Examination Electrical Machines and Drives (ET4117)

4 November 2005 from 9.00 to 12.00.

This examination consists of 4 problems on 3 pages. The fourth page can be used to answer question 4 b.

The number before a question indicates how many credits you can earn with the question.

This examination has to be made without using a book, old examinations or notes.

30 Problem 1

When DC machines are loaded, there is armature reaction. The problems due to armature reaction can be reduced by using interpoles and sometimes also compensating windings.

5 a Sketch a cross-section of a DC machine with electrical excitation including interpoles. Indicate the direction of the currents in all the windings with dots and crosses.

3 b Explain which problems may arise due to armature reaction.

In questions c to g, the DC machine with independent electrical excitation is connected to a DC voltage source. Armature reaction is neglected.
The voltage is V_t.
The motor constant is K.
The armature resistance is R.
In questions c to f, the pole flux is $\Phi=\Phi_0$.

3 c Give the (steady-state) voltage equation and the equivalent circuit.

2 d Give an expression for the no-load speed.

2 e Give an expression for the stall torque (the torque at stand still, with blocked rotor).

2 f Sketch the torque-speed characteristic including the no-load speed and the stall torque.

The pole flux is reduced to $\Phi=\Phi_0/2$.

2 g In the same figure as question f, sketch the torque-speed characteristic including the no-load speed and the stall torque.

3 h What is the most common reason for using flux weakening? Explain.

2 i What type of converter can be used to control the speed of this motor when it is fed from a DC source (e.g. as in the Dutch railways)?

3 j Sketch this converter between the dc source and the DC load.

3 k Explain how this converter can be used to control the speed of a DC machine and explain the function of the diode.

13 Problem 2

4 a Explain why a rotating magnetic field in the air gap of a three-phase induction machine causes its rotor to start rotating and explain at which speed the torque is zero.

2 b What is the synchronous speed of a 4-pole induction machine connected to a 50 Hz source?

3 c Sketch a torque-speed characteristic of a single-phase induction motor.

4 d Explain why a single-phase induction motor with an auxiliary winding starts rotating when it is connected to a single-phase supply.

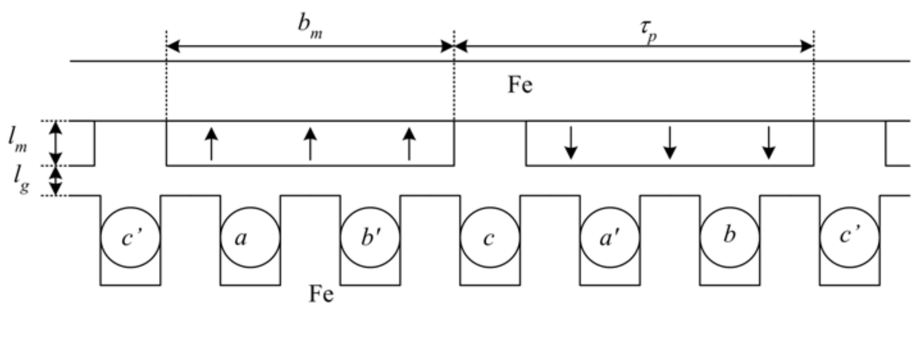
12 **Problem 3**

A synchronous generator is connected to a grid with a line voltage of 20 kV and a frequency of 50 Hz.
It delivers a power of 100 MW.
The power factor is $\cos\varphi = 0.8$.
The generator delivers a leading current to the grid.
The synchronous reactance is X=5 Ω.
The stator resistance is negligible.

2 a Draw the equivalent circuit.
10 b Sketch the phasor diagram and calculate the current, the excitation voltage and the load angle.

35 **Problem 4**

The figure below depicts a cross-section of two pole-pitches of the magnetic circuit of a permanent magnet generator for the Archimedes Wave Swing. The upper part is the translator (moving part) with the permanent magnets, the lower part is the stator with coils. The parts with Fe in it, are iron. The parts with arrows in it are magnets. The copper conductors are round 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.
- The air-gap length is l_g.
- The width of the magnet is b_m.
- The pole pitch is τ_p.
- The axial stack length (in the direction perpendicular to the plane of the drawing) is l_s.
- The magnets have a remanent flux density B_{rm}, a relative recoil permeability $\mu_{rm} = 1$ and the BH-characteristic in the second quadrant of the BH-plane is a straight line.
- The number of poles is p.
- The total number of turns of a phase winding is N_s. The number of conductors per slot is $2N_s$/p.

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.
- For the calculation of the flux density, the stator slots may be neglected, which means that you can calculate as if the air gap were constant (l_g) and the conductors are in the air gap.
- The wires of the turns are very thin and the windings are concentrated (which means that the winding factor is 1).

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 of the machine to which you can apply Ampere's law to calculate the magnetic flux density in the air gap due to the magnets. You can use the cross section of the machine in the figure on the last page of the exam.

In questions c to i, the stator currents are zero.

2 c Give an equation for the BH-characteristic of the magnet in the second quadrant.

4 d Derive an expression for the air-gap flux density B_g using Ampere's law.

In questions e to i, the air-gap flux density is B_g.

2 e Give an expression for the flux per pole, the pole flux.

2 f Write down the second of Maxwell's equations or Faraday's law.

2 g Describe the contour and the surface to which you can apply the second of Maxwell's equations to derive the voltage induced in phase c.

3 h Sketch the flux linkage of phase c as a function of time if the translator moves with a constant speed.

3 i Sketch the no-load voltage of phase c as a function of time if the translator moves with a constant speed.

In the following questions, you have to calculate the self-inductance of phase c. This can be done by calculating the magnetic flux density due to this current while the other currents and the remanent flux density of the magnets are zero.

4 j Calculate the flux density in the air gap due to the current in phase c. (Neglect the field of the magnets.)

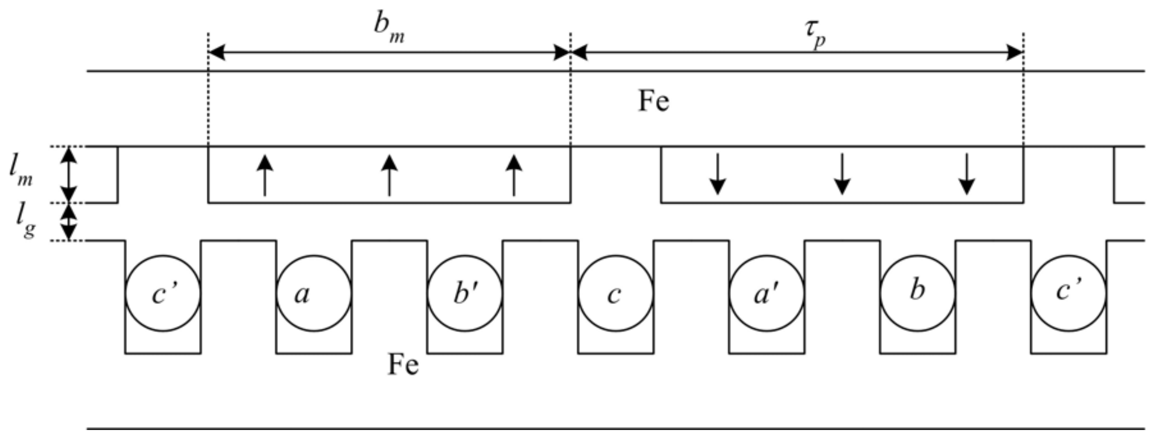
2 k Calculate the pole flux due to the current in phase c.

2 l Calculate the flux linkage of phase c.

2 m Calculate the self inductance of phase c.

2 n What type of converter can be used to connect this generator to the three-phase grid?

Page available answering problem 4 b.



Answers to the examination of 4 November 2005

30 Problem 1

5 a

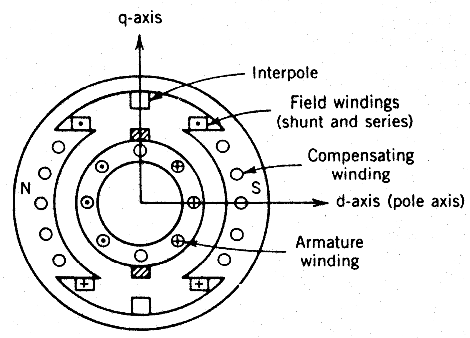


FIGURE 4.10 Schematic diagram of a dc machine.

The direction of the currents in the compensating windings and the currents around the interpoles is opposite to the direction of the current in the armature. Therefore, in the right half of the machine, there should be dots in the compensating windings and around the interpoles, and in the left half of the machine there should be stars.

3 b One problem is saturation, which leads to a decrease of the pole flux.
A second problem is commutation problems due to the fact that the commutating coil is not in the field-free zone while commutating, which leads to sparks and additional wear.

3 c $V_t = R_a I + E_a$

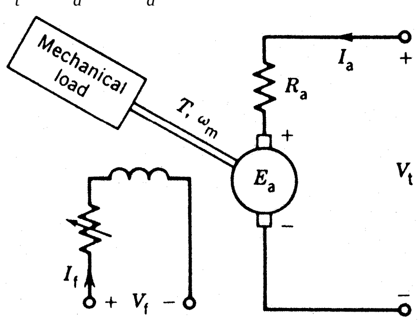


FIGURE 4.50 Separately excited dc motor.

2 d In no-load, the current is zero, therefore $V_t = E_a = K\Phi\omega$

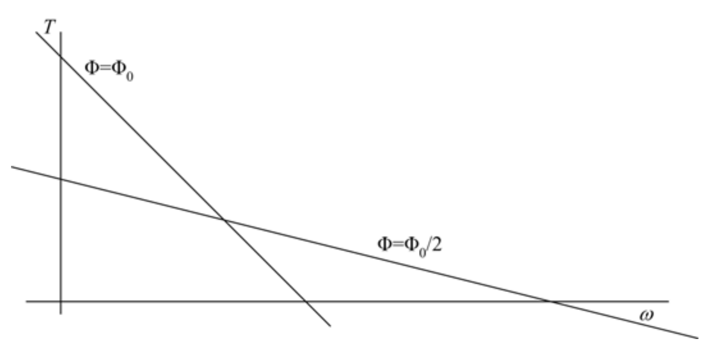
Therefore, $\omega = \dfrac{V_t}{K\Phi}$

2 e The stall torque is the torque when the speed is zero, therefore, $V_t = R_a I$.

The torque is then $T = K\Phi I = K\Phi \dfrac{V_t}{R_a}$

2 f

2 g



3 h To increase the speed above the base speed. To control the speed from zero to the base speed, the terminal voltage is increased from zero to the rated value. To control the speed above base speed, the field current is reduced.

2 i chopper

3 j see fig 4.62

3 k Fig 4.62 also gives waveforms. When the switch S is closed, voltage over the machine is V and the through the machine and the torque of the machine increase. When the switch S is open, the current will continue to flow via the diode and the voltage over the machine is 0 and the current through the machine and the torque of the machine decrease. The torque controls the speed.
The diode is necessary because the current cannot stop when the switch S is opened.

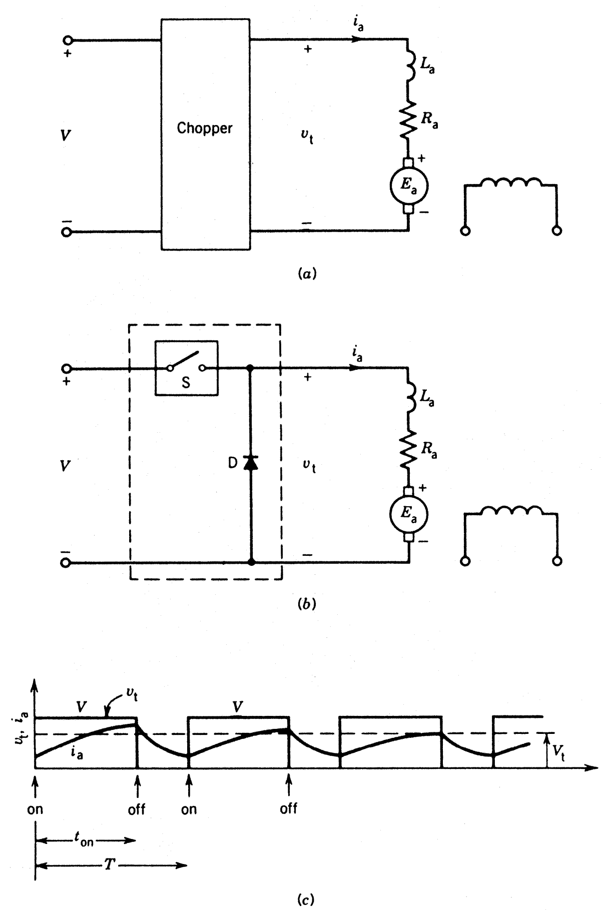


FIGURE 4.62 Chopper circuit and its operation.

13 Problem 2

4 a The rotating magnetic field induces voltages in the rotor bars if the rotor is rotating with a different speed than the magnetic field. Because these rotor bars are short-circuited, there are currents in these windings. The interaction between these currents and the rotating magnetic field creates a torque. Eddy currents always oppose the change of the magnetic field. Therefore, the torque has such a direction that it tries to synchronize the rotor with the magnetic field.

2 b 1500 rpm

3 c See fig. 7.6

4 d A single-phase induction motor with auxiliary winding has two windings. The axes of the windings are 90 degrees shifted. The impedance of the auxiliary winding is different from the impedance of the main winding (sometimes because a capacitor is connected in series with

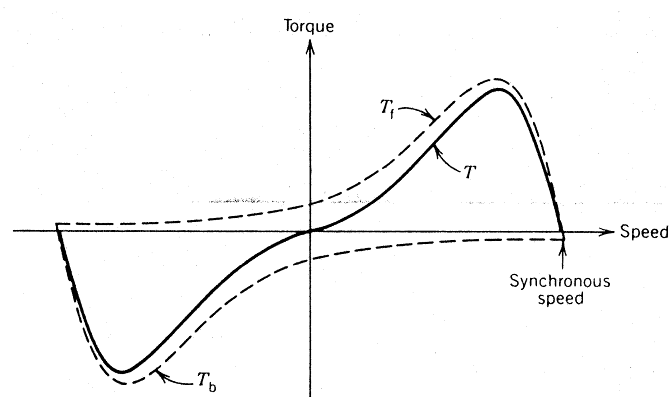


FIGURE 7.6 Actual torque–speed characteristic of a single-phase induction motor taking into account changes in the forward and backward flux waves.

this winding). Therefore, there is a phase shift between the currents in the two windings. The combination of two windings with different axes and two currents with different phase gives the magnetic field in the air gap a rotating component that is enough to start the machine.

12 Problem 3

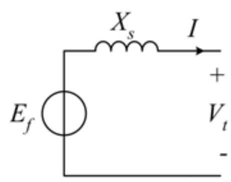
2 a

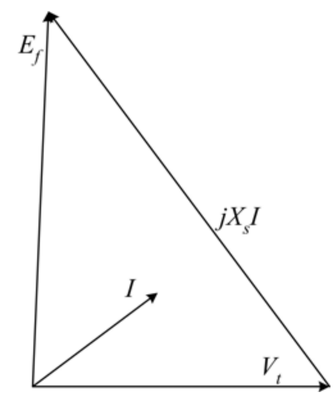
10 b The phase voltage is

$V_t = \frac{20000}{\sqrt{3}} V = 11547V$

The phase current is

$I = \frac{P}{3V_t \cos\varphi} = 3608A$





The terminal voltage phasor is chosen in the real axis:

V_t=11547V .

The power factor is 0.8 with leading current.

Therefore, the phasor for the current can be written as

$I = 2888 + j2165A$

The phasor for the excitation voltage can be calculated as

$E_f = V_t + jXI = 11547 - 10825 + j14434V = 722 + j14434V$

The RMS value of the excitation voltage is

$E_f = \sqrt{722^2 + 14434^2} = 14455V$

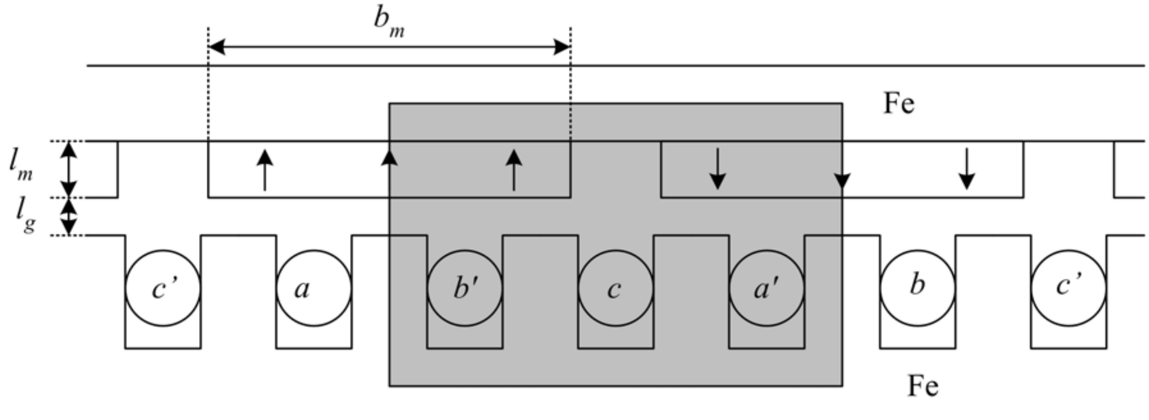
The load angle is

$\delta = \arctan(\frac{14434}{722}) = 1.521rad = 87.14°$

35 Problem 4

2 a $\oint_{C_m} \vec{H} \cdot d\vec{l} = \iint_{S_m} \vec{J} \cdot d\vec{A}$

3 b The surface area is made grey. The boundary of the surface is the contour.



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

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

Using the BH relations for magnets and air:

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

Flux continuity: $\oiint_A \vec{B} \cdot d\vec{A} = 0$

$$B_g A_g = B_m A_m \Rightarrow B_g = B_m$$

Substitution gives

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

$$B_g = \frac{l_m}{l_g + l_m} B_{rm}$$

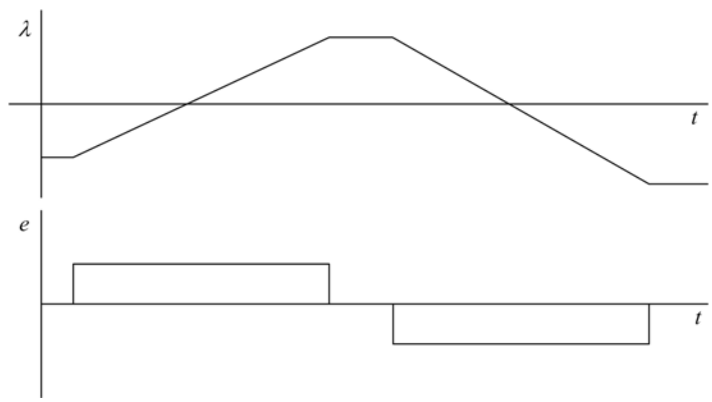
2 e $\Phi_p = B_g l_s b_m$

2 f $\oint_{C_e} \vec{E} \cdot d\vec{l} = -\frac{d}{dt} \iint_{S_e} \vec{B} \cdot d\vec{A}$

2 g The contour is the boundary of the surface. The contour is chosen in the electrical circuit, in the wire.

3 h

3 i



4 j $\oint_{C_m} \vec{H} \cdot d\vec{l} = \iint_{S_m} \vec{J} \cdot d\vec{A}$

$$2H_g (l_g + l_m) = 2\frac{N_s}{p} i_c$$

$$H_g = \frac{N_s i_c}{p(l_g + l_m)}$$

$$B_g = \mu_0 H_g = \frac{\mu_0 N_s i_c}{p(l_g + l_m)}$$

2 k $\Phi_p = B_g l_s \tau_p = \dfrac{\mu_0 N_s l_s \tau_p i_c}{p(l_g + l_m)}$

2 l $\lambda = N_s B_g l_s \tau_p = \dfrac{\mu_0 N_s^2 l_s \tau_p i_c}{p(l_g + l_m)}$

2 m $L = \dfrac{\lambda}{i_c} = \dfrac{\mu_0 N_s^2 l_s \tau_p}{p(l_g + l_m)}$

2 n voltage source inverter