20 Motors and Actuators

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Contents

20.1 Energy conversion

Electromagnetic machines convert electrical into mechanical energy in devices with a limited stroke (actuator, brake, relay etc.) or continuous angular rotation (motor), or linear motion (linear motor).

Mechanical energy involves a force f_m acting over a distance x or a torque M_m acting over an angular displacement θ. Electrical energy involves the displacement of a charge q (a current i for a time t) through a potential difference (p.d.) v. The energies W and corresponding powers $P = \mathrm{d}W/\mathrm{d}t$ are

Mechanical:

$$W_m = f_m x \quad P_m = f_m(\mathrm{d}x/\mathrm{d}t) = f_m u \qquad \text{(linear)}$$

$$W_m = M_m\theta\varsigma \quad P_m = M_m(\mathrm{d}\theta/\mathrm{d}t) = M_m\omega_r \qquad \text{(rotary)}$$

Electrical:

$$W_e = vq \qquad P_e = v(\mathrm{d}q/\mathrm{d}t) = vi$$

where $u = \mathrm{d}x/\mathrm{d}t$ is the translational speed and $\omega_r = \mathrm{d}\theta/\mathrm{d}t$ is the rotational speed. In an electromagnetic machine the basic physical conversion mechanism between the two forms of energy is the magnetic field, a characteristic property of electric current. The elements of electromagnetic/mechanical conversion are set out in Sections 2.4.1 to 2.4.3.

20.2 Electromagnetic devices

20.2.1 Electromagnets

Electromagnets for stroke-limited devices (e.g. actuators) are such that estimation of the flux distribution in the air gap (the working region) is difficult. The total magnetomotive force (m.m.f.) produced by a current i in an N-turn coil is $F = Ni$.

20.2.1.1 Coil windings

Most coils for magnetic-circuit excitation are wound by one of the following (usually automated) methods: (1) on a former with end-cheeks; (2) on a bobbin that forms an integral part of the coil and comprises a moulded or fabricated construction of a suitable insultant; or (3) by a winding machine that feeds insulated wire into a self-supporting form, with an epoxy-resin binder.

The coil design is based on the provision of the required m.m.f. for a specified voltage (or current), with an acceptable coil temperature rise on a specified duty cycle.

D.c. excitation For direct current (d.c.), the current i at a coil terminal voltage v is determined by the coil resistance $R = V/i = \rho L_{mt} N/a$, where the N turns have a mean turn length L_{mt} and the conductor, of resistivity, ρ, has a cross-sectional area a. Then

$$a = \rho L_{mt}(Ni)/V = \rho L_{mt} F/V$$

for a total m.m.f. F. The current cannot be determined until the cooling conditions are established. Let the conductor current density be J, so that $i = Ja$; then $N = F/Ja$. The total conducting cross-section of the coil is Na and the gross cross-sectional area of the wound coil is Na/k, where k is the *space factor*.

The power taken by the coil is $P = Vi$, and the consequent temperature rise on continuous operation is $\theta_m = P/cS$. Here c is a cooling coefficient representing the power dissipation per unit of the coil surface area S per degree Celsius rise of surface temperature above ambient. The value of θ_m for continuously rated coils is usually specified. On intermittent or short-time rating the rise is a function of the thermal capacity of the coil.

A.c. excitation For alternating current (a.c.) the current i at voltage V is determined by the coil impedance $Z = R + j\omega L$ at angular frequency ω. An a.c. coil therefore tends to have fewer turns than one for d.c. Further, the coil inductance L varies widely, depending on the saturation of the ferromagnetic parts and in particular on the length of the air gap. A wide gap increases the magnetic reluctance and reduces L, but as the gap length reduces (e.g. by movement of the working parts) the inductance rises. If $\omega L \gg R$, as is usual, the root-mean-square (r.m.s.) value of the m.m.f. approximates to $F = VN/\omega L$ with L estimated for the range of air gap lengths.

In practice, performance is based on data obtained on test. A particular feature is the double-frequency fluctuation of the mechanical force, which produces a characteristic 'chatter' in the closed position of the device; this may have to be mitigated by means of a shading ring.

20.2.1.2 Coil design

Space factor A simple coil wound from a circular-section wire of diameter d, and insulated to a diameter d_i, will pack down in a manner that is affected by the method of winding, one layer partly occupying the troughs in the layer beneath it; the space factor may then approximate to $k = 0.85(d/d_i)^2$. Conductors of small diameter bed less effectively, and the space factor is reduced.

Cooling coefficient A typical value of the cooling coefficient c is 0.075 W/m^2 per °C above ambient. However, cooling conditions vary widely with the efficacy of ventilation.

20.2.1.3 Operating conditions

Whether d.c. or a.c. excited, the current in an operating coil is affected by that movement of the working parts that closes or opens the air gap. Let a quiescent spring-loaded relay (*Figure 20.1*(*a*)) in the open position be connected to a direct source voltage V. The coil current begins to rise exponentially, but the armature does not move until the magnetic force exceeds the spring restraint. Thereafter, the shortening gap increases the coil inductance, setting up a counter electromotive force (e.m.f.) and checking the current rise and the attracting force. Finally, the armature reaches the closed position at the end-stop, dissipating kinetic energy in noise, bounce and mechanical deformation. The sequence of events, in terms of the gap length x, armature speed u, coil current i and time t, is shown in *Figure 20.1*(*b*).

If the coil is energised from an a.c. source there are two further effects: the closing time depends on the instant in the cycle at which the voltage is applied and (more importantly) the operating force fluctuates. Ferromagnetic parts must be laminated to prevent excessive core loss and the counter-effects of eddy currents. Suitable sheet steel for the purpose has a core loss of less than 5 W/kg.

The force fluctuation can be reduced (but not eliminated) by a *shading* ring (*Figure 20.2*) embedded in one of the pole faces flanking the gap. Currents induced in the ring delay part of the pole flux. Thus the combination of shaded and unshaded flux gives a resultant that still fluctuates but does not at any instant fall to zero.

20.2.2 Tractive electromagnets

Two forms of tractive electromagnet are shown in *Figure 20.3*. Type (*a*) usually has cylindrical poles, sometimes with shouldered ends to retain the coils, a rectangular yoke to which the

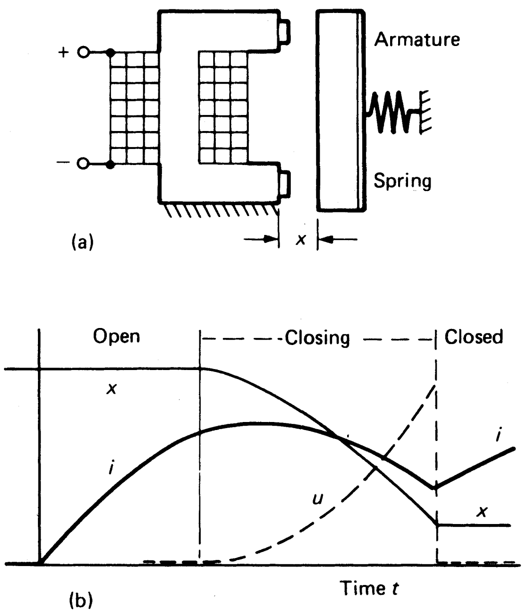


Figure 20.1 Operation of a d.c. relay

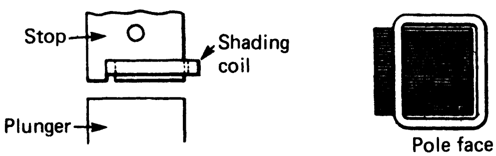


Figure 20.2 Shading coil or ring

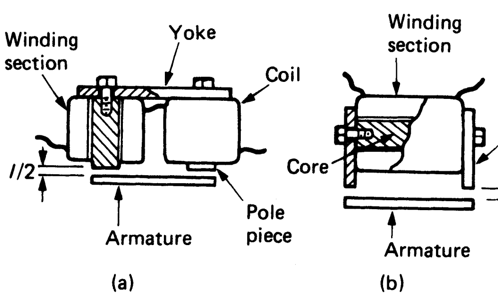


Figure 20.3 Tractive electromagnets

poles are screwed or bolted, and a rectangular armature. Two exciting coils are used; they are connected to give opposite polarities at the respective pole ends. Type (*b*) has a single coil mounted on a cylindrical core to which the rectangular pole-pieces are attached. In both cases the total air gap length is the sum of the gaps at the respective poles; in some designs, however, the armature is hinged to the pole-piece at one end. In this case the free end forms the major gap.

In (*a*) let each polar surface have an area of 250 mm^2 and be required to exert a total force of 1.0 N on the armature when both gaps are 3.0 mm long. Then with *d.c. excitation*, $f = 400\,000 B^2 A$ giving $B = 70$ mT, for which $H = 57\,000$ A-t/m. For a total gap of 6 mm the gap m.m.f. required is 340 A-t. Adding 10% for the iron circuit and 25% for leakage, the total excitation required is about 450 A-t, from which the coil design follows.

With *a.c. excitation* it is necessary to estimate the inductance in the open and closed positions, and to adjust the number of turns for a given operating voltage so that adequate force is available. The change of magnetic flux between the two extreme armature positions is very much less than with d.c. operation, so that for the same (average) force in the open position, that in the closed position is only a little greater.

20.2.3 Actuators

20.2.3.1 D.c. actuators

Three typical arrangements for d.c. actuators are shown in *Figure 20.4*. Form (*a*) is convenient for small devices as the frame can be bent from strip; it is common for overcurrent and undervoltage relays. Form (*b*) may have a cast frame, and provides parallel flux paths through the iron. In (*c*) the cylindrical iron circuit presents a low reluctance, the circuit being completed by a lid attached by studs or screwed into the cylindrical body.

The iron *end-stop* should project well into the coil to improve flux concentration. It may be integral with the frame or screwed into it (in which case it can be used to locate and secure the operating coil). The plunger passes through the frame at the *throat*, the reluctance of which can be reduced by minimising the annular gap and extending the effective axial length, as shown at (*b*) and (*c*).

A typical iron clad actuator in part section is shown in *Figure 20.5*. With the dimensions $a = 220$ mm, $d = 65$ mm, $x = 63$ mm and $y = 450$ mm, the coil may develop about 15 kA-t to give a pull of 400 N across a 25 mm gap in the open position. The brass pin forms a stop, and cushions the plunger by expelling air through the vent.

With a flat-ended plunger the stroke is equal in length to the magnetic air gap. Maximum work (force × displacement) occurs with a short stroke. By using a coned plunger (see *Figure 20.5*), maximum work is obtained with a longer stroke. If the cone angle is 60°, the comparable stroke is twice that for a flat-ended plunger for about the same magnetic pull. It is possible to obtain a wide variety of characteristics by modifying the shapes of the stop and plunger ends.

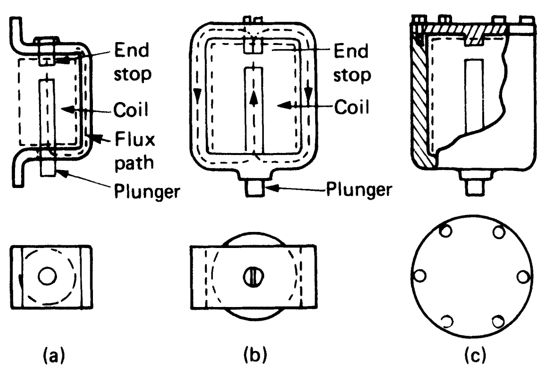


Figure 20.4 D.c. actuators

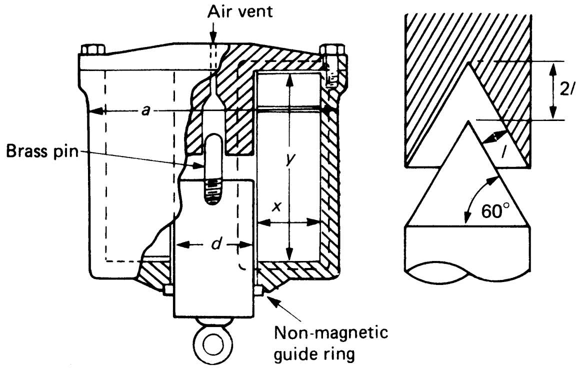


Figure 20.5 Iron clad 'pot' actuator

20.2.3.2 A.c. actuators

A common arrangement for a single-phase device is that shown in *Figure 20.6*. The E-type laminations are clamped. In the plunger, rivets should lie in a line in the flux direction to minimise eddy currents. To keep down the 'holding' current the plunger and stop ends should be flat.

Because of the many variables concerned, the design is complicated. An empirical rule is to allow 1.5 mm^2 of plunger cross-section for every 1 N of force; this corresponds to a peak flux density of 0.8 T in the laminations. The size of the coil (and therefore the main dimensions) may be taken as having a length 2.5–3 times the stroke and a depth equal to the stroke. The number of turns N is estimated from

$$N = \mathcal{V}/4.4fB_mA$$

where B_mA is the peak flux and f is the frequency. Final adjustment of N is made on test; it is reduced if the force is too low.

20.2.3.3 Polyphase actuators

A three-phase actuator has three limbs. Because of the phasing, the net force on the laminated bar armature assembly is never zero, and shading is not necessary.

The typical unit (*Figure 20.7*) is for operating a brake. It has three limb-coils E connected in star. The armature A is shown in the lifted (energised) condition. The plunger rod, fitted with a piston in the dashpot D, cushions the end of the stroke. A valve in the piston allows unretarded drop-out for quick brake application.

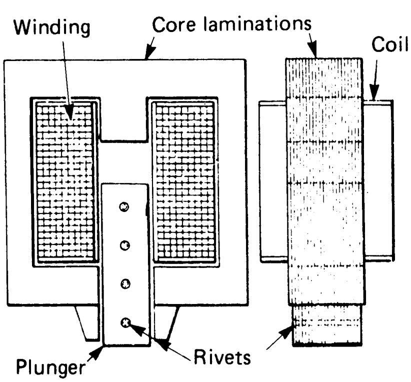


Figure 20.6 Single-phase actuator

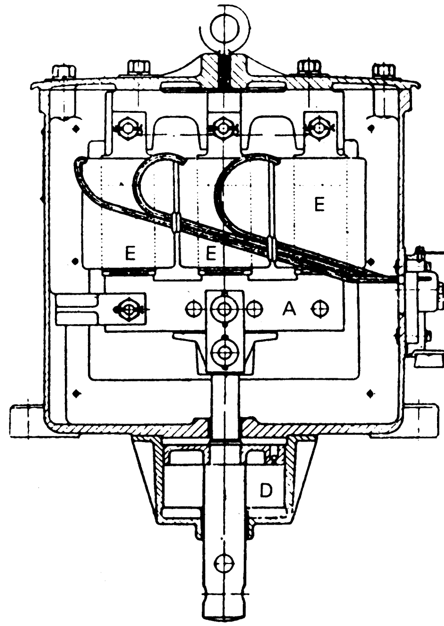


Figure 20.7 Three-phase actuator

20.2.4 Lifting magnets

Lifting magnets are of use in the handling of iron and steel, as they dispense with hooks and slings. The maximum load of a magnet varies with the material to be lifted. A magnet capable of lifting 1 t of scrap may raise a 20 t load in the form of a thick solid piece with a flat upper surface. As the excitation is limited by temperature rise of the coil, the lifting capacity is also dependent on the duty cycle. For the comparatively arduous conditions normally ruling in industrial use, a robust and weatherproof construction is essential.

20.2.4.1 Circular magnets

The essential features of a circular magnet are shown in *Figure 20.8*. As the magnetic properties of the material lifted and the air gaps between the magnet poles and the material are both arbitrary and subject to wide variation, the design of a lifting magnet is generally based on thermal considerations. A given carcass and winding are assigned an empirically derived power rating such that the temperature rise of the coil is not excessive. The designer's aim is then to secure the maximum effective ampere-turn excitation and working flux density by adjustments of iron and conductor materials and heat dissipation. Allowances in design must be made for the development of adequate pull under conditions of low line voltage (e.g. 80% or less of nominal), and high conductor resistivity when hot.

The majority of lifting magnets, except those of small size, have a winding of flat strip, which is more adaptable than wires of circular section to the attainment of a good space factor with the large conductor areas generally necessary. Aluminium is sometimes employed in preference to copper for the advantage of weight economy: the weight of a magnet is

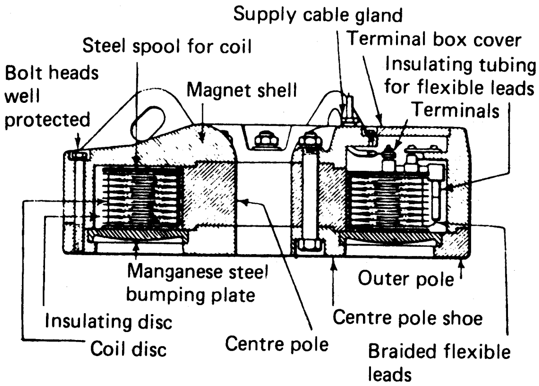


Figure 20.8 Circular lifting magnet

important as it represents a useless additional load to be moved every time its crane is operated. The winding in *Figure 20.8* is shown diagrammatically: it comprises a number of flat spirals with heat-resistant insulation.

The general dimensions are such that the diameter of the inner pole-face is about one-third of the overall diameter d. The load lifted is proportional to d^2 and the power rating (in kilowatts) is of the order of $4d^2$ (with d in metres). As regards the load, only in exceptional cases does close and uniform contact occur between magnet and load surfaces. The tendency for flux concentration over small contact regions develops local saturation and increases the effective gap.

20.2.4.2 *Rectangular magnets*

Materials of regular shape, such as sheets, bars, pipes, etc., are well suited to lifting by rectangular magnets. The general construction is similar to that of the circular type, the body being formed of a box-shaped steel casting with a central projection to give the inner polar surface.

The approximate lifting capacities of circular and rectangular magnets are given in *Table 20.1*.

20.2.4.3 *Control*

Simple on/off switching is not practicable because of the high level of stored magnetic energy. The general control features needed are: (1) discharge resistors connected across the winding just prior to disconnection to reduce contact arcing and limit inductive e.m.f; (2) auxiliary resistors introduced into the coil circuit after a predetermined time to limit coil temperature rise; and (3) reversal of polarity at a low current level to overcome remanence and so release small pieces such as turnings or scrap.

20.2.5 Crack detectors

Electromagnetic crack detection depends on the fact that, in magnetic material, the magnetic susceptibility of a fault is markedly inferior to that of the surrounding material. The success of the whole technique of magnetic crack detection depends largely on the care taken to ensure correct strength and direction of magnetisation. The following methods are used:

(1) *Needle method.* The surface to be tested is explored with a small magnetic needle. This needle carries a pointer which moves over a scale, with a right and left motion as the needle turns on its pivot to align with the field distortion passing beneath it in the direction of the arrow. Thus the fault is detected. The sensitivity is increased by using a mirror and light beam.
(2) *Powder method.* The part to be tested, previously cleaned, is laid across the arms of the machine, and the circuit-

Table 20.1 Approximate lifting capacities

Circular magnets: *load lifted* (t)

Material	*Magnet diameter* (m)				
	1.6	*1.4*	*1.2*	*1.0*	*0.6*
Skull-cracker ball	18	15	10	7	3
Slabs	27	23	16	9	3
Pig-iron	1.3	1.0	0.6	0.3	0.1
Broken scrap	0.8	0.5	0.4	0.3	0.1
Cast-iron borings	1.0	0.7	0.5	0.3	0.1
Steel turnings	0.5	0.3	0.2	0.1	0.005

Rectangular magnets: *plate area lifted* (m^2)

Plate stack			*Magnet dimensions* (m)			
Plate thickness (mm)	*Longest plate* (m)	*Maximum No. of plates in stack*	*0.6 × 0.4*	*1.0 × 0.4*	*1.4 × 0.4*	*2.0 × 0.4*
0.4	1.5	80	0.9	2.3	3.5	4.6
1	2.8	20	1.8	4.3	6.5	8.7
3	4.2	10	2.4	5.5	8.3	11
6	6.7	5	2.8	6.5	9.7	13
12	9.5	3	3.2	7.5	11.3	15
25	13.5	2	3.2	7.5	11.3	15

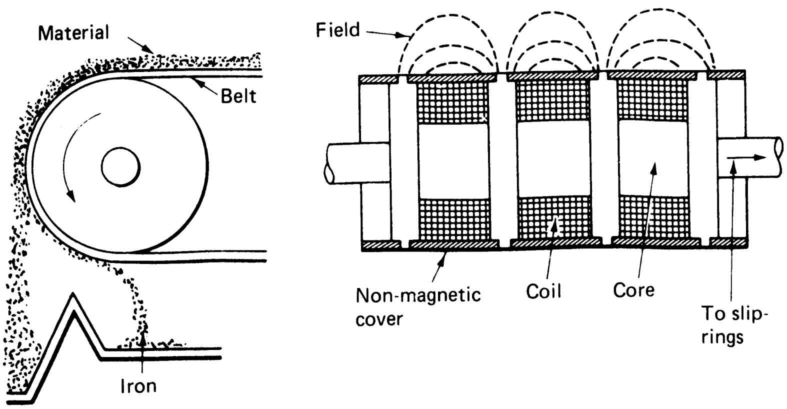


Figure 20.9 Magnetic pulley separator

closing push-button switch depressed and released quickly. The article is then removed and sprinkled with special powder, the excess of which is blown away or shaken off; it will then be found that the defects are clearly indicated by the magnetic patterns.

(3) *Fluid method.* This resembles the powder method but employs a fluid (e.g. paraffin) containing finely divided magnetic material in suspension.

Each of these techniques can be applied to the detection of cracks or other flaws in parts which have been magnetised. There are two methods of attaining this magnetisation in normal commercial use.

In the first method the part to be tested is placed between the poles of an electromagnet, in which case the direction of the field is from pole to pole. The second method utilises the fact that a concentric magnetic field forms round an electric current. A heavy low-voltage current is passed through the part itself, or through a current-bar adjacent to it or threaded through it.

As only those cracks or flaws will be shown up which cut across the magnetic field, it will readily be understood that the first method is most suited to the detection of transverse cracks, the second to the detection of longitudinal ones. However, apparatus designed for testing by means of the second method may be adapted to the detection of transverse cracks by encircling the part with several turns of cable through which the heavy current is passed.

20.2.6 Separators

The bulk handling of material, particularly where the process involves crushing or grinding, may require the use of a magnetic separator for removing unwanted or tramp iron and steel, or for quickly separating ferrous from nonferrous scrap metals. Successful operation depends on uniformity of the feed thickness, and often an installation must include a suitable conveyor/feeder.

20.2.6.1 Types

Magnetic pulley This form of separator (*Figure 20.9*) comprises a number of circular cores and poles, the magnetic axis being that of the shaft. Coils encircle the cores, with d.c. (or rectified a.c.) excitation, and set up a magnetic field pattern. Iron attracted to the pulley surface is removed by aid of the conveyor belt, the material being drawn away from the magnetic field region. When the belt speed or width, or the thickness of the feed, is unsuitable for a single pulley, two may be used, one at each end of a short auxiliary belt that receives its feed from the main conveyor.

Drum This has an advantage over the pulley type in respect of its more effective separation. A drum can operate in conjunction with a belt conveyor if placed below the head pulley and a suitable guide. Feed is readily arranged down a chute or directly on to the feeder tray, if one is provided. A common type of feeder has the tray oscillated by an eccentric motion, or vibrated in a straight-line motion, at about 15 Hz.

Suspension A structure resembling a lifting magnet is suspended over a conveyor belt. It operates successfully on feeds containing awkward shapes of tramp iron at a belt speed up to 2.5 m/s. The magnet will not automatically discharge its load, but the large gap can contain a considerable load. The power rating is large.

Disc Most machines utilise rotating discs with a sharp or serrated periphery, set above the conveyor belt and over the magnet. Separation of iron depends on the change of polarity of a given region of the disc as it rotates, so that ferrous particles can be released.

Induction roll A powerful magnet (*Figure 20.10*) is provided with a return path plate. Rollers set between them are

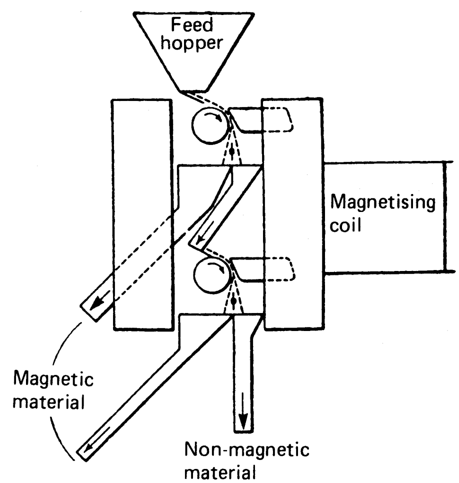


Figure 20.10 Induction roll separator

magnetised by induction. Material is fed into the top. Non-magnetic pieces fall through under gravity, while ferrous material adheres to the roller and is carried round and detached. Up to eight rollers in tandem may be used.

Wetherill The Wetherill separator has a single magnet unit mounted either side of a conveyor belt on which the material to be treated is passed beneath the upper magnet pole (*Figure 20.11*). Another belt is arranged over the upper pole of each magnet to take off the extracted ferrous material. The success of the separator depends on the shape of the magnet poles: the lower is flat and the upper is arranged with a ridge to concentrate the field. As the material passes under the magnets, each ferrous particle jumps towards the upper pole and is intercepted by the take-off belt, which in turn carries it to the side where it is discharged in a continuous operation. In practice, several magnets are used; the number of products that can be separated in a single operation is determined by the number of take-off belts, of which there are two per magnet unit.

20.2.6.2 Ore separation

For dealing with material in large lumps the magnetic field must have a deep penetration. This involves widening out the poles. The flux density is inevitably weakened. Thus, while feed depths of 250 mm are usual with a drum of 1 m diameter for the removal of tramp iron, the depth must be cut to, say, 75 mm when feebly magnetic material is operated on.

An important branch of separation deals with the subdivision and concentration of ores, the constituents of which have permeabilities very much lower than that of iron. Data on this point are given in *Table 20.2*. The process may be performed in several ways. A single product can be removed from the bulk; several constituents may be removed, each separately, in a single operation; or the separation may be carried out by a wet process.

The general design for feebly magnetic materials differs from that for the removal of tramp iron, essentially in the necessary flux density. A material with a permeability of 1% of that of iron may require a gap density exceeding 1.6 T, and the field must be divergent. For this purpose the lower pole over which the material passes is made flat; the upper pole, whether fixed or moving, is provided with a concentrating V-edge so that particles travel to it out of the general bulk of the material treated.

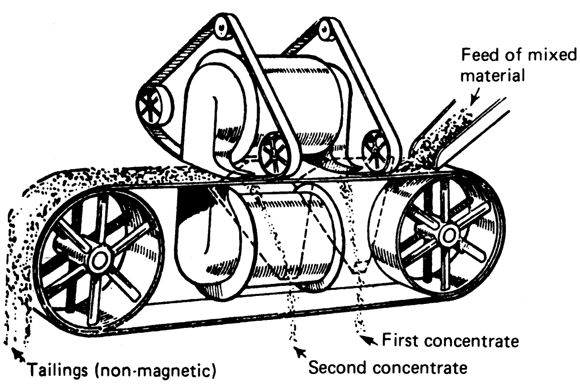


Figure 20.11 Wetherill separator

20.2.7 Clutches

The conventional clutch consists essentially of two members: the field member, which carries the exciting winding, and the armature member, consisting virtually of a steel ring which becomes attracted to the field member when the winding is energised. The engaging surfaces of these members have a friction lining for taking up the load when the clutch engages, and means are provided for spring disengagement of the armature when the winding is de-energised. As the clutch rotates in operation, it is necessary to employ slip-rings and brushes for the current supply.

A special type of clutch with a double friction lining is shown in section in *Figure 20.12*. In this case the field and armature members rotate together on the same shaft. The other shaft carries on a spring plate the lining carrier member. The two friction surfaces on this member engage between the armature and field members when the field coil is energised. General particulars for representative sizes of this type of clutch are given in *Table 20.3*.

20.2.8 Couplings

Eddy-current couplings resemble induction motors in that they develop torque by ‘slip’, and the throughput efficiency falls with decrease of speed. In selecting a coupling the critical factors are the speed range and the load torque variation therein.

The essential features are shown in *Figure 20.13*. The outer member (the loss drum) is mounted on the shaft extension of the drive motor, and the inner member (the pole system) on the driven shaft. Operation depends on the induction of current in the loss drum by e.m.f.s resulting from the speed difference between the driving and driven shafts. The two types illustrated are:

(1) *Interdigitate*. This is common for drives transferring up to about 100 kW. The loss drum is of plain ferromagnetic material of low resistivity, normally with forced cooling. The ‘claw’-shaped pole structure gives a multipolar field by means of a single exciting coil. There is substantial interpolar leakage flux.
(2) *Inductor*. The toothed rotor produces an alternating flux density pattern in the loss drum by the modulation of the airgap permeance. An annular exciting coil, fixed or rotary, causes the two air gaps to have opposite polarity,

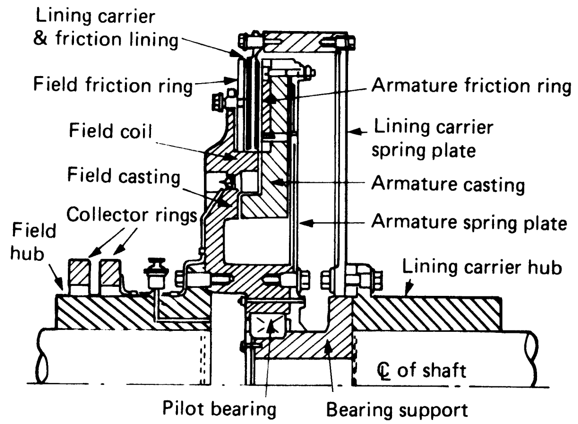


Figure 20.12 Electromagnetic clutch with double friction lining

Table 20.2 Relative attraction force (iron = 100) of various materials

Apatite	0.2	Dolomite	0.2	Lithium	0.5	Quartz	0.4
Argentite	0.3	Fluorite	0.1	Magnesium	0.8	Rutile	0.4
Biotite	3.2	Franklinite	35.4	Magnetite	40.2	Siderite	1.8
Bornite	0.2	Garnet	0.4	Manganese	8.9	Strontium	3.4
Cerium	15.4	Haematite	1.3	Molybdenite	0.3	Titanium	1.2
Chromium	3.1	Ilmenite	24.7	Palladium	5.2	Tungsten	0.3
Corundum	0.8	Limonite	0.8	Pyrrhoite	6.7	Zircon	1.0

Table 20.3 Clutches with double friction linings

Overall diameter (m)	*Max. power per 100 rev/min* (kW)	*Max. torque* (kN-m)	*Max. speed* (rev/min)	*Kinetic energy at 100 rev/min* (kJ)	*Mass* (kg)	*Current at 240 V* (A)
0.6	33	3	1200	0.5	300	0.9
0.8	95	9	900	1.8	520	1.4
1.0	200	20	700	5	960	2.1
1.2	360	36	600	11	1300	2.6
1.5	670	67	480	31	2200	3.2
1.8	1250	125	400	67	3400	4.2
2.1	1600	160	250	125	4700	4.7

the flux between them completing its path through the loss drum.

20.2.9 Brakes

The three basic forms of brake are: (i) solenoid-operated, (ii) tractive, and (iii) a thruster (electrohydraulic). In each case a brake-band or (more commonly) a brake-shoe is pressed against the brake-drum, either by weights or by springs operating through a lever. The use of springs is preferable, especially with large brakes, as the cushioning of the shock due to a falling weight introduces additional problems of design as well as limiting the positions in which the brake may be mounted. The brake is released by the operating force acting against the force due to the resetting spring. The brake is held in the off position for as long as the controlling circuit is energised.

The pressure used on the friction surfaces and the coefficient of friction are of the same order as for clutches. The pressure employed should be such as to give a reasonable rate of wear, and the figure chosen will determine the width of shoe required for a given operating force and wheel diameter. In general practice there are two brake-shoes, each embracing about one-quarter of the wheel circumference.

20.2.9.1 Solenoid brake

The brake is held 'off' by a solenoid/plunger device acting through leverage against spring loading, the latter being adjustable to suit the brake-torque requirements. If the brake is energised only for short periods, with intervening periods of rest (with the brake on), it is usually possible to fit a coil giving more ampere-turns than are obtainable with a continuous rating and thus to use a greater resetting spring pressure, giving increased braking torque.

20.2.9.2 Tractive brake

The example in *Figure 20.14* embodies a tractive electromagnet operating on inner and outer disc armatures A when the magnetising coil B is energised. The mechanical features are the adjusting wedge C, the brake-shoes D, the adjusting nuts E for the outer shoe-lever F, the torque spring G and its adjuster H, the tie-rod J, the terminals K, and the shoe-clamping screws L. Armatures AA rest in slots in the base and tend to remain against the slot abutments as a result of spring pressure and magnetic force. The powerful mainspring forces the armatures AA apart, causing the inner to apply pressure to the right-hand shoe and the outer to the left-hand shoe through the tie-rod J. When coil B is energised, the armatures AA mutually attract, so releasing the brake.

20.2.9.3 Thruster brake

The thruster brake employs a hydraulic thruster cylinder, with a piston acting under the fluid pressure produced by a small motor-driven pump unit. The power consumption is relatively low, but there is a short time-lag in brake response.

20.2.10 Magnetic chucks

In cases where awkwardly shaped ferrous-metal parts have to be machined in any quantity, the electromagnetic chuck forms a valuable auxiliary to various kinds of machine tools. The chuck contains a number of distributed windings which when energised from a d.c. source produce a concentrated and uniform field at the surface of the chuck, which is ground flat so as to form a suitable base-plate for accurate machining operations. The magnetic pull on ferrous materials in contact with the chuck surface is sufficient to prevent movement under all normal machining stresses.

When the current is switched off, the residual magnetism is in some cases sufficient to prevent easy removal of the part. The usual form of control switch accordingly has a demagnetising position.

The principle can be applied to rotating chucks, in which case slip-rings are necessary to convey exciting current to the windings.

In some cases *permanent-magnet* chucks can be employed. Hold and release of the workpiece are effected by an operating

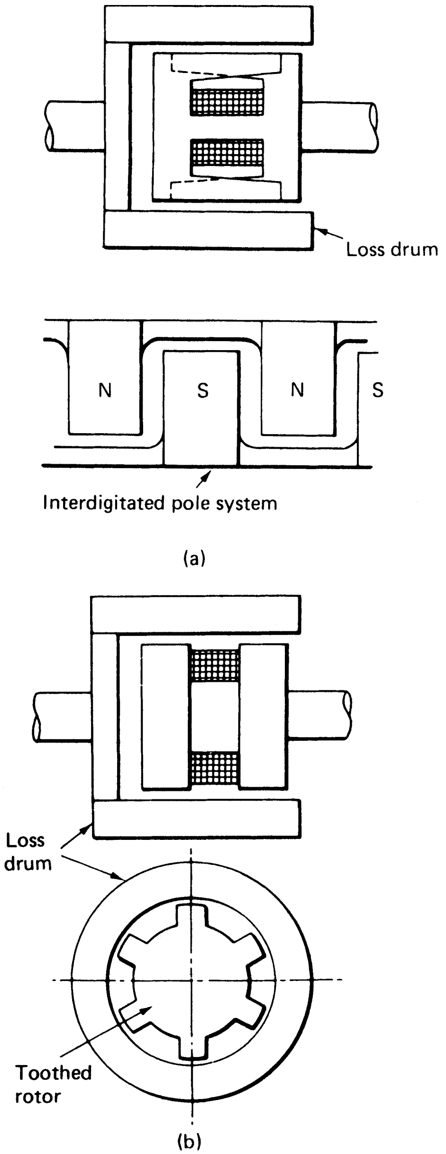


Figure 20.13 Eddy-current couplings

lever which, in the off position, closes the flux paths of the magnets through high-permeability bridges and reduces the flux through the work. With either electro- or permanent-magnet forms, the workpiece may have to be demagnetised after machining.

20.2.11 Vibrators

A vibrator generator develops a vibro-motive force of adjustable magnitude and frequency for the noise, fatigue and vibration testing of small structures and for the assessment of mechanical resonance.

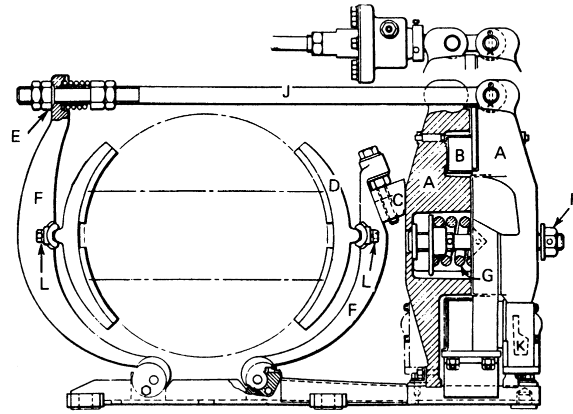


Figure 20.14 Tractive electromagnetic brake

20.2.11.1 Electrodynamic vibrator

Figure 20.15(*a*) shows the essential features of an electrodynamic vibrator, which are those of a powerful loudspeaker mechanism in which a circular coil, carrying an alternating current and lying in a constant radial magnetic field, develops vibratory force and displacement of corresponding frequency. A construction of the form shown can be adapted to develop torsional vibration by pivoting the armature centrally.

20.2.11.2 Magnetostrictive vibrator

The magnetostriction effect can be employed by placing the a.c. exciting coil around a stack of magnetostrictive material (*Figure 20.15*(*b*)). Mechanical amplification of the very small displacement is provided by a truncated drive rod. Vibrators of this kind are generally fixed-frequency devices, but they are suitable for relatively high frequencies only.

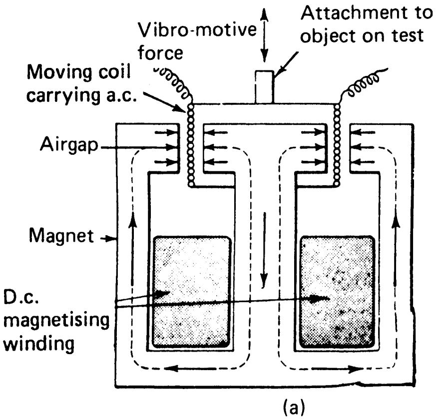
Single-frequency low-power vibrators can be constructed with piezo-electric drive. As large crystals are not readily available, these vibrators are usable only in the ultrasonic frequency range.

20.2.12 Relays and contactors

Relays and contactors, a.c. or d.c. excited, are widely employed for low- and high-power switching. The basic features are shown in *Figure 20.16*.

20.2.12.1 Contactors

The term ‘contactor’ applies to power-control devices. For d.c. operation the contactor is made single- or double-pole as required. When the coil is energised, a magnetic field is established across the air gap and the armature is attracted to the pole to close the contacts. The moving contact has a flexible conductor attached to it in order to avoid passing current through the hinge. The destructive effects of d.c. arcs are such as to make necessary an arc shield and magnetic blow-out arrangement. The blow-out winding carries the main current and its connection is so arranged that the arc is expelled from the contact region when the contacts separate.



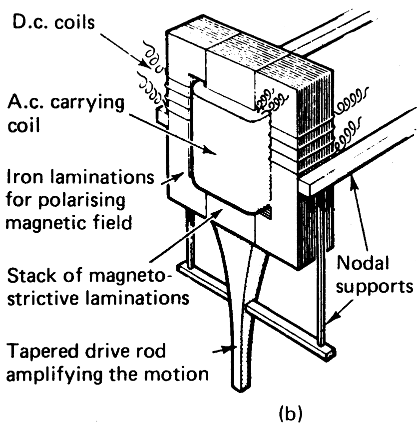


Figure 20.15 Vibrators

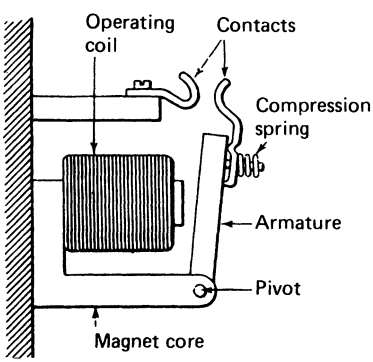


Figure 20.16 Elements of a contactor

For a.c. service the contactor normally has two or three poles. The magnetic circuit is laminated and the pole-face has a shading coil to reduce 'chatter'. Blow-out coils may not be provided because the principle operates less effectively on a.c.; reliance may be placed on extinction at a current zero. A typical a.c. contactor is illustrated in *Figure 20.17*.

Ratings These have been standardised. The severity of operating conditions varies considerably according to the class of service. Although the cleaning action on the contacts due to frequent operation is desirable in removing cumulative high-resistance films which tend to increase heating, this class of service causes greater contact wear and erosion for a given loading than would occur with less frequent operation. Conversely, very infrequent operation which involves the contacts carrying current for long periods is not onerous from the viewpoint of wear and erosion but is conducive to the formation of high-resistance surface films unless a suitably low temperature is maintained so as to limit the formation of the films. The permissible temperature rise for different types of contact is given in *Table 20.4*. Operation must be satisfactory with the shunt windings at final rated temperature and with reduced operating voltage (80% of normal for d.c., 85% for a.c.).

Table 20.4 Temperature limits for contacts

Type of contact	*Temperature rise* (°C)
Solid copper in air	
Standard rating	65
Uninterrupted rating	45
Solid copper in oil	45
Laminated copper in air or in oil	40
Solid silver or silver faced in air	80
Carbon	100

20.2.12.2 Relays

The electromagnetic relay operates one or more sets of contacts by the attraction of a movable armature towards a magnetised core. The representative types shown in *Figure 20.18* are: (a) the 'telephone' type with pivoted armature; (b) the 'commercial' version of (a); (c) a mercury switch with hinged armature; and (d) a spring-suspended armature. An important feature is the operating time.

High-speed operation may be obtained by one or more of the following methods: (i) lamination of the magnetic circuit to minimise eddy-current delay; (ii) reduction of the mass of moving parts; (iii) use of a large coil power; or (iv) reduction of coil inductance.

Low-speed operation, sometimes needed to introduce a time-lag, is obtained by: (i) use of a lag (or *slugging*) coil comprising an additional and separate short-circuited loop or winding; (ii) use of a series inductor or shunt capacitor; or (iii) addition of an external time-delay relay.

Design features Contact sets may be normally open or normally closed, and both types may be fitted on the same relay mechanism. The arrangement is determined by the operating sequence required: i.e. make, break, change-over, make-before-break, break-before-make. The contact size and material must be chosen in accordance with the rating and electrical characteristics of the circuits controlled.

Ideally, the contacts should operate cleanly and with no bounce. They should be of adequate size and of the most suitable material. In extremely low-voltage circuits the contact resistance is usually an important consideration and special precautions may also have to be taken to ensure reliable operation under conditions of vibration or shock.

Similarly, in cases of high-current switching it may be necessary to ensure wide separation of the contacts or even to

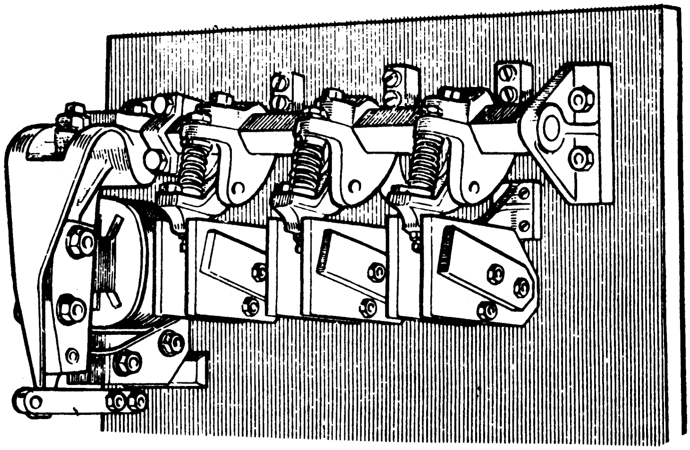


Figure 20.17 Triple-pole a.c. contactor

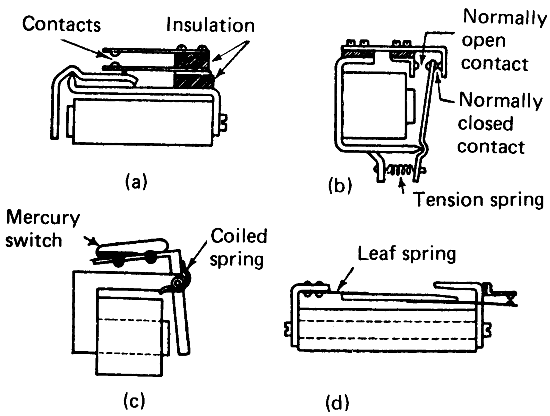


Figure 20.18 Electromagnetic relays

arrange for several gaps to operate in series. In some cases it may be necessary to use arc-suppressing circuits.

The number and type of the contacts and springs determines the switching operation to be performed by the relay; this factor also determines the work to be done by the magnetic circuit. It follows, therefore, that the choice of a suitable coil and iron circuit design is determined by the contact arrangement of any particular relay. Various configurations of magnetic circuits and materials are used in the relays under review, depending upon their particular application. For example, in the high-sensitivity relays, where the air gap has to be kept to a minimum, it is necessary to use materials having a very low residual magnetism and high permeability.

The power required to operate the relay is determined by the spring-set arrangement and the magnetic circuit. The method of construction is important, since it largely determines the safe operating temperature of the winding and this, in turn, governs the coil power and the maximum pull available at the armature. By increasing the area of the flux path while maintaining the ampere-turns and coil power constant, the total air gap flux, and therefore the armature pull, can be increased and the increased coil area will permit cooler operation of the coil. This may, however, lead to a relay that is physically larger than can be tolerated. In practice, therefore, it is more reasonable to build a relay of a given size and to use other means to amplify the controlling power.

The continuous power input to a given relay coil is limited only by the maximum temperature that the coil insulation can withstand without breakdown. This temperature is governed by the environmental conditions as well as by the coil construction and the quality of the insulating material.

Many of the functions performed by the electromagnetic relay have been taken over by solid-state switching.

20.2.13 Miniature circuit-breakers

The miniature circuit-breaker (m.c.b.) is, for the control of small motors and domestic subcircuits, considered primarily as an alternative to the fused switch. The appropriate British Standard is BS 3871, which lays down specific technical requirements. The usual form of the m.c.b. embodies total enclosure in a moulded insulating material. As the operating mechanism must be fitted with an automatic release independent of the closing mechanism, the m.c.b. is such that the user cannot alter the overcurrent setting nor close the breaker under fault conditions. At the same time the m.c.b. must tolerate harmless transient overloads while clearing short circuits. For most practical conditions, a change-over from time-delay switching to 'instantaneous' tripping at currents exceeding 6–10 times full-load rating is suitable.

20.2.13.1 Tripping mechanisms

Methods of achieving the required operating characteristics can be classified as (i) thermomagnetic, (ii) assisted thermal and (iii) magnetohydraulic. In the *thermomagnetic* method the time-delay is provided by a bimetal element, and the fast trip by a separate magnetically operated mechanism based on a trip coil. In the *assisted thermal* method the bimetal is itself subjected to magnetic force. The *magnetohydraulic* mechanism incorporates a sealed dashpot with a fluid and a spring restraint, the dashpot plunger being of iron and subject to the magnetic pull of the trip coil. The essential features are illustrated in *Figure 20.19*.

Thermomagnetic The bimetal element shown in *Figure 20.19(a)* may carry the line current or, for low current ratings, be independently heated. Its flexure operates the trip latch through a crank. On overcurrent the magnetic force acts directly on the latch bar, with or without the aid of the bimetal deflection.

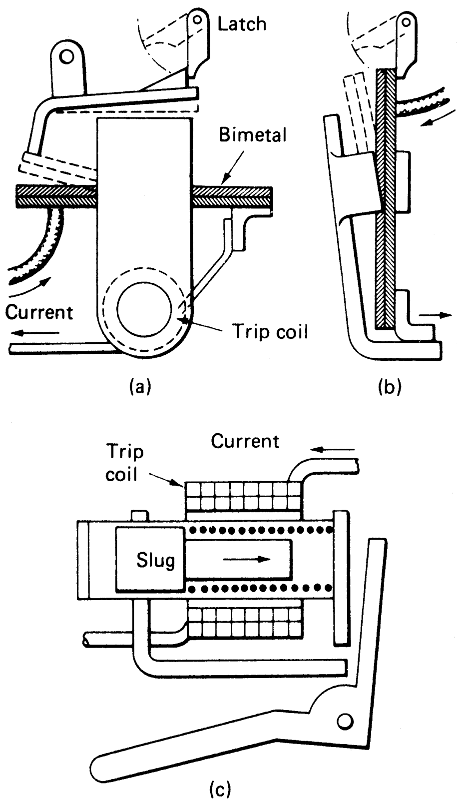


Figure 20.19 M.c.b. trip mechanisms

Assisted thermal The time-delay characteristic is provided by a bimetal element, and instantaneous tripping by magnetic deflection of the bimetal. The operation is shown in *Figure 20.19*(*b*). A bar of magnetic material is placed close to the bimetal element, and the magnetic field set up by the current develops a pull on the bimetal such as to increase its deflection and release the trip latch. The magnetic effect is proportional to the square of the current and so becomes significant on overcurrent. However, as the position of the bimetal element on the occurrence of a short circuit is arbitrary, there is no well-defined change-over point at which instantaneous tripping occurs.

The method is cheap and simple, but is difficult to design for low-current (e.g. 5 A) breakers because the operation tends to be sluggish, particularly at fault-current levels that are less than 500 A.

Magnetohydraulic This method, shown in *Figure 20.19*(*c*), combines in one composite magnetic system a spring-loaded dashpot with magnetic slug in a silicone fluid, and a normal magnetic trip. When the line current flows, the magnetic field produced by the trip coil moves the slug against the spring towards the fixed pole-piece, so reducing the reluctance of the flux path and increasing the magnetic pull on the trip lever. If it reaches the end of the dashpot, the pull is sufficient to operate this lever and trip the circuit-breaker. On sudden overcurrent exceeding 6–10 times full-load value, there is sufficient pull at the fixed pole-piece to attract the armature of the trip lever regardless of the position of the slug in the dashpot. The characteristic is more definite and satisfactory for low-current ratings than that of the assisted thermal mechanism.

20.2.13.2 Operating features

Thermal operation by bimetal elements implies that the effective current rating is a function of the ambient temperature. It is the practice, if complete ambient compensation is not fitted, to rate m.c.b.s in such a way as to allow for the type of enclosure. With magnetohydraulic devices the tripping is independent of the ambient temperature over a specified range, the small variations due to change of viscosity of the damping fluid being minimised by use of a fluid with a nearly flat viscosity–temperature characteristic.

The combination of thermal and magnetic functions is not easily controlled for low current ratings, and for m.c.b.s with such ratings the tolerances on operation must be wider than they are for larger currents.

Normally, m.c.b.s are suitable only for a.c. circuits. As with all a.c. switchgear, the problems of breaking efficacy are associated not only with the actual short-circuit current but also with its asymmetry and power factor.

As m.c.b.s can be linked to give two- and three-pole versions, so arranged that a fault on one pole will produce complete circuit isolation, the risk of single-phasing in motor control is effectively eliminated. In other directions, however, m.c.b.s cannot necessarily replace fuses: they do not possess the high short-circuit breaking capacity of the modern h.r.c. fuse, nor do they have its inherent fault-energy limitation. If, therefore, conditions are such that back-up protection has to be provided for m.c.b.s, the 'take-over' zone should be of the order of 1.0–1.3 kA.

20.2.14 Particle accelerators

Modern accelerators produce high-energy beams of electrons, ions, X-rays, neutrons or mesons for nuclear research, X-ray therapy, electron irradiation and industrial radiography. If a particle of charge e is accelerated between electrodes of p.d. V it acquires a kinetic energy eV electron-volts ($1\,\text{MeV} = 1.6 \times 10^{-13}$ J). Accelerators are classified as *direct*, in which the full accelerating voltage is applied between the two electrodes; *indirect*, in which the particles travel in circular orbits and cyclically traverse a region of electric or magnetic field, gaining energy in each revolution; and *linear*, in which the particles travel along a straight path, arriving in correct phase at gaps in the structure having high-frequency excitation, or move in step with a travelling electromagnetic wave.

20.2.14.1 Direct accelerators

The Cockcroft–Walton multiplier circuit has two banks of series capacitors, alternately connected by rectifiers acting as change-over switches according to the output polarity of the energising transformer. The upper limit of energy, about 2 MeV, is set by insulation. A typical target current is 100 μA.

The Van de Graaff electrostatic generator is capable of generating a direct potential of up to about 8 MV of either polarity. It has an endless insulating belt on to which charge is sprayed from 'spray-set' needle-points at about 50 kV. The charge is carried upwards to the interior of the high-voltage (h.v.) electrode, a metal sphere, to which it is transferred by means of a second spray set. H.v. insulation difficulties are overcome by operating the equipment in a tank filled with a high-pressure gas, e.g. nitrogen–freon mixture at 1500 kN/m^2. In two-stage Van de Graaff generators for higher energies, negative hydrogen ions are accelerated from earth potential to

6 MeV; they are then fired into a thin beryllium foil 'stripper' which removes the electrons from the outer shells of the atom and leaves the remanent ions moving on with little change of energy but with a positive charge. The second stage brings these ions back to earth potential and the total energy gain is 12 MeV. To bring ions on to a small target the accelerating and deflecting fields must be accurately controlled, and scattering limited by evacuating the accelerator tubes to very low pressure. The energies are sufficient for the study of nuclear reactions with the heaviest elements.

20.2.14.2 Indirect (orbital) accelerators

Indirect (orbital) accelerators may have orbits of approximately constant radius with a changing magnetic field (betatrons and synchrotrons) or orbits consisting of a series of arcs of circles of discrete and increasing radii in a constant magnetic field (cyclotrons and microtrons).

Betatron The betatron is unique in that the magnetic field not only directs particles into circular orbits but also accelerates them. The magnet has an alternating field of which only one quarter-period is used. Electrons are accelerated in an evacuated toroidal chamber between the poles of the magnet. They are injected at an energy corresponding to a low magnetic field, which bends them in circular orbits round the toroid. A cross-section of the poles and vacuum chamber is shown in *Figure 20.20*. As the magnetic flux through an electron orbit increases during the cycle of alternation, the electron experiences a tangential force, and its gain in energy per revolution is the voltage that would be induced in a loop of wire in the orbit. As the electron gains energy, the magnetic guide field intensity at the orbit increases at a suitable rate. To keep the electron on a constant radius from injection to peak energy requires the rate of change of intensity at the orbit to be half that of the mean flux per unit area within the orbit. At peak energy (or earlier) the electrons are caused to move away from their equilibrium orbit and to strike a target inside the vacuum chamber, producing X-rays or corresponding energy. The output consists of short pulses of radiation whose repetition rate is the frequency of the magnet excitation. Energy limitations are set by the size and cost of the magnet and the radiation loss when a high-energy electron has circular motion.

Synchrotron The synchrotron uses an annular magnetic guide field which increases as the particles gain energy, as in the betatron, so that they maintain a constant orbit radius. Electrons are initially accelerated by the action of central 'betatron bars' which saturate when the main magnetic field corresponds to an energy of 2–3 MeV when electrons travel at a velocity only 1–2% less than the velocity of light. Further gain of energy is produced by radio-frequency (r.f.) power at the frequency of orbital rotation (or a multiple of it) that is fed to resonators inside the vacuum chamber. The particles become bunched in their orbits so that they pass across the accelerating gap in the resonator at the correct phase of the r.f. field. The limitation on electron acceleration is now mainly set by radiation losses due to circular motion.

Protons are injected at about 500 keV, which produces a velocity of only 3% of that of light. Further acceleration changes the frequency of orbital rotation. For a proton synchrotron the magnetic guide field strength and the r.f. power frequency have to be varied accurately over large ranges.

Cyclotron This early form of accelerator consists of a vacuum chamber between the poles of a fixed-field magnet containing two hollow D-shaped electrodes which load the end of a quarter-wave resonant line so that a voltage of frequency 10–20 MHz appears across the accelerating gap between the 'D's. Positive ions or protons are introduced at the centre axis of the magnet and are accelerated twice per rotation as they spiral out from the centre. The relation between particle mass m, charge e, magnetic flux density B and frequency f is $f = Be/2\pi m$. Energy limitation is set by the relativistic increase of mass, which limits the speed of high-energy particles so that their phase retards with respect to the r.f. field.

Synchrocyclotron In this device the energy limitation of the cyclotron can be removed by modulating the oscillator frequency to a lower value as a bunch of particles gains energy.

Microtron In the microtron, or electron cyclotron, electrons are accelerated in a vacuum chamber between the poles of a fixed-field magnet. The orbits consist of a series of discrete circular arcs which have a common tangent at a resonant cavity in which the electrons gain their successive increases of energy from an r.f. electric field. The highest energy achieved with such a machine is 6 MeV, and mean currents are less than 1 μA.

20.2.14.3 Linear accelerators

Indirect accelerators of protons have so far used a resonant cavity in which drift-tube electrodes are introduced that distort the fields and enable particles to be shielded from field reversals. Particles are accelerated between gaps and move between centres of successive gaps in one complete period of oscillation (*Figure 20.21*). Oscillators operating at about 200 MHz and a pulse power of 1–2 MW are used to excite the cavity for some hundreds of microseconds. Injection is by a Cockcroft–Walton or Van de Graaff device.

An important device for electron acceleration is the travelling-wave accelerator, using megawatt pulses of r.f. power at 3000 MHz. The power is propagated along a cylindrical waveguide loaded with a series of irises. A travelling wave is set up with an axial electric-field component, and correct dimensioning of the iris hole radius a and the waveguide

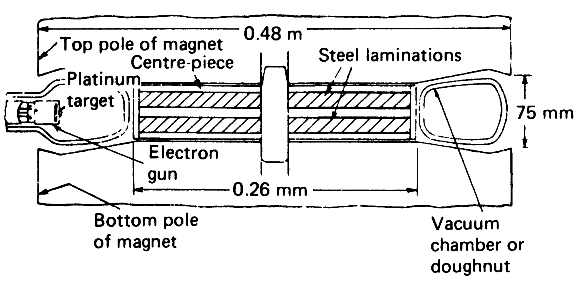


Figure 20.20 Cross-section of a 20-MeV betatron

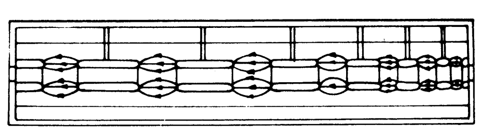


Figure 20.21 Field resonant cavity for a proton accelerator

radius b (*Figure 20.22*) enables the propagation velocity and the field-intensity/power-flow relation to be varied. An electron injected along the axis with an energy of the order of 45 keV is accelerated by the axial field, and as its velocity changes it remains in correct phase with the travelling field, the propagation velocity of which is varied to match. A fixed axial field is required to provide for electron focusing.

High-energy machines with low beam-currents have been used in the USA, low-energy machines with high beam-currents in the UK. The 25 MeV Harwell accelerator has a length of 6 m divided into six sections, each fed by a 6 MW klystron amplifier to give a peak beam-current of 1 A and a mean outpot power of 30 kW.

20.2.14.4 Large machines

The Harwell proton synchrotron gives the particles an energy of 7 GeV in an orbit of radius 19 m within a 7000 t magnet. The magnet takes 10 kA to raise the orbit flux density to about 1.4 T in 0.75 s, to hold this value for 0.25 s and to reduce it to zero in 0.75 s, with a repetition frequency of about two cycles per hour. The inductance of the magnet is about 1.1 H, and to produce a rate of change of current of 10/0.75 = 13.3 kA/s the magnet supply voltage must be about 14 kV. The peak stored energy is 40 MJ. The supply is from a pair of 3750 kW/75 MW motor/generators through rectifiers.

The new accelerator for CERN near Geneva is to use the existing 25 GeV machine to inject particles into a 300 GeV proton synchrotron with an orbit of diameter about 2.2 km. The magnet will employ superconducting exciting windings giving a flux density of 4–6 T. The design is such that it can be built initially with only alternate magnet sections, and upgraded in energy later without basic alteration of the main structure, possibly to 800 GeV.

20.3 Industrial rotary and linear motors

The elements discussed in Section 2.4.3.6 indicate that there are two methods of developing a mechanical force in an electromagnetic machine.

(1) *Interaction*. The force f_e on a conductor carrying a current i and lying in a magnetic field of density B is $f_e = Bi$ per unit length, provided that the directions of B and i are at right angles; the direction of f_e is then at right angles to both B and i. This is the most common arrangement.
(2) *Alignment*. Use is made of the force of alignment between two ferromagnetic parts, either or both of which may be magnetically excited. The principle is less often applied, but appears in certain cases, e.g. in salient-pole synchronous machines and in reluctance motors.

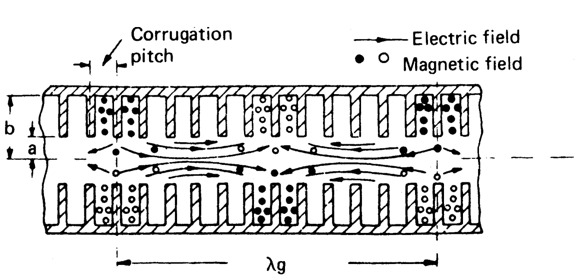


Figure 20.22 Fields in a corrugated waveguide

20.3.1 Prototype machines

Three basic geometries (*Figure 20.23*) satisfy the requirement for the relative orientations of B, i and f_e. For a rotary case the *cylindrical* form is the most common, while the *disc* with its short axial length suits particular applications. The *flat* form is employed for linear motion.

Such machines are almost exclusively *heteropolar* (i.e. have alternate north and south poles). To maintain unidirectional interaction force, the direction of the current in a given rotor conductor must reverse as it passes from a north pole to a south pole region.

20.3.1.1 Heteropolar cylindrical machine

A heteropolar cylindrical machine for a two-pole magnetic circuit is shown in *Figure 20.24*. The active region is the air gap between stator and rotor. In *Figure 20.24*(*a*) the stator conductors are arranged (normally in slots) on the surface and are connected so as to develop the current-sheet pattern indicated, giving rise to a distributed m.m.f. of peak value F_1 on the axis of the winding. A corresponding rotor current-sheet pattern sets up an m.m.f. F_2. If the m.m.f. distributions are assumed to be sinusoidal, the torque on the rotor can be shown to be

$$M_e = kF_1F_2 \sin \lambda$$

where λ is the *torque angle* between the stator and rotor winding axes, and k is a function of the air gap dimensions. For $\lambda = 0$ the m.m.f.s F_1 and F_2 are in alignment and there is no torque. Displacement of the rotor increases the torque, which reaches a maximum for $\lambda = \pi/2$ rad. For further displacement the torque falls, to become zero again for $\lambda = \pi$ rad.

The machine in *Figure 20.24*(*b*) has a fixed optimum torque angle $\lambda = \pi/2$ rad. Here the rotor must have a closed winding and be provided with a commutator or alternative switching device so that each conductor, as it passes from a north to a south polar region, has its current automatically reversed. Then the direction of F_2 is fixed for all operating conditions. As the direction of F_1 is also fixed, it is usually developed by salient poles.

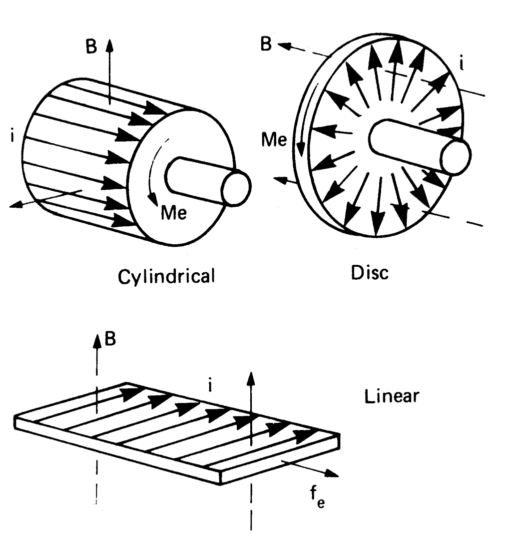


Figure 20.23 Basic geometries for electromagnet machines

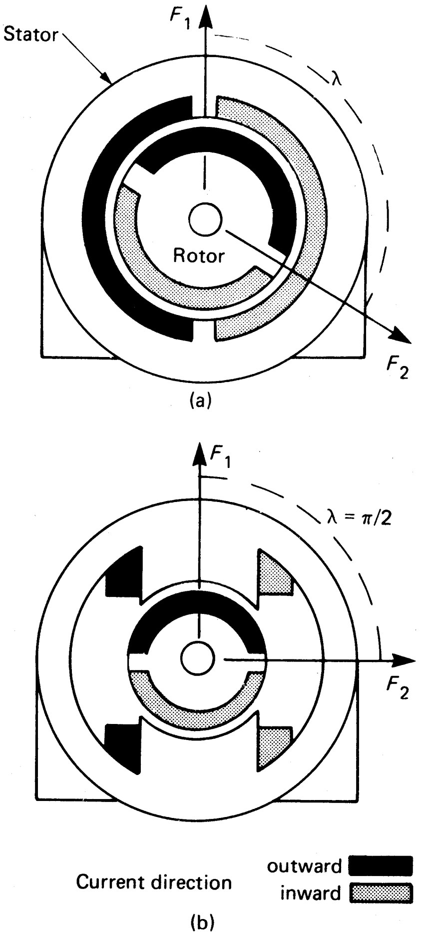


Figure 20.24 Prototype two-pole cylindrical machines

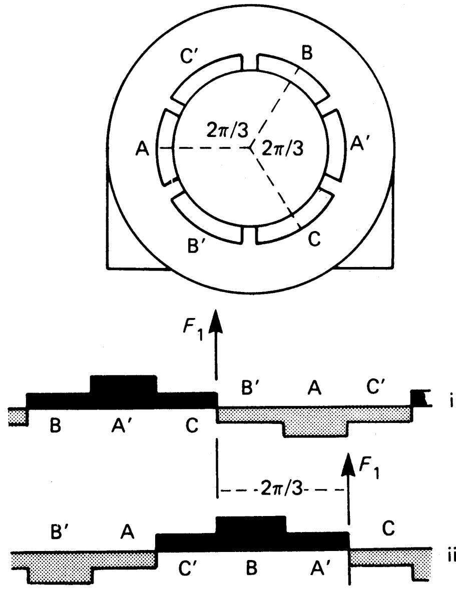


Figure 20.25 Production of a travelling-wave field

20.3.1.2 Types of machine

The three most common machines—synchronous, induction (asynchronous) and commutator—are all heteropolar and have at least one member cyclindrical. They are distinguished by the nature of the supply (a.c. or d.c.) and that of the air gap flux (travelling wave or fixed axis).

Travelling-wave gap flux The stator current-sheet pattern in *Figure 20.24*(*a*) is set up by a three-phase winding ABC as in *Figure 20.25* for a two-pole machine. With the phase windings excited by balanced symmetrical three-phase currents of frequency f_1, the sequential cyclic reversal of currents in the displaced windings shifts the current-sheet pattern, as shown for peak current (i) in phase A and (ii) in phase B (one-third of a period later). Thus the stator m.m.f. F_1 produces a travelling wave of m.m.f. and air gap flux (often called a 'rotating field') moving at synchronous speed $n_s = f_1$ (rev/s) or angular speed $\omega_1 = 2\pi f_1$ for a three-phase supply of frequency f_1 to a two-pole machine; in general $n_s = f_1/p$ and $\omega = 2\pi f_1/p$ for a machine with p pole-pairs.

Let the rotor, rotating at angular speed ω_r, have a three-phase winding carrying currents of frequency f_2; then it has an m.m.f. F_2 rotating at angular speed $\omega_2 = 2\pi f_2$ with respect to the *rotor* body, and therefore at $\omega_r \pm \omega_2$ with respect to the *stator*. For a steady unidirectional torque to be developed, F_1 and F_2 must rotate in synchronism to preserve unchanging the torque angle λ. Thus $\omega_r \pm \omega_2 = \omega_1$ is the essential running condition.

Synchronous machine The rotor is d.c. excited, so that F_2 is 'fixed' to the rotor body; then $\omega_2 = 0$ and $\omega_r = \omega_1$. The rotor must therefore rotate synchronously with the stator travelling-wave field. The torque angle accommodates to the torque demand up to a maximum for the torque angle $\lambda = \pi/2$ rad. The machine can operate in both generator and motor modes by simple reversal of the torque angle.

Induction machine The rotor winding, isolated and closed, derives its current inductively from the stator. If the rotor spins at synchronous speed, its conductors move with the stator field and no rotor current can be induced. However, if ω_r is less than ω_1 by a fractional 'slip' $s = (\omega_1 - \omega_2)/\omega_1$, the rotor conductors lie in a field changing at slip frequency $s\omega_1$, and currents of this frequency are induced to provide an m.m.f. F_2 travelling around the rotor at this frequency. This gives $\omega_r = \omega_2 = \omega_1$, the required condition. Torque is developed for any slip s other than zero (synchronous speed), with F_1 and F_2 mutually displaced by the torque angle. By driving the machine above synchronous speed the slip and torque are reversed, and the machine generates.

Fixed-axis gap flux In the usual constructional form (*Figure 20.24*(*b*)), the gap flux is produced by the stator m.m.f. F_1, generally with the poles salient. The rotor m.m.f. F_2 has the optimum torque angle $\lambda = \pi/2$ rad. As the rotor spins, the current of an individual conductor is reversed as it passes from the outward- to the inward-directed region of the current sheet in the process of *commutation*. In consequence the machine can develop torque at standstill and at any practicable speed.

D.c. commutator machine Both stator and rotor windings are d.c. excited. The torque is smooth and continuous, with simple control of speed and both motor and generator operation. In small d.c. motors the stator may be magnetised by permanent magnets, dispensing with the exciting winding.

Single-phase commutator machine As simultaneous reversal of F_1 and F_2 does not affect the direction of the torque, the d.c. motor can be operated on a one-phase supply with the stator and rotor windings connected in series. However, the torque has a double-frequency pulsation about a unidirectional mean.

Other forms There are many variants, especially in small and miniature machines. Single-phase induction motors require special starting techniques ('split-phase', 'shaded-pole'). Some operate on alignment torque ('reluctance', 'hysteresis', 'brushless', 'stepper'). A few large homopolar d.c. machines have been devised.

Disc motors The geometry shown in *Figure 20.23* has been applied with permanent-magnet multipolar field systems to machines that must have a very short axial length, e.g. for driving cooling fans for motor vehicles.

Linear motors These are most usually based on the three-phase induction-motor principle.

20.3.2 D.c. motors

In spite of the fact that a standard d.c. motor costs 1.5–2 times as much as a cage induction motor, and that alternating current is universal for general power distribution, the scope for d.c. motors is still large, particularly for drives requiring speed control or some other special feature. D.c. motors are built in all sizes from fractional-kilowatt up to about 4 MW, the upper limit being imposed by commutation problems.

In addition to the standard types of motor (shunt, series or compound) which are normally fed from a constant-voltage d.c. supply, many modern d.c. motors incorporate thyristors enabling them to operate from a standard a.c. supply. The thyristors rectify the alternating voltage and, by gate control, enable the resulting direct voltage to be varied, thereby giving a wide range of speed control.

20.3.2.1 Characteristics

The connections and basic torque–current and speed–torque characteristics of standard shunt, series and compound motors are given in *Figure 20.26*. Motors with separately excited fields are often used for control purposes.

When connected to a d.c. supply of voltage V a motor takes a current $I = P/V\eta$ when developing a useful output power P. The efficiency η varies with the rating: typical rated currents are given in *Table 20.6* for a range of operating voltages. The rotational e.m.f. in an armature of resistance r over the brushes and carrying a current I_a is $E = V - I_a r_a$. The power-conversion relation is $EI_a = M\omega_r$, where M is the torque and $\omega_r = 2\pi n$ is the angular speed. Then

$$E = V - I_a r_a = 2(p/a)nN\Phi = Kn\Phi \quad M = K\Phi I_a/2\pi$$

where Φ is the flux. Here $K = 2(p/a)N$ involves the number of pole-pairs (p), the total number of turns (N) on the armature and the number of pairs of parallel paths (a) of the winding. For simple lap and wave windings, $a = 1$ and $a = p$, respectively. In a shunt-connected machine the total input current I is the sum of the armature and field currents, $I = I_a + I_f$. In a series-connected machine the same current I flows in both field and armature windings.

Shunt excitation The field winding has the constant terminal voltage applied to it so that the flux will be approximately constant and the torque will be proportional to the armature current. Speed is proportional to E and is approximately constant since $I_a r_a$ is normally not more than 3–5% of V at full load. In practice, the flux will, owing to armature reaction, be distorted when the machine is loaded, the flux density under the leading pole tips being increased and that under the trailing pole tips decreased. Owing to saturation of the iron in the teeth under the leading pole tips, the increase in density there is less than the decrease in density under the trailing tips, so that there is a net reduction of flux of 2–3% at full load. The drop in speed from no load to full load is therefore less than

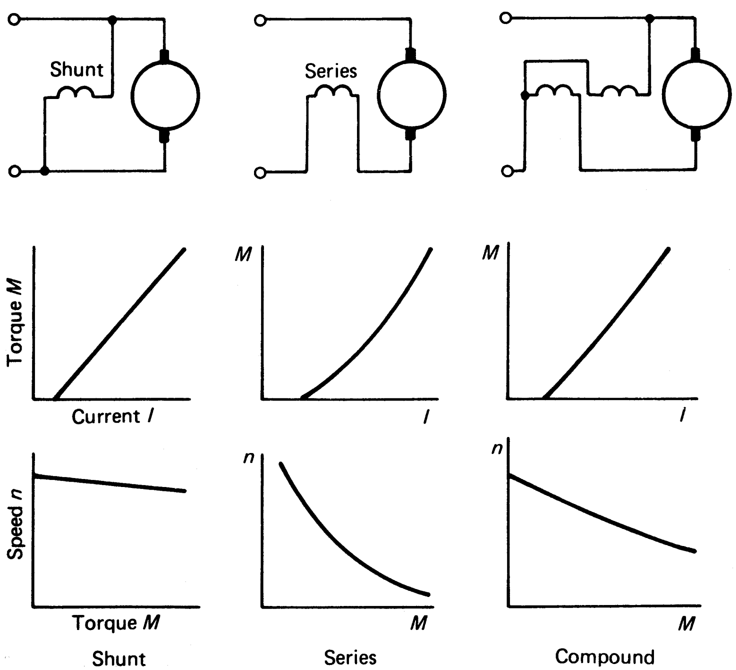


Figure 20.26 D.c. motors: basic characteristics

would be expected from the speed equation—in some cases this action even gives a rising speed characteristic, a disadvantage which can be corrected by the use of a small series field winding. Increase in temperature from cold to hot raises the resistance of the field winding and reduces the current in it, thereby reducing the flux and increasing the speed for a given load.

Motors designed to give a wide range of speed control by variation of the field or to be used in situations where sudden and heavy load fluctuations occur are often fitted with a compensating winding in the pole face to neutralise the effect of armature reaction and prevent flux distortion; such windings are connected in series with the armature so that neutralisation is correct at all loads.

The shunt motor can be used for the drive of machine tools, pumps and compressors, printing machinery and all forms of industrial drive requiring a speed which is approximately constant and independent of the load.

Separate excitation This is applied widely to control motors, particularly where speed variation is required over a considerable range. For a given field voltage, the characteristics resemble those of a shunt motor. Separate excitation (but without the facility of field control) applies to small motors with permanent-magnet field systems.

Series excitation The field m.m.f. is produced by the motor current so that at low currents where the iron is unsaturated Φ is approximately proportional to I, but at high currents (1.5–2 times full-load current) Φ tends to become constant as the iron saturates. The starting torque, when the current is above the full-load value, is thus greater than for a shunt motor with corresponding full-load current and flux. The speed at heavy currents drops to a low value on account of the increase of flux.

The high starting torque and falling speed–torque characteristic make the series motor suitable for driving hoists and cranes, for traction and rope haulage and for driving fans, centrifugal pumps or other apparatus where there is no danger of the motor being run light.

Compound excitation Where a drop in speed between no load and full load greater than that obtainable with a plain shunt motor is required, a series winding may be added to assist the shunt winding, giving a speed–torque characteristic having any desired amount of droop. Instability of a shunt motor due to the weakening of the field by armature reaction can also be cured by the addition of a series winding known as a *series stability* winding. The chief application of the compound motor arises when the motor is used in conjunction with a flywheel—a fairly steep droop to the speed–torque characteristic is then necessary in order to enable the flywheel to give up its stored energy when a sudden load comes on. Compound motors are also used for driving pumps, compressors and other heavy-duty machinery.

If the series winding is arranged to oppose the shunt winding, a motor with a flat or even a rising speed–torque characteristic can be designed, such a motor being known as a differentially compound motor. Such motors are, however, very rarely used.

20.3.2.2 Construction

Motor design aims at economy of materials and the reduction of loss. Further, as most industrial d.c. machines are fed from an a.c. supply through thyristors, an all-laminated magnetic circuit reduces the effect of supply harmonics. There is increasing use of square frames, either of rolled steel or of laminations.

Poles Constructed separately, the pole body and shoe are assembled from laminations, or a solid body is provided with a laminated shoe. The poles are bolted to the yoke and retain the field windings. Commutating poles may be solid or, more usually, laminated. Motors of rating below about 10 kW may have half as many commutating as main poles.

Field windings Main *shunt-field* windings are of circular- or rectangular-section wire, insulated and wound on a former. The whole is then taped, impregnated, slipped on to the pole and held by the pole-shoe. Large machines may have the turns wound on a bobbin of pressboard or of steel lined with micanite. *Series windings* to carry currents exceeding 50 A are more generally of copper strip wound on edge, and a similar construction is used for *compole* windings.

Armature core This is built from core-steel laminations (0.35–0.6 mm), coated on one side with an insulating varnish and bolted or clamped between thick end-plates. For diameters up to about 1 m the stampings may be made in disc form; above this size they are in sectors keyed to the shaft hub. If the core length exceeds about 20 cm, radial ducts are provided, each 5–6 cm. Axial ducts are employed with small machines. Machines of ratings up to 50 kW may have slots skewed to reduce noise.

Commutator and brushgear The commutator is conventionally made by assembling hard-drawn copper sectors inter-leaved with 0.7–2 mm sheet mica, these separators being 'undercut' by about 1 mm. The brushes, of a suitable carbon/graphite content, are mounted in boxes with spring loading to hold them against the commutator surface with a medium to strong pressure depending on the application. The circumferential brush width is typically 2–3 sector widths (10–20 mm) and about 30 mm axially. One brush-arm per pole is employed except for certain four-pole wave-wound machines which have two brush-arms in adjacent positions to facilitate maintenance.

Armature winding Almost all motors other than very large machines use a simple two-circuit wave-winding. Conductor wires of section 1 mm^2 or less are circular and enamel insulated, the conductors of a coil being taped half-lap before being placed in the slots. Larger machines have former-wound coils of rectangular-section conductors, insulated by half-lapped tape. The coils are assembled from the conductors and taped before insertion. The slots are lined with pressboard, and the two layers separated by a pressboard spacer. Various recent developments in epoxy resins have made possible the use of better insulants at higher temperatures. Typical slot sections are shown in *Figure 20.27*. The coils are contained in the slots by wedges or by steel or glass-cord binding.

In small wire-wound armatures the coil ends are soldered direct into grooves in the commutator sectors. For strip windings, the sectors carry 'risers' for connection to the ends of the coils.

Bearings End-shield bearings are usual for ratings up to 250 kW, above which pedestal bearings are employed. Journal bearings are fitted where ball or roller bearings are unsuitable.

Enclosure and ventilation Recent standards define the conditions to be met by machines for a variety of ambient conditions (e.g. drip-proof, splash-proof, hose-proof, weather-proof, and flame-proof).

Cooling air is drawn into the machine directly or through cowls, pipes or screens except in totally enclosed machines, for which there is no communication between the outside air

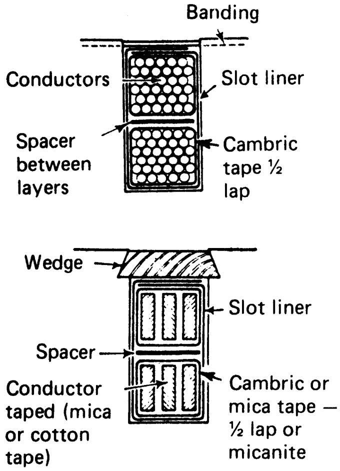


Figure 20.27 Typical slot sections

and the interior of the motor. As cooling must then be solely by dissipation from the outside of the carcass, the rating is limited to about 75 kW. Cooling can be improved by shaft-mounted fans, by inlet and outlet pipes or by closed-circuit ventilation. In the latter case the fan-assisted air circulating through the machine is cooled by passing it through an air/air (c.a.c.a.) heat-exchanger or an air/water (c.a.c.w.) exchanger mounted on the motor frame.

20.3.2.3 Commutation

Modern motors can be made to commutate sparklessly up to 1.5–2 p.u. load. To secure this behaviour, commutating poles are fitted to all motors in the integral-kilowatt range.

Compoles Before the commutator sectors connected to a particular armature coil reach a brush, the coil will be carrying current in a certain direction; while the sectors connected to the coil are passing under the brush the coil will be short circuited by the brushes, and after leaving the brushes the coil will be carrying current in the opposite direction. The current must thus be reversed during the time for which the coil is short-circuited (the time of commutation). At normal commutator peripheral speeds of 10–30 m/s this time will usually lie between 2.5 and 0.2 ms. Owing to the inductance of the coil, the current cannot reverse in this time without some external assistance; it is necessary to induce in the short-circuited coil an e.m.f. to assist the change of current, i.e. an e.m.f. in a direction opposite to that of its e.m.f. when, after leaving the commutating zone, it enters to next pole region. Compoles are therefore fitted to influence the coil-sides undergoing commutation; the compoles have an excitation proportional to the armature current and the polarity of the successive main pole. The arrangement (i) neutralises the main armature m.m.f. in the commutating zone and (ii) produces the necessary commutation flux density there. The compole flux required is proportional to the armature current, and the compole windings are therefore connected in series with the armature.

Commutation in a machine not fitted with compoles can be effected by brush-shifting backward (against the direction of rotation) so that the commutating flux is provided by the succeeding pole. This cannot be done if the motor is required to run in both directions.

Sparking Sparking causes burning and pitting of the commutator surface, so intensifying the trouble. The origins of sparking, and the remedies, are as follows.

Mechanical defects The chief causes are: the sticking of brushes in holders; 'high' or 'low' commutator bars; flats, irregularities or dirt on the commutator surface; badly bedded brushes. The commutator can be cleaned while running with a commutator stone, but irregularities make it necessary to grind the commutator. Small sparks between sectors, starting a few centimetres away from the brush, are probably due to partial short circuits caused by dirt on the mica surfaces. Correct bedding is essential to ensure that the brushes carry current over the whole of their contact surface. It can be carried out by adjusting the brush springs to give a fairly heavy tension and passing, first coarse and finally fine, glass-paper between the brush and the commutator; care must be taken to remove all trace of dust after the operation.

Incorrect brush position The correct position of the brush rocker is usually marked by the manufacturer, but it may tend to move in service. If the marking is obliterated, the correct position can be found by determining the neutral position. If the machine has no compoles the brushes will have to be moved backward from the neutral position by two or three sectors, the best position being found by trial. With a compole motor the brushes should be almost exactly on the neutral position, although they may be moved forward by a small distance so that the compole flux adds to that of the preceding main pole and prevents any tendency of the speed to rise as the load comes on, the compole winding acting as a series stability winding. Incorrect spacing between adjacent brush arms may occur; this should be checked very carefully by a steel tape, not by counting the sectors.

Winding defects Open- and short-circuited coils in the armature will cause severe sparking. An open-circuited coil will cause sparks to go all round the commutator with severe burning at the bars connected to the open-circuited coil. A short-circuited coil will cause overheating of the faulty coil and segments and is often due to molten solder falling between the commutator risers. In either case the presence of a fault can be verified by carrying out a drop test.

Incorrect compole excitation The compole strength can be checked by the brush-drop or black-band tests. Incorrect strength can be remedied by inserting or removing thin steel shims between the back of the compole and the yoke: removing a shim increases the air gap and weakens the compole. Weakening can also be obtained by shunting a resistor diverter across the compole winding, but this is not fully effective in transient conditions.

Thyristor-assisted commutation The speed and output limitations imposed by commutation have encouraged attempts to use thyristors to perform the switching function, leaving the brush to act as a simple current collector. Success would enable the voltage per sector (30–40 V peak, 15–20 V mean) to be raised, fewer sectors could be employed and high-power high-voltage d.c. machines achieved. Promising results have been obtained with the arrangement of *Figure 20.28*. The armature coils are connected to two separate commutators with alternately 'live' and 'dead' sectors, the latter shown shaded. In the diagram, brush D has just come fully into contact with active sector 2, and thyristor T_x has been turned on; the e.m.f. E_c in the coil that has just been commutated must, acting through brush A, be enough to turn off thyristor T_y. Separation of the brushes into two parts, AB and CD, is

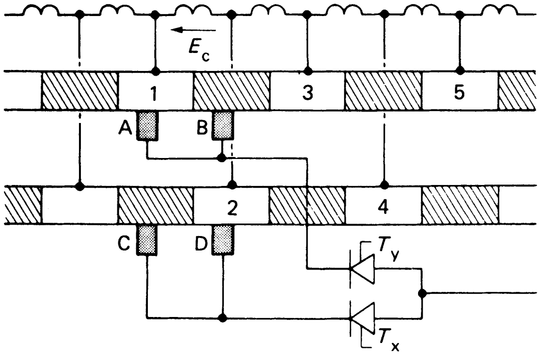


Figure 20.28 Thyristor-assisted commutation

necessary to ensure that the part-brush is fully on to an active sector before it begins to carry current; otherwise contact damage occurs. Although the switching procedure is satisfactory, current collection difficulties, causing commutator damage and arising from the transient current changes, have not yet been overcome.

20.3.2.4 Starting

If a d.c. motor is to be started from a constant-voltage supply, its normally low resistance must be augmented to limit the current to a safe value, e.g. 1.5–2 times full-load value. The starting rheostat is cut out as the motor speed rises and the counter-e.m.f. imposes a limit on the current.

Shunt motor For maximum starting torque, the field must be fully established at starting; the starting rheostat is therefore connected only in the armature circuit. The total starting resistance R is determined by the maximum starting current $I = V/(R + r_a)$, where the armature resistance r_a has the typical values:

Motor rating (kW)	1	2	5	10	50	100
Armature resistance (Ω)						
at 110 V	1.4	0.8	0.2	0.1	0.08	0.006
at 230 V	6.0	3.0	0.8	0.5	0.10	0.025
at 460 V	22	13	3.0	2.0	0.50	0.010

Traditional face-plate starters are obsolescent. Usually a fully automatic push-button system is employed.

Series motor The starting rheostat is in series with the motor, the resistance of which is about twice the value given for r_a in the table above. Industrial series motors are often used in cranes and hoists, and the starting resistance is commonly utilised also for speed control.

20.3.2.5 Speed control: standard motors

A prime reason for the continued use of d.c. motors is the possibility of simple and economic speed control over a wide range. Reference to the expression in Section 20.3.2.1 shows that speed can be controlled by varying the applied voltage, the flux or the armature resistance.

Shunt motor In a shunt machine the variation of the supply voltage does not greatly affect the speed because the result is also a comparable change in flux.

Field control The field current (and therefore the flux) is varied by adding resistance into the field circuit (*Figure 20.29*). For a given setting of the field regulator the speed is approximately independent of the load, giving a series of flat speed–torque curves. The upper limit of speed for a standard motor is about 30–50% above normal, fixed partly by mechanical considerations and partly by weak-field flux distortion. However, a 3:1 range can be obtained by suitable design, although very low speeds cannot be obtained in this way. For a given armature current, a flux reduction raises the speed but reduces the torque to yield a *constant-power* characteristic, *P* in *Figure 20.29*. The loss in the field-regulator resistance is small, so that the efficiency of the machine is not affected.

Armature-circuit resistance control The speed for a given value of resistance added into the armature circuit falls with the load, giving a group of speed–torque characteristics (*Figure 20.29*). The flux remains constant so that for a given current the torque will not vary with speed (*constant-torque* characteristic); power output therefore falls proportionately with speed. Owing to the losses in the added resistance the efficiency is low and approximately proportional to the speed: e.g. with a 60% speed drop the efficiency will be a little less than 40%. The resistance required is $R = x(V - I_a r_a)/I_a$ where x is the desired fractional speed reduction and I_a is the armature current at the reduced speed, the latter depending on the type of load.

Diverter control With series armature-circuit resistance control a large resistance is required to obtain low speed on small load, and the machine is unstable in that there is a large change of speed with load. This can be overcome by adding a variable resistor in parallel with the armature circuit. The efficiency is low, and the method is justified only as a temporary measure or with very small motors.

Ward–Leonard control The main d.c. motor M is separately excited with a constant field current, the armature being supplied with a controlled variable voltage obtained from a d.c. generator G driven by a constant-speed motor (*Figure 20.30*). Control of the generator field varies the main motor armature voltage and consequently the armature speed: a range of 25:1 is obtainable, and reversal is possible if the generator field excitation can be reversed. Each setting of the generator field provides for a 'shunt' operating characteristic in the main motor, with a torque proportional to the armature current. The method is economical in energy and is applicable to mine winding gear and machine-tool drives, but it is high in capital cost; consequently for smaller ratings the motor–generator is replaced by a thyristor bank.

Series motor The three basic methods of speed control are shown in *Figure 20.31*.

Field control This is obtained by a diverter rheostat in parallel with the field circuit. Only on small machines is a continuous speed variation obtainable, and the diverter must generally be varied in one or two discrete steps. An alternative, commonly used with traction motors, is to tap each field winding so that part of the winding is cut out to reduce the field m.m.f. and raise the speed. Both methods can give only a speed rise. In some cases it is possible to arrange the field windings in two groups, which can then be connected in series or parallel, the latter giving 20–30% higher speed for a given current than the former.

Resistance control A variable resistor in series with the motor reduces its terminal voltage and lowers the speed.

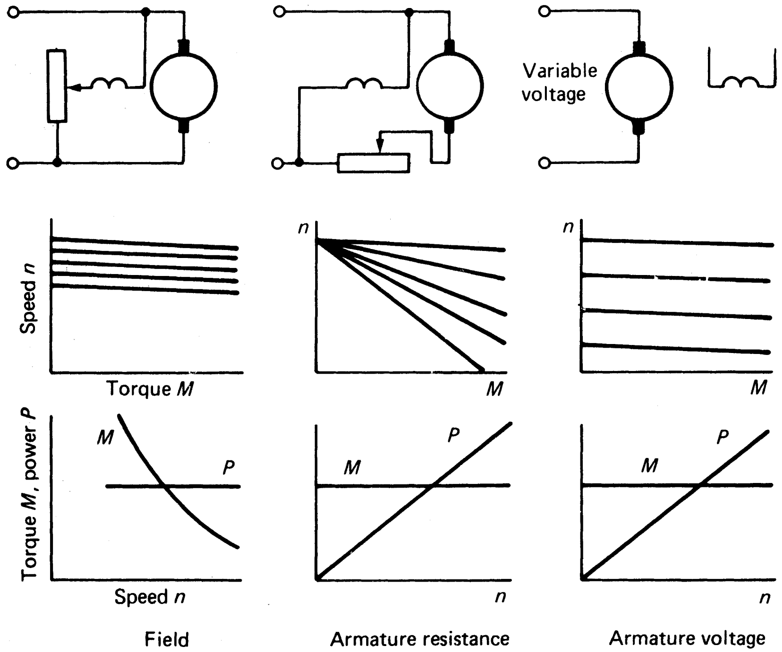


Figure 20.29 Shunt motor: speed control

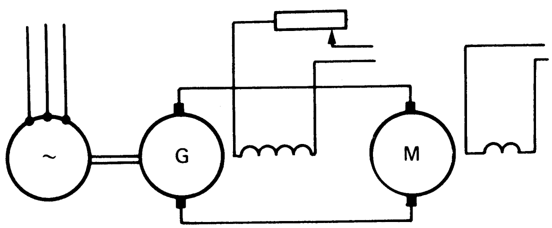


Figure 20.30 Ward–Leonard control

Although the method involves I^2R loss, it is commonly employed for cranes, hoists and similar plant, the resistance steps being used also for starting.

Series/parallel control If two series motors are connected mechanically to ensure the same speed for each (as is usual in d.c. traction systems) series/parallel voltage control can be obtained by connecting the motors electrically in parallel or in series, the former giving full voltage and the latter one-half voltage to each motor. Intermediate speeds can be obtained by resistance or field control. The full-parallel speed is, for a given motor current, approximately twice that in full-series.

A scheme known as *parallel/series* control is sometimes applied to battery vehicles, the battery being arranged in halves that can be paralleled for starting and low speed, and in series for full speed.

20.3.2.6 *Speed control: thyristor-fed motors*

A separately excited motor may be fed from a constant-voltage a.c. supply through thyristors, which rectify the current and also (by delaying the commutation angle α by controlled gate signals) furnish a variable-voltage supply to the armature. The field current is obtained from the a.c. supply through semiconductor diodes or thyristors. The main thyristor equipment thus replaces the motor-generator set of the Ward–Leonard speed control in ratings up to about 500 kW and, being static, is more economical and commercially viable even down to fractional-kilowatt sizes.

Connections The choice of thyristor circuit is a compromise between cost (i.e. the fewest thyristors, which with their firing circuits are more expensive than diodes) and operational difficulties arising from harmonic production or poor commutation, both accentuated by the use of a small number of thyristors. For economy, half-controlled circuits in which half the units are thyristors and half are diodes are common, but such circuits cannot regenerate.

The thyristors may be fed direct from an a.c. supply of r.m.s. voltage V_a as in *Figure 20.32*. The mean direct voltage available with zero commutation delay ($\alpha = 0$) is $V_{a0} = 0.9\,V_a$ for the one-phase and $V_{d0} = 0.43\,V_a$ for the three-phase arrangement. With commutation delayed by angle α the mean direct voltages are

Fully controlled $V_d = V_{d0} \cos \alpha$

Half-controlled $V_d = V_{d0} \frac{1}{2}(1 + \cos \alpha)$

The one-phase half-controlled arrangement of *Figure 20.32(a)* is very widely used for ratings up to about 5 kW. The current tends to be discontinuous, causing bad commutation, and sufficient inductance should be included in the circuit to avoid this except at large delay angles; a separate inductor may be used or, in the smaller ratings, the motor winding may be designed to have a sufficiently high inductance.

The three-phase half-controlled circuit (*b*) has been used for outputs up to about 200 kW but recent practice tends towards the use of the fully controlled circuit from about 25 kW up to 1000 kW. The fully controlled circuit (*c*) gives rise to a 300 Hz ripple on the direct voltage but the half-controlled circuit gives 150 Hz over most of its range, rising to 300 Hz when α approaches zero.

The transformer-fed networks in *Figure 20.32* give the designer a free hand in choosing the operating voltage of the d.c. motor. The one-phase centre-tap connection (*d*) has

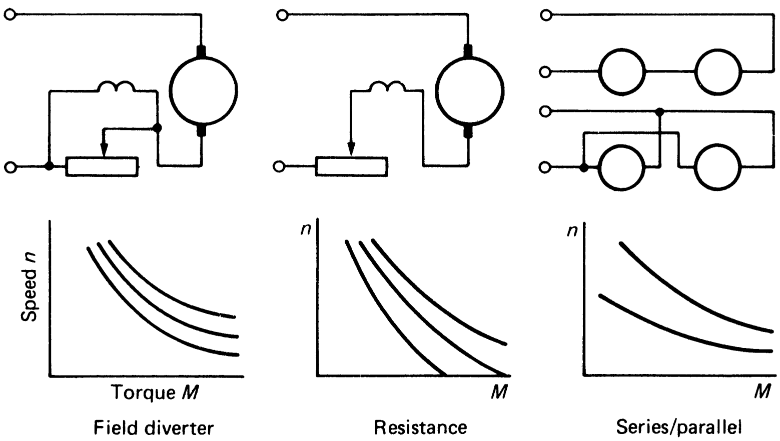


Figure 20.31 Series motor: speed control

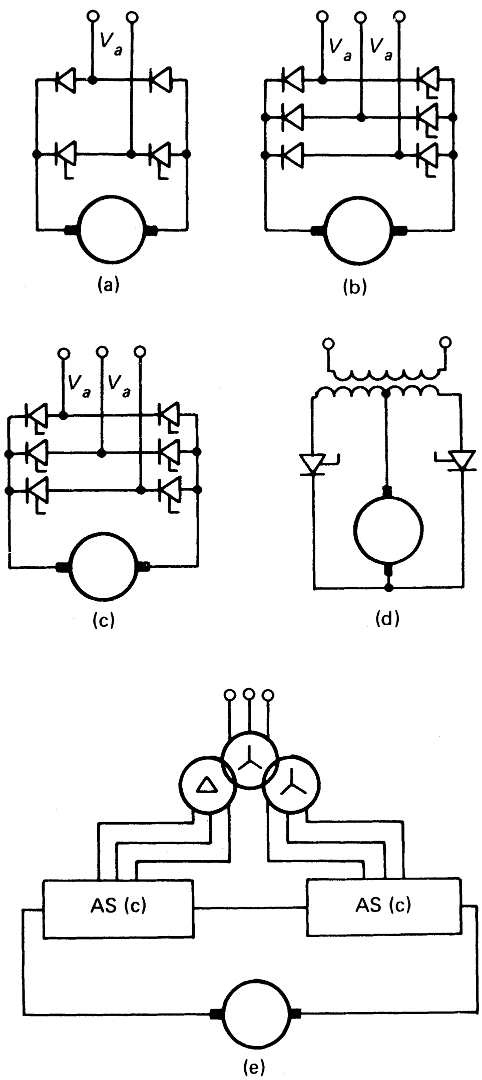


Figure 20.32 Thyristor control

the advantage over the one-phase bridge of making regeneration possible.

By connecting in series two six-pulse units, the supplies to which are obtained respectively from delta- and star-connected windings of a three-winding transformer (*Figure 20.32*(*e*)) a 30° phase-shift is obtained giving a 12-pulse operation and a 600 Hz ripple of small amplitude. Such an arrangement is generally desirable for outputs above 1 MW and up to 5 MW (the upper limit for a d.c. motor).

The field supply for the motor is generally obtained from the a.c. supply through a 1-phase bridge or centre-tap connection using diodes. If field control is desired in addition to armature voltage control it can be achieved by a conventional field resistor or by using thyristors instead of diodes.

Harmonics In addition to the harmonics on the d.c. side which may interfere with commutation, harmonics also appear on the a.c. side and can cause interference with communication and control circuits and difficulties with other plant connected to the system, particularly overloading of shunt capacitors and possible resonances at the 11th and 13th harmonics. For these reasons the rating of plant connected to a single point on the supply is limited by the Supply Authority, typically from 250 kW at 0.4 kV to 3 MW at 33 kV for six-pulse units, and from 750 kW to 7 MW for 12-pulse units.

Motor construction As a result of harmonics on the d.c. side, a motor may have to be derated by 15–20%. To minimise commutation troubles, compoles and main poles and yokes may all be laminated.

Thyristor firing The signals applied to the thyristor gates are usually high-frequency pulses (2–8 kHz). For large units the pulse current may be 1–2 A in amplitude with a rise-time less than 1 µs. The electronic equipment to generate the signals comprises a power supply, timer and phase-shift units, pulse generator and amplifier, and output unit. The control of the gate pulse may be manual, or by signals from a closed-loop control system.

20.3.2.7 Braking

Rheostatic, regenerative and plug braking are applicable, but they cannot hold a motor at rest: for that a mechanical brake is necessary.

Shunt motor The electric braking methods are shown in *Figure 20.33*.

Rheostatic braking The field connection to the supply is maintained but the armature is disconnected and then reconnected on to a resistor. The machine generates, dissipating power in the resistor. The braking effect is controlled by varying the field current. For a total armature-circuit resistance R, the armature current is $I = E/R = k_1 n\phi/R$ and the braking torque is $M = k_2 EI/n = k_3 n\phi^2/R$. If the excitation is constant, then the braking torque is directly proportional to the speed n and decreases as the motor speed falls.

Plugging The armature connections are reversed, and the motor torque tends to retard the machine and then run it up in the opposite direction. The applied voltage and the armature e.m.f. are additive, so that a resistance of about twice starting value must be included to limit the current. For a total armature-circuit resistance R, the armature current is $I = (V + E)/R = (V + k_1 n\phi)/R$ and the braking torque is $M = (k_4\phi + k_3 n\phi^2)/R$. With constant excitation the braking torque is $k_5 + k_6 n$. Braking by plugging gives a greater torque and a more rapid stop, but current is drawn from the supply during the braking period, and this energy together with the stored kinetic energy has to be dissipated in resistance. A relay must be provided to open-circuit the motor at rest in order to prevent it from running up in reverse.

Regenerative braking If a load (such as a descending hoist) overruns the motor at a speed higher than normal, the counter-e.m.f. E exceeds the terminal voltage V and the machine generates. This is a very convenient method of 'holding' a load, but not at low speeds unless excessive field current is supplied.

With *thyristor-controlled* motors regeneration is possible if fully controlled connections are used. It is necessary to reverse the polarity of the motor terminals relative to those of the thyristor unit. This can be done by reversing either the armature or the field terminals at the moment of entering regeneration, the reversal being effected by conventional reversing contactors. Armature reversal requires about 150 ms but field reversal may require up to 2000 ms. Where a very rapid reversal is required it is necessary to employ separate thyristor units for motoring and regenerating, these being connected in 'anti-parallel'. Only switching of the gate pulses is then required, a process that can be achieved in about 10 ms.

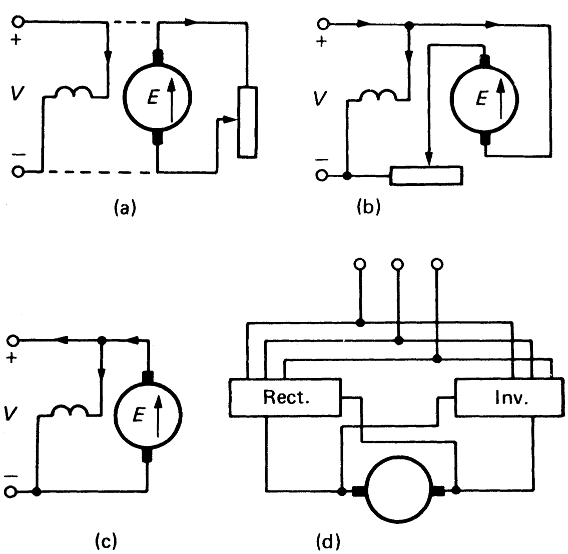


Figure 20.33 Electric braking of a shunt motor: (a) rheostatic; (b) plugging; (c) regeneration; (d) thyristor

Series motor The electric braking methods are shown in *Figure 20.34*.

Rheostatic braking The motor acts as a series generator loaded on resistance. It is necessary to reverse the field connections at the instant of changing from motoring to braking. Further, the load resistance must be below a critical value if the machine is to self-excite. In practice the starting resistance, the value of which is well below the critical, is used for braking. The braking torque is approximately $M = kI^2$.

Plugging The conditions are generally similar to those in the shunt machine.

Regenerative braking This is not practicable with series motors. In traction, regeneration is sometimes effected by separately exciting the motors.

20.3.2.8 Design data

Some general and typical data are given here. Small motors up to 5 kW at 1000 rev/min normally have two poles, up to 50 kW four poles and up to 200 kW six poles. Larger motors have more, the number being such that the 'speed frequency' is 20–30 Hz and the pole-pitch between 45 and 55 cm.

The rated output power P is related to the main dimensions (diameter D, length l), the speed n and the specific magnetic and electric loadings B and A by

$$D^2 l n = P/\pi^2 \eta BA$$

where B is the mean gap flux density of value up to about 0.55 T and A varies between 5 and 35 kiloampere-conductors per metre of armature periphery.

The maximum safe peripheral speed is 30–40 m/s for the armature and 25–30 m/s for the commutator. The number of slots is about six per pole for fractional-kilowatt motors and 10–14 per pole for machines of 100 kW. The total current per

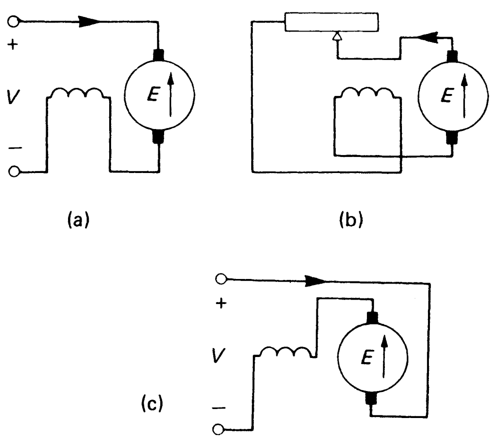


Figure 20.34 Electric braking of a series motor: (a) motoring, $E < V$; (b) rheostatic; (c) plugging $E > V$

slot is about 700 A for the latter rating. The number of slots must suit the winding required. A simple wave winding is used for nearly all industrial motors except in ratings of several hundred kilowatts for which lap (parallel-circuit) windings with equalising connectors may be used. The number of conductors is $Z = E/(p/a)n\phi$; the number of coils and commutator sectors is $2pV/e$, where the mean voltage e between sectors is usually between 12 and 15 V.

The field m.m.f. is 1.15–1.25 times the full-load armature m.m.f., and in designing the magnetic circuit the pole pleakage (about 15%) must be taken into account. The length of the air gap is governed by the requirement that the field distortion shall not be excessive.

20.3.2.9 Disc motors

The disc-armature machine has been developed for special applications such as small pumps, freezer-compressor drives, domestic sewing machines, computer spool drives and light battery vehicles. The basic geometry can be realised in the diagrams shown in *Figure 20.35*. A ring of permanent magnets of alternate polarity provides the axial field. In (i), two magnet rings M flank the armature A. In (ii), one of the magnet rings is replaced by a flux-conveying steel 'yoke' Y. In (iii), the yoke is carried by the armature, increasing its inertia but reducing the effective air gap length. The wave or lap winding (of which a single turn is shown) has an angular span equal to the angular pole-pitch. A multipolar structure, in which a front-face conductor is paired with another on the back of the armature disc, is employed to reduce the length of the 'overhang'. In small low-inertia motors the winding is punched from a copper or aluminium sheet and then placed on either side of an epoxy-resin-impregnated glass-fabric disc. The resin is then given a completion cure. Larger motors have wire-wound armatures with face or barrel commutators.

The magnets are usually of sector rather than circular shape to increase the working flux density towards the outer radius, where it is the most effective. Consider a machine in which the magnets, set between outer and inner radii R and r, produce in this annulus a uniform mean flux density B. Then for an

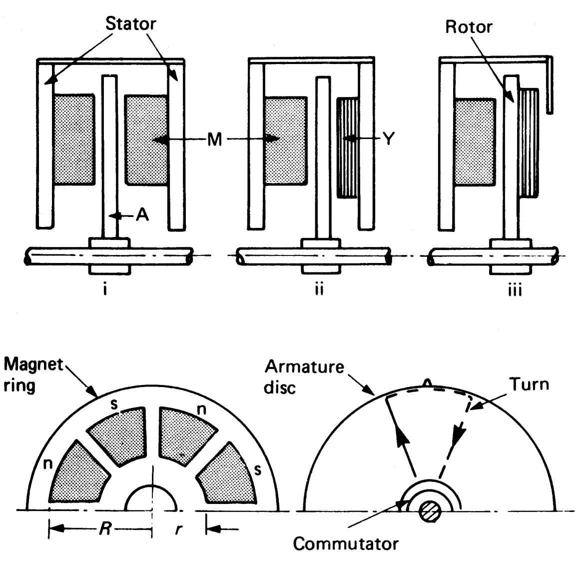


Figure 20.35 Elements of a disc motor

angular speed n and a current loading A (in A/rad) the e.m.f. in a conductor and the torque developed are respectively.

$$E_r = \pi(R^2 - r^2)Bn \quad \text{and} \quad M_e = \tfrac{1}{2}(R^2 - r^2)BA$$

showing the influence of the outer radius in increasing the output. However, R is limited by rotational stress, flexure of the disc and any operational constraints on the armature inertia.

Homopolar motors A homopolar d.c. motor is an embodiment of the Faraday disc. The voltage is inevitably low (less than 200 V) and the current high. Such machines as generators have been built to supply electromagnetic pumps and electrochemical processes requiring very large currents. Homopolar motors have also been built, notably a 2.5 MW 200 rev/min machine for a power-station pump where the motor has a superconducting field system developing a working flux density of nearly 4 T by means of an m.m.f. of 3×10^6 A-t.

20.3.3 Three-phase induction motors

The great majority of industrial, commercial and agricultural electric motors above the fractional-kilowatt size are three-phase induction machines, on account of their simple, cheap and robust construction and the almost universal availability of three-phase supplies.

The induction motor has a 'shunt' speed–torque characteristic, the operating speed n falling slightly below the synchronous speed $n_s = f/p$, where f is the supply frequency and p is the number of pole-pairs for which the three-phase stator winding is arranged. The drop in speed below n_s is the *slip*, given by $s = (n_s - n)/n_s$. The slip increases from nearly zero on no load to 0.03–0.05 on full load. Most industrial motors are four-pole machines with a synchronous speed of 1500 rev/min, but two-pole machines ($n_s = 3000$ rev/min) are sometimes of use, and lower speeds obtained with six, eight or more poles may be used in large ratings.

The *cage* motor has a rotor winding internally short circuited on itself with no external access. The *slip-ring* motor has the polyphase rotor winding brought to three slip-rings so that connection can be made to it for starting or speed control; for normal operation, however, the rotor winding is short circuited. In each type the stator carries a conventional three-phase winding, fed from the main supply and generally delta-connected. Almost all induction motors are of the cage type, with slip-ring machines used normally only in ratings above about 100 kW.

20.3.3.1 Operating principle

Currents in the stator windings set up an air gap travelling-wave magnetic field of almost constant magnitude and moving at synchronous speed. The field cuts the rotor conductors at slip speed, inducing a corresponding e.m.f. and causing currents to flow in the short-circuited windings. The interaction of these currents with the travelling-wave field produces torque to turn the rotor in the direction of the field. The magnitude of the rotor currents depends on the slip and on the impedance (comprising resistance, and inductive reactance proportional to slip) of the rotor windings. With the rotor running at synchronous speed, the rotor slip is zero, the rotor inductive reactive vanishes and, as the gap flux does not cut the rotor conductors, the induced e.m.f. is zero; as a consequence there is no rotor current and no torque is developed. Since there must always be a small torque to overcome mechanical loss, the motor cannot quite achieve synchronous speed. As the motor is loaded, it slows so that the slip becomes a small finite quantity, rotor e.m.f. is developed and rotor current flows; the rotor circuits are mainly resistive but a small inductive reactance is introduced. The various interactions yield the torque-speed curve A in *Figure 20.36*. It has been taken into the region of reverse rotation (slip greater than unity), for which the machine acts as a brake. The normal working range of the machine as a motor is the region for small positive slips: here the torque-speed relation is almost linear, corresponding to that of the d.c. shunt motor.

Reversal of the direction of rotation of the motor is obtained by interchanging two of the stator terminal connections, thus reversing the direction of the travelling-wave field.

20.3.3.2 Equivalent circuit

The performance is most readily predicted with the aid of an equivalent circuit (*Figure 20.37*) assembled from the various resistances and inductances (i.e. magnetising and leakage) of the machine, taken as independent of current, frequency and saturation conditions. The essential parameters are as follows, it being assumed for convenience that the rotor and stator windings are identical; all electric-circuit quantities are *per phase*:

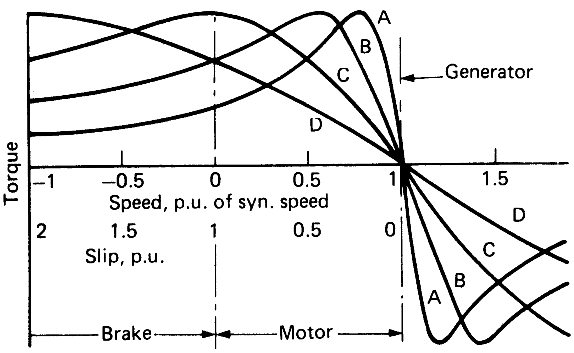


Figure 20.36 Three-phase induction motor: torque–speed characteristics

V_1	stator applied voltage
E_1, E_2	stator e.m.f., rotor e.m.f. at standstill
r_1, x_1	stator resistance and leakage reactance
r_2, x_2	rotor resistance and leakage reactance at supply frequency (corresponding to standstill, $s = 1$)
r_m, x_m	resistance representing core loss, magnetising reactance
I_1, I_2	stator current, rotor current
I_0	no-load current given by $\sqrt{(I_m^2 + I_c^2)}$, where $I_c = E_1/r_m$ and $I_m = E_1/x_m$

The basic equivalent circuit is shown in *Figure 20.37(a)*: it is similar to that of a transformer on short circuit except that the transformer ratio varies with slip (and therefore with the speed). With unity turns-ratio and a division of the rotor parameters by the slip s, equivalent circuit (*b*) is obtained. For easier calculation the approximate circuit (*c*) can be used, with an error not exceeding 2% or 3% provided that the operating conditions are not abnormal. The rotor resistance r_2/s has been split into r_2 for the rotor I^2R loss, and $r_2(1-s)/s$ in which the I^2R value represents the power conversion to the mechanical form.

Equations The following relations can be developed from the approximate equivalent circuit:

Rotor current:	$I_2 = V_1/[(r_1 + r_2/s)^2 + (x_1 + x_2)^2]^{1/2}$
Stator current:	$I_1 = I_2 + I_0$
Power division:	rotor input : rotor I^2R: gross output $= 1 : s : (1-s)$
Gross torque:	$M = V_1 I_2 (r_2/s)/2\pi n_s$

The peak torque, which is independent of the actual value of rotor resistance, is approximately

$$M_m = V_1^2/(x_1 + x_2)4\pi n_s \quad \text{at } s = r_2/(x_1 + x_2)$$

and its value is normally 2–2.5 times the full-load torque.

The losses in the machine comprise the core loss, stator and rotor I^2R loss, and mechanical loss in windage and friction. The no-load input current is 0.25–0.3 of the full-load current, at a lagging power factor in the range 0.15–0.2. At standstill on normal voltage the stator current is 4–6 times full-load current. Typical full-load values for conventional induction motors are:

10 kW motor:	p.f., 0.87 (4-pole), 0.75 (12-pole); efficiency, 0.85
1000 kW motor:	p.f., 0.94 (4-pole), 0.91 (12-pole); efficiency, 0.95

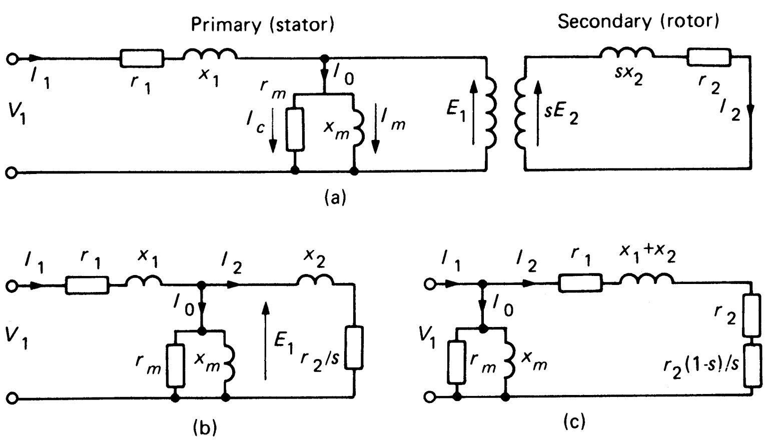


Figure 20.37 Three-phase induction motor: equivalent circuit per phase

20.3.3.3 Construction

As the working flux is alternating, the stator and rotor cores must be laminated, using plates 1.0–1.5 mm thick.

Stator The core comprises annular stampings for small and segmental plates for large machines; it is mounted in a welded steel frame that does not form part of the magnetic circuit.

The voltage for which the stator is wound is normally between 380 and 440 V for motors up to 250 kW. Larger machines are wound for higher voltages, the minimum economic sizes being about 250 kW for 3.3 kV, 400 kW for 6.6 kV and 750 kW for 11 kV.

Rotor Slip-ring rotors may be wound to develop an e.m.f. when stationary of about 100 V for small and up to 1 kV for large machines, with insulation to correspond. The winding of a cage rotor comprises copper or aluminium bars located in slots (usually without insulation) and welded or brazed at each end to a continuous end-ring. The joints between bars and end-ring may prove to be points of weakness unless carefully made. Small cage motors generally have aluminium bars and rings cast into the rotor in one piece, with the end-rings shaped to form simple fan blades. To minimise the magnetising current the air gap is made as small as is mechanically practicable, e.g. from 0.25 mm for small motors up to about 3 mm for large motors.

Enclosure This follows standard practice. The *flameproof* construction is available for motors used in hazardous atmospheres classified as ‘Division 1 Areas’ (mines, petroleum plants, etc.): it is a total enclosure with all joints flanged so that any flame generated by an internal explosion will be cooled by its passage through the joint and will not ignite external explosive gases. Cage motors, which have no slip-rings, are well suited to such situations, and they may be used without flame-proofing in ‘Division 2 Areas’ where flammable gas is not present unless there is some breakdown in the plant.

20.3.3.4 Starting

The factors of importance are (i) the starting torque and (ii) the starting current drawn from the supply. If the motor is to be started on full load, the starting torque must be 50–100% above full-load torque to overcome static friction and to ensure that the motor runs up in a reasonably short time to avoid overheating. Lower values are acceptable if the motor is always to be started on no load, and may be desirable in order to avoid too abrupt a start. The starting current should be as low as practicable to avoid overheating. Occasionally, supply authorities limit the starting current that may be drawn from the supply in order to avoid excessive voltage drops interfering with other consumers; it must also be remembered that, since torque is proportional to (voltage)^2, any voltage drop will significantly reduce the available starting torque. The torque and current may be expressed in terms of full-load values, but a more significant comparison between motors of different efficiencies and power factors is had by expressing the starting kVA in terms of the full-load output in kilowatts.

The curves A, B, C, D in *Figure 20.36*, drawn for different resistances, show that the rotor resistance has a major effect on the starting torque.

Slip-ring motor By adding external resistance to the rotor circuit any desired starting torque, up to the maximum-torque value, can be achieved; and by gradually cutting out the resistance a high torque can be maintained throughout the starting period. The added resistance also reduces the starting current so that up to 2–2.5 times full-load torque can be obtained with 1–1.5 times full-load current.

Cage motor For high efficiency, the rotor resistance must necessarily be low, and the starting torque on direct starting (when the motor is switched on to full voltage) is likely to be 0.75–1 times full-load torque with a stator input of 4–6 times full-load current. The table below gives typical values of the ratio (starting kV-A)/(full-load kW) for a range of conventional motors with direct starting are:

Range, kW:					
1–6	6–40	40–250	250–500	500–1500	1500–4000
kV-A/kW:					
10	9	8	7.7	7.4	7.2

These values are acceptable to supply authorities in most cases.

From the relations already given for the division of the power input to the rotor, the starting torque M_s for a starting current I_s is, in terms of the full-load values M_1 and I_1 and the full-load slip s_1, given by

$$M_s/M_1 = (I_s/I_1)^2 s_1$$

If direct starting is not admissible by reason of the initial current and/or the impulsive torque, then the voltage must be reduced for starting, bearing in mind that torque is proportional to (voltage)^2.

Series resistance A resistor in each line to the stator terminals can reduce the current to any fraction x of the direct-starting value, but the torque will be the fraction x^2. Although cheap and simple, this method is acceptable only for motors that start on no load.

Autotransformer Usually no more than three tappings (50%, 70% and 80%) are provided. With a tapping giving the fraction x of normal voltage, both current and starting torque are reduced to x times the direct-start values. The cost of the transformer and contactors is high, especially if special connections are used to avoid disconnection of the supply when tap-changing.

Star–delta switch This starts the motor in star connection, and changes it to the normal delta connections as the speed approaches normal. Both current and torque at starting are one-third of their respective direct-start values. All six stator phase-ends must be available. The momentary disconnection can cause significant transient effects during the change-over.

Current displacement This relies on the change of leakage reactance with rotor frequency to give enhanced starting and run-up torque, but with some sacrifice in pull-out torque. The inner cage in (*a*) and the inner region of the deep bar in (*b*) of *Figure 20.38* have a high leakage inductance, and at low speed (i.e. at higher rotor frequency) current is forced mainly into the outer cage in (*a*) and the upper region of the deep bar in (*b*). Thus most of the rotor current flows in the higher resistance outer cage or in the constricted region of the deep bar.

Solid state For loads with a rising torque/speed load demand, a ‘soft’ start can be obtained by including anti-parallel thyristors in the stator circuits, using phase control. At starting, stator voltage control can be obtained by appropriate triggering, or stator impedance control by use of a gapped-core inductor.

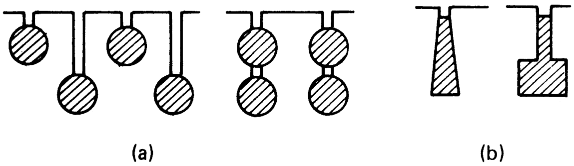


Figure 20.38 High-torque rotor cages: (a) double cage; (b) deep bar

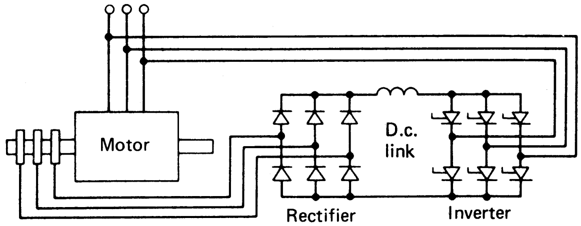


Figure 20.39 Thyristor slip-energy recovery

20.3.3.5 Speed control

The speed for an induction motor is $n = (1 - s)f/p$. The frequency f is normally fixed, the machine is built with p pole-pairs and, as the operating slip s lies generally between the limits 0.03 and 0.05, the motor is a substantially constant-speed machine with a working range as shown on curve A of *Figure 20.36*. Speed variation is often needed and, with some additional cost and complication, can be achieved by varying the slip, the number of poles or the frequency. For small motors a limited control can also be obtained by varying the applied voltage.

Slip control This, applicable only to slip-ring motors, requires connection into the rotor circuit of a device producing an adjustable volt drop or counter-e.m.f. The rotor induced e.m.f. sE_2 must overcome this to enable torque-producing current to flow, so that the slip must change in accordance with the magnitude of the injected volt drop or e.m.f.

Resistance control A variable volt drop is set up in the rotor circuit by variable resistors in each phase, giving a series of torque–speed characteristics (A, B, C, D in *Figure 20.36*). Only the low-slip parts can give normal operation, as the lower speeds may be unstable. The starting resistors, if continuously rated, can be used for speed control. The method is cheap and simple, but results in high I^2R ('slip energy') especially for low speeds. The efficiency is a little less than $1 - s$, the speed varies widely with load, and low speeds are not obtainable at low loads. This form of control is used only where small or infrequent speed reductions are called for.

Slip-energy recovery Here the slip energy is not dissipated in resistance but is returned to the supply (constant-torque drive, as with resistance control) or added to the shaft output of the main motor (constant-power drive). Commutator machines have in the past been employed to deal with the slip energy. A modern method (*Figure 20.39*) is to rectify the slip-frequency currents in a diode bridge network; the unidirectional output current is smoothed and passed on to a three-phase line-commutated inverter at a rate depending on the supply voltage, the rectified direct voltage and the thyristor firing angle. The inverted current has a fixed waveform and a constant conduction angle of $2\pi/3$ rad. The onset of conduction with respect to the phase-voltage zero is controlled by the firing angle. As power flow through the rectifier is unidirectional, only subsynchronous speeds are feasible.

Pole changing Switching the stator winding to give two (sometimes three) different numbers of pole-pairs gives two (or three) alternative running speeds. Cage rotors are normally employed, as slip-ring windings must be pole-changed to correspond always to the stator. Pole-changing motors with a 2:1 ratio have been used for many years, a typical arrangement being that in *Figure 20.40*. A more recent innovation is the pole-amplitude-modulated method.

Pole-amplitude modulation The m.m.f. (and flux) distribution around the air gap produced by one phase of a conventional machine can be expressed as $F(\theta) = A \sin p\theta$ where θ represents an instantaneous angular position. If $F(\theta)$ is modulated by making $A = C \sin k\theta$, the m.m.f. becomes

$$F(\theta) = \tfrac{1}{2}C[\cos(p - k) - \cos(p + k)]$$

which is an m.m.f. comprising two superimposed waves of pole-number $p - k$ and $p + k$. One wave can be eliminated by adjusting the chording and relative position of the phase windings so that the machine has p pole-pairs (unmodulated) and either $p - k$ or $p + k$ pole-pairs (modulated). The modulation is effected by reversing half of each phase winding and, in some cases, isolating certain coils. Two basic forms of connection are given in *Figure 20.41*. The coils that are isolated for the unmodulated connection are in the sections A′A, B′B and C′C. For designs that do not need coil isolations the phase terminals during modulation are A′B′C′.

In general, when the distribution of coil groups per pole and per phase is not uniform, some coils are isolated for modulation; with a more uniform distribution, however, a simple reversal of the second half of each phase winding is sufficient. The latter is more suitable for power outputs that are required to be similar at the two speeds.

This simple theory led to the design of successful industrial motors with close speed ratios from, for example, 8/10 or 12/14 poles. The recent development of a more general theory has made possible wide ratios from, for example, 10/2 and 16/4 poles, and also three-speed motors. There is virtually no limit to the size and speed ratio available, even in fractional-kilowatt ratings. The pole-amplitude-modulated (p.a.m.) motor is thus superseding the two-winding change-speed motors commonly used in the past, as the starting torques, power factors and efficiencies of p.a.m. machines are comparable with those of single-speed standard machines and have optimum performance on all ranges. The rating for a given frame-size is about 90% of that of a normal single-speed motor.

Frequency variation Development of the static thyristor inverter has made possible the provision from a three-phase supply of an a.c. source of controllable voltage and of frequency infinitely variable from zero up to three or more times the supply frequency. Wide speed variation with such a source is possible with a cage motor. To maintain a constant motor flux, the voltage applied to the motor must be proportional to the frequency. The speed-torque characteristics (*Figure 20.42*) show that the peak torque is approximately the same at all operating frequencies.

D.c.-link converter A rectifier converts the a.c. of mains frequency to d.c., and a thyristor inverter converts this to a.c. of the desired frequency in the d.c.-link converter

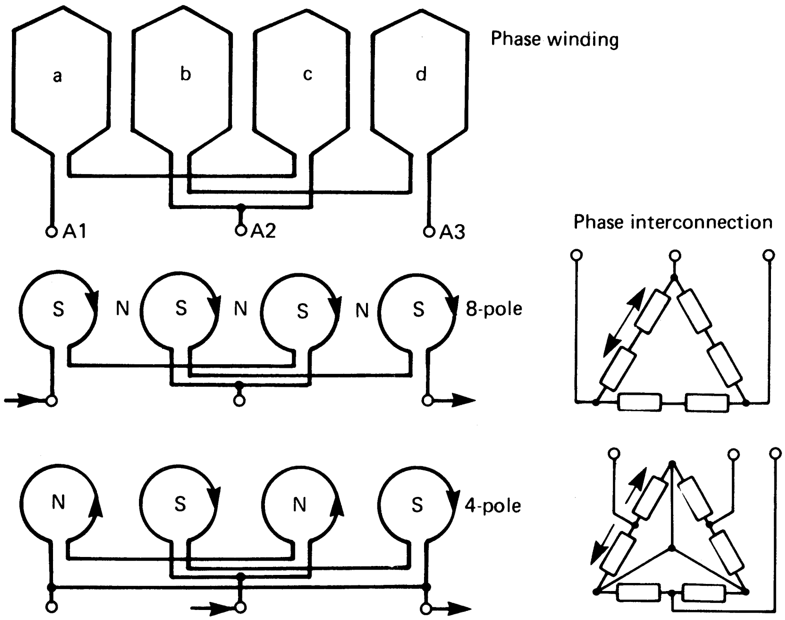


Figure 20.40 Pole change in the ratio 2:1

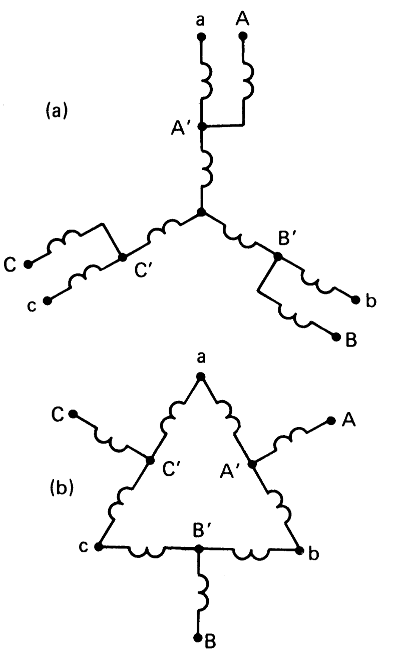


Figure 20.41 Pole-amplitude modulation. Unmodulated/modulated connections: (a) parallel-Y/series-Y; (b) parallel-Y/series-delta. Poles $2p$: supply to ABC with abc joined. Poles $2(p \pm 1)$: supply to abc with ABC isolated

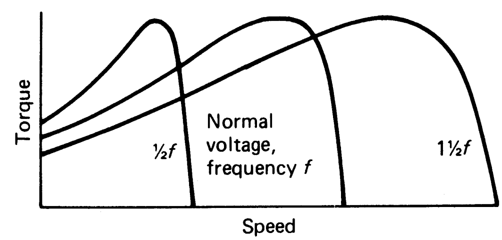


Figure 20.42 Torque–speed relationships for variable frequency

(*Figure 20.43*). The direct voltage is varied by a thyristor chopper instead of by a controlled thyristor equipment in order to mitigate harmonics in the supply. The inverter produces a waveform with about 20% of fifth and 14% of seventh harmonic, and these may cause small additional losses in the motor; however, the impairment may be reduced by series inductors in the motor circuit. It must be remembered that although the motor has the usual overload capacity, the converting equipment has no such reserve and must be rated for the peak power.

An upper frequency of about 150 Hz is usual, permitting the speed range of a two-pole machine to be from zero to 9000 rev/min. For small machines and with thyristors having very fast switching characteristics, higher frequencies can be generated and speeds up to 100 000 rev/min achieved.

Cyclo-converter In this alternative equipment, sections of the normal mains-frequency wave are selected and used to build up an outgoing wave of lower frequency, usually not higher than about two-thirds of the mains frequency, in a single static unit. The equipment has an efficiency higher than that of the d.c.-link converter, but a considerably more complicated control network: basically 18 thyristors are required for a three-phase motor. The cyclo-converter employs natural commutation and may be more reliable than the forced commutation in the d.c.-link converter under abrupt changes of load; it can also be made reversible for regenerative braking without the additional complication that a d.c.-link converter would involve for this duty.

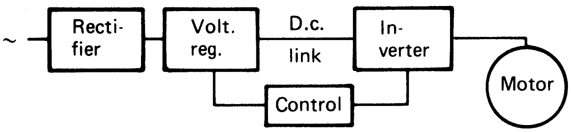


Figure 20.43 Basic d.c.-link converter system

Voltage variation As the peak torque of an induction motor is proportional to the square of the voltage, a limited speed control can be effected by voltage variation. Typical speed–torque curves for a small motor operating at 100% and 70% of rated voltage are given in *Figure 20.44*. For a constant-torque load the speed is reduced from A to B; for a torque proportional to the square of the speed, as for a fan, the greater reduction from C to D is obtained. Greater variation occurs if the motor has a high rotor resistance/reactance ratio, so that the method is ineffective for motors of rating more than a few kilowatts; it is, in fact, used chiefly with small mass-produced motors. The voltage variation may be achieved by means of series rheostats (cheap but wasteful) or by thyristors in the supply circuit (expensive, efficient and harmonic-producing).

20.3.3.6 Braking

Braking may be required to bring a motor and its load to rest rapidly in an emergency or as part of a production process, or to hold the motor at a set speed against gravity, as in a descending hoist. Mechanical brakes must be used if a motor is to be held at rest, but motional braking can be electrical and may not need much auxiliary control equipment.

Plugging If a motor, operating with a small slip s, has a pair of its supply leads interchanged, the direction of its travelling-wave air-gap field reverses and the slip becomes $2 - s$. A braking torque is developed, retarding the motor towards standstill, $s = 1$. The braking torque normally varies from about one-half the value of the starting torque initially, up to the starting torque when the machine comes to rest, and the braking current throughout is approximately equal to the starting current. Unless the motor is disconnected when it stops, it will start up again in the opposite direction.

D.c. injection The three-phase supply to the stator is disconnected and immediately replaced by a d.c. supply giving a stationary field in the air gap. The rotor conductors, moving in this field, develop e.m.f.s and currents that exert a braking torque, initially about equal to the starting torque but falling

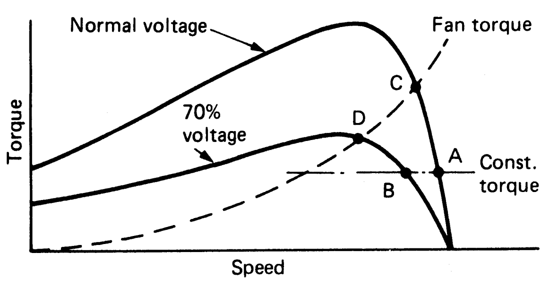


Figure 20.44 Torque–speed reationships for variable voltage

with the speed and vanishing as the motor is brought to rest by friction. The direct current is fed into the stator by two terminals, leaving the third isolated if the stator winding is star-connected.

Regeneration When a load overdrives the motor to a speed exceeding synchronous (i.e. with negative slip) as with a descending hoist load, the machine acts as an induction generator and sets up a braking torque (see *Figure 20.36*). Such braking cannot bring the motor to rest but it can limit the speed to a value a little above synchronous, the power from the load being partly returned to the supply. With two-speed pole-change motors a high braking torque can be obtained if, when running at the higher speed, the motor is switched to the larger pole-number.

20.3.4 Three-phase commutator motors

The recovery of slip energy can be achieved in a single machine by incorporating in the rotor a commutator winding. The *Schrage* (rotor-fed) and *doubly fed* (stator-fed) motors have some commercial importance. Both have a 'shunt' speed–torque characteristic and can operate both above and below synchronous speed. A three-phase commutator motor with a 'series' characteristic is also available.

20.3.4.1 Schrage motor

The Schrage motor has its primary winding on the rotor, connected to the supply through slip-rings and brushes. The rotor also carries a low-voltage commutator winding with conductors located in the same slots as, and above, those of the primary. The secondary winding is on the stator. The primary and secondary windings are similar to those of a conventional induction motor. The brushgear comprises two movable rockers, each fitted with three brush spindles per pair of poles. The two rockers are geared together, each being fitted with a toothed segment. The two segments mesh with pinions fitted to a short shaft to which either a handwheel or a small pilot motor is connected. The gearing is so arranged that the movement of the handwheel or pilot motor causes the brush rockers to move in opposite directions.

The brushes attached to each rocker move over separate portions of the commutator surface to enable these brushes to be placed 'in line' or to be moved in either direction, so that more or fewer commutator sectors are included between a brush on one rocker and the corresponding brush on the other.

The bus-rings of each rocker are connected to the secondary (stator) winding as in *Figure 20.45*, which represents a two-pole machine.

As the primary winding is on the rotor, e.m.f.s of slip frequency are induced in the secondary (stator) winding. The e.m.f.s at the brushes are also of this frequency. The e.m.f. induced in each coil of the commutator winding is constant at all speeds, and therefore the e.m.f.s injected, via the brushes, into the secondary winding are proportional to the number of commutator sectors included between corresponding brushes on the two rockers, i.e. between the brushes connected to a particular phase of the secondary. Thus, when these brushes are in line, the secondary winding has no e.m.f. injected into it and the motor will run with its natural slip. When the brushes are moved so that the injected e.m.f. opposes the current, the speed is reduced (slip positive); for the opposite movement the speed is increased (slip negative).

Performance In a machine with a synchronous speed n_s and a brush-separation electrical angle θ, the no-load speed is

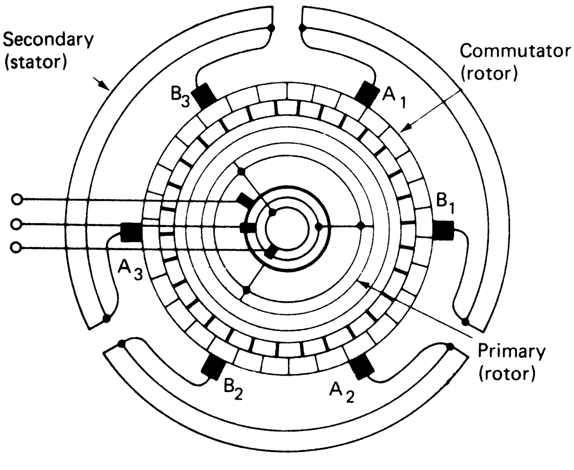


Figure 20.45 Schrage motor; stator and rotor circuits

$$n = n_s(1 - k\sin\tfrac{1}{2}\theta)$$

where k is a constant depending on the numbers of turns in the secondary and commutator windings. A typical relation between n and θ is given in *Figure 20.46(a)* for a motor with a 4:1 speed range—about the practical limit. For a given brush position the speed is nearly constant up to 1.5–2 times full-load torque, as shown in *Figure 20.46(b)*. The speed drop with increasing load is greater than for a plain induction motor because of the brush resistance and the impedance of the tertiary commutator winding. At synchronous speed, when $\theta = 0$ and the secondary is short circuited through the brushes, the overall efficiency is similar to that of an induction motor. At other speeds the efficiency is perhaps 5% lower on account of the tertiary I^2R loss and the stator core loss. The power factor approaches unity at speeds above synchronous as the negative slip results in a capacitive effect. At subsynchronous speeds the power factor falls; however, it can be raised in non-reversing motors by arranging that the brush movement is asymmetric with respect to the 'in-line' position, the axis bisecting a corresponding pair of brushes being progressively displaced in a direction opposite to that of the rotor rotation.

Starting can be effected by direct switching with the brushes set in the lowest-speed position, the starting torque being about 1.5 times full-load value with 1.5–2 times full-load current. Commutation limits the output to about 20 kW/pole and the speed range to 4:1. The maximum output for a motor is thus about 200 kW. With limited speed range, rather higher ratings, e.g. 350 kW and 1.5:1, can be achieved. As the primary winding is supplied through slip-rings the supply voltage is restricted to about 600 V.

20.3.4.2 Doubly fed motor

The stator resembles that of a conventional induction motor; it is fed from the supply at any desired voltage up to 11 kV. The rotor carries a commutator winding and has six (occasionally three) brushes per pole-pair (see *Figure 20.47*). The rotor voltage is necessarily low (200–300 V) and the brushes are connected to the supply through a variable-ratio transformer. The gap flux travels at synchronous speed, and as a result of the commutating function the e.m.f.s at the brushes are of supply frequency at any speed. A variable e.m.f. can thus be obtained from the transformer and injected into the rotor circuits to give speed control from standstill to 1.5–2 times synchronous speed. In practice the variable-voltage transformer is an induction regulator to give smooth speed control. It must be a double regulator to avoid changing the phase angle of the injected voltage.

Performance At the zero-voltage position of the regulator the brushes are short circuited through the regulator winding and the machine operates as an induction motor, though with a higher rotor effective impedance. Moving the regulator in one or other direction introduces an e.m.f. into the rotor circuit, to give speed–torque relations similar to those of the Schrage motor. The overall power factor tends to be low owing to the magnetisation of the regulator, but it can be improved by special means.

With the regulator in the lowest-speed position the motor can be direct-started to give about 1.5 times full-load torque with 1.5–2 times full-load current. The regulator must carry the slip power, so that speed variation down to zero requires it to be of a physical size comparable to that of the motor. Machines of some thousands of kilowatts can be economically built for speed ranges of ±15% or 20% of synchronous speed.

Unlike the Schrage motor the stator-fed commutator motor is not self-contained, but it can be made in larger ratings and for higher voltages. Again, the simpler brush arrangements makes the machine economic in ratings down to 2 or 3 kW.

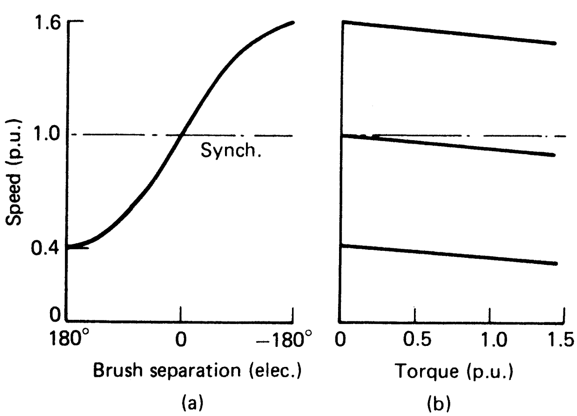


Figure 20.46 Schrage motor: characteristics

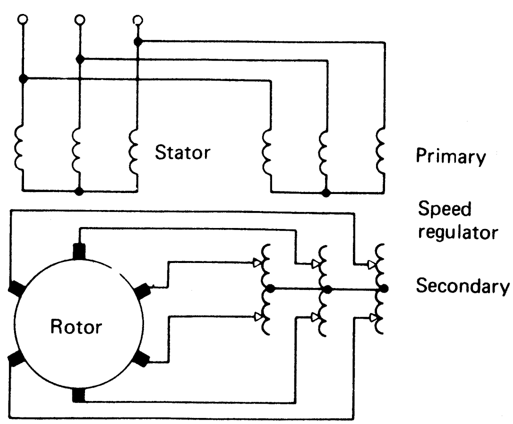


Figure 20.47 Stator-fed three-phase commutator motor

20.3.4.3 Three-phase series motor

It is possible to connect the rotor brushes in series with the stator winding to give a machine with a 'series' speed–torque characteristic and with speed variation by moving the brush position. To limit the rotor voltage, however, a transformer is necessary between stator and rotor. If the transformer is that of the induction-regulator type the brushes can be fixed and the speed adjusted by means of the regulator. The series commutator motor is uncommon, but if a steeper characteristic than that furnished by the stator-fed machine is desirable or acceptable, as for fan drives, there is some economy because of the smaller losses and the simpler regulator.

20.3.5 Synchronous motors

Any synchronous generator will operate as a motor and run at precisely synchronous speed up to its pull-out torque of 2–2.5 times full-load torque. Other significant features of the motor are the controllability of its power factor up to unity or leading values, the necessity of a d.c. excitation circuit and the fact that the motor is not inherently self-starting. In ratings above 300–500 kW, however, the synchronous motor, although more expensive than the induction motor, has a higher efficiency and lower running cost and, therefore, often gives a more economic drive. Except for 3000 rev/min motors the salient-pole construction is generally adopted.

20.3.5.1 Starting

If the motor is always to be started on no load it can be run up to speed by a small pony motor, usually an induction motor, and then allowed to pull into synchronism when the excitation is switched on. If the motor has solid poles and pole-shoes it may be possible to start it by induction-motor action resulting from eddy currents induced in them when the supply is switched on.

Induction start Most synchronous motors are started by use of a cage winding embedded in the pole-faces to give an induction-motor torque when the stator is energised, by direct switching on through an autotransformer. When the speed approaches synchronous the d.c. excitation is applied and the motor synchronises. During starting, high voltages may be induced in the field winding, and it is usual to short-circuit this winding during the start through a resistor which is disconnected after the machine has pulled into step. The current in the field winding adds significantly to the starting torque.

To ensure that the motor closely approaches synchronous speed at the end of an induction start, the resistance of the cage winding should be low; however, for good torque production at low speeds the cage resistance should be high, so some compromise is required.

With direct switching the starting torque is about one-half of full-load torque with 2–3 times full-load current. For machines rated above 200 kW an autotransformer is needed for starting.

20.3.5.2 Excitation

The conventional method of excitation is by a shunt-connected d.c. exciter mounted on the motor shaft, control being effected by variation of the exciter field current; the exciter should, however, be disconnected from the motor field winding during starting on account of the alternating currents that would otherwise be induced in it and which could destroy residual magnetism and prevent the build-up of the excitation.

An a.c. mains-fed rectifier with d.c. output fed to the rotor through the slip-rings could replace the d.c. exciter, but modern practice favours *brushless excitation*, in which an a.c. exciter feeds the rotor field winding through rectifiers, the whole arrangement being incorporated in the rotor. The a.c. exciter field is energised by means of a small permanent-magnet generator to ensure build-up of the excitation under all conditions.

Excitation control can be made automatic, but it is more usually pre-set to give unity or leading power factor at full load. The increased reactive leading power at lighter loads helps to raise the overall system power factor and to improve the transient stability of the motor when it is subject to disturbances.

20.3.5.3 Synchronous-induction motor

Where high starting torques (e.g. 2–2.5 times full-load) are required, the synchronous-induction motor is suitable. It resembles a slip-ring induction motor and is started on resistance when it is up to nearly synchronous speed, d.c. excitation is switched on to the rotor through the slip-rings and the machine synchronises.

The air gap of the synchronous-induction motor is longer than that of the normal induction motor in order to achieve synchronous stability, and the rotor winding resistance is lower in order to ensure pulling into step. An exciter must also, of course, be provided. Another difficulty is the adaptation of the rotor for the dual purpose of starting and excitation; the direct current is normally fed into two of the slip-rings, the third being isolated so that the winding is not all usefully employed during running. Moreover, the relatively few turns and the large current for which the winding is usually designed necessitate an abnormal design for the exciter, i.e. a low-voltage, high-current machine. The starting performance is similar to that of a slip-ring induction motor, but the running performance is better in that the efficiency is 1–2% higher and the power factor may be made unity or leading. The pull-out torque in the synchronous mode is about 1.5 times full-load torque, but if the machine pulls out it can continue to run as an induction motor with a peak torque up to 2.5 times full-load value.

Where the compromise characteristics of the synchronous-induction motor are inadequate, large salient-pole synchronous motors may be built with a slip-ring pole-face winding, so that the starting and synchronous functions may each be optimised.

20.3.6 Reluctance motors

The reluctance motor is a cheap and reliable synchronous motor that requires no d.c. excitation. Commercial motors are available in ratings of 20 kW or more. The machine has a three-phase stator winding similar to that of an induction motor, and a rotor without windings. For a given frame the output is about 60% of that of an induction machine, and the motor has a slightly lower efficiency. It has, however, advantages for drives such as the accurate positioning of nuclear-reactor rods, the operation of rotating stores in computers, and in synchronised multi-motor drives.

The essential feature of the rotor is a strong 'saliency' effect obtained in ways such as those illustrated in *Figure 20.48*. The obvious saliency in (*a*) is, in modern machines, replaced by designs based on studies of flux patterns to give the greatest difference in the reluctance offered respectively in the direct and quadrature axes—a condition of good saliency effect. The rotor iron may be solid but is more usually laminated.

Reluctance torque is maintained only at synchronous speed, so that some form of cage winding must be incorporated for starting. Direct switching is employed, giving starting currents

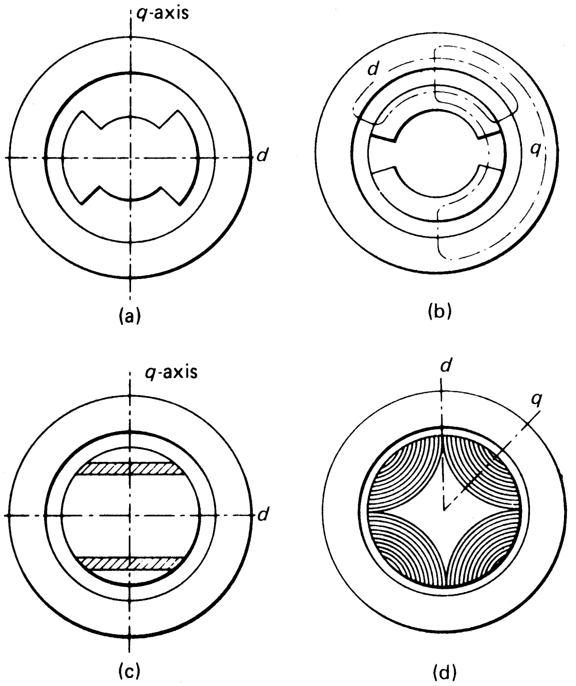


Figure 20.48 Reluctance motors: (a) salient two-pole; (b) segmental two-pole; (c) flux-barrier two-pole; (d) axially laminated four-pole

up to 4–6 times full-load current. The effective rotor resistance has an important influence on the starting and pull-in torques.

The requirements for a satisfactory motor are good synchronous performance (efficiency, power factor and pull-out torque), good pull-in torque (especially for high-inertia loads) and stability. Some of these conflict: increasing the ratio of *d*- and *q*-axis reluctances gives higher output and pull-out torque, but lower pull-in torque and impaired stability. The design is influenced particularly by the load inertia. For a motor of 5 kW rating typical data are: reluctance ratio, 3–6; efficiency, 70–80%; power factor, 0.6–0.75 lagging; pull-out torque, 2–2.5 p.u.; pull-in torque, 0.9–1.2 p.u.

Motors with change-speed windings are possible, and motors can be built for variable frequency (20–200 Hz) but these are liable to instability at the lower end of the range.

20.3.7 Single-phase motors

Single-phase motors are rarely rated above 5 kW. Fractional-kilowatt motors, most of which are one-phase, account for 80–90% of the total number of motors manufactured and for 20–30% of the total commercial value. A typical modern home may have 10 or more one-phase motors in its domestic electrical equipment.

20.3.7.1 Series motor

As the direction of rotation and of torque in a d.c. series motor are independent of the polarity of the supply, such a motor can operate on a.c. provided that all ferromagnetic parts of the magnetic circuit are laminated to minimise core loss.

Universal motor In the fractional-kilowatt sizes the series motor has the advantage, since it is non-synchronous, of being able to run at speeds up to 10 000 rev/min. It is very well adapted to driving suction cleaners, drills, sewing machines and similar small-power rotary devices. Its facility of operating on d.c. and a.c. is not now important, but is the origin of the term 'universal'. The machine has a 'series' speed–torque characteristic, the no-load speed being limited by mechanical losses. The power factor is between 0.7 and 0.9 (mainly the result of armature inductance), but this is of no significance in small ratings. Typical characteristics for a motor for d.c. and 50 Hz supplies of the same nominal voltage are shown in *Figure 20.49*.

In all a.c. commutator motors the commutation conditions are more onerous than on d.c. because the coils undergoing commutation link the main alternating flux and have e.m.f.s induced of supply frequency. The e.m.f.s are offered a short-circuited path through the brushes and contribute to sparking at the commutator. As the e.m.f.s are proportional to the main flux, the frequency and the number of turns per armature coil, these must be limited; a further limit on the current in a short-circuited coil is provided by high-resistance carbon brushes.

Compensated motor Series a.c. commutator motors up to 700–800 kW rating are used in several European railway traction systems. For satisfactory commutation the frequency must be low, usually $16\frac{2}{3}$ Hz, and the voltage must also be low (400–500 V), this being provided by a transformer mounted on the locomotive. The inductance of the armature winding is necessarily rather high, so that a compensating winding must be fitted to neutralise armature reaction in order to ensure a reasonable power factor.

Motors of this type have been built, of limited output, for operation on modern 50 Hz traction systems but have now been superseded by rectifier- or thyristor-fed d.c. motors.

20.3.7.2 Repulsion motor

The repulsion motor is a form of series motor, with the rotor energised inductively instead of conductively. The commutator rotor winding is designed for a low working voltage. The brushes are joined by a short circuit and the brush axis is displaced from the axis of the one-phase stator winding

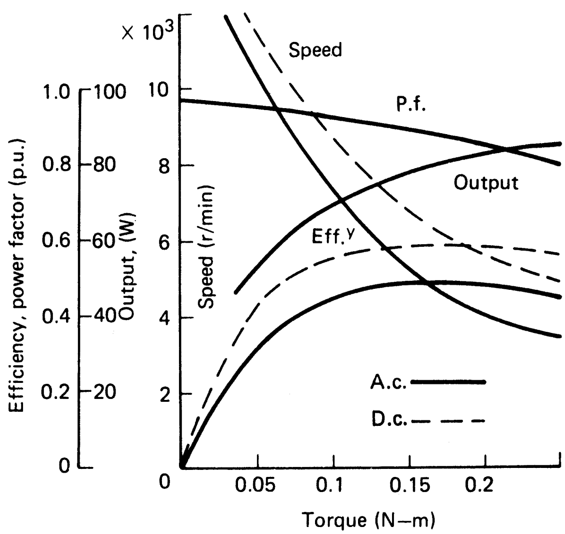


Figure 20.49 Characteristics of a 75 W universal motor

(*Figure 20.50*). With non-reversing motors (*Figure 20.50*(*a*)) a single stator winding suffices; however, for reversing motors the stator has an additional winding, connected in one or other sense in series with the first winding to secure the required angle between the rotor and effective stator axes for the two directions of rotation, as in *Figure 20.50*(*b*).

A stator winding of N_1 turns as in (*a*) can be resolved into two component windings respectively coaxial with and in quadrature with the axis of the rotor winding, and having respectively turns $N_1 \sin \alpha$ and $N_1 \cos \alpha$. Windings (*b*) give the two axis windings directly, although here the turns can be designed for optimum effect. The coaxial winding induces e.m.f.s and currents in the rotor, and these currents lying in the field of the other stator winding develop torque; since both stator and rotor currents are related, the motor has a 'series' characteristic.

When the motor is running, the direct and quadrature axis fluxes have a phase displacement approaching 90°, so producing a travelling-wave field of elliptical form which becomes nearly a uniform synchronously rotating field at speeds near the synchronous. Near synchronous speed, therefore, the rotor core losses are small and the commutation conditions are good.

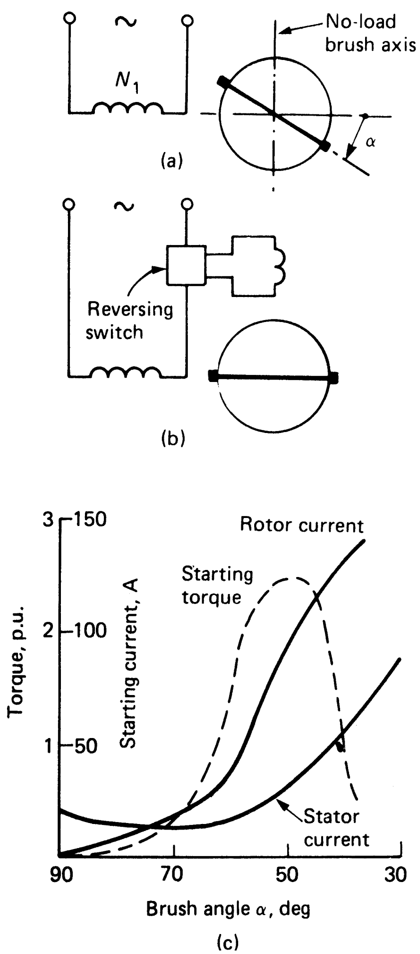


Figure 20.50 Repulsion motor: alternative forms and starting characteristics

Small motors can readily be direct-switched for starting, with 2.5–3 times full-load current and 3–4 times full-load torque. The normal full-load operating speed is chosen near, or slightly below, synchronous speed in order to avoid excessive sparking at light load. Repulsion motors are used where a high starting torque is required and where a three-phase supply is not available. For small lifts, hoists and compressors their rating rarely exceeds about 5 kW.

20.3.7.3 *Induction motors*

The one-phase induction motor is occasionally built for outputs up to 5 kW, but is normally made in ratings between 0.1 and 0.5 kW for domestic refrigerators, fans and small machine tools where a substantially constant speed is called for. The behavior of the motor may be studied by the rotating-field or the cross-field theory. The former is simpler and gives a clearer physcial concept.

Rotating-field theory The pulsating m.m.f. of the stator winding is resolved into two 'rotating' m.m.f.s of constant and equal magnitude revolving in opposite directions. These m.m.f.s are assumed to set up corresponding gap fluxes which, with the rotor at rest, are of equal magnitude and each equal to one-half the peak pulsating flux. When the machine is running, the forward field component *f*, i.e. that moving in the same direction as the rotor, behaves as does the field of a polyphase machine and gives the component torque–speed curve marked 'forward' in *Figure 20.51*; the backward component *b* gives the other torque component, and the net torque is the algebraic sum. At zero speed the component torques cancel so that the motor has no inherent starting torque, but if it is given a start in either direction a small torque in the same direction results and the machine runs up to near synchronous speed provided that the load torque can be overcome.

The component torques in *Figure 20.51* are, in fact, modified by the rotor current. Compared with the three-phase induction motor, the one-phase version has a torque falling to zero at a speed slightly below synchronous, and the slip tends to be greater. There is also a core loss in the rotor produced by the backward field, reducing the efficiency. Moreover, there is a double-frequency torque pulsation generated by the backward field that can give rise to noise. The efficiency lies between about 40% for a 60 W motor and about 70% for a 750 W motor, the corresponding power factors being 0.45 and 0.65, approximately.

The equivalent circuit of *Figure 20.52* is based on the rotating-field theory, using parameters generally similar to

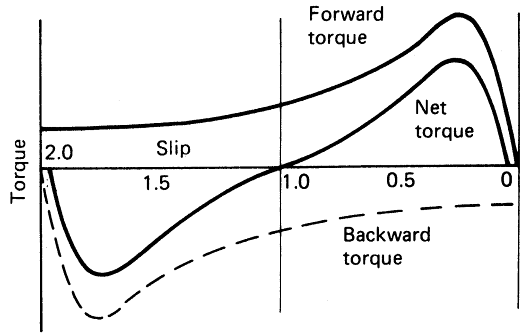


Figure 20.51 Torque components in a single one-phase induction motor

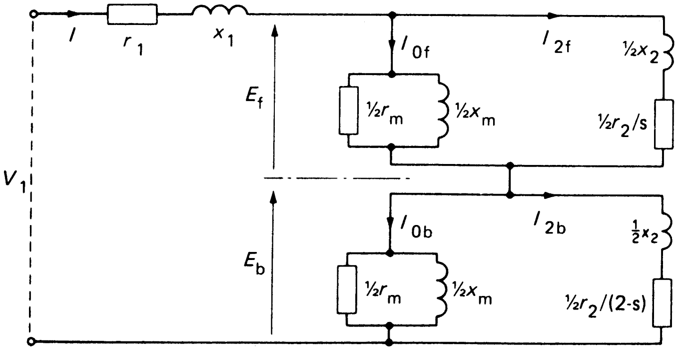


Figure 20.52 Simple one-phase induction motor: equivalent circuit

those for the three-phase machine. The e.m.f.s E_f and E_b are generated respectively by the forward and backward field components and are proportional thereto. The respective component torques are proportional to $I_{2f}^2 r_2/2s$ and $I_{2b}^2 r^2/[2(2-s)]$, the next torque being their difference.

Starting To start a one-phase induction motor, means are provided to develop initially some form of travelling-wave field. The arrangements commonly adopted give rise to the terms 'shaded-pole' and 'split-phase'.

Shaded-pole motor The stator has salient poles, with about one-third of each pole-shoe embraced by a shading coil. That flux which passes through the shading coil is delayed with respect to the flux in the main part of the pole, so that a crude shifting flux results. The starting torque is limited, the efficiency is low (as there is a loss in the shading coil), the power factor is 0.5–0.6 and the pull-out torque is only 1–1.5 times full-load torque. Applications include small fans of output not greatly exceeding 100 W.

Resistance split-phase motor The additional flux is provided by an auxiliary starting winding arranged spatially at 90° (electrical) to the main (running) winding. If the respective winding currents are I_m and I_s with a relative phase angle α, the torque is approximately proportional to $I_m I_s \sin \alpha$. At starting, the main-winding current lags the applied voltage by 70–80°. The starting winding, connected in parallel with the main winding, is designed with a high resistance or has a resistor in series so that I_s lags by 30–40°. The effect of this resistance on the starting characteristic is shown in *Figure 20.53(a)*. With given numbers of turns per winding and a given main-winding resistance, then for a specified supply voltage and frequency there is a particular value of starting-winding resistance for maximum starting torque. The relation can be obtained from the phasor diagram. *Figure 20.53(b)*, in which V_1 is the supply voltage and I_m at phase angle ϕ_m is the main-winding current. The locus of the starting-current phase I_s with change in resistance is the semicircle of diameter OD (which corresponds to zero resistance). The torque is proportional to $I_m I_s \sin(\phi_m - \phi_s)$ and is a maximum for the greatest length of the line AC. From the geometry of the diagram it can be shown that for this condition $\phi_s = \frac{1}{2}\phi_m$.

Direct switching is usual. To reduce loss, the auxiliary winding is open-circuited as soon as the motor reaches running speed. The starting torque for small motors up to 250 W is 1.5–2 times full-load torque, and that for larger motors rather less, in each case with 4–6 times full-load current. The operating efficiency is 55–65% and the power factor 0.6–0.7.

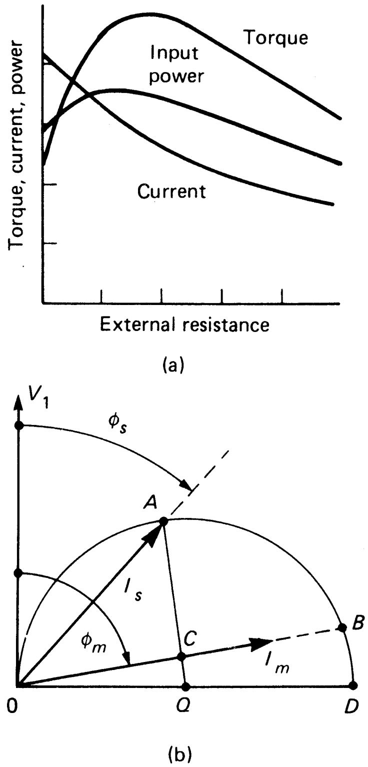


Figure 20.53 Single-phase induction motor: split-phase resistance start

Capacitor split-phase motor A greater phase difference $(\phi_m - \phi_s)$ can be obtained if a series capacitor is substituted for the series resistor of the auxiliary winding. Maximum torque occurs for a capacitance such that the auxiliary current leads the main current by $(\frac{1}{2}\pi - \alpha)/2$. The capacitor size is from 20–30 μF for a 100 W motor to 60–100 μF for a 750 W motor. For economic reasons the capacitor is as small as is consistent with producing adequate starting torque, and some manufacturers quote alternative sizes for various levels of starting torque.

If the capacitor is left in circuit continuously (*capacitor-run*) the power factor is improved and the motor runs with less noise. Ideally, however, the value of capacitance for running should be about one-third of that for the best starting. If a single capacitor is used for both starting and running, the starting torque is 0.5–1 times full-load value and the power factor in running is near unity.

Repulsion-induction motor Machines have been designed to combine the high starting torque capability of the repulsion motor with the constant-speed running characteristic of the induction motor.

Repulsion-start motor This motor has a stator winding like that of a repulsion motor and a lap commutator winding, with the addition of a device to short circuit the commutator sectors together by centrifugal action when the speed reaches about 75% of normal. The device may also release the brushes immediately thereafter. Thus the commutator rotor winding becomes, in effect, a short-circuited 'induction'-type winding for running. Small motors direct-switched give 3–4 times full-load torque with about three times full-load current. A lower starting current is obtained by connecting a graded resistor in series with the stator winding.

Repulsion-induction motor The machine has a repulsion-type stator winding but the change from the repulsion-mode to the induction-mode operation is gradual as the machine runs up to speed. The rotor has two windings in slots resembling those of a double-cage induction motor. The outer slots carry a commutator winding with brushgear, the inner slots contain a low-resistance cage with cast aluminium bars and end-rings, and its deep setting endows it with a high inductance. During acceleration the reactance of the cage falls and its torque increases, tending to counterbalance the falling torque of the commutator winding. At speeds above synchronous the cage torque reverses, giving a braking action which holds the no-load speed to a value only slightly above synchronous speed. The commutation is better than that of a plain repulsion motor, and the motor is characterised by a good full-load power factor (e.g. 0.85–0.9 lagging). With direct switching the starting torque is 2.5–3 times and the current 3–3.5 times full-load value.

20.3.8 Motor ratings and dimensions

Motors of small and medium rating are built to the standards of IEC 72, which list a coherent range of main structural dimensions with centre heights between 56 and 1000 mm. BS 3939 gives the standard ratings for the UK. *Table 20.5* lists data for rotating machines up to 1 MW. Approximate values of rated current for three-phase, one-phase and d.c. machines are set out in *Table 20.6* for machines up to 150 kW and for a range of supply voltages. Voltages for d.c. machines correspond to nominal values obtained from rectified a.c. supplies.

Table 20.5 Rotating machines: recommended ratings and shaft heights

Rating (kW)
0.06, 0.09, 0.12, 0.18, 0.25, 0.37, 0.55, 0.75, 1.1, 1.5, 2.2, 3.7, 5.5, 7.5, 11, 15, 18.5, 22, 30, 37, 45, 55, 75, 90, 110, 132, 150, 160, 185, 200, 220, 250, 280, 300, 315, 335, 355, 375, 400, 425, 450, 475, 500, 530, 560, 600, 630, 670, 710, 750, 800, 850, 900, 950, 1000
Shaft-centre height (mm)
56, 63, 71, 80, 90, 100, 112, 132, 160, 180, 200, 225, 250, 280, 315, 355, 400, 450, 500, 630, 710, 800, 900, 1000

20.3.9 Testing

Tests on machines after manufacture or after erection on site are made in accordance with standard Specifications. They cover (i) insulation resistances, (ii) winding resistances, (iii) temperature rise, and (iv) losses. Further tests on particular types of machine (e.g. commutation, starting) are required to meet customers' requirements or to obtain design data. Where a batch of similar machines is concerned, a 'type test' on one for detailed performance is usually acceptable.

20.3.9.1 Insulation

'Megger' testing of the insulation resistance between windings, and from windings to frame, must be performed before any live connections are made. The insulation resistance (in mega-ohms) should not be less than 1, or less than $V/(1+S)$ for a machine of rating S (in kilovolt-amperes), where V is the rated voltage. It may be necessary, if the insulation resistance is low, to 'dry out' the machine. The winding continuity having been checked, an insulation test should immediately precede a h.v. test and also be made prior to energising the machine for the first time.

20.3.9.2 Resistance

Measured resistances of the windings check the design figures and are required for calculating losses: winding temperatures must be noted. An ammeter/voltmeter method is usual; alternatively a bridge method may be used if there are no brush contacts in the circuit. For a commutator winding, the volt drop is taken between the commutator sectors under the brushes, the brush drop being taken separately.

20.3.9.3 Temperature rise

The permissible temperature rise of a machine on rated load depends on the insulation class. Temperatures are measured at a number of points (particularly at or near likely 'hot spots') and, where possible, during a heat run with the machine operating at rated load, until a steady temperature has been reached. The rated load may be a *maximum continuous rating*, or a *short-time rating*, or some special rating based on a duty cycle. The duration of the heat run varies from 2 h for small machines to 8 h or more for large ones. Temperature readings are taken (where feasible) every 15 or 30 min. The following three methods of temperature measurement are in use.

Thermometer Mercury or alcohol thermometers may be used, the latter being preferable especially on large machines, as eddy currents in the mercury caused by stray fluxes may cause high readings; also mercury from a broken thermometer can cause damage to certain alloys. Good contact must be made between the thermometer bulb and the surface concerned, and the bulb should be well covered by a non-heat-conducting material such as felt or putty.

The thermometers should be located on the stator core and windings and read at intervals throughout the run, and then affixed to the rotor core and windings and to the commutator, if any, as quickly as possible after shut-down. They should be placed where temperatures are likely to be highest; however, only the surface temperature is measured, and not the true hot-spot temperature.

Resistance The resistance–temperature coefficient of the winding material can give an average winding temperature.

Table 20.6 Approximate rated motor currents (A)

Rating (kW)	*Induction motors*					*D.c. motors*			
	Three-phase			*One-phase*					
	350 V	*415 V*	*500 V*	*240 V*	*415 V*	*170 V*	*290 V*	*440 V*	*570 V*
0.06	—	—	—	0.7	0.4	0.6	0.4	0.3	0.2
0.09	—	—	—	0.9	0.5	0.9	0.5	0.4	0.3
0.12	—	—	—	1.2	0.7	1.1	0.6	0.5	0.4
0.18	—	—	—	1.5	0.9	1.6	0.9	0.6	0.5
0.25	—	—	—	1.9	1.1	2.0	1.2	0.8	0.6
0.37	1.3	1.1	0.9	2.8	1.6	2.8	1.7	1.1	0.9
0.55	1.8	1.6	1.3	4.0	2.3	4.1	2.4	1.6	1.2
0.75	2.4	2.0	1.7	5.0	2.9	5.3	3.0	2.0	1.6
1.1	3.4	2.9	2.4	7.2	4.1	7.5	4.4	3.0	2.3
1.5	4.5	3.7	3.1	9.3	5.4	10	6.0	4.0	3.1
2.2	6.3	5.3	4.4	13	7.8	15	8.7	5.8	4.4
3.7	10	8.4	7.0	22	13	24	14	9.6	7.4
5.5	13	12	10	32	18	36	21	14	11
7.5	18	16	13	43	25	49	29	19	15
11	28	23	19	62	36	—	42	28	21
15	35	30	25	82	48	—	57	38	29
18.5	45	38	31	100	58	—	70	47	36
22	53	44	37	118	68	—	83	56	43
30	68	56	48	—	—	—	114	76	58
37	85	72	60	—	—	—	138	92	71
45	100	85	71	—	—	—	169	112	86
55	125	105	88	—	—	—	206	137	106
75	165	137	113	—	—	—	280	187	144
90	185	150	125	—	—	—	337	225	173
110	210	175	145	—	—	—	408	270	210
130	245	215	180	—	—	—	480	320	247
150	320	250	210	—	—	—	555	370	285

For copper, the temperature θ_2 corresponding to a measured resistance R_2 is related to the resistance R_1 at θ_1 by

$$\theta_2 = (R_2/R_1)(\theta_1 - 235) - 235$$

Embedded detector Thermocouples or resistance thermometers can be embedded in the core and windings during manufacture, a site between the coil-sides of a double-layer winding being common. At least six detectors, suitably distributed, should be installed. When well sited, detectors can give a closer estimate of hot-spot temperatures than other methods.

Temperature limits The three techniques above do not measure the same quantities, nor do they measure actual hot-spot temperatures. The values must therefore be in most cases significantly lower than the limits appropriate to the insulation class. Typical values for various locations as laid down in BS 2613 are given in *Table 20.7*.

20.3.9.4 Losses and efficiency

Efficiency may be determined by direct output/input ratio, by the total loss and either input or output, or by loss summation. As the efficiency of a large machine may have to be guaranteed within 0.01%, accurate determination is essential.

Output/input Electric power is readily measured, but mechanical power measurement requires some form of dynamometer, often of limited accuracy. Test rigs with instrumentation are used for small motors, but for large machines an adequate estimation of efficiency by this method may be impossible.

Back-to-back If two similar machines are available, one as a motor can drive the other as a generator. The net input is then the total loss, which can be accurately measured. This method can be applied for heat runs with comparative economy.

Loss summation A separate determination of each separable loss is made; the items are then summed to give the total loss, and thence the efficiency. The losses to be determined are:

core,
stator I^2R,
rotor I^2R,
load (stray),
brush-contact,
excitation, and
friction and windage.

Apart from the stray loss, each of these can be determined without loading the machine (although it must be run at normal speed). For uniformity the current losses are

Table 20.7 Temperature limits (°C)

Part of machine	*Method**	*Insulation class*				
		A	*E*	*B*	*F*	*H*
A.c. windings						
5000 kVA or core length over 1 m	T, D	60	70	80	100	125
5000 kVA	T	60	75	80	100	125
Commutator windings	R	50	65	70	85	105
	T	60	75	80	100	125
Field windings						
Low-resistance	R, T	60	75	80	100	125
Other windings	R	50	65	70	85	105
	T	60	75	80	100	125
Single-layer windings with bare or varnished metal	R, T	65	80	90	110	135
Permanently short-circuited windings	T	60	75	80	100	125
Iron core in contact with insulated windings	T	60	75	80	100	125
Commutators and slip-rings	T	60	70	80	90	100

Temperature measurement: T, thermometer; R, resistance, D, embedded detector.

found from the measured resistances referred to a standard temperature of 75 °C.

Stray losses These are, in practice, largely proportional to (current)^2 and, although insignificant in small machines up to a few kilowatts, they become very important in large machines. It is possible to estimate the stray loss from certain tests, as described later for particular machines; in other cases, however, they must be estimated from experience.

20.3.9.5 H.v. tests

The final test carried out before shipping a machine is the h.v. test in which a specified voltage at a frequency between 25 and 100 Hz is applied for 1 min between windings and earth and between windings. The specified voltage is usually (twice rated voltage + 1000) volts, although certain exceptions to this are given in BS 2613.

The purpose of the test is to ensure that the insulation has a sufficient factor of safety to guard against fortuitous voltage transients which may occur in practice. The test should, however, only be carried out once as repeated applications may damage the insulation. It may be desirable in some cases to repeat the test after the machine has been assembled on site, in which case a voltage of not more than 80% of the original test voltage should be applied.

20.3.9.6 D.c. motors

The following tests are related specifically to d.c. machines.

Armature volt-drop test This is carried out on the armature winding before assembly or if it has developed a fault. Current is fed into the armature by clamped connectors and the voltage between sectors is measured around the commutator. A placing of the connectors a *pole-pitch* apart is suitable for most industrial two- or four-pole wave-connected armatures: the direction of the volt drop changes at each pole-pitch. A *diametral* connection is suitable for small lap-connected rotors and for six-pole wave-connected rotors: the direction of the drop reverses at the lead-in points. With the *bar-to-bar* connection the current is led into adjacent sectors and repeated all round the commutator, and all measured drops should be the same. An alternative test for wave windings is to lead the current into the commutator at sectors separated by the *commutator pitch* of the winding. This is repeated all round the commutator and all readings of volt drop should be the same: this checks each individual coil.

Neutral setting Adjustment of the brush rocker so that the brushes are in the correct neutral position can most conveniently be done by applying about half normal voltage to the field winding with a low-reading voltmeter connected between the positive and negative brushes. The position of the rocker should be adjusted until there is no kick on the voltmeter when making or breaking the field circuit. It is desirable to remove all brushes except the two being used, and these should be bevelled so that they do not cover more than one segment.

If the exact position of a coil on the armature can be observed, the armature can be moved until this coil is symmetrically placed with its centre line opposite the centre line of a pole; the brush rocker should then be moved until a set of brushes stands on the commutator segment connected to this coil and it will then be in the neutral position. Occasionally one of the armature coils is specially marked by the manufacturers to facilitate this method of setting the neutral.

No-load test The power input to the motor running on no load with normal field current and at normal speed gives the sum of the core, friction and windage losses, together with a small armature I^2R loss which can be calculated and deducted. A *shunt* motor is run at normal field current, the speed being adjusted to normal full-load value by varying the applied armature voltage. The core and mechanical loss so determined is the *fixed* or *constant* loss, so called because it changes only slightly with load. A *series* motor is run with separate excitation to the field, and an armature voltage that will give (for a specified field current) the speed corresponding to load conditions at rated voltage. The voltage to be applied is equal to the counter-e.m.f. under load conditions, i.e. rated voltage less the volt drop in field and armature resistances.

The mechanical loss alone can be estimated by running the motor on no load in normal connection but with a low applied voltage that is adjusted to give the speed required. Then the power input corrected for I^2R loss is substantially the mechanical loss alone.

Loss summation The core, friction and windage losses from the no-load test are added to calculated armature and field I^2R losses (corrected to 75 °C) and to the brush loss taken generally as that due to a total brush volt drop of 2 V. The stray loss is allowed for by a deduction of 1% from the efficiency calculated from the losses mentioned above. If the machine has a compensating winding to counteract the distorting effect of armature reaction, the deduction is 0.5%.

Back-to-back

Shunt motors *Figure 20.54* shows the connections for a back-to-back test for similar machines. The motor M drives the generator G, the excitation of which is adjusted until there is no voltage across switch S; this is then closed. Raising the excitation of G causes it to generate and supply most of the power required for driving M. The two machines operate with both field and armature currents slightly differing in magnitude, but except for small machines the differences are minor.

Series motors Back-to-back tests are more common for series motors, which are not easily loaded with safety. Many series motors are, however, operated in pairs as in traction. The four most common methods are set out in *Figure 20.55*. Method (*a*) is not strictly a back-to-back test as the generator output is dissipated in resistance. Putting the generator field in series with the motor ensures that the generator will always excite. In method (*b*) a variable-voltage booster B is included in the circuit of G to raise its voltage and enable power to be returned to the supply. In both (*a*) and (*b*) it is desirable to boost the supply so that the voltage applied to M can be held at a correct value. Method (*c*) requires an auxiliary drive motor to supply the core and mechanical losses, and a low-voltage booster to supply the I^2R loss. Method (*d*) requires a separate source of excitation, although for small machines the field winding can be connected in series with G and controlled by a diverter.

Commutation The compole setting can be checked by measuring the *volt drop* between the brush and the commutator at three points along the brush width with the machine running on load (*Figure 20.56*(*a*)). The drop should be approximately the same at all points, as in *Figure 20.56*(*b*); if it is greater at the trailing edge, commutation is being delayed and the compoles are too weak. If it is higher at the leading edge the opposite is the case.

The *black-band* test is an alternative method. The compole current is varied independently of the armature current, and at each constant armature current the compole excitation is raised and lowered until sparking occurs. In the zone between these limits (*Figure 20.56*(*c*)), commutation is 'black', i.e. spark-free. The black band should be symmetrical about the axis of armature current.

20.3.9.7 Induction motors

The following are related specifically to three-phase induction motors. Most of the necessary data are obtained from the no-load and short-circuit tests.

No load The motor is run on no load at rated voltage and frequency, and the current and power input are measured. The input power supplies core and mechanical losses plus the stator I^2R loss; the rotor I^2R loss on no load can be neglected. If required, the motor may be operated at voltages above and below normal (*Figure 20.57*) and the power input and current plotted. Extrapolation of the power curve to zero voltage gives the friction and windage loss.

Short circuit (locked rotor) The short-circuit current and power are measured by holding the rotor stationary and applying a low voltage to the stator, it being usual to adjust the voltage to obtain full-load current. In the case of a cage motor the starting torque may also be measured. If the motor is connected for star–delta starting, the actual starting current and torque may be measured direct. The short-circuit current at full voltage is calculated by assuming the current to be proportional to voltage, although on some machines the short-circuit current is actually higher because the leakage reactance is reduced by saturation. This is more noticeable on two- and four-pole motors designed for a high flux density. The starting torque is approximately proportional to (phase voltage)^2.

The short-circuit current is 4–8 times full-load current, depending on the speed and type of motor. A multipolar motor works on a lower flux density to allow a reasonably good power factor. To this end some overload capacity may be sacrificed and the short-circuit current is therefore low.

Parameters The parameters of the equivalent circuit (*Figure 20.37*) can be evaluated from test results. The no-load test gives r_m and x_m if the stator leakage impedance drop is neglected (which is usually justifiable). Neglecting r_m and x_m in the short-circuit test gives the total motor effective resistance

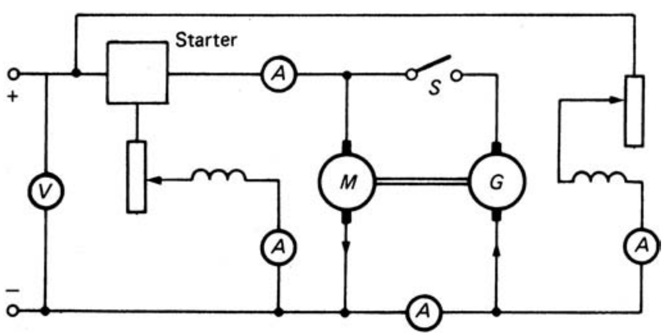


Figure 20.54 D.c. shunt motors: back-to-back test

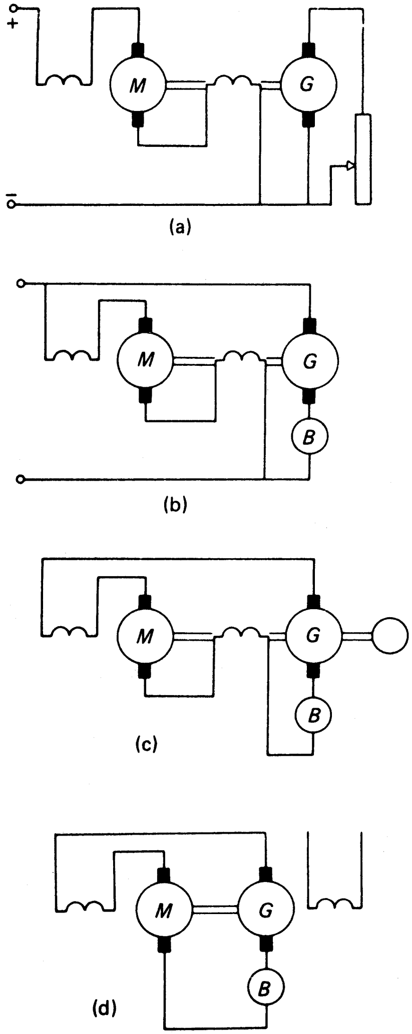


Figure 20.55 D.c. series motors: back-to-back tests

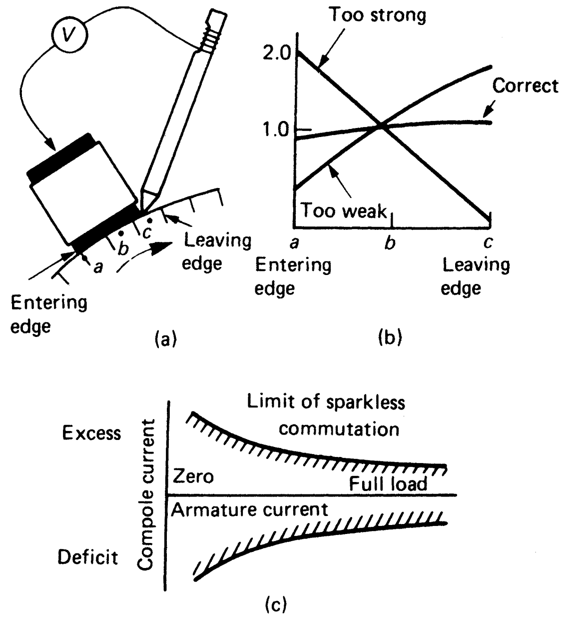


Figure 20.56 Commutation tests

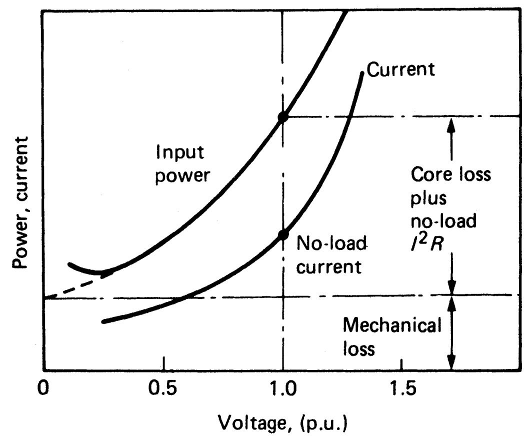


Figure 20.57 Induction motor: no-load characteristics

and leakage reactance, r_1+r_2 and x_1+x_2. The stator resistance r_1 can be measured directly and r_2 found; however, it is not possible to separate the two leakage reactances and it is usual to assume that they are equal.

Stray loss Stray loss is included in the short-circuit power. If, as in a slip-ring machine, both r_1 and r_2 (actual and referred) are measurable, the 'true' I^2R loss can be calculated and the stray loss found by subtraction. Where efficiency is calculated by loss summation, a deduction from the calculated efficiency is made (e.g. 0.0625 p.u. at rated load).

Back-to-back For large machines this test is essential. There must be provision for accommodating the speed difference resulting from the positive and negative slips of the motor and generator machines. Methods available are: (i) a close-ratio gearbox where at least one of the machines has a slip-ring rotor for slip control; (ii) a fluid coupling where both are cage machines; and (iii) an adaptation of the automobile differential.

In (iii), the test machines are coupled to the 'road-wheel' shafts. The torque shaft, driven slowly by a geared auxiliary motor, depresses the speed of the motoring machine and raises that of the generator. The main supply of rated voltage and frequency to the two stators provides the mechanical, core and stator I^2R loss and magnetising currents. The torque shaft controls the drive-power exchange between the two test machines.

20.3.9.8 Synchronous motors

Relevant procedures are given below. Again use is made of the open- and short-circuit tests, for which the machine is driven at rated speed by an auxiliary motor, preferably calibrated.

Open circuit The stator is on open circuit and the field current is varied. The stator e.m.f. gives the *magnetisation characteristic* or open-circuit characteristic (o.c.c.) (*Figure 20.58*). The power input to the test machine comprises core and mechanical losses, which can be separated.

Short circuit The stator windings are short circuited. The field current is increased to give stator current up to slightly above full-load value. The power input to the test machine comprises the stator I^2R, mechanical and stray losses, the core loss usually being negligible. An approximation to the stray loss is obtained by subtracting from the input power to the calculated I^2R loss and the mechanical loss (from the o.c.c. test).

Excitation The excitation for given load conditions is derived as for a generator, with reversed current and load angle. The appropriate phasor diagrams are given in *Figure 20.58*. Typical V-curves, relating the stator and field currents for specified output powers, are plotted in *Figure 20.59*.

Loss summation The friction and windage and the core losses can be obtained from the open-circuit tests, and the stray loss from the short-circuit test, as already described. For any given load the field current can be determined and the field power obtained therefrom. To the summation must be added the loss in the exciter or excitation circuit, and the efficiency can then be calculated.

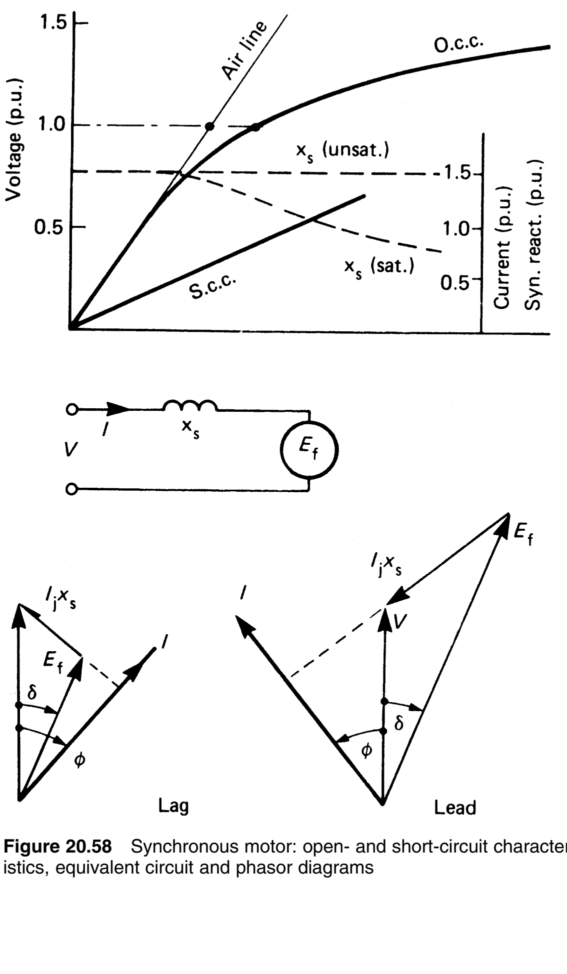


Figure 20.58 Synchronous motor: open- and short-circuit characteristics, equivalent circuit and phasor diagrams

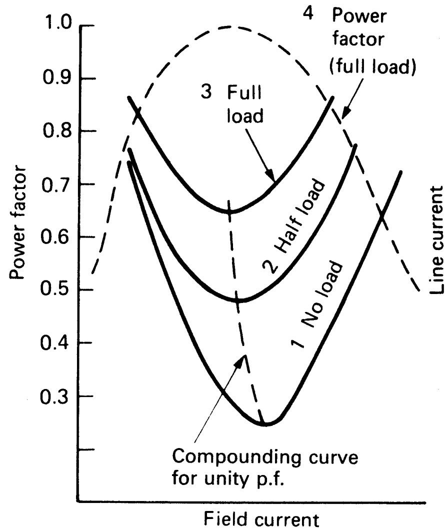


Figure 20.59 Synchronous motor: V-curves

Back to back If two similar machines are mechanically coupled so that their e.m.f.s are in phase, and they are driven mechanically at normal speed then, if they are connected in parallel electrically, a reactive current can be made to circulate between them by suitable adjustment of the field currents or by a booster transformer fed from an external source. The total electrical and mechanical input represents the total loss, but as the machines are not operating at their rated power factors the results are not valid for calculating full-load efficiencies. The test is, however, convenient for carrying out heat runs.

With the machines coupled so that their e.m.f.s are phase-displaced by an angle equal to twice the full-load load-angle, then full-load active and reactive powers can be circulated under conditions closely simulating normal load operation.

Zero power factor A pseudo full-load test can be carried out by loading the machine on inductors so that it operates at normal voltage and current but at a power factor near zero. The air-gap flux will be 4–5% above its normal full-load value and the field current will be up by 20–30%. If the machine is used for a heat run, temperatures will be higher than those that would obtain at rated load; however, appropriate adjustments can be made to simulate rated conditions more closely. Results from the zero-power-factor test can be used as described in BS 4296 to predetermine the field current on load.

20.3.10 Linear motors

Linear machines have translational instead of rotary motion. They can be applied to the drive of a conveyor belt, of a traversing crane on a limited track, of liquid metal in the heat-exchanger of a nuclear reactor plant, or of trains on a high-speed railway system. Short-stroke linear machines are suitable for powerful thrusting action.

20.3.10.1 Forms

A linear machine can be regarded initially as resembling a normal rotating machine that has been cut and opened out flat. Of the two elements derived respectively from the stator and rotor, either may move. The member connected to the supply is called the *primary*, the other the *secondary*. In use, either member is fixed as the *stator*, while the other becomes the movable *runner*.

Two forms of linear machine (*Figure 20.60*) are the *flat* machine (geometrically an 'unrolled' rotary structure) and the *tubular* machine, which is equivalent to a flat machine 'rerolled' around the longitudinal axis. For electromagnetic force to be developed, it is necessary to ensure that interaction between the working flux and the working currents should be achieved: the directions of the two components in and around the air gap must be at right angles. In the flat machine (*Figure 20.60*(*a*)) the secondary interaction currents are arranged to flow across the element from front to back, with suitable end-connectors to complete the secondary circuits. In the tubular machine the flux enters the pencil-shaped secondary in a radial direction, so that the secondary interaction currents must flow circumferentially.

In both of the shapes in *Figure 20.60* there are certain practical difficulties: (i) how to deal with a linear movement which, if continued, must eventually cause a runner of finite length to part company with its stator; (ii) how to support a very strong magnetic pull tending to cause runner and stator to adhere; (iii) how to supply electrical energy to a linear-moving runner. In the flat machine, and in the tubular machine if it is not precisely centred, the otherwise unbalanced attraction force must be sustained by some suitable mechanical arrangement. The linear machine is inherently a device lacking some of the symmetry and balance of the normal rotary form.

20.3.10.2 D.c. and a.c. machines

Any arrangement possible in a rotary machine can be realised in the flat form. The outlines in *Figure 20.60* show that the most convenient type is likely to be that corresponding to the cage induction motor, for then the stator can often be made the primary because of the convenience of its supply, while the moving secondary member will correspond to the cage rotor and will require a very simple winding with no supply connections. However, this arrangement is by no means the rule, and much depends on the particular conditions of a given application.

The d.c. and induction forms are the most common. Because of the essential secondary current supply, the d.c. linear motor is usually found as an electromagnetic pump for liquid metal. There is more freedom of shape in the induction machine, as indicated in *Figure 20.61*. The short-primary arrangement (*a*) suits cases in which the total distance to be travelled is great, for it would be uneconomic to wind a long three-phase primary, with only that part in the neighbourhood of the secondary being effective at any one time. The short-secondary form (*b*) is useful if the total excursion is limited and the moving secondary must be comparatively light. In both (*a*) and (*b*) the secondary is shown as a flattened 'cage'. A conducting sheet or plate (*c*) is often as effective, and it obviates magnetic attraction. The now

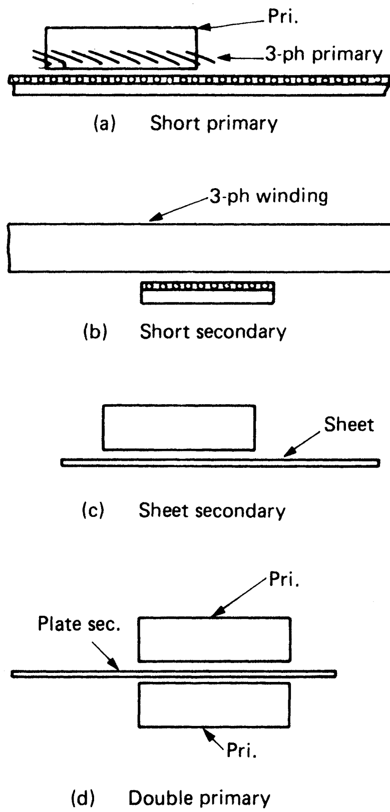


Figure 20.61 Polyphase linear-induction motors

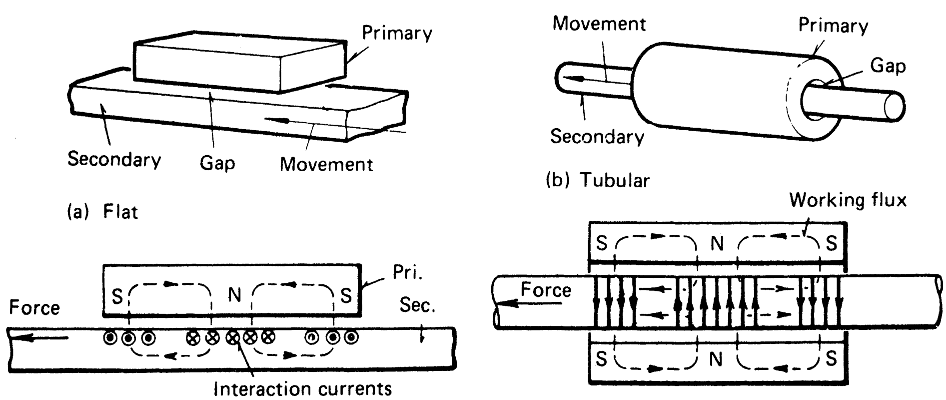


Figure 20.60 Linear motors: (a) flat; (b) tubular

indefinite 'gap', which increases the non-useful leakage flux, can be shortened by the use of a double primary (*d*).

Long-established methods for the design of orthodox rotary machines are not applicable to the radically changed geometry of linear flat or tubular machines. Lacking cylindrical symmetry, the magnetic flux is heavily distorted near the ends of the short element, and as the primary and secondary move relatively to one another, 'dead' regions of the secondary abruptly enter a magnetised gap, and 'live' regions abruptly leave it at the other side. As a result there are important transient effects, the elimination or mitigation of which will impose quite unusual restrictions on the design, affecting not only the length and number of poles of the primary, but also its optimum working frequency.

20.3.10.3 Duty

There are, in general, three operating duties, which influence the design and construction.

Power (drive) This is concerned with the transport of loads in conveyors, haulers, electromagnetic pumps, travelling cranes and railway traction with acceptable overall *power* efficiency.

Energy (accelerator) Here the duty is to accelerate a mass from rest within a specified time and distance, as in rope-break and car-crash test rigs and the launching of aircraft. The criterion is the *energy* efficiency, i.e. the ratio of the energy imparted to the load and the total primary electrical energy input, a figure that cannot exceed 0.5.

Force (actuator) This develops a thrust at rest, or over a short stroke, as in the operation of stop-valves, impact metal-forming, door closers and small thrustors. The criterion is the *force* per unit electrical power.

20.3.10.4 General principles

The following analysis, applying to power (drive) types of linear motor, outlines in simplified terms the basic principles.

Speed The speed of a d.c. linear machine is associated with the secondary applied voltage and the flux per pole in a way comparable to the relationship between these variables in a rotary machine.

The speed of an induction-type linear machine is associated with the synchronous speed u, which is given by $u_1 = f\lambda$ for a supply frequency f, where λ is the wavelength (i.e. the length of a double pole-pitch). The actual speed u differs from u_1 because of the slip. If $\lambda = 1$ m and the supply frequency is 50 Hz, then $u_1 = 50$ m/s $= 180$ km/h. For lower translational speeds on a 50 Hz supply it is necessary to shorten the wavelength. However, if λ is less than about 0.2 m, corresponding to $u_1 = 10$ m/s $= 36$ km/h, the performance is impaired because the pole-pitch is short compared with the gap length. The effect is most significant in machines with an 'open' magnetic circuit (*Figure 20.61*(*c*)). Much better low-speed performance can be achieved if a low-frequency supply is available. In some cases in which starting from rest at high translational force is sought, a primary with a graded pole-pitch may be of advantage; alternatively the frequency can be raised during the starting period if the method can be economically justified.

Power If in a secondary member the surface current density is J and the gap flux density is B, the force developed per unit area of gap surface is BJ, and the motional e.m.f. developed at a translational speed u is Bu per unit width. The working voltage to be supplied to maintain motion is $v = Bu + J\rho$ per unit width, where ρ is the resistivity of the secondary surface current conducting path. Where the secondary is a conducting sheet (solid or liquid) the secondary current paths are ill-defined, so that estimation of performance is not straightforward.

In an induction linear machine with a two- or three-phase winding fed at frequency f and providing a travelling wave of gap flux at synchronous speed $u_1 = f\lambda$, the runner moves in the same direction at a lower speed u, i.e. with a slip given by $s = (u_1 - u)/u_1$. At a point in the gap where the instantaneous gap flux density is B_x, the e.m.f. induced in the secondary is $e_x = B_x s u_1$ per unit width, producing a secondary current of linear density $J_x = e_x/\rho$ (ignoring inductive effects in the current path). The interaction force per unit width is therefore $B_x J_x = B_x^2 s u_1/\rho$. Summed over a wavelength (one double pole-pitch of length λ) the force is $\frac{1}{2}\lambda s u_1 B_m^2/\rho$, where B_m is the peak density of the travelling wave of magnetic field. As the runner moves at speed $u_1(1-s)$, the mechanical power produced per wavelength and per unit width is

$$P_m = \tfrac{1}{2}s(1-s)u_1^2 B_m^2/\rho$$

This is a maximum for $s = 0.5$. The simple analysis applies only to wavelengths remote from the ends of the shorter member of the machine. In general, the precise current circuit of the secondary is somewhat indefinite, there are effects of leakage inductance, and near the ends of the primary block the 'dead' regions of the secondary abruptly enter the magnetised gap while 'live' regions as abruptly leave it. As a result there are transient 'entry and exit' effects, the mitigation of which imposes restrictions on the design that are absent in rotary types.

20.3.10.5 Applications

Some typical applications are described.

Electromagnetic pump The electromagnetic pump utilises the good electrical conductivity of the liquid metal being pumped to establish electromagnetic forces directly within the liquid itself. The liquid is contained in a simple pipe, which can be welded to the rest of the circuit, so that valves, seals and glands are avoided; this is desirable since the low-melting-point metals are highly reactive chemically. Because of the absence of glands and moving parts, the pump reliability should be high and maintenance costs low. In addition, the pump itself is often smaller and the amount of liquid contained sometimes less, which is important when expensive liquids are being handled. Moreover, in favourable cases, particularly with high-conductivity liquid metals, the pump is likely to be cheaper.

The most important applications for circulating liquid metal are in nuclear energy projects where the metal is used as a coolant: sodium, sodium–potassium and lithium are the metals chiefly concerned. Most other industrial applications are restricted to low-melting-point metals, as in the die-casting industry or in chlorine plants for pumping mercury, but a form of liquid-metal pump has been found useful for stirring molten steel in arc furnaces.

The liquids mentioned divide into two distinct classes: (1) sodium, sodium–potassium and lithium; and (2) bismuth, mercury, lead and lead–bismuth, which have much poorer pumping properties. For example, the resistivity of bismuth is nearly eight times that of sodium, its viscosity is five times higher and its density is 11 times higher. A high resistivity lowers the efficiency, while high viscosity and density make the pump appreciably larger, for, to reduce hydraulic losses, the liquid velocity must be low, and this increases the size of the pump duct.

The wide difference in liquid pumping properties influences the type of pump and the efficiency obtainable. Liquids like bismuth usually necessitate conduction pumps, in which current is supplied directly to the liquid through the tube walls. In contrast, sodium can be pumped by conduction or induction.

D.c. conduction pump The general arrangement is shown in *Figure 20.62*. The magnetic field can be produced by a permanent-magnet system or by an electromagnet. A series-excited electromagnet is preferred for large pumps as it is usually smaller and cheaper and involves only the provision of a few turns around the pole, as close as possible to the gap, to carry the main operating current. The supply requirements vary from 5 kA at 0.5 V for a pump of 0.05–0.1 m^3/min capacity at a pressure differential of 350 kN/m^2, up to 250 kA at 3–4 V for a nuclear reactor pump delivering 25 m^3/min at 500 kN/m^2. These inconvenient requirements form the major disadvantage of the d.c. pump; the compensating advantages are the minimal insulation levels (desirable if the liquid is hot or radioactive), the accommodating performance which can deal with a wide range of flow rates and pressures with good efficiency, and the adaptability to a variety of metals, including bismuth.

In d.c. pump design it is important to assess the field distortion due to the current in the liquid metal and to apply compensation if necessary, by returning the current to the electrode between the pole and the pump duct, usually as a pole face winding. It is also important for good efficiency to restrict the useless components of electrode current, which flows in the tube wall and in the liquid outside the pole region. The tube-wall current can usually be limited only by choosing a thin-walled tube of high intrinsic resistivity. The useless current can be substantially reduced by fringing the field to match the natural fringing of the current density between the electrodes. It is also important in design to limit magnetic leakage by appropriately positioning the magnetising turns and by shaping the iron.

The operation can be approximately described in terms of the flow of a quantity q of liquid at velocity u in a tube of width b in the current direction and effective length c in the direction of the liquid movement, the liquid having a resistivity ρ:

Electrodes: voltage $V_0 = (Bu + J\rho)b$;
current $I_0 = I = I_t = I_s$

Pump: gross pressure $p = (B_m I)c$;
gross power $P_0 = pq$

Here B is the flux density, of mean value B_m, and J is the current density. The electrode current I_0 includes the useful current I, and non-useful shunt currents I_t in the tube walls and I_s in the liquid outside the magnetised region. The gross pressure p includes the hydraulic pressure, drop in skin friction, etc.

A.c. induction pump The two basic forms are the flat and the annular. The flat type (*Figure 20.63*) has a straight duct 10–25 mm wide and up to 1 m across. Copper bars are attached to each side of the channel to form the equivalent of the 'end-rings' of a normal cage winding. A flat polyphase winding is placed on each side of the duct. A heat-insulating blanket is usually necessary between duct and winding, which is force cooled. The annular form is similar except that the cross-section of the duct is an annulus and embraces a radially laminated magnetic core. The polyphase winding comprises a number of pancake coils surrounding the duct and set in comb-like stacks of radial punchings. If the duct is made re-entrant, with inlet and outlet at the same end, it is possible to remove the primary windings for repair and maintenance, should this become necessary, without disturbing the pipe-work.

Cranes Two linear induction motors can be applied to the traversing of an overhead crane, replacing the conventional rotary cage motor, gearing, drive shaft and control equipment. Maintenance is simplified and, as the linear motors are unaffected by atmospheric conditions, the likelihood of breakdown is reduced. The arrangement for one of the motors is shown schematically in *Figure 20.64*. Each motor comprises a horizonal pack of laminations carrying a three-phase winding. Motors are located at each end of the crane gantry and directly below the tracks from which the crane is suspended. The track functions as the secondary, the arrangement being basically that of *Figure 20.61(c)*.

Traction Several schemes have been proposed for railway traction. One uses a short-primary form of motor on the locomotive and a fixed 'plate' secondary secured to the track. The moving primary demands either that power be supplied to the moving train or that a prime mover and three-phase generator be carried on board. Some recent

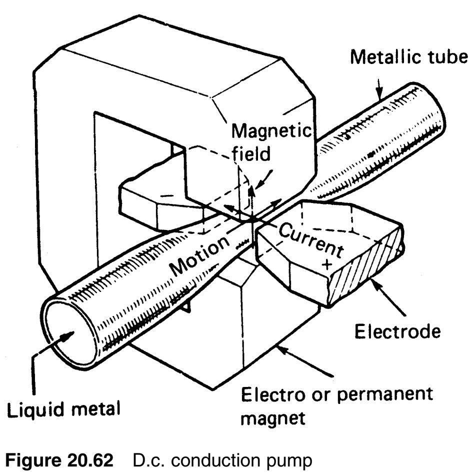


Figure 20.62 D.c. conduction pump

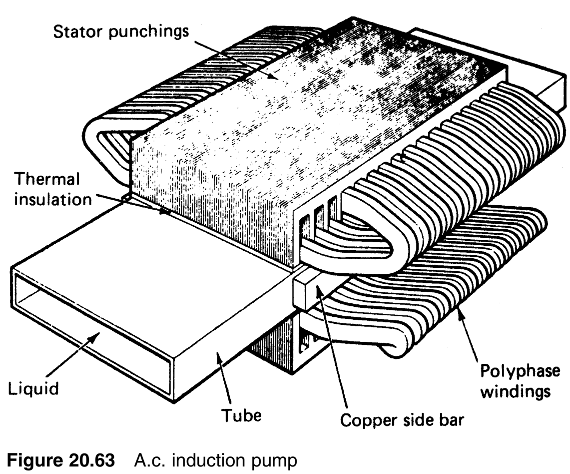


Figure 20.63 A.c. induction pump

developments exploit magnetic levitation and the elimination of running wheels.

Stirring The stirring of molten metal in furnaces can be done by external application of short linear induction motors. The process has considerable metallurgical advantage in improving the casting properties of aluminium and copper, and in accelerating the deoxidation processes in steel. The primary of the motor does not come into contact with the melt, is readily controlled and can be arranged for vertical, rotary or horizontal stirring.

Short-stroke devices The linear induction motor offers a compact and readily controllable means for the automation of punching, stamping and impact extrusion. With the wavelength graded on the fixed primaries to raise the 'synchronous' speed as the short secondary runner approaches the workpiece, end speeds of 30 m/s and considerable kinetic energy can be attained. Other industrial applications include the following:

Sliding doors: here an advantage is that, should the supply fail, the motor does not impede movement of the door by hand.

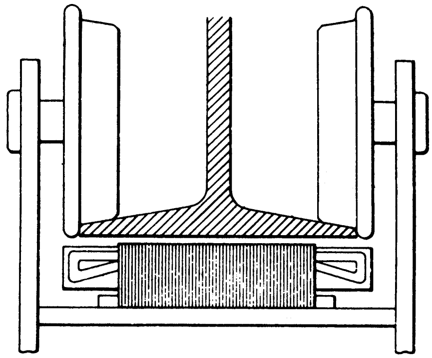


Figure 20.64 Linear traversing crane motor

Goods lifts: the arrangement is that of *Figure 20.64* turned vertically, the linear motor stator providing some of the counterweight.

Tensioning machines: the linear motor gives readily controllable tension for testing ropes, aluminium strip, etc.

Section E
Environment