Chapter 4

Power Systems Stability

LEARNING OBJECTIVES

After reading this chapter, you will be able to understand:

- Steady state stability
- The swing equation
- Multi-machine systems
- Steady state stability analysis
- Transient stability analysis
- Equal area criterion
- Principal type of transient disturbances
- Sudden change in mechanical input
- Switching operation
- 3-phase

Introduction

The stability of a system refers to the ability of a system to return back to its steady state when subjected to a disturbance. Power is generated by synchronous generators that operate in synchronism with the rest of the system. A generator is synchronized with a bus when both of them have same frequency, voltage and phase sequence. So, the stability is also defined as the ability of the power system to return to steady state without losing synchronism. The power system stability is categorized as follows:

1. Steady-state stability
2. Transient stability
3. Dynamic stability

Steady-state Stability

Steady-state stability is restricted to small and gradual changes in the system operating conditions. This stability basically concentrates on restricting the bus voltage close to their nominal values. Steady-state stability ensures that phase angle between two buses are not too large and check for the overloading of the power equipment and transmission lines.

Transient Stability

Transient stability involves study of the power system following a major disturbance. Following a large disturbance the synchronous alternator power angle changes due to sudden acceleration of the rotor shaft.

Dynamic Stability

The ability of a power system to maintain stability under continuous small disturbances is investigate under the name of dynamic stability. It is also known as small signal stability.

Power-angle Relationship

Consider the single machine infinite bus system shown in the figure. In this the reactance 'X' includes the reactance of the transmission line and the synchronous reactance or the transient reactance of the generator. The sending end voltage is then the internal emf of the generator. Let the sending end and receiving end voltages be given by

$$V_s = V_1 \angle \delta, V_R = V_2 \angle 0°$$

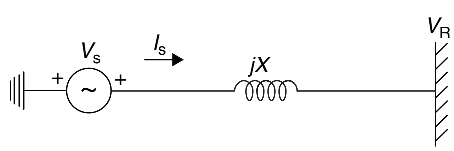


Figure 1 An SMIB system

We then have

$$I_s = \frac{V_1\angle\delta - V_2}{jX} = \frac{V_1 \cos\delta - V_2 + jV_1 \sin\delta}{jX}$$

The sending end real power and reactive power are given by

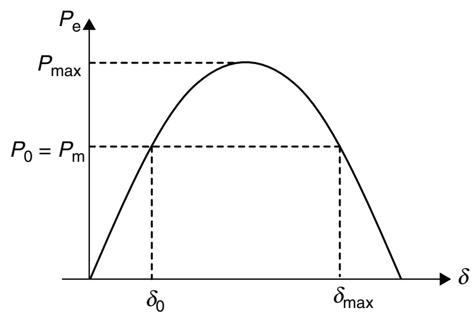
$$P_s + jQ_s = V_s I_s^* = V_1(\cos\delta + j\sin\delta)\frac{V_1\cos\delta - V_2 + jV_1\sin\delta}{jX}$$

$$P_s + jQ_s = \frac{V_1V_2\sin\delta + j\left(V_1^2 - V_1V_2\cos\delta\right)}{X}$$

Since the line is lossless, the real power dispatched from the sending end is equal to the real power received at the receiving end. We can therefore write.

$$P_e = P_s = P_R = \frac{V_1V_2}{X}\sin\delta = P_{max}\sin\delta$$

where $P_{max} = \frac{V_1V_2}{X}$ is the maximum power that can be transmitted over the transmission line. The power angle curve is shown in figure below



From the figure, we can see that for a given power 'P_0' there are two possible values of the angle $\delta \rightarrow \delta_0$ and δ_{max}.

The angles are given by

$$\delta_0 = \sin^{-1}\left(\frac{P_0}{P_{max}}\right)$$

$$\delta_{max} = 180° - \delta_0$$

The Swing Equation

Figure shows the torque, speed and flow of mechanical and electrical powers in a synchronous machine. It is assumed that the windage, friction and iron-loss are neglected. The differential equation governing the rotor dynamics can be written as

$$J\cdot\frac{d^2\theta_m}{dt^2} = T_m - T_e$$

where θ_m = Angle in rad (mechanical)

T_m = Turbine torque in Nm

T_e = Electromagnetic torque developed in Nm

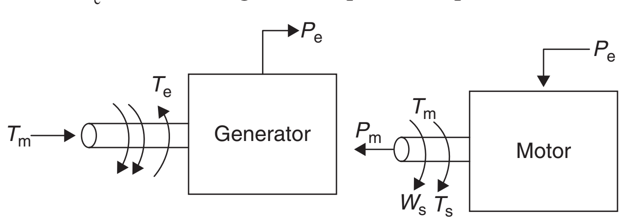


Figure 2 Flow of mechanical and electrical power in a synchronous machine

$$J\,\omega_{sm}\cdot\frac{d^2\theta_m}{dt^2} = P_m - P_e$$

ω_{sm} = Synchronous speed

P_m = Mechanical power input in MW

P_e = Electrical power output in MW

$$J\left(\frac{Z}{P}\right)^2 \times \omega_s\cdot\frac{d^2\theta_e}{dt^2} = P_m - P_e$$

$$M\cdot\frac{d^2\theta_e}{dt^2} = P_m - P_e$$

where M = Moment of inertia $= J\cdot\left(\frac{2}{P}\right)^2\omega_s$

If the angular position of the rotor is with respect to the synchronous rotating reference frame

Torque angle (δ) = $\theta_e - \omega_s t$

$$\frac{d^2\delta}{dt^2} = \frac{d^2\theta_e}{dt^2}$$

$$\therefore \quad M.\frac{d^2\delta}{dt^2} = P_m - P_e$$

$$\frac{GH}{\pi f}.\frac{d^2\delta}{dt^2} = P_m - P_e$$

$\frac{H}{\pi f}.\frac{d^2\delta}{dt^2} = P_m - P_e$ in p.u. of machine base ratings

$$M.\frac{d^2\delta}{dt^2} = P_m - P_e,$$

where $M_{p.u.} = \frac{H}{\pi f}$

The above equation is called the swing equation.

Multi-machine Systems

In a stability study of a power system with many synchronous machines only one MVA base common to all parts of the system can be chosen. This is accomplished by converting 'H' for each machine based on its own individual rating to a value determined by the system base

$$H_{system} = H_{mech}\cdot\frac{S_{mech}}{S_{system}}$$

Consider a power plant with two generators connected to the same bus which is electrically remote from the network disturbances. The swing equations on the common base are

$$\frac{2H_1}{\omega_s}.\frac{d^2\delta_1}{dt^2} = P_{m_1} - P_{e_1} \text{ per unit}$$

$$\frac{2H_2}{\omega_s}.\frac{d^2\delta_2}{dt^2} = P_{m_2} - P_{e_2} \text{ per unit}$$

If both the machines swing together, adding the two equations and denoting δ_1 and δ_2 by 'δ'

$$\frac{2H}{\omega_s}\cdot\frac{d^2\delta}{dt^2}=P_m-P_e \text{ per unit}$$

where $H = (H_1 + H_2)$, $P_m = P_{m_1} + P_{m_2}$,

$$P_e = P_{e_1} + P_{e_2}$$

For any pair of non-coherent machines in a system, the resultant two machine swing equation can be written as

$$\frac{d^2\delta_1}{dt^2}-\frac{d^2\delta_2}{dt^2}=\frac{\omega_s}{2}\left(\frac{P_{m_1}-P_e}{H_1}-\frac{P_{m_2}-P_{e_2}}{H_2}\right)$$

$$\frac{2}{\omega_s}\left(\frac{H_1H_2}{H_1+H_2}\right)\frac{d^2(\delta_1-\delta_2)}{dt^2}=\frac{P_{m_1}H_2-P_{m_2}H_1}{H_1+H_2}-\frac{P_{e_1}H_2-P_{e_2}H_1}{H_1+H_2}$$

which can be written as

$$\frac{2}{\omega_s}.H_{12}.\frac{d^2\delta_{12}}{dt^2}=P_{m_{12}}-P_{e_{12}}$$

where $\delta_{12} = \delta_1 - \delta_2$

$$H_{12}=\frac{H_1H_2}{H_1+H_2}$$

$$P_{m_{12}}=\frac{P_{m_1}H_2-P_{m_2}H_1}{H_1+H_2}$$

$$P_{e_{12}}=\frac{P_{e_1}H_2-P_{e_2}H_1}{H_1+H_2}$$

Steady-state Stability Analysis

Assumptions made in steady-state stability analysis:

1. The study considers small amplitude, long duration disturbances.
2. The damping term in the characteristicequation is absent, because of assumption of a loss less system and neglecting the effect of damper windings.
3. Non linearities are ignored, and hence the linearized form of the swing equation can be used.
4. The response of the governor and the exciter are ignored. This results in the mechanical power and electrical power to be constant throughout the transient period.

In a single machine infinite bus system, dynamics of a synchronous machine are described by the swing equation.

$$M.\frac{d^2\delta}{dt^2}=P_m-P_e$$

where $M.\frac{H}{\pi f}$ and $P_e=\frac{|E||V|}{X_{12}}\sin\delta=P_{max}\sin\delta$

Let the system be operating initially at equilibrium. Then the steady-state power transfer $P_{e_0}=P_m$ with losses neglected and a rotor angle of δ_0. Assume a small increment ΔP in the electric power output with the mechanical input P_m as fixed. This change causes the torque angle to change to $(\delta_0 + \Delta\delta)$. From the small disturbance, linearized equation can be written as

$$\Delta P_e=\left(\frac{\partial P_e}{\partial \delta_0}\right)\Delta\delta$$

Swing equation can be written as

$$M.\frac{d^2\Delta\delta}{dt^2}=P_m-\left(P_{e_0}+\Delta P_e\right)=-\Delta P_e$$

$$M\frac{d^2\Delta\delta}{dt^2}+\left[\frac{\partial P_e}{\partial\delta}\right]\Delta\delta=0$$

Characteristic equation is given by

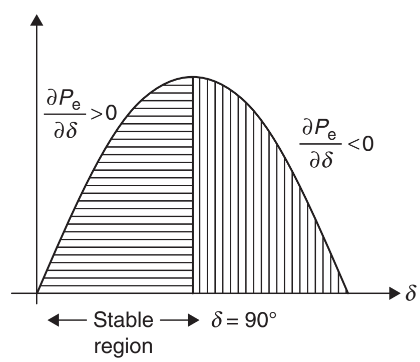
$$MD^2+\left(\frac{\partial P_e}{\partial\delta_0}\right)=0$$

Roots of the characteristic equation are

$$D=\pm\left[\frac{-\left(\frac{\partial P_e}{\partial\delta}\right)_0}{M}\right]^{\frac{1}{2}}$$

When $\frac{\partial P_e}{\partial\delta}$ is positive, the roots of the characteristic equation lie on the $j'\omega'$(imaginary) axis, and the system rotor angle behaviour is oscillating about 'δ_0'. The line resistance and damper winding of machine which have been ignored in the above modelling cause the system oscillations to decrease. The system is therefore be stable for a small increment in electrical power.

If $\frac{\partial P_e}{\partial\delta}$ is negative, the roots be real with one of them being positive and other negative but of equal magnitude which is 'unstable and causes rotor angle to increase without bound upon occurrence of a small power increment.



The term $\left(\frac{\partial P_e}{\partial\delta}\right)$ is known as 'synchronizing power coefficient'. This is also called stiffness of the synchronous machine.

The system is unstable if $\frac{\partial P_e}{\partial\delta}<0$ which implies $\delta > 90°$, so the system is unstable if $\delta > 90°$. The maximum power that can be transferred without loss of stability (steady state) occurs for $\delta = 90°$ and it is given by

$$P_{\max} = \frac{EV}{X_{12}}$$

$P_{\max}$ is known as steady-state stability limit.

Methods for Improving Steady-state Stability Limit

1. Reduce the reactance of the transmission lines.
   - By adding parallel lines which also increases the reliability of the system.
   - Series capacitors which also provides better voltage regulation.
2. Increasing either or both $|E|$ and $|V|$ by means of excitation control.

Solved Examples

Example 1: A sending end bus transfer power P_0 through a transmission line of p.u. impedance 0.1 If the steady-state stability margin is 40% and the bus voltages at both the ends is 1.0 p.u. The operating power angle and magnitude of P_0 are

(A) 36.87°, 6 p.u. (B) 36.87°, 4 p.u.
(C) 23.57°, 0.6 p.u. (D) 23.57°, 0.4 p.u.

Solution: (A)

Steady-state stability margin

$$= \frac{P_{\max} - P_0}{P_{\max}} \times 100$$

$$40 = \left(1 - \frac{P_0}{P_{\max}}\right) \times 100$$

$$0.4P_{\max} - P_{\max} = -P_0$$

$$P_0 = 0.6P_{\max} = P_{\max}\sin\delta$$

$$\delta = \sin^{-1}(0.6) = 36.87°$$

$$\text{Magnitude of } P_0 = \frac{V_1V_2}{X_{12}}\sin\delta_0$$

$$= \frac{1}{0.1}\sin\delta_0 = 6 \text{ p.u.}$$

Example 2: The sending end and receiving end voltages of a transmission line at 100 MW load are equal at 230 kV, per phase line impedance is $(4 + j8)$. Steady-state stability limit of the system is

(A) 1090 MW/ph (B) 363.3 MW/ph
(C) 3,269.8 MW/ph (D) 1,887.8 MW/ph

Solution: (A)

When the line resistance is considered

$$P_{\max} = \frac{V_SV_R}{|Z|} - \frac{R|V_R^2|}{|Z|^2}$$

where $$V_S = V_R = \frac{230}{\sqrt{3}} = 132.8 \text{ kV}$$

$$P_{\max} = \frac{(132.8)^2}{\sqrt{4^2+8^2}} - \frac{4\times(132.8)^2}{\left(\sqrt{8^2+4^2}\right)^2}$$

$$= 1971.74 - 881.8$$

$$= 1089.948 \cong 1090 \text{ MW/Ph}$$

Example 3: A 500 MVA, 11 kV, 50 Hz, 4-pole turbo-generator has an inertia constant of $H = 7.5$ MJ/MVA. If the mechanical power input is 552 MW and the electrical power output of 400 MW and stator copper loss is assumed to be negligible, then the angular acceleration is

(A) 182.4 rpm/s²
(B) 364.8 rpm/s²
(C) 25.33 rpm/s²
(D) 50.66 rpm/s²

Solution: (C)

From the swing equation

$$\frac{H}{\pi f}\cdot\frac{d^2\delta}{dt^2} = P_m - P_e \text{ in p.u.}$$

$$\frac{7.5}{180\times 50}\frac{d^2\delta}{dt^2} = \frac{552-400}{500}$$

$$\frac{d^2\delta}{dt^2} = 364.8 \text{ elec degree/s}^2$$

For a four pole machine

$$\frac{d^2\delta}{dt^2} = \frac{364.8}{2} = 182.4 \text{ mech.dec/s}^2$$

$$\text{Angular acceleration} = \frac{182.4}{360}\times 50$$

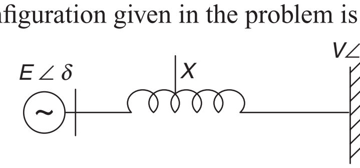
$$= 25.33 \text{ rpm/s}^2$$

Example 4: An alternator having a reactance of 1.3 p.u. is connected to an infinite bus as shown in the figure. It delivers 1.0 p.u. current at 0.8 p.f. lagging at V = 1.0 p.u. The steady-state stability limit of the system is

(A) 0.58 (B) 1.584
(C) 1.3 (D) 1.7

Solution: (B)

System configuration given in the problem is given by



For the given power factor of 0.8, current delivered from the source is $I = (0.8 - j0.6) = 1\angle{-36.86}$

Sending end voltage $E = V + jIX_d$

$$= 1.0 + j(0.8 - j0.6) \times 1.3$$

$$= 2.06 \angle 30.3$$

Steady-state stability limit $P_{\text{max}} = \frac{EV}{X_{\text{d}}} = \frac{2.06\times 1}{1.3}$

$$P_{\text{max}} = 1.584 \text{ p.u.}$$

Example 5: A 250 MVA synchronous generator having inertia constant 5 MJ/MVA is connected in parallel with a 200 MVA generator having inertia constant of 4 MJ/MVA. Both the generators are swinging coherently. The equivalent inertia constant of the machine on a base of 100 MVA is

(A) 20.5 MJ/MVA (B) 12.5 MJ/MVA
(C) 8 MJ/MVA (D) 9 MJ/MVA

Solution: (A)

Both the inertia constants are to be represented with same base

$$H_{\text{p.u.}} = \frac{H_{\text{p.u.}_{\text{old}}}}{P_{\text{base}_{\text{new}}}} \times P_{\text{base}_{\text{new}}}$$

$$H_{\text{p.u.}} = \frac{5\times 250}{100} = 12.5 \text{ MJ/MVA}$$

$$H_{2_{\text{p.u.}}} = \frac{4\times 200}{100} = 8 \text{ MJ/MVA}$$

$$H_{\text{eq}} = H_{1_{\text{p.u.}}} + H_{2_{\text{p.u.}}} = 12.5 + 8$$

$$= 20.5 \text{ MJ/MVA}$$

Example 6: A synchronous generator is connected to a 11 kV infinite bus through a transmission line. The reactances of the generator and transmission line are 1.1 and 0.7 , respectively. The terminal voltage of the synchronous generator is 15 kV. If the generator delivers 75 MW power to the infinitely bus, the load angle (δ) for stable operation is

(A) 55° (B) 125°
(C) Both A and B (D) 63.4°

Solution: (A)

Power angle equation is given by

$$P_{\text{e}} = \frac{|E||V|}{X_{12}} \sin\delta$$

$$75 = \frac{11\times 15}{(1.1+0.7)} \sin\delta$$

$$\delta = 55°$$

Transient Stability Analysis

If the disturbance is large, changes in angular difference may be well enough to cause the loss of synchronism of the machines. The types of disturbances are mostly the faults, sudden. Large load changes may also cause instability of the machines. This type of instability is known as 'transient instability'.

Assumptions in Transient Stability Analysis

1. Resistance of the transmission lines and synchronous machine are neglected.
2. Synchronous machine damper winding is ignored which contributes damping term.
3. Rotor speed is assumed to be synchronous even though it varies insignificantly during the stability transients.
4. Mechanical input to machine is assumed to remain constant the transients.
5. Voltage behind transient reactance is assumed to remain constant.
6. Shunt capacitors ignored in stability study which does not cause any significant error.
7. Loads are modelled as constant admittances.

Equal Area Criterion

To examine the stability of a two machine system without solving the swing equation, a direct approach is given as follows.

Consider a swing equation.

$$H\frac{d^2\delta}{dt^2} = P_{\text{m}} - P_{\text{e}} = P_{\text{a}} = \text{Accelerating power}$$

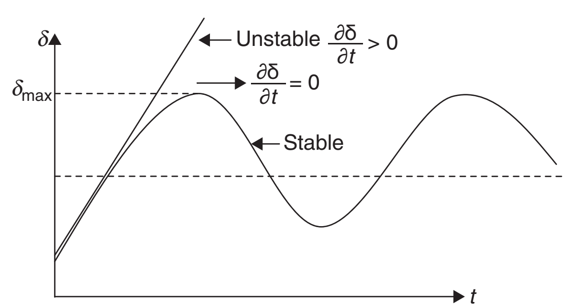
If the system is stable, $\delta(t)$ performs oscillations, whose aptitude decreases in actual practice because of damping terms (Which are neglected in the swing equation) on the other hand, if the system is unstable 'δ' continues to increase indefinitely with time and the machine loses synchronism. So when the system is stable, then $\delta(t)$ will go to maximum and start to reduce. This fact can be stated as stability criterion, that the system is stable if at some time

$$\frac{d\delta}{dt} = 0$$

and system is unstable if

$$\frac{\partial\delta}{\partial t} > 0 \text{ for sufficiently long time.}$$

The stability criterion stated above can be converted into a simple and easily applicable form for a single machine infinite bus system.



Multiply both sides of swing equation by $\left(2.\frac{d\delta}{dt}\right)$, we get $2.\frac{d\delta}{dt}.\frac{d^2\delta}{dt^2}=\frac{2P_a}{M}.\frac{d\delta}{dt}$

Integrate on both sides,

$$\frac{d\delta^2}{dt}=\frac{2}{M}\int_{\delta_0}^{\delta} P_a.d\delta$$

$$\frac{d\delta}{dt}=\left(\frac{2}{M}\int_{\delta_0}^{\delta} P_a.d\delta\right)^{1/2}$$

where 'δ_0' is the initial rotor angle before it begins to swing due to disturbance.

The condition for stability can be written as

$$\left(\frac{2}{M}\int_{\delta_0}^{\delta} P_a.d\delta\right)^{1/2}=0$$

$$\Rightarrow \qquad \int_{\delta_0}^{\delta} P_a.d\delta=0$$

The condition for stability is stated as:

- The system is stable if the area under accelerating power $(P_a)-\delta$ curve reduces to zero at some value of δ.

(or)

- Positive area under $P_a-\delta$ curve must equal the negative area and hence the name 'equal area' criterion of stability.

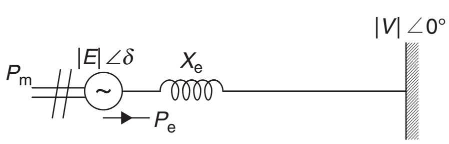
Principal Type of Transient Disturbances

For transient stability studies we have to consider the effect of

1. Sudden change in mechanical input
2. Switching operations
3. Fault with subsequent circuit isolation of the system

Sudden Change in Mechanical Input

Let us consider a synchronous machine connected to infinite bus as shown in the following figure.



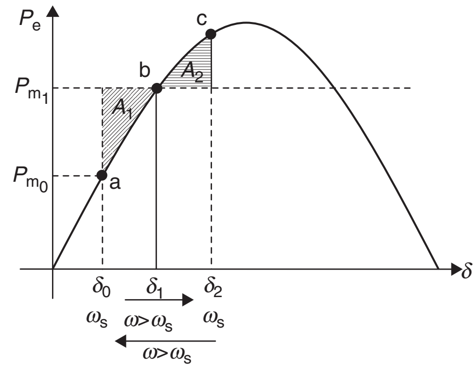
Electric power transmitted is given by

$$Pe=\frac{|E||V|}{X_e}\sin\delta=P_{max}\sin\delta$$

Under steady operating conditions

$$P_m=P_{eo}=P_{max}\sin\delta_0.$$

Let the mechanical input to the rotor be suddenly increased to P_{m1} by increasing steam input. The accelerating power $P_a=P_{m1}-P_e$ causes the rotor speed to increase and so does the rotor angle. At angle δ_1, $P_{m1}-P_e=P_a=0$ (At point b). but the rotor angle continues to increase as $\omega>\omega_s$. P_a now becomes negative, the rotor speed begins to reduce but the angle continues to increase till at angle δ_2, $\omega=\omega_s$ once again (at point 'c'), the decelerating area A_2 equals the accelerating area A_2 i.e., $\int_{\delta_0}^{\delta_2} P_a d\delta=0.$



As the oscillation decay out because of damping, the system settles to the new steady state when

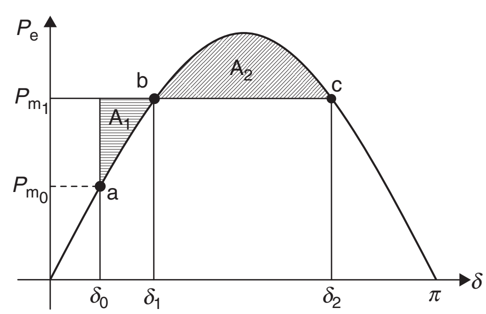
$$P_{m_1}=P_e=P_{max}\sin\delta_1,$$

From the power angle diagram, the expression for A_1 and A_2 can be written as.

$$A_1=\int_{\delta_0}^{\delta_1}\left(P_{m_1}-P_e\right)d\delta$$

$$A_2=\int_{\delta_1}^{\delta_2}\left(P_e-P_{m_1}\right)d\delta$$

For the system to be stable, it should be possible to find 'δ_2' such that $A_1=A_2$. As P_{m_1} increases, a limiting condition is finally reached when A_1 equals the area above the P_{m_1} line as shown in the figure below.

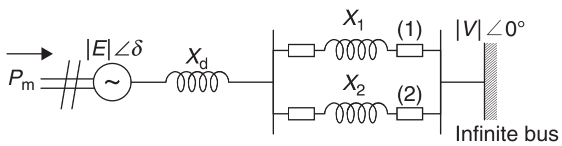


Under these conditions, δ_2 acquired the maximum value such that

$$\delta_2=\delta_{max}=\pi-\delta_1=\pi-\sin^{-1}\left(\frac{P_{m_1}}{P_{max}}\right)$$

Switching Operation

Consider a single machine connected to infinite bus through two parallel lines as shown in the figure.



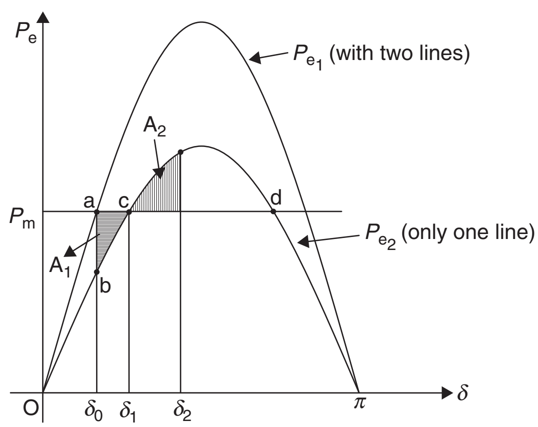
For stability analysis, consider the case when one of the lines is suddenly switched off with the system operating at a steady load. Before switching off the line, power transfer expression is given by

$$P_{e_1} = \frac{|E||V|}{X_d + (X_1 // X_2)} \cdot \sin\delta = P_{max} \sin\delta.$$

Immediately after the line '2' is switched off

$$P_{e_2} = \frac{|E||V|}{X_d + X_1} \sin\delta = P_{max_2} \sin\delta.$$

Since $(X_d + X_1) > (X_d + (X_1 // X_2))$, the relation between the maximum powers in two cases becomes $P_{max_2} < P_{max_1}$. The system is operating initially with a steady power transfer $P_e = P_m$ at a torque angle δ_0 on curve *I*.



Immediately after switching off line 2, operating point on curve 1 shifts to curve 2 (From point '*a*' to point '*b*') thereafter, operation of the system will be exactly same as sudden change in mechanical input case.

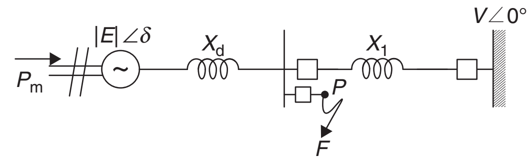
When an area A_2 corresponding to the decelerating energy is equal to an area A_1 corresponding to accelerating area, the system will be stable and finally operates at '*C*' corresponding to a new rotor angle $\delta_1 > \delta_0$. This is because a single line after larger reactance and larger rotor angle is needed to transfer the same steady power.

For the limiting case of stability, δ_1 has a maximum value given by

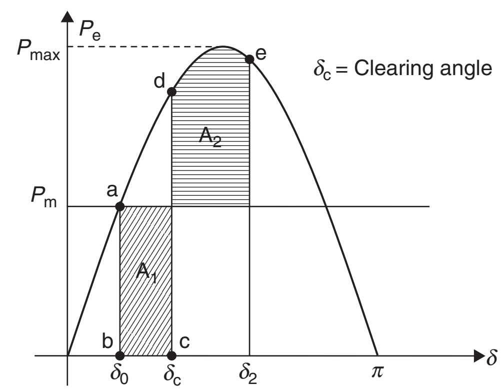
$$\delta_1 = \delta_{max} = \pi - \delta_c$$

Three-phase Fault on Radial Line

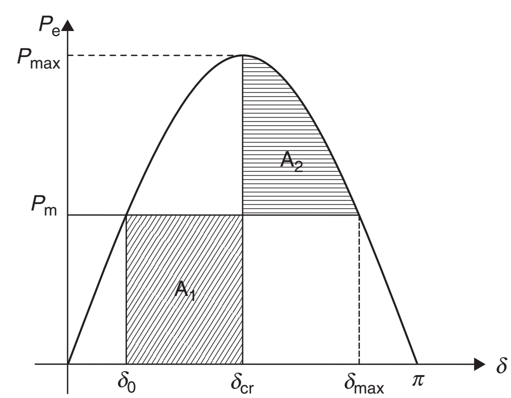
Consider a system operating in steady state and configured as shown in figure below.



If the fault is at point '*p*' on the radial line, the electrical output of the generator (power transferred to the load) will reduce to zero. (state point is '*b*') The rotor angle of the system starts increasing with the accelerating area and state point moves along path BC. If the fault is cleared by opening circuit breakers at time t_c corresponding to angle δ_c. Value of t_c and δ_c are known as clearing time and clearing angle, respectively. The system once again becomes healthy and transmits $P_0 = P_{max} \sin\delta$. The rotor now decelerates along de. If an angle δ_1 can be found such that $A_1 = A_2$, the system is found to be stable. The system finally settles down to the steady operating point '*a*' in an oscillatory manner because of inherent damping.



As the clearing of the fault line is delayed, A_1 increases and does δ_1 to find $A_2 = A_1$ till $\delta_1 = \delta_{max}$ as shown in figure below. For a clearing time larger than this value, the system would be unstable as $A_2 < A_1$ the maximum allowable value of clearing time angle for the system to remain stable are, respectively, known as critical clearing time and angle.



From the above figure $\delta_{max} = \pi - \delta_0$

For a system to be stable $A_1 = A_2$

$$\Rightarrow \quad \int_{\delta_o}^{\delta_{cr}} (P_m - 0)\, d\delta = \int_{\delta_{cr}}^{\delta_{max}} (P_{max} \sin\delta - P_m)\, d\delta$$

$$\Rightarrow \qquad \delta_{cr} = \cos^{-1}\left[(\pi - 2\delta_0)\sin\delta_0 - \cos\delta_0\right]$$

where δ_{cr} = critical clearing angle.

From the swing equation

$$\frac{d^2\delta}{dt^2} = \frac{\pi f}{H} P_m \; [\because P_e = 0]$$

Integrating twice, we get

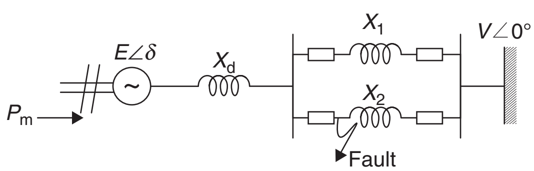
$$\delta_{cr} = \frac{\pi f}{2H} P_m t_{cr}^2 + \delta_0$$

$$t_{cr} = \sqrt{\frac{2H(\delta_{cr} - \delta_0)}{\pi f P_m}},$$

t_{cr} = Critical clearing time

Fault at One End of Parallel Lines

If fault occurs at one of the parallel lines connected between synchronous machine and infinite bus.



Before occurrence of a fault, power transfer expression is given by

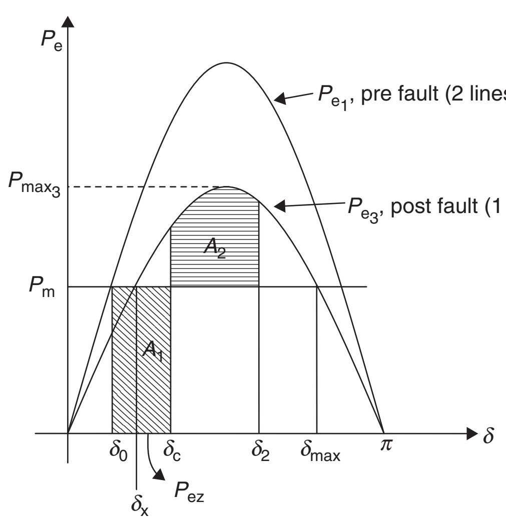
$$P_{e_1} = \frac{|E||V|}{X_d + (X_1 \parallel X_2)} \cdot \sin\delta = P_{max_1} \sin\delta$$

During the period of fault, $P_{e_2} = 0$

After fault is cleared,

$$P_{e_3} = \frac{|E||V|}{X_d + X_1} \sin\delta = P_{max\,3} \sin\delta.$$

Since $[X_d + (X_1//X_2)] < [X_d + X_1,]$ the relation between the maximum power transfer in both the cases is related as $P_{max_3} < P_{max_1}$



For stable operation

$$\delta_{max} = \pi - \delta_x = \pi - \sin^{-1}\left(\frac{P_m}{P_{max_3}}\right)$$

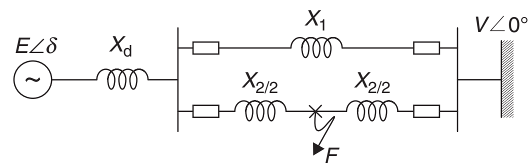
$$A_1 = A_2$$

$$\int_{\delta_0}^{\delta_2} (P_m - 0)\, d\delta = \int_{\delta_C}^{\delta_2} \left(P_{max_3}\sin\delta - P_m\right) \sin\delta$$

For stable operation of the system, clearing time must be less than critical clearing time at which δ_2 is equal to δ_{max}.

Fault Away From One of the Parallel Lines

When the fault occurs away from line end, there is some power flow during the fault though considerably reduces, as different from previous case, where $P_e = 0$. Circuit model of the system during fault is shown below.



Power angle curve before fault

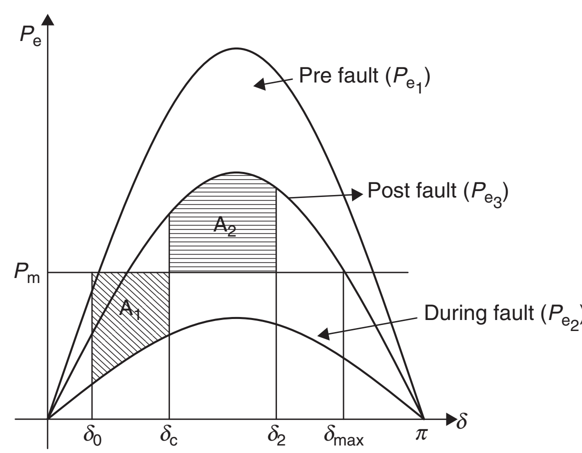
$$P_{e_1} = \frac{|E||V|}{X_d + (X_1/X_2)} \sin\delta$$

Power angle curve during fault

$$P_{e_2} = \frac{|E||V|}{X_F} \sin\delta.$$

If the fault is cleared by removing faulted line after fault is cleared,

$$P_{e_3} = \frac{|E||V|}{X_d + X_1} \sin\delta$$



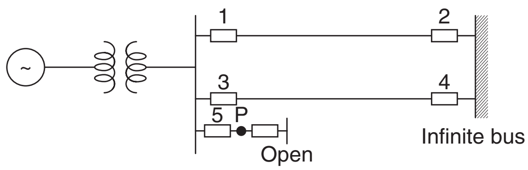
Critical clearing angle

$$\cos\delta_{cr} = \frac{\frac{\pi}{180} P_m(\delta_{max} - \delta_0) - P_{max_2}\cos\delta_0 + P_{max_3}\cos\delta_{max}}{P_{max_3} - P_{max_2}}$$

Design methods for improving transient stability

1. Improved steady-state stability; achieved by:
   (a) Higher system voltage
   (b) Additional transmission lines
   (c) Smaller reactances in transmission lines and transformers
   (d) Series capacitive compensation
   (e) Using FACTS
2. High-speed fault clearing
3. High-speed reclosure of circuit breakers
4. Larger machine inertia
5. Fast valving

Example 7: For single-line diagram of three-phase power system given below, the generator is delivering 1.0 p.u. power to infinite bus. The pre fault power angle equation is $P_e = 2.1 \sin\delta$.



Calculate the critical clearing angle and critical clearing time when the system is subjected to a 3-F fault at point 'P'. The fault is cleared by breaker 5. The inertia constant $H = 50$ MJ/MVA.

Solution: Before the fault occurrence

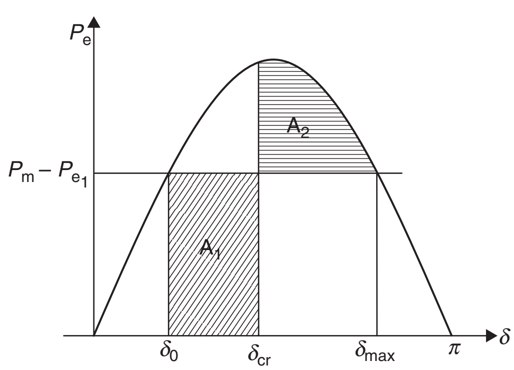
$$P_e = P_{max} \sin\delta = 2.1 \sin\delta$$

Power transferred $\quad P_e = P_m = 1 = 2.1 \sin\delta$

$$\delta_0 = 28.43°$$

$$\therefore \quad \delta_{max} = \pi - \delta_0 = 151.56°$$

When the fault occurs, power angle curve is as shown in the figure.



For the system to be stable at critical clearing angle,

$$A_1 = A_2$$

$$\Rightarrow \quad \int_{\delta_o}^{\delta_{cr}} P_m . d\delta = \int_{\delta_{cr}}^{\delta_{max}} \left(P_{max} \sin\delta - P_m\right) d\delta$$

$$\int_{\delta_o}^{\delta_{cr}} P_m . d\delta = \int_{\delta_{cr}}^{\delta_{max}} \left(2.1 \sin\delta - P_m\right) d\delta$$

$$P_m(\delta_{cr} - \delta_0) = 2.1(\cos\delta_{cr} - \cos\delta_{max}) - P_m(\delta_{max} - \delta_{cr})$$

$$\Rightarrow \quad \cos\delta_{cr} = 0.144$$

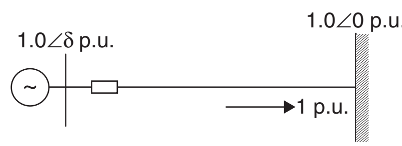
Critical clearing $\delta_{cr} = 81.72°$

$$t_{cr} = \left[\frac{2H\left(\delta_{cr} - \delta_0\right)}{\pi f P_m}\right]^{\frac{1}{4}} \quad t_{cr} = 0.243 \text{ sec}$$

Example 8: The transient stability of the power system can be effectively improved by
(A) Excitation improved
(B) Phase-shifting transformer
(C) Single-pole switching of circuit breakers
(D) Increase the turbine value opening

Solution: (C)

Example 9: A loss less single machine infinite bus power systems is shown below.



The synchronous generator transfers 1.0 p.u. of power to the infinite bus. The critical clearing time of the circuit breaker is 0.4 sec. If another identical generator is connected in parallel to the existing generator and each generator is scheduled to supply 0.5 p.u. of power, then the critical clearing time of the circuit breaker will be
(A) Reduce to 0.2 s
(B) Reduce but will be more than 0.2 s
(C) Remains constant at 0.4 s
(D) Increase beyond 0.4 s

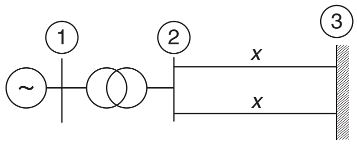
Solution: (D)

Critical clearing time $t_{cr} = \sqrt{\dfrac{2H}{\pi f} \dfrac{\left(\delta_{cr} - \delta_0\right)}{P_i}}$

$$\therefore \quad t_{cr} \propto \sqrt{H}$$

When two identical generators are added in parallel, resultant inertia will be $2H$. Then critical clearing time will increase.

Example 10: A generator with constant 1.0 p.u. terminal voltage supplies power through a step-up transformer of 0.14 p.u. reactance and a double circuit line to an infinite bus bar as shown in the figure. The infinite bus voltage is maintained at 1.0 p.u. Neglecting the resistance and susceptance of the system, the steady-state stability power limit of the system is 6.5 p.u. If one of the double-circuit is tripped, then resulting steady-state stability power limit in p.u. will be



(A) 6.5 p.u.
(B) 3.25 p.u.
(C) 5.96 p.u.
(D) 2.98 p.u.

Solution: (C)

Steady-state stability limit $= \dfrac{V_1 V_2}{X_{12}} = 6.5$

$$\frac{1.0 \times 1.0}{\left(0.14 + \dfrac{X}{2}\right)} = 6.5$$

$$X = 2\left(\frac{1}{6.5} - 0.14\right)$$

$\Rightarrow$ $X = 0.0277.$

New steady-state stability limit $= \dfrac{V_1 V_2}{0.14 + X}$

$$= \frac{1}{0.14 + 0.0277} = \frac{1}{0.1677} = 5.96 \text{ p.u.}$$

Example 11: A synchronous generator delivers 0.5 p.u. power in the steady state to an infinite bus through a transmission line of reactance 0.5 p.u. The generator no load voltage is 1.5 p.u. and infinite bus voltage is 1 p.u. The inertial constant of the generator is 5 MW-s/MVA and the generator reactance is 1 p.u. The critical clearing angle, in degrees, for a 3-Ø dead short-circuit fault at the generator terminal is

(A) 79.4° (B) 30°
(C) 150° (D) 100.6°

Solution: (A)
Power transferred before fault

$$P_e = \frac{V_1 V_2}{X_{12}} \sin\delta = 0.5 \text{ p.u.}$$

Maximum power can be transferred

$$= \frac{V_1 V_2}{X_{12}} = \frac{1 \times 1.5}{1 + 0.5} = 1 \text{ p.u.}$$

$$\sin\delta_0 = \frac{0.5}{1} = 0.5$$

$\Rightarrow$ $\delta_0 = \sin^{-1}(0.5) = 30°$

$$\delta_{max} = \pi - 30° = 150°.$$

Critical clearing angle (δ_c)

$$= \cos^{-1}\left[\frac{P_e(\delta_{max} - \delta_0) + P_{m_3} \cos\delta_{max}}{P_{m_3}}\right]$$

$= 79.45°$

Exercises

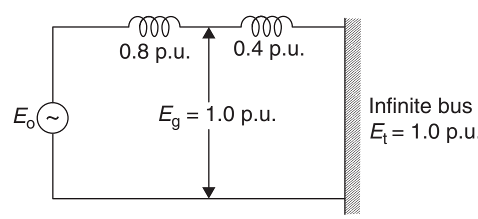
Practice Problems I

Directions for questions 1 to 15: Select the correct alternative from the given choices.

1. A 60 MW, 11 kV, 0.85 lag p.f. water wheel generator has an inertia constant of 4 MJ/MVA. The energy stored in the rotor at synchronous speed is
   (A) 36.5 MJ
   (B) 180 kJ
   (C) 282.3 MJ
   (D) 282.3 kJ

2. Which of the following statement is true
   (A) Steady-state stability limit can be increased by increasing its reactance
   (B) Steady-state stability limit is equal to transient stability limit
   (C) Steady-state stability of a power system is improved by increasing generator inertia
   (D) Steady-state stability can be improved by using double circuit line instead of single circuit line

3. A generator of equivalent reactance of 0.8 p.u. is connected to an infinite bus through a series reactance of 0.4 p.u. The terminal voltage of the generator (E_g) is 1.0 p.u. and voltage of infinite bus is 1.0 p.u. The steady-state stability limit is



   (A) 2.17 p.u. (B) 1.6 p.u.
   (C) 3.98 p.u. (D) 1.0 p.u.

4. If the mechanical input of a 4-pole, 50 Hz, 20 MVA turbo generator is suddenly raised to 75 MW for an electrical load of 30 MW, the rotor acceleration is (Neglect mechanical and electrical losses and take Inertia constant as 6.0 MJ/MVA)
   (A) 4.82 electrical degrees/s^2
   (B) 337.5 electrical degrees/s^2
   (C) 3375 electrical degrees/s^2
   (D) 280 electrical/rad/s^2

5. A 60 MW, 0.85 lag p.f. synchronous generator operates on full load at a frequency of 50 Hz. The load is suddenly reduced to 30 MW. The steam valve begins to close after 0.3 s due to time lag in governor system. The change in frequency that occurs in this time is [Given $H = 4$ MJ/MVA]

(A) 50.79 Hz (B) 0.79 Hz
(C) 0.69 Hz (D) 0.59 Hz

6. To an infinite bus operating at a voltage of 1 p.u., a 50 Hz generator with a synchronous reactance of 1.2 p.u. is connected. The generator no load voltage is 1.0 p.u. and the inertia constant is 4 MJ/MVA. The frequency of the resulting natural oscillations of the generator when it is suddenly loaded to 60 per cent of its maximum power limit is

(A) 1.03 Hz (B) 2.89 Hz
(C) 60.42 Hz (D) 50 Hz

7. A 100 MVA synchronous machine has $H_1 = 4.2$ MJ/MVA and a 1200 MVA machine has $H_2 = 3.2$ MJ/MVA. The two machines operate in parallel. The equivalent H constant for the two in 200 MVA base is

(A) 2.4 MJ/MVA (B) 11.6 MJ/MVA
(C) 21.3 MJ/MVA (D) None of these

8. A 50 Hz, 4-pole turbo generator is rated 200 MVA, 2.2 kV and has an inertia constant of 7.5. Assume the generator is synchronized with a large power system and has a zero accelerating power while delivering a power of 450 MW. Suddenly its input power is changed to 475 MW. The speed of generator in rpm at the end of a period of 10 cycles is

(A) 1400 pm (B) 1500 rpm
(C) 1600 rpm (D) 1508.178 rpm

9. For an HVDC valve, the value of output voltage, when the firing angle is 30° and maximum value of line voltage is 200 V is

(A) 233.83 V (B) 150 V
(C) 100 V (D) 220 V

10. The maximum additional load that can be suddenly applied on a transmission line inter connector carrying 100 MW if the power angle diagram is given by $P = 120 \sin \alpha$

$P \rightarrow$ Power transmitted in MW

$\alpha \Rightarrow$ Displacement between voltage phasors at the two ends

(A) 4.87 MW (B) 3.87 MW
(C) 2.87 MW (D) 1.87 MW

11. It is preferred to transmit bulk power over long distances using high-voltage DC system. This is due to

(A) Reduced harmonics
(B) Protection system being simple
(C) Low cost of HVDC terminals
(D) Minimum line power losses

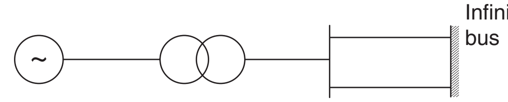
12. A 250 MVA, 50 Hz 3-ϕ turbo alternator produces power at 11 kV. The alternator is Y-connected and the neutral is solidly grounded. The sequence reactance are $X_0 = 0.05$ p.u., $X_1 = 0.2$ p.u.
$X_2 = 0.2$ p.u. The system is running on no load at rated voltage. The magnitude of positive sequence line current for a single line to ground fault at generator terminal would be

(A) 2.5 p.u. (B) 2.22 p.u.
(C) 5 p.u. (D) 4.44 p.u.

13. A 400 kV transmission line has a maximum power transfer capability P_{max} at 400 kV. If the line voltage is increased to 800 kV, with series reactance unchanged, the maximum power transfer capability is approximately

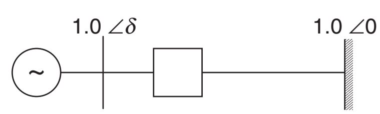
(A) 4 P (B) 2 P (C) P (D) P/4

14. An alternator with terminal voltage of 1 p.u. supplies power through a transformer of 0.10 p.u. reactance and a double circuit line to an infinite bus bar. The infinite bus voltage is maintained at 1 p.u. Susceptances and resistance are neglected. The steady-state stability power limit of the system is 8 p.u. If one of the lines of the double circuit is tripped, the resulting the steady-state stability power limit will be



(A) 8 p.u. (B) 3.33 p.u.
(C) 6.67 p.u. (D) 4 p.u.

15. A single machine infinite bus power system is as shown



The alternator transfers 1 p.u. of power to infinite bus. The critical clearing time of circuit breaker is 0.4 s. If another alternator is connected in parallel to the existing alternator and each alternator is scheduled to supply 0.5 p.u. of power, the critical clearing time of breaker

(A) Reduces to 0.2 s
(B) Reduces but will be greater than 0.2 seconds
(C) Remains at 0.4 s
(D) Increases beyond 0.4 s

Directions for questions 16 to 19**:** Consists of two statements: one is Assertion (A) and the other is Reason (R). You have to examine these two statements and select the answer using the code given below.

(A) Both A and R are individually correct and R is the correct explanation of A
(B) Both A and R are individually correct, but R is not the correct explanation of A
(C) A is true but R is false
(D) A is false but R is true

16. A: The most extensively used form of differential relay is the percentage differential or biased beam relay.

R: Percentage differential relay is more sensitive in comparison to differentially connected over current relay.

17. A: In comparison to the making capacity of a circuit breaker, breaking capacity is normally higher.

R: The breaking capacity of a circuit breaker is expressed as $\sqrt{3} \times V \times I \times 10^{-6}$ MVA, where V is the rated service. Voltage in volts and I is the RMS value of symmetrical breaking current in amperes.

18. A: Extinction of DC arc is much difficult than that of an AC arc.

R: In an AC circuit, current wave passes through zero point twice during each cycle but in dc circuit full current has to be broken.

19. A: It is not desirable to operate a high voltage 3-ϕ system of considerable capacitance with an isolated neutral.

R: There is no zero-sequence current in an isolated neutral power system.

Practice Problems 2

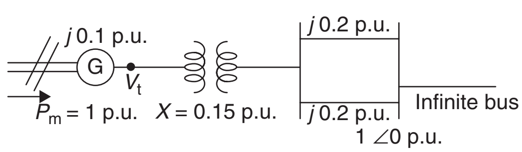
Directions for questions 1 to 15: Select the correct alternative from the given choices.

1. Swing equation relates
(A) Power with load angle
(B) Load angle and time
(C) Relative motion of rotor with respect to the stator field as a function of time
(D) Both (B) and (C)

2. A 4-pole 50 Hz, 40 MVA, 13.2 kV turbo alternator has an inertia constant of $H = 6$ kW sec/kVA. The kinetic energy stored in the rotor is
(A) 240 MJ (B) 380 kJ
(C) 220 MJ (D) 260 kJ

3. An alternator is connected to an infinite bus. It delivers 1.6 p.u. current at 0.9 p.f. lag and a voltage of 1.0 p.u. The reactance is 1.1 p.u. Keeping the active power fixed, the excitation is reduced. The critical excitation emf corresponding to operation at stability limit is
(A) 1.089 p.u. (B) 2.45 p.u.
(C) 1 p.u. (D) None of these

4. The maximum power that can be transferred from the generator connected to infinite bus is
[Given $V_c = 1.2$ p.u.]



(A) 1 p.u. (B) 5 p.u.
(C) 0.5 p.u. (D) 3 p.u.

5. For a 2-pole 50 Hz, 40 MVA turbo alternator, inertia constant is given by 4 MJ/MVA. The moment of inertia is
(A) 3.24 kg-m^2 (B) 0.5095 kg-m^2
(C) 286.5×10^3 kg-m^2 (D) 2×10^3 kg/m^3

6. The inertia constants of two groups of machines which do not swing together are M_1 and M_2. The equivalent inertial constant of the system is:
(A) $M_1 + M_2$ (B) $M_1 - M_2$ if $M_1 > M_2$
(C) $\dfrac{M_1 + M_2}{M_1 M_2}$ (D) $\dfrac{M_1 M_2}{M_1 + M_2}$

7. The inertia constant of a 500 MVA alternator is 1 p.u. The value corresponding to 1000 MVA is
(A) 2 p.u. (B) 1 p.u.
(C) 0.5 p.u. (D) 0.25 p.u.

8. Two groups of machines swinging together have their inertia constants M_1 and M_2. The inertia constant of the system is
(A) $M_1 + M_2$ (B) $\dfrac{M_1 + M_2}{M_1 M_2}$
(C) $M_1 - M_2$, $M_1 > M_2$ (D) $\dfrac{M_1 M_2}{M_1 + M_2}$

9. A high-voltage DC transmission system, reactive power is needed for rectifier at sending end and inverter at receiving end. During the operation of such a DC link,
(A) Inverter supplies leading reactive power and rectifier receives lagging reactive power.
(B) Inverter supplies lagging reactive power and rectifier receives leading reactive power.
(C) Inverter supplies lagging reactive power and the rectifier receives lagging reactive power.
(D) Inverter supplies leading reactive power and rectifier receives leading reactive power.

Data for Linked Questions

I. Question Nos.: 10 and 11

A 100 km, 3-phase, 50 Hz transmission line has the line constants $A = D = 0.853\angle 1.8°$, $B = 126.5\angle 50.4$, $C = 0.002\angle 90°$. The sending end voltage is 400 kV.

10. The receiving end voltage when the load is disconnected will be
(A) $2 + j60$ kV (B) $210\angle 90°$ kV
(C) $1.51\angle 0°$ kV (D) $270.7\angle -1.8°$ kV

11. The sending end current is
(A) $541.4\angle 88.2$ A (B) $541.4\angle 60$ A
(C) $17.006 + j541.13$ A (D) Both (A) and (C)

II. Question Nos.: 12 and 13

A 50 Hz, 4-pole turbo generator of rating 30 MVA, 13.2 kV has inertia constant of 8 kW sec/kVA.

12. Angular momentum of rotor in MJ-sec/electrical deg is

(A) $\frac{1}{150}$ (B) $\frac{4}{150}$ (C) $\frac{4}{6}$ (D) $\frac{40}{600}$

13. If the input rotational losses is 25,100 HP and the electric power developed is 10 MW, the acceleration developed will be

(A) 2.8 rad/s^2 (B) 5.72 rad/s^2
(C) 3.4 rad/s^2 (D) 4 rad/s^2

III. Question Nos.: 14 and 15

A 50 Hz, 4-pole 100 MVA, 11 kV turbo alternator has an inertia constant of 4.5 kW s/kVA. The input to the alternator is 134102 HP and the electrical power developed is 96 MW.

14. The angular momentum of the rotor is MJ-s/elect deg is

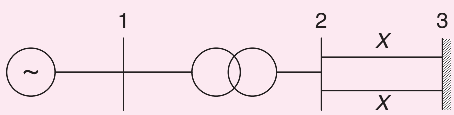
(A) $\frac{1}{50}$ (B) $\frac{1}{20}$ (C) $\frac{1}{32}$ (D) $\frac{1}{48}$

15. The acceleration of the rotor is

(A) 1.39 rad/s^2 (B) 0.39 rad/s^2
(C) 2.39 rad/s^2 (D) 3.39 rad/s^2

Previous Years' Questions

1. A generator with constant 1.0 p.u. terminal voltage supplies power through a step-up transformer of 0.12 p.u. reactance and a double-circuit line to an infinite bus bas as shown in Figure. The infinite bus voltage is maintained at 1.0 p.u. Neglecting the resistances and susceptances of the system, the steady-state stability power limit of the system is 6.25 p.u. If one of the double-circuit is tripped, the resulting steady-state stability power limit in p.u. will be **[2005]**



(A) 12.5 p.u. (B) 3.125 p.u.
(C) 10.0 p.u. (D) 5.0 p.u.

Common Data for Questions 2 and 3:

A generator feeds power to an infinite bus through a double circuit transmission line. A three-phase fault occurs at the middle point of one of the lines. The infinite bus voltage is 1 p.u., the transient internal voltage of the generator is 1.1 p.u. and the equivalent transfer admittance during fault is 0.8 p.u. The 100 MVA generator has an inertia constant of 5 MJ/MVA and it was delivering 1.0 p.u. power prior of the fault with rotor power angle of 30°. The system frequency is 50 Hz.

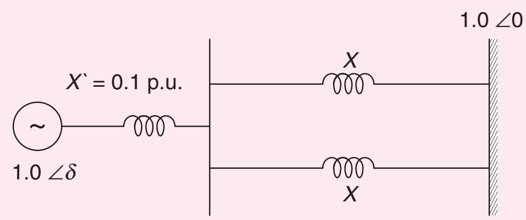
2. The initial accelerating power (in p.u.) will be **[2006]**

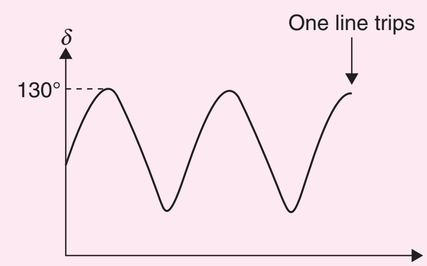
(A) 1.0 (B) 0.6 (C) 0.56 (D) 0.4

3. If the initial accelerating power is X p.u., the initial acceleration in elect deg/s^2, and the inertia constant in MJ-s/elect deg, respectively, will be **[2006]**

(A) 31.4X, 18 (B) 1800X, 0.056
(C) X/1800, 0.056 (D) X/31.4, 18

4. Consider a synchronous generator connected to an infinite bus by two identical parallel transmission lines. The transient reactance x of the generator is 0.1 p.u. and the mechanical power input to it is constant at 1.0 p.u. Due to some previous disturbance, the rotor angle (d) is undergoing an undamped oscillation, with the maximum value of $d(t)$ equal to 130°. One of the parallel lines trips due to relay mal-operation at an instant when $d(t)$ = 130° as shown in the figure. The maximum value of the per unit line reactance, x, such that the system does not lose synchronism subsequent to this tripping is **[2007]**





(A) 0.87 (B) 0.74 (C) 0.67 (D) 0.54

5. An isolated 50 Hz synchronous generator is rated at 15 MW which is also the maximum continuous power limit of its prime mover. It is equipped with a speed governor with 5% droop. Initially, the generator is feeding three loads of 4 MW each at 50 Hz. One of these loads is programmed to trip permanently if the frequency falls below 48 Hz. If an additional load of 3.5 MW is connected then the frequency will settle down to **[2007]**

(A) 49.417 Hz (B) 49.917 Hz
(C) 50.083 Hz (D) 50.583 Hz

6. A lossless single machine infinite bus power system is shown below

The synchronous generator transfers 1.0 per unit of power to the infinite bus. Critical clearing time of circuit breaker is 0.28 s. If another identical synchronous generator is connected in parallel to the existing generator and each generator is scheduled to supply 0.5 per unit of power. Then the critical clearing time of the circuit breaker will **[2008]**

(A) Reduce to 0.14 s
(B) Reduce but will be more than 0.14 s
(C) Remain constant at 0.28 s
(D) Increase beyond 0.28 s

7. A cylindrical rotor generator delivers 0.5 p.u. power in the steady state to an infinite bus through a transmission line of reactance 0.5 p.u. The generator no-load voltage is 1.5 p.u. and the infinite bus voltage is 1 p.u. The inertia constant of the generator is 5 MW-s/MVA and the generator reactance is 1 p.u. The critical clearing angle, in degrees, for a three-phase dead short-circuit fault at the generator terminal is **[2012]**

(A) 53.5 (B) 60.2 (C) 70.8 (D) 79.6

8. The angle δ in the swing equation of a synchronous generator is the **[2013]**

(A) Angle between stator voltage and current
(B) Angular displacement of the rotor with respect to the stator.
(C) Angular displacement of the stator mmf with respect to a synchronously rotating axis.
(D) Angular displacement of an axis fixed to the rotor with respect to a synchronously rotating axis.

9. A synchronous generator is connected to an infinite bus with excitation voltage $E_f = 1.3$ p.u. The generator has a synchronous reactance of 1.1 p.u. and is delivering real power (P) of 0.6 p.u. to the bus. Assume the infinite bus voltage to be 1.0 p.u. Neglect stator resistance. The reactive power (Q) in p.u. supplied by the generator to the bus under this condition is _______. **[2014]**

10. There are two generators in a power system. No-load frequencies of the generators are 51.5 Hz and 51 Hz, respectively, and both are having droop constant of 1 Hz/MW. Total load in the system is 2.5 MW. Assuming that the generators are operating under their respective droop characteristics, the frequency of the power system in Hz in the steady state is________. **[2014]**

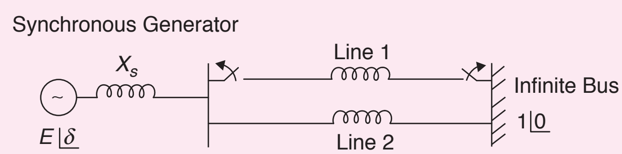
11. A non-salient pole synchronous generator having synchronous reactance of 0.8 p.u. is supplying 1 p.u. power to a unity power factor load at a terminal voltage of 1.1 p.u. Neglecting the armature resistance, the angle of the voltage behind the synchronous reactance with respect to the angle of the terminal voltage in degrees is ___________. **[2014]**

12. The figure shows the single line diagram of a single machine infinite bus system.

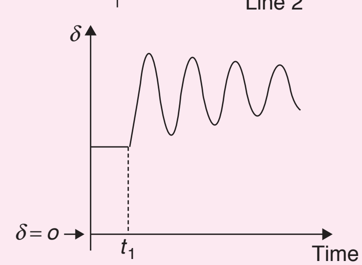
The inertia constant of the synchronous generator $H = 5$ MW-s/MVA. Frequency is 50 Hz. Mechanical power is 1 p.u. The system is operating at the stable equilibrium point with rotor angle δ equal to 30°. A three-phase short circuit fault occurs at a certain location on one of the circuits of the double-circuit transmission line. During fault, electrical power in p.u. is $P_{max} \sin\delta$. If the values of δ and $d\delta/dt$ at the instant of fault clearing are 45° and 3.762 radian/s, respectively, then P_{max} (in p.u.) is________. **[2014]**

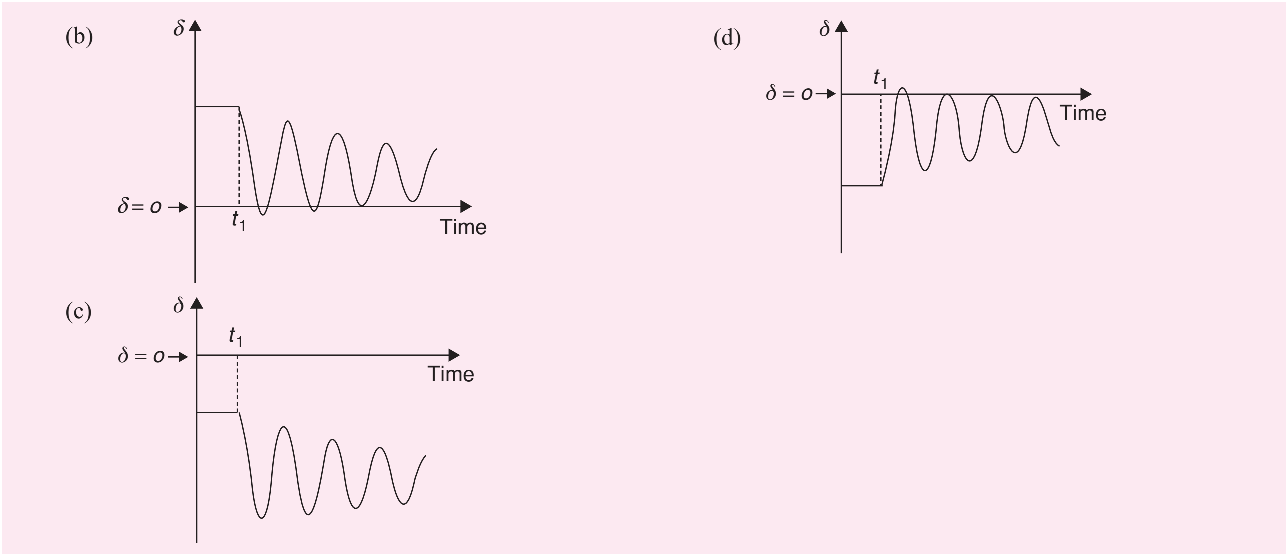
13. A 50 Hz generating unit has H-constant of 2 MJ/MVA. The machine is initially operating in steady state at synchronous speed, and producing 1 pu of real power. The initial value of the rotor angle δ is 5°, when a bolted three phase to ground short circuit fault occurs at the terminal of the generator. Assuming the input mechanical power to remain at 1 pu, the value of δ in degrees, 0.02 second after the fault is _____. **[2015]**

14. The synchronous generator shown in the figure is supplying active power to an infinite bus via two short, lossless transmission lines, and is initially is steady state. The mechanical power input to the generator and the voltage magnitude E are constant. If one line is tripped at time t_1 by opening the circuit breakers at the two ends (although there is no fault), then it is seen that the generator undergoes a stable transient. Which one of the following waveforms of the rotor angle δ shows the transient correctly? **[2015]**



(a)





Answer Keys

Exercises

Practice Problems 1

1. C	**2.** D	**3.** A	**4.** C	**5.** B	**6.** A	**7.** C	**8.** D	**9.** A	**10.** D
11. D	**12.** B	**13.** A	**14.** C	**15.** B	**16.** C	**17.** D	**18.** A	**19.** B	

Practice Problems 2

1. D	**2.** A	**3.** A	**4.** B	**5.** A	**6.** D	**7.** C	**8.** A	**9.** A	**10.** D
11. D	**12.** B	**13.** B	**14.** B	**15.** A					

Previous Years' Questions

1. D	**2.** C	**3.** B	**4.** C	**5.** A	**6.** D	**7.** D	**8.** D	**9.** **0.**109	**10.** 50
11. 33.61	**12.** 0.24	**13.** 5.90	**14.** D						