Student Name: **Student ID#:** **Serial #:**

Q # 1 (6)	Q # 2 (10)	Q # 3 (5)	Q # 4 (7)	Q # 5 (12)	Q # 6 (10)	GRADE
6	10	5	7	12	10	50/50

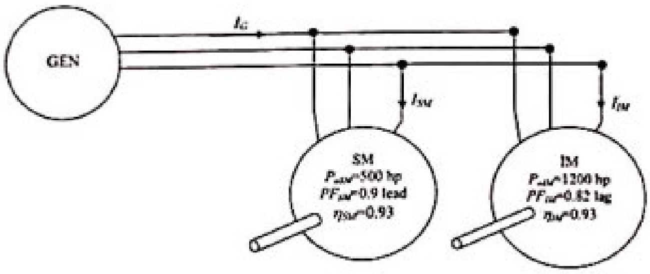
Question # 1 (6 marks) **ABET Outcome *h* Assessment**

I. Assume that a manufacturing plant has a three-phase in-plant generator is supplying three-phase induction motor totaling 1200-hp at 2.4-kV with a lagging power factor of 0.82 and efficiency of 0.93. Find

a.	the required kVA capacity S_G of the generator	S_G =	1173.9	kVA
b.	the magnitude of the required generator current $\|I_G\|$ to serve the IM load	$\|I_G\|$ =	282.4	A

II. Assume that additional 500-hp load in the form of synchronous motor operating with a leading power factor of 0.9 and efficiency of 0.93 has been added. Find

c.	the new required kVA capacity S_{Gnew} of the generator.	S_{Gnew} =	1444.5	kVA
d.	the magnitude of the required new generator current $\|I_{Gnew}\|$ to serve the IM and SM loads	I_{Gnew} =	347.5	A
e.	the overall power factor PF_{new}	PF_{new} =	0.944	lag



Solution:

$$P_{iIM} = \frac{P_{oIM}}{\eta_{IM}} = \frac{1200 \times 746}{0.93} = 962.6\,kW, \quad S_G = \frac{P_{iIM}}{PF_{IM}} = \frac{962.6k}{0.82} = \mathbf{1173.9\ kVA}$$

(I) $$|I_G| = |I_{IM}| = \frac{P_{iIM}}{\sqrt{3} \times V_{LL} \times PF_{IM}} = \frac{962.6kW}{\sqrt{3} \times 2.4kV \times 0.82} = \mathbf{282.4}\ A$$

$$\theta_{IM} = \cos^{-1}(0.82) = 34.9°, Q_{IM} = P_{iIM}\tan(\theta_{IM}) = 962.6k \times \tan(34.9°) = 671.5\ kVAR$$

....

(II) $$P_{iSM} = \frac{P_{oSM}}{\eta_{SM}} = \frac{500 \times 746}{0.93} = 401\,kW, \quad I_{SM} = \frac{P_{iSM}}{\sqrt{3} \times V_{LL} \times PF_{SM}} = \frac{401kW}{\sqrt{3} \times 2.4kV \times 0.90} = 107.2\ A$$

$$\theta_{SM} = \cos^{-1}(0.90) = 25.8°, \quad Q_{SM} = -P_{SM}\tan(\theta_{SM}) = -401k \times \tan(25.8°) = 193.9\ kVAR$$

$$P_{sys} = (P_{iIM} + P_{iSM} = 962.6 + 401)k = 1363.6\ kW, \quad Q_{sys} = Q_{IM} + Q_{SM} = 671.5k - 193.9 = 477.6\ kVAR$$

$$Q_{sys} = P_{sys}\tan(\theta_{sys}) \Rightarrow \theta_{sys} = \tan^{-1}\left(\frac{477.6}{1363.6}\right) = 19.3°, \quad PF_{new} = \cos(\theta_{new}) = \cos(19.3°) = 0.944\ lagging$$

$$S_{Gnew} = \frac{P_{sys}}{PF_{new}} = \frac{1363.6k}{0.944} = \mathbf{1444.5\ kVA}$$

$$I_{Gnew} = \frac{P_{sys}}{\sqrt{3} \times V_{LL} \times PF_{new}} = \frac{401kW}{\sqrt{3} \times 2.4kV \times 0.944} = 347.5\ A$$

Question # 2 (10 marks) **SHOW YOUR CALCULATIONS**

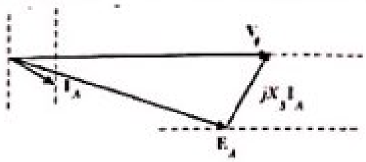
A 480-V, 60 Hz, 400-hp 0.8-PF-leading six-pole Δ-connected synchronous motor has a synchronous reactance X_s of 1.1 Ω and negligible armature resistance. Ignore its friction, windage, and core losses for the purposes of this problem.

I. If this motor is supplying 400 hp at 0.8 PF lagging, draw the motor's phasor diagram then find

a.	the magnitude and phase angle of the armature phase current	I_a =	259	A
		θ =	-36.9	°
b.	the magnitude of the induced phase voltage and the power angle	E_a =	384	V
		δ =	-36.4	°
c.	the developed torque	T_d =	2375	Nm

II. If E_a is increased by 15 %, draw the new phasor diagram then find

d.	the new magnitude of the induced phase voltage and power angle	E_a =	441.6	V
		δ =	31.1	°
e.	the new magnitude and new phase angle of the armature current	I_a =	227	A
		θ =	-24.1	°
f.	the new motor power factor	PF =	0.913	lead lag



Solution:

$P_{in} = P_{out} = 400 \times 746 = 298.4$ kW

$$I_L = \frac{P_{in}}{\sqrt{3} \times V_{LL} \times PF} = \frac{298.4\,kW}{\sqrt{3} \times 480 \times 0.8} = 449\ A$$

Because the motor is Δ-connected, the corresponding phase current is $I_a = \frac{I_L}{\sqrt{3}} = \frac{449}{\sqrt{3}} = 259\ A$

$$\overline{E}_a = \overline{V}_t - jX_s\overline{I}_a = 480\angle 0° - 1.1\angle 90° \times 259\angle -36.9° = 384\angle -36.4°\ V$$

This motor has 6 poles and an electrical frequency of 60 Hz, so its rotation speed is $n_s = 1200\ rpm$

$$T_d = 9.55 \times \frac{P_d}{n_s} = 9.55 \times \frac{298.4 \times 10^3}{1200 \times 1.1} = 2375\ Nm$$

$E_{a2} = 1.15 \times E_{a1} = 1.15 \times 384 = 441.6$ V

$$P_{d1} = P_{d2} \Rightarrow E_{a1} \sin\delta_1 = E_{a2} \sin\delta_2 \Rightarrow \delta_2 = \sin^{-1}\left(\frac{E_{a1}}{E_{a2}} \sin\delta_1\right) = \sin^{-1}\left(\frac{384}{441.6} \sin(-36.4)\right) = -31.1°$$

$$\overline{I}_{a2} = \frac{\overline{V}_t - \overline{E}_{a2}}{jX_s} = \frac{480\angle 0° - 441.6\angle -31.1°}{1.1\angle 90°} = 227\angle -24.1°\ A$$

$$PF_2 = \cos(-24.1°) = 0.913\ lag$$

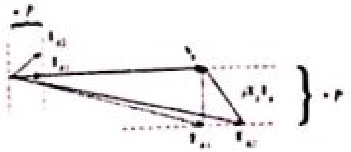
Question # 3 (5 marks) **SHOW YOUR CALCULATIONS**

A 208-V, Y-connected synchronous motor is drawing 40 A at 1.0 PF from a 208-V power system. The field current flowing under these conditions $I_f = 2.7$ A. Its synchronous reactance $X_s = 0.8\ \Omega$.

I. Assume a linear open-circuit characteristic, find

a.	the torque angle δ	$\delta =$	-14.9 °
b.	the field current required to make the motor operate at 0.8 PF leading	$I_f =$	3.2 A
c.	the new torque angle δ in part (b)	$\delta =$	-12.5 °

II. Draw the phasor diagrams for both cases



Solution:

$$\bar{E}_a = \bar{V}_\phi - jX_s\bar{I}_a = 120\angle 0° - 0.8\angle 90° \times 40\angle 0° = 124\angle -14.9°\ V$$

$$P_{in1} = P_{in2} \Rightarrow I_{a1}\cos\theta_1 = I_{a2}\cos\theta_2 \Rightarrow I_{a2} = \frac{\cos\theta_1}{\cos\theta_2} I_{a1} = \frac{1.0}{0.8} \times 40 = 50\ A$$

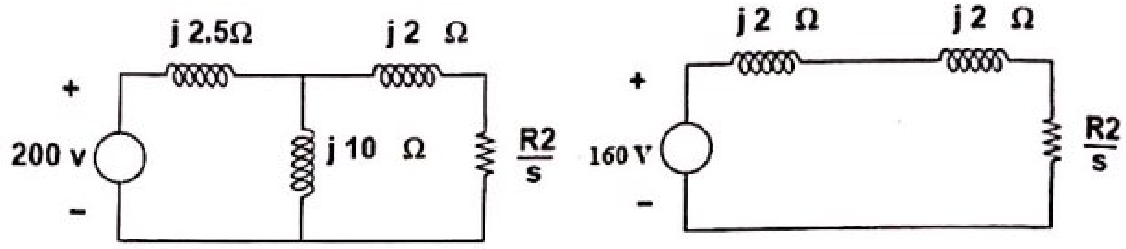
$$\bar{E}_{a2} = \bar{V}_\phi - jX_s\bar{I}_{a2} = 120\angle 0° - 0.8\angle 90° \times 50\angle 36.9° = 147.5\angle -12.5°\ V$$

$$\frac{E_{a2}}{E_{a2}} = \frac{I_{f2}}{I_{f1}} = I_{f2} = \frac{E_{a2}}{E_{a1}} \times I_{f1} = \frac{147.5}{124} \times 2.7 \Rightarrow I_{f2} = 3.2\ A$$

Question # 6 (10 marks) **SHOW YOUR CALCULATIONS**

The single phase equivalent circuit of a 3-phase, 4-pole Y-connected induction motor with negligible armature resistance is shown below. The machine is connected to a 3-phase voltage source with line-neutral voltage of 200 V and a frequency of 400 rad/s. The motor reaches maximum torque at a rotor speed of 160 rad/s. Reduce the circuit into its Thevenin equivalent and determine:

a.	the motor's slip at maximum torque	s_{max} =	0.2	
b.	the maximum developed torque	T_{max} =	48	Nm
c.	the rotor resistance	R_2=	0.8	Ω
d.	the starting developed torque	T_{st} =	18.5	Nm
e.	the starting rotor current	I_{2st} =	39.2	Nm



Solution:

$$\omega_s = \frac{2}{P}\omega_e \frac{2}{4} \times 400 = 200\ rad/s$$

$$\omega_m = (1 - s_{\max})\omega_s \Rightarrow 160 = (1 - s_{\max}) \times 200 \Rightarrow (1 - s_{\max}) = \frac{160}{200} = 0.8 \Rightarrow s_{\max} = 0.2$$

Maximum Torque occurs when $\frac{R_2}{s_{\max}} = |j(2+2)| = 4$

$$\overline{V}_{th} = \frac{jX_m}{j(jX_1 + X_m)} \times \overline{V}_1 = \frac{j10}{j(j2.5+10)} \times 200\angle 0° = 160\angle 0°\ V$$

$$Z_{th} = \frac{jX_m \times jX_1}{j(jX_1 + X_m)} \times \overline{V}_1 = \frac{j10 \times j2.5}{j(j2.5+10)} j2.\Omega$$

$$T_{\max} = \frac{3V_{th}^2}{\omega_s} \times \frac{\frac{R_2}{s_{\max}}}{\left(R_{th} + \frac{R_2}{s_{\max}}\right)^2 + (X_{th} + X_2)^2} = \frac{3 \times 160^2}{200} \times \frac{4}{4^2 + 4^2} = 48\ Nm$$

$$T_{\max} = \frac{3V_{th}^2}{2\omega_s} \times \frac{1}{R_{th} + \sqrt{R_{th}^2 + (X_{th} + X_2)^2}} = \frac{3 \times 160^2}{2 \times 200} \times \frac{1}{\sqrt{4^2}} = 48\ Nm$$

$$\frac{R_2}{s_{\max}} = |j(2+2)| = 4 \Rightarrow R_2 = 4 \times 0.2 = 0.8\Omega$$

$$T_{st}(s=1) = \frac{3V_{th}^2}{\omega_s} \times \frac{R_2/s}{(R_{th} + \frac{R_2}{s})^2 + (X_{th} + X_2)^2} = \frac{3 \times 160^2}{200} \times \frac{0.8}{(0.8)^2 + (4)^2} = \frac{3 \times 160^2}{200\sqrt{2}} = 18.5\ Nm$$

$$|I_{2st}| = \frac{|V_{th}|}{\sqrt{(R_{th} + R_2)^2 + (X_{th} + X_2)^2}} = \frac{160}{\sqrt{(0.8)^2 + (4)^2}} = 39.2\ A$$

Question # 5 (12 marks) **SHOW YOUR CALCULATIONS**

A three phase, 20 hp, 440 V, 60 Hz, Y-connected, class-A induction motor has been tested to determine its parameters. Readings from machine tests are provided in the table. Find the equivalent circuit parameters of this motor.

Test	Voltage (V)	Current (A)	Power (W)	Frequency (Hz)
No Load	440	9	3750	60
Blocked Rotor	62	24	1800	60
DC Resistance	25	34		

$R_1 =$	0.368	Ω
$R'_2 =$	0.674	Ω
$X_1 =$	0.533	Ω
$X'_2 =$	0.533	Ω
X_M	23.1	Ω
$P_{rot} =$	3660	W

	A, D	B	C
X_1	$0.5X_{BR}$	$0.4X_{BR}$	$0.3X_{BR}$
X_2	$0.5X_{BR}$	$0.6X_{BR}$	$0.7X_{BR}$

Solution:

$R_1 = \frac{1}{2}\left(\frac{V_{DC}}{I_{DC}}\right) = \frac{1}{2}\left(\frac{25}{34}\right) = 0.368\Omega$

$P_{rotational} = P_{nl} - 3I_{nl}^2 R_1 = 3750 - (3)(9^2)(0.368) = 3660\,W$

$R_{nl} = \frac{P_{nl}}{3I_{nl}^2} = \frac{3750}{3(9^2)} = 15.432\Omega$

$Z_{nl} = \frac{V_{nl}}{\sqrt{3}\,I_{nl}} = \frac{440}{\sqrt{3}\,(9)} = 28.226\Omega$

$X_{nl} = \sqrt{Z_{nl}^2 - R_{nl}^2} = \sqrt{(28.226)^2 - (15.432)^2} = 23.634\Omega$

$R_{bl} = \frac{P_{bl}}{3I_{bl}^2} = \frac{1800}{(3)(24^2)} = 1.042\Omega$

$Z_{bl} = \frac{V_{bl}}{\sqrt{3}\,I_{bl}} = \frac{62}{\sqrt{3}(24)} = 1.491\Omega$

$X_{bl} = \sqrt{Z_{bl}^2 - R_{bl}^2} = \sqrt{1.491^2 - 1.042^2} = 1.066\Omega$

$X_1 = X_2 = \frac{1}{2}X_{bl} = \frac{1}{2}(1.066) = 0.533\Omega$

$X_m = X_{nl} - X_1 = 23.634 - 0.533 = 23.1\Omega$

$R_2 = R_{bl} - R_1 = 1.042 - 0.368 = 0.674\Omega$

Question # 4 (7 marks) **SHOW YOUR CALCULATIONS**

A 3-phase, 230 V, 50 Hz, 100 hp, 6 pole, Y-connected induction motor operating at rated conditions has an efficiency of 91% and draws a line current of 248 A. The core loss = 1.7 kW, stator copper loss = 2.8 kW, and rotor conductor loss = 1.55 kW. Determine:

a.	the input power absorbed by the motor	$P_{in} =$	81.98		kW
b.	the air gap power	$P_g =$	77.48		kW
c.	the developed power	$P_d =$	75.93		kW
d.	the rotor speed	$n_m =$	980		rpm
e.	the motor's PF	$PF=$	0.830	lead	lag
f.	the fill-load developed torque	$T_d =$	739.9		Nm

Solution:

$$P_{in} = \frac{P_{out}}{\eta} = \frac{100\times 746}{0.91} = 81.98\,kW$$

$$P_g = P_{in} = P_{cu1} - P_{core} = .81.98 - (2.8+1.7)k = 77.48\,kW$$

$$P_d = P_g - P_{cu2} = .77.48 - 1.55 = 75.93\,kW$$

$$P_{cu2} = s.P_g \Rightarrow = .s = \frac{P_{cu2}}{P_g} = \frac{1.55}{77.48} = 0.02$$

$$n_s = \frac{120\times f}{P} = \frac{120\times 50}{6} = 1000\,rpm$$

$$n_m = (1-s)n_s = (1-0.02)\times 1000 = 980\,rpm$$

$$PF = \frac{P_{in}}{\sqrt{3}V_L I_L} = \frac{81.98\times 10^3}{\sqrt{3}\times 230\times 248} = \frac{81.98\times 10^3}{98.80\times 10^3} = 0.830\,lag$$

$$T_d = 9.55\times\frac{P_g}{n_s} = 9.55\times\frac{P_d}{n_m} = 9.55\times\frac{77.48\times 10^3}{1000} = \mathbf{739.9}\,Nm$$