ECE 522 - Power Systems Analysis II
Spring 2021

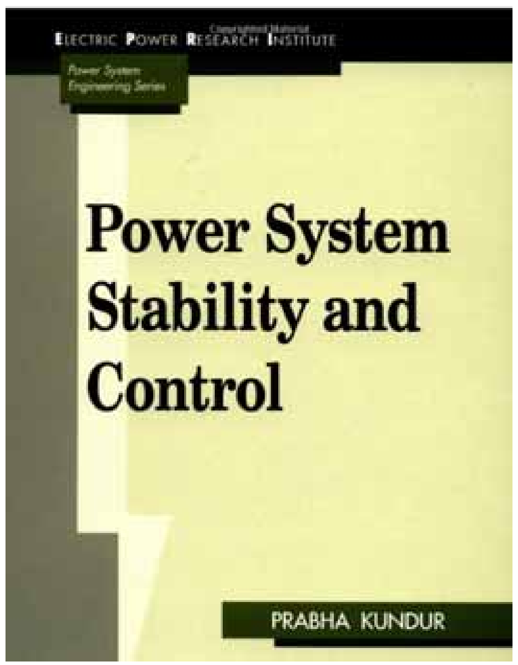
Course Outline

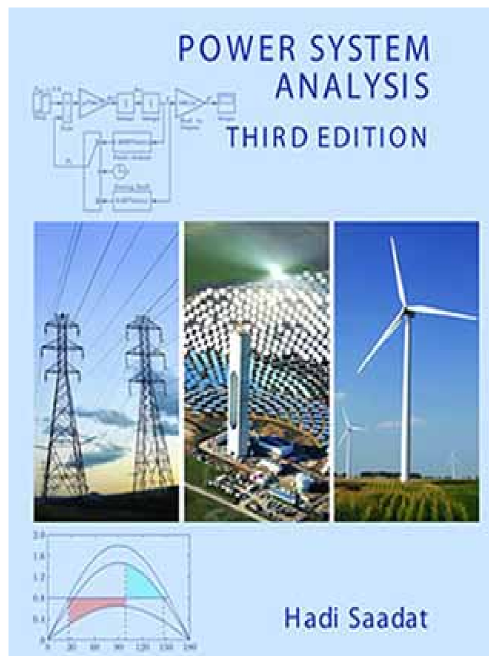
Spring 2021

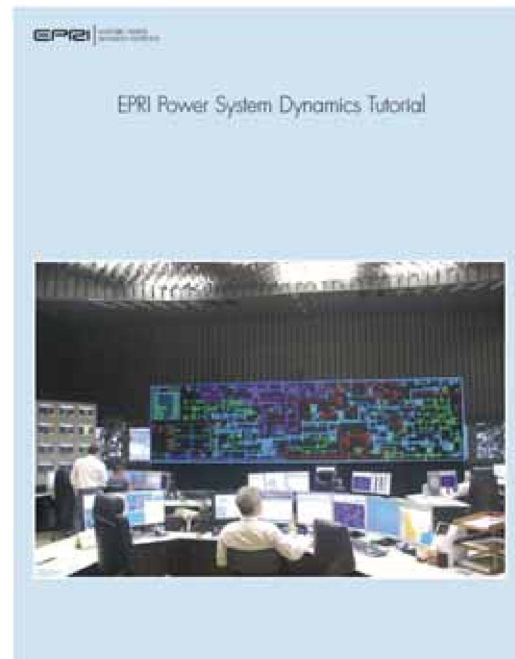
Instructor: Kai Sun

Information

- **Prerequisite:** ECE421 & ECE422
- **References**
  - P. Kundur, *Power System Stability and Control*, McGraw-Hill, 1994 (the course covers 12 of 17 chapters)
  - H. Saadat, *Power System Analysis (3rd Edition)*, McGraw-Hill, 2010 (text of ECE421/422; used for some homework)
  - EPRI Power System Dynamics Tutorial, EPRI, Product ID: 1016042, 2009 http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000000001016042







Course objectives

- An in-depth understanding of basic approaches to modeling of power system dynamics under disturbances
- A broad familiarity with analytical methods, engineering criteria and control measures for power system stability problems, and
- Knowledge in emerging issues and techniques in planning and operating modern interconnected power systems.

Course Outline

1. **General background on modern power systems** (2-3 lectures, Kundur's Ch. 1&2)
   - Overview of grid operations and planning (NERC reliability criteria)
   - Fundamental definitions and classification of power system stability
2. **Power system modeling** (7 lectures, Ch. 3-5&7,)
   - **Synchronous machines** (Park's transformation; equivalent circuits; classic and detailed models; equations of motion)
   - **Loads** (static and dynamic loads; acquisition of model parameters)
3. **Power system control** (6 lectures, Ch. 8&9): focusing on modeling of frequency and voltage regulators/controllers
   - **Frequency regulation and control** (governing systems; AGC)
   - **Voltage regulation and control** (excitation systems; var compensators)
4. **Power system stability** (11 lectures, Ch. 12-14)
   - **Small-signal stability** (power oscillation; eigenanalysis; measurement-based modal analysis; power system stabilizer)
   - **Transient stability** (direct methods; numerical methods and DSA)
   - **Voltage stability** (voltage collapse; P-V and V-Q curves and other analysis methods; mitigation measures)

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General Background

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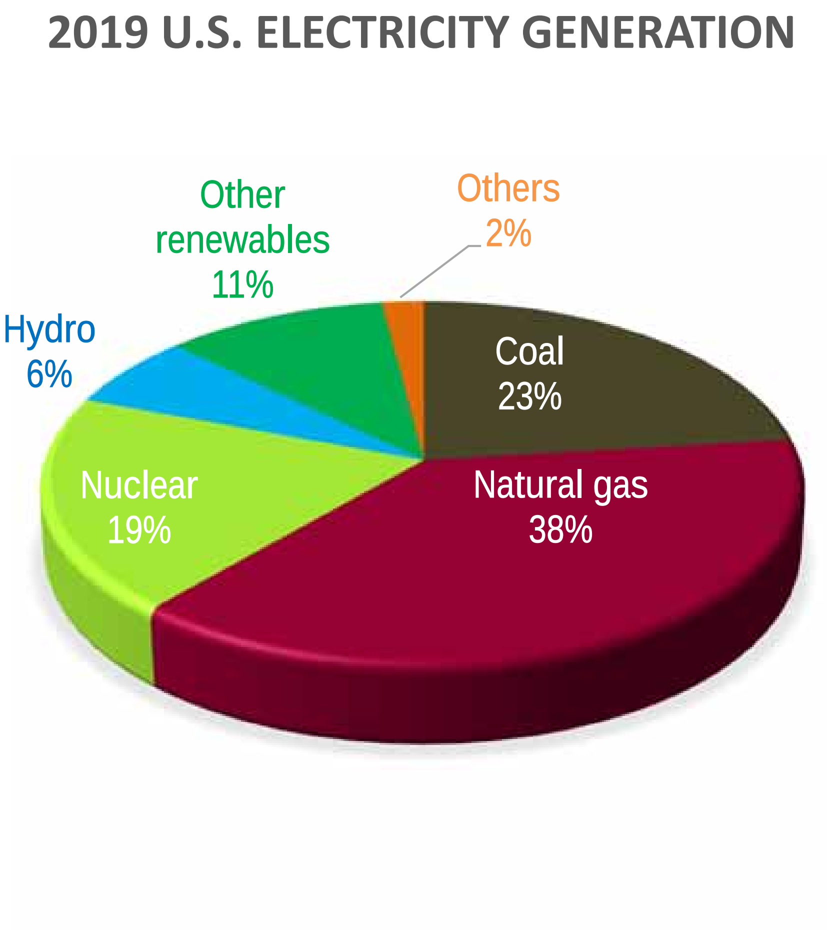
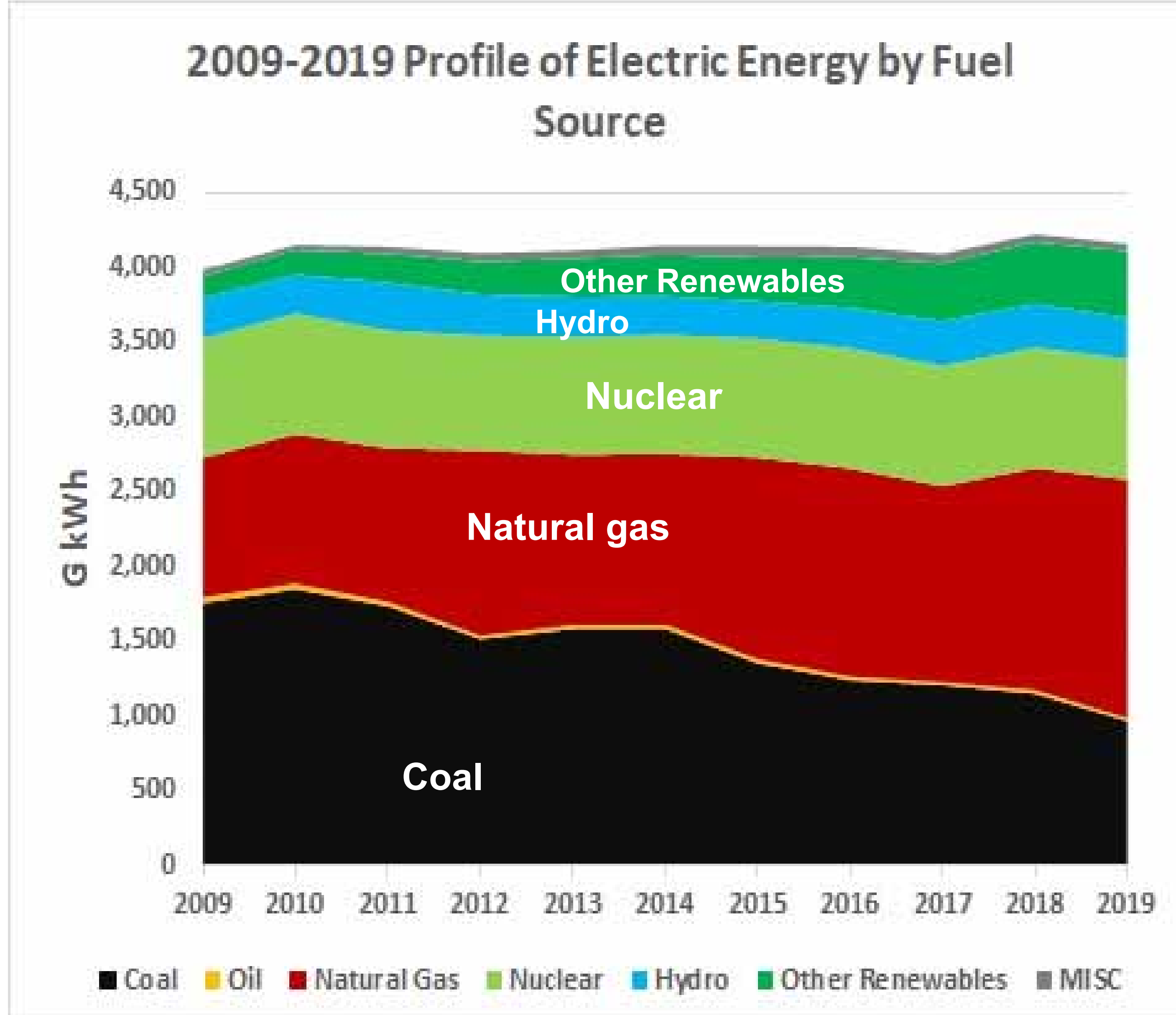
General Background: Outline

- Overview of power system operations and NERC reliability guidelines
- Introduction of power system stability (basic concepts, definitions and examples)
- Materials
  - Part I (Chapters 1&2) of Kundur's book
  - IEEE/CIGRE Joint Task Force on Stability Terms and Definitions, "Definition and Classification of Power System Stability," IEEE Transactions on Power Systems, Vol. 19, No. 2., pp. 1387 – 1401, May 2004
  - Reliability Standards for the Bulk Electric Systems of North America, NERC, December 2020

https://www.nerc.com/pa/Stand/Reliability%20Standards%20Complete%20Set/RSCompleteSet.pdf

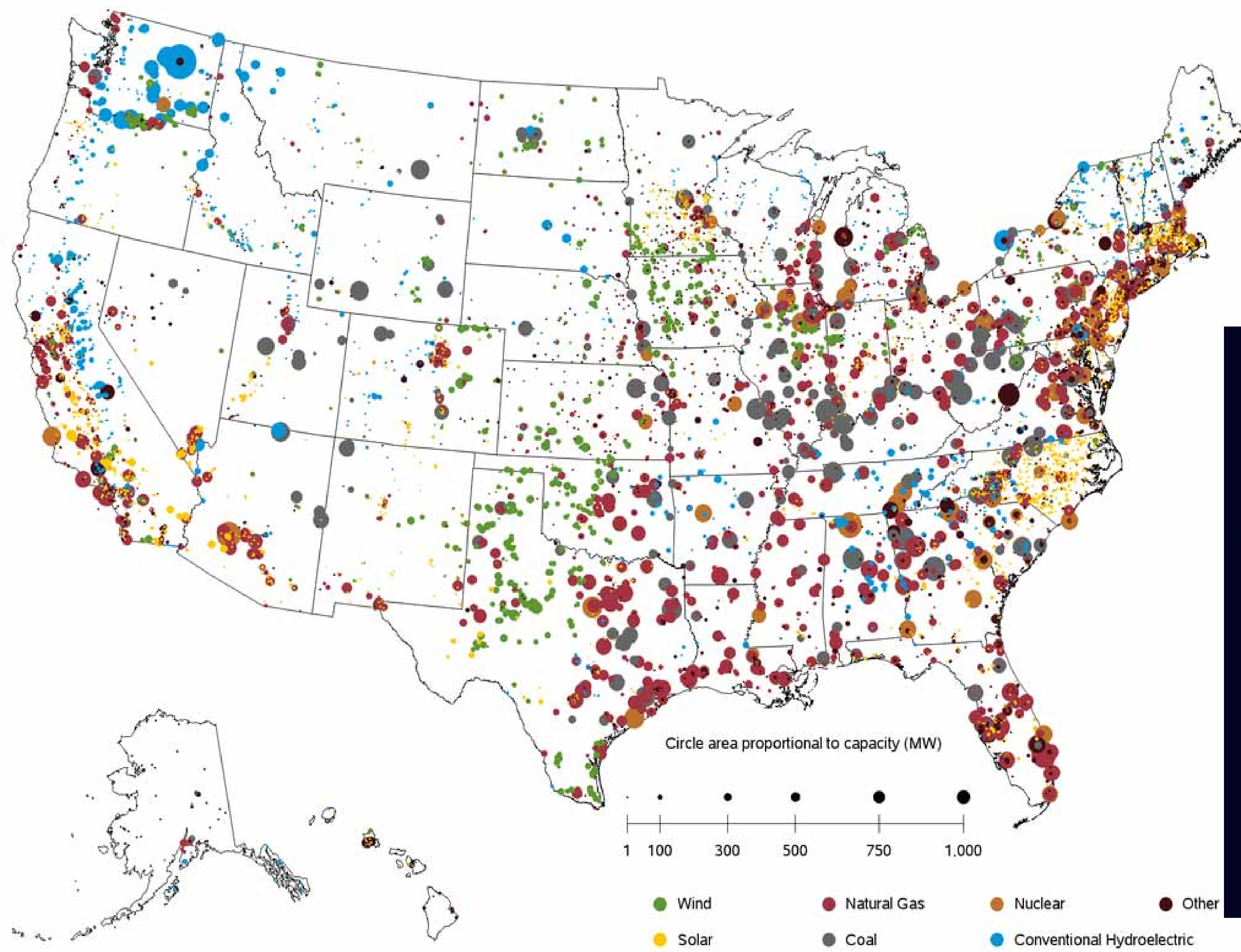
US Energy Resources for Electricity Generation





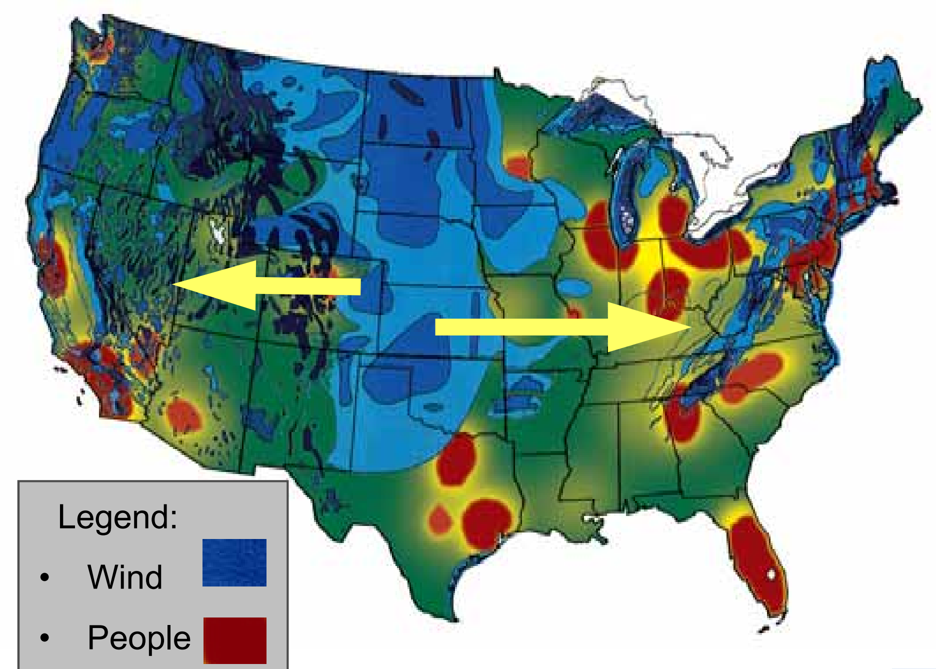
From www.wikipedia.org

Operable utility-scale generating units as of December 2018



Sources: U.S. Energy Information Administration, Form EIA-860, 'Annual Electric Generator Report' and Form EIA-860M, 'Monthly Update to the Annual Electric Generator Report.'

Reliability Challenges with Integration of Wind Power



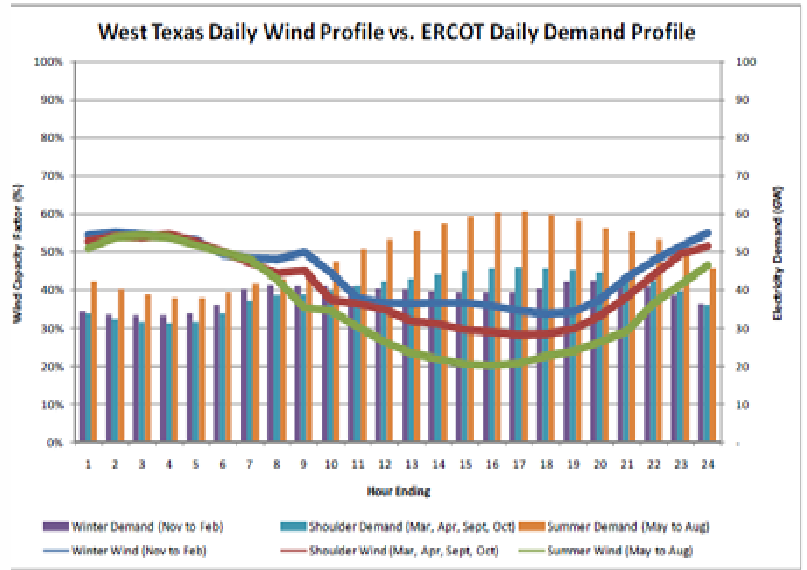
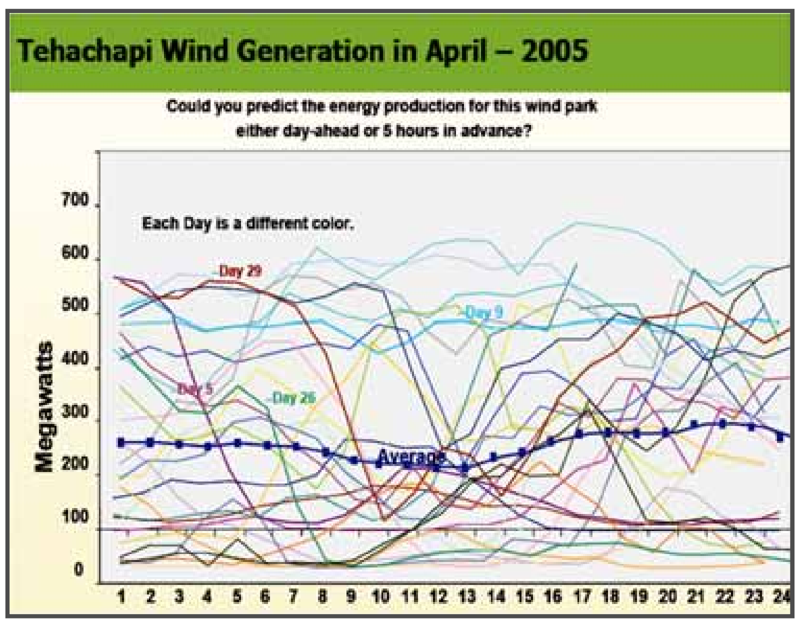


Image Source: LCG Consulting



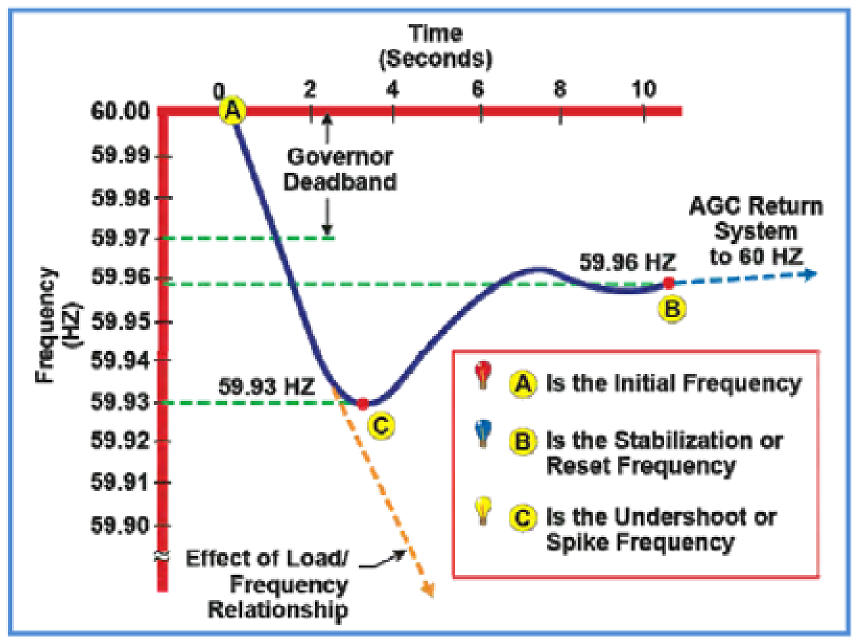


Figure 4-54. Plot of a Simulated Frequency Disturbance

- Geographical and temporal mismatches in supply and demand.
- Uncertainties due to inaccurate short-term wind forecasting.
- Decreased system inertia and frequency response.

Additional costs for either upgrading transmission to prevent congestion or installing energy storages and spinning reserves for load ramp flexibility. *Wind power is not free!*

Reliability Challenges with Integration of Solar Power

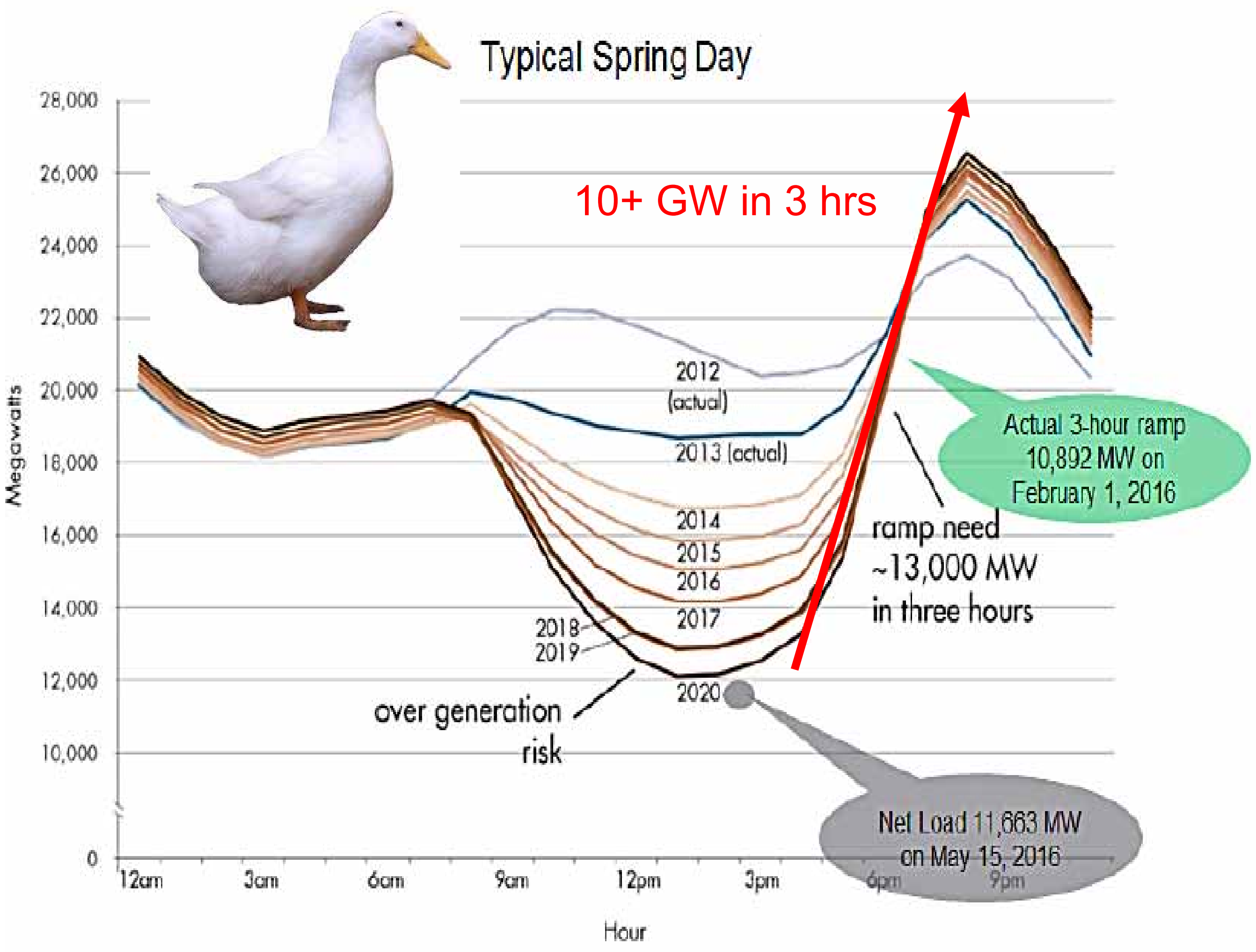


Figure 2: The duck curve shows steep ramping needs and overgeneration risk

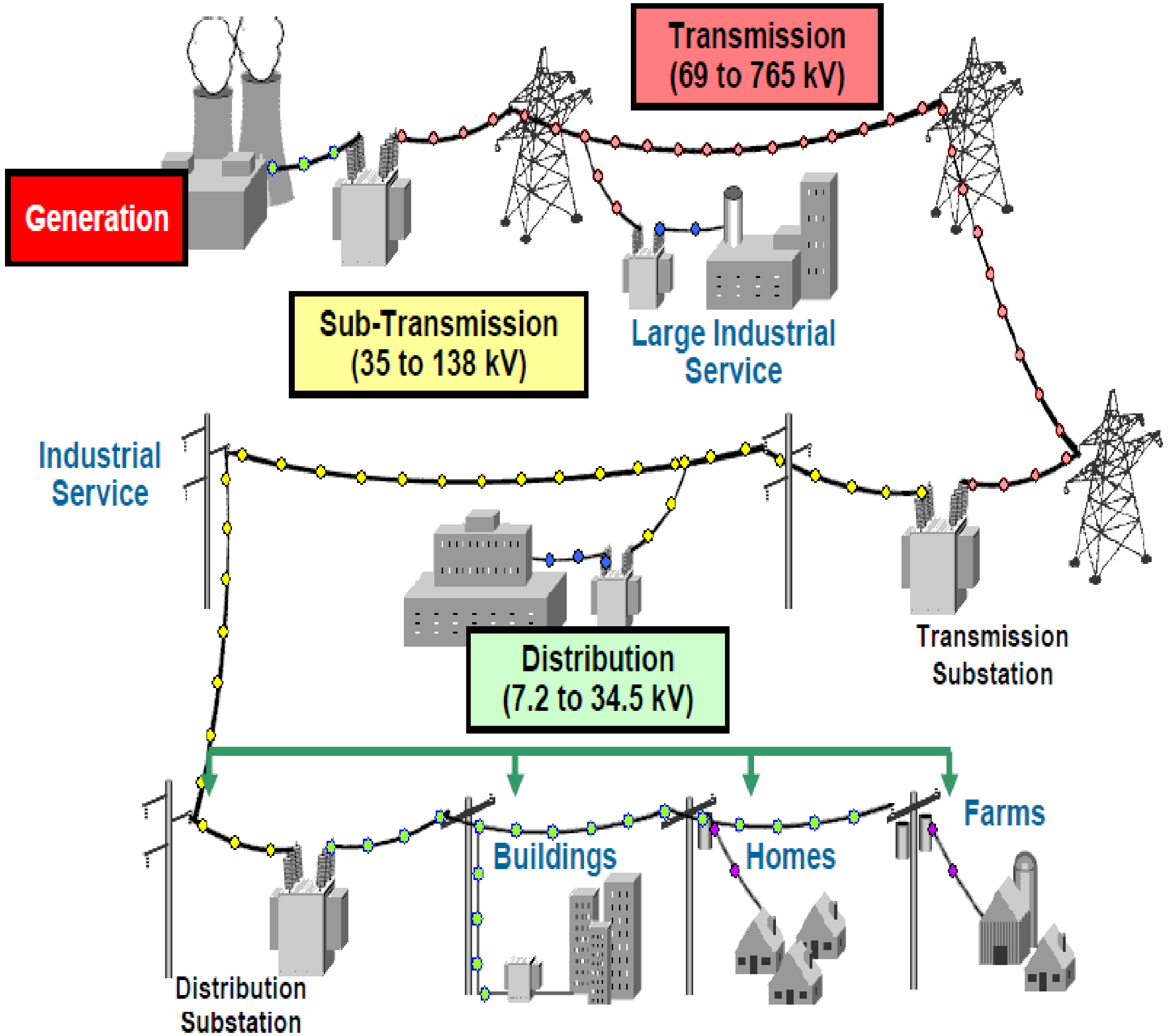
- "Duck Curve" in California toward a goal of 50% from renewables by 2030
  - Two short steep ramps ~ 3-4GW/hr starting around 4:00 AM and 4:00 PM
  - Oversupply risk during the day with high solar irradiance.
  - Decreased frequency response due to no AGC on solar power generation.

Solar power is not free!

Source: "What the duck curve tells us about managing a green grid," CAISO Fast Facts, 2016

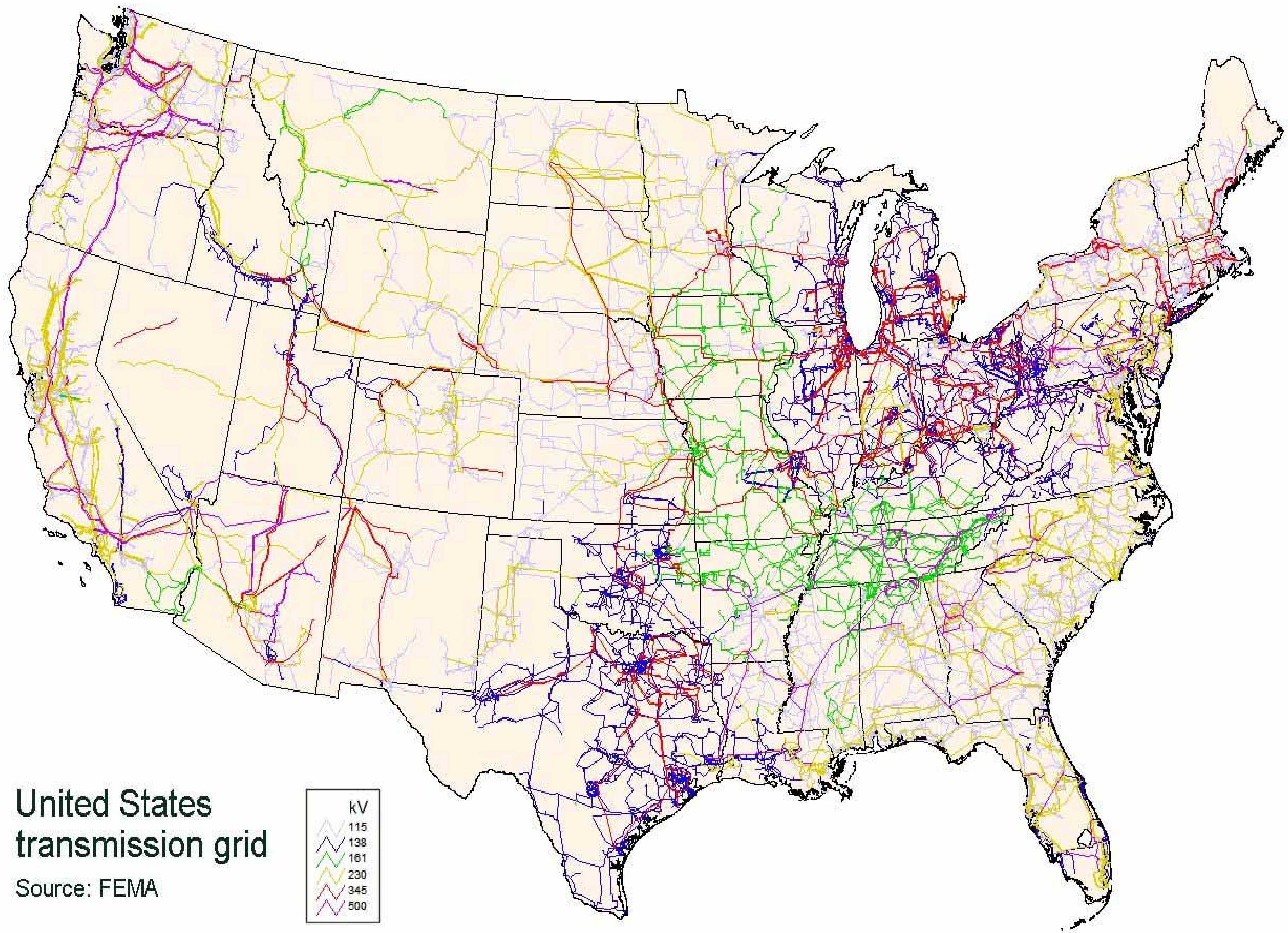
AC System Structure

- Generation
  - Low voltages <25kV due to insulation requirements
- Transmission system
  - Backbone system connecting major power plants (11-35kV) and load center areas
  - 161kV, 230kV, 345kV, 500kV, 765kV, etc.
- Sub-transmission system
  - Transmitting power to distribution systems
  - Typically, 35/69kV-138kV
- Distribution system
  - Typically, 4kV-34.5kV



Source: *Green Transmission Efficiency Initiative: A Series of Workshops.* EPRI PID 1019531, 2009.

Electric Transmission Grids in North America



US Electric Power Industry

- 3,000+ electric utilities in the US in 1996. Fewer than 1000 engaged in power generation

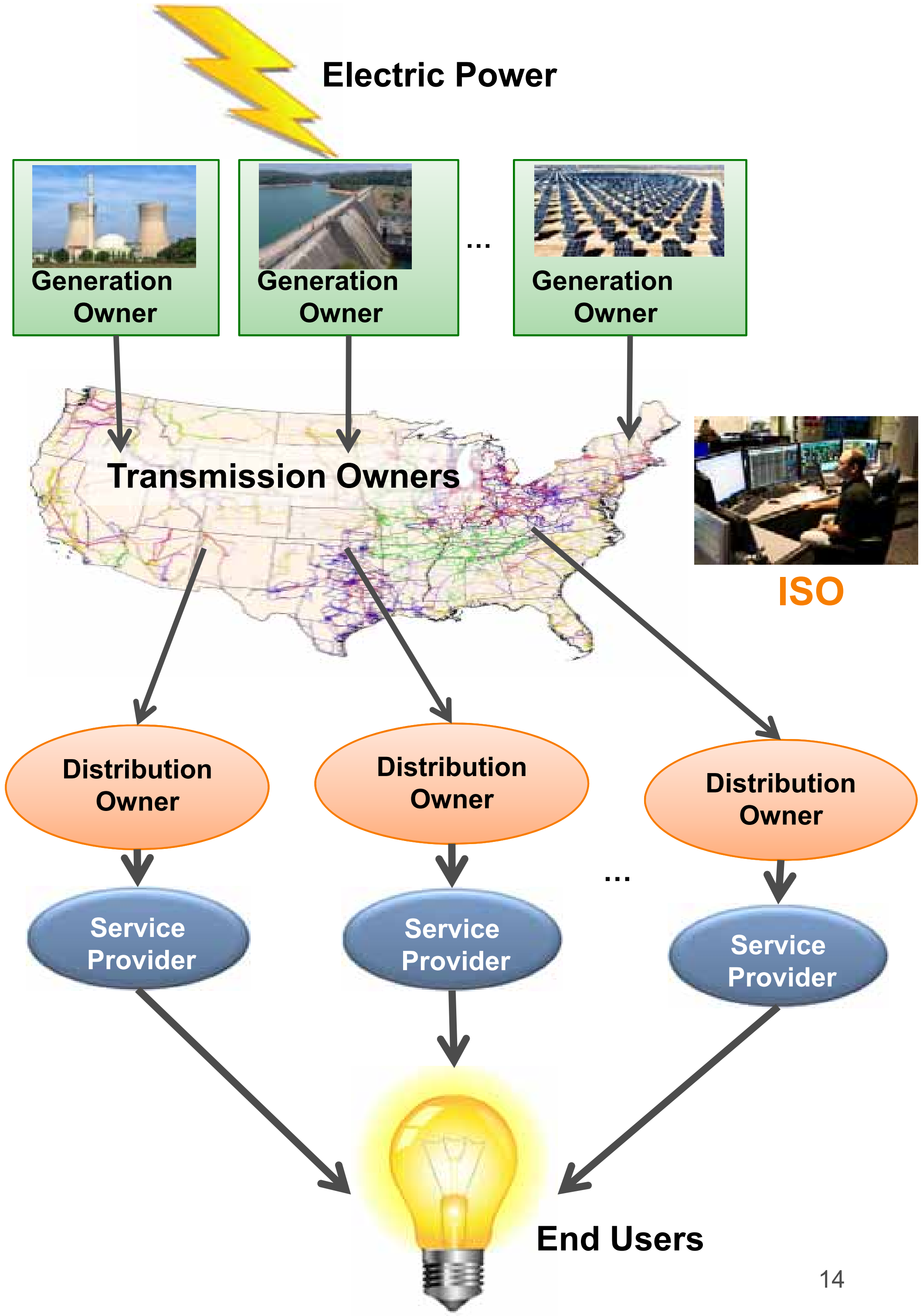
Categories	Examples
Investor-owned utilities 240+ (360+ in 2015), 66.1% of electricity	AEP, American Transmission Co., ConEd, Dominion Power, Duke Energy, Entergy, Exelon, First Energy, Florida Power & Light, Hawaii Electric Co., MidAmerican, National Grid, Northeast Utilities, Oklahoma Gas & Electric, Oncor, Pacific Gas & Electric, Southern California Edison, Tampa Electric Co., We Energies, Xcel Energy, etc.
Publicly owned utilities 2000+, 10.7%	Nonprofit state and local government agencies, including Municipals, Public Power Districts, and Irrigation Districts, e.g. New York Power Authority (NYPA), Long Island Power Authority (LIPA),
Federally owned utilities ~10, 8.2%	Tennessee Valley Authority (TVA), Bonneville Power Administration (BPA), Western Area Power Administration (WAPA), etc.
Cooperatively owned utilities ~1000, 3.1%	Owned by rural farmers and communities
Others 11.9% (growing)	Generating power for own use and/or for sale in whole-sale power markets, e.g. Independent Power Producers (IPPs) such as wind farm operators

E. F. Giles, K. L. Brown, "2015 UDI Directory of Electric Power Producers and Distributors," (123rd Ed), Platts, McGraw Hill Financial, 2014

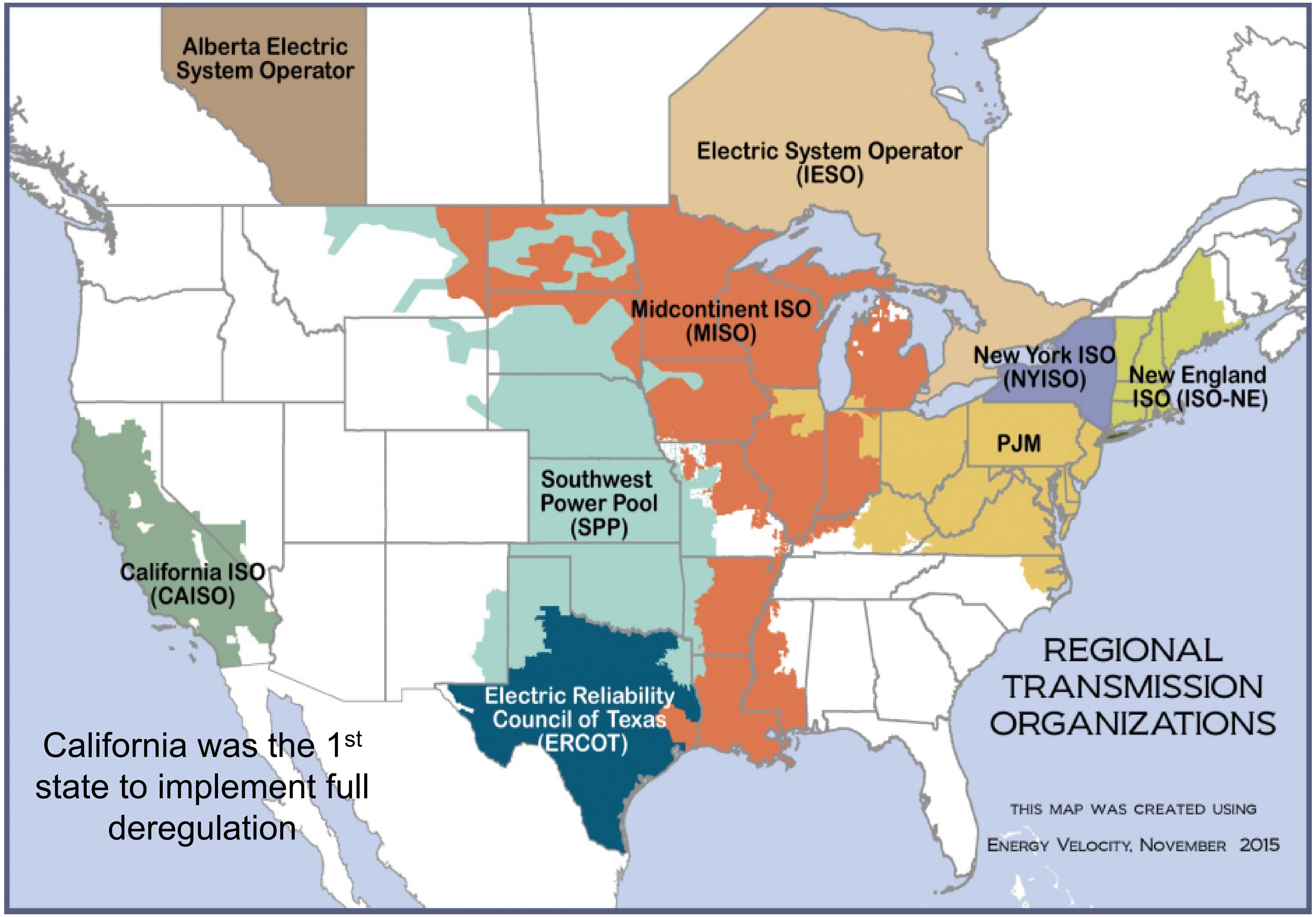
Deregulation

- **Competitive US Power Market Structure**
  - Government sets down rules and laws for market participants to comply with

- Typically, **ISO (Independent System Operator)** determines electricity prices by bid-based, security-constrained, economic dispatch
  - In a day-ahead market, ISO determines a nodal price by
    - matching offers from generation owners to bids from consumers at each node
    - calculating a supply-demand equilibrium of power flows on hourly basis.
  - A locational marginal price (LMP) is the weighted average of nodal prices calculated separately for each load zone.
  - The real-time market establishes the real-time LMP by balancing the differences between day-ahead commitments and actual demands.



Regional Transmission Organizations (RTO) & Independent System Operators (ISO)



Reliability Concerns with Deregulation

"California Electricity Crisis" in 1999-2001

- Before passage of the deregulation law, there was only one Stage-3 rolling blackout (intentional load shedding by utilities) declared.
- After passage, California had 38 Stage-3 rolling blackouts, mainly as a result of a poorly designed market system that was manipulated by traders and marketers.
- In order to sell electricity at a higher price, some trader intentionally encouraged suppliers to shut down plants (removing power from the market) for unnecessary maintenance.

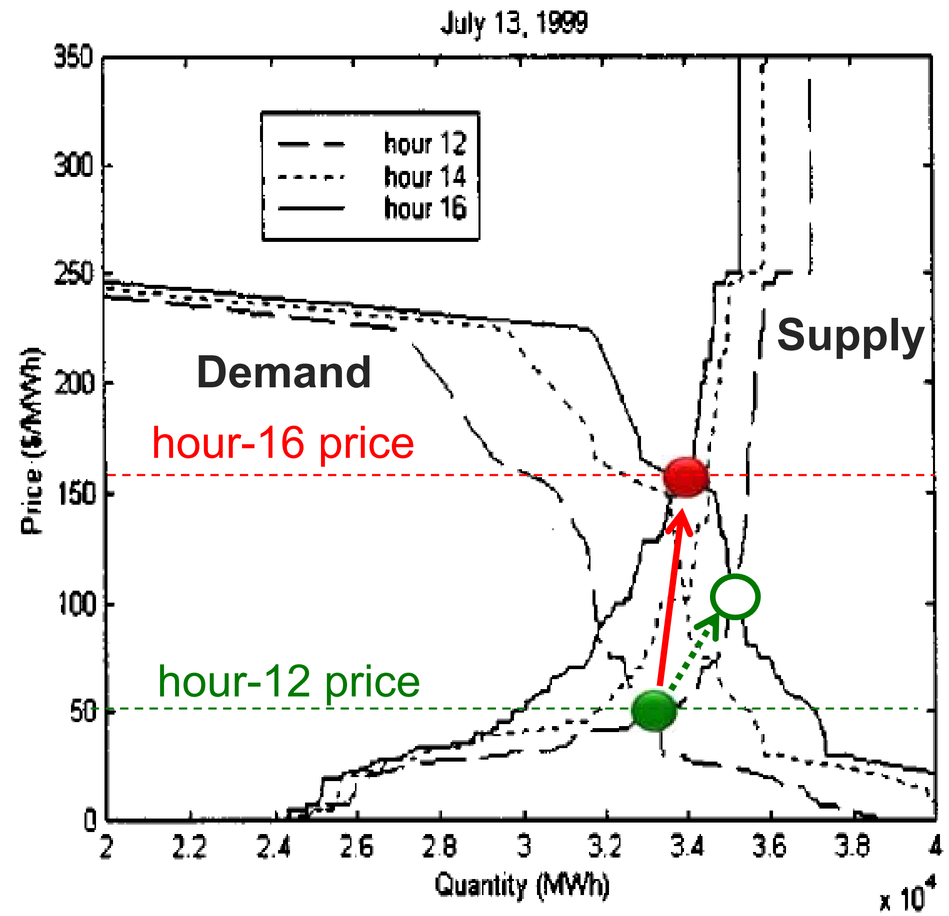
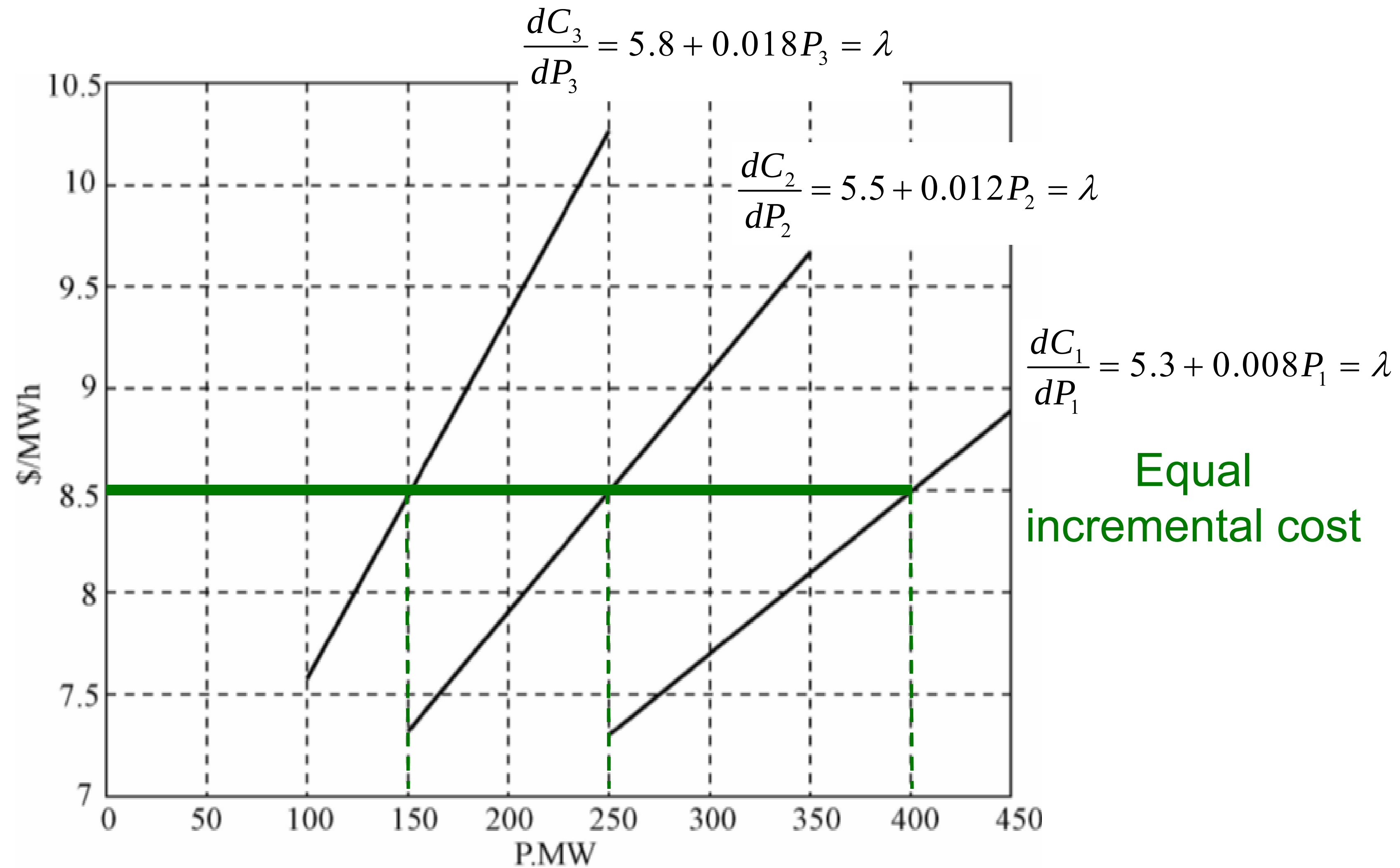


Fig. 7. Aggregated bids for hours 12, 14, and 16, July 13, 1999.

(Source: Wikipedia.org and paper "Gaming and Price Spikes in Electrical Power Market," by X. Guan, et al, on IEEE Trans. Power Systems, Vol. 16, No. 3, Aug 2001.)

- In a traditional economic dispatch, actual fuel cost function C_i of each power plant is known by the dispatcher to decide generations and prices for the equal incremental cost.

- In an electricity market, C_i depends on the bidding strategy and is unnecessarily equal to the fuel cost, so the trader/supplier can play with the bidding strategy for the maximum profit.



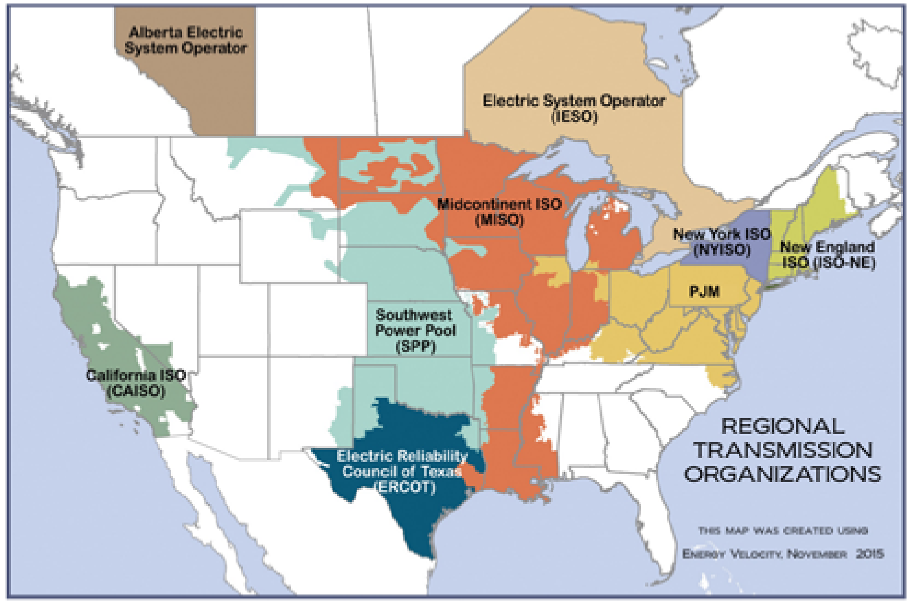
NERC (North American Electric Reliability Corporation)

- As a non-government organization, formed by the electric utility industry in 1968 to promote the reliability of bulk power systems in North America.
- Initially membership was voluntary and member systems followed the reliability criteria for planning and operating bulk power systems to prevent major system disturbances following severe contingencies
- As of June 2007, FERC (U.S. Federal Energy Regulatory Commission) granted NERC the legal authority to enforce reliability criteria with all users, owners, and operators of the bulk power systems in the U.S.
- NERC Membership is now mandatory and member systems comply with NERC's Reliability Standards (approved by FERC) to both promote reliable operations and to avoid costly monetary penalties if caught non-compliant. Every system operator should read, understand and follow NERC's Reliability Standards. (Visit http://www.nerc.com for more information on NERC.)

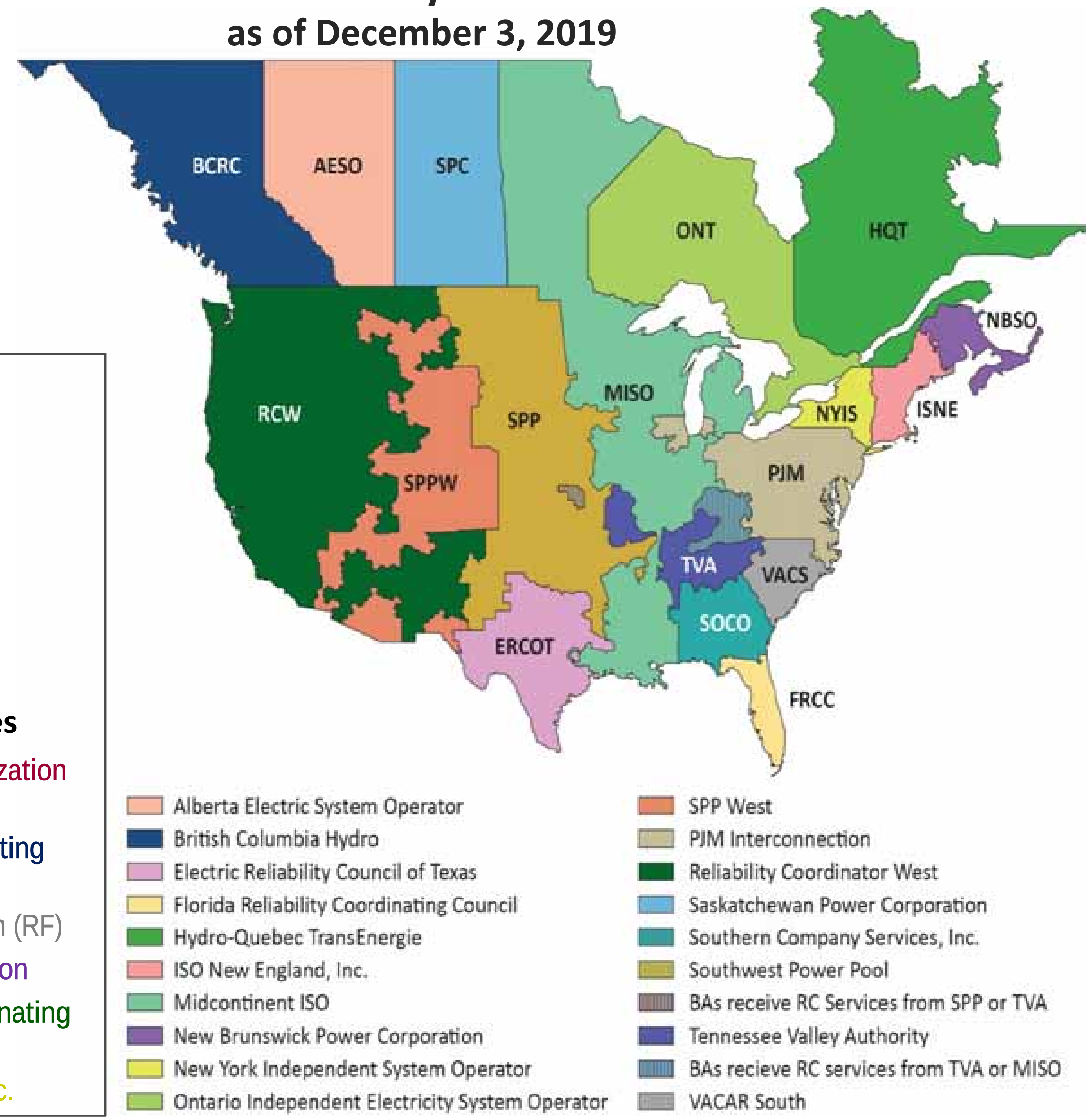
Bulk Power System (BPS) and Bulk Electric System (BES)

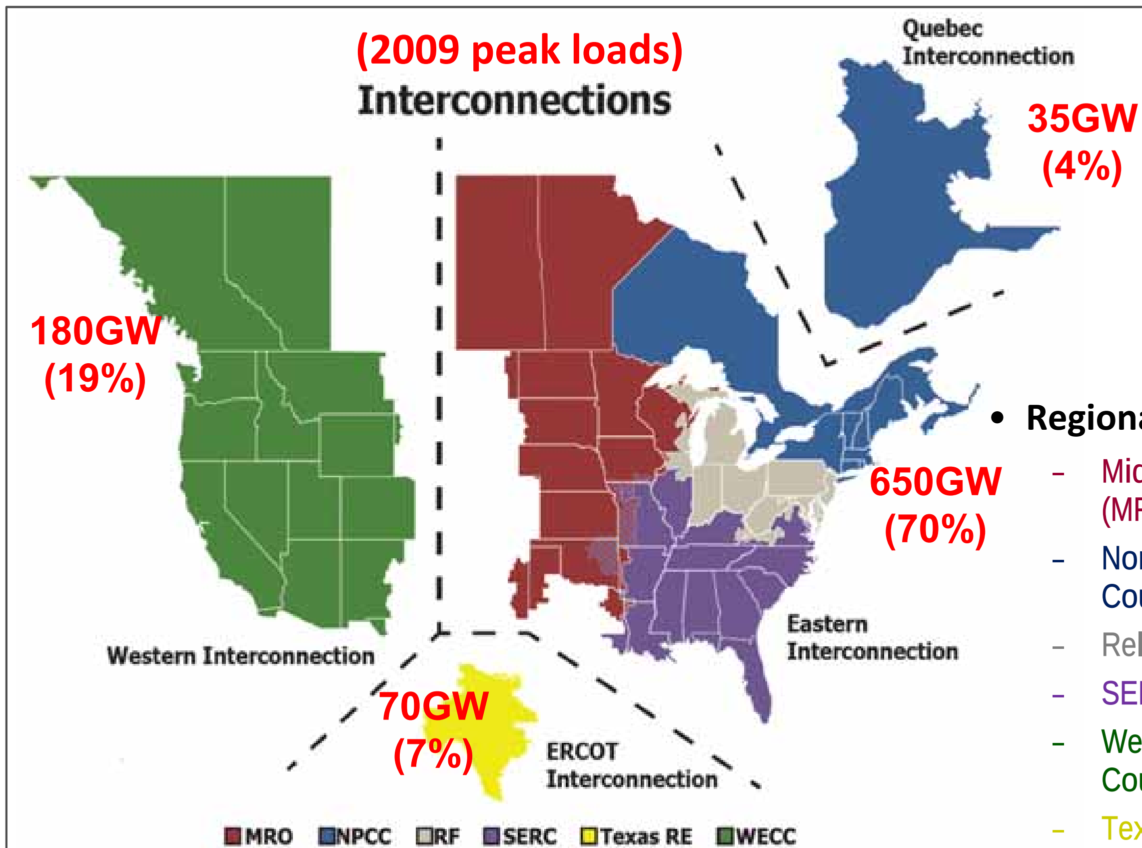
- **"Bulk Power System" (BPS) defined by the Energy Policy Act of 2005**
  - It includes "facilities and control systems necessary for operating an interconnected electric energy transmission network (or any portion thereof) and electric energy from generation facilities needed to maintain transmission system reliability, … not including facilities used in the local distribution of electric energy."
  - BPS is the term to use when generally speaking about the interconnected network or power grid, which includes "Bulk Electric System" (BES).
- **"Bulk Electric System" (BES) defined by NERC**
  - It is a term commonly applied to the portion of an electric utility system that integrates "the electrical generation resources, transmission lines, interconnections with neighboring systems, and associated equipment, generally operated at voltages of 100 kV or higher." Radial transmission facilities serving only load with one transmission source are generally not included in this definition
  - For short, a BES is the part of the transmission/sub-transmission system connecting power plants, major substations, and HV transmission lines
  - BES should be used in the context of applicability of Reliability Standards.

NERC Interconnections, Regions, Coordinators



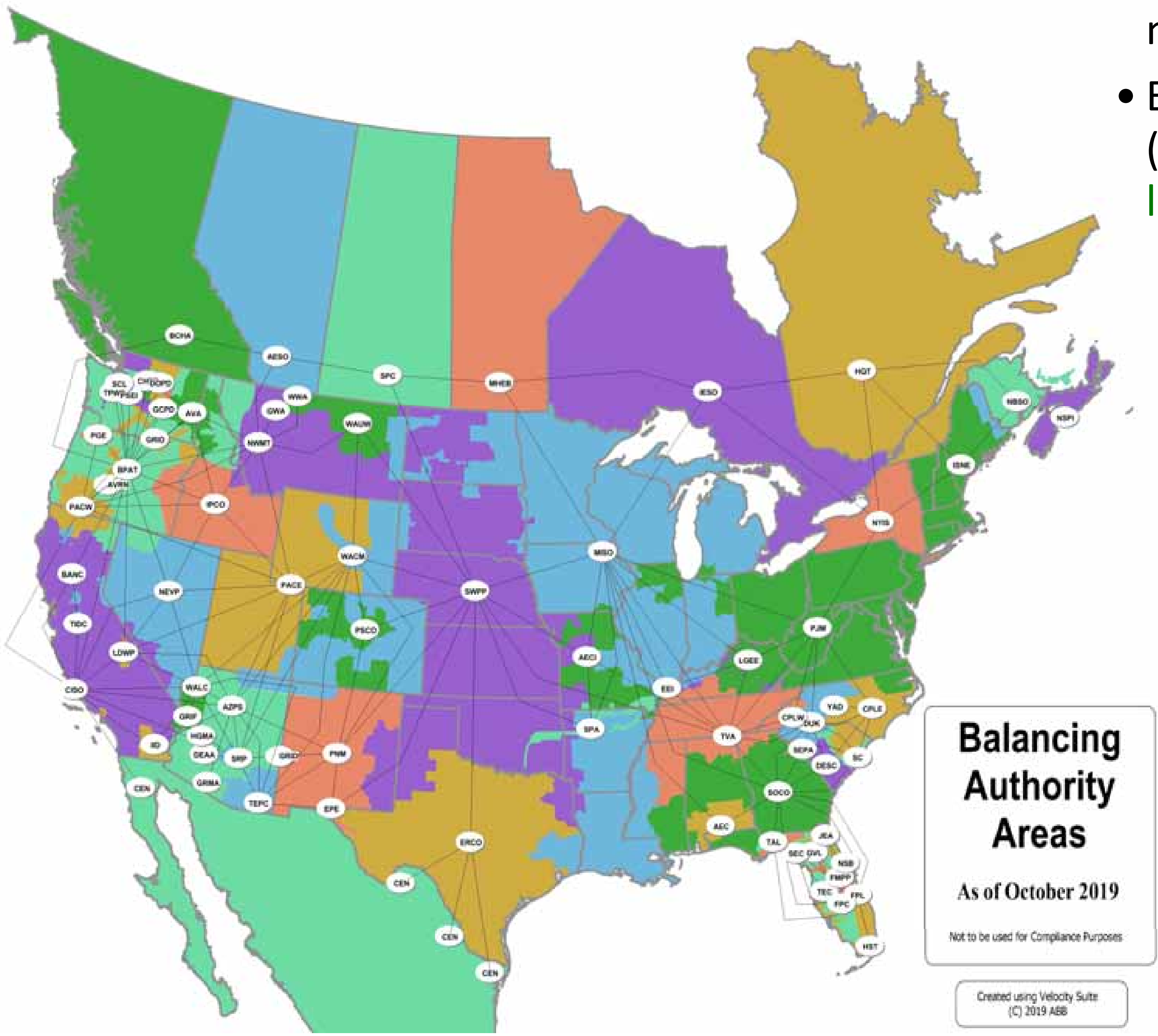
NERC Reliability Coordinators
as of December 3, 2019



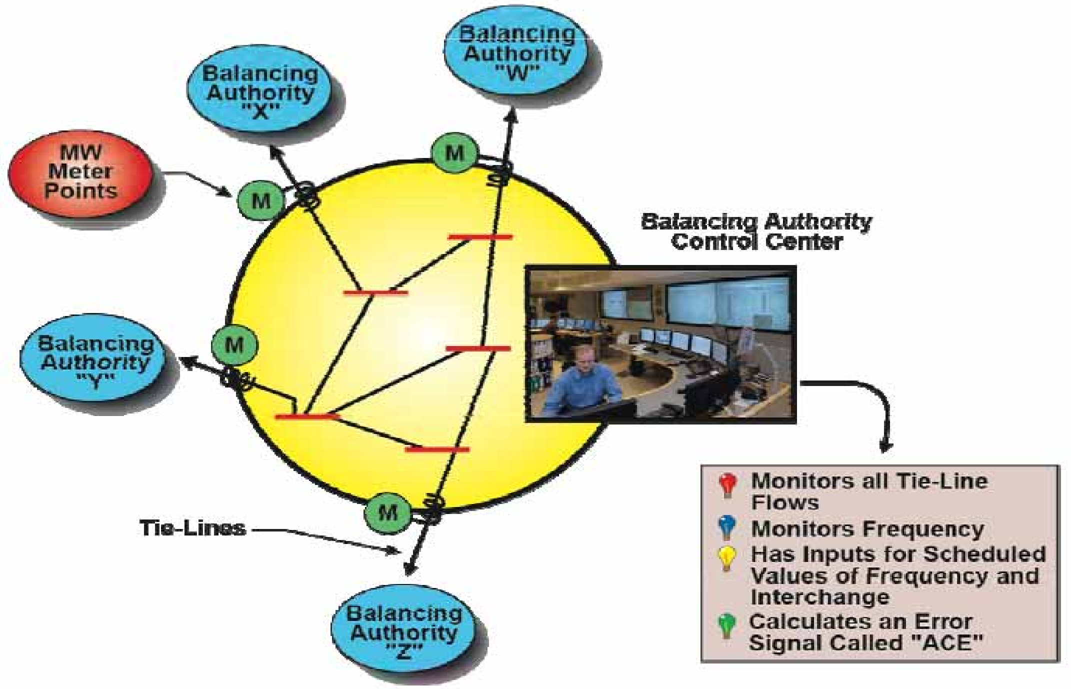


- **Regional Reliability Entities**
  - Midwest Reliability Organization (MRO)
  - Northeast Power Coordinating Council, Inc. (NPCC)
  - ReliabilityFirst Corporation (RF)
  - SERC Reliability Corporation
  - Western Electricity Coordinating Council (WECC)
  - Texas Reliability Entity, Inc.

NERC Balancing Authorities



- Each Balancing Authority (BA) area is responsible for meeting its own load.
- Each BA operates an Automatic Generation Control (AGC) system to balance its generation resources to load requirements:
  - Generation resources: internal or purchased from other BAs and transferred over tie-lines between BAs.
  - Load requirements: internal customer load, losses, or scheduled sales to other BAs.



NERC Functional Model

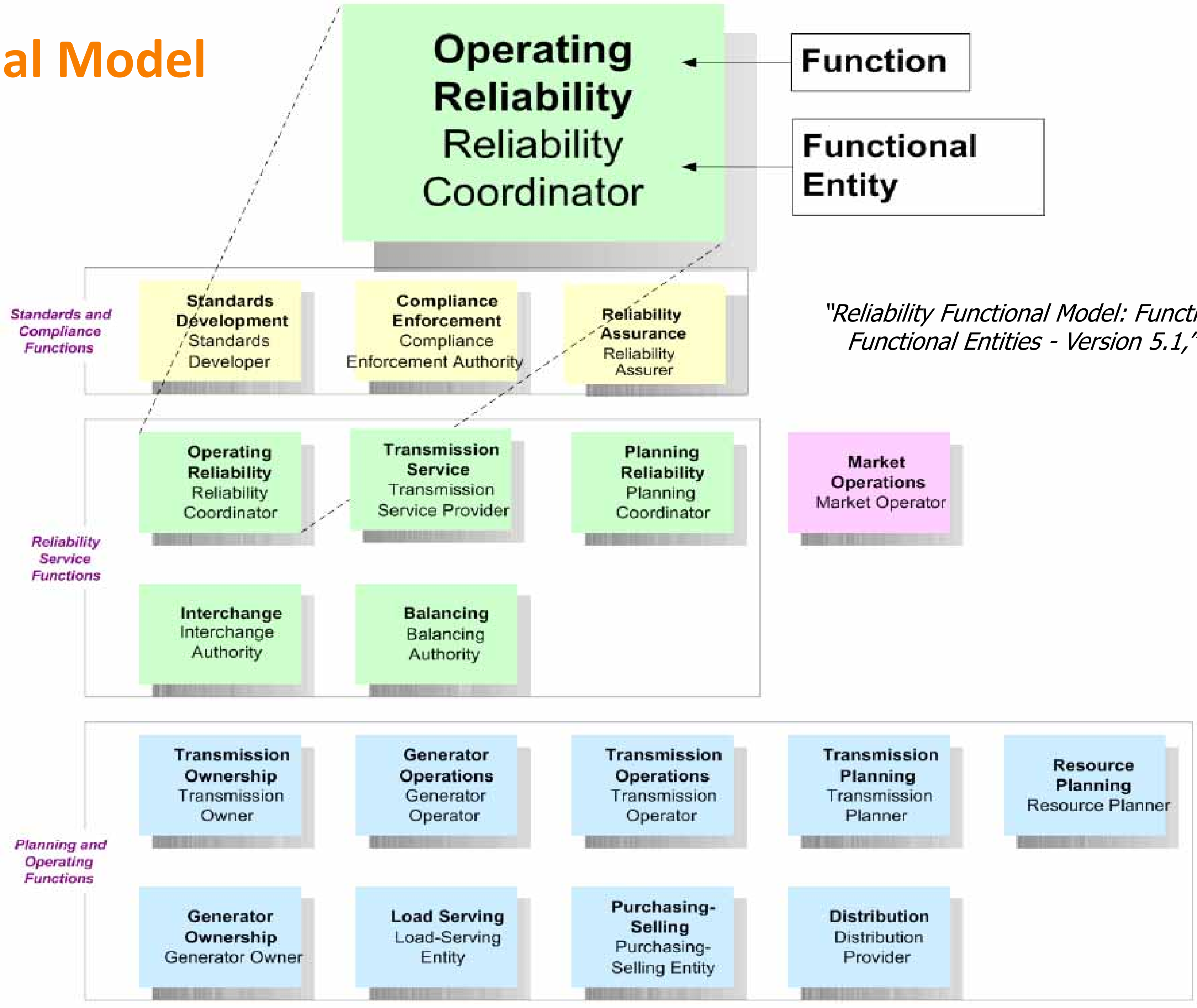


Figure 3 – Function and Functional Entity

"Reliability Functional Model: Function Definitions and Functional Entities - Version 5.1," NERC, 12/2018

System Control Centers

Duke Energy Control Center

(source: Patrick Schneider Photo.Com)

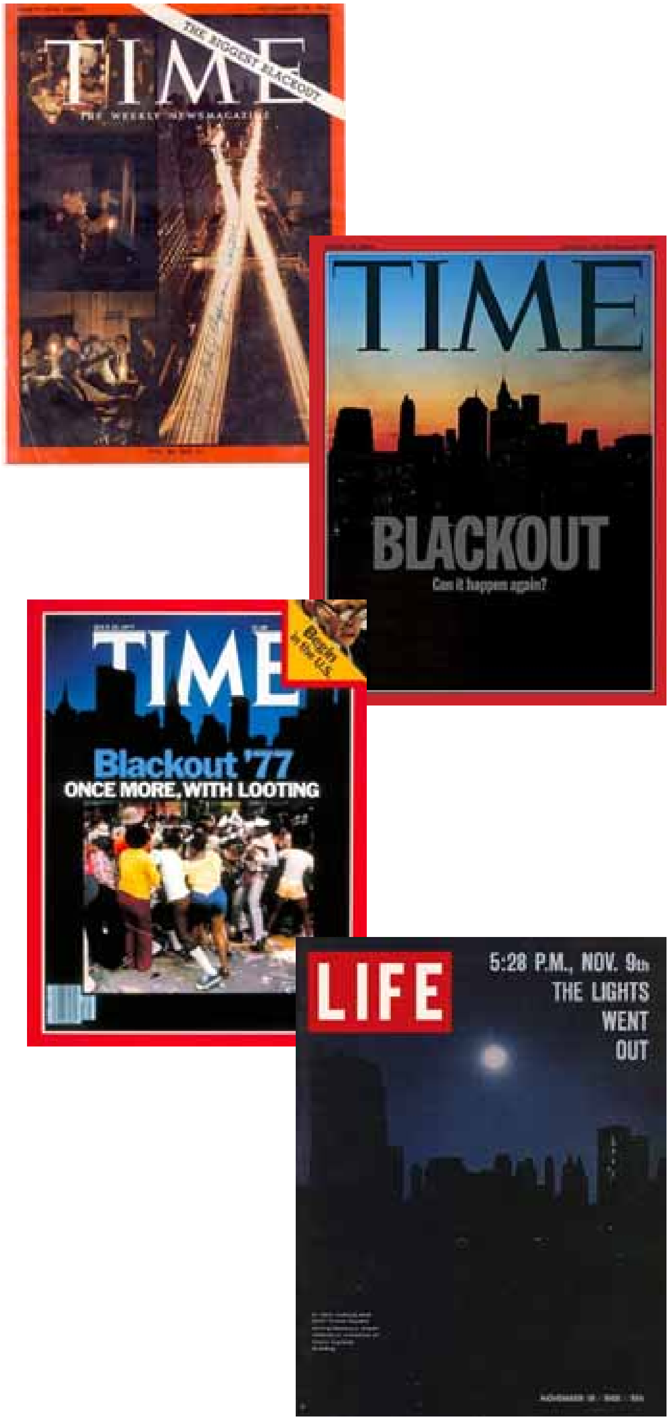
(Source: bayjournal.com)

TVA Control Center

(source: TVA.com)

Power Blackouts in North America

Date	Area	Impacts	Duration
Nov 9, 1965	North America (NE)	20,000+MW, 30M people	13 hrs
Jul 13, 1977	North America (NY)	6,000MW, 9M people	26 hrs
Dec 22, 1982	North America (W)	12, 350 MW, 5M people	
Jul 2-3, 1996	North America (W)	11,850 MW, 2M people	13 hrs
Aug 10, 1996	North America (W)	28,000+MW, 7.5M people	9 hrs
Jun 25, 1998	North America (N-C)	950 MW, 0.15MK people	19 hrs
Aug 14, 2003	North America (N-E)	61,800MW, 50M people	2+ days
Sep 8, 2011	US & Mexico (S-W)	4,300MW, 5M people	12hrs



Contributing Causes of Power Outages

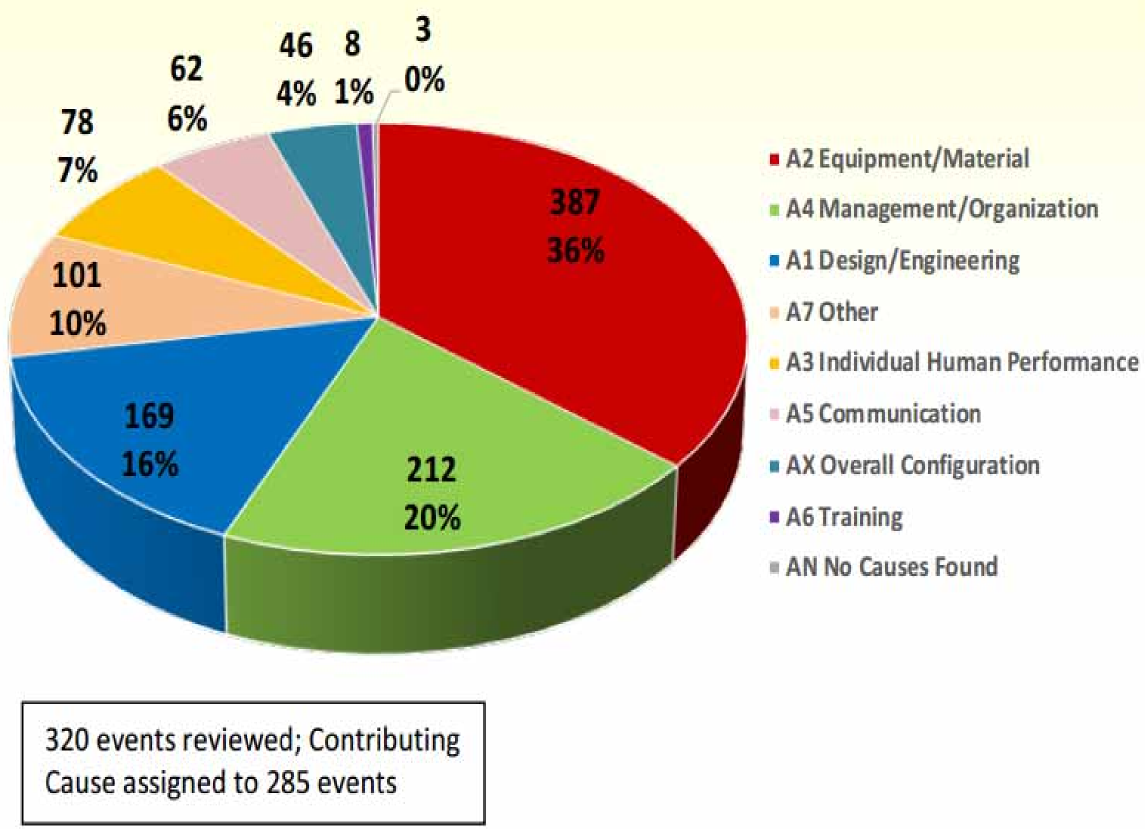


Figure 5.3: The Percentage of Contributing Causes by Major Category

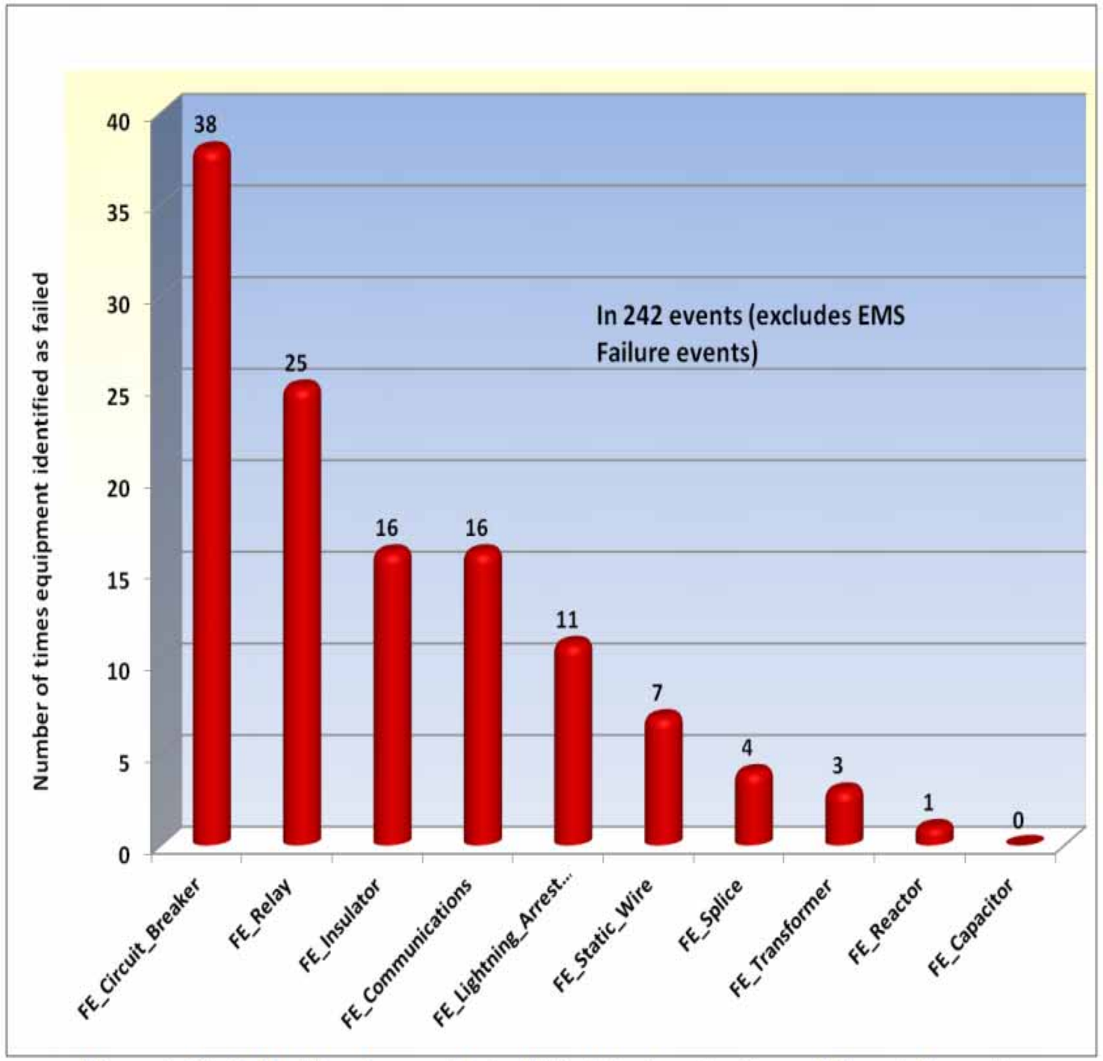


Figure 5.4: Failed Equipment Identified during Review of Event Reports

Source: State of Reliability 2014, NERC, May 2014

Reliability of Bulk Electric Systems

- Power systems should be built and operated to ACHIEVE A RELIABLE ELECTRIC POWER SUPPLY AT THE MOST ECONOMICAL COST

- **Reliability** is defined using two terms:
  - **Adequacy** (planning): The ability of the electric systems to supply the **aggregate electrical demand** and energy requirements of their customers at all times, taking into account scheduled and reasonably expected unscheduled outages of system elements.
  - **Security** (operations): The ability of the electric systems to withstand **sudden disturbances** such as electric short circuits or unanticipated loss of system elements

Reliability of Bulk Electric Systems (cont'd)

- Requirements of a reliable electric power service
  - Voltage and frequency are held within close tolerances
  - Synchronous generators are kept running in parallel with adequate capacity to meet the load demand
  - The "integrity" of the bulk power network (avoid cascading outages) are maintained.

- How are reliability standards used:
  - In Planning, reliability standards should never be violated in designing the system.
  - In Operations, reliability standards should never be intentionally violated although, sometimes, violations do occur due to mis-operations or delayed awareness of the real-time situation.

NERC Planning Events (2013-)

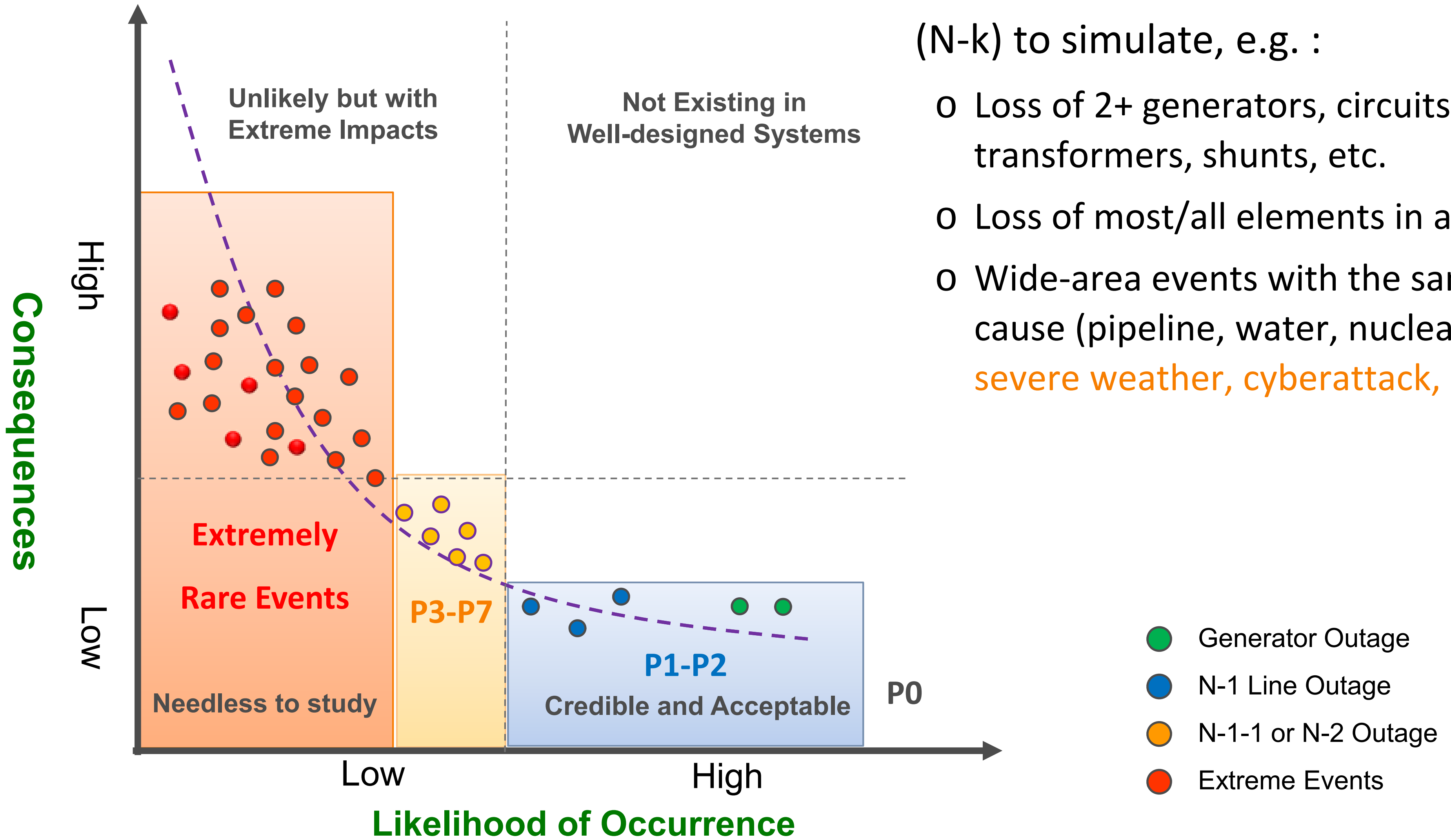
Source: https://www.nerc.com/pa/Stand/Reliability%20Standards/TPL-001-4.pdf

	Category	Initial Condition	Event [1]	Fault Type [2]	BES Level [3]	Interruption of Firm Transmission Service Allowed [4]	Non-Consequential Load Loss Allowed
N-0	**P0** No Contingency	Normal System	None	N/A	EHV, HV	No	No
N-1	**P1** Single Contingency	Normal System	Loss of one of the following: 1. Generator 2. Transmission Circuit 3. Transformer [5] 4. Shunt Device [6]	3Ø	EHV, HV	No[9]	No[12]
			5. Single Pole of a DC line	SLG			
N-1	**P2** Single Contingency	Normal System	1. Opening of a line section w/o a fault [7]	N/A	EHV, HV	No[9]	No[12]
			2. Bus Section Fault	SLG	EHV	No[9]	No
					HV	Yes	Yes
			3. Internal Breaker Fault [8] (non-Bus-tie Breaker)	SLG	EHV	No[9]	No
					HV	Yes	Yes
			4. Internal Breaker Fault (Bus-tie Breaker) [8]	SLG	EHV, HV	Yes	Yes
N-1-1	**P3** Multiple Contingency	Loss of generator unit followed by System adjustments[9]	Loss of one of the following: 1. Generator 2. Transmission Circuit 3. Transformer [5] 4. Shunt Device [6]	3Ø	EHV, HV	No[9]	No[12]
			5. Single pole of a DC line	SLG			
N-2	**P4** Multiple Contingency *(Fault plus stuck breaker[10])*	Normal System	Loss of multiple elements caused by a stuck breaker [10](non-Bus-tie Breaker) attempting to clear a Fault on one of the following: 1. Generator 2. Transmission Circuit 3. Transformer [5] 4. Shunt Device [6] 5. Bus Section	SLG	EHV	No[9]	No
					HV	Yes	Yes
			6. Loss of multiple elements caused by a stuck breaker[10] (Bus-tie Breaker) attempting to clear a Fault on the associated bus	SLG	EHV, HV	Yes	Yes
N-2	**P5** Multiple Contingency *(Fault plus relay failure to operate)*	Normal System	Delayed Fault Clearing due to the failure of a non-redundant relay[13] protecting the Faulted element to operate as designed, for one of the following: 1. Generator 2. Transmission Circuit 3. Transformer [5] 4. Shunt Device [6] 5. Bus Section	SLG	EHV	No[9]	No
					HV	Yes	Yes
N-1-1	**P6** Multiple Contingency *(Two overlapping singles)*	Loss of one of the following followed by System adjustments.[9] 1. Transmission Circuit 2. Transformer [5] 3. Shunt Device[6] 4. Single pole of a DC line	Loss of one of the following: 1. Transmission Circuit 2. Transformer [5] 3. Shunt Device [6]	3Ø	EHV, HV	Yes	Yes
			4. Single pole of a DC line	SLG	EHV, HV	Yes	Yes
N-2	**P7** Multiple Contingency *(Common Structure)*	Normal System	The loss of: 1. Any two adjacent (vertically or horizontally) circuits on common structure [11] 2. Loss of a bipolar DC line	SLG	EHV, HV	Yes	Yes

Summary of NERC Contingencies

Category	Events
P0 No contingency (~ Category A before 2013)	• Normal system (N-0)
P1-P2 Single Contingency (~ Category B before 2013)	• Normal system losing 1 element (e.g. generator, line, transformer, shunt and bus section) with or without a fault (N-1)
P3-P7 Multiple Contingency (~ Category C/D before 2013)	• N-1 system losing 1 element (N-1-1) • Normal system losing multiple elements (N-k) at the same location due to a stuck breaker or delayed fault clearing • Normal system losing 2 adjacent circuits (N-2)

NERC Contingencies

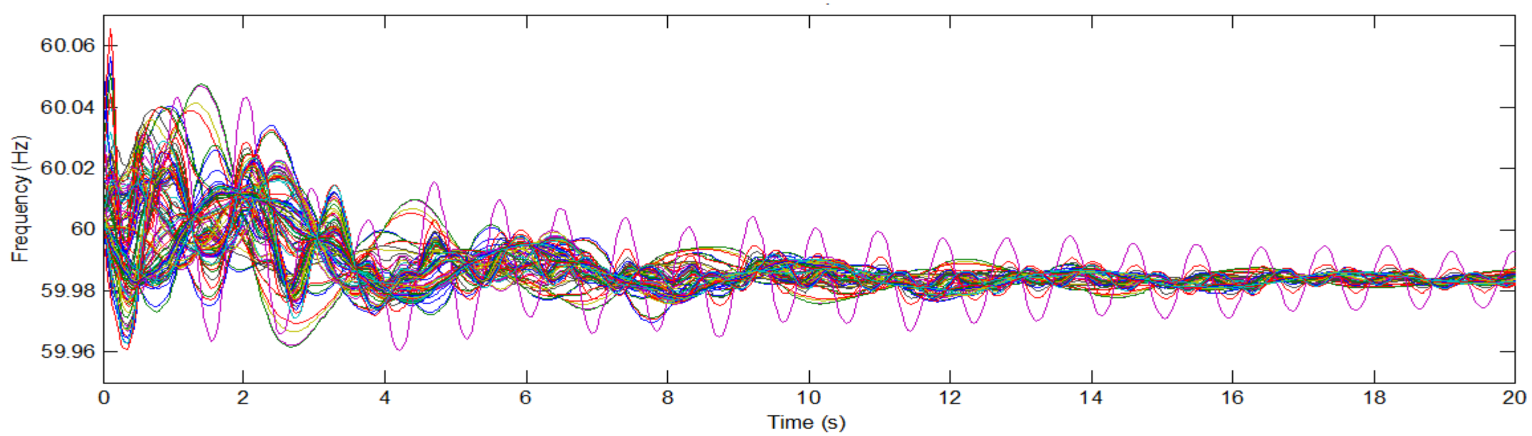


- Utilities select some of extreme events (N-k) to simulate, e.g. :
  - Loss of 2+ generators, circuits, transformers, shunts, etc.
  - Loss of most/all elements in a local area
  - Wide-area events with the same root cause (pipeline, water, nuclear, wildfires, severe weather, cyberattack, etc.)

Some extreme events may happen more often when system is stressed (e.g. under severe weather conditions)

Terminology

- Operating quantities: Physical quantities (measured or calculated) that can be used to describe the operating conditions of a power system, e.g. real, reactive and apparent powers, RMS values/phasors of alternating voltages and currents.
- Steady-state operating condition of a power system: An operating condition of a power system in which all the operating quantities that characterize it can be considered to be constant for the purpose of analysis.
- Synchronous operation:
  - A machine is in synchronous operation with another machine or a network to which it is connected if its average electrical speed ($=\omega \cdot p/2$) is equal to the electric speed of the other machine or the angular frequency of the ac network.
  - A power system is in synchronous operation if all its connected synchronous machines are in synchronous operation with the ac network and with each other.

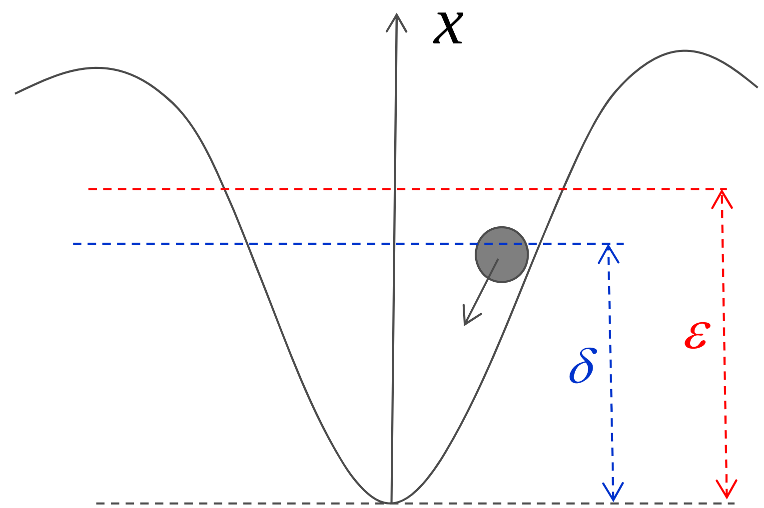


Stability on a General Dynamical System

- In mathematics, stability theory addresses the stability of solutions of a set of differential equations, or in other words, stability of trajectories of a dynamical system under small perturbations of an initial condition.
- **Lyapunov Stability:** Consider a nonlinear dynamical system

$$\dot{x} = f(t, x) \qquad (1)$$

Assume origin x=0 is an equilibrium, i.e. $f(t, 0) = 0, \forall\, t \geq 0$

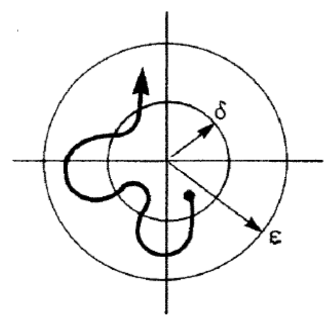


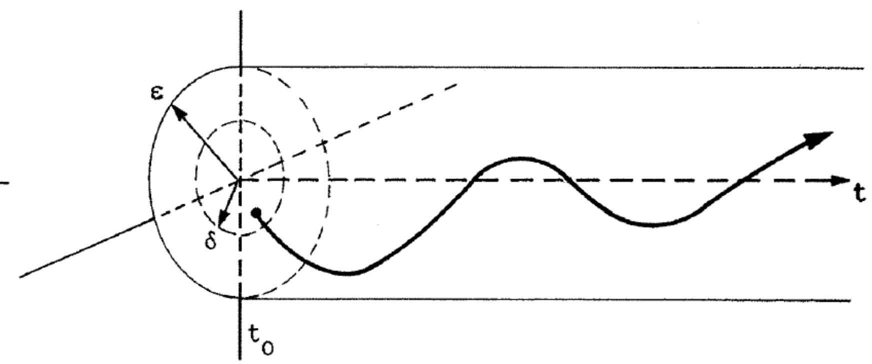
The equilibrium point x=0 is stable in the sense of Lyapunov

if, for each $\varepsilon > 0$, there is $\delta = \delta(\varepsilon, t_0) > 0$ such that

$$\|x(t_0)\| < \delta \Rightarrow \|x(t)\| < \varepsilon, \quad \forall\, t \geq t_0 \geq 0 \qquad (2)$$

In other words, the system variable will stay in any given small region (<ε) around the equilibrium point once becoming close enough (<δ) to that point.



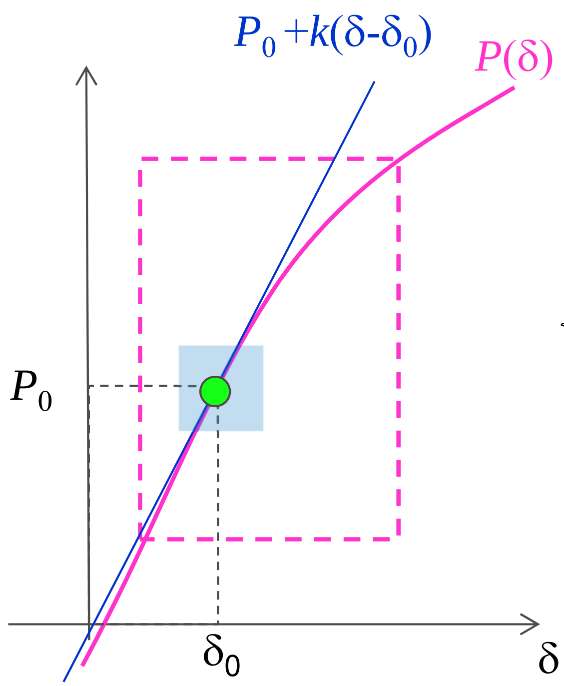


Terminology (cont'd)

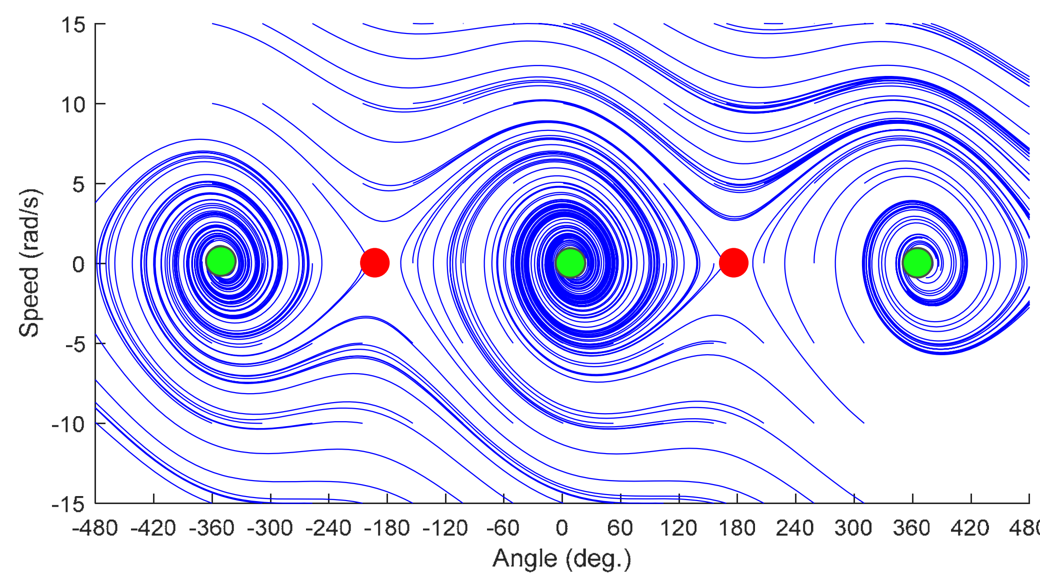
- Power system stability is the ability of a power system, for a given initial operating condition, to regain an acceptable state of operating equilibrium (either original or different) after being subjected to a disturbance
  - Stability of a power system is concerned on the state variables that are defined.
  - Considering an interconnected, multi-machine power system as a whole
    - its conventional stability problem is mainly to maintain synchronous operation of all synchronous machines (generators or motors)
  - Considering parts of the system
    - A particular generator or group of generators may lose stability (synchronism) and then be disconnected without causing instability of the main system.
    - Motors in particular loads may lose stability (stalling) without causing instability of the main system.

Terminology (cont'd)

- Disturbance is a sudden change or a sequence of changes in one or more parameters or operating quantities of the power system.
  - Small disturbance: if the system model can be linearized without affecting the accuracy of stability analysis. An example is a load change. What exactly happened is unimportant to analysis.
  - Large disturbance: if the system model cannot be linearized. Examples are a short circuit and loss of a generator or load. Details of the disturbance are important to accurate analysis.



$$\begin{cases} \dfrac{d\omega}{dt} = \dfrac{1}{2H}P_m - \dfrac{1}{2H}P(\delta) \\ \dfrac{d\delta}{dt} = \omega \end{cases}$$



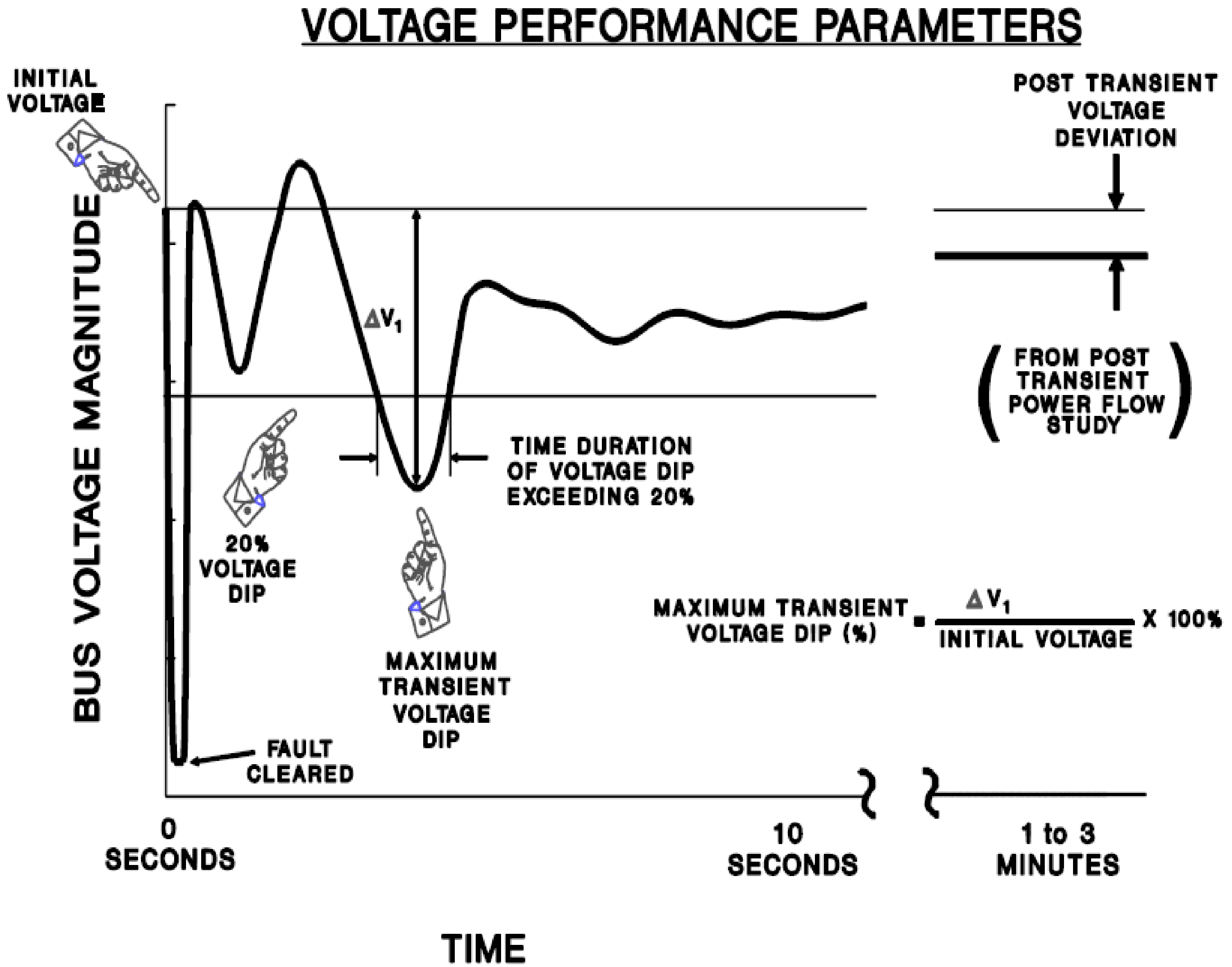
Why dynamic analysis

- In designing and operating an interconnected power system, its dynamic performance subjected to changes (i.e. contingencies, either small or large) is considered.

- It is important that when the changes are completed, the system settles to a new operating condition without violation of constraints.

- In other words, not only should the new operating condition be acceptable (as revealed by steady-state analysis) but also the system must survive the transition to the new condition. This requires dynamic analysis.

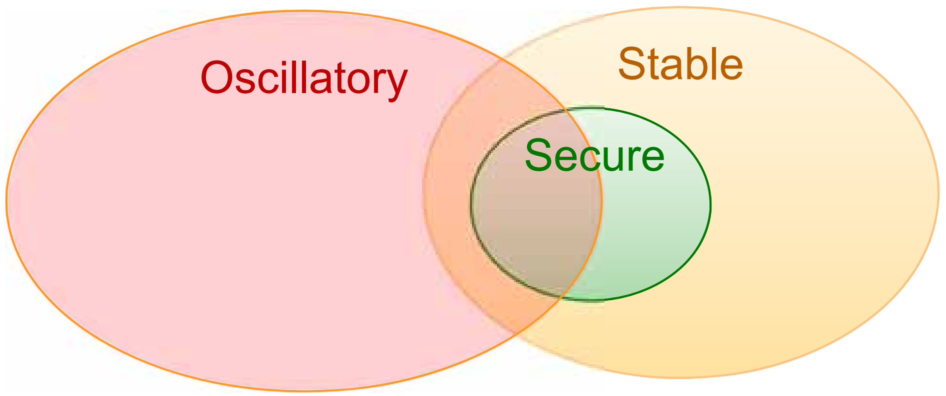
Example: FIDVR (Fault-Induced Delayed Voltage Recovery)



NERC/WECC Planning standards require that following a single contingency,

- Voltage dip should not exceed 25% at load buses or 30% at non-load buses
- Voltage dip should not exceed 20% for more than 20 cycles at load buses
- Post-transient voltage deviation not exceed 5% at any bus

Some Close Terms on Power System Dynamic Performance



Secure (vs. Insecure)

No violation of given security criteria

Stable (vs. Unstable)

Able to regain an equilibrium following a disturbance.

(A stable power system may not be secure if the equilibrium or the transition to the equilibrium violates security criteria)

Oscillatory

An operating quantity repetitively changes at some frequency around a central value (equilibrium).

(When oscillation becomes uncontrollable to damage generators and other equipment, the system will become insecure and even unstable)

Classification of Power System Stability

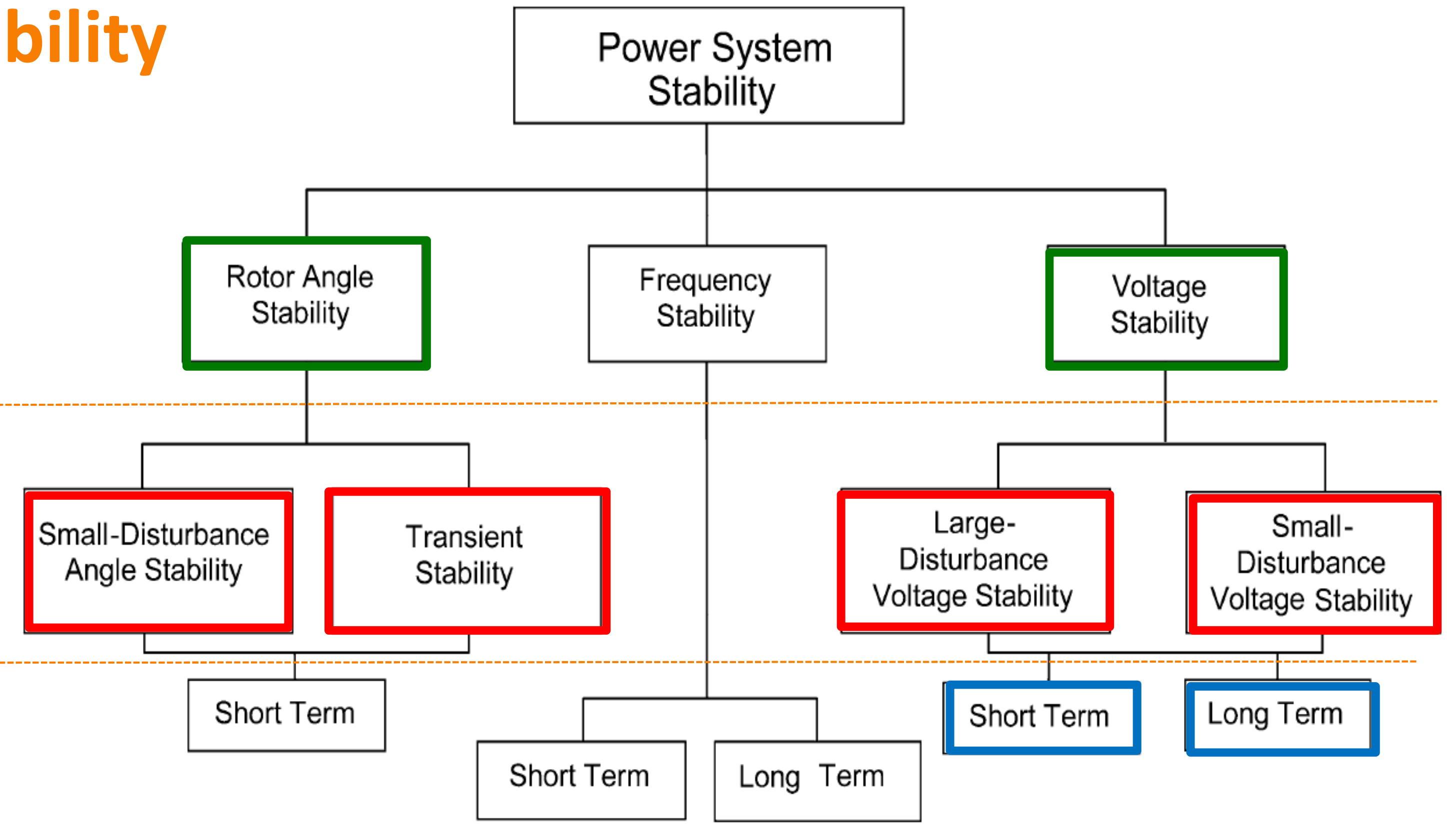
- Power system stability is essentially a single, nonlinear system stability problem.

- However, the various forms of instabilities that a power system may undergo cannot be properly understood and effectively dealt with by treating it as a single problem.

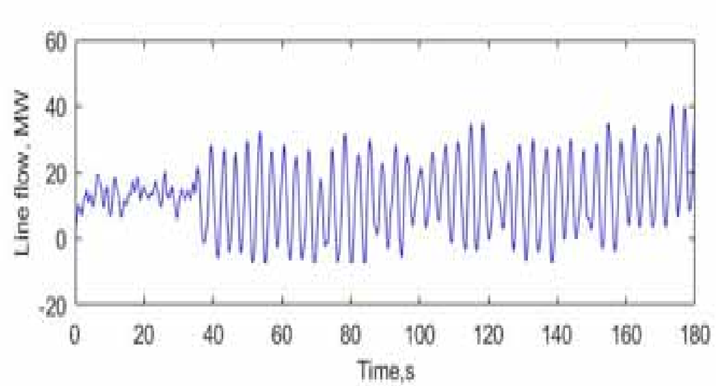
- Because of high dimensionality and complexity of stability problems, it helps to make simplifying assumptions to analyze specific types of problems using an appropriate degree of detail of system representation and appropriate analytical techniques.

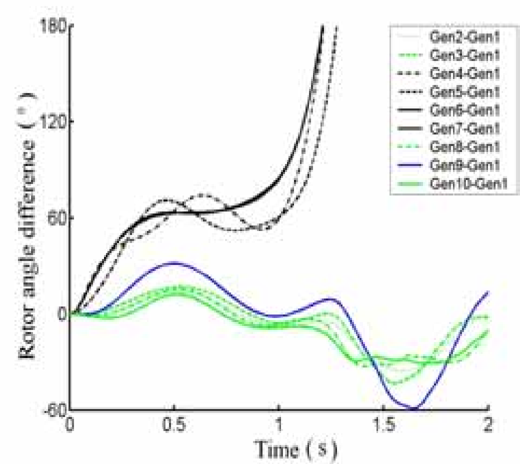
- Analysis of stability, including identifying key factors that contribute to instability and devising methods of improving stable operation, is greatly facilitated by classification of stability into appropriate categories

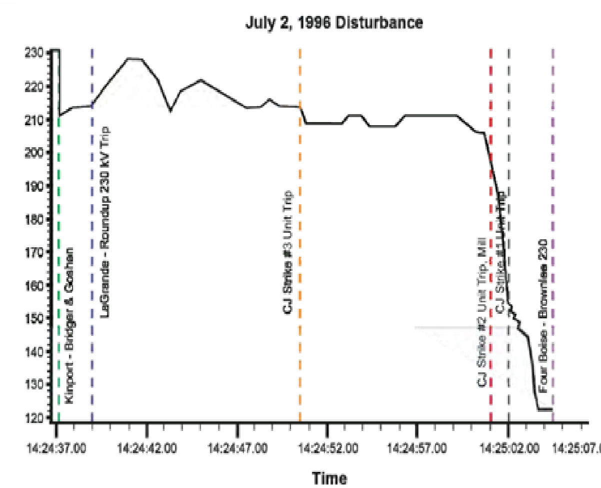
Classification of Power System Stability



- By the physical nature of the resulting mode of instability as indicated by the main system variable (angle, frequency or voltage) in which instability can be observed.
- By the size of the disturbance (small or large) considered, which influences the method of calculation and prediction of stability.
- By the devices, processes and time span that must be taken into consideration in order to assess stability. Typical ranges of time periods:
  - Transient or short-term: 0-10s
  - Mid-term: 10s to several minutes
  - Long-term: several to tens of minutes



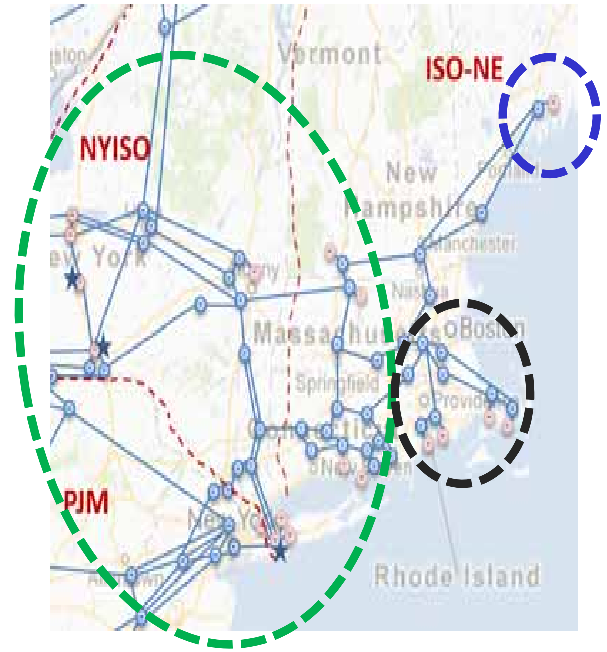




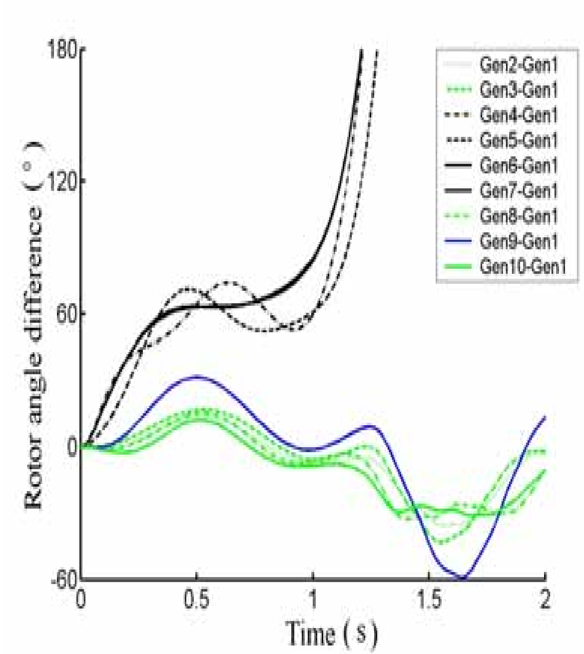
IEEE/CIGRE Joint Task Force on Stability Terms and Definitions, "Definition and Classification of Power System Stability," IEEE TPWRS, May 2004.

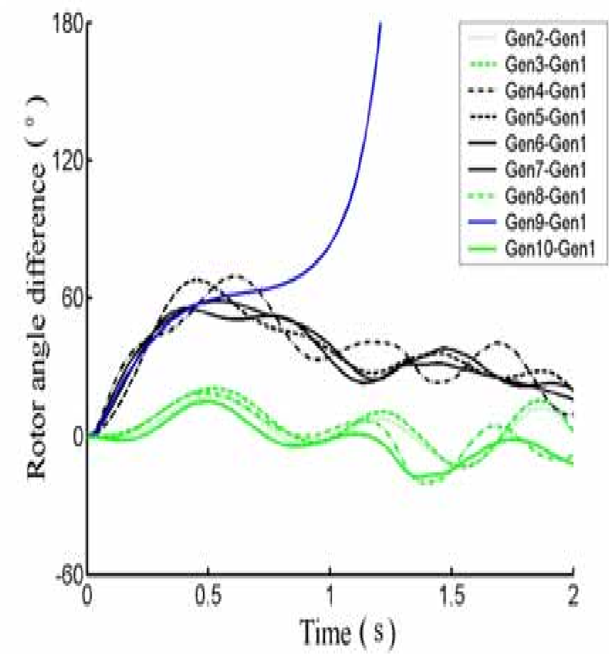
Rotor Angle Stability

- Rotor Angle Stability (also called angle stability or angular stability) refers to the ability of synchronous machines of an interconnected power system to remain in synchronism after being subjected to a disturbance.
- Phenomenon of instability: increasing angular swings of some generators leading to their loss of synchronism with others.



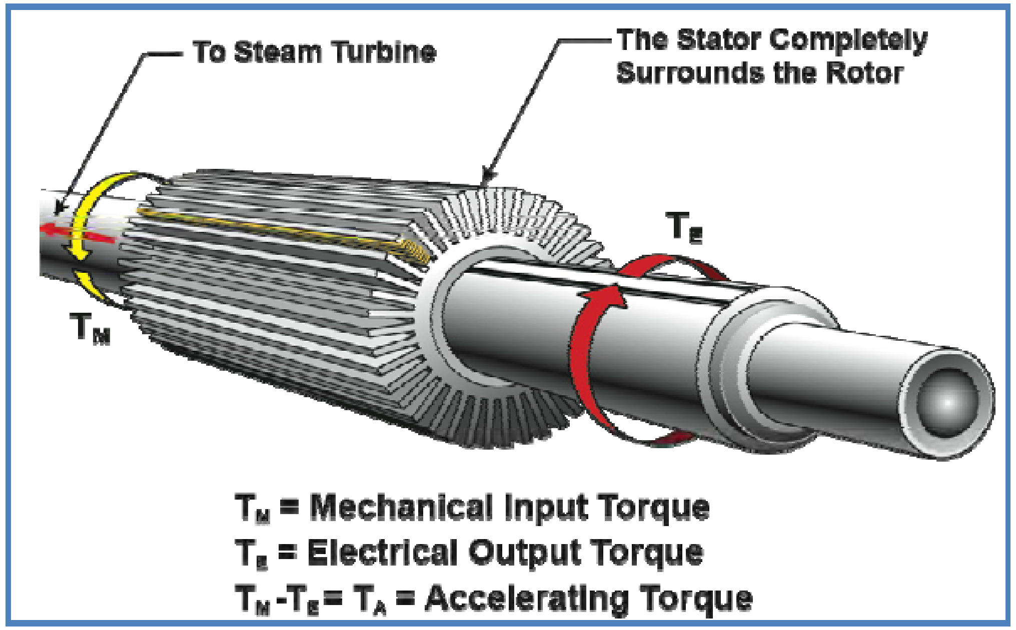
- The term "dynamic stability" appeared in some old literature meaning a class of rotor angle stability.
  - In North American literature, it mostly denotes small signal stability.
  - In European literature, it denotes transient stability.
  - Both CIGRE and IEEE recommended against its usage.

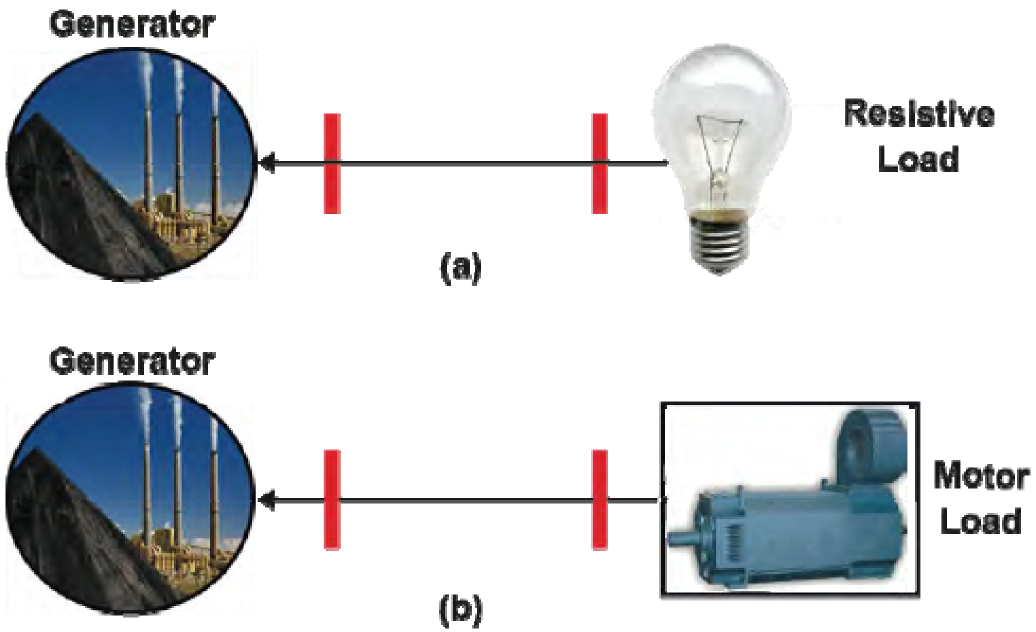




Rotor Angle Stability (cont'd)

- Rotor angle stability depends on the ability to maintain/restore equilibrium between the mechanical torque (controlled) and electromagnetic torque (somehow uncontrolled subject to the load) of each synchronous machine in the system.
- For a simple power system having only one generator tied to a load bus, only when both sides have rotating mass, rotor angle stability can be a concern.

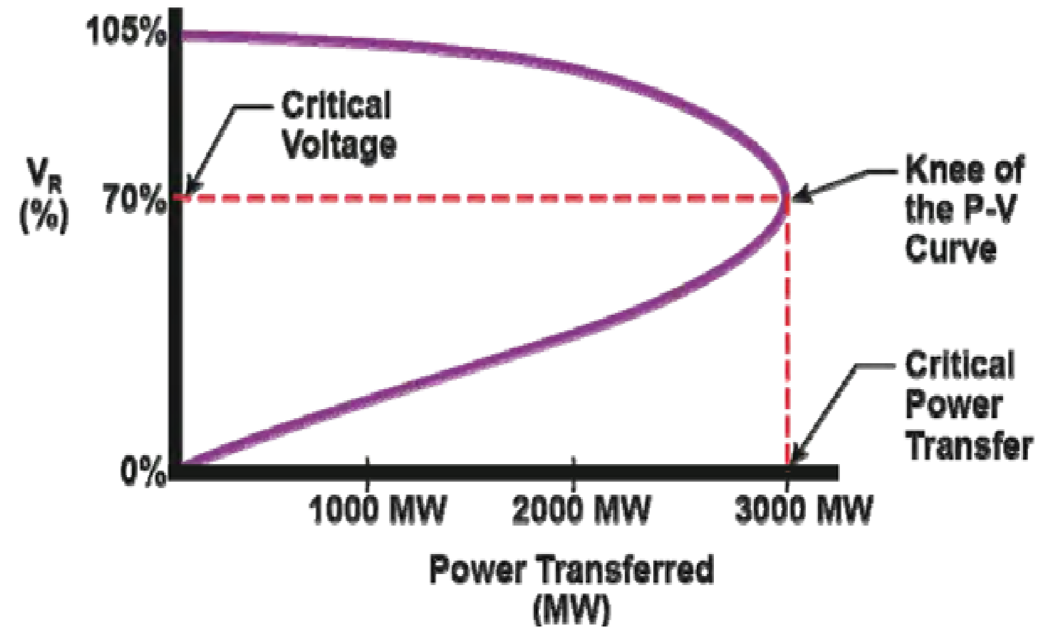




Voltage Stability

- Voltage stability refers to the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition.

- The term voltage collapse is also often used. It is the process by which the sequence of events accompanying voltage instability leads to a blackout or abnormally low voltages in a significant part of the power system.



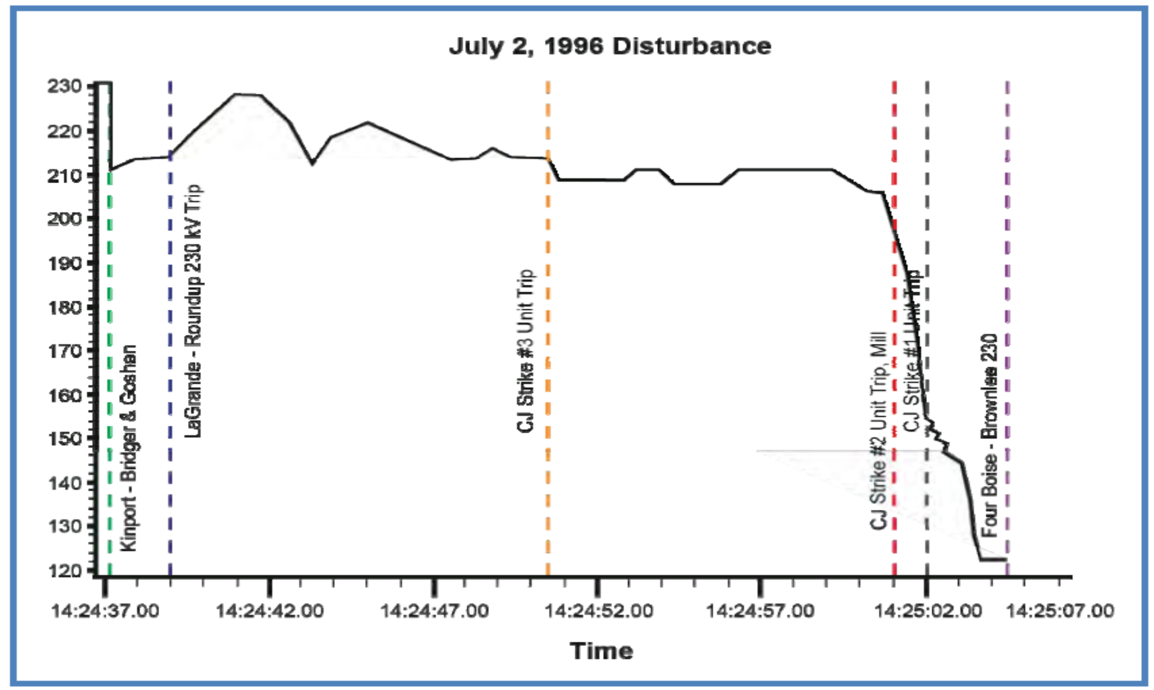
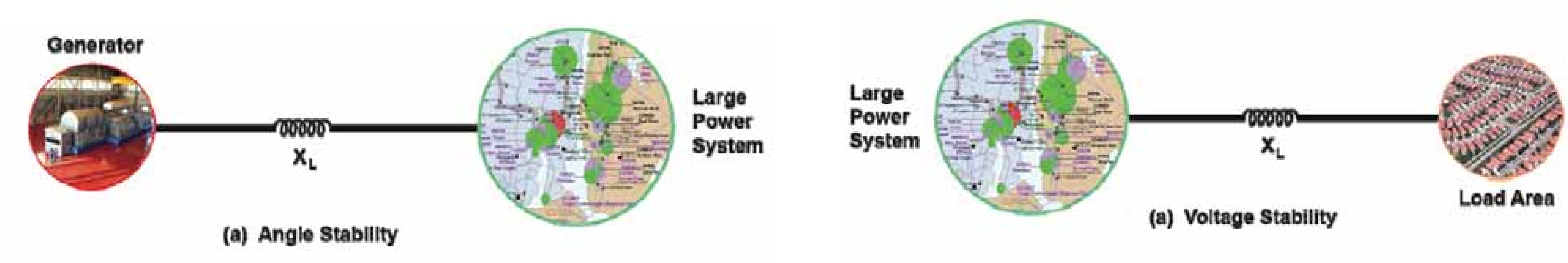


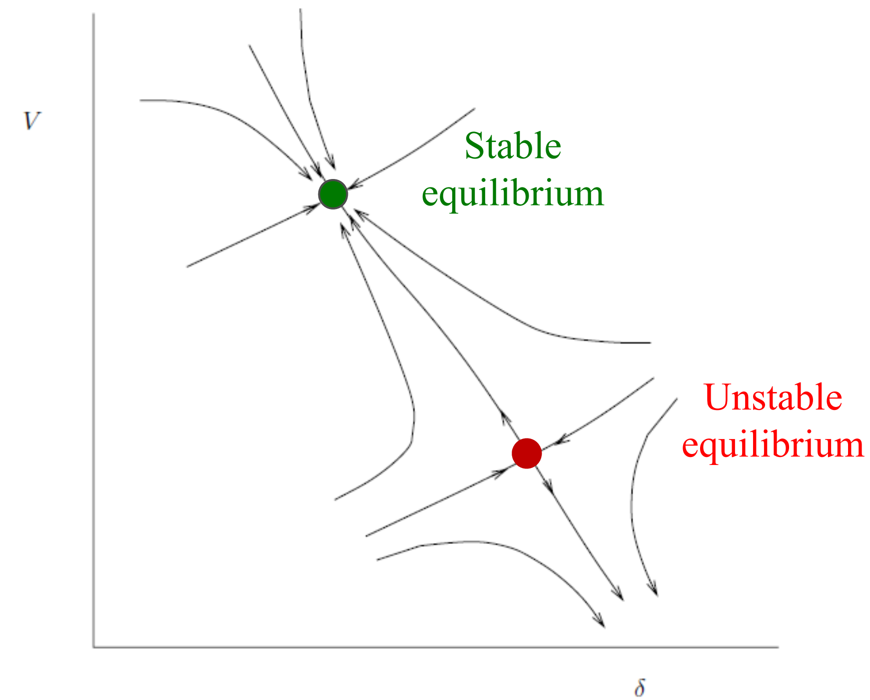
Figure 6-23. Boise 230 kV Voltage Collapse

Rotor Angle Stability vs. Voltage Stability

- Typical systems vulnerable to two stability problems

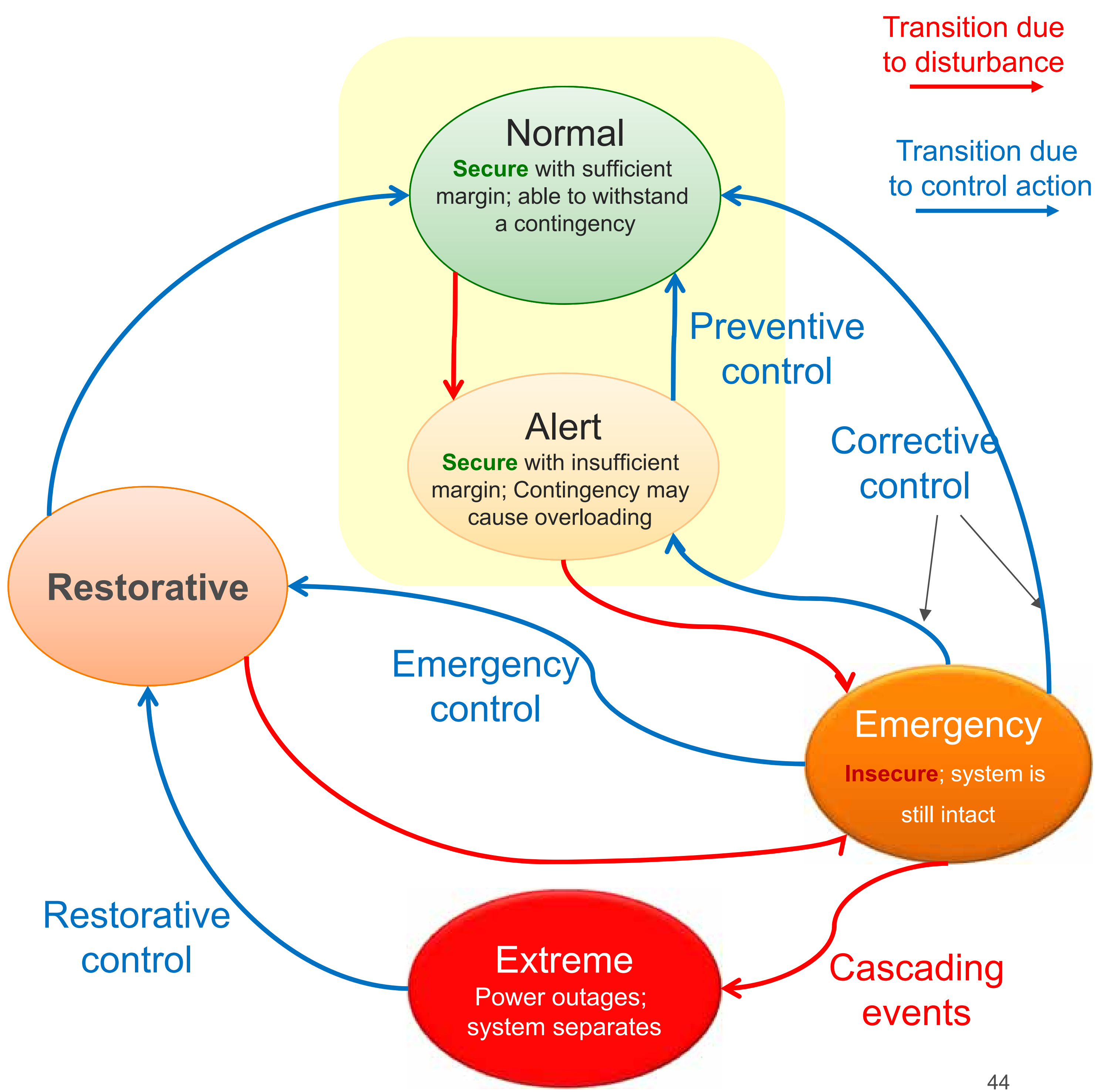


- However, the phenomena of two instabilities often occur together
  - As rotor angles between two groups of generators approach 180°, the loss of synchronism causes rapid voltage drops at intermediate points in the network (this is a principle of out of step protection).
  - The outages caused by voltage collapse or from operating conditions that violate generator field current limits may result in loss of synchronism of some generators.
- Difference in causes:
  - Rotor angle instability occurs when the angle/speed of a rotor does not go back to its stable equilibrium under a disturbance (*exiting the domain of attraction of a stable equilibrium*).
  - Voltage instability occurs when the stable equilibrium itself disappears or changes due to a switch in the system or a load increase (*bifurcation*).



System Operations

- Establish most economical operating conditions under "normal" circumstances
- Operate the system such that if an unscheduled event occurs, it does not result in uncontrolled or cascading outages
- Use reliability criteria in designing and operating the system to ensures:
  - for all frequently occurring contingencies (i.e. N-1 and N-2), the system will, at worst, transit from the normal state to the alert state, rather than to a more severe state such as the emergency state or the extreme state;
  - when the system enters the alert state following a contingency, operators can take actions to return the system to the normal state.



Structure of a Power System and Associated Controls