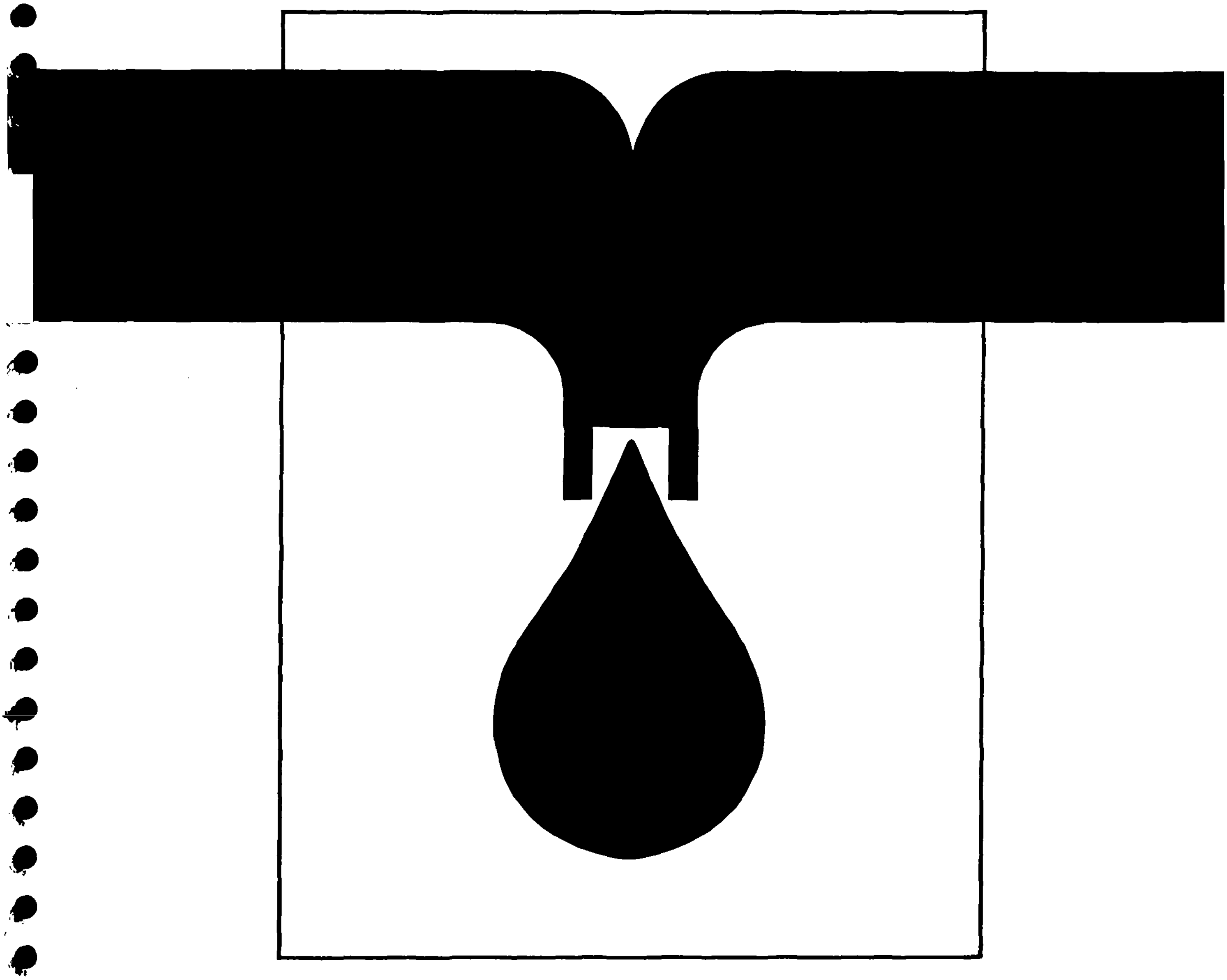
TRAINING MODULES
FOR
WATERWORKS PERSONNEL



Special Knowledge

2.3 b

Maintenance and repair of electric motors

Foreword

Even the greatest optimists are no longer sure that the goals of the UN "International Drinking Water Supply and Sanitation Decade", set in 1977 in Mar del Plata, can be achieved by 1990. High population growth in the Third World combined with stagnating financial and personnel resources have led to modifications to the strategies in cooperation with developing countries. A reorientation process has commenced which can be characterized by the following catchwords:

- use of appropriate, simple and – if possible – low-cost technologies,
- lowering of excessively high water-supply and disposal standards,
- priority to optimal operation and maintenance, rather than new investments,
- emphasis on institution-building and human resources development.

Our training modules are an effort to translate the last two strategies into practice. Experience has shown that a standardized training system for waterworks personnel in developing countries does not meet our partners' varying individual needs. But to prepare specific documents for each new project or compile them anew from existing materials on hand cannot be justified from the economic viewpoint. We have therefore opted for a flexible system of training modules which can be combined to suit the situation and needs of the target group in each case, and thus put existing personnel in a position to optimally maintain and operate the plant.

The modules will primarily be used as guidelines and basic training aids by GTZ staff and GTZ consultants in institution-building and operation and maintenance projects. In the medium term, however, they could be used by local instructors, trainers, plant managers and operating personnel in their daily work, as check lists and working instructions.

45 modules are presently available, each covering subject-specific knowledge and skills required in individual areas of waterworks operations, preventive maintenance and repair. Different combinations of modules will be required for classroom work, exercises, and practical application, to suit in each case the type of project, size of plant and the previous qualifications and practical experience of potential users.

Practical day-to-day use will of course generate hints on how to supplement or modify the texts. In other words: this edition is by no means a finalized version. We hope to receive your critical comments on the modules so that they can be optimized over the course of time.

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and
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It is my sincere wish that these training modules will be put to successful use and will thus support world-wide efforts in improving water supply and raising living standards.

Dr. Ing. Klaus Erbel
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Eschborn, May 1987

Title: Electric motor

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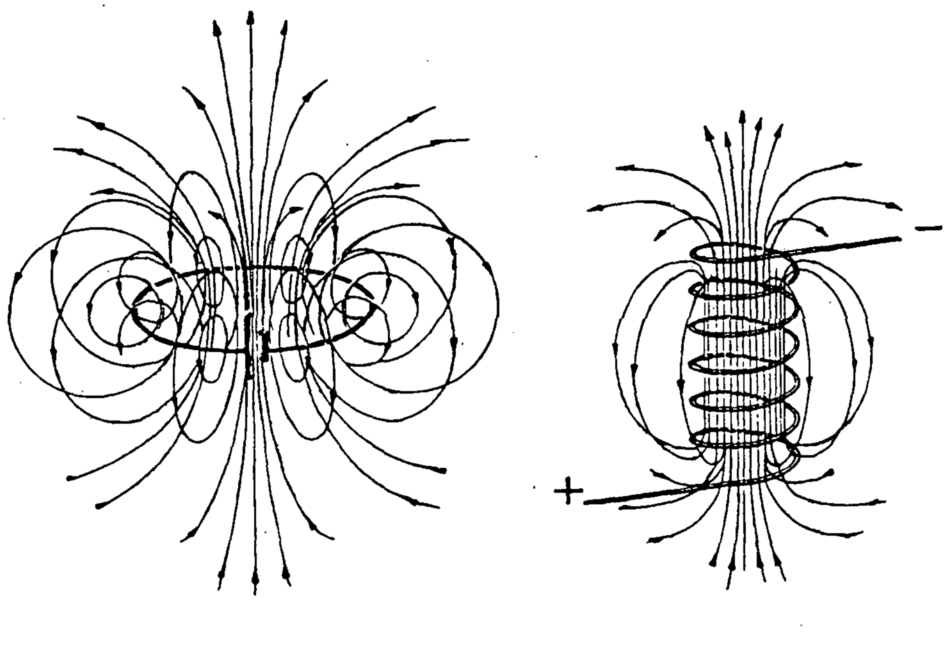
0. Introduction:

The generally known effect of magnetism is that unlike poles attract and like poles repel. If you take a bar magnet in each hand and attempt to move the north poles of the magnets towards each other, you can feel a repulsive force in your fingers. If one of the magnets is then released, this force causes a mechanical movement - the magnet is pushed away. Conversely, if the south pole of one bar magnet is moved towards the north pole of the other magnet, a force of attraction can be felt. In addition to this permanent natural magnetism, there is also electromagnetism, which has the same properties.

Every current flowing in a metal conductor builds up a circular magnetic field around the conductor (Fig. 1a).

If several conductors with currents flowing in the same direction are placed together, the magnetic field becomes stronger. Conversely, it becomes weaker if conductors with currents flowing in opposite directions are placed together (Fig. 1b).



a) b)

Fig. 1: a) The magnetic field generated by a current in a circular conductor

b) The magnetic field of a long coil

In order to generate mechanical movement with the aid of electromagnetic fields, the following experiment can be performed (Fig. 2):

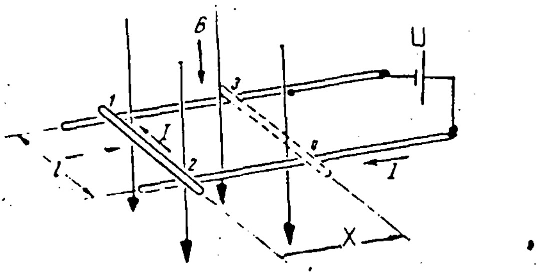


Fig. 2: Conductor rod in a consistently uniform (homogeneous) magnetic field with constant induction B

Two parallel bars made of a highly conductive material (e.g. copper) are connected to a voltage source U. A rod made of the same material is placed across the bars at right angles so that the circuit is closed and a current I can flow. The plane formed by the bars is penetrated vertically by the lines of flux (or lines of force) of a magnet. The rod will now move in direction X. If the current is switched off it will stop. If the direction of current flow is reversed, or if the poles of the magnetic field are interchanged, the rod will move back in the opposite direction to X.

In order to obtain a rotary motion, the experiment will be continued:

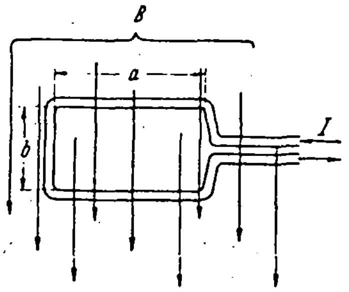


Fig. 3: Conductor loop in a homogeneous magnetic field with constant induction B

Instead of a rod we will now use a conductor loop (Fig. 3), which is mounted such that it can rotate in a magnetic field as described above. If a current is now made to flow through the conductor loop, the loop will turn in one direction until a neutral point, or point of equilibrium is reached, where the torsional forces on the two longitudinal sides of the loop become equal and the loop ceases to move or - in other words - when the north pole of the loop is aligned with the south pole of the magnetic field.

If the current is switched off shortly before the point of equilibrium is reached, so that the loop is carried past this point by its momentum, and if the current is then switched on again with the polarity reversed, the loop will continue to rotate. Reversal of the polarity interchanges the magnetic poles of the loop. which means that the poles of the loop and of the fixed magnet once again repel each other at the right moment. As a mechanical movement can be generated with the aid of a magnetic field and an electric current, the reverse process is also possible. By moving a conductor in a magnetic field, or by moving or altering the magnetic field at right angles to a conductor, an electric current can be generated in this conductor.

Every electric motor can therefore also be used as a current generator.

Almost all rotating electric machines are based on the above principle (Figs. 4 and 5).

A rotating electric machine consists of two major parts. The stationary part - known as the stator - comprises a frame with bearings, laminated stator core and copper winding. The rotating part - known as the rotor - consists of a shaft, a laminated rotor core, a copper winding and - depending on machine type - segments (commutator) or slip rings for current transmission. The laminated cores each consist of numerous individual sheet metal punchings made of a special iron material which are electrically insulated with respect to one another by means of varnishing in order to prevent undesired currents (eddy currents) in the iron. The laminated core also contains the recesses or slots in which the copper wires - the current-carrying parts - are inserted.

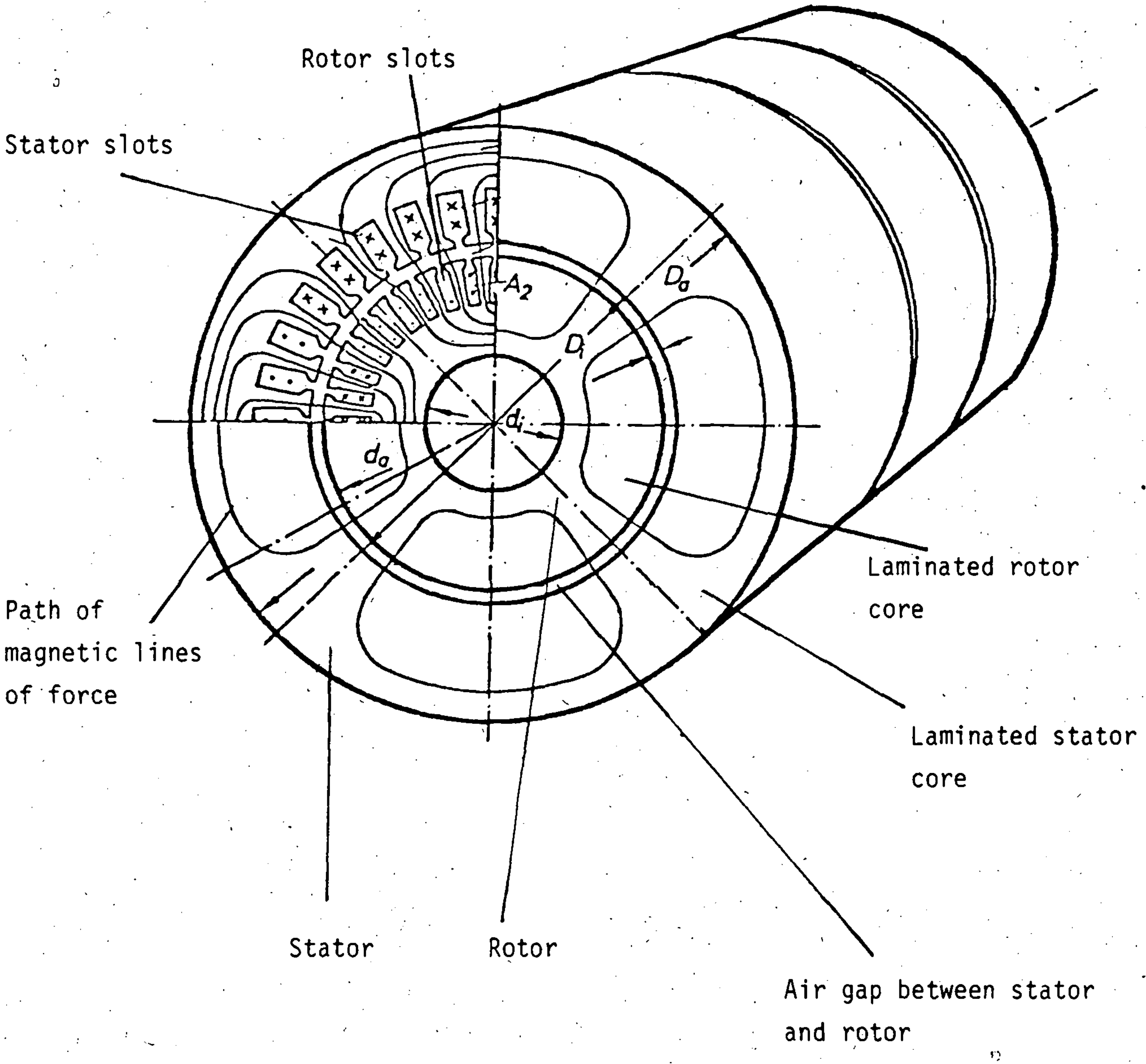


Fig. 4 : Structure of a rotating electric machine; the stator frame and the shaft are not shown.
In the stator and rotor slots are the current-carrying copper coils (indicated by crosses and dots).

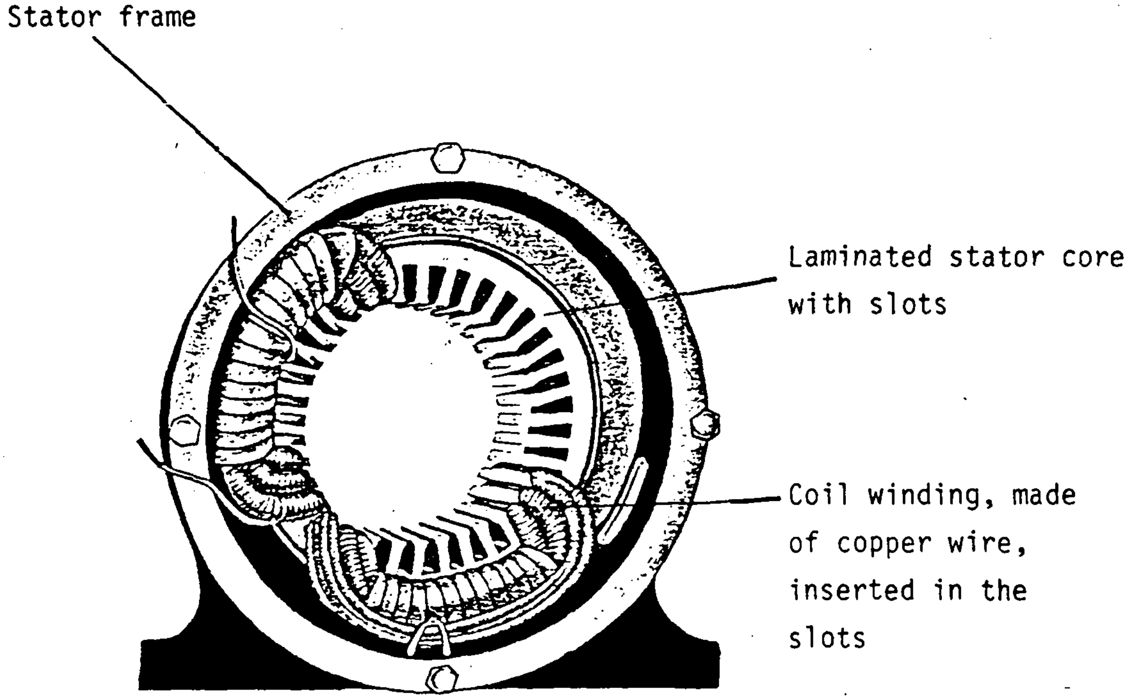


Fig. 5: Stator frame with laminated stator core and partially inserted stator winding

Rotating electric machines are classified in three major groups:

1. Direct-current machines
2. Synchronous machines
3. Asynchronous machines

1 The direct-current machine

Fig. 6 shows the design of a direct-current machine in simplified form:

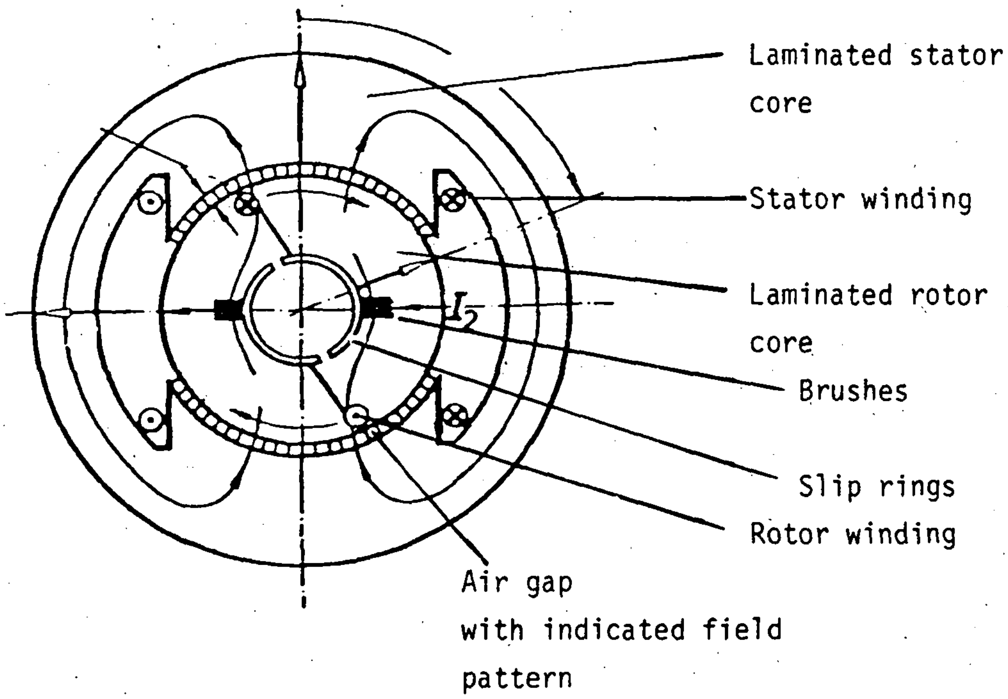


Fig. 6: Design of a direct-current machine

In the technical construction of direct-current machines the magnet poles are designed such that the air gap between rotor and stator is as small as possible and a magnetic field which is as homogeneous as possible is achieved. Around the stator poles are located the field coils; the excitation current flowing in these coils builds up the stator's magnetic field. The rotor (also known as the armature) consists of a rotatable soft iron core which, as described earlier on, consists of laminations insulated with respect to one another in order to prevent eddy currents. In the recesses or slots of this laminated iron core are located the conductor coils with the number of turns required for the armature voltage.

A small magnetic resistance is achieved with the aid of the iron core.

The conductor ends of the windings are connected to the segments of the commutator. These are small copper plates which are insulated with respect to one another and arranged longitudinally around the shaft. The carbon brushes slip on these for the purpose of current transmission.

The conductors of the armature coils are always moved perpendicular to the lines of force in the area of the pole arcs. The direction of current flow in the armature conductors relative to the stator is thereby always the same, i.e. as shown in Fig. 6 for example, directed into the armature body in the upper conductor.

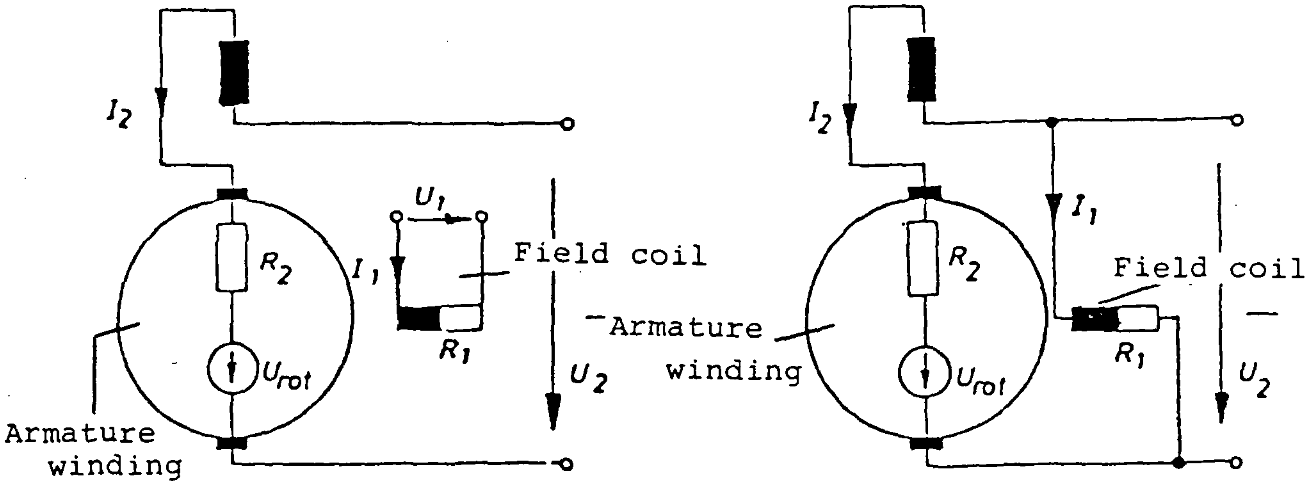
The commutator automatically ensures that this is the case. The function of the commutator is to reverse, or commutate, the current at the right moment, i.e. when the coil is in the "neutral zone". This is done by the carbon brushes moving from one segment to the next. The torque is therefore always in the same direction. It becomes zero in the case of the model with only one conductor coil if the coil enters the gap between the poles.

Direct-current machines are therefore designed today with a large number of coils and a correspondingly large number of commutator segments.

There are two fundamentally different forms of connection for direct-current machines, exhibiting differing speed characteristics. The two categories are:

I. Shunt-wound machine
II. Series-wound machine

There is also the compound-wound machine, which is a combination of the two.



a) Separate excitation b) Shunt excitation

Fig. 7: Shunt-wound machine

In a shunt-wound machine, the field winding, or excitation winding, is supplied by an external voltage source (Fig. 7a) or the field coil is connected in parallel with the armature winding (Fig. 7b).

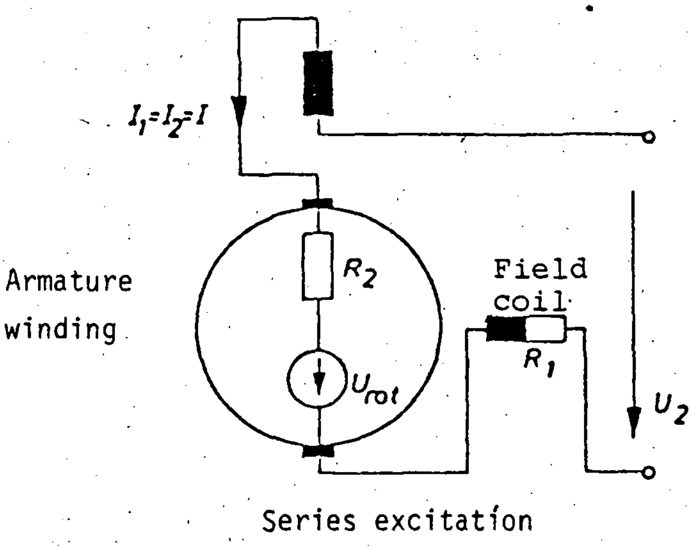


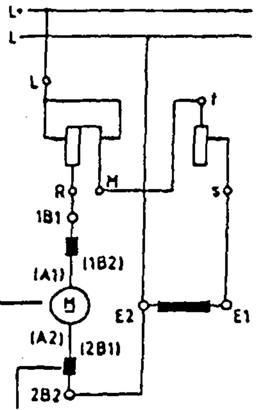
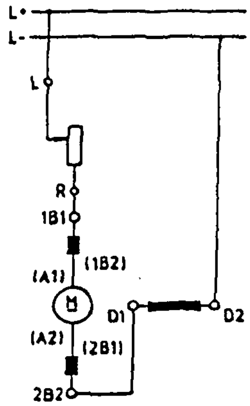
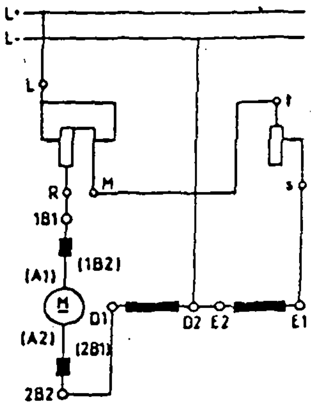
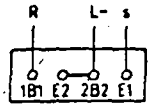
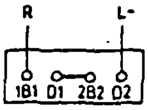
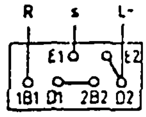
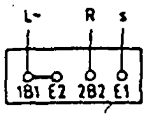
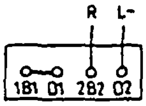
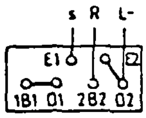
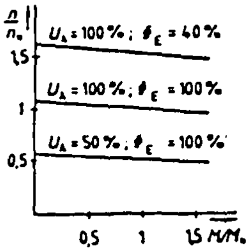
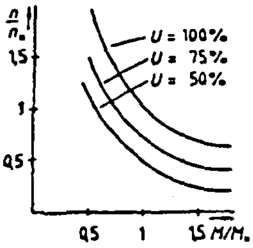
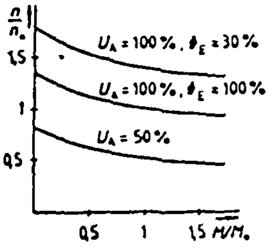
Fig. 8: Series-wound machine

In series-wound machines, the field winding and the armature winding are connected in series so that the same current flows through both. This leads to a speed characteristic totally different from that of the shunt-wound machine.

This can be clearly seen from Table 1:

Table 1: Direct-current motors

Armature winding and field coil
Arrangement on terminal board
Commutating pole or compensating resistor

Direct-current motors			
Motor	Shunt-wound motor	Series-wound motor	Compound-wound motor
Circuit diagram Clockwise rotation			
Connection Clockwise rotation			
Anti-clockwise rotation			
Speed torque characteristics (standardized representation)			
Features	If armature voltage and excitation remain constant, changes in load have little influence on the rotational frequency (speed). By means of field weakening, the rated rotational frequency can be exceeded up to approx. 3:1. With a constant load, it is possible to go below the rated rotational frequency only if the armature voltage is reduced.	The series-wound motor develops a very high breakaway torque. Total removal of the load (no-load operation) can lead to "racing" (destruction). The rotational frequency drops quickly when a load is applied. Increasing of rotational frequency beyond the rated value is effected by means of resistor connected in parallel with the field winding.	The speed-torque characteristic is between that of the shunt-wound motor and that of the series-wound motor. The no-load rotational frequency is limited. The rotational frequency is adjusted as for the shunt-wound motor. For reasons of stability, current must flow through the field windings in the same direction.

Explanation of symbols

L_+, L_- = Outer conductors (external connection)
R, L, M = Connections at starting resistor
s, t = Connections at shunt resistor
E_1 - E_2 = Shunt field winding
B_1 - B_2 = Commutating-pole winding
A_1 - A_2 = Armature winding
D_1 - D_2 = Series winding
n = Rate speed
n_s = Synchron. speed
M = Torque
M_N = Rated torque
U_A = Starting voltage
Φ_E = Field excitation
U = Outer conductor voltage

Fig. 9 shows the detailed construction of a direct-current machine:

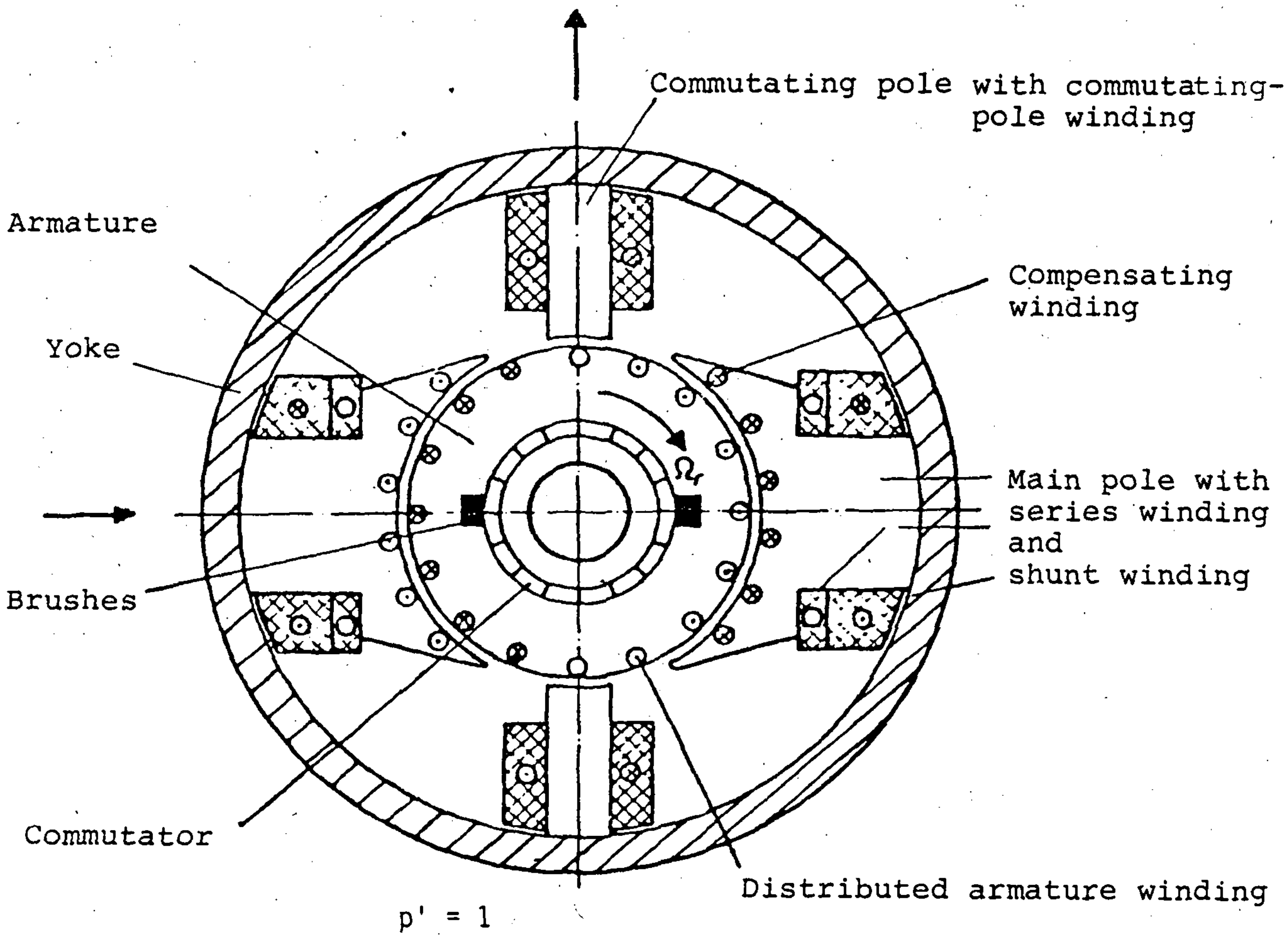


Fig. 9: Basic structure of a direct-current

The commutating-field winding and the compensating winding are electrical measures which aim to facilitate commutation and avoid sparking at the commutator as a result of high induced voltages. Both windings are connected in series with the armature winding, which means that the armature current flows through them. They generally have only a few turns.

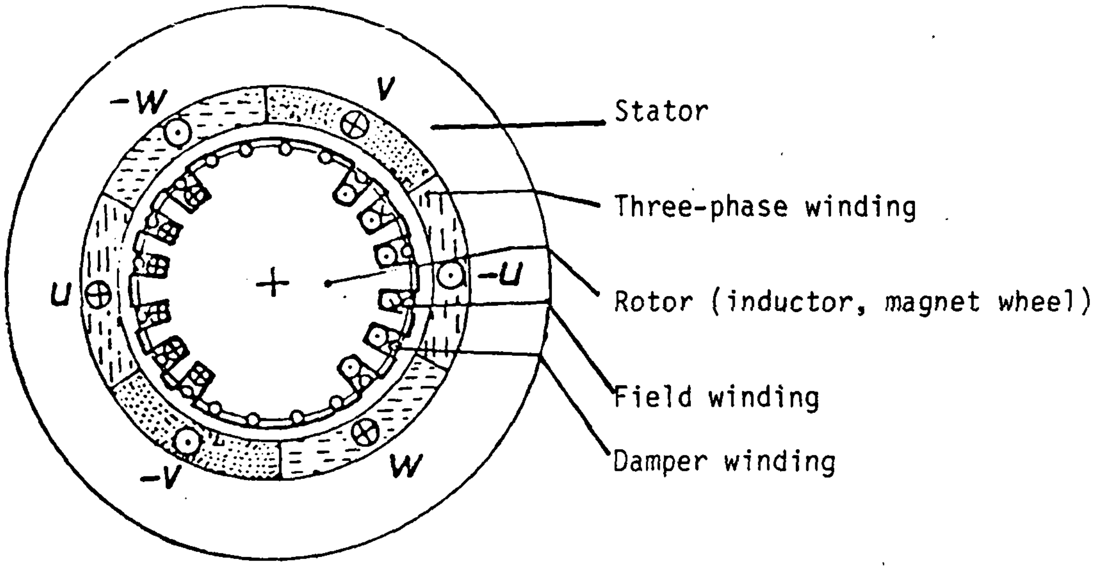
Two factors restrict the use of direct-current machines. Firstly, a direct-current supply is seldom available. Secondly, the construction costs for direct-current machines are almost three to four times as high as those for comparable asynchronous machines. The direct-current motor does have an advantage over the asynchronous motor, however, in that its rotational speed can be altered over a wide range using fairly simple means. Direct-current motors are frequently used today in conjunction with modern semiconductor rectifiers (thyristors) wherever exact speed stability is required.

Direct-current motors are also still used today in many power stations as emergency drives, with lead storage batteries serving as the voltage source.

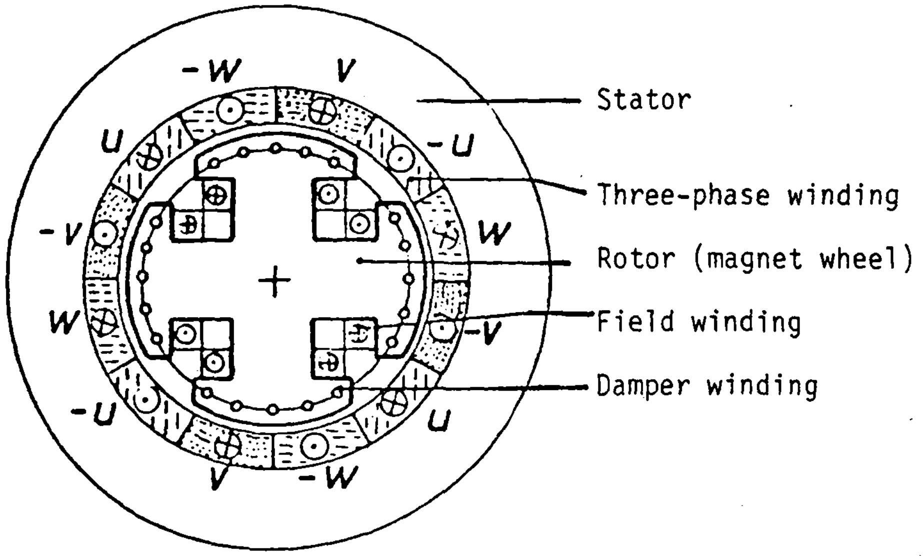
2. The synchronous machine

The synchronous machine, as a three-phase generator with unit ratings up to values in excess of 1 gigawatt, is the most important electromechanical energy converter. As a motor, it is used both in cases where a high drive power is required and in special constructions - e.g. for clocks - in applications where a few watts or less are necessary. Synchronous machines are also used as phase modifiers for pure reactive-power generation.

Fig. 10 shows a synchronous machine, again in simplified form:



a) Smooth core machine (p' = 1, i.e. with one pair of poles)



b) Salient-pole machine (p' = 2, i.e. 2 pairs of poles)

Fig. 10: Structure of a synchronous machine

In the stator slots is the stator winding as seen in Fig. 4. This winding is divided up into three parts - u, v, w - and the beginning and end of each of these individual windings are brought out onto a terminal board.

In terms of rotors, a distinction is made between a smooth core rotor (Fig. 10a) and a salient-pole rotor (Fig. 10 b).

On the rotor the field winding is either accommodated in slots, as is the case in the smooth core rotor, or takes the form of a compact coil body, as is found in the salient-pole rotor.

The ends are brought out to two slip rings, against which carbon brushes slip and via which the rotor current flows. A direct current flows through the field winding; a magnetic field which is constant in relation to the rotor thus builds up around the rotor. If the rotor is now turned, these magnetic lines of force cut the copper conductors in the stator. The north pole, a "neutral zone", the south pole and another "neutral zone" now move in succession past the three windings u, v and w; the sequence then starts again with the north pole. The movement or alteration of a magnetic field at right angles to a conductor of course induces a voltage which, if the circuit is closed, drives a current through the conductors. This is also what happens in synchronous machines. The voltage in the individual windings first rises (as the north pole passes), falls again, becomes zero (neutral zone), rises once again with reversed polarity (south pole) and then falls to zero again (neutral zone).

In this way, three alternating voltages L1, L2 and L3 are generated, and together form the three-phase system. As a result of the circular movement of the rotor field, each voltage is sinusoidal and shifted in time with respect to the other voltages in accordance with the offset arrangement of the windings in the stator; or, in other words, there is a phase shift of 120°. With the two-pole arrangement, the frequency of the voltages corresponds to the rotational frequency of the rotor.

If the rotor is designed with two north poles and two south poles, i.e. with p' = 2 pairs of poles, and if the windings in the stator are likewise doubled (Fig. 10b), the rotor needs to make only one quarter of a revolution for a pole to pass once in full over the three winding phases and thus generate the same voltage as is produced by one half revolution of a machine with one pair of poles. In other words, the higher the number of pairs of poles p', the lower the rotational speed of the machine at a previously determined system frequency.

Speed $n = \frac{f \cdot 60}{p'} \frac{\text{revs.}}{\text{min.}}$ f = System frequency (often 50 Hz or 60 Hz)

Smooth core rotors are generally used for speeds of 3000 rpm (p' = 1) and 1500 rpm (p' = 2). Such machines are used primarily in thermal power stations and for coupling to gas turbines.

For speeds of 1000 rpm (p' = 3) and below (low-speed machines), salient-pole rotors are used, since the diameter (space required for the windings) also increases as the number of pairs of poles becomes greater and less sheet iron is needed for such rotors. There are also a number of mechanical and design-related reasons.

If a three-phase system - L1, L2 and L3 - generated in this way is connected to a three-phase stator winding with the same structure, alternating magnetic fields are built up in succession around the three windings; by way of superposition, they combine to form a rotating magnetic field. If the magnetic lines of force could be made visible, it would be possible to see the circular movement of the individual poles along the periphery.

If a rotor with magnetic fields having the same number of pairs of poles as is the case for the stator (derived from a permanent magnet or an electromagnet) is installed in the stator, nothing will happen to start with. The rotating field is too fast (at f = 50 Hz or 60 Hz) to pull the rotor with it. The rotor must first be brought to a rotational speed almost as high as that of the rotating field - in other words, it must be started - so that the rotating field then pulls the rotor with it. The rotor then rotates synchronously with the rotating field at a speed of $n = \frac{f \cdot 60}{p'}$.

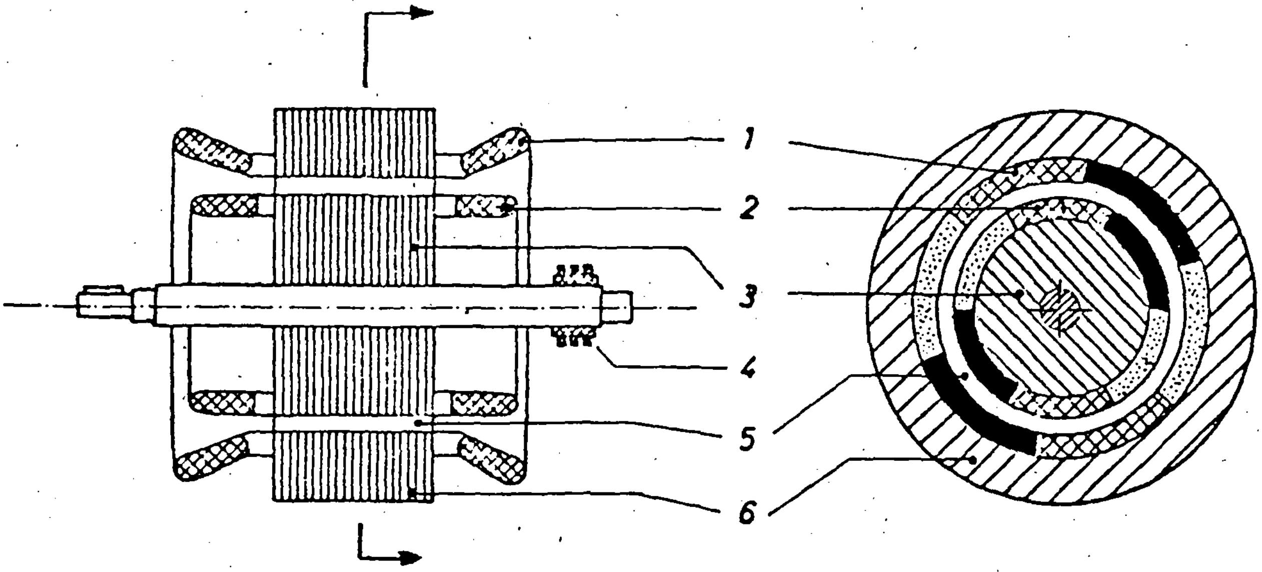
There are also design measures which can be applied in order to bring a synchronous motor up to synchronous speed without the use of an additional machine. This is done by means of a so-called damper cage which can be used to effect asynchronous run-up almost as far as the synchronous speed. The rotor then pulls into step of its own accord.
During starting, the mode of operation of the damper cage

corresponds to that of the squirrel-cage rotor of an asynchronous machine (see Section 3). It is additionally required to have a damping effect on the rotor in the event of load fluctuations such that the rotor will fall "out of step" and the motor will stop if the load becomes too great.

3. The asynchronous machine

The asynchronous or induction motor is probably the most commonly used type. Thanks to its simple and robust design, it represents the ideal drive motor wherever on the one hand no continual speed variation over a large speed range is required and where on the other hand small, load-dependent speed fluctuations can be tolerated. It can be used, for example, in fans, pumps, mills, machine tools (stamping presses, lathes etc.) and many other applications.

Fig. 11 shows the basic design of an asynchronous machine:



1: Three-phase stator winding U, V, W
2: Three-phase (slip-ring) rotor winding u, v, w
3. Laminated rotor core
4. Slip rings
5. Air gap between stator and rotor
6. Laminated stator core

Fig. 11: Basic structure of an asynchronous machine

The design of the stator corresponds to that in the synchronous machine. In accordance with the desired rotational speed the $n = \frac{f \times 60}{p'} \cdot \frac{\text{rev.}}{\text{min}}$ three-phase windings with the corresponding number of pairs of poles p' are accommodated in the slots of the laminated stator core (see also Fig. 4). Upon connection to a three-phase system, this causes the generation of a rotating field with rotional speed n (see also Section 2).

The asynchronous machine differs from the synchronous machine in that it has a differently designed rotor. A distinction is made between two types:

3.1 - the squirrel-cage rotor or short-circuited rotor
3.2 - the slip-ring rotor

3.1 The squirrel-cage rotor

a) Design

Asynchronous motors with squirrel-cage rotor are used for small to medium power outputs. The rotor consists of a laminated rotor core pressed onto a shaft. The recessed longitudinal slots of the rotor contain copper or aluminium conductor bars, which are connected in parallel (short-circuited) by being welded or brazed together with so-called short-circuiting rings, made of the same material, at both ends; this can be seen in Fig. 12a.

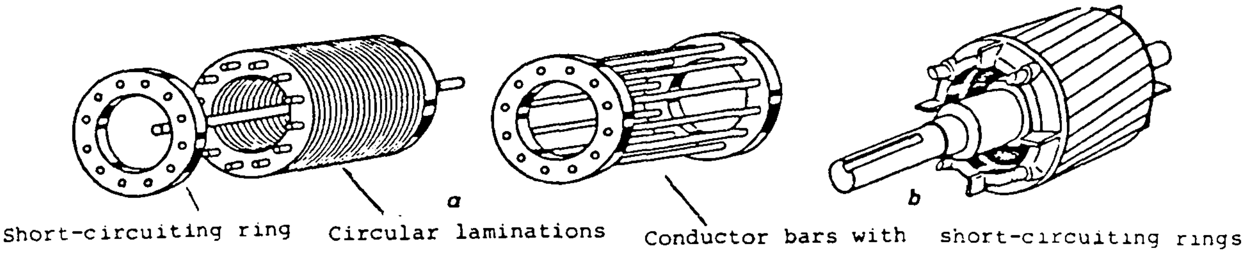


Fig. 12: Design of the squirrel-cage rotor

In smaller motors the conductor bars and the short-circuiting rings are directly cast or die-cast into the already laminated rotor.

In order to reduce vibratory forces and noise generation, the slots are at an angle to the shaft (Fig. 12b).

In order to improve starting performance (see Section 3.1b - Mode of operation), there are numerous special designs with a wide variety of names, e.g. current-displacement rotor, current-limiting rotor squirrel-cage rotor, deep-bar cage rotor, double squirrel-cage rotor etc.

In the double squirrel-cage rotor two squirrel-cage windings are contained in the rotor (see Fig. 13g).

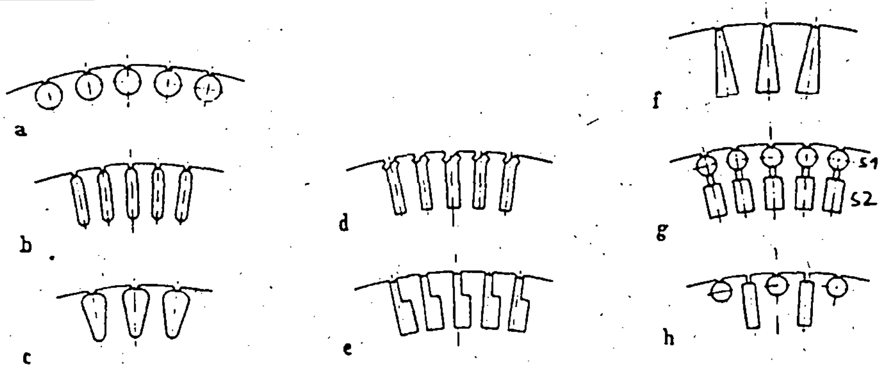


Fig. 13: Various slot and bar types for squirrel-cage rotors:

a) Round bar for cast and soldered windings made of copper or aluminium
b) Deep bar (multi-slot rotor) made of copper or aluminium, cast or soldered
c) Cast winding made of aluminium
d) Pressed deep bars made of copper
e) L-bar made of copper
f) Key bar made of copper or bronze
g) Starting winding made of bronze, power winding made of copper
h) Double squirrel-cage rotor with tangentially offset windings

The outer cage consists of thin bars (S 1) made of material having a high ohmic resistance. By way of contrast, the second cage, which is located further into the laminated rotor core, has bars (S 2) with a larger cross-section, made of a material with a low ohmic resistance.

In asynchronous motors with deep-bar rotor, the effect achieved during starting is similar to that obtained with a double squirrel-cage rotor, albeit not so marked.

b) Mode of operation

The operating principle of an asynchronous motor is based on the fact that not only the rotating field in the stator, but also the necessary magnetic field of the rotor, is generated by the current flowing in the stator windings. No excitation source of current is required. At the moment of switch-on - as has already been repeatedly described - a rotating magnetic field is built up in the stator; the lines of force of this field cut the initially stationary conductors of the rotor. As a result, voltages are induced in these conductors and, as a result of the short-circuit connections, these voltages cause high currents to flow through the conductors. These currents for their part then form magnetic fields which are superposed on one another.

The magnetic fields built up in this way in the stator and rotor are now superposed on one another such that a force is in turn exerted on the rotor, causing it to rotate and initially accelerating it.

As the rotor speed increases, the speed of the rotating field relative to the conductor bars is reduced. The speed at which the lines of force of the rotating field cut the conductor bars therefore also decreases. This means that the induced voltage in the rotor cage is likewise reduced.

If the rotor were now to turn at exactly the same speed as the rotating field, i.e. if it were to run synchronously, the rotating field would be stationary in relation to the rotor - a voltage would no longer be induced in the rotor. The rotor current and thus the rotor field would become zero and a force would no longer be acting on the rotor. If the rotor then reduces its speed, the rotating field starts to move again relative to the rotor and voltages are once again induced in the rotor. In other words, the rotor speed must always be slightly lower than the speed of the rotating field so that the motor can deliver power and a torque. The rotor turns asynchronously with respect to the rotating field of the stator.

The difference between the rotor speed and the speed of the rotating field is known as "slip". In normal motors, the slip is around 3 - 5 %. Thus, if a motor is of the four-pole type, for example, the synchronous speed would be 1500 revolutions per minute.

In the case of the asynchronous motor, however, the slip, amounting to around 4 %, must be subtracted; the speed is thus only around 96 % of 1500 = 1440 rpm. The "rated speed" of an asynchronous motor is therefore always lower than the synchronous speed of the rotating field by an amount corresponding to the slip.

Starting characteristics of squirrel-cage motors:

As starting behaviour represents a major problem with this type of motor, this topic will now be discussed in somewhat more detail.

At the moment of switch-on, an asynchronous motor behaves in the same way as a transformer, the secondary winding of which (corresponding to the stationary rotor) is short-circuited. The frequency of the voltage and of the current in the rotor is, at the moment of starting, the same as that for the stator. The product of the inductance and the frequency of the rotor yields at this moment a high inductive reactance, which is far greater than the ohmic resistance of the conductor bars. The magnitude of the rotor current is therefore limited almost exclusively by this inductive reactance.

The result is at the moment of starting, the rotor current lags behind the rotor voltage by almost 90°. The absorbed active power, and thus also the torque delivered, however, is very small despite the high stator current, since according to the laws of the transformer, the high rotor current is accompanied by a correspondingly high stator current with the same phase shift with respect to the stator voltage; this means that cos is almost zero.

As the rotor speed increases, the voltage and frequency in the rotor winding - as already described previously - become lower. The inductive reactance thus also decreases. The phase shift between current and voltage becomes smaller and the efficiency cos increases.

The potential torque which can be delivered thus also increases until it reaches a maximum - the so-called breakdown torque - and then decreases again, as the rotor is approaching the synchronous speed.

This speed-torque characteristic is illustrated for various rotor types in Fig. 14.

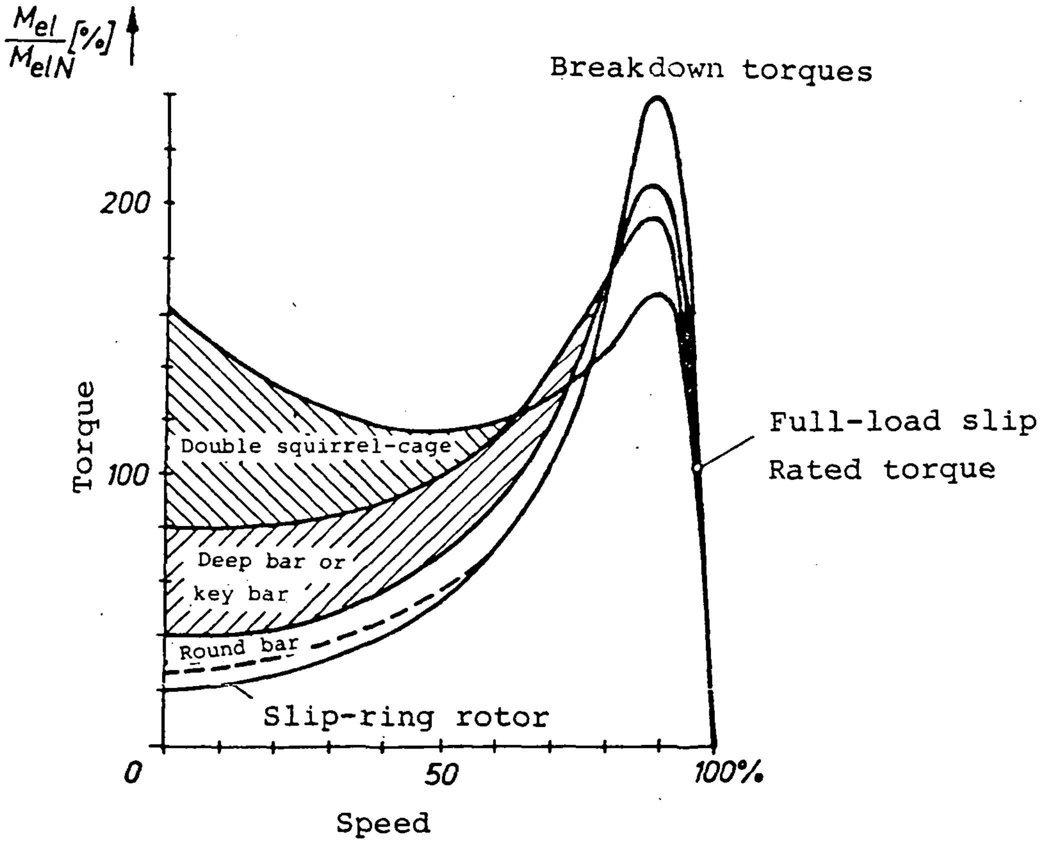


Fig. 14: Speed-torque characteristics of various rotor types

On the basis of the starting characteristics described above, it would be more desirable to have a smaller starting current and a greater breakaway torque. The special rotors described in Section 3.1a were developed for this purpose. It is not sufficient to reduce the starting current by simply increasing the rotor's ohmic resistance. This would mean that efficiency at the rated operating point (operating point with optimum utilization of the machine) would deteriorate and that the slip would increase, i. e. the speed would drop sharply under load. These disadvantages can be avoided if the rotor is designed such that it has a high resistance only during starting and this resistance is no longer effective during operation at the rated operating point. A special rotor must consequently fulfil the following requirements:

1.) For the moment of starting, it must have a squirrel-cage winding with ohmic resistance which is as high as possible and a low inductive reactance value, so that the starting current is small and the breakaway torque (as a result of a small phase shift) is as high as possible.

2.) For operating conditions, it must have a squirrel-cage winding with a low ohmic resistance. The inductance can be greater, since the frequency of the rotor current is low when the motor is running.

This problem has been solved by means of various rotor slot shapes or through the installation of several cages in the rotor, as described in Section 3.1a.

Mode of operation of special rotors with double cage (Fig. 13g):

Upon starting, high-frequency currents, as already described, flow through the cage bars, as the rotor is still stationary. The smaller cage with the bars S 2 has a far higher inductive reactance upon starting than the larger cage with the bars S 1, because it is embedded more deeply in the iron core. The rotor currents will use the bars S 1, which have a high ohmic resistance, primarily during starting. When the rotor speed increases, the rotor bars are cut less often by the lines of force of the rotating field, i.e. the frequency of the rotor current decreases and at the same time the inductive reactance of the inner cage thus becomes smaller. As a result of the larger conductor cross-section and the highly conductive material, the inner cage has a very low ohmic resistance. During operation around the rated operating point, therefore, the currents will for the most part use the bars of the inner cage.

An effect similar to that achieved with the double squirrel-cage rotor is possible in the case of the asynchronous motor with deep-bar cage rotor. During starting, the conductor layers deeper inside the iron core are surrounded by a greater number of lines of force than those located further towards the outside. They thus have a greater inductive reactance. The current is, so to speak, forced upwards and towards the outside. During operation the current will then use the entire conductor cross-section, as the inductive reactance becomes smaller as the rotor speed increases on account of the decreasing frequency of the rotor current.

Fig. 15 shows a complete asynchronous motor with squirrel-cage rotor:

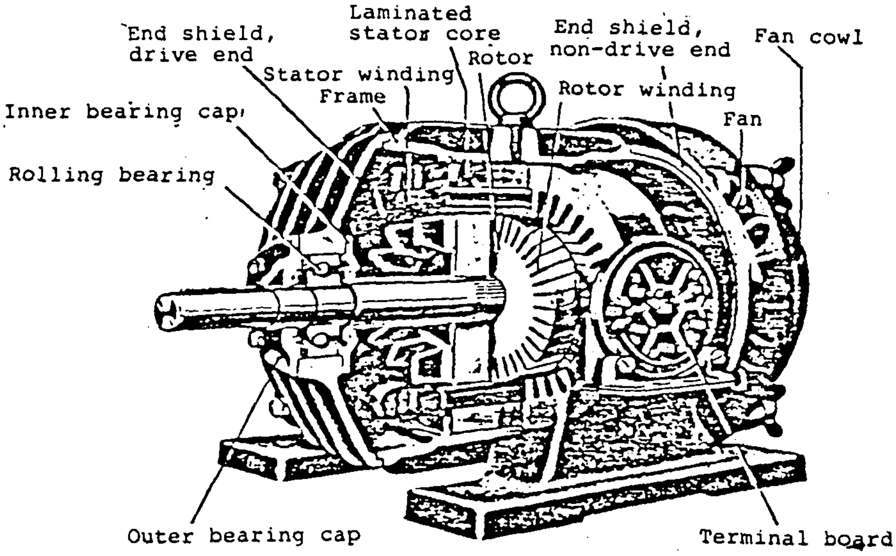


Fig. 15: Asynchronous motor with squirrel-cage rotor

3.2 The slip-ring rotor

In order to permit external intervention or control during starting, as well as to allow limited speed control, use is made of the asynchronous motor with slip-ring rotor. This type of motor operates in the same way as an asynchronous motor with squirrel-cage rotor.

Fig. 16 shows the complete structure of an asynchronous motor with slip-ring rotor.

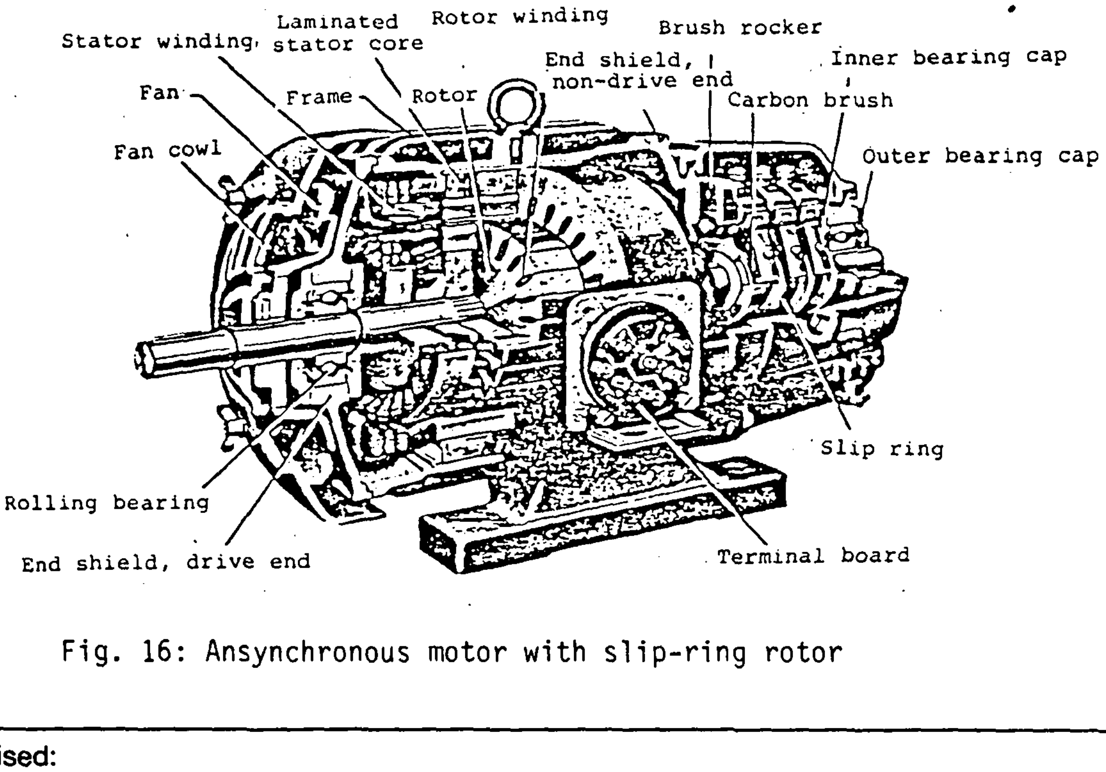


Fig. 16: Ansynchronous motor with slip-ring rotor

a) Design:

There is no difference between the stator of the asynchronous motor with slip-ring rotor and that of a motor with squirrel-cage rotor.

Instead of bars, the rotor slots contain coils made of copper wire. Depending on the size of the motor, the rotor will have a two-phase or three-phase winding. In the case of the three-phase winding (Fig. 17a), one end of each winding is connected to one ends of each of the other two (star point). The other three end are each brought out to a slip ring located on the shaft; each of these rings is insulated with respect to the other two. The windings are thus connected to a starting resistor via carbon brushes. This resistor consists of a three-part variable ohmic resistance connected in series with the three phases of the rotor winding. During operation at the rated operating point, the resistor, and thus also the rotor winding, is short-circuited.

b) Mode of operation:

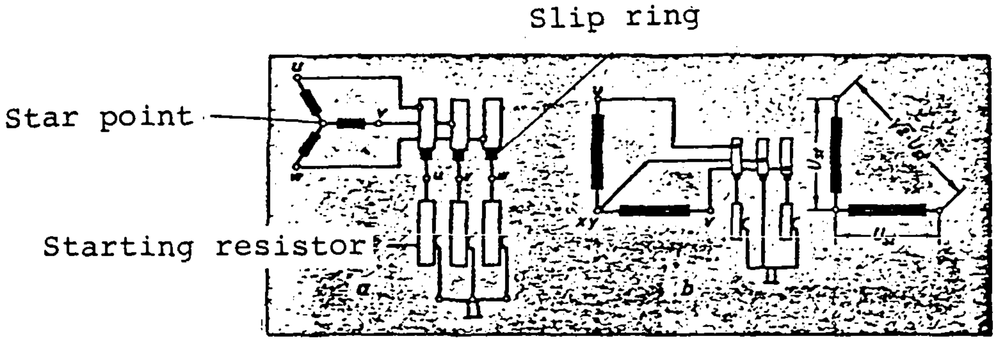
The principle of the variable resistance in the rotor circuit is the same as in the case of the various forms of special squirrel-cage rotor. The difference is that the rotor resistance can be specifically altered at any moment during operation and thus the motor current specifically influenced from outside by appropriately trained personnel.

Speed control is thus also possible, but can take place only under load. The starting resistor, which can be adjusted in steps, is then designed for continuous loading.

If, during operation, the rotor resistance is increased by switching in the starting resistor, the rotor current initially decreases, while the rotor voltage remains constant. As a result, the possible torque which the machine can deliver becomes smaller and the rotor is braked by the load. This braking process continues until the rotor voltage, which is now rising on account of the increased cutting speed of the lines of force of the rotating field, is high enough to drive a rotor current equivalent to the load torque through the winding once again, so that motor torque and load torque are once again in equilibrium - at a speed which is now somewhat lower.

Load fluctuations, however, also give rise to considerable speed fluctuations. The machine becomes "compliant". This method of speed regulation is therefore not used very often.

Further disadvantages of the slip-ring rotor are the greater manufacturing complexity, combined with higher manufacturing costs, and the greater maintenance outlay required (slip rings, brushes).



a) Three-phase
b) Two-phase

Fig. 17: Connections for slip-ring rotor windings

Pole-changing asynchronous motors:

Another way of altering the speed of an asynchronous motor is to change the number of stator poles.

This can be done on the one hand within a simple winding; in this case it is possible only to halve or double the number of poles and thus to halve or double the synchronous speed of the rotating field, e.g. 1500/750 rpm or 1000/500 rpm etc.

Alternatively, two windings isolated from each other can be fitted in the stator slots. Two arbitrary speeds - albeit determined by the winding - are then possible. This form of speed alteration is always effected in step changes.

Asynchronous motors with slip-ring rotor are extremely versatile. They are used wherever
- only small starting currents are permissible,
- machines must be driven under full load and thus require high breakaway tooques,
- machines with large rotating masses have to be started and

- the starting energy in the rotor to be converted into heat is for the most part to be shifted to the starting resistors located outside the motor.

3.3 Asynchronous motor connections

In the cas of the stator, both ends of each phase winding are always brought out onto a terminal board. In the case of the slip-ring rotor, the star point is permanently wired up from the outset and only one end of each phase winding is brought out onto the terminal board as shown in Fig. 18:

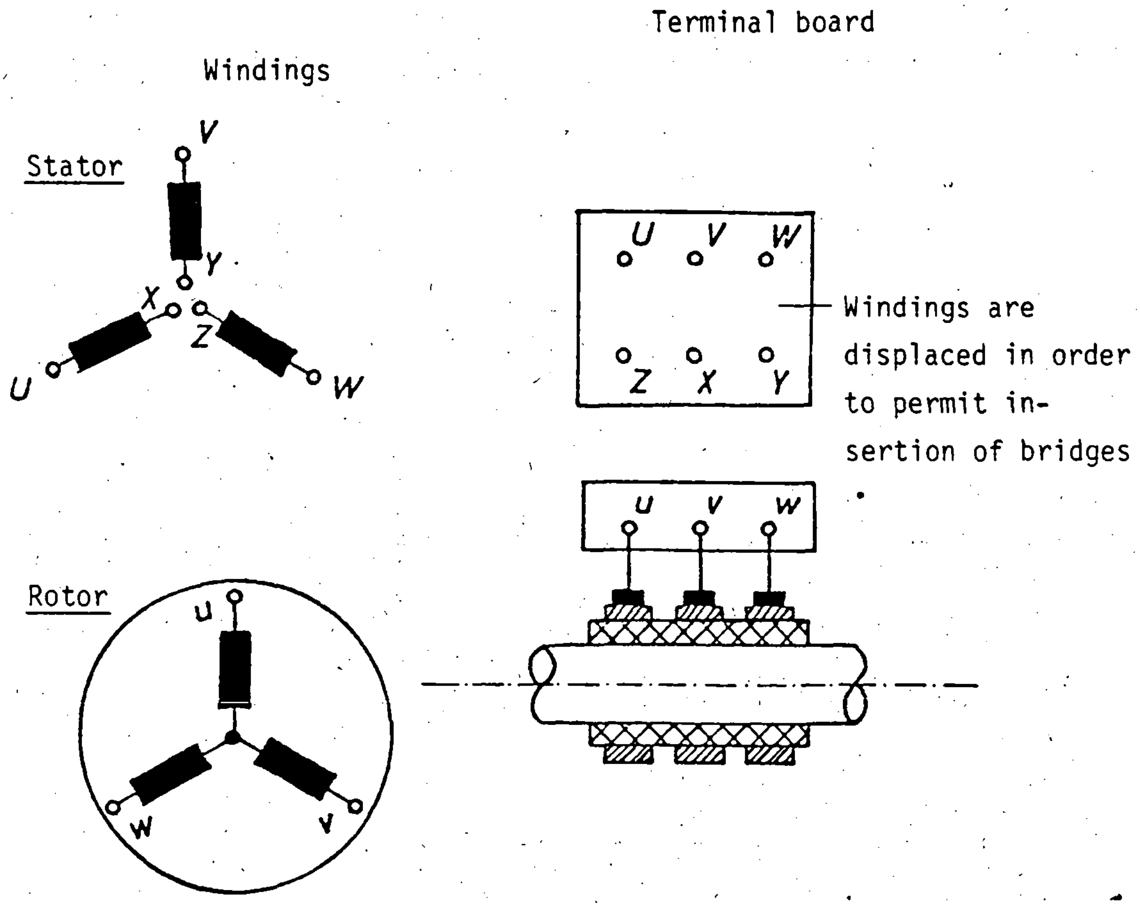


Fig. 18: Schematic representation of windings and terminals

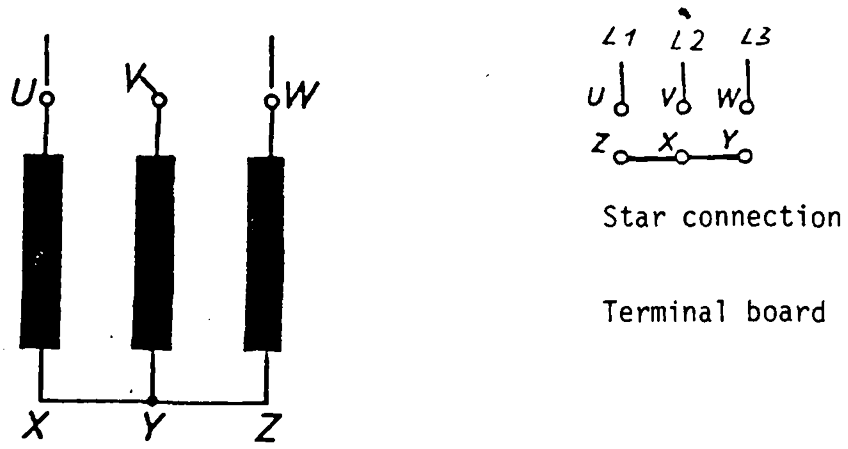


Fig. 19: Star connection of stator winding

In the star connection the voltage load of the individual windings is not as high as in the delta connection. Only the phase voltage is applied to the windings. However, for the same power output, a higher current is required than in the case of delta connection. Fig. 19 shows the way in which the individual phase windings are wired with one another and on the terminal board in the case of star connection.

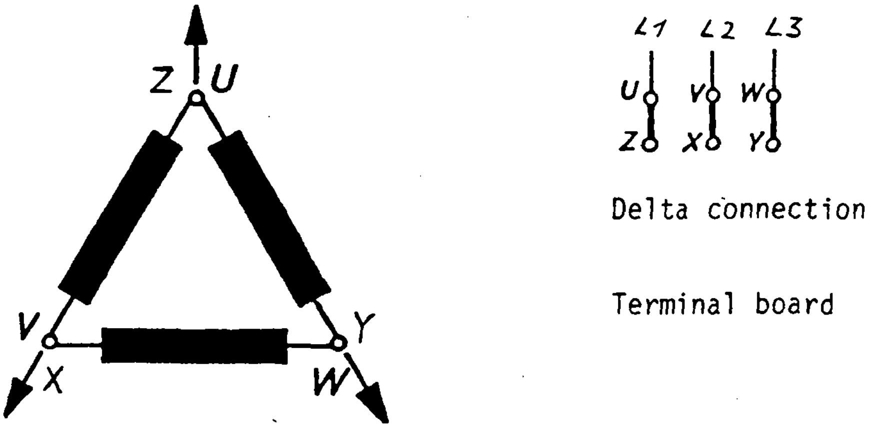


Fig. 20: Delta connection of stator winding.

In the delta connection, the voltage load of the individual windings is greater by a factor of 3 than in the case of star connection. The windings have more turns. However, by comparison with star connection, a correspondingly smaller current is required for the same power output. Fig. 20 shows the way in which the individual phase windings are wired with one another and on the terminal board in the case of delta connection.

3.4 Starting circuits and contactor circuits for asynchronous motors

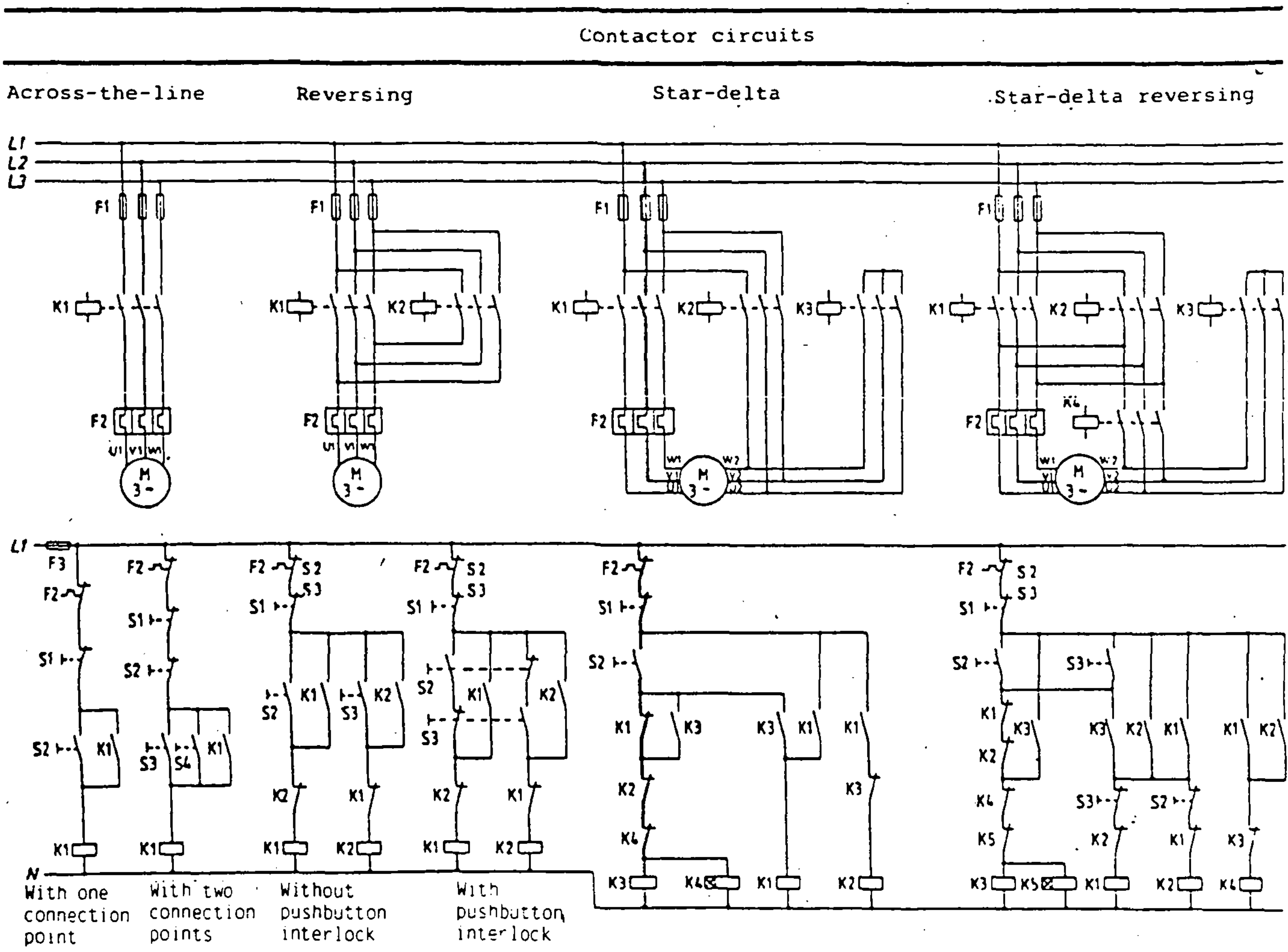
In addition to across-the-line starting, probably the most common starting method is

star-delta starting.

The motor is switched on with the windings star-connected. They are, however, designed for delta connection and thus for phase-to-phase voltage (= phase voltage x 3). As a result of the star connection, a reduced voltage (phase voltage) is initially applied to them. The starting current is also correspondingly smaller. Once the motor has almost reached the final speed possible in this form of connection, the windings are switched to delta connection and the motor can then deliver its full output.

Further starting circuits are shown in Figs. 21 and 22. The term "reversing circuit" means that the motor reverses its direction of rotation; this is done by interchanging two phases, i.e. two supply voltages of the three-phase system, at the motor connection.

This simply changes the order in which the individual alternating magnetic fields are built up, causing the resulting rotating field to rotate in the opposite direction.



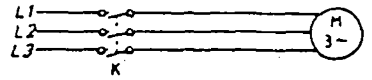
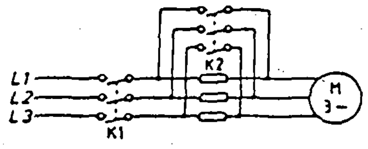
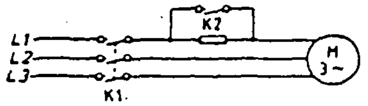
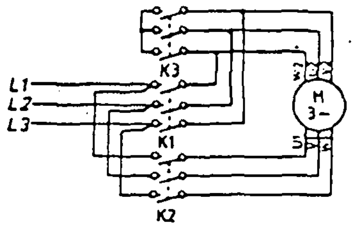
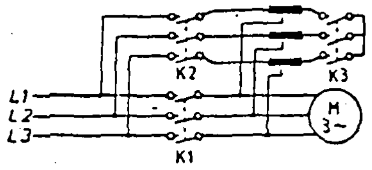
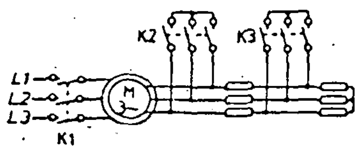
Explanation of symbols

L1...L3 = Outer conductors (external cable connection)   F1... = Fuses (protection)   K1 ... = Contactors   S1 = Switches

M = Motor   N = Neutral conductor U_1, V_1, W_1 = Start of winding U_2, V_2, W_2 = End of winding

S2 = Clockwise rotation   S3 = Anticlockwise rotation

Fig. 21: Various contactor circuits

Three-phase self-starters	
	Across-the-line starting This method is always chosen if the mains conditions and the driven machine so permit. In accordance with VDEW regulations (Association of German Electricity Generating Stations), across-the-line starting on 380 V is limited to 2.2 kW for single squirrel-cage motors and to 4 kW for current-displacement motors.
	Three-phase stator resistance starter The voltage at the motor can be reduced as required. The starting current drops in proportion to the voltage, whereas the starting (breakaway) torque is reduced as the square of this voltage. A relatively small drop in current contrasts with a disproportionately large reduction in starting torque. Systems of this type are therefore not widespread and are used only if the starting torque is to be substantially reduced.
	Single-phase stator starter If a reduction in the starting current is not required and only smooth starting is desired, the stator-resistance starting circuit is chosen. The starting current is reduced only in the winding phase with series resistor.
	Star-delta starter This is the most widespread method used for reducing the starting current of three-phase squirrel-cage motors. The motor winding is designed for the operating voltage in the delta connection and is star-connected upon starting. This causes the voltage per winding phase to fall to 1/ 3 of the rated voltage, the starting torque and starting current are reduced to one third of the values for across-the-line starting. In accordance with VDEW regulations, star-delta starting on 380 V is limited to 4 kW for single squirrel-cage motors and to 7.5 kW for current-displacement motors.
	Autotransformer starter The current drawn from the mains and the starting torque decrease in proportion to the square of the motor voltage; given the same decrease in the starting torque, the starting current drops to a considerably greater extent than with stator resistance starters. Autotransformers are frequently used for starting high-voltage motors. As the starter requires only three lines to the motor, submersible pumps in narrow bores are often also started by means of autotransformer starters.
	Three-phase rotor starter Three-phase rotor starters serve to reduce the starting current of motors with slip-ring rotor, with the starting torque being increased simultaneously. Given appropriate resistance values, the starting torque can be chosen such that it is equal to the breakdown torque. If the resistors are designed for continuous duty, speed control by means of changing of the slip is thus also possible.

Explanation of symbols

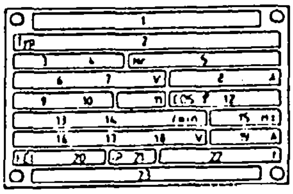
L 1...L3 = Outer conductors (extern.cable connect.)
K 1 = Contactors
M = Motor
U_1, V_1, W_1 = Start of winding
U_2, V_2, W_2 = End of winding

Fig. 22: Starting circuits

3.5 Rating plate

The most important operating data of a machine are given on the rating plate or nameplate, which must be attached to the machine. Table 2 explains the basic structure of a rating plate in accordance with DIN 42961:

Table 2 : General structure of a rating plate



Explanation of individual items

1 Manufacturer

2 Type, also frame size for standard motors

3 Type of current - Graphical symbol as per DIN 40 700 Part 4 (see p. 5-1)

4 Type of machine
e.g. Generator Gen.
Motor Mot.
Phase converter P.c.
Transformer Tr.

5 Serial number (or type identifier) and year of manufacture

6 Type of connection of the winding of AC machines, graphical symbol as per DIN 40 710

7 Rated voltages

8 Rated current

9 Rated power output

10 Unit and rating

11 Duty-type rating - Abbreviation and conditions as per VDE 0530

12 Power factor
In the case of reactive-power absorbing synchronous machines and phase converters, the letter "u" (underexcited) is added.

13 Direction of rotation as per DIN 42 401

14 Rated speed and, if necessary, permissible overspeed and maximum permissible top speed during operation

15 Rated frequency for AC machines

16 Excitation
for DC machines, synchronous machines or rotary converters

17 Type of connection (graphical symbol) of rotor winding if there is not three-phase winding

18 *Rated excitation voltage*
for DC and synchronous machines

19 Excitation current for operation under rated conditions for DC and synchronous machines

20 *Insulation class*
Code letters as per VDE 0530 and 0532 or temperature rise limit. If they are different, the insulation class of the stator winding is to be given first and then - separated by an oblique stroke - that of *the rotor winding*

21 Degree of protection
Code letters for protection against accidental contact, ingress of foreign bodies and water as per DIN 40 050

22 Weight (approximate) in tons for machines with a gross weight exceeding 1 ton

23 Additional information
e.g. amount of coolant in the case of separate cooling, moment of inertia or inertia constant, year of repair etc.

Fig. 23 shows an example of a rating plate:

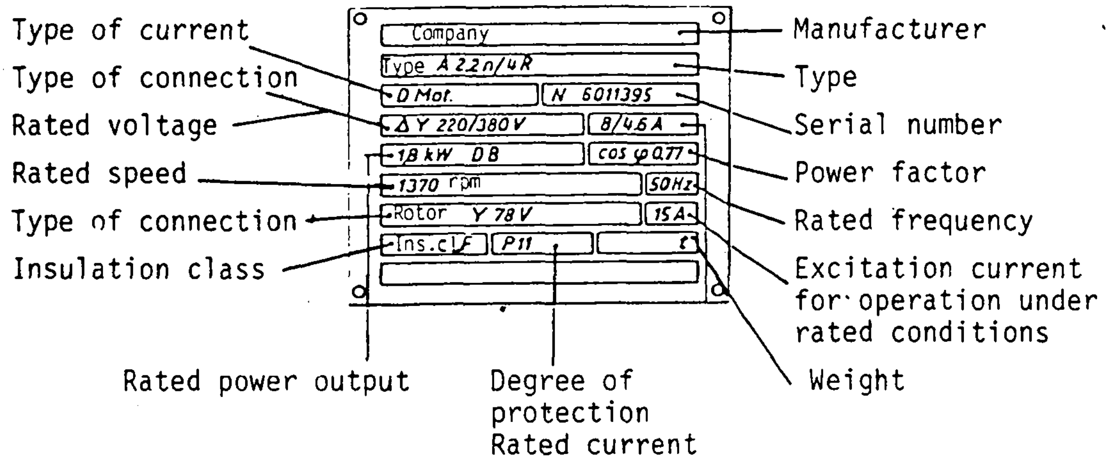


Fig. 23: Rating plate

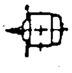
3.6 Table showing types of construction

Table 3 contains a list of the types of construction and mounting of electric machines and can be consulted when ordering new motors.

Table 3: Types of construction and mounting arrangements of rotating electrical machinery as per DIN 42 950

Types of construction and mounting arrangements of rotating electrical machinery
DIN 42 950 (draft 8.77)

This standard relates only to rotating electric machines with end shield bearing and one shaft end. The designation consists of the letters IM (International Mounting), followed by another letter and a number. Letter B: horizontal mounting; letter V: vertical mounting

Symbol	Diagram	Explanation	Symbol	Diagram	Explanation
B3		Installation on substructure	V3		Mounting flange at drive end. Access from the rear
B35		Installation on substructure with additional flange. Access from the rear	V36		Mounting on wall or on substructure with additional flange at top on drive end
B34		Installation on substructure with additional flange. No access from the rear	V4		Flange mounting at top at non-drive end. Access from the rear
B5		Flange mounting Access from the rear	V5		Mounting on wall or on substructure. Construction as for B3
B6		Wall mounting; feet on left as seen from drive end. Type B3; end shields rotated 90° if necessary	V6		Mounting on wall or on substructure
B7		Wall mounting; feed on right as seen from drive end. Type B3; end shields rotated 90° if necessary	V8		Attachment at housing end face, drive end, at bottom. Type V1 or V18 without end shield and without rolling bearing at drive end
B8		Ceiling mounting, type B3; end shields rotated 90° if necessary	V9		Attachment at housing end face, drive end, at top. Type V3 or V19 without end shield and without rolling bearing at drive end
B9		Attachment at housing end face, drive end. Type B5 or B14, but without end shield and without rolling bearing at drive end	V10		Mounting flange at drive end. Access from the rear
B10		Mounting flange at drive end. Access from the rear	V14		Mounting flange at drive end. Access from the rear
B14		Mounting flange at drive end. No access from the rear	V16		Mounting flange at drive end. No access from the rear
B15		Mounting on substructure Attachment at housing end face, drive end. Type B3 without end shield at drive end	V18		Mounting flange at drive end. No access from the rear
B20		Let into substructure, feet roughly at shaft height	V19		Mounting flange at drive end. No access from the rear
B30		Installation in duct or pipe. 3 or 4 dogs on one or both end shields or on housing	V21		Mounting flange at drive end. Access from the rear
V1		Flange mounting at bottom on drive end. Access from the rear	V30		Installation in duct or pipe. 3 or 4 dogs on one end shield, both end shields or housing
V15		Wall mounting and additional flange at bottom. Access from the rear	V31		Installation in duct or pipe. 3 or 4 dogs on one end shield, both end shields or housing
V2		Mounting flange at non-drive end. Access from the rear			

4. Bibliography

The literature used in Module 2.3b is listed below. Passages have in some cases been taken word for word from the sources mentioned.

a. AEG-Telefunken	Hilfsbuch der Elektrotechnik 2, 1979
b. Arnold-Steher	Fachkunde für Elektriker, Ernst Klett Verlag
c. Benedikt Gruber	Sieben Formeln genügen, Oldenburg Verlag
d. Friedrich	Tabellenbuch der Elektrotechnik, Dümmlers Verlag, 1982
e. Loher & Söhne	Der neuzeitliche Drehstrommotor
f. Gerthsen, Kneser	Physik-Lehrbuch zum Gebrauch neben Vorlesungen, Springer-Verlag, 11th revised edition
g. Langewellpott-Schwering	Elektrotechnik für Sie, Teil 2 Hueber-Holtzmann Verlag, Munich, 1973
h. Andresen, Becker	Notes to accompany lectures on "Theory of electric machines I", winter semester 1971/72, Technical University of Darmstadt

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TRAINING MODULES FOR WATERWORKS PERSONNEL

List of training modules:

Basic Knowledge

0.1 Basic and applied arithmetic
0.2 Basic concepts of physics
0.3 Basic concepts of water chemistry
0.4 Basic principles of water transport
1.1 The function and technical composition of a watersupply system
1.2 Organisation and administration of waterworks

Special Knowledge

2.1 Engineering, building and auxiliary materials
2.2 Hygienic standards of drinking water
2.3a Maintenance and repair of diesel engines and petrol engines
2.3b Maintenance and repair of electric motors
2.3c Maintenance and repair of simple driven systems
2.3d Design, functioning, operation, maintenance and repair of power transmission mechanisms
2.3e Maintenance and repair of pumps
2.3f Maintenance and repair of blowers and compressors
2.3g Design, functioning, operation, maintenance and repair of pipe fittings
2.3h Design, functioning, operation, maintenance and repair of hoisting gear
2.3i Maintenance and repair of electrical motor controls and protective equipment
2.4 Process control and instrumentation
2.5 Principal components of water-treatment systems (definition and description)
2.6 Pipe laying procedures and testing of water mains
2.7 General operation of water main systems
2.8 Construction of water supply units
2.9 Maintenance of water supply units Principles and general procedures
2.10 Industrial safety and accident prevention
2.11 Simple surveying and technical drawing

Special Skills

3.1 Basic skills in workshop technology
3.2 Performance of simple water analysis
3.3a Design and working principles of diesel engines and petrol engines
3.3b Design and working principles of electric motors
3.3c –
3.3d Design and working principle of power transmission mechanisms
3.3e Installation, operation, maintenance and repair of pumps
3.3f Handling, maintenance and repair of blowers and compressors
3.3g Handling, maintenance and repair of pipe fittings
3.3h Handling, maintenance and repair of hoisting gear
3.3i Servicing and maintaining electrical equipment
3.4 Servicing and maintaining process controls and instrumentation
3.5 Water-treatment systems: construction and operation of principal components: Part I - Part II
3.6 Pipe-laying procedures and testing of water mains
3.7 Inspection, maintenance and repair of water mains
3.8a Construction in concrete and masonry
3.8b Installation of appurtenances
3.9 Maintenance of water supply units Inspection and action guide
3.10 –
3.11 Simple surveying and drawing work

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