UNIVERSITY OF TORONTO
FACULTY OF APPLIED SCIENCE AND ENGINEERING

FINAL EXAMINATION, APRIL 2001
Third Year - Program 7
ECE315S - Electromechanical Energy Conversion
Exam Type: B
Examiner : R. Bonert

A complete examination paper consists of the answers to all four problems.
All problems (1) to (4) are of equal weight of 25 points each.

NO AIDS other than the attached formula sheet ALLOWED!

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(1) Design of a DC to DC emergency power supply

A telecom station has as an emergency power supply a Hydrogen fuel cell. The fuel cell has a DC-voltage of 24 V and can provide maximal 500W power for three hours. The station requires a DC-voltage of 50 V and consumes between 200 to 500W of power. A DC/DC converter connected to the fuel cell output voltage is used to provide the station with the required power.

To reduce interference with the telecommunication equipment the switching frequency of the converter has been chosen to be 48 kHz. To simplify the control the converter should always operate in continuous current mode. The ripple of the output voltage should not exceed 1% of the rated voltage.

a) What type of converter is required ?

b) Determine the value of the required filter components L and C of the converter, considering the station as a resistive load.

c) For the given voltages and a load of 200 W draw to scale for one complete switching period:
   1) The control signal for the electronic switch
   2) The current in the inductor
   3) The current through the switch
   4) The current through the diode
   5) The current into the station
   6) The voltage across the diode

d) Explain shortly what happens, if the station is accidentally disconnected from the converter out put without switching off the converter.

(2) DC-machine operation

A golf-cart with an 48 V battery is driven by a permanent magnet DC-machine. The machine voltage is controlled by a two quadrant chopper connected to the battery. The data of the DC-machine are : 2 kW, 1000 rpm, 48 V , 50 A, armature resistance 0.1 Ohm.

The gear ratio between the DC-motor and the wheels of the golf-cart is such the cart moves with 16 km/h at the rated speed of the DC-machine.

a) The golf-cart drives up a hill which has constant slope, at the speed of 8 km/h. This requires rated current operation of the DC-motor.
Determine the point of operation of the DC-machine specified in speed in rpm and internal torque in Nm. Determine the required pulse width for the two quadrant chopper.

b) After driving up the hill the driver drives a loop and drives down the hill, leaving the pulse width of the chopper the same. At what speed does the golf-cart go down the hill ? (neglect mechanical losses in these considerations)

c) Draw a speed torque diagram showing the speed torque characteristic of the DC-machine and mark the two points of operation described in a) and b). Comment on the point of operation described in b).

d) How much power is returned to the battery going down hill, if the chopper has an efficiency of 95% ?

(3) Dynamometer testing of an electronically controlled Synchronous Machine

A permanent magnet three phase synchronous machine (PM-SM) is operated by a converter providing sinusoidal currents. This system is often also called a brushless DC-machine.

a) Describe the above system and its major components, provide a drawing showing the major components. What are the two control parameters which determine the torque of the machine ?

b) To test the electronically controlled PM-SM a DC-machine dynamometer is used. The dynamometer machine is operated with constant field and a resistor Rs connected to the armature terminals. The data of the dynamometer are : DC-motor 1 kW, 1200 rpm, 120 V, 12.5 A, armature resistance 0.75 Ohm.
The PM-SM machine controls are set such, that the PM-SM machine provides a torque of 5 Nm. The PM-SM machine should be tested at different speeds in the first quadrant only.
(continuation see next page)

1) Determine the minimum speed which can be tested with the described system. Determine the required value of the resistor Rs.
2) Determine the required resistor Rs, if the test speed should be 1000 rpm.
3) Draw to scale a speed torque diagram showing the characteristic of the electronically controlled PM-SM and both characteristics of the dynamometer for the operating points describe in 1) and 2).

4) Induction Machine operation with variable frequency and voltage

A three phase induction motor (IM) with a squirrel cage rotor has the following rated data: 600V, 60Hz, 10 kW, 1700 rpm, the IM can be operated mechanically up to a speed of 2700 rpm
(neglect mechanical losses)
The motor is supplied by a voltage source inverter providing variable voltage from 6V to 600V and variable frequency from 1 Hz to 90 Hz.

The motor is used to operate a crane, which requires at full lifting load a torque of 40 Nm and at no load (moving only the hook) a torque of 5 Nm.

d) Determine the required voltage and frequency to operate the motor at the following three different points of operation :
   1) full lifting at zero speed (starts lifting)
   2) full lifting load at rated motor speed
   3) no load (hook only) at maximum possible speed

e) Determine the maximum possible motor speed for the operation described in a 3).

f) Draw to scale a speed torque characteristic showing the three motor characteristics and the operating points for the operations described in 1) to 3)

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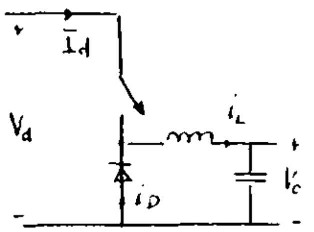
attachment :

aid sheet provided by instructor, 1 page double sided

Buck Converter



$$\frac{i_{ripple}}{2} = I_{L\ average}, \quad I_{LB} = \frac{V_d \cdot T_s (1-D) D}{2L}, \quad D = \frac{T_{on}}{T_s}$$

ripple worst case $D = 0.5$, $I_{LB_{max}} = \frac{V_d \cdot T_s}{8L}$

continuous current: $V_o = V_d \frac{T_{on}}{T_s}$; $I_o = \frac{I_d}{D}$

discontinuous current $V_o = V_d \cdot \frac{1}{1 + \frac{I_o}{I_{LB_{max}}} \cdot \frac{1}{4 \cdot D^2}}$

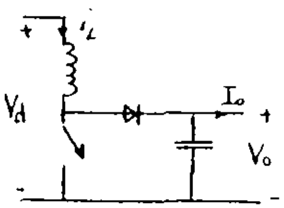
Capacitor voltage ripple $\frac{\Delta V}{V_o} = \frac{1-D}{8LC \cdot f_s^2}$, $f_s = \frac{1}{T_s}$

Harmonic analysis: $V(t)$ switched voltage $V_o = V_d \cdot D$

$$V_n = \left[\frac{2 \cdot V_d}{n\pi} \sin(n\pi D)\right] \frac{1}{\sqrt{2}} \quad n = 1,2,3$$

$I_n = \frac{V_n}{Z_n}$; $Z_n = \sqrt{R^2 + (n\omega L)^2}$, if battery as load $I_o = \frac{V_o - V_b}{R}$,

Boost Converter



$V_o = V_d \frac{1}{1-D}$, $I_o = I_d(1-D)$, $I_o = I_i(1-D)$

$I_{LB} = \frac{T_s \cdot V_o}{2L} D(1-D)$ or $I_{oB} = \frac{V_o T_s}{2L} D(1-D)^2$;

$\Delta V_o = \frac{\Delta Q}{C} = \frac{I_o \cdot D \cdot T_s}{C}$; $\frac{V_o \cdot D \cdot T_s}{R \cdot C} = \Delta V_o$ resistive load

2Q-chopper 3 operating modes: conduction of different elements, V, I like basic chopper

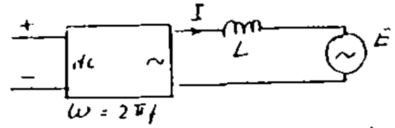
DC/AC Converter half bridge $\hat{V}_n = \frac{4}{\pi}\left(\frac{V_d}{2}\right)\frac{1}{n}$; $n = 1,3,5\cdots$ full bridge $\hat{V}_n = \frac{4}{\pi} V_d \frac{1}{n}$

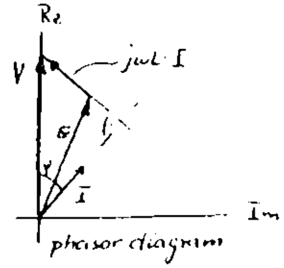
$I_n = \frac{V_n}{Z_n}$; $I_n = \frac{\hat{I}_n}{\sqrt{2}}$ In is rms value! $I = \sqrt{I_1^2 + I_3^2 + \cdots I_n^2}$

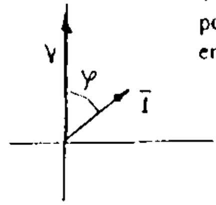
Sinusoidal PWM can eliminate lower harmonics, disadvantage high switching frequency

$\hat{V}_1 = m \cdot V_d$; $V_1(t) = \hat{V}_1 \sin \omega t$ if $m \le 1$ $V_m = 0$ $m = 3,5,7\cdots$

AC/DC Converter Switch-mode







φ indicates lagging
power factor
energy from DC → AC

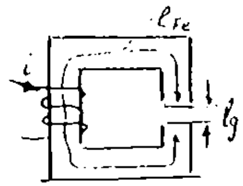
Diode Rectifiers full bridge single phase $V_o = 0.9 \cdot V_{s,rms}$ (continuous current)

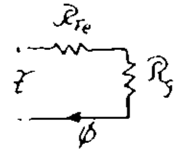
3 phase full bridge $V_o = 1.35 \cdot V_{ll,rms}$

Single phase: ideal smooth DC side current → line current is square save

$I_{n,rms} = \frac{4}{n\pi} \frac{I_d}{\sqrt{2}}$ $n = 1,3,5\cdots$ total harmonic distortion $THD = \sqrt{\sum_{n=3,5}^{\infty} I_n^2} \cdot \frac{100\%}{I_1}$

Calculations of linear magnetic circuits using equivalent reluctance circuits





$\mathcal{F} = N \cdot i$ $\phi = B \cdot A_{Fe}$ $\mathcal{R}_{Fe} = \frac{l_{Fe}}{A_{Fe} \cdot \mu_o \mu_{Fe}}$

$\phi = \frac{\mathcal{F}}{\mathcal{R}_{Fe} + \mathcal{R}_g}$ $\mathcal{R}_g = \frac{l_g}{A_g \cdot \mu_o}$

Steady State DC-machine armature equation $V_a = E + i_a \cdot R_a$; $E = (k\phi) \cdot \omega_m$; $T_e = k\phi \cdot i_a$

$k\phi$ proportional to $i_f = \frac{V_f}{R_f}$ rated; $k\phi$ from rated data using $V_a = \omega_m \cdot k\phi + i_a \cdot R_a$;

$\omega_m = \frac{V_a}{k\phi} - \frac{R_a}{(k\phi)^2} \cdot T_e$;

efficiency: $P_{mech} = \omega_m \cdot T_{shaft}$, $T_{shaft} < T_e$, by mechanical losses

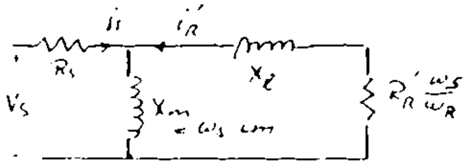
Motor: $\eta = \frac{P_{out}}{P_{in}}$; $P_{in} = V_f i_f + V_a \cdot i_a$, armature losses, field losses

Mechanic: T_{φ} motor $= T_q$ load in steady state,

typical dynamometer equation: $\omega_m = \frac{V_{thm}}{k\phi_{thm}} + \frac{R_{thm}}{(k\phi_{thm})^2} T_{\varphi thm}$ (in Coord. of machine to be tested)

El machine size is proportional to torque
Short time overload depends on thermal capacity and cooling

Induction Machine Steady State equivalent single phase circuit



Line to neutral voltage V_s

V_{ll} line to line voltage $V_{ll} = \sqrt{3}\, V_s$

flux in machine $\lambda_m = L_m \cdot i_m = L_m \frac{V_m}{X_m} = \frac{V_m}{\omega_s}$,

therefore flux proportional to $\frac{V_m}{f_s}$ and as $V_s \approx V_m$ the flux is proportional to $\frac{V_s}{f_s}$

efficiency and power $P_m = 3V_s \cdot i_s \cdot \cos\varphi$, copper losses $3i_s^2 R_s + 3i_R'^2 \cdot R_R'$;

$3i_R'^2 \cdot R_R' = P_m \frac{\omega_R}{\omega_s}$; $P_m = T_\varphi \frac{\omega_s}{\frac{p}{2}}$, $P_{mech} = T_\varphi \cdot \omega_m$, $P = T_{q\,shaft} \cdot \omega_m$

toque max internal torque $T_{\varphi max} = 3\frac{p}{2}\left(\frac{V_m}{\omega_s}\right)^2 \frac{R_R'}{L_\ell^2 \cdot \omega_R}$;

in linear range of operation where $\omega_R \cdot L_\ell << R_R'$,

$T_\varphi i = 3\frac{p}{2}\left(\frac{V_m}{\omega_s}\right) \cdot i_R' = 3\frac{p}{2}\left(\frac{V_m}{\omega_s}\right)^2 \frac{\omega_R}{R_R'}$,

T_φ proportional to ω_R, T_φ proportional to $\lambda_m \cdot i_R$

machine characteristic

for $(\omega_R L_\ell << R_R')$: $\omega_m = \frac{\omega_s}{\frac{p}{2}} - \frac{R_R'}{3\left(\frac{p}{2}\right)^2\left(\frac{V_m}{\omega_s}\right)^2} T_\varphi = \frac{\omega_s}{\frac{p}{2}} - \frac{T_\varphi}{(k\lambda_m)^2}$

with $k\lambda_m = \sqrt{\frac{T_\varphi}{\frac{\omega_s}{\frac{p}{2}} - \omega_m}}$ and $T_\varphi = \frac{P}{\omega_m}$

therefore with approximation: $\omega_m = \frac{\omega_s}{\frac{p}{2}} - \frac{T_\varphi}{(k\lambda_{m\,rated})^2\left(\frac{V_s}{V_{s\,rated}} \cdot \frac{f_{s\,rated}}{f_s}\right)^2}$

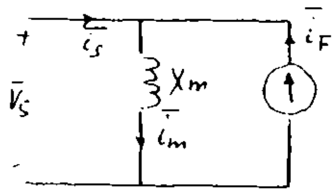
wound rotor induction machine R_R, R_{ex} external rotor resistance

$\omega_m = \frac{\omega_s}{\frac{p}{2}} - \frac{\left(1 + \frac{R_{ex}}{R_R}\right)}{(k\lambda_m)^2} T_\varphi$ (for proportional range $\omega_R L_\ell << R_R' + R_{ex}'$)

Synchronous Machine, SM

Operation with fixed voltage and frequency - line connected $\omega_m = \frac{\omega_s}{\frac{p}{2}}$

Equivalent circuit

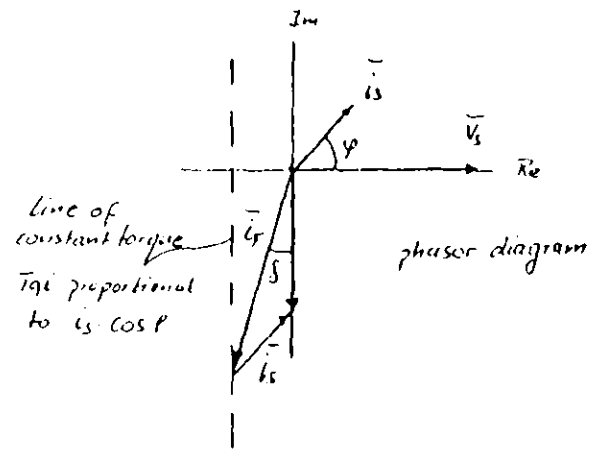


$|i_m| = \frac{V_s}{X_m}$

$T_{\varphi} = -3\frac{p}{2} L_m i_m \cdot i_F \sin\delta$

power factor $PF = \cos\varphi$

T_φ proportional to $|i_s| \cdot \cos\varphi$



Attachment ECE 3155, 2001