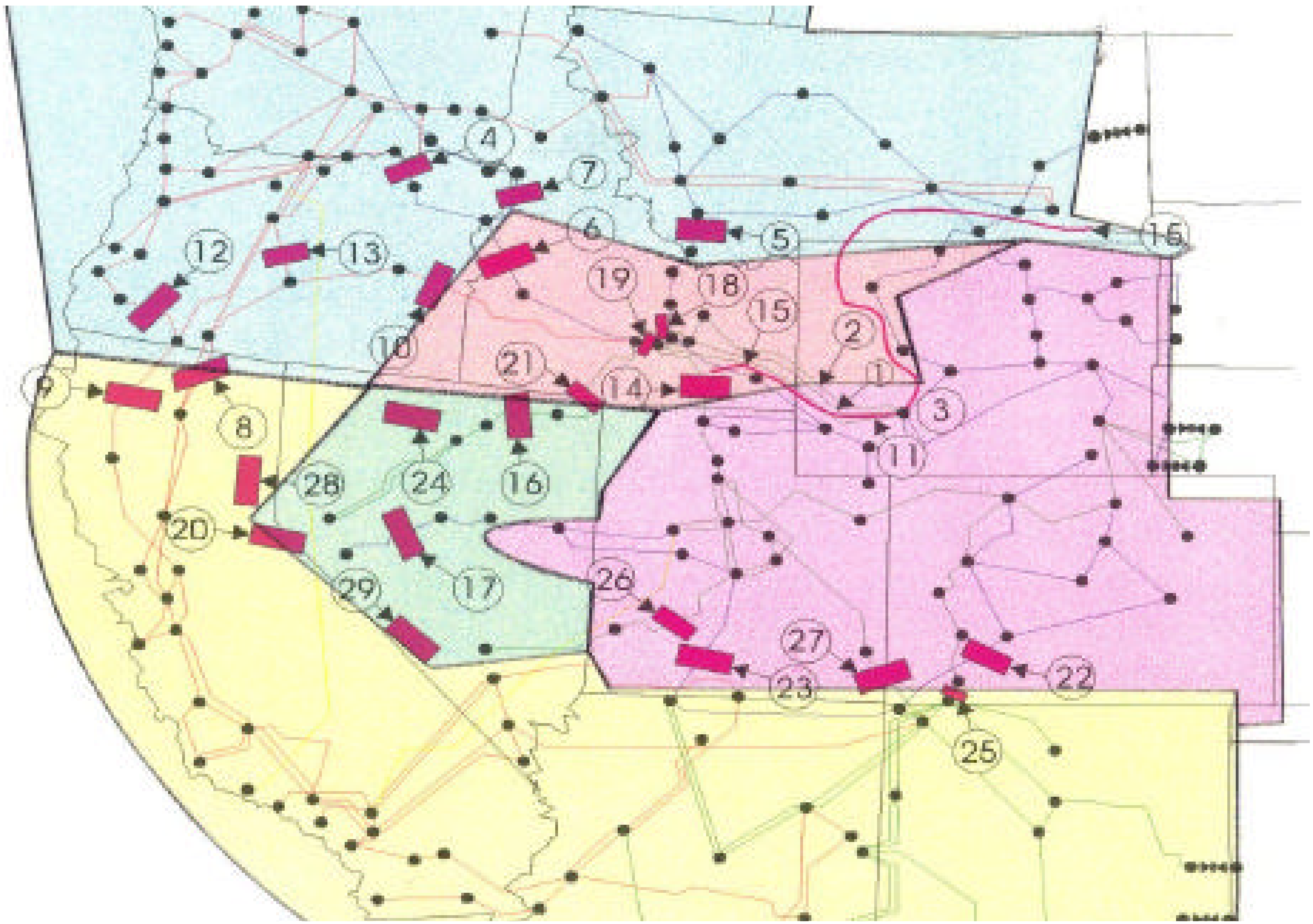
power flows
BEFORE



power flows
AFTER

FERC/NERC
Staff Report

Sequence of outages in Western blackout, July 2 1996



from NERC 1996 blackout report

How do outages propagate in blackouts?

- many mechanisms do not move along the graph topology (e.g. overloads propagate along cutsets)
- That is, the graph describing how outages propagate is not the transmission line graph (see Roy-Verghese-Lesieutre influence model)

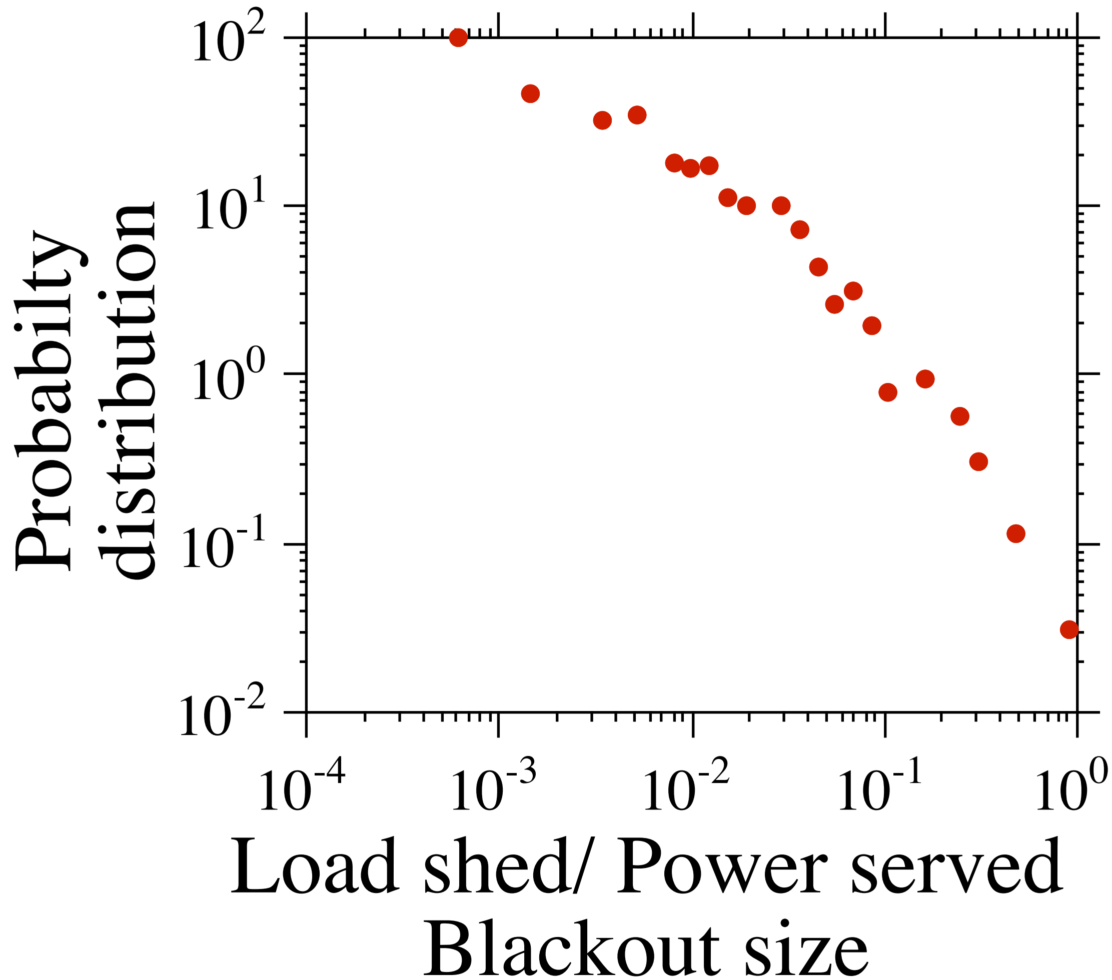
  For the purpose of counting line outages with branching processes, zeroth level approximation is that an outage causes other outages by sampling from many other lines, each with small probability
- both local and global effects

Power grids are engineered and evolving networks, *not* general networks
– engineers coordinate the parameters and operating rules to provide reliable function at minimum cost

1) These remarks obvious in biological systems!
2) Use realistic power system parameters, OR
3) Model the engineering feedback. Example: complex systems feedback of upgrading parts that outage in blackouts can self-organize system towards criticality and explain power laws in observed blackout size distributions

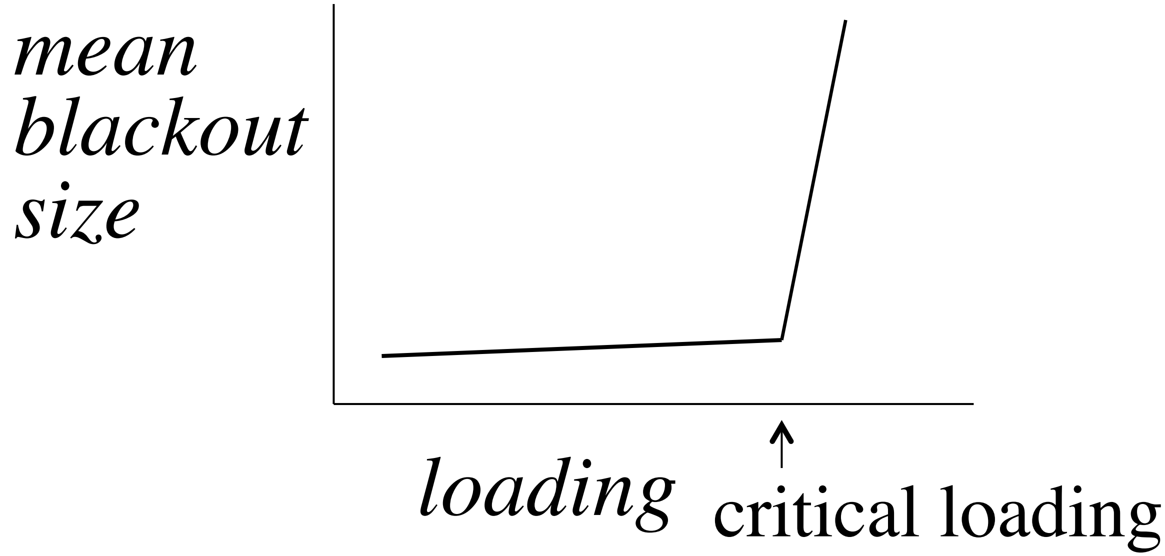
Blackout size data shows power law

- Large blackouts more likely than expected; caused by cascading
- Consistent with complex system near criticality
- Large blackouts rare, but have high impact and significant risk



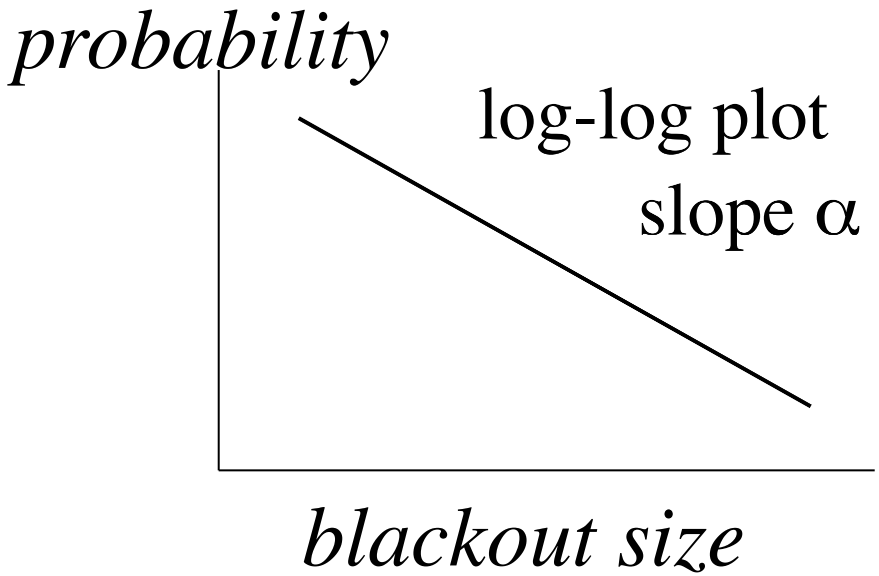
critical loading

(1) Kink in mean blackout size



(2) Power law in pdf of blackout size at critical loading

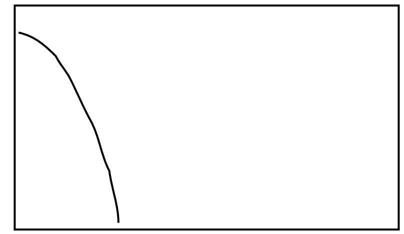
probability ~ $(\text{size})^{\alpha}$



Effect of Loading

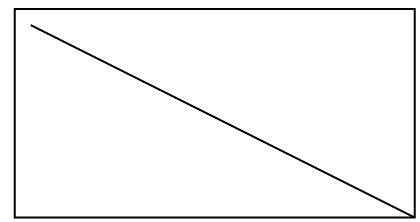
log log plots

probability

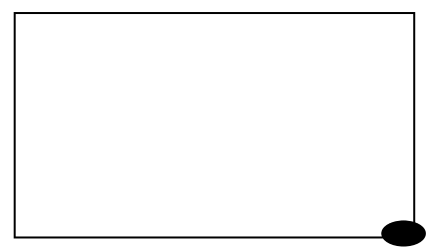


blackout size

- VERY LOW LOAD
  - failures independent
  - exponential tails



- CRITICAL LOAD
  - power tails



- VERY HIGH LOAD
  - total blackout likely

Summary of OPA blackout model (open loop; fast cascading time scale)

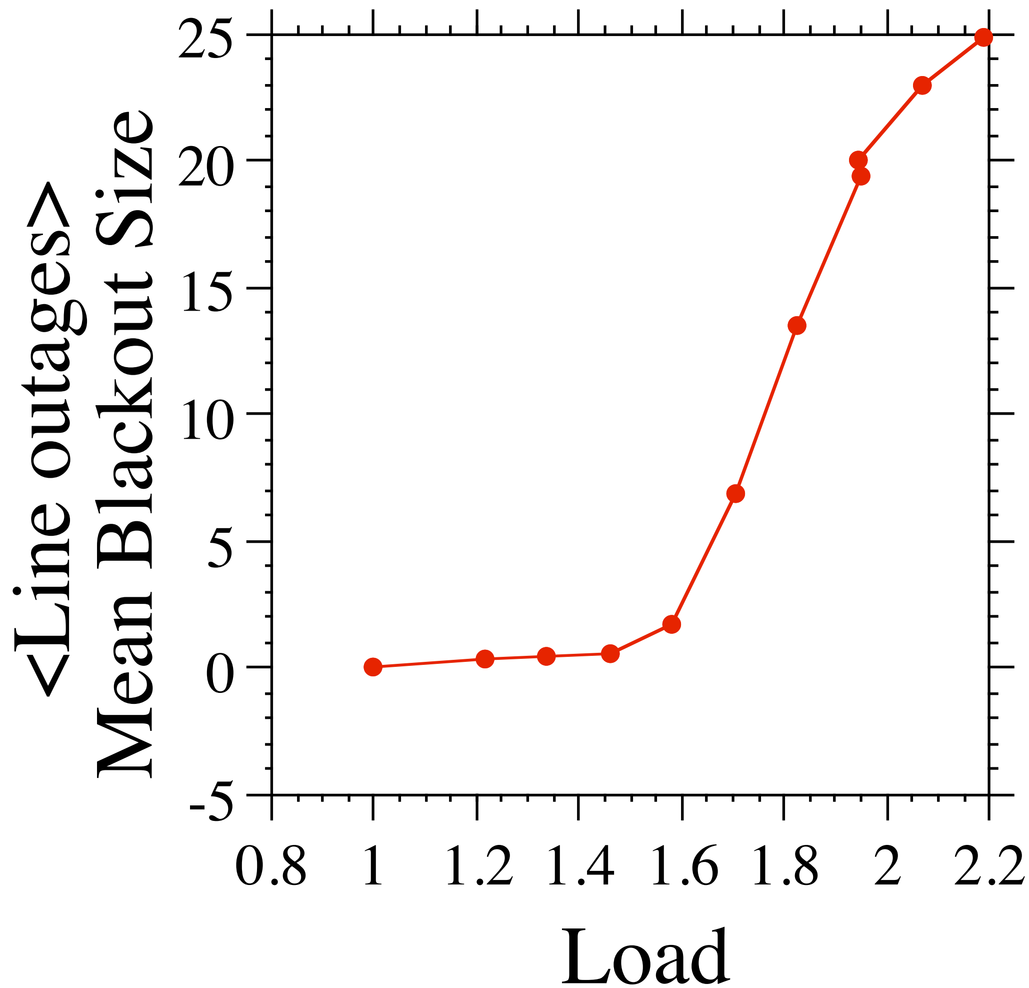
- DC load flow
  Generation to balance load decided by linear programming optimization.
- Random initial disturbance, overloads, and probabilistic cascading line outages

…. simplest cascading outage model using some elements of power system modeling

OPA model Summary (closed loop, slow evolution)

- underlying slow load growth + noisy load variations
- engineering responses to blackouts: upgrade lines involved in blackouts; upgrade generation: Respond to failures by fixing and improving the weakest parts!
- conventionally look at short-term reliability of a fixed network; here we are looking at long-term reliability accounting for evolution under complex system dynamics.

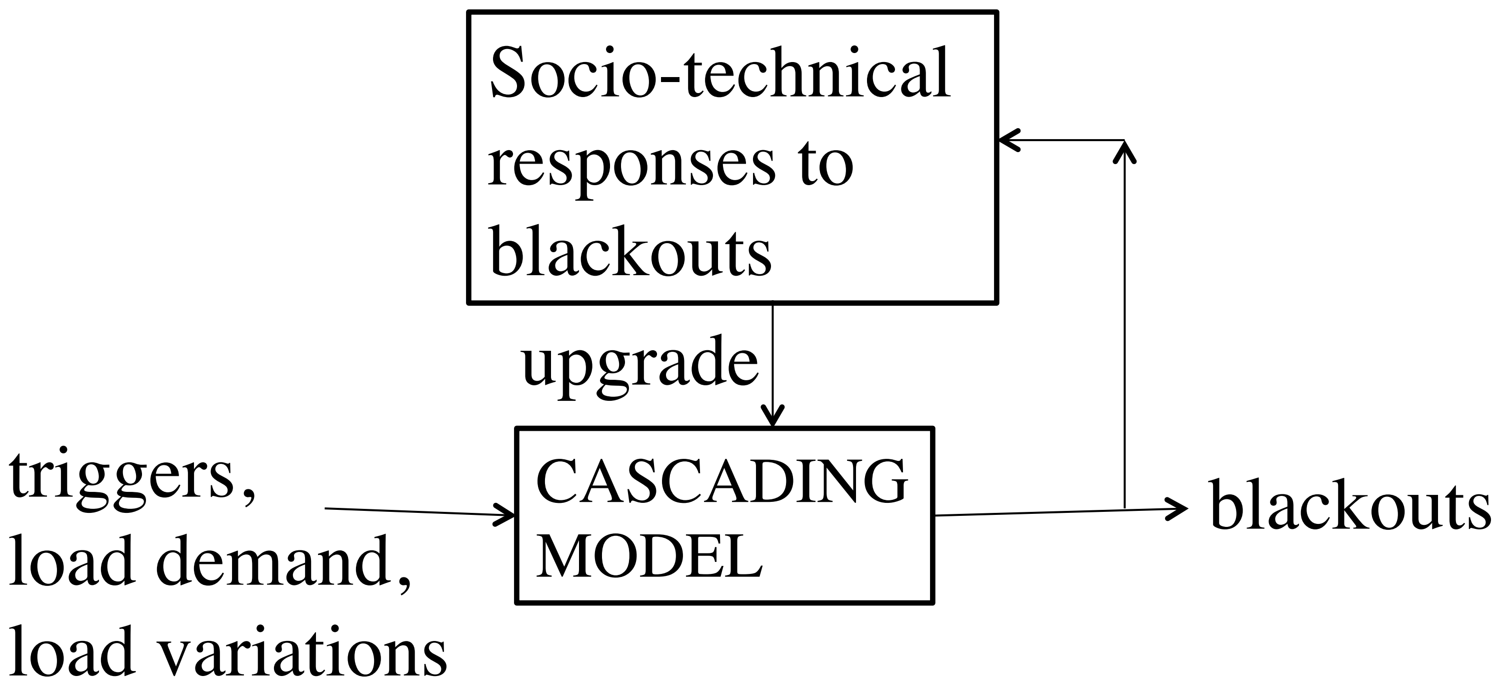
An explanation of power system operating near criticality



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

Strong economic and engineering forces drive system to near critical loading

Modeling with complex systems feedback upgrading system



Analogy with control theory suggests that outcome largely depends on feedback and depends much less on cascading model

Problems in simulating cascading outages

- Many mechanisms with different emphases and time scales; a modeling nightmare
- Huge number of possibilities, rare events on large network
- Need to sample properly and enough to get good statistics
- Need tractable computation time

Conclusion:
we must cut corners on the modeling

State of the art in simulating cascading outages

Select and model a small subset of the mechanisms (the subset varies, but there is a bias towards the better understood and easier physical mechanisms)

We don’t know which mechanisms and how much detail is needed for useful results

Models of cascading outages come from:
(1) **physics** of subset of outage mechanisms
(2) **postulated patterns** summarizing outage mechanisms

Need validation of all models
to get defensible conclusions
about power systems

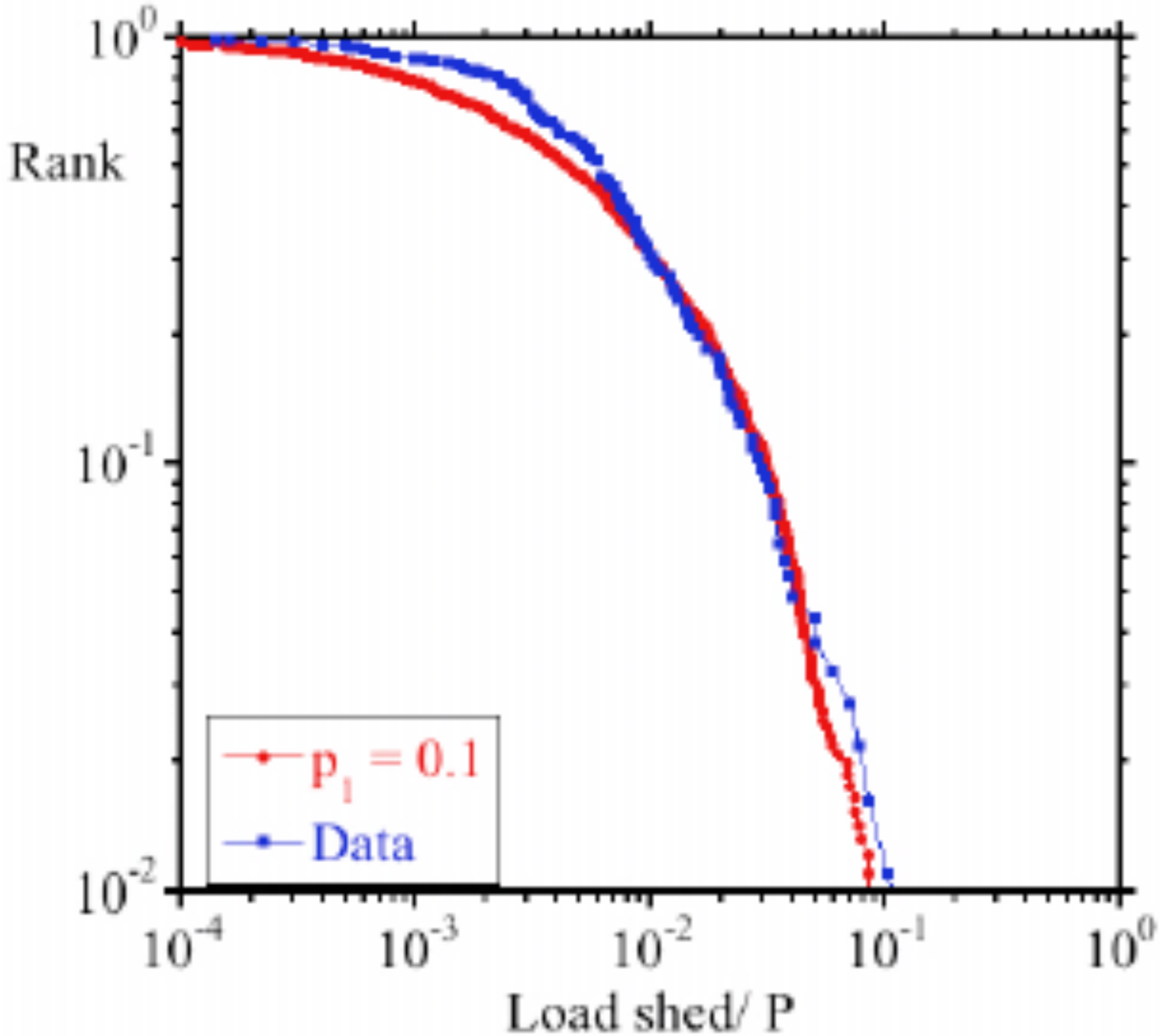
Validation

- Want plausible cascades that could happen in a power system
- Thresholding and sampling imply that we cannot always expect to reproduce individual outage cascades (useful exception for post mortem analysis of individual large blackouts)
- Compare form and parameters of statistical patterns to observed data

Data for validation

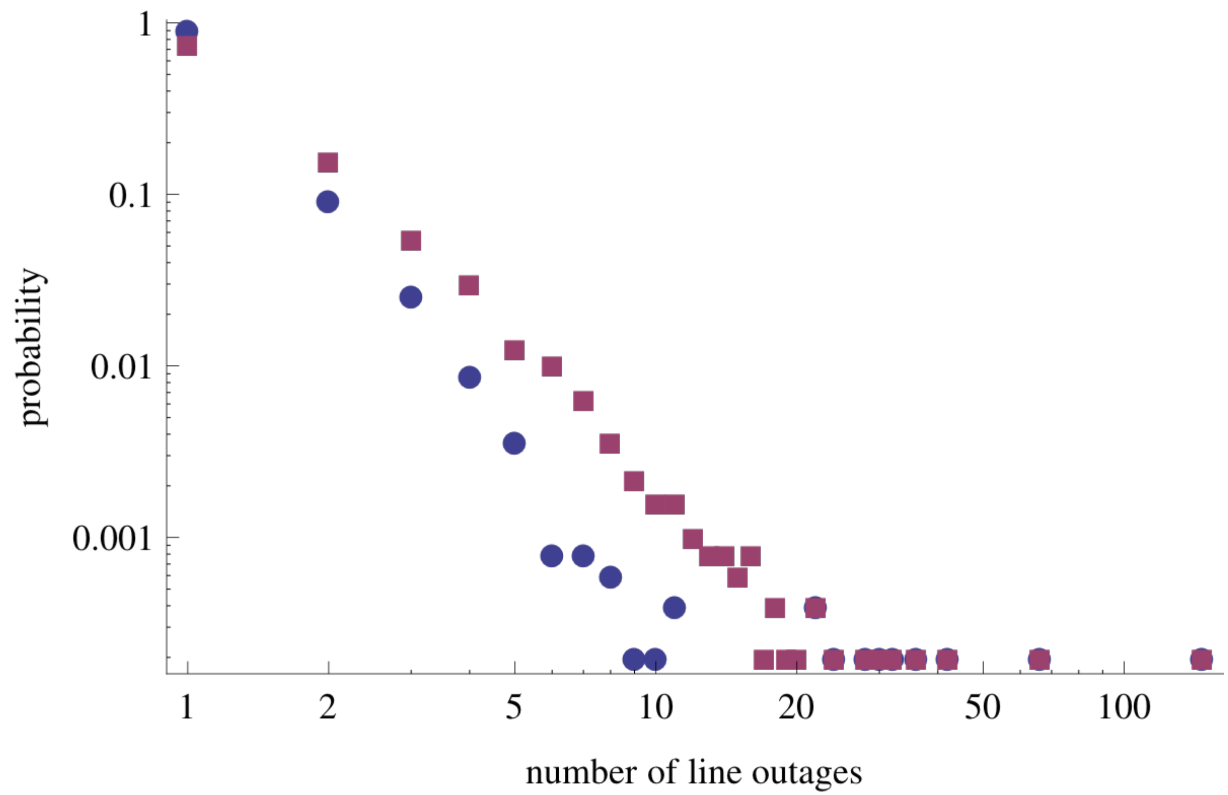
- NERC historical blackout statistics
- BPA TADS line trip data (BPA website)
- various blackout reports
- IEEE Power & Energy Society working group on cascading outages is starting to develop cases

Distribution of blackout size: match between OPA on 1553 node model of WECC and NERC data



Empirical distributions of line outages in BPA data

Probability

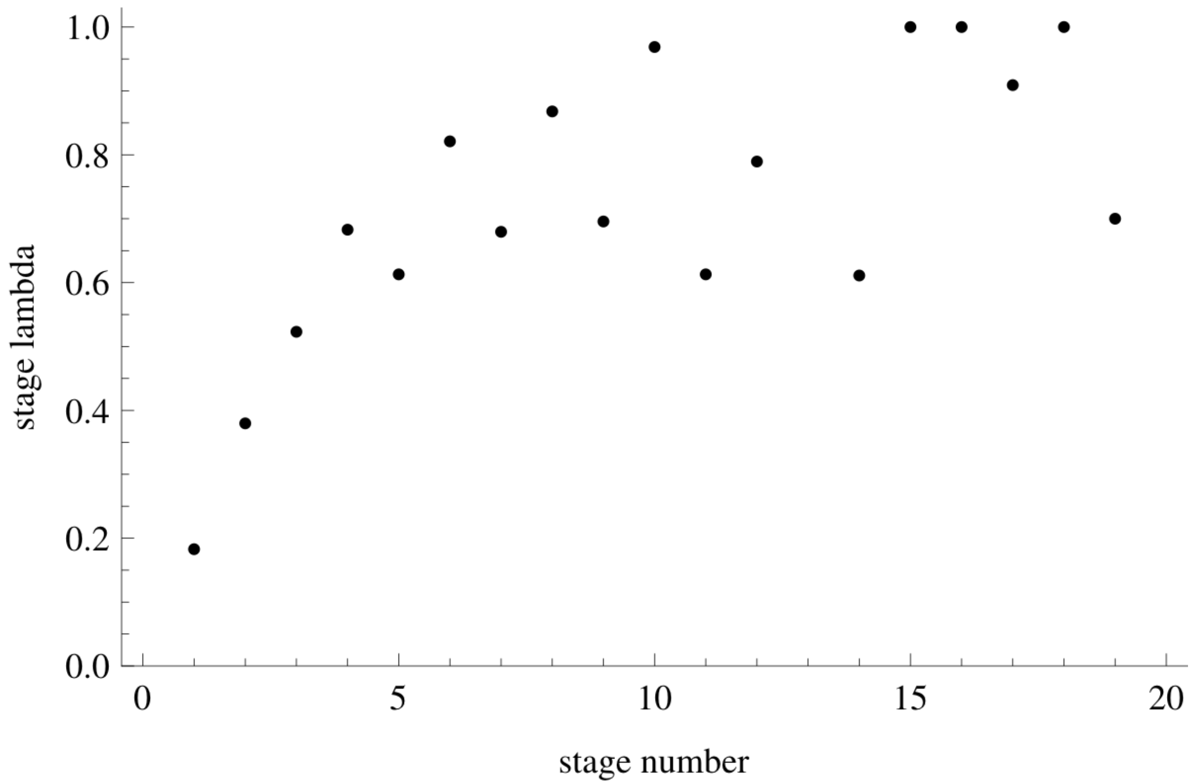


Number of line outages

Blue dots: initial line outages (generation 0) in each cascade
Purple squares: total line outages in each cascade

The increasing propagation λ from data

Propagation
λ
in each
generation



Generation number

$\lambda 1 = 0.18, \ \lambda 2 = 0.38, \ \lambda 3 = 0.52, \ \lambda 4 = 0.68, \lambda 5{+} = 0.75$

Conclusions

- cascading outages hard to model
- power system models > network
- power grids are evolving engineered networks
- power law in blackout size explained by slow self-organizing feedbacks. Model robustness via modeling socio-technical feedback?
- physics-based models select and approximate mechanisms whereas summarizing models are postulated
- need models validated with data.

for details, google Ian Dobson papers