UiA University of Agder

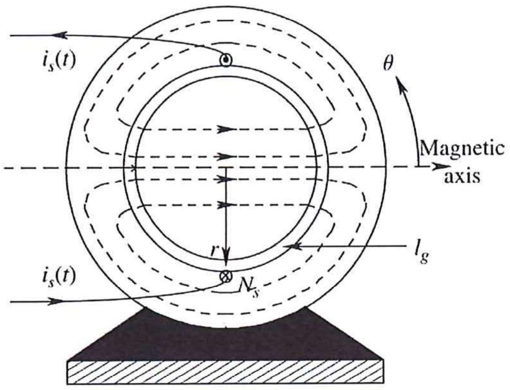
FACULTY OF ENGINEERING AND SCIENCE

EXAM

Course code:	**MAS409**
Course name:	**Electric Motor Drives**
Date:	22nd May 2019
Duration:	3 hours
Number of pages incl. front page:	5
Resources allowed:	Approved pocket calculator. (No written material)

Formulas and theory that may be useful:

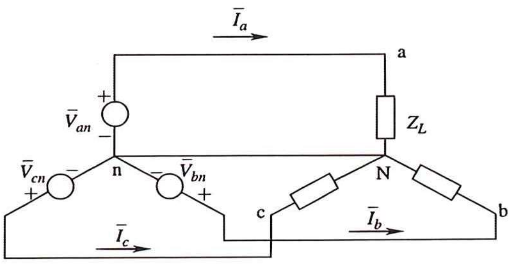
Production of Magnetic Field:



Flux density in air gap produced by a concentrated stator winding with N_s turns with current i:

$$B = \mu_0 \frac{N_s i}{2 l_g}; \qquad \mu_0 = 4\pi \cdot 10^{-7}\ \text{H/m} \qquad (1)$$

Balanced Three Phase Circuits:



$$\bar{V}_{an} + \bar{V}_{bn} + \bar{V}_{cn} = 0 \qquad (2)$$

$$\bar{I}_a + \bar{I}_b + \bar{I}_c = 0 \qquad (3)$$

$$\bar{V}_{LL} = \sqrt{3}\bar{V}_{ph}\angle 30^\circ \qquad (4)$$

Power Electronic Inverter

Bipolar switching:

$$v_{\text{cntrl}} = \left(\frac{1}{2} + \frac{\bar{v}_0}{2V_d}\right)\hat{V}_{tri} \qquad (5)$$

if $v_{\text{cntrl}} > v_{tri}$ then $(A, B) = (1, 0)$ else $(A, B) = (0, 1)$

Induction motors:

Synchronous speed: $n_{sync} = \dfrac{120 f_{se}}{p}$ [rpm]

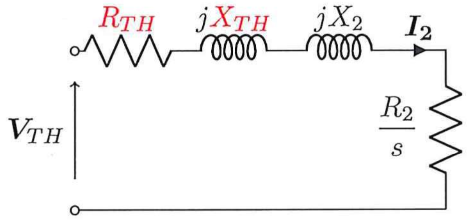
f_{se} = stator frequency [Hz]

p = number of poles

Slip: $s = \dfrac{n_{sync} - n_m}{n_{sync}}$ [-]

n_m = motor speed

Thevenin circuit for the stator side (R_1: stator resistance, X_1: reactance, X_M: mutual reactance):



$$\bar{V}_{TH} = \frac{jX_M}{R_1 + jX_1 + jX_M}\bar{V}_{ph} \qquad (6)$$

$$Z_{TH} = \frac{jX_M(R_1 + jX_1)}{R_1 + jX_1 + jX_M} = R_{TH} + jX_{TH} \qquad (7)$$

Induced torque:

$$\tau_{ind} = \frac{3\frac{R_2}{s}V_{TH}^2}{\omega_{sync}\left[\left(R_{TH} + \frac{R_2}{s}\right)^2 + (X_{TH} + X_2)^2\right]} \qquad (8)$$

Slip at pullout torque:

$$s_{\tau_{max}} = \frac{R_2}{\sqrt{R_{TH}^2 + (X_{TH} + X_2)^2}} \qquad (9)$$

Maximum torque:

$$\tau_{max} = \frac{3V_{TH}^2}{2\omega_{sync}\left(R_{TH} + \sqrt{R_{TH}^2 + (X_{TH} + X_2)^2}\right)} \qquad (10)$$

Problem 1: Phasors and Space vectors [30%]

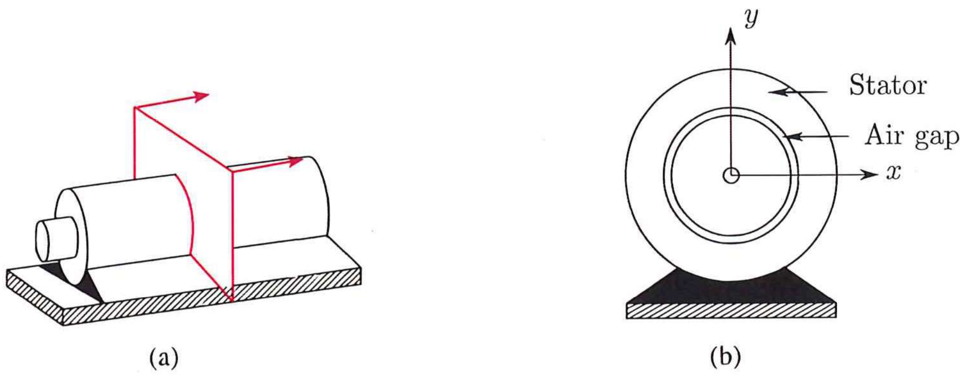


Figure 1: Motor construction a) "cut" perpendicular to the shaft-axis; b) cross-section seen from one side.

Fig. 1 shows the cross section of a stator with a rotor electrically open-circuited. This stator is of a three-phase, 2-pole ac machine with $N_s = 90$ turns for each phase winding, with air-gap length $l_g = 1.5$ [mm] and draws a total electrical power of 10 [kW] at a power factor of 0.85. The phase-a current is $i_a(t) = 30\cos(\omega t)$ [A], where ω is the angular frequency in [rad/s]. The voltages are applied to the stator phases in a positive sequence resulting in counterclockwise rotation of the magnetic field.

a) **[10%]** Calculate the rms value V_{LL} of the line to line voltage applied to this stator.

b) **[6.6%]** Which one of the phasor diagrams shown in Fig. 2 is correct? Explain your answer.

c) **[6.7%]** Calculate the net flux density $\vec{B_{net}}$ produced by the stator at instant t such that $\omega t = 120°$.

d) **[6.7%]** Which one of the space vector diagrams shown in Fig. 3 is correct?

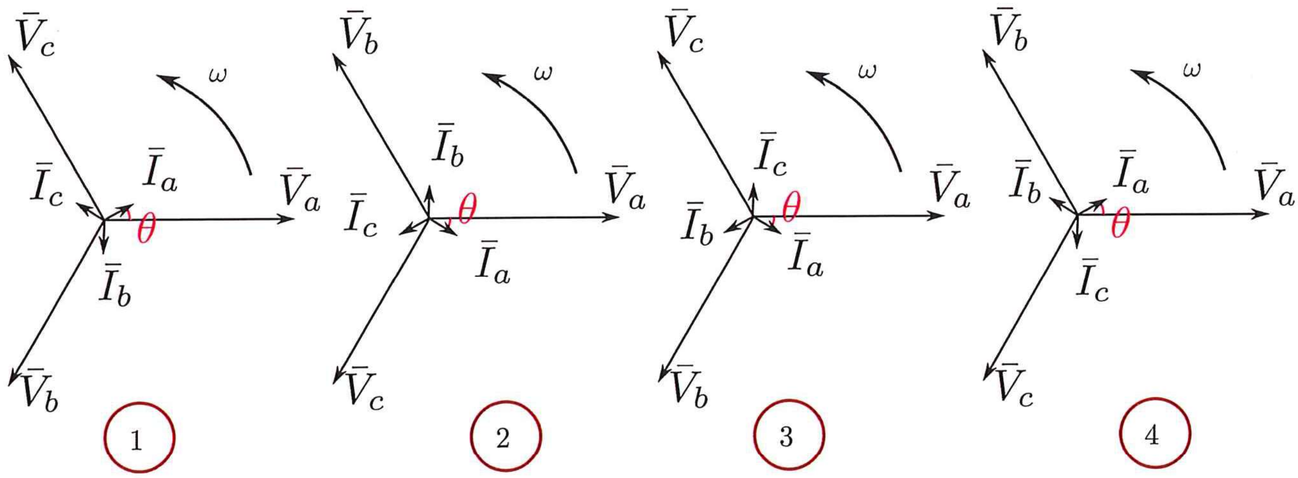


Figure 2: Phasor diagrams.

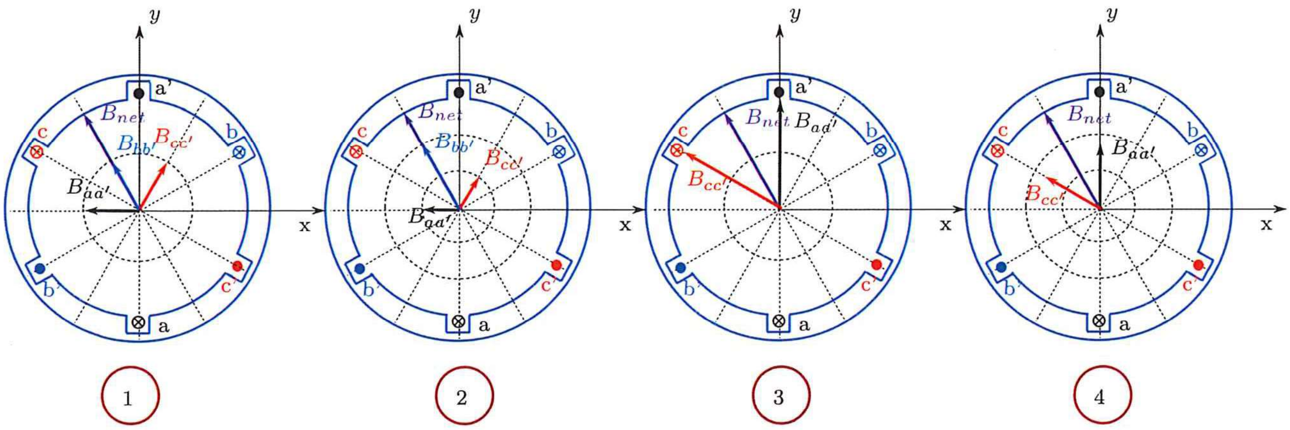


Figure 3: Space vector diagrams.

Problem 2: Power Electronic Inverter [30%]

A switch-mode dc-dc converter shown in Fig. 4 with $V_d = 400$ V is controlled using a **bipolar** switching mode, comparing a control signal, v_{cntrl} with a triangular signal $v_{tri}(t)$ plotted in Fig. 5. A DC motor is connected to the dc-dc converter and has the following parameters: $R_a = 0.30\ \Omega$ and $L_a = 5$ mH.

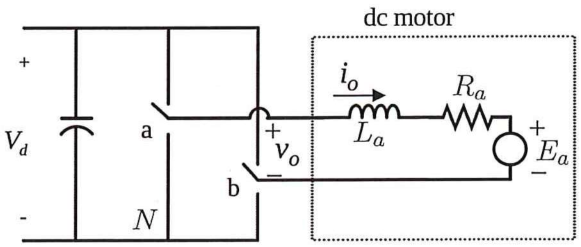


Figure 4: Two poles dc-dc converter and DC motor

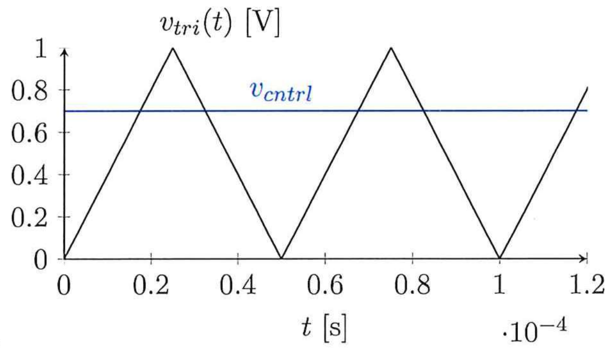


Figure 5: Triangular shaped carrier waveform

In a given steady state with constant motor speed, (the speed ripples are neglected), the back emf of the motor is $E_a = 40$ V and the control signal is $v_{cntrl} = 0.7$ V.

a) **[6.7%]** Calculate the pole gain $\boldsymbol{k_A}$ for pole A of the dc-dc converter. Deduce the average voltage $\overline{v_{aN}}$.

b) **[6.6%]** Calculate the average voltage $\overline{v_{bN}}$ and deduce the average output voltage $\overline{v_o} = \overline{v_{aN}} - \overline{v_{bN}}$.

c) **[3.3%]** Calculate the average output current $\overline{i_o}$.

d) **[10%]** Calculate the peak-peak ripple $\boldsymbol{\Delta i_{0,ripple}}$ of the output current.

e) **[3.4%]** What is the frequency $\boldsymbol{f_{out}}$ of the output voltage?

Problem 3: Modeling of IM machines [40%]

A 460-V, four-pole, 75-hp, 60-Hz Y-connected, three-phase induction motor develops its full-load induced torque at 3.5 percent slip when operating at 60 Hz and 460 V. The per-phase circuit model impedances of the motor are:

$$R_1 = 0.58\ \Omega; \quad R_2 = 0.07\ \Omega; \quad X_M = 18\ \Omega;$$
$$X_1 = 0.32\ \Omega; \quad X_2 = 0.386\ \Omega;$$

Mechanical, core and stray losses may be neglected in this problem, i.e. $\tau_{ind} = \tau_{load}$.

a) **[10%]** Calculate the full-load torque τ_{load} and the rated motor velocity n_n in [rpm].

b) **[16.7%]** Calculate the maximum torque τ_{max} in Nm as well as the corresponding slip $s_{\tau_{max}}$ and motor velocity $n_{\tau_{max}}$ in rpm.

c) **[6.6%]** Calculate the starting torque τ_{start} in Nm and the corresponding slip s_{start}.

d) **[6.7%]** With the help of Fig. 6, determine to which Nema class (A, C or D) this motor belongs and which design its rotor slot has (1, 2 or 3). Also link each rotor slot (1,2 or 3) with its corresponding Nema class (A, C or D). Explain your answer by considering low and high slip, rotor leakage reactance and variable rotor resistance.

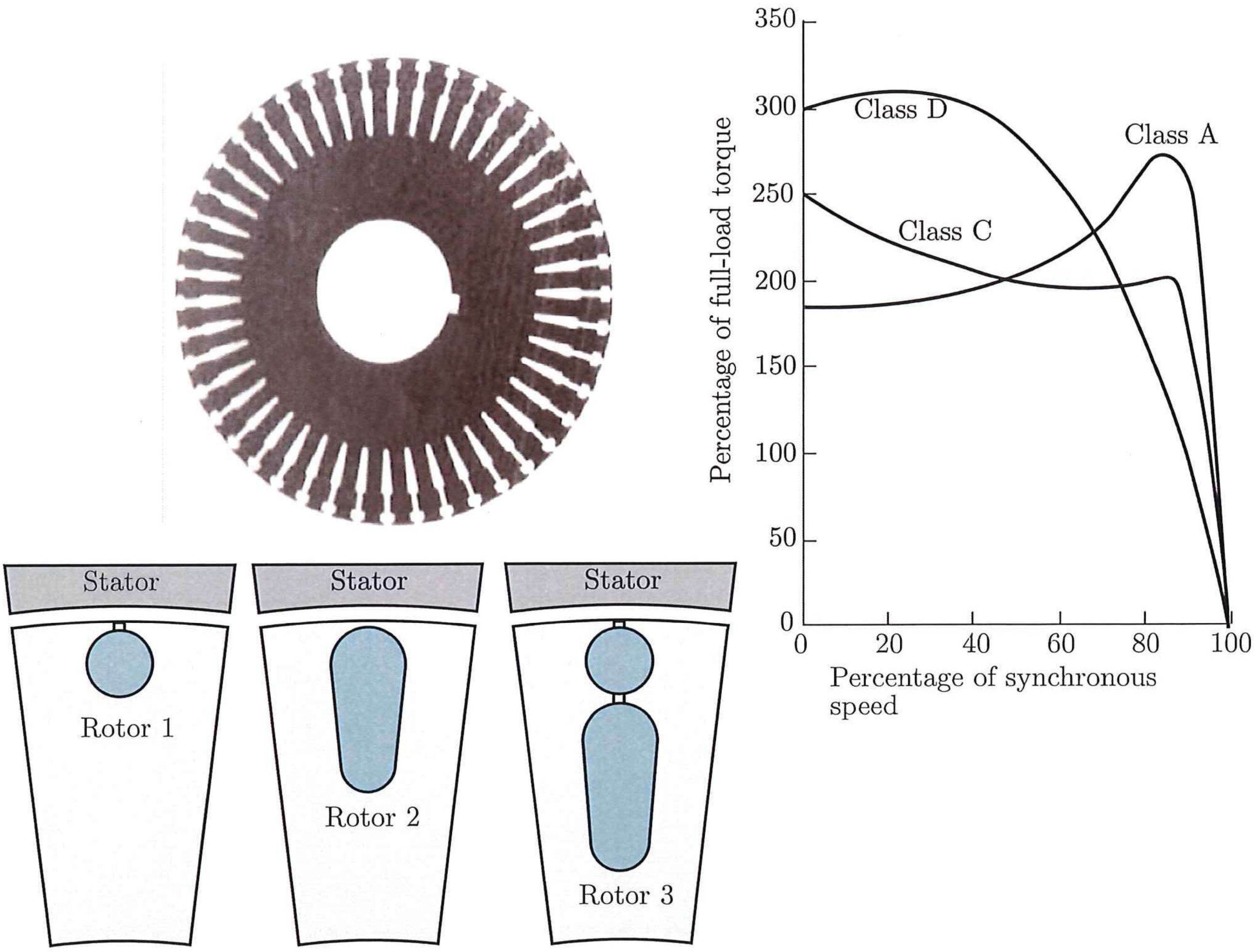


Figure 6: Torque-Speed Curves for Different Rotor Designs