Coordinated Attacks against Substations and Transmission Lines in Power Grids

Yihai Zhu, Jun Yan, Yufei Tang, Yan (Lindsay) Sun, Haibo He

Presenter: Yihai Zhu, Ph.D.

University of Rhode Island

Email: yhzhu@ele.uri.edu

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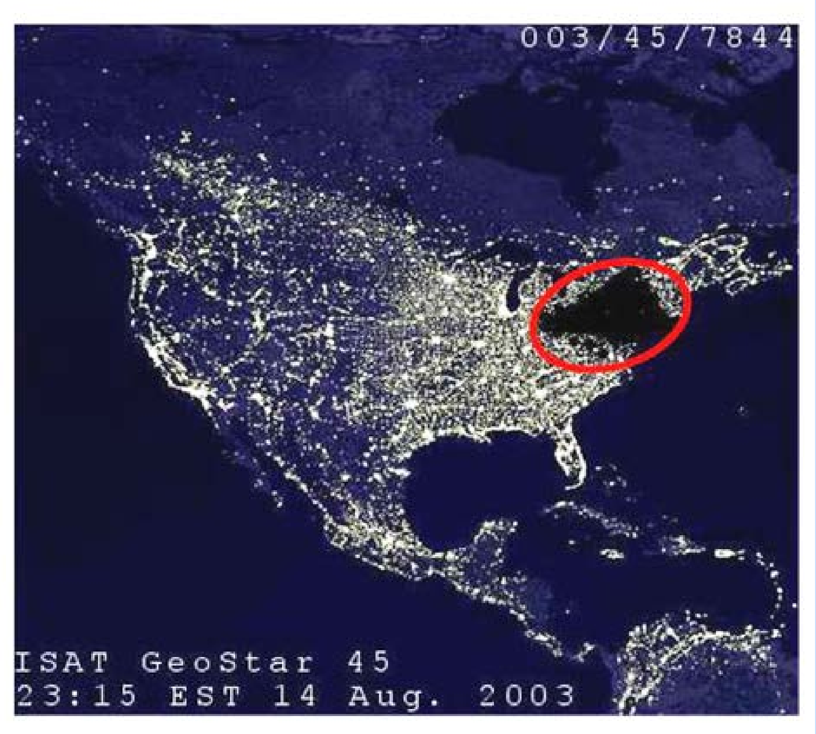
Massive Blackouts

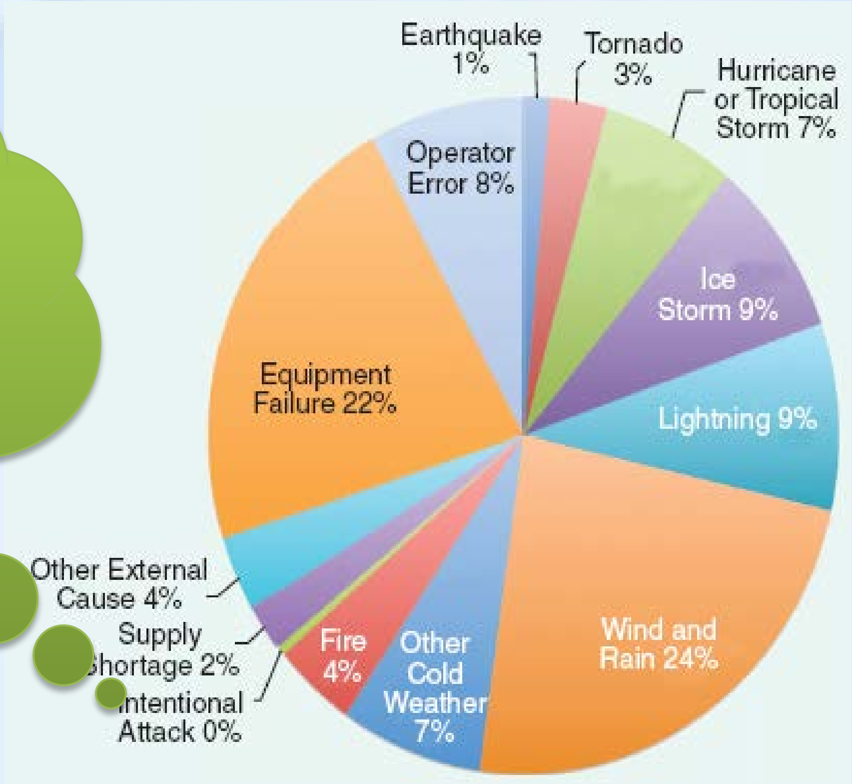
- **Power Grids**
  - Critical infrastructures
  - Experiences of power outages
- **Massive Blackouts**
  - Large-scale power outage
  - Affecting millions of people
  - Tremendous economic loss
- **Northeast Blackout in 2003** [1]
  - 50 million people
  - 10 billion U.S. dollar



The 2003 Northeast Blackout as a seen from space (NASA provided)

Reasons of Power Outages

Attacks



Exterior reasons of blackouts affecting at least 50,000 customers between 1984 and 2006. Data from NERC records. [2]

Media Report

- **Truthstream Media** (August 30, 2013) [3]

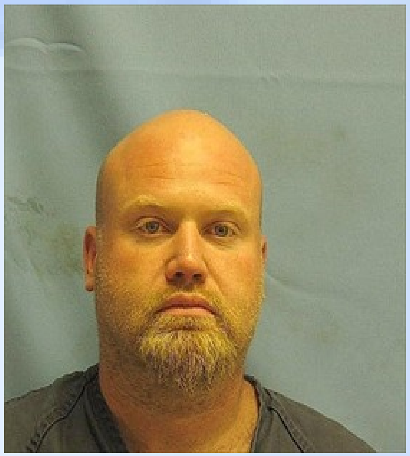
  "The former DHS chief Janet Napolitano says: Cyber Attack Will Bring Down Power Grid: 'When Not If' "

- **The Wall Street Journal** (February 5, 2014) [4]

  "Assault on California Power Station Raises Alarm on Potential for Terrorism"

Two Real-life Cases

- **Case I: The attack from an individual** [5]
  - On Oct. 6, 2013, a man attacked a high-voltage transmission line near Cabot, Arkansas, USA.
  - 10,000 customers lost power.



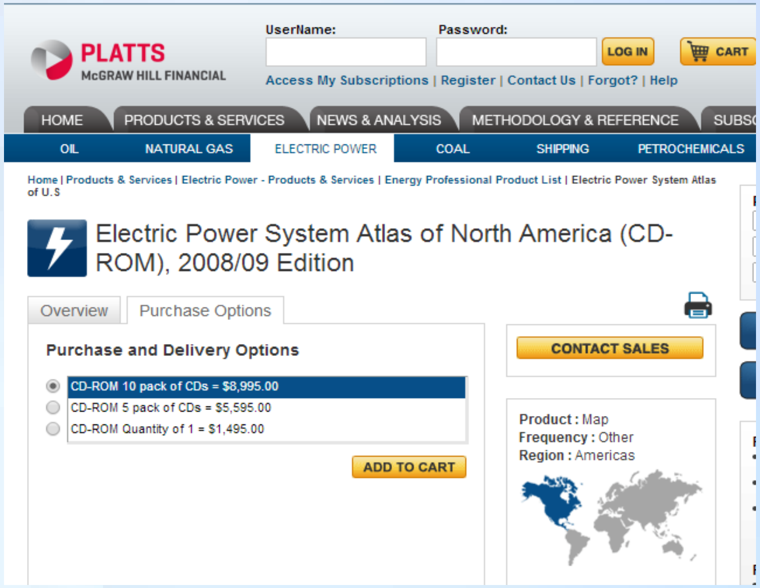
Jason Woodring

- **Case II: The attack from a team** [6]
  - On Apr. 16, 2013, a team of armed people shot on a substation near San Jose, California, USA.
  - 17 giant transformers were knocked out, and this substation was closed for a month.
- **Case III: Simulated Cyber attacks** [7]
  - Aurora Generator Test in 2007: A diesel-electric generator is destroyed.

Power Grid Information Collection

- **Ways of Information Collection**
  - Online tools
  - Purchasing the grid's information
  - Hacking or spying
- **Online tools are useful to collect the topological information.**
  - Google Maps
  - Online websites
    - Topology of the high-voltage transmission lines in U.S.

Substation from Google Map



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Outline

- Background
- Related Work
- Joint substation-transmission line Attack
  - Motivation & Challenge
  - Cascading Failure Simulator
  - Vulnerability Analysis
  - Metric Study
- Summary & Future Work

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Related Work

Vulnerability Analysis of Power Grids

Cascading Failure Models[10,11,12]

Contingency Analysis[12]

Cyber Vulnerability Analysis[16]

Defense Analysis[17]

Attack Analysis:

- Substation-only attack [13,14]
- Transmission-line only attack [15]
- Joint substation-transmission line attack

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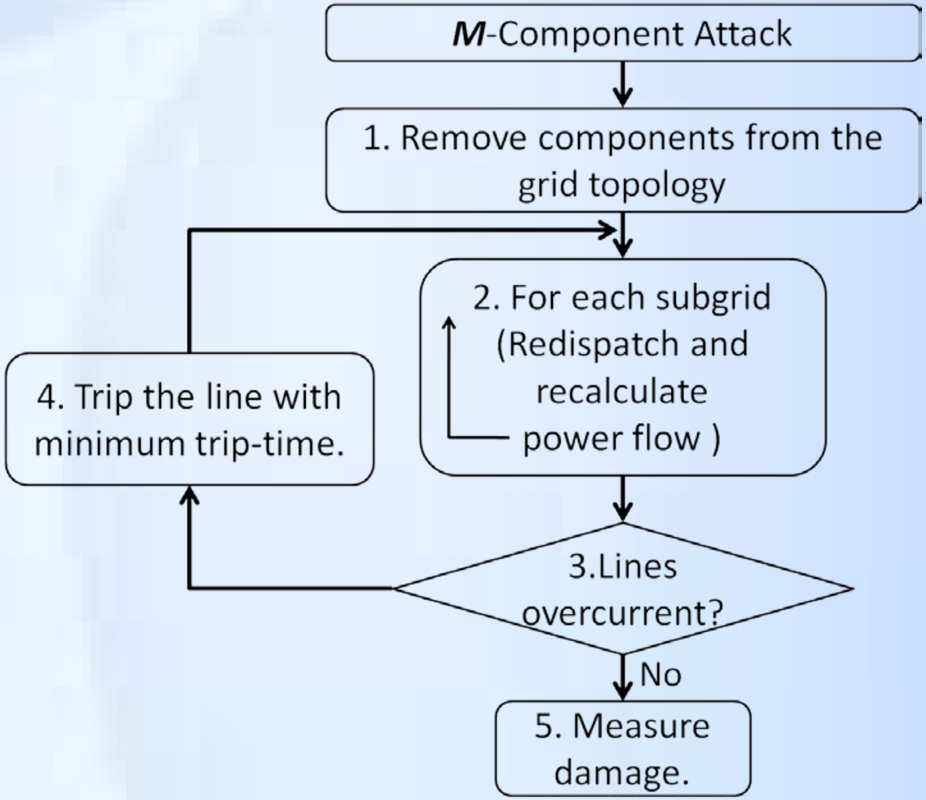
Joint substation-transmission line Attack

- **Motivation**
  - The attackers are able to launch multiple-target attacks against both substations and lines.
  - Provide a new angle to conduct the vulnerability analysis of power transmission systems.
- **Challenges**
  - Model development
  - Conducting vulnerability analysis
  - Studying metrics to find strong joint substation-transmission line attacks

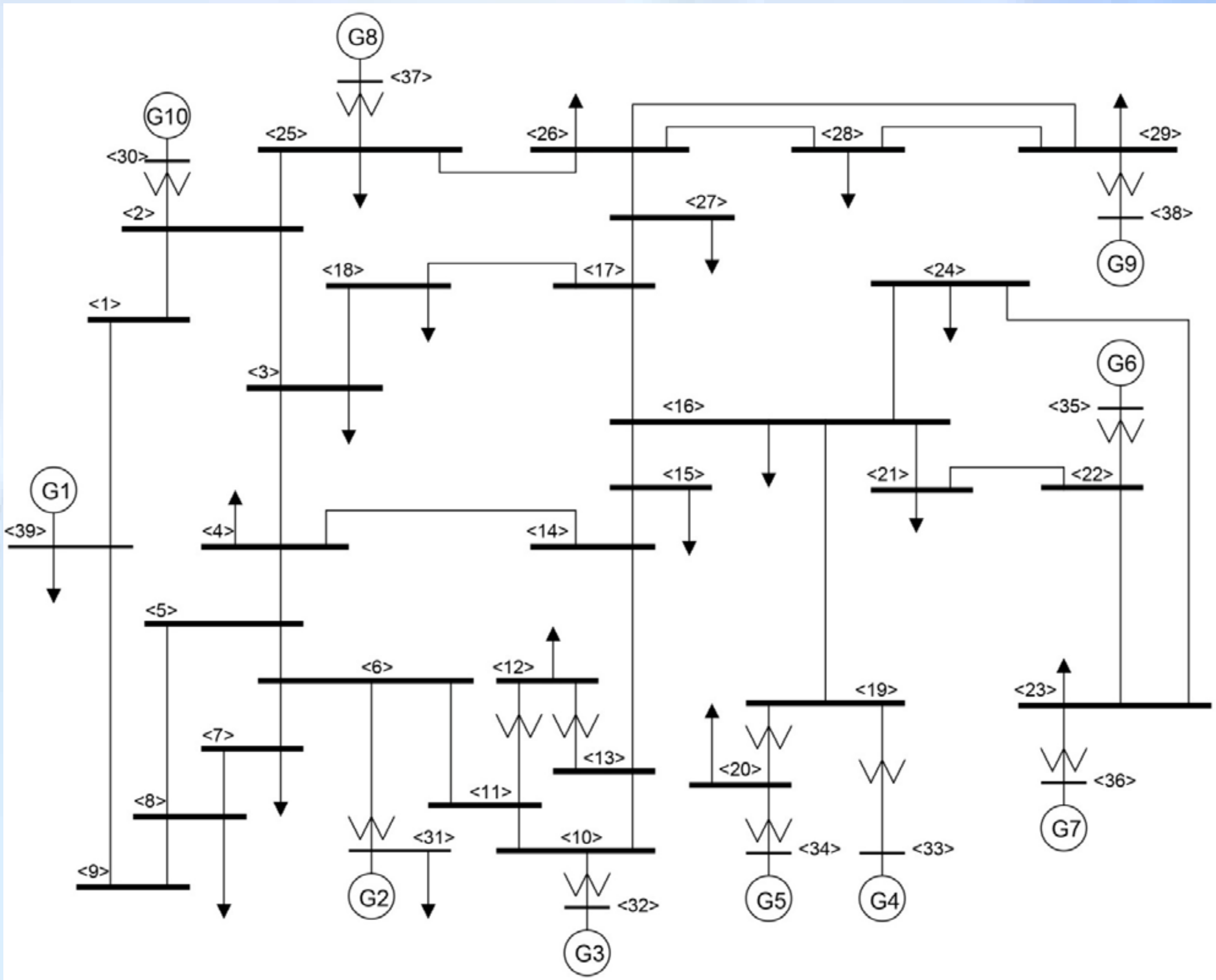
Cascading Failure Simulator

- **DC power-flow model** [14]
- **Five steps**
  - Step 1: Conduct *M*-component attacks.
  - Step 2: Build subgrids, and redispatch power and recalculate power flows.
  - Step 3: Check overloading lines. If NO, goes to Step 5.
  - Step 4: Trip the line with minimum trip-time, and goes to Step 2.
  - Step 5: Evaluate the damage.
- **Assessment measure**
  - Blackout size (***B***): total power loss, normalized to 0 ~ 100% .



Flowchart of cascading failure simulator (CFS)

Test benchmark: IEEE 39 Bus System



< #>: Substation Index (G#): Generator Index ↓ : Demand Substation

39 substations (10 generators and 21 demand substations), and 46 transmission lines

Vulnerability Analysis

❖ Concepts

- Power grid → Network (Substation → node; line → link)
- A *M-component combination* consists of *M* network components (nodes, links, or both).
  - Node-only combination: *M* nodes
  - Link-only combination: *M* links
  - Joint-node-link combination: *M* components, but at least one node and one link
- For one *M-component combination* → Blackout size (***B***).

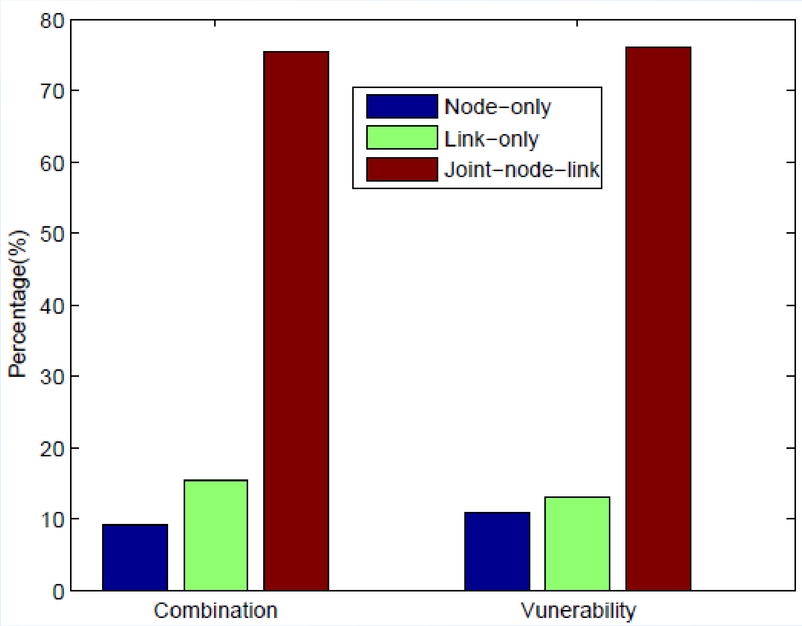
  B value is called the strength of this combination attack.
- Vulnerability: the combination that can yield large attack strength. In particular, $B \geq \eta$ (eta is the threshold.)
- Three types of vulnerability: Node-only vulnerabilities, Link-only vulnerabilities, Joint-node-link vulnerabilities

❖ Demonstration of Vulnerabilities

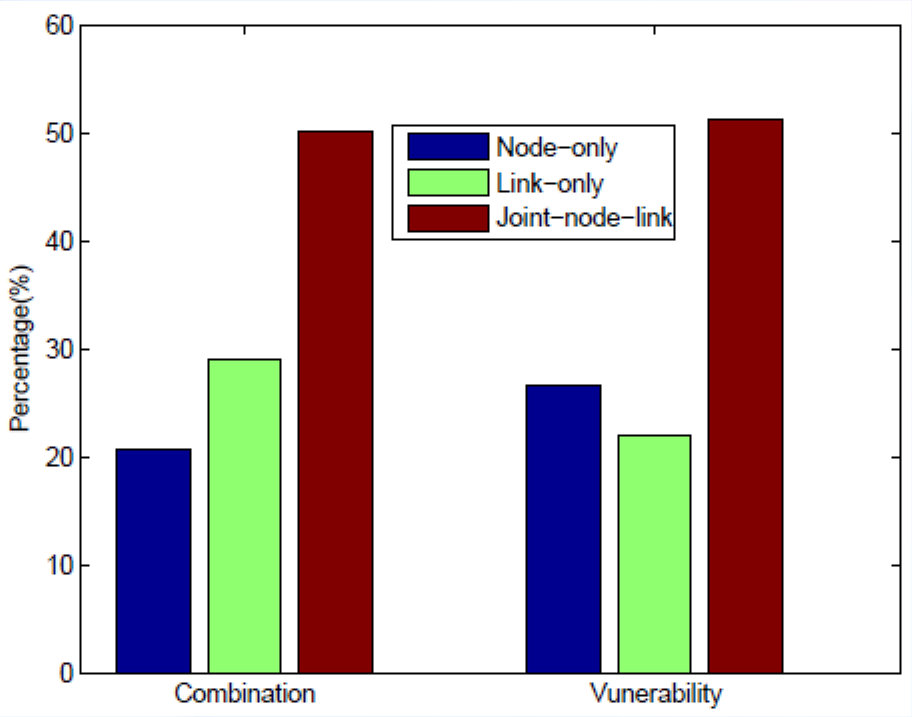
- IEEE 39 bus system(39 nodes & 46 links→ 85 components)
- Let *M = 3,*
  - Node-only combinations: $\binom{39}{3} = 9{,}139$
  - Link-only combinations: $\binom{46}{3} = 15{,}180$
  - Joint-node-link combinations:

$$\binom{85}{3} - \binom{39}{3} - \binom{46}{3} = 74{,}451$$

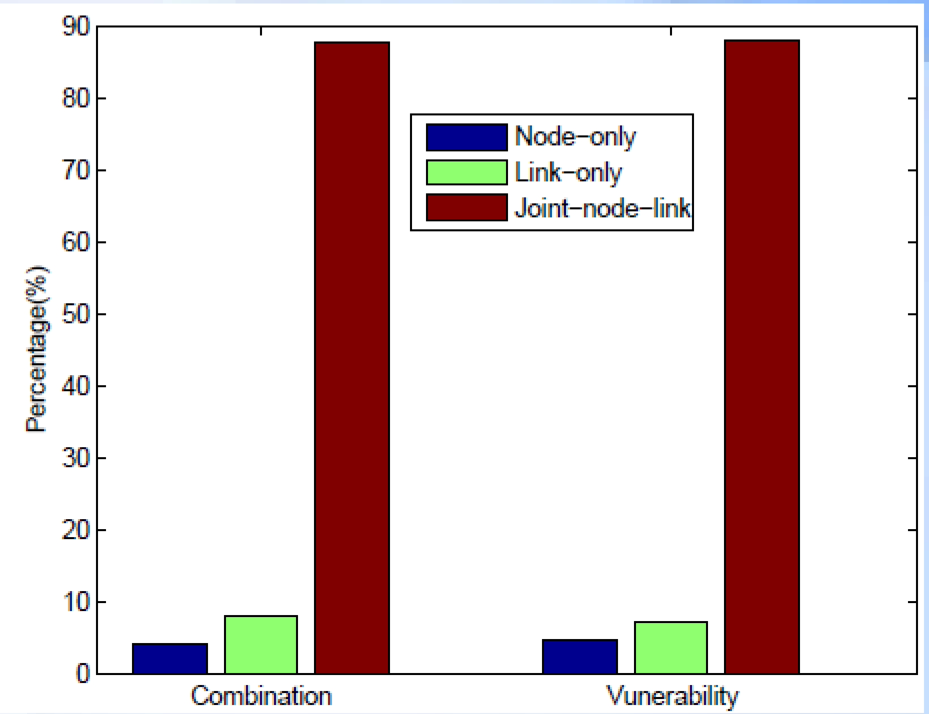
- Use CFS to obtain attack strength (***B***) for each combination and set eta to be 0.2 (20% of power loss)
  - Node-only vulnerabilities: 7,406 (10.96%)
  - Link-only vulnerabilities: 8,780 (12.98%)
  - Joint-node-link vulnerabilities : 51,416 (76.06%)



Percentage comparison regarding *three-component* combinations and vulnerabilities



Percentage comparison regarding *two-component* combinations and vulnerabilities



Percentage comparison regarding *four-component* combinations and vulnerabilities

❖ Observation

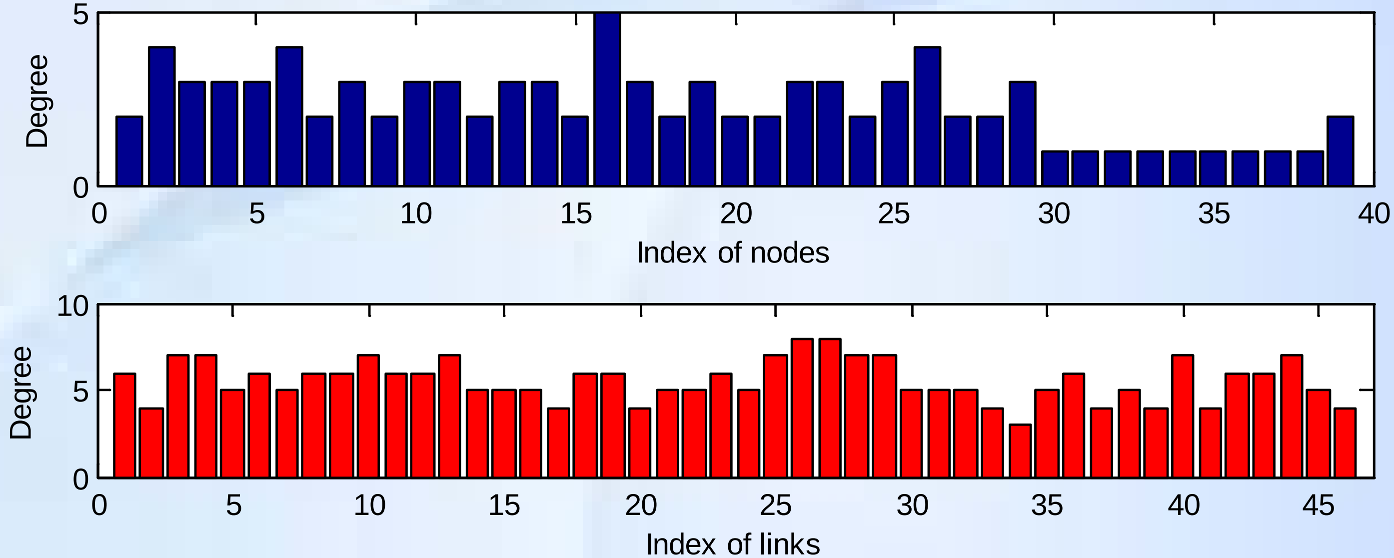
- Joint-node-link vulnerabilities take the largest portion of all vulnerabilities and are critical to the power grid.
- As M increases, Joint-node-link vulnerabilities increase sharply and provide more chances to find strong attacks.

Metric Study

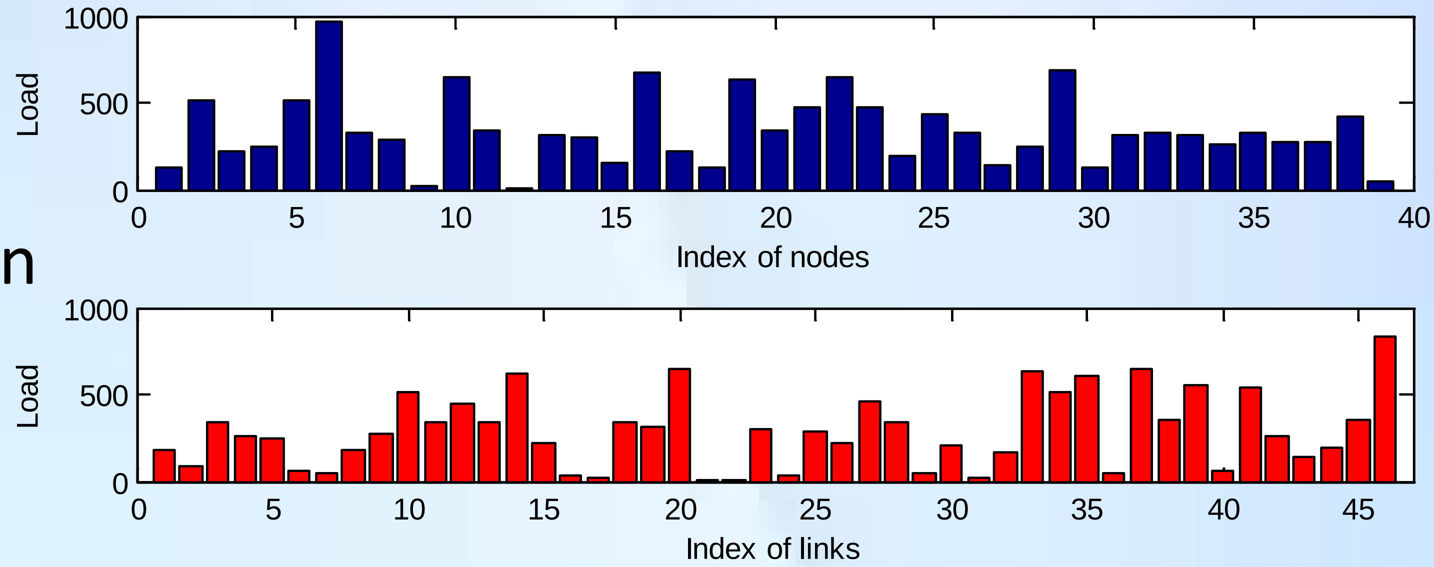
- **Goal**
  - Study existing metrics to identify strong Joint-node-link targeted attack strategies.
- **Two existing metrics**
  - ***Metric 1***: Degree
    - *Degree of a node*: the number of links connecting to this node
    - *Degree of a link* : the summation of two nodes' degree. These two nodes are connected by this link.
  - ***Metric 2***: Load:
    - *Load of a link*: the power flow goes through this link.
    - *Load of a node*: the summation of all power flows going through the links connecting to this node.

Distribution of Degree and Load on IEEE 39 Bus System

Degree distribution



Load distribution



Metric Study

❖ Degree-based Attack Strategies

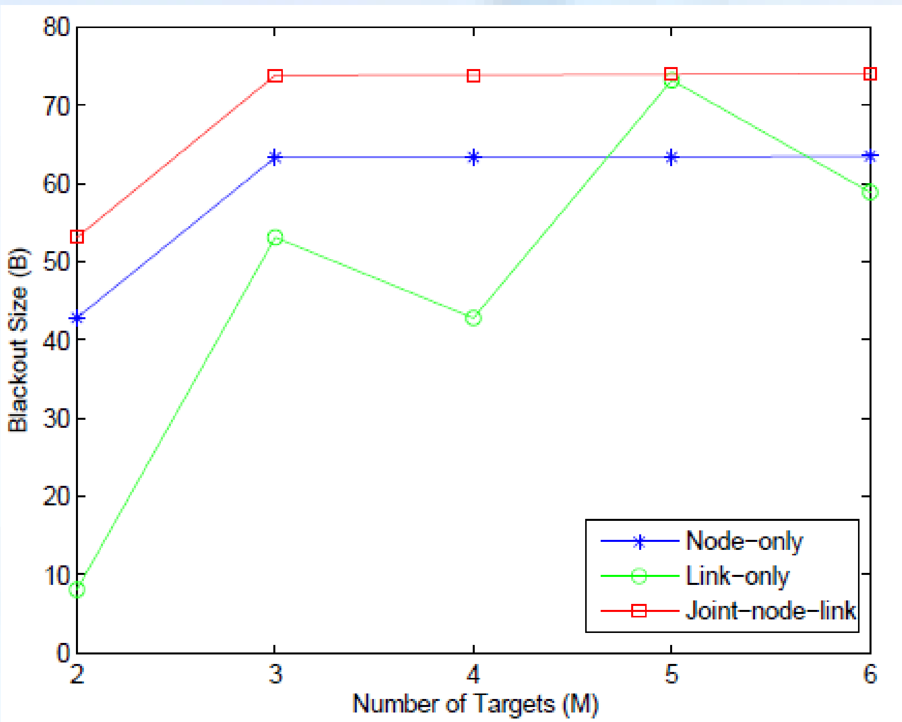
- ***Degree-based node-only attack strategy***: Sort all nodes descendingly according to *nodes' degrees*, and select first *M* nodes as targets.
- ***Degree-based link-only attack strategy***: Sort all links descendingly according to *links' degrees*, and select first *M* links as targets.
- ***Degree-based Joint-node-link attack strategy***:
  - Select *M* nodes and *M* links together as candidate targets based on *degree* values.
  - Among these *2M* candidate targets, generate all *M*-target combinations, which are in total $\binom{2M}{M}$. There are $\binom{2M}{M}-2$ joint-node-link combinations.
  - Conduct simulations for these joint-node-link combinations and find the combination with the largest ***B*** value (attack strength). The components in this combination are the chosen targets for this attack strategy.

❖ Load-based Attack Strategies

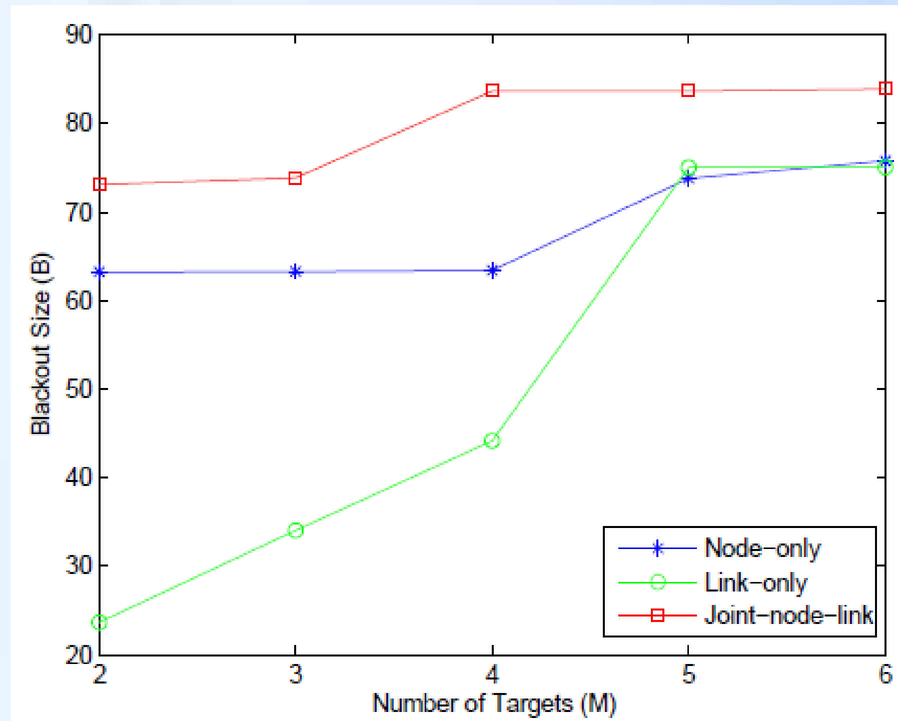
- Three attack strategies are conducted similarly, except replacing *degree* by *load*.

Simulation Results

- Set up
  - Test benchmark : IEEE 39 bus system
  - *M* is set to be 2, 3, 4, 5 and 6.



Comparison among *degree*-based attack strategies



Comparison among *load*-based attack strategies

Comparison between two joint-node-link attack strategies

Metric	Measured by B				
	$M=2$	$M=3$	$M=4$	$M=5$	$M=6$
Degree	53.15	**73.86**	73.89	73.98	74.1
Load	**73.08**	**73.86**	**83.64**	**83.64**	**83.87**

Comparison of the search space between different schemes

Attack Strategy	$M=2$	$M=3$	$M=4$	$M=5$	$M=6$
Node-only	0	0	0	0	0
Link-only	0	0	0	0	0
Joint-node-link $\binom{2M}{M}-2$	4	18	68	250	922

❖ Observation

- Joint-node-link attack strategy can obtain better performances.
- Metric *load* is more insightful than metric *degree*.
- As M increases, the complexity of the joint-node-link attack strategy will sharply increase.

Summary & Future Work

❖Summary

- Propose the joint-substation-transmission-line perspective to study power grid vulnerability.
- Discover many joint-node-link vulnerabilities.
- Adopt two existing metrics, degree and load, to study joint-node-link attack strategies.

❖Future Work

- Design new metrics to study joint- joint-node-link attack strategies → low complexity

  Yihai Zhu, Jun Yan, Yufei Tang, Yan Sun, Haibo He, "*Joint Substation-Transmission line Vulnerability Assessment against the Smart Grid*", IEEE Transactions on Information Forensics and Security (T-IFS), 2014, Accept with minor revision.

- Defense of targeted attacks against power girds.

Reference

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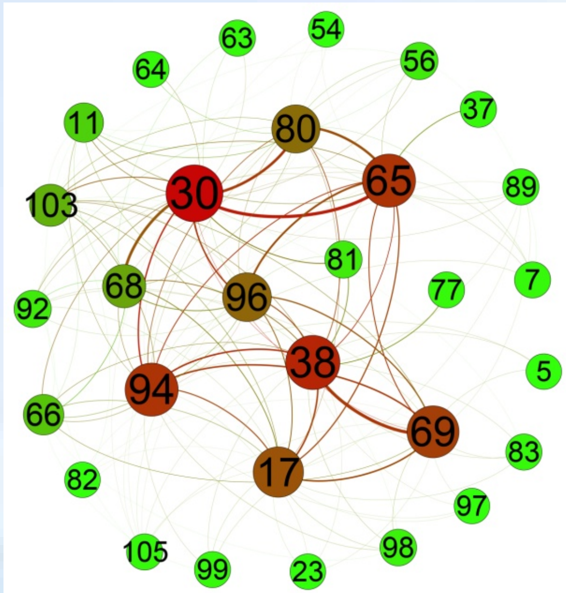
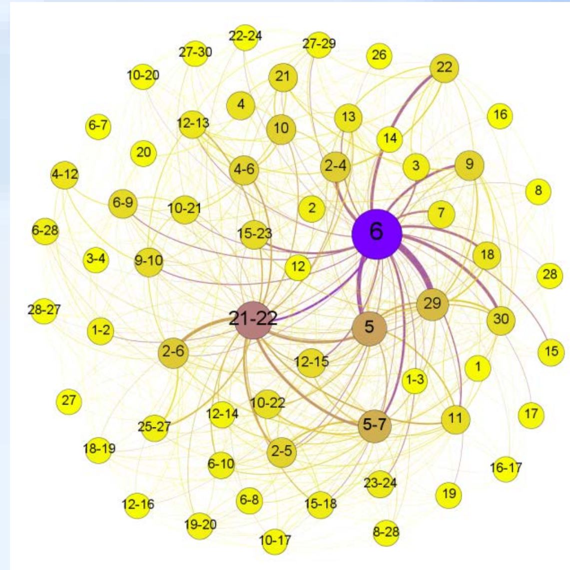
Advertising Time

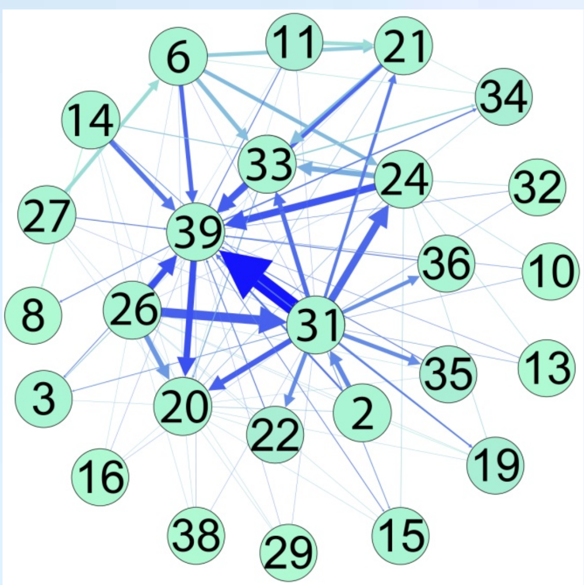
Risk Graph

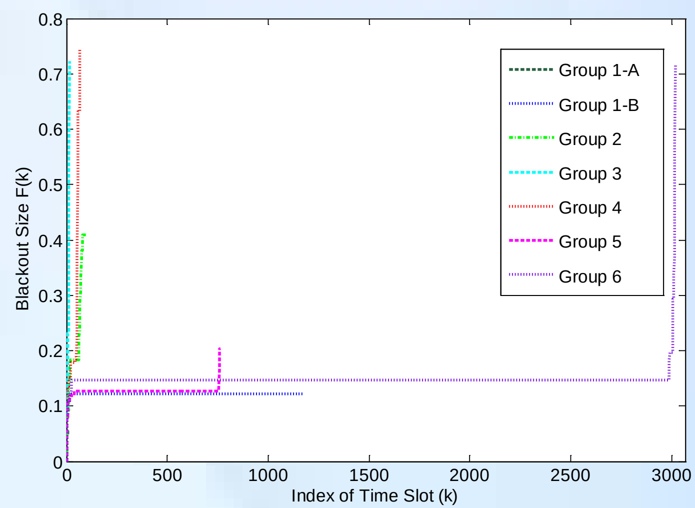




Component Interdependency Graph

Sequential Attack Graph





Diversity of Cascading Processes

Thanks
Any Questions?

Take my business card

or

Email: yhzhu@ele.uri.edu
Web: www.ele.uri.edu/~yhzhu

Models of Cascading Failures

CASCADE mode	• Topology	• Identical components • Randomly choosing load values between a range • Overloading when the load exceeds a threshold.
Wang-Rong model	• Topology	• Identical components • Using the degree to calculate load • Overloading when the load exceeds the capacity. • The capacity is proportional to the initial load.
Motter-Lai model	• Topology	• Identical components • Calculating the betweenness as the load • Overloading when the load exceeds the capacity • The capacity is proportional to the initial load.
Betweenness model	• Topology	• Identical components • Calculating betweenness to calculate the load • Overloading when the load exceeds a threshold.
Efficiency model	• Topology • Substation type	• Calculating the betweenness as the load. • Overloading components can be recovered. • Network efficiency
Extended model	• Topology • Substation type • Line impedance	• Calculating the extended betweenness as the load, based on PTDFs. • Overloading when the load exceeds the capacity. • Net-ability

Hines model	• Topology • Substation type • Line impedance • DC power flows	• Calculating DC power flows • Generation dispatch and load shedding • Trip lines due to overheat. • Blackout Size
OPA model	• Topology • Substation type • Line impedance • DC power flows • Probability of line failure	• Calculating DC power flows • Generation dispatch and load shedding • Trip lines with probability. • Both fast and slow dynamics
Hidden failure model	• Topology • Substation type • Line impedance • DC power flows • Probability of line failure	• Calculating DC power flows • Generation dispatch and load shedding • Trip lines with probability. • Hidden failures
Manchester model	• Topology • Substation type • Line impedance • AC power flows	• Calculating AC power flows • Tripping lines • System convergence • Fast dynamics

Attackers and Means of Attacks

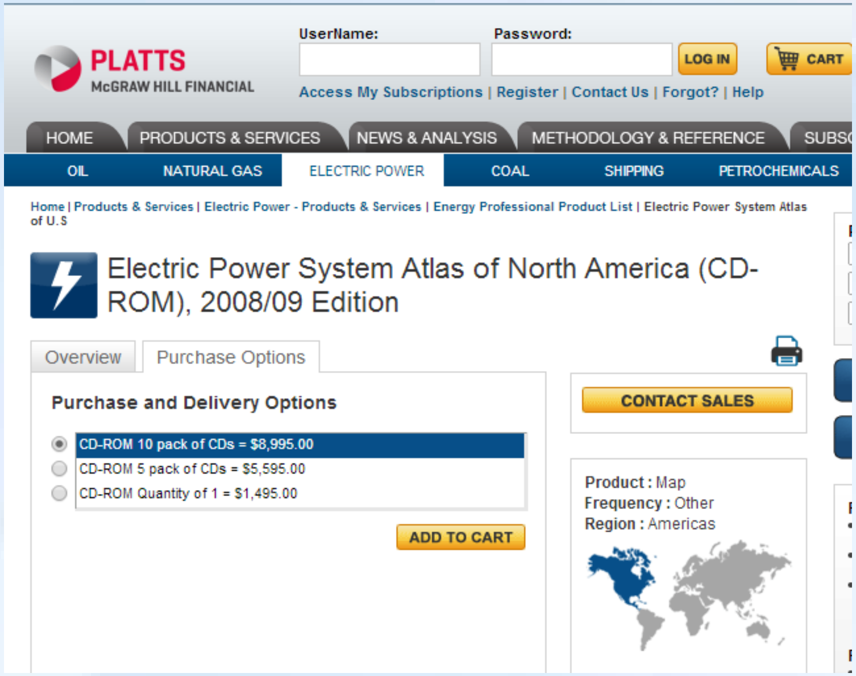
- **Attackers**
  - Disgruntled individuals
  - Terrorist teams
  - Computer hackers
  - Energy companies
  - Hostile Countries
- **Attacker can be from inside and outside.**
- **Attackers can well organize the attacks, aiming to cause large damage.**

- **Means of Attacks**
  - Physical sabotages
    - Failing down poles that support high-voltage transmission lines.
    - Cutting a tree to fail a line
    - Fire on substations
    - Air force attacks
    - EMP attacks
    - Etc.
  - Cyber intrusions
    - Cyber attacks
    - Cyber worms
    - Etc.

Cyber Attacks

- **Simulated Cyber Attack**
  - Name: *Aurora Generator Test*
  - Participants : Idaho National Laboratories (INL) and Department of Homeland Security, USA
  - Time: 2007
  - Object: A large diesel-electric generator
  - Procedure: Researchers sent malicious commands to force the generator overheat and shut down.
  - Results: the generator was completely destroyed.
  - Effects: Cyber vulnerabilities of many generators that are currently in use in USA.

Commercially Available



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FID	Shape	CHARID	NAME	COMPANY	COMPID	MAXKV	CIRCUITS	POS_REL	SUBID	ASTATUS
0	Point	3337420229	Pajaro Valley	Unknown	-99	0	0	Not verified to be within 1 mile	3337420229	-1
1	Point	3337432042	Watsonville	Pacific Gas and Electric Co.	100540	69	3	Within 40 feet	3337432042	9
2	Point	3337432043	Watsonville Cogeneration Partn	Unknown	-99	69	0	Not verified to be within 1 mile	3337432043	-1
3	Point	3337408226	Buena Vista Landfill	Unknown	-99	0	0	Not verified to be within 1 mile	3337408226	-1
4	Point	3365669834	Buena Vista Landfill		-99	0	0	Not verified to be within 1 mile	3365669834	-1
5	Point	3341135614	Tap	Pacific Gas and Electric Co.	100540	69	3	Within 1 mile	3341135614	8
6	Point	3341135615	Erta	Pacific Gas and Electric Co.	100540	69	1	Within 1 mile	3341135615	8
7	Point	3337413924	Green Valley	Pacific Gas and Electric Co.	100540	115	7	Within 40 feet	3337413924	8
8	Point	3337426023	Tap	Pacific Gas and Electric Co.	100540	115	3	Within 40 feet	3337426023	8
9	Point	3337422061	Rob Roy	Pacific Gas and Electric Co.	100540	115	1	Within 40 feet	3337422061	8
10	Point	3337420437	Paul Sweet	Pacific Gas and Electric Co.	100540	115	2	Within 165 feet	3337420437	8
11	Point	3337429483	UC Santa Cruz Cogeneration	Unknown	-99	0	0	Not verified to be within 1 mile	3337429483	-1
12	Point	3360294987	Unknown		-99	-99	1	Within 40 feet	3360294987	7
13	Point	3337413473	Gilroy (CPN)	Pacific Gas and Electric Co.	100540	115	3	Within 40 feet	3337413473	9
14	Point	3337413474	Gilroy Energy Co.	Pacific Gas and Electric Co.	100540	10	1	Within 40 feet	3337413474	-1
15	Point	3337416916	Llagas	Pacific Gas and Electric Co.	100540	115	3	Within 1 mile	3337416916	8
16	Point	3337426018	Tap	Pacific Gas and Electric Co.	100540	115	3	Within 40 feet	3337426018	8
17	Point	3337426019	Tap	Pacific Gas and Electric Co.	100540	115	3	Within 165 feet	3337426019	8
18	Point	3341135624	Lone Star		-99	69	1	Within 40 feet	3341135624	8
19	Point	3341135625	Tap	Pacific Gas and Electric Co.	100540	69	3	Within 40 feet	3341135625	8
20	Point	3337408555	Camp Evers	Pacific Gas and Electric Co.	100540	115	2	Within 1 mile	3337408555	8
21	Point	3341135626	Crusher	Pacific Gas and Electric Co.	100540	69	1	Within 1 mile	3341135626	8
22	Point	3341135627	Pt. Moretti	Pacific Gas and Electric Co.	100540	69	1	Within 1 mile	3341135627	8

GIS raw data

Bay Area power grid