University of Jordan | Faculty of Engineering & Technology | Electrical Engineering Department

EE471: Electrical Machines II | Second Exam | Second Semester 2016-2017 | 5/4/2017 | Time: 1 Hour

Student Name [redacted] **Student ID:** [redacted] **Serial #:** 30

Q # 1 (5)	Q # 2 (5)	Q # 3 (7)	Q # 4 (13)	GRADE
5	0	4	12.5	22 /30

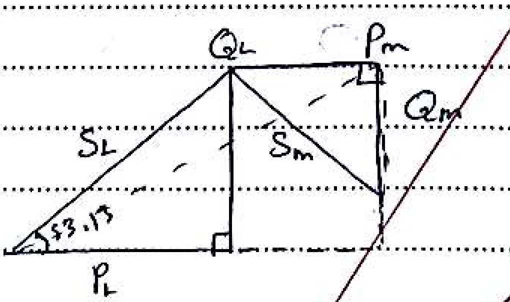
Question # 1 (5 marks) **ABET Outcome *h* Assessment** **SHOW YOUR CALCULATIONS**

A 3-phase, load of an industrial plant takes a total power of 240 kW at a PF of 0.6 lagging from a 220-V supply. An additional motor load of 200 hp must be added to the plant. If a synchronous motor operating at 0.8 PF leading and having an efficiency of 90% is added in parallel with the load. (pf correction)

Part I: Determine:

a.	the reactive power Q_L and the magnitude of the load current $\lvert I_L \rvert$, taken by the load.	Q_L = 320	kVAR
		$\lvert I_L \rvert$ = 1049.7	A
b.	the motor's real power, P_m, and reactive power, Q_m, and the magnitude of the motor current, I_m taken by the motor.	P_m = 165.7	kW
		Q_m = 124.3	kVAR
		$\lvert I_m \rvert$ = 543.8	A
c.	the system total real power, P_s, and reactive power, Q_s, and the magnitude of the line current, I_s supplied by the power supply.	P_s = 405.7	kW
		Q_s = 195.7	kVAR
		$\lvert I_s \rvert$ = 118298	A
d.	e. the overall (combined) system power factor, $PF_{overall}$.	$PF_{overall}$ = 0.9	lag

Part II: Draw the power triangles for the load, motor and system.



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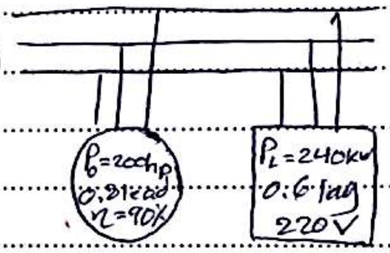
Q7

$Q_L = P_L \tan(\cos^{-1} 0.6) = 320 \text{ kVAR}$ (absorbed)



$|I_L| = \dfrac{P_L/pf}{\sqrt{3} \times V_{LL}} = \dfrac{240K/0.6}{\sqrt{3} \times 220} = 1049.72 \text{ A}$

$P_o = 200 \times 746 = 149200 \text{ W}$

$P_{in} = P_m = \dfrac{P_{out}}{\eta} = \dfrac{149200}{0.90} = 165.7 \text{ KW}$

$Q_m = P_m \tan(\cos^{-1} 0.8) = 124.3 \text{ KVAR}$ (supplied, capacitive)

$I_m = \dfrac{P_m}{\sqrt{3} \cdot V_{LL} \cdot pf} = \dfrac{165.7k}{\sqrt{3} \times 220 \times 0.8} = 543.8$

$P_s = P_m + P_L = 165.7K + 240K = 405.7 \text{ kW}$

$Q_s = Q_m + Q_L = -124.3K + 320K = 195.7 \text{ KVAR}$

$pf_{overall} \Rightarrow \tan^{-1}\left(\dfrac{Q_s}{P_s}\right) = 25.7 \quad pf_s = \cos(25.7) = 0.9$

$|I_s| = \dfrac{P_s/pf}{\sqrt{3} \times V_{LL}} = \dfrac{405.7K/0.9}{\sqrt{3} \times 220} = 1182.98$

$|I_s| = I_m + I_L =$ ~~1049.72 + 543.8 = 1593.52~~

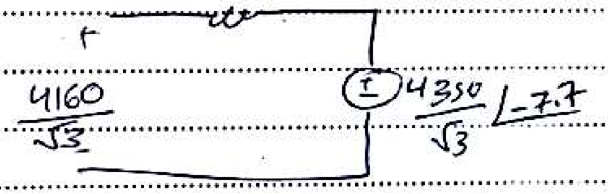
$303.4k = 3 \times \frac{V_t \times E_a}{X_s}$ ($\delta = 90$) $\Rightarrow E_a = \frac{303.4k \times 8}{3 \times \frac{4160}{\sqrt{3}}} = 336.8\,V$

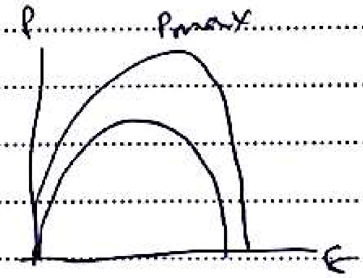
$\Rightarrow E_{a_{LL}} = \sqrt{3} \times 336.8 = 583.46$

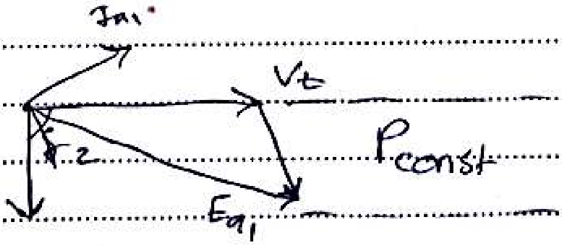
$I_a = \frac{\frac{4160}{\sqrt{3}} - 336.8\angle -90}{j8} = 303.15 \angle -82$

$pf = \cos(82) = 0.139$

$Q = \sqrt{3} \times 4160 \times 303.15 \sin(82) = -2163.0$







Question # 2 (5 marks) **SHOW YOUR CALCULATIONS** 1 hp = 746 W

$V_L = V_\phi$, $I_L = \sqrt{3} I_\phi$

A 440-V, 60-Hz, 6-pole, 3-ph, Δ-connected synchronous motor draws a line current I_L = 86.6 A on full-load with rotational losses P_{rot} = 3 kW. The field current is adjusted to obtain an open-circuit voltage E_a equal to 440 V. The synchronous reactance X_s = 5 Ω per phase and the winding resistance is negligible. Draw the phasor diagram and determine:

a.	the torque angle δ	δ = 90	°
b.	the power factor *PF*	*PF* = 0.707	lag
c.	the power input P_{in}	P_{in} = 116.16	kW
d.	the output power P_{out}	P_{out} = 113.16	kW
e.	the net output torque T_{out}	T_{out} = 900.52	Nm

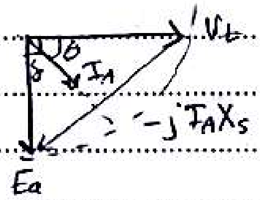
$V_L = 440V$ $f = 60 Hz$ Δ-con $I_L = 86.6 A$ $P_{rot} = 3 kW$

$E_{a_{LL}} = 440V$ $X_s = 5 \Omega/\phi$ $R_a \approx 0.0$ $P = 6$

$P_{dev} = P_{in} = \sqrt{3} \times V_L \times I_L \times \cos\theta$

$E_A \sin\delta = I_a X_s \cos\theta$

$P_{in} = \frac{3 V_t E_a \sin\delta}{X_s}$



full load ⇒ $\delta = 90$

$E_A \sin\delta = I_a X_s \cos\theta$

$440 \times 1 = \frac{86.6}{\sqrt{3}} \times 5 \times \cos\theta$ ⇒ $\cos\theta = 1.76$??

$P_{in} = P_{max} = \frac{3 V_t E_a}{X_s} = \frac{3 \times 440 \times 440}{5} = 116.16 KW$

$P_{in} = 3 V_t I_A \cos\theta$ ⇒ $\cos\theta = \frac{116.16K}{3 \times 440 \times \frac{86.6}{\sqrt{3}}} = 1.76$??

$P_{out} = P_{in} - P_{rot} = 116.16k - 3K = 113.16 kW$

$T_{out} = \frac{P_{out}}{\omega_s} = \frac{113.16K}{125.66} = 900.52$ Nm

$\omega_s = 2\pi \times \frac{\frac{120 \times 60}{6}}{60} = \frac{2\pi \times 1200}{60} = 125.66$ rad/s

$I_a = \frac{V_t\angle 0 - E_a\angle -90}{X_s} = 124.2 \angle 45$

Question # 3 (7 marks)

A 208-V Y-connected synchronous motor is drawing 50 A at unity power factor from a 208-V power system. The field current flowing under these conditions is 2.7 A. Its synchronous reactance X_s is 1.6 Ω.

Part I: Assume a linear O.C. characteristic, draw the phasor diagram for this condition and find

a.	the magnitude of the induced phase voltage E_a and torque angle δ.	E_a = 144.29	V
		δ = 33.6	°
b.	the steady-state stability power limit.	P_{max} = 32.5	kW

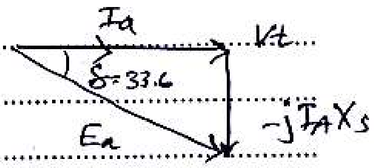
Part II: If the field current is adjusted to make the motor operate at 0.80 PF leading, determine.

c.	the magnitude of the new armature current I_a, induced phase voltage E_a and field current I_f.	$\lvert I_a \rvert$ = 112.76	A
		E_a = 270.16	V
		I_f = 1.44	A
d.	the new torque angle in part(c)	δ = 32.27	°

$V_L = 208V$ $I_L = 50A$ $pf = 1$ $I_f = 2.7A$ $X_s = 1.6\,\Omega/0$

(I) $\vec{E_A} = V_t - jI_AX_s = \frac{208}{\sqrt{3}}\angle 0 - 50\angle 0 \cdot (j1.6)$

$= 144.29 \angle -33.6$

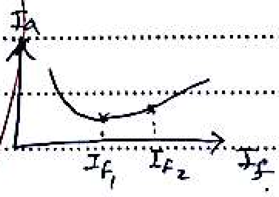


$P_{max} = \frac{3 \times \frac{208}{\sqrt{3}} \times 144.29}{1.6} = 32.5\ kW$

(II) $pf = 0.8$ leading $\Rightarrow \theta = 36.86$

$I_{a_1} = 50 \rightarrow pf = 1$

$I_{a_2} = ??$ $\rightarrow pf_2 = 0.8$



$P = \frac{3 \times \frac{208}{\sqrt{3}} \times E_a \sin\delta}{1.6} = 32.5\ kW$

$I_f \uparrow$ $E_a \uparrow$ $\delta \downarrow$ (power is const)

$\rightarrow 32.5k = 3 \times V_t \times I_a \cos\theta \Rightarrow I_a = \frac{32.5k}{3 \times \frac{208}{\sqrt{3}} \times 0.8} = 112.76\ A$

$\vec{E_A} = V_t - jI_AX_s = \frac{208}{\sqrt{3}} - (j1.6) \times 112.76\angle 36.9 = 270.16 \angle -32.27$

$E_{A1} I_{f1} = E_{A2} I_{f2} \Rightarrow I_{f2} = \frac{E_{A1}}{E_{A2}} \times I_{f1} = \frac{144.29}{270.16} \times 2.7 = 1.44 ??$

Question # 4 (13 marks) **SHOW YOUR CALCULATIONS**

A three-phase, 4160-V, Y-connected, cylindrical-rotor synchronous motor has a synchronous reactance of 8 Ω per phase and a negligible armature resistance. The combined rotational losses (friction and windage plus core loss) amount to 5 kW. The highest excitation voltage possible is 4350 V. The motor delivers an output of 400 hp to a mechanical load connected to its shaft.

Part I: If the field current is increased to give the maximum excitation voltage, find:

a.	the power developed by the motor P_d.	P_d = 303.4 ✓	kW
b.	the torque angle δ.	δ = 7.7 ✓	°
c.	the magnitude of the motor's armature current I_a and PF.	I_a = 43.4 ∠14.5	A
		PF = 0.96 ✓	lead
d.	the motor efficiency η_m.	η_m = 98.3 ✓	%
e.	the maximum developed power P_{max} at the above excitation voltage.	P_{max} = 2.262 ✓	MW

Part II: If the field current is reduced without changing the load, find: (const power)

f.	the new maximum developed power P_{max} which the motor will remain in synchronism (stable operation).	P_{max} = 303.4 ✓	kW
g.	the magnitude of the smallest excitation phase voltage E_a and torque angle δ	E_a = 583.5 ✓	V
		δ = 90 ✓	°
h.	the magnitude of the armature current I_a and PF at the smallest excitation voltage of part (g).	I_a = 303.5 ∠82 ✓	A
		PF = 0.13 ✓	lag
i.	the reactive power Q absorbed/supplied by the motor.	Q = 2.163.0 ✗	MVAR

Draw the equivalent circuit, phasor and power angle-curve diagrams to illustrate your solution.

$P_{out} = 400\ hp = 298.4\ kW$

$V_L = 4160$, $X_s = 8\Omega/\phi$, $R_a \approx 0.0$, $\Sigma P_{loss} = 5kW$, $E_A = 4350$

(I) $P_{dev} = P_{in} = P_{out} + P_{losses} = 298.4K + 5K = 303.4KW$

$303.4K = \frac{3 \times 4160/\sqrt{3} \times 4350/\sqrt{3}}{8} \sin\delta \Rightarrow \sin\delta = 0.13 \Rightarrow \delta = 7.7$

$I_A = \frac{4160/\sqrt{3}\angle 0 - 4350/\sqrt{3}\angle -7.7}{j8} = 43.4\angle 14.5$ $pf = \cos(14.5) = 0.96$

$\eta = \frac{P_{out}}{P_{in}} = \frac{298.4}{303.4} \times 100\% = 98.3\%$

$P_{max} = \frac{4160 \times 4350}{8} = 2.262\ MW$

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Question # 1 (~~20~~ 5 marks) **ABET Outcome *h* Assessment** **SHOW YOUR CALCULATIONS**

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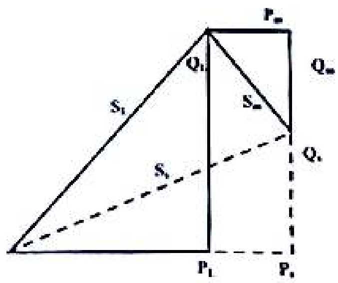
Part I: Determine:

a.	the reactive power Q_L and the magnitude of the load current $\|I_L\|$, taken by the load.	Q_L =	320	kVAR
		$\|I_L\|$ =	1049.7	A
b.	the motor's real power, P_m, and reactive power, Q_m, and the magnitude of the motor current, I_m taken by the motor.	P_m =	165.8	kW
		Q_m =	124.3	kVAR
		$\|I_m\|$ =	543.8	A
c.	the system total real power, P_s, and reactive power, Q_s, and the magnitude of the line current, I_s supplied by the power supply.	P_s =	405.8	kW
		Q_s =	195.6	kVAR
		$\|I_s\|$ =	1182.5	A
d.	e. the overall (combined) system power factor, $PF_{overall}$.	$PF_{overall}$ =	0.900	lag

Part II: Draw the power triangles for the load, motor and system.



Question # 2 (5 marks) **SHOW YOUR CALCULATIONS** 1 hp = 746 W

A 440-V, 60-Hz, 6-pole, 3-ph, Δ-connected synchronous motor draws a line current I_L = 86.6 A on full-load with rotational losses P_{rot} = 3 kW. The field current is adjusted to obtain an open-circuit voltage E_a equal to 440 V. The synchronous reactance X_s = 5 Ω per phase and the winding resistance is negligible. Draw the phasor diagram and determine:

a.	the torque angle δ	$\delta=$	33	°
b.	the power factor PF	$PF=$	0.96	lag
c.	the power input P_{in}	$P_{in}=$	63.36	kW
d.	the output power P_{out}	$P_{out}=$	60.36	kW
e.	the net output torque T_{out}	$T_{out}=$	480.3	Nm

Solution

$$I_a=\frac{I_L}{\sqrt{3}}=\frac{86.6}{\sqrt{3}}=50\,A$$

$$\bar{V}_t=\bar{E}_a+j\bar{I}_aX_s\Rightarrow\bar{I}_a=\frac{\bar{V}_t-\bar{E}_a}{jX_s}$$

$$|\bar{I}_a|^2=\frac{|\bar{V}_t|^2+|\bar{E}_a|^2-2|\bar{V}_t||\bar{E}_a|\cos\delta}{X_s^2}\Rightarrow 50^2=\frac{440^2+440^2-2\times440\times440\cos\delta}{5^2}\Rightarrow\delta=33^\circ$$

$$\bar{I}_a=\frac{\bar{V}_t-\bar{E}_a}{jX_s}=\bar{I}_a=\frac{440\angle0^\circ-440\angle-33^\circ}{5\angle90^\circ}\Rightarrow\bar{I}_a=50\angle-16.5^\circ\,A$$

$$PF=\cos(16.5^\circ)=0.959\ lag$$

$$P_{in}=\sqrt{3}V_LI_L\cos\theta=\sqrt{3}\times440\times86.6\times0.959=63.36\ kW$$

$$P_{out}=P_{in}-P_{rot}=(63.36-3)=60.36\ kW$$

$$T_{out}=\frac{P_{out}}{\omega_s}=\frac{P_{out}}{\frac{2\pi N_s}{60}}=\frac{P_{out}}{\frac{2\pi}{60}\times\frac{120f}{P}}=\frac{60.36\times10^3}{\frac{2\pi}{60}\times\frac{120\times60}{6}}=\frac{60.36\times10^3}{125.7}\Rightarrow T_{out}=480.3\ Nm$$

Question # 2 (11 Points)

A 208-V Y-connected synchronous motor is drawing 50 A at unity power factor from a 208-V power system. The field current flowing under these conditions is 2.7 A. Its synchronous reactance is 1.6 Ω.

Part I: Assume a linear O.C. characteristic, draw the phasor diagram for this condition and find

a.	the magnitude of the induced phase voltage E_a and torque angle δ.	$E_a =$ 144	V
		$\delta =$ -33.7	°
b.	the steady-state stability power limit.	$P_{max} =$ 32.4	kW

Part II: If the field current is adjusted to make the motor operate at 0.80 PF leading, determine.

c.	the magnitude of the new armature current I_a, induced phase voltage E_a and field current I_f.	$I_a =$ ~~37~~ 62.5	A
		$E_a =$ 197	V
		$I_f =$ 3.7	A
d.	the new torque angle in part(c)	$\delta =$ -23.9	°

Solution:

(a) The phase voltage of this motor is V_ϕ = 120 V, and the armature current is $\mathbf{I}_A = 50\angle 0° \text{ A}$

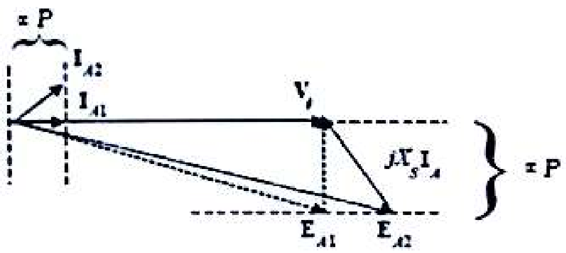
Therefore, the internal generated voltage is

$$\mathbf{E}_A = \mathbf{V}_\phi - R_A\mathbf{I}_A - jX_S\mathbf{I}_A$$

$$\mathbf{E}_A = 120\angle 0° \text{ V} - j(1.6\ \Omega)(50\angle 0° \text{ A})$$

$$\mathbf{E}_A = 144\angle -33.7° \text{ V}$$

The torque angle δ of this machine is –33.7°.



The static stability power limit is given by

$$P_{max} = \frac{3V_\phi E_A}{X_S} = \frac{3(120 \text{ V})(144 \text{ V})}{(1.6\ \Omega)} = 32.4 \text{ kW}$$

A phasor diagram of the motor operating at a power factor of 0.78 leading is shown below.

Since the power supplied by the motor is constant, the quantity $I_A \cos\theta$, which is directly proportional to power, must be constant. Therefore,

$$I_{A2}(0.8) = (50 \text{ A})(1.00) \quad \Rightarrow \quad \mathbf{I}_{A2} = 62.5\angle 36.87° \text{ A}$$

The internal generated voltage required to produce this current would be

$$\mathbf{E}_{A2} = \mathbf{V}_\phi - R_A\mathbf{I}_{A2} - jX_S\mathbf{I}_{A2}$$

$$\mathbf{E}_{A2} = 120\angle 0° \text{ V} - j(1.6\ \Omega)(62.50\angle 36.87° \text{ A})$$

$$\mathbf{E}_{A2} = 197\angle -23.9° \text{ V}$$

The internal generated voltage E_A is directly proportional to the field flux, and we have assumed in this problem that the flux is directly proportional to the field current. Therefore, the required field current is

$$I_{F2} = \frac{E_{A2}}{E_{A1}} I_{F1} = \frac{197 \text{ V}}{144 \text{ V}}(2.7 \text{ A}) = 3.70 \text{ A}$$

The new torque angle δ of this machine is –23.9°.

Question #4 (25 marks) **SHOW YOUR CALCULATIONS**

A three-phase, 4160-V, Y-connected, cylindrical-rotor synchronous motor has a synchronous reactance of 8 Ω per phase and a negligible armature resistance. The combined rotational losses (friction and windage plus core loss) amount to 5 kW. The highest excitation voltage possible is 4350 V. The motor delivers an output of 400 hp to a mechanical load connected to its shaft.

Part I: If the field current is increased to give the maximum excitation voltage, find:

a.	the power developed by the motor P_d.	$P_d =$	303.08	kW
b.	the torque angle δ.	$\delta =$	-7.7	°
c.	the magnitude of the motor's armature current I_a and PF.	$I_a =$	43.5	A
		$PF =$	0.968	lead
d.	the motor efficiency η_m.	$\eta_m =$	98.4	%
e.	the maximum developed power P_{max} at the above excitation voltage.	$P_{max} =$	2.262	MW

Part II: If the field current is reduced without changing the load, find:

f.	the new maximum developed power P_{max} which the motor will remain in synchronism (stable operation).	$P_{max} =$	303.08	kW
g.	the magnitude of the smallest excitation phase voltage E_a and torque angle δ	$E_a =$	583.5	V
		$\delta =$	- 90	°
h.	the magnitude of the armature current I_a and PF at the smallest excitation voltage of part (g).	$I_a =$	303.2	A
		$PF =$	0.1389	lag
i.	the reactive power Q absorbed/supplied by the motor.	$Q =$	2.164	MVAR

Draw the equivalent circuit, phasor and power angle-curve diagrams to illustrate your solution.