Energy System Risk Assessment

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Workshop on Overarching Issues in Risk Analysis

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Five Infrastructure Problems

Objective: Present five energy infrastructure problems involving risk, with *some* level of approach to each.

1. Transmission control center economy/security system maneuvering
2. Responding to low probability, high consequence events with blackout potential
3. Maintenance: maximizing cumulative risk reduction with limited resources
4. ~~Investing in capital-intensive infrastructure under uncertainty~~
5. Reliability/economy of national energy transportation system: electric, gas, coal.

Energy control centers

Security assessment

- Security: ability of the power system to withstand any of a defined set of next contingencies
- Contingencies:
  - faults followed by removal of faulted element(s)
  - "N-k": k is # of removed elements. Prob ↓ as k ↑
  - Industry plans for, prepares for: N-1, some N-2.
- Consequences:
  - Circuit overload
  - Low voltage

  } All control centers analyze these; they are precursors to next level consequences.
    - Voltage instability
    - Cascading
      - Uncontrolled load interruption → Blackouts

Reducing risk?

- Action must be taken if any one prescribed contingency violates performance criteria
- Action: Redispatch generation (involves $$)

<u>Prob 1: Optimal Power Flow (OPF)</u>

Minimize GenCosts

subject to

1. Power flow equations
2. Normal condition constraints

<u>Prob 2: Security-constrained OPF</u>

Minimize GenCosts

subject to

1. Power flow equations
2. Normal condition constraints
3. Security constraints

But risk is not quantified in these formulations:

- Contingency probability varies
- Probability of voltage instability/cascading varies

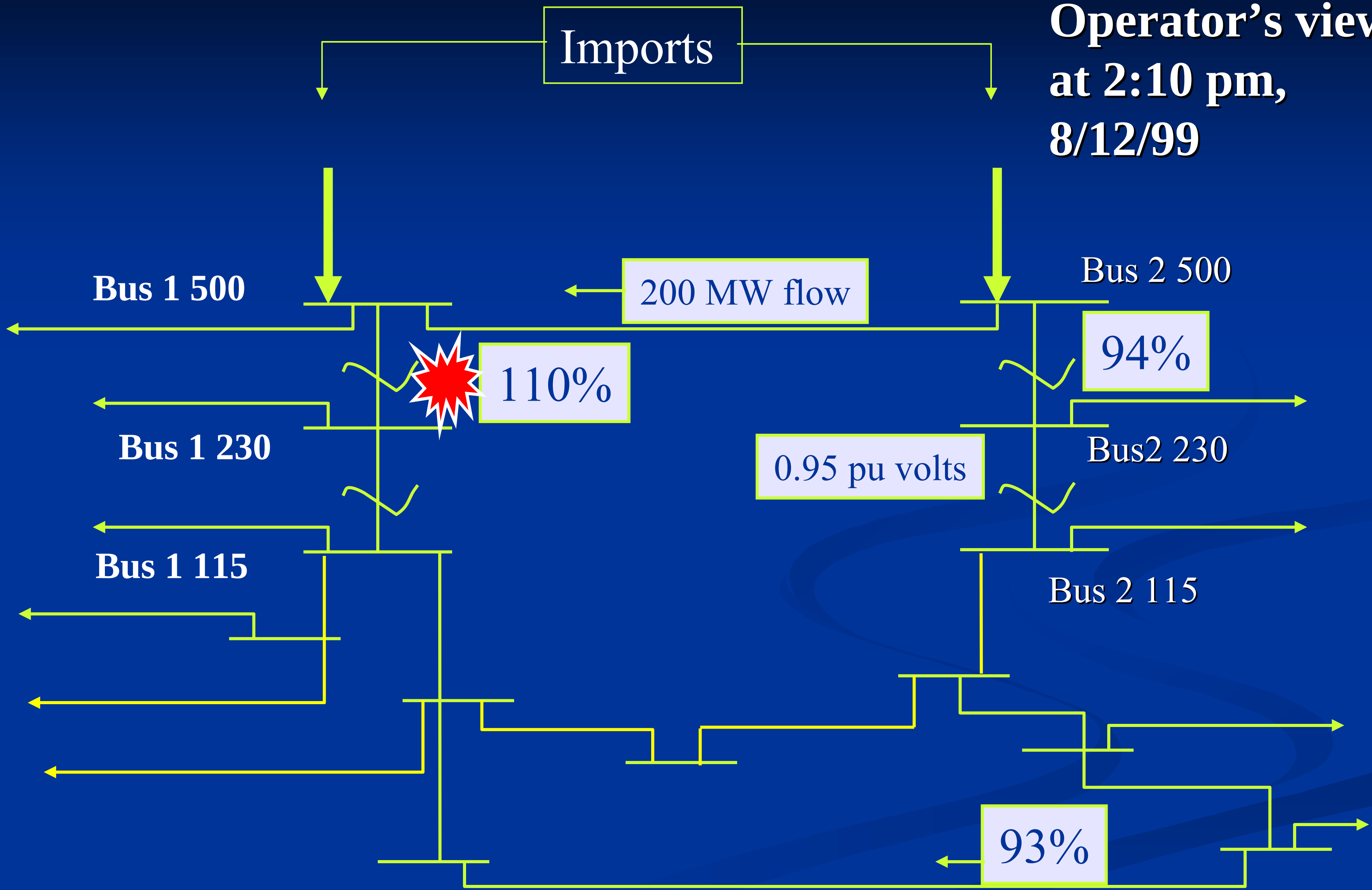
A Stressed System

- August 12, 1999, Thursday, 2 pm
- Ambient temperature is ~103 degrees F and still rising
- Large city control center
- Loading above that in 1999 summer peak planning case

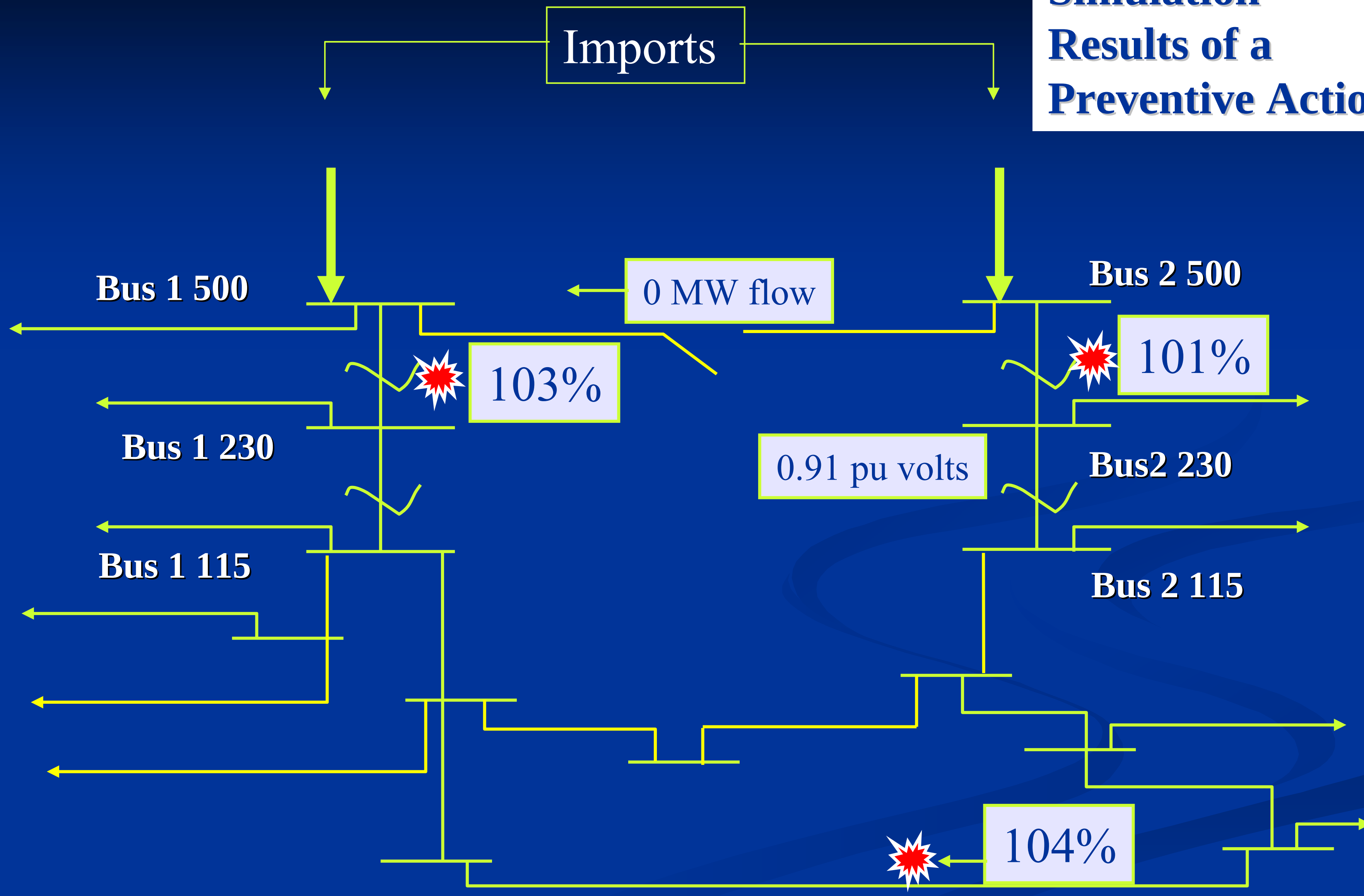
•System is heavily stressed, but there are many companies making lots of $$ for their shareholders !

- Bus1 500/230 kV bank has been over 100% since noon
- It's loss will result in collapse
- Now, at 2:10 pm, it is 110%

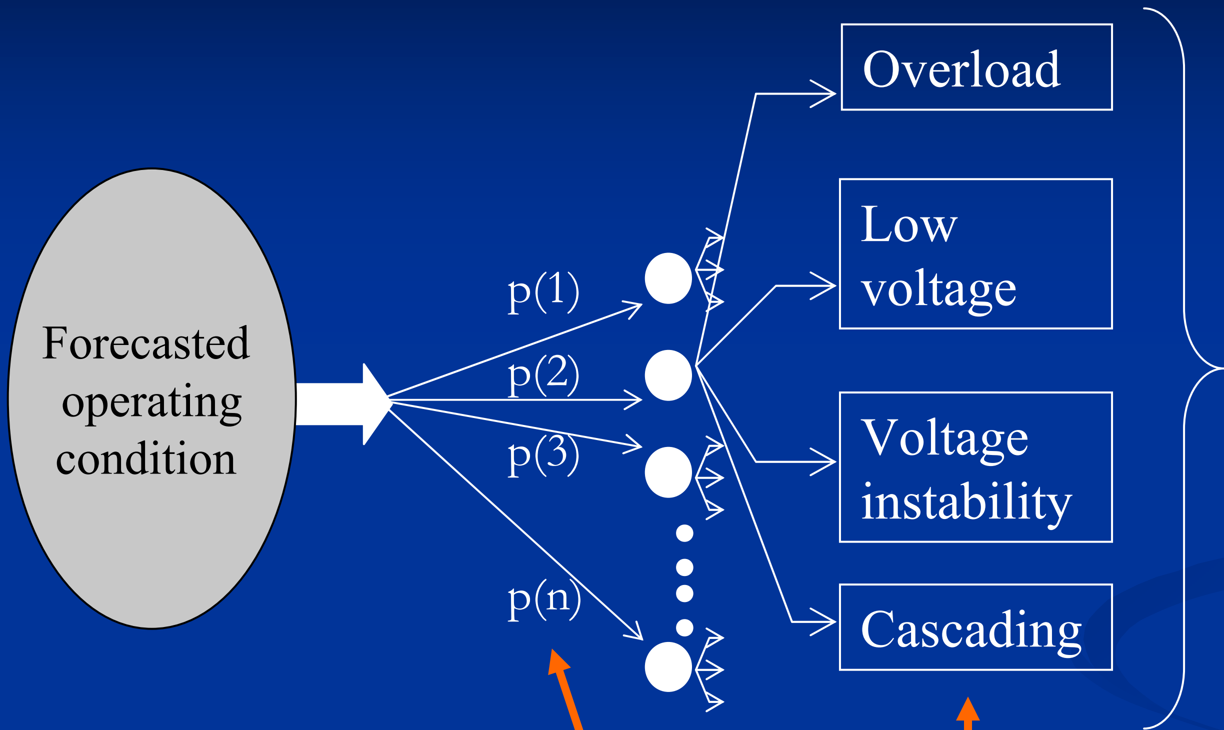
Operator's view at 2:10 pm, 8/12/99



Simulation Results of a Preventive Action



Risk Calculation



Evaluated using variants of power flow calculation (Newton-Raphson iterative solution to high dimensional nonlinear algebraic equations)

$$Risk(X) = \sum_{\substack{contingencies\\ k}} p(k) \sum_{\substack{problem\\ type\\ j}} Sev_j(X \mid k)$$

Severity functions...

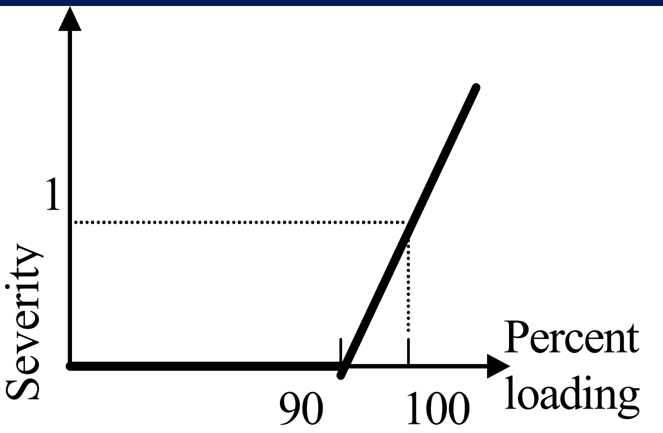


Fig 6.7: Overload severity function

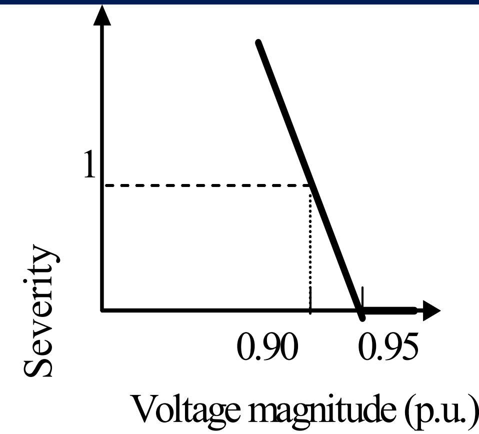


Fig 6.4: Low voltage severity function

- Risk: Expected severity in next hour.
- Severity=1.0 at imposed limit.
- Risk=1.0 is equivalent to one violation.

This value assigned to provide Risk=1.0 if lowest probability contingency (p=1E-6) results in voltage instability.

This amount of risk equates to what industry has indicated is unacceptable.

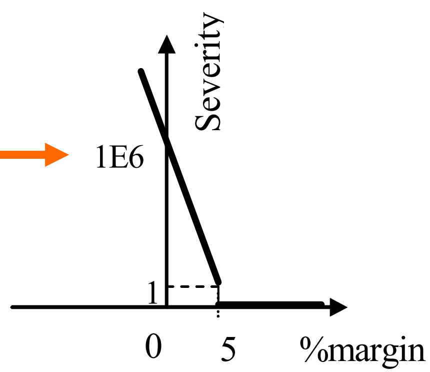


Fig 6.9: Voltage instability severity function

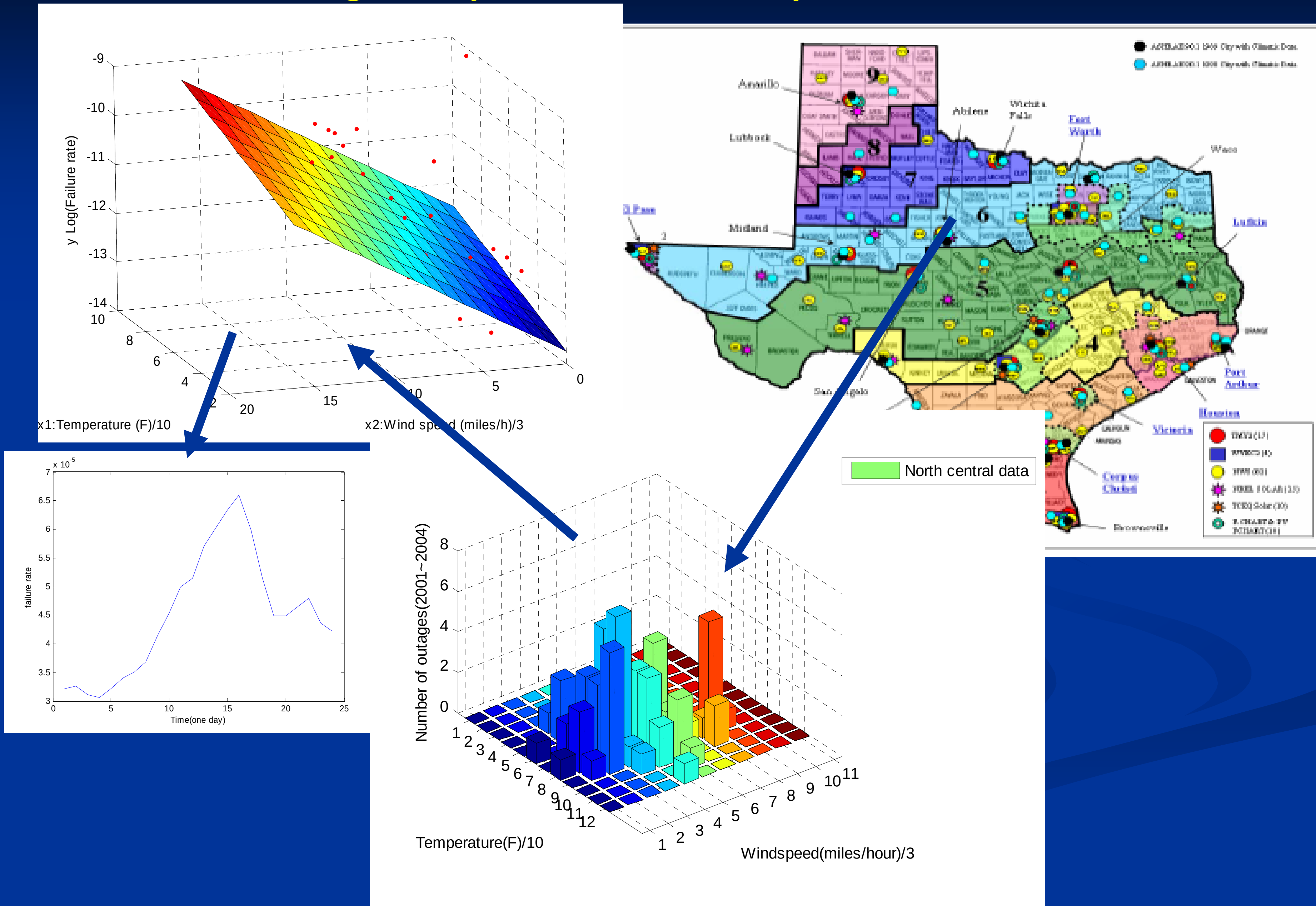
Contingency Probability Estimation

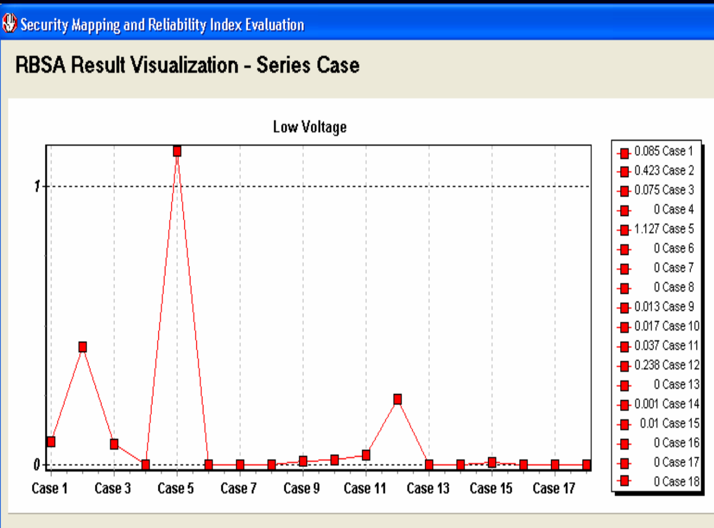
➔Distinguish between contingency probabilities based on

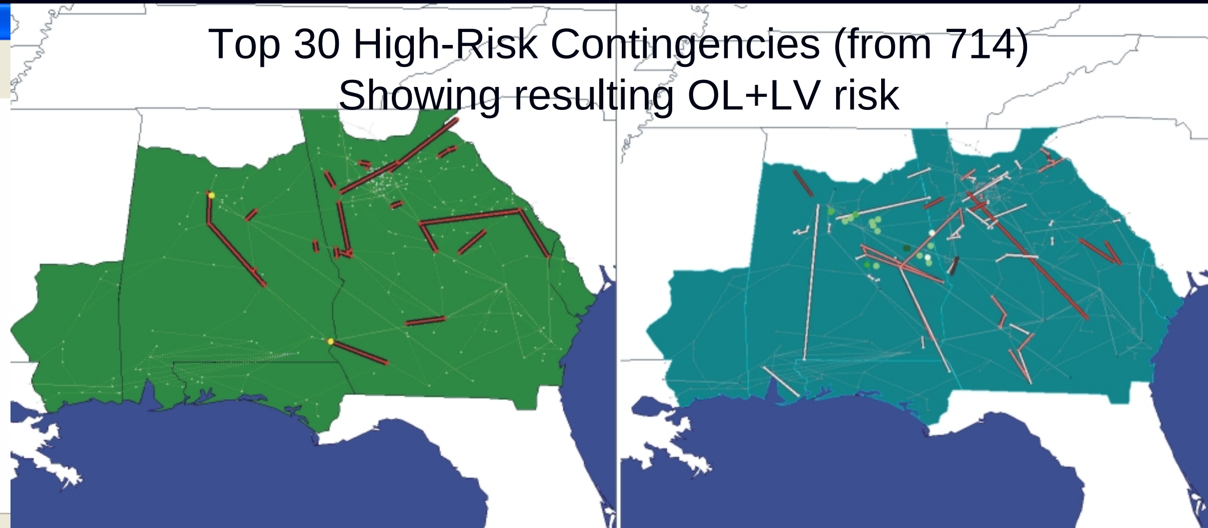
- Historical outage data
- Physical attributes: length, voltage level, geography
- Temporal attributes: weather

1. Separate outage data into 24 pools (8 zones x 3 kV levels)
2. For each pool,
   - separate outage data into "weather blocks" and compute failure rate/mile for each block, resulting in about 30 values
   - Use linear regression to determine dependence of failure rate on weather
3. On-line, evaluate failure rates/mile for each pool, multiply by line length for each circuit.

Contingency Probability Estimation



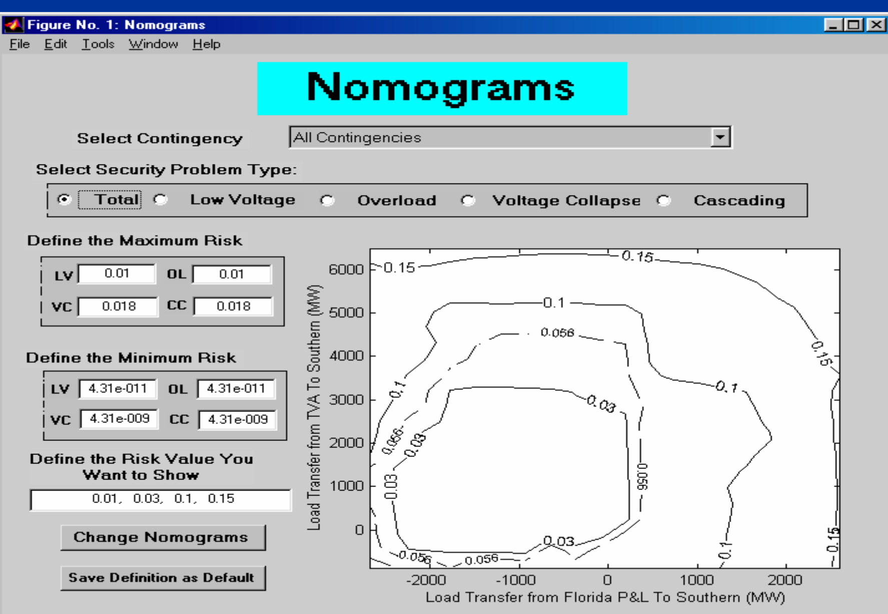


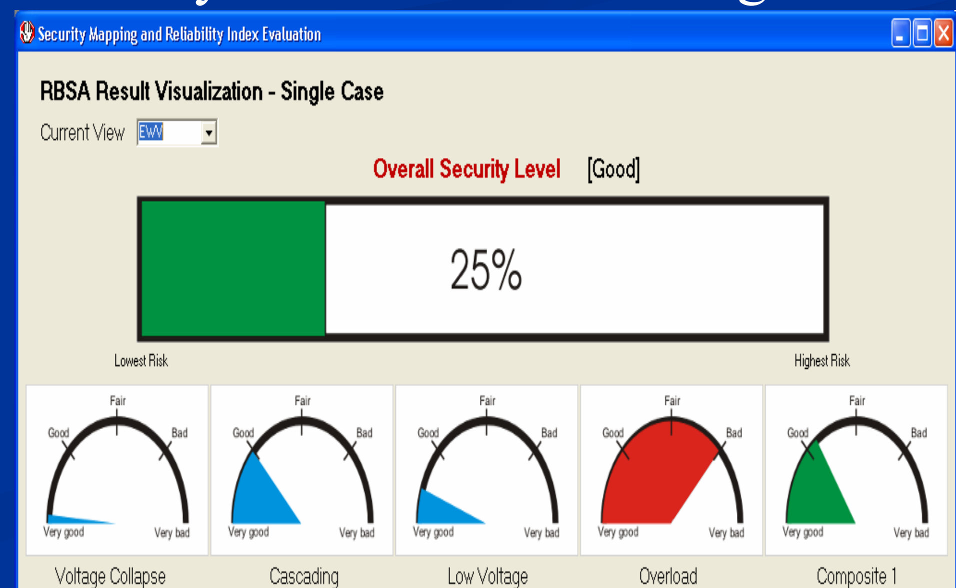


Visualization over time

…and space

and the ability to drill-down to identify nature & cause of high risk





…and operating conditions

Risk reduction using "targeting" redispatch

<u>Prob 2: Security-constrained OPF</u>

Minimize GenCosts

subject to

1. Power flow equations
2. Normal condition constraints
3. Security constraints

<u>Prob 3: Risk-Objective SCOPF</u>

Minimize GenCosts +β×Risk

subject to

1. Power flow equations
2. Normal condition constraints
3. Security constraints

- This formulation requires sensitivity of risk to each generator injection.
- Why is this formulation an improvement?

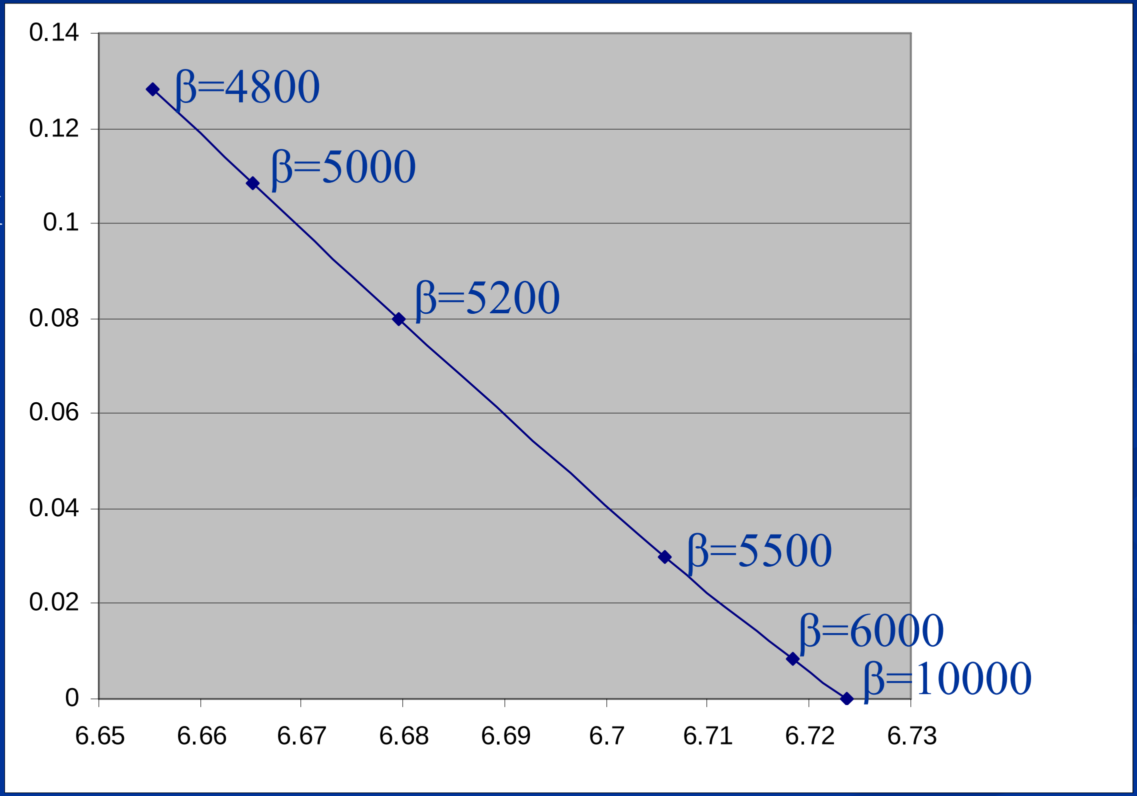
  ➔ Deterministic security limits (normal and contingency) are enforced, on targeted basis

  ➔ Overall risk is reduced.

  ➔ The balance between cost and risk reduction may be observed (and controlled).

Risk reduction using “targeting” redispatch

Risk



Cost of redispatch

N-k contingencies

What to say, operationally, about high-order (N-k, k>1) contingencies?

- If probability is high, put it in contingency list and treat it as any other N-1 contingency (e.g., take preventive actions as needed)
- If probability is low, monitor it, perhaps identify corrective actions for it should it occur, but do not spend money in preventive actions.

How to identify high-probability N-k contingencies?

Probability Order

<u>Definition</u>: the probability order of a contingency is the number of independent events necessary for occurrence of that contingency.

Probability order is a rough way of comparing probabilities of different contingencies.

Assume the probability of any single event (faulted line, protection failure, etc) is $10^{-4.}$

Then, for independent events, occurrence of
- two events is $P(A)*P(B)=10^{-8}$ (order 2),
- three events $P(A)*P(B)*P(C)=10^{-12}$ (order 3), etc.

But probability of 2 dependent events is $P(A)P(B|A)$, and $P(B|A)$ can be 1.0, so the probability of the two dependent events is $P(A)$.

Classification of N-k contingencies

- Protection system failures (NERC category C or D):
  - Inadvertent operation, failure is exposed after a first-fault
  - Failure to operate when needed.

  Both cases require fault+existence of protection failure: order=2.

- Are there single events that cause N-k outages? Yes,…
  1. Common mode outage (NERC class D) such as hurricane, earthquake, airplane
  2. Breaker fault (NERC class D)
  3. Substation topology problem (maintenance or careless switching)
  4. Cascading following a first-fault

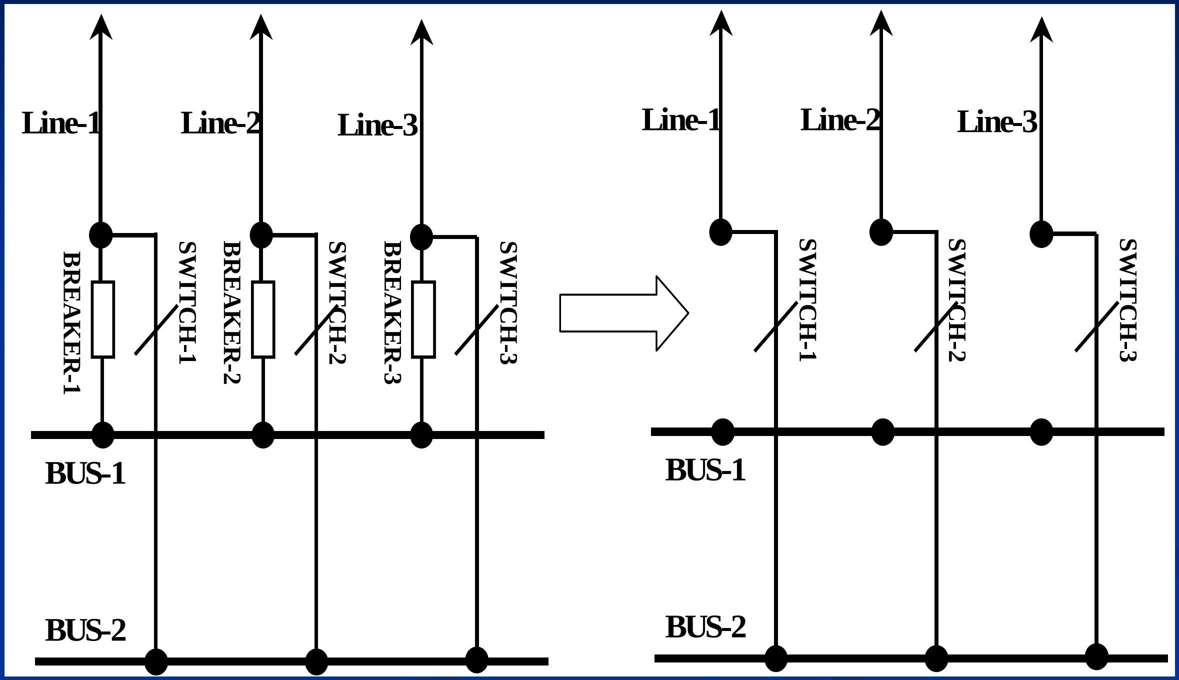
  But common mode and breaker faults have probabilities closer to order 2. This leaves #3 and#4.

  Since #3 requires only a single fault, it has order 1.

  Since #4 is dependent, it can have order close to 1.

Example of topological weakness

Remove bus 1 from service, and a single fault on any line results in N-3 contingency.



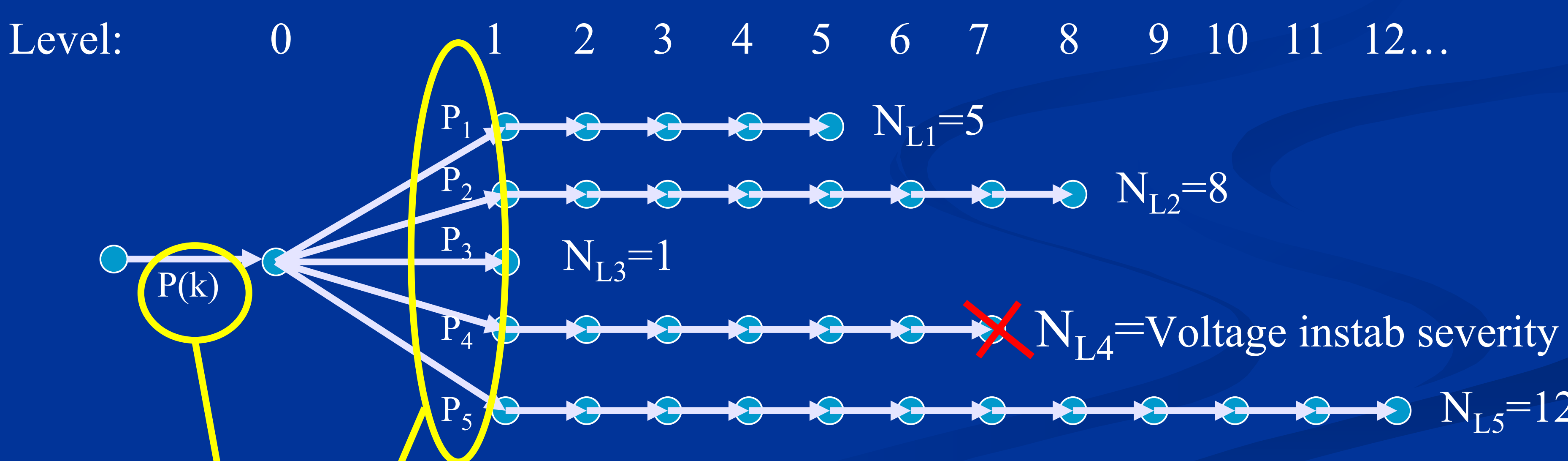
There are thousands of such substations in a model.

We perform a topological graph search using the breaker/switch and connectivity data to identify these high-probability N-k contingencies.

Cascading

Cascading risk depends on:

- Occurrence probability of a first contingency k (Level 0).
- Probability of all possible Level 1 trips, computed as a function of post-contingency loading on remaining circuits
- Severity of cascading sequence following each Level 1 trip, computed as a function of number of circuits lost, or if no convergence, as a function of voltage collapse severity.



$$Risk(k) = P(k)\sum_{i=1}^{m} P_i * N_{Li}$$

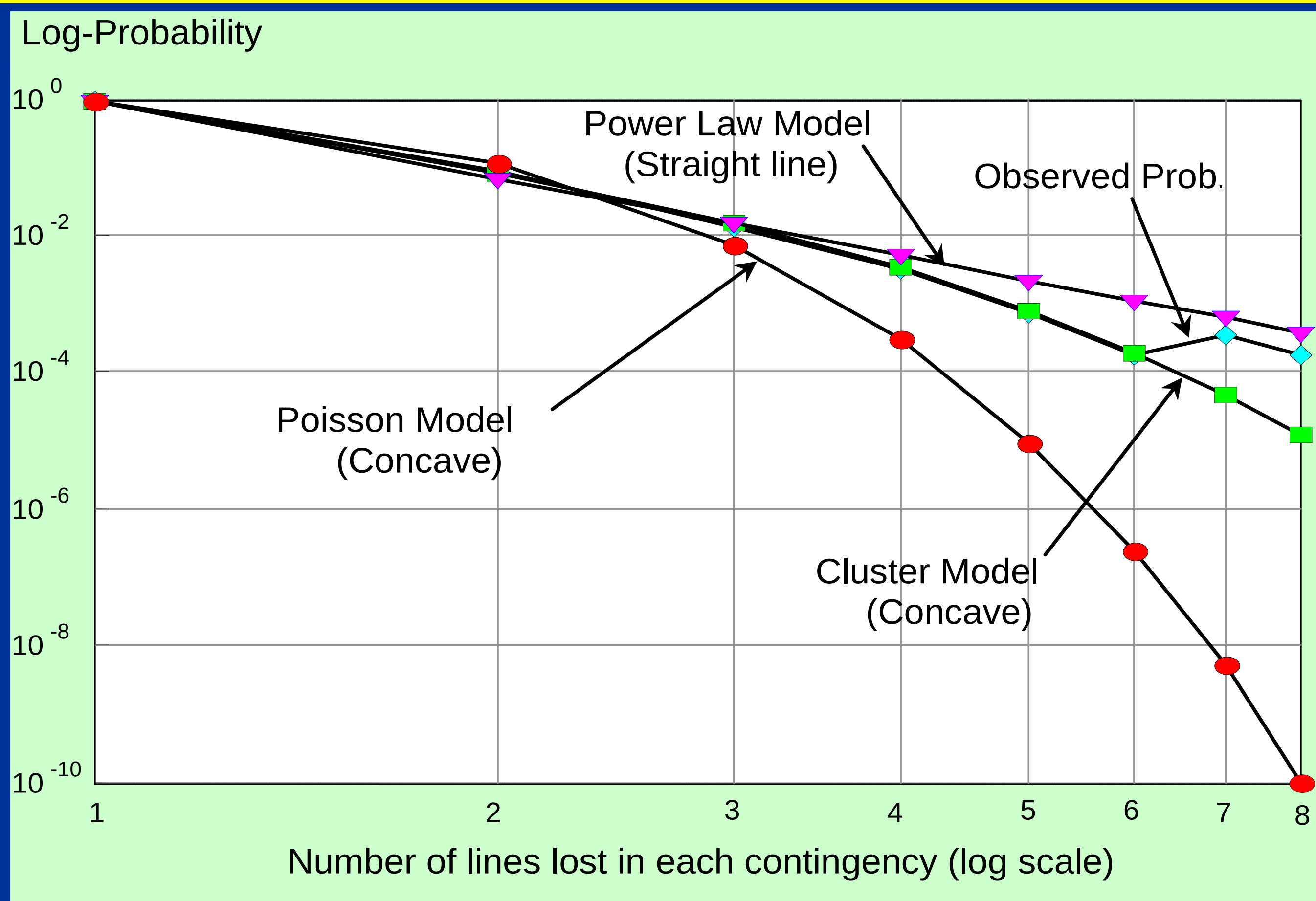
Final result for maximum likelihood estimation of parameters for the three probability models

$$\Pr(X = x \mid \alpha = 3.115, \mu = 1.12657) = \binom{3.115^{-1} + x - 2}{x - 1} \times \left(\frac{1.1266 - 1}{1.1266 - 1 + 3.115^{-1}}\right)^{x-1} \times \left(\frac{3.115^{-1}}{1.1266 - 1 + 3.115^{-1}}\right)^{3.115^{-1}} \quad \text{for cluster model}$$

$$\Pr\left(X = x \mid \lambda = 0.12657\right) = e^{-0.12657} 0.12657^{x-1} / (x-1)! \quad \text{for poisson model}$$

$$\Pr(X = x \mid p = 3.78) = 0.9098 x^{-3.78} \quad \text{for power law model}$$

Graphic comparison of different probability models for N-k contingencies



INITIATING EVENT

1. 12:05	Conesville Unit 5 (rating 375 MW)
2. 1:14	Greenwood Unit 1 (rating 785 MW)
3. 1:31	Eastlake Unit 5 (rating: 597 MW)
4. 2:02	Stuart – Atlanta 345 kV
5. 3:05	Harding-Chamberlain 345 kV
6. 3:32	Hanna-Juniper 345 kV
7. 3:41	Star-South Canton 345 kV
8. 3:45	Canton Central-Tidd 345 kV
9. 4:06	Sammis-Star 345 kV
10. 4:08:58	Galion-Ohio Central-Muskingum 345 kV
11. 4:09:06	East Lima-Fostoria Central 345 kV
12. 4:09:23-4:10:27	Kinder Morgan (rating: 500 MW; loaded to 200 MW)
13. 4:10	Harding-Fox 345 kV
14. 4:10:04 – 4:10:45	20 generators along Lake Erie in north Ohio, 2174 MW
15. 4:10:37	West-East Michigan 345 kV
16. 4:10:38	Midland Cogeneration Venture, 1265 MW
17. 4:10:38	Transmission system separates northwest of De
18. 4:10:38	Perry-Ashtabula-Erie West 345 kV
19. 4:10:40 – 4:10:44	4 lines disconnect between Pennsylvania & New York
20. 4:10:41	2 lines disconnect and 2 gens trip in north Ohio,1868MW
21. 4:10:42 – 4:10:45	3 lines disconnect in north Ontario, New Jersey, isolates NE part of Eastern Interconnection, 1 unit trips, 820 mw
22. 4:10:46 – 4:10:55	New York splits east-to-west. New England and Maritimes separate from New York and remain intact.
23. 4:10:50 – 4:11:57	Ontario separates from NY w. of Niagara Falls & w. of St. Law. SW Connecticut separates from New York, blacks out.

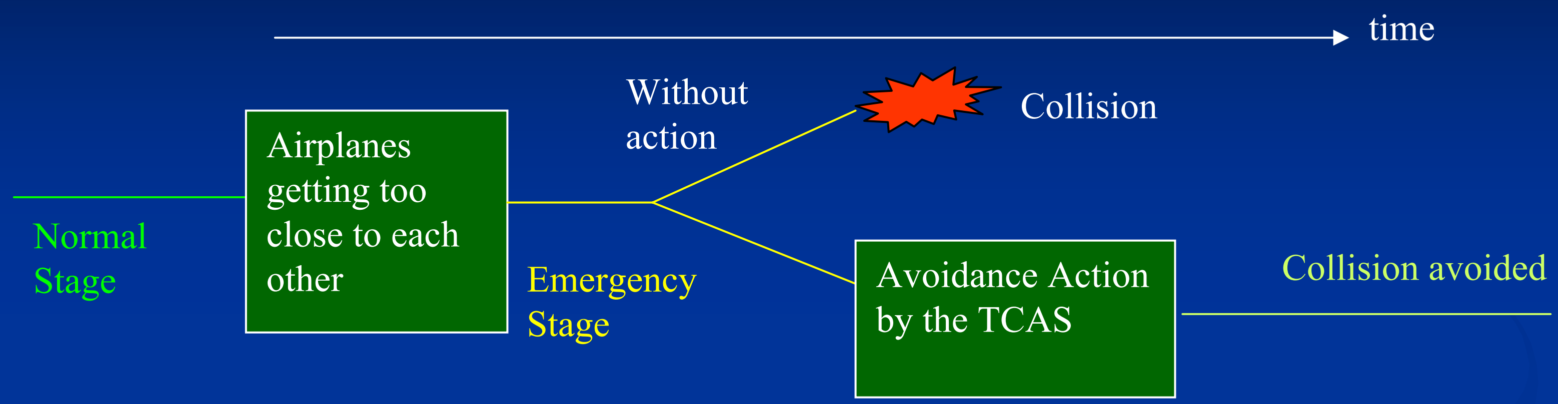
SLOW PROGRESSION

FAST PROGRESSION

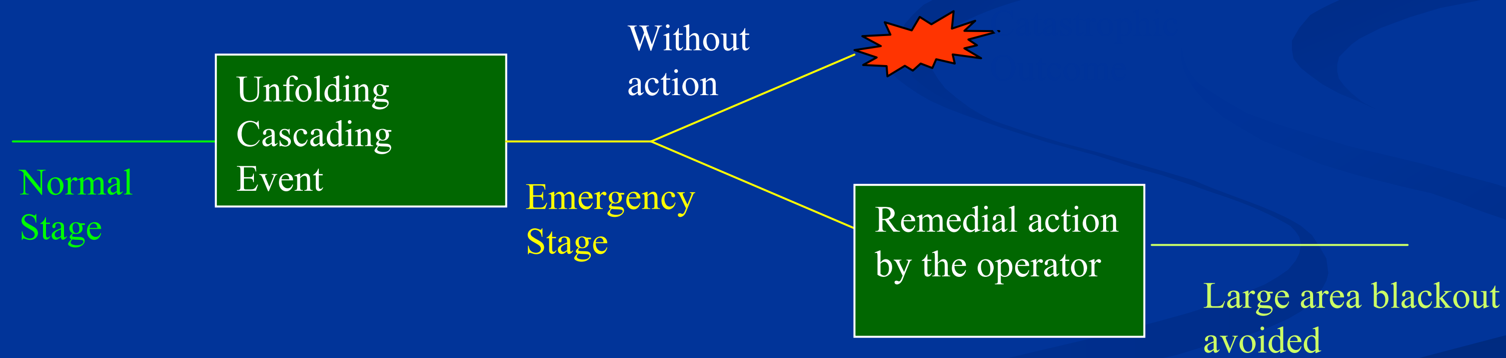
Larger Blackouts in Last 40 years

Location	Date	Scale in term of MW or Population	Collapse time
US-NE	10/9/65	20GW, 30M people	13 mins
New York	7/13/77	6GW, 9M people	1 hour
France	1978	29GW	26 mins
Japan	1987	8.2GW	20mins
US-West	1/17/94	7.5GW	1 min
US-West	12/14/94	9.3GW	
US-West	7/2/96	11.7GW	36 seconds
US-West	7/3/96	1.2GW	> 1 min
US-West	8/10/96	30.5GW	> 6 mins
Brazil	3/11/99	25GW	30 secs
US-NE	8/14/03	62GW, 50M people	> 1 hour
London	8/28/03	724 MW, 476K people	8 secs
Denmark & Sweden	9/23/03	4.85M people	7mins
Italy	9/28/03	27.7GW, 57M people	27mins

An Analogy to Air Traffic Control

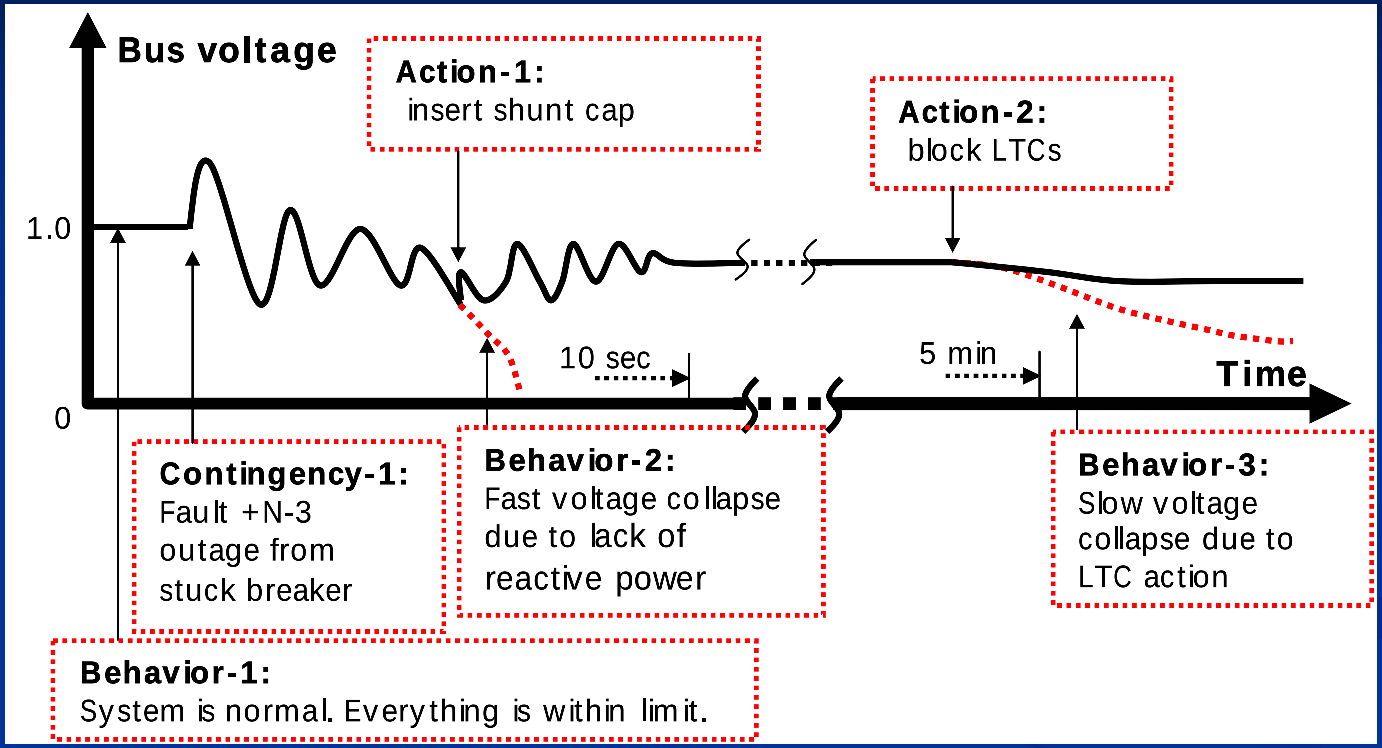


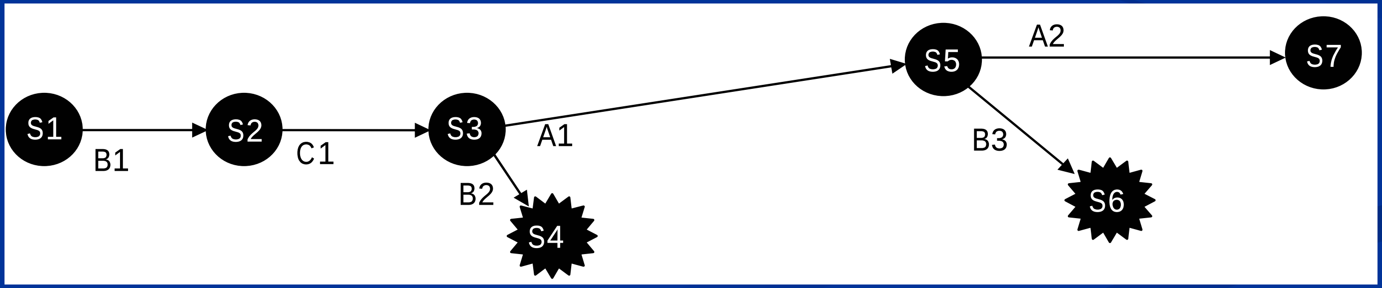
Traffic Alert and Collision Avoidance System



Emergency Response System

Rapid Response to Unfolding Events

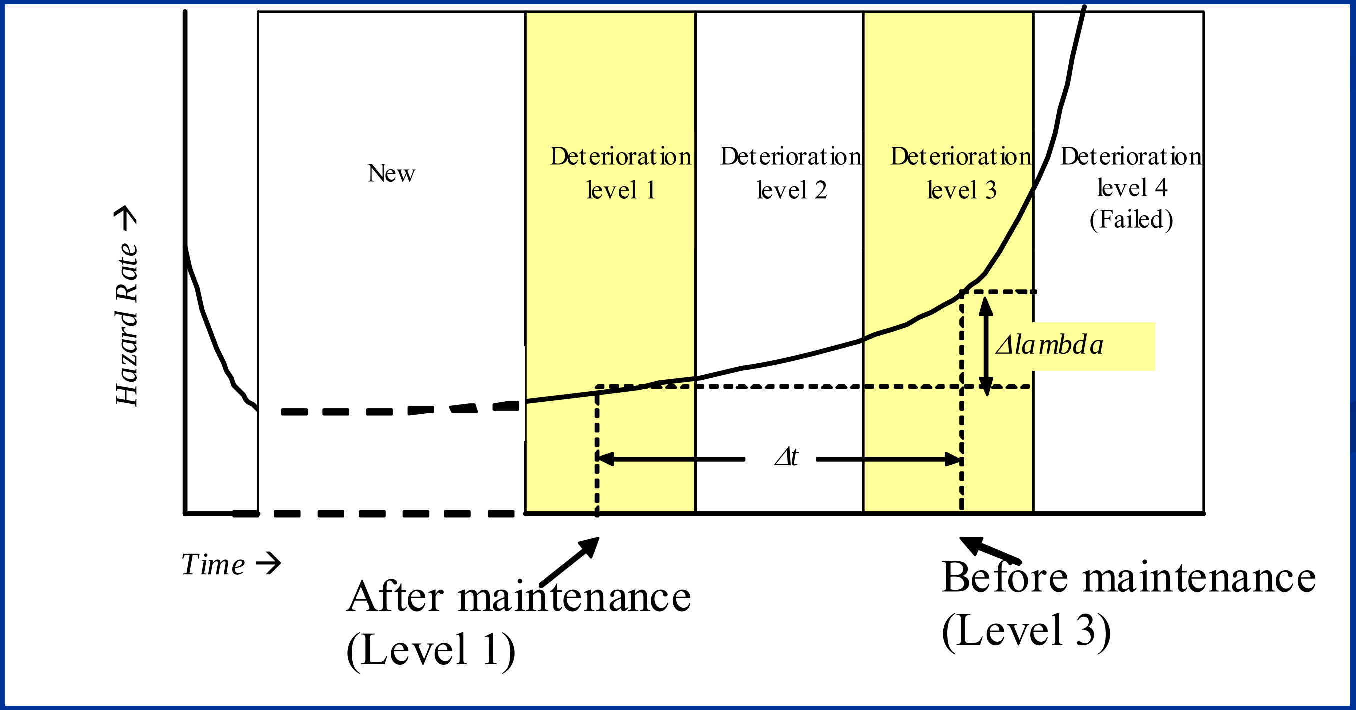




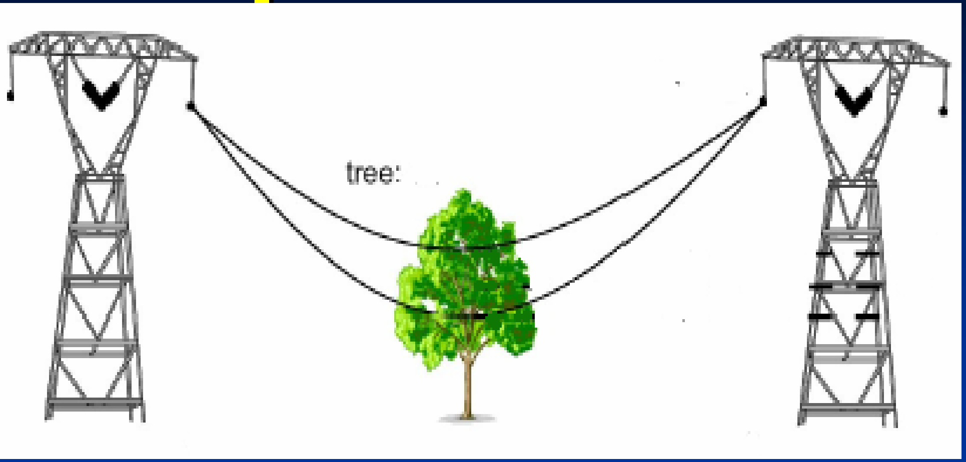
A Dynamic Decision Event Tree

Power System Maintenance (actually an interesting subject)

When maintenance needs require resources that exceed available resources, how to strategically allocate available resources to maximize benefit gained from them?

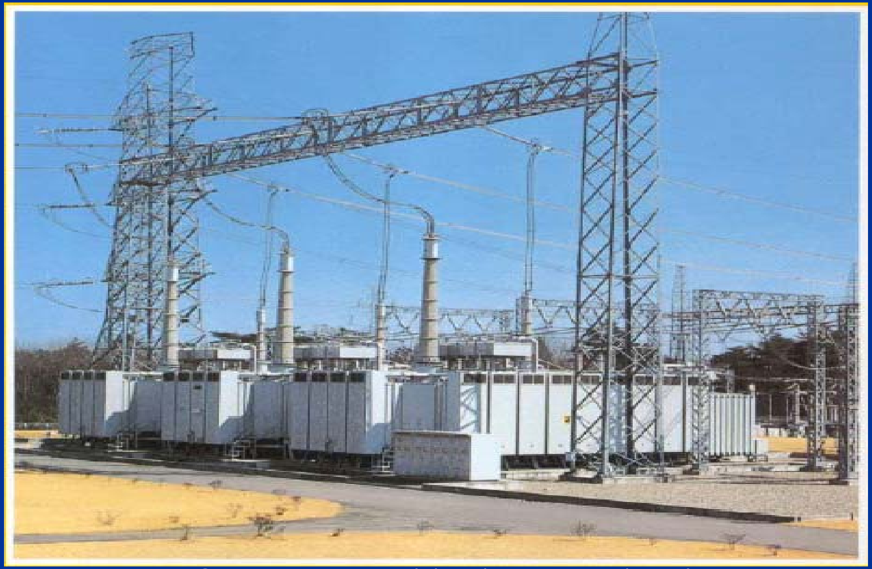


Examples of failure modes & maintenance



Fault from power line to trees

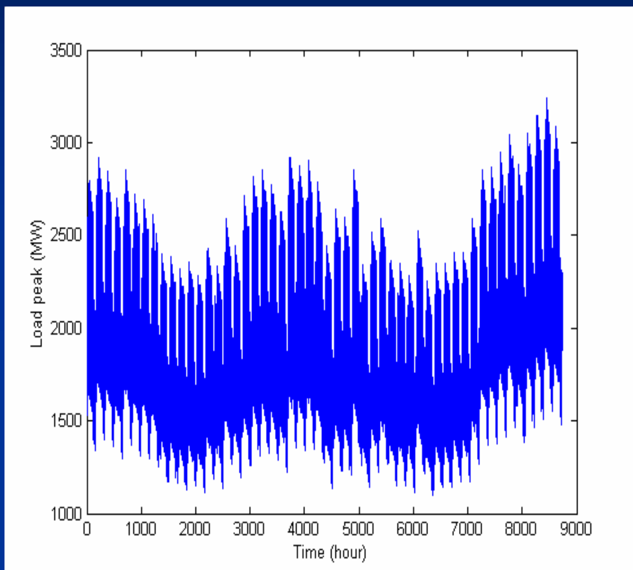
Tree trimming



Transformer oil degradation and insulation failure

Oil Reconditioning

Cumulative risk calculation



Mid-term load forecast

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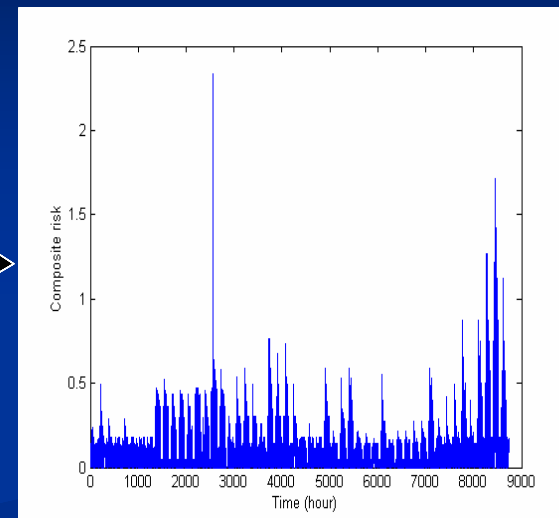
Power system simulator

↑

Contingency probabilities

→

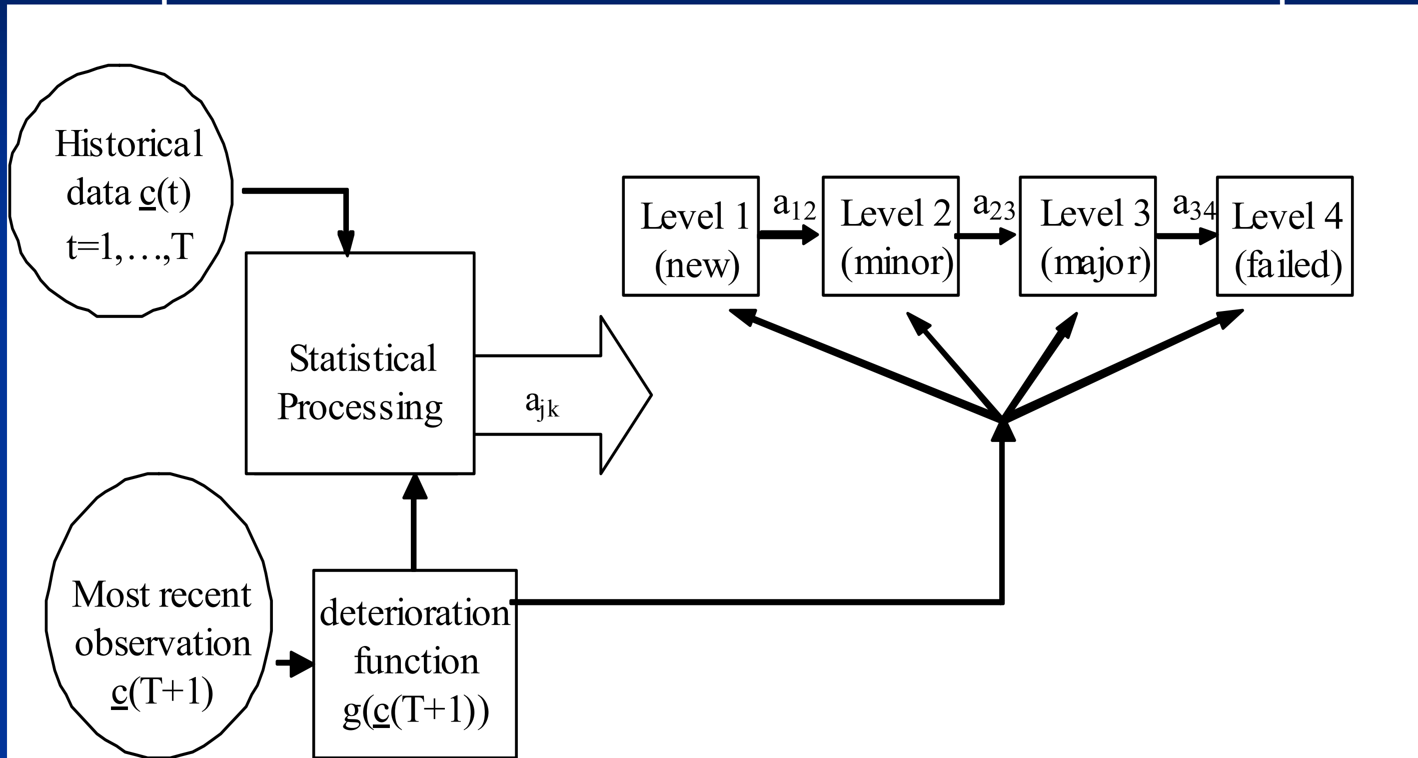


Year long, hourly risk variation for each contingency

Benefit: Maintenance reduces contingency probabilities which reduces cumulative-over-time risk

Obtaining failure rate reduction

Developed for each failure mode of each component



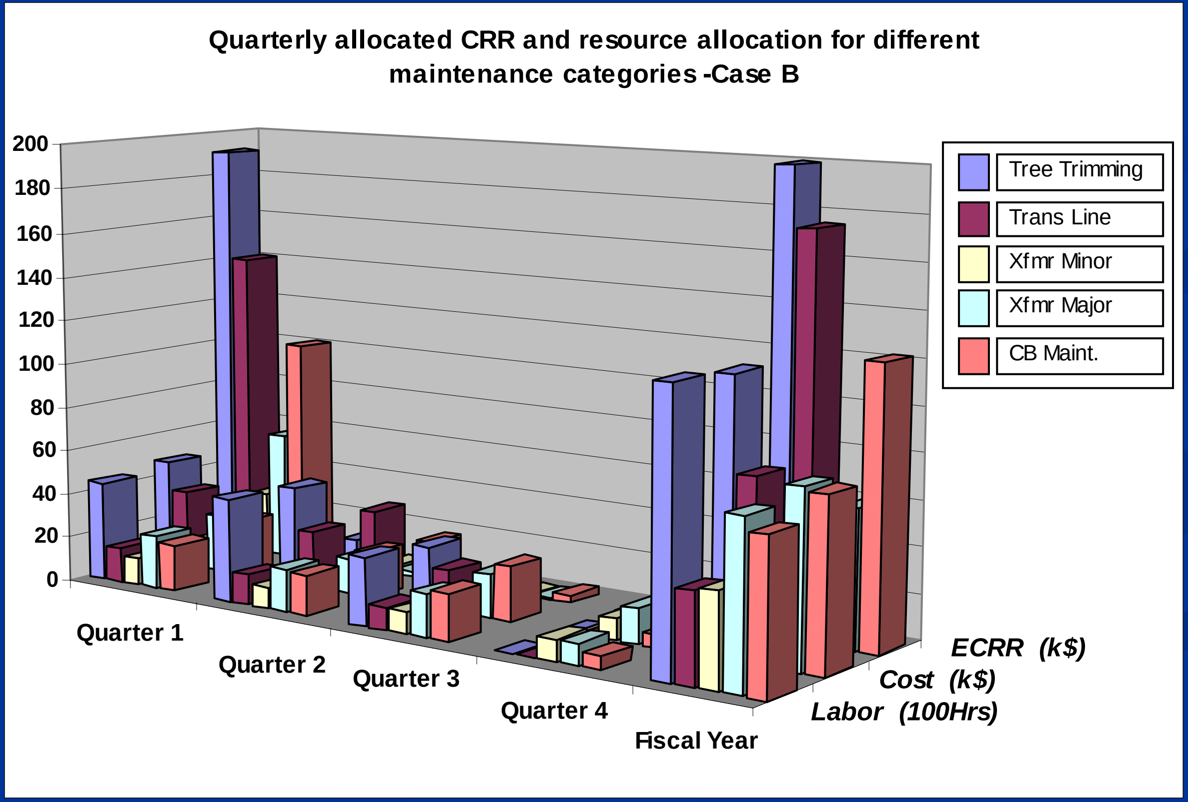
$$\Delta CumRisk(m,k,t_0) = \frac{\Delta p(m,k,t_0)}{p(k)}\left\{CumRisk(k,t_0) = \sum_{t_0}^{8760} R(k,t)\right\}$$

Optimization

$$\text{maximize} \quad \sum_{component} \sum_{task} \sum_{time} \text{RiskReduction}(\text{component, task, time})$$

subject to:

budget limits,
crew constraints for different maintenance categories,
timing constraints for maintenance tasks requiring outages



The National Electric Energy System

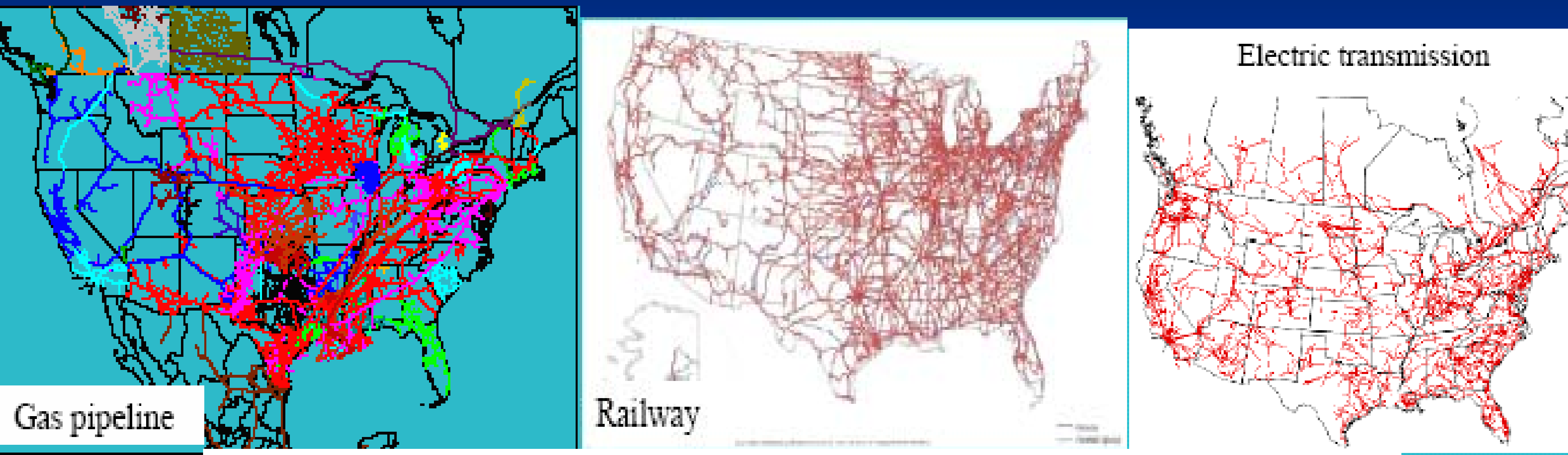
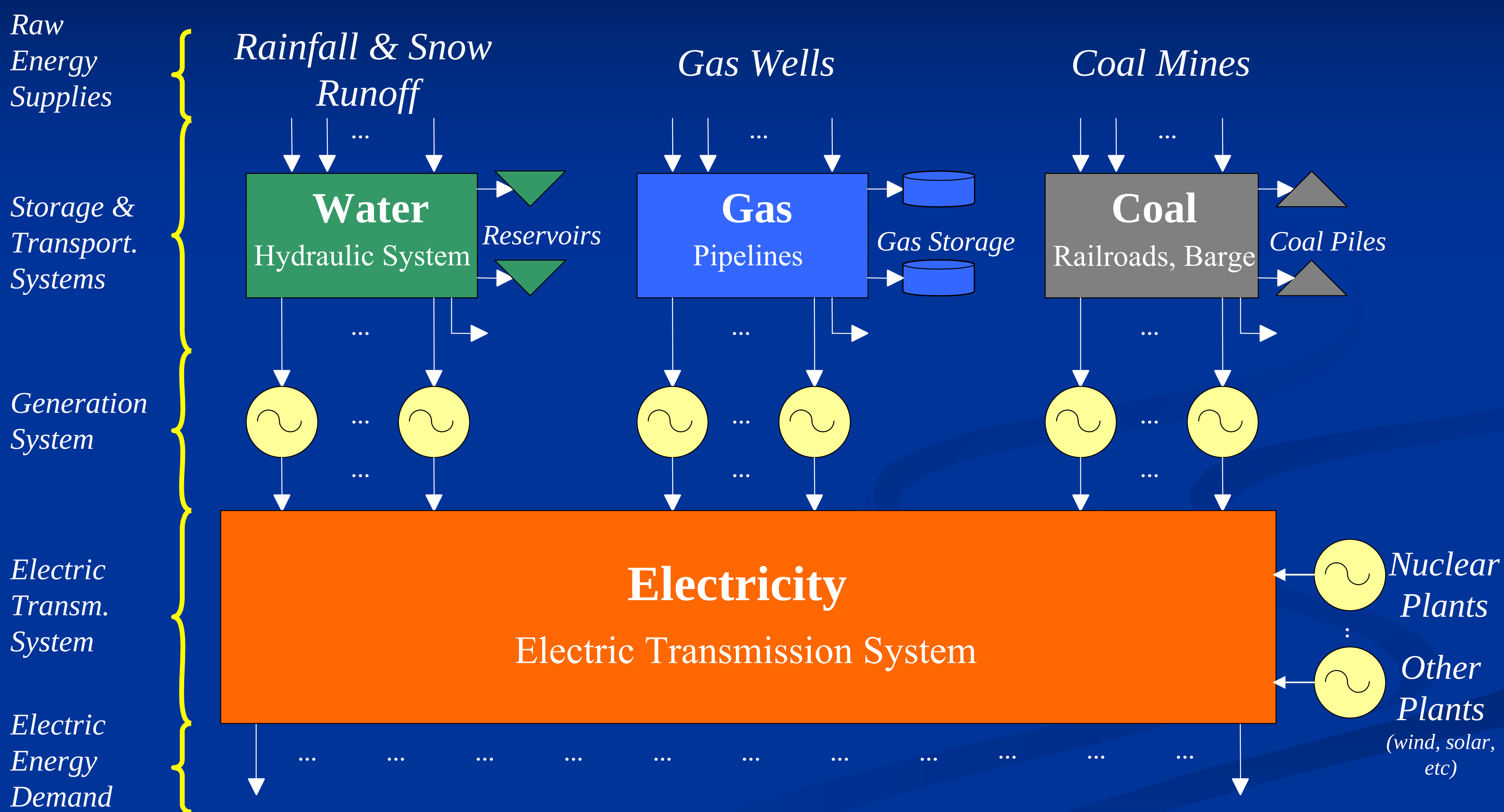


Fig. 1: Gas, Rail, and Electric Transportation Systems

The National Electric Energy System

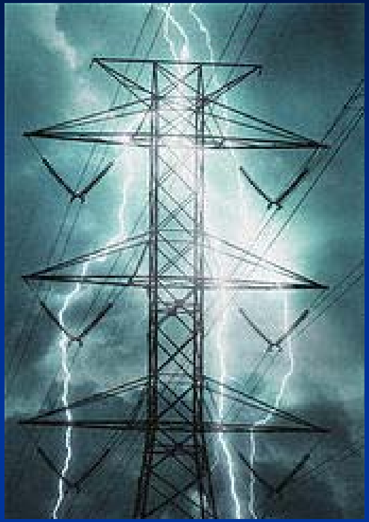
- **NEES:** integrated infrastructure associated with production, transportation, storage, end-use of four energy forms: electricity, gas, coal, and water.
- NEES integrity depends on
  - electric generation and transmission subsystems
  - ability to produce and transport the fuel
- Vulnerability to disruptions is due to natural causes, equipment failure, labor unavailability, communication failures, terrorist attacks.

The NEES



Raw Energy Supplies
Storage & Transport. Systems
Generation System
Electric Transm. System
Electric Energy Demand
Rainfall & Snow Runoff
Gas Wells
Coal Mines
Water
Hydraulic System
Reservoirs
Gas
Pipelines
Gas Storage
Coal
Railroads, Barge
Coal Piles
Electricity
Electric Transmission System
Nuclear Plants
Other Plants
(wind, solar, etc)

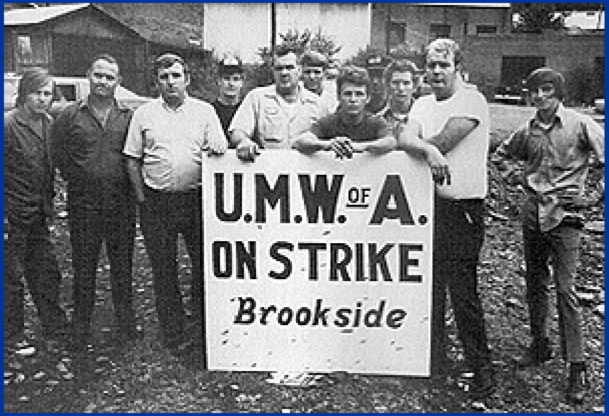
Examples of Disruptions



Lightning strike

Ellet Valley, VA, 2003: Norfolk Southern coal train derailed

El Paso, NM, 2000: Gas pipeline rupture



Labor strikes

Pekin, IL: 13 345kV transmission lines destroyed by a tornado in May 2003

Examples of Disruptions

1993 Flood Stops Barge Traffic

Black Thunder, WY, 2005: Coal train derailment

Disruption to Gulf Coast Gas Production from Katrina/Rita

Examples of Disruptions

On August 22, 2000, a 30 inch pipeline ruptured in New Mexico, and was forced out of service, taking with it two parallel lines that together form a major artery into California. This decreased availability of gas in California, significantly driving up price as seen by owners of gas-fired electricity suppliers as well as residential and commercial gas end-users. At the same time, California was experiencing a decrease in precipitation, forced outage of several large coal-fired units, and a weakened transmission system. These factors contributed to what is now well known as the California energy crisis, characterized by electricity shortages and high prices. Yet, electricity end-users were insulated from the electricity price increases because of regulatory price caps. Therefore, as gas prices rose, and electricity prices did not, many consumers quite naturally switched from gas heat to electric heat, further exacerbating the electricity shortage.

Examples of Disruptions

The 1993 Mississippi River flood caused major disruptions in the U.S. energy supply. The Mississippi River itself is a crucial part of the Midwest's economic infrastructure. Barges carry 20% of the nation's coal, a third of its petroleum, and half of its exported grain. Barge traffic was halted for two months; carriers lost an estimated $1 million per day. Some power plants along the river saw their coal stocks dwindle from a two-month supply to enough to last just for a few days.

Examples of Disruptions

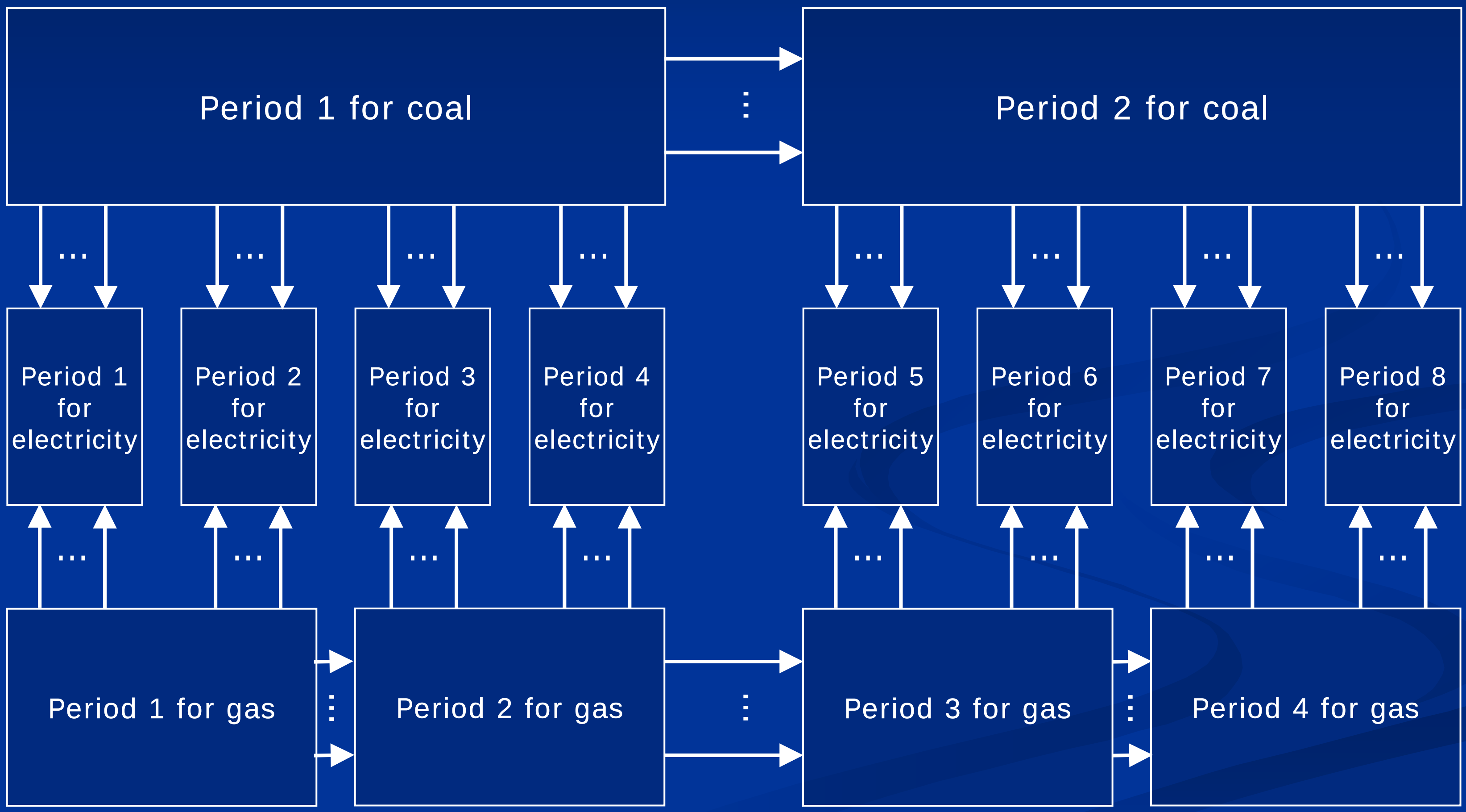
Ten giant coal mines in Wyoming 's Powder River Basin produce nearly 40% of the U.S. supply. And coal powers more than half of U.S. electricity generation. A heavy snowstorm blanketed Wyoming on May 11 2005, just as the ice in the surrounding mountains had begun to thaw. Icy water and coal dust merged into a thick, dirty slurry and oozed across a 100-mile section of railroad freight track, causing two derailments with major track damage. Spot-market prices for the basin's coal are up nearly 70% year to date. The hot summer weather left power plants with especially low stockpiles exiting the summer, so utilities may not be able to rebuild stockpiles until after next year. As a result, electric utilities have been relying more on natural gas-fired plants to satisfy demand. Then the full effects of Katrina and Rita on coal (Mississippi barge traffic) and on gas (Gulf wells) are not yet known.

How will prices and availability of electric energy evolve in the next year?

Reliability of the NEES

- Identify conditions that significantly impact price and availability of electrical energy.
- Assess the overall reliability of the energy system in order to elaborate preventive and corrective plans to avoid massive energy shortages.
- Present an network flow optimization model for reliability assessment of the NEES, where the subsystems are analyzed together in a single integrated mathematical framework for the energy production, transportation, storage, generation, and transmission.

High-level Representation



Stochastic Network Model

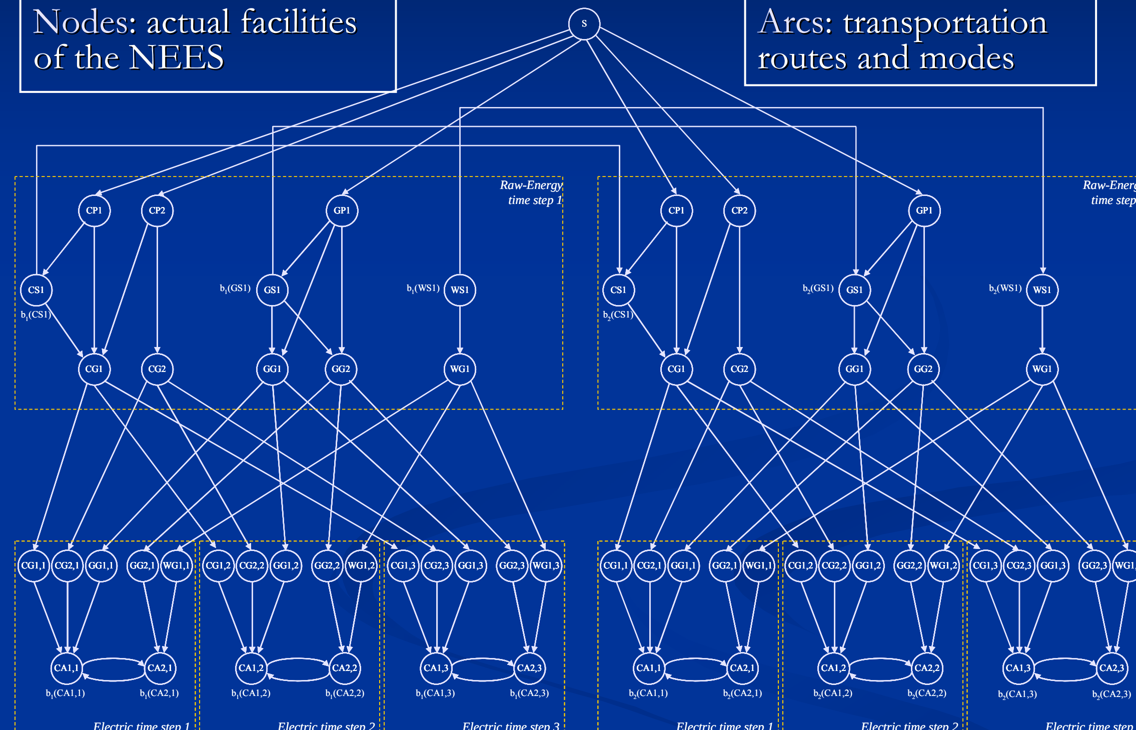
Why a Network Model?

- Energy system facilities can be represented adequately by arcs and nodes.
- A network model allows representation of capacities, costs, and efficiencies.
- Bulk energy movements can be represented as flows.
- Take advantage of fast and existent network optimization algorithms:
  - Generalized minimum cost (GMC)
  - Generalized maximum flow (GMF)

Example of network representation

Nodes: actual facilities of the NEES

Arcs: transportation routes and modes



Where is the Randomness in the Network Model?

- Capacities: uncertainty due to disruptions
- Costs/prices: market uncertainty
- Demand: end user uncertainty

Research Outline

- Build an operational model, which should integrate and assess reliability of the NEES.
- Gather & organize the necessary data of the different subsystem networks.
- Predict and represent uncertainty associated with extreme contingencies: It is necessary to build a model to represent the uncertainty associated to catastrophic events and their effects in the energy grid.
- Define plausible and credible multiple contingency scenarios, using 2 different criteria: Cascading events and common mode events.
- Evaluate the impact on the NEES of the contingency's scenarios
- Evaluate how the effects of those contingencies propagate geographically and in time.

Conclusions

- Transmission system risk assessment and related decision depends on:
  - Identification of contingencies and their probabilities
  - Rigorous analysis of contingency consequences
  - Appropriate operator decision-support tools for both preventive and corrective control
  - Long-term implementation of strategic resource allocation for maintenance
  - Risk-informed decisions in facility investment
- Delivering reliable and economic electric energy also depends on understanding the entire, integrated energy system from fuel source to electric distribution substation.