ECEN 615
Methods of Electric Power Systems Analysis

Lecture 27: Power System Restoration and Visualization

Prof. Tom Overbye
Dept. of Electrical and Computer Engineering
Texas A&M University
overbye@tamu.edu

TEXAS A&M UNIVERSITY

Announcements

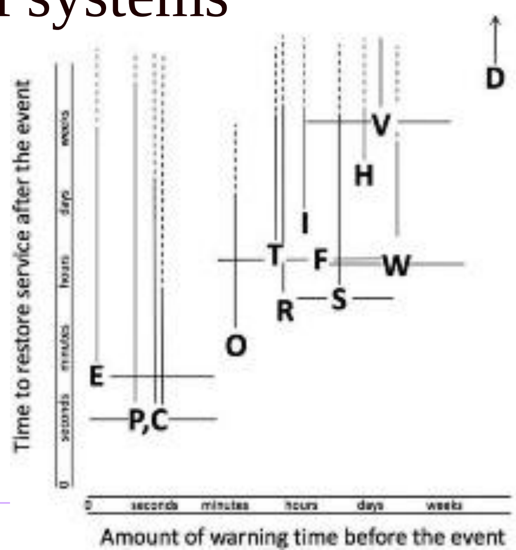
- Final exam is Wednesday Dec 12, 1 to 3pm
  - Closed book, closed notes. Two 8.5 by 11 inch notesheets allowed; calculators allowed

Where We've Come

Course Syllabus	Approx. # of hours
Introduction to Power Systems	4
Overview of Power System Modeling and Operation	4
Power Flow	6
Sparse Matrices in Power System Analysis	6
Sensitivity Analysis and Equivalents	6
Power System Data Analytics and Visualization	3
Optimal Power Flow and Power Markets	6
Power System State Estimation	5
Blackstart Analysis	3
Total	43

Blackout in Power Systems

- Blackout
  - Loss of the electricity supply to a part/whole of the power system
- What causes blackouts
  - Disasters such as Earthquake or Tsunamis
  - Overloading/damage of transmission lines
  - Failure of protection/control systems
  - Severe weather events
  - Physical/cyber attacks
  - Operation errors
  - Combination of above

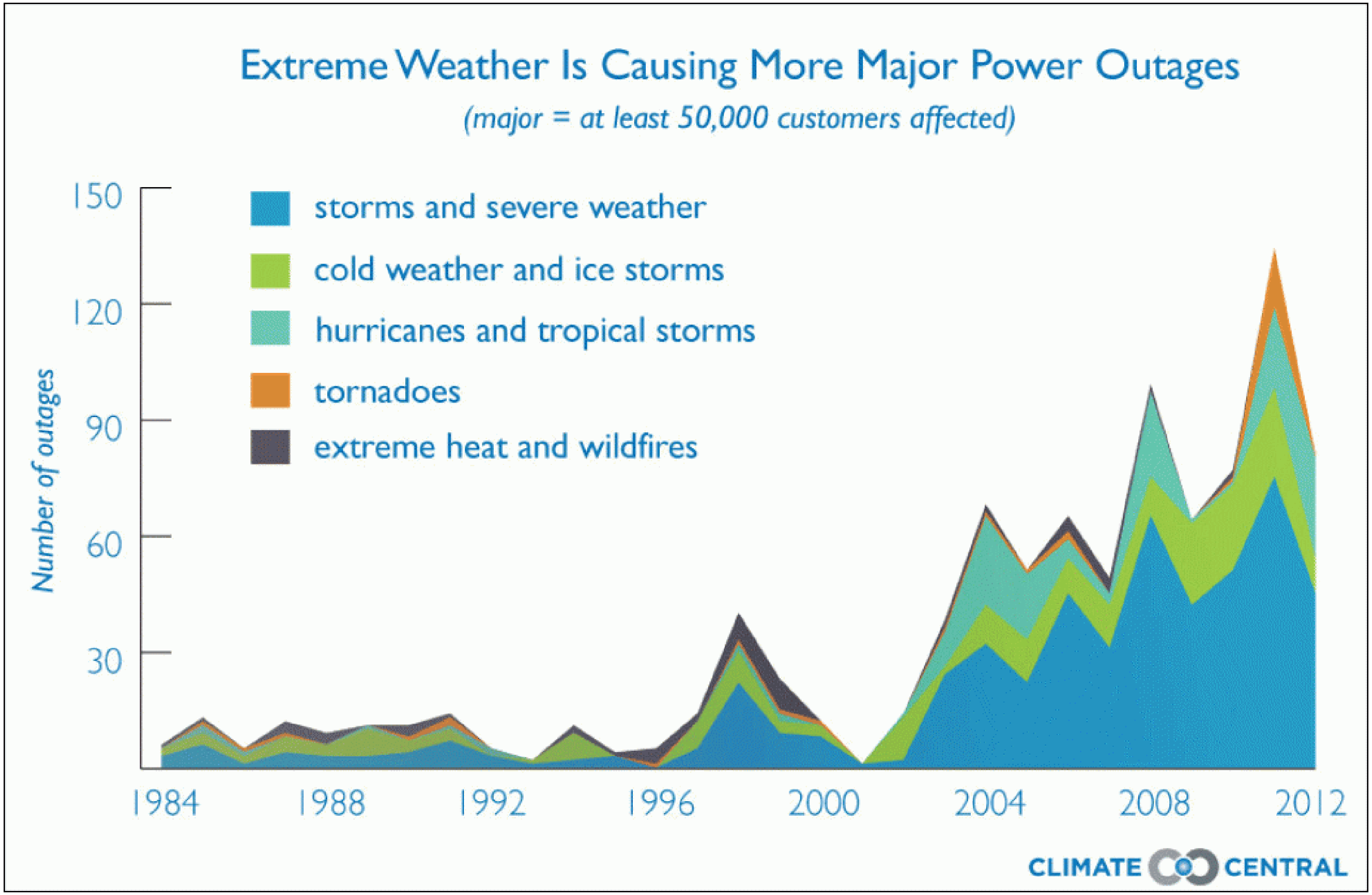


C = cyber attack (ranging from state/pro on left to good hacker on right)
D = drought and associated water shortage
E = earthquake (in some cases with warning systems)
F = flood/storm surge
H = hurricane
I = ice storm
O= major operations error
P = physical attack
R = regional storms and tornadoes
S = space weather
T = tsunami
V = volcanic events
W= wildfire

Source: nap.edu

Blackout in Power Systems

- Weather-related Blackouts Doubled Since 2003



Source: climatecentral.org

Blackout in Power Systems

- Impact of blackouts
  - Economic losses
    - Power system equipment damage
    - Money system fails
    - Factories shut down
    - Transportation system stops
  - Limited basic activities
    - Food distribution systems cease
    - Difficult to cook
    - Lack of municipal water
    - No heating/cooling
  - Social chaos and violence
  - Etc.

Blackout in Power Systems

- 7 major disturbances in US in the order of impact

Year	Location	Load	Customers	Duration	Scale
		P (GW)	C (Million)	T (Hour)	$R = \log(P \cdot C \cdot T)$
2003 Aug.	North East and Ontario	62	50	48	5.17
1965 Nov.	North East	20	30	13	3.89
1977 Jul.	New York City	6	9	26	3.15
1982 Dec.	West Coast	12.4	5	18	3.05
1996 Jul.	West Coast	11.9	2	36	2.93
1996 Aug.	West Coast	28	7.5	9	2.93
1998 Jun.	North Central and Ontario	0.95	0.15	19	0.44

Source: 2003 US-Canada Blackout Report

2003 Aug. Blackout


SPECIAL ★ ★ ★ ★ EDITION

DAILY NEWS

50¢ www.nydailynews.com NEW YORK'S HOMETOWN NEWSPAPER Friday, August 15, 2003

SUSANA BATES

BLACKOUT

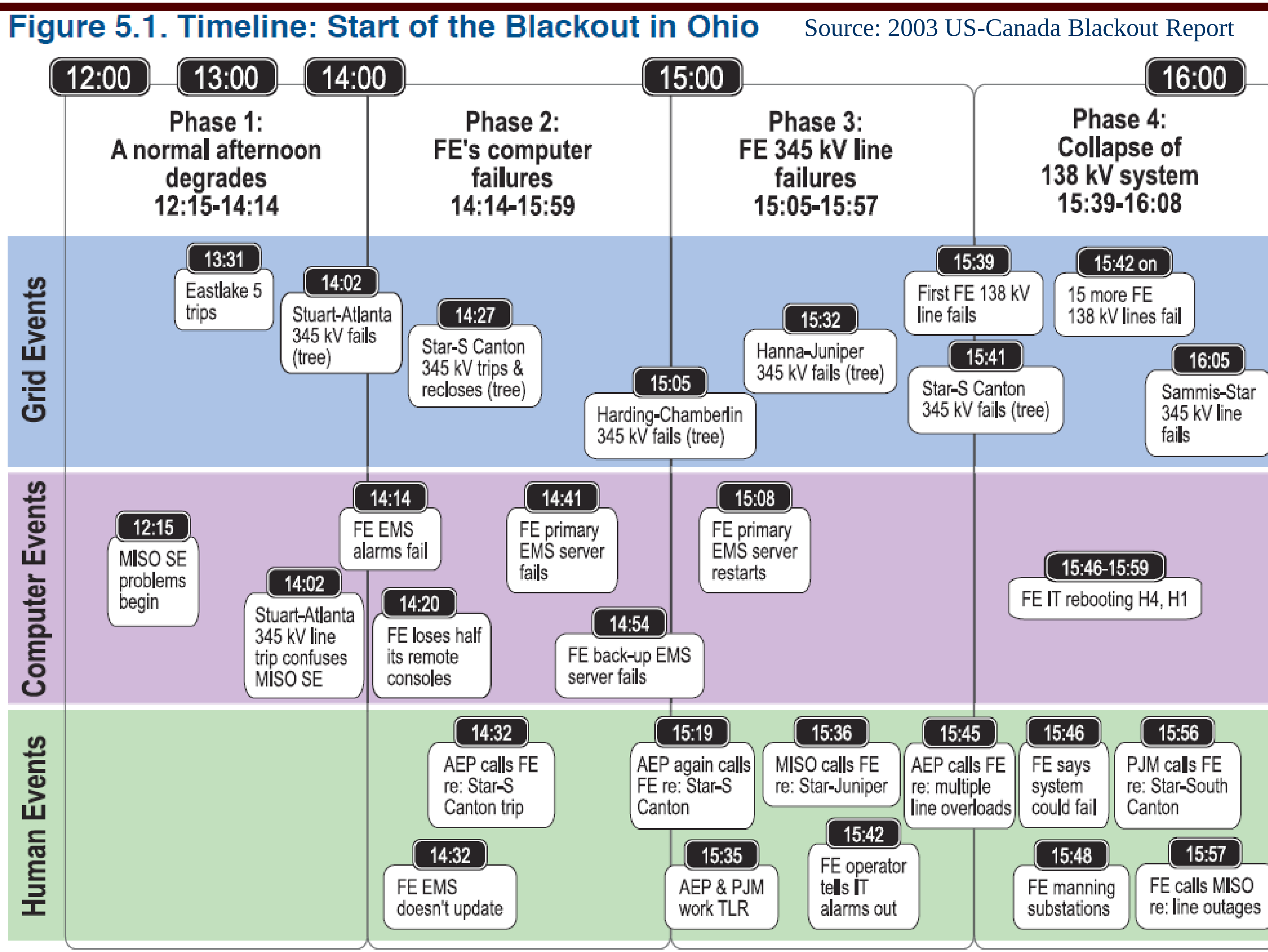
- 50 MILLION LOSE POWER
- CITY SWELTERS TO A HALT
- RUSH-HOUR CHAOS TODAY

Source: nydailynews.com

2003 Aug. Blackout

- Causes
  - State estimator and contingency analysis of MISO were not fully functioning
  - Power plant unit (Eastlake Unit 5) tripping with inadequate system understanding
  - Power line tripping caused by the short circuit to ground fault due to tree contacts
  - Alarm/logging system not functioning
  - Insufficient coordination and communication between transmission system operators
- Investigation performed
  - Final Report on the August 14, 2003 Blackout in the US and Canada: Causes and Recommendations

2003 Aug. Blackout



Power System Restoration

- Power System Restoration or blackstart
  - A procedure to restore power in the event of a partial or total shutdown of the power system
  - A highly complex decision problem
- Object is to serve the load as soon as possible without violating operating constraints
  - Actions are time critical
- Primarily manual work by operators
- Offline restoration planning usually based on simulations
- Limited online implementation due to the nature

Power System Restoration

- Common characteristics of restoration (even though strategies are different)
  - Immediate resupply of station service
  - Time consuming nature of switching operation
  - Start-up timings of thermal units
  - Voltage rise problems of energizing unloaded transmission lines
  - Frequency response of prime movers to a sudden load pickup
  - Cold load inrush, power factors and coincident demand factors

System Restoration Efforts - IEEE

- After 1977 New York City blackout, DOE required operating companies to develop a power system restoration plan, train personnel, regularly update and maintain the plan.
- In response to this requirement in 1978, the Power System Operation Committee established the Power System Restoration Task Force within the System Operation Subcommittee of the Power System Engineering Committee.
- A few years later, the PSR TF was upgraded to PSR WG.

System Restoration Efforts - IEEE

- In 1993
- A 110 page brochure was prepared by PSR WG and published by the IEEE PES
- Includes:
  - 14 IEEE Committee Reports
  - 5 SRWG member papers in IEEE publication
  - 13 related IEEE transaction papers

IEEE Power Engineering Society

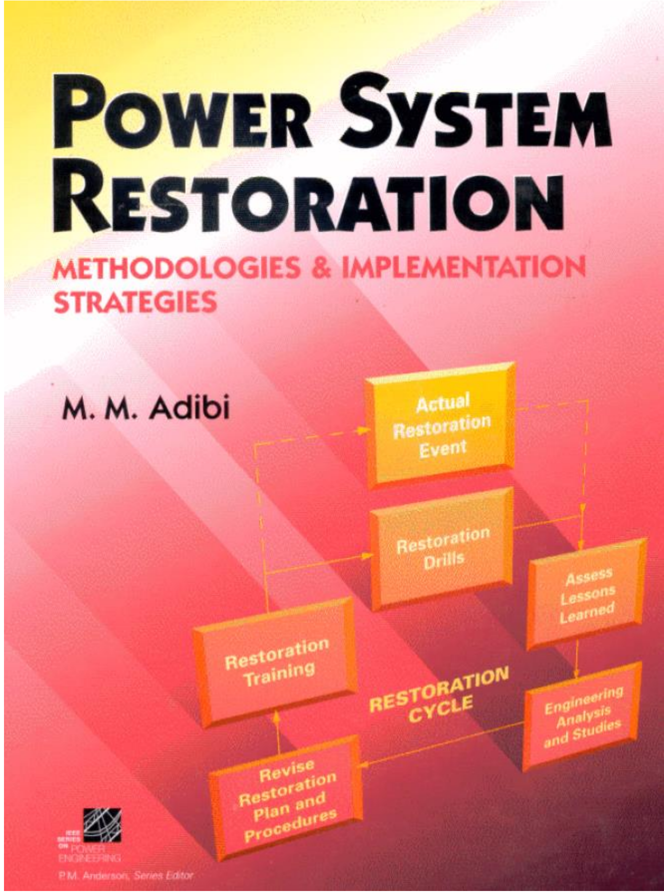
POWER SYSTEM RESTORATION

Prepared by the
Power System Restoration Working Group

Sponsored by the
System Operations Subcommittee

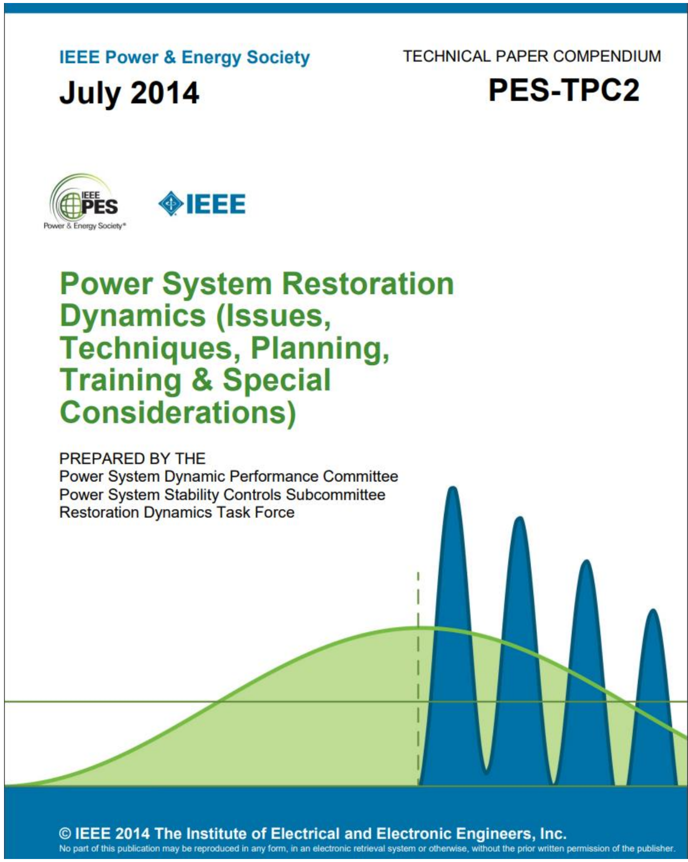
System Restoration Efforts - IEEE

- In 2000
- 700 page book is prepared by PSRWG and published by Wiley-IEEE Press
- Includes 87 papers including 14 papers in the original 1993 collection



System Restoration Efforts - IEEE

- In 2014
- 40 IEEE papers by 110 authors
- Including 42 panelists of Restoration Dynamics Task Force
- Covers:
  - Real power balance and control of frequency
  - Reactive power balance and control of voltages
  - Critical tasks (time sensitive functions)
  - Analyses and simulations


IEEE Power & Energy Society
July 2014
TECHNICAL PAPER COMPENDIUM
PES-TPC2

Power System Restoration Dynamics (Issues, Techniques, Planning, Training & Special Considerations)

PREPARED BY THE
Power System Dynamic Performance Committee
Power System Stability Controls Subcommittee
Restoration Dynamics Task Force

Mahmood Mike Adibi (1924 – 2018)

- The godfather of power system restoration
- B.S.E. in 1950 from University of Birmingham, U.K.
- M.S.E in 1960 from Polytech Institute of Brooklyn, NY
- IEEE Life Fellow
- Founder and chairman of the IEEE System Restoration Working Group in 1979
- Author of the book, "Power System Restoration – Methodologies and Implementation Strategies"
  - A great review book of IEEE papers between 1987 and 1999
- Developed restoration plans for over a dozen utilities

Other Good References

- PJM Manual 36: System Restoration
- EPRI, “Development of Power System Restoration Tool Based on Generic Restoration Milestones,” 2010.
- PSERC, “Development and Evaluation of System Restoration Strategies from a Blackout,” 2009.
- IESO, “Part 7.8: Ontario Power System Restoration Plan,” 2017.
- K. Sun et al., “Power System Control Under Cascading Failures: Understanding, Mitigation, and System Restoration,” Wiley-IEEE Press. 2019.
- Yutian Liu, Rui Fan, and Vladimir Terzija, “Power system restoration: a literature review from 2006 to 2016,” *J. Mod. Power Syst. Clean Energy*, 2016, 4(3), pp. 332-341

NERC Standards on Restoration

- NERC System Restoration and Blackstart standards
  - EOP-005-2 & EOP-005-3
    - System Restoration from Blackstart Resources
    - Ensure plans, Facilities, and personnel are prepared to enable System restoration from Blackstart Resources to assure reliability is maintained during restoration and priority is placed on restoring the Interconnection
  - EOP-006-2 & EOP-006-3
    - System Restoration Coordination
    - Ensure plans are established and personnel are prepared to enable effective coordination of the System restoration process to ensure reliability is maintained during restoration and priority is placed on restoring the Interconnection.

Common Issues during Restoration

- Active power balance and frequency control
  - Need to maintain system frequency within limits by system stability and protection settings
  - Can be accomplished by picking up loads in increments
- Reactive power balance and overvoltage control
  - Energizing few high voltage lines
  - Operating generators at minimum voltage levels
  - Deactivating switched shunt capacitors
  - Connecting shunt reactors
  - Adjusting transformer taps
  - Picking up reactive loads

Common Issues during Restoration

- Transient switching voltages
  - Switching surges occur when energizing equipment
- Self-excitation
  - When the charging current is high relative to the size of generators
  - When opening a line at the sending end but leaving the line connected to a large motor
  - This causes overvoltage and damages equipment
- Cold load pickup
  - When load has been de-energized for several hours or more
  - Inrush current can be as high as 8 – 10 times of the normal value

Common Issues during Restoration

- System stability
  - Voltage should be within limits
  - Angle stability have to be maintained
  - Frequency is the main issue in stability assessment
- Protective systems and load control
  - Continuous change in system configuration and in operating conditions may trigger undesirable operation of relays
  - Load shedding can be useful in case of low frequency conditions

Common Issues during Restoration

- Partitioning system into islands
  - Necessary to speed up the process, especially for large systems
  - NERC standards
    - Each islands must have sufficient blackstart capability
    - Each islands should have enough cranking paths to gens and loads
    - Each islands should be able to match generation and load within prescribed frequency limits
    - Each islands should have adequate voltage controls
    - All tie points must be capable of synchronization with adjacent subsystems
    - All islands should share information with other islands

Generic Restoration Steps

- Preparation stage (1 – 2 hours)
  - Evaluate pre- and post-disturbance conditions
  - Define the target system
  - Restart generators and rebuild transmission network
- System restoration stage (3 – 4 hours)
  - Energize transmission paths
  - Restore load to stabilize generation and voltage
  - Synchronize islands and reintegrate bulk power system
- Load restoration stage (8 – 10 hours)
  - Load restoration is the governing control objective
  - Load pickup is scheduled based on generation availability
  - Load restoration is effected in increasingly larger steps

System Restoration Tasks

- Know the status of the grid
- List and rank critical loads by priority
- List and rank initial sources of power by availability
  - Maximize generation capabilities with the available black start resources
- Determine the most effective ways of brining the two together
  - Schedule tasks and resources during restoration
  - Establish transmission capability and paths while meeting operating constraints

Initial Power and Load

- Initial source of power

Type	Time (min)	Success probability
Run-of-the-River Hydro	5-10	High
Pump-Storage Hydro	5-10	High
Combustion Turbine	5-15	Medium
Tie-line with Adjacent Systems	Short	

- Initial critical loads

Type	Priorities
Cranking drum-type units	High
Pipe-type cables pumping plants	High
Transmission stations	High to Medium depending on location
Distribution stations	High to Medium depending on location
Industrial loads	Medium to low

Algorithm for Restoration Automation

- Assumption
  - Each Area/island has a BSU and critical loads
  - Input: a PW case
- Overall process
  - Restore each area in parallel
  - Stabilize each area
  - Synchronize all the areas
- 4 Criteria to be set up first
  1. Whether a generator or a load to pick up next
     - Pick up a generator if available online GenMW is smaller than the next load to pickup
     - Pick up a load if available online GenMW is larger than the next load to pickup

Algorithm for Restoration Automation

2. For selecting which offline Gen to pick up next
   - Largest MWMax
   - Time related characteristics such as startup time, ramp time, personnel dispatch time, etc.
   - Distance from online area or control center
   - Others
3. For selecting which offline load to pick up next
   - Largest MW
   - Smallest MW
   - Distance from online area
   - Others
4. For stopping the restoration process
   - 90% of the total loads is online
   - others

Algorithm for Restoration Automation

- Pre-process
  1. Get data from case
  2. Check device status
  3. Compare total generation and total load in each area

- 1st stage: From BSU to Critical Loads
  1. Close BSU
  2. Find cranking path to critical loads
  3. Energy the path and pick up the load
  4. Commit more generators if necessary

Algorithm for Restoration Automation

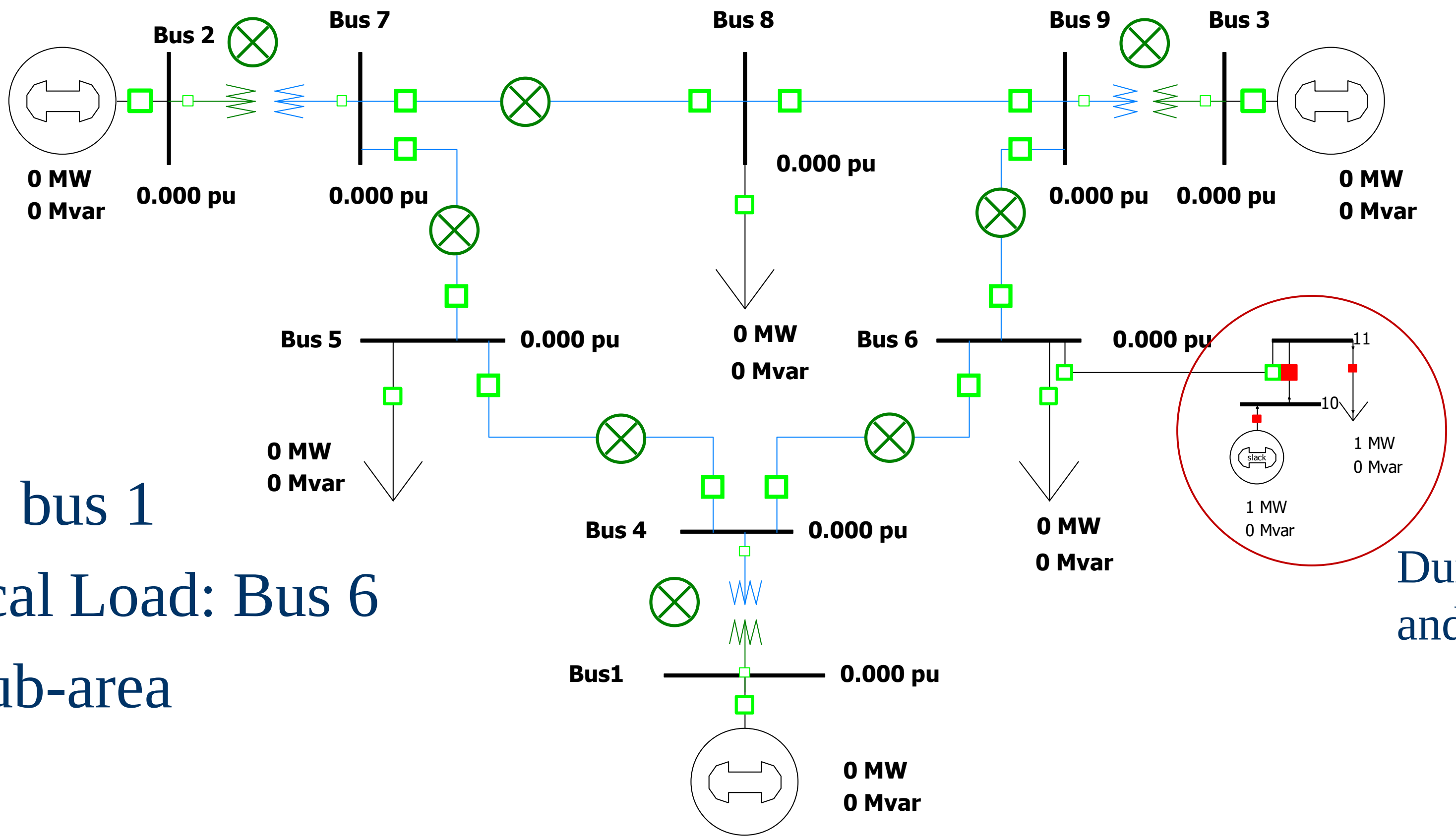
- 2nd stage: Restore the remaining system
  1. While *Criterion 4: stopping restoration process* is not met
  2. Select gen or load to pick up next with *Criterion 1, 2 and 3*
  3. Find cranking path (shortest path) from online area
  4. Energize the path
  5. Pick up load

- 3rd stage (optional)
  1. Close offline branches and generators
  2. Change transformer tap setting

- 4th stage: Connect areas

Example - WSCC 9-bus Case

- Before restoration



BSU: bus 1

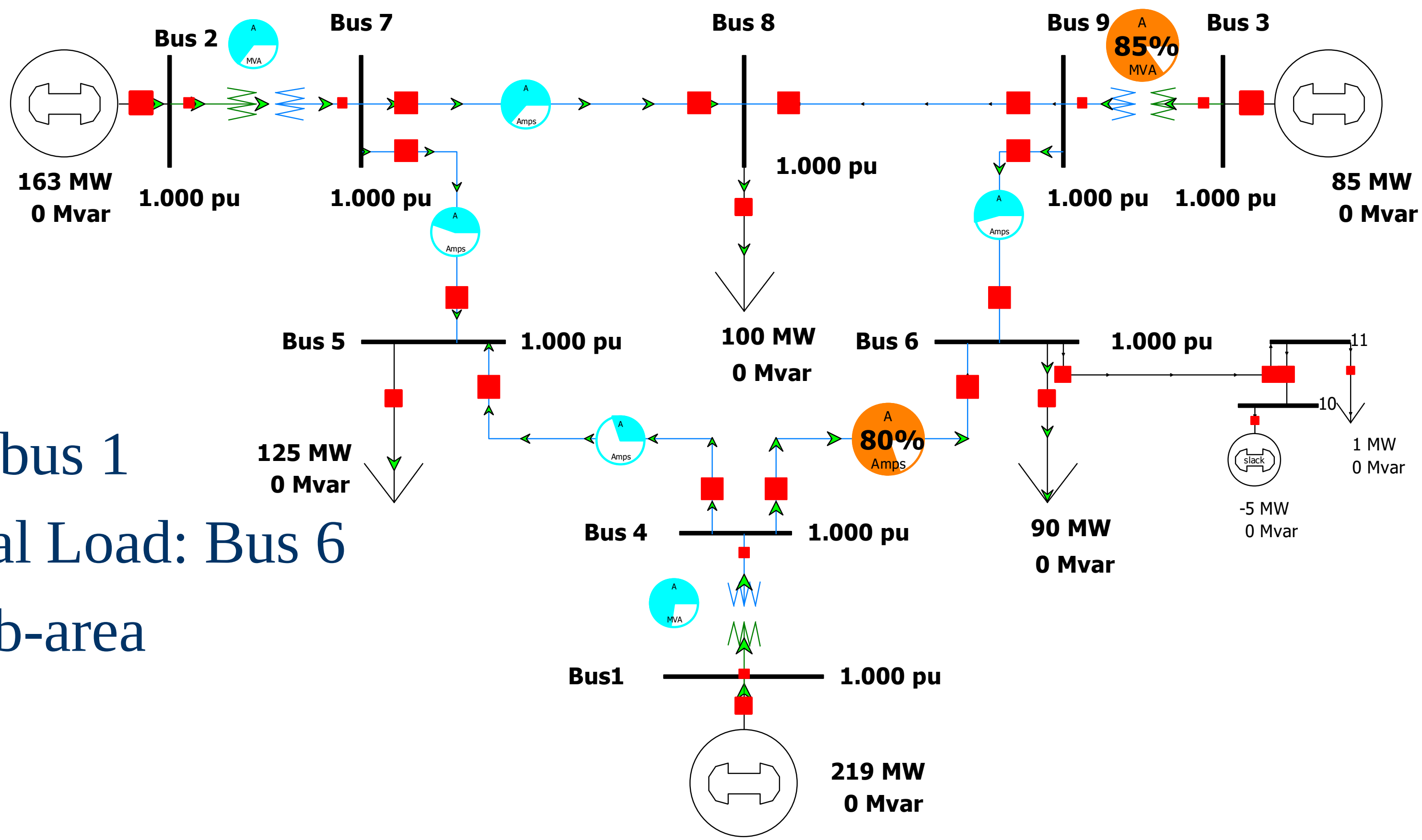
Critical Load: Bus 6

No sub-area

Dummy gen and load

Example - WSCC 9-bus Case

- Steady state after restoration



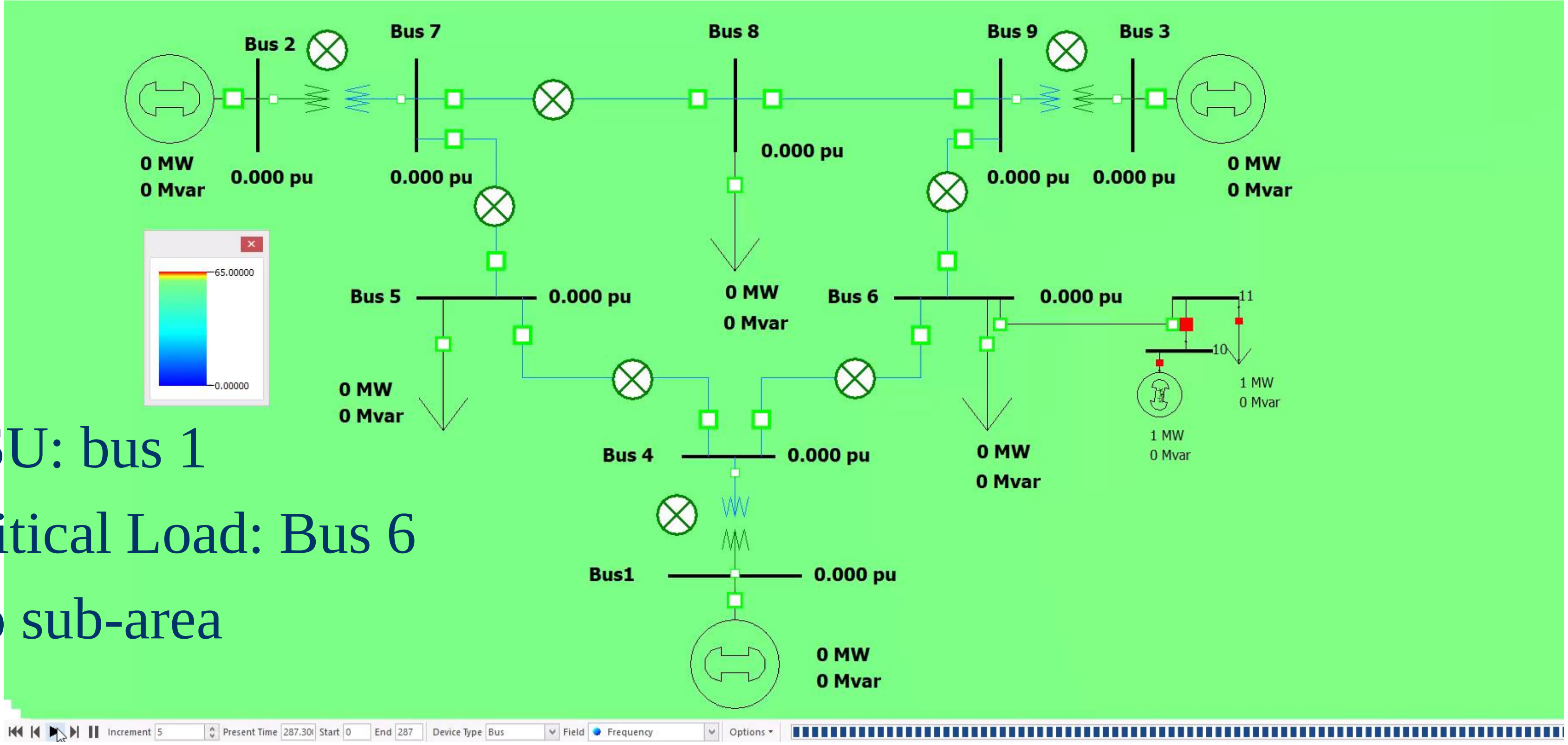
BSU: bus 1

Critical Load: Bus 6

No sub-area

Example - WSCC 9-bus Case

- During restoration



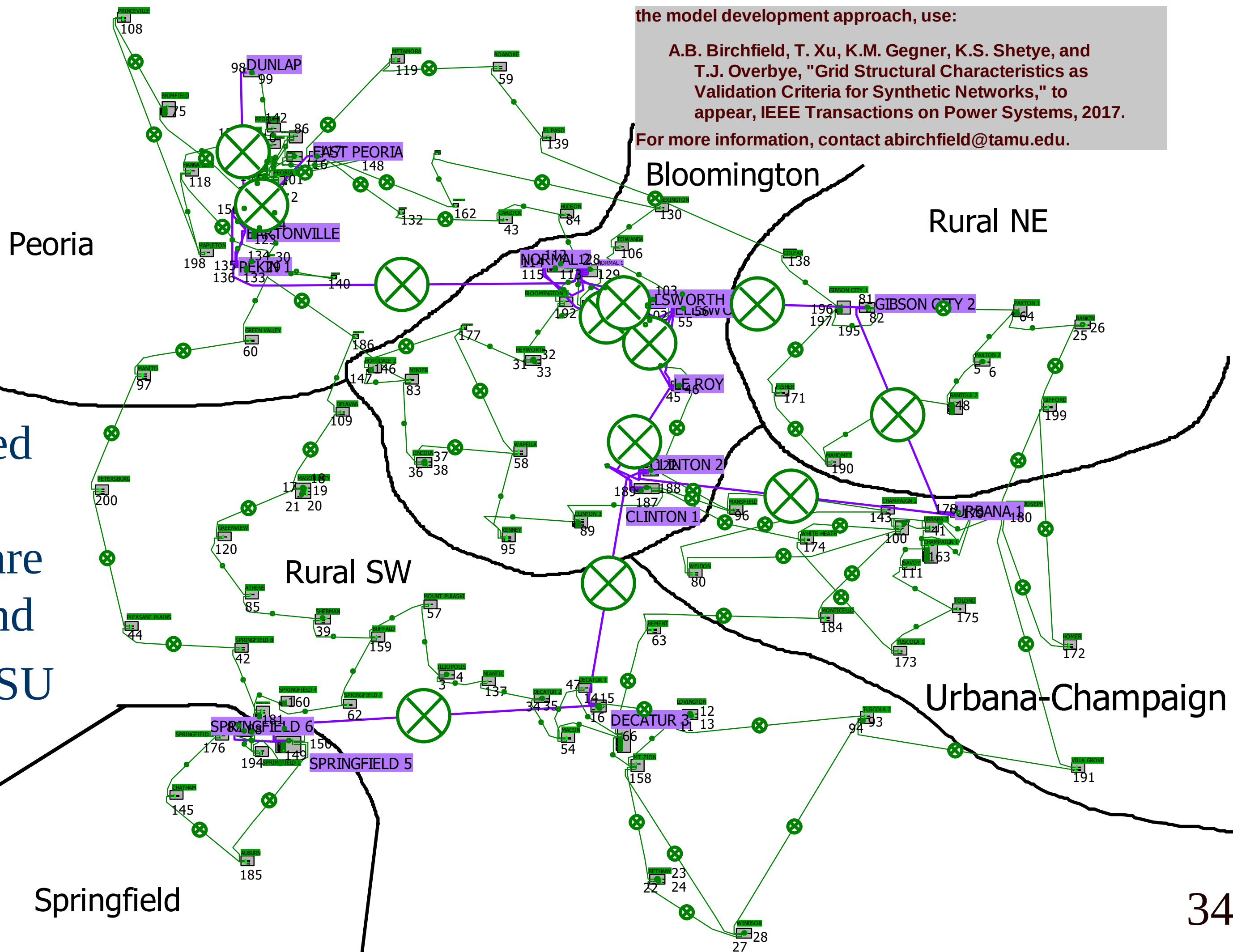
BSU: bus 1

Critical Load: Bus 6

No sub-area

Example – Synthetic 200-bus Case

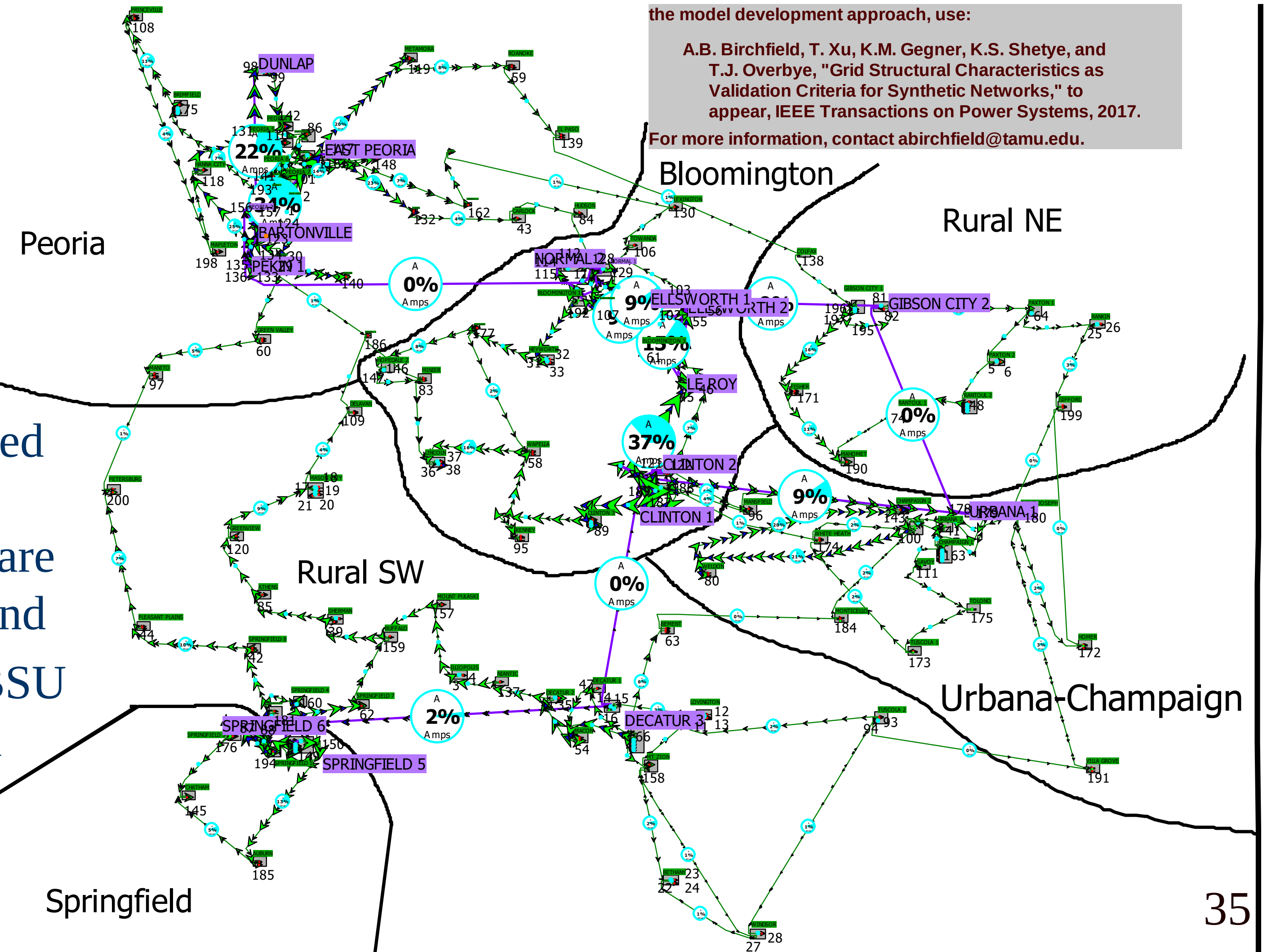
- Before restoration



- 6 Zones are restored independently in parallel, and they are connected at the end
- Each zone has a BSU and 1 or 2 Critical Loads

Example – Synthetic 200-bus Case

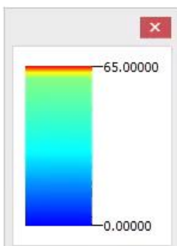
- Steady state after restoration

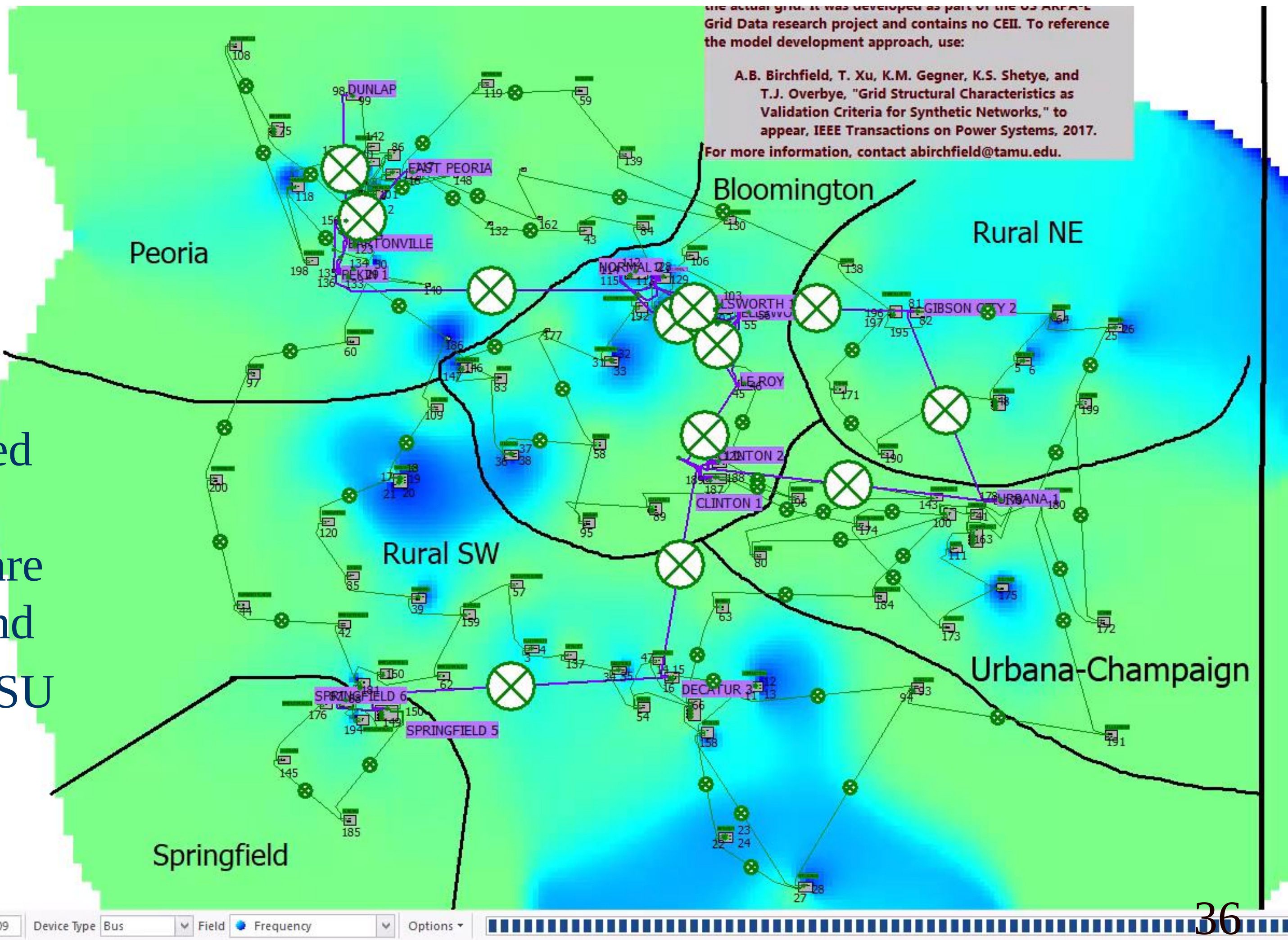


- 6 Zones are restored independently in parallel, and they are connected at the end
- Each zone has a BSU and 1 or 2 Critical Loads

Example – Synthetic 200-bus Case

- During restoration





- 6 Zones are restored independently in parallel, and they are connected at the end
- Each zone has a BSU and 1 or 2 Critical Loads

Restoration Automation

- Things to consider
  - Status of devices has to be tracked
    - This prevents duplicate actions
  - Closing a large load can fail restoration in simulation
    - Loads are gradually picked up if it is larger than a threshold
  - Distributed generators are not picked up during restoration
  - If the area cannot support all the loads with the generators in it, loads should be curtailed
  - Line overloading has to be monitored
  - May close offline branches and generators after the restoration process is done

Restoration Automation Challenges

- Dynamic and protection issues
  - Frequency excursion
    - Under frequency occurs during restoration when large loads are picked up
    - Balance between generation and load need careful coordination
  - Overvoltage issue
    - Transient overvoltage due to switching actions
    - Sustained overvoltage due to harmonics
  - Voltage collapse
    - Generator under excitation
    - Startup of motor loads require a lot of reactive power
  - Control and protective schemes have to be coordinated
  - Capability of each BSU has to be determined in advance

Restoration Automation Challenges

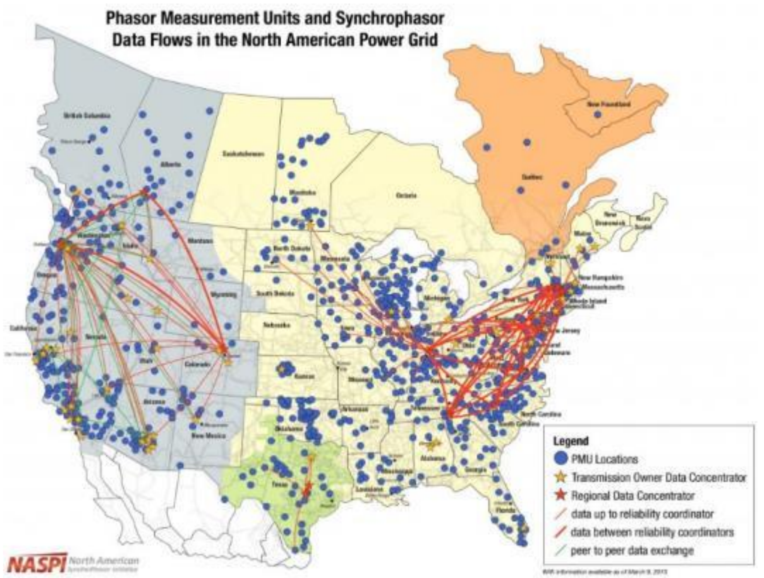
- Network configuration
  - Forming islands with adequate amount of real/reactive power and load
  - Establishing a stable backbone network
  - Unit start-up sequence to maximize generation capacity
  - Restoration path section problem
    - Which path to energize?
- Load restoration time/amount
- Time consuming process
  - A lot of try-and-errors for better results
  - Feedback loop results in huge time consumption

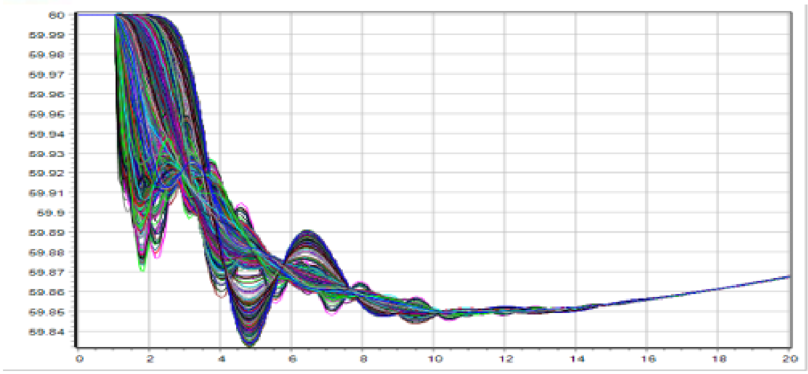
Wide-Area Power System Visualization

- Power system operations and planning are generating more data than ever
  - In operations thousands of PMUs are now deployed
  - In planning many thousand of studies are now routinely run, with a single transient stability run creating millions of values
- How data is transformed into actionable information is a crucial, yet often unemphasized, part of the software design process
- Presentation addresses some issues associated with dealing with this data

Examples of Power System "Big Data"

- Power system operations and planning are a rich source of data
  - SCADA has traditionally provided a grid data at scan rates of several seconds
  - Thousands of PMUs are now deployed providing data at 30 times per second
  - In planning many thousand of studies are now routinely run, with a single transient stability run creating gigabytes





Examples of Power System "Big Data"

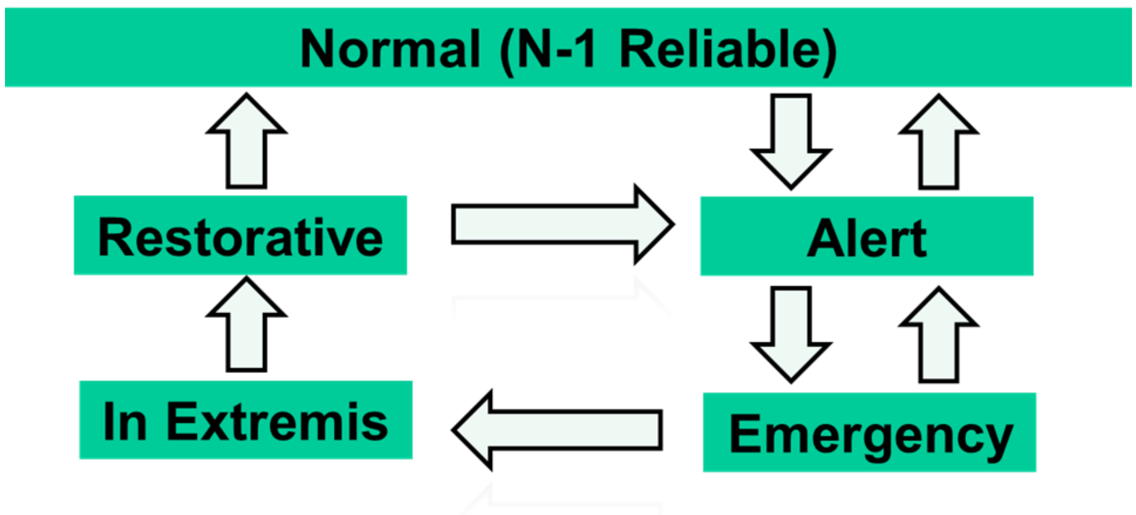
- A 100,000 bus grid solved hourly for one year generates 100K times 8760 = 876 million values
- Each hourly simulation may have 10,000 contingencies, giving 8.76 trillion bus values
- Each contingencies could also be run as a time domain simulation, which is sampled at PMU frequency (30 per second) for 30 seconds each gives about 8 quadrillion bus values

Visualization Software Design

- Key question: what are the desired tasks that need to be accomplished?
  - Needs for real-time operations might be quite different than what is needed in planning
- Understanding the entire processes in which the visualizations are embedded is key
- Software should help humans make the more complex decisions, i.e., those requiring information and knowledge
  - Enhance human capabilities
  - Alleviate their limitations (like adding up bus flows)

Power System Operating States

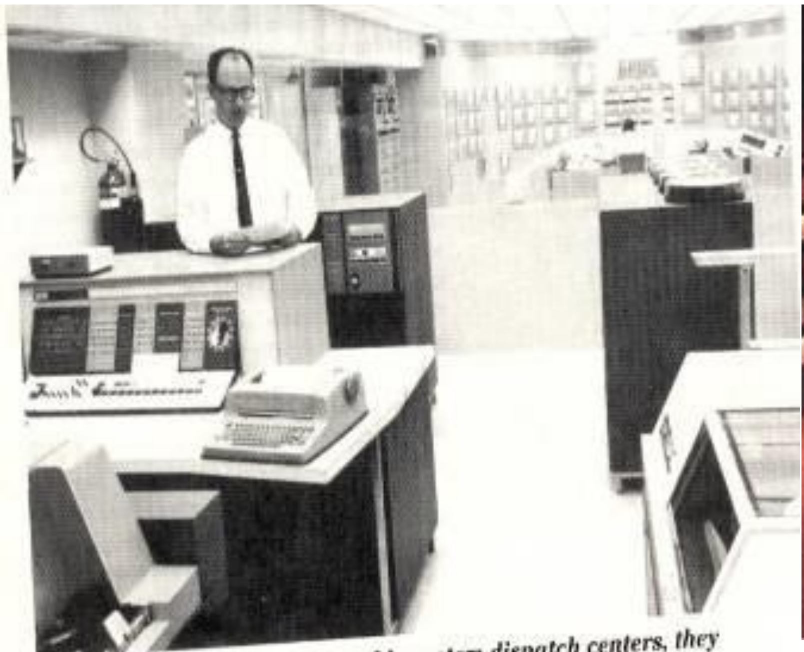
- Effective data analysis and visualization for operations requires considering the different operating states



- Effective visualization is most needed for the more rare situations and for planning

Image Derived From L.H. Fink and K. Carlsen, Operating under stress and strain, *IEEE Spectrum*, March 1978, pp. 48-53

Power System Visualization History



When computers were first used in system dispatch centers, they augmented the traditional analog systems. These systems were referred to as digital-directed analog control computers. As the digital computer became more reliable, it assumed full control.

PSE&G Control Center in 1988

Left Source: W. Stagg, M. Adibi, M. Laughton, J.E. Van Ness, A.J. Wood, “Thirty Years of Power Industry Computer Applications,” IEEE Computer Applications in Power, April 1994, pp. 43-49

Right Source: J.N. Wrubel, R. Hoffman, “The New Energy Management System at PSE&G,” IEEE Computer Applications in Power, July 1988, pp. 12-15.

Present: PJM Control Center

Image Source: http://tdworld.com/site-files/tdworld.com/files/imagecache/large_img/uploads/2013/07/pjmcontrolroom117.jpg

Blackouts and Operator Intervention

- Many large-scale blackouts have time scales of several minutes to a few dozen minutes
  - this time scale allows for operator intervention, but it must occur quickly to be effective (extreme emergency control)
- Operators can’t respond effectively if they do not know what is going on– they need “situational awareness”

Extreme Emergency Control

- How the control room environment might be different during such an event
  - advanced network analysis applications could be unavailable or overwhelmed
  - system state could be quite different, with unfamiliar flows and voltages
  - lots of alarms and phone calls
  - high level of stress for control room participants with many tasks requiring their attention
  - large number of decision makers might be present
- Designing software for extreme conditions is challenging since conditions seldom encountered

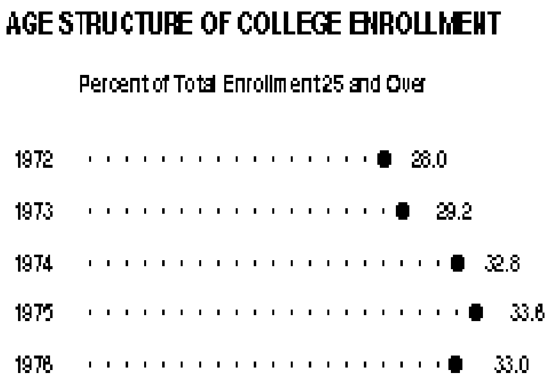
A Visualization Caution!

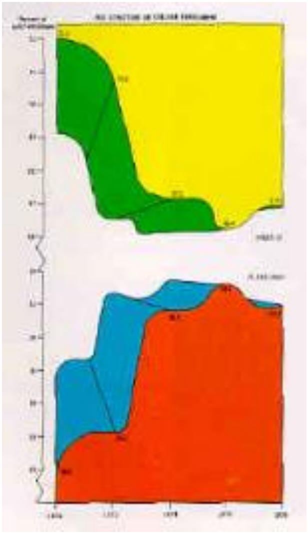
- Just because information can be shown graphically, doesn't mean it should be shown
- Three useful design criteria from 1994 EPRI visualization report:

  1. natural encoding of information

  2. task specific graphics

  3. no gratuitous graphics

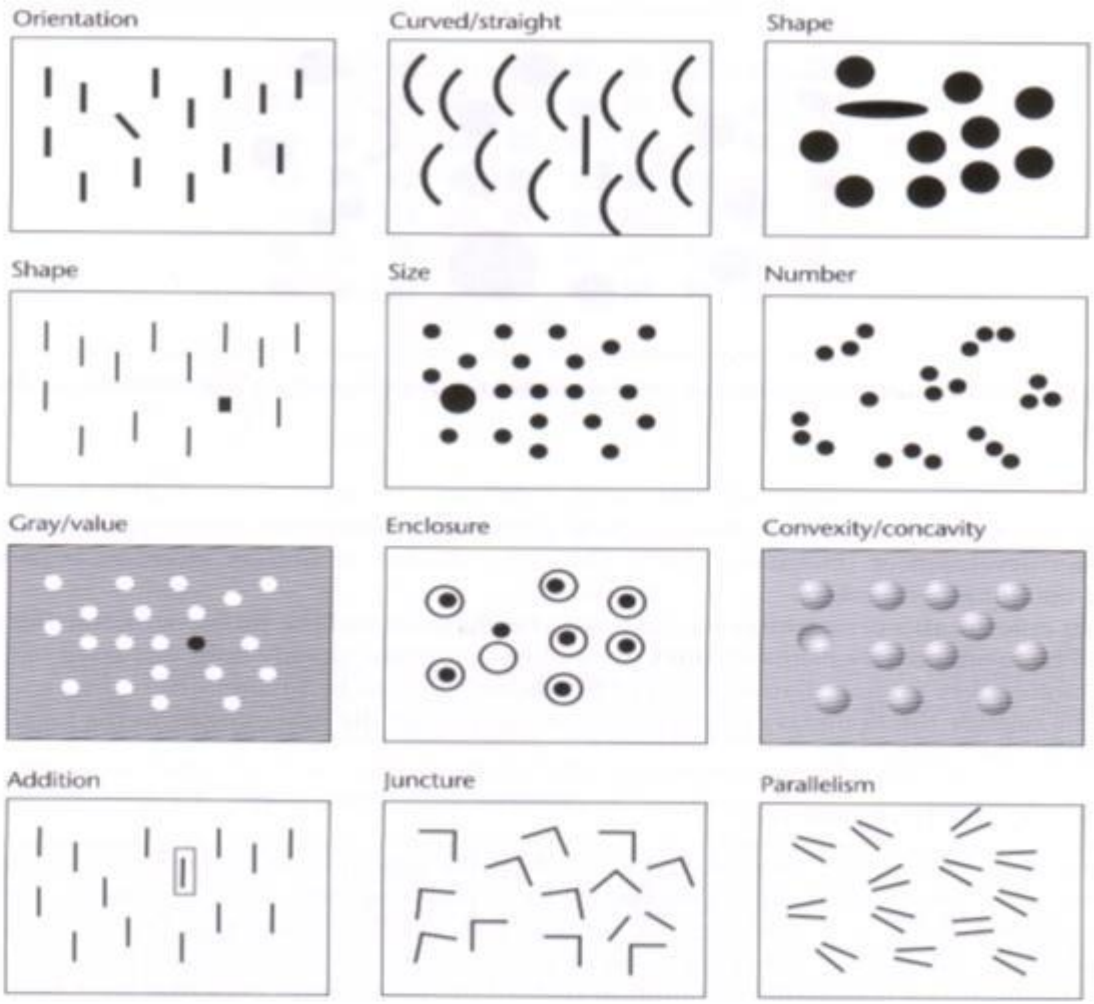




Visualization Background: Preattentive Processing

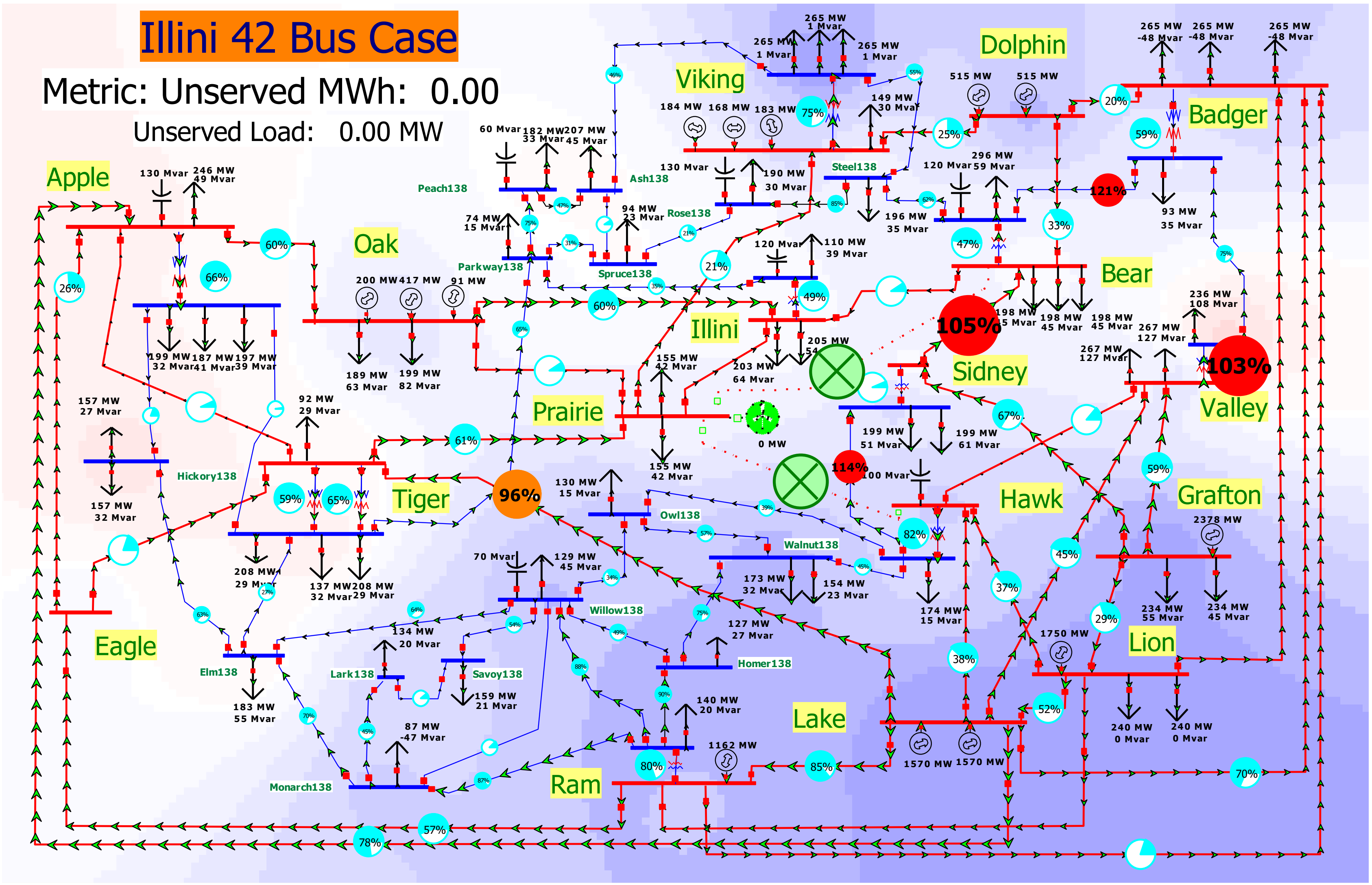
- Good reference book: Colin Ware, *Information Visualization: Perception for Design*, Third Edition, 2013
- When displaying large amounts of data, take advantage of preattentive cognitive processing
  - With preattentive processing the time spent to find a "target" is independent of the number of distractors
- Graphical features that are preattentively processed include the general categories of form, color, motion, spatial position

All are Preattentively Processed Except Juncture and Parallelism



Source: *Information Visualization* by Colin Ware, Fig 5.5

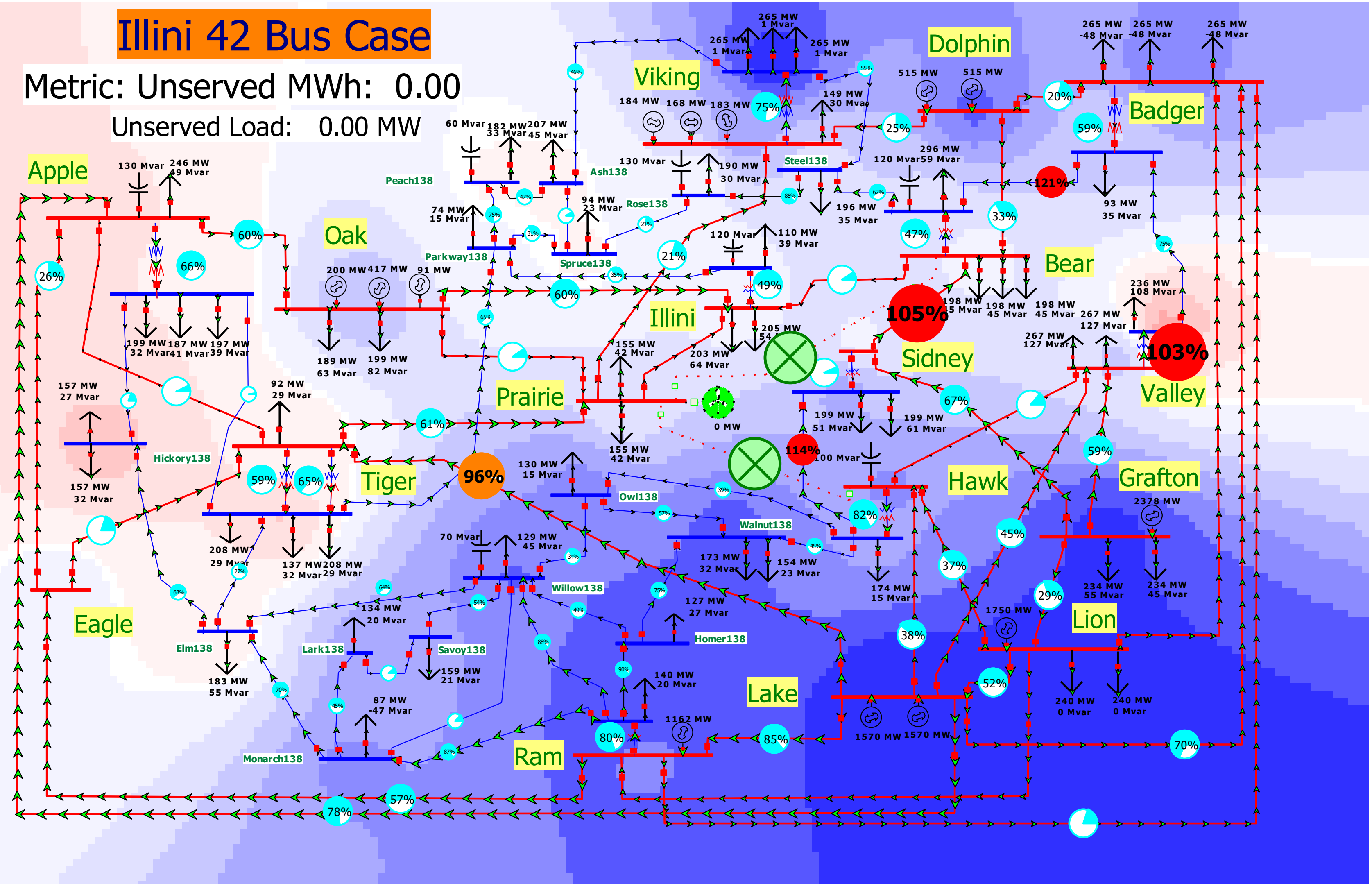
Preattentive Processing with Color & Size



Use of Color

- Some use of color can be quite helpful
  - 10% of male population has some degree of color blindness (1% for females)
- Do not use more than about ten colors for coding if reliable identification is required
- Color sequences can be used effectively for data maps (like contours)
  - Grayscale is useful for showing forms
  - Multi-color scales (like a spectrum) have advantages (more steps) but also disadvantages (effectively comparing values) compared to bi-color sequences

Color Sequence Example: Blue/Red, Discrete



Color Sequence Example: Spectrum, Continuous