Power System Stability

Power system stability is defined as the property of a power system that enables it to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance.

Disturbances can be small or large.

1. Small Disturbances
   - Incremental changes in load
   - Incremental changes in generation
2. Large Disturbances
   - Loss of a large generator or load
   - Faults on transmission lines

Classification of Power System Stability

1. Rotor Angle Stability
   - Ability to maintain synchronism after being subjected to a disturbance.
   - Torque balance of synchronous machines.
2. Voltage Stability
   - Ability to maintain steady acceptable voltage at all buses after being subjected to a disturbance.
   - Reactive power balance.

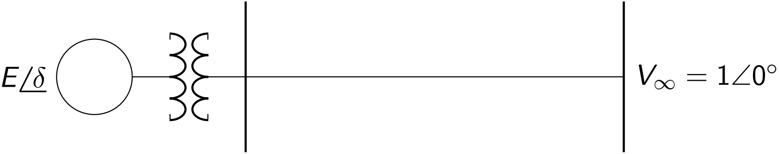
Rotor Angle Stability

Rotor angle stability is the ability of interconnected synchronous machines of a power system to remain in synchronism after being subjected to a disturbance.

1. Small disturbance (small signal) stability
    - Ability to maintain synchronism under small disturbances.
    - Since disturbances are small, nonlinear differential equations can be linearized.
    - It is easy to solve.
2. Large disturbance (Transient) stability
    - Ability to maintain synchronism under large disturbances.
    - Since disturbances are large, nonlinear differential equations can not be linearized.
    - It has to be solved numerically. It is difficult..
    - However, we can use a graphical approach called *Equal Area Criterion* for analyzing the stability of a single machine connected to an infinite bus using the classical model.

Power-Angle Relationship:

Consider a single machine infinite bus (SMIB) system:



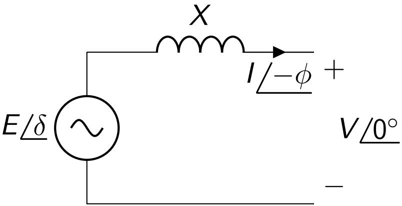


Figure: Per phase equivalent circuit

Where $X = X_g + X_{Tr} + X_{TL}$ in p.u.

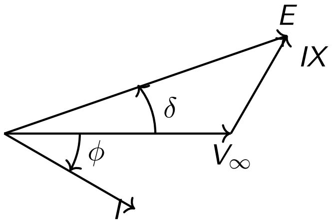


Figure: Phasor diagram

To find the real power output of the machine:

$$I = \frac{E\angle\delta - V\angle 0^\circ}{\jmath X}$$

$$S_S = EI^*$$

$$S_S = E\angle\delta \left(\frac{E\angle -\delta - V\angle 0^\circ}{-\jmath X} \right)$$

$$S_S = \frac{E^2\angle 90^\circ}{X} - \frac{EV\angle 90^\circ + \delta}{X}$$

$$P_S = \frac{EV \sin\delta}{X}$$

$$Q_S = \frac{E^2}{X} - \frac{EV \cos\delta}{X}$$

Since the system is lossless, the real power delivered at the infinite bus is also the same.

$$P_R = P_S = \frac{EV \sin\delta}{X} = P_e$$

$$P_e = P_{max} \sin\delta$$

where $P_{max} = \dfrac{EV}{X}$.

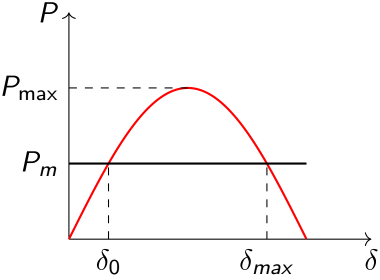


Figure: Power angle curve

For a given mechanical power (P_m), there are two operating angles.

$$\delta_0 = \sin^{-1}(\frac{P_m}{P_{max}})$$

$$\delta_{max} = \pi - \delta_0$$

- δ_0 is a stable equilibrium point.
- δ_{max} is an unstable equilibrium point.

Stability Phenomena

- Stability is a condition of equilibrium between opposing forces.
- Under steady-state conditions, there is equilibrium between the input mechanical torque and the output electrical torque and the speed remains constant.
- If there is perturbation, the equilibrium will be upset.

The change in electrical torque of a synchronous machine following a perturbation can be resolved as follows:

$$\Delta T_e = T_S \Delta\delta + T_D \Delta\omega$$

where $T_S \Delta\delta$ is the synchronizing torque component and T_S is the synchronizing torque coefficient.
$T_D \Delta\omega$ is the damping torque component and T_D is the damping torque coefficient.

1. Small Signal (small-disturbance) Stability
   Instability can be due to
   1. steady increase in rotor angle due to lack of sufficient synchronizing torque.
   2. rotor oscillations of increasing amplitude due to lack of sufficient damping torque.

   In today's practical power systems, small-signal stability is problem of insufficient damping of oscillations.

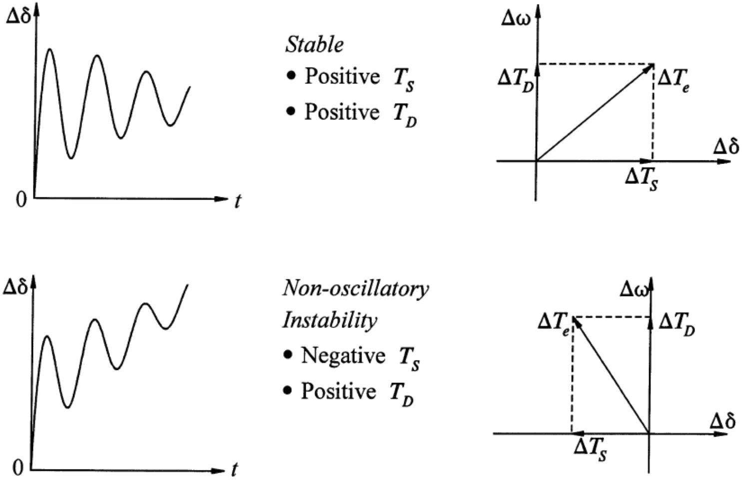


Figure: Nature of small disturbance response - Constant field voltage

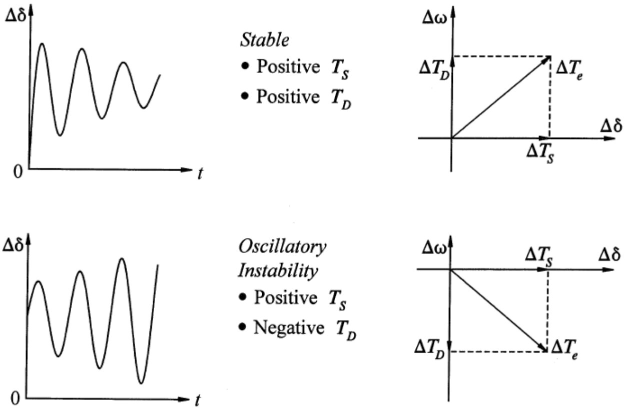


Figure: Nature of small disturbance response - Excitation control

The stability of the following types of oscillations is of concern:

- Local modes - Swinging of units at a generating system with respect to the rest of the system.
- Inter area modes - Swinging of many machines in one part of the system against machines in other parts. They are caused by weak tie lines.
- Control modes - They are associated with generating units and controls. Poorly tuned exciters, speed governors, HVDC converters and static var compensators are the reasons for theses modes.
- Torsional modes - They are associated with the turbine-generator shaft system rotational components. These modes may be caused by interaction with excitation controls, speed governors, HVDC controls and series-capacitor compensated lines.

2. Transient Stability

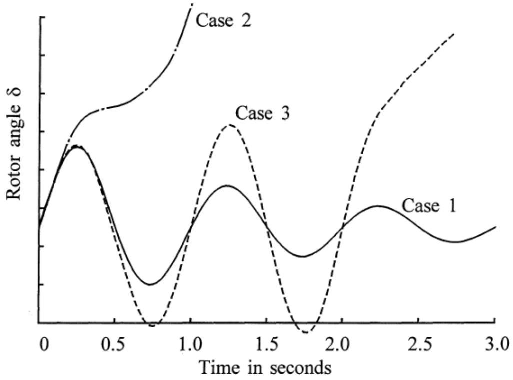


Figure: Rotor angle response to a transient disturbance

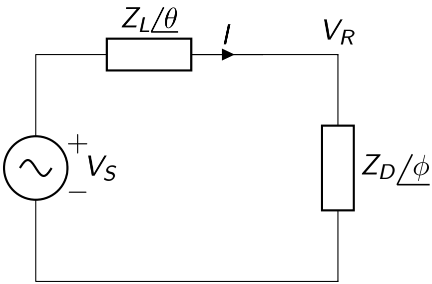
1. Case 1 - It is a stable case.
2. Case 2 - It is an unstable case. This form is called as “first-swing” instability which is caused by insufficient synchronizing torque.
3. Case 3 - It is also unstable case. This form occurs when the post fault steady state condition is small-signal unstable.

- In large power systems, transient stability may not occur as first-swing instability.
- In transient stability studies, the study period is usually limited to 3 to 5 seconds after the disturbance.

Voltage Stability

Voltage stability is the ability of a power system to maintain steady acceptable voltages at all buses in the system under normal operating conditions and after being subjected to a disturbance.

- A system is voltage stable if $V - Q$ sensitivity is positive for every bus.
- A system is voltage unstable if $V - Q$ sensitivity is negative for at least one bus.



$$I = \frac{V_S}{Z_L\angle\theta + Z_D\angle\phi}$$

The magnitude of the current is given by

$$I = \frac{V_S}{\sqrt{(Z_L\cos\theta + Z_D\cos\phi)^2 + (Z_L\sin\theta + Z_D\sin\phi)^2}}$$

The magnitude of V_R is

$$V_R = IZ_D$$

$$V_R = \frac{V_S}{\sqrt{(Z_L \cos\theta + Z_D \cos\phi)^2 + (Z_L \sin\theta + Z_D \sin\phi)^2}} Z_D$$

The real power supplied to the load is

$$P_R = V_R I \cos\phi$$

$$P_R = \frac{V_S I}{(Z_L \cos\theta + Z_D \cos\phi)^2 + (Z_L \sin\theta + Z_D \sin\phi)^2} Z_D \cos\phi$$

Let us normalize them.

$$I_{\text{norm}} = \frac{I}{I_{SC}}$$

where

$$I_{SC} = \frac{V_S}{Z_L}$$

$$I_{\text{norm}} = \frac{V_S}{\sqrt{(Z_L \cos\theta + Z_D \cos\phi)^2 + (Z_L \sin\theta + Z_D \sin\phi)^2}} \times \frac{Z_L}{V_S}$$

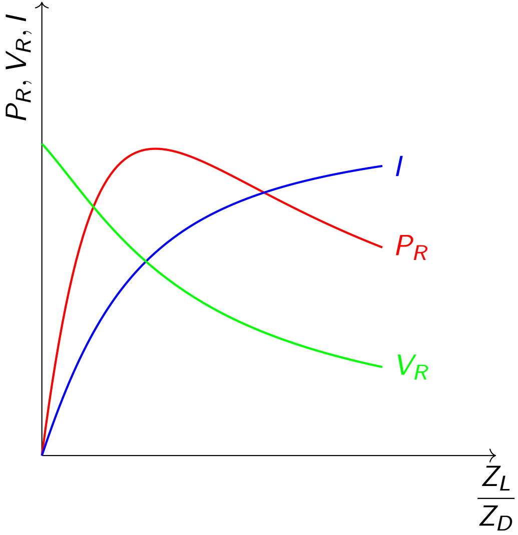
$$I_{\text{norm}} = \frac{Z_L/Z_D}{\sqrt{(\frac{Z_L}{Z_D}\cos\theta + \cos\phi)^2 + (\frac{Z_L}{Z_D}\sin\theta + \sin\phi)^2}}$$

$$V_{R,\text{norm}} = \frac{V_R}{V_S}$$

$$V_{R,\text{norm}} = \frac{V_S}{V_S\sqrt{(Z_L \cos\theta + Z_D \cos\phi)^2 + (Z_L \sin\theta + Z_D \sin\phi)^2}} Z_D$$

$$V_{R,\text{norm}} = \frac{}{\sqrt{(\frac{Z_L}{Z_D}\cos\theta + \cos\phi)^2 + (\frac{Z_L}{Z_D}\sin\theta + \sin\phi)^2}}$$

$$P_{R,\text{norm}} = \frac{Z_L/Z_D}{(\frac{Z_L}{Z_D}\cos\theta + \cos\phi)^2 + (\frac{Z_L}{Z_D}\sin\theta + \sin\phi)^2}\cos\phi$$


P_R, V_R, I
I
P_R
V_R
$\frac{Z_L}{Z_D}$

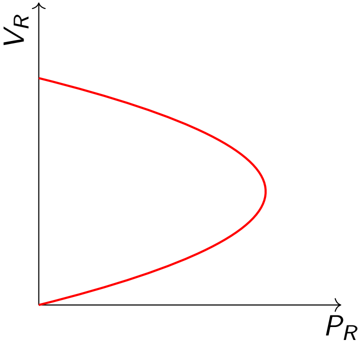


Figure: Power-voltage characteristics

Voltage Stability - Classification

1. Large-disturbance voltage stability
   - It is concerned with a system's ability to control voltages following large disturbances.
   - It requires a dynamic analysis.
   - The study period may extend from a few seconds to tens of minutes.
   - It is a long-term study.

A criterion for large-disturbance voltage stability is that following a given disturbance and following system control actions, voltages at all buses reach acceptable steady state levels.

2. Small-disturbance voltage stability
   - It is concerned with a system's ability to control voltages following small perturbations.
   - It requires a steady state analysis.

A system is voltage stable if $V - Q$ sensitivity is positive for every bus and unstable if $V - Q$ sensitivity is negative for at least one bus.

Power System Stability - A Complete Picture