Exam 1

Name: ____

The exam is taken remotely. Any material is allowed.

1.1 Analysis and Modeling of a Motor Drive System

Consider the three-phase inverter drive system shown in Fig. 1. A two-level converter with the total dc-link voltage V_{dc} is connected to a squirrel-cage induction machine. The rated machine values are provided in Table 1. The system parameters are summarized in Table 2.

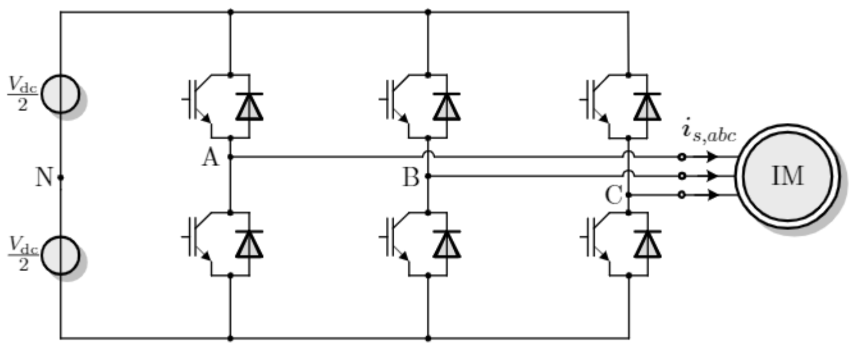

Figure 1: Two-level three-phase inverter driving an induction machine

Parameter	Symbol	SI value
Voltage	V_R	400 V
Current	I_R	4.4 A
Apparent power	S_R	3.048 kVA
Angular stator frequency	ω_{sR}	$2\pi 50$ rad/s

Table 1: Rated values of the induction machine

1. Compute the per unit (p.u.) values of the stator and rotor resistances, R_s and R_r, respectively, stator and rotor leakage reactances, X_{ls} and X_{lr}, respectively, mutual reactance X_m, and dc-link voltage V_{dc}. (2 points)

2. The voltage equations of the drive system in the stationary reference frame (i.e., $\alpha\beta$ plane) are

$$\boldsymbol{v}_{s,\alpha\beta} = R_s \boldsymbol{i}_{s,\alpha\beta} + \frac{\mathrm{d}\boldsymbol{\psi}_{s,\alpha\beta}}{\mathrm{d}t}$$

$$\boldsymbol{v}_{r,\alpha\beta} = R_r \boldsymbol{i}_{r,\alpha\beta} + \frac{\mathrm{d}\boldsymbol{\psi}_{r,\alpha\beta}}{\mathrm{d}t} - \omega_r \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \boldsymbol{\psi}_{r,\alpha\beta}\,.$$

Transform the differential equations from stationary orthogonal coordinates into a rotating dq coordinate system which rotates with the angular stator frequency ω_s. (4 points)

Parameter	Symbol	SI value
Stator resistance	R_s	$2.7\,\Omega$
Rotor resistance	R_r	$2.4\,\Omega$
Stator leakage inductance	L_{ls}	$9.868\,\mathrm{mH}$
Rotor leakage inductance	L_{lr}	$11.777\,\mathrm{mH}$
Main inductance	L_m	$394.704\,\mathrm{mH}$
Number of pole pairs	p	1
Dc-link voltage	V_{dc}	$650\,\mathrm{V}$

Table 2: Drive parameters in the SI of the two-level inverter drive system

3. Draw the equivalent circuit representation of the drive system in the dq rotating reference frame. Draw one representation in the d- and another one in the q-axis. (2 points)

4. Consider the per unit electromagnetic torque

$$T_e' = \frac{1}{\mathrm{pf}} \boldsymbol{\psi}_{s,dq}' \times \boldsymbol{i}_{s,dq}' ,$$

where $\mathrm{pf} = \cos(\phi)$ is the power factor and the superscript $'$ denotes p.u. quantities. Show that the base value for the electromagnetic torque is $T_B = \mathrm{pf}\, p \frac{S_B}{\omega_B}$, where S_B denotes the base apparent power and p the number of pole pairs. (4 points)

1.2 Modulation Techniques for AC Drives

Consider a two-level inverter driving an induction machine.

1. What is the maximum modulation index for linear operating range with carrier-based pulse width modulation (CB-PWM), without any common-mode voltage injection? Justify your answer. (2 points)

2. What is the maximum modulation index for linear operating range with space vector modulation (SVM)? Justify your answer. (2 points)

3. What is the maximum modulation index with optimized pulse patterns (OPPs)? Justify your answer. (2 points)

4. Consider two-level OPPs with $u_0 = -1$. Derive the objective function and formulate the optimization problem that computes the OPPs for d switching angles and modulation index m. (4 points)

5. Assume OPP with $d = 2$. The switching angles for phase a as a function of the modulation index m are shown in Fig. 2. What are the switching angles in phase a over one fundamental period for the modulation index $m = 0.8$? (1 point)

6. Assume that the fundamental frequency is $f_1 = 25\,\mathrm{Hz}$ and $m = 4/\pi$. What is the switching frequency of each active semiconductor switch? (1 point)

7. What is the voltage amplitude of the 7^{th} and 9^{th} harmonic of the switch position u_α, i.e., the α-component of the switch position? Assume the OPP is applied to the inverter with the dc-link voltage mentioned in Table 2. (5 points)

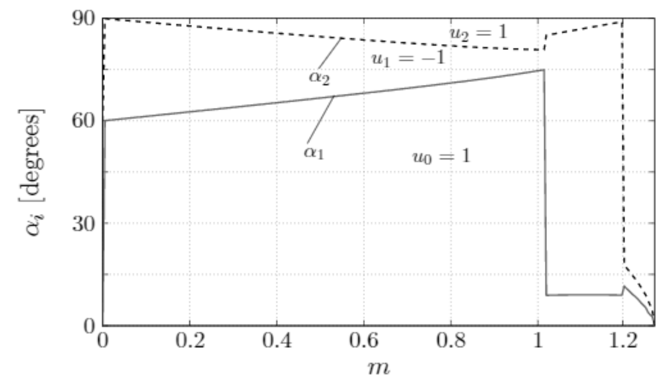

Figure 2: Primary switching angles $\alpha_1(m)$ and $\alpha_2(m)$ of the OPP with pulse number $d = 2$

1.3 Control Methods for AC Drives

Consider a two-level inverter driving an induction machine as shown in Fig. 1, with the rated machine values in Table 1 and parameters in Table 2.

1. Assume that the drive is controlled with scalar control (V/f) and OPPs. What is the theoretical maximum value of the ratio V/f at rated speed? (1 point)

2. Assume that the drive is controlled with field oriented control (FOC) with stator field orientation. The reference plane rotates with the angular frequency of the stator ω_s. At nominal steady-state operating conditions the electromagnetic torque and stator flux magnitude are T_e and Ψ_s, respectively. Given these, compute the (steady-state) stator and rotor currents in the dq-reference frame as a function of the stator and rotor fluxes, i.e., $\boldsymbol{i}_{s,dq} = f(\boldsymbol{\psi}_{s,dq}, \boldsymbol{\psi}_{r,dq})$ and $\boldsymbol{i}_{r,dq} = g(\boldsymbol{\psi}_{s,dq}, \boldsymbol{\psi}_{r,dq})$. Hint: Consider as state variables the stator and rotor fluxes, i.e., $\boldsymbol{x} = [\boldsymbol{\psi}_{s,dq}^T \; \boldsymbol{\psi}_{r,dq}^T]^T$. (5 points)

3. Assume that the drive is controlled with direct torque control (DTC). The stator flux vector $\boldsymbol{\psi}_{s,\alpha\beta}$ rotates counterclockwise. The stator flux magnitude is too high, and the developed electromagnetic torque is too low, with both control errors exceeding their respective bounds. If the angular position of $\boldsymbol{\psi}_{s,\alpha\beta}$ is $-\pi/6$, what voltage vector should be applied to the inverter? (3 points)

4. Assume that the drive is controlled with direct model predictive control (MPC). There are three control objectives, namely, the elimination of the torque and stator flux magnitude errors, and the minimization of the switching effort. Given the reference values for the torque and flux magnitude, T_e^* and Ψ_s^*, respectively, define the objective function that needs to be minimized. (3 points)

1.4 General Questions

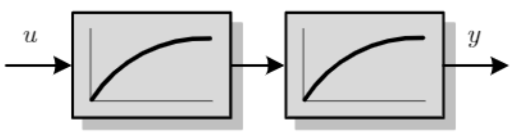

Figure 3: System with one big delay and another equivalent delay which is less than a quarter of the big delay, i.e., $4T_e < T_1$

1. What is the difference between direct and indirect control schemes? (1 point)

2. What is the main difference between CB-PWM and OPPs regarding the switching instants? (2 points)

3. Consider a system which can be represented by first order delays, one of which is four times as large as the sum of the remainder, i.e., $T_1 > 4T_e$, where T_1 is the big delay of the first system and T_e is the equivalent delay, see Fig. 3. Choose a proper controller for this system and find its parameters. Hint: Use symmetrical optimum and assume $A_R A_S \gg 1$. (2 points)
4. Assume that the controlled system has an integrating element and a first order delay. Is modulus optimum control suitable for this system? Justify your answer. (1 point)
5. Why does FOC require an observer? (1 point)
6. What factors affect the switching frequency when DTC is used? (2 points)