MIDDLE EAST TECHNICAL UNIVERSITY

ELECTRICAL AND ELECTRONICS ENGINEERING DEPARTMENT

EE 462 Utilization of Electrical Energy

Final Examination 09 June 2017

Exam Rules:

You are allowed to	You are NOT allowed to
• Use any additional material, books, etc. in the exam • Use your laptops to access internet, download extra materials • Use scientific calculators for your calculations • Have a short break, have a coffee etc.	• Use your mobile phones (not even as a calculator) • Communicate(talk, instant messaging, email etc) within or outside the class. • Take photograph of the exam questions • Share books or other materials

NAME:

SURNAME:

STUDENT NO:

Q1	
Q2	
Q3	
Q4	
Q5	
Q6	
Total	

Q1 – (12 pts) Short Answer Questions
Explain the following your OWN sentences. Answers directly copied from internet/books will not be accepted even if the answer is correct.

a) Explain line notching in DC motor drives and propose a way to correct it.

b) Explain armature reaction, and its effects on the DC motor performance.

c) What are the main harmonics in an induction motor drive system and possible methods to reduce them.

d) Rotors of induction motors are usually skewed. Why?

e) Compare resolver, encoder and hall effect sensors in terms of advantages/disadvantages and their application areas.

f)Mention two benefits of using 3-phase instead of 1-phase AC

Q2 – (9 pts) Questions about the experiments

a) What is the reason we use parabolic V/f in some applications?

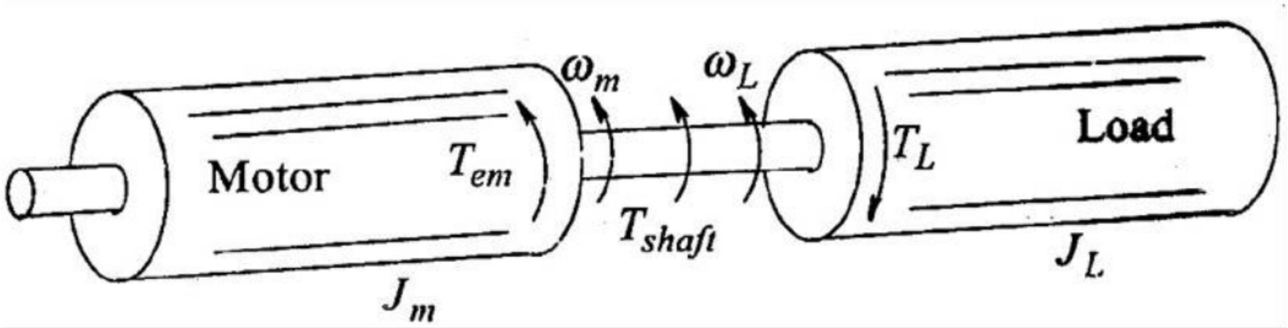
b) Which one of the following would you prefer for a crane-hoist system (like the one you experimented on)? Note that you may select any of the methods, but you need to explain your reasoning.

- Direct on-line control (with no drive)
- Constant V/f control with voltage boost (with no speed feedback)
- Vector control with speed feedback

c) Consider the recorded harmonic components of the grid side line current in Experiment 3. Why are the harmonics order of which are integer multiples of 3 are very low? Prove your statement analytically.

Q3 – (12 pts) Mechanical System Modeling

Assume you have a mechanical system as in given in the figure below.



a) Draw the equivalent circuit of the mechanical system using electrical equivalents (inductances, capacitors etc). Derive the transfer function of the mechanical system (take motor torque as input, load torque as output).

b)Repeat your calculations with the following dimensions and calculate the cut-off frequency of the mechanical shaft.

- Rotor diameter: 15cm
- Rotor axial length 30 cm
- Load diameter: 25 cm
- Load axial length: 20 cm
- Shaft stiffness constant: 1400 Nm/rad

Note: Assume the rotor and load are solid iron cylinders. Neglect the inertia of the shaft.

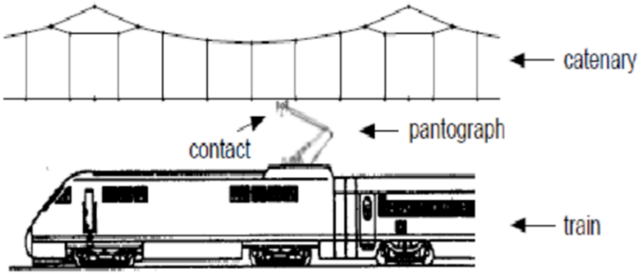
c) What are the effects of operating close to or above of that frequency?

d) Assume the rotor is running with a constant-torque load at 3000rpm, is it a problem considering the cut-off frequency?

e) What happens to the cut-off frequency if we double every dimension (ie rotor diameter, rotor length, etc) and also shaft stiffness? Does the cut-off frequency increase or decrease?

Q4 – (25 pts) Traction drive

In this problem, you are asked to design the traction system of an electric locomotive for a freight train, which is supplied from overhead catenary lines via a pantograph as shown in the figure below. The standard catenary line voltage in Turkey is single-phase, 25kV, 50Hz. You may assume the catenary line as an infinite bus throughout the question.



Squirrel cage asynchronous motors are commonly used in locomotive traction systems. You are given the following data for the traction motors:

Maximum available rated power: 1.5 MW
Line-to-line voltage rating: 1350 V_{rms}

The train has the following specifications:

- Total weight: 1000 tons
- Rated speed: 70 km/h
- Wheel diameter: 0.7 m
- Gearbox ratio: 2.64:1 (speed is reduced at the load side)
- Drag force:

$$F_d = \frac{1}{2} \rho A C_d v^2$$

where C_d is the dimensionless drag coefficient (0.8), A is the front surface area (8 m^2), ρ is the density of air (1.225 kg/m^3) and v is the velocity of the train (m/s).

- The force corresponding to the mechanical losses (rail friction, rotational losses etc.) has the following characteristics: $F_f = Kv$

where K is a coefficient (45 kg/s).

The requirements for the traction system are as follows:

- The drive should be **regenerative**; i.e., the braking energy should be fed to the catenary line.
- The drive system should have **galvanic isolation** for safety purposes.
- The drive should be **four-quadrant** (two-quadrant for each train direction).
- The maximum slope or the track is **±1.5 degrees**. The train should be capable of travelling on this slope at the rated speed.

a) Calculate the required total rated output mechanical power of the traction system.

b) Determine the number of motors that should be used? (There can be more than one answer, so please justify your reasoning)

c) Calculate the rated speed and rated torque of the motors.

d) Each motor of the traction system is driven by a conventional 3-phase inverter. What is the minimum possible DC link voltage of this inverter? Note that there should be no low order harmonics in the motor waveform.
HINT: *Space Vector PWM technique yields 15% magnitude increase compared to square wave PWM operation.*

e) Propose the part of the traction drive system between the catenary line and DC link which can meet the given requirements (AC/DC conversion). Note that there is only one catenary line, but multiple traction drives. Sketch the circuit diagram. Explain its operation briefly. ***HINT:*** *Your proposition should be practical and implementable.*

f) Calculate the values of the control variable(s) in motoring mode at rated power and rated speed. ***HINT:*** *Control variable examples: Modulation index for an inverter, duty cycle for a chopper, firing angle for a thyristor etc.*

g) Calculate the values of the control variable(s) in regenerative braking mode at rated power and rated speed.

h) Evaluate the proposed drive in terms of the following:

- Harmonics injected into the grid
- Reactive power injection (or absorption)
- Total harmonic distortion
- Individual harmonic components

i) Traction converters at such power levels have liquid cooling systems. Why do you think this is so?

Q5- (30 pts) Motor drive design and component selection
In this problem, you will design a motor drive for the system given below.
Supply:

- 3-phase, 400V line-to-line, 50 Hz (fixed)
- 3-phase diode bridge rectifier (DC Link LC filter included and assume voltage ripple is negligible)

Motor:

- Y connected 4-pole 3-phase asynchronous motor
- 36 slot, double layer stator (full-pitch)
- Turns per coil side: 8
- Rated power output: 7.2 kW
- Rated power factor at the input terminals: 0.9
- Estimated full-load efficiency: 90%
- Fundamental frequency: 50 Hz
- Rated speed: 1440 rpm
- Motor dimensions:
    - Rotor (bore) diameter: 150 mm
    - Outer diameter: 230 mm
    - Axial length: 150 mm

PART I: Machine parameters

a) Calculate the rated slip and rated torque of the motor.
b) Calculate slots per pole per phase (q).
c) Calculate the winding factor of the stator.
d) Suppose the air gap average flux density is 0.6 Tesla. Calculate the flux per pole.
e) Calculate the induced emf (in rms) of any phase.
HINT: *First, calculate the number of turns per phase (N_{ph}).*

PART II: Drive parameters

The motor drive topology is a standard inverter.

a) Derive and calculate the average DC link voltage.
b) Estimate the rated modulation index used by the inverter in case Sinusoidal PWM is used.
c) Comment on the result. What is the drawback? What can you do to deal with it?
d) Calculate the rated current on any phase in rms.

PART III: Design

a) Select an IGBT for this application from the given devices in the table below. Explain your reasoning!
b) Select a switching frequency for the drive. You do not have to calculate, but explain your selection in a few words.
***HINT**: Consider power ratings, practical limitations and the type of the device used.*

Device	Manufacturer	I_{dc}, 25 ^{0}C	V_{dc}	V_{sat}	Configuration	Cost/item
FP15R12KT3BOSA1	Infineon	25 A	1200 V	1.7 V	Six-pack	54,08 €
SKM75GB12V	Semikron	114 A	1200 V	1.85 V	Half-bridge	53,94 €
FP30R06W1E3	Infineon	30 A	600 V	1.55 V	Six-pack	31,18 €
FS25R12W1T4	Infineon	25 A	1200 V	1.85 V	Six-pack	30,66 €
FS25R12KT3BOSA1	Infineon	40 A	1200 V	1.7 V	Six-pack	58,47 €
VS-GA200SA60UP	Vishay	200 A	600 V	1.92 V	Single	38,14 €
SKM75GB176D	Semikron	80 A	1700 V	2.0 V	Half-bridge	96,80 €

** Be aware that configuration of each item is different and cost is given per item. A six-pack IGBT is composed of 6 IGBTs with 3-phase inverter configuration.*

c) Using the approximate method in the attached sheet and using the datasheet values of the selected IGBT, calculate the losses of the drive at rated conditions.
d) Find the efficiency of the drive considering only power semiconductor losses you found above.
e) *What can you do to increase the efficiency? You are free to change devices, drive topology etc. However, your proposition should be implementable.*

Equations for Power Loss Calculation for Sinusoidal Inverters

IGBT Loss

(1) Steady-state loss per switching IGBT

$$P_{SS} = I_{CP} \cdot V_{CE}(SAT) \cdot \frac{1}{2\pi}\int_0^{\pi} \sin^2 X \cdot \frac{1+\sin(x+\theta)\cdot D}{2}\,dx = I_{CP} \cdot V_{CE(SAT)} \cdot \left(\frac{1}{8} + \frac{D}{3\pi}\cos\theta\right)$$

(P.F. = $\cos\theta$)

(2) Switching Loss per switching IGBT

$$P_{SW} = (E_{SW(on)} + E_{SW(off)}) \cdot f_{SW} \frac{1}{2\pi}\int_0^{\pi} \sin x\,dx = (E_{SW(on)} + E_{SW(off)}) \cdot f_{SW} \frac{1}{\pi}$$

(3) Total loss per IGBT

$$P_Q = P_{SS} + P_{SW}$$

Diode Loss

(1) Steady-state loss per diode

$$P_{DC} = I_{EP} \cdot V_{EC} \cdot \left(\frac{1}{8} - \frac{D}{3\pi}\cos\theta\right)$$

(2) Recovery Loss per Diode

$$P_{rr} = 0.125 \cdot I_{rr} \cdot t_{rr} \cdot V_{CE}(pk) \cdot f_{SW}$$

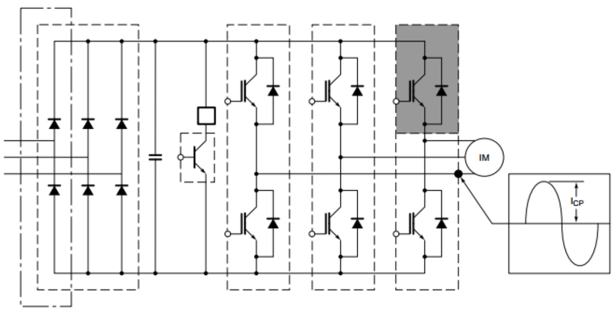
Loss per Arm (shaded part)

$$P_A = P_Q + P_D = P_{SS} + P_{SW} + P_{DC} + P_{rr}$$

Symbology:

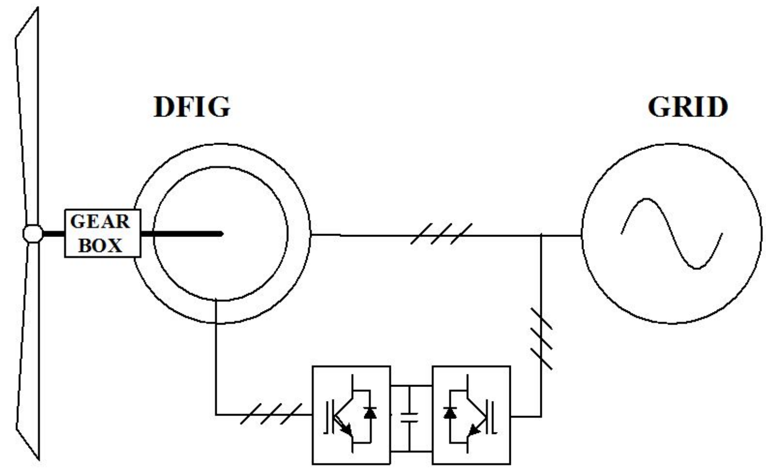
$E_{SW(on)}$:	IGBT's turn-on switching energy per pulse at peak current, I_{CP} and T = 125°C
$E_{SW(off)}$:	IGBT's turn-off switching energy per pulse at peak current, I_{CP} and T = 125°C
f_{SW}:	PWM switching frequency for every inverter arm-switch (normally, $f_{SW} = f_C$)
I_{CP}:	Peak value of sinusoidal output current ($I_{CP} = I_{EP}$)
$V_{CE}(sat)$:	IGBT saturation voltage drop @I_{CP} and T = 125°C
V_{EC}:	FWD forward voltage drop @ I_{EP}
D:	PWM duty factor (modulation depth)
θ:	Phase angle between output voltage and current
I_{rr}:	Diode peak recovery current
t_{rr}:	Diode reverse recovery time
$V_{CE}(pk)$:	Peak voltage across the diode at recovery

Figure 3.10 Typical VVVF Inverter Circuit and Output Waveform



Q6- (12 pts) Doubly-fed induction generators

Doubly-fed induction generators are the most common power take-off system in MW sized wind turbines. DFIG is simply a wound-rotor induction generator, in which rotor currents are controlled using power electronics.



a) What are the advantages and disadvantages of this system compared to a power take-off system with back-to-back converters

b) Explain the main operating principles of this topology, and control algorithm parameters.

c) Assume you have a 6-poles DFIG, connected to a 50 Hz grid, which is operating at 1150 rpm. Total mechanical input to the generator is 2.2 MW,

- Calculate the slip
- Determine the frequency of the current that should be produced by the power electronic converter.
- Is it possible to send power to thr grid if the rotor is rotating at 900 rpm.