ECEN 667
Power System Stability

Lecture 24: Oscillations, Energy Methods, Power System Stabilizers

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Special Guest Lecture by TA Hanyue Li

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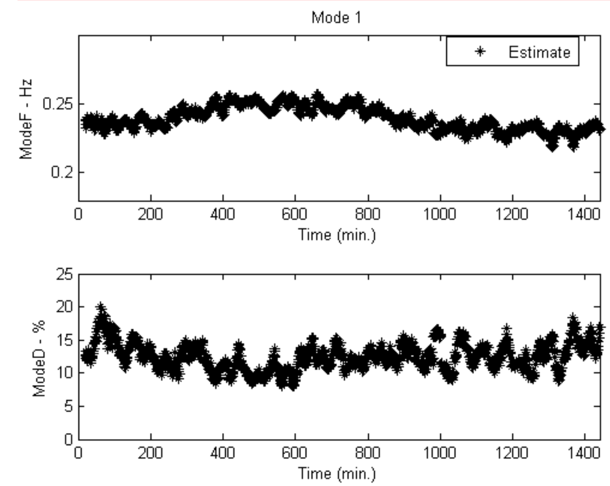
Announcements

- Read Chapter 9
- Homework 6 is due on Tuesday December 3
- Final is at scheduled time here (December 9 from1pm to 3pm)

Inter-Area Modes in the WECC

- The dominant inter-area modes in the WECC have been well studied
- A good reference paper is D. Trudnowski, "Properties of the Dominant Inter-Area Modes in the WECC Interconnect," 2012
  - Four well known modes are NS Mode A (0.25 Hz), NS Mode B (or Alberta Mode), (0.4 Hz), BC Mode (0.6 Hz), Montana Mode (0.8 Hz)

Below figure from paper shows NS Mode A On May 29, 2012

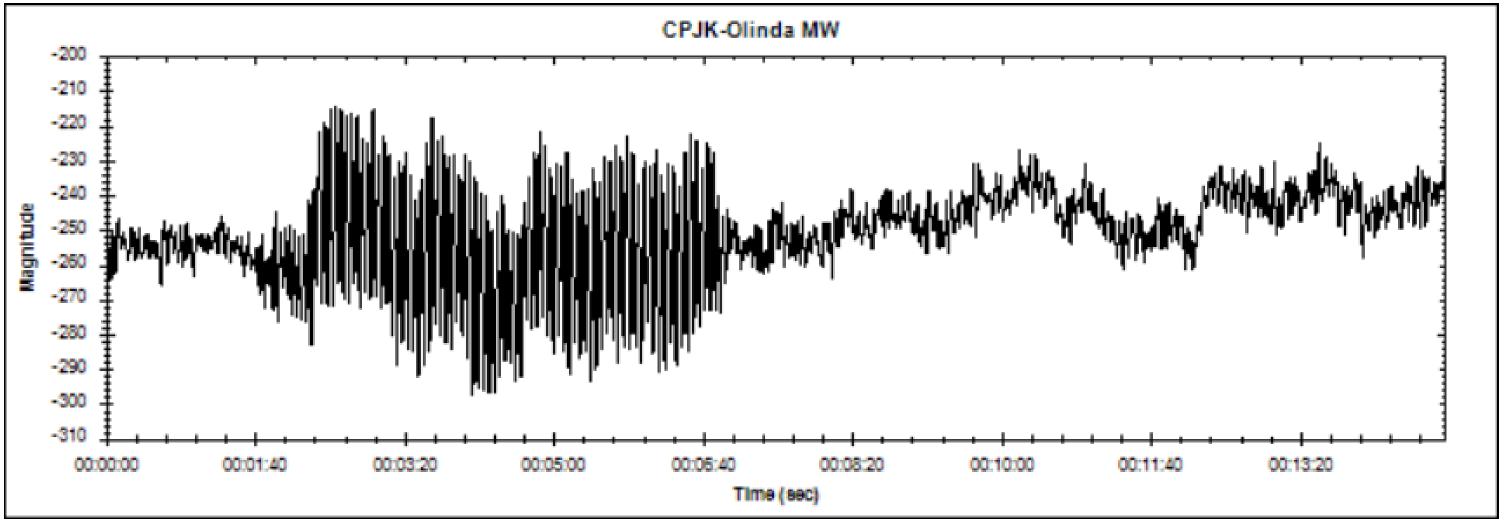


Resonance with Interarea Mode [1]

- Resonance effect high when:
  - Forced oscillation frequency near system mode frequency
  - System mode poorly damped
  - Forced oscillation location near the two distant ends of mode
- Resonance effect medium when
  - Some conditions hold
- Resonance effect small when
  - None of the conditions holds

1. M. Venkatasubramanian, "Oscillation Monitoring System", June 2015
http://www.energy.gov/sites/prod/files/2015/07/f24/3.%20Mani%20Oscillation%20Monitoring.pdf

Medium Resonance on 11/29/2005



- 20 MW 0.26 Hz Forced Oscillation in Alberta Canada
- 200 MW Oscillations on California-Oregon Inter-tie
- System mode 0.27 Hz at 8% damping
- Two out of the three conditions were true.

1. M. Venkatasubramanian, “Oscillation Monitoring System”, June 2015
http://www.energy.gov/sites/prod/files/2015/07/f24/3.%20Mani%20Oscillation%20Monitoring.pdf

An On-line Oscillation Detection Tool

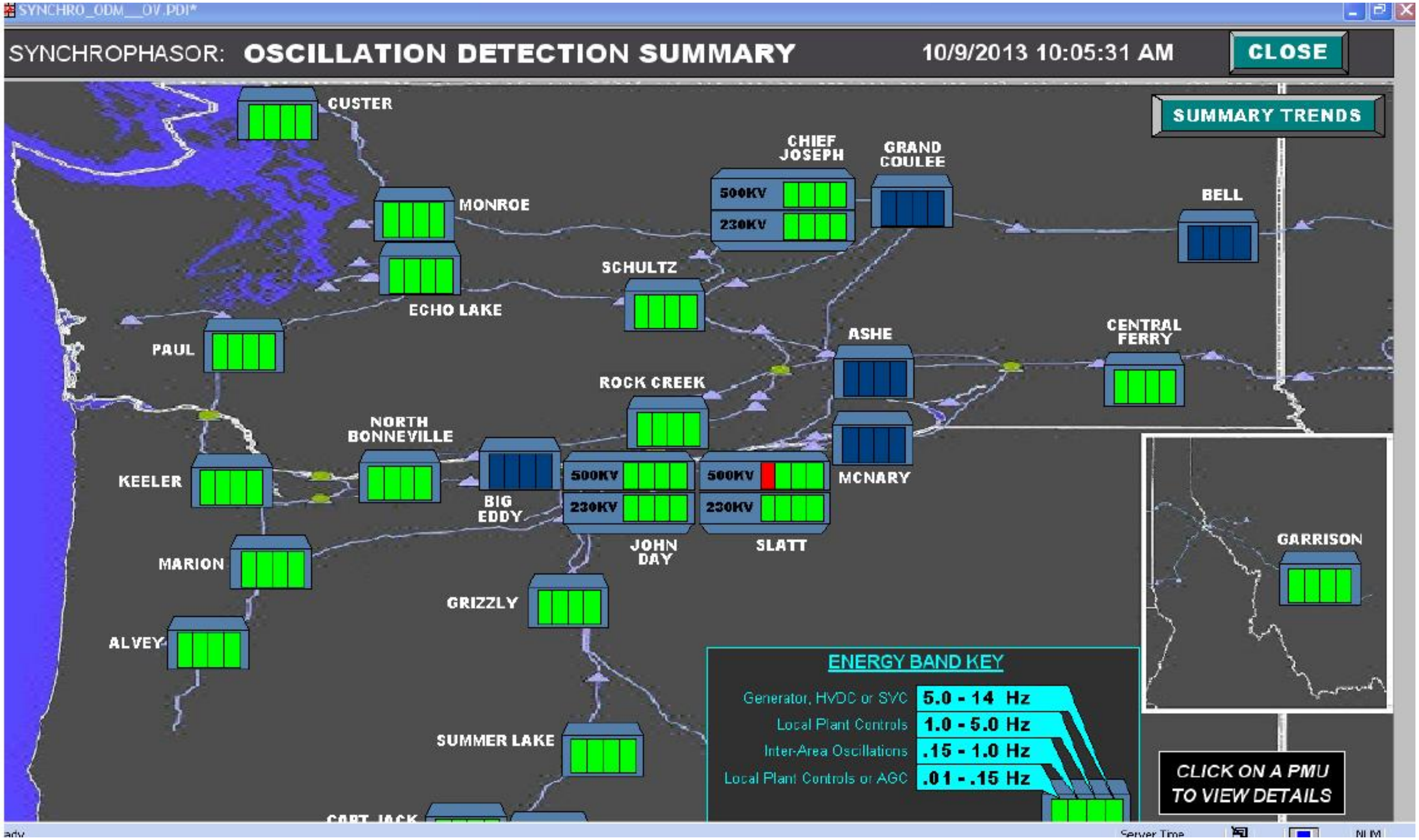


Image source: WECC Joint Synchronized Information Subcommittee Report, October 2013

Stability Phenomena and Tools

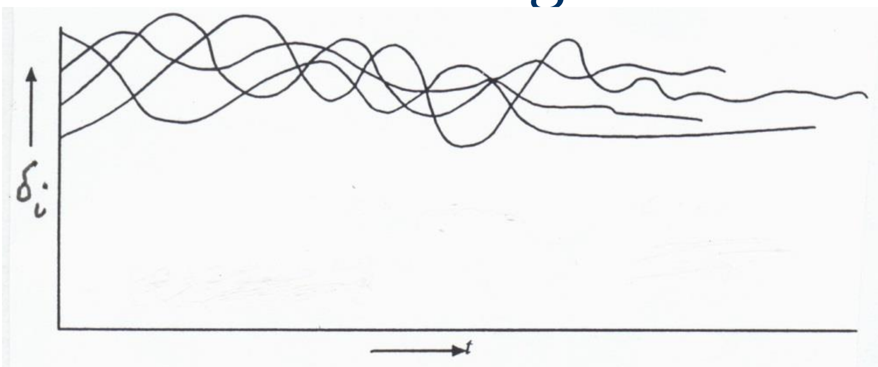
- Large Disturbance Stability (Non-linear Model)
- Small Disturbance Stability (Linear Model)
- Structural Stability (Non-linear Model)
  Loss of stability due to parameter variations.
- <u>Tools</u>
  - Simulation
  - Repetitive time-domain simulations are required to find critical parameter values, such as clearing time of circuit breakers.
  - Direct methods using Lyapunov-based theory (Also called Transient Energy Function (TEF) methods)
    - Can be useful for screening
  - Sensitivity based methods.

Transient Energy Function (TEF) Techniques

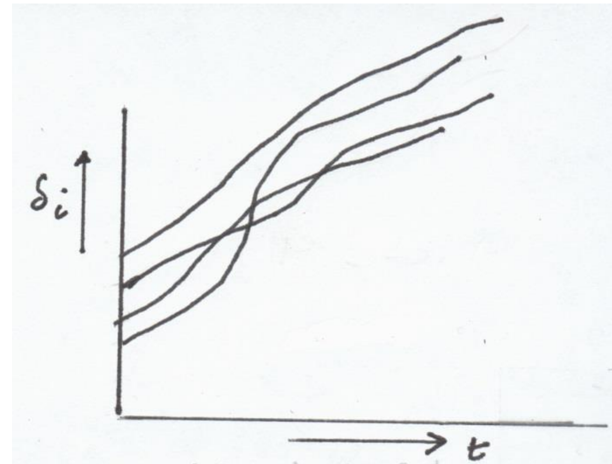
- No repeated simulations are involved.
- Limited somewhat by modeling complexity.
- Energy of the system used as Lyapunov function.
- Computing energy at the "controlling" unstable equilibrium point (CUEP) (critical energy).
- CUEP defines the mode of instability for a particular fault.
- Computing critical energy is <u>not</u> easy.

Judging Stability / Instability

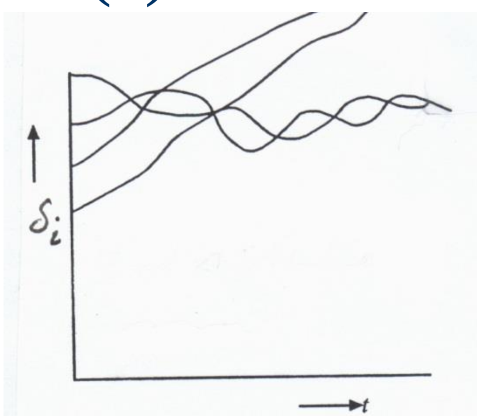
Monitor Rotor Angles



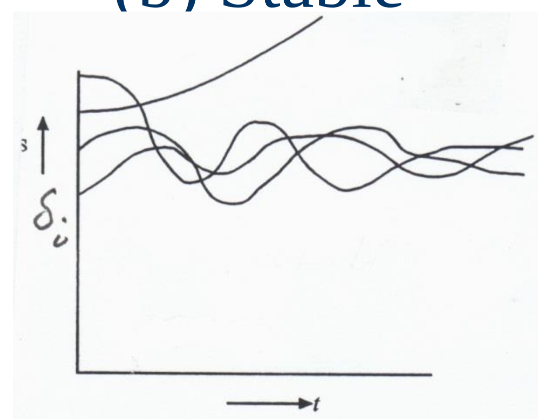
(a) Stable



(b) Stable



(c) Unstable



(d) Unstable

Stability is judged by Relative Rotor Angles.

Mathematical Formulation

- A power system undergoing a disturbance (fault, etc), followed by clearing of the fault, has the following model

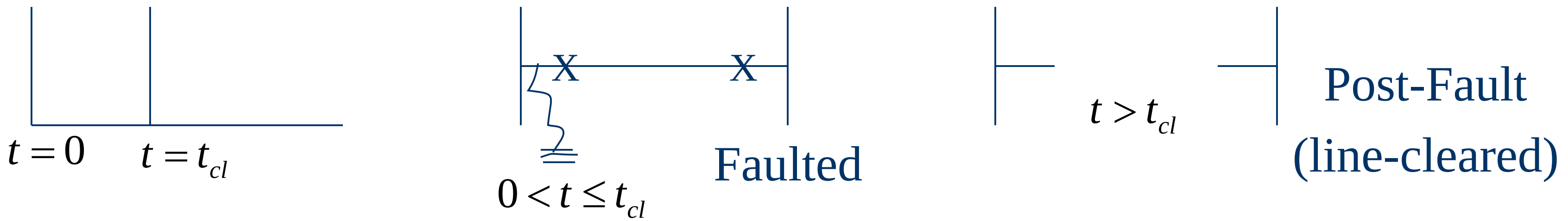
$$\dot{\mathbf{x}}(t) = \mathbf{f}^{\mathbf{I}}(\mathbf{x}(t)) \quad -\infty < t \le 0 \qquad (1)$$

$$\dot{\mathbf{x}}(t) = \mathbf{f}^{\mathbf{F}}(\mathbf{x}(t)) \quad 0 < t \le t_{cl} \qquad (2)$$

$$\dot{\mathbf{x}}(t) = \mathbf{f}(\mathbf{x}(t)) \quad t_{cl} < t \le \infty \qquad (3)$$

  – (1) Prior to fault (Pre-fault)
  – (2) During fault (Fault-on or faulted)
  – (3) After the fault (Post-fault)

T_{cl} is the clearing time

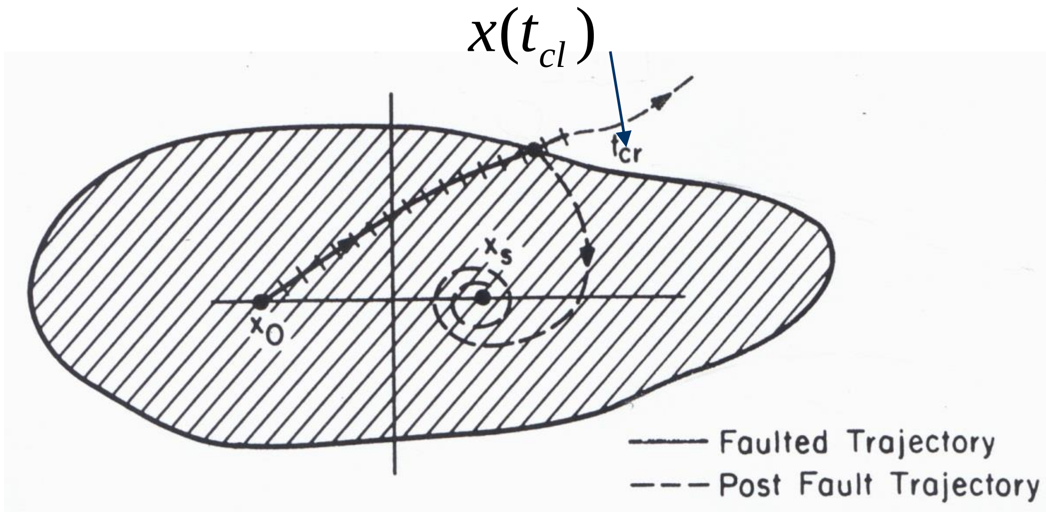


Critical Clearing Time

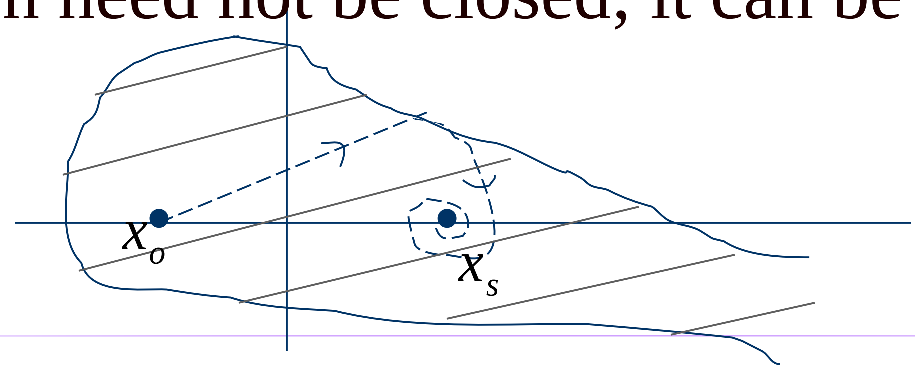
- Assume the post-fault system has a stable equilibrium point $\mathbf{x}_s$
- All possible values of $\mathbf{x}(t_{cl})$ for different clearing times provide the initial conditions for the post-fault system
  – Question is then will the trajectory of the post fault system, starting at $\mathbf{x}(t_{cl})$, converge to $\mathbf{x}_s$ as $t \rightarrow \infty$
- Largest value of t_{cl} for which this is true is called the critical clearing time, t_{cr}
- The value of t_{cr} is different for different faults

Region of Attraction (ROA)

All faulted trajectories cleared before they reach the boundary of the ROA will tend to $\mathbf{x}_s$ as $t \rightarrow \infty$ (stable)



The region need not be closed; it can be open:



Methods to Compute RoA

- Had been a topic of intense research in power system literature since early 1960's.
- The stable equilibrium point (SEP) of the post-fault system, $\mathbf{x}_s$, is generally close to the pre-fault EP, $\mathbf{x}_0$
- Surrounding $\mathbf{x}_s$ there are a number of unstable equilibrium points (UEPs).
- The boundary of ROA is characterized via these UEPs

$$\mathbf{x}_{u,i}\ , i = 1, 2 \ldots$$

$$\mathbf{f}(\mathbf{x}) = 0 \quad i.e. \quad \mathbf{f}(\mathbf{x}_{u,i}) = 0 \quad i = 1, 2 \ldots$$

Characterization of RoA

- Define a scalar energy function V(**x**) = sum of the kinetic and potential energy of the post-fault system.
- Compute $V(\mathbf{x}_{u,i})$ at each UEP, i=1,2,…
- Defined V_{cr} as

$$V_{cr} = Min\, V(\mathbf{x})\Big|_{\mathbf{x}_{u,i}}$$

  – RoA is defined by $V(\mathbf{x}) < V_{cr}$
  – But this can be an extremely conservative result.
- Alternative method: Depending on the fault, identify the critical UEP, $\mathbf{x}_{u,cr}$, towards which the faulted trajectory is headed; then $V(\mathbf{x}) < V(\mathbf{x}_{u,cr})$ is a good estimate of the ROA.

Lyapunov's Method

- Defining the function V(**x**) is a key challenge
- Consider the system defined by

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}), \quad \mathbf{f}(\mathbf{x}_s) = \mathbf{0}$$

- Lyapunov's method: If there exists a scalar function V(**x**) such that

1) $V(\mathbf{x}_\mathrm{s}) = 0$

2) $V(\mathbf{x}) > 0$ for all $\mathbf{x}$ around $\mathbf{x}_s$

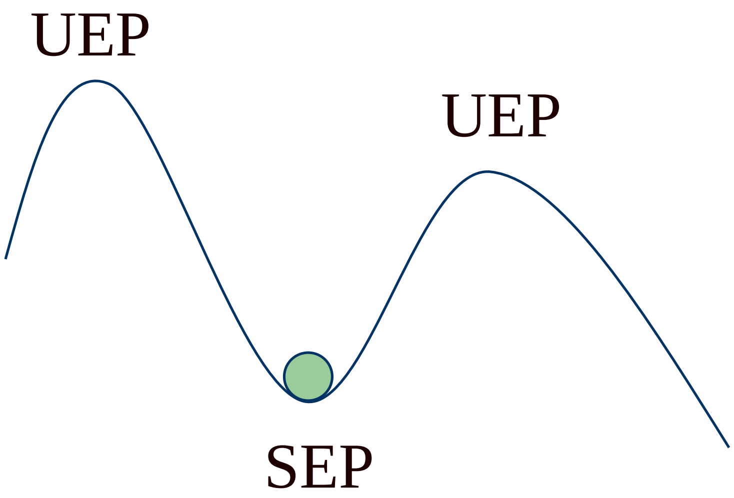
3) $\dot{V}(\mathbf{x}) \leq 0$ for all $\mathbf{x}$ around $\mathbf{x}_\mathrm{s}$

Then $\mathbf{x}_\mathrm{s}$ is stable in the sense of Lyapunov

EP $\mathbf{x}_\mathrm{s}$ is asympotically stable if $\dot{V}(\mathbf{x}) < 0$ for $\mathbf{x} \neq \mathbf{x}_s$ around $\mathbf{x}_s$

Ball in Well Analogy

- The classic Lyapunov example is the stability of a ball in a well (valley) in which the Lyapunov function is the ball's total energy (kinetic and potential)



- For power systems, defining a true Lyapunov function often requires using restrictive models

Power System Example

- Consider the classical generator model using an internal node representation (load buses have been equivalenced)

$$M_i \frac{d^2\delta_i}{dt^2} + D_i \frac{d\delta_i}{dt} = P_i - \sum_{\substack{j=1 \\ j\neq i}}^{m} (C_{ij}\sin\delta_{ij} + D_{ij}\cos\delta_{ij})$$

$$P_i = T_{Mi} - E_i^2 G_{ii}$$

C_{ij} are the susceptance terms, D_{ij} the conductance terms

Functionally

$$M_i \frac{d^2\delta_i}{dt^2} + D_i \frac{d\delta_i}{dt} = P_i - P_{ei}(\delta_1, \ldots, \delta_m) \qquad i = 1, \ldots, m$$

$$\dot{\delta}_i = \omega_i - \omega_s$$

$$\dot{\omega}_i = \frac{1}{M_i}\left(P_i - P_{ei}(\delta_i, \ldots, \delta_m) - D_i(\omega_i - \omega_s)\right)$$

Constructing the Transient Energy Function (TEF)

- The reference frame matters. Either relative rotor angle formulation, or COI reference frame.
  - COI is preferable since we measure angles with respect to the "mean motion" of the system.
- TEF for conservative system (i.e., zero damping)

$$\delta_o = \frac{1}{M_T}\sum_{i=1}^{m} M_i\delta_i$$ With center of speed as $$\omega_o = \frac{1}{M_T}\sum_{i=1}^{m} M_i\omega_i$$

where $M_T = \sum_{i=1}^{m} M_i$. We then transform the variables to the COI variables as $\theta_i = \delta_i - \tilde{\delta}_o$, $\omega_i = \omega_i - \omega_o$.

It is easy to verify $\dot{\theta}_i = \dot{\delta}_i - \dot{\delta}_o = \omega_i - \tilde{\omega}_o \triangleq \omega_i$

TEF

- We consider the general case in which all M_i's are finite. We have two sets of differential equations:

$$M_i \frac{d\tilde{\omega}_i}{dt} = f_i^F(\theta) \quad 0 < t \le t_{cl} \qquad (Faulted)$$

$$\frac{d\theta_i}{dt} = \tilde{\omega}_i, \quad i = 1, 2, ..., m$$

And

$$M_i \frac{d\tilde{\omega}_i}{dt} = f_i(\theta) \quad t > t_{cl} \qquad (Post\ fault)$$

$$\frac{d\theta_i}{dt} = \tilde{\omega}_i, \quad i = 1, 2, ..., m$$

- Let the post fault system has a SEP at $\boldsymbol{\theta} = \boldsymbol{\theta}^s, \tilde{\boldsymbol{\omega}} = \mathbf{0}$
- This SEP is found by solving

$$\mathbf{f}_i(\boldsymbol{\theta}) = \mathbf{0}, \ i = 1, .., m$$

TEF

- Steps for computing the critical clearing time are:
  - Construct a Lyapunov (energy) function for the post-fault system.
  - Find the critical value of the Lyapunov function (critical energy) for a given fault
  - Integrate the faulted equations until the energy is equal to the critical energy; this instant of time is called the critical clearing time
- Idea is once the fault is cleared the energy can only decrease, hence the critical clearing time is determined directly
- Methods differ as to how to implement steps 2 and 3.

Potential Energy Boundary Surface

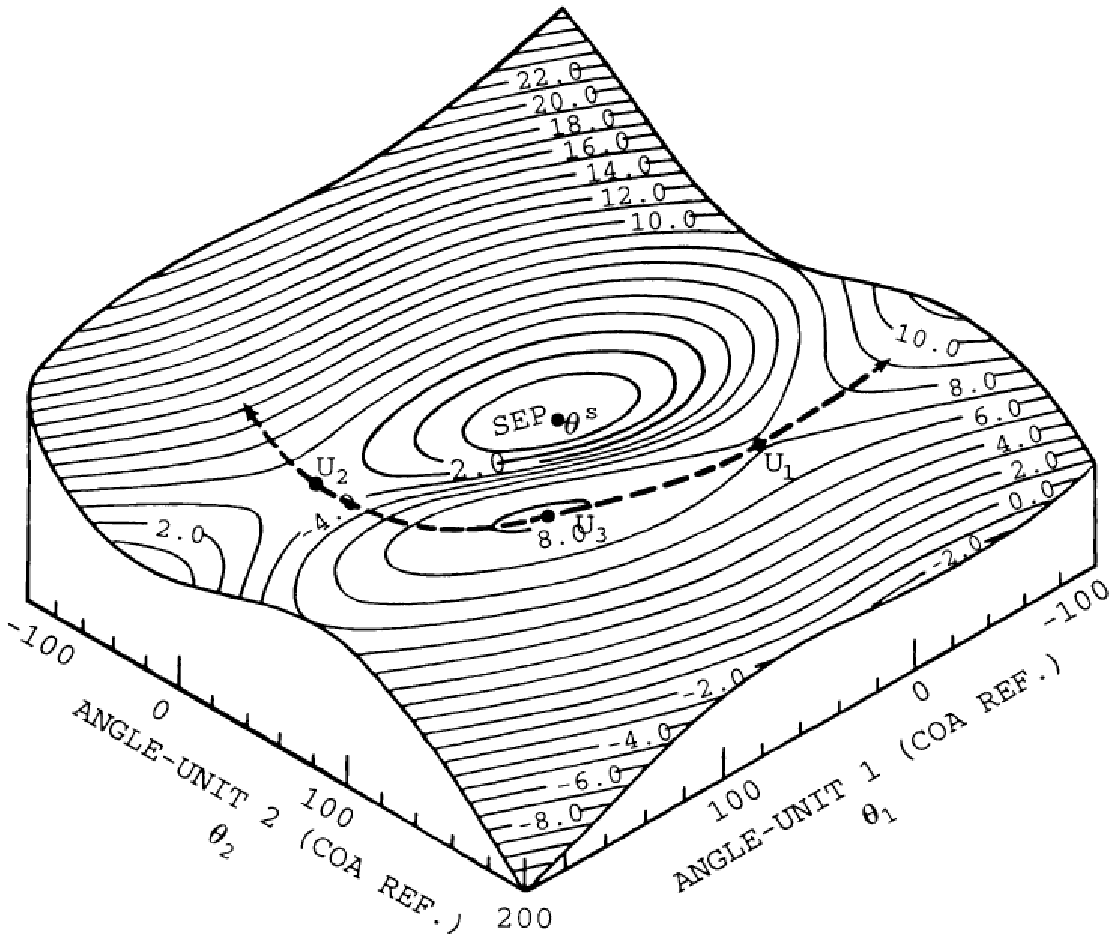


Figure 9.10: The potential energy boundary surface (reproduced from [97]

Figure from course textbook

TEF

- Integrating the equations between the post-fault SEP and the current state gives

$$V(\theta,\omega)=\frac{1}{2}\sum_{i=1}^{m}M_i\omega_i^2-\sum_{i=1}^{m}\int_{\theta_i^s}^{\theta_i}f_i(\theta)d\theta_i$$

$$=\frac{1}{2}\sum_{i=1}^{m}M_i\omega_i^2-\sum_{i=1}^{m}P_i(\theta_i-\theta_i^s)-\sum_{i=1}^{m-1}\sum_{j=i+1}^{m}[C_{ij}(\cos\theta_{ij}-\cos\theta_{ij}^s)$$

$$-\int_{\theta_i^s+\theta_j^s}^{\theta_i+\theta_j}D_{ij}\cos\theta_{ij}d(\theta_i-\theta_j)]$$

$$=V_{KE}(\omega)+V_{PE}(\theta)$$

C_{ij} are the susceptance terms, D_{ij} the conductance terms; the conductance term is path dependent

TEF

- $V(\boldsymbol{\theta}, \tilde{\boldsymbol{\omega}})$ contains path dependent terms.
- Cannot claim that $V(\boldsymbol{\theta}, \tilde{\boldsymbol{\omega}})$ is p.d.
- If conductance terms are ignored then it can be shown to be a Lyapunov function
- Methods to compute the UEPS are
  - Potential Energy Boundary Surface (PEBS) method.
  - Boundary Controlling Unstable (BCU) equilibrium point method.
  - Other methods (Hybrid, Second-kick etc)

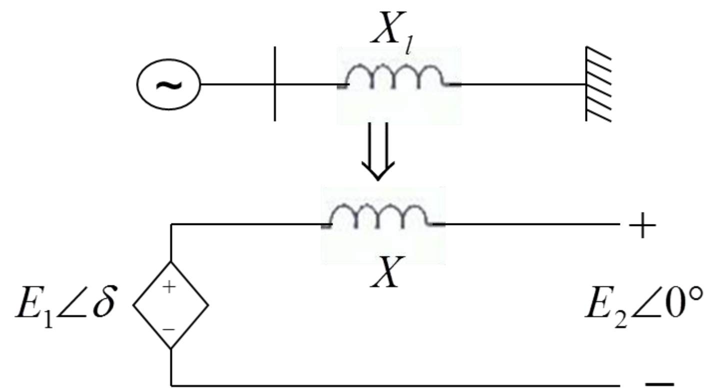
(a) and (b) are the most important ones.

Equal Area Criterion and TEF

- For an SMIB system with classical generators this reduces to the equal area criteria
  - TEF is for the post-fault system
  - Change notation from T_m to P_m

$$M\frac{d^2\delta}{dt^2} = P_m - P_e^{\max}\sin\delta \qquad (1)$$

$$P_e^{\max} = \frac{E_1 E_2}{X^I}\sin\delta \qquad (2)$$



$$X = X^F \quad (Faulted)$$

$$X = X^I \quad (Post-fault)$$

$$P_e = \frac{E_1 E_2}{X^F}\sin\delta \quad (Faulted)$$

$$P_e = \frac{E_1 E_2}{X^I}\sin\delta \quad (Post-fault)$$

TEF for SMIB System

$$M\frac{d^2\delta}{dt^2} = P_m - P_e^{\max}\sin\delta \qquad (1)$$

The right hand side of (1) can be written as $-\dfrac{\partial V_{PE}}{\partial\delta}$,where

$$V_{PE}(\delta) = -P_m\delta - P_e^{\max}\cos\delta \qquad (2)$$

Multiplying (1) by $\frac{d\delta}{dt}$, re-write

$$\frac{d}{dt}\left[\frac{M}{2}\left(\frac{d\delta}{dt}\right)^2 + V_{PE}(\delta)\right] = 0 \quad \text{since} \quad \frac{d\delta}{dt} = \omega$$

i.e $\dfrac{d}{dt}\left[\dfrac{1}{2}M\omega^2 + V_{PE}(\delta)\right] = 0$

i.e $\dfrac{d}{dt}[V(\delta,\omega)] = 0$

Hence, the energy function is

$$V(\delta,\omega) = \frac{1}{2}M\omega^2 + V_{PE}(\delta)$$

TEF for SMIB System (contd)

- The equilibrium point is given by

$$0 = P_m - P_e^{\max} \sin\delta \qquad (1)$$

$$\delta^s = \sin^{-1}\left(\frac{P_m}{P_e^{\max}}\right) \qquad (2)$$

- This is the stable e.p.
- Can be verified by linearizing.
- Eigenvalues on jω axis. (Marginally Stable)
- With slight damping eigenvalues are in L.H.P.
- TEF is still constructed for undamped system.

TEF for SMIB System

- The energy function is

$$V(\delta,\omega) = V_{KE} + V_{PE}(\delta) = \tfrac{1}{2}M\omega^2 - P_m\delta - P_e^{\max}\cos\delta$$

- There are two UEP: $\delta^{u1} = \pi - \delta^s$ and $\delta^{u2} = -\pi - \delta^s$
- A change in coordinates sets $V_{PE}=0$ for $\delta=\delta^s$

$$V_{PE}(\delta,\delta^s) = -P_m(\delta-\delta^s) - P_e^{\max}(\cos\delta - \cos\delta^s)$$

- With this, the energy function is

$$V(\delta,\omega) = \tfrac{1}{2}M\omega^2 - P_m(\delta-\delta^s) - P_e^{\max}(\cos\delta - \cos\delta^s)$$
$$= V_{KE} + V_{PE}(\delta,\delta^s)$$

- The kinetic energy term is $V_{KE} = \tfrac{1}{2}M\omega^2$

Equal-Area Criterion

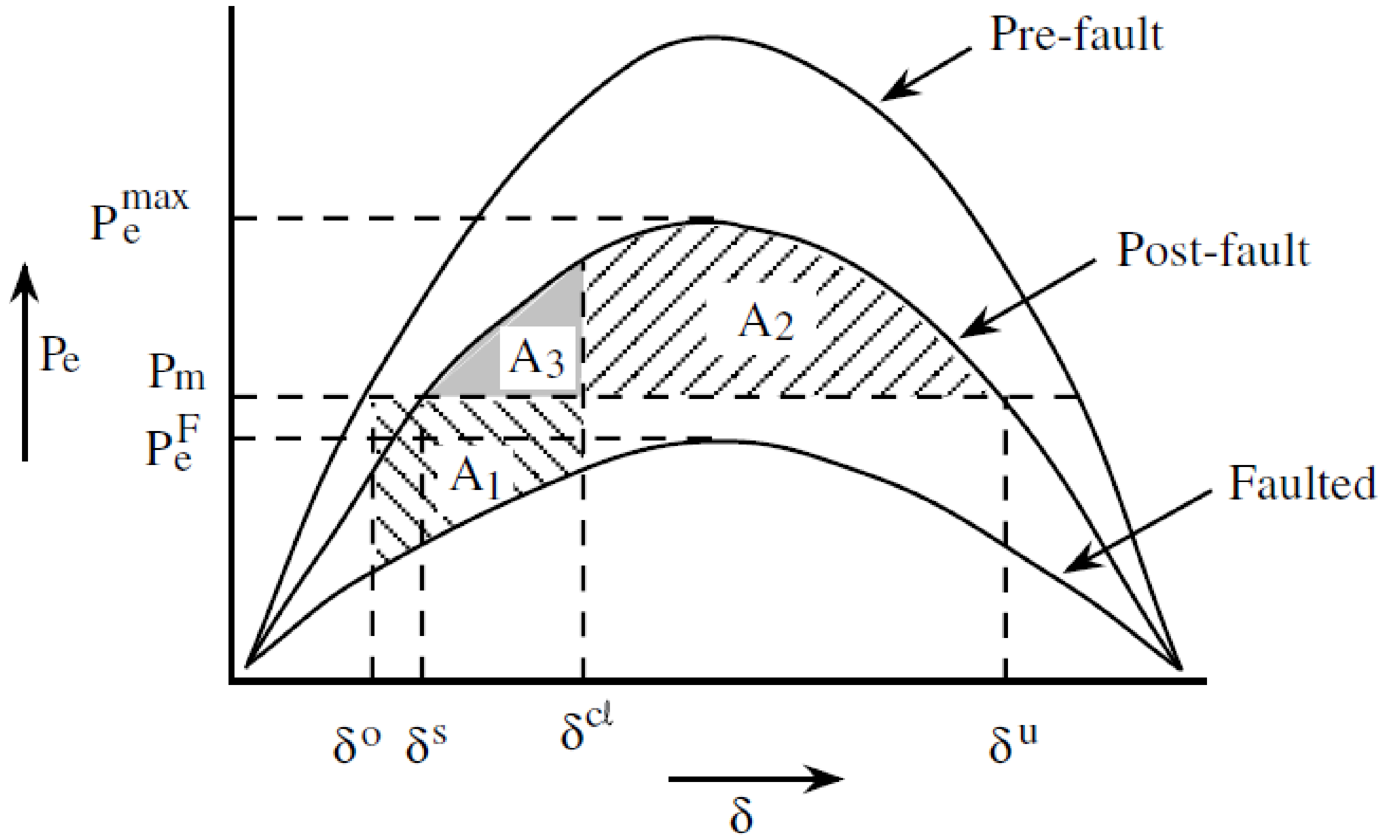


Figure 9.9: Equal-area criterion for the SMIB case

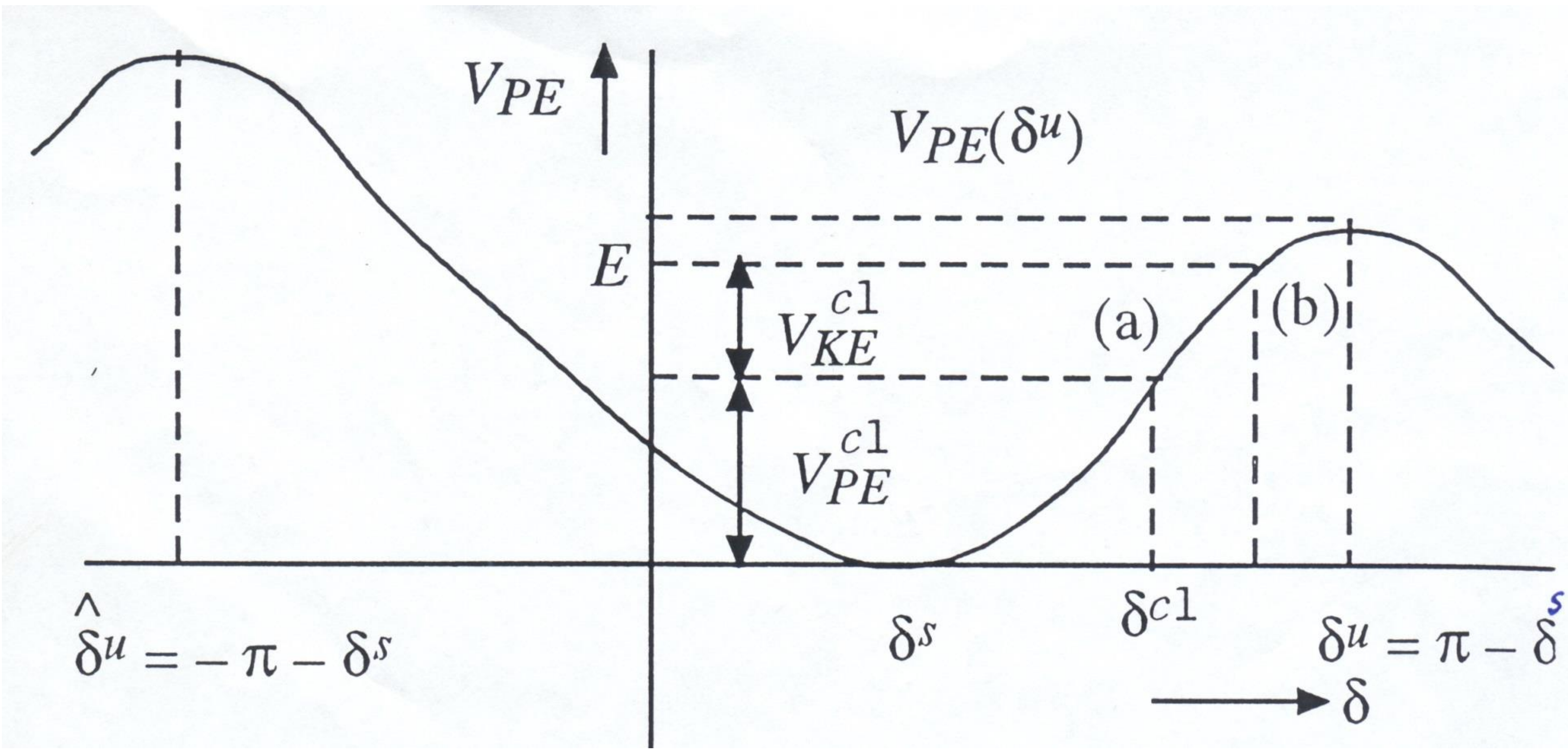
During the fault A_1 is the gain in the kinetic energy and A_3 the gain in potential energy

Figure from course textbook

Energy Function for SMIB System

- $V(\delta,\omega)$ is equal to a constant E, which is the sum of the kinetic and potential energies.
- It remains constant once the fault is cleared since the system is conservative (with no damping)
- $V(\delta,\omega)$ evaluated at $t=t_{cl}$ from the fault trajectory represents the total energy *E* present in the system at $t=t_{cl}$
- This energy must be absorbed by the system once the fault is cleared if the system is to be stable.
- The kinetic energy is always positive, and is the difference between *E* and $V_{PE}(\delta, \delta^s)$

Potential Energy Well for SMIB System



- Potential energy "well" or P.E. curve

- How is E computed?

Structure Preserving Energy Function

- If we retain the power flow equations

$$\dot{\theta}_i = \omega_i - \omega_s \quad (9.69)$$

$$M_i \dot{\omega}_i = T_{Mi} - \sum_{j=1}^{n+m} V_i V_j B_{ij} \sin(\theta_i - \theta_j)$$

$$i = n+1, \ldots, n+m \quad (9.70)$$

$$P_{Li}(V_i) = \sum_{j=1}^{n+m} V_i V_j B_{ij} \sin(\theta_i - \theta_j) \;\; i = 1, \ldots, n \quad (9.71)$$

$$Q_L(V_i) = -\sum_{j=1}^{n+m} V_i V_j B_{ij} \cos(\theta_i - \theta_j) \;\; i = 1, \ldots, n. \quad (9.72)$$

Structure Preserving Energy Function

- Then we can get the following energy function

$$V(\tilde{\omega}, \tilde{\theta}, V) = V_{KE}(\tilde{\omega}) + V_{P1}(\tilde{\theta}, V) + V_{P2}(\tilde{\theta}) \tag{9.73}$$

where

$$V_{KE}(\tilde{\omega}) = \frac{1}{2}\sum_{i=1}^{m} M_i \tilde{\omega}_i^2$$

$$V_{p1}(\tilde{\theta}, V) = -\sum_{i=n+1}^{n+m} T_{Mi}(\tilde{\theta}_i - \tilde{\theta}_i^s) + \sum_{i=1}^{n} \int_{V_i^s}^{V_i} \frac{Q_{Li}(V_i)}{V_i} dV_i \tag{9.74}$$

$$\frac{1}{2}\sum_{1}^{n} B_{ii}(V_i^2 - (V_i^s)^2) \tag{9.75}$$

$$-\sum_{i=1}^{n+m-1} \sum_{j=i+1}^{n+m} B_{ij}(V_i V_j \cos\tilde{\theta}_{ij} - V_i^s V_j^s \cos\tilde{\theta}_{ij}^s) \tag{9.76}$$

$$V_{p2}(\tilde{\theta}) = -\sum_{1}^{n} P_{Li}(\tilde{\theta}_i - \tilde{\theta}_i^s). \tag{9.77}$$

Energy Functions for a Large System

- Need an energy function that at least approximates the actual system dynamics
  - This can be quite challenging!
- In general there are many UEPs; need to determine the UEPs for closely associated with the faulted system trajectory (known as the controlling UEP)
- Energy of the controlling UEP can then be used to determine the critical clearly time (i.e., when the fault-on energy is equal to that of the controlling UEP)
- For on-line transient stability, technique can be used for fast screening

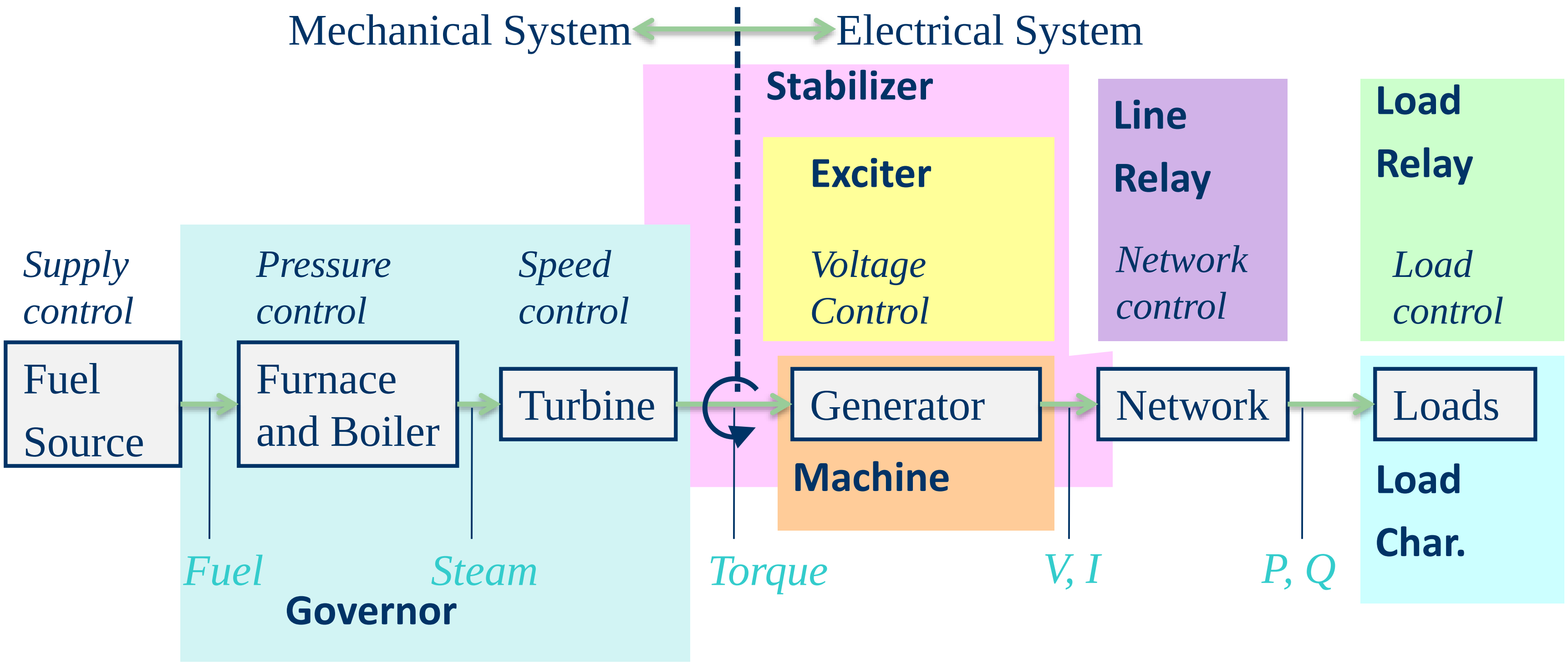
Damping Oscillations: Power System Stabilizers (PSSs)

- A PSS adds a signal to the excitation system to improve the generator's damping
  - A common signal is proportional to the generator's speed; other inputs, such as like power, voltage or acceleration, can be used
  - The Signal is usually measured locally (e.g. from the shaft)
- Both local modes and inter-area modes can be damped.
- Regular tuning of PSSs is important

Stabilizer References

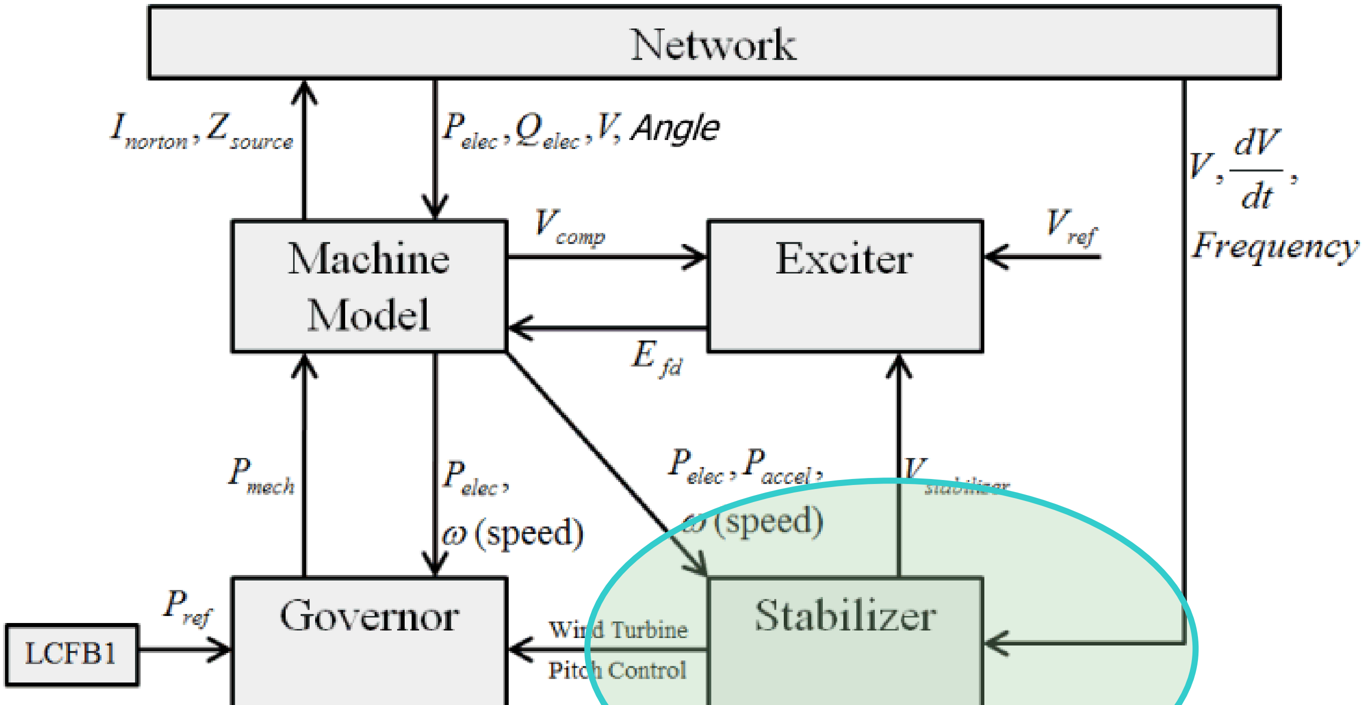
- A few references on power system stabilizers
  - E. V. Larsen and D. A. Swann, "Applying Power System Stabilizers Part I: General Concepts," in IEEE Transactions on Power Apparatus and Systems, vol.100, no. 6, pp. 3017-3024, June 1981.
  - E. V. Larsen and D. A. Swann, "Applying Power System Stabilizers Part II: Performance Objectives and Tuning Concepts," in IEEE Transactions on Power Apparatus and Systems, vol.100, no. 6, pp. 3025-3033, June 1981.
  - E. V. Larsen and D. A. Swann, "Applying Power System Stabilizers Part III: Practical Considerations," in IEEE Transactions on Power Apparatus and Systems, vol.100, no. 6, pp. 3034-3046, June 1981.
  - *Power System Coherency and Model Reduction*, Joe Chow Editor, Springer, 2013

Dynamic Models in the Physical Structure



P. Sauer and M. Pai, *Power System Dynamics and Stability*, Stipes Publishing, 2006.

Power System Stabilizer (PSS) Models



P_{elec} = Electrical Power

Q_{elec} = Electrical Reactive Power

V = Voltage at Terminal Bus

$\frac{dV}{dt}$ = Derivate of Voltage

V_{comp} = Compensated Voltage

P_{mech} = Mechanical Power

ω(speed) = Rotor Speed (often it's deviation from nominal speed)

P_{accel} = Accelerating Power

$V_{stabilizer}$ = Output of Stabilizer

V_{ref} = Exciter Control Setpoint (determined during initialization)

P_{ref} = Governor Control Setpoint (determined during initialization)

Classic Block Diagram of a System with a PSS

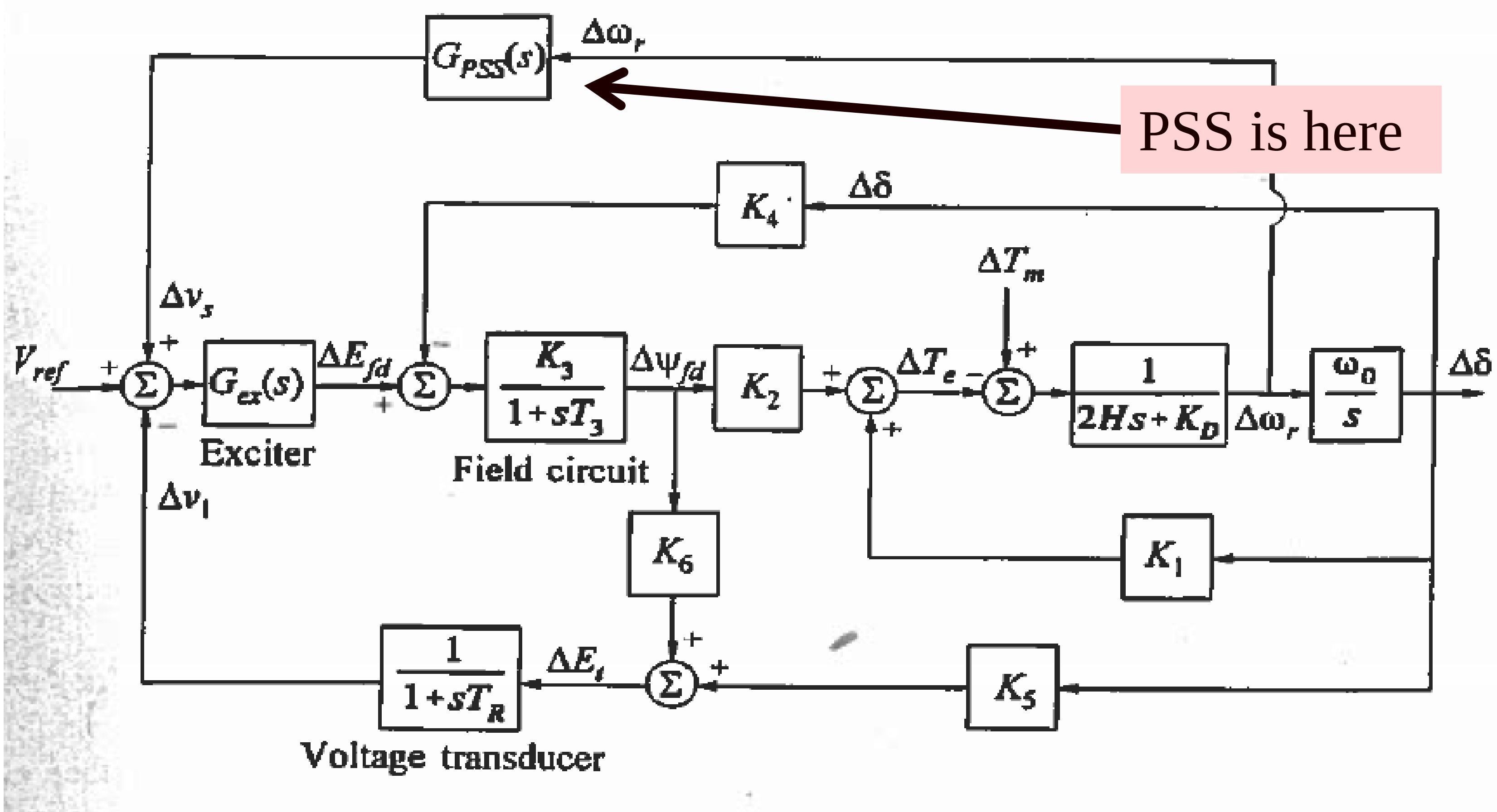
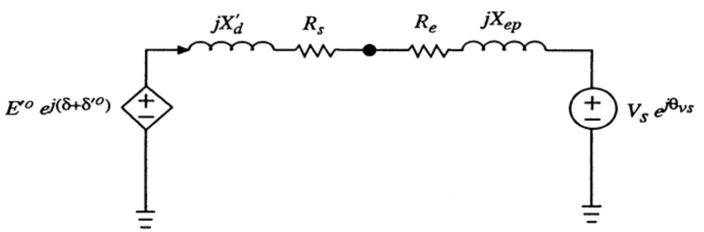


Figure 12.13 Block diagram representation with AVR and PSS

Image Source: Kundur, *Power System Stability and Control*

PSS Basics

- Stabilizers can be motivated by considering a classical model supplying an infinite bus



$$\frac{d\delta}{\mathrm{dt}} = \omega - \omega_s = \Delta\omega$$

$$\frac{2H}{\omega_0}\frac{d\Delta\omega}{dt} = T_M^0 - \frac{E'V_s}{X'_d + X_{ep}}\sin(\delta) - D\Delta\omega$$

- Assume internal voltage has an additional component

$$E' = E'_{org} + K\Delta\omega$$

- This can add additional damping if sin(δ) is positive
- In a real system there is delay, which requires compensation

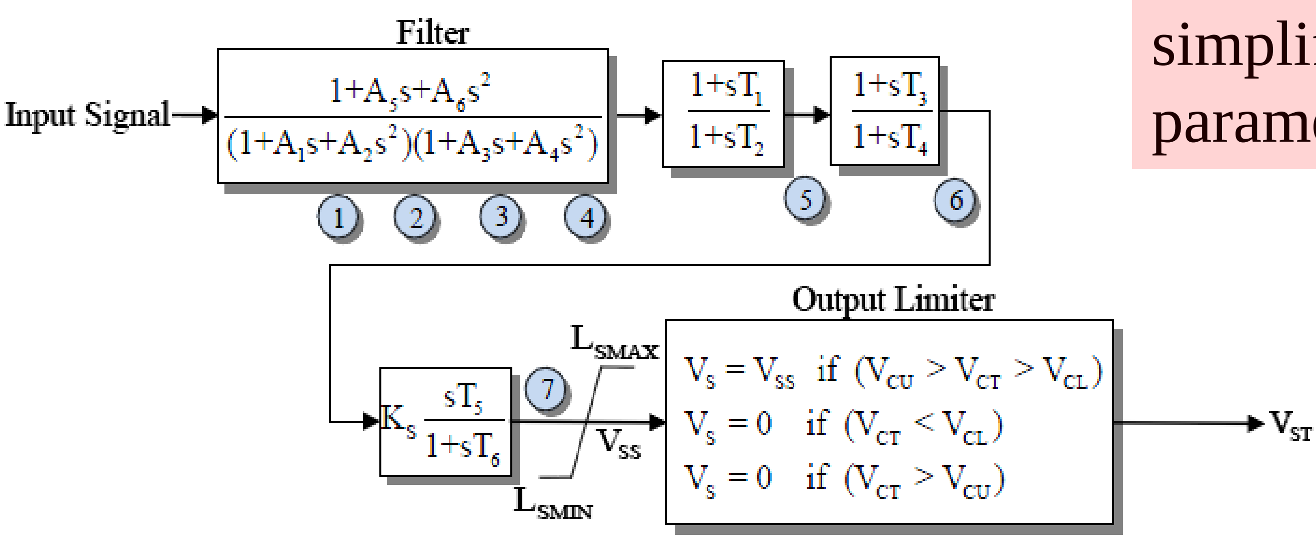
PSS Focus Here

- Fully considering power system stabilizers can get quite involved
- Here we'll just focus on covering the basics, and doing a simple PSS design. The goal is providing insight and tools that can help power system engineers understand the PSS models, determine whether there is likely bad data, understand the basic functionality, and do simple planning level design

Example PSS

- An example single input stabilizer is shown below (IEEEST)
  - The input is usually the generator shaft speed deviation, but it could also be the bus frequency deviation, generator electric power or voltage magnitude

The model can be simplified by setting parameters to zero



V_{ST} is an input into the exciter

Another Single Input PSS

- The PSS1A is very similar to the IEEEST Stabilizer and STAB1

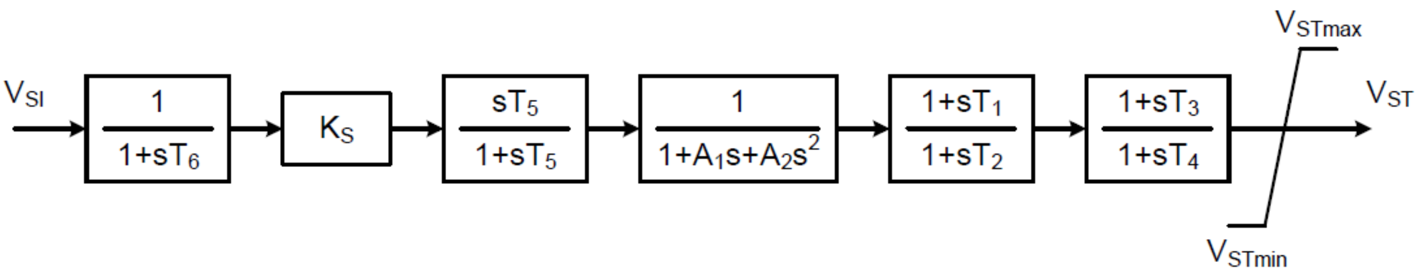
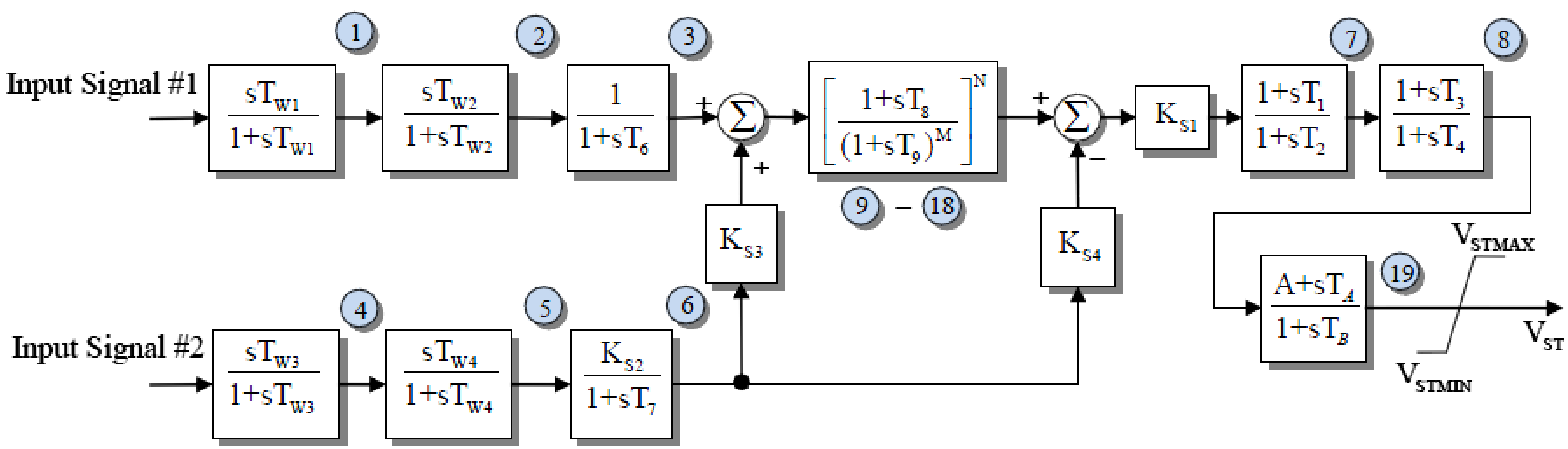


Figure 31 —Type PSS1A single-input power system stabilizer

IEEE Std 421.5 describes the common stabilizers

Example Dual Input PSS

- Below is an example of a dual input PSS (PSS2A)
  - Combining shaft speed deviation with generator electric power is common
  - Both inputs have washout filters to remove low frequency components of the input signals



IEEE Std 421.5 describes the common stabilizers

Washout Filters and Lead-Lag Compensators

- Two common attributes of PSSs are washout filters and lead-lag compensators

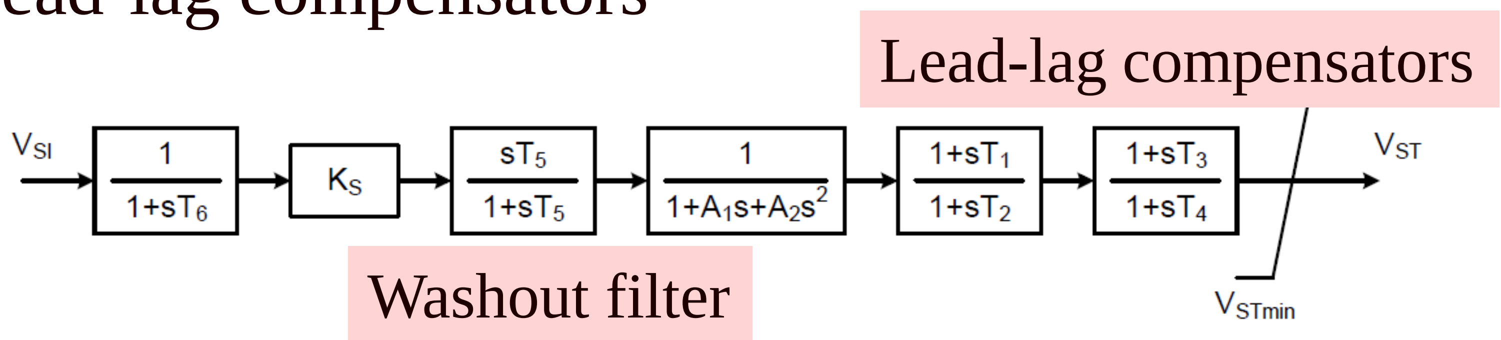
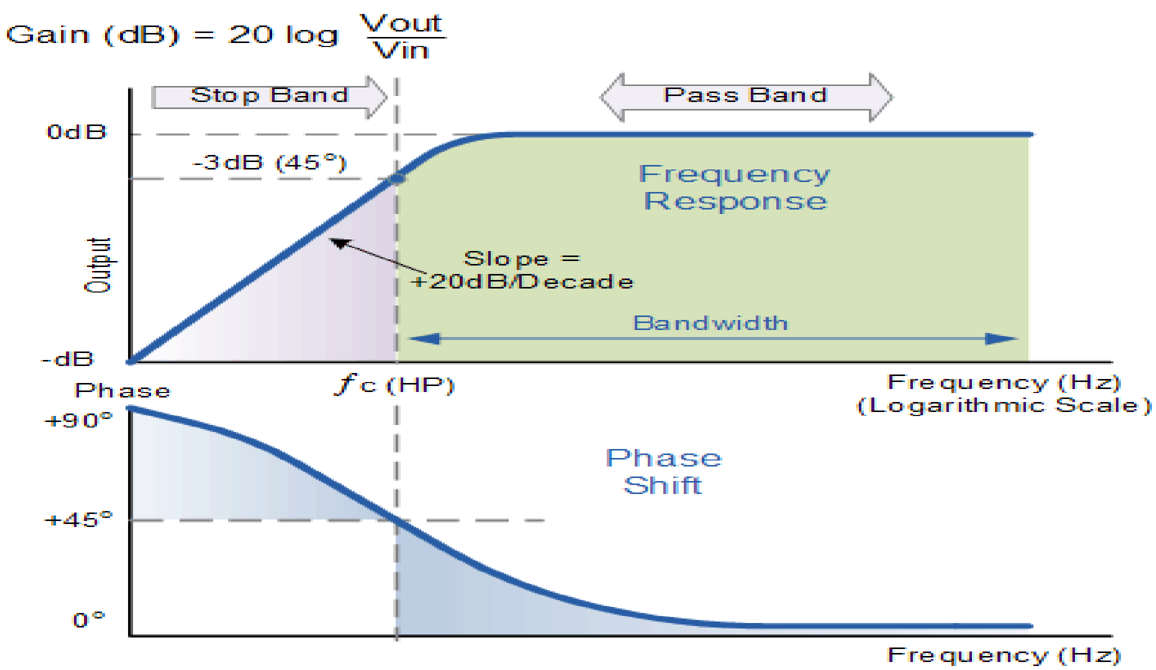


Figure 31 —Type PSS1A single-input power system stabilizer

- Since PSSs are associated with damping oscillations they should be immune to slow changes. These low frequency changes are "washed out" by the washout filter; this is a type of high-pass filter.

Washout Filter

- The filter changes both the magnitude and angle of the signal at low frequencies



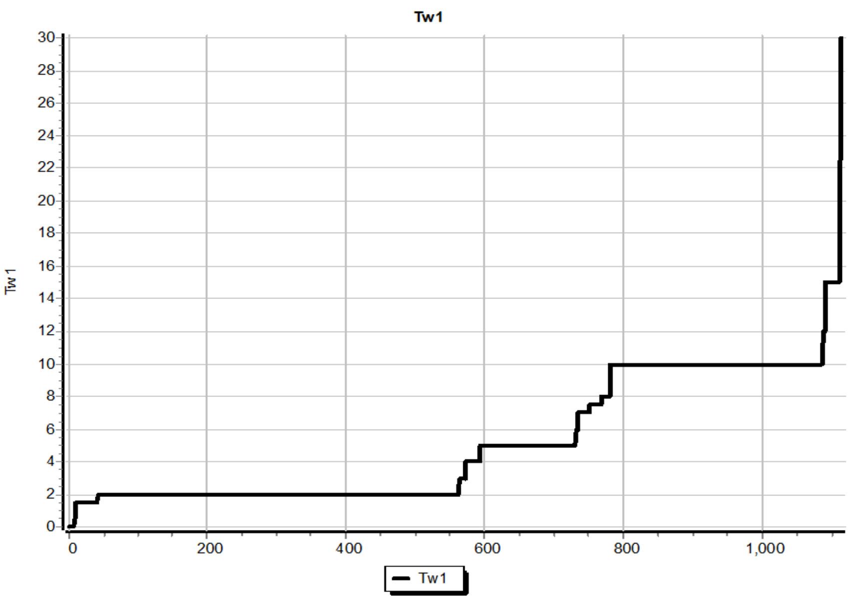
The breakpoint frequency is when the phase shift is 45 degrees and the gain is -3 dB (1/sqrt(2))

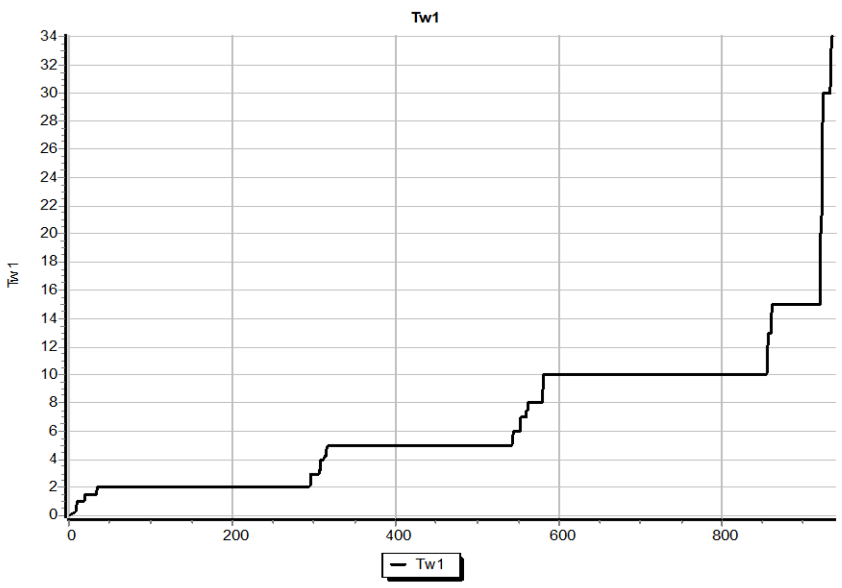
A larger T value shifts the breakpoint to lower frequencies; at T=10 the breakpoint frequency is 0.016 Hz

Image Source: www.electronics-tutorials.ws/filter/filter_3.html

Washout Parameter Variation

- The PSS2A is the most common stabilizer in both the 2015 EI and WECC cases. Plots show the variation in T_{W1} for EI (left) and WECC cases (right); for both the x-axis is the number of PSS2A stabilizers sorted by T_{W1}, and the y-axis is T_{W1} in seconds

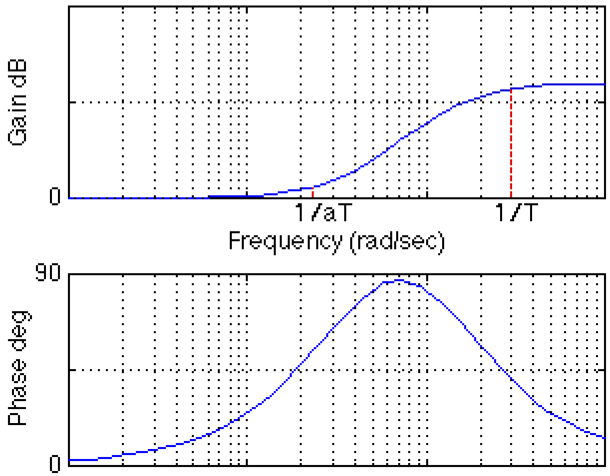




Lead-Lag Compensators

- For a lead-lag compensator of the below form with α <= 1 (equivalently a >= 1)

$$\frac{1+sT_1}{1+sT_2}=\frac{1+sT_1}{1+s\alpha T_1}=\frac{1+asT}{1+sT}$$



- There is no gain or phase shift at low frequencies, a gain at high frequencies but no phase shift
- Equations for a design maximum phase shift α at a frequency f are given

$$\alpha=\frac{1-\sin\phi}{1+\sin\phi},\ T_1=\frac{1}{2\pi f\sqrt{\alpha}}$$

$$\sin\phi=\frac{1-\alpha}{1+\alpha}$$

Stabilizer Design

- As noted by Larsen, the basic function of stabilizers is to modulate the generator excitation to damp generator oscillations in frequency range of about 0.2 to 2.5 Hz
  - This requires adding a torque that is in phase with the speed variation; this requires compensating for the gain and phase characteristics of the generator, excitation system, and power system (GEP(s))
  - We need to compensate for the phase lag in the GEP
- The stabilizer input is often the shaft speed

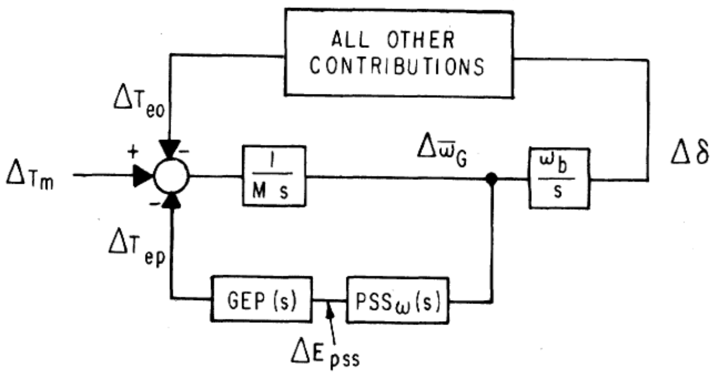


Image Source: Figure 1 from Larsen, 1981, Part 1

Stabilizer Design

- T_6 is used to represent measurement delay; it is usually zero (ignoring the delay) or a small value (< 0.02 sec)
- The washout filter removes low frequencies; T_5 is usually several seconds (with an average of say 5)
  - Some guidelines say less than ten seconds to quickly remove the low frequency component
  - Some stabilizer inputs include two washout filters

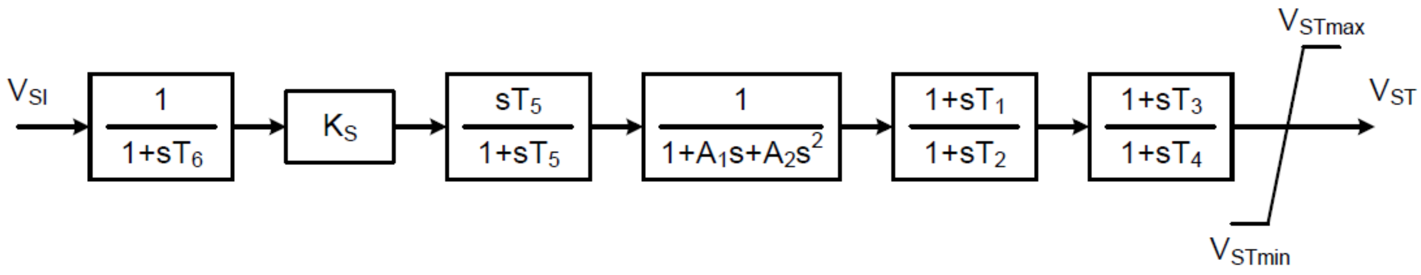


Figure 31 —Type PSS1A single-input power system stabilizer

Image Source: IEEE Std 421.5-2016

Stabilizer Design Values

- With a washout filter value of $T_5 = 10$ at 0.1 Hz ($s = j0.2\pi = j0.63$) the gain is 0.987; with $T_5 = 1$ at 0.1 Hz the gain is 0.53
- Ignoring the second order block, the values to be tuned are the gain, K_s, and the time constants on the two lead-lag blocks to provide phase compensation
  - We'll assume $T_1=T_3$ and $T_2=T_4$

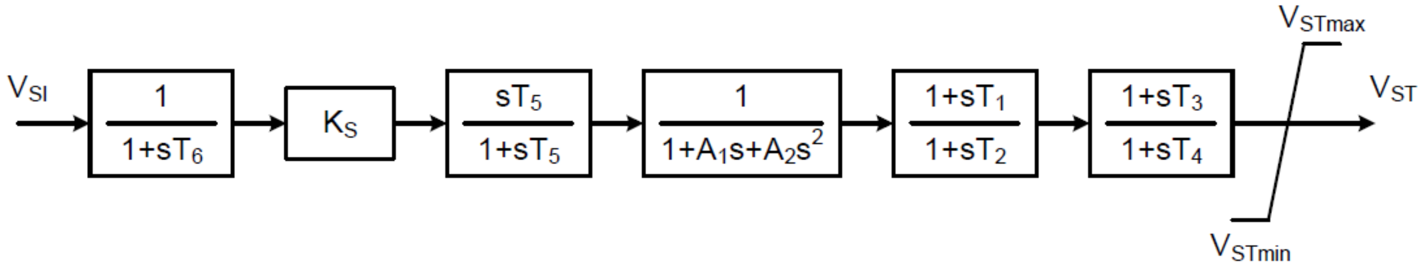


Figure 31 —Type PSS1A single-input power system stabilizer

Stabilizer Design Phase Compensation

- Goal is to move the eigenvalues further into the left-half plane
- Initial direction the eigenvalues move as the stabilizer gain is increased from zero depends on the phase at the oscillatory frequency
  - If the phase is close to zero, the real component changes significantly but not the imaginary component
  - If the phase is around -45° then both change about equally
  - If the phase is close to -90° then there is little change in the real component but a large change in the imaginary component