University of Jordan | School of Engineering | Electrical Engineering Department

EE471: Electrical Machines II | Second Exam | First Semester 2016-2017 | 23/11/2016 | Time: 85 Minutes

Q # 1.1 (4.5)	Q # 1.2 (2.5)	Q # 1.3 (2.5)	Q # 1.4 (2.5)	Q # 1.5 (6)	Q # 2 (12)	GRADE
4.5	2.5	2.5	2.5	6	12	30/30

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

Question # 1 (18 points) **SHOW YOUR CALCULATIONS** 1 hp = 746 W

1.1	A 3-ph, Y-connected, 7 hp, 220 V, 50 Hz, 6-pole induction motor has the following constants in Ω/phase referred to the stator: $R_1 = 0.294\ \Omega$; $R_2 = 0.144\ \Omega$; $X_1 = 0.42\ \Omega$; $X_2 = 0.209\ \Omega$; $X_m = 11.04\ \Omega$. The total friction, windage and core losses, P_{rot}, may be assumed to be constant at 403W, independent of load. The motor is operated at rated voltage, rated frequency and a slip s=2%. Using the IEEE model of IM, compute:		
a.	the motor's speed, n_m.	$n_m = 980$	rpm
b.	the motor's output power P_{out} and output torque T_{out}.	$P_{out} = 5.23$ $T_{out} = 51$	kW N.m
c.	the motor developed power P_d and developed torque T_d.	$P_d = 5.63$ $T_d = 54.8$	kW N.m
d.	The equivalent impedance seen by the source Z_{eq}	$Z_{eq} = 5.2 + j3.8$ $Z_{eq} = 6.44\angle 35.9°$	Ω Ω
e.	the magnitude of the motor's armature current, $\|I_a\|$ and PF.	$\|I_a\| = 19.74$	A
f.	the motor's power factor, PF.	PF =0.810	lag
g.	the overall motor efficiency η_m.	η_m = 85.8	%

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

$$P_{out} = \frac{7\times 746}{1000} = 5.23\,kW \Rightarrow T_{out} = \frac{P_{out}}{\omega_m} = \frac{5633}{\frac{2\pi\times 980}{60}} = 51\ Nm$$

$$P_d = P_{out} + P_{rot} = \frac{5230+403}{1000} = 5.63\,kW \Rightarrow T_d = \frac{P_d}{\omega_m} = \frac{5633}{\frac{2\pi\times 980}{60}} = 54.8\ Nm$$

$$Z_{eq} = R_1 + jX_1 + \frac{jX_m \times \left(\frac{R_2}{s} + jX_2\right)}{\left(\frac{R_2}{s} + j(X_2 + X_m)\right)} = 5.2 + j3.8\ \Omega = 6.44\angle 35.9°\ \Omega$$

$$\bar{I}_a = \frac{\bar{V}_1}{Z_{eq}} = \frac{220/\sqrt{3}}{6.44\angle 35.9°} = 19.74\angle -35.9°\ A \Rightarrow PF = \cos(-35.9°) = 0.810\ lag$$

$$P_{in} = \sqrt{3}\times 220\times 19.74\times\cos(35.9°) = 6.09\ kW$$

$$\eta_m = \frac{P_{out}}{P_{in}}\times 100 = \frac{5.23}{6.09}\times 100 = 85.8\%$$

1.2	The power input to the rotor of a 440 V, 50 Hz, 6-pole, 3 phase induction motor is 20 kW. For a slip $s = 4$ %, calculate :		
a.	the frequency of rotor currents, f_r	$f_r = 2$	Hz
b.	the rotor speed nm.	$n_m = 960$	rpm
c.	the rotor copper losses, P_{cu2}.	$P_{cu2} = 800$	W
d.	mechanical power developed P_d.	$P_d = 19.2$	kW
e.	the rotor resistance R_2 per phase if rotor current I_2 is 65 A.	$R_2 = 0.063$	Ω

Solution

$V = 400$ V, $f = 50$ Hz, $P = 6$, $s = 4\,\% = 0.04$

P input rotor $= P_{AG} = 22$ kW

a) Frequency of rotor current $f_r = s \times f = 0.04 \times 50 = 2$ Hz

b) Synchronous speed $n_s = 120\,f / P = 120 \times 50/6 = 1000$ rpm

Rotor speed $n_r = (1 - s)\, n_s = (1 - 0.04) \times 1000 = 960$ rpm

c) Rotor cu loss $P_{cur} = s\,P_{AG} \rightarrow P_{cu2} = 0.04 \times 20 = 0.8$ kW $= 800$ W

d) $P_{dev} = (1\text{-}s)\,P_{AG} = (1 - 0.04) \times 20 = 19.2$ kW $= 19200$ W

or $P_{dev} = P_{AG} - P_{cur} = (20 - 0.8) = 19.2$ kW $= 19200$ W

e) Let R_2 be the rotor resistance per phase, then

$3\,I_2^2.R_2 = P_{cur} = 800 \rightarrow 3\,(65)^2\,R_2 = 800 \rightarrow R_2 = 800 / (3 \times 65^2) = 0.063\ \Omega$

1.3	A 230-V, 6-pole, 3-ph, 50-Hz, 20.1 hp induction motor drives a **constant torque load** at rated frequency, rated voltage and rated kW output and has a speed of 980 rpm and an efficiency of 93%. If there is a 10% drop in voltage and 5% drop in frequency while all motor rotational losses are negligible, calculate:			
a.	the motor's slip in percent at rated load conditions.	$s_1 = 0.02$	2	%
b.	the motor's developed torque T_d at rated load conditions.	$T_d = 146.2$		N.m
c.	the motor's slip, speed and developed power at the new load conditions.	$s_2 = 0.0235$	2.35	%
		$n_{m2} = 928$		rpm
		$P_{dnew} = 14.2$		kW

Solution

$V_2 = 0.9 \times 230 = 207\ V \qquad f_2 = 0.95 \times 50 = 47.5\ Hz$

$N_{s1} = 120 \times 50/6 = 1000\ rpm \qquad N_{s2} = 120 \times 47.5/6 = 950\ rpm$

$$s_1 = \left(\frac{N_{s1} - N_{m1}}{N_{s1}}\right) = \left(\frac{1000 - 980}{1000}\right) = 0.02$$

$$T_d \alpha \frac{sV^2}{f} \Rightarrow \frac{s_1 V_1^2}{f_1} = \frac{s_2 V_2^2}{f_2} \Rightarrow s_2 = \left(\frac{f_2}{f_1}\right) \times \left(\frac{V_1}{V_2}\right)^2 \times s_1 = \left(\frac{47.5}{50}\right) \times \left(\frac{230}{207}\right)^2 \times 0.02 \Rightarrow s_2 = 0.0235$$

$$N_{m2} = (1 - s_2)N_{s2} = (1 - 0.0235) \times 950 = 927.7\ rpm$$

$$T_{d1} = T_{d2} \Rightarrow \frac{P_{d1}}{\omega_{m1}} = \frac{P_{d2}}{\omega_{m2}} \Rightarrow \frac{P_{d2}}{P_{d1}} = \frac{n_{m2}}{n_{m1}} \Rightarrow P_{d2} = \frac{n_{m2}}{n_{m1}} \times P_{d1}$$

$$P_2 \alpha T_2 N_{m2} \Rightarrow \frac{P_2}{P_1} = \frac{T_2 N_{m2}}{T_1 N_{m1}} = \frac{N_{m2}}{N_{m1}} = \frac{927.7}{980} \Rightarrow P_2 = \frac{927.7}{980} \times 15\,kW = 14.2\,kW$$

1.4	A 1492 kW, unity power factor 3-ph, star-connected, 2300 V, 50 Hz, 2-pole synchronous motor has a synchronous reactance X_s of 1.95 Ω/ph. The field excitation is adjusted to the value which would result in unity power factor at rated load. Assuming alls losses are negligible, draw the phasor diagram at this load condition and compute:		
a.	the motor's rotor angular speed ω_m	$\omega_m = 314.16$	rad/s
b.	the magnitude of the generated phase voltage $\lvert E_a \rvert$ and rotor angle δ	$\lvert E_a \rvert = 1515.5$ δ= -28.8	V o
c.	the maximum developed power P_{dmax} which this motor can deliver.	$P_{dmax} = 3096$	kW
d.	the maximum torque T_{dmax} which this motor can deliver.	$T_{dmax} = = 9855$	N.m

Solution

$S_{rated\text{-}3ph} = 1492$ kVA, $S_{rated\text{-}1ph} = 14923/3 = 497.3$ kVA

$V_{ph} = 2300/\sqrt{3} = 1327.9$ V, → I_L=497.333 ×1000/1327.906=374.5 A

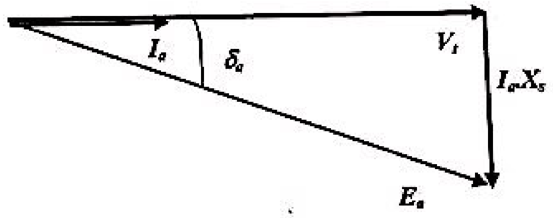
$$\omega_s = \frac{2\pi \times n_s}{60} = \frac{2\pi \times \left(\frac{120\times 50}{2}\right)}{60} = \frac{2\pi \times 3000}{60} = 314.16\ rad/s$$

$$|E| = \sqrt{V^2 + I\cdot X} = \sqrt{1327.91^2 + 374.5\times 1.95} = 1515.5 \text{ V}$$

$$P_{\max ph} = \frac{E\cdot V}{X} = \frac{1515.5\times 1327.9}{1.95} = 1032\ kW/ph$$

$$P_{\max 3ph} = \frac{3E\cdot V}{X} = \frac{3\times 1515.5\times 1327.9}{1.95} = 3096\ kW$$

$$T_{\max 3ph} = \frac{P_{\max 3ph}}{\omega_s} = \frac{3E\cdot V}{\omega_s \cdot X_s} = \frac{3\times 1515.5\times 1327.9}{314.16\times 1.95} = 9855\ N.m$$



1.5	A factory takes 600 kVA at a lagging power factor of 0.6 from 11 kV. A synchronous motor is to be installed to raise the overall power factor to 0.9 lagging when the motor is taking 200 kW. Calculate:	
a.	the real power, P_L, and reactive power, Q_L, and the magnitude of the load current, I_L taken by the load.	$P_L = 360$ kW $Q_L = 480$ kVAR $\lvert I_L \rvert = 31.5$ A
b.	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.	$P_s = 560$ kW $Q_s = 270.7$ kVAR $\lvert I_s \rvert = 32.7$ A
c.	the motor's real power, P_m, and reactive power, Q_m, the power factor PF_m, and the magnitude of the current, I_m.	$P_m = 200$ kW $Q_m = 209.3$ kVAR $PF_m = 0.691$ lag **lead** $\lvert I_m \rvert = 15.2$ A
d.	Is the motor over- or under excited?	**over excited** under excited

Draw the power triangles to illustrate your solution.

Solution:

$PF_L = \cos(\varphi) = 0.6 \rightarrow \varphi = 36.9^\circ \rightarrow \sin(\varphi) = 0.8$

$S_L = 600$ kVA, $P_L = S_L \times \cos(\varphi) = 600k \times 0.6 = 360$ kW, $Q_L = S_L \times \sin(\varphi) = 600k \times 0.8 = 480$ kVAR

$P_m = 200$ kW, $Q_L = S_L \times \sin(\varphi) = 600k \times 0.8 = 480$ kVAR

$P_s = P_L + P_m = (200+360) = 560$ kW

$PF_{Overall} = \cos(\alpha) = 0.9$ lag $\rightarrow \alpha = 25.8^\circ$,

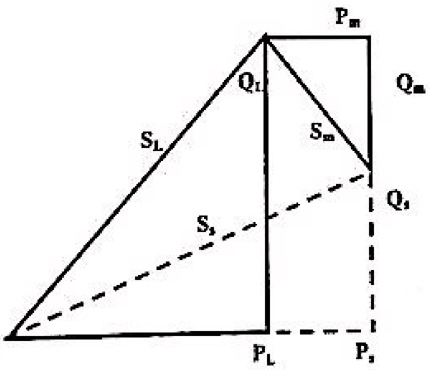
$$Q_s = P_{tot} \times \tan(\alpha) = (360+200)k \times \tan(25.8^\circ) = 560k \times 0.484 = 270.7\,kVAR$$

$$Q_m = Q_L - Q_s = (480 - 270.7)k = 209.3\ kVAR\ (capacitive)$$

$$\theta_m = \tan^{-1}\frac{Q_m}{P_m} = \tan^{-1}\left(\frac{209.3}{200}\right) = 46.3^\circ \Rightarrow PF_m = \cos(46.3^\circ) = 0.691\ leading$$

$$I_m = \frac{Q_m}{\sqrt{3} \times V_L \times \sin(\theta_m)} = \frac{209.3 \times 10^3}{\sqrt{3} \times 11 \times 10^3 \times \sin(46.3^\circ)} = 15.2\,A \quad or$$

$$I_m = \frac{P_m}{\sqrt{3} \times V_L \times \cos(\theta_m)} = \frac{200 \times 10^3}{\sqrt{3} \times 11 \times 10^3 \times \cos(46.3^\circ)} = 15.2\,A$$



Question # 2 (12 points) **SHOW YOUR CALCULATIONS**

A three-phase, 4160-V, Y-connected, cylindrical-rotor synchronous motor has a synchronous reactance of 8 Ω/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.	$\lvert I_a \rvert$ = 43.5 PF =0.968 lag	A lead
d.	the motor efficiency η_m.	η_m = 98.4	%
e.	the maximum developed power P_{max} at the above excitation voltage.	P_{dmax} = 2.262	MW

$$P_d = P_{out} + P_{rot} = \left(\frac{400\times 746}{1000}+5\right)kW = (298.4+5) = 303.4\ kW$$

$$P_d = \frac{|V_{LL}|\times|E_{aL}|}{X_s}\sin(\delta) = \frac{4160\times 4350}{8}\sin(\delta) = 2262\times 10^3\sin(\delta) = 303.4\times 10^3 W$$

$$\Rightarrow \sin(\delta) = \frac{303.4}{2262} \Rightarrow \delta = 7.7°$$

$$I_a = \frac{\overline{V}_t - \overline{E}_a}{jX_s} = \frac{4160/\sqrt{3}\angle 0° - 4350/\sqrt{3}\angle -7.7°}{8\angle 90°} = 43.5\angle +14.5° \Rightarrow PF = \cos(14.5°) = 0.968\ leading$$

$$P_{in} = P_d = \sqrt{3}V_L I_L\cos(\theta) = \sqrt{3}\times 4160\times 43.5\times 0.968 = 303.4\ kW \Rightarrow$$

$$\eta_m = \frac{P_{out}}{P_{in}}\times 100 = \frac{298.4}{303.4}\times 100 = 98.4\%$$

$$P_{d\,max} = \frac{4160\times 4350}{8}\sin(90°) = 2262\times 10^3 = 2{,}262\ kW$$

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

a.	the new maximum developed power P_{max} which the motor will remain in synchronism (stable operation). Illustrate your solution using Power-Angle curve.	P_{max} =303.4	kW
b.	the smallest excitation voltage E_a and torque angle δ	E_{aph} = 336.9 E_aLL = 583.5 δ = - 90°	V V °
c.	the magnitude of the armature current $\lvert I_a \rvert$ and PF at the smallest excitation voltage of part (c)	$\lvert I_a \rvert$ = 303.2 PF =0.139 lag	A lead
d.	the reactive power Q_m absorbed/supplied by the motor.	Q_m = 2163	kVAR

$$P_{d\,max} = \left.\frac{|V_{LL}|\times|E_{aL}|}{X_s}\right|_{\delta=90°} = \frac{4160\times|E_{aL\,min}|}{8} = 303.4kW \Rightarrow |E_{aL\,min}| = 583.5\ V_{LL} \Rightarrow |E_{aph\,min}| = 336.9V$$

$$I_a = \frac{\overline{V}_t - \overline{E}_a}{jX_s} = \frac{4160/\sqrt{3}\angle 0° - 583.3/\sqrt{3}\angle -90°}{8\angle 90°} = 303.2\angle +82° \Rightarrow PF = \cos(82.5°) = 0.139\ lagging$$