ECEN 460
Power System Operation and Control
Spring 2025

Lecture 17: Power System Stability

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TEXAS A&M UNIVERSITY

Design Project Overview

- The goal of the project is to give experience in planning new transmission for a relatively large-scale electric grid while working as part of a four person engineering design team
- Project is motivated by the July 2024 ERCOT report to plan for new transmission in the Permian Basin to accommodate large amounts of new load

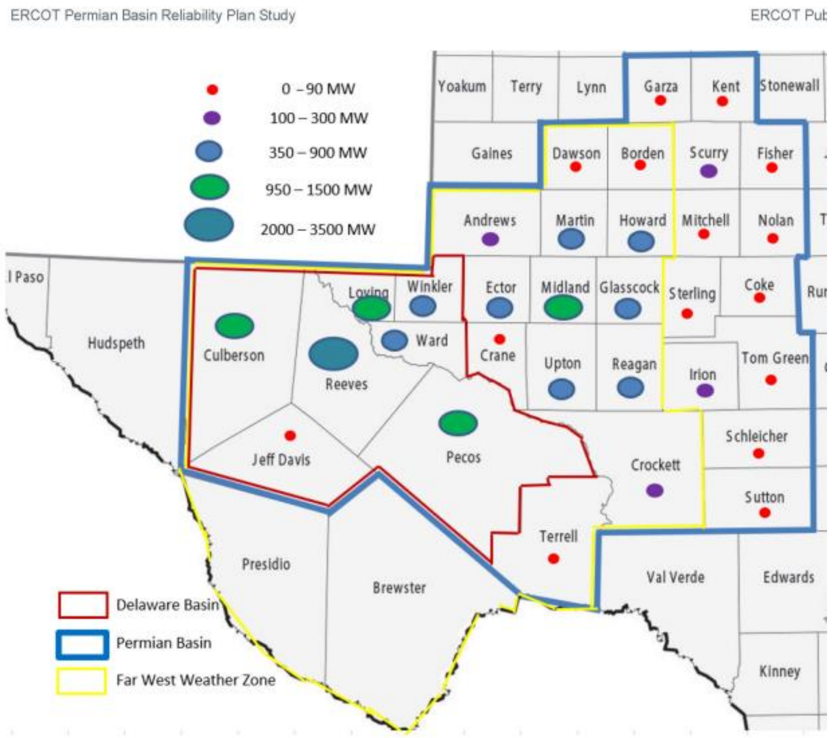


Figure 2.3: County-Level S&P Global Permian Basin Load Forecast in 2039

Summer Net Coincident Peak Demand Forecast 2024-2033

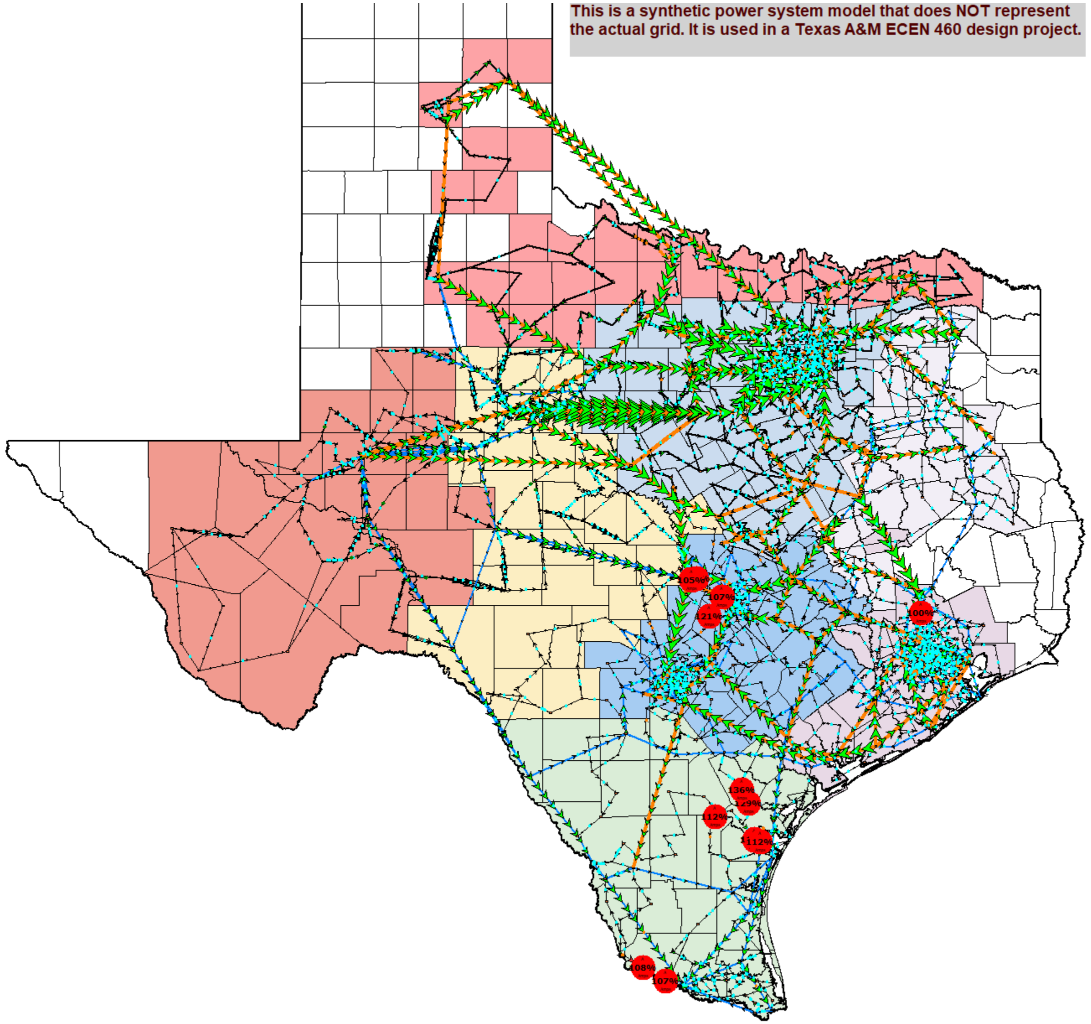
	COAST	EAST	FWEST	NCENT	NORTH	SCENT	SOUTH	WEST	ERCOT
2024	21,093	2,836	8,348	26,653	2,653	15,223	7,161	2,051	86,017
2025	21,257	2,858	8,760	26,715	4,677	15,707	7,551	2,946	90,472
2026	21,902	2,924	12,784	30,470	5,901	18,851	7,763	5,810	106,405
2027	24,670	2,959	13,915	34,012	6,246	20,411	10,638	8,290	121,140
2028	25,460	2,894	16,142	38,692	8,484	22,372	14,674	8,601	137,319
2029	25,663	2,917	17,264	38,950	8,587	23,092	15,481	8,917	140,872
2030	26,063	2,960	19,083	41,833	8,698	23,637	16,766	8,938	147,977
2031	26,348	2,986	19,588	42,226	8,797	24,023	16,835	8,956	149,758
2032	26,626	3,012	20,085	42,614	8,895	24,404	16,902	8,973	151,510
2033	26,901	3,040	20,567	42,996	8,992	24,776	16,968	8,990	153,230

This includes an assumption of LFL reduction to 15% of normal consumption and includes contracts and officer

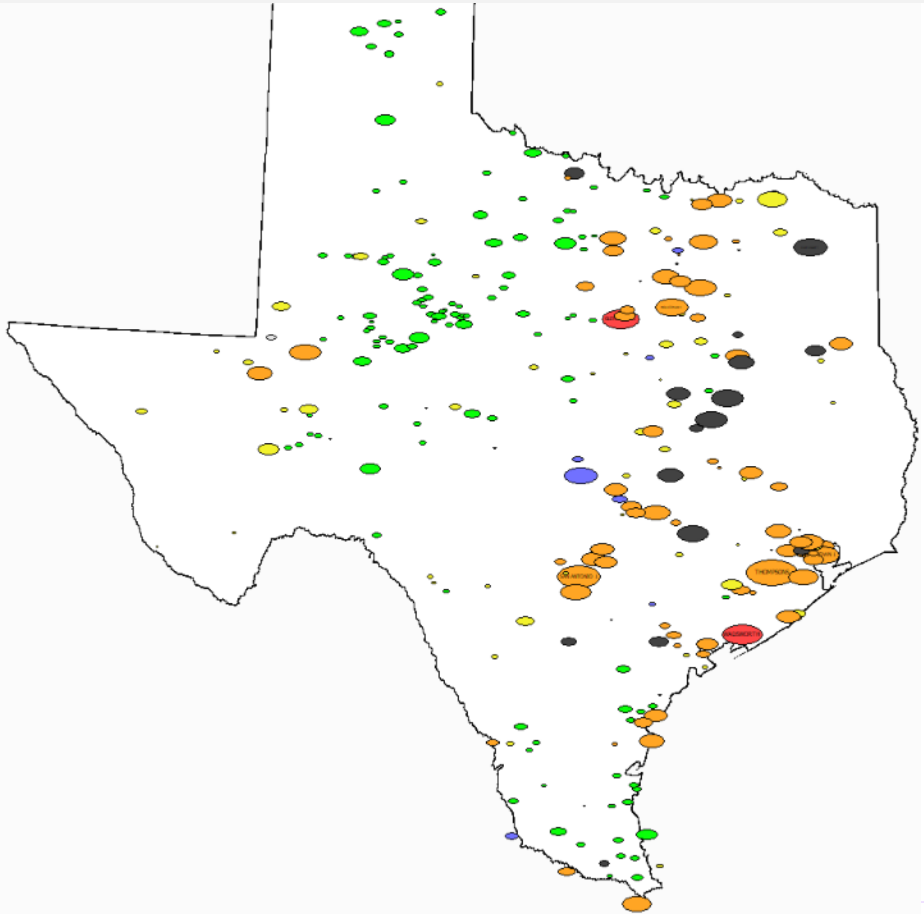
Design Project Overview, cont.

- Since the actual grid models are not publicly available due to them being CEII, you'll be working with an enhanced version of the 2000 bus grid we've been using in 460
  - This enhanced grid has much more wind and solar and a higher load; this grid uses at 500/230/161/115 kV transmission grid
- Your design goal is to optimally provide reliable electricity to 5 new loads in (or close to) the Permian Basin, with each load requiring 1000 MW at 161 kV
- There will be a number of assumptions to simplify the project, including using a DC OPF, only considering three distinct operating points, and ignoring all contingencies except those associated with your new transmission lines and transformers

Design Project Overview: Starting Grid Flows and Generation by Fuel Type



Available generation by fuel type (black-coal, orange-natural gas, red-nuclear, green-wind, yellow-solar, blue-hydro)



Design Project Overview: Starting Grid Flows and Generation by Fuel Type

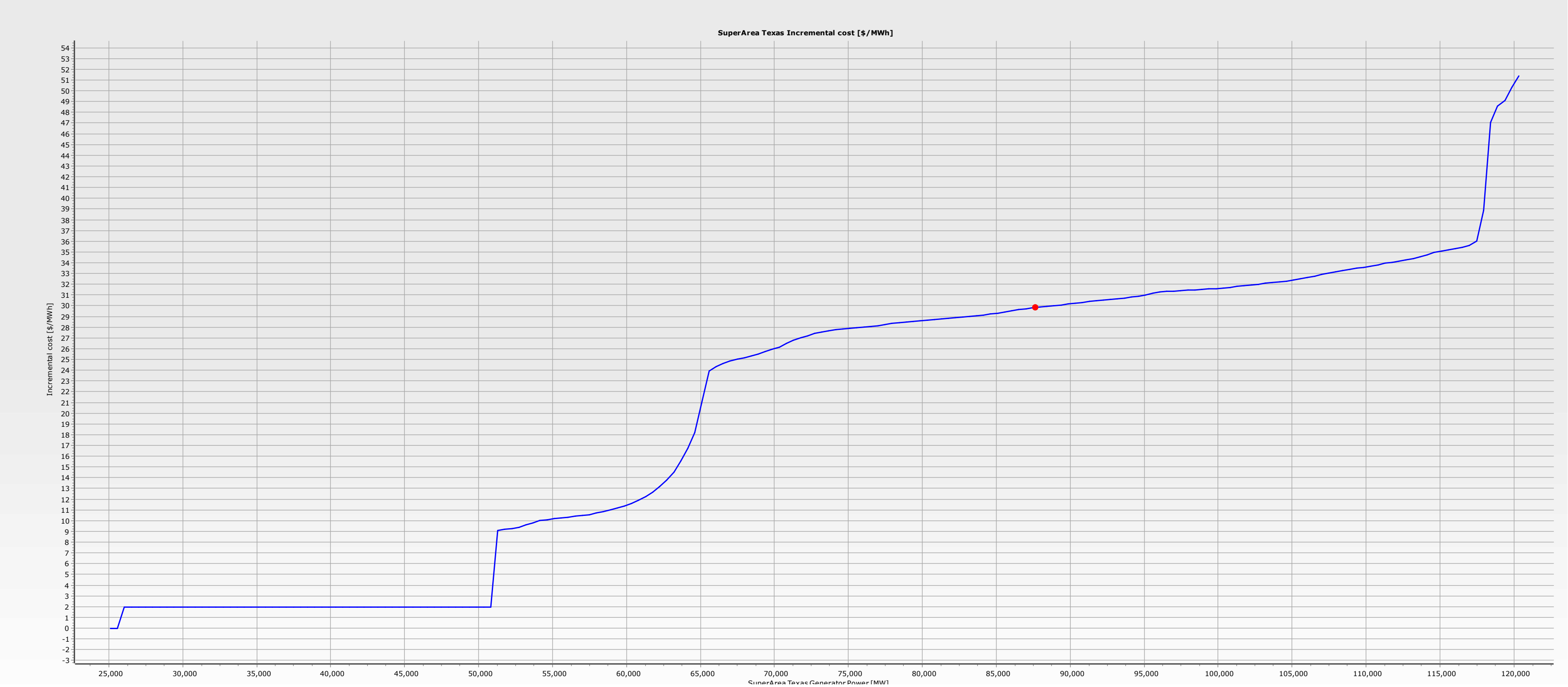
Generation by Generic Fuel Type

Availability by Insevice Date Status

(●) All ( ) Available ( ) Retired ( ) Future

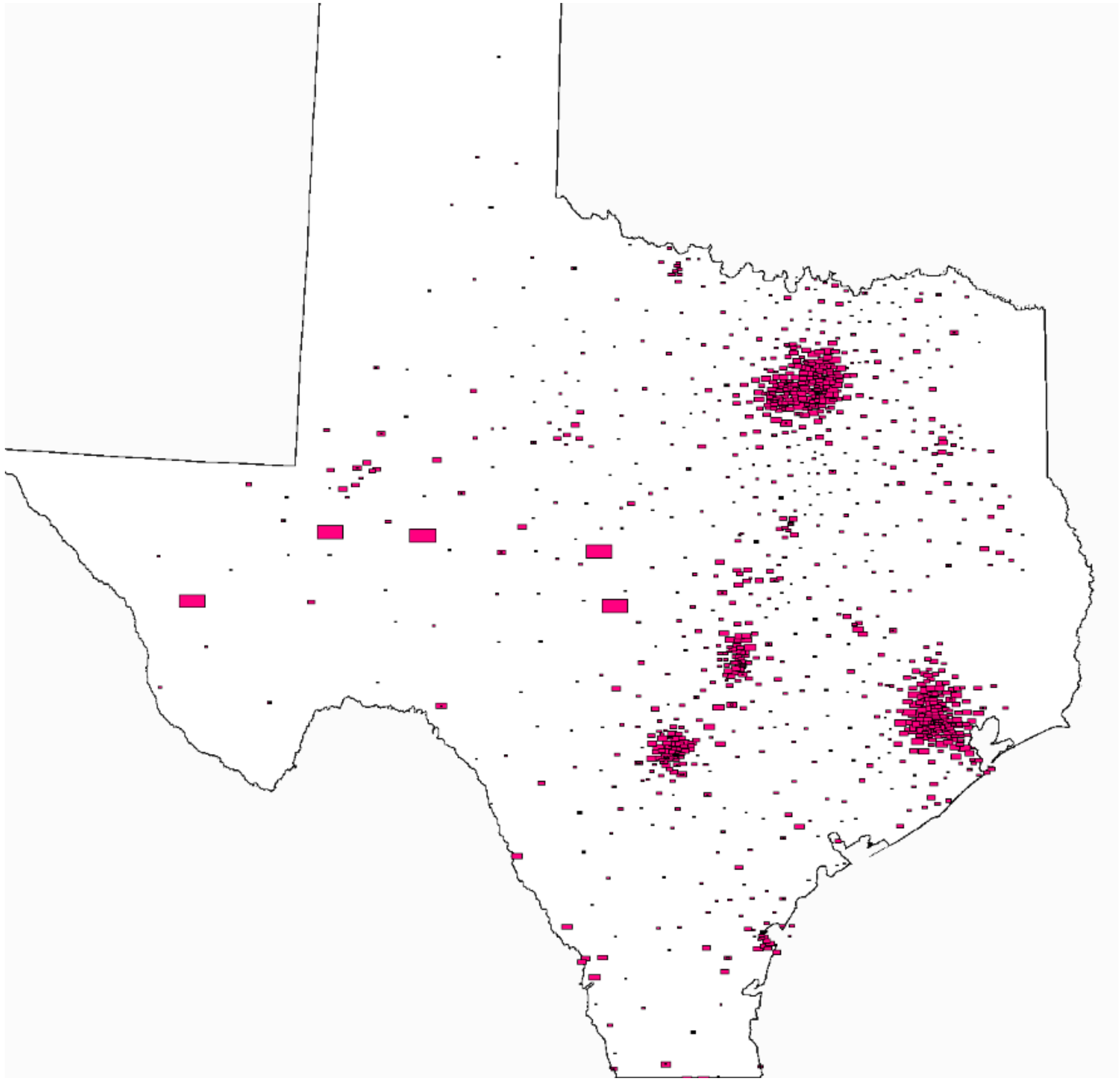
	Actual MW	Max MW (On)	Max MW (All)
Total All	87627.5	120303.9	120303.9
Natural Gas	32744.6	63810.2	63810.2
Coal	13875.2	14501.6	14501.6
Wind	21073.9	22058.4	22058.4
Nuclear	5138.6	5138.6	5138.6
Solar	11327.7	11327.7	11327.7
Hydro	3278.9	3278.9	3278.9
DFO	0.0	0.0	0.0
Storage	0.0	0.0	0.0
Wood/Bio	0.0	0.0	0.0
Jef Fuel	0.0	0.0	0.0
Geothermal	0.0	0.0	0.0
HydroPS	0.0	0.0	0.0
Waste Heat	0.0	0.0	0.0
RFO	0.0	0.0	0.0
Other	0.0	0.0	0.0
Unknown	188.5	188.5	188.5

Supply Curve



Existing and New Load

- This image shows the existing load, with the rectangles proportional to the load
- The five large rectangles towards the left represent the new, currently not connected, load



You are Encouraged to Read the ERCOT Report

- It will be included with the design project. This image is a solution presented in the report. However, they are designing for the existing 345/138 kV grid, not your 500/161 kV grid
- The ERCOT report is estimating costs on the order of $ 13 billion

ERCOT Permian Basin Reliability Plan Study

ERCOT Public

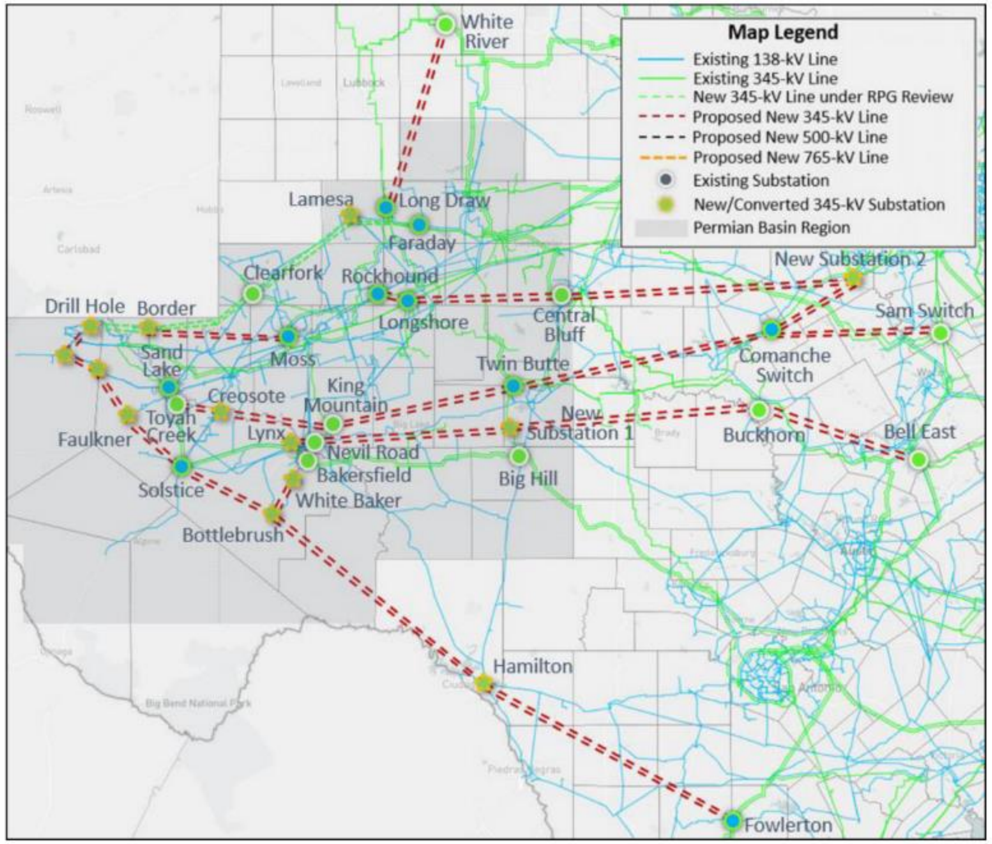
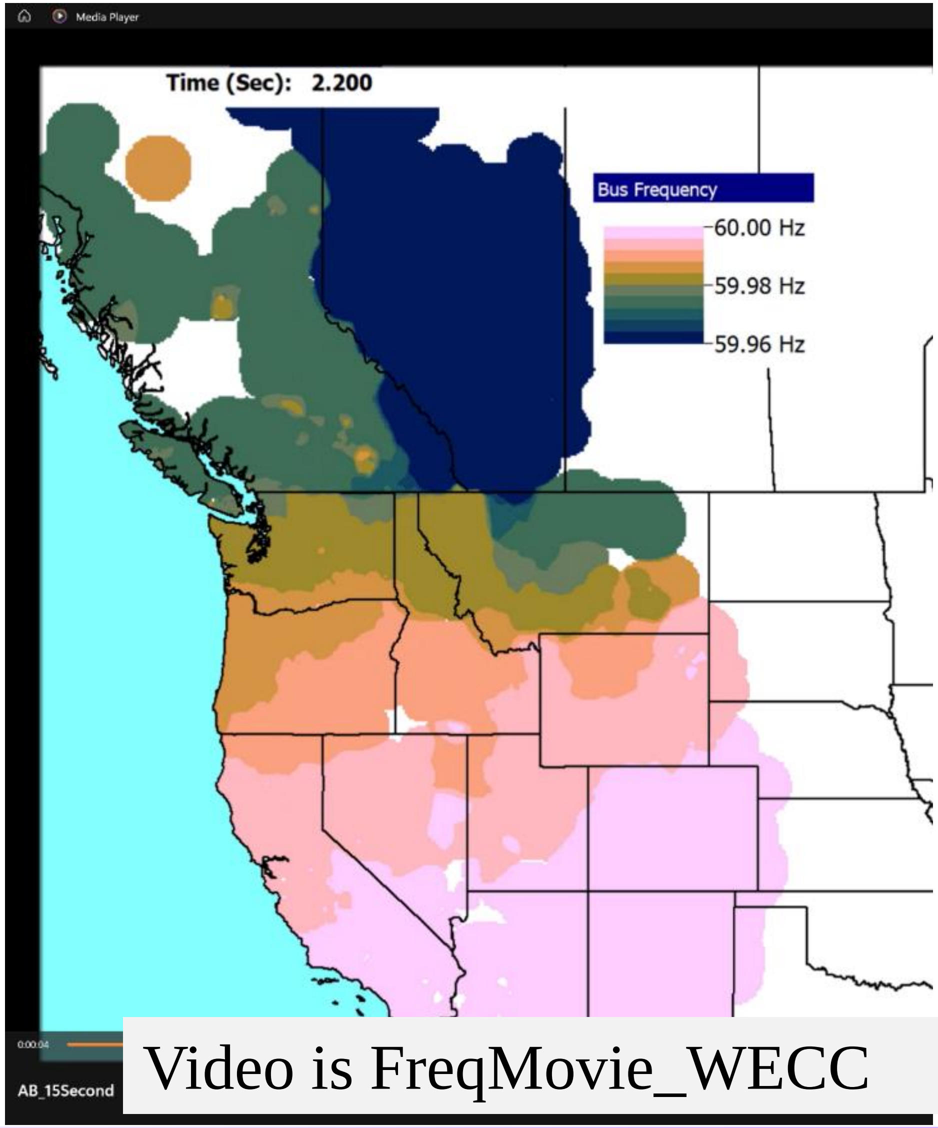
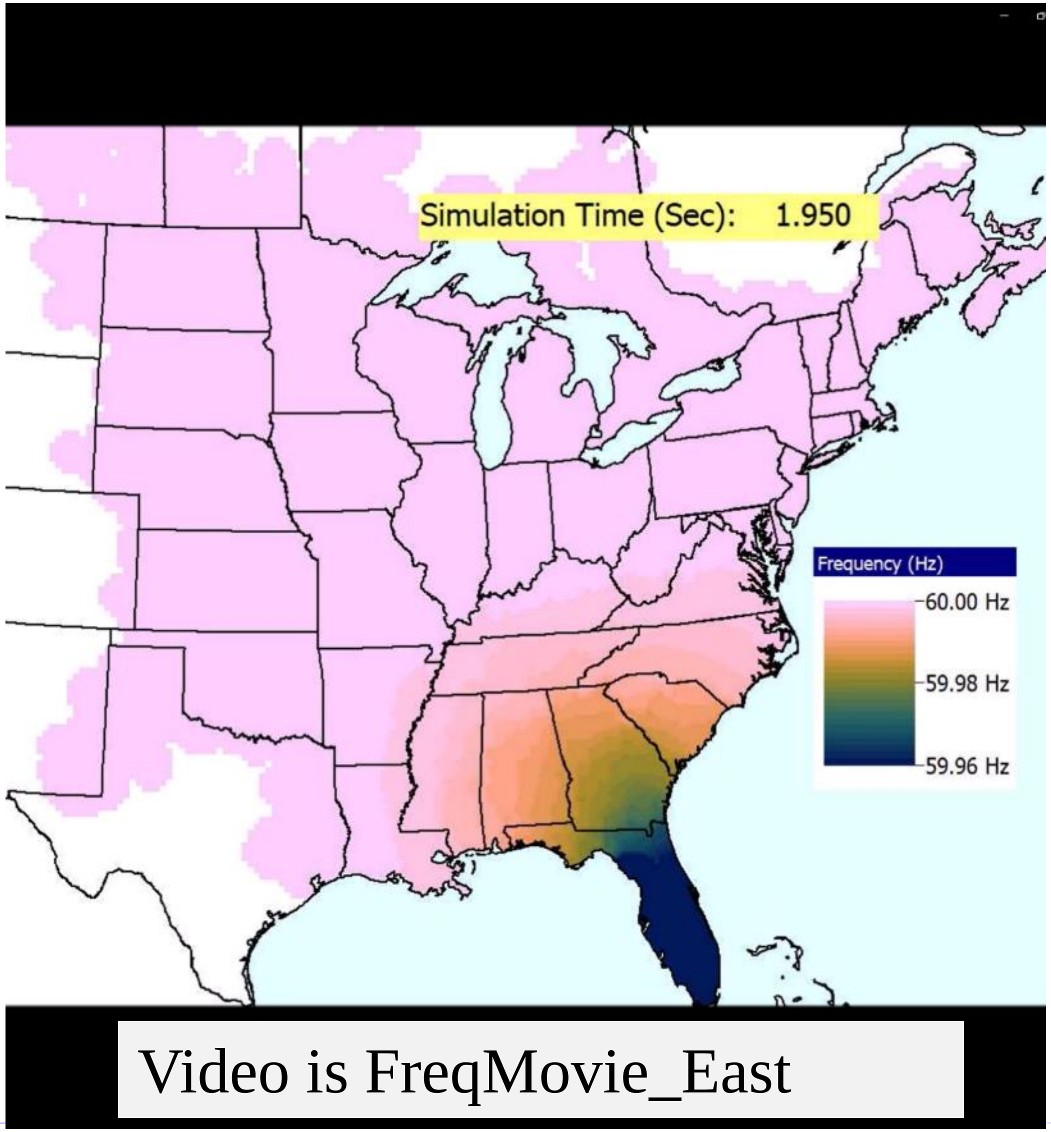


Figure 5.8: 345-kV Import Paths in 2038 (Includes Import Paths Needed in 2030)

Back to Stability: The Frequency Contour Videos for the West and East from Last Lecture

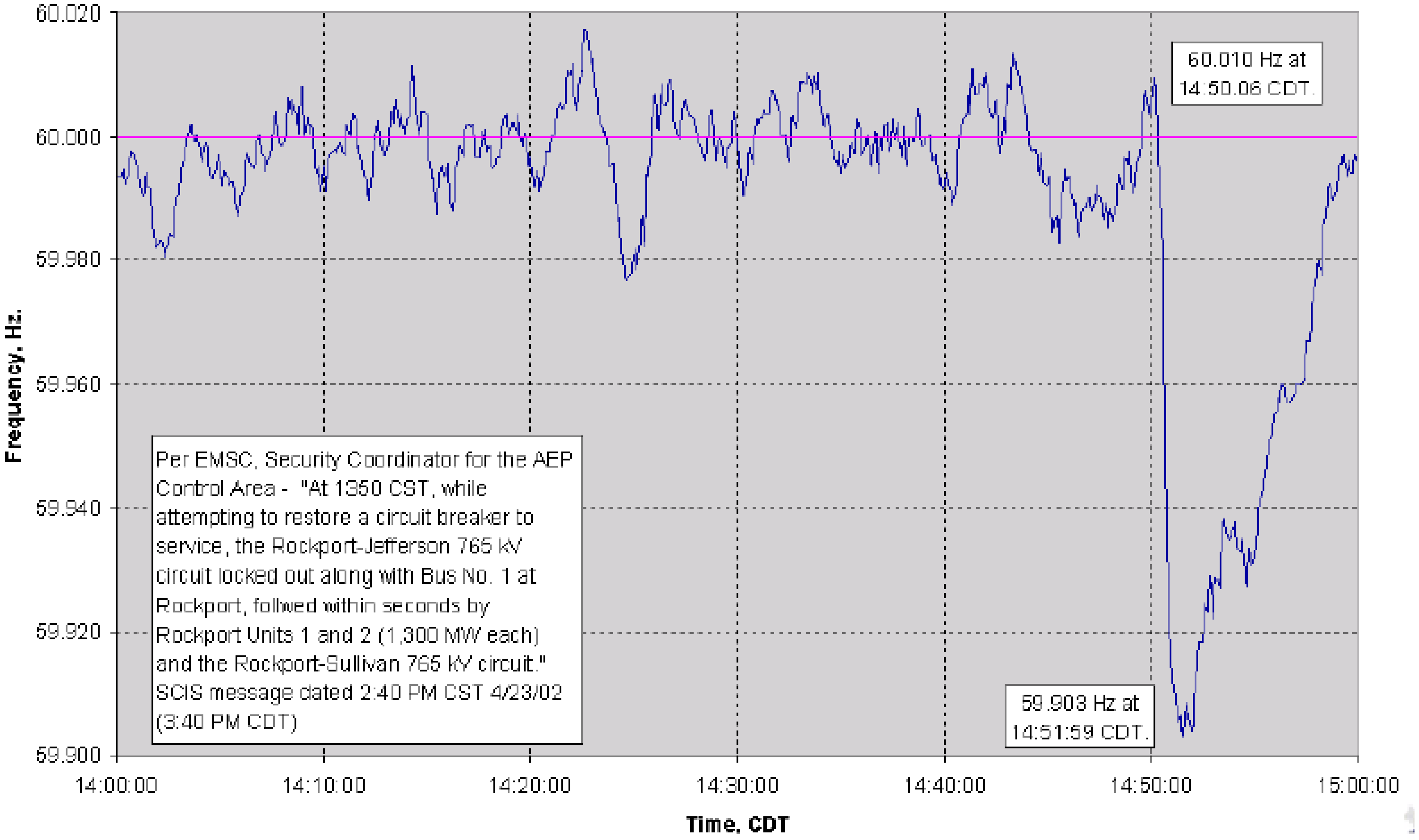


Video is FreqMovie_WECC



Video is FreqMovie_East

Longer Term Frequency Recovery



Normally the frequency recovers in about ten minutes

ERCOT Winter Storm Uri Frequency (2/15/21)

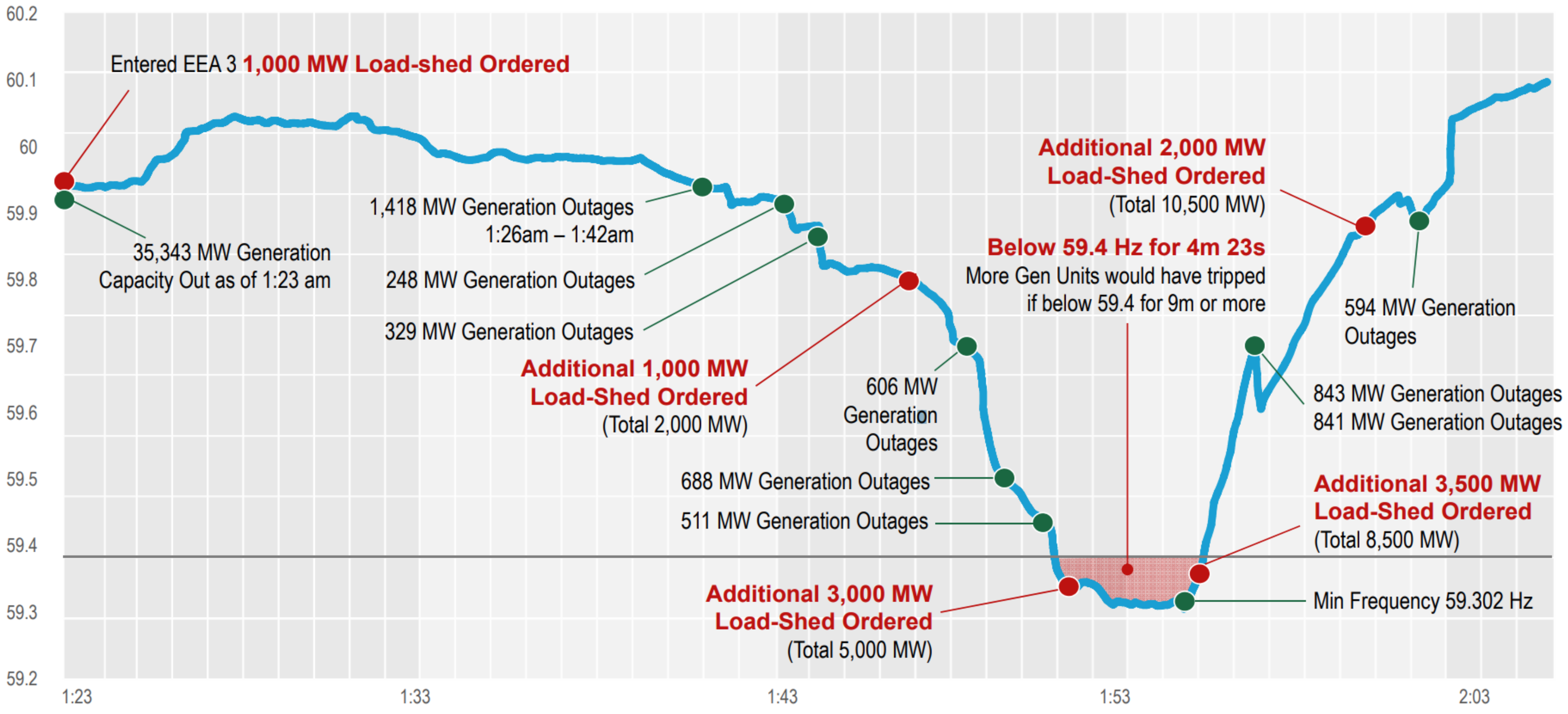


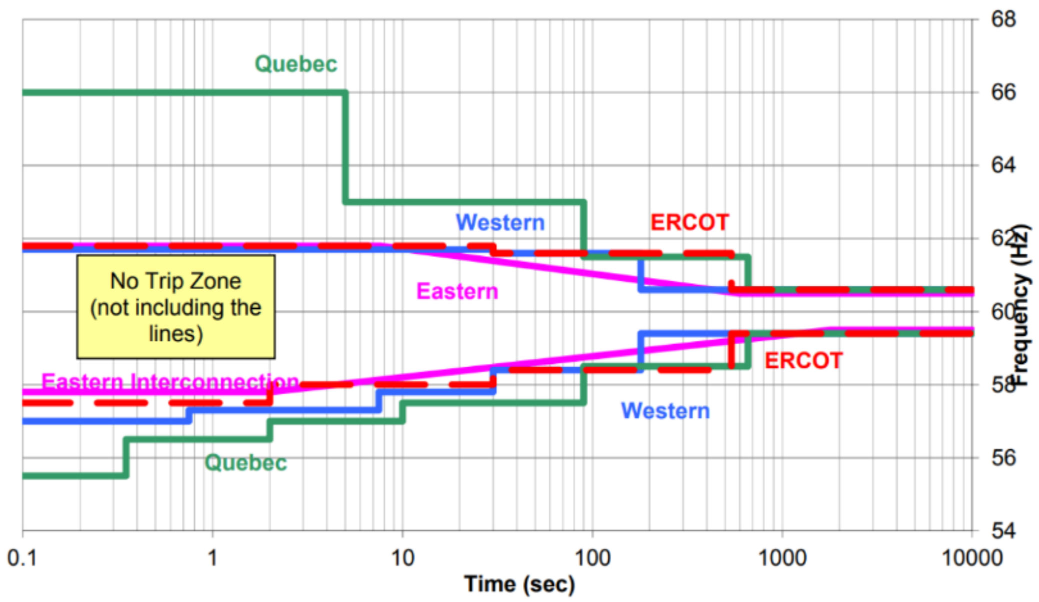
Image source: https://www.ercot.com/files/docs/2021/03/03/Texas_Legislature_Hearings_2-25-2021.pdf

Generator Under and Over Frequency Protection

- Generators have automatic protection systems to trip them if the frequency goes out of range for too long (also their voltage)

PRC-024 — Attachment 1

OFF NOMINAL FREQUENCY CAPABILITY CURVE

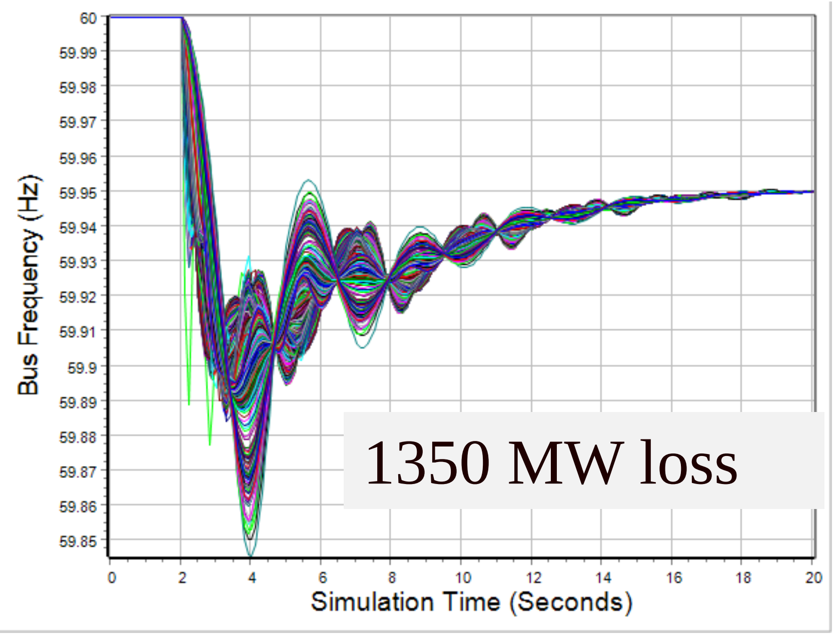


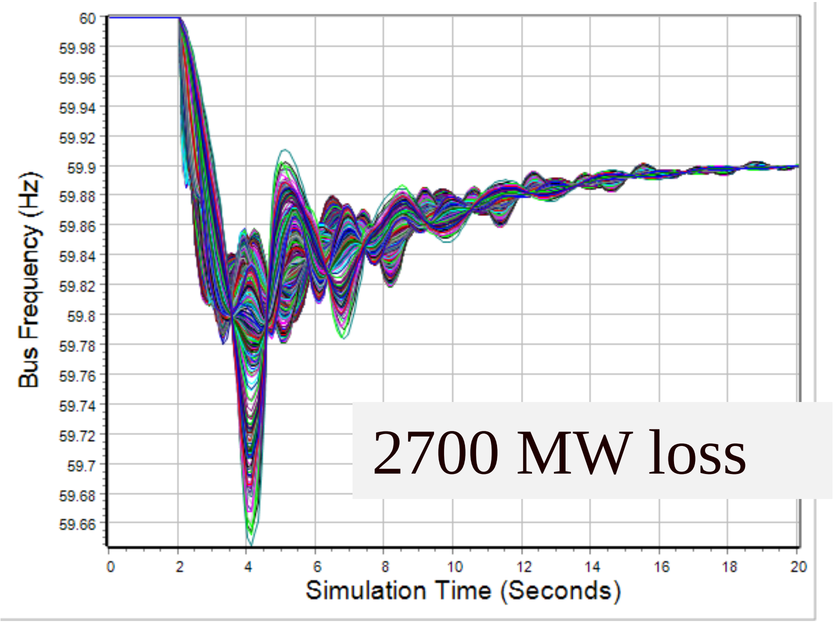
NERC Standard PRC-024.1

A typical concern with off-nominal frequency operation is the turbine (i.e., not the synchronous machine) operating at close to one of its natural frequencies, resulting in accelerated aging (metal fatigue); this is often shown using a Campbell diagram; see IEEE C37.106.2022

2000 Bus Generator Outage Example

- To do an example larger case generator drop stability study, open the case **Texas2000_GenDrop**
  - Case has 67,000 MW of load; contingency is the loss of a 1350 MW generator
  - Go to the Transient Stability form and click **Run Transient Stability**
  - Rerun but drop two generators (one event is initially disabled)





Generator Transient Stability Models

- In order to study the transient response of a power system we need to develop models for the generator valid during the transient time frame of several seconds following a system disturbance
- We need to develop both electrical and mechanical models for the generators

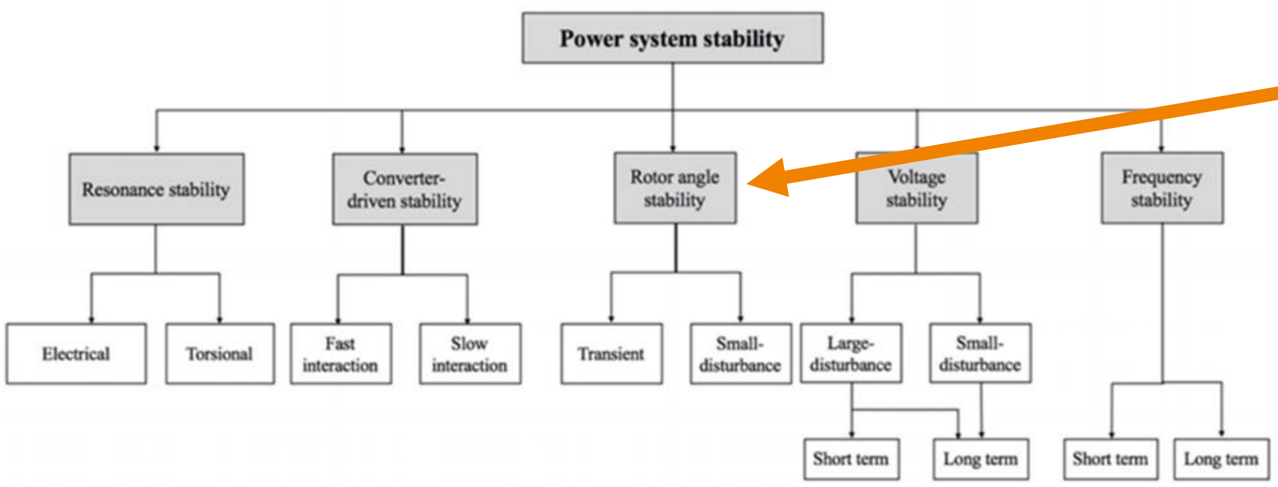
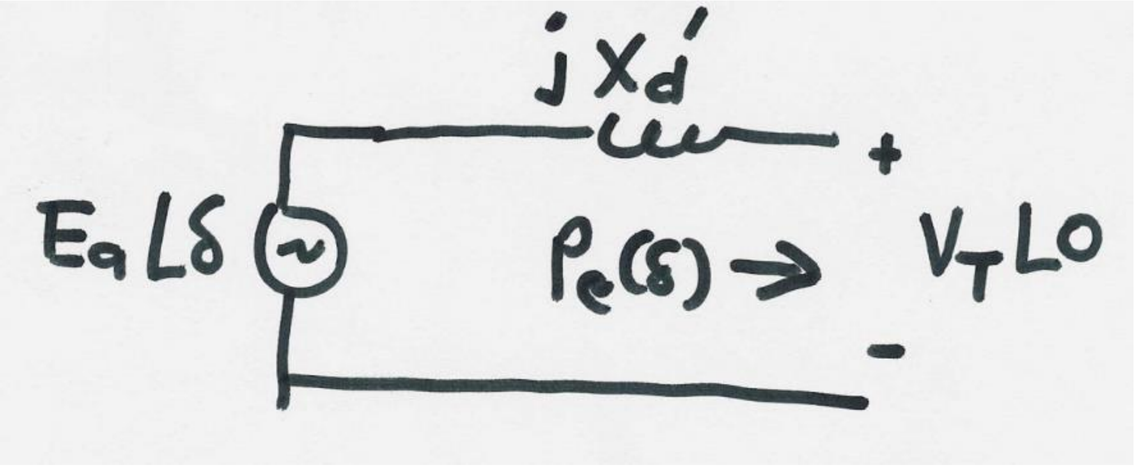


Fig. 4. Classification of power system stability

With the models, we're starting here

Generator Electrical Model

- The simplest generator model, known as the classical model, treats the generator as a voltage source behind the direct-axis transient reactance; the voltage magnitude is fixed, but its angle changes according to the mechanical dynamics

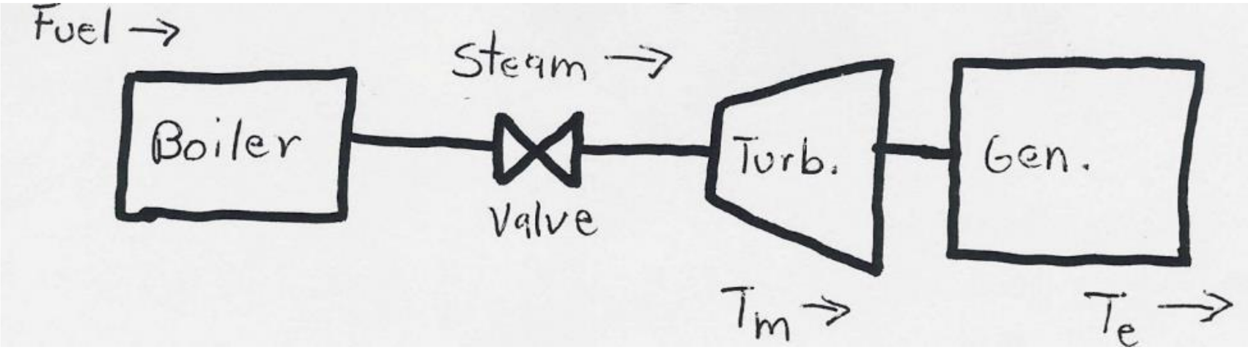


$$P_e(\delta) = \frac{|V_T||E_a|}{X_d^{'}} \sin\delta$$

This is an old model that is no longer used in practice, but is a good place to start

Generator Mechanical Model

Generator Mechanical Block Diagram



$$T_m = J\alpha_m + T_D + T_e(\delta)$$

T_m = mechanical input torque (N-m)

J = moment of inertia of turbine & rotor

α_m = angular acceleration of turbine & rotor

T_D = damping torque

$T_e(\delta)$ = equivalent electrical torque

Generator Mechanical Model, cont'd

In general power = torque × angular speed

Hence when a generator is spinning at speed ω_s

$$T_m = J\alpha_m + T_D + T_e(\delta)$$

$$T_m\,\omega_s = (J\alpha_m + T_D + T_e(\delta))\,\omega_s \triangleq P_m$$

$$P_m = J\alpha_m\omega_s + T_D\omega_s + P_e(\delta)$$

Initially we'll assume no damping (i.e., $T_D = 0$). Then

$$P_m - P_e(\delta) = J\alpha_m\omega_s$$

P_m is the mechanical power input, which is assumed initially to be constant throughout the study time period

Constant mechanical power is no longer used in studies, but it is a good place to start

Generator Mechanical Model, cont'd

$$P_m - P_e(\delta) = J\alpha_m\omega_s$$

$$\theta_m = \omega_s t + \delta = \text{rotor angle}$$

$$\omega_m = \frac{d\theta_m}{dt} = \dot{\theta}_m = \omega_s + \dot{\delta}$$

$$\alpha_m = \dot{\omega}_m = \ddot{\delta}$$

$$P_m - P_e(\delta) = J\omega_s\alpha_m = J\omega_s\ddot{\delta}$$

$$J\omega_s = \text{inertia of machine at synchronous speed}$$

Convert to per unit by dividing by MVA rating, S_B,

$$\frac{P_m}{S_B} - \frac{P_e(\delta)}{S_B} = \frac{J\omega_s\ddot{\delta}}{S_B}\frac{2\omega_s}{2\omega_s}$$

Generator Mechanical Model, cont'd

$$\frac{P_m}{S_B} - \frac{P_e(\delta)}{S_B} = \frac{J\omega_s\ddot{\delta}}{S_B}\frac{2\omega_s}{2\omega_s}$$

$$\frac{P_m - P_e(\delta)}{S_B} = \frac{J\omega_s^2}{2S_B}\frac{1}{\pi f_s}\ddot{\delta} \qquad (\text{since } \omega_s = 2\pi f_s)$$

Define $\frac{J\omega_s^2}{2S_B} \triangleq H$ = per unit inertia constant (sec)

All values are now converted to per unit

$$P_m - P_e(\delta) = \frac{H}{\pi f_s}\ddot{\delta} \qquad \text{Define } M = \frac{H}{\pi f_s}$$

Then $P_m - P_e(\delta) = M\ddot{\delta}$

Generator Swing Equation

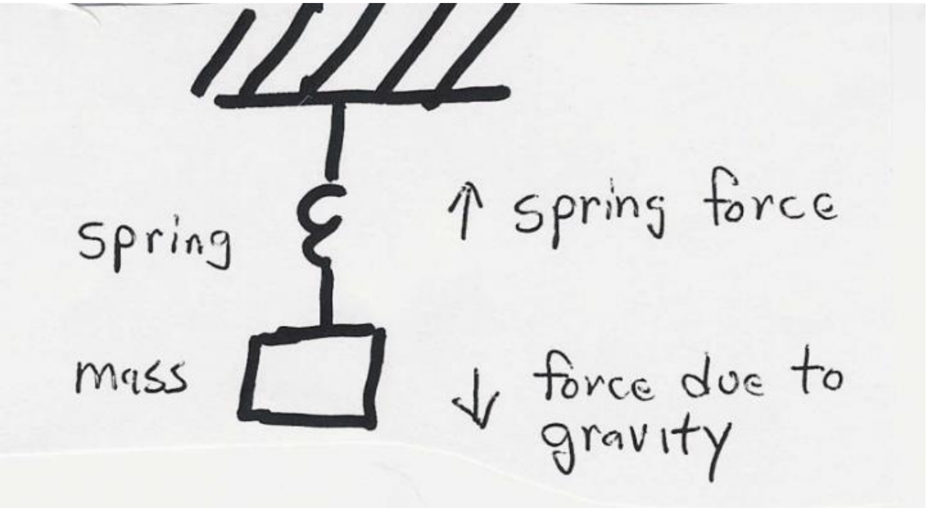
This equation is known as the generator swing equation

$$P_m - P_e(\delta) \quad = \quad M\ddot{\delta}$$

Adding damping we get

$$P_m - P_e(\delta) \quad = \quad M\ddot{\delta} + D\dot{\delta}$$

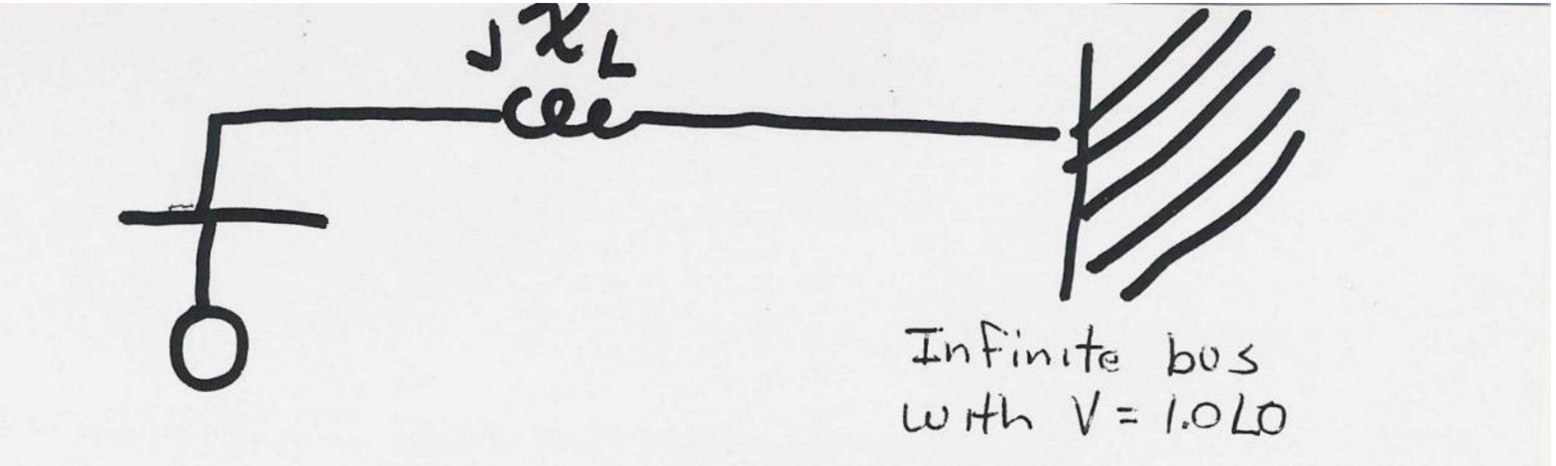
This equation is analogous to a mass suspended by a spring



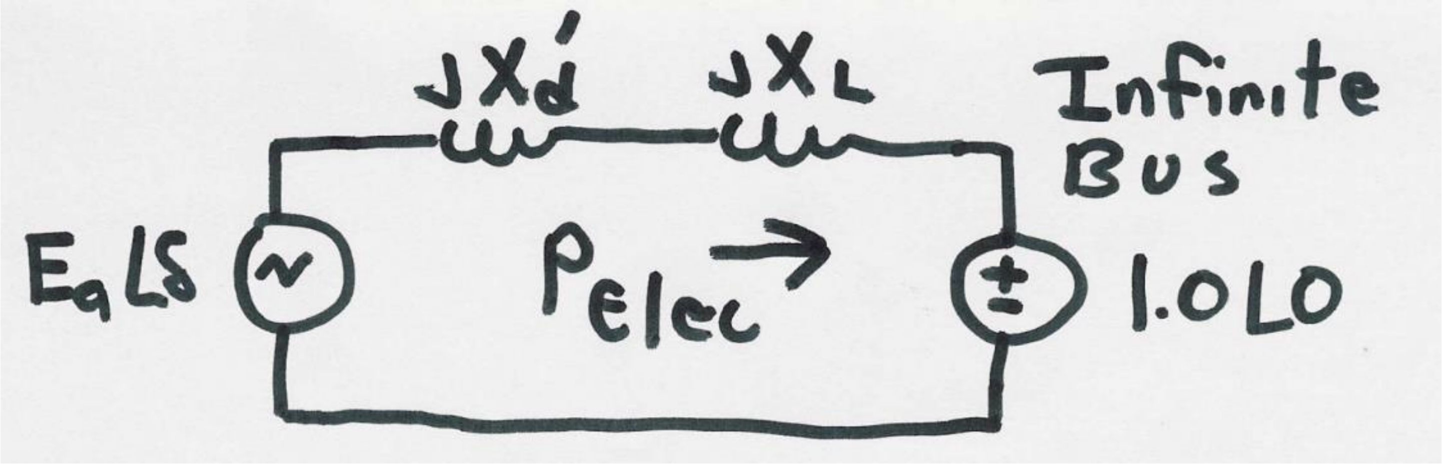
$$kx - gM = M\ddot{x} + D\dot{x}$$

Single Machine Infinite Bus (SMIB)

- To understand the transient stability problem we'll first consider the case of a single machine (generator) connected to a power system bus with a fixed voltage magnitude and angle (known as an infinite bus) through a transmission line with impedance jX_L



SMIB, cont'd



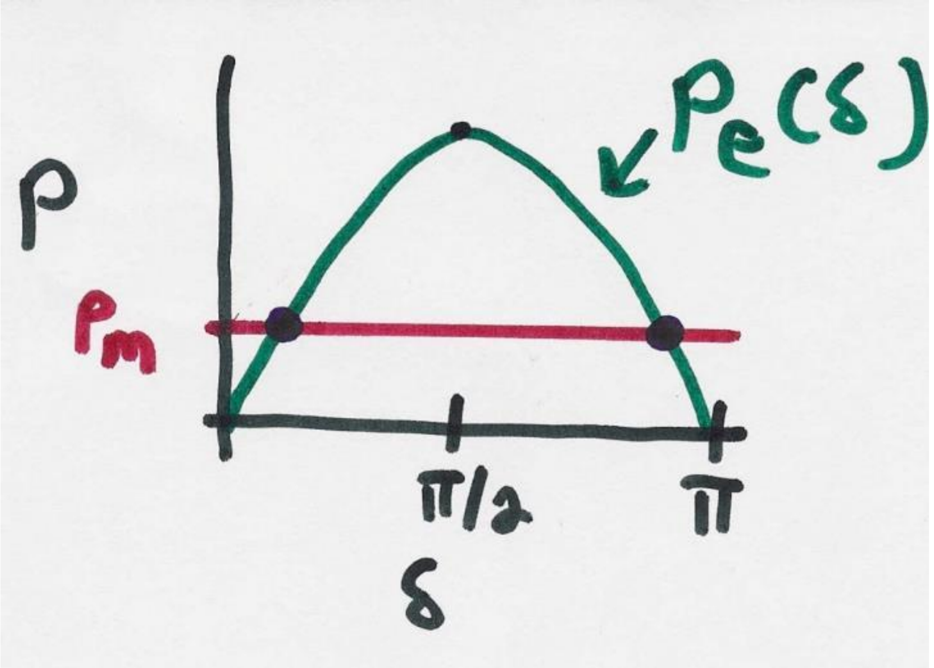
$$P_e(\delta) = \frac{E_a}{X_d^{'} + X_L}\sin\delta$$

$$M\ddot{\delta} + D\dot{\delta} = P_M - \frac{E_a}{X_d^{'} + X_L}\sin\delta$$

SMIB Equilibrium Points

Equilibrium points are determined by setting the right-hand side to zero

$$M\ddot{\delta} + D\dot{\delta} \quad = \quad P_M - \frac{E_a}{X_d^{'} + X_L}\sin\delta$$



$$P_M - \frac{E_a}{X_d^{'} + X_L}\sin\delta = 0$$

Define $X_{th} = X_d^{'} + X_L$

$$\delta \quad = \quad \sin^{-1}\left(\frac{P_M X_{th}}{E_a}\right)$$

Transient Stability Analysis

- For classical transient stability analysis we need to consider three systems
  1. Prefault - before the fault occurs the system is assumed to be at an equilibrium point
  2. Faulted - the fault changes the system equations, moving the system away from its equilibrium point
  3. Postfault - after fault is cleared the system hopefully returns to a new operating point

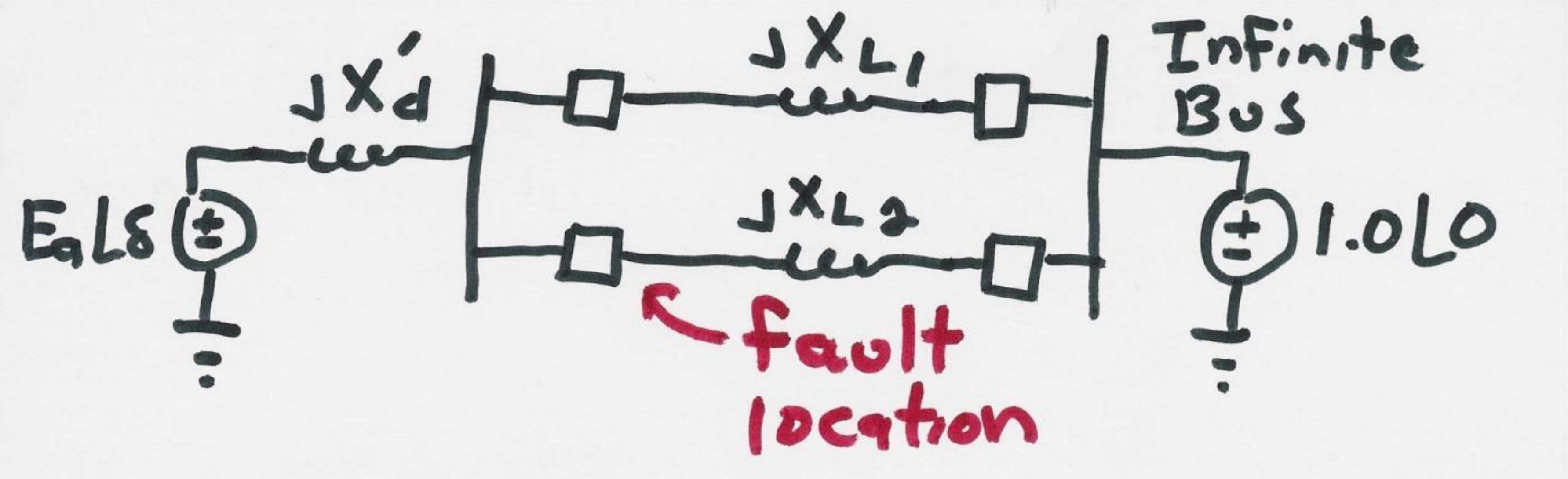
Actual stability studies can have multiple events and can be much more involved; however, this is a good place to start

Transient Stability Solution Methods

- There are two methods for solving the transient stability problem
  1. Direct or energy methods; for a two bus system this method is known as the equal area criteria
     - mostly used to provide an intuitive insight into the transient stability problem
  2. Numerical integration
     - this is by far the most common technique, particularly for large systems; during the fault and after the fault the power system differential equations are solved using numerical methods

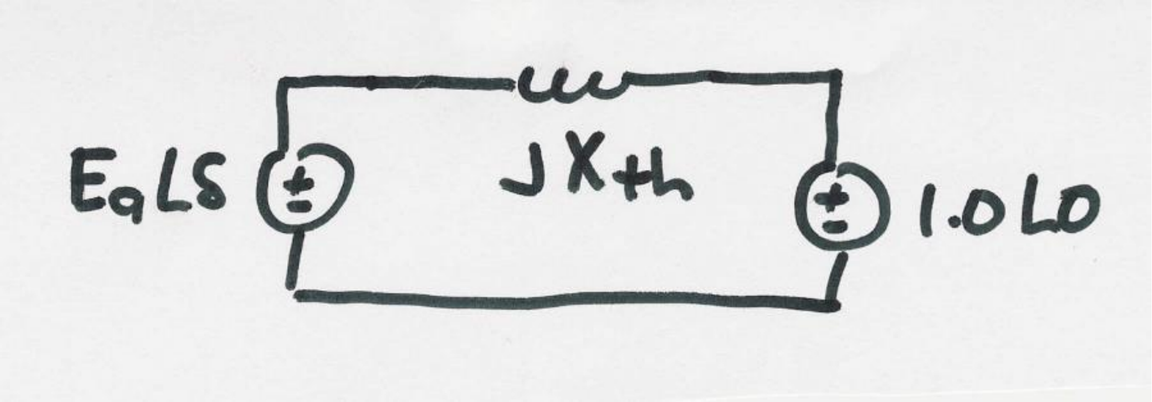
SMIB Direct Method Example

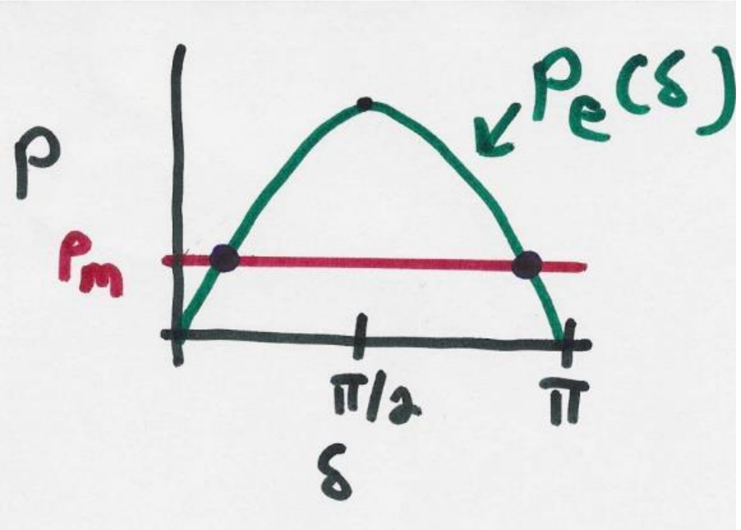
- Assume a generator is supplying power to an infinite bus through two parallel transmission lines. Then a balanced three phase fault occurs at the terminal of one of the lines. The fault is cleared by the opening of this line's circuit breakers.



SMIB Example, cont'd

- Simplified prefault system



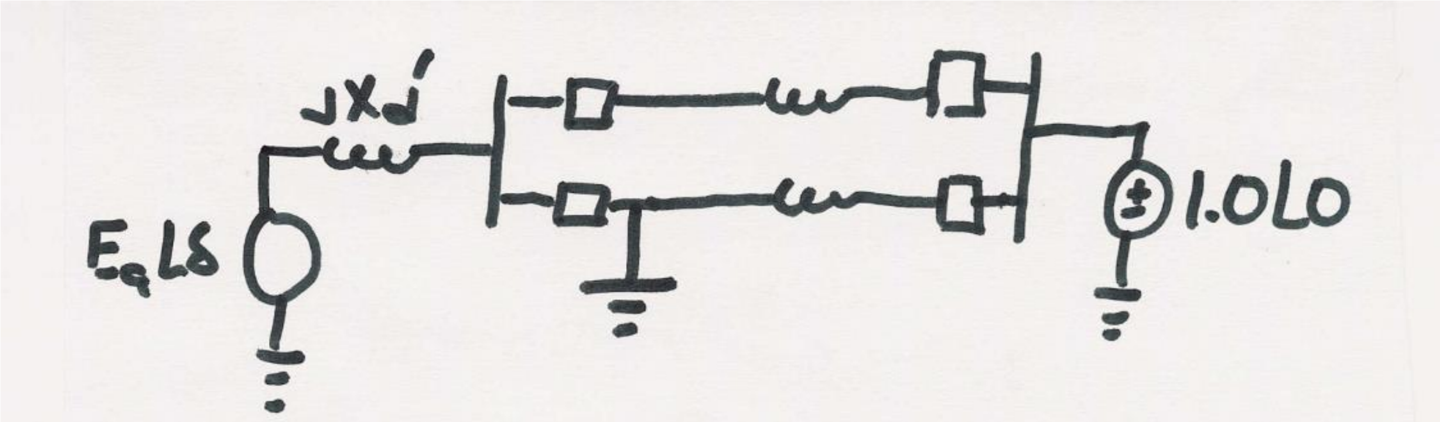


The prefault system has two equilibrium points; the left one is stable, the right one unstable

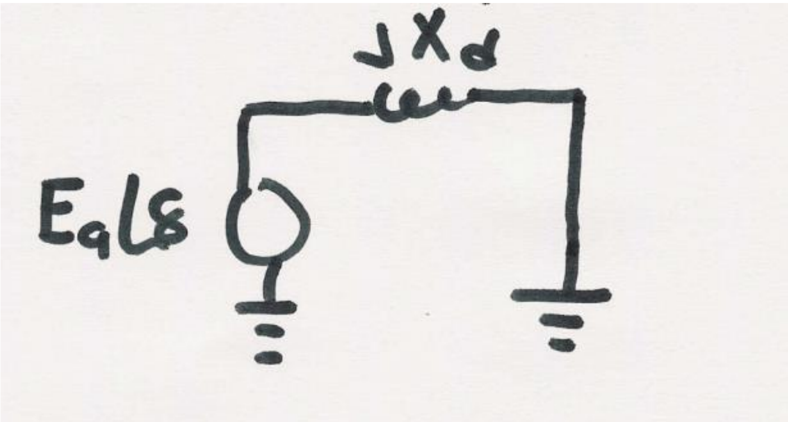
$$\delta = \sin^{-1}\left(\frac{P_M X_{th}}{E_a}\right)$$

SMIB Example, Faulted System

- During the fault the system changes



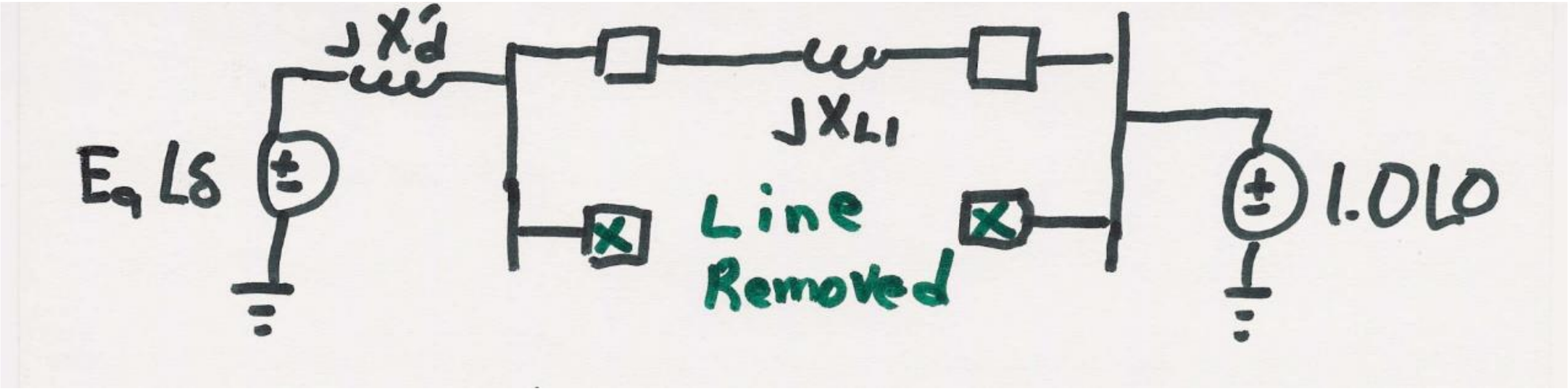
- The equivalent system during the fault is then



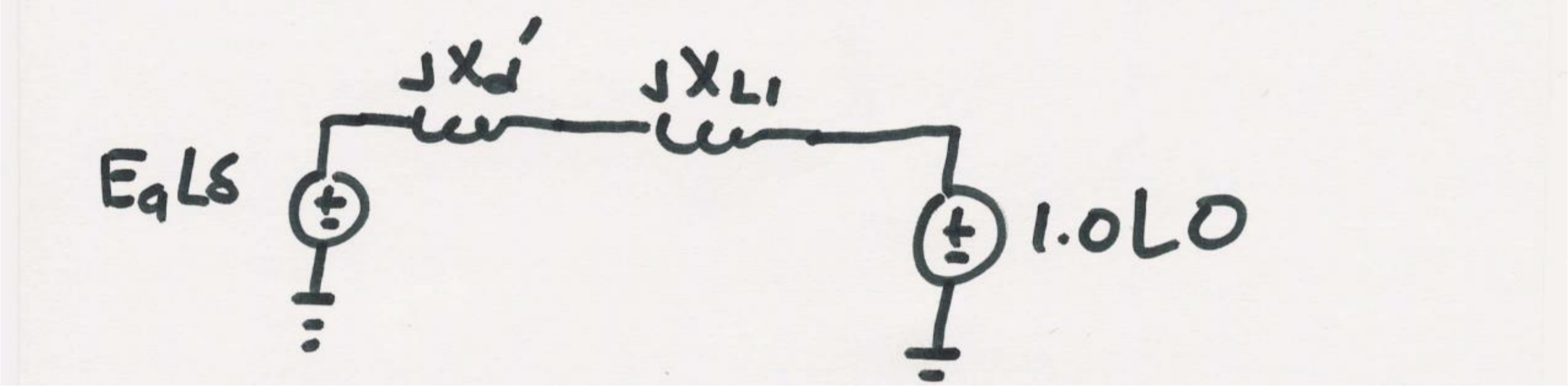
During this fault (i.e., a balanced three-phase one) no power can be transferred from the generator to the system

SMIB Example, Post Fault System

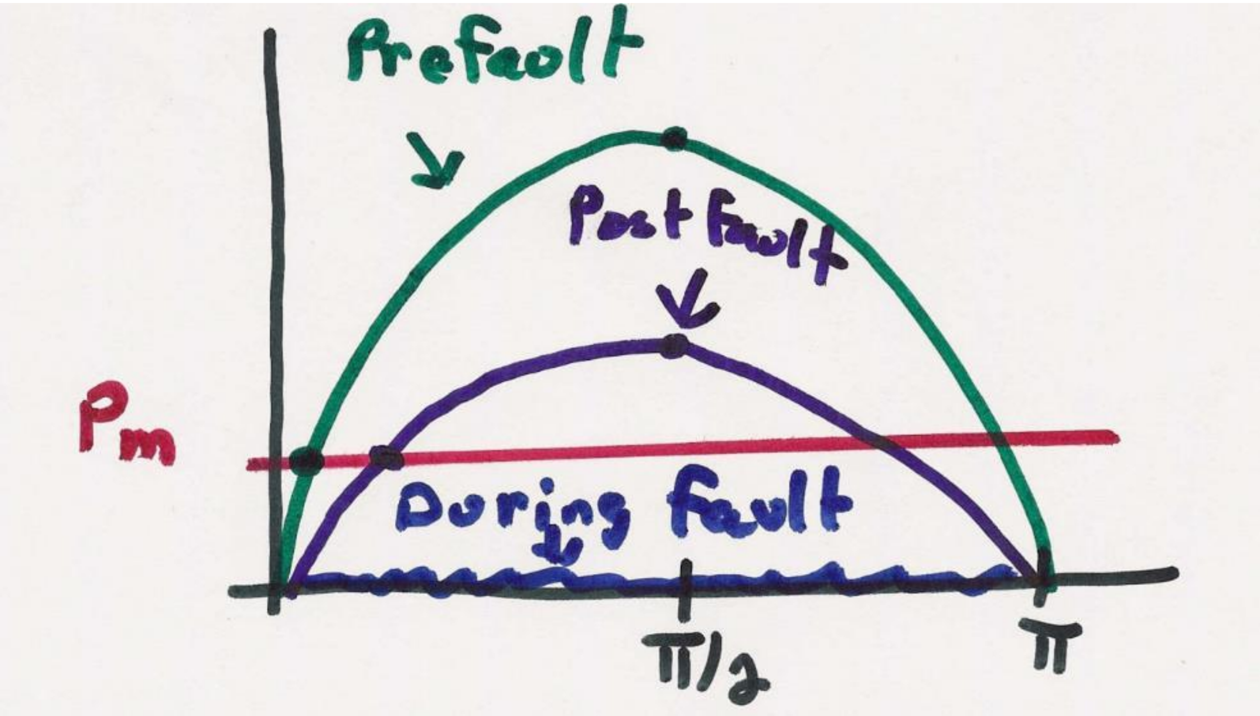
- After the fault the system again changes



- The equivalent system after the fault is then



SMIB Example, Dynamics

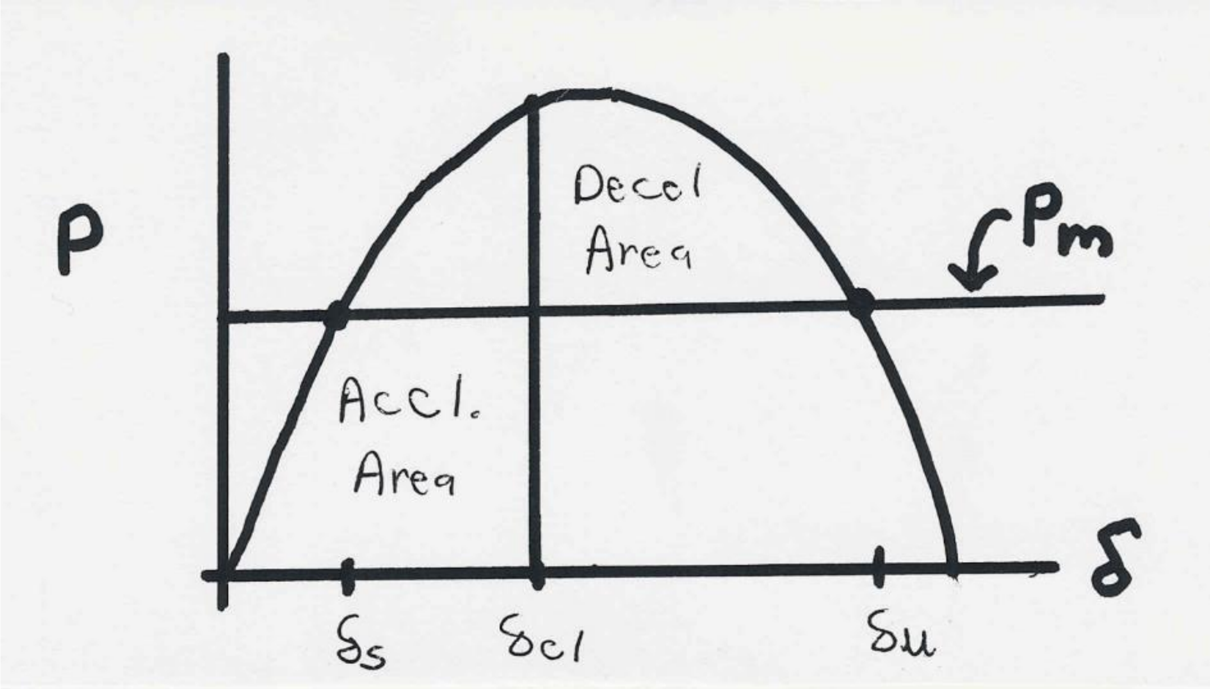


During the disturbance the form of $P_e(\delta)$ changes, altering the power system dynamics:

$$\ddot{\delta} = \frac{1}{M}\left[P_M - \frac{E_a V_{th}}{X_{th}}\sin\delta\right]$$

Equal Area Criteria

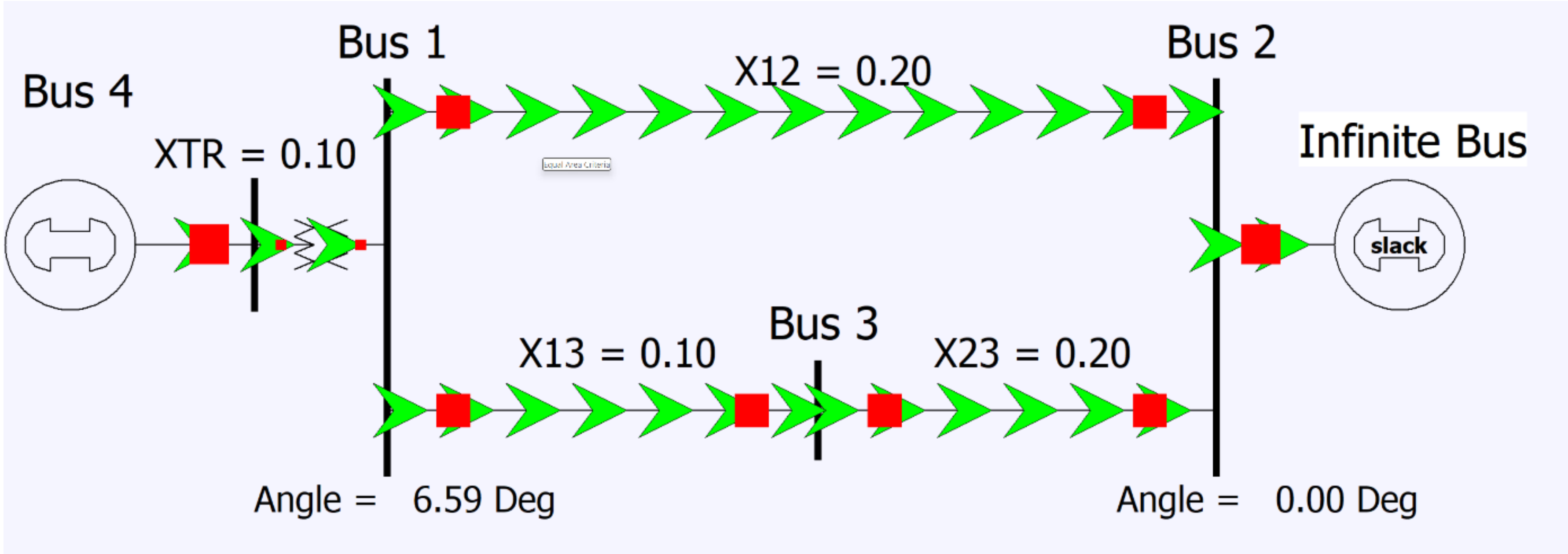
- The goal of the equal area criteria is to try to determine whether a system is stable or not without having to completely integrate the system response.



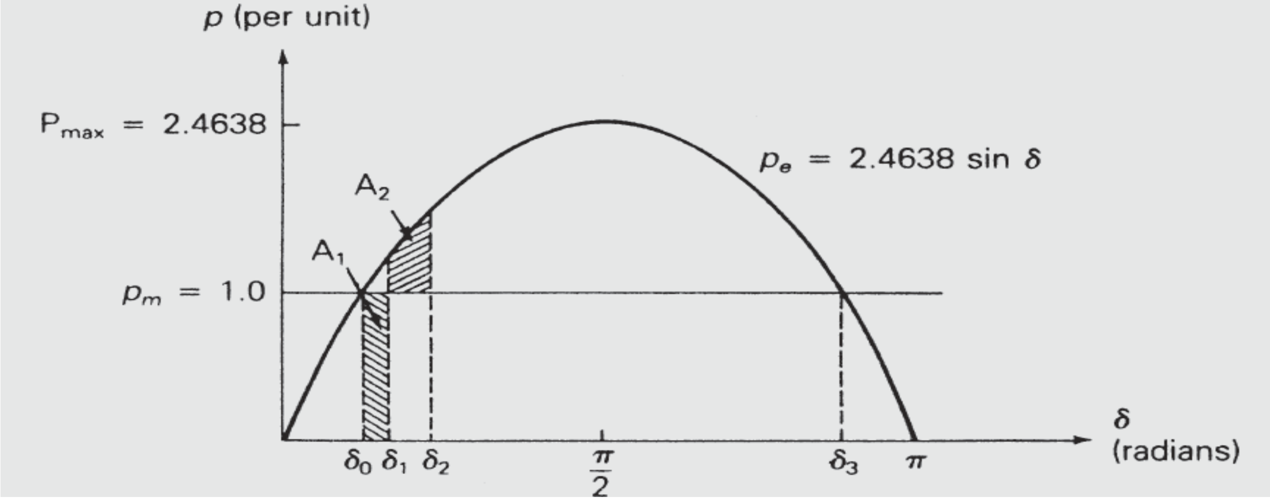
System will be stable after the fault if the deceleration (Decel) area is greater than the acceleration (Accel.) area

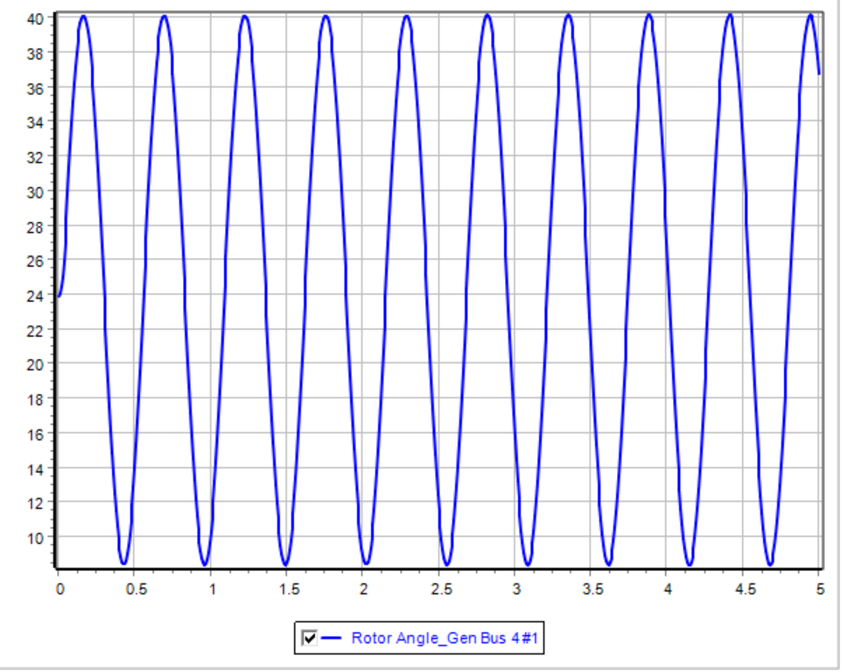
Example 12.4: Undamped

- Assume there is a balanced three-phase fault at Bus 1, meaning that during the fault no power can be transferred from the generator to the rest of the system.



Examples 12.4 and 5: Equal Area





With $\delta_0 = 0.4179$ rad, $\delta_1 = 0.4964$ rad, $p_m = 1.0$

$$A_1 = \int_{\delta_0}^{\delta_1} p_m d\delta = A_1 = \int_{\delta_0}^{\delta_1} 1.0 d\delta = (\delta_1 - \delta_0) = 0.0785$$

$$A_2 = \int_{\delta_1}^{\delta_2} (p_e(\delta) - p_m) d\delta = \int_{0.4964}^{\delta_2} (2.4638 \sin\delta - 1.0) d\delta$$

For $A_1 = A_2 = 2.4638[\cos(0.4964) - \cos\delta_2] - (\delta_2 - 0.4964)$

$$2.4638 \cos\delta_2 + \delta_2 = 2.5843$$

Solving iteratively gives $\delta_2 = 0.7003$ rad

The critical clearing time is slightly less than 0.19 seconds