QUESTION 1

(i) Star - Delta transformation:

$$Z_{AB} = Z_A + Z_B + \frac{Z_A Z_B}{Z_C}$$

$$Z_{BC} = Z_B + Z_C + \frac{Z_B Z_C}{Z_A}$$

$$Z_{CA} = Z_C + Z_A + \frac{Z_C Z_A}{Z_B}$$

Now from the star connected network:

$Z_A = (25 + j60)$ $Z_B = (15 + j20)$ $Z_C = (40 - j25)$

$$\therefore Z_{AB} = (25 + j60) + (15 + j20) + \frac{(25 + j60)(15 + j20)}{(40 - j25)}$$

$$= 96.36 \angle 84.38^\circ \, \Omega$$

$$\therefore Z_{BC} = (15 + j20) + (40 - j25) + \frac{(15 + j20)(40 - j25)}{(25 + j60)}$$

$$= 69.93 \angle -15^\circ \, \Omega$$

$$\therefore Z_{CA} = (40 - j25) + (25 + j60) + \frac{(40 - j25)(25 + j60)}{(15 + j20)}$$

$$= 181.82 \angle -0.76^\circ \, \Omega$$

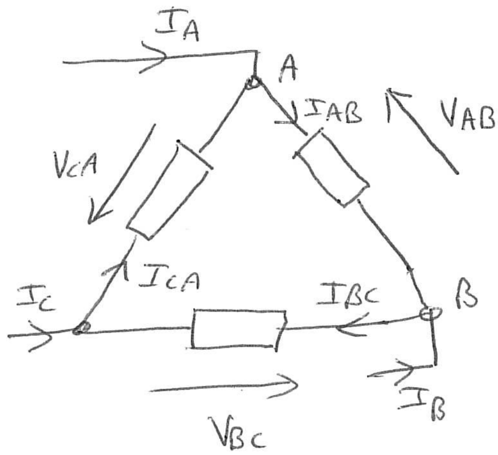
The effective phase currents in the equivalent delta can now be calculated: (V_{AB} is reference)

$$I_{AB} = \frac{6600 \angle 0^\circ}{96.36 \angle 84.38^\circ} = 68.49 \angle -84.38^\circ$$

$$I_{BC} = \frac{6600\angle -120°}{69.93\angle 15°} = 94.38\angle -105° \text{ A}$$

$$I_{CA} = \frac{6600\angle -240°}{181.82\angle -0.76°} = 36.30\angle 120.76° \quad (\text{or } 36.30\angle -239.24°)$$

Find the line currents:



$\therefore I_A = I_{AB} - I_{CA} = \underline{\underline{102.52\angle -75.73° \text{ A}}}$

$I_B = I_{BC} - I_{AB} = \underline{\underline{38.71\angle -143.545° \text{ A}}}.$

$I_C = I_{CA} - I_{BC} = \underline{\underline{122.5\angle 87.26° \text{ A}}}$

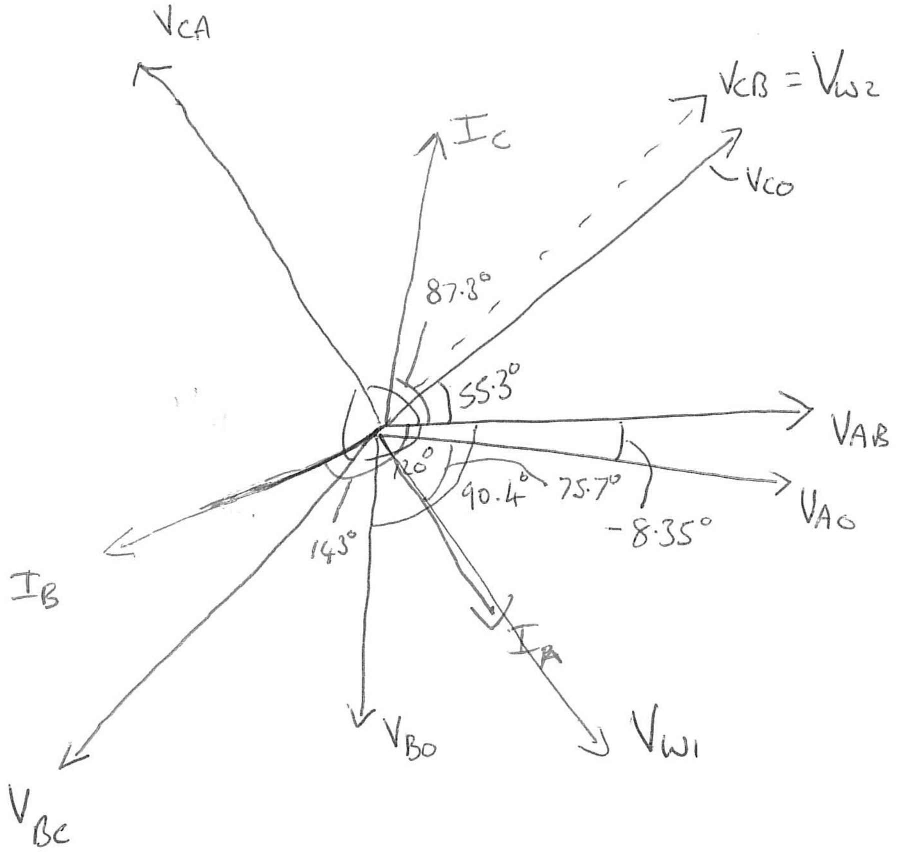
(ii) Voltage across each phase of the load:

$$V_{AO} = I_A . Z_A = 102.52\angle -75.73° \times (25 + j60) = \underline{\underline{6663.8\angle -8.35° \text{ V}}}$$

$$V_{BO} = I_B Z_B = 38.71\angle -143.545° \times (15 + j20) = \underline{\underline{967.775\angle -90.415° \text{ V}}}$$

$$V_{CO} = I_C Z_C = 122.5\angle 87.26 \times (40 - j25) = \underline{\underline{5778.3\angle 55.25 \text{ V}}}$$

(b) (i) Phasor diagram



The voltage across the coil of $W_2 = V_{CB} = 6600\angle 60°$

The voltage across the coil of W_1 is the voltage across the 25Ω resistor in phase A:

$$V_{W1} = I_a . 25 = 2563\angle -75.73° \text{ V}$$

(ii) Wattmeter W1 reads:

$$W_1 = V_{W1} . I_A . \cos\phi_1$$

where ϕ_1 is the angle between V_{W1} and $I_a = 0°$

$$\therefore W_1 = 2563 \times 102.52 = 262.7\text{kW}$$

Wattmeter W_2 reads:

$$W_2 = V_{CB} . I_C . \cos\phi_2$$

where ϕ_2 = angle between V_{CB} and I_C = 27.3°

$$W_2 = 6600 \times 122.5 \cos 27.3^\circ = \underline{\underline{718.4\,kW}}$$

If W_1 was correctly connected $W_1 + W_2$ would measure the total power, but neither reading would mean anything by itself. With this incorrect connection W_1 actually measures the power in phase A. $(W_1 + W_2 = 981.1\,kW)$

(c)(i). The voltage coil of W_1 should be removed from the midpoint of the load on phase A and reconnected to phase B to measure V_{AB}.

W_1 now reads $V_{AB} \times I_A \times \cos\phi_3$

where ϕ_3 is the angle between V_{AB} and $I_A = 75.7^\circ$

$$\therefore W_1 = 6600 \times 102.52 \times \cos 75.7^\circ = 167.1\,kW$$

Hence now $W_1 + W_2 = 167.1 + 718.4 = \underline{\underline{885.7\,kW}}$

(c)(ii) Power dissipated:

$$P_T = I_A^2 R_A + I_B^2 R_B + I_C^2 R_C$$

$$= 102.52^2 \times 25 + 38.71^2 \times 15 + 122.5^2 \times 40$$

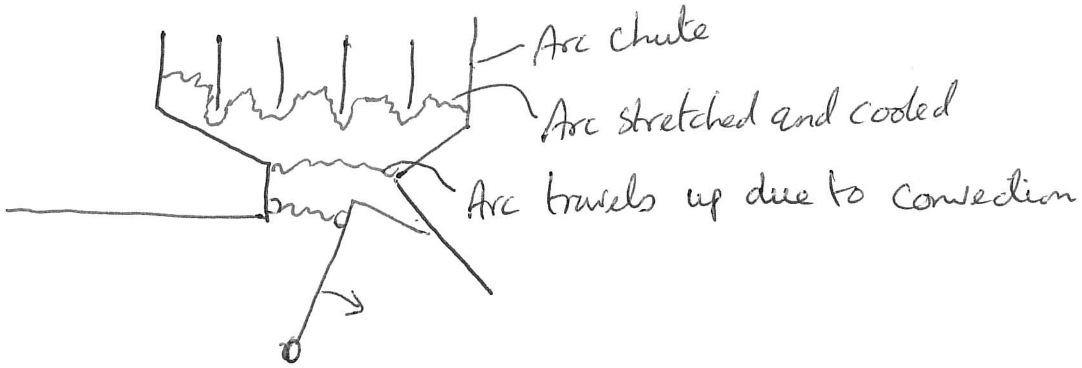
$$= \underline{\underline{885.5\,kW}}$$

(iii) This is clearly an unbalanced system so when the star point is connected to the neutral point of the supply a current will flow in the neutral conductor. Hence the wattmeters will give incorrect readings.

QUESTION 2

(a) Plain air-break circuit breakers

Arc chute



- Used at bottom end of system
- Use of convection due to heating to move arc upwards into arc-chutes which stretch and split the arc (arc chute type)
- Blow out coil uses magnetic field to move arc (blow out coil)

(b) Per-Unit is the value of any quantity expressed as a ratio or fraction of an arbitory base value of the same quantity. In power systems the base values selected are normally the rated values of a particular piece of equipment specified - normally rated MVA and line-voltage.

(c) (i). Before the link is connected choose a base value of 50MVA.

G2 is unchanged at 0.1pu

$$T2 = 0.12 \times \frac{50}{60} = 0.1\text{pu}$$

$$X_T = 0.2\text{pu}$$

$$MVA_{Fpu} = \frac{1}{X_T} = \underline{\underline{5\text{pu}}}$$

Therefore the fault level at busbar B before the link is connected is:

$$MVA_F = MVA_B \times MVA_{Fpu} = 50 \times 5 = \underline{\underline{250\text{MVA}}}$$

(ii) After the link is added, refer other quantities to the same MVA base:-

$$G1 = 0.11 \times \frac{50}{90} = 0.0611\text{pu}$$

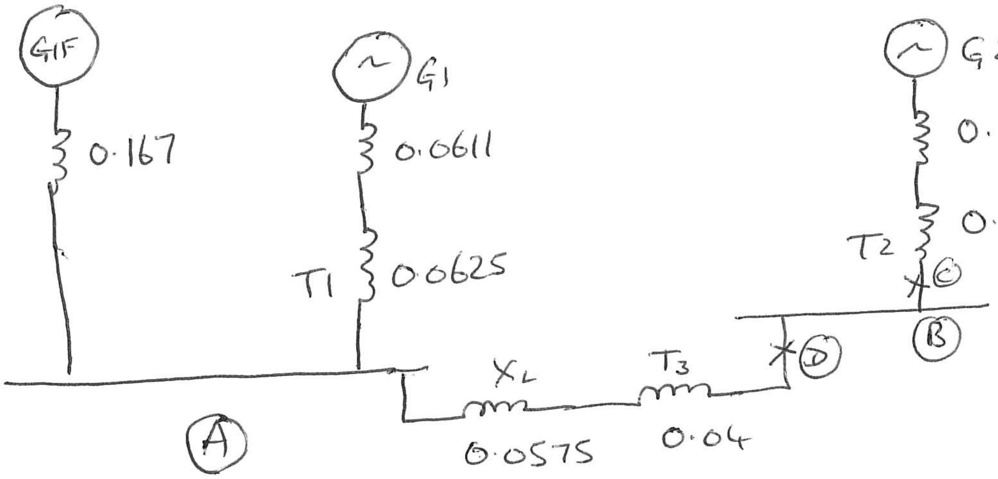
$$T1 = 0.15 \times \frac{50}{120} = 0.0625\text{pu}$$

$$T3 = 0.08 \times \frac{50}{100} = 0.04\text{pu}$$

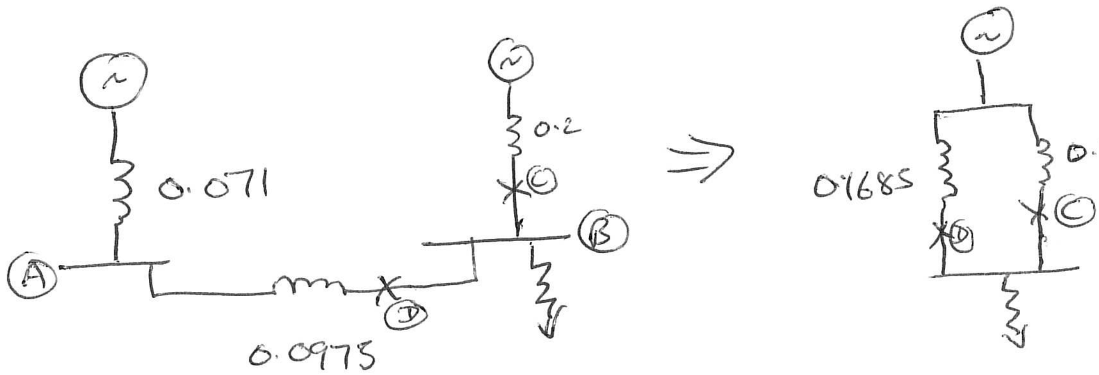
$$\text{Grid Infeed} = 1.0 \times \frac{50}{300} = 0.167\text{pu}$$

$$Z_{Base}\ (\text{line}) = \frac{V_B^2}{MVA_B} = \frac{(132000)^2}{50 \times 10^6} = 348\Omega$$

$$\therefore X_{pu\ line} = \frac{20}{348} = 0.0575\text{pu}.$$



Simplifying:



$\therefore X_T = 0.09145\,pu \qquad \therefore MVA_{Fpu} = \frac{1}{0.09145} \times 50 = \underline{\underline{546.7\,MVA}}$

MVA through breaker C $= \frac{1}{0.2} \times 50 = 250\,MVA$

MVA through breaker D $= \frac{1}{0.1685} \times 50 = 296.7\,MVA$

Fault current through breaker C $= \frac{MVA}{\sqrt{3}V_b} = \frac{250\times10^6}{\sqrt{3}\times 66000} = \underline{\underline{2.19\,kA}}$

Fault current through breaker D $= \frac{MVA}{\sqrt{3}V_b} = \frac{296.7\times10^6}{\sqrt{3}\times 66000} = \underline{\underline{2.59\,kA}}$

(iii) Refering back to earlier diagrams the p.u. fault current through the 132kV branch is:

$$I_{pu} = \frac{1}{0.1685} = 5.93\,pu$$

Hence pu current in G1 is $\frac{0.167}{0.167+0.0611+0.0625} \times 5.93 = 3.41\,pu$

I_B at G1 is $\dfrac{50\times10^6}{\sqrt{3}\times25000} = 1155A$

Hence fault current at G1 is $\underline{\underline{3938A}}$

(IV). If the fault level at B is to be limited to 500MVA then the fault level from the 132kV line must be limited to:

$$500 - 250 = 250MVA$$

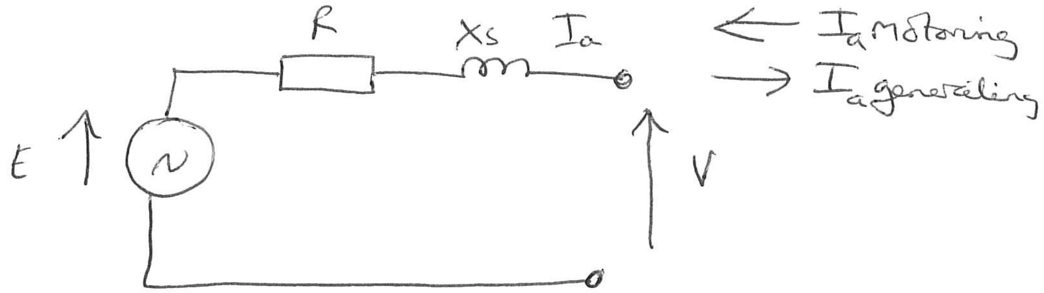
Since $MVA_F = \dfrac{1}{X_T} \times MVA_B \Rightarrow X_T = 0.2pu$

The current reactance of the 132kV system is 0.1685 then the additional reactance required is:

$$X_{add} = 0.2 - 0.1685 = \underline{\underline{0.0315\ pu}}$$

QUESTION 3

(a) (i)



Ia - Input / output stator phase current (A)

V - Supply (or terminal) voltage per phase (V)

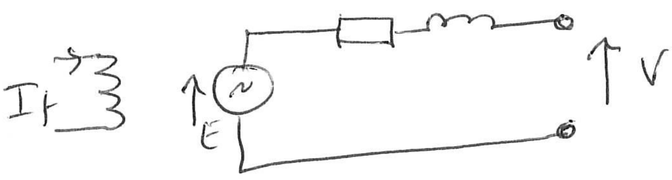
E - Induced emf per phase due to the dc excited field on the rotor (V)

R - Stator winding resistance per phase (Ω)

Xs - Synchronous reactance - effective reactance due to the self-, mutual-, and leakage fluxes produced by the stator winding.

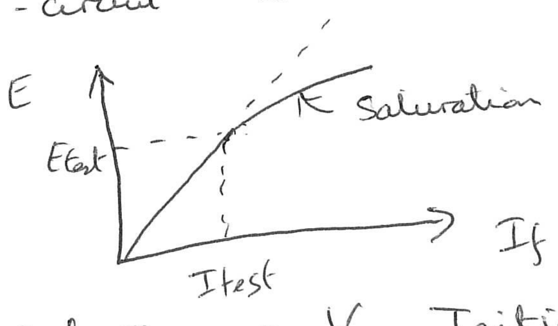
(ii) Perform an open-circuit and short-circuit test.

Open-circuit test / EMF test.



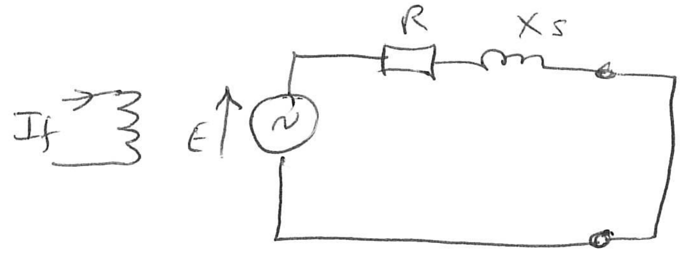
Rotate the machine at synchronous speed and pass DC current through the field winding.

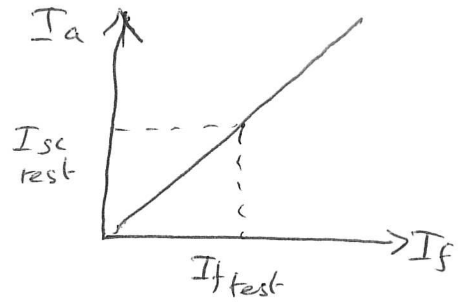
On open-circuit $I_a = 0$ $\therefore V = E$



Increase If and measure V. Initially E varies linearly with If as the reactance of the magnetic circuit is dominated by the airgap. If If increases further saturation occurs and reluctance of the iron circuit becomes significant.

(ii) Short circuit test.





Perform test at $I_{sc} = I_{rated}$ (ie. non-saturated region) by spinning the machine at synchronous speed and adjusting If.

$$Z = R + jX_s = \frac{E_{Test}}{I_{Test}}$$

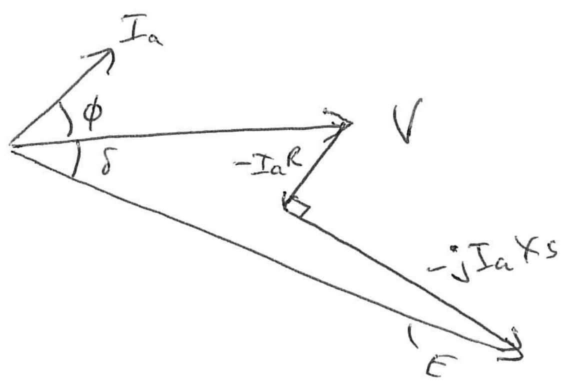
R can be obtained by direct resistance measurement then

$$X_s = \sqrt{Z^2 - R^2}.$$

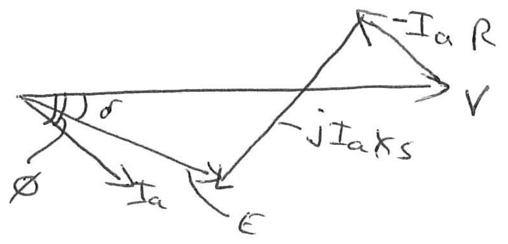
(iii) For a machine acting as a motor:

$$\bar{E} = \bar{V} - \bar{I}_a R - j\bar{I}_a X_s$$

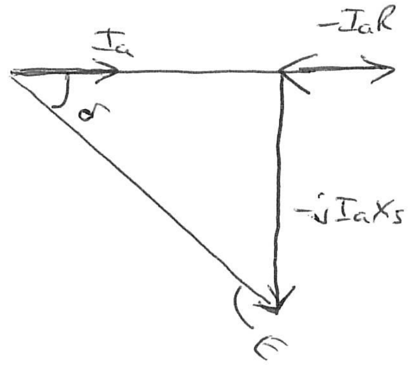
leading p.f.



lagging power factor:



Unity power factor:



(b)(i) Since $VA = \sqrt{3}\, V_L I_L$

$$\therefore I_L = \frac{VA}{\sqrt{3}\, V_L} = 92.4A$$

at a power-factor of 0.75 lagging $(= -41.4^\circ)$

For a generator:

$$E\angle\delta = V\angle 0^\circ + j\bar{I}_a X_s$$

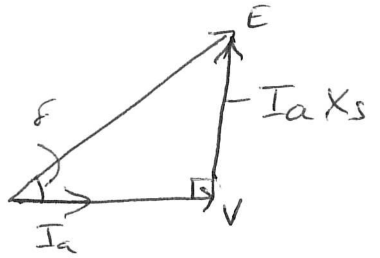
$$= \frac{50000}{\sqrt{3}}\angle 0^\circ + 92.4\angle{-41.4} \times 8\angle 90^\circ$$

$$= 28868\angle 0^\circ + 739.2\angle 48.6^\circ = 29362\angle 1.08^\circ$$

$\therefore$ Excitation voltage is $\underline{\underline{29362V}}$ (= 50856 line).

Percentage regulation $= \left(\frac{E-V}{V}\right) \times 100 = \frac{29362 - 28868}{28868} \times 100 = \underline{\underline{1.7\%}}$.

(ii) If the excitation remains unchanged at 29362 V and the input power is increased, the load angle will increase until I_a is in phase with V:



$$(I_a X_s)^2 = E^2 - V^2$$

$$= 29362^2 - 28868^2$$

$$\therefore I_a = \underline{\underline{670.4A}}$$

and the load angle δ is $\cos^{-1}\left(\frac{28868}{29362}\right) = \underline{\underline{10.5^\circ}}$

(iii) The power input to the generator remains at 8MVA × p.f = 6MW

But total power $= \frac{3 V_{ph} E_{ph} \sin\delta}{X_s}$

Now excitation is decreased by 12%

$$\therefore E_{ph\_new} = 29362 \times 0.88 = 25839 V$$

$$\therefore 6 \times 10^6 = \frac{3 \times 28868 \times 25839 \sin\delta}{8}$$

$$\therefore \sin\delta = \frac{6 \times 10^6 \times 8}{3 \times 28868 \times 25839} = 0.0215$$

$$\therefore \delta = 1.23^\circ$$

Since $E\angle\delta = V\angle 0^\circ + I\angle\phi \cdot 8\angle 90$

then $I\angle\phi = \frac{E\angle\delta - V\angle 0^\circ}{8\angle 90^\circ} = \frac{25839\angle 1.23^\circ - 28868\angle 0^\circ}{8\angle 90^\circ}$

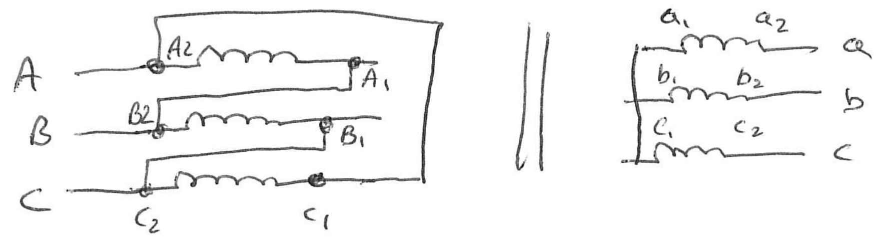
$$= \underline{\underline{385.6\angle 79.6^\circ A}}$$ (p.f. = 0.18 leading)

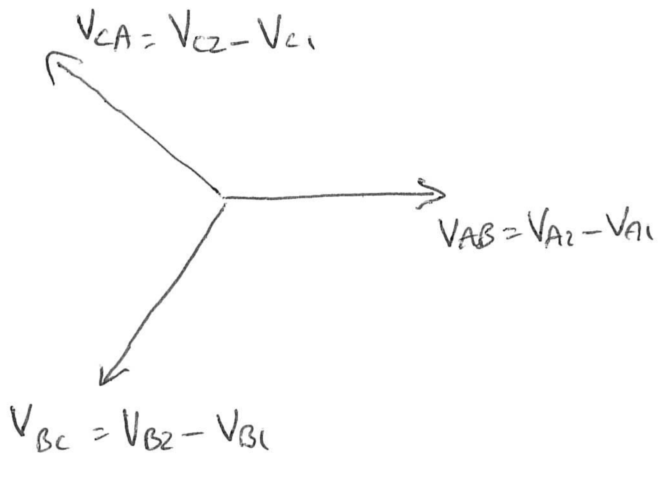
QUESTION 4

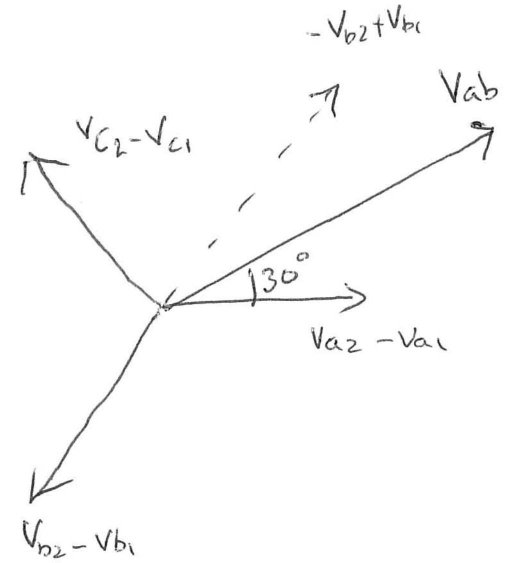
(a) Conditions preferred when operating transformers in parallel:

- Same no-load voltage ratios - small differences will lead to circulating currents even on no-load, and incorrect load sharing
- Same per unit impedance - magnitude only would lead to correct sharing of MVA, but not at the same power factors. Difference will lead to unbalanced sharing
- Ideally same R/X ratio as well as above to ensure loads shared at the same power-factor.
- Must have the same phase sequence / same phase group.

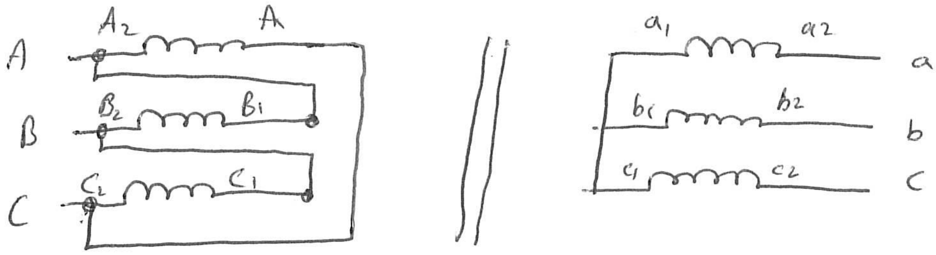
(b) Dy11 Delta - star connection

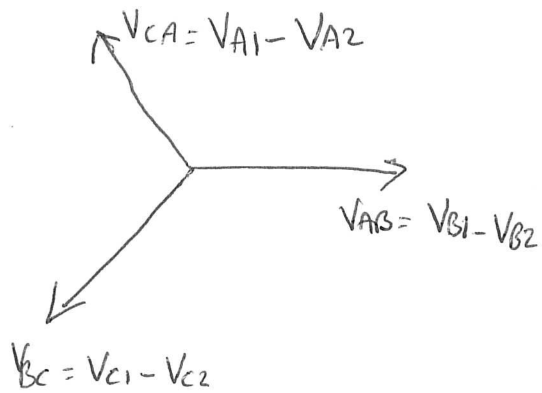


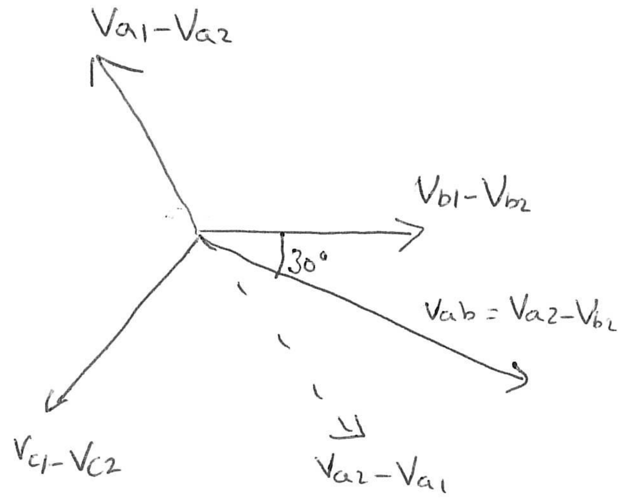




Primary voltage is in phase with respective secondary voltage but scaled by the turns ratio. Consequently for the Dy11 there is a 30° forward phase shift between secondary and primary terminals.







For Dy1 there is a 30° lagging phase shift between the secondary and primary terminals.

(c)(i) Choose a base of 8 MVA:-

$$Z_{pu1} = 0.03 + j0.06 = 0.0671\angle 63.4^\circ$$

$$Z_{pu2} = (0.05 + j0.15) \cdot \frac{8}{4} = 0.1 + j0.3 = 0.3162\angle 71.6^\circ$$

$$Z_{puT} = Z_{pu1} + Z_{pu2} = 0.13 + j0.36 = 0.383\angle 70.14^\circ$$

$$VA_1 = 10\angle 45.6^\circ \times \left(\frac{0.3162\angle 71.6^\circ}{0.383\angle 70.14^\circ}\right)^* = 10\angle 45.6 \times \left(0.826\angle 1.46^\circ\right)^*$$

$$= \underline{\underline{8.26\angle 44.14^\circ \text{ MVA}}}$$

(p.f. = 0.718)

$$VA_2 = 10\angle 45.6^\circ \times \left(\frac{0.0671\angle 63.4^\circ}{0.383\angle 70.14^\circ}\right)^* = 10\angle 45.6^\circ \times \left(0.175\angle -6.74^\circ\right)^*$$

$$= \underline{\underline{1.75\angle 52.34^\circ \text{ MVA}}}$$

(p.f. = 0.611 lag)

(c)(ii) Transformer 1 (8MVA Unit) operates at $\frac{8.26}{8} \times 100 = 103\%$ of its full load rating (ie. overloaded)

Transformer 2 (4MVA unit) operates at $\frac{1.75}{4} \times 100 = 43.8\%$ of its full load rating (ie underloaded)

(d)(i) For the transformers to share the load correctly the per unit impedances, relative to the transformers own MVA rating must be equal:

Unit 1 $(0.03 + j0.06)$ on an 8MVA base
Unit 2 $(0.05 + j0.15)$ on a 4MVA base

Since unit 1 is overloaded the reactor must be placed in series with this unit

$\therefore$ The size of the reactor is $(0.05 + j0.15) - (0.03 + j0.06) = \underline{\underline{0.02 + j0.09}}$ and its rating is $\underline{8MVA}$

$\therefore Z_{pu_1} + \text{reactor} = 0.05 + j0.15 = 0.158\angle 71.6°$

(ii) $$\text{New } Z_{puT} = (0.05 + j0.15) + (0.1 + j0.3) = 0.15 + j0.45 = 0.474\angle 71.6°$$

Hence $$VA_1 = 10\angle 45.6° \times \left(\frac{0.3162\angle 71.6}{0.474\angle 71.6}\right)^* = \underline{\underline{6.67\angle 45.6° \text{ MVA}}}$$

$$VA_2 = 10\angle 45.6 \times \left(\frac{0.158\angle 71.6}{0.474\angle 71.6}\right)^* = \underline{\underline{3.33\angle 45.6 \text{ MVA}}}$$

i.e. both units operate at 83% of there full load capacity

(e) Existing demand $= 10\text{ MVA} @ 0.7\text{ lag} = 7MW + 7.14MVAR$
Synchronous machine $= 4MVA @ 0.8\text{ lead} = 3.2MW - 2.4MVAR$
$\therefore$ New demand is $10.2MW + 4.74MVAR \equiv \underline{11.23\angle 24.9° \text{ MVA}}$

Since at full load the transformers could supply $\frac{10}{0.83} = 12.04MVA$ then the should be able to cope with the addition of the synchronous machine