Problem 1 (25 points)

A food-services company with a 480 V, three-phase service entrance has the following set of loads:

$= 75\text{KBTU}$

- L_1 A 75,000 BTU/hr food dehydrator[1]
- L_2 A conveyor belt system consisting of 10 continuous-duty induction motors: each 5 HP, 81% efficient, PF = 0.73 lagging
- L_3 A 7 ton walk-in refrigeration unit:[2] COP of 1.2 and 0.78 lagging power factor
- L_4 A 20 kVA T8 fluorescent lighting system with electronic ballasting (PF = 0.93 leading)

Consider the case when all systems are fully loaded. Calculate the reactive power required to compensate this customer's load to a 0.92 lagging power factor.

LOAD 1:

$\rightarrow 75\text{K BTU/HR}$

$$|S_1| = 75{,}000 \frac{\text{BTU}}{\text{HR}} \cdot \frac{1\text{ KW}}{3.4\text{KBTU/HR}} = 22.1\text{ KW}$$

$$\boxed{\bar{S}_1 = 22.1\text{KVA}\angle 0^\circ}$$

LOAD 2:

$$P_{MECH} = (5\text{ HP})\left(\frac{0.746\text{KW}}{1\text{HP}}\right) = 3.73\text{KW}$$

$$P_{ELEC} = \frac{P_{MECH}}{\eta} = \frac{3.73\text{ KW}}{0.81} = 4.60\text{ KW}$$

$$|S_2| = \frac{4.60\text{KW}}{0.73} = 6.31\text{KVA}$$

$$\theta_2 = \cos^{-1}(0.73) = 43.1^\circ$$

$$\therefore \boxed{\bar{S}_2 = 6.31\text{KVA}\angle 43.1^\circ}$$

LOAD 3

$$(7\text{ TON})\left(\frac{3.517\text{KW}}{1\text{TON}}\right) = 24.6\text{KW}_{THERMAL}$$

$$P_{OUT} = \text{C.O.P.} \cdot P_{IN}$$

$$\rightarrow P_{THERMAL} = COP \cdot P_{ELEC} \quad \text{SO} \quad 24.6\text{ KW} = (1.2)P_{ELEC}$$

$$P_{ELEC} = 20.5\text{KW} = P_3$$

$$S_3 = \frac{P_3}{pf_3} = \frac{20.5\text{KW}}{0.78} = 26.3\text{KVA}$$

$$\theta_3 = \cos^{-1}(0.78) = 38.7^\circ$$

$$\text{SO} \quad \boxed{\bar{S}_3 = 26.3\text{KVA}\angle 38.7^\circ}$$

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[1] 1kW = 3.4kBTU/hr

[2] 1 ton of refrigeration = 3.517kW. COP = η/100%

LOAD 4

$\overline{S_4} = 20kVA \angle -\cos^{-1}(0.93)$

$= \boxed{20kVA \angle -21.6^\circ}$

SO

$S_{TOTAL} = \overline{S_1} + 10 \cdot \overline{S_2} + \overline{S_3} + \overline{S_4}$

$= 22.1kVA \angle 0^\circ + 10(6.31kVA \angle 43.1^\circ) + 26.3kVA \angle 38.4^\circ + 20kVA \angle -21.6^\circ$

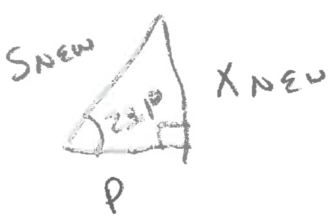
$= 119317 \angle 26^\circ$

$= 107296W + j52196.2VAR$

NOW

$\overline{S_{NEW}} = S_{NEW} \angle \cos^{-1}(0.92) = S_N \angle 23.1^\circ$

$S_N = \frac{P}{PF_{NEW}} = \frac{107296W}{0.92} = 116626VA$



$\sin(23.1^\circ) = \frac{X_{NEW}}{116626VA}$

$X_{NEW} \approx 45.8kVAR$

SO,

$X_{NEW} = Q_L + Q_C$

$45.8kVAR = 52.2kVAR + Q_C$

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$\boxed{Q_C = -6.4kVAR}$ ← REACTIVE POWER REQUIRED TO COMPENSATE CONSUMER LOAD

Problem 2 (25 points)

Open-circuit and short-circuit tests were performed under rated conditions on the primary side of a 250 kVA, single-phase 7.62k-277 V distribution transformer[3]. Test data are presented in Table 1. The transformer is load regulated.

a. Determine the primary-side cantilever equivalent circuit for the transformer.
b. Determine the transformer voltage regulation (load regulated) under full load with a 0.90 lagging PF.

Table 1 Short-circuit and open-circuit test data

Open-Circuit Test Data	Short-Circuit Test Data
I_{OC} = 15 A	V_{SC} = 360 V
P_{OC} = 4.5 kW	P_{SC} = 5500 W

$V_{oc} = 7.62\,kV$ $\quad I_{sc} = 250\,kVA / 7.62\,kV = 32.8\,A$

$S_{rated} = 250\,kVA$

a) $Y_{oc} = \dfrac{I_{oc}}{V_{oc}} = 1.97\,mS$, $\theta_{oc} = \cos^{-1}\left(\dfrac{P_{oc}}{V_{oc} I_{oc}}\right) = 87.7°$

$\bar{Y}_{oc} = 1.97\,mS \angle 87.7°$
$= \underbrace{0.079}_{G} + j\underbrace{1.97}_{B}\,mS$

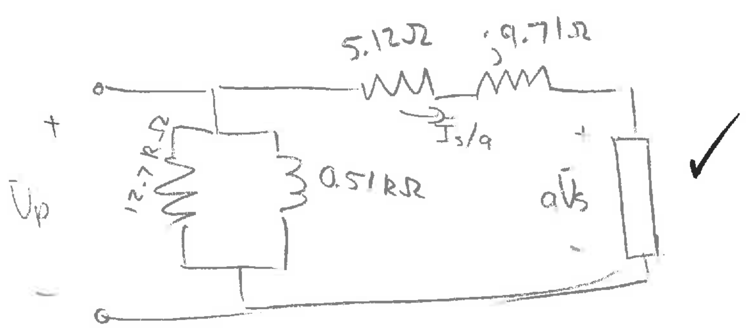
$R_{core} = \dfrac{1}{G} = 12.7\,k\Omega$

$X_m = \dfrac{1}{B} = 0.51\,k\Omega$

$Z_{sc} = \dfrac{V_{sc}}{I_{sc}} = 10.98\,\Omega$, $\theta_{sc} = \cos^{-1}\left(\dfrac{P_{sc}}{V_{sc} I_{sc}}\right) = 62.2°$

$\bar{Z}_{sc} = 10.98\,\Omega \angle 62.2°$
$= 5.12 + j\,9.71$

$R_{eq,P} = 5.12\,\Omega$
$X_{eq,P} = 9.71\,\Omega$



[3] Designed for a 12.47kV-120/240V step down service.

b) $\bar{I}_{s/a} = \left(\frac{\bar{S}}{\bar{V}}\right)^* = \left(\frac{250\text{ kVA} \angle 25.8°}{7.62\text{ kV}}\right)^*$

$= 32.8\text{ A} \angle -25.8°$

$\bar{V}_p = \bar{V}_{drop} + a\bar{V}_s$

$= (32.8\text{ A} \angle -25.8°)(5.12 + j9.71\Omega) + 7.62\text{ kV}$

$= 7.91\text{ kV} \angle 1.55°$

$|\bar{V}_p|\Big|_{f.l} = |\bar{V}_p| = 7.91\text{ kV}$

$|\bar{V}_p|\Big|_{n.l} = 7.62\text{ kV}$

$VR\Big|_{\text{load reg}} = \frac{|\bar{V}_p|\big|_{f.l} - |\bar{V}_p|\big|_{n.l}}{|\bar{V}_p|\big|_{n.l}} = \frac{7.91 - 7.62}{7.62} = 0.038$

$= 3.8\%$

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Problem 3 (25 points)

A three-phase, variable-frequency drive (VFD) draws lagging non-sinusoidal line current, resulting in significant waveform distortion. The VFD is connected to a 480 V service and draws 80 kW.

Spectral analysis of the current reveals the following:

Table 2 Harmonic RMS line current magnitudes

N	I_{RMS} (A)
1	102
3	62
5	32
7	11
9	2

a. Calculate the Distortion power factor[4].

b. Calculate the Displacement power factor.

c. Calculate the neutral current magnitude.

a) Since only the current is distorted,

$$PF_{Distortion} = \frac{1}{\sqrt{1+\left(\frac{THD_I}{100\%}\right)^2}}$$

$$THD_I = \frac{\sqrt{\sum_{n=3,5,7,9} I_{n,rms}^2}}{I_{1,rms}} \cdot 100\% = \frac{\sqrt{(62)^2+(32)^2+(11)^2+(2)^2}}{102} \cdot 100\% = 69.3\%$$

So $PF_{Distortion} = \frac{1}{\sqrt{1+(0.693)^2}} = \boxed{0.82}$

b) $PF_{displacement} = \frac{P}{S_{fundamental}}$ $\quad S_{Total,fundamentals} = \sqrt{3}\, V_{LL}\, I_L = \sqrt{3}\,(480\,V)(102\,A) = 84.8\,kVA$

So $PF_{displacement} = \frac{80\,kW}{84.8\,kVA} = \boxed{0.94}$

[4] IEEE THD definition

c) $I_{neutral,rms}$ is the RMS of the sum of the triplens harmonics in each line, so

$$I_{neutral,rms} = \sqrt{(3 \cdot 62\,A)^2 + (3 \cdot 2\,A)^2}$$

$$= \boxed{186\ A}$$

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Problem 4 (25 points)

A 60 Hz, pad-mount three-phase transformer for an off-shore wind turbine must be designed to handle 4.5 MVA and have a bank ratio of 1000 V-34.5 kV.

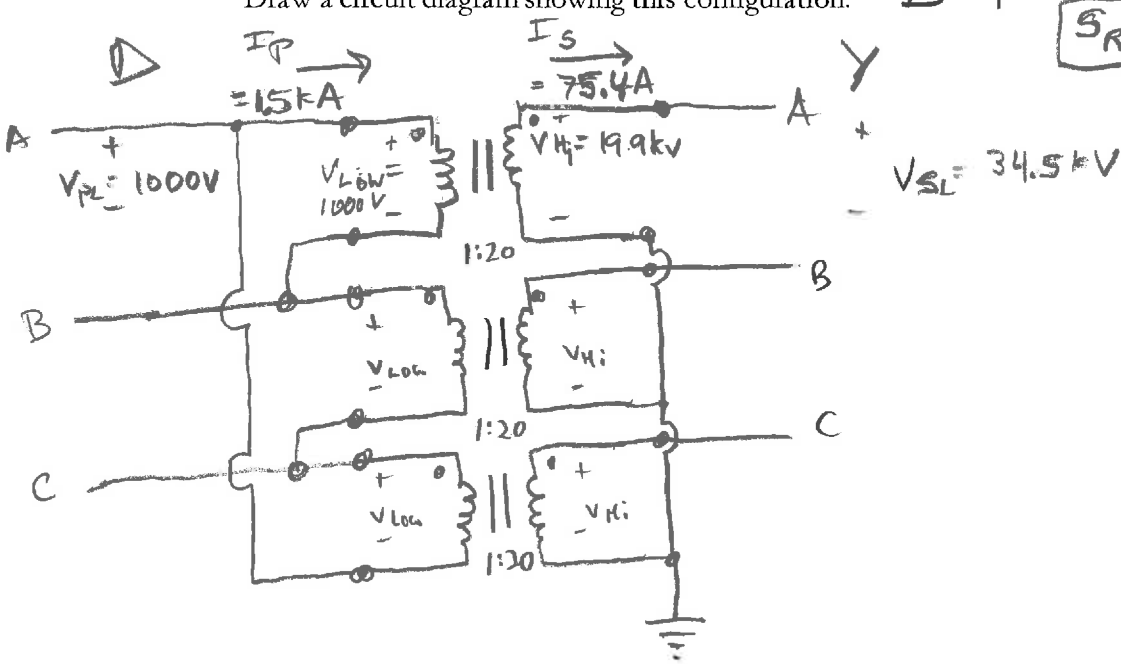
The transformer shall be built using three 60 Hz single-phase transformers. Specify the high and low side voltages, rated power, rated coil currents, and the turns ratio of these transformers if they are to be connected in a Δ-Wye configuration. The transformer bank shall be grounded.

Draw a circuit diagram showing this configuration.

Δ - Y

$S_{1\phi} = \frac{S_{3\phi}}{3} = \frac{4.5\text{MVA}}{3} = 1.5\text{MVA}$

$\boxed{S_{Rated\ 1\phi} = 1.5\text{MVA}}$



$V_{Hi} = \frac{34.5}{\sqrt{3}} = 19.9\text{kV}$

$V_{LOW} = 1000\text{V}$

$I_{P_{rated}} = 1.5\text{kA}$

$I_{S_{rated}} = 75.4\text{A}$

$a = \frac{1}{19.9} \approx \frac{1}{20}$

$I_S = \frac{1.5\text{MVA}}{19.9\text{kV}} = 75.4\text{A}$

$I_P = \frac{1.5\text{MVA}}{1\text{kV}} = 1.5\text{kA}$

$a = \frac{V_P}{V_S} = \frac{1000\text{V}}{19.9\text{kV}} = 5.03 \times 10^{-2} = \frac{1}{19.9}$

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