INSTITUT FÜR ELEKTRISCHE MASCHINEN
RHEINISCH-WESTFÄLISCHE TECHNISCHE HOCHSCHULE AACHEN

Lab *Electrical Power Engineering I*

Test 2: Operating behaviour of the DC machine

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[0] July 9, 2003

1 Objective of the experiment

In the past the majority of DC machines was used in closed-loop controlled drives, due to the fact that the control has a simple structure. With the development of power semiconductors AC machines are mainly used for closed-loop controlled drives, because the cost of maintenance is significantly lower due to the absence of a commutator. There are still several applications of DC machines such as high-precision drives and cheap household appliances.

DC machines allow easy investigation and description of the typical behaviour of an electrical machine. The main focus of the test is to become familiar with the behaviour of DC machines through a series of experiments and to gain a fundamental understanding of electrical machines.

2 Experiment preparation

2.1 Principle of DC machine

2.1.1 Construction

A DC machine can operate as a motor or as a generator. This kind of machine is usually realized as an internal rotor/external- pole machine. The ring-coat-shaped housing of the machine is also used as a magnetic yoke for the magnetic field through the armature and poles (Fig. 1).

The excitation winding (field winding) is located directly on the main poles of the stator. A current that flows in this winding generates the main field. Since the machine is operated with DC current,the magnetic field in the stator is constant and so all iron parts of the stator can be made of massive material. Nevertheless the main poles and the commutating poles are often laminated because of easier manufacture. Modern DC machines, used in closed-loop controlled drives, with a fast change in armature current and main field consist of one completely laminated magnetic circuit. A massive iron construction would strongly influence the dynamics and the efficiency of the machine due to the appearance of eddy currents.

The rotating part of the machine holds on its shaft the armature with the commutator. Since the alternating flux flows through the armature, iron parts must be built from laminated, mutually insulated and slotted magnetic steel sheets. The coils of the armature winding are placed in the slots, their ends are connected to the commutator segments. The current is fed into the commutator by carbon brushes. As the rotor revolves, conductors revolve with it. The brushes contact the commutator segments

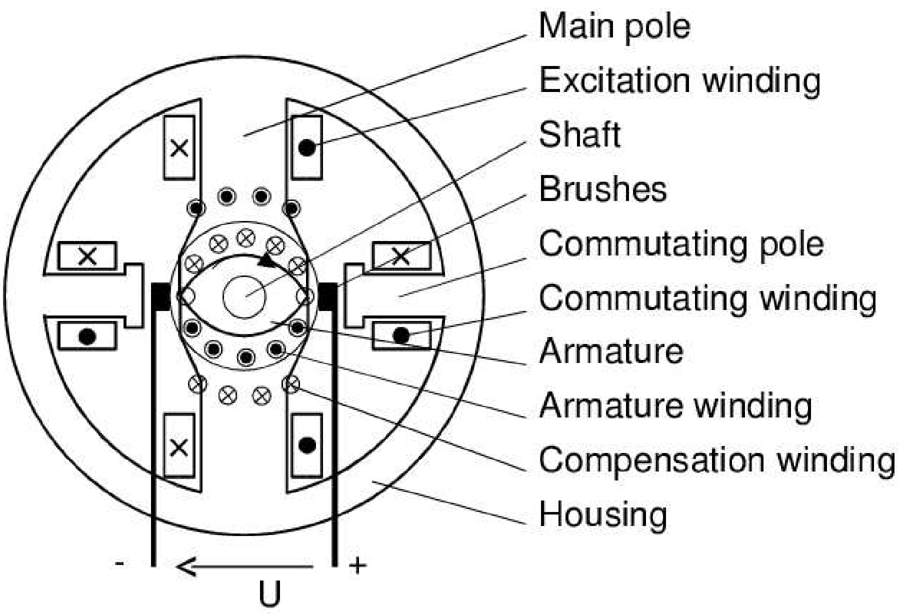

Figure 1: Schematic cross-section of a two-pole machine

in sequence. This results in a constant direction of the armature field due to the commutation. The magnetic flux of the armature is ideally vertical to the direction of the main field. Due to this configuration there is no induced voltage at the turn connected to brushes. (Fig. 2). This area is called the neutral zone.

When the load of the machine increases, the armature field is no more neglectible and causes a shift of the neutral zone because of the superposition of main field and armature field: The main field is distorted and (because of the effects of saturation) weakened. This interference between the main field and the armature cross field, which causes a loss of torque, can be reduced using a compensating winding in the stator of the DC machine. The conductors of this compensating winding are arranged in axial slots of the main pole (Fig 1). The compensating winding is connected in series to the armature, so that the total magnetic flux under one pole with compensating conductors and armature conductors create no magnetic field transverse to the main pole.

The shift of the neutral zone also causes brush fire because commutation doesn't take place in the neutral zone anymore: the windings carry an induced voltage greater than zero when short-circuited by the commutator. This results in faster deterioration of the commutator.

Large machines are therefore equipped with additional commutating poles. Their coils are connected in series to the armature winding. The commutating poles generate a counter field in the area of the short-circuited armature conductor in such a way that voltages induced by this field compensate the ones resulting from the commutation of

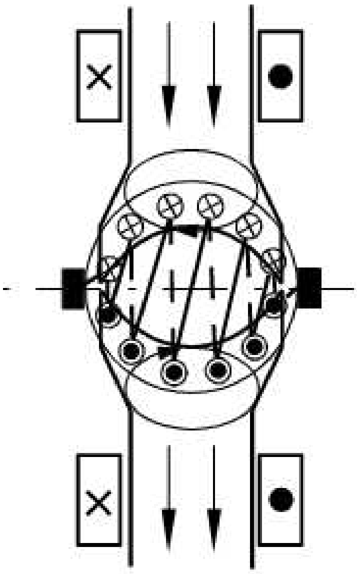

Figure 2: Armature as a coil

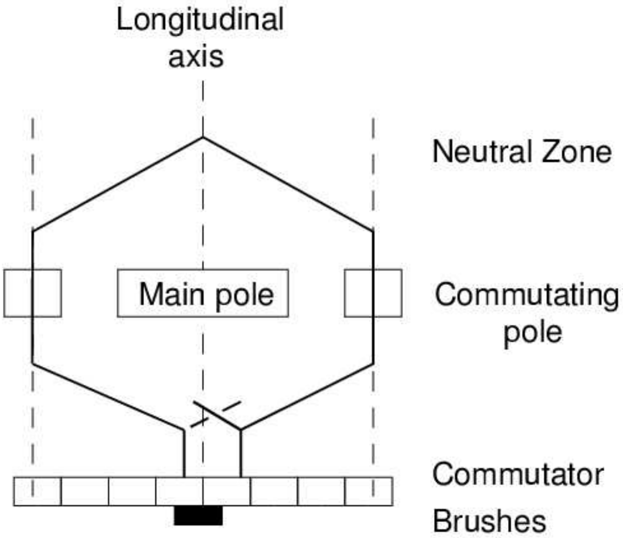

Figure 3: Armature unwinding

the armature currents, so that a commutating free of sparks is achieved.

2.1.2 Principle of operation

The main field in the air gap, created by the field winding, produces togehter with the current in the armature winding a force on these conducturs according to the relation $\vec{F} = I \cdot \vec{l} \times \vec{B}$, where $\vec{F}$ is the force vector, $\vec{l}$ is the vector in the direction of the length of armature conductors, I is the current and $\vec{B}$ is the vector of the air gap induction. The force effecting the circumference of the armature produces the torque of the machine. A change in direction of the torque and the rotation sense can be achieved by changing either the direction of the field current or the direction of the armature current: if the direction of the field current and the current are changed both at the same time, the direction of the torque remains unchanged.

2.1.3 Voltage and torque equations

When the main poles are excited and the machine rotates, a voltage is induced in the armature. This voltage increases with the excitation or the speed of the rotation ($\sim \Phi$,flux of each pole; $\sim n$). This results in the first equation of the DC machine:

$$U_i = \mathrm{k}_1 \cdot \Phi \cdot n \tag{1}$$

The constant k_1 depends on the geometric design of the machine. The terminal voltage is obtained considering the entire ohmic voltage drop in the armature circuit:

$$U = U_i + R_{tot} \cdot I = \mathrm{k}_1 \cdot \Phi \cdot n + R_{tot} \cdot I \tag{2}$$

A positive sign is defined for motor operation and a negative sign for generator operation. A DC machine can operate as a motor or as a generator, where for the motor operation $U_i < U$ while for the generator operation $U_i > U$. The rotational speed n is:

$$n = \frac{U - R_{tot} \cdot I}{\mathrm{k}_1 \cdot \Phi} \tag{3}$$

There are different possibilities for controlling the rotational speed:

- At a constant voltage and a constant current, the rotational speed is changed if the magnetic flux is changed. The rotational speed is higher with a smaller magnetic flux (field weakening).
- At a constant flux and a constant current, the rotational speed can be varied with the voltage U (changing of the rotation speed by variation of the armature voltage).
- With constant voltage, constant current and constant flux, the rotational speed is altered when the resistance R_{tot} is changed by adding a series resistor to the armature circuit. This possibility, however, is not economically useful and rarely used due to the losses on the series resistance.

When acceleration the machine as a motor from standstill, it is important to consider that there is no induced voltage at $n = 0$. The resulting machine current at startup is

$$I = \frac{U}{R_{tot}} \tag{4}$$

This current is way to high and would destroy the windings. Therefore R_{tot} has to be increased using a series resistance during the starting process of the machine.

The internal power of the machine is obtained by multiplying U_i (1) and the armature current I:

$$P_i = U_i \cdot I = \mathrm{k}_1 \cdot \Phi \cdot n \cdot I \tag{5}$$

This internal power differs from the consumed electrical power due to the copper losses. The torque on the shaft is:

$$M_i = \frac{P_i}{2\pi n} = \frac{\mathrm{k}_1}{2\pi} \cdot \Phi \cdot I \tag{6}$$

2.1.4 Wiring types

The dynamic behaviour of the DC machine is mainly determined by the type of the connection between the excitation winding and the armature winding including the commutation and compensation winding:

1. **Separately excited DC machine:** excitation and armature winding supplied at separate voltages

2. **Shunt DC machine:** excitation and armature winding are connected in parallel (i.e. fed by the same source)

3. **Series-wound machine:** the excitation and the armature winding connected in series; if the stator is laminated, series-wound machines can operate at AC current

4. **Compound machine:** This is a combination of 2 and 3 (both shunt and series winding are available)

5. In special cases shunt-, series-, and separate excitation can be combined.

2.2 Separately excited DC machine

2.2.1 No-load characteristic

Given that the machine is excited separately and rotated mechanically at no-load conditions, the armature current is zero and therfore there is no voltage drop on the armature resistance, so that the induced voltage can be measured at the terminals $(U_i = U_0)$.

The curve $U_0 = \mathrm{f}(I_f)$, obtained at a constant rotational speed, is called the no-load characteristic (see Fig. 4). If the iron has a remenant induction due to previous magnetizations, a small voltage is induced even without any excitation current. Apart from this remanent voltage, the induced voltage is practically proportional to the excitation current except for the range with high excitation currents, where the iron is saturated and the relation between the excitation current and the voltage is no longer linear.

2.2.2 Self excitation of the shunt DC machine

The remanent voltage enables operation of the DC machine as a generator, with no additional voltage source. When the machine is connected in shunt connection, i.e. the excitation circuit with a field weakening resistor R_{fv} shunt to the armature circuit, and mechanically driven to a certain rotational speed, a small current flows through the excitation winding, on the account of the remanent voltage. If the winding is connected in such a way that this current amplifies the residual effect, the voltage for the excitation circuit can be generated on its own. This is called self excitation wiring. The opposite case where the current caused by the remanent induction weakens the field is called ”suicidal wiring”.

The value of the induced voltage can be adjusted by a field weakening resistor R_{fv} and determined at the intersection point of the resistance line $(R_f + R_{fv}) \cdot I_f$ with the no-load characteristic. (Fig. 4). If R_{fv} and consequently the angle ρ in Fig. 4 are increased, a smaller voltage is obtained until the critical value of the angle is exceeded. At the angle $\rho_{critical}$ there is no definite intersection point between the no-load characteristic and the resistance line, so that the resulting terminal voltage is strongly load dependent; at no-load conditions the upper and under load the lower mutual point of the graphs are the points of operation.

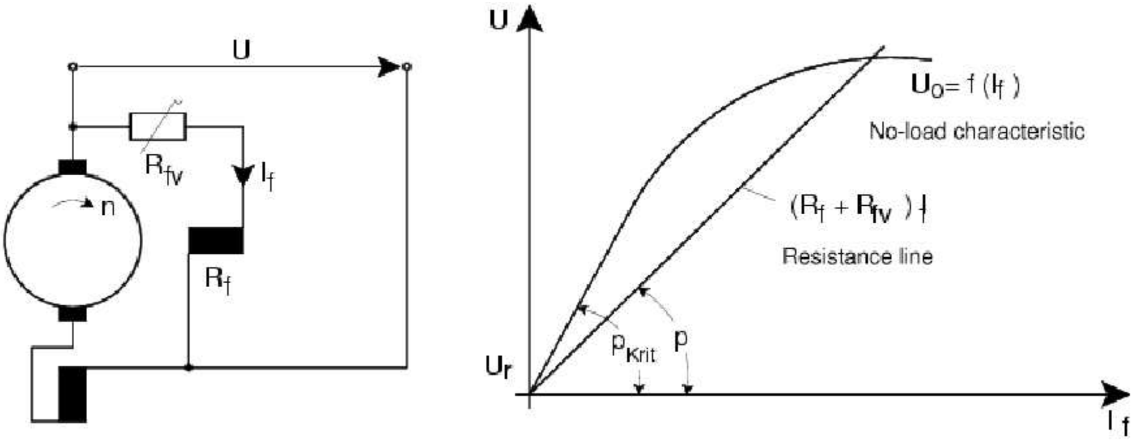

Figure 4: Self excitation of a shunt generator

2.2.3 Operating behaviour and control of rotational speed

DC machines with separate excitation are similar to those with shunt excitation considering the torque vs. rotation speed characteristics. The main flux resp. the excitation current are load-independent. The equation for the rotational speed n, obtained from the voltage equations for the DC machine, explains the behaviour of the rotational speed and possibilities of speed control (compare general introduction):

$$n = \frac{U - R_{tot} \cdot I}{\mathrm{k}_1 \cdot \Phi} \quad \Longleftrightarrow \quad n = \frac{U}{\mathrm{k}_1 \cdot \Phi} - \frac{2\pi R_{tot}}{(\mathrm{k}_1 \cdot \Phi)^2} \cdot M_i \tag{7}$$

The rotational speed of the machine under no-load conditions $I = 0$ and with a certain excitating current, is defined as a single-value n_0. It decreases linearly with an increase in mechanical load $I \geq 0$. At speed values above n_0 (speed at no-load conditions) the machine operates as a generator. Since $I \cdot R \ll U$, the rotation speed does not change a lot with the load; it is the characteristic of a shunt machine, that the rotational speed has a small drop with increasing load. (Abb 5).

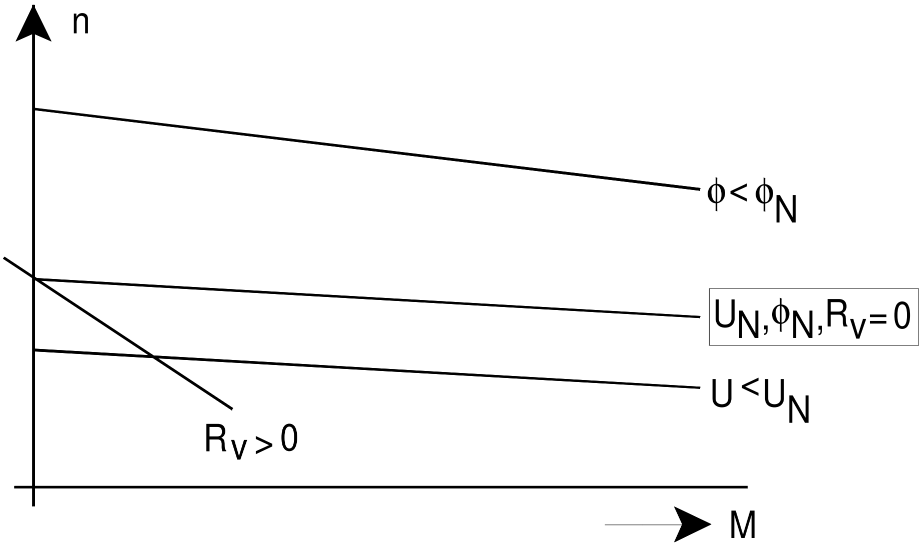

Figure 5: Rotational speed control

There are three methods for adjusting the machine speed:

1. **Varying the flux, i.e. the excitation current** (concerning the saturation in the excitation circuit, only a weakening of the flux is possible) $\Rightarrow$ the regulation of the rotational speed at a constant armature voltage is possible only to speed values above the rated rotational speed, i.e. beyond the rotational speed at maximum flux resp. maximum permitted excitating current. Limit: mechanical stress (centrifugal force) and commutation (brush fire, sparking)
2. **Reducing the armature voltage** $U \Rightarrow Rightarrow$ The regulation of the rotational speed is possible only to speeds below the rated rotation speed, to avoid possible fire on the brushes at higher voltages; (voltage switching, e.g. from 220 V to 110 V or supply at DC motor controller, Leonard set).
3. Increasing R_{tot} with an additional series resistance R_v (starter) in the armature circuit. This possibility is rarely used due to the additional losses and strong load dependency of the speed.

2.2.4 Application field

The DC machine is used as a motor when there is a demand for a continuos regulation of rotational speed. Although there is a disadvantage due to the fact that brushes are not without friction, it requires considerably less cost for the supply equipment, which makes the DC machines sometimes more economical than three-phase drives.

The Application areas of a DC machine are electric rolling mill drives, conveyor drives or machine tools. In the last application,the machine is excited with permanent magnets instead of using electrical excitation in order to reduce the size of construction and losses in the excitation circuit.

The DC generator is used as a Leonard generator, as an excitation machine for synchronous generators or as permanent excited tachometer generator.

2.3 Series-wound machine

2.3.1 Equations and operating behaviour

The excitation winding and the armature circuit are connected in series according to Fig. 6. The resistances R_v resp. R_p are used for start-up resp. field weakening.

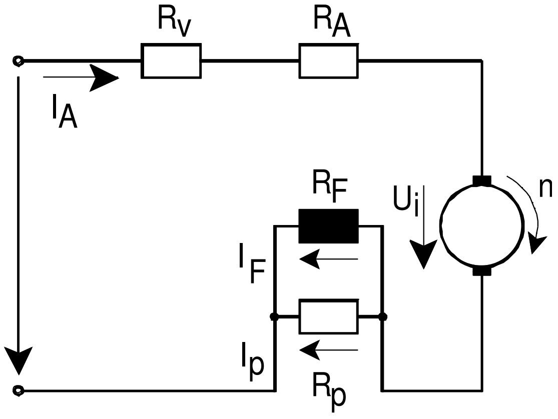

Figure 6: Series-wound machine

Commutating poles and the compensating winding, which exist in larger machines, are not shown. If present, they are connected in series to the armature circuit.

The voltage equation of the machine is:

$$U = k \cdot \Phi \cdot n + R_g \cdot I_A \tag{8}$$

with

$$R_g = R_A + R_v + R_K + R_W + \frac{R_f \cdot R_p}{R_f + R_p} \tag{9}$$

R_g is the total resistance in the circuit. It consists of an armature resistance, a series resistance, the resistance of the compensating winding and commutating pole windings and the resistance of the excitation circuit.

For a magnetically linear i.e. unsaturated machine, the air gap flux is proportional to the excitation current:

$$\Phi \sim I_f \quad \Rightarrow \quad k\Phi = L'_h I_f \tag{10}$$

The proportionality factor L'_h has the dimension of an inductance. The exact derivation is given in lectures.

For the machine without field weakening ($R_p \to \infty$) we have:

$$I_f = I_A \quad \Rightarrow \quad k\Phi = L'_h I_A \tag{11}$$

From this the torque is obtained:

$$M = \frac{1}{2\pi} k\Phi I_A = \frac{1}{2\pi} L'_h I_A^2 \tag{12}$$

The equation for the rotational speed is:

$$n = \frac{U}{L'_h I_A} - \frac{R_g}{L'_h} \tag{13}$$

or:

$$n = \frac{U}{\sqrt{2\pi L'_h M}} - \frac{R_g}{L'_h} \tag{14}$$

In Fig. 7 the response rotational speed vs torque is plotted for different resistances R_g .

As the diagram shows,the machine has two characteristic properties:

1. A high no-load rotational speed which is restricted only by friction. That is why the machine must not be completely unloaded.
2. A high starting torque and a "soft" rotational speed-torque characteristic.

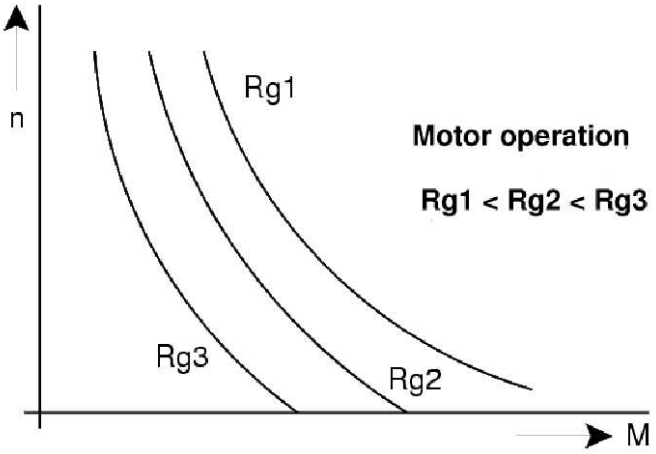

Figure 7: Rotation speed - torque characteristic

Because of the rotational speed / torque characteristic, the series machine is mainly used as a traction drive in DC railways and electric vehicles and as a starter motor in automobile industry.

2.3.2 Speed control

Possibilities of rotational speed control are:

1. **Changing the voltage U:** This is possible with a controllable rectifier, a DC motor controller or through a series-parallel-connection of two machines in one vehicle.
2. **Adding a variable resistance R_v to the armature circuit:** Since large losses will be produced, the series resistance is in practice only applied for the limitation of the starting current and not for rotational speed control.
3. **Field weakening:** This is achieved by adding a shunt resistor to the field winding.

Without special measures, the DC series wound machine can not operate as a generator. Special devices are needed in order to allow for feeding into a network at constant voltage. If the terminals of the machine are connected to a resistance, the machine can operate as a braking generator.

2.4 Universal motor

2.4.1 Torque and transforming voltage

In contrast to the separately-excited and the shunt machine, the series-wound machine is suitable for the operation at AC voltage. Since the field direction is changed simultaneously with the armature current, the machine always develops a torque in the same direction. The series connection of the armature and the excitation winding assures that there is no phase shift between both torque forming values.

If the machine is fed with an AC current $i = \sqrt{2} I \sin \omega t$, the torque has one constant part and one part that pulsates at double supply frequency (Fig. 8):

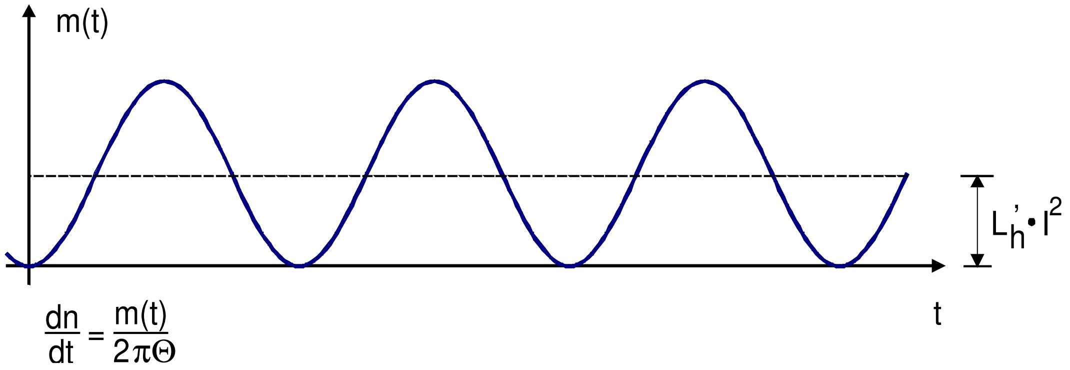

Figure 8: Torque curve at AC current supply

When the moment of inertias of armature and drive are large enough, the torque oscillation has no effect on the rotational speed. The rotational speed-torque-response is in that case the same as the rotation speed-torque characteristic of the series-wound machine fed with DC current. Since the flux in the machine changes in time ($\varphi = \Phi \sin \omega t$), an additional voltage known as the transforming voltage is induced in the armature besides the rotatory voltage.

This voltage increases the voltage between the segments of the commutator and complicates the commutation of the current in the part of the armature winding which is short-circuited by brushes (Fig. 9).

2.4.2 Construction and application

Since the excitation winding and the armature of a series-wound machine are connected in series, a high armature current flows through the field winding. This is the reason why series-wound machines have a smaller number of turns and a large conductor cross section. For the operation at AC current, the stator is built from separate, mutually isolated steel sheets in order to decrease eddy-current losses. Such motors are suitable for operation at DC or AC current and can be used as an universal motor.

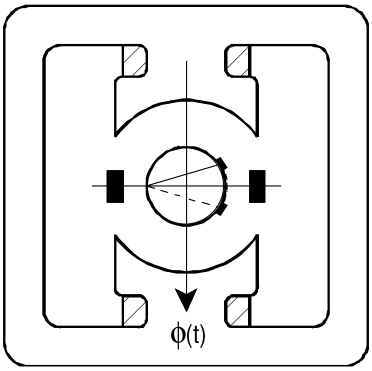

Figure 9: Formation of transformating voltage

Smaller machines of this type are used in large quantities as high-speed drives for household- and handicraft machines.

Larger machines (up to 1500 kW), particulary used as drive motors in electrical railways (16 2/3 Hz in Federal Republic of Germany), have additional commutating poles and a compensation winding. The stator is laminated as shown in Fig. 10

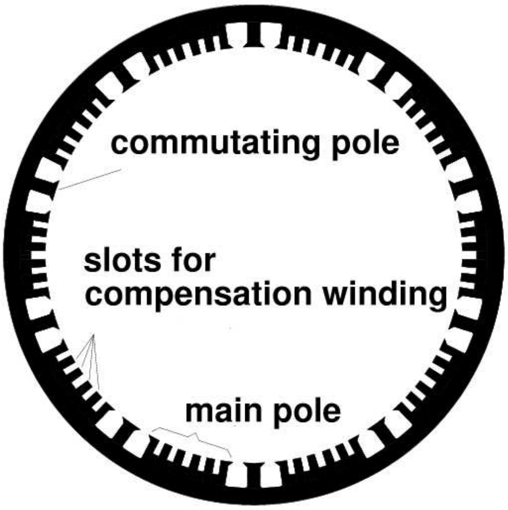

Figure 10: Stator sheet of a large series-wound machine

3 Experiment realisation

In the following experiments the DC machine will operate coupled with an pendulum induction machine. Depending on the operating point, the pendulum machine can operate as load or driving machine. The corresponding control unit of the pendulum machine can drive the machine either speed- or torque controlled. The torque is measured by the elongation of strain gauges between the base frame and the twistable stator of the pendulum machine.

For the excitation of the DC machine a separate, controllable voltage source is available.

3.1 Safety requirements

Experiments will be performed at mains voltage. Every change in wiring must be done under no-voltage conditions. For the switching of DC voltages special precautions have to be taken. Please ask the supervisor.

Rotating machine parts may harm you! Therefore: Pay attention to clothes or long hair.

Inform yourself about the location of the closest emergency-switch. Equipment that is not used in the actual test should be put aside. Take care of a clearly arranged experimental setup.

3.2 Objective of each test

The theoretically presented types of machines are now practically investigated. The operating behaviour of the shunt machine will be investigated; the no-load characteristic will be taken with the help of the separately excited DC machine due to the ease of adjusting the excitation. The operating behaviour of the series wound machine will be examined at AC and DC voltage.

3.3 Measuring of the no-load characteristic

You have two DC machines available; the universal motor and the shunt motor. The no-load characteristic of one of these two motors should be determined. Which motor must be used considering given instruments and the voltage supply? Record the no-load characteristic of the chosen motor. Be careful not to overload it. Draw the characteristic.

3.4 Universal motor at AC voltage

3.4.1 Experimental set-up

Start up the experimental equipment consisting of an universal motor at AC voltage system (220V) and the pendulum machine. Think about how the machines should be connected and which components you may possibly need in addition.

3.4.2 Load characteristics

Record the load characteristic of the universal motor. Think about the speed range in which these values are reasonable and measurable without overloading the machine. Measure the values.

Torque M
Speed n
Current I
Power factor $\cos\varphi$
Absorbed power P_1
Delivered power P_2
Efficiency η

Draw the curves depending on the torque.

3.5 Universal motor at DC voltage

3.5.1 Experimental set-up

Now the universal motor should operate at the DC network(220V) together with the pendulum machine. First think how to connect the machines and which components you may possibly need in addition. Start up the machine set.

3.5.2 Load characteristics

According to the experiment 3.4.2, the load characteristics of the universal motor should be taken at the DC network. Determine the speed range in which these values are reasonable and measurable and find out the values according to experiment 3.4.2: Draw these curves depending on the torque.

3.6 DC shunt motor

3.6.1 Experimental set-up

In this experiment the load characteristic of the DC shunt motor should be determined. Start up the machine set consisting of the pendulum machine and the shunt motor. Proceed as in 3.4.1. Connect the shunt machine with the commutating and compensation windings.

3.6.2 Load characteristics

The following values must be recorded for the load characteristics of the shunt motor:

Torque M
Speed n
Armature current I_A
Excitating current I_F
Absorbed power P_1
Delivered power P_2
Efficiency η

Draw the curves depending on the torque.

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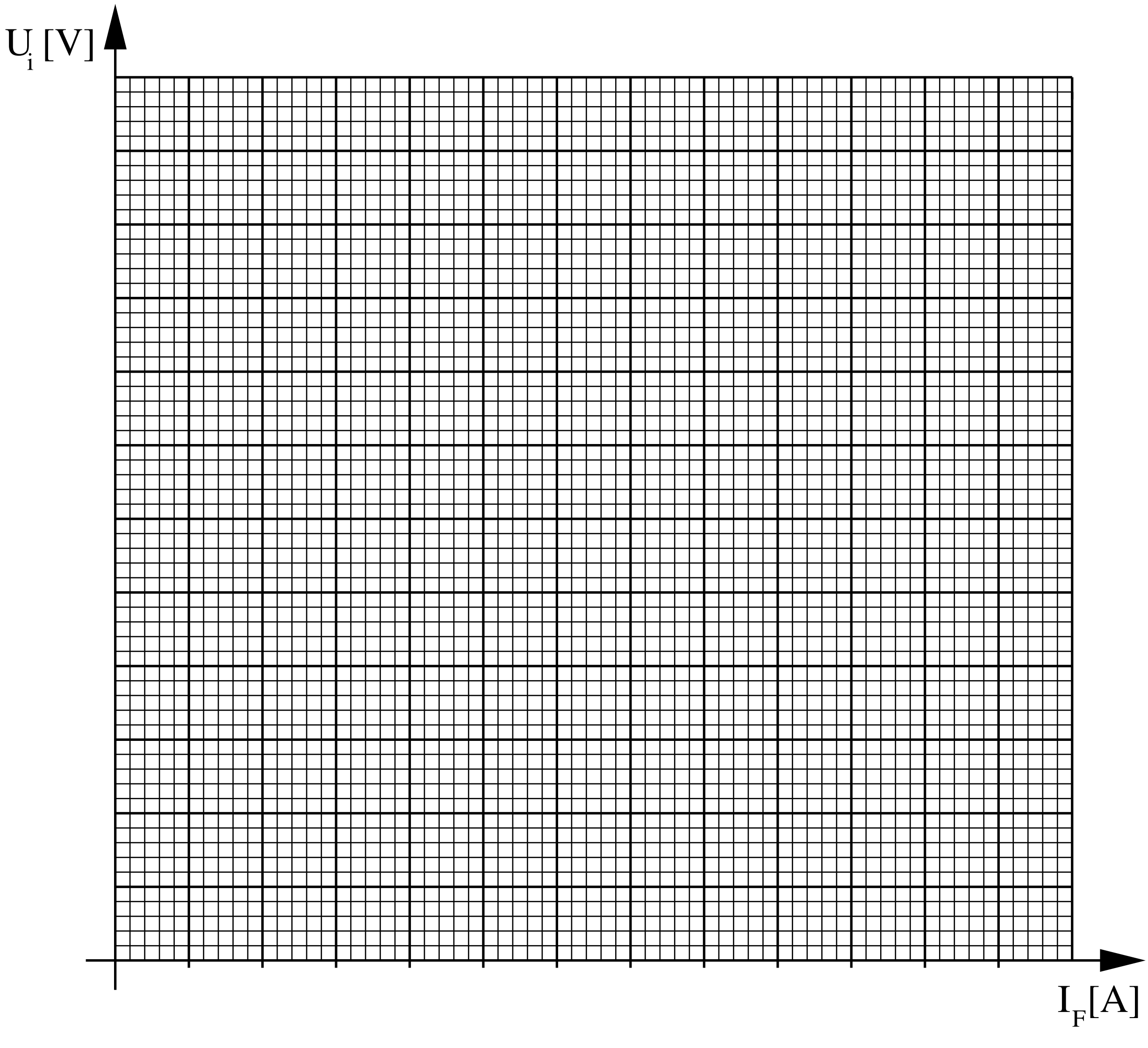
Worksheet
No-load characteristic

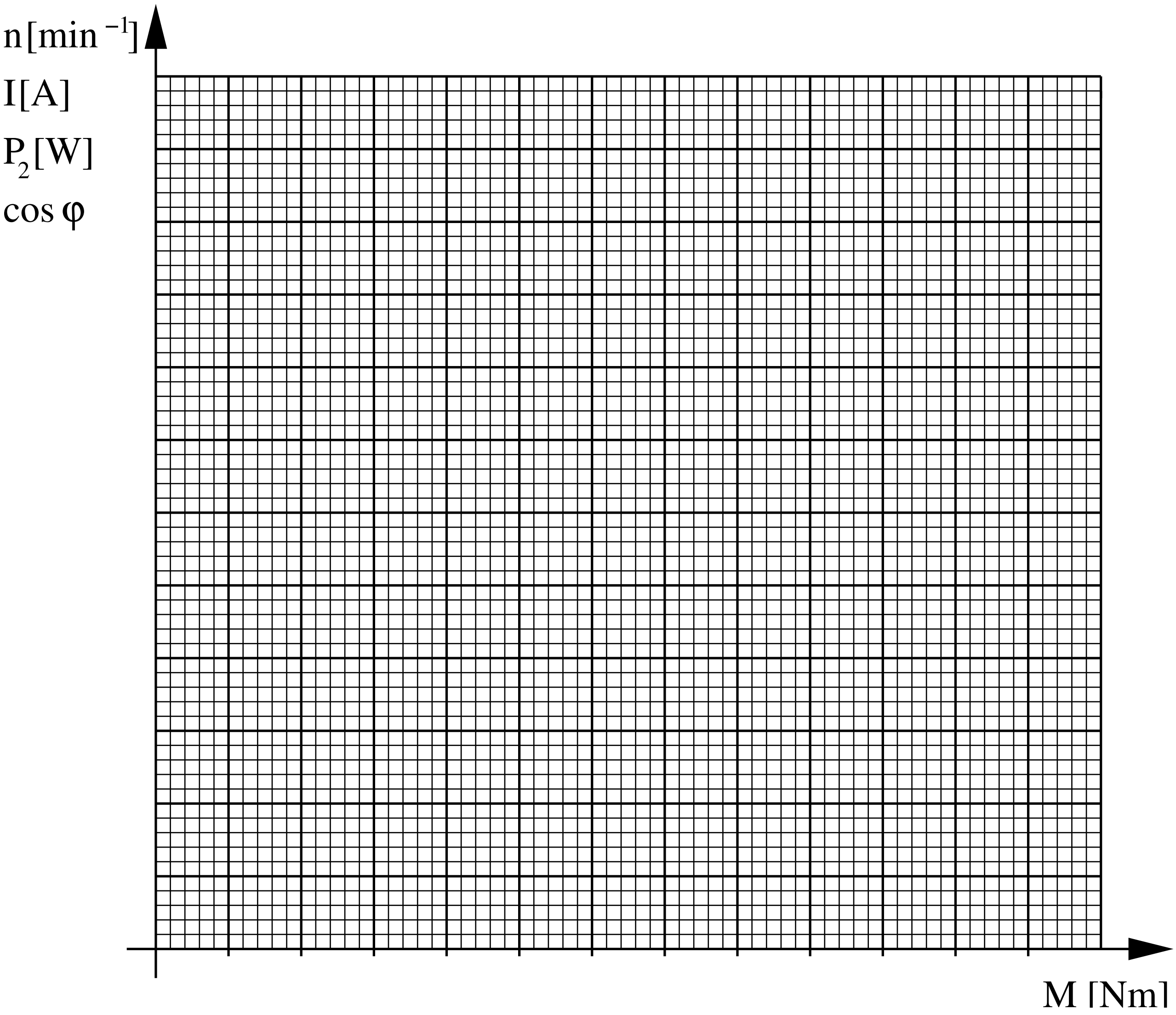
Remark: $U_{i1} = U_i$ at $n = 1500/\mathrm{min}^{-1}$ and $U_{i2} = U_i$ at $n = 3000/\mathrm{min}^{-1}$

I_F/A	0	0,5	1,5	2,0	2,5	3,0	3,5	4,0	4,5	5,0
U_{i1}/V										
U_{i2}/V										



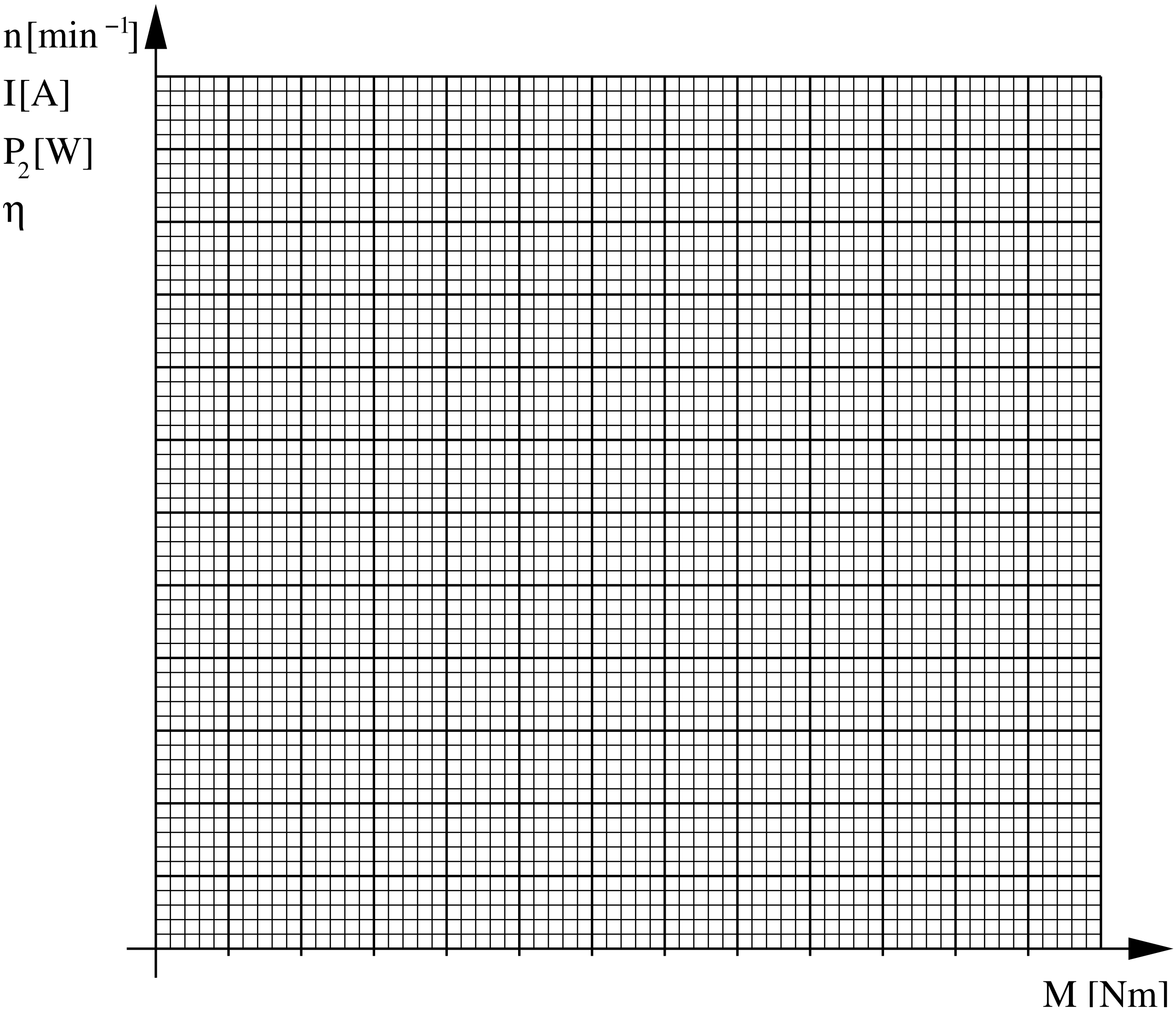
Worksheet
Universal motor (AC)

M/Nm	1,0	1,2	1,4	1,6	1,8	2,0
n/min^{-1}						
I/A						
$\cos\varphi$						
P_1/W						
P_2/W						
η						



Worksheet
Universal motor (DC)

M/Nm	1,0	1,5	2,0	2,5	3,0	3,5
n/min^{-1}						
I/A						
P_1/W						
P_2/W						
η						



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Worksheet
DC shunt motor

M/Nm	0	1	2	3	4	5
n/min^{-1}						
I_A/A						
I_E/A						
I_{ges}/A						
P_1/W						
P_2/W						
η