QUESTION 1

(a) Consider the first section of the transposed line:

The flux linking conductor 'a', λ_a is given by the sum of the fluxes produced by 'a', 'b' and 'c':–

$$\lambda_{a_1} = \frac{\mu_0}{2\pi} I_a \ln\left(\frac{D_p}{r'}\right) + \frac{\mu_0}{2\pi} \cdot I_b \ln\left(\frac{D_p}{D}\right) + \frac{\mu_0}{2\pi} I_c \ln\left(\frac{D_p}{2D}\right)$$

In the middle section:

$$\lambda_{a_2} = \frac{\mu_0}{2\pi} I_a \ln\left(\frac{D_p}{r'}\right) + \frac{\mu_0}{2\pi} I_b \ln\left(\frac{D_p}{D}\right) + \frac{\mu_0}{2\pi} I_c \ln\left(\frac{D_p}{D}\right)$$

and in the third section:

$$\lambda_{a_3} = \frac{\mu_0}{2\pi} I_a \ln\left(\frac{D_p}{r'}\right) + \frac{\mu_0}{2\pi} I_b \ln\left(\frac{D_p}{2D}\right) + \frac{\mu_0}{2\pi} I_c \ln\left(\frac{D_p}{D}\right)$$

Summing the 3 components and averaging:–

$$\lambda_a = \frac{\mu_0}{2\pi} \cdot \frac{1}{3}\left[3 I_a \ln\left(\frac{D_p}{r'}\right) + 2(I_b + I_c)\ln\left(\frac{D_p}{D}\right) + (I_b + I_c)\ln\left(\frac{D_p}{2D}\right)\right]$$

for balanced systems $I_a = -I_b - I_c$

$$\lambda_a = \frac{\mu_0 I_a}{6\pi}\left[3\ln\left(\frac{D_p}{r'}\right) - 2\ln\left(\frac{D_p}{D}\right) - \ln\left(\frac{D_p}{2D}\right)\right]$$

$$= \frac{\mu_0 I_a}{6\pi}\left[\ln\left(\frac{D_p^3}{r'^3}\right) + \ln\left(\frac{D^2}{D_p^2}\right) + \ln\left(\frac{2D}{D_p}\right)\right]$$

$$= \frac{\mu_0 I_a}{6\pi}\left[\ln\left(\frac{D_p^3}{r'^3} \times \frac{D^2}{D_p^2} \times \frac{2D}{D_p}\right)\right] = \frac{\mu_0 I_a}{6\pi} \ln\left(\frac{2D^3}{r'^3}\right)$$

$$= \frac{\mu_0 I_a}{2\pi}\left[\frac{1}{3}\ln\left(\frac{2D^3}{r'^3}\right)\right] = \frac{\mu_0 I_a}{2\pi} \ln\left(\frac{\sqrt[3]{2}\, D}{r'}\right)$$

Now $L_a = \dfrac{\lambda_a}{I_a} = \dfrac{\mu_0}{2\pi} \ln \dfrac{\sqrt[3]{2}\,D}{r'}$ (6)

(b) (i) For a line having a single solid conductor per phase with a radius of 12mm:-

$GMR = 0.7788 \times 12 = 9.35\,mm \equiv 0.00935\,m$

The geometric mean distance between phases is:

$GMD = \sqrt[3]{2}\,.\,1.5 = 1.89\,m$

Hence the inductance per phase per metre is:-

$\dfrac{\mu_0}{2\pi} \ln\left(\dfrac{GMD}{GMR}\right) = \dfrac{\mu_0}{2\pi} \ln\left(\dfrac{1.89}{0.00935}\right) = 1.062 \times 10^{-6}\,H/m$

For a 20km line:

$L_{TOT} = 1.062 \times 10^{-6} \times 20000 = \underline{\underline{0.0212\,H}}$ (4)

(ii) For a line having stranded conductors:

$GMR = \sqrt[16]{(r'.d.d.\sqrt{2}d)^4} = \sqrt[4]{r' d^3.\sqrt{2}} = 10.3\,mm \equiv 0.0103\,m$

GMR remains unchanged from (i)

$\therefore L = \dfrac{\mu_0}{2\pi} \ln\left(\dfrac{1.89}{0.0103}\right) = 1.042 \times 10^{-6}\,H/m$

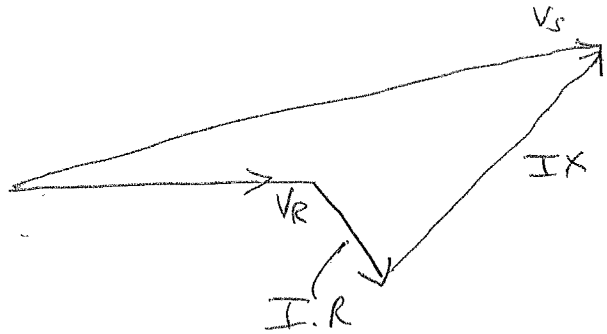
$\therefore$ For the 20km line:

$L_{TOT} = 1.042 \times 10^{-6} \times 20000 = \underline{\underline{0.0208\,H}}$ (4)

(c) For a 20km long line operating at 50Hz:

Resistance $= 20 \times 0.04 = 0.8\,\Omega$

Reactance $= 2\pi \times 50 \times 0.0208 = 6.53\,\Omega$



$$V_S^2 = \left(V_R + IR\cos\phi + IX\sin\phi\right)^2 + \left(IX\cos\phi - IR\sin\phi\right)^2$$

Now $V_R = \dfrac{33000}{\sqrt{3}} = 19052.6\,V$

and since $P = \sqrt{3}\ V_L I_L \cos\phi$

then $I_L = \dfrac{900 \times 10^3}{\sqrt{3}.33000.0.9} = 17.5A$

$$\therefore V_S^2 = \left[19052.6 + (17.5 \times 0.8 \times 0.9) + (17.5 \times 6.53 \times 0.436)\right]^2$$
$$+ \left[(17.5 \times 6.53 \times 0.9) - (17.5 \times 0.8 \times 0.436)\right]^2$$
$$= \left[19052.6 + 12.6 + 49.82\right]^2 + \left[102.85 - 6.104\right]^2 = 19115^2 + 96.75^2$$

(4)

$\therefore V_S = 19115\,V$ (phase) $\quad \underline{\underline{V_{SL} = 33108 \text{ (line)}}}$

(d) The reason for using bundled conductors on HV lines is to further increase the GMR and therefore reduce the reactance of the line. It also reduces the likelyhood of corona discharge by reducing the electric field gradient.

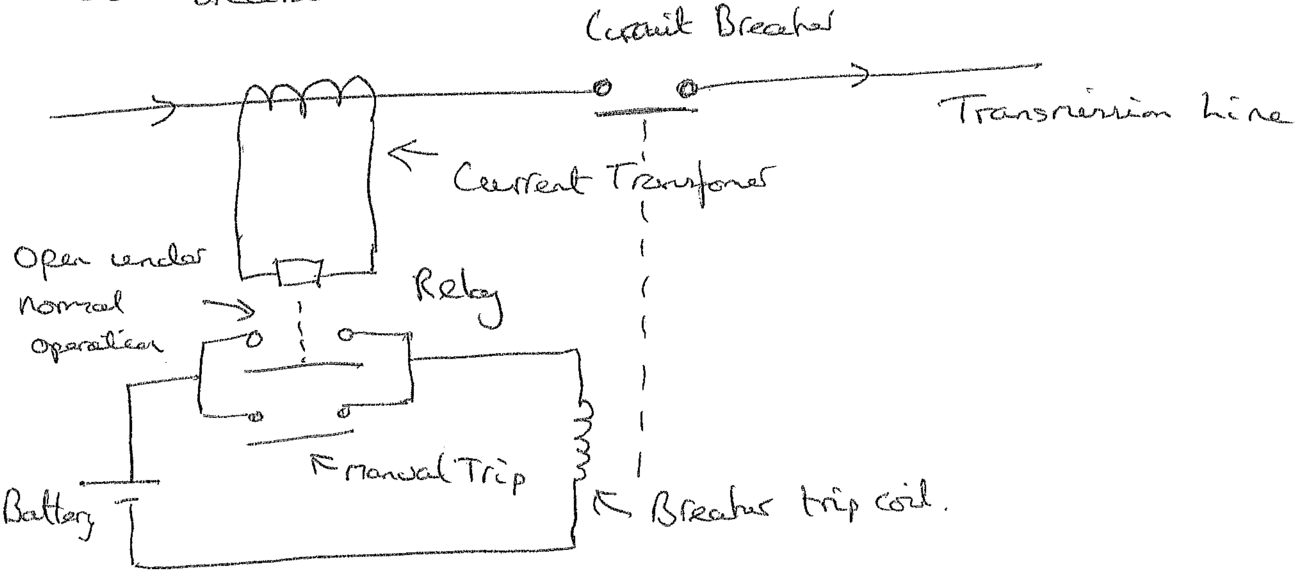
(2)

QUESTION 2

4

(a)(i) Protection is needed to save personnel from risk of electrocution and to help prevent risk of fire or explosion and damage to plant. (1)

(ii) Protection systems are made up of 3 key components:
Instrument transformer
Relay
Circuit Breaker

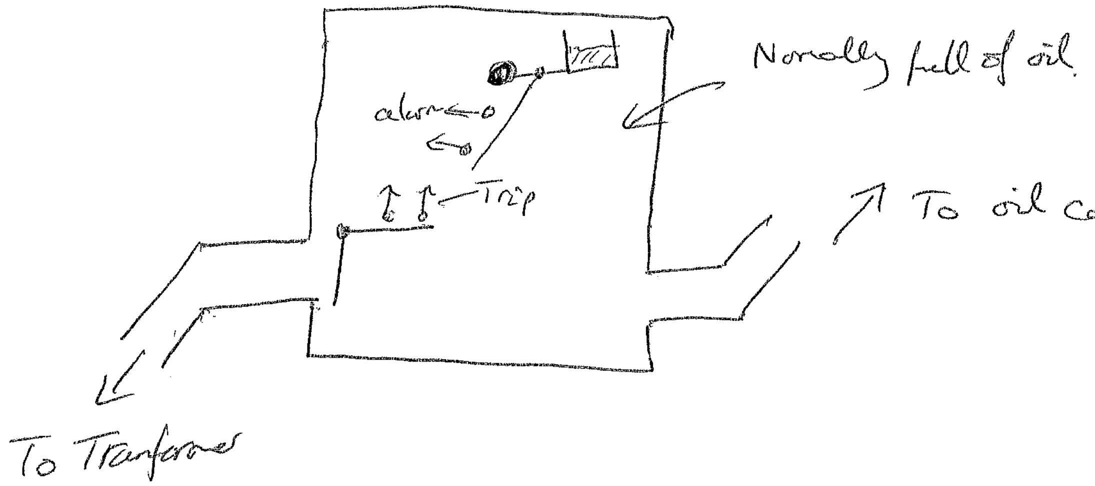


When overcurrent detected relay closes trip contacts (or these can be closed manually) causing current to flow through trip coil, opening the CB contacts. (3)

(b) Buchholz Relay

In oil immersed transformers an internal fault is always accompanied by the release of gas, since oil temperature is increased to vaporising point in the vicinity of the fault. Since some faults (e.g. earth fault close to the neutral point involving only a few turns) produce insufficient fault current to operate the protection relays, a gas operated relay is used.

This consists of 2 pivoted buckets carrying mercury tilt switches. When a slight fault occurs gas is trapped in the relay housing. As the gas accumulates the oil level in the relay falls. This causes the bucket to tilt and completes the alarm circuit. When a serious fault occurs a sudden surge of gas impinges on the lower bucket causing it to tilt the mercury switch, closing the circuit to trip the circuit breaker.



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(c) Tap changing transformers are used to compensate for varying voltage drops in the system caused by load fluctuations, and also to control reactive power flow over transmission lines. A transformer which can alter its voltage ratio, either automatically or manually whilst carrying the load current is called an on-load tap changing transformer. An off-load tap changing transformer needs to be disconnected and isolated (ie off-load) before the taps can be changed, which can cause a disruption to the supply.

2

(d) For the 2 circuits to be electrically equivalent the no-load transformation ratio and the short circuit impedances must be equal.

1. no-load voltages:

Primary to Secondary $R = \dfrac{A}{A+C}$ 1

Secondary to Primary:

$$\frac{1}{k} = \frac{B}{B+C} \qquad (2)$$

Short circuit impedances:

Impedance measured at primary with secondary short circuited:

$$Z = \frac{AC}{A+C} \qquad (3)$$

Impedance measured at secondary with primary short circuited

$$\frac{Z}{k^2} = \frac{BC}{B+C} \qquad (4)$$

From (1) and (3): $C = Z/k$

Back substituting in (1): $k = \dfrac{A}{A+\frac{Z}{k}} = \dfrac{kA}{kA+Z}$

$$\therefore A = \frac{Z}{1-k}$$

Back substituting in (2):

$$\frac{1}{k} = \frac{B}{B+\frac{Z}{k}} \Rightarrow B = \frac{Z}{k(k-1)} \qquad 4$$

(e) On the nominal tap $Z_{HL} = j0.08\,pu$ $\quad k=1$

On the +10% tap $Z_{HL}' = k_{H}^2 . Z_{HL} = 1.1^2 . 0.08 = j0.0968$

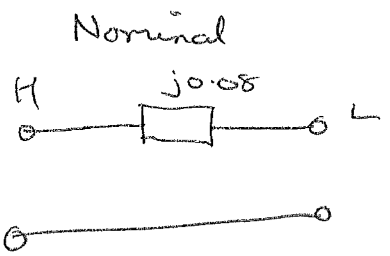
$$\therefore A = \frac{Z}{1-k} = \frac{j0.0968}{-0.1} = -j0.968$$

$$B = \frac{Z}{k(k-1)} = \frac{j0.0968}{1.1 \times 0.1} = j0.88$$

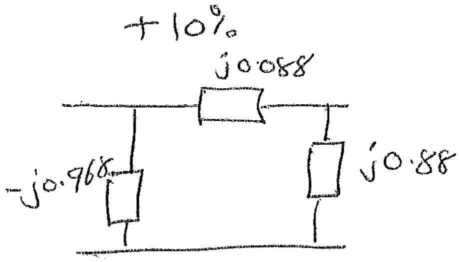
$$C = \frac{Z}{k} = \frac{j0.0968}{1.1} = j0.088$$

QUESTION 2 (CONTINUED)

Nominal



+10%



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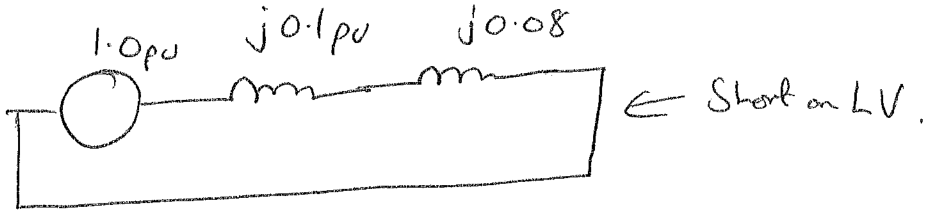
(f) Converting Grid Infeed to 100 MVA base:

$$Z_{sys} = \frac{100}{1000} \times j1.0 = j0.1\,pu$$

Nominal tap:

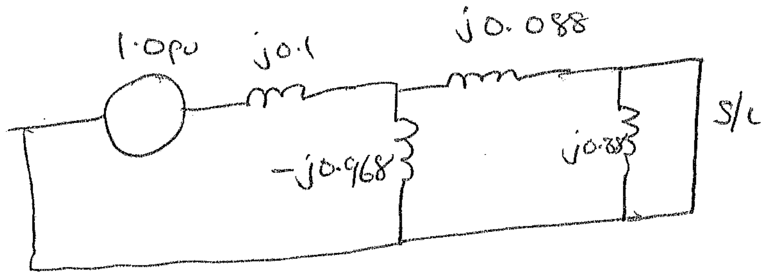


$$I_{f\,pu} = \frac{1.0}{j0.18} = -j5.56$$

$$I_{base\ at\ fault} = \frac{100\times10^{6}}{\sqrt{3}\times 6\cancel{6000}} = 8\cancel{75}A \quad 437A$$

$$\therefore |I_f| = \cancel{4868A} \quad 2429.7$$

For the ~~+~~ 10% tap:



$$I_f = \frac{1.0}{j(0.1+0.0968)} = -j5.08\,pu$$

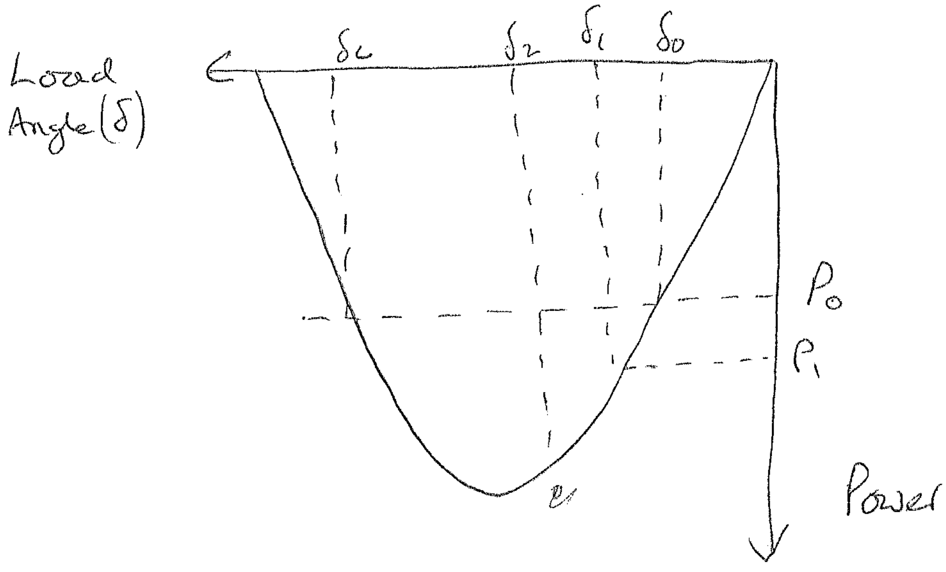
$$\therefore |I_F| = I_{base} \times I_{f\,pu} = \cancel{4445A}$$

2220A

3

QUESTION 3

(a)

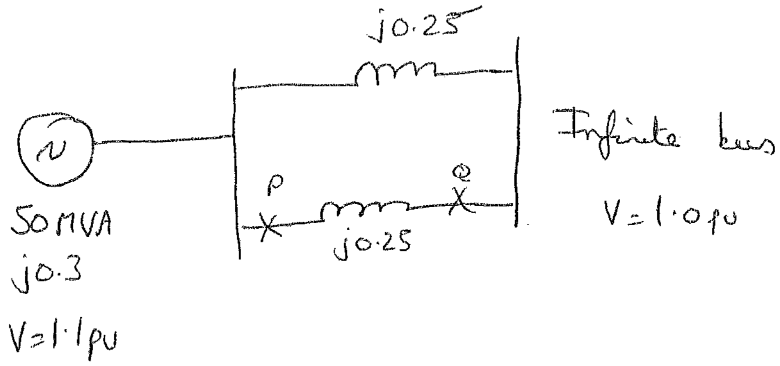


Assume initially the motor is delivering mechanical power P_0 at a load angle δ_0. The load suddenly increases to P_1

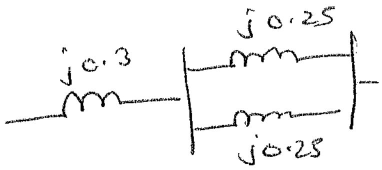
Due to machine inertia δ_0 does not alter instantaneously to the value required to transmit the required electrical power to the motor. Therefore the rotor slows down and the speed falls below the synchronous speed and δ increases, As δ increases towards δ_1 the power difference decreases. The power difference at δ_1 is zero and hence the acceleration is zero. However the velocity relative to the Synchronous speed is not zero and δ will continue to increase. However now the electrical power is greater than the mechanical load so the rotor accelerates with a steady reduction in the rate of increase of δ. When the rotor attains synchronous speed δ stops increasing (max overshoot of δ is δ_2). Since $P_e > P_M$ the rotor speed increases above synchronous speed and δ falls below δ_2. With no damping δ oscillates between δ_0 and δ_2

If δ_2 exceeds δ_c then stability will be lost.

(b)



(i) Before the fault the total system reactance is:



$= j0.425\,pu$

Now since $P_{eb} = \dfrac{V_S V_R}{X} \sin\delta$

$$P_{eb} = \frac{1.1 \times 1.0}{0.425} \sin\delta = \underline{\underline{2.59 \sin\delta}}$$

Expressing the load as a pu value:

$$\frac{40MW}{50MVA} = 0.8\,pu.$$

Therefore the pre-fault load angle may be found:

$$0.8 = 2.59 \sin\delta \Rightarrow \underline{\underline{\delta = 18.0^\circ \ (0.314\,rad)}}$$ 3

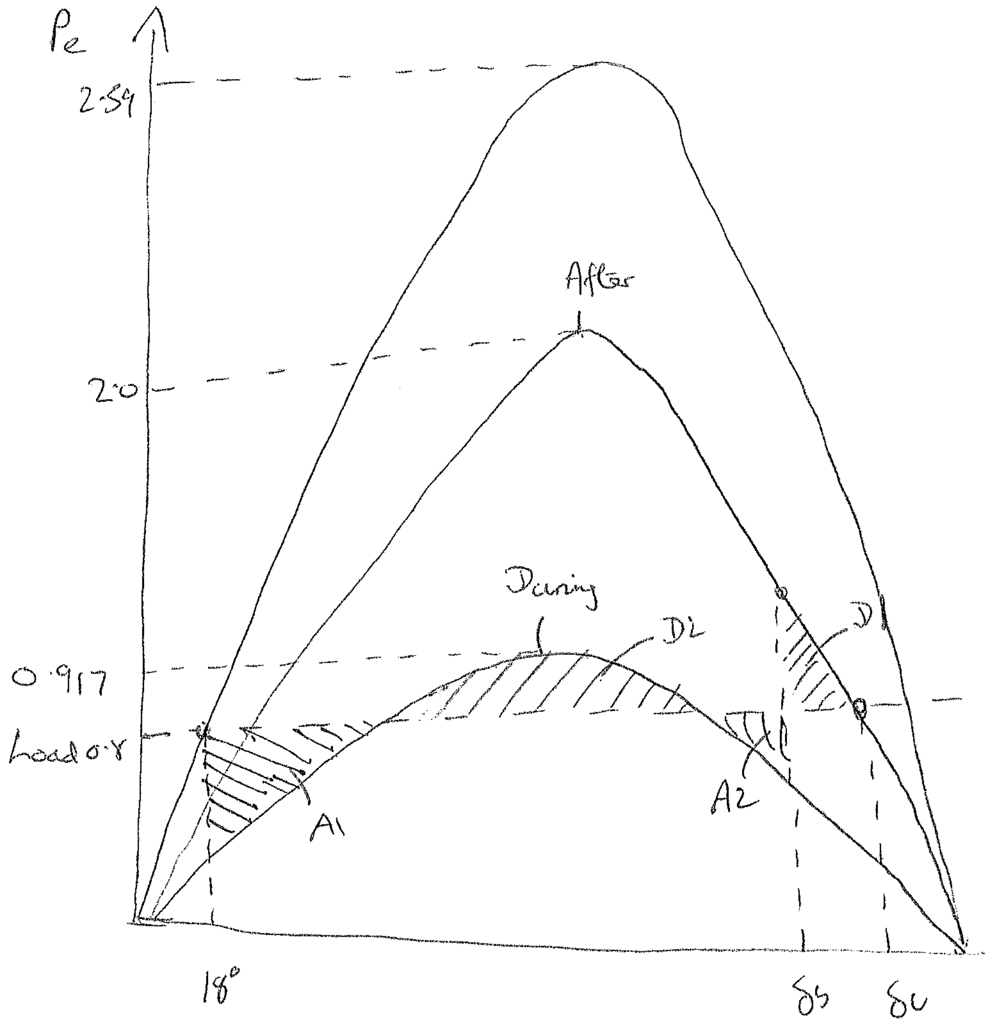
(ii) During the fault the new power-load angle equation becomes:

$$P_{ed} = \frac{1.1 \times 1.0 \sin\delta}{1.2} = \underline{\underline{0.917 \sin\delta}}$$ 1

(iii) After the fault has been cleared the system reactance is:

$$j0.3 + j0.25 = j0.55\,pu$$

$$P_{ea} = \frac{1.1 \times 1.0 \sin\delta}{0.55} = \underline{\underline{2 \sin\delta}}$$ (1)



critical angle

critical clearance angle

(4)

A1 + A2 Accelerating areas

D1 + D2 Decelerating areas

For the equal area criteria:

Accelerating Area = Decelerating Area

$$\delta_c = \arcsin\left(\frac{0.8}{2}\right) = 180° - 23.6° = 156.4° \ (2.729 \text{ rad}).$$

$$\int_{\delta_0}^{\delta_s} (P_m - 0.917 \sin\delta)\, d\delta = \int_{\delta_s}^{\delta_c} (2.0 \sin\delta - P_m)\, d\delta$$

QUESTION 3 (CONTINUED)

$$\therefore \left[0.8\delta + 0.917\cos\delta\right]_{\delta_0}^{\delta_s} = \left[-2\cos\delta - 0.8\delta\right]_{\delta_s}^{\delta_c}$$

$$\therefore \cancel{0.8\delta_s} + 0.917\cos\delta_s - 0.8\delta_0 - 0.917\cos\delta_0$$
$$= -2\cos\delta_c - 0.8\delta_c + 2\cos\delta_s + \cancel{0.8\delta_s}$$

$$\therefore 1.083\cos\delta_s = 0.8(\delta_c - \delta_0) - 0.917\cos\delta_0 + 2\cos\delta_c$$

$$1.083\cos\delta_s = 0.8(2.729 - 0.314) - 0.872 - 1.833$$
$$= 0.773$$
$$\therefore \delta_s = 135°$$

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(d) The transient stability could be enhanced by:

(i) Increasing the system voltage
(ii) Reducing the system reactance
(iii) Using faster circuit Breakers
(iv) Increasing the generator inertia constant

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QUESTION 4

Generator A: – All values already given on base of 30MVA

Generator G:

$$X_+ = j0.1 \times \frac{30}{50} \times \frac{22^2}{25^2} = j0.0465 \text{ pu}$$

$$X_- = j0.08 \times \frac{30}{50} \times \frac{22^2}{25^2} = j0.0372 \text{ pu}$$

$$X_0 = j0.05 \times \frac{30}{50} \times \frac{22^2}{25^2} = j0.0232 \text{ pu}$$

Transformer B: Already on correct base

Transformer C:

$$X_+ = X_- = X_0 = j0.3 \times \frac{30}{40} = j0.225 \text{ pu}$$

Lines D and E:

$$Z_{base} = \frac{(132000)^2}{30 \times 10^6} = 581\,\Omega$$

$$\therefore X_+ = X_- = \frac{j20}{581} = j0.0344 \text{ pu}$$

$$X_0 = \frac{j30}{581} = j0.0516 \text{ pu}$$

Transformer F: Already on correct base.

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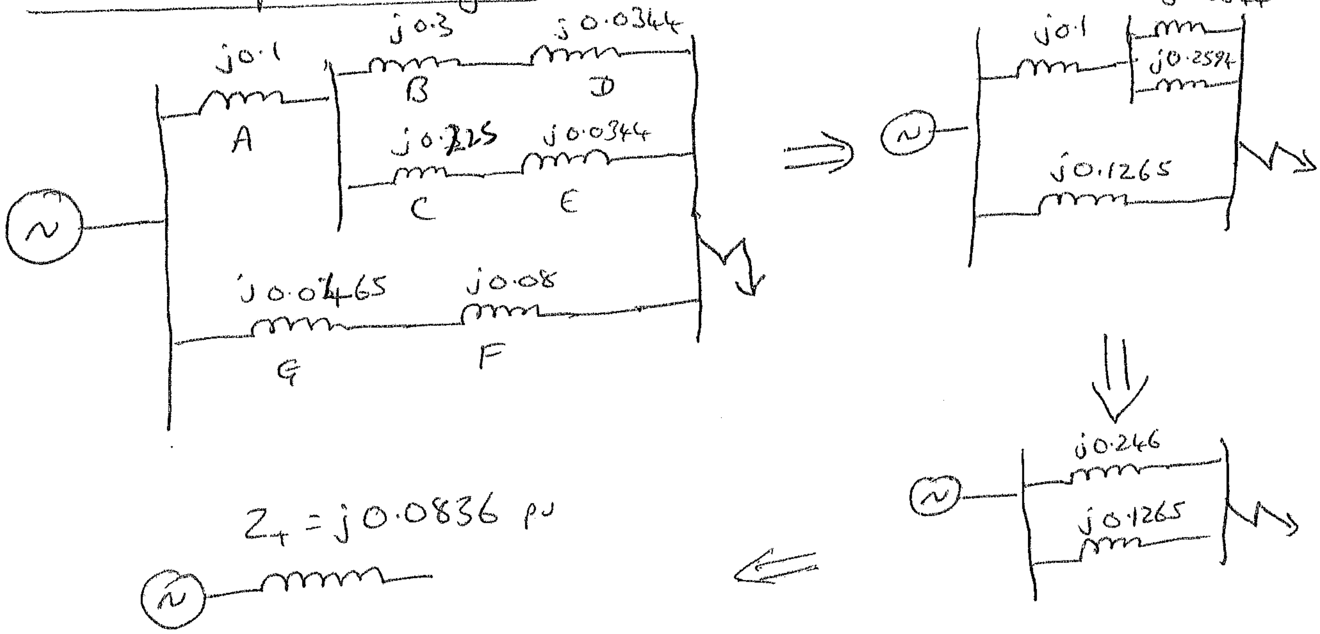
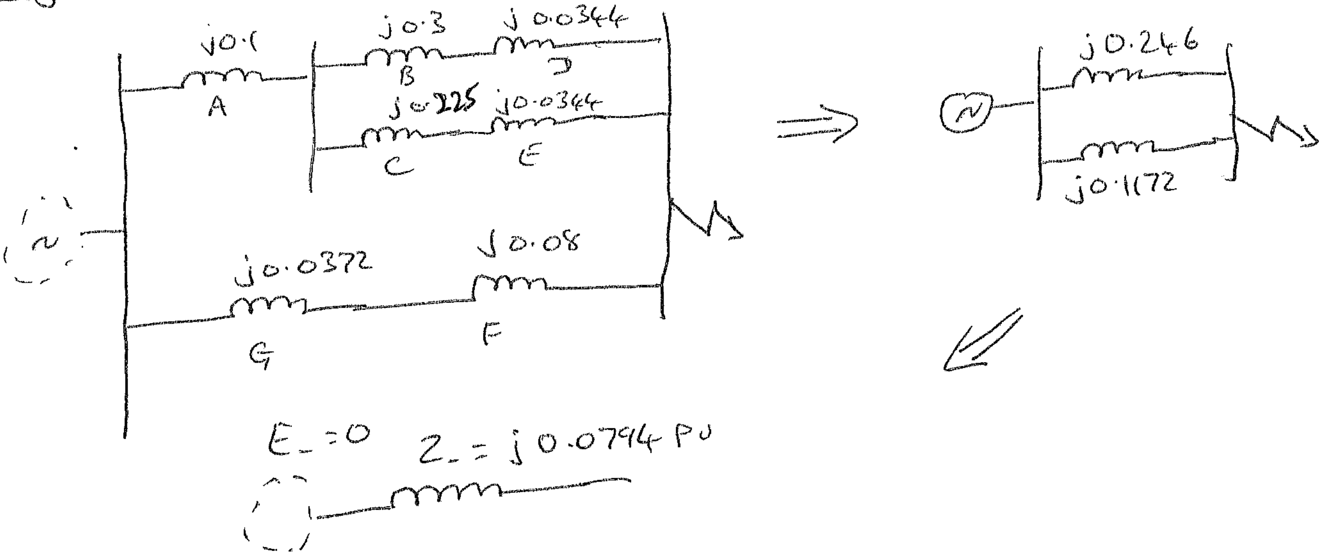
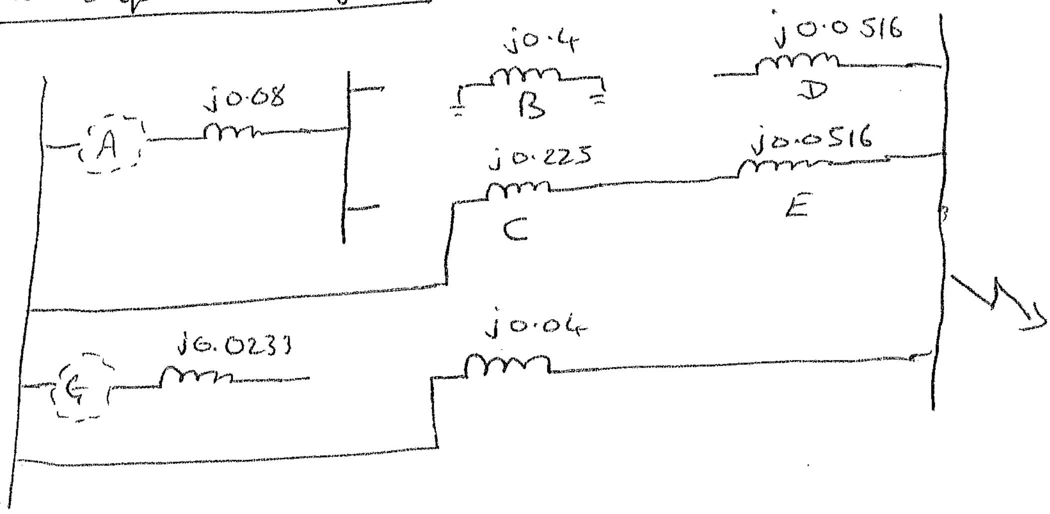
(b) Positive sequence diagram



Negative sequence diagram.



Zero sequence diagram



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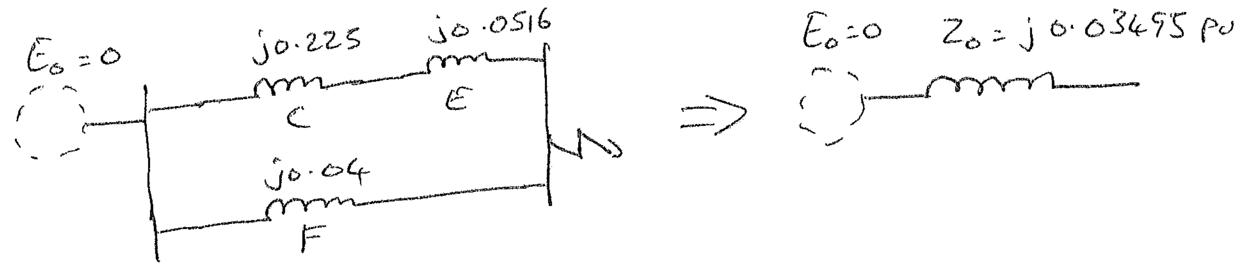
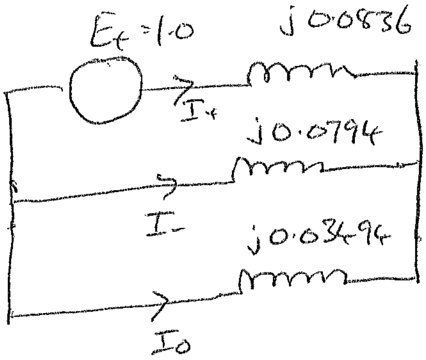


(c) For a 2 phase to Earth fault connect the sequence networks in parallel:



$$I_+ = \frac{1.0}{j0.0836 + \underbrace{\left(j0.0794\right)/\!/\left(j0.03494\right)}_{j0.11434}} = \frac{1}{j0.1078} = -j9.28_{pu}$$

$$I_- = -I_+ \cdot \frac{j0.03494}{\left(j0.03494 + j0.0794\right)} = -\left(-j9.28\right) \times 0.306 = j\,2.84_{pu}$$

$$I_0 = -I_+ - I_- = j6.44 \text{ pu}$$

$$I_A = I_0 + I_+ + I_- = -j9.28 + j2.84 + j6.44 = 0 \quad \text{(As expected)}$$

$$I_B = I_0 + a^2 I_+ + a I_- = j6.44 + 1\angle 240^\circ.\left(-j9.28\right) + 1\angle 120^\circ.\left(j2.84\right)$$
$$= -10.5 + j9.66 \text{ pu}$$

$$I_C = I_0 + a I_+ + a^2 I_- = j6.44 + 1\angle 120^\circ\left(-j9.28\right) + 1\angle 240^\circ\left(j2.84\right)$$
$$= 10.5 + j9.66 \text{ pu}$$

$\therefore$ Total fault current $= I_B + I_C = -10.5 + 10.5 + j9.66 + j9.66$

$$= j19.32 \text{ pu}$$

Base current at point of fault

$$= \frac{MVA_b}{\sqrt{3}V_b} = \frac{30 \times 10^6}{\sqrt{3} \times 132 \times 10^3} = 131.2\,A$$

$\therefore$ Magnitude of total fault current $= 131.2 \times 19.32 = \underline{\underline{2535\,A}}$

Sequence voltages at fault:

$$V_+ = V_- = V_0 = 1.0 - (-j9.28)(j0.0836) = 0.225\,pu$$

$$V_A = V_0 + V_+ + V_- = 3.\,0.225 = 0.675\,pu$$

$$\left(\begin{array}{l} \text{check } V_B = V_0 + a^2 V_+ + aV_- = 0.225 + 1\angle 240^\circ, 0.225 + 1\angle 120^\circ\, 0.225 = 0 \\ V_C = V_0 + aV_+ + aV_- = 0.225 + 1\angle 120^\circ.\, 0.225 + 1\angle 240^\circ.\, 0.225 = 0 \end{array}\right)$$

$$\text{Base phase voltage} = \frac{132 \times 10^3}{\sqrt{3}} = 76.2\,kV$$

$$\therefore V_{A\,ph} = 0.675\,.\,76.2 = 51.4\,kV$$

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Hence $\underline{\underline{|V_{AB}| = 51.4\,kV \quad |V_{CA}| = 51.4\,kV}}$

(d). Since generator A plays no part in the zero sequence diagram the addition of a star point reactor will have no effect on the fault current.

1