UNIVERSITY OF KWAZULU-NATAL

Electrical, Electronic and Computer Engineering Discipline

FINAL EXAMINATIONS: SEPTEMBER 2015

ENEL4MB S2 – ELECTRICAL MACHINES IV

DURATION: 3 HOURS **TOTAL MARKS: 100**

Examiners: Dr I E Davidson (Internal)
Prof Azeem Khan (External)

Instructions: This examination paper consists of 4 pages (inclusive of this front page)
Attempt <u>ALL</u> questions. All questions carry equal marks.

Please take note of the formulae provided below, some of which you may find useful in answering the questions in this examination. Any formulae that do not appear below are considered required knowledge for this course. No other formula sheets will be allowed into the examination.

Permeability of free space: $\mu_0 = 4\pi \times 10^{-7}$ H/m

Electromagnetic Power: $P_g = \dfrac{P_M}{1-s}$

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Output Power: $E.I_a = T.\omega$

Rotor Current: $\tau_1 = X_1/X_m$

$$I_2^{'} = \frac{V_1}{\sqrt{\left[R_1 + \left(R_2^{'}/s\right)\left(1+\tau_1\right)\right]^2 + \left[X_1 + X_2^{'}\left(1+\tau_1\right)\right]^2}}$$

Electromagnetic (developed) torque

$$T_d = \frac{m_1}{2\pi n_s} \frac{V_1^2\left(R_2^{'}/s\right)}{\left[R_1 + \left(R_2^{'}/s\right)\left(1+\tau_1\right)\right]^2 + \left[X_1 + X_2^{'}\left(1+\tau_1\right)\right]^2}$$

Critical value of slip

$$s_{cr} = \pm \frac{R_2^{'}\left(1+\tau_1\right)}{\sqrt{R_1^2 + \left[X_1 + X_2^{'}\left(1+\tau_1\right)\right]^2}} \approx \pm \frac{R_2^{'}\left(1+\tau_1\right)}{X_1 + X_2^{'}\left(1+\tau_1\right)} \approx \pm \frac{R_2^{'}}{X_1 + X_2^{'}}$$

Maximum (pull-out) torque:

$$T_{d\max} = T_{d(s=s_{cr})} = \pm \frac{m_1 V_1^2}{4\pi n_s\left(1+\tau_1\right)} \frac{1}{\left\{\sqrt{\left(R_1^2 + \left[X_1 + X_2^{'}\left(1+\tau_1\right)\right]^2\right)} \pm R_1\right\}} \approx \pm \frac{m_1 V_1^2}{4\pi n_s\left(1+\tau_1\right)} \frac{1}{\left[X_1 + X_2^{'}\left(1+\tau_1\right)\right]^2}$$

Starting Torque Ratio $STR = T_{st}/T_d$

Rotor Winding Loss: $P_{2w} = s.P_g$

Kloss's formula; $\dfrac{T_d}{T_{d\max}} \approx \dfrac{2}{s_{cr}/s + s/s_{cr}}$

Heyland's Coefficient, $\tau_1 = \dfrac{X_1}{X_m}$

Starting Torque $T_{dst} = T_{d(s=1)} = \dfrac{m_1 V_1^2}{2\pi n_s} \dfrac{R_2^{'}}{\left[R_1 + R_2^{'}\left(1+\tau_1\right)\right]^2 + \left[X_1 + X_2^{'}\left(1+\tau_1\right)\right]^2}$

Approximate per-phase torque: $T \approx \dfrac{T_m\, 2\, s\, s_m}{s^2 + s_m^2}$

Overload Capacity Factor: $OCF = T_{\max}/T_d$

Single-phase induction motor parameters: $R_a = \dfrac{X_a}{X_m}\left(R_m + \left|Z_m\right|\right)$

Developed Torque: $T_d = \dfrac{P_g}{2\pi \, n_s/60}$

Induced EMF: $E. = 4.44.f.\Phi_m.N$

Eddy current loss: $P_e = k_e Vol\, B_{\max}^2\, t^2\, f^2$

Hysteresis loss: $P_h = k_h Vol\, B_{\max}^n\, f$ where n is the Steinmetz Index

All symbols have the usual meaning.

Question 1 **[25 Marks]**

(a) Sketch and label the equivalent circuit of a three-phase induction motor? Explain what is R_{Fe} and X_m. [6]

(b) Sketch and label a suitable block diagram showing the sequence of power flow and energy transfer in an induction motor. [6]

(c) The voltage induced per phase in the stator winding is given by: $E_1 = 4\sigma_f fN_1k_{w1}\Phi$ or $E_1 = \pi\sqrt{2}\, fN_1k_{w1}\Phi = 4.44\, fN_1k_{w1}\Phi$. The slip-dependent voltage (e.m.f.) that is induced in the rotor winding (per phase) is: $E_2(s) = 4\sigma_f(sf)N_2k_{w2}\Phi$ where sf is the slip frequency (i.e. the frequency of the rotor current), the slip-dependent rotor impedance is: $Z_2(s) = R_2 + jX_2(s) = R_2 + j2\pi sfL_2 = R_2 + jsX_2$ where L_2 is the rotor winding inductance, and $X_2 = 2\pi fL_2$ is the rotor inductance for $s = 1$.

Beginning from first principles, and using the equivalent circuit of a 3-phase induction motor or otherwise, derive an expression for the developed torque in an induction motor: [13]

$$T_d = \frac{3}{2\pi N_s}\frac{E_r^2}{\left[R_2^{'2} + (sX_0)^2\right]}\frac{R_2^{'2}}{s}$$

Question 2 **[25 Marks]**

(a.) Clearly explain and distinguish between the following using suitable illustrations: [3]

(i.) Mechanical braking
(ii.) Plugging
(iii.) DC Braking

How would you achieve synchronous operation of an induction motor? [1]

(b.) A 40-kW 4-pole 50-Hz induction machine has a friction and windage torque of 20.4 N-m. The stator-losses are equal the rotor circuit loss. Calculate:

(i.) The synchronous speed and slip when running at 1450 rpm. [4]

(ii.) The input power to the stator when delivering full-load output at a speed of 1450 rpm. [6]

(iii.) The developed torque and stator output power when running at a speed of 1560 rpm. [8]
[The stator losses are as in (ii.) above and the windage and friction torque is unchanged.]

(c.) Under what operating conditions will an electrical machine operate at optimum (maximum) efficiency? Be detailed in your explanation. [3]

Question 3 **[25 Marks]**

(a.) For the rotating part of a machine describe the phenomena of the critical speed ω_r and derive an expression which relates it to the eccentricity '*e*', deflection δ, mass *m* and *K* the deflection proportionality constant. [8]

(b.) A 3-phase, 12-pole, 60 Hz, 420V (line-line), Y-connected, 10-kW, cage induction motor has the following equivalent circuit parameters:

$$R_1 = 0.8\Omega \qquad X_1 = 2.24\Omega$$

$$R_2' = 0.8\Omega \qquad X_2' = 2.24\Omega \qquad X_m = 43.50\Omega$$

The machine operates with a slip of 0.05. The rotational loss is P_{rot} = 250 W and the stray loss is P_{stray} = 60 W.

For rated conditions of frequency, input voltage and a rated slip of 0.05, calculate:

(i.) The stator and rotor currents at slip 0.05 [4]

(ii.) The stator and rotor winding losses [2]

(iii.) The mechanical power and output power. [1]

(iv.) The input power, efficiency and power factor [2]

(v.) The air-gap power and electromagnetic (or developed) torque [1]

(vi.) The STR (i.e., the ratio of starting torque to the maximum torque) [3]

(vii.) Explain the performance of this machine if it is now operated at **50Hz**, but rated voltage. [2]

[*Assume the core losses are neglected (R_{Fe}) and the skin effect in the rotor bars is also negligible*.]

(c.) What are the important factors or specifications required in selecting an electrical machine for a specified application? [2]

Question 4 [25 Marks]

(a.) Discuss the starting and mode of operation of a single-phase induction motor? Explain the function of the main and auxiliary windings in single-phase motors? [5]

(b.) A 120 V, 60 Hz, 4-pole, single phase induction motor gave the following standstill impedances when tested at rated frequency:

Main Winding: $=1.5 + j4.0\ \Omega$

Auxiliary winding: $=3.0 + j6.0\ \Omega$

(i.) Determine the value of external resistance to be inserted in series with the auxiliary winding to obtain maximum starting torque as a resistor split-phase motor. [6]

(ii.) Determine the value of the capacitor to be inserted in series with the auxiliary winding to obtain maximum starting torque as a capacitor start motor. [6]

(c.) For each of the following applications, specify ONE suitable electrical machine: [8]

[Do not limit yourself to only 3-phase induction machines.]

	Application	**Specified Electric Machine**
1	Analogue clocks and timers	
2	Office desktop computer printer	
3	520 km/h High-Speed Maglev trains	
4	960MW Power Generation	
5	2.5W Electric fan	
6	750W High-starting torque, low-starting current	
7	Traction drives for mining operations	
8	15000 rpm industrial siren	

End of Exam