UNIVERSITY OF TORONTO
FACULTY OF APPLIED SCIENCE AND ENGINEERING

FINAL EXAMINATION, DECEMBER 2001
Third Year - Program 7
ECE315F - Electromechanical Energy Conversion
Exam Type: B
Examiner : R. Bonert

A complete examination paper consists of the answers to all five problems.
The weight of problem (1) and (2) is 25 points each; the weight of problem (3) and (4) is 10 points each; the weight of problem (5) is 35 points.

NO AIDS other than the attached formula sheet ALLOWED!

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(1) Power supply design of cordless power drill

A cordless power drill is equipped with a 9.6 V , 4 Ah (ampere hours) NiMH battery. The permanent magnet DC-motor driving the drill with variable speed is rated at 32V and 3 A. Design a suitable DC/DC converter including the required filter.

The specification for the output power are : minimum current at continuous current operation is 20% of the rated drill motor current. The voltage ripple can be 10% of the rated output voltage. The battery voltage varies due to discharge between 9.8V and 8.5 V.

The required capacitor for the filter of the DC/DC converter is related to the properties of the DC-motor and is specified to be 50uF.

a) What type of converter is required ?

b) Determine the value of the required filter component L for the worst case battery voltage and calculate the required switching frequency to fullfill the given specifications.

c) For the worst case battery voltage and rated motor load 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 voltage across the diode
   6) The current through the capacitor
   7) The current into the motor

(2) 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 3000 rpm

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 tested using a dynamometer with a permanent magnet DC-machine. The DC-machine armature terminals are connected to a variable external resistor. The variable resistor can be adjusted between 0 Ohm to 10 Ohm.

The DC-machine data are : 18 kW, 3000 rpm, 400 V, 50 A, Ra = 0.8 Ohm

a) What is the maximum possible speed at which the induction machine can operate, if the dynamometer is disconnected ? Do not neglect mechanical losses and assume that the mechanical loss torque is constant and the mechanical losses are 3% of the rated power at rated operation.

For the following calculations NEGLECT the mechanical losses of both machines.

b) Determine the required voltage and frequency to operate the motor with the given dynamometer at the following three different points of operation :

1) lowest possible speed at maximum continuous load
2) highest continous power with full induction motor flux
3) highest possible speed

c) Draw to scale a speed torque diagram showing for each operating point the motor characteristic (solid line) and the dynamometer charcteristic (dashed line).

(3) Emergency Power Supply

An emergency power supply uses a 24V battery and should provide 120V 60Hz AC-voltage. Furthermore it should be possible to recharge the battery from the 120V, 60Hz AC-system. Discuss the principle circuit. What converter and filter components are required ? What controls are preferably used for the required converters ? Estimate the voltages and current ratings of the components, if 500 W of power should be supplied. Discuss issues arising from connecting such a supply to the AC-line.

(4) Experiment #3, DC-machine and 2-Q chopper

In the experiment #3 DC-machine and dynamometer, the DC-motor is connected to a two quadrant chopper , so it can operate at positive speed when supplied by the chopper.

a) Draw the circuit of the two quadrant chopper with the DC-motor

b) What happens, if the DC-voltage to the chopper and the field of the motor is switched on, but the gating pulses for the chopper are still turned off (S1 off) and the dynamometer turns the motor in the negative speed direction ? Discuss, if there is an operating point and if meaningful draw a speed torque diagram illustrating your explanation.

(5) DC-machine operation and dynamometer testing

A permanent magnet DC-motor has the following name plate data :
5kW at 2000 rpm, 250 V, 22.5 A. The armature resistor is given to be 0.5 Ohm. The motor armature voltage is supplied by a 2 quadrant chopper. The chopper input voltage is 300V.

For testing the motor is coupled to a DC-dynamometer. The DC-dynamometer is a DC-machine with seperately excited field. The armature of the DC-dynamometer is connected to a second 2 quadrant chopper supplied from the same 300 V DC-voltage as the motor. The field voltage is controlled by a DC/DC converter controlling the field current between 100% and 30% of the rated field current. The DC/DC converter supplying the field is also conneted to the 300 V DC-source.

The name plate data of the dynamometer are 12 kW at 1200 rpm, 300 V, 44 A . The armature resistor is given to be 0.4 Ohm.

a) Draw a circuit diagram showing the described test arrangement of the DC-motor and the dynamometer.

b) Calculate the efficiency of the DC-motor, when it is operated at half rated speed and full load torque. Determine the mechanical losses.

Neglect for the following calculations c) to d) the mechanical losses and use the internal torque of the machines for the calculations :

c) The DC-motor is supplied by its chopper with variable voltage between zero volts and its rated voltage by varying the duty ration (Dm) of the motor chopper. To test the motor under load the dynamometer is used to set several desired points of operation. This can be done by controlling the duty ratio of the dynamometer chopper (Dd) and the field current of the dynamometer.

(continuation on next page)

(continuation problem (5))

The desired test points or points of operation are :

1) rated motor torque at the minimum speed possible with the given test system
2) rated motor torque when the dynamometer controls are set at rated dynamometer armature voltage and rated dynamometer flux
3) rated motor torque and rated motor speed
4) generator operation of the motor at rated armature current

c1) SKETCH a speed torque diagram showing for each operating point the motor characteristic (solid line) and the dynamometer charcteristic (dashed line). Mark each operating point using numbers 1 to 4 and provide for each point a comment how IN PRINCIPLE the motor and dynamometer controls have to be set to achieve the desired point of operation.

c2) Determine the speed and torque at each point of operation and calculate the required control settings for each operating point. (hint : multiple solutions exist for some points, use good engineering reasoning to make choices which keep the calculations as simple as possible)

c3) DRAW TO SCALE a speed torque diagram showing for each operating point the motor characteristic (solid line) and the dynamometer charcteristic (dashed line). Mark each operating point using numbers 1 to 4 .

d) Is it necessary to use a dynamometer with 12 kW rated power or is it possible to use a smaller power rating ?

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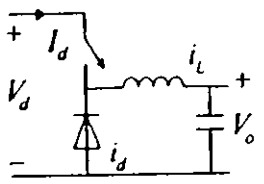
attachment :

aid sheet provided by instructor, 1 page double sided

Buck Converter



$$D = \frac{T_{on}}{T_s}$$

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

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

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

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

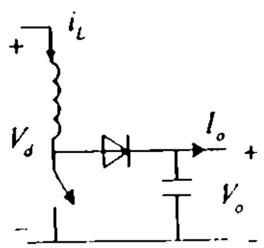
Capacitor voltage ripple $\frac{\Delta V}{V_o} = \frac{1-D}{8LC \cdot f_s^2}$; $\quad f_s = \frac{1}{T_s}$

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

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

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

Boost Converter



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

$I_{LB} = \frac{T_s \cdot V_o}{2L} D(1-D) \quad or \quad I_{0B} = \frac{V_o T_s}{2L} D(1-D)^2$;

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

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

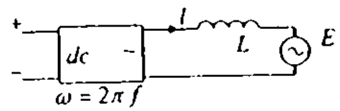
DC/AC Converter half bridge $\hat{V}_n = \frac{4}{\pi}\left(\frac{V_d}{2}\right)\frac{1}{n}$; $n = 1,3,5\cdots$ full bridge $\hat{V}_n = \frac{4}{\pi} V_d \frac{1}{n}$

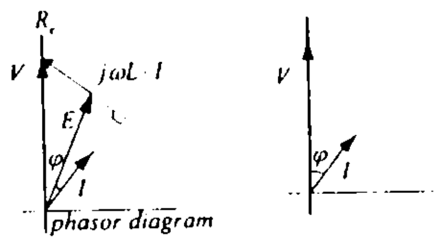
$I_n = \frac{V_n}{Z_n}$; $\quad I_n = \frac{\hat{I}_n}{\sqrt{2}}$ In is rms value! $\quad I = \sqrt{I_1^2 + I_3^2 + \cdots I_n^2}$

Sinusoidal PWM can eliminate lower harmonics, disadvantage high switching frequency

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

AC/DC Converter Switch-mode





φ indicates lagging

power factor

energy from DC → AC

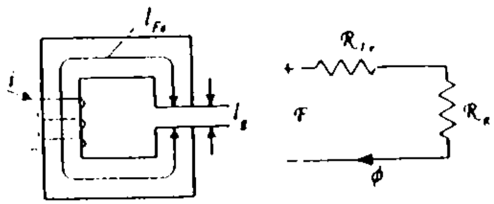
Diode Rectifiers full bridge single phase $V_o = 0.9 \cdot V_{ac\,rms}$ (continuous current)

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

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

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

Calculations of linear magnetic circuits using equivalent reluctance circuits



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

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

Steady State DC-machine armature equation $V_a = E + i_a \cdot R_a$; $\quad E = (k\phi) \cdot w_m$; $\quad T_{qi} = (k\phi) \cdot i_a$;

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

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

efficiency: $P_{out} = \omega_m \cdot T_{q\,shaft}$; $T_{q\,shaft} < T_{qi}$ by mechanical losses

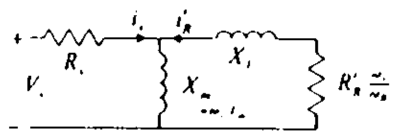
Motor: $\eta = \frac{P_{out}}{P_{in}}$; $P_{in} = V_f i_f + V_a \cdot i_a$; armature losses, field losses

Mechanic: T_{qi} motor = T_q load in steady state;

typical dynamometer equation: $\omega_m = \frac{V_{dyn}}{k\phi_{dyn}} + \frac{R_{dyn}}{(k\phi_{dyn})^2} T_{qdyn}$ (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_{ee} 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 $P_{in} = 3V_s \cdot i_s \cdot \cos\varphi$, copper losses $3i_s^2 R_s + 3i_R'^2 \cdot R_R'$.

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

torque: max internal torque $T_{qi\,max} = 3\frac{p}{2}\left(\frac{V_m}{\omega_s}\right)^2 \frac{R_R'}{L_e^2 \cdot \omega_R}$;

in linear range of operation where $\omega_R \cdot L_e << R_R'$.

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

T_{qi} proportional to ω_R, T_{qi} proportional to $\lambda_m \cdot i_R$

machine characteristic

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

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

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

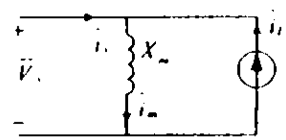
wound rotor induction machine R_R, R_{ex} external rotor resistance

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

Synchronous Machine, SM

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

Equivalent circuit



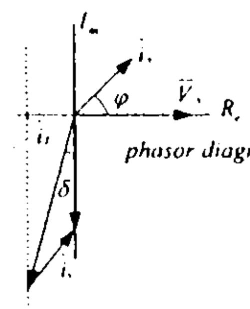
$|i_m| = \frac{V_s}{X_m}$

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

power factor $PF = \cos\varphi$

T_{qi} proportional to $|i_s| \cdot \cos\varphi$

line of constant toque T_{qi} propotional to $i_s \cos\varphi$



phasor diagram