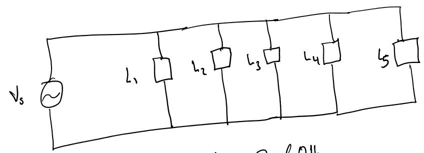
Tuesday, January 23, 2024 5:13 PM

Single phase $V_{rms} = 416V$ source Voltage
5 Loads // connectn



All Loads operate @ 416V @ 60Hz

@ L_1 $S_{L1} = \underbrace{40KW}_{P_{L1}} + j\underbrace{25KVAR}_{Q_{L1}}$ inductn motor

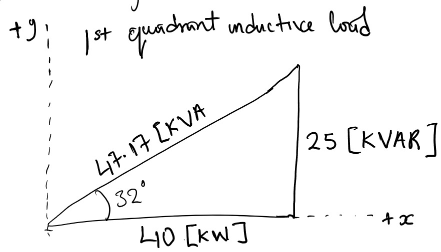
$$\theta_{L1} = \tan^{-1}\left(\frac{Q_{L1}}{P_{L1}}\right) = \tan^{-1}\left(\frac{25K}{40K}\right)$$

$$\theta_{L1} = 32.0^\circ$$

$$|S_{L1}| = \sqrt{40^2 + 25^2}\ [KVA]$$

$$|S_{L1}| = 47.17\,[KVA]$$

Power Triangle @ L_1



@ L_2 Synchronous Motor with 30Hp output
@ 80% efficiency & 0.95 pf leading

note Conversion rate for Hp → KW
1Hp → 0.746KW

real Power: $P = 30\cancel{Hp} \times 0.746\dfrac{KW}{\cancel{Hp}}$

$P = 22.38\,[KW]$

$P_{L2} = \dfrac{P}{Efficiency} = \dfrac{22.38\,KW}{0.8}$

$P_{L2} = 27.98\,[KW]$

Apparent Power: $|S_{L2}| = \dfrac{P_{L2}}{p.f} = \dfrac{27.98\,KW}{0.95}$) KVA

$S_{L2} = 29.45\,KVA$

Reactive Power $Q_{L2} = \sqrt{S_{L2} - P_{L2}} = \sqrt{29.45^2 - 27.98^2}\ [KVAR]$

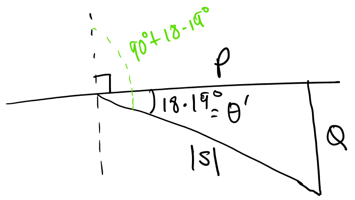
$Q_{L2} = 9.19\,[KVAR]$

p.f = 0.95 leading

$\theta = \cos^{-1}(0.95) + 90^\circ = 18.19^\circ + 90^\circ$

$\theta = 108.19^\circ$

Reactive Power: Q_{L2} first sketch the Power triangle



$\therefore S_{L_2} = P_{L_2} + jQ_{L_2}$

$S_{L_2} = 27.98\,KW + j\,9.19\,KVAR$

$S_{L_2} = P_{L_2} + jQ_{L_2}$

$S_{L_2} = 27.98\,KW + j\,9.19\,KVAR$

@ L_3 single phase transformer drawing primary current $I = 52\angle -25^\circ\ A$

for Transformer the primary side is where Input power comes through

we are interested in input Power

$V_{input} = 416\,V$ @ $60\,Hz$

let $\phi_{V_{input}} = 0^\circ$

$\therefore V_{input} = 416\cos(2\pi(60)t + 0^\circ)$

$V_{input} = 416\cos(377t) = 416\angle 0^\circ$

$I_{prime} = 52\angle -25^\circ\ A = 47.13 - j\,21.98\ [A]$

real Power: $P_{L_3} = |V||I|\cos(\phi_V - \phi_I)$

$P_{L_3} = (416)(52)\cos(0 - (-25))$

$P_{L_3} = 19.61\,[KW]$

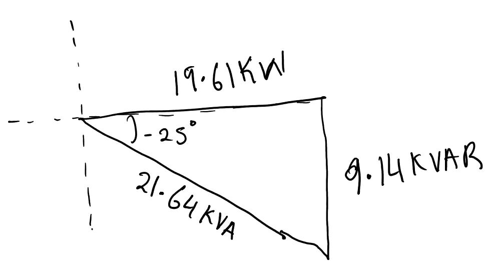
Apparent Power: $S_{L_3} = \dfrac{P_{L_3}}{\cos(\theta)} = \dfrac{19.61\,K}{\cos(25)}$

$S_{L_3} = 21.64\,[KVA]$

Reactive power: $Q_{L_3} = |V||I|\sin(\theta) = 416 \times 52\sin(25)$

$Q_{L_3} = 9.14\,[KVAR]$

Power Triangle @ L_3



@ L_4 electronic ballast light drawing 22KW real power

p.f of 0.96 lagging

Apparent Power: $|S_{L_4}| = \dfrac{P_{L_4}}{p.f} = \dfrac{22\,KW}{0.96}$

$|S_{L4}| = 22.92 \text{ KVA}$

Reactive Power: $Q_{L4} = \sqrt{S_{L4}^2 - P_{L4}^2}$

$Q_{L4} = \left(\sqrt{22.92^2 - 22^2}\right) \text{ KVAR}$

$Q_{L4} = 6.42 \text{ [KVAR]}$ lagging

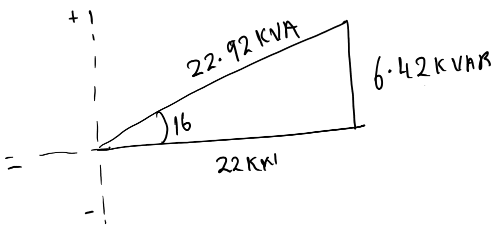
$S_{L4} = P_{L4} + jQ_{L4}$

$S_{L4} = (22 + j6.42) \text{ [KVA]}$

$\theta = \tan^{-1}\left(\frac{Q}{L}\right) = \tan^{-1}\left(\frac{6.42}{22}\right)$

$\theta = 16^\circ$

Power Triangle @ L_4



@ L_5 miscellaneous loads $|S_{L5}| = 12 \text{ KVA} \angle 20^\circ$

$S_{L5} = P_{L5} + jQ_{L5}$

$P_{L5} = |S_{L5}| \cos\theta$

$P_{L5} = 12\cos(20) \text{ [KW]}$

$P_{L5} = 11.28 \text{ [KW]}$

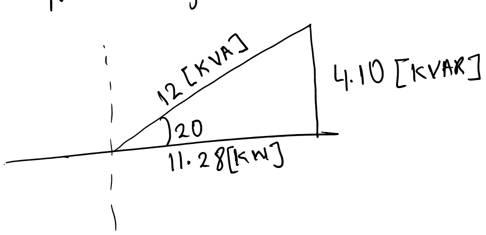
$Q_{L5} = |S_{L5}| \sin\theta$

$Q_{L5} = 12\sin(20) \text{ [KVAR]}$

$Q_{L5} = 4.10 \text{ [KVAR]}$

$S_{L5} = (11.28 + j4.10) \text{ [KVA]}$

Power triangle @ L_5



1b

$P_T = P_{L1} + P_{L2} + P_{L3} + P_{L4} + P_{L5}$

$P_T = 40\text{ KW} + 27.98\text{ KW} + 19.61\text{ KW} + 22\text{ KW} + 11.28\text{ KW}$

$P_T = 120.87 \text{ KW}$

$P_T = 120.87\ \text{kW}$

$Q_T = Q_{L_1} + Q_{L_2} + Q_{L_3} + Q_{L_4} + Q_{L_5}$

$Q_T = 25\ \text{kVAR} + 9.19\ \text{kVAR} + 9.14\ \text{kVAR} + 6.42\ \text{kVAR} + 4.10\ \text{kVAR}$

$Q_T \quad 53.83\ \text{kVAR}$

$S_T = \sqrt{P_T^2 + Q_T^2} = \sqrt{120.87^2 + 53.83^2}\ [\text{kVA}]$

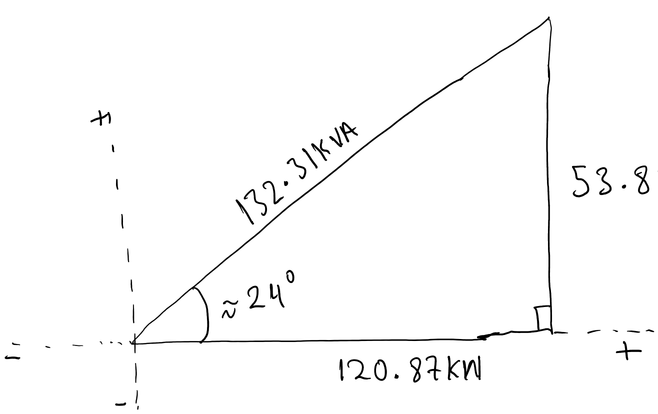
$S_T \approx 132.31\ \text{kVA}$

from above $S_T = \sum_{n=1}^{5} S_{Ln} = 133.18\ \text{kVA}$

$\theta = \tan^{-1}\left(\frac{Q_T}{P_T}\right) = \tan^{-1}\left(\frac{53.83}{120.87}\right)$

$\theta = 24^\circ$

1c



1d

Total current delivered to the load $I_T = \frac{\text{Power delivered } (S_T)}{\text{Supplied Voltage}}$

$I_T = \frac{132.31\ \text{K}\cancel{\text{V}}\text{A}}{416\ \cancel{\text{V}}}$

$I_T = 318.05\ \text{A}$

1^{st} phase 4.16V @ 60Hz ⇒ $V_{(s)}$

500KVA @ 0.75 lagging ⇒ load

desired p.f correctn = 0.96 lagging or higher

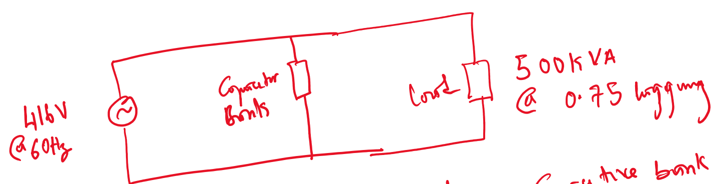
p.f Capacitive bank ⇒ 0.25mF × n   n = # of Capacitors

↳ // with the load

Target ⟶ Determine the # of Capacitors needed to get to the desired p.f of 0.96 lagging

↳ Actual p.f seen @ the load after all Caps are switched ON

Step 1 Draw the Circuit & Power triangle



Step 2 Determine power triangle without the Capacitive bank

$P.f_1 = \frac{P}{S_1}$ where $P.f_1 = 0.75$ lagging
$S = 500KVA$

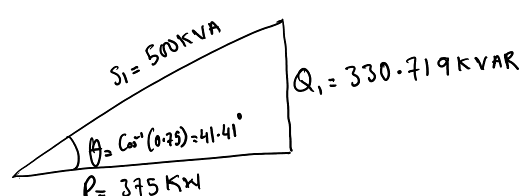
$P = p.f_1 \; S$

$P = 0.75 \times 500KVA = 375KW$

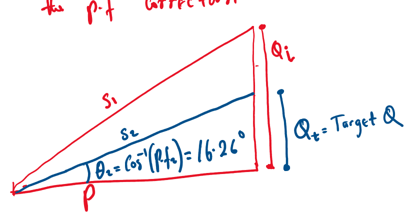
$Q_1 = \sqrt{S^2 - P^2} = \sqrt{500^2 - 375^2}$ KVAR

$Q_1 = 330.719KVAR$

Power Triangle 1



Step 3 use desired p.f to determine Reactive power Needed for the p.f correction



$Q_t = \tan(\theta_2) \times P$

$Q = \tan(16.26) \times 375KW$

$Q_t = 109.375KVAR$

$.719 - 109.375$ [KVAR]

$Q = \tan(16.26) \times 375kW$

$Q_t = 109.375 KVAR$

$Q_{needed} = Q_i - Q_t = 330.719 - 109.375\ [KVAR]$

$Q_{needed} = 221.344 KVAR$

$Q = \frac{V_{rms}^2}{X_{CT}}$ $\quad X_{CT}$ = total capacitance @ Capacitive Bank

$V_{rms} = 416V$

$X_{CT} = \frac{(416)^2 V}{221.344 KVAR} = 0.782\,\Omega$

$X_c = \frac{-1}{j\omega c} = \frac{1}{\omega c}$ where $\omega = 2\pi f = 2\pi(60)$

$C_T = \frac{1}{\omega X_{CT}} = \frac{1}{2\pi(60)(0.782\Omega)}$

$C_T = 3.393\,mF$

Assuming the capacitors that make up the Capacitive Bank are in parallel

$\#\ \text{Capacitors} = \frac{C_T}{C}$ $\quad C = 0.25\,mF$, $C_T = 3.393\,mF$

$\#\ \text{Capacitors} = \frac{3.393\,mF}{0.25\,mF} = 13.572$ capacitors

$\#\ \text{Capacitors} \approx 14$ capacitors of $0.25\,mF$

Step 4 find p.f seen at the load after all capacitors are switch ON

$P_{(real\ power)} = 375\,KW$

$Q_{CT} = \frac{V_{rms}^2}{X_{CT_f}}$

$X_{CT_f} = \frac{1}{\omega C_{T_f}} = \frac{1}{2\pi(60)(14 \times 0.25\,mF)}$

$X_{CT_f} = 0.758\,\Omega$

$Q_{CT} = \frac{(416)^2 V}{0.758\,\Omega} = 228.306\,KVAR$

$\therefore$ Reactive power at Capacitive Bank $= 228.30\,KVAR$

Q_f = final Reactive power after all capacitor are turned ON

$Q_f = Q_i - Q_{CT}$

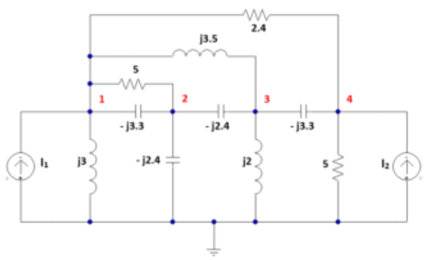
$Q_f = 330.719 - 228.306\ [KVAR]$

$Q_f = 102.413\,KVAR$

$p.f = \cos\left[\tan^{-1}\left(\frac{Q_f}{P}\right)\right]$ Since Real Power (P) for the system will stay the same

$p.f = \cos\left[\tan^{-1}\left(\frac{102.413\,KVAR}{375\,KW}\right)\right]$

$p.f = 0.965$



$I_1 = 30\cos(2\pi 60t + 35°)\ A;\ I_2 = 45\cos(2\pi 60t - 50°)\ A$

$\vec{V} = \vec{I} \cdot \vec{Z_K} \Rightarrow \bar{I} = \frac{\vec{V}}{Z_K} = \vec{I} = \vec{Y}\vec{V} \qquad \vec{Y} = \frac{1}{Z_K}$

Apply Nodal Analysis @ node 1

$$I_1 = \frac{V_1}{j3} + \frac{V_1 - V_2}{-j3.3} + \frac{V_1 - V_2}{5} + \frac{V_1 - V_3}{j3.5} + \frac{V_1 - V_4}{2.4}$$

$$I_1 = V_1\left[\frac{1}{j3} - \frac{1}{j3.3} + \frac{1}{5} + \frac{1}{j3.5} + \frac{1}{2.5}\right] + V_2\left[\frac{1}{j3.3} - \frac{1}{5}\right] + V_3\left[\frac{-1}{j3.5}\right] + V_4\left[\frac{-1}{2.4}\right]$$

Using Matlab

$I_1 = V_1[0.6 - j0.316] + V_2[-0.2 - j0.303] + V_3[0 + j0.286] + V_4[-0.417]$ interms of Impedance Z_K

$I_2 = 30A\angle 35°$

$30A\angle 35° = V_1[1.305 + j0.687] + V_2[-1.517 + j2.297] + V_3[0 - j3.5] + V_4[-2.4]$ interms of admittance $Y = \frac{1}{Z_K}$

Apply Nodal Analyses @ node 2

0 current @ summing junction

$$0 = \frac{V_2}{-j2.4} + \frac{V_2 - V_1}{-j3.3} + \frac{V_2 - V_1}{5} + \frac{V_2 - V_3}{-j2.4}$$

$$0 = V_1\left[\frac{1}{j3.3} - \frac{1}{5}\right] + V_2\left[\frac{-1}{j2.4} - \frac{1}{j3.3} + \frac{1}{5} - \frac{1}{j2.4}\right] + V_3\left[\frac{1}{j2.4}\right]$$

Using Matlab

$0 = V_1[-0.2 - j0.303] + V_2[0.2 + j1.136] + V_3[0 - j0.417]$ interms of Impedance Z_K

$0 = V_1[-1.517 + j2.299] + V_2[0.150 - j0.854] + V_3[0 + j2.4]$ interms of admittance Y

Apply Nodal Analysis @ Node 3

0 current @ Summing junction

$$0 = \frac{V_3 - V_2}{-j2.4} + \frac{V_3}{j2} + \frac{V_3 - V_1}{j3.5} + \frac{V_3 - V_4}{-j3.3}$$

$$0 = V_1\left[\frac{-1}{j3.5}\right] + V_2\left[\frac{1}{j2.4}\right] + V_3\left[\frac{-1}{j2.4} + \frac{1}{j2} + \frac{1}{j3.5} - \frac{1}{j3.3}\right] + V_4\left[\frac{1}{j3.3}\right]$$

$$0 = V_1[0 + j0.286] + V_2[0 - j0.417] + V_3[0 - j0.066] + V_4[0 - j0.303]$$ interms of Zs

$$0 = V_1[0 - j3.5] + V_2[0 + j2.4] + V_3[0 + j15.148] + V_4[0 + j3.3]$$ interms of Y

Apply Nodal Analysis @ Node 4

$$I_2 = \frac{V_4 - V_1}{2.4} + \frac{V_4 - V_3}{-j3.3} + \frac{V_4}{5}$$

$$I_2 = V_1\left[\frac{-1}{2.4}\right] + V_3\left[\frac{1}{j3.3}\right] + V_4\left[\frac{1}{2.4} - \frac{1}{j3.3} + \frac{1}{5}\right]$$

$$I_2 = V_1[-0.417] + V_3[0 - j0.303] + V_4[0.617 + j0.303]$$

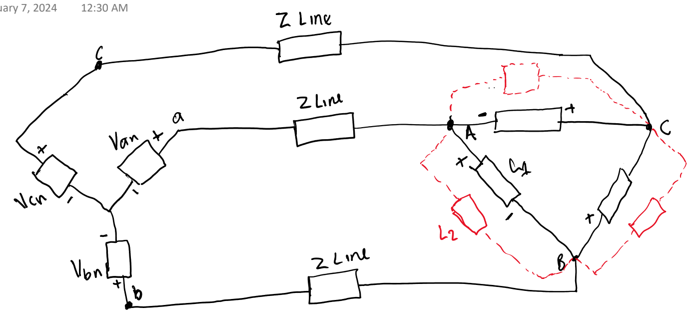
$$I_2 = 45A\angle 50^\circ$$

$$45A\angle 50^\circ = V_1[-2.4] + V_3[0 + j3.3] + V_4[1.306 - j0.642]$$

4x4 admittance Matrix

$$\vec{I} = \vec{Y} \cdot \vec{V}$$

$$\begin{bmatrix} 30A\angle 35^\circ \\ 0 \\ 0 \\ 45A\angle 50^\circ \end{bmatrix} = \begin{bmatrix} 1.305 + j0.687 & -1.517 + j2.299 & 0 - j3.5 & -2.4 \\ -1.517 + j2.299 & 0.150 - j0.854 & 0 + j2.4 & 0 \\ 0 + j3.5 & 0 + j2.4 & 0 + j15.148 & 0 + j3.3 \\ -2.4 & 0 & 0 + j3.3 & 1.306 - j0.642 \end{bmatrix} \cdot \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix}$$



$Z_{Line} = 2 + j\,\Omega$ $\quad V_S = @\ 60Hz$

$L_1 =$ Inductive 3ϕ $8.66KV$ $\quad S_{L_1} = 750KVA$ @ $0.6pf$ lagging

$L_2 =$ Lighting 3ϕ $8.66KV$ $\quad P_{L_2} = 540KW$ @ unity p.f $\therefore p.f = 1$

@ L_1: $V_{Load} = 8.66KV$ 3ϕ Δ $\qquad S_{L_1}/\phi = \frac{S_{L_1}}{3} = \frac{750KVA}{3} = 250KVA$

$V_{L-N} = \frac{V_{Load}}{\sqrt{3}} \approx 5KV$

$P_{L_1} = pf \times S_{L_1} = 0.6 \times 750KVA$

$P_{L_1} \approx 450KW$ $\qquad Q_{L_1} = \sqrt{S_{L_1}^2 - P_{L_1}^2}$

$P_{L_1}/\phi = \frac{P_{L_1}}{3}$ $\qquad Q_{L_1} = 600KVAR$

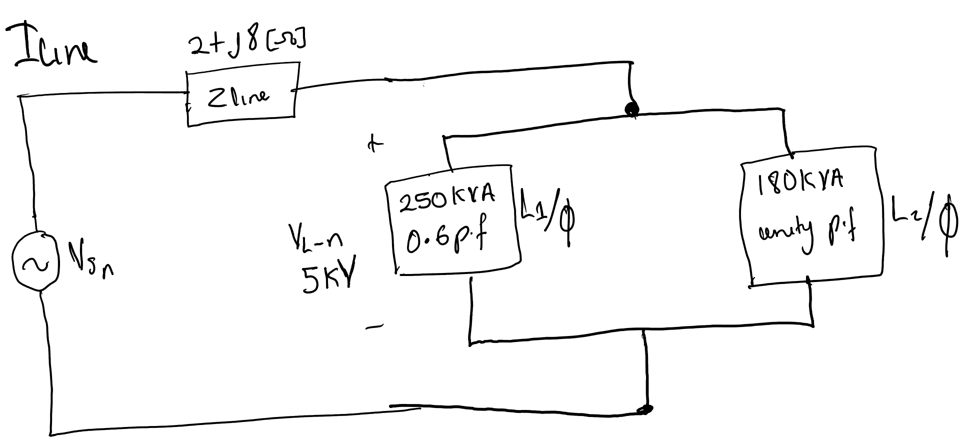
$P_{L_1}/\phi = 150KW$ $\qquad Q_{L_1}/\phi = \frac{Q_{L_1}}{3}$

$Q_{L_1}/\phi = 200KVAR$

@ L_2 with unity p.f $\quad S_{L_2} = P_{L_2}$ & $Q_{L_2} = 0$

$P_{L_2}/\phi = \frac{540KW}{3} = 180KW$

$S_{L_2}/\phi = 180KVA$



4b Magnitude of line Current

(4b) Magnitude of line Current

$$I_{Line} = \frac{S_T}{\sqrt{3}\, V_{Line}}$$ where $S_T = [P_{L_1} + P_{L_2}] + j\,[Q_{L_1} + Q_{L_2}]$

$S_T = [450K + 540K]W + j\,[600K + 0]VAR$

$S_T = 990KW + j\,600KVAR$

$S_T = \sqrt{990^2 + 600^2}\ [KVA] \angle \tan^{-1}\frac{600K}{990K}$

$S_T = 1157.63KVA \angle 31.22°$

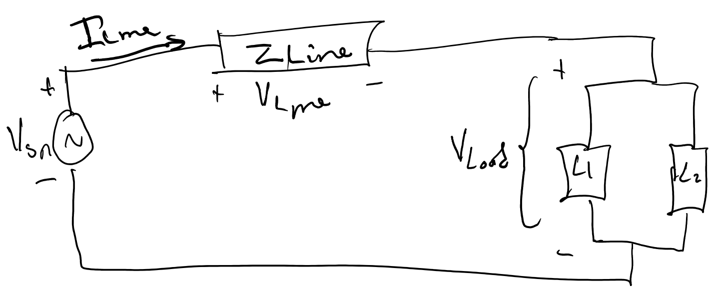
$$|I_{Line}| = \frac{1157.63\cancel{K}\cancel{V}A}{\sqrt{3} \times 8.66\cancel{K}\cancel{V}} = \boxed{77.18\ A}$$

4c) $V_{Line} = I_{Line} \cdot Z_{Line}$ where $I_{line} = 77.18A \angle -31.22°$ Current lags Voltage

$Z_{Line} = 2 + j8 = 8.25\Omega \angle 75.96°$

$V_{Line} = 77.18\,A \times 8.25\Omega \angle -31.22° + 75.96°$

$V_{Line} = \boxed{636.735V \angle 44.74°}$



$V_{sn} = V_{Load} + V_{Line}$

$V_{sn} = 5KV\angle 0° + 636.735V \angle 44.74°$

$V_{sn} \approx 5.45K + j\,448.19\ [V]$

$V_{sn} \approx \boxed{5.47KV \angle 4.70°}$ V_{s-n} @ Source

$V_{L-L} \approx \sqrt{3}\,V_{sn} = \boxed{9.47K\angle 4.7°[V]}$ V_{L-L} @ Source

4d) $Z_L = 2 + j8$

$P_{Z_L} = |I_{Line}|^2 \times Z_L(Real)$

$P_{Z_L} = 77.18^2 A \times 2$

$P_{Z_L} = 11.913\,KW$

$Q_{Z_L} = |I_{Line}|^2 \times Z_L\ Reactive$

$Q_{Z_L} = 77.18^2 A \times 8$

$Q_{Z_L} = 47.654\,KVAR$

$S_{Line}\ (\text{Polar form}) = 49.12 \angle 75.96^\circ\ [KVA]$

4e) 3ϕ power @ the source

$S_{3\phi} = I_{Line} \times V_{L-L} \times \sqrt{3}$ where $I_{Line} = 77.18A \angle -31.22^\circ$

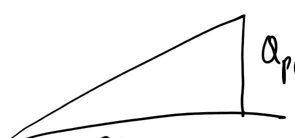
$V_{L-L} = 9.47KV \angle 4.7^\circ$

$S_{3\phi} = 77.18A \times 9.47\,KV \times \sqrt{3} \angle 32.22^\circ + 4.7^\circ$

$S_{3\phi} = 1265.94 \angle 36.92^\circ\ [KVA]$

$S_{3\phi} = 1012.09 + j760.44\ [KVA]$

4f) Power triangle @ Delta load using $S_T = 990 + j600\ [KVA]$



at unity p.f $Q = 0\ KVAR$

Q_{needed} for unity p.f $= Q_{present} - Q_{target}$

$Q_{needed} = 600\ KVAR$

$X_c = \dfrac{V_{L\Delta}^2}{Q_{needed}} = \dfrac{8.66^2\,K^2\,V}{600\,KVAR}$

$X_c = 124.99\,\Omega$

$C_T = \dfrac{1}{2\pi f X_c} = \dfrac{1}{2\pi(60)124.99}$

$C_T = 2.124 \times 10^{-5}\,F$

$C_T = 21.24\,\mu F$

for 3ϕ Delta Correction $C_\Delta = \dfrac{C_T}{3}$

$$C_\Delta = \frac{21.24\,\mu F}{3}$$

$$C_\Delta \approx 7.08\,\mu F$$

4g $\text{New } I_{Line} = \frac{\text{New } S_T}{\sqrt{3}\, V_{Line}}$ where $\text{New } S_T = 990\,\text{KVA}$ since $Q = 0$

$$\text{New } I_{Line} = \frac{990\,\cancel{\text{KV}}A}{\sqrt{3} \times 8.66\,\cancel{\text{KV}}}$$

$$\text{New } I_{Line} = 66.00\,A \angle 0^\circ$$

$$Z_L = 8.25 \angle 75.96^\circ\ [\Omega]$$

$$\text{Power loss @ Line} = (\text{New } I_{Line})^2 \times Z_{Line}$$

$$= (66.0A)^2 \times 8.25\,\Omega \angle 0^\circ + 75.96^\circ$$

$$= 35.94 \angle 75.96^\circ\ [\text{KVA}]$$

$$= 8.72 + j34.86\ [\text{KVA}]$$

$$\% \text{ improvement in real Power loss} = \frac{11.913 - 8.72}{11.913} \times 100$$

$$= 26.80\ \%\ \text{improvement}$$

4 Extra Credit

Power Cost = \$25 / MVA per hour

Generator Capacity Before unity p.f correction = $1265.94\ \cancel{KVA} \times \frac{1\ MVA}{1000\ \cancel{KVA}} = 1.265\ MVA$

Production Cost per hour = $\$ \frac{25}{\cancel{MVA}\ \text{per hour}} \times 1.265\ \cancel{MVA} = \$\ 31.63$ per hour

Annual Cost of production = $365 \times 24\ \cancel{hours} \times \$\ 31.63 / \cancel{hour} = \boxed{\$\ 277078.80}$

After p.f correction

$S_{3\phi} = \text{New } \hat{I}_{Line} \times V_{L-L} \times \sqrt{3}$

$= 66 \times 9.47 \times \sqrt{3} \angle 4.7$

$= \boxed{1082 \angle 4.7^\circ\ [KVA]}$ = New Capacitor of generator

New hourly production Cost = $\$ \frac{25}{\cancel{MVA}\ \text{per hour}} \times 1.082\ \cancel{MVA} = \$27.05$ per hour

New Annual production Cost = $365 \times 24\ \cancel{hours} \times \$\ 27.05 / \cancel{hours} = \boxed{\$\ 236958}$

Annual Savings After p.f correction = $\boxed{\$\ 40120.8}$