



Cyprus
University of
Technology

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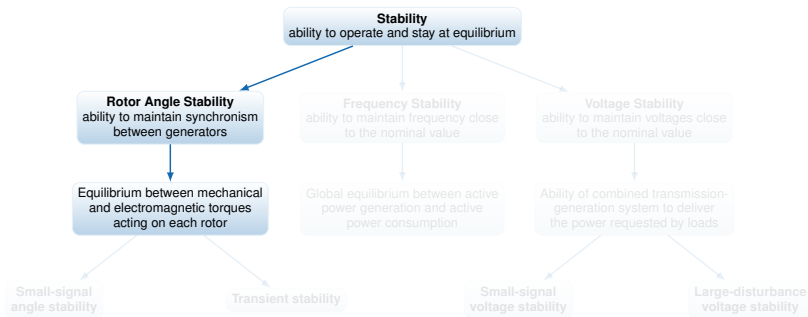
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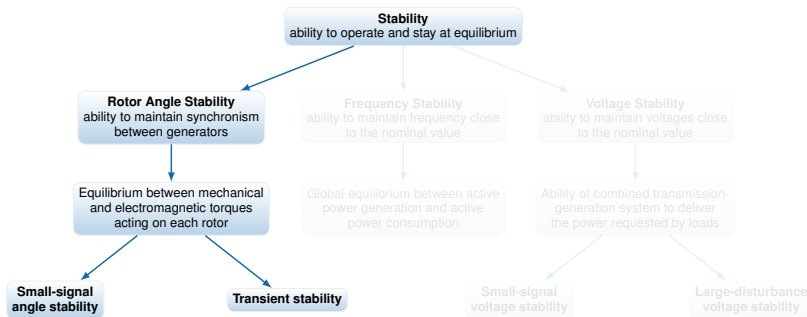
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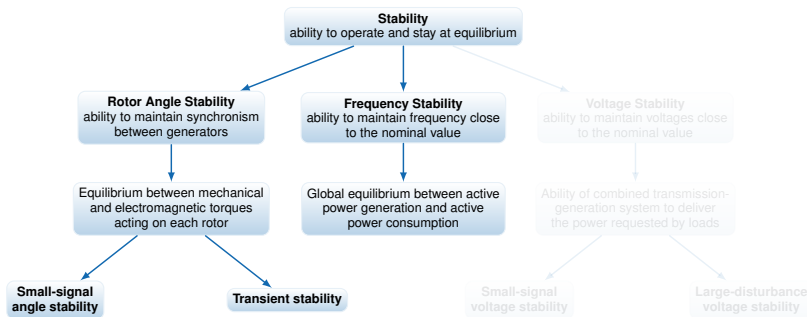
After this part of the lecture and additional reading, you should be able to ...

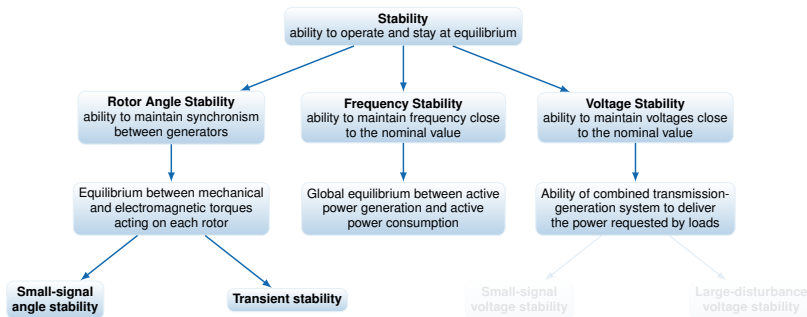
- ① ... understand the basic classifications of power system stability;
- ② ... be able to identify and perform stability analysis problems; and,
- ③ ... propose methods for stabilizing power systems.

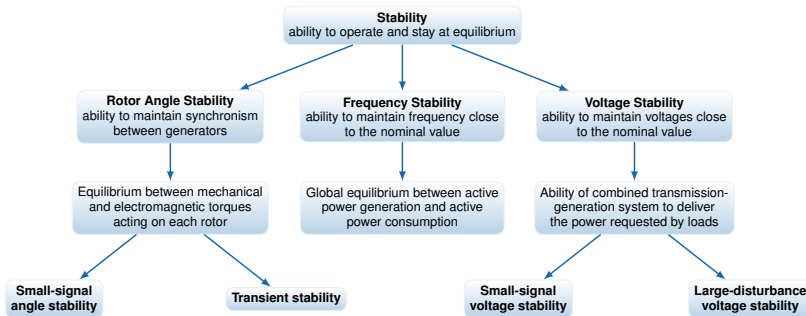
- 1 Introduction**
- 2 Voltage Stability
- 3 Rotor Angle Stability
- 4 References

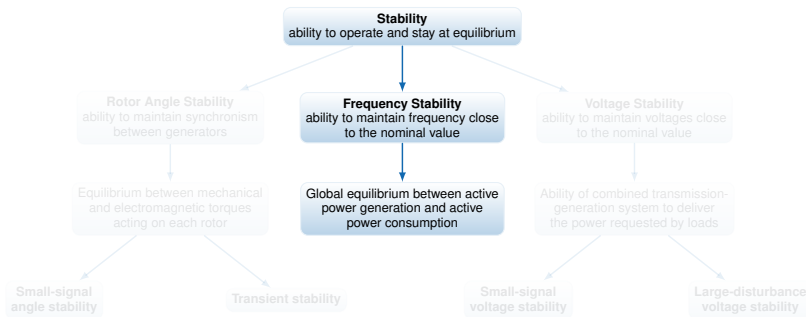


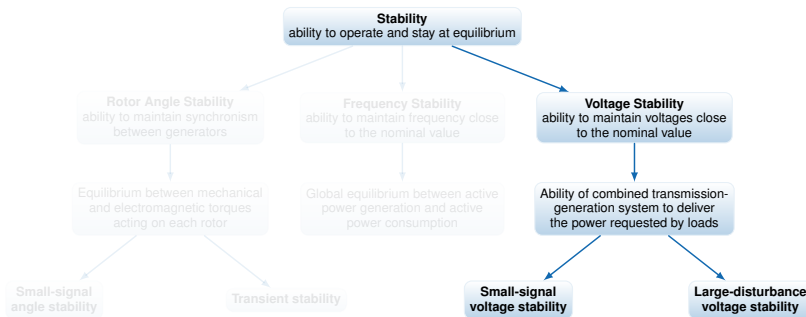






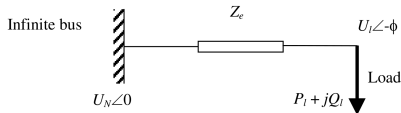






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2 Voltage stability fundamentals

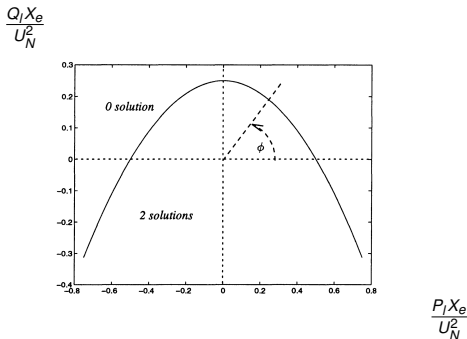


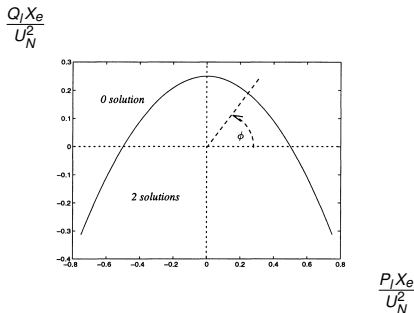
$$P_I = \frac{U_I U_N}{X_e} \sin \phi \quad Q_I = \frac{U_I U_N \cos \phi - U_I^2}{X_e}$$

$$P_I^2 + \left(Q_I + \frac{U_I^2}{X_e} \right)^2 = \left(\frac{U_I U_N}{X_e} \right)^2 \Rightarrow \left(U_I^2 \right)^2 + (2Q_I X_e - U_N^2) U_I^2 + X_e^2 (P_I^2 + Q_I^2) = 0 \quad (2.1)$$

To have (at least) one solution:

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





- any P_I can be reached provided Q_I is adjusted (but U_I may be unacceptable)
- dissymmetry between P_I and Q_I due to reactive transmission impedance
- locus symmetric w.r.t. Q_I 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):

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

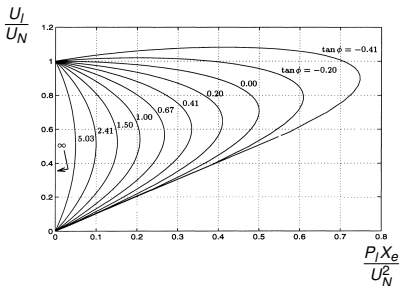
Then, we get the maximum power:

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

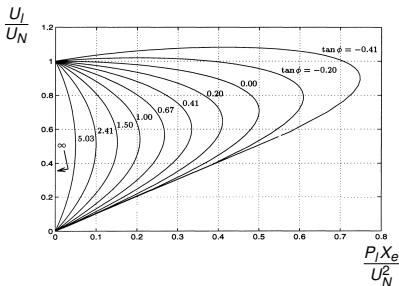
Or, for the extreme cases:

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

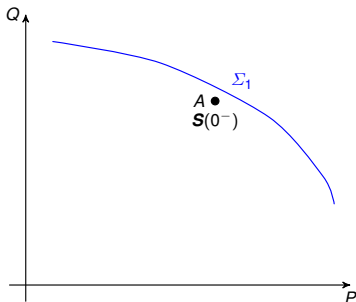
$$\cos \phi = 0 : \quad P_l^{max} = 0 \quad Q_l^{max} = \frac{U_N^2}{4X_e} \quad U_l^{max} = \frac{U_N}{2}$$



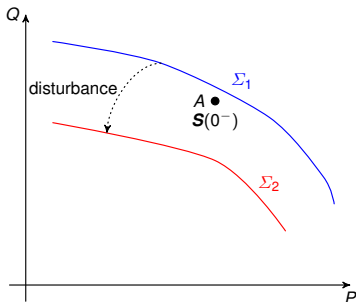
- for given power (P_l)
 - 1 solution with “high” voltage and “low” current (normal operating point)
 - 1 solution with “low” voltage and “high” current
- compensating the load increases the maximum power but the “critical” voltage approaches normal values
- curves that provide similar information:
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



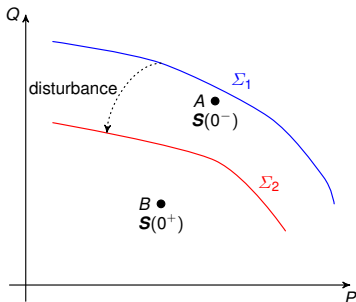
- in real systems, much more complicated
 - no infinite bus, voltage control by generators (AVR)
 - multiple loads and generators
 - complex, meshed transmission system with resistive components as well
 - voltage sensitive loads and restorative behavior
 - etc.



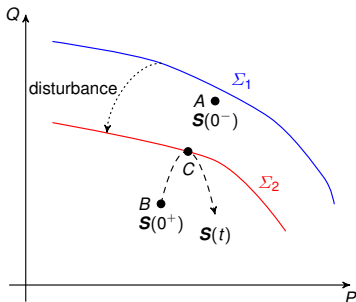
- Pre-fault loadability curve of the system (Σ_1)
- Fault occurs in the system
 - ① Loadability curve is shrunk to Σ_2
 - ② Post-fault consumption is decreased due to depressed voltages (voltage sensitive loads).
If point B is outside Σ_2 then there is no solution and we have **short-term voltage instability**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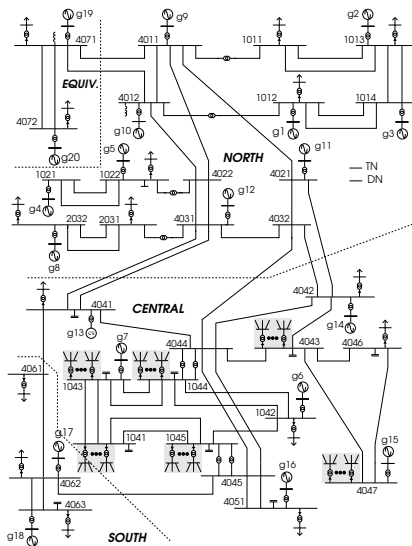


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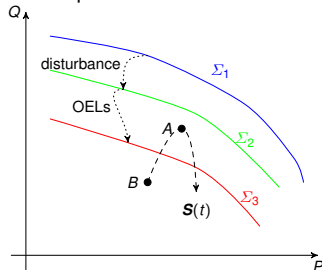
2 Voltage instability: example (RAMSES with Nordic system)



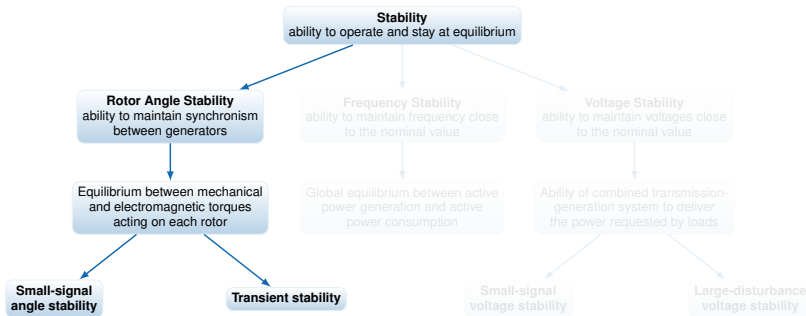
Disturbance: 5-cycle short-circuit near bus 4032, cleared by opening line 4032-4042

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



- 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



1 Introduction

2 Voltage Stability

3 Rotor Angle Stability

- Transient stability
- Small-disturbance angle stability
- Summary

4 References

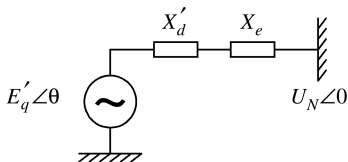
- most of the electrical energy today is generated by synchronous machines
- in normal system operation:
 - all synchronous machines rotate at the same electrical speed $\omega_0 = 2\pi f_n$
 - the mechanical and electromagnetic torques acting on the rotating masses of each generator balance each other

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

- 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**

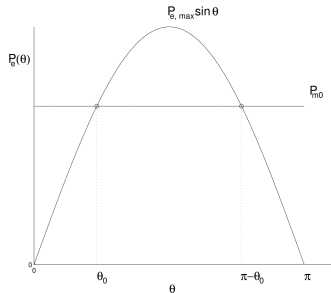
- Transient (angle) stability deals with the ability of the system to keep synchronism after being subject to a **large** disturbance
- typical “large” disturbances:
 - short-circuit cleared by opening of circuit breakers
 - more complex sequences: backup protections, line autoreclosing, etc.
- the nonlinear 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



$$\frac{2H}{\omega_0} \frac{d^2\theta}{dt^2} = P_{m0} - P_{e,max} \sin \theta \Rightarrow$$
$$M\ddot{\theta} = P_{m0} - P(\theta) \quad (3.1)$$

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



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

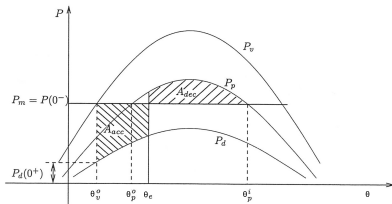
$$\frac{1}{2}M\dot{\theta}^2 - \int_0^t (P_{m0} - P(\theta)) \dot{\theta} dt = C$$

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



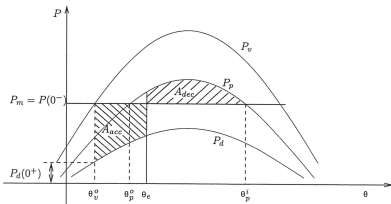
The system is stable if there exists an angle θ_p^i such that the areas are equal ($A_{acc} = A_{dec}$)

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

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

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

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



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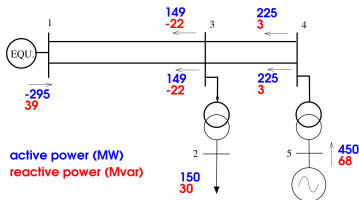
Curves:

- **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 ($t_e = t_c$):

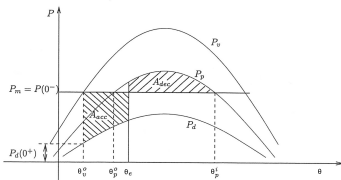
- Maximum fault duration so that the system returns to equilibrium
- When the system is at the stability limit : $A_{acc} - A_{dec} = 0$ and $\theta_e = \theta_c = \theta(t_c)$

3.1 Transient (angle) stability: example (RAMSES with 5-bus system)



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



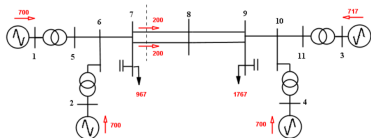
- Modifying the pre-disturbance operating point:
 - reducing the active power generation
 - operating with higher excitation
- Automatic emergency controls:
 - actions on network: line auto-reclosing, fast series capacitor reinsertion, fast fault clearing - single pole breaker operation
 - actions in 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:

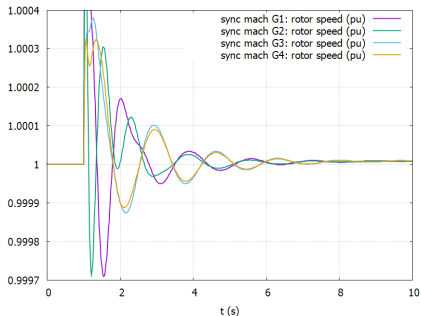
$$\Delta T_e = K_s \Delta \delta + K_d \Delta \omega$$

$K_s \Delta \delta$: synchronizing torque $K_d \Delta \omega$: 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 ~ 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:

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

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

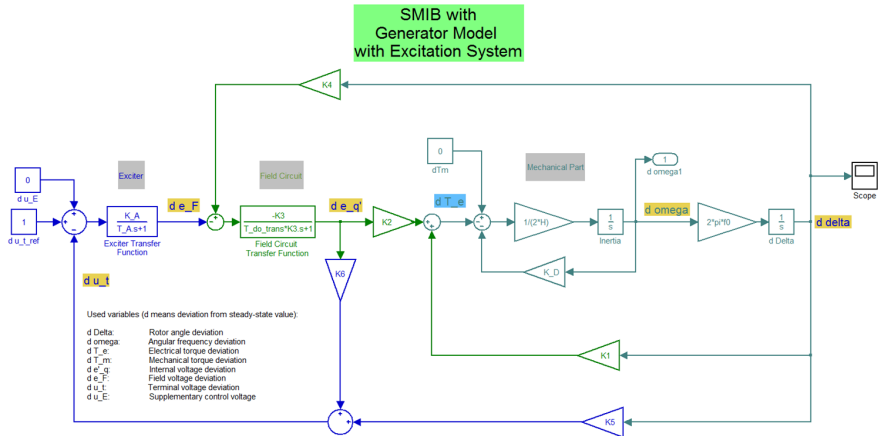
- If we linearize the system around the operating point and ignore higher order terms:

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

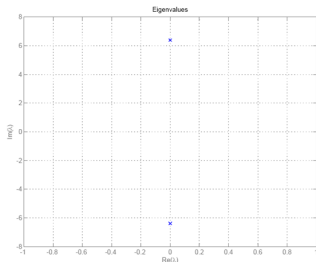
where $\frac{\partial \mathbf{f}}{\partial \mathbf{x}}$ is the Jacobian of \mathbf{f} with respect to \mathbf{x} , and $\mathbf{A} = \left. \frac{\partial \mathbf{f}}{\partial \mathbf{x}} \right|_{\mathbf{x}=\mathbf{x}^*}$ is the state matrix of the linearized system.

- Let λ be a real eigenvalue of matrix \mathbf{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 \mathbf{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: $f = \frac{\omega}{2\pi}$
 - Damping ratio: $\zeta = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}}$

3.2 Dynamic Analysis of the Heffron-Phillips Model



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

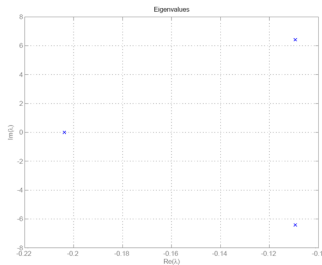


Eigenvalues, synchronizing and damping torque coefficients

	$\sigma \pm j\omega$	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

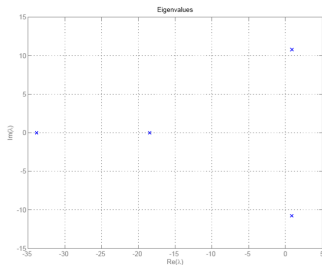


Eigenvalues, synchronizing and damping torque coefficients

	$\sigma \pm j\omega$	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 → System is unstable!

3.2 Left and right eigenvectors

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

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

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

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

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

- In matrix form:

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

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

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

$$\dot{\mathbf{x}} = \mathbf{Ax} + \mathbf{Bu}$$

$$\mathbf{z} = \mathbf{Cx} + \mathbf{Du}$$

- We change the variables ($\mathbf{y} = \mathbf{Wx}$)

$$\dot{\mathbf{y}} = \mathbf{WAVy} + \mathbf{WBu} = \mathbf{\Lambda y} + \mathbf{WBu}$$

$$\mathbf{z} = \mathbf{CVy} + \mathbf{Du}$$

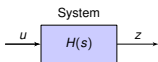
- For the i -th “mode” λ_i of the state matrix \mathbf{A} :
 - the larger $(\mathbf{WB})_i = \mathbf{w}_i^T \mathbf{B}$, the more the mode can be controlled by \mathbf{u}
 - the larger $(\mathbf{CV})_i = \mathbf{Cv}_i$, the more the mode can be observed in \mathbf{z}

We can now build the transfer function of the system:

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

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 z as input and acting on u :

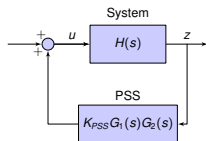
- Which condition should be satisfied by the transfer function of the PSS in order to stabilize the critical mode λ_c of the uncompensated system?

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:

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



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

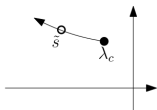
- Which condition should be satisfied by the transfer function of the PSS in order to stabilize the critical mode λ_c of the uncompensated system?

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:

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



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:

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

- In the complex plane $\lim_{K_{PSS} \rightarrow 0} \frac{\tilde{s} - \lambda_c}{K_{PSS}}$ 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

- **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:**

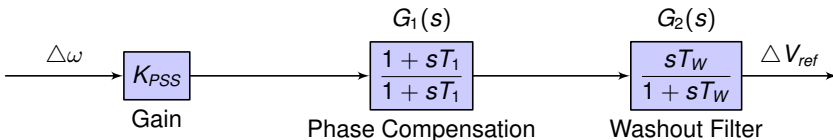


Figure: Block diagram of a simple PSS

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:

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

Gain K_{PSS} :

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

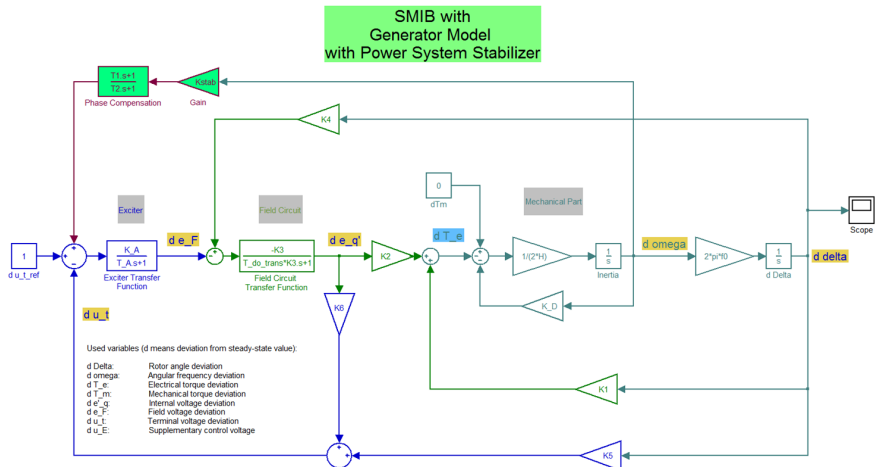
$$\zeta = \frac{-\Re(\tilde{\lambda}_c)}{\sqrt{\Re(\tilde{\lambda}_c)^2 + \Im(\tilde{\lambda}_c)^2}} \geq 0.05 - 0.10$$

- 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***)

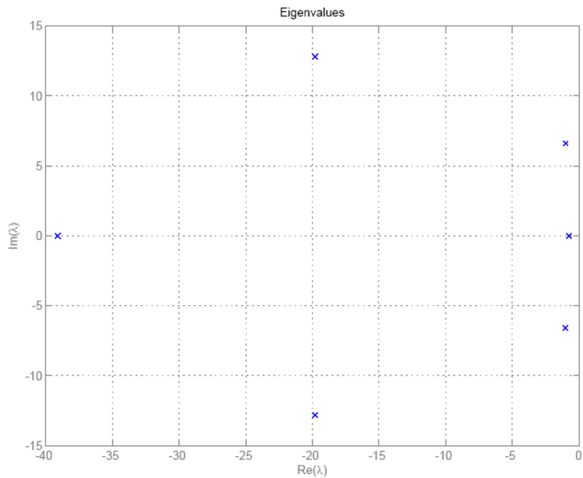
Low-pass Filter G_3 (optional):

- 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

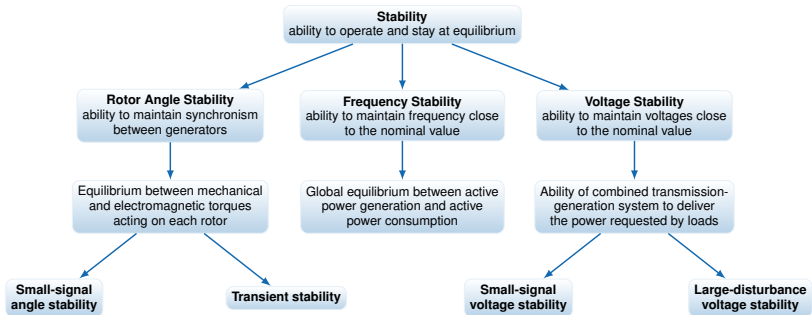


Transient stability:

- 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)



- 1 Introduction
- 2 Voltage Stability
- 3 Rotor Angle Stability
- 4 References**

- [1] P. Kundur, J. Paserba, V. Ajjarapu, G. Andersson, A. Bose, T. Van Cutsem, C. Canizares, N. Hatziaargyriou, 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.