Data Provided: None

The University Of Sheffield.

DEPARTMENT OF ELECTRONIC AND ELECTRICAL ENGINEERING

Spring Semester 2014-15 (3.0 hours)

EEE6201 Advanced Control of Electric Drives

Answer **FOUR** questions. **No marks will be awarded for solutions to a fifth question.** Solutions will be considered in the order that they are presented in the answer book. Trial answers will be ignored if they are clearly crossed out. **The numbers given after each section of a question indicate the relative weighting of that section.**

1. **a.** Figure 1 illustrates a three-phase voltage source inverter with resistive shunt current sensing.

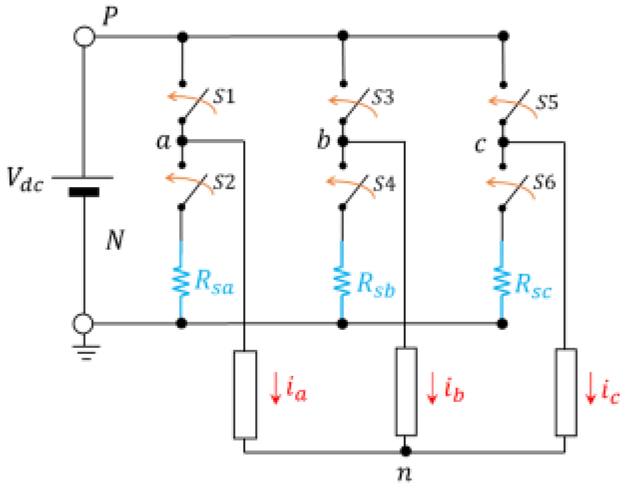

Figure 1

i. Explain the advantages and disadvantages of this current measurement technique. Suggest an alternative technique which does not suffer from these disadvantages. **(2)**

ii. If the maximum load currents are $I_{rms} = 25A_{rms}$ and the sensing circuitry can measure voltages in the range $\pm 5V$, calculate the maximum value of the sensing resistors R_s. **(1)**

iii. At what point during the PWM switching cycle can the current measurements be taken? **(1)**

b. A quadrature incremental encoder with 720 pulses per revolution has output signals **A**, **B** with **A** leading **B** for positive rotation. The signals shown in Figure 2 are measured.

i. Assuming that both rising and falling edge transitions are counted, and that the initial position is 0°, what is the final measured position?

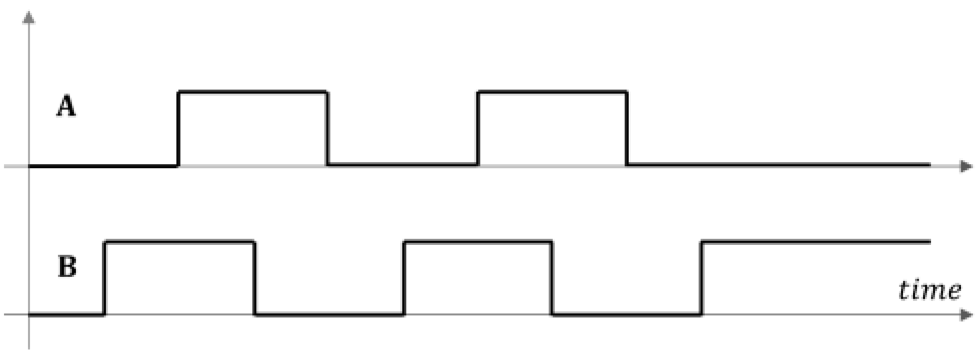

Figure 2 **(2)**

ii. Describe the main differences between incremental and absolute encoders. **(2)**

c. i. Calculate the angular resolution in rad that can be obtained with a 12-bit absolute encoder. **(2)**

ii. Calculate the minimum number of bits for an encoder in order to achieve a resolution of $\frac{1}{10}1° = 0.00174rad$. **(2)**

d. Figure 3 illustrates the principle of operation of a resolver.

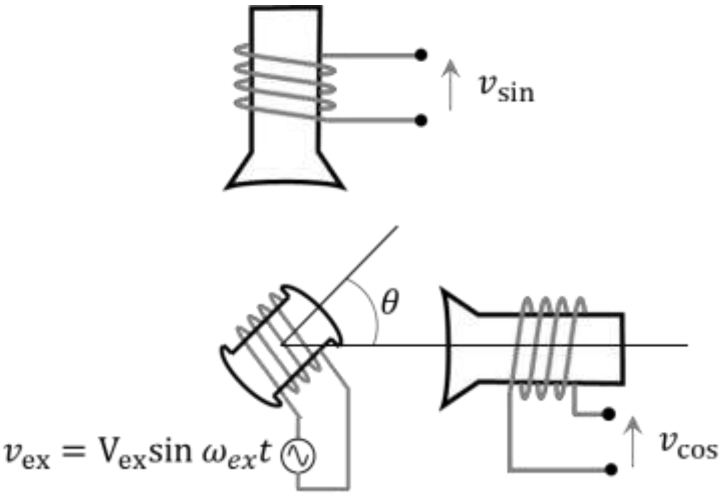

Figure 3

i. Assuming a transformer ratio n between rotor and stator, what is the voltage measured at the stator sine and cosine windings $v_{\sin}$, $v_{\cos}$ when $\theta = 30°$ and $\theta = 90°$? **(2)**

ii. Illustrate, with the aid of a block diagram and describing relevant signals, a methodology for the extraction of the angle information θ from the measurements of $v_{\sin}$, $v_{\cos}$. **(6)**

2. A three-phase star-connected 4-poles induction motor has the following parameters referred to the stator:

Stator resistance: $R_s = 0.3\Omega$.

Rotor resistance: $R_r = 0.25\Omega$.

Stator inductance: $L_s = 50mH$.

Rotor inductance: $L_r = 55mH$.

Mutual inductance: $L_m = 40mH$.

The motor is in steady-state conditions and is supplied with a balanced 3-phase voltages at 50Hz. In the stator synchronous reference frame, the voltages supplied to the motor are:

$$\begin{aligned} v_d^s &= -324\,V \\ v_q^s &= \;\;172\,V \end{aligned}$$

In these conditions the measured stator currents are:

$$\begin{aligned} i_d^s &= 10\,A \\ i_q^s &= 50\,A \end{aligned}$$

Calculate:

a. The stator flux linkages: ψ_d^s, ψ_q^s. **(2)**

b. The rotor currents: i_d^r, i_q^r. **(2)**

c. The rotor flux linkages: ψ_d^r, ψ_q^r . **(2)**

d. The rotor mechanical speed ω_m in revolutions per minute [rpm]. **(4)**

e. The electromechanical torque developed by the machine. **(2)**

f. The input electrical power into the motor. **(2)**

g. The output mechanical power. **(2)**

h. Stator and rotor resistive losses. **(2)**

i. The efficiency of the drive neglecting iron losses. **(2)**

3. A three-phase Permanent Magnet Synchronous Machine (PMSM) with phase resistance $R_s = 0.1\Omega$, is rotating in open circuit conditions at a mechanical speed $\omega_m = 10000\ [rpm]$ (revolutions per minute).

In these conditions, the measured line to line voltage v_{ab} is shown in Figure 4 below.

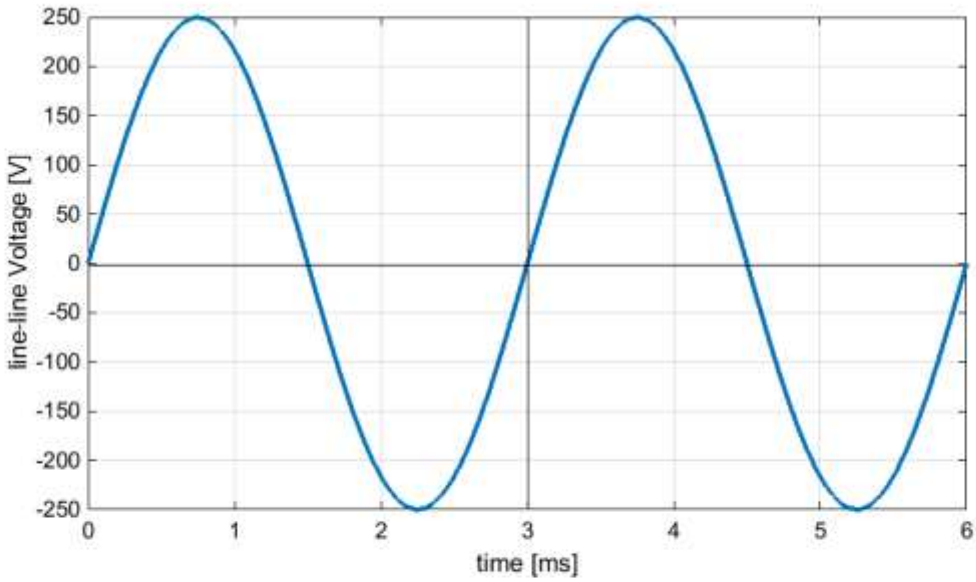

Figure 4

For this machine:

a. Calculate the number of rotor magnetic poles. **(2)**

b. Calculate the magnet flux ψ_m. **(2)**

c. The motor is subsequently operated in steady-state conditions at $10000\ rpm$ with the following voltages applied in the synchronous reference frame:

$$\begin{aligned} v_d &= -214\ [V] \\ v_q &= 102\ [V] \end{aligned}$$

which result in the measured stator currents:

$$\begin{aligned} i_d &= -50\ [A] \\ i_q &= 100\ [A] \end{aligned}$$

Calculate the $d-$ and $q-$axis inductances L_d and L_q. **(3)**

d. Assuming ideal cross-coupling compensation, calculate the proportional Kp_d, Kp_q and integral gains Ki_d, Ki_q for the $d-$ and $q-$axis PI current controllers such that the closed loop step response to a current demand has a time constant $\tau = 2\ ms$. **(5)**

e. Calculate the maximum output torque that the motor can produce with a total stator current $I = 200\ A$. **(8)**

4. A 6-poles three-phase surface mounted Permanent Magnet Synchronous Machine (PMSM) has negligible phase resistance, synchronous inductance $L = 800\ \mu H$, and rotor flux $\psi_m = 0.08\ Vs$. The motor is driven by an inverter having maximum current limited to $I_{max} = 75\ A$.

a. On the i_d, i_q plane sketch the operating region satisfying the current constraint and the maximum torque per unit current (MTPA) trajectory up to I_{max}. **(2)**

b. Calculate the maximum torque that the motor can produce at zero speed. **(2)**

c. The inverter driving the motor is operated with sine-triangle PWM and is supplied by a dc-link voltage $V_{dc} = 100\ V$. Calculate the maximum mechanical speed ω_b in revolutions per minute $[rpm]$ at which the motor can produce the maximum torque (this is the base speed for constant torque operation). **(5)**

d. Verify that the drive has an absolute maximum speed limit beyond which positive torque production is not possible. Calculate the maximum mechanical speed ω_{max} in $[rpm]$. **(5)**

e. Sketch a block diagram of a controller suitable for closed-loop field weakening control and describe its principle of operation. **(6)**

5. A 4-poles three-phase Permanent Magnet Synchronous Motor (PMSM) has the following parameters in nominal conditions:

Stator resistance: $R_s = 0.1\Omega$.

d −axis inductance: $L_d = 1\, mH$.

q −axis inductance: $L_q = 2mH$.

Rotor flux: $\psi_m = 0.1\, Vs$.

The motor is operated under angle sensorless control with $\hat{i_d} = 0, \hat{i_q} = 100\, A$ where the 'hat' $\widehat{(\cdot)}$ symbol denotes quantities in the estimated reference frame. The tracking algorithm produces an estimated rotor angle $\hat{\theta}$ with an error with respect to the actual rotor angle θ:

$$\theta_{err} = \theta - \hat{\theta} = 13.3° \, [elec.deg.]$$

a. With the help of a vector diagram, calculate what is the effect of the angle estimation error on the actual currents i_d, i_q, i.e. the currents in the real rotor reference frame. **(5)**

b. Calculate the reduction in torque due to the angle estimation error θ_{err}. **(3)**

c. The block diagram in Figure 5, illustrates an algorithm suitable for sensorless estimation of the rotor speed and angle.

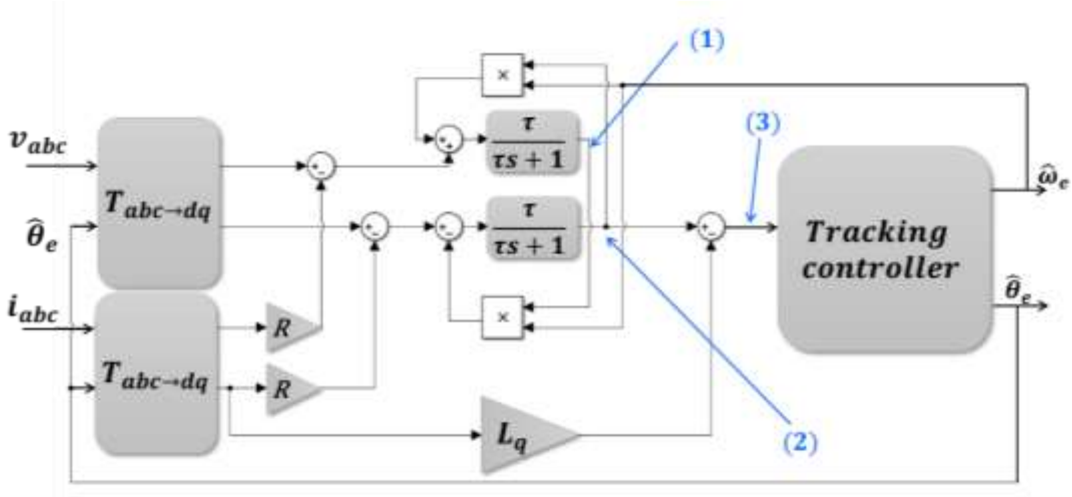

Figure 5

i. Explain what is the purpose of the blocks with the first order transfer functions $\frac{\tau}{\tau s+1}$. **(3)**

ii. Describe the signals identified in the diagram with (1), (2), (3) and calculate them in steady-state conditions. **(6)**

iii. Describe, with the help of a block diagram, a suitable tracking controller that can be used in the algorithm of Fig. 5 to produce the estimates of rotor speed and angle: $\widehat{\omega_e}, \widehat{\theta_e}$. **(3)**

6. A three-phase star-connected 4-poles induction motor (IM) has the following parameters referred to the stator:

Stator resistance: $R_s = 0.2\Omega$.

Rotor resistance: $R_r = 0.15\Omega$.

Stator inductance: $L_s = 20mH.$

Rotor inductance: $L_r = 25mH.$

Mutual inductance: $L_m = 15mH.$

The motor is in steady-state conditions and is operated under indirect Field Oriented Control (FOC) at $1500\ [rpm]$. The measured stator currents in the synchronous reference frame are:

$i_d^s = 20\ A$

$i_q^s = 100\ A$

a. With the help of a block diagram, explain the operation of the IM synchronous current control using the indirect FOC. **(5)**

b. Calculate the slip frequency ω_{slip} and the stator frequency ω_e. **(4)**

c. Calculate the stator voltages v_d^s, v_q^s. **(3)**

d. Assuming ideal cross-coupling compensation, calculate the proportional Kp_d, Kp_q and integral gains Ki_d, Ki_q for the $d-$ and $q-$axis PI current controllers such that the closed loop step response to a current demand has a time constant $\tau = 5\ ms$ **(8)**

AG.GJL