UNIT IV

TRANSIENT STATE STABILITY ANALYSIS

STABILITY

- The tendency of a power system to develop restoring forces equal to or greater than the disturbing forces to maintain the state of equilibrium.
- Ability to keep the machines in synchronism with another machine

Swing Equation

- The equation governing the motion of the rotor of a synchronous machine

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

where

J=The total moment of inertia of the rotor(kg-m^2)

θ_m =Singular displacement of the rotor

T_m=Mechanical torque (N-m)

T_e=Net electrical torque (N-m)

T_a=Net accelerating torque (N-m)

$$\theta_m = \omega_{sm} t + \delta_m$$

$$\frac{d\theta_m}{dt} = \omega_{sm} + \frac{d\delta_m}{dt}$$

$$\frac{d^2\theta_m}{dt^2} = \frac{d^2\delta_m}{dt^2}$$

$$J\omega_m \frac{d^2\delta_m}{dt^2} = p_a = p_m - p_e$$

- Where p_m is the shaft power input to the machine

  p_e is the electrical power

  p_a is the accelerating power

$$J\omega_m = M$$

$$M\,\frac{d^2\delta_m}{dt^2} = p_a = p_m - p_e$$

$$M = \frac{2H}{\omega_{sm}}\,S_{machine}$$

$$\frac{2H}{\omega_{sm}}\,\frac{d^2\delta_m}{dt^2} = \frac{p_a}{S_{machine}} = \frac{p_m - p_e}{S_{machine}}$$

$$\frac{2H}{\omega_s}\,\frac{d^2\delta}{dt^2} = p_a = p_m - p_e$$

H=machine inertia constant

$$\omega_s = 2\pi f$$

$$\frac{H}{\pi f_0}\,\frac{d^2\delta}{dt^2} = p_a = (p_m) - p_e$$

$$\frac{d^2\delta}{dt^2} = \frac{\pi f_0}{H}\left(p_m - p_{2\max}\sin\delta\right) = \frac{\pi f_0}{H}\,p_a$$ p.u

δ and ω_s are in electrical radian

$$\frac{d\delta}{dt} = \Delta\omega$$

$$\frac{d\Delta\omega}{dt} = \frac{\pi f_0}{H}\,p_a = \frac{d^2\delta}{dt^2}$$ p.u

Swing Equation for Multimachine System

$S_{machine}$ =machine rating(base)

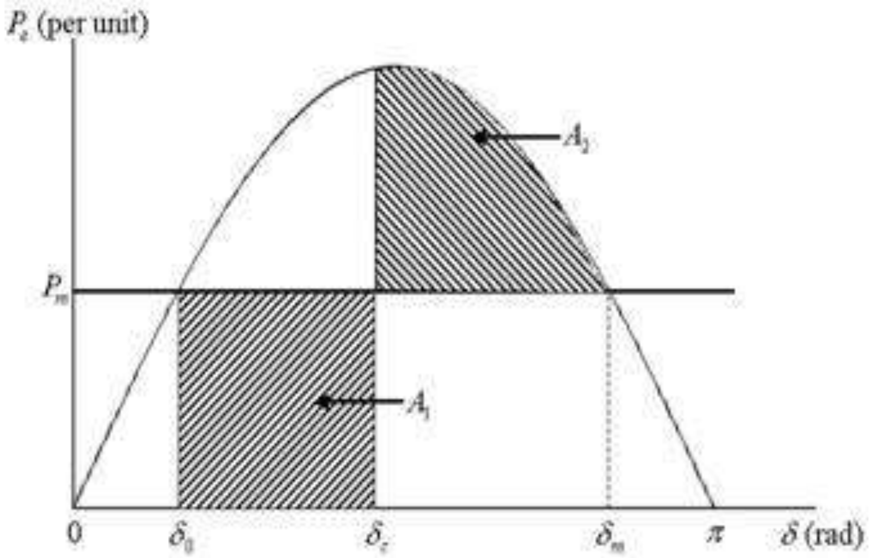
S_{system} =system base

$$\frac{H_{system}}{\pi f}\frac{d^2\delta}{dt^2} = p_a = p_m - p_e \quad \text{p.u}$$

$$H_{system} = H_{machine}\frac{S_{machine}}{S_{system}}$$

Equal Area Criterion

- This is a simple graphical method to predict the transient stability of two machine system or a single machine against infinite bus.
- This criterion does not require swing equation or solution of swing equation to determine the stability condition.
- The stability conditions are determined by equating the areas of segments on power angle diagram.



Power-angle curve for equal area criterion

multiplying swing equation by $d\delta/dt$ on both sides

$$\frac{H}{\omega_s}\frac{d}{dt}\left(\frac{d\delta}{dt}\right)^2 = (P_m - P_e)\frac{d\delta}{dt}$$

$$\frac{d}{dt}\left(\frac{d\delta}{dt}\right)^2 = 2\left(\frac{d\delta}{dt}\right)\left(\frac{d^2\delta}{dt^2}\right)$$

Multiplying both sides of the above equation by dt and then integrating between two arbitrary angles δ_0 and δ_c

$$\frac{H}{\omega_s}\left(\frac{d\delta}{dt}\right)^2\Bigg|_{\delta_0}^{\delta_c} = \int_{\delta_0}^{\delta_c}\left(P_m - P_e\right)d\delta$$

Once a fault occurs, the machine starts accelerating. Once the fault is cleared, the machine keeps on accelerating before it reaches its peak at δ_c ,

The area of accelerating A1

$$A_1 = \int_{\delta_0}^{\delta_c}\left(P_m - P_e\right)d\delta = 0$$

The area of deceleration is given by A_2

$$A_2 = \int_{\delta_c}^{\delta_m}\left(P_e - P_m\right)d\delta = 0$$

If the two areas are equal, i.e., $A_1 = A_{2,}$ then the power system will be stable

Critical Clearing Angle (δ_{cr}) maximum allowable value of the clearing time and angle for the system to remain stable are known as critical clearing time and angle.

δ_{cr} expression can be obtained by substituting $\delta_c = \delta_{cr}$ in the equation A1 = A2

$$\int_{\delta_0}^{\delta_{cr}} (P_m - P_e)\, d\delta = \int_{\delta_{cr}}^{\delta_{m}} (P_e - P_m)\, d\delta$$

Substituting $P_e = 0$ in swing equation

$$\frac{d^2\delta}{dt^2} = \frac{\omega_s}{2H} P_m$$

Integrating the above equation

$$\frac{d\delta}{dt} = \int_0^t \frac{\omega_s}{2H} P_m dt = \frac{\omega_s}{2H} P_m t$$

$$\delta = \int_0^t \frac{\omega_s}{2H} P_m t\, dt = \frac{\omega_s}{4H} P_m t^2 + \delta_0$$

Replacing δ by δ_{cr} and t by t_{cr} in the above equation, we get the critical clearing time as

$$t_{cr} = \sqrt{\frac{4H}{\omega_s P_m}\left(\delta_{cr} - \delta_0\right)}$$

Factors Affecting Transient Stability

- Strength of the transmission network within the system and of the tie lines to adjacent systems.
- The characteristics of generating units including inertia of rotating parts and electrical properties such as transient reactance and magnetic saturation characteristics of the stator and rotor.
- Speed with which the faulted lines or equipments can be disconnected.

Numerical Integration methods

- Modified Euler's method

- Runge-Kutta method

Numerical Solution of the swing equation

- Input power p_m=constant
- At steady state p_e=p_m,

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

$$p_{1\max} = \frac{|E'||V|}{X_1}$$

- At synchronous speed

$$\Delta\omega_0 = 0$$

$$p_{2\max} = \frac{|E'||V|}{X_2}$$

Runge-Kutta Method

- Obtain a load flow solution for pretransient conditions
- Calculate the generator internal voltages behind transient reactance.
- Assume the occurrence of a fault and calculate the reduced admittance matrix
- Initialize time count K=0,J=0
- Determine the eight constants

$$K_1^k = f_1(\delta^k, \omega^k)\Delta t$$

$$l_1^k = f_2(\delta^k, \omega^k)\Delta t$$

$$K_2^k = f_1(\delta^k + \frac{K_1^k}{2}, \omega^k + \frac{l_1^k}{2})\Delta t$$

$$l_2^k = f_2(\delta^k + \frac{K_1^k}{2}, \omega^k + \frac{l_1^k}{2})\Delta t$$

$$K_3^k = f_1(\delta^k + \frac{K_2^k}{2}, \omega^k + \frac{l_2^k}{2})\Delta t$$

$$l_3^k = f_2(\delta^k + \frac{K_2^k}{2}, \omega^k + \frac{l_2^k}{2})\Delta t$$

$$K_4^k = f_1(\delta^k + \frac{K_3^k}{2}, \omega^k + \frac{l_3^k}{2})\Delta t$$

$$l_4^k = f_2(\delta^k + \frac{K_3^k}{2}, \omega^k + \frac{l_3^k}{2})\Delta t$$

$$\Delta\delta^k = \frac{\left(K_1^k + 2K_2^k + 2K_3^k + K_4^k\right)}{6}$$

$$\Delta\omega^k = \frac{\left(l_1^k + 2l_2^k + 2l_3^k + l_4^k\right)}{6}$$

- Compute the change in state vector

$$\Delta\delta^k = \frac{\left(K_1^k + 2K_2^k + 2K_3^k + K_4^k\right)}{6}$$

$$\Delta\omega^k = \frac{\left(l_1^k + 2l_2^k + 2l_3^k + l_4^k\right)}{6}$$

- Evaluate the new state vector

$$\delta^{k+1} = \delta^k + \Delta\delta^k$$

$$\omega^{k+1} = \omega^k + \Delta\omega^k$$

- Evaluate the internal voltage behind transient reactance using the relation

$$E_p^{k+1} = \left|E_p^k\right| \cos\delta_p^{k+1} + j\left|E_p^k\right| \sin\delta_p^{k+1}$$

- Check if $t<t_c$ yes K=K+1
- Check if j=0,yes modify the network data and obtain the new reduced admittance matrix and set j=j+1
- set K=K+1
- Check if K<Kmax, yes start from finding 8 constants

Methods to improve Stability

- Use of Bundled Conductors
- Use of Double-Circuit Lines
- Operate Transmission Lines in Parallel
- Series Compensation of the Lines
- Series Compensation of the Lines
- High-Speed Excitation Systems
- Fast Switching
- Breaking Resistors
- Single-Pole Switching
- HVDC Links
- Load Shedding