Exam Electrical Machines and Drives (ET4117)
11 November 2011 from 14.00 to 17.00.
This exam consists of 5 problems on 4 pages.
Page 5 can be used to answer problem 4 question b.
The number before a question indicates how many credits you can earn by answering that question. A partly correct answer may give a part of the credits.
This examination has to be made without using a book, old examinations, notes, dictionaries or programmable calculators; a pocket calculator may be used.

22 Problem 1

A train is driven by a DC machine with independent electrical excitation. At a speed of 1500 rpm, the following magnetization characteristic has been measured.

E_A (V)	50	420	780	950	1120	1180	1260
I_F (A)	0	4.0	8.0	10.0	12.8	14.4	28.8

3 a Sketch the equivalent circuit of the DC machine.
2 b Why is a voltage induced in the armature when the excitation current is zero?
2 c Why does the induced voltage at high excitation currents not increase proportional to the excitation current?

The machine runs at 1500 rpm and the train has a speed of 20 m/s. The armature terminal voltage is 790 V. The current is 50 A. The armature resistance is 0.2Ω.

3 d Calculate the product of the motor constant and the pole flux $K\Phi$ in this operating point.
2 e Calculate the torque.

3 f In a train application, how does the load torque change as a function of speed?

The excitation current is halved while the terminal voltage remains constant. It can be assumed that the motor constant *K* remains constant. After some time, a new steady-state situation is reached.
3 g Give an estimate of the new speed of the motor (in rpm).
4 h Sketch a power electronic converter (switches and diodes) that can be used to control the voltage on the machine terminals and that enables regenerative braking.

24 Problem 2

This problem deals with three-phase induction machines. First a few general questions.

4 a Explain why a three-phase induction machine works (you do not need to use mathematics).
3 b Sketch the IEEE recommended equivalent circuit of the induction machine.
3 c Sketch the torque-speed characteristic of an induction machine and indicate the three modes of operation.

In the course, it has been shown that by splitting the rotor resistance in the equivalent circuit into a pure resistance and a part depending on the slip, the air gap power P_{ag} can be split into losses P_2 and mechanical power P_{mech} and that they relate as:
$P_2 : P_{mech} : P_{ag} = s : (1-s) : 1$

In most modern wind turbines, a doubly-fed induction machine is used as generator. We are now going to consider the basic operating principle of such a generator. The doubly-fed induction generator is a wound-rotor induction machine. There is a power electronic converter between the grid and the rotor slip rings. In a wind turbine, this converter is controlled in such a way that the frequency induced in the stator windings is 50 Hz, so that the stator windings can be directly connected to the 50 Hz grid. The converter makes it possible to operate the wind turbine at variable speed.
The doubly-fed induction generator of a wind turbine has 3 pole pairs (6 poles) and is connected to the 50 Hz AC grid. It operates as a generator at a speed of n = 1100 rpm and the total mechanical input power is P_{mech} = - 2.2 MW.

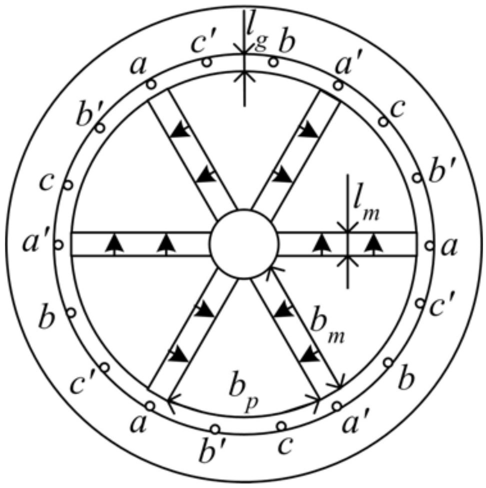
3 d Calculate the slip.
2 e Determine the frequency that has to be produced by the power electronic converter connected to the rotor slip rings.
4 f Calculate the air-gap power P_{ag} and the rotor power P_2 (which is not completely dissipated in this case).
2 g What is the direction of the power flow between the power electronic converter and the rotor?
3 h What kind of power electronic converter do we need between the rotor slip rings and the grid? Pay attention both at the grid side and the machine side.

20 Problem 3

A three-phase synchronous generator is driven by a gas turbine.
The synchronous reactance is X=4 Ω.
The losses in the generator may be neglected.
It has been just been connected to an infinite bus with a phase voltage of 20 kV and a frequency of 50 Hz in a proper way.

2 a Sketch the equivalent circuit of the synchronous machine.
4 b Which 4 conditions that have to be satisfied before a synchronous machine can be connected to the grid?
2 c Calculate the stator current just after the proper grid connection.
5 d The excitation current is doubled while the power remains the same. Calculate the stator current phasor (value and angle or real and imaginary part) and sketch the phasor diagram.
7 e The shaft power is increased to 300 MW while the excitation current remains the same at double the value during grid connection. Sketch the phasor diagram and calculate the stator current phasor (value and angle or real and imaginary part) and the load angle.

24 Problem 4



The figure depicts a cross-section of the magnetic circuit of a permanent magnet motor. The parts with arrows in it are magnets. The conductors are drawn in the air gap with an indication for the phase (a, b or c).
The machine has the following characteristics (most of them are in the figure).

- The magnet length in the direction of magnetization is l_m=5 mm.
- The air-gap length is l_g=1 mm.
- The width of the magnet is b_m=30 mm.
- The width of a rotor pole is b_p=30 mm.
- The axial stack length (in the direction perpendicular to the plane of the drawing) is l_s=100 mm.
- The total number of turns of each of the stator windings is N_s=100.
- The remanent flux density of the magnets is B_{rm}=1.3 T.
- The relative recoil permeability of the magnets μ_{rm} =1.
- The BH-characteristic in the second quadrant of the BH-plane is a straight line.

In the calculations, it may be assumed that

- The magnetic permeability of iron is infinite.
- The flux density crosses the magnets and the air gap perpendicularly.
- The wires of the turns are very thin.
- The stator currents are zero.

2 a Write down Ampere's law (a simplified form of the first of Maxwell's equations).
3 b Sketch a contour and a surface in the cross section to which you can apply Ampere's law to calculate the magnetic flux density in the air gap.
2 c Give an equation for the BH characteristic of the magnet in the second quadrant.
5 d Calculate the air-gap flux density B_g using Ampere's law.
2 e Write down the second of Maxwell's equations or Faraday's law.

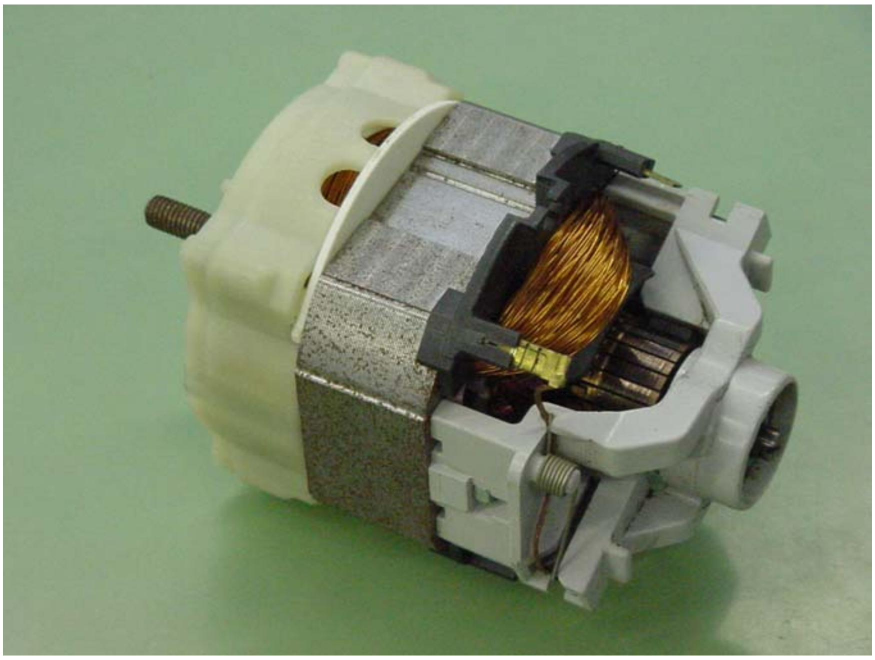
In the next questions, the air-gap flux density above the poles is B_g=1.3 T.
The machine rotates at 3000 rpm.

2 f Calculate the pole flux (the flux of a pole).
2 g Calculate the maximum value of the flux linkage of the stator windings.
2 h Calculate the frequency of the voltages induced in the stator windings.
2 i Is it necessary to laminate the stator iron? Why or why not?
2 j Is it necessary to laminate the rotor iron? Why or why not?

10 Problem 5

6 a Sketch a cross section of a switched reluctance machine and explain the principle of operation.

4 b Describe the machine on the picture as accurately as you can (machine type, number of poles).

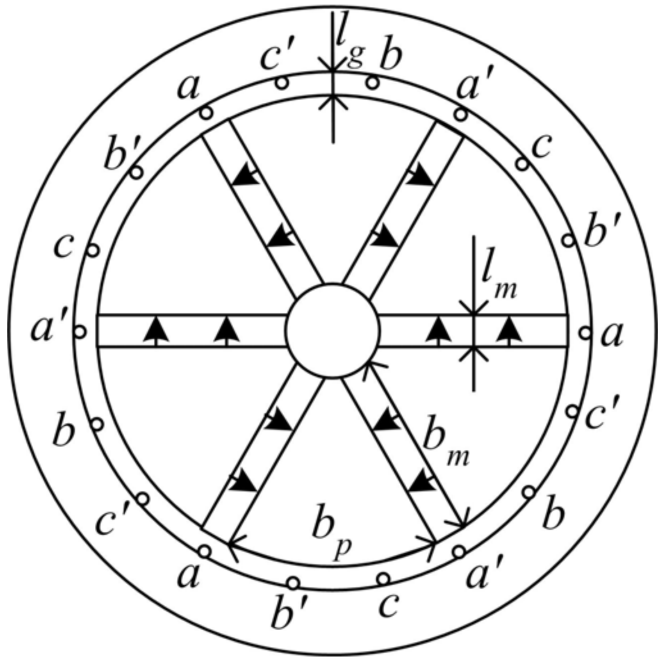


Examination Electrical Machines and Drives ET4117
Friday, November 11, 2011 from 14.00 to 17.00

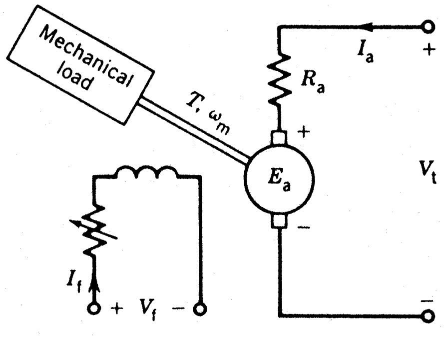
Name:

Student number:

Answer to question 4b



Answers to the exam Electrical Machines and Drives ET4117



22 Problem 1

3 a

2 b When the excitation current is made zero, there is still some magnetic field due to the hysteresis of the magnetic material, which induces a small voltage.

2 c When the flux density in iron increases to values above 1.7 T, the iron saturates, and the flux density does not increase proportional to the excitation.

3 d $E_a = K\Phi\omega_m$

$$K\Phi = \frac{E_a}{\omega_m} = \frac{V_t - R_a I_a}{\omega_m} = 4.966\,\text{Vs/rad}$$

2 e $T = K\Phi I_a = 248.3\,\text{Nm}$

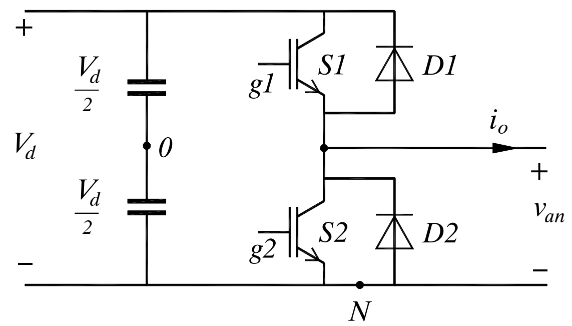
3 f The load torque consists of two parts:
- a friction torque in bearings and other mechanical components which is mainly constant, independent from speed, and
- air friction between the train and the surrounding air, which is mainly proportional to the square of the speed.

$$T(\omega) = T_0 + k\omega^2$$

At low speeds, mechanical friction is dominant, at high speeds, air friction is dominant.

3 g If the torque would remain constant, the speed would double because the motor constant $K\Phi$ halves. However, the torque increases, so the voltage drop over the resistance increases, so the increase of the speed will be slightly smaller than a factor of 2.

4 h



24 Problem 2

4 a A three phase stator (the axes of the windings are displaced 120 degrees spatially) connected to a three-phase supply (the voltages are 120 degrees displaced in time) makes a rotating magnetic field in the air gap. This magnetic field induces a voltage in the rotor bars. Because the rotor is short circuited, currents are induced in the rotor bars. The combination of the rotating magnetic field and the rotor currents generates a torque.

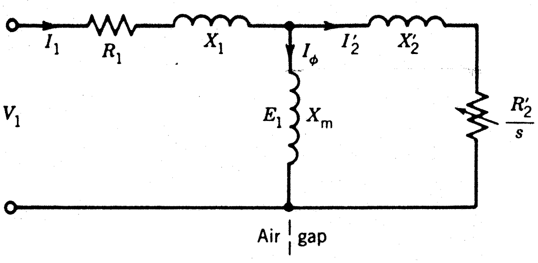


FIGURE 5.15 IEEE-recommended equivalent circuit.

3 b

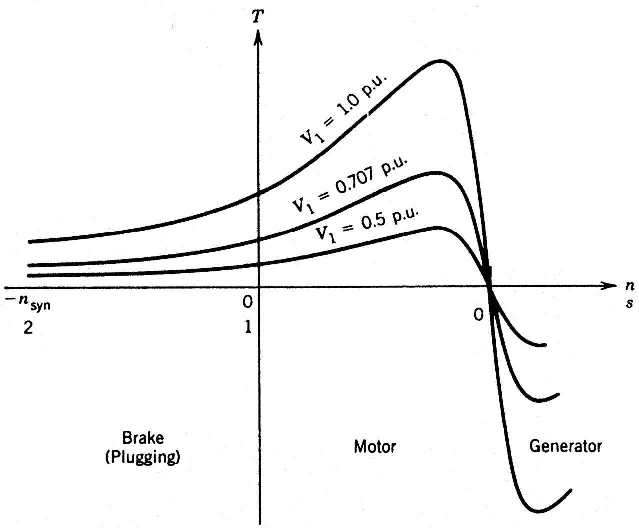


FIGURE 5.17 Torque–speed profile at different voltages.

3 c

3 d If p is the number of poles,

$$n_s = \frac{120f}{p} = 1000\,\text{rpm}$$

$$s = \frac{n_s - n}{n_s} = -0.1$$

2 e $f_{rotor} = sf_{stator} = 5\,\text{Hz}$

4 f The machine is generating power, while motor convention is normally used. Therefore, the mechanical power must be negative:

$$P_{mech} = -2.2\,\text{MW}$$

$$P_{mech} = (1-s)P_{ag} \quad \Rightarrow \quad P_{ag} = \frac{P_{mech}}{1-s} = -2\text{MW}$$

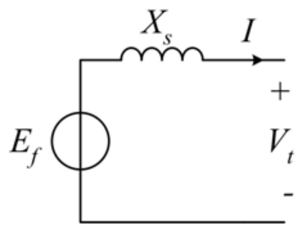
$$P_2 = sP_{ag} = 200\,\text{kW}$$

2 g 200 kW is going into the rotor and would have to be dissipated if there was no converter to take it from the rotor and feed it into the grid. So the direction of the power is from rotor to converter (to grid).

3 h A back-to-back voltage source inverter, which means that the grid side of the converter and the rotor side of the converter have a full inverter with active switching elements. This is necessary because the direction of the power flow is from grid to rotor at speeds below synchronous speed, and from rotor to grid at speeds above synchronous.

20 Problem 3

2 a equivalent circuit



4 a Before connecting a synchronous machine to the infinite bus, the following 4 conditions have to be met:

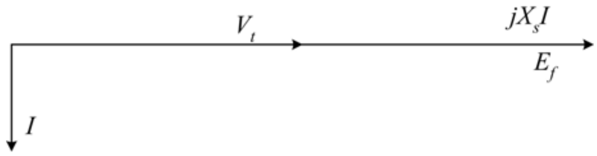
- voltage of machine and bus are equal
- frequency of machine and bus are equal
- phase order of machine and bus are equal
- phase of machine and bus are equal

2 c Before grid connection, the rotor runs synchronously with the grid (frequency of machine and bus are equal). The power level is just high enough to overcome friction and windage losses and iron losses, there is no additional torque. The voltage of the machine and the bus are equal: $E_f = V_t$.

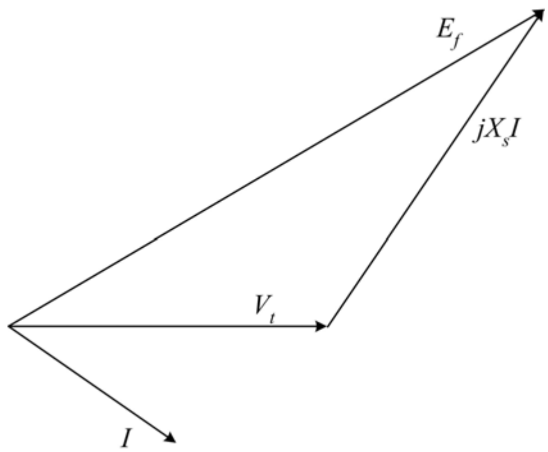
Therefore $I = \dfrac{E_f - V_t}{jX_s} = 0$

5 d $E_f = 2V_t$, therefore

$$I = \frac{E_f - V_t}{\mathrm{j}X_s} = \frac{V_t}{\mathrm{j}X_s} = -\mathrm{j}5\,\mathrm{kA}$$



7 e The phasor diagram will have a form like sketched.



The power is 300 kW. Therefore, the real part of the current can be calculated as

$$\mathrm{Re}(I) = \frac{P}{3V_t} = 5\,\mathrm{kA}$$

Therefore, the imaginary part of the excitation voltage can be calculated as

$$\mathrm{Im}(E_f) = X\,\mathrm{Re}(I) = 20\,\mathrm{kV}$$

Therefore, the load angle can be calculated as

$$\delta = \arcsin\left(\frac{\mathrm{Im}(E_f)}{E_f}\right) = \frac{\pi}{6} = 30°$$

Another way of calculating the load angle is using the expression:

$$P = \frac{3E_f V_t}{X}\sin(\delta)$$

Using this expression, the load angle can be calculated as

$$\delta = \arcsin\left(\frac{XP}{3E_f V_t}\right) = \frac{\pi}{6} = 30°$$

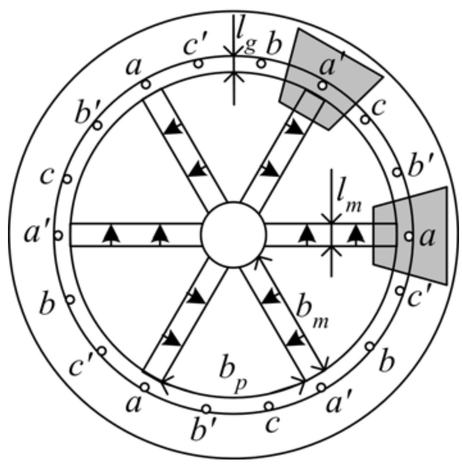
Using this:

$$I = \frac{E_f - V_t}{\mathrm{j}X} = \frac{34.64 + \mathrm{j}20 - 20}{4\,\mathrm{j}}\,\mathrm{kA} = 5 - \mathrm{j}3.66\,\mathrm{kA}$$

24 Problem 4

2 a $\displaystyle\oint_{C_m} \vec{H}\cdot\vec{\tau}\,\mathrm{d}s = \iint_{S_m} \vec{J}\cdot\vec{n}\,\mathrm{d}A$

3 b Two possible contours and two possible surfaces are indicated. The boundary of the surface is the contour.



2 c $B_m = \mu_0 \mu_{rm} H_m + B_{rm}$

5 d $2H_g l_g + H_m l_m = 0$

Using the BH relations for magnets and air:

$$\frac{2B_g l_g}{\mu_0} + \frac{(B_m - B_{rm})l_m}{\mu_0 \mu_{rm}} = 0$$

Flux continuity:

$$\oiint_A \vec{B} \cdot \vec{n}\, \mathrm{d}A = 0 \quad \Rightarrow \quad B_g A_g = B_m A_m$$

$$B_g l_s \frac{1}{2} b_p = B_m b_m l_s \Rightarrow B_g l_{Fe} = 2 B_m b_m$$

Substitution gives

$$\frac{2B_g l_g}{\mu_0} + \frac{(B_g \frac{b_p}{2b_m} - B_{rm})l_m}{\mu_0 \mu_{rm}} = 0$$

$$B_g = \frac{2 l_m b_m}{4\mu_{rm} l_g b_m + b_p l_m} B_{rm} = 1.43\,\mathrm{T}$$

2 e $\oint_{C_e} \vec{E} \cdot \vec{\tau}\, \mathrm{d}s = -\frac{\mathrm{d}}{\mathrm{d}t} \iint_{S_e} \vec{B} \cdot \vec{n}\, \mathrm{d}A$

2 f $\Phi_p = B_g l_s b_p = 3.9\,\mathrm{mWb}$

2 g $\hat{\lambda} = \Phi_p = N_s B_g l_s b_p = 0.39\,\mathrm{Wb}$

2 h $f = \frac{n}{60} \frac{p}{2} = 150\,\mathrm{Hz}$

2 j Yes, if the stator was not laminated, the changing magnetic field would induce very large eddy currents.

2 j No, the magnetic field does not change very much, so the eddy currents may be acceptable.

10 **Problem 5**

6 a See figure 6.42

When two stator poles that are 180 degrees displaced (e.g. phase A in the figure) are excited, the rotor poles that are most close, are attracted and move to the aligned position. As soon as the aligned position is reached, the excitation is removed from this phase and the next phase is excited, e.g. phase B in the figure. This will attract poles b of the rotor. So if the stator poles are excited counter-clockwise, the rotor will move clockwise and at a much lower speed.

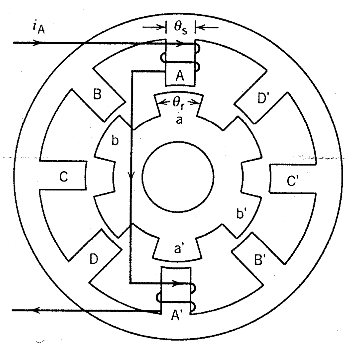


FIGURE 6.42 Cross section of a switched reluctance motor (SRM).

4 b This machine is 2-pole universal motor.