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CMR Institute of Technology, Bangalore
DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING
III - INTERNAL ASSESSMENT

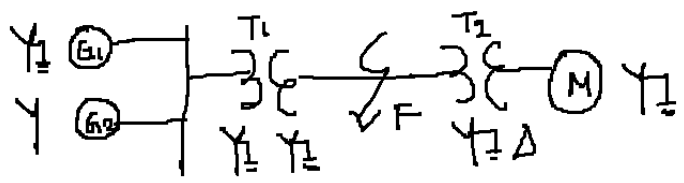
Semester: 6-CBCS 2018
Subject: POWER SYSTEM ANALYSIS – 1 (18EE62)
Faculty: Ms Keka Mukhopadhyaya

Date: 29 Jul 2021
Time: 09:00 AM - 10:30 AM
Max Marks: 50

Instructions to Students :

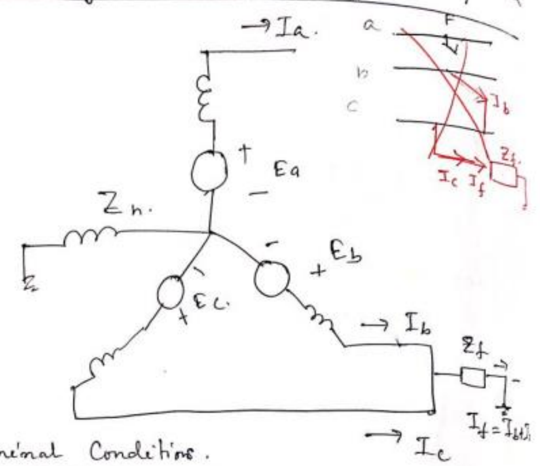
Answer any Five Full questions.

Answer any 5 question(s)

Q.No			Marks	CO	PO	BT/CL
1	a	A double line to ground fault occurs at the terminals of an unloaded generator. Derive an expression for the fault currents. Also draw connections of sequence net work	5	CO4	PO1,PO2,PO3,PO4,PO5,PO8,PO9,PO10,PO12	L1
	b	A three phase generator with line to line voltages of 400V is subjected to an LLG fault. If Z1=j2Ω, Z2= j0.5Ω, Z0=j0.25Ω , determine the fault current and terminal voltages.	5	CO4	PO1,PO2,PO3,PO4,PO5,PO8,PO9,PO10,PO12	L3
2	a	Discuss briefly open-conductors fault in power system.	5	CO4	PO1,PO2,PO3,PO4,PO5,PO8,PO9,PO10,PO12	L1
	b	A single line to ground fault occurs at the terminals of an unloaded generator. Derive an expression for the fault currents. Also draw connections of sequence net work.	5	CO4	PO1,PO2,PO3,PO4,PO5,PO8,PO9,PO10,PO12	L2
3		A synchronous motor is receiving 60 MW at 0.8 pf lagging at 6kV. A line to ground fault occurs at the midpoint "F" of the transmission line through a fault impedance of 0.05Ω as shown in figure. Determine the fault current; choose base values of 100 MVA and 11kV on generator circuit. G1 and G2: 100 MVA, 11kV, X1=0.2 pu, X2=0.1 pu, X0=0.1 pu M: 160 MVA, 6.3kV, X1=X2=0.3 pu, X0=0.1 pu T1=180 MVA, 11.5Y/115Y, X=0.1 pu T2:170 MVA,110Y/6.6Δ, X=0.1 pu, transmission line :X1=X2=30Ω, X0=60Ω 	10	CO4	PO1,PO2,PO3,PO4,PO5,PO8,PO9,PO10,PO12	L4
4		Define the following: Steady State Stability, Transient Stability Limit, Steady state stability Limit ,Transient Stability	10	CO5	PO1,PO2,PO3,PO4,PO5,PO8,PO9,PO10,PO12	L1
5		Derive Power angle equation for salient pole machine with usual notations along with phasor diagram.	10	CO5	PO1,PO2,PO3,PO4,PO5,PO8,PO9,PO10,PO12	L2
6		Explain equal area criteria concept when one of the parallel transmission line to transfer power to infinite bus bar is switched off. Draw necessary reactance diagram along with power angle curve.	10	CO5	PO1,PO2,PO3,PO4,PO5,PO8,PO9,PO10,PO12	L2
7	a	A loss free alternator supplies 50MW to an infinite bus, the SSSL being 100MW. Determine if the alternator will remain stable if the input to the prime mover of the alternator is abruptly increased by 40 MW.	5	CO5	PO1,PO2,PO3,PO4,PO5,PO8,PO9,PO10,PO12	L3
	b	Two power stations X and Y are located close together. Station X has three identical generators each rated 200MVA, 10MJ/MVA whereas station Y has five sets each rated 150MVA, 5MJ/MVA. Calculate the inertia constant of the equivalent machines of both stations on 100 MVA base.	5	CO5	PO1,PO2,PO3,PO4,PO5,PO8,PO9,PO10,PO12	L3

1 a

Double line to ground fault (LLG) on an unloaded generator through a fault impedance



Terminal Conditions.

$I_a = 0$

$V_b = (I_b + I_c) Z_f$

$V_c = (I_b + I_c) Z_f$

Symmetrical component relations

$V_{a1} = \frac{1}{3}(V_a + \alpha V_b + \alpha^2 V_c)$.

$= \frac{1}{3}\left[V_a + (\alpha + \alpha^2) V_b\right] = \frac{1}{3}\left[V_a - V_b\right]$

$V_{a2} = \frac{1}{3}\left[V_a + \alpha^2 V_b + \alpha V_c\right]$.

$= \frac{1}{3}\left[V_a + (\alpha^2 + \alpha) V_b\right] = \frac{1}{3}(V_a - V_b)$

$V_{a0} = \frac{1}{3}(V_a + V_b + V_c) = \frac{1}{3}(V_a + 2V_b)$

$V_{a1} = V_{a2}$

$V_{a0} - V_{a2} = \frac{1}{3}(3V_b) = V_b$.

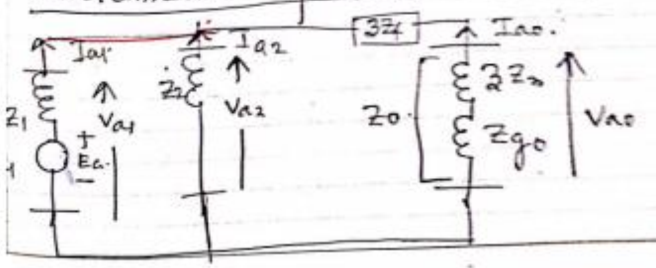
$= (I_b + I_c) Z_f = 3 I_{a0} Z_f$

$= I_{a0} \times 3 Z_f$

$V_{a0} = V_{a2} + 3 I_{a0} Z_f$.

$I_a = 0$, $I_{a0} + I_{a1} + I_{a2} = 0$

Interconnection of sequence networks.



Sequence Quantities

$$I_{a1} = \frac{E_a}{Z_1 + \frac{Z_2 (3Z_f + Z_0)}{Z_2 + 3Z_f + Z_0}}$$

$$I_{a2} = -\frac{I_{a1} (Z_0 + 3Z_f)}{(Z_0 + Z_2 + 3Z_f)}$$

$$I_{a0} = -\frac{I_{a1} Z_2}{(Z_0 + Z_2 + 3Z_f)}$$

→ current division formula

Fault Current

$$I_f = I_b + I_c$$

$$= (I_{a0} + \alpha^2 I_{a1} + \alpha I_{a2}) + (I_{a0} + \alpha I_{a1} + \alpha^2 I_{a2})$$

$$= 2I_{a0} + (\alpha^2 + \alpha) I_{a1} + (\alpha + \alpha^2) I_{a2}$$

$$= 2I_{a0} - I_{a1} - I_{a2}$$

$$= 2I_{a0} - (I_{a1} + I_{a2})$$

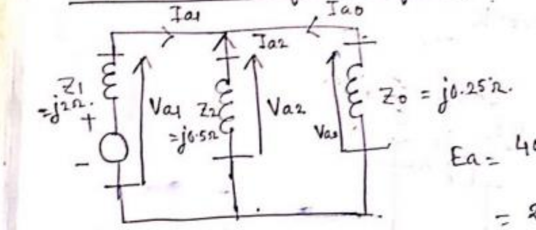
$$= 2I_{a0} - (-I_{a0}) = 3I_{a0}$$

$$I_f = -3 I_{a1} \left(\frac{Z_2}{Z_0 + Z_2 + 3Z_f} \right)$$

$Z_n = \infty$, $Z_0 \Rightarrow \infty$. $I_f = 0$

1b

Sequence Network for LLG fault



$E_a = 400/\sqrt{3} \angle 0^\circ$

$= 230.94 \angle 0^\circ$

$$I_{a1} = \frac{230.94 \angle 0^\circ}{j\left[2 + \frac{0.5 \times 0.25}{0.75}\right]} = -j106.58\,A.$$

$$I_{a2} = -I_{a1}\left(\frac{Z_0}{Z_0+Z_2}\right) = -(-j106.58)\left(\frac{j0.25}{j0.25+j0.5}\right)$$

$= +j35.53\,A.$

$$I_{a0} = -I_{a1}\left(\frac{Z_2}{Z_0+Z_2}\right) = -(-j106.58)\left(\frac{j0.5}{j0.25+j0.5}\right)$$

$= +j71.05\,A.$

$I_f = 3|I_{a0}| = 3(71.05) = 213.15\,A.$

To find terminal voltages

$V_{a1} = V_{a2} = V_{a0} = E_a - I_{a1} Z_1$

$= 230.94 \angle 0^\circ - (-j106.58)(j2).$

$= 17.76\,V.$

$V_{A1} = j\sqrt{3}\, V_{a1} = 30.76 \angle 90^\circ\,V,$

$V_{A2} = -j\sqrt{3}\, V_{a2} = 30.76 \angle -90^\circ\,V$

$V_{A0} = 0$ (line component of zero seq. voltage is always zero).

terminal voltages.

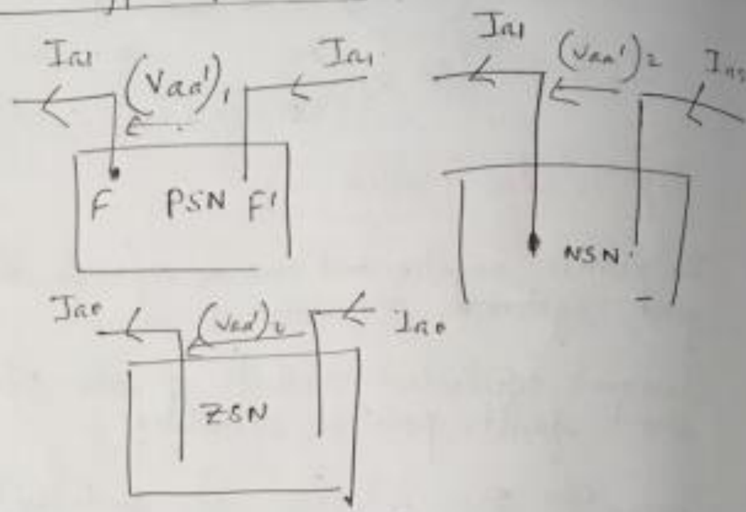
$V_A = V_{A0} + V_{A1} + V_{A2} = 0\,V.$

$V_B = V_{A0} + \alpha^2 V_{A1} + \alpha V_{A2} = 53.26\,V.$

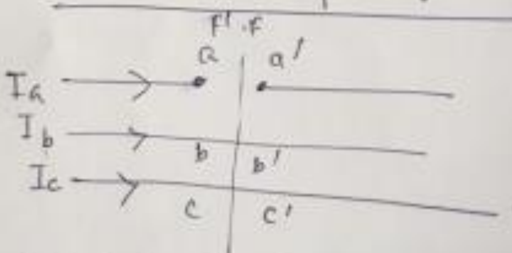
$V_C = V_{A0} + \alpha V_{A1} + \alpha^2 V_{A2} = -53.26\,V.$

2a

Series types of Faults



One Conductor open fault



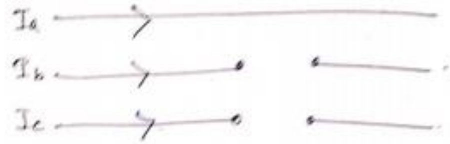
Terminal Condition

$$I_a = 0$$

$$V_{bb'} = 0$$

$$V_{cc'} = 0.$$

Two Conductors open fault



Terminal Condition . $I_b = 0$

$I_c = 0$

$V_{aa'} = 0$.

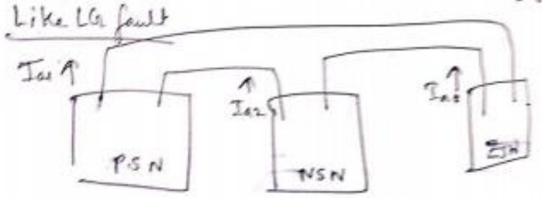
Symmetrical Component Relation

$$I_{a0} = \frac{1}{3}\left(I_a + I_b + I_c\right) = \frac{1}{3} I_a$$

Illy $I_{a1} = \frac{1}{3} I_a$, $I_{a2} = \frac{1}{3} I_a$

as $V_{aa'} = 0$ $\therefore (V_{aa'})_0 + (V_{aa'})_1 + (= 0$

Like LG fault



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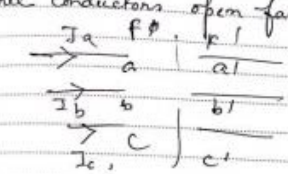
Three conductors open fault



Terminal Condition. $I_a + I_b + I_c = 0$

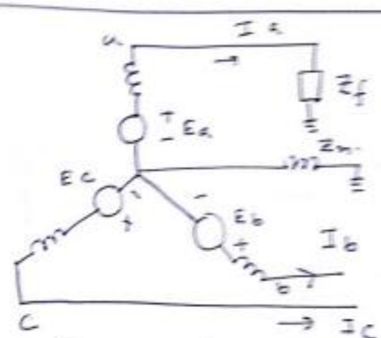
$I_{a0} = I_{a1} \pm I_{a2} = 0$.

$\Rightarrow$ Open circuit

2b

Faults through Impedance

* single line to ground (LG) fault on an unloaded generator through a fault impedance



Circuit Diagram for an LG fault of an unloaded generator through a fault impedance Z_f.

Terminal Condition

$V_a = I_a Z_f$

$I_b = 0$

$I_c = 0$.

Symmetrical Component relations

$I_{a0} = \frac{1}{3}(I_a + I_b + I_c) = \frac{1}{3} I_a$

$I_{a1} = \frac{1}{3}(I_a + \alpha I_b + \alpha^2 I_c) = \frac{1}{3}(I_a + 0 + 0) = \frac{1}{3} I_f$

$I_{a2} = \frac{1}{3}(I_a + \alpha^2 I_b + \alpha I_c) = \frac{1}{3} I_a$

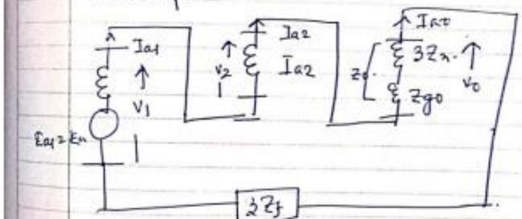
$\therefore I_{a1} = I_{a2} = I_{a0} = \frac{1}{3} I_a$

$V_a = I_a Z_f$

$V_{a0} + V_{a1} + V_{a2} = I_a Z_f = 3 I_{a0} Z_f$

$= I_{a0} \times 3Z_f$

As all sequence currents are equal and the sum of sequence voltages equal $3 I_{a0} Z_f$



Interconnection of Sequence Network.

Sequence Quantities.

$I_{a0} = I_{a1} = I_{a2} = \frac{E_a}{Z_1 + Z_2 + Z_0 + 3Z_f}$

$V_{a1} = E_a - I_{a1} Z_1 = E_a \left(\frac{Z_2 + Z_0 + 3Z_f}{Z_1 + Z_2 + Z_0 + 3Z_f}\right)$

$V_{a2} = -I_{a2} Z_2 = \frac{-E_a Z_2}{(Z_1 + Z_2 + Z_0 + 3Z_f)}$

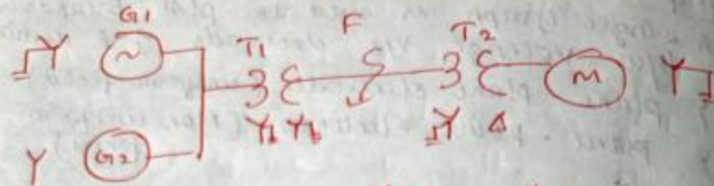
$V_{a0} = -I_{a0} Z_0 = \frac{-E_a Z_0}{Z_1 + Z_2 + Z_0 + 3Z_f}$

Fault Current

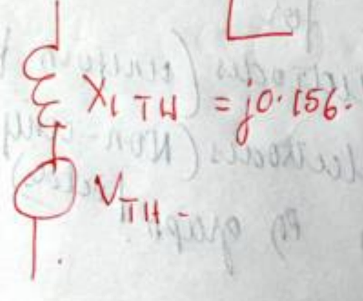
$I_f = I_a = 3 I_{a0} = 3 \times \left(\frac{E_a}{Z_1 + Z_2 + Z_0 + 3Z_f}\right)$

If neutral is ungrounded $Z_0 = \infty$, $I_f = 0$.

3.

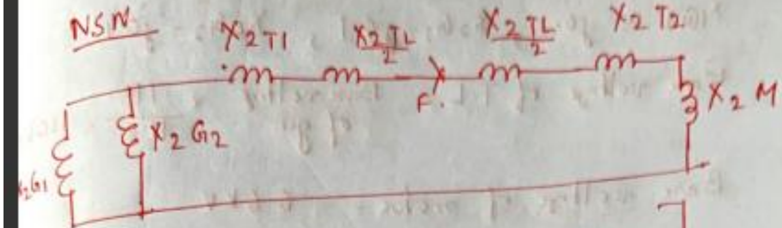


$$X_{1TH} = \left[\left(X_1G_1 \parallel X_1G_2 \right) + X_1T_1 + \frac{X_1TL}{2} \right] \parallel \left[\frac{X_1TL}{2} + X_1M + X_1T_2 \right].$$



$$V_{TH} = V_{tM} + I_{pu}\left(X_1 M + \frac{X_{1TL}}{2}\right)$$

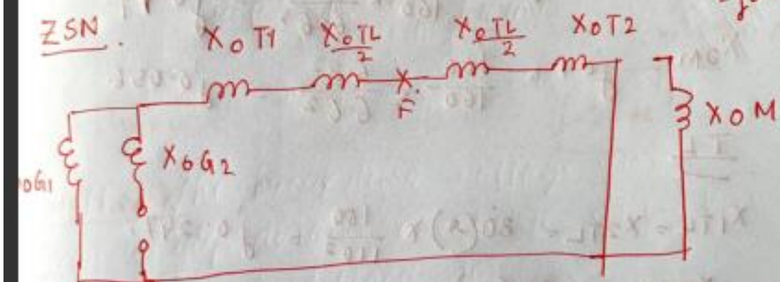
NSN.



$$X_{2TH} = \left[\left(X_1G_1 \parallel X_1G_2\right) + X_2T_1 + \frac{X_2TL}{2}\right] + \left[\frac{X_2TL}{2} + X_2T_2 + X_2M\right].$$

NSN $X_{2TH} = j0.14$

ZSN.



$$X_{0TH} = \left(X_0G_1 + X_0T_1 + \frac{X_0TL}{2}\right) \parallel \left(\frac{X_0TL}{2} + X_0T_2\right)$$

$X_{0TH} = j0.173.$

Base voltage G_1 and G_2 = 11 kV.

$X_1G_1 = j0.2, \quad X_2G_1 = j0.1, \quad X_0G_1 = j0.1$

$X_1G_2 = j0.2, \quad X_2G_2 = j0.1, \quad X_0G_2 = j0.1$

Base voltage of T.L = Base voltage of gen $\times \frac{115}{11.5} = 110\,kV$

Base voltage of motor = 6.6 kV

$X_1T_1 = X_2T_1 = X_0T_1 = j0.1 \times \frac{100}{180} \times \frac{11.5^2}{11^2} = j0.06$

$X_1T_2 = X_2T_2 = X_0T_2 = j0.1 \times \frac{100}{170} \times \frac{110^2}{110^2} = j0.058$

$X_1M = X_2M = j0.3 \times \frac{100}{160} \times \frac{6.3^2}{6.6^2} = j0.17$

$X_0M = j0.1 \times \frac{100}{160} \times \frac{6.3^2}{6.6^2} = j0.056$

T.L

$X_1TL = X_2TL = 80(\Omega) \times \frac{100}{110^2} = j0.247$

$X_0TL = 60(\Omega) \times \frac{100}{110^2} = j0.495$

$$V_{tf} = V_{tm} + I\left(\frac{X_{1TL}}{2} + X_{1T2}\right)$$

$$= j0.909\angle 0^\circ + 0.825\angle -36.86^\circ\,(j0.123 + j0.058)$$

$$= 1.0\angle 6.55^\circ$$

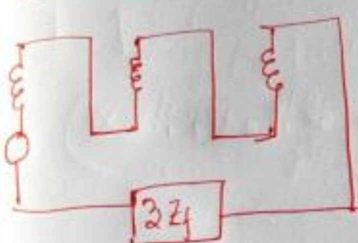
$$V_{tm} = \frac{6}{6.6}\angle 0^\circ = 0.909\angle 0^\circ$$

$$I_B = \frac{100\times10^6}{\sqrt{3}\times 6.6\times10^3}\,A = 8747.7\,A$$

$$I_m = \frac{60\times10^6 \angle -\cos^{-1}0.8}{\sqrt{3}\times 6\times10^3\times 0.8}\,A = 7216.8\angle -36.86^\circ\,A$$

$$I_{mpu} = \frac{I_m}{I_B} = 0.825\angle -36.86^\circ$$

LG Fault



$$Z_f = j0.05\,pu$$

$$I_{a0} = \frac{V_{TH}}{X_{1TH} + X_{2TH} + X_{0TH} + 3Z_f}$$

$$= \frac{1.0 \angle 6.55^\circ}{j0.156 + j0.14 + j0.17 + j0.15}$$

$$= 16.23 \angle -83.4^\circ \text{ p.u.}$$

$$I_f = 3I_{a0} = 48.7 \angle -83.4^\circ \text{ pu}$$

4.

(a) Small Signal Rotor angle Stability / Steady state stability.

It is the ability of the power system to maintain synchronism under small disturbances.

- Stability depends only on initial operating state of the system and not on the disturbance.

Such disturbances occur on the system because of small variations in load and generation.
instability may result in

a) A non oscillatory / periodic increase of rotor angle

b) Increasing amplitude of rotor oscillation due to insufficient damping

10 to 20 sec after disturbance

(b) Large Signal Rotor angle stability or Transient stability This refers to the ability of the power system to maintain synchronism under sudden large disturbances due to sudden load change, heavy switching operation, loss or generation or faults in system

3 to 5 secs following the disturbance.

Depends on initial operating point, disturbance parameters like location, type, magnitude etc.

Stability Limits:

Steady state stability Limit (SSSL), refers to the maximum flow of power possible through a particular point in the system without the loss of stability when a small & gradual disturbance occurs in the system.

Transient stability Limit (TSL) refers to to the maximum flow of power possible through a particular point in the system without the loss of stability when a large and sudden disturbance occurs in the system. TSL is lower than SSSL.

5.

Power Angle Equation of a Salient Pole Synchronous Machine

~~Machine~~ Phasor diagram neglecting m/c. armature resistance

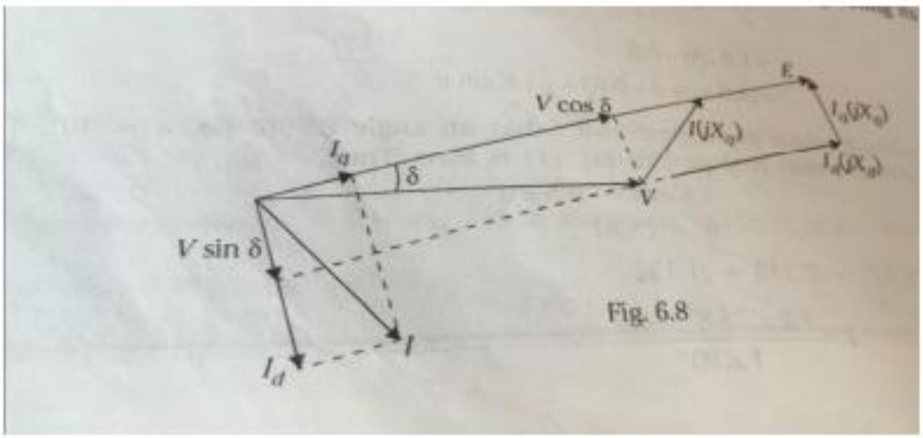


Fig. 6.8

$E\angle\delta$ ⇒ Generated emf in the syn m/c.

$V\angle 0^\circ$ = Bus bar voltage (taken as ref).

X_d = direct axis syn reactance

X_q = quadrature axis syn reactance

I = current delivered at lagging pf ϕ.

$$P = |V| \cos\delta \, |I_q| + |V| \sin\delta \, |I_d|.$$

$$|I_q X_q| = |V \sin\delta|.$$

$$|I_q| = \frac{|V| \sin\delta}{X_q}$$

$$|I_d X_d| = |E - V\cos\delta|.$$

$$|I_d| = \frac{|E| - |V|\cos\delta}{X_d}$$

$$P = |V| \cos\delta \frac{(|V| \sin\delta)}{X_q} + |V| \sin\delta + \frac{(|E| - |V|\cos\delta)}{X_d}.$$

$$= \frac{|V|^2 \sin 2\delta}{2X_q} + \frac{|V||E| \sin\delta}{X_d} - \frac{V^2 \sin 2\delta}{2X_d}$$

$$= |V|^2 \frac{\sin 2\delta}{2} \left(\frac{1}{X_q} - \frac{1}{X_d}\right) + |V||E| \frac{\sin\delta}{X_d}$$

$$P = \frac{|V||E| \sin\delta}{X_d} + \frac{|V|^2 \sin 2\delta}{2} \left(\frac{X_d - X_q}{X_d \cdot X_q}\right)$$

Reluctance Power.

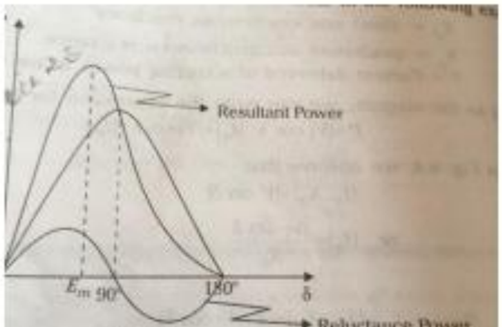


Fig. 6.9

6.

Equal Area Criterion (EAC).

Transient stability is the ability of the system to remain stable under large disturbances like short circuits, line outage, generation or load loss.

⇒ evaluation of T.S required for planning, designing power system.

⇒ Analysis deals with actual solution of non-linear differential equations describing the dynamics of m/cs and their controls.

⇒ stability for a given fault can be established by solving the swing equation.

⇒ But laborious.

⇒ Simple systems like Single M/C connected to an Infinite Bus bar (SMIB) transient stability analysis can be carried out by <u>Equal Area Criterion</u> (EAC).

⇒ It provides qualitative analysis of stability of syn m/c. without

...ing swing equation

Consider swing equation of a single machine connected to an infinite bus

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

Multiplying both sides of the equation by

$\frac{2}{M}\frac{d\delta}{dt}$, we get

$$2\frac{d\delta}{dt} \times \frac{d^2\delta}{dt^2} = \frac{2}{M}P_a\frac{d\delta}{dt}$$

$$\frac{d}{dt}(x^2) = 2x\frac{dx}{dt}.$$

or $$\frac{d}{dt}\left(\frac{d\delta}{dt}\right)^2 = \frac{2}{M}\,P_a\frac{d\delta}{dt}$$

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

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

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

$$\frac{d\delta}{dt} = 0. \quad \text{i.e.} \sqrt{\frac{2}{M}\int_{\delta_0}^{\delta} P_a . d\delta} = 0$$

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

Application of Equal Area Criterion

Illustration of EAC of stability for several types of disturbances in SMIB

Assumption.

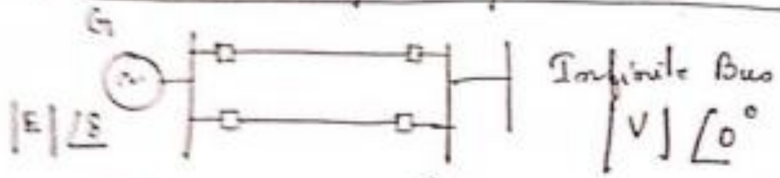
1) T.L and syn m/c resistance are neglec
2) Rotor speed of syn m/c is constant.
3). Mech I/P to m/c constant.
4) Voltage behind transient reactance const
5). Effect of damper winding neglected.

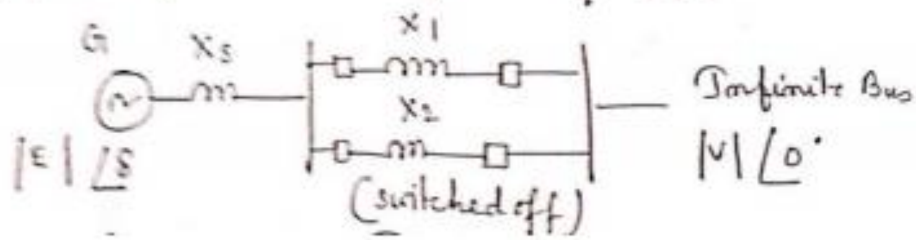
There is an upper limit to sudden increase in mechanical I/P $(P_s' - P_s)$.

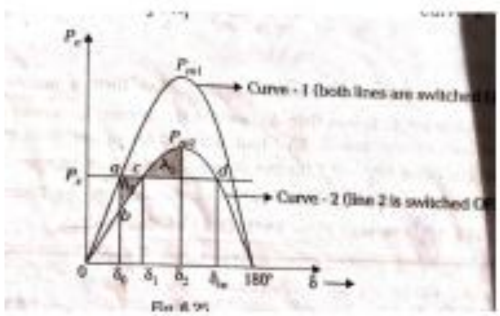
$P_s' \Rightarrow$ Transient stability limit.

TSL (P_s') is less than steady state stability limit (SSSL).

b). <u>Sudden Loss of one of the Parallel Lines</u>.







Case (1) Before switching OFF, the power angle equation is

$$P_{e1} = \frac{|E||V|}{X_s + (X_1 \| X_2)} \sin\delta = P_{m1} \sin\delta \quad \dots \text{curve 1.}$$

Case (2) on switching OFF, line 2.

$$P_{e2} = \frac{|E||V|}{X_s + X_1} \sin\delta = P_{m2} \sin\delta \rightarrow \text{curve 2}$$

$P_{m2} < P_{m1}$ as $(X_s + X_1) > (X_s + (X_1 \| X_2))$

⇒ As soon as line 2 was switched off, original operating point a on curve-1 is shifted to point b on curve-2.

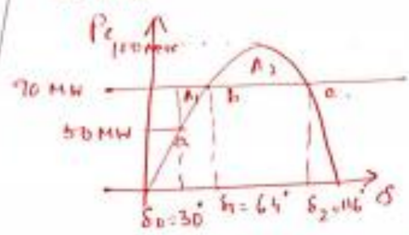
Accelerating energy corresponding to area A_1 is put into rotor followed by decelerating energy.

If area A_2 = area A_1 then stable finally operates at C & δ_1.

$\delta_1 > \delta_0$

7a

6.15 A loss free alternator supplies 50 MW to an infinite bus, the SSSL being 100 MW. Determine if the alternator will remain stable if the input to the prime mover of the alternator is abruptly increased by 40 MW



Let δ_0 be the power angle when load is 50 MW

$50 = 100 \sin \delta_0$

$\delta_0 = 30^\circ$

at point b when load is $50 + 40 = 90$ MW,

$$\delta_1 = \sin^{-1} \frac{90}{100} = 64^\circ$$

at point c, $\delta_2 = 180^\circ - 64^\circ = 116^\circ$

$$A_1 = \int_{30^\circ}^{64^\circ} (90 - 100 \sin \delta) \, d\delta$$

$$= 90 (64^\circ - 30^\circ) \frac{\pi}{180^\circ} + 100 (\cos 64^\circ - \cos 30^\circ)$$

$$= 10.6$$

$$A_2 = \int_{64°}^{116°} (100 \sin\delta - 90)\, d\delta$$

$$= -100(\cos 116° - \cos 64°) - 90(116° - 64°) \times \frac{\pi}{180}$$

$$= 5.99$$

as $A_1 > A_2$ ⇒ m/c will fall out of synchronism when I/P is suddenly increased by 40 MW.

7b

(b) Soln:-

$G_1 = 200\,MVA$ $G_2 = 150\,MVA$

$H_1 = 10\,MJ/MVA$ $H_2 = 5\,MJ/MVA$

$G_{Base} = 100\,MVA$

$$H_{eq} = 3\left(\frac{G_1 H_1}{G_{base}}\right) + 5\left(\frac{G_2 H_2}{G_{base}}\right)$$

X Y

$$= 3\left(\frac{200 \times 10}{100}\right) + 5\left(\frac{150 \times 5}{100}\right)$$

$$\boxed{H_{eq} = 97.5\ MJ/MVA}$$