EEN452 - Control and Operation of Electric Power Systems

Part 6: Power system stability fundamentals

https://sps.cut.ac.cy/courses/een452/

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Today's learning objectives

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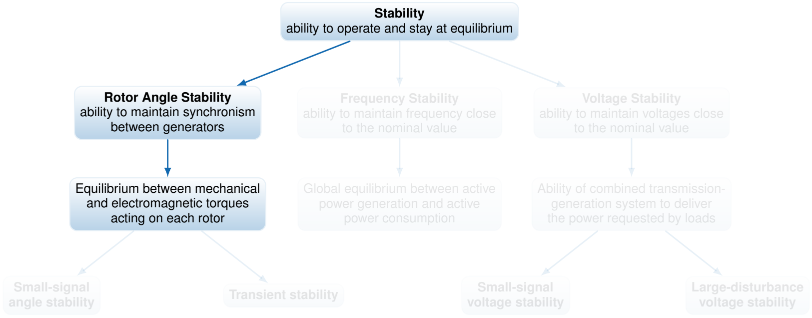
After this part of the lecture and additional reading, you should be able to . . .

1. . . . understand the basic classifications of power system stability;
2. . . . be able to identify and perform stability analysis problems; and,
3. . . . propose methods for stabilizing power systems.

1 Outline

1 Classification [1]



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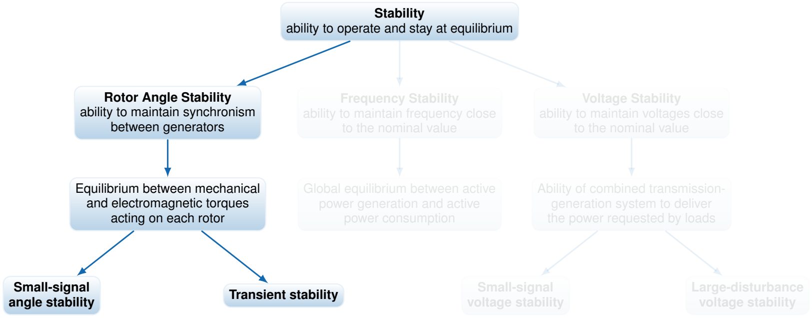

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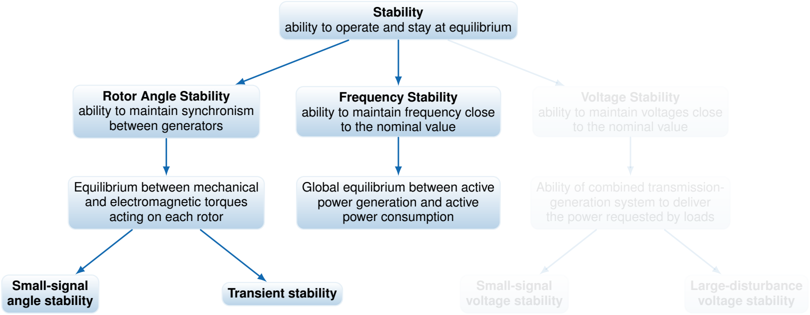

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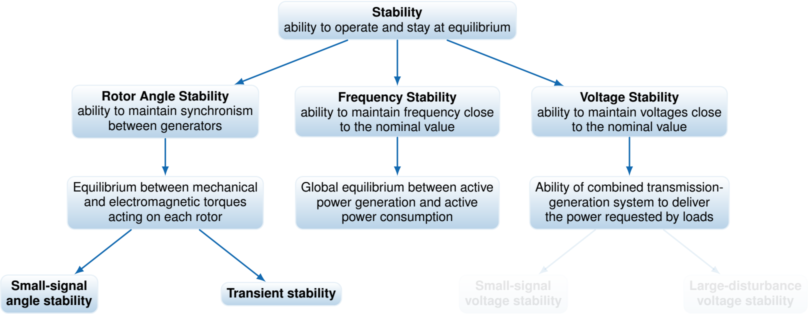

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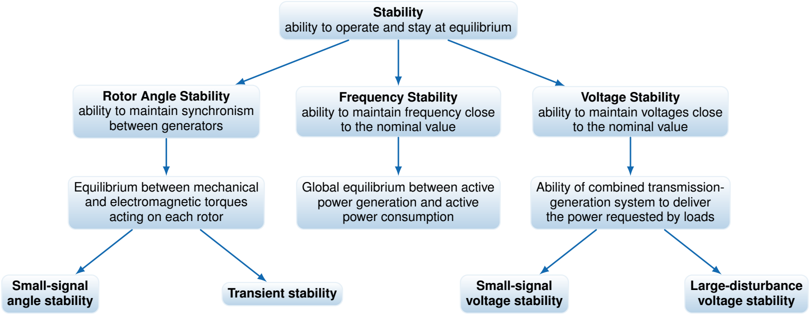

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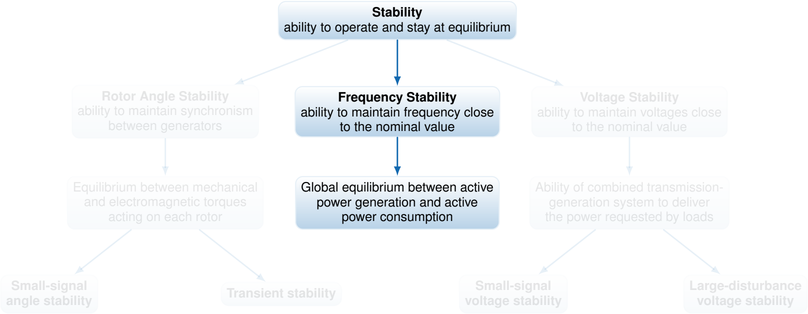

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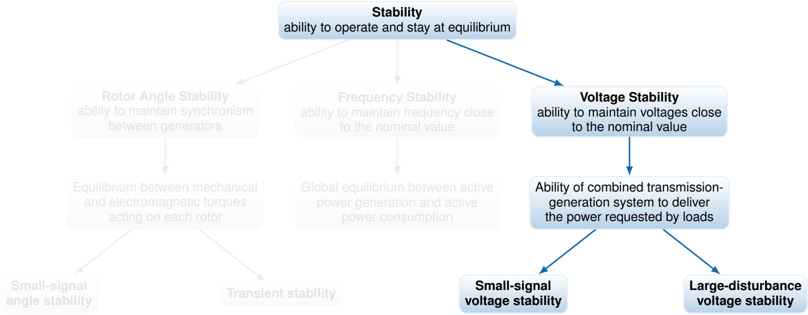
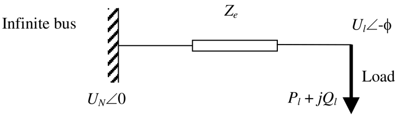




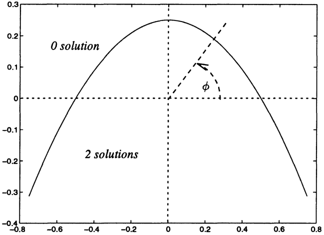
$$P_l = \frac{U_l U_N}{X_e} \sin\phi \qquad Q_l = \frac{U_l U_N \cos\phi - U_l^2}{X_e}$$

$$P_l^2 + \left(Q_l + \frac{U_l^2}{X_e}\right)^2 = \left(\frac{U_l U_N}{X_e}\right)^2 \Rightarrow \left(U_l^2\right)^2 + (2Q_l X_e - U_N^2)U_l^2 + X_e^2(P_l^2 + Q_l^2) = 0 \tag{2.1}$$

To have (at least) one solution:

$$\left(2Q_l X_e - U_N^2\right)^2 - 4X_e^2\left(P_l^2 + Q_l^2\right) \geq 0 \Rightarrow -\left(\frac{P_l X_e}{U_N}\right)^2 - \frac{Q_l X_e}{U_N^2} + 0.25 \geq 0$$

$\frac{Q_l X_e}{U_N^2}$



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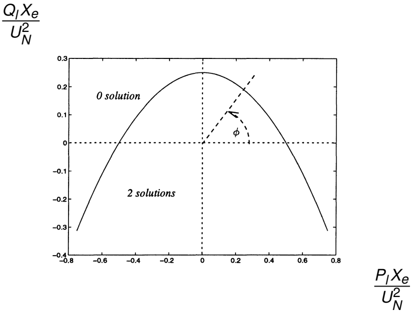


- any P_l can be reached provided Q_l is adjusted (but U_l may be unacceptable)
- dissymmetry between P_l and Q_l due to reactive transmission impedance
- locus symmetric w.r.t. Q_l axis; this does no longer hold when transmission resistance is included

Under a constant load power factor $\cos\phi$ (i.e., $Q_l = P_l \tan\phi$), we get from Eq. (2.1):

$$P_l^2 + \frac{U_N^2}{X_e}\tan\phi P_l - \frac{U_N^4}{4X_e^2} = 0$$

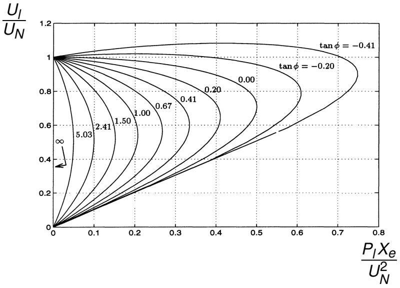
Then, we get the maximum power:

$$P_l^{max} = \frac{\cos\phi}{1+\sin\phi}\frac{U_N^2}{2X_e} \qquad Q_l^{max} = \frac{\sin\phi}{1+\sin\phi}\frac{U_N^2}{2X_e} \qquad U_l^{max} = \frac{U_N}{\sqrt{2}\sqrt{1+\sin\phi}}$$

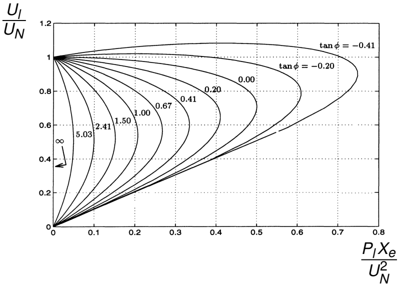
Or, for the extreme cases:

$$\cos\phi = 1: \qquad P_l^{max} = \frac{U_N^2}{2X_e} \qquad Q_l^{max} = 0 \qquad U_l^{max} = \frac{U_N}{\sqrt{2}}$$

$$\cos\phi = 0: \qquad P_l^{max} = 0 \qquad Q_l^{max} = \frac{U_N^2}{4X_e} \qquad U_l^{max} = \frac{U_N}{2}$$

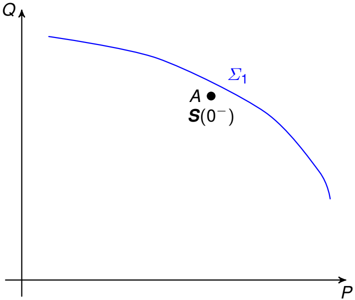


- for given power (P_l)
  - 1 solution with "high" voltage and "low" current (normal operating point)
  - 1 solution with "low" voltage and "high" current
- compensating the load increases the maximum power but the "critical" voltage approaches normal values
- curves that provide similar information:
  - $Q - V$ or $S - V$ under constant $\tan\phi$, $Q - V$ under constant P, etc.

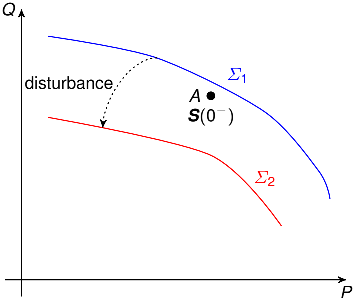


- in real systems, much more complicated
  - no infinite bus, voltage control by generators (AVR)
  - multiple loads and generators
  - complex, meshed transmission system with resistive components as well
  - voltage sensitive loads and restorative behavior
  - etc.

2 Voltage instability mechanisms



- Pre-fault loadability curve of the system (Σ_1)
- Fault occurs in the system
  1. Loadability curve is shrunk to Σ_2
  2. Post-fault consumption is decreased due to depressed voltages (voltage sensitive loads). If point B is outside Σ_2 then there is no solution and we have ***short-term voltage instability***
- Loads try to restore consumption to pre-fault point A now outside the loadability curve
- ***Long-term instability*** leading to voltage collapse



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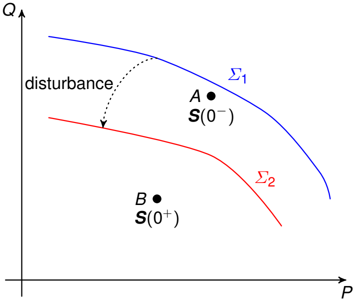

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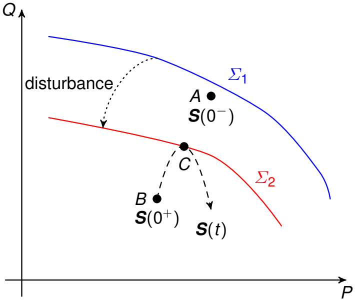

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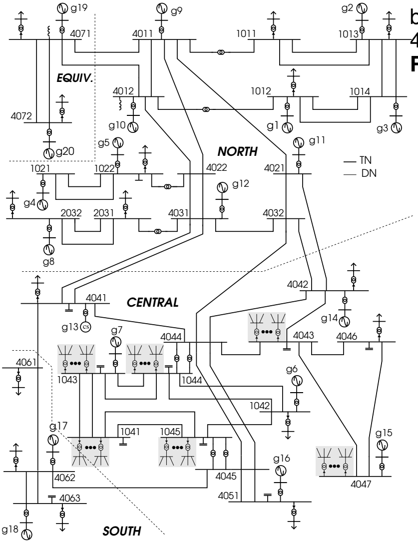
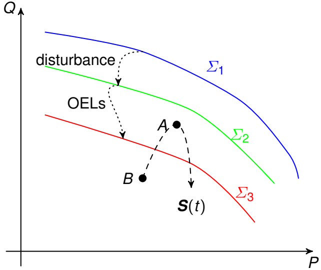


Disturbance: 5-cycle short-circuit near bus 4032, cleared by opening line 4032-4042

Result:

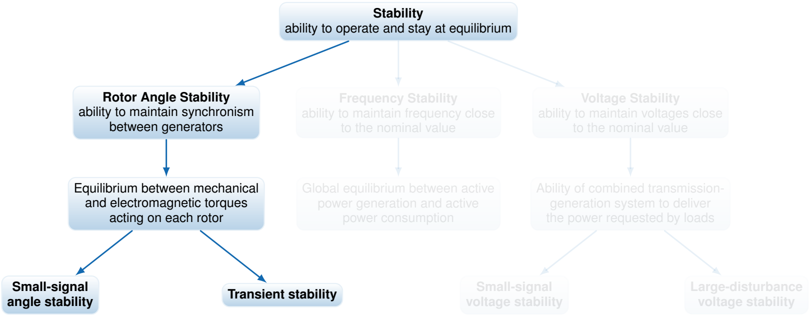
- the loadability curve is shrunk but the pre disturbance point *A* is still within the feasible region
- a series of generator OverExcitation Limiter (OEL) actions further shrink the feasible region leading to a system collapse



2 Voltage instability countermeasures

- Series compensation: very effective but expensive
- Shunt compensation: cheapest mechanism
- SVC and STATCOM devices
- Adjustment of generator active power productions
- Adjustment of generator voltages
- Block load restoration (e.g., through load tap changers) : effective but sometimes too slow
- Undervoltage load shedding : effective but expensive, last resort

2 Classification [1]



- most of the electrical energy today is generated by synchronous machines
- in normal system operation:
  - all synchronous machines rotate at the same electrical speed $\omega_0 = 2\pi f_n$
  - the mechanical and electromagnetic torques acting on the rotating masses of each generator balance each other

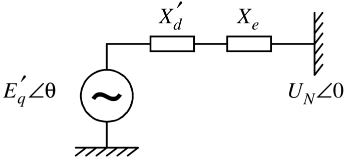
$$\dot{\omega}_i = \frac{\omega_0}{2H_i}(T_{mi} - T_{ei})$$

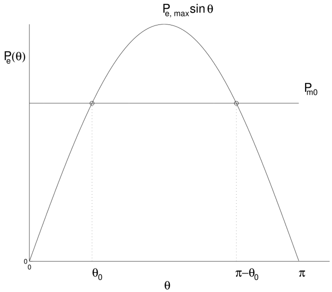
  - the phase angle differences between the internal e.m.f.'s of the various machines are constant (synchronism)
- **following a disturbance, there is an imbalance between the two torques and the rotor speed varies**
- **rotor angle stability deals with the ability to keep/regain synchronism after being subject to a disturbance**

3.1 Transient (angle) stability

- Transient (angle) stability deals with the ability of the system to keep synchronism after being subject to a **large** disturbance
- typical “large” disturbances:
  - short-circuit cleared by opening of circuit breakers
  - more complex sequences: backup protections, line autoreclosing, etc.
- the nonlinear behavior of the generator and its controllers must be taken into account
  - numerical integration of the differential-algebraic equations is used
- unacceptable consequences of transient instability:
  - generators tripped due to loss of synchronism (to avoid equipment damages)
  - long-lasting voltage dips created by large angle swings (disturb customers)

3.1 Transient (angle) stability





$$\frac{2H}{\omega_0}\frac{d^2\theta}{dt^2} = P_{m0} - P_{e,max}\sin\theta \Rightarrow$$

$$M\ddot{\theta} = P_{m0} - P(\theta) \qquad (3.1)$$

where in steady-state $P_{m0} = P_{e,max}\sin\theta_0$

3.1 Transient (angle) stability: equal area criterion

Multiplying both sides of Eq. (3.1) with $\dot{\theta}$ and integrating:

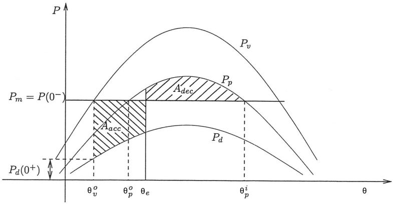
$$\frac{1}{2}M\dot{\theta}^2 - \int_0^t (P_{m0} - P(\theta))\,\dot{\theta}dt = C$$

Changing the integration variable ($x = \theta(t)$)

$$\frac{1}{2}M\dot{\theta}^2 + \int_{\theta_0}^{\theta} (P(x) - P_{m0})\,dx = C$$

”kinetic” energy + ”potential” energy = Constant

3.1 Transient (angle) stability: equal area criterion



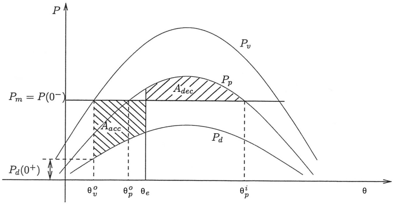
Type	symbol	time
pre-fault	u	$t < 0$
during	d	$0 \leq t < t_e$
post-fault	p	$t \geq t_e$

$$A_{acc} = \int_{\theta_u^0}^{\theta_e} (P_d(x) - P_{m0})\, dx$$

$$A_{dec} = \int_{\theta_e}^{\theta_p^i} (P_p(x) - P_{m0})\, dx$$

The system is stable if there exists an angle θ_p^i such that the areas are equal ($A_{acc} = A_{dec}$)

Or, for a given θ_e, $A_{acc} - A_{dec} < 0$



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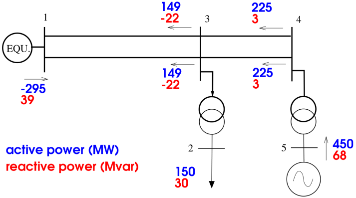
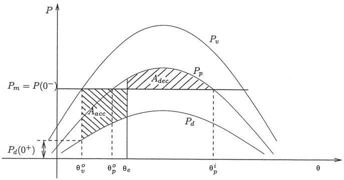
Curves:

- ***during fault***: capability of evacuating power on the network decreased due to low voltages
- ***post-fault***: system weaker owing to the fault clearing actions (e.g., line tripping)

Critical clearing time ($t_e = t_c$):

- Maximum fault duration so that the system returns to equilibrium
- When the system is at the stability limit : $A_{acc} - A_{dec} = 0$ and $\theta_e = \theta_c = \theta(t_c)$





Disturbances:

- 6-cycle (120ms) short-circuit without impedance on line "1-3", next to bus 3, cleared by opening that line, when the generator produces 450 MW
- the same fault cleared without line opening, when the generator produces 450 MW
- the same sequence as above, but with the generator producing 400 MW

3.1 Transient (angle) instability countermeasures

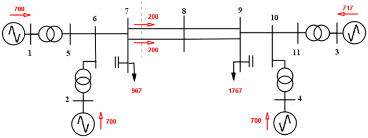
- Modifying the pre-disturbance operating point:
  - reducing the active power generation
  - operating with higher excitation
- Automatic emergency controls:
  - actions on network: line auto-reclosing, fast series capacitor reinsertion, fast fault clearing - single pole breaker operation
  - actions in generators: (turbine) fast valving, generation shedding
  - action on “load”: dynamic braking
- Other means:
  - equip generators with fast excitation system
  - control voltage at intermediate points in a long corridor: through synchronous condensers or static var compensators.

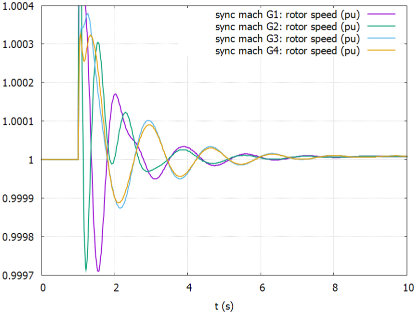
- Small-signal (or small-disturbance) angle stability deals with the ability of the system to **keep synchronism** after being subject to a "small disturbance"
- "small disturbances" are those for which the system equations can be **linearized** around an equilibrium point
  - tools from linear system theory can be used (in particular eigenvalue and eigenvector analysis)
- following a small disturbance, the variation in electromagnetic torque T_e can be decomposed into:

$$\triangle T_e = K_s \triangle \delta + K_d \triangle \omega$$

$K_s \triangle \delta$: synchronizing torque $\quad$ $K_d \triangle \omega$: damping torque

- **a decrease in synchronizing torque will eventually lead to aperiodic instability (machine "going out of step")**
- **a decrease in damping torque will eventually lead to oscillatory instability (growing oscillations)**





- A small ”nudge” to the system (1 ms fault at bus 7) to excite the interarea modes.
- Oscillation of machines 1 and 2 against machines 3 and 4
- Period $\sim$ 2 s

Local modes (involve a small part of the system)

- rotor angle oscillations of a single generator or a single plant against the rest of the system: ***local plant mode***
  - can be studied using a one-machine infinite-bus system
- oscillations between rotors of a few generators close to each other: ***inter-machine or inter-plant mode oscillations***
- typical range of frequencies of local plant and inter-plant modes: ***0.7 to 2 Hz***
- may also be associated with inappropriate tuning of a control equipment (excitation system, HVDC converter, SVC, etc.): ***control mode***

Global modes (involve large areas of the system, widespread effects)

- oscillations of a large group of generators in one area swinging against a group of generators in another area: ***interarea mode***
- usually, the larger the group of generators, the slower the oscillations
- typical range of frequencies of interarea modes: ***0.1 to 0.7 Hz***
- more complex to analyze and to damp

- Let's consider an autonomous system described by the differential equations:

$$\dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x})$$

  and $\boldsymbol{x}^*$ is an equilibrium point: $\boldsymbol{f}(\boldsymbol{x}^*) = \mathbf{0}$

- If we linearize the system around the operating point and ignore higher order terms:

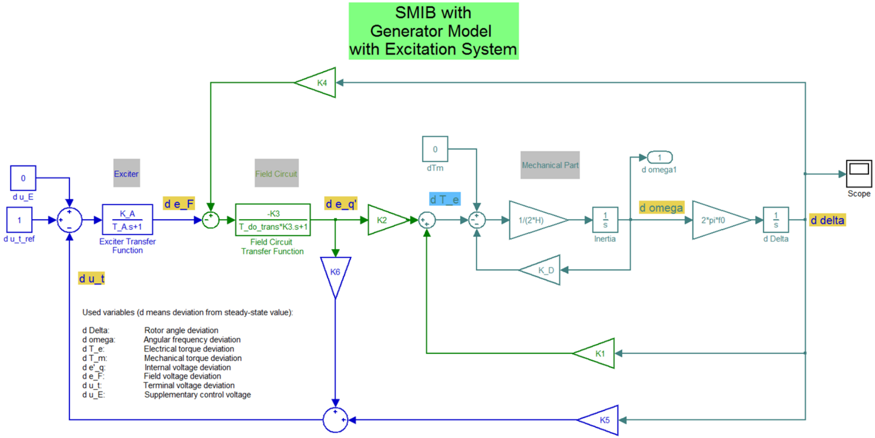
$$\dot{\triangle\boldsymbol{x}} = \dot{\boldsymbol{x}} = \left.\frac{\partial \boldsymbol{f}}{\partial \boldsymbol{x}}\right|_{\boldsymbol{x}=\boldsymbol{x}^*} \boldsymbol{x} = \boldsymbol{A}\boldsymbol{x}$$

  where $\frac{\partial \boldsymbol{f}}{\partial \boldsymbol{x}}$ is the Jacobian of $\boldsymbol{f}$ with respect to $\boldsymbol{x}$, and $\boldsymbol{A} = \left.\frac{\partial \boldsymbol{f}}{\partial \boldsymbol{x}}\right|_{\boldsymbol{x}=\boldsymbol{x}^*}$ is the state matrix of the linearized system.

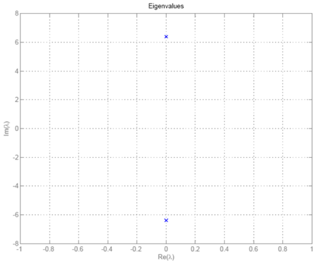
3.2 Stability of the equilibrium x^*

- Let λ be a real eigenvalue of matrix $\boldsymbol{A}$:
  - $\lambda < 0$: The corresponding mode is stable (decaying exponential).
  - $\lambda > 0$: The corresponding mode is unstable (growing exponential).
  - $\lambda = 0$: The corresponding mode has integrating characteristics.
- Let $\lambda_{1,2} = \sigma \pm j\omega$ be a complex conjugate pair of eigenvalues of $\boldsymbol{A}$:
  - $\Re(\lambda_{1,2}) < 0$: The corresponding mode is stable (decaying oscillation).
  - $\Re(\lambda_{1,2}) > 0$: The corresponding mode is unstable (growing oscillation).
  - $\Re(\lambda_{1,2}) = 0$: The corresponding mode is critically stable (undamped oscillation).
  - The following dynamic properties can be established:
    - Oscillation frequency: $f = \dfrac{\omega}{2\pi}$
    - Damping ratio: $\zeta = \dfrac{-\sigma}{\sqrt{\sigma^2 + \omega^2}}$

3.2 Dynamic Analysis of the Heffron-Phillips Model



SMIB with classical generator model (mechanical damping torque $K_D = 0$)

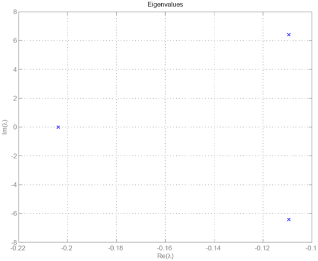


Eigenvalues, synchronizing and damping torque coefficients

	$\sigma \pm j\omega$	ζ	f [Hz]	K_{sync}	K_{damp}
$\lambda_{1,2}$	$0 \pm j6.39$	-	1.02	0.76	0

Eigenvalues on imaginary axis $\longrightarrow$ system is critically stable

SMIB including field circuit dynamics

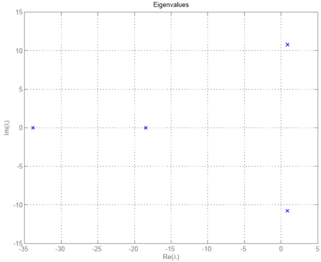


Eigenvalues, synchronizing and damping torque coefficients

	$\sigma \pm j\omega$	ζ	f [Hz]	K_{sync}	K_{damp}
$\lambda_{1,2}$	$-0.11 \pm j6.41$	0.02	1.02	-0.0008	1.53
λ_3	$-0.20 \pm j0$	1.0	-	-0.77	0

Eigenvalues moved to the left because field circuit adds damping torque

SMIB including excitation system



Eigenvalues, synchronizing and damping torque coefficients

	$\sigma \pm j\omega$	ζ	f [Hz]	K_{sync}	K_{damp}
$\lambda_{1,2}$	$0.88 \pm j10.79$	-0.08	1.72	0.27	-10.60
λ_3	$-33.83 \pm j0$	1.0	-	-19.81	0
λ_4	$-18.46 \pm j0$	1.0	-	-7.01	0

Eigenvalues moved to the right by the excitation system $\longrightarrow$ System is unstable!

3.2 Left and right eigenvectors

Let's assume again the linearized system with the state matrix $\boldsymbol{A}$ $(n \times n)$ and λ_i is one of its non-zero eigenvalues. Then:

- $\boldsymbol{v}_i$ is the right eigenvector of λ_i:

$$\boldsymbol{A}\boldsymbol{v}_i = \lambda_i \boldsymbol{v}_i$$

- $\boldsymbol{w}_i$ is the left eigenvector of λ_i:

$$\boldsymbol{A}^T \boldsymbol{w}_i = \lambda_i \boldsymbol{w}_i$$

- In matrix form:

$$\boldsymbol{V} = [\boldsymbol{v}_1 \dots \boldsymbol{v}_n] \qquad \boldsymbol{W} = \begin{bmatrix} \boldsymbol{w}_1^T \\ \vdots \\ \boldsymbol{w}_n^T \end{bmatrix}$$

- It can be shown that: $\boldsymbol{W} = \boldsymbol{V}^{-1}$ and $\boldsymbol{W}\boldsymbol{A}\boldsymbol{V} = diag(\lambda_i) = \boldsymbol{\Lambda}$

3.2 Controllability and observability

Now, consider a system with state vector $\boldsymbol{x}$, input vector $\boldsymbol{u}$ and a scalar output $\boldsymbol{z}$:

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}\boldsymbol{u}$$
$$\boldsymbol{z} = \boldsymbol{C}\boldsymbol{x} + \boldsymbol{D}\boldsymbol{u}$$

- We change the variables ($\boldsymbol{y} = \boldsymbol{W}\boldsymbol{x}$)

$$\dot{\boldsymbol{y}} = \boldsymbol{W}\boldsymbol{A}\boldsymbol{V}\boldsymbol{y} + \boldsymbol{W}\boldsymbol{B}\boldsymbol{u} = \boldsymbol{\Lambda}\boldsymbol{y} + \boldsymbol{W}\boldsymbol{B}\boldsymbol{u}$$
$$\boldsymbol{z} = \boldsymbol{C}\boldsymbol{V}\boldsymbol{y} + \boldsymbol{D}\boldsymbol{u}$$

- For the i-th "mode" λ_i of the state matrix $\boldsymbol{A}$:
  - the larger $(\boldsymbol{W}\boldsymbol{B})_i = \boldsymbol{w}_i^T\boldsymbol{B}$, the more the mode can be controlled by $\boldsymbol{u}$
  - the larger $(\boldsymbol{C}\boldsymbol{V})_i = \boldsymbol{C}\boldsymbol{v}_i$, the more the mode can be observed in $\boldsymbol{z}$

3.2 Transfer function and residues

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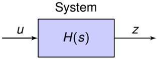
We can now build the transfer function of the system:

$$
\begin{aligned}
H(s) &= \frac{Z(s)}{U(s)} \\
&= \boldsymbol{C}\boldsymbol{V}(s\boldsymbol{I} - \boldsymbol{\Lambda})^{-1}\boldsymbol{W}\boldsymbol{B} + \boldsymbol{D} \\
&= [\boldsymbol{C}\boldsymbol{v}_1 \dots \boldsymbol{C}\boldsymbol{v}_n]\, diag(\frac{1}{s - \lambda_i}) \begin{bmatrix} \boldsymbol{w}_1^T\boldsymbol{B} \\ \vdots \\ \boldsymbol{w}_n^T\boldsymbol{B} \end{bmatrix} + \boldsymbol{D} \\
&= \sum_{i=1}^{n} \frac{\boldsymbol{C}\boldsymbol{v}_i\boldsymbol{w}_i^T\boldsymbol{B}}{s - \lambda_i} + \boldsymbol{D} = \sum_{i=1}^{n} \frac{R_i}{s - \lambda_i} + \boldsymbol{D}
\end{aligned}
$$

The residue R_i relative to the i-th mode λ_i:

- depends on both the observability and the controllability of the mode
- would be zero in case of exact zero-pole cancellation



Consider a compensator using $\boldsymbol{z}$ as input and acting on $\boldsymbol{u}$:

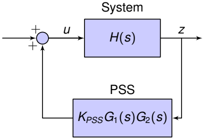
- Which condition should be satisfied by the transfer function of the PSS in order to stabilize the critical mode λ_c of the uncompensated system?

The closed-loop transfer function is:

$$\frac{H(s)}{1 - K_{PSS}H(s)G_1(s)G_2(s)}$$

If $\tilde{s}$ is one of the closed-loop poles:

$$1 - K_{PSS}H(\tilde{s})G_1(\tilde{s})G_2(\tilde{s}) = 0 \Leftrightarrow 1 - K_{PSS}\left[\sum_{i=1}^{n} \frac{R_i}{\tilde{s} - \lambda_i} + \boldsymbol{D}\right] G_1(\tilde{s})G_2(\tilde{s}) = 0$$



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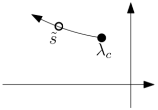

Let's consider a closed-loop pole $\tilde{s}$ lying on the branch of the root locus which starts from the open-loop pole λ_c. When the compensator gain K_{PSS} tends to zero, $\tilde{s}$ tends to λ_c.

- Keeping only the dominant terms:

$$1 - R_c G_1(\lambda_c) G_2(\lambda_c) \lim_{K_{PSS}\to 0} \frac{K_{PSS}}{\tilde{s} - \lambda_c} = 0 \Leftrightarrow R_c G_1(\lambda_c) G_2(\lambda_c) = \lim_{K_{PSS}\to 0} \frac{\tilde{s} - \lambda_c}{K_{PSS}}$$

  - In the complex plane $\lim_{K_{PSS}\to 0} \frac{\tilde{s} - \lambda_c}{K_{PSS}}$ is a vector tangent to the branch of the root locus starting from λ_c.

- In order to shift the eigenvalue to the left:
  - the branch of the root locus should leave λ_c at an angle of 180 degrees. Thus, $G_1(\lambda_c)G_2(\lambda_c)$ must be such that $\angle G_1(j\omega_c)G_2(j\omega_c) = \pm 180 - \angle R_c$
  - $R_c G_1(\lambda_c) G_2(\lambda_c)$ should be a real negative number

3.2 Power System Stabilizer

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- **Purpose:**
  Provide additional ***damping torque*** component in order to prevent the system from becoming unstable.
- **Approach:**
  Insert a feedback between ***angular frequency*** and ***voltage setpoint*** to “stabilize” a critical mode λ_c.
- **Block diagram:**

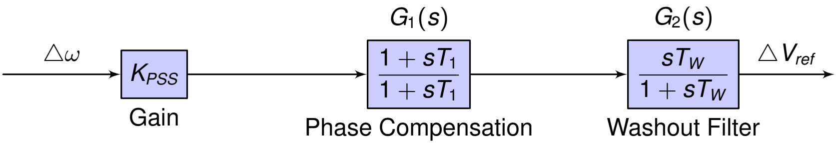


Figure: Block diagram of a simple PSS

Phase Compensation G_1:

- shifts λ_c to the left in the complex plane by bringing a phase compensation according to the residue method :

$$\angle G_1(\lambda_c) \simeq \angle G_1(j\omega_c) = \pm 180 - \angle R_c$$

- $G_1(s)$corresponds to one or several lead-lag filters
- the latter are “tuned” to provide their maximum phase shift ϕ_m at the frequency ω_c

Washout Filter G_2:

- in steady state and for slow variations, the PSS must not affect voltage regulation
- $G_2(s)$ is a high-pass filter
- T_w is taken large enough to not modify the phase angle of $G_1(s)$ for frequencies around ω_c . For instance:

$$\frac{10}{T_w} \backsimeq \frac{\omega_c}{10}$$

Gain K_{PSS}:

- adjusted until the corrected mode $\tilde{\lambda}_c$ has a damping ratio :

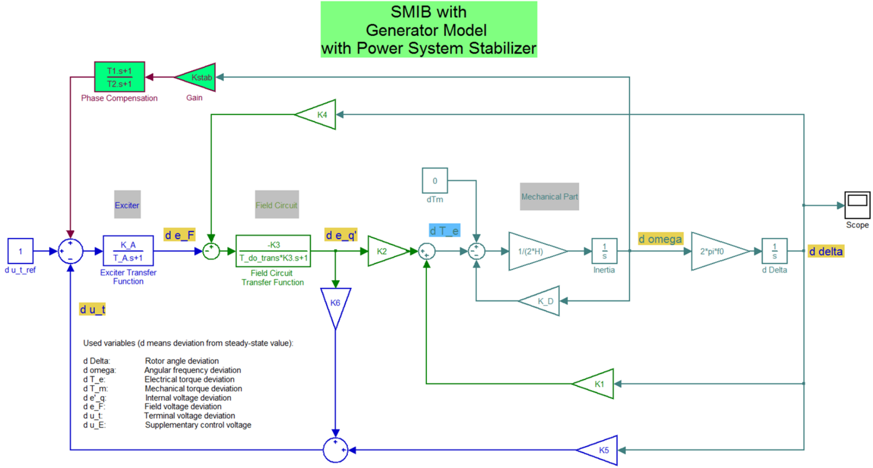
$$\zeta = \frac{-\Re(\tilde{\lambda}_c)}{\sqrt{\Re(\tilde{\lambda}_c)^2 + \Im(\tilde{\lambda}_c)^2}} \geq 0.05 - 0.10$$

- while K_{PSS} is increased, the other eigenvalues are monitored since they might move to the right (***the residue method allows controlling a single mode***)
- for excessive values of K_{PSS}, the branch of the root locus that starts from λ_c might "bend" to the right (***the residue method focuses on a neighborhood of the mode to correct***)

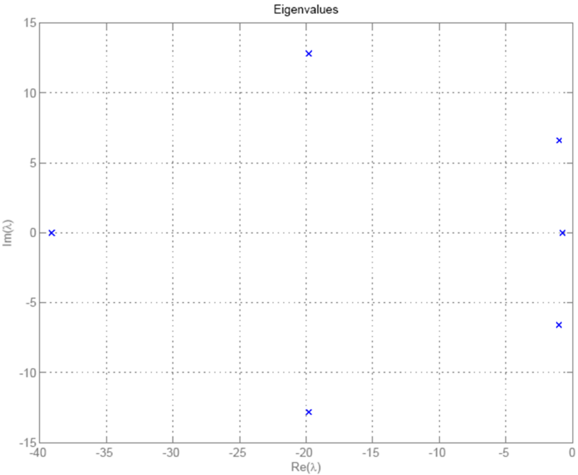
Low-pass Filter G_3 (optional):

- in a thermal power plant, the turbine stages, the generator and the exciter are mounted on a relatively long shaft. The latter has torsional oscillation frequencies in the range 10 – 15 Hz and higher
- the PSS must not excite those frequencies
- the risk is higher for a PSS using the rotor speed as input signal
- in this case, G_3 is a low-pass filter so that the PSS contribution is negligible at the lowest torsional frequency and above.

3.2 Power System Stabilizer



3.2 Power System Stabilizer



3.3 (Rotor) angle stability: Remarks

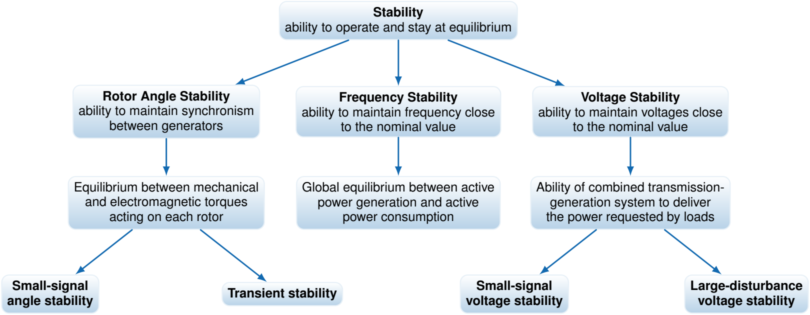
Transient stability:

- depends on operating point and system parameters
- depends also on the disturbance
  - the system may be stable for disturbance 1 but not disturbance 2
  - if so, the system is insecure for 2, but as long as 2 does not happen, it can operate
  - usually, an N-1 security is required

Small-disturbance angle stability:

- depends on operating point and system parameters
- does not depend on the disturbance (assumed infinitesimal and arbitrary)
- is a necessary condition for operating a power system (small disturbances are **always** present)

3.3 Classification [1]



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4 Slides based on

[1] P. Kundur, J. Paserba, V. Ajjarapu, G. Andersson, A. Bose, T. Van Cutsem, C. Canizares, N. Hatziargyriou, D. Hill, V. Vittal, A. Stankovic, and C. Taylor, "Definition and Classification of Power System Stability IEEE/CIGRE Joint Task Force on Stability Terms and Definitions," IEEE Trans. Power Syst., vol. 19, no. 3, pp. 1387–1401, Aug. 2004.

[2] M. J. Gibbard, P. Pourbeik, and D. J. Vowles, "Small-signal stability, control and dynamic performance of power systems", University of Adelaide Press, Adelaide, 2015.