Module 7 : Out of Step Protection

Lecture 24 : Power Swings and Distance Relaying

Objectives

In this lecture we will learn the following:

- Introduction to power swings.
- Distance relaying perspective of power swings.
- Characterization of power swings.
- Electrical center and unstable power swings.

In this lecture, we will introduce the concept of power swings. It will be shown that the post fault power swings may encroach the relay characteristics. This can lead to nuisance tripping of distance relays which can sacrifice the system security.

Analysis of Two Area System

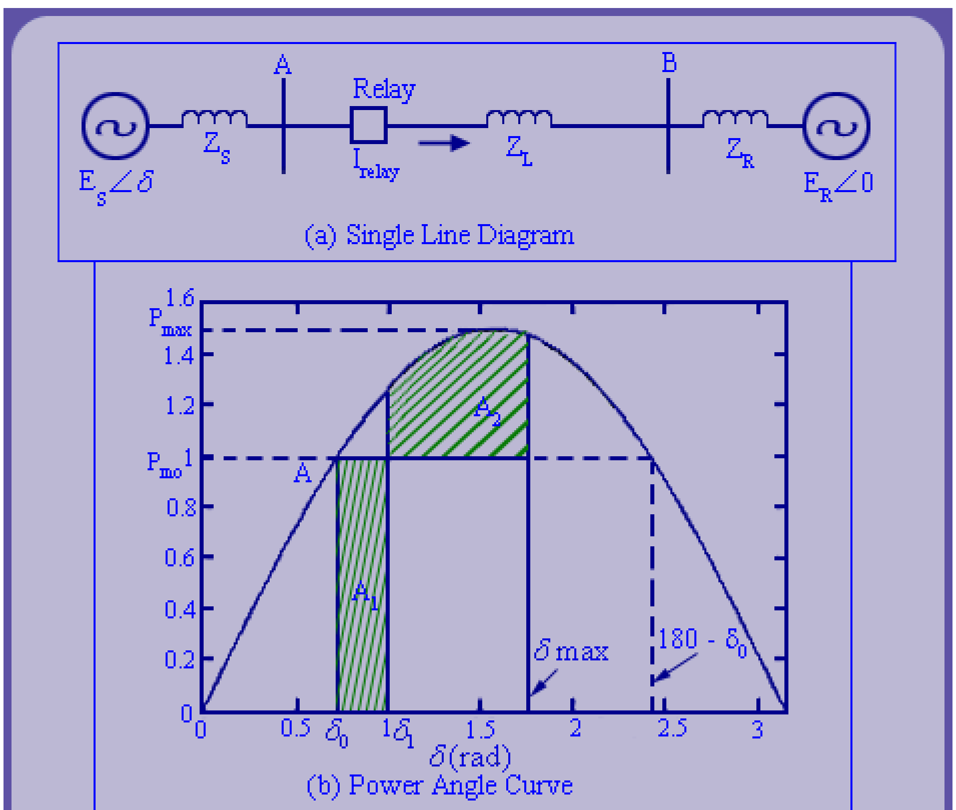

Fig 24.1 A Simple Two Machine System

Power swings refer to oscillation in active and reactive power flows on a transmission line consequent to a large disturbance like a fault. The oscillation in the apparent power and bus voltages is seen by the relay as an impedance swing on the R-X plane. If the impedance trajectory enters a relay zone and if stays there for sufficiently long time, then the relay will issue a trip decision on power swing. Tripping on power swings is not desirable. We now investigate this phenomenon and then discuss remedial measures.

Let us consider a simple two machines system connected by a transmission line of impedance Z_L as shown in fig 24.1(a). E_S and E_R are the generator voltages at two ends and we assume that the system is purely reactive.

The voltage E_S leads E_R by an angle δ so that power flows from A to B during steady state. The relay under consideration is located at bus A end. The power angle curve is shown in fig 24.1(b) . The system is operating at initial steady operating point A with P_{mo} as output power and δ_0 as initial rotor angle.

From the power angle curve, initial rotor angle, δ_0 is given by:

$$\delta_0 = \sin^{-1}\left(\frac{P_{m0}}{P_{max}}\right) \qquad (1)$$

Analysis of Two Area System (contd..)

Now, suppose, that a self clearing transient three phase short circuit fault occurs on the line. During the fault, the electrical output power P_e drops to zero. The resulting rotor acceleration advances rotor angle to δ_1. After a time interval t_{cr}, corresponding to angle δ_1, the fault is cleared and the operating point jumps back to the sinusoidal curve. As per equal area criteria, the rotor will swing up to maximum rotor angle δ_{max}, such that,

Accelerating Area (A_1) = Decelerating Area (A_2)

Rotor angle δ_1 corresponding to fault clearing time t_{cr} can be computed by swing equation,

$$\frac{2H}{\omega_s}\frac{d^2\delta}{dt^2} = P_{mo} - P_e = P_a \qquad (2)$$

where H is the equivalent rotor angle inertia.
During fault, P_e = 0, hence,

$$\frac{2H}{\omega_s}\frac{d^2\delta}{dt^2} = P_{mo} \qquad (3)$$

On integrating both the sides with respect to variable t,

$$\frac{d\delta}{dt} = \frac{\omega_s P_{mo}}{2H}(t - t_0) \qquad (4)$$

Recall that prior to fault, δ_0 is a stationary point. Hence, the initial condition of $\frac{d\delta}{dt}$ is specified as follows:

$$\left.\frac{d\delta}{dt}\right|_{t=t_0} = 0$$

Analysis of Two Area System (contd..)

Integrating equation (4) and substituting $\delta = \delta_1$ at time t = t_1, with $t_1 - t_2 = t_{cr}$,

$$\delta_1 = \frac{\omega_s P_{mo}}{4H}(t_{cr}^2) + \delta_0 \qquad (5)$$

Thus, accelerating area A_1 is given by,

$$A_1 = \int_{\delta 0}^{\delta 1} P_{mo} d\delta = P_{mo}(\delta_1 - \delta_0) \quad (6)$$

Substituting equation (5) in equation (6),

$$A_1 = \frac{\omega_s P_{m0}^2 (t_{cr}^2)}{4H} \quad (7)$$

Similarly, decelerating area, A_2, can be calculated as follows.

$$A_2 = \int_{\delta 1}^{\delta \max} P_{\max} \sin\delta . d\delta - P_{m0}(\delta_{\max} - \delta_1) = P_{\max}(\cos\delta_1 - \cos\delta_{\max}) - P_{mo}(\delta_{\max} - \delta_1) \quad (8)$$

Since for a stable swing, $A_1 = A_2$

$$P_{mo}(\delta_1 - \delta_0) = P_{\max}(\cos\delta_1 - \cos\delta_{\max}) - P_{mo}(\delta_{\max} - \delta_1) \quad (9)$$

i.e.

$$\cos\delta_{\max} = \cos\delta_1 - \frac{P_{m0}}{P_{\max}}(\delta_{\max} - \delta_0) \quad (10)$$

Since, δ_0 is a function of P_{mo} from equation (1) and δ_1 is function of P_{mo} as well as t_{cr} from equation (5), it follows from equation (10) that $\delta_{\max}$ depends on P_{mo} and t_{cr}.

i.e. $$\delta_{\max} = f(P_{m0}, t_{cr}) \quad (11)$$

Analysis of Two Area System (contd..)

The variation of $\delta_{\max}$ versus P_{mo} for different values of t_{cr} is shown in fig 24.2.

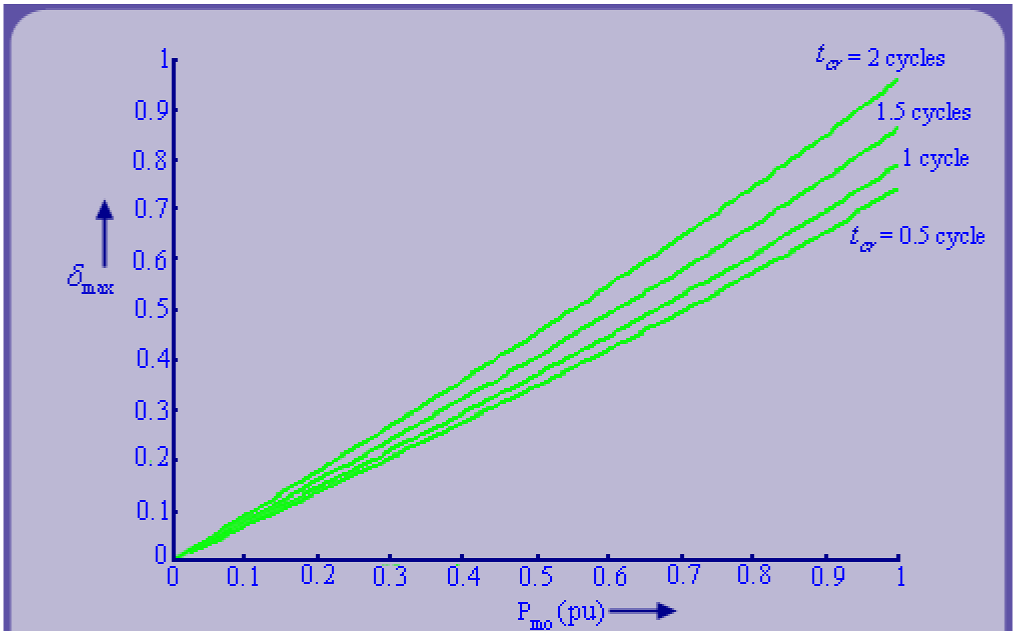

Fig 24.2 Plots of $\delta_{\max}$ versus P_{mo}, for different values of t_{cr}

Now that we have reviewed, the rotor angle dynamics, we proceed to discuss the relay's perception of the dynamical system.

Determination of power swing locus

A distance relay may classify power swing as a phase fault if the impedance trajectory enters operating characteristic of the relay. We will now derive the apparent impedance seen by the relay R on the R-X plane. Again consider simple two machine system connected by a transmission line of impedance Z_L as shown in fig 24.1(a). For the sake of convenience machine B is treated as a reference and it's angle is set to zero.

$$I_{relay} = \frac{E_S\angle\delta - E_R}{Z_T} \quad (12)$$

Where, $Z_T = Z_S + Z_L + Z_R$ (13)

Determination of power swing locus (contd..)

Now, the impedance seen by relay is given by the following equation,

$$Z_{seen}(relay) = \frac{V_{relay}}{I_{relay}} = \frac{E_S\angle\delta - I_{relay}Z_S}{I_{relay}}$$

$$= -Z_S + \left(\frac{E_S\angle\delta}{E_S\angle\delta - E_R}\right)Z_T \quad (14)$$

$$= -Z_S + Z_T\left(\frac{1}{1 - \frac{E_R}{E_S}\angle - \delta}\right)$$

Let us define $k = \left|\frac{E_S}{E_R}\right|$. Assuming for simplicity, both the voltages as equal to 1pu, i.e. k = 1. Then,

$$Z_{seen}(relay) = -Z_S + Z_T\left(\frac{1}{1-\cos\delta + j\sin\delta}\right) = -Z_S + \frac{Z_T}{2}\left(\frac{1}{\sin^2\frac{\delta}{2} + j\sin\frac{\delta}{2}\cos\frac{\delta}{2}}\right)$$

$$= -Z_S + \frac{Z_T}{2\sin\frac{\delta}{2}}\left(\sin\frac{\delta}{2} - j\cos\frac{\delta}{2}\right)$$

$$= -Z_S + \frac{Z_T}{2}\left(1 - j\cot\frac{\delta}{2}\right) \quad (15)$$

$$= \underbrace{-Z_S + \frac{Z_T}{2}}_{\text{a constant offset}} - \underbrace{j\frac{Z_T}{2}\cot\frac{\delta}{2}}_{\text{perpendicular line segment}}$$

Determination of power swing locus (contd..)

From equation (15) at $\delta = 180°$, $\cot\delta = 0$, $Z_{seen} = -Z_S + \frac{Z_T}{2}$

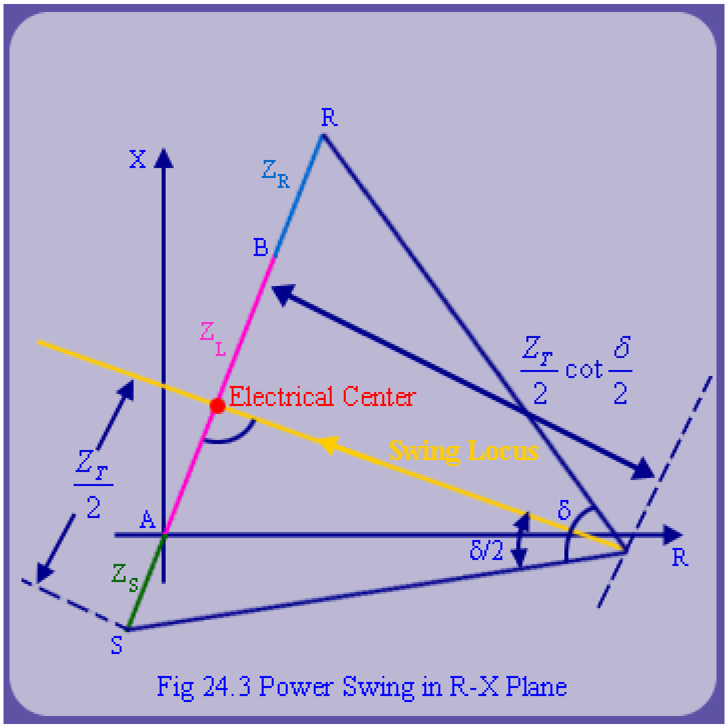

Fig 24.3 Power Swing in R-X Plane

There is a geometrical interpretation of above equation. The vector component $-Z_S+\frac{Z_T}{2}$ in equation (15) is a constant in R – X plane. The component $-j\frac{Z_T}{2}\cot\frac{\delta}{2}$ lies on a straight line, perpendicular to line segment $\frac{Z_T}{2}$. Thus, the trajectory of the impedance measured by relay during the power swing is a straight line as shown in fig 24.3. The angle subtended by a point in the locus on S and R end points is angle δ. For simplicity, angle of $\vec{Z_S}$, $\vec{Z_R}$ and $\vec{Z_L}$ are considered identical. The swing intersects the line AB, when $\delta=180°$.

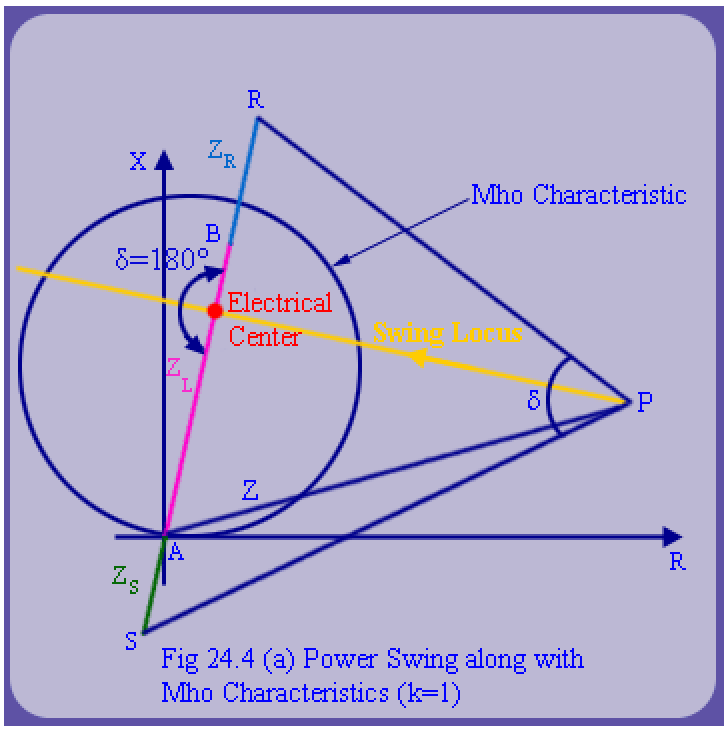

Fig 24.4 (a) Power Swing along with Mho Characteristics (k=1)

The corresponding point of intersection of swing impedance trajectory on the impedance line is known as electrical center of the swing. (fig 24.4(a)). The angle, δ between two sources can be mapped graphically as the angle subtended by source points E_S and E_R on the swing trajectory. At the electrical center, angle between two sources is $180°$. The existence of the electrical center is an indication of system instability, the two generators now being out of step.

If the power swing is stable, i.e. if the post fault system is stable, then δ_{max} will be less than $180°-\delta_0$. In such an event, the power swing retraces its path at δ_{max}.

Determination of power swing locus (contd..)

If $\frac{E_S}{E_R}=k\neq 1$, then the power swing locus on the R – X is an arc of the circle. (See fig 24.4(b)).

It can be easily shown that

$$\frac{E_S}{E_S-E_R}=\frac{k(\cos\delta+j\sin\delta)}{k(\cos\delta+j\sin\delta)-1}=\frac{k[(k-\cos\delta)-j\sin\delta]}{(k-\cos\delta)^2+\sin^2\delta} \quad (16)$$

Then,

$$Z_{seen}=-Z_S+\frac{k[(k-\cos\delta)-j\sin\delta]}{(k-\cos\delta)^2+\sin^2\delta}Z_T$$

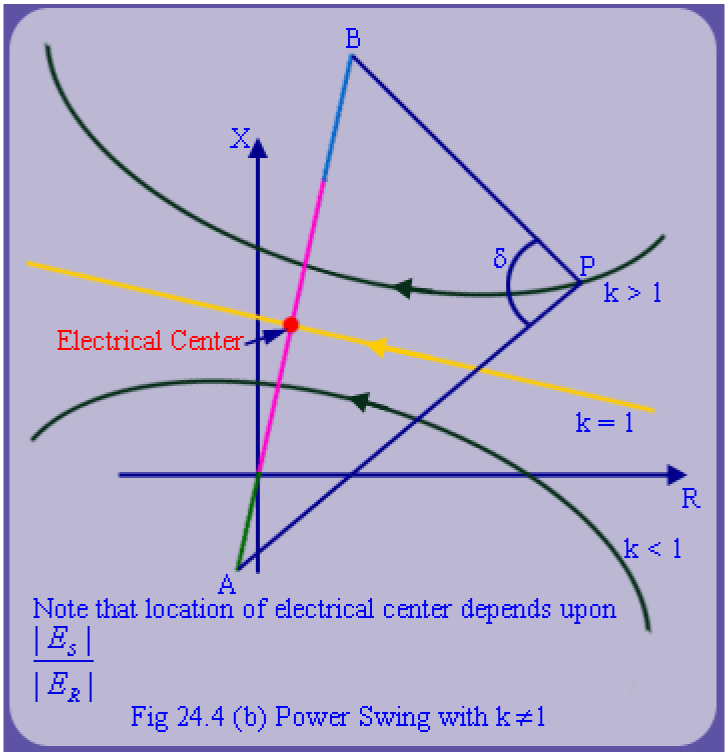

Fig 24.4 (b) Power Swing with k ≠ 1

It is also clear from fig 24.4 (b), that the location of the electrical center is dependent upon the $\frac{|E_S|}{|E_R|}$ ratio. Appearance of electrical center on a transmission line is a transient phenomenon. This is because, during unstable transient, δ is not stationary. As the rotor angles separate in time electrical center arises during out-of-step condition. When $\delta = 180°$, the rotors are said to have slipped a pole. However, once past $\delta = 180°$, the corresponding phasors start coming closer to each other. Thus, electrical center vanishes after sometime. When δ = 0, another transient point, the rotor is said to have slipped by 2 - poles.

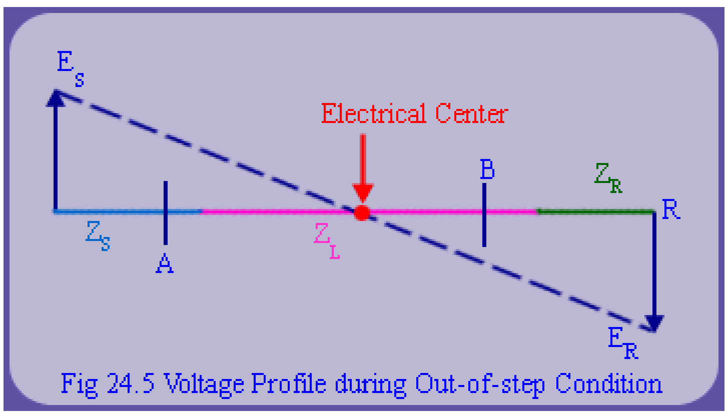

Fig 24.5 Voltage Profile during Out-of-step Condition

The voltage profile across the transmission system at the point of occurrence of electrical center is shown in fig 24.5.
At the electrical center, the voltage is exactly zero. This means that relays at both ends of the line perceive it as a bolted three phase fault and immediately trip the line. Thus, we can conclude that existence of electrical center implies (1) system instability (2) likelihood of nuisance tripping of distance relay.

Determination of power swing locus (contd..)

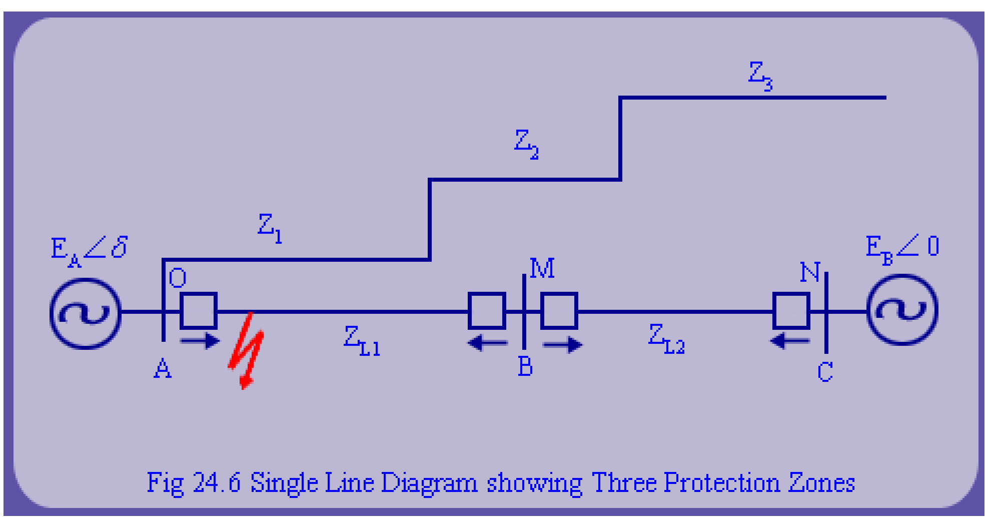

Fig 24.6 Single Line Diagram showing Three Protection Zones

Now consider a double-end-fed transmission line with three stepped distance protection scheme having Z_1 , Z_2 and Z_3 protection zones as shown in fig 24.6. The mho relays are used and characteristics are plotted on R-X plane as shown in fig 24.7. Swing impedance trajectory is also overlapped on relay characteristics for a simple case of equal end voltages (i.e. k = 1) and it is perpendicular to line AB.

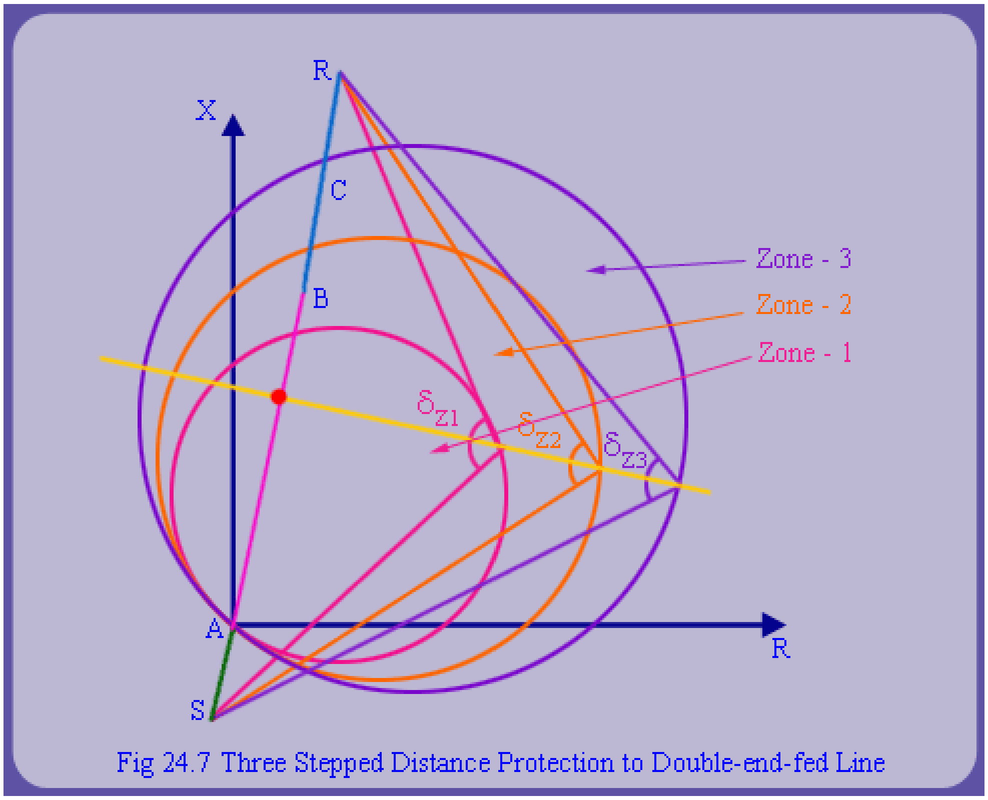

Fig 24.7 Three Stepped Distance Protection to Double-end-fed Line

From fig 24.6, δ_{Z1}, δ_{Z2} and δ_{Z3} are rotor angles when swing just enters the zone Z_1 , Z_2 and Z_3 respectively and it can be obtained from the intersection of swing trajectory with the relay characteristics. Recall that δ_{max} is the maximum rotor angle for stable power swing. Following inferences can be drawn.

If $\delta_{max} < \delta_{Z3}$, then swing will not enter the relay characteristics.

If $\delta_{Z3} \le \delta_{max} \le \delta_{Z2}$, swing will enter in zone Z_3. If it stays in zone - Z_3 for larger interval than its TDS, then the relay will trip the line.

If $\delta_{Z2} \le \delta_{max} \le \delta_{Z1}$, swing will enter in both the zones Z_2 and Z_3. If it stays in zone 2, for a larger interval than its TDS, then the relay will trip on Z_2. Typically, TDS of Z_2 is less than TDS of Z_3.

If $\delta_{max} \ge \delta_{Z1}$, swing will enter in the zones Z_1, Z_2 and Z_3 and operate zone 1 protection without any intentional delay.

So far, we have discussed power swings for a 2-machine system. Evaluation of power swings on a multimachine system requires usage of transient stability program. By using transient stability program, during post fault the relay end node voltage and line currents can be monitored and then the swing trajectory can be traced on a impedance plane.

TOP

Review Questions

1. Define a power swing and elaborate its consequences on distance relaying performance.
2. Derive the expressions for apparent impedance seen by a relay in a two area system as function of angle of separation

   δ . Show that the locus is a straight line if $|E_A|$ = $|E_B|$ and a circle if $|E_A| \neq |E_B|$.

3. What are assumptions made on the system behaviour in above derivation?

Recap

In this lecture we have learnt the following:

- Characterized the swing locus seen by distance relay.
- Defined electrical center.
- Highlighted the possibility of distance relay tripping on power swing.