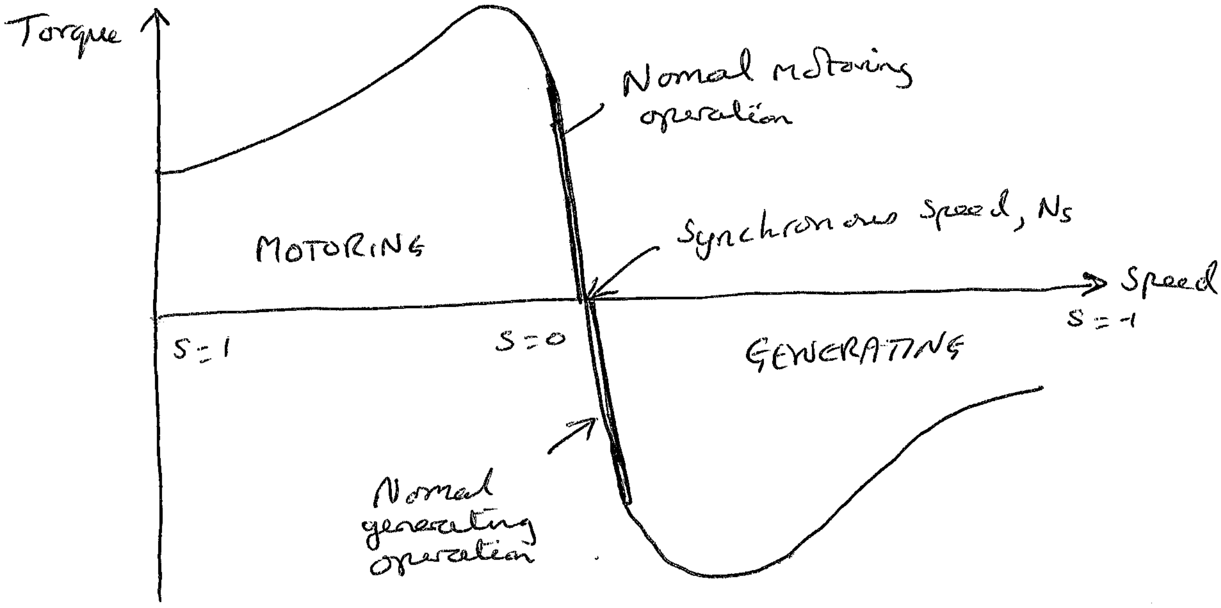
(a) Typical torque-speed characteristics of an Induction machine:



(b) $R_1 = 0.9\Omega \quad jX_1 = j8\Omega \quad R_2' = 1.7\Omega \quad jX_2' = j6.5\Omega$

$R_m = 850\Omega \quad jX_m = j200\Omega$

For a 50Hz supply and a 6 pole machine the synchronous speed in rpm is:

$$N_s = \frac{f.60}{PP} = \frac{50 \times 60}{3} = 1000 \text{ rpm}$$

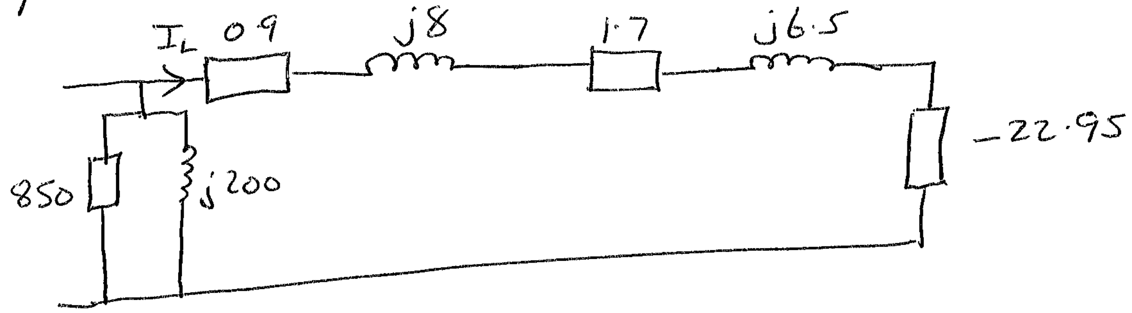
Since the generator is operating at 1080rpm (N_R)

$$\text{slip} = \frac{N_s - N_R}{N_s} = \frac{1000-1080}{1000} = -0.08$$

The resistance representing the mechanical input power to the machine is:

$$\frac{R_2'(1-s)}{s} = \frac{1.7(1-(-0.08))}{-0.08} = -22.95\Omega$$

Now the current can be obtained from the equivalent circuit:



$$I_L = \frac{11000}{\sqrt{3}} \times \frac{1}{(0.9+1.7-22.95)+j(8+6.5)} = 254.16\angle -144.53^\circ$$

Magnetizing branch

$$I_M = \frac{11000}{\sqrt{3}}\left(\frac{1}{850}+\frac{1}{j200}\right) = 32.62\angle -76.76^\circ \text{ A}$$

$\therefore$ Total phase current $= I_L + I_M = 254.16\angle -144.53 + 32.62\angle -76.76^\circ$
$= 268.2\angle -138.07^\circ$ A

Apparent power, $S = \sqrt{3}\, V_L I_L^* = \sqrt{3} \times 11000 \times 268.2\angle +138.07$
$= -3.802$ MW $+ 3.415$ MVAR.

I.E. 3.802 MW generated real power
3.415 MVAR reactive power.

(ii) Turbine mechanical input power:

$$P_{IN} = 3 I_L^2 \frac{R_2'(1-s)}{s} = 3 \times 254.16^2 \times (-22.95)$$
$$= \underline{-4.448 \text{ MW}}$$

Hence efficiency $= \frac{3.802}{4.448} \times 100 = \underline{\underline{85.4\%}}$

Check: Copper losses $= 3 I_L^2 (R_1 + R_2') = 3 \times 254.16^2 \times 2.6 = 0.504$ MW

Iron losses $= 3 \times \left(\frac{11000}{\sqrt{3}}\right)^2 \times \frac{1}{850} = 0.1424$ MW

Hence output + losses $= 3.802 + 0.504 + 0.1424 = \underline{\underline{4.448 \text{ MW}}}$

(iii) Factory base load = 15MVA @ 0.7 p.f. lag.

= 10.5MW + 10.712 MVAR

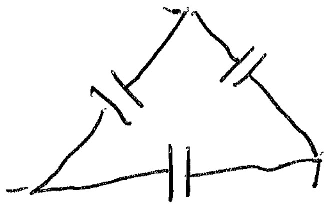
$\therefore$ Total including generator:

$$S = (10.5 - 3.802) + j(10.712 + 3.415)$$

$$= 6.698\,\text{MW} + 14.127\,\text{MVAR} = 15.63\angle 64.7\,\text{MVA}$$

Energy demand has fallen from 10.5 to 6.69MW, however the maximum demand tariff will increase by approx 4.2%
(15MVA $\rightarrow$ 15.63MVA)

(c) For the capacitor bank:



$$X_C = \frac{1}{2\pi f C} = 63.66\,\Omega.$$

$\therefore$ Reactive power supplied by the capacitor bank

$$Q_C = 3 \times \frac{11000^2}{63.66} = 5.702\,\text{MVAR}.$$

(i) Without generator:

Base load + Capacitors:

$$S_1 = 10.5\,\text{MW} + (10.712 - 5.702)\,\text{MVAR}$$

$$= 10.5\,\text{MW} + 5.01\,\text{MVAR} = 11.63\angle 25.5^\circ$$

p.f. = 0.9 lag.

(ii) With generator:

Base load + Capacitor + generator

$$S_2 = (10.5 - 3.802)\,\text{MW} + (10.712 - 5.702 + 3.415)\,\text{MVAR}$$

$$= 6.688\,\text{MW} + 8.425\,\text{MVAR} = 10.76\angle 51.5^\circ$$

p.f. = 0.622 lag.

(d) Installing the capacitor bank has advantages even when the generator is not running. Although the energy demand remains at 10.5MW the MVA rating has fallen from 15MVA to 11.63MVA resulting in reduced Maximum Demand and Availability Charge tariffs.

With the generator running there is a reduction in the energy charge from 10.5MW to 6.698MW. The Maximum Demand and Availability Charge are also reduced as the MVA rating is now 10.76MVA compared to 15MVA initially.

(a) $$P = \frac{V_S V_R \sin\delta}{X}$$

Power flow is increased by:

→ Increasing operating voltage ($P \propto V^2$)

However this requires large transmission towers (clearance)

Increase insulation requirements

Corona loss needs to be limited

Design of switchgear

Switching transient problems

→ Reduce line reactance

Use parallel circuits

Use bundled conductors

However reducing X increases fault levels.

(b) Fault levels are reduced by:

- inserting fault limiting reactors such as sectionalised busbar reactors, tiebar reactors, generator reactors, feeder reactors
- Use dc links to interconnect separate parts of a large power system.
- Reduce system interconnection by having normally open isolators and rings which still enable system security by providing alternative routes once a fault has been isolated.

(c) (i) In order to determine the required MVA rating of the circuit breakers we need to find the fault level at points A and B.

Using a reference base of 120MVA

G1 and G2 remain unchanged at 0.25pu

G3 (0.15pu on 90MVA base):

$$= 0.15 \times \frac{120}{90} = 0.2\,pu$$

GRID INFEED (250MVA into 1.0pu reactor)

$$= 1.0 \times \frac{120}{250} = 0.48\,pu$$

T1 (0.6pu on 300MVA base):

$$= 0.6 \times \frac{120}{300} = 0.24\,pu$$

T2 (0.4pu on 300MVA base):

$$= 0.4 \times \frac{120}{300} = 0.16\,pu$$

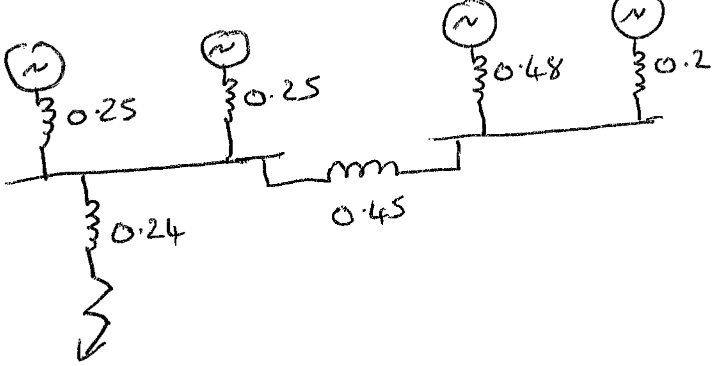
Reactor:

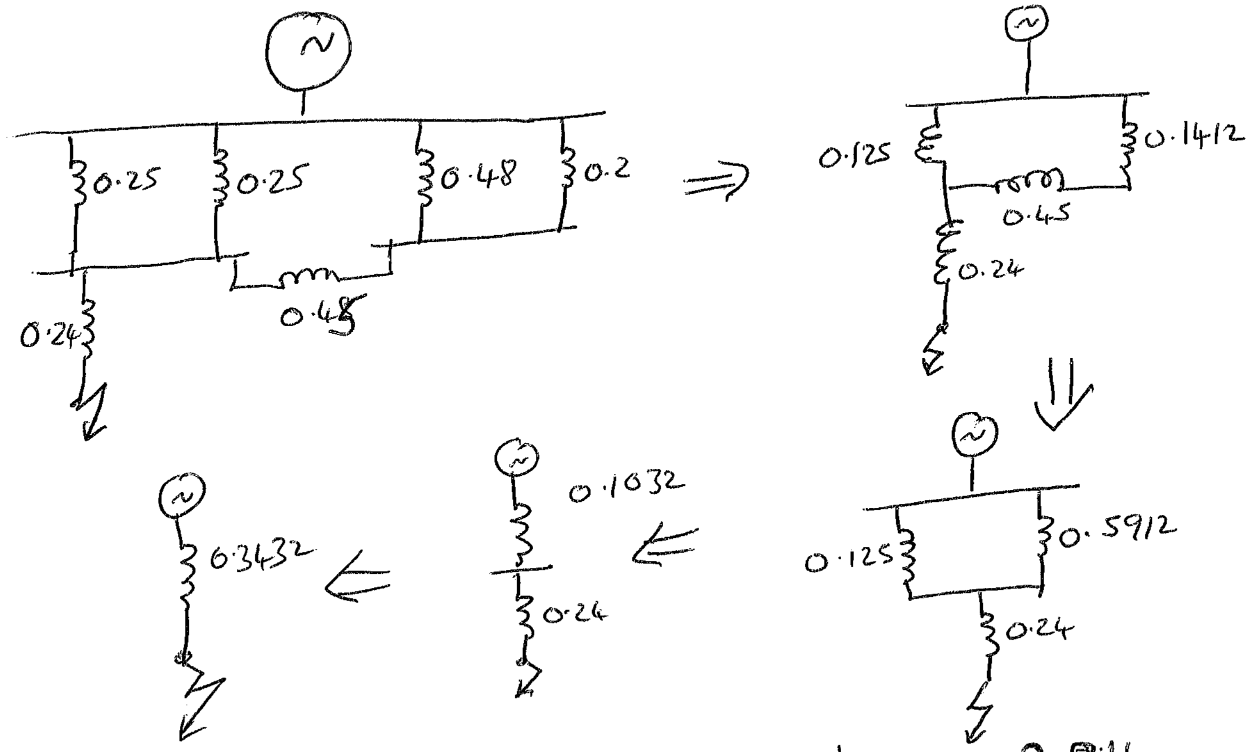
First calculate base impedance:

$$Z_b = \frac{V_b^2}{MVA_b} = \frac{20000^2}{120 \times 10^6} = 3.333\Omega$$

$$\therefore Z_{pu} = \frac{1.5}{3.333} = 0.45\,pu$$

For fault at point A:



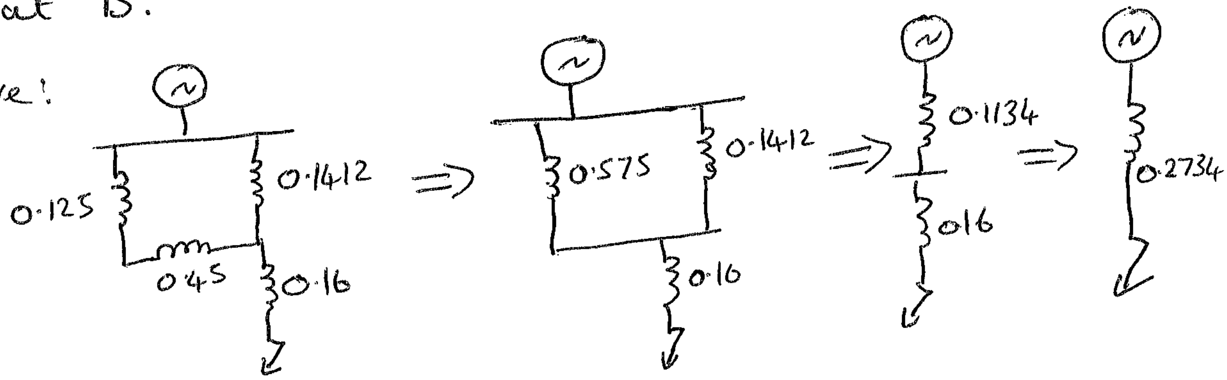


Therefore pu fault level at A $= \frac{1}{X_{pu}} = \frac{1}{0.3432} = 2.914\,pu$

Actual fault level at A $= 120 \times 2.914 = 349.7 \simeq \underline{\underline{350\,MVA}}$

For fault at B:

From above:



Therefore pu fault level at B $= \frac{1}{X_{pu}} = \frac{1}{0.2734} = 3.66\,pu$

Actual fault level at B $= 120 \times 3.66 = 439.2 \simeq \underline{\underline{440\,MVA}}$

(ii) First we need to find the pu fault current in G1 – work back through diagrams:

For a 3-phase fault at B the pu fault current is:

$$I_{pu} = \frac{1}{X_{pu}} = 3.66\,pu$$

From previous diagrams the pu current in the left hand branch (G1 & G2) is:

$$I_{puLH} = \frac{3.66 \times 0.1412}{(0.575 + 0.1412)} = 0.7216\text{pu}$$

Since G1 and G2 have the same pu impedance then the current divides equally.

$$I_{pu\_gen1} = \frac{0.7216}{2} = 0.3608 \text{ pu}$$

Base current at G1:

$$I_B = \frac{MVA_B}{\sqrt{3}\, V_B} = \frac{120 \times 10^6}{\sqrt{3} \times 20 \times 10^3} = 3464\text{A}$$

∴ Line current for gen 1 is:

$$I_{LINE} = 0.3608 \times 3464 = 1249\text{A}$$

However the generator is delta connected hence:

$$I_{phase-gen1} = \frac{1249}{\sqrt{3}} = \underline{\underline{721\text{A}}}$$

(iii) Maximum current will flow when reactance is minimum, ie for a fault on one of the busbars.

For fault on busbar 1:

$$I_{pu} = \frac{1}{X_{pu}} = \frac{1}{0.1032} = 9.69\text{pu}$$

Hence pu current through reactor is $9.69 \times \frac{0.125}{(0.125 + 0.5912)} = 1.691\text{ pu}$

For fault on busbar 2:

$$I_{pu} = \frac{1}{X_{pu}} = \frac{1}{0.1134} = 8.818\text{pu}$$

Hence pu current through reactor is $\frac{8.818 \times 0.1412}{(0.1412 + 0.575)} = 1.738\text{ pu}$

Worst case is for fault on busbar 2.

Current through reactor $= I_{pu} \times I_B = 1.738 \times 3464 = \underline{\underline{6020\text{A}}}$

(a) $Z_A = 10 - j3 = 10.44\angle{-16.7^\circ}\ \Omega$

$Z_B = 7 + j12 = 13.89\angle 59.74^\circ\ \Omega$

$Z_C = 9 + j5 = 10.3\angle 29.1^\circ\ \Omega$

$V_{AN} = \frac{400}{\sqrt{3}}\angle 0^\circ$ (REFERENCE) $\quad V_{BN} = \frac{400}{\sqrt{3}}\angle{-120^\circ} \quad V_{CN} = \frac{400}{\sqrt{3}}\angle{-240^\circ}$

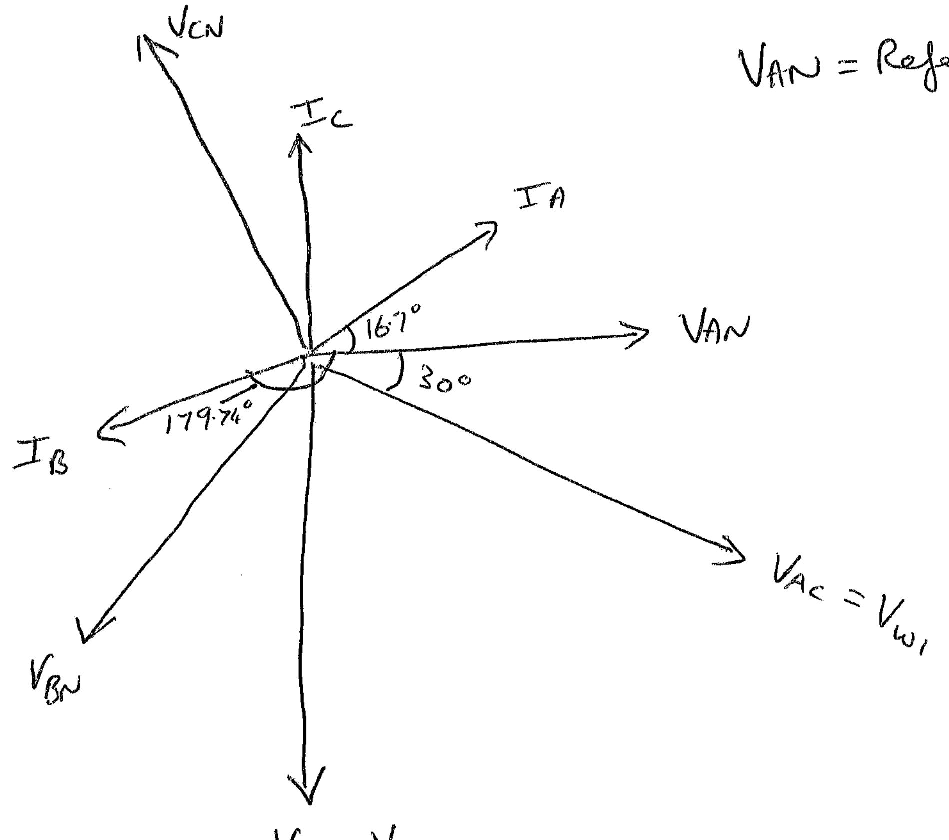
$$I_A = \frac{230.9\angle 0^\circ}{10.44\angle{-16.7^\circ}} = \underline{\underline{22.12\angle 16.7^\circ\ A}}$$

$$I_B = \frac{230.9\angle{-120^\circ}}{13.89\angle 59.74^\circ} = \underline{\underline{16.62\angle{-179.74^\circ}\ A}}$$

$$I_C = \frac{230.9\angle{-240^\circ}}{10.3\angle 29.1^\circ} = \underline{\underline{22.42\angle{-269.1^\circ}\ A}}$$

$$I_N = I_A + I_B + I_C = \underline{\underline{29.01\angle 81.64^\circ\ A}}$$

(b)(i)



V_{AN} = Reference.

Wattmeter W1 reads $P_1 = V_{AC} \cdot I_A \cos\phi_1$

ϕ_1 is the angle between V_{AC} and I_A

$$\phi_1 = 16.7^\circ + 30^\circ = 46.7^\circ$$

Wattmeter W_2 reads $P_2 = V_{BC} \cdot I_B \cdot \cos\phi_2$

ϕ_2 is the angle between V_{BC} and I_B

$$\phi_2 = 179.74 - 90 = 89.74^\circ$$

$$\therefore P_1 = 400 \times 22.12 \times \cos 46.7^\circ = 6068.1\,W$$

$$P_2 = 400 \times 16.62 \times \cos 89.74^\circ = 30.17\,W$$

$$\therefore P_1 + P_2 = 6068.1 + 30.17 = \underline{\underline{6098.27\,W}}$$

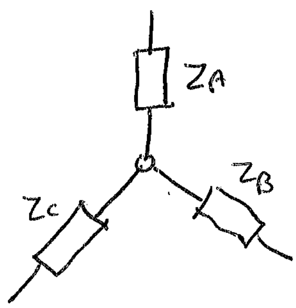
(iii) Compare with the sum of the I^2R in each phase:

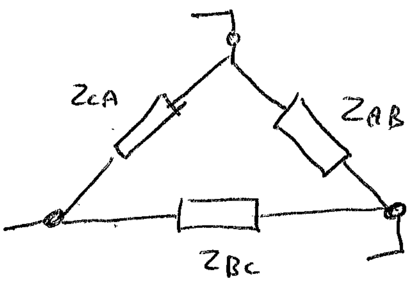
$$P_{ACT} = (22.12^2 \times 10) + (16.62^2 \times 7) + (22.42^2 \times 9) = \underline{\underline{11350\,W}}$$

$$\therefore \text{Error} = \frac{11350 - 6098.27}{11350} = \underline{\underline{46.3\%}}$$

(iv) The two wattmeter method is only applicable to balanced systems or 3-wire unbalanced systems (i.e. $I_N = 0$). To measure power in a 4-wire system use 3 wattmeters with voltage coils between each line and neutral, or use 1 wattmeter and switch between phases.

(c) The neutral is now open circuit so use star-delta transformation to find line currents:





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

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

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

$$Z_{AB} = Z_A + Z_B + \frac{Z_A Z_B}{Z_C} = (10-j3)+(7+j12)+\frac{(10-j3)(7+j12)}{(9+j5)}$$

$$= 30.67 + j12.406$$

$$Z_{BC} = Z_B + Z_C + \frac{Z_B Z_C}{Z_A} = (7+j12)+(9+j5)+\frac{(7+j12)(9+j5)}{(10-j3)}$$

$$= 12.34 + j30.20$$

$$Z_{CA} = Z_A + Z_C + \frac{Z_C Z_A}{Z_B} = (10-j3)+(9+j5)+\frac{(10-j3)(9+j5)}{(7+j12)}$$

$$= 24.24 - j3.694$$

Taking V_{AB} as reference.

$$I_{AB} = \frac{400\angle 0^\circ}{(30.67+j12.406)} = 12.09\angle -22.03^\circ \text{ A}$$

$$I_{BC} = \frac{400\angle -120^\circ}{(12.34+j30.20)} = 12.26\angle 172.23^\circ \text{ A}$$

$$I_{CA} = \frac{400\angle -240^\circ}{(24.24-j3.694)} = 16.313\angle 128.66^\circ \text{ A}$$

$$\therefore I_A = I_{AB} - I_{CA} = \underline{\underline{27.5\angle -38.9^\circ}} \text{ A}$$

$$I_B = I_{BC} - I_{AB} = \underline{\underline{24.16\angle 165.15}} \text{ A}$$

$$I_C = I_{CA} - I_{BC} = \underline{\underline{11.25\angle 79.99^\circ}} \text{ A}$$

$$V_{AO} = I_A Z_A = \underline{\underline{287.1\angle -55.6^\circ}} \text{ V}$$

$$V_{BO} = I_B Z_B = \underline{\underline{335.64\angle -135.1^\circ}} \text{ V}$$

$$V_{CO} = I_C Z_C = \underline{\underline{115.83\angle 109.04^\circ}} \text{ V}$$

(ii) Since V_{AB} is reference $V_{AC} = 400\angle -60^\circ$ $V_{BC} = 400\angle -120^\circ = 400\angle 240^\circ$ and currents calculated above are with respect to V_{AB}.

Wattmeter W_1 reads,

$$W_1 = 400 \times 27.5 \times \cos(60 - 38.9) = 10262.5\,W$$

Wattmeter W_2 reads

$$W_2 = 400 \times 24.16 \cos(240 - 165.16) = 2527.3\,W$$

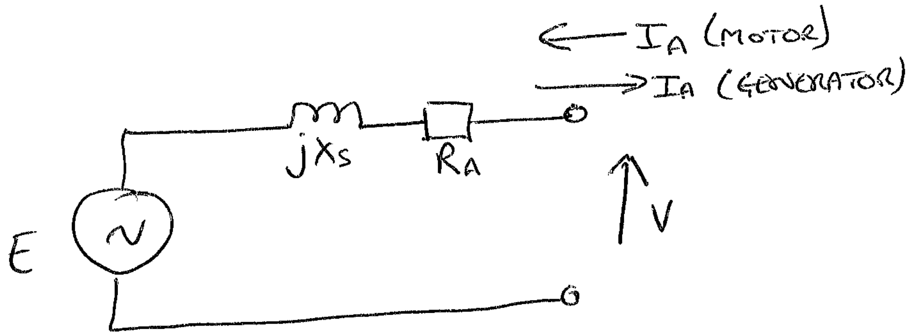
$$W_1 + W_2 = \underline{\underline{12789.8\,W}}$$

(iii) $P_{ACT} = I_A^2 R_A + I_B^2 R_B + I_C^2 R_C$

$$= (27.5^2 \times 10) + (24.16^2 \times 7) + (1.25^2 \times 9)$$

$$= \underline{\underline{12787.6\,W}}$$ (correct within tolerances).

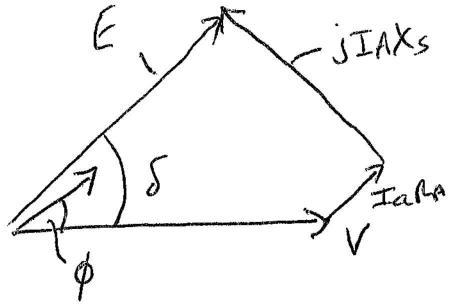
(a)



For a motor: $V = E + I_A R_A + jI_A X_S$

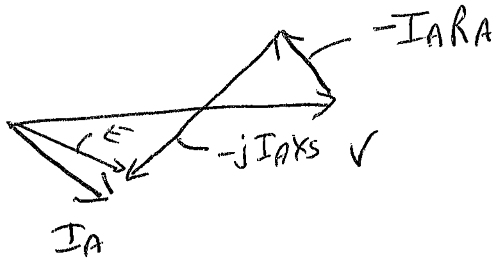
For a generator: $V = E - I_A R_A - jI_A X_S$

Phasor diagram for generator on leading p.f.



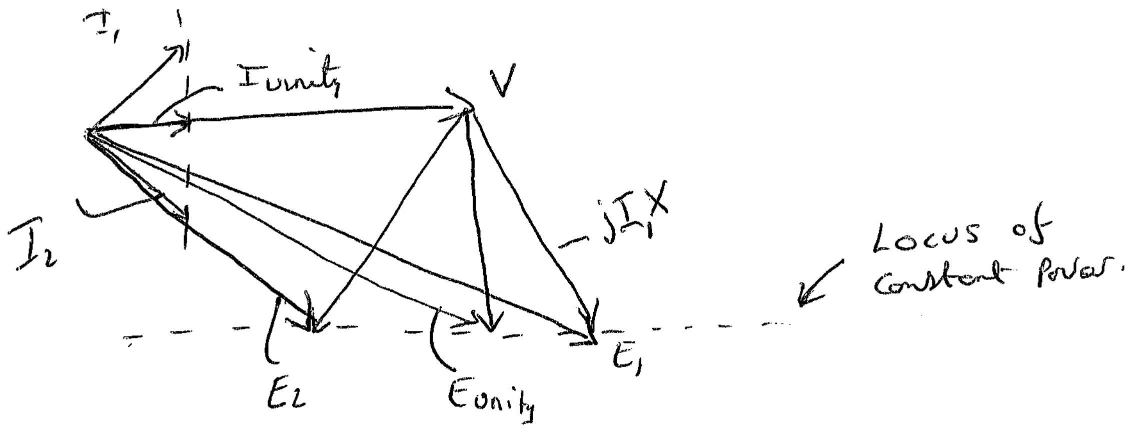
$V + I_A R_A + jI_A X_S = E$

Phasor diagram for motor on lagging p.f



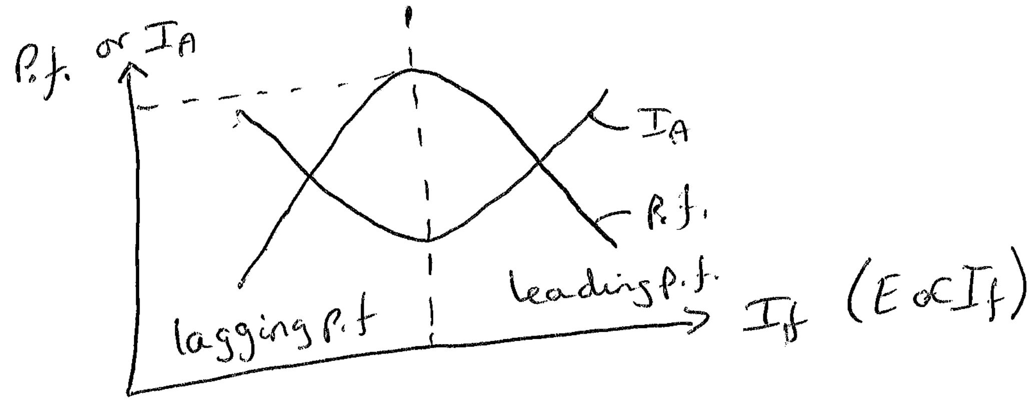
$V - I_A R_A - jI_A X_S = E$

(b) Phasor diagram when working on an infinite busbar supplying a constant mechanical load power whilst the excitation is varied:



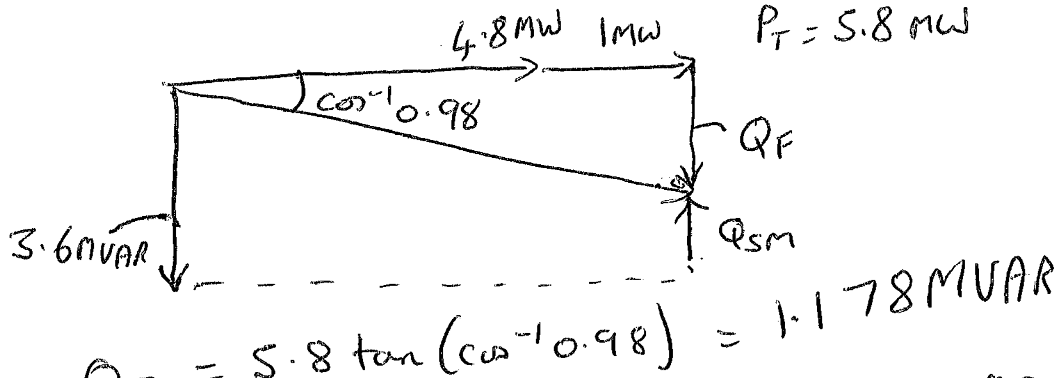
E follows the locus of constant power ($E \sin\delta$ is constant). The current phasors are at 90° to the jIX phasors. These also will follow another locus of constant power (vertical dotted line).
When the motor operates at unity p.f. $\phi = 0$ and the current has its minimum value (I unity).

This results in "V" curves.



(c) Manufacturing company general load 6MVA at 0.8 p.f. lag
$$S = 4.8\,MW + 3.6\,MVAR.$$

The syncronous machine provides an additional 1MW of power and will be used to reduce the reactive power to a p.f. of 0.98 lagging.



$$Q_F = 5.8 \tan(\cos^{-1} 0.98) = 1.178\,MVAR$$

$$\text{Hence } Q_{SM} = 3.6 - 1.178 = 2.422\,MVAR$$

The MVA rating of the synchronous machine is:

$$S = \sqrt{1^2 + 2.422^2} = \underline{\underline{2.62\,MVA}}$$

and its power-factor is, $\cos\phi = \dfrac{1}{2.62} = \underline{\underline{0.382 \text{ leading}}}$

(ii) Since $S = \sqrt{3}\, V_L I_L$

then $I_L = \dfrac{S}{\sqrt{3}\, V_L} = \dfrac{2.62 \times 10^6}{\sqrt{3} \times 11000} = 137.5A$

and this leads the voltage by $\cos^{-1} 0.382 = 67.55°$

ie. $\underline{\underline{I_L = 137.5 \angle 67.55° \; A}}$

For a synchronous motor

$$E\angle\delta = V\angle 0° - jIX = \frac{11000}{\sqrt{3}}\angle 0° - 137.5\angle 67.55° \times 12\angle 90°$$

$$= 6351\angle 0° - 1644\angle 157.55$$

$$= 7895.4\angle -4.56°$$

Excitation Emf $= 7895.4V$

Load angle $= 4.56°$

(iii) Overnight the power is reduced to 800kW:

Since $P = \dfrac{3VE}{X}\sin\delta \Rightarrow \sin\delta = \dfrac{PX}{3VE}$

$$\therefore \sin\delta = \frac{800 \times 10^3}{3} \times \frac{12}{6351 \times 7000} = 0.072$$

$$\therefore \delta = 4.13°$$

$$I\angle\phi = \frac{V\angle 0° - E\angle\delta}{X\angle 90°} = \frac{6351\angle 0° - 7000\angle -4.13}{12\angle 90}$$

$$= \underline{\underline{67.3\angle 51.4° \; A}}$$

(d) Large industrial customers charged by 2 tier tariff structures (both peak VA and energy consumed). Hence improving the p.f. will reduce the VA which in turn reduces the Maximum Demand charge (and the Availability charge.)