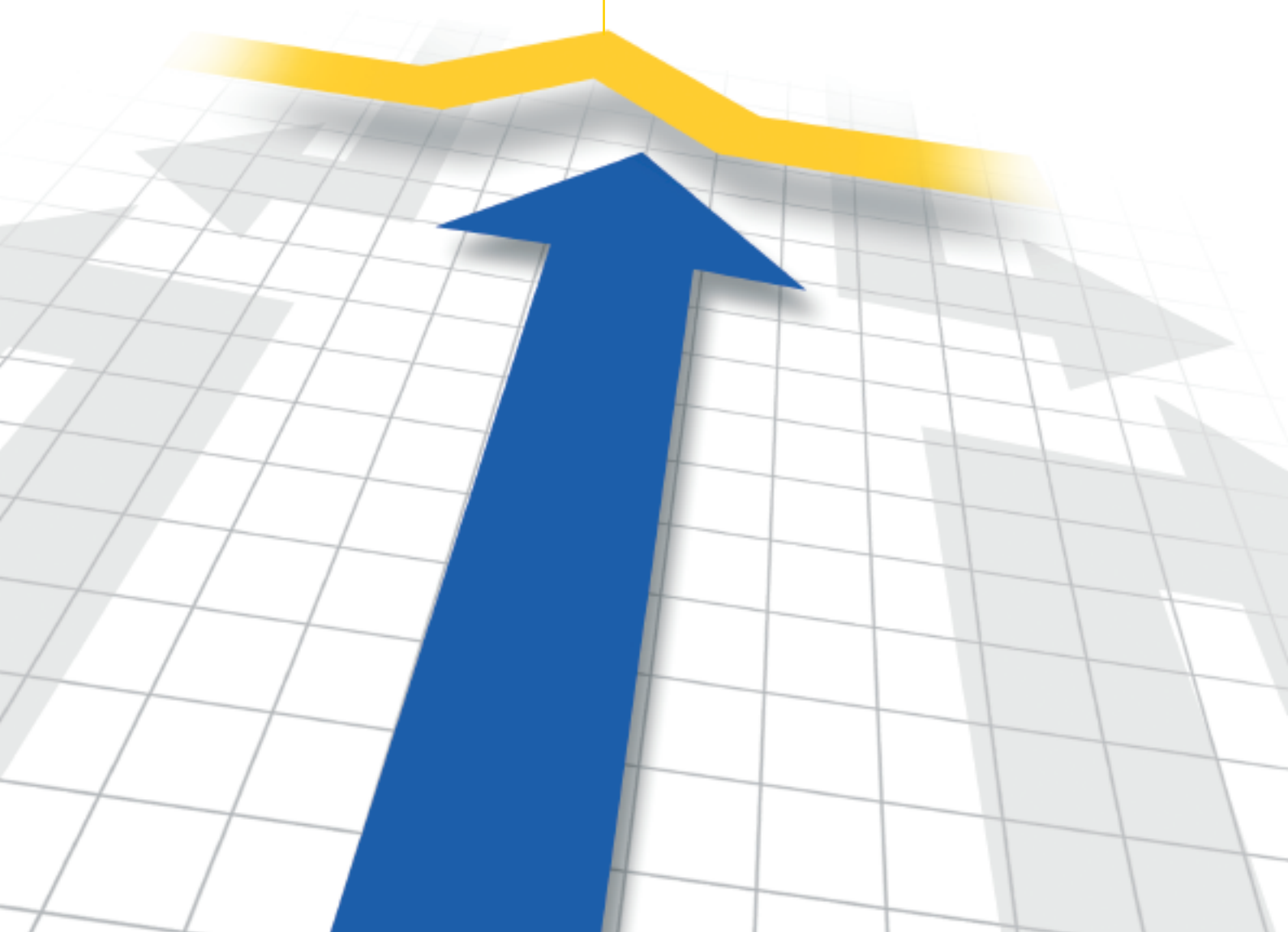


3 chapter

Motors and loads

Introduction to motor technology

Information on loads and motor electrical behaviour

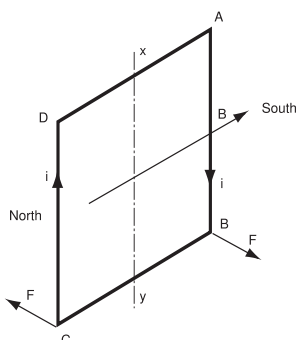


3.1	Three phase asynchronous motors	38
3.2	Single-phase motors	42
3.3	Synchronous motors	43
3.4	Direct current motors commonly named DC motors	45
3.5	Operating asynchronous motors	47
3.6	Electric motor comparison	50
3.7	Types of loads	51
3.8	Valves and electric jacks	56

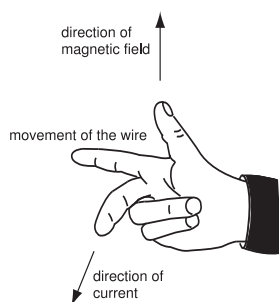
This section describes the physical and electrical aspects of motors. The operating principle of the most common types of motors is explained in detail.

The powering, starting and speed control of the motors are explained in brief. For fuller information, see the relevant section.

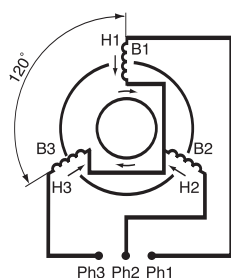
3.1 Three phase asynchronous motors



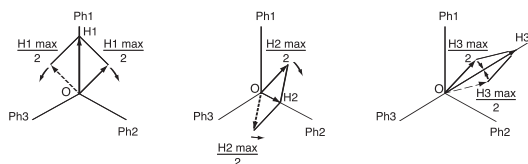
↑ Fig. 1 An induced current is generated in a short-circuited shading ring



↑ Fig. 2 Rule of three fingers of the right hand to find the direction of the force



↑ Fig. 3 Principle of the 3-phase asynchronous motor



↑ Fig. 4 Fields generated by the three phases

The first part deals with 3-phase asynchronous motors, the one most usually used for driving machines. These motors have a number of advantages that make them the obvious choice for many uses: they are standardised, rugged, easy to operate and maintain and cost-effective.

■ Operating principle

The operating principle of an asynchronous motor involves creating an induced current in a conductor when the latter cuts off the lines of force in a magnetic field, hence the name “induction motor”. The combined action of the induced current and the magnetic field exerts a driving force on the motor rotor.

Let’s take a shading ring ABCD in a magnetic field B, rotating round an axis xy (⇒ Fig. 1).

If, for instance, we turn the magnetic field clockwise, the shading ring undergoes a variable flux and an induced electromotive force is produced which generates an induced current (Faraday’s law).

According to Lenz’s law, the direction of the current is such that its electromagnetic action counters the cause that generated it. Each conductor is therefore subject to a Lorentz force F in the opposite direction to its own movement in relation to the induction field.

An easy way to define the direction of force F for each conductor is to use the rule of three fingers of the right hand (action of the field on a current, ⇒ Fig. 2).

The thumb is set in the direction of the inductor field. The index gives the direction of the force.

The middle finger is set in the direction of the induced current. The shading ring is therefore subject to a torque which causes it to rotate in the same direction as the inductor field, called a rotating field. The shading ring rotates and the resulting electromotive torque balances the load torque.

■ Generating the rotating field

Three windings, offset geometrically by 120, are each powered by one of the phases in a 3-phase AC power supply (⇒ Fig. 3).

The windings are crossed by AC currents with the same electrical phase shift, each of which produces an alternating sine-wave magnetic field. This field, which always follows the same axis, is at its peak when the current in the winding is at its peak.

The field generated by each winding is the result of two fields rotating in opposite directions, each of which has a constant value of half that of the peak field. At any instant t1 in the period (⇒ Fig. 4), the fields produced by each winding can be represented as follows:

- field H1 decreases. Both fields in it tend to move away from the OH1 axis,
- field H2 increases. Both fields in it tend to move towards the OH2 axis,
- field H3 increases. Both fields in it tend to move towards the OH3 axis.

The flux corresponding to phase 3 is negative. The field therefore moves in the opposite direction to the coil.

If we overlay the 3 diagrams, we can see that:

- the three anticlockwise fields are offset by 120° and cancel each other out,
- the three clockwise fields are overlaid and combine to form the rotating field with a constant amplitude of $3H_{max}/2$. This is a field with one pair of poles,
- this field completes a revolution during a power supply period. Its speed depends on the mains frequency (f) and the number of pairs of poles (p). This is called “synchronous speed”.

■ Slip

A driving torque can only exist if there is an induced current in the shading ring. It is determined by the current in the ring and can only exist if there is a flux variation in the ring. Therefore, there must be a difference in speed in the shading ring and the rotating field. This is why an electric motor operating to the principle described above is called an “asynchronous motor”.

The difference between the synchronous speed (N_s) and the shading ring speed (N) is called “slip” (s) and is expressed as a percentage of the synchronous speed.

$$s = [(N_s - N) / N_s] \times 100.$$

In operation, the rotor current frequency is obtained by multiplying the power supply frequency by the slip. When the motor is started, the rotor current frequency is at its maximum and equal to that of the stator current.

The stator current frequency gradually decreases as the motor gathers speed.

The slip in the steady state varies according to the motor load. Depending on the mains voltage, it will be less if the load is low and will increase if the motor is supplied at a voltage below the rated one.

■ Synchronous speed

The synchronous speed of 3-phase asynchronous motors is proportional to the power supply frequency and inversely proportional to the number of pairs in the stator.

Example: $N_s = 60 f/p$.

Where: N_s : synchronous speed in rpm
f: frequency in Hz
p: number of pairs of poles.

The table ($\Rightarrow$ Fig. 5) gives the speeds of the rotating field, or synchronous speeds, depending on the number of poles, for industrial frequencies of 50Hz and 60Hz and a frequency of 100Hz.

In practice, it is not always possible to increase the speed of an asynchronous motor by powering it at a frequency higher than it was designed for, even when the voltage is right. Its mechanical and electrical capacities must be ascertained first.

As already mentioned, on account of the slip, the rotation speeds of loaded asynchronous motors are slightly lower than the synchronous speeds given in the table.

□ Structure

A 3-phase asynchronous squirrel cage motor consists of two main parts: an inductor or stator and an armature or rotor.

□ Stator

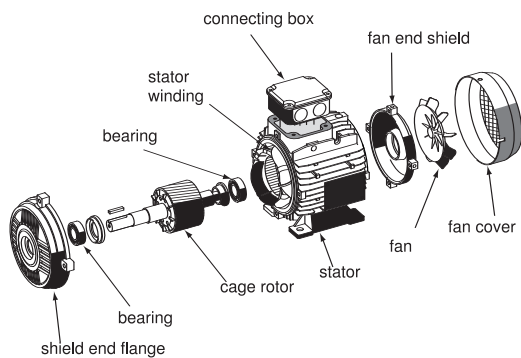
This is the immobile part of the motor. A body in cast iron or a light alloy houses a ring of thin silicon steel plates (around 0.5mm thick). The plates are insulated from each other by oxidation or an insulating varnish.

The “lamination” of the magnetic circuit reduces losses by hysteresis and eddy currents.

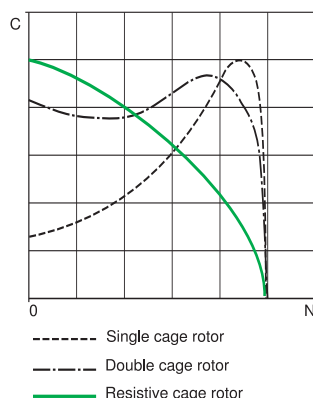
Number of poles	Speed of rotation in rpm		
	50 Hz	60 Hz	100 Hz
2	3000	3600	6000
4	1500	1800	3000
6	1000	1200	2000
8	750	900	1500
10	600	720	1200
12	500	600	1000
16	375	540	750

↑ Fig. 5

Synchronous speeds based on number of poles and current frequency



↑ Fig. 6 Exploded view of a squirrel cage motor



↑ Fig. 7 Torque/speed curves of cage motor types (at nominal voltage)

The plates have notches for the stator windings that will produce the rotating field to fit into (three windings for a 3-phase motor). Each winding is made up of several coils. The way the coils are joined together determines the number of pairs of poles on the motor and hence the speed of rotation.

□ Rotor

This is the mobile part of the motor. Like the magnetic circuit of the stator, it consists of stacked plates insulated from each other and forming a cylinder keyed to the motor shaft.

The technology used for this element divides asynchronous motors into two families: squirrel cage rotor and wound slip ring motors.

■ Types of rotor

□ Squirrel cage rotors

There are several types of squirrel cage rotor, all of them designed as shown in *figure 6*.

From the least common to the most common:

• Resistant rotor

The resistant rotor is mainly found as a single cage (see the definition of single-cage motors below). The cage is closed by two resistant rings (special alloy, reduced section, stainless steel rings, etc.).

These motors have a substantial slip at the rated torque. The starting torque is high and the starting current low (⇒ *Fig. 7*).

Their efficiency is low due to losses in the rotor.

These motors are designed for uses requiring a slip to adapt the speed according to the torque, such as:

- several motors mechanically linked to spread the load, such as a rolling mill train or a hoist gantry,
- winders powered by Alquist (see note) motors designed for this purpose,
- uses requiring a high starting torque with a limited current inrush (hoisting tackle or conveyors).

Their speed can be controlled by changing the voltage alone, though this function is being replaced by frequency converters. Most of the motors are self-cooling but some resistant cage motors are motor cooled (drive separate from the fan).

Note: these force cooled asynchronous high-slip motors are used with a speed controller and their stalling current is close to their rated current; they have a very steep torque/speed ratio. With a variable power supply, this ratio can be adapted to adjust the motor torque to the requisite traction.

• Single cage rotor

In the notches or grooves round the rotor (on the outside of the cylinder made up of stacked plates), there are conductors linked at each end by a metal ring. The driving torque generated by the rotating field is exerted on these conductors. For the torque to be regular, the conductors are slightly tilted in relation to the motor axis. The general effect is of a squirrel cage, whence the name.

The squirrel cage is usually entirely moulded (only very large motors have conductors inserted into the notches). The aluminium is pressure-injected and the cooling ribs, cast at the same time, ensure the short-circuiting of the stator conductors.

These motors have a fairly low starting torque and the current absorbed when they are switched on is much higher than the rated current (⇒ *Fig. 7*).

On the other hand, they have a low slip at the rated torque. They are mainly used at high power to boost the efficiency of installations with pumps and fans. Used in combination with frequency converters for speed control, they are the perfect solution to problems of starting torque and current.

- **Double cage rotor**

This has two concentric cages, one outside, of small section and fairly high resistance, and one inside, of high section and lower resistance.

- On first starting, the rotor current frequency is high and the resulting skin effect causes the entire rotor current to circulate round the edge of the rotor and thus in a small section of the conductors. The torque produced by the resistant outer cage is high and the inrush is low ($\Rightarrow$ Fig. 7).
- At the end of starting, the frequency drops in the rotor, making it easier for the flux to cross the inner cage. The motor behaves pretty much as though it were made from a single non-resistant cage. In the steady state, the speed is only slightly less than with a single-cage motor.

- **Deep-notch rotor**

This is the standard rotor.

Its conductors are moulded into the trapezoid notches with the short side on the outside of the rotor.

It works in a similar way to the double-cage rotor: the strength of the rotor current varies inversely with its frequency.

Thus:

- on first starting, the torque is high and the inrush low,
- in the steady state, the speed is pretty much the same as with a single-cage rotor.

- **Wound rotor (slip ring rotor)**

This has windings in the notches round the edge of the rotor identical to those of the stator ($\Rightarrow$ Fig. 8).

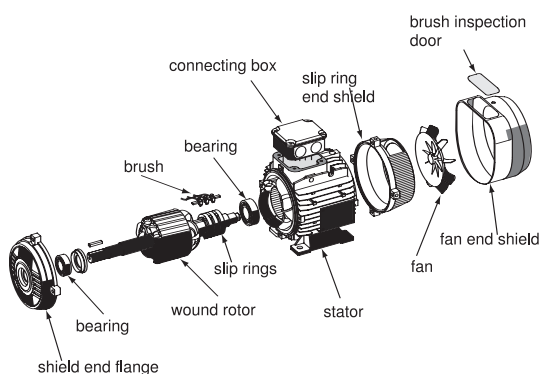
The rotor is usually 3-phase. One end of each winding is connected to a common point (star connection). The free ends can be connected to a centrifugal coupler or to three insulated copper rings built into the rotor.

These rings are rubbed by graphite brushes connected to the starting device.

Depending on the value of the resistors in the rotor circuit, this type of motor can develop a starting torque of up to 2.5 times the rated torque.

The starting current is virtually proportional to the torque developed on the motor shaft.

This solution is giving way to electronic systems combined with a standard squirrel cage motor. These make it easier to solve maintenance problems (replacement of worn motor brushes, maintenance of adjustment resistors), reduce power dissipation in the resistors and radically improve the installation's efficiency.



↑ Fig. 8 Exploded view of a slip ring rotor motor

3.2 Single-phase motors

The single-phase motor, though less used in industry than the 3-phase, is fairly widely used in low-power devices and in buildings with 230V single-phase mains voltage.

■ Squirrel cage single-phase motors

For the same power, these are bulkier than 3-phase motors.

Their efficiency and power factor are much lower than a 3-phase motor and vary considerably with the motor size and the manufacturer.

In Europe, the single-phase motor is little used in industry but commonly used in the USA up to about ten kW.

Though not very widely used, a squirrel cage single-phase motor can be powered via a frequency converter, but very few manufacturers offer this kind of product.

□ Structure

Like the 3-phase motor, the single-phase motor consists of two parts: the stator and the rotor.

• Stator

This has an even number of poles and its coils are connected to the mains supply.

• Rotor

Usually a squirrel cage.

□ Operating principle

Let's take a stator with two windings connected to the mains supply L1 and N ($\Rightarrow$ Fig. 9).

The single-phase alternating current generates a single alternating field H in the rotor – a superposition of the fields H1 and H2 with the same value and rotating in opposite directions.

At standstill, the stator being powered, these fields have the same slip in relation to the rotor and hence generate two equal and opposing torques.

The motor cannot start.

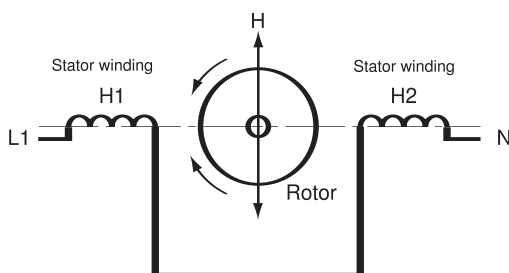
A mechanical pulse on the rotor causes unequal slips. One of the torques decreases while the other increases. The resulting torque starts the motor in the direction it was run in.

To overcome this problem at the starting stage, another coil offset by 90° is inserted in the stator.

This auxiliary phase is powered by a phase shift device (capacitor or inductor); once the motor has started, the auxiliary phase can be stopped by a centrifugal contact.

Another solution involves the use of short circuit phase-shift rings, built in the stator which make the field slip and allow the motor to start. This kind of motor is only found in low-power devices (no more than 100W) ($\Rightarrow$ Fig. 10).

A 3-phase motor (up to 4kw) can also be used in a single phase arrangement: the starting capacitor is fitted in series or parallel with the idle winder. This system can only be considered as a stopgap because the performance of the motors is seriously reduced. Manufacturers leaflets give information regarding wiring, capacitors values and derating.



↑ Fig. 9 Operating principle of a single-phase asynchronous motor



↑ Fig. 10 Single phase short circuit phase-shift rings

3. Motors and loads

3.2 Single-phase motors

3.3 Synchronous motors



↑ Fig. 11 Universal single phase motor

■ Universal single-phase motors

Though little used in industry, this is most widely-made motor in the world. It is used in domestic appliances and portable tools.

Its structure is similar to that of a series wound direct current motor (⇒ Fig. 11). As the unit is powered by alternating current, the flux in the machine is inverted at the same time as the voltage, so the torque is always in the same direction.

It has a wound stator and a rotor with windings connected to rings. It is switched by brushes and a collector.

It powers up to 1000W and its no-load rotation speed is around 10,000 rpm. These motors are designed for inside use.

Their efficiency is rather poor.

3

3.3 Synchronous motors

■ Magnetic rotor synchronous motors

□ Structure

Like the asynchronous motor, the synchronous motor consists of a stator and a rotor separated by an air gap. It is different in that the flux in the air gap is not due to an element in the stator current but is created by permanent magnets or by the inductor current from an outside source of direct current powering a winding in the rotor.

• Stator

The stator consists of a body and a magnetic circuit usually made of silicon steel plates and a 3-phase coil, similar to that of an asynchronous motor, powered by a 3-phase alternating current to produce a rotating field.

• Rotor

The rotor has permanent magnets or magnetising coils through which runs a direct current creating intercalated north-south poles. Unlike asynchronous machines, the rotor spins at the speed of the rotating field with no slip.

There are thus two distinct types of synchronous motor: magnetic motors and coil rotor motors.

- In the former, the rotor is fitted with permanent magnets (⇒ Fig. 12), usually in rare earth to produce a high field in a small space.

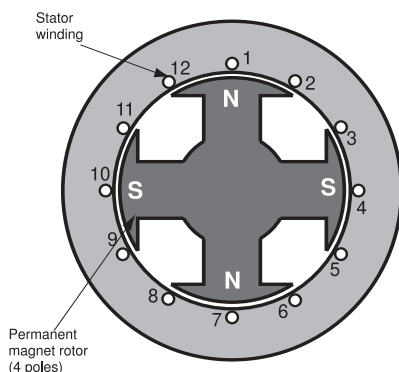
The stator has 3-phase windings.

These motors support high overload currents for quick acceleration.

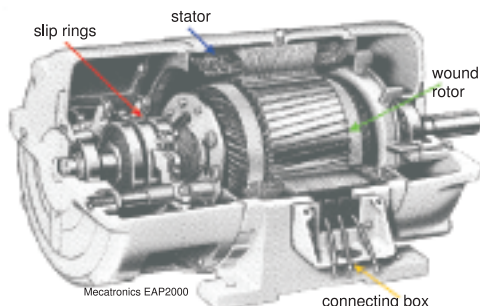
They are always fitted with a speed controller. Motor-speed controller units are designed for specific markets such as robots or machine tools where smaller motors, acceleration and bandwidth are mandatory.

- The other synchronous machines have a wound rotor (⇒ Fig. 13). The rotor is connected rings although other arrangements can be found as rotating diodes for example. These machine are reversible and can work as generators (alternators) or motors. For a long while, they were mainly used as alternators – as motors they were practically only ever used when it was necessary to drive loads at a set speed in spite of the fairly high variations in their load torque.

The development of direct frequency converters (of cycloconverter type) or indirect converters switching naturally due to the ability of synchronous machines to provide reactive power has made it possible to produce variable-speed electrical drives that are powerful, reliable and very competitive compared to rival solutions when power exceeds one megawatt.



↑ Fig. 12 Cross section of a 4 pole permanent magnet motor



↑ Fig. 13 Synchronous wound rotor motor

Though industry does sometimes use asynchronous motors in the 150kW to 5MW power range, it is at over 5MW that electrical drives using synchronous motors have found their place, mostly in combination with speed controllers.

□ Operating characteristics

The driving torque of a synchronous machine is proportional to the voltage at its terminals whereas that of an asynchronous machine is proportional to the square of the voltage.

Unlike an asynchronous motor, it can work with a power factor equal to the unit or very close to it.

Compared to an asynchronous motor, a synchronous one has a number of advantages with regard to its powering by a mains supply with constant voltage and frequency:

- the motor speed is constant, whatever the load,
- it can provide reactive power and help improve the power factor of an installation,
- it can support fairly big drops in voltage (around 50%) without stalling due to its overexcitation capacity.

However, a synchronous motor powered directly by a mains supply with constant voltage and frequency does have two disadvantages:

- it is difficult to start; if it has no speed controller, it has to be no-load started, either directly for small motors or by a starting motor which drives it at a nearly synchronous speed before switching to direct mains supply,
- it can stall if the load torque exceeds its maximum electromagnetic torque and, when it does, the entire starting process must be run again.

■ Other types of synchronous motors

To conclude this overview of industrial motors, we can mention linear motors, synchronised asynchronous motors and stepper motors.

□ Linear motors

Their structure is the same as that of rotary synchronous motors: they consist of a stator (plate) and a rotor (forcer) developed in line. In general, the plate moves on a slide along the forcer.

As this type of motor dispenses with any kind of intermediate kinematics to transform movement, there is no play or mechanical wear in this drive.

□ Synchronised asynchronous motors

These are induction motors. At the starting stage, the motor works in asynchronous mode and changes to synchronous mode when it is almost at synchronous speed.

If the mechanical load is too great, it can no longer run in synchronous mode and switches back to asynchronous mode.

This feature is the result of a specific rotor structure and is usually for low-power motors.

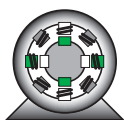
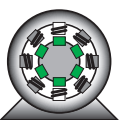
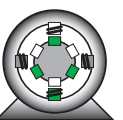
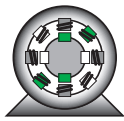
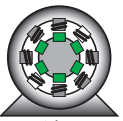
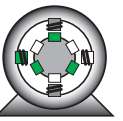
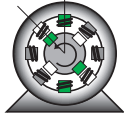
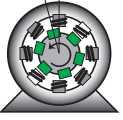
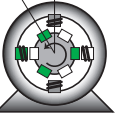
□ Stepper motors

The stepper motor runs according to the electrical pulses that power its coils. Depending on the electricity supply, it can be:

- unipolar if the coils are always powered in the same direction by a single voltage;
- bipolar if the coils are powered first in one direction then in the other. They create alternating north and south poles.

Stepper motors can be variable reluctance, magnetic or both (⇒ Fig. 14).

The minimum angle of rotation between two electrical pulse changes is called a step. A motor is characterised by the number of steps per revolution (i.e. 360°). The common values are 48, 100 or 200 steps per revolution.

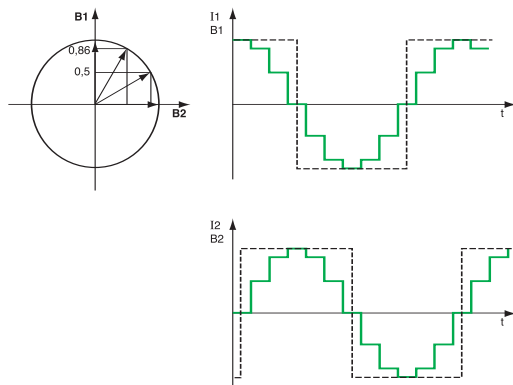
Type	Permanent magnet bipolar	Variable reluctance unipolar	Hybrid Bipolar
Characteristics	2 phases, 4 wires	4 phases, 8 wires	2 phases 14 wires
No. of steps/rev.	8	24	12
Operating stages			
Step 1			
Intermediate state			
Step 2			

↑ Fig. 14 Type of stepper motors

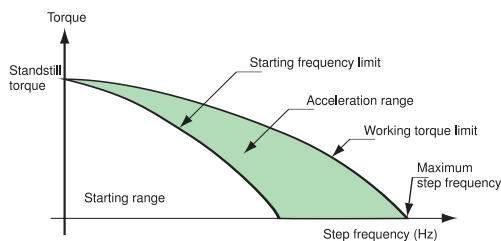
3. Motors and loads

3.3 Synchronous motors

3.4 Direct current motors commonly named DC motors



↑ Fig. 15 Current steps in motor coils to shorten its step



↑ Fig. 16 Maximum torque depending on step frequency

The motor rotates discontinuously. To improve the resolution, the number of steps can be increased electronically (micro-stepping). This solution is described in greater detail in the section on electronic speed control.

Varying the current in the coils by graduation (⇒ Fig. 15) results in a field which slides from one step to the next and effectively shortens the step.

Some circuits for micro-steps multiply by 500 the number of steps in a motor, changing, e.g. from 200 to 100,000 steps.

Electronics can be used to control the chronology of the pulses and count them. Stepper motors and their control circuits regulate the speed and amplitude of axis rotation with great precision.

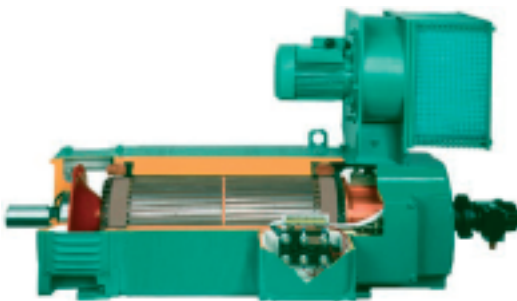
They thus behave in a similar way to a synchronous motor when the shaft is in constant rotation, i.e. specific limits of frequency, torque and inertia in the driven load (⇒ Fig. 16).

When these limits are exceeded, the motor stalls and comes to a standstill.

Precise angular positioning is possible without a measuring loop. These motors, usually rated less than a kW, are for small low-voltage equipment. In industry, they are used for positioning purposes such as stop setting for cutting to length, valve control, optical or measuring devices, press or machine tool loading/unloading, etc.

The simplicity of this solution makes it particularly cost-effective (no feedback loop). Magnetic stepper motors also have the advantage of a standstill torque when there is no power. However, the initial position of the mobile part must be known and integrated by the electronics to ensure efficient control.

3.4 Direct current motors commonly named DC motors



↑ Fig. 17 DC motor

Separate excitation, DC motors (⇒ Fig. 17) are still used for variable speed drive, though they are seriously rivalled by asynchronous motors fitted with frequency converters.

Very easy to miniaturise, they are ideal for low-power and low-voltage machines. They also lend themselves very well to speed control up to several megawatts with inexpensive and simple high-performance electronic technologies (variation range commonly of 1 to 100).

They also have features for precise torque adjustment in motor or generator application. Their rated rotation speed, independent of the mains frequency, is easy to adapt for all uses at the manufacturing stage.

On the other hand, they are not as rugged as asynchronous motors and their parts and upkeep are much more expensive as they require regular maintenance of the collectors and brushes.

■ Structure

A DC motor consists of the following components:

□ Inductor or stator

This is a part of the immobile magnetic circuit with a coil wound on it to produce a magnetic field, this winding can be replaced by permanent magnets specially in the low power range. The resulting electromagnet has a cylindrical cavity between its poles.

□ Armature or rotor

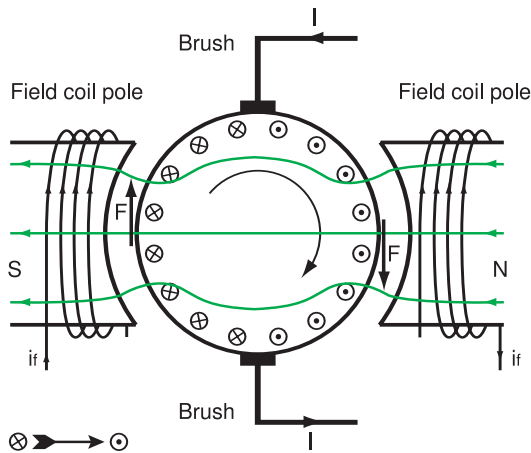
This is a cylinder of magnetic plates insulated from each other and perpendicular to the cylinder axis. The armature is mobile, rotates on its axis and is separated from the inductor by an air gap. The conductors are distributed regularly around it.

□ Collector and brushes

The collector is built into the armature. The brushes are immobile and rub against the collector to power the armature conductors.

3. Motors and loads

3.4 Direct current motors commonly named DC motors



↑ Fig. 18 Production of torque in a DC motor

■ Operating principle

When the inductor is powered, it creates a magnetic field (excitation flux) in the air gap, directed by the radii of the armature. The magnetic field “enters” the armature on the north pole side of the inductor and “leaves” it on the south pole side.

When the armature is powered, its conductors located below one inductor pole (on the same side as the brushes) are crossed by currents in the same direction and so are subjected to a Lorentz law force. The conductors below the other pole are subjected to a force of the same strength and in the opposite direction. Both forces create a torque which rotates the motor armature (⇒ Fig. 18).

When the motor armature is powered by a direct or rectified voltage U and the rotor is rotating, a counter-electromotive force E is produced. Its value is $E = U - RI$.

RI represents the drop in ohm voltage in the armature. The counter-electromotive force E is related to the speed and excitation by $E = k \omega \phi$

where:

- k is a constant of the motor itself,
- ω is the angular speed,
- ϕ , is the flux.

This relationship shows that, at constant excitation, the counter-electromotive force E , proportional to ω , is an image of the speed.

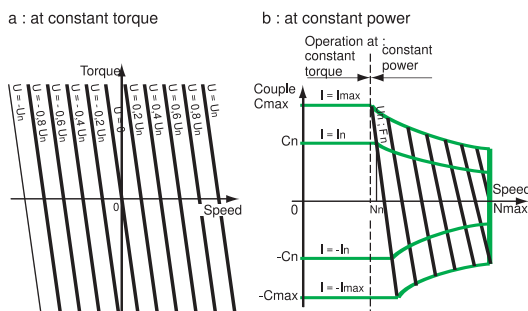
The torque is related to the inductor flux and the current in the armature by:

$$T = k \phi I$$

When the flux is reduced, the torque decreases.

There are two ways to increase the speed:

- increasing the counter-electromotive force E and thus the supply voltage: this is called “constant torque” operation,
- decreasing the excitation flux and hence the excitation current, and maintain a constant supply voltage: this is called “reduced flux” or constant power operation. This operation requires the torque to decrease as the speed increases (⇒ Fig. 19).

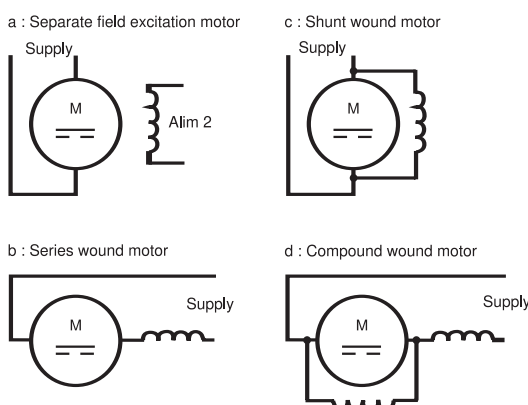


↑ Fig. 19 Torque/speed curves of a separate excitation motor

Furthermore, for high constant power ratios, this operation requires motors to be specially adapted (mechanically and electrically) to overcome switching problems.

Operation of such devices (direct current motors) is reversible:

- if the load counters the rotation movement (resistant load), the device produces a torque and operates as a motor,
- if the load makes the device run (driving load) or counters slowdown (standstill phase of a load with a certain inertia), the device produces electrical power and works as a generator.



↑ Fig. 20 Diagrams of direct current motor types

■ Types of direct current wound motors (⇒ Fig. 20)

• a and c parallel excitation motor (separate or shunt)

The coils, armature and inductor are connected in parallel or powered by two different sources of voltage to adapt to the features of the machine (e.g.: armature voltage of 400V and inductor voltage of 180V). Rotation is reversed by inverting one of the windings, usually by inverting the armature voltage because of the much lower time constants. Most bi-directional controllers for DC motors work this way.

• b series excitation motor

This has a similar structure to the shunt excitation motor. The inductor coil is connected in series with the armature coil, hence the name. Rotation is reversed by inverting the polarities of the armature or the inductor. This motor is mainly used for traction, in particular in trolleys powered by accumulator batteries. In locomotive traction, the older TGVs were driven by this sort of motor; the later ones use asynchronous motors.

3. Motors and loads

3.4 Direct current motors commonly named DC motors

3.5 Operating asynchronous motors

- **series parallel motor (compound)**

This technology combines the benefits of the series and parallel excitation motors. It has two windings. One is parallel to the armature (shunt winding) or is a separate excitation winding. It is crossed by a current that is weak compared to the working current. The other is in series. The motor has an added flux under the combined effect of the ampere-turns of both windings. Otherwise, it has a subtracted flux, but this system is rarely used because it causes operating instability at high loads.

3.5 Operating asynchronous motors

3

■ Squirrel cage motors

□ Consequences of variation in voltage

- **Effects on the current**

Voltage increase has two effects. During the starting phase the inrush current will be higher than nominal and when the machine will be running, the absorbed current increases steeply and the machine is likely to overheat, even when operating at low load. This increase is due to the saturation of the machine.

- **Effect on speed**

When the voltage varies, the synchronous speed is not altered but, when a motor is loaded, an increase in voltage causes the slip to decrease slightly. In practical terms, this property cannot be used due to the saturation of the motor, the current increases steeply and the machine is likely to overheat. Likewise, if the supply voltage decreases, the slip increases and the absorbed current increases to provide the torque, which may also cause overheating. Furthermore, as the maximum torque decreases with the square of the voltage, there is a likelihood of stalling if the voltage drops steeply.

□ Consequences of a variation in frequency

- **Effect on the torque**

As in any electrical machine, the torque of an asynchronous motor is of the type: $T = K I \phi$.

(K = constant factor dependent on the machine) .

In the equivalent diagram as shown ($\Rightarrow$ Fig. 21), the coil L produces the flux and I_0 is the magnetising current. Note that the equivalent schema of an asynchronous motor is the same as that of a transformer and both devices are characterised by the same equation.

In an initial approximation, forgetting the resistance and considering the magnetising inductance only (i.e. for frequencies of a few Hertz) the I_0 current is expressed as: $I_0 = U / 2\pi L f$ and the flux expressed as:

$$\phi = k I_0.$$

The machine torque is therefore expressed as:

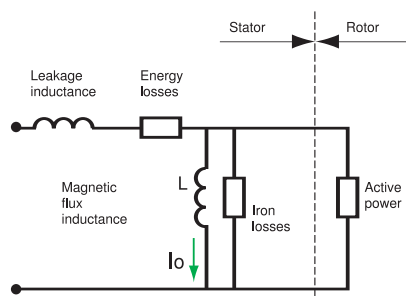
$$T = K k I_0 I. \quad I_0 \text{ and } I \text{ are the rated currents the motor is sized for.}$$

To keep within the limits, I_0 must be maintained at its rated value, which can only be the case if the U/f ratio remains constant.

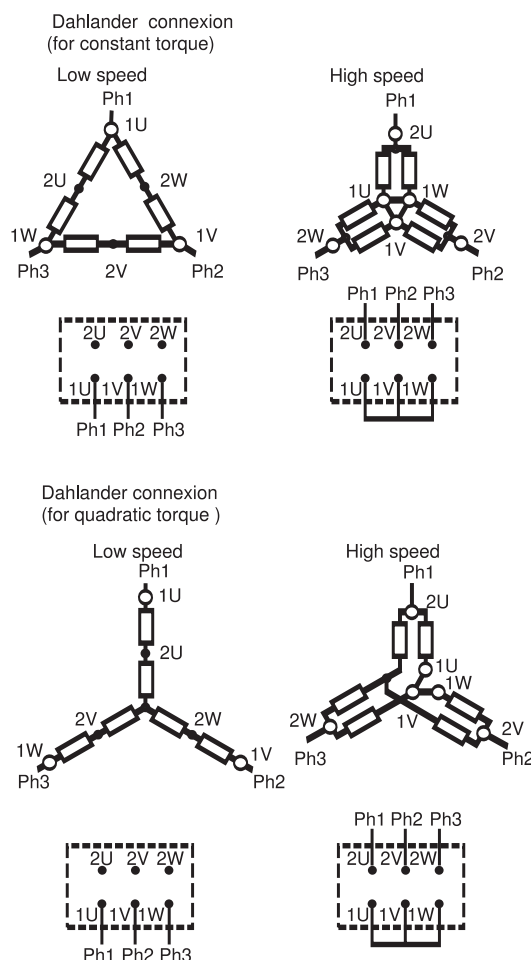
Consequently, the torque and rated currents can be obtained as long as the supply voltage U can be adjusted to the frequency.

When this is not possible, the frequency can still be increased, but the I_0 current decreases and so does the working torque since it is not possible to exceed the machine's rated current continuously without running the risk of overheating it.

To operate with a constant torque at any speed the U/F ratio must be kept constant. This is what a frequency converter does.



↑ Fig. 21 Equivalent diagram of an asynchronous motor



↑ Fig. 22 Types of Dahlander connections

• Effect on speed

The rotation speed of an asynchronous motor is proportional to the frequency of the supply voltage. This property is often used to operate specially designed machines at high speed, e.g. with a power supply at 400Hz (grinders, laboratory or surgical devices, etc.). Speed can also be varied by adjusting the frequency, for example from 6 to 50Hz (conveyor rollers, hoisting equipments, etc.).

□ Speed control in 3-phase asynchronous motors

For a long time, there were not many ways of controlling the speed of asynchronous motors. Squirrel cage motors mostly had to be used at their rated RPM.

Set speeds could practically only be obtained by motors with pole changing or separate stator windings, which are still widely in use.

With frequency converters i.e. AC drives, squirrel cage motors are now often speed-controlled, so can be used for purposes hitherto confined to direct current motors.

□ Pole-changing motors

As we have already seen, the speed of a squirrel cage motor depends on the mains supply frequency and the number of pairs of poles. So a motor with two or more speeds can be made by combining windings in the stator to correspond to different numbers of poles.

This type of motor can only have 1/2 speed ratios (4 and 8 poles, 6 and 12 poles, etc.). It has six terminals (⇒ Fig.22).

For one of these speeds, the mains supply is connected to the three corresponding terminals. For the other, these terminals are connected to each other and the mains is connected to the remaining three.

Mostly, for both high and low speed, the motor is started direct on line involving no special device (direct starting).

In some cases, if the operating conditions require it and the motor allows it, the starting device automatically moves into low speed before changing to high speed or before stopping.

Depending on the currents absorbed by the Low Speed (LS) or High Speed (HS) changes, both speeds can be protected by a single thermal relay or by two relays (one for each speed).

Such motors usually have low efficiency and a fairly low power factor.

□ Separate stator winding motors

These motors, with two electrically separate stator windings, can produce two speeds in any ratio. However, their electrical characteristics are often affected by the fact that the low speed windings have to support the mechanical and electrical stress of high speed operation. So motors in low speed mode sometimes absorb more current than they do in high speed mode.

Three or four speed motors can be made by changing the poles on one or both of the stator windings. This solution requires additional connectors on the coils.

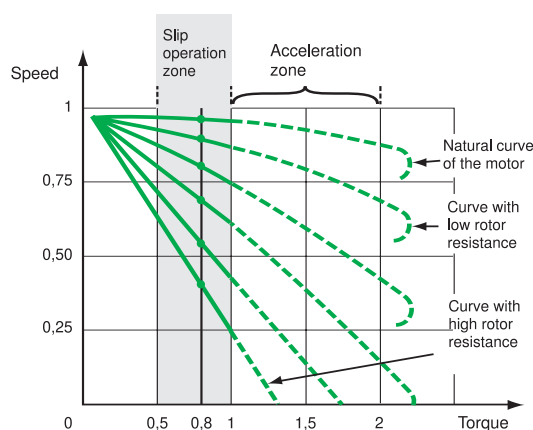
■ Slip-ring motors

□ Rotor resistance

The resistor externally inserted into the rotor circuit in this kind of motor defines:

- its starting torque,
- its speed.

A resistor permanently connected to the terminals of a slip-ring motor lowers its speed and the higher its value, the more the speed drops. This is a simple solution for speed variation.



↑ Fig. 23 Torque speed characteristics of a slip ring motor

□ Slip-ring speed control

Slip-ring rotor resistors can be short-circuited in several steps to adjust speed discontinuously or accelerate gradually and fully start the motor. They have to support the entire duration of operation, especially when they are intended for speed control. This implies they can be bulky and costly.

This very simple process is used less and less because it has two major drawbacks:

- at low speed, a great deal of power from the mains supply is dissipated and lost in the resistors,
- the speed obtained is not independent of the load but varies with the load torque the machine exerts on the motor shaft (⇒ Fig. 23).

For any one resistor, the slip is proportional to the torque. For instance, the drop in speed caused by a resistor can be 50% at full load and only 25% at half load, whereas at no load, the speed hardly changes and is closed to the synchronous speed minus the slip.

If the machine is constantly monitored by an operator, this one can change the resistor value as required to set the speed in a certain area for fairly high loads, but adjustment is practically impossible at no load condition. To reach a point of “low speed at low torque”, it inserts a very high resistance and then the slightest variation in the load torque changes the speed from zero to nearly 100%. This is too unstable.

Adjustment can also be impossible for machines with specific variation of the load torque relevant to the speed.

Example of slip ring operation. For a variable load exerting a load torque of 0.8 Cn, different speeds can be obtained as represented by the sign • in the diagram (⇒ Fig. 23).

For the same torque, the speed decreases as the rotor resistance increases.

■ Other speed control systems

□ Variable voltage regulator

This device is only used in low-powered asynchronous motors. It requires a resistant squirrel cage motor.

The speed is controlled by increasing the motor slip once the voltage drops.

Its use was fairly widespread in cooling systems, pumps and compressors, uses for which its torque availability gives satisfactory results. It is gradually giving way to more cost-effective frequency converters.

□ Other electromechanical systems

The other electromechanical speed control systems mentioned below are less used now that electronic speed controllers are in common use.

• AC squirrel cage motors (Schrage)

These are special motors where the speed is controlled by varying the position of the brushes on the collector in relation to the neutral.

• Eddy current drives

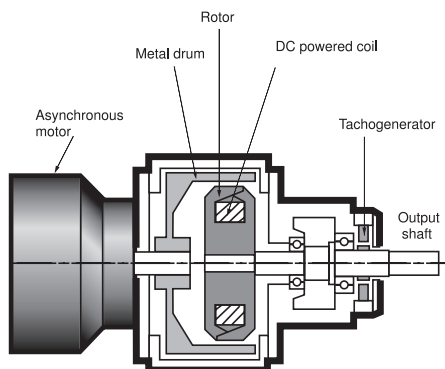
This consists of a drum connected directly to an asynchronous motor running at constant speed and a rotor with a coil fed with direct current (⇒ Fig. 24).

The movement is transmitted to the output shaft by electromagnetic coupling. The slip of the unit can be adjusted by adjusting coil excitation.

A built-in tacho-generator is used to control velocity with precision.

A ventilation system is used to evacuate the losses due to the sleep. This was a principle widely used in hoisting apparatus, cranes in particular.

Its structure makes it a robust system with no wearing parts that can be used for occasional purposes and up to a power of 100kW.

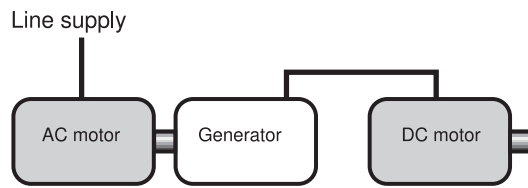


↑ Fig. 24 Cross section of an eddy current drive

3. Motors and loads

3.5 Operating asynchronous motors

3.6 Electric motor comparison



↑ Fig. 25 Ward Leonard arrangement

• Ward Leonard motor generator set

This device, once very widespread, is the forerunner of DC motor speed controllers. It has a motor and a DC generator which feeds a DC motor (⇒ Fig. 25).

The speed is controlled by regulating the excitation of the generator. A very small current is used to control powers of several hundred kW in all the torque and speed quadrants. This type of controller was used in rolling mills and pithead lifts.

This was the most efficient speed control system before it was made obsolete by the semiconductor.

□ Mechanical and hydraulic speed controllers

Mechanical and hydraulic speed controllers are still in use.

Many mechanical speed control systems have been designed (pulleys/belts, bearings, cones, etc.). The drawbacks of these controllers are that they require careful maintenance and do not lend themselves easily to servocontrol. They are now seriously rivalled by frequency converters.

Hydraulic speed controllers are still widely used for specific purposes.

They have substantial power weight ratios and a capacity to develop continuous high torques at zero speed. In industry, they are mostly used in power-assisted systems.

As this type of speed controller is not relevant to this guide, we shall not describe it in detail.

3.6 Electric motor comparison

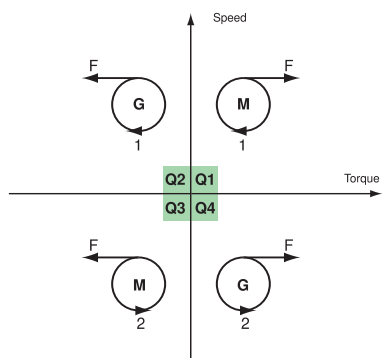
The table (⇒ Fig. 26) gives a brief summary of all the types of electric motor available, their main feature and fields of use.

We should point out the place held by 3-phase squirrel cage motors where the description “standard” is all the more relevant since the development of electronic speed control devices has fitted them perfectly to fit closely to the application.

Type of motor	Asynchronous squirrel cage	Asynchronous slip-ring	Synchronous wound rotor	Rare earth rotor	Stepper	Direct current
	3 phases	Single-phase				
Cost of motor	Low	Low	High	High	Low	High
Sealed motor	Standard	Possible	Option, expensive	Option, expensive	Standard	Possible Very expensive
Starting direct on line	Easy	Easy	Special starting device	Impossible after a few kW	Not designed for	Not designed for
Speed control	Easy	Very unusual	Possible	Frequent	Always	Always
Cost of speed control solution	Increasingly cost-effective	Very cost-effective	Cost-effective	Cost-effective	Fairly cost-effective	Very cost-effective
Speed control performance	High to very high	Very low	Average	High to very high	Very high	High to very high
Mode	Constant or variable speed	Mainly constant speed	Constant or variable speed	Constant or variable speed	Variable speed	Variable speed
Industrial use	Universal	For low powers	Decreasing	High powers at medium voltage	High-dynamic machine tools	Open loop positioning for low powers

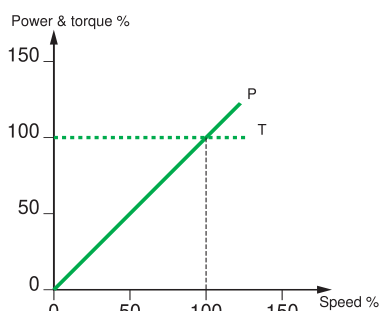
↑ Fig. 26 Comparison of electric motors

3.7 Types of loads

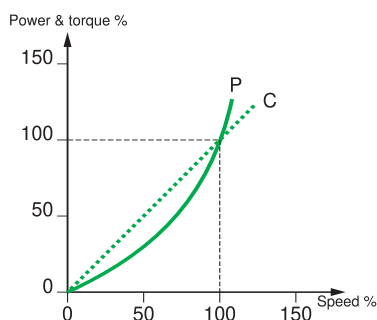


Rotation direction	Mode	Torque T	Speed S	Product TS	Quadrant
1 (clockwise)	Driver	yes	yes	yes	1
	Generator	yes	yes	yes	2
2 (anticlockwise)	Driver	yes	yes	yes	3
	Generator	yes	yes	yes	4

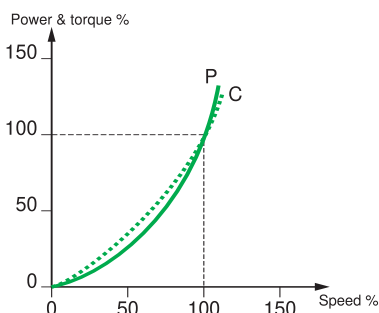
↑ Fig. 27 The four possible situations for a machine in a torque-speed diagram



↑ Fig. 28 Constant torque operation curve



a



b

↑ Fig. 29 a/b Variable torque operation curve

We can classify the loads in two families:

- the active loads which put moving a mobile or a fluid or which change its state like the gas state in the liquid state,
- the passive loads which do not get a driving force like lighting or the heating.

■ Active loads

This term covers all systems designed to set a mobile object or a fluid in motion.

The movement of a mobile object involves changing its speed or position, which implies applying a torque to overcome its resistance to movement so as to accelerate the inertia of the load. The speed of movement is directly related to on the torque applied.

□ Operating quadrants

The figure 27 illustrates the four possible situations in the torque-speed diagram of a machine.

Note that when a machine works as a generator it must have a driving force. This state is used in particular for braking. The kinetic energy in the shaft is either transferred to the power system or dissipated in a resistor or, for low power, in machine losses.

□ Types of operation

• Constant torque operation

Operation is said to be constant torque when the charge's characteristics in the steady state are such that the torque required is more or less the same whatever the speed (⇒ Fig. 28).

This is the operating mode of machines like conveyors, crushers or hoists. For this kind of use, the starter device must be able to provide a high starting torque (1.5 times or more the nominal rate) to overcome static friction and accelerate the machine (inertia).

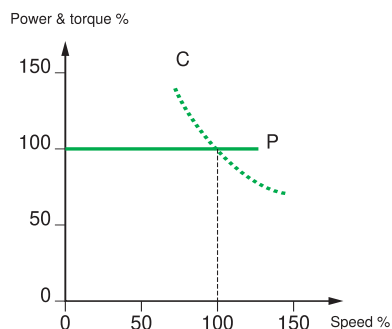
• Operation with torque increasing with speed

The characteristics of the charge imply that the torque required increases with the speed. This particularly applies to helical positive displacement pumps where the torque increases linearly with the speed (⇒ Fig. 29a) or centrifugal machines (pumps and fans) where the torque varies with the speed squared (⇒ Fig. 29b).

The power of displacement pumps varies with the speed squared.

The power of centrifugal machines varies with the speed cubed.

A starter for this type of use will have a lower starting torque (1.2 times the motor's nominal torque is usually enough).



↑ Fig. 30 Decreasing torque operation

• Operation with torque decreasing with speed

For some machines, the torque required decreases as the speed increases. This particularly applies to constant-power operation when the motor provides a torque that is inversely proportional to the angular speed ($\Rightarrow$ Fig. 30).

This is so, for example, with a winder, where the angular speed needs to drop as the diameter of the winder increases with the build-up of material. It also applies to spindle motors on machine tools.

The constant-power operating range limited by its very nature: at low speed by the available current from the speed controller and at high speed by the torque the motor can provide. The driving torque on asynchronous motors and the switching capacity of DC motors should therefore be checked carefully.

The table ($\Rightarrow$ Fig. 31) gives a list of common machines with their torque law depending on speed.

Type of machine	Torque law depending on speed
Conveyor	Constant
Rotary press	Constant
Helical displacement pump	Torque increasing linearly with speed
Metering pump	Constant
Centrifugal pump	Torque increasing with the speed squared
Fans and blowers	Torque increasing with the speed squared
Screw compressor	Constant
Scroll compressor	Constant
Piston compressor	Constant
Cement kiln	Constant
Extruding machine	Constant or decreasing linearly with speed
Mechanical press	Constant
Winders, unwinders	Constant or decreasing linearly with speed
Pulpers	Constant
Sectional machine	Constant
Crusher	Constant
Mixer	Torque increasing linearly with speed
Kneader, calender	Constant or decreasing linearly with speed
Centrifuge	Torque increasing with the speed squared
Machine tool spindle	Constant or decreasing linearly with speed
Hoist	Constant

↑ Fig. 31 Torque characteristic per machine

When a machine starts, it often happens that the motor has to overcome a transitory torque, such as in a crusher when it starts with a full hopper. There can also be dry friction which disappears when a machine is running or a machine starting from a cold stage may need a higher torque than in normal operation when warm.

■ Passive loads

There are two types of passive charge used in industry:

- heating,
- lighting.

□ Heating

Heating is a costly item for industrial premises. To keep these costs down, heat loss must be reduced; this is a factor which depends on building design and is beyond the scope of this guide.

Every building is a specific case and we cannot allow ourselves to give vague or irrelevant answers.

That said, proper management of the building can provide both comfort and considerable savings. For further information, please see the Schneider Electric *Electrical Installation Guide* or the *Cahier Technique 206* available from the Schneider Electric website.

If necessary, the best solution may be found by asking the advice of the electrical equipment supplier's experts.

□ Lighting

• Incandescent lighting

Incandescent lighting (trademarked by Thomas Edison in 1879) was an absolute revolution and, for many years afterwards, lighting was based on devices with a filament heated to a high temperature to radiate visible light. This type of lighting is still the most widely used but has two major disadvantages:

- extremely low efficiency, since most of the electricity is lost in heat consumption,
- the lighting device has a lifetime of a few thousand hours and has to be regularly changed. Improvements have increased this lifetime (by the use of rare gases, such as krypton, or halogen).

Some countries (Scandinavian ones in particular) plan to ban this type of lighting eventually.

• Fluorescent lighting

This family includes fluorescent tubes and fluocompact lamps. The technology used is usually "low-pressure mercury".

Fluorescent tubes

These were introduced in 1938. In these tubes, an electric discharge makes electrons collide with mercury vapour, which excites the mercury atoms and results in ultraviolet radiation.

The fluorescent matter lining the inside of the tube transforms the radiation into visible light.

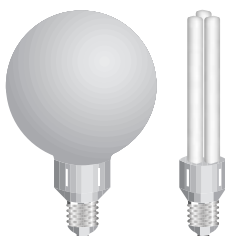
Fluorescent tubes dissipate less heat and last longer than incandescent lamps but require the use of two devices: one to start them and one called a ballast to control the current of the arc once they are switched on.

The ballast is usually a current limiting reactor connected in series with the arc.

Fluocompact lamps (⇒ Fig.32)

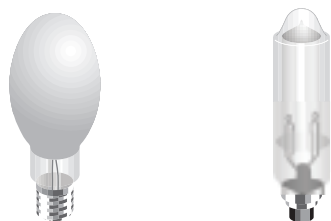
These work to the same principle as a fluorescent tube. The starter and ballast functions are performed by an electronic circuit in the lamp, which enables the tubes to be smaller and to be folded.

Fluocompact lamps were developed as an alternative to incandescent lamps: they save a significant amount of power (15W instead of 75W for the same brightness) and last much longer (8000 hours on average and up to 20,000 for some).



↑ Fig. 32

Fluo compact lamps



↑ Fig. 33

Discharge lamps

Discharge lamps (⇒ Fig.33)

Light is produced by an electric discharge created by two electrodes within a gas in a quartz bulb. Such lamps all require a ballast, usually a current limiting reactor, to control the current in the arc.

The emission range depends on the gas composition and is improved by increasing the pressure. Several technologies have been developed for different functions.

Low-pressure sodium vapour lamps

These have the best lighting capacity but they have a very poor colour rendition because they radiate a monochrome orange light.

Uses: motorway lighting, tunnels.

High-pressure sodium vapour lamps

These emit a white light tinged with orange.

Uses: urban lighting, monuments.

□ High-pressure mercury vapour lamps

The discharge is produced in a quartz or ceramic bulb at pressures exceeding 100kPa. The lamps are known as fluorescent bulbs and are characterised by the bluish white light they emit.

Uses: car parks, supermarkets, warehouses.

• Metal halide lamps

This is the most recent technology. The lamps emit a colour with a wide spectrum.

The tube is in ceramic to enhance lighting capacity and colour stability.

Uses: stadiums, shops, spotlighting.

• LED (Light Emitting Diodes)

This is one of the most promising technologies. LEDs emit light by means of an electric current through a semiconductor.

LEDs are used for many purposes but the recent development of blue or white diodes with a high lighting capacity opens up new avenues, in particular for signage (traffic lights, safety displays or emergency lighting) and motor vehicle lighting.

A LED has an average current of 20mA, with a voltage drop of 1.7 to 4.6 depending on the colour. Such properties are suited to very low voltage power supply, for batteries in particular.

Mains power requires the use of a transformer, which is economically perfectly feasible.

The advantage of LEDs is their low power consumption which results in a very low operating temperature and an almost unlimited lifetime. In the near future, it will be possible to incorporate such a lighting into buildings at the construction stage.

However, a basic diode has a very low lighting capacity. Powerful lighting therefore requires a great many units to be connected in a series.

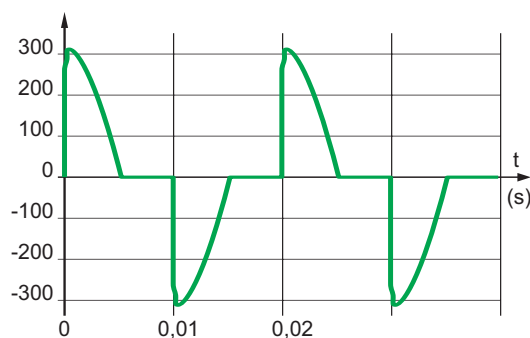
As LEDs have no thermal inertia, they can be used for innovating purposes such as simultaneous transmission of light and data. To do this, the power supply is modulated with high frequency. The human eye cannot detect this modulation but a receiver with the right interface can detect the signals and use them.

□ Powering incandescent lamps

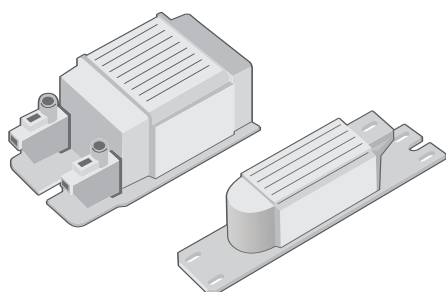
• Constraints of direct powering

The resistance of the filament varies widely due to the very high temperatures (up to 2500°C) it can reach during operation.

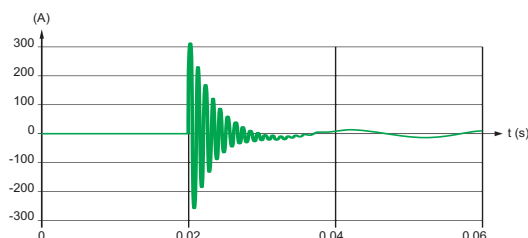
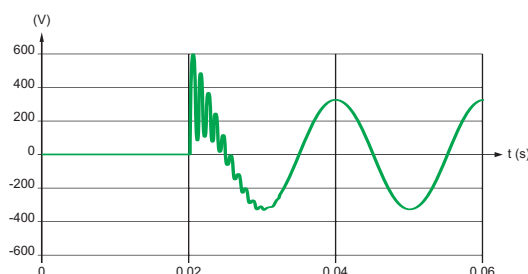
When cold, resistance is low, resulting in a power inrush current for a few to several dozen milliseconds when the lamp is switched on and which can be 10 to 15 times that of the nominal current.



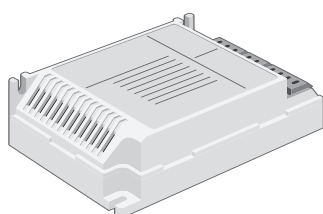
↑ Fig. 34 Current waveform



↑ Fig. 35 Magnetic ballast



↑ Fig. 36 Voltage and current waveforms



↑ Fig. 37 Electronic ballast package

This constraint applies equally to ordinary and halogen lamps. It requires reducing the maximum number of lamps that can be powered by the same device such as a remote control, modular contactor or relay on ready-made circuits.

• Light dimming

This can be achieved by varying the RMS voltage powering the lamp.

Voltage is usually adjusted by a triac used to vary the triggering angle in the mains voltage cycle.

The waveform of the voltage applied to the lamp is illustrated (⇒ Fig. 34).

Gradual powering of the lamp also reduces, or even eliminates, the power surge when it is switched on.

Note that light dimming:

- alters the colour temperature,
- shortens the life of halogen lamps when low voltage is maintained for long periods. The filament is not regenerated so efficiently at low temperature.

Some halogen lamps are powered at low voltage through a transformer.

Magnetisation in a transformer can produce power surges 50 to 75 times greater than the nominal current for a few milliseconds.

Suppliers also offer static converters which do away with this disadvantage.

• Powering fluorescent lamps and discharge lamps

Fluorescent tubes and discharge lamps require control of arc intensity.

This function is performed by a ballast device inside the bulb itself.

The magnetic ballast (i.e. limiting current reactor (⇒ Fig. 35)) is commonly used in domestic appliances.

A magnetic ballast works in conjunction with the starter device. It has two functions: to heat the electrodes in the tube and to generate a power surge to trigger the tube.

The power surge is induced by triggering a contact (controlled by a bimetal switch) which breaks the current in the magnetic ballast.

When the starter is working (for about 1 sec.), the current absorbed by the light is about twice the nominal current.

As the current absorbed by the tube and ballast together is mainly inductive, the power factor is very low (0.4-0.5 on average). In fixtures with a large number of tubes, a capacitor must be used to improve the power factor.

This capacitor is usually applied to each light appliance.

Capacitors are sized to ensure that the overall power factor exceeds 0.85.

In the most common type, the parallel capacitor, the average active power is 1μF for 10W for all types of lamp.

The parallel capacitor layout creates stress when the lamp is switched on.

As the capacitor is initially discharged, switching on creates a power surge (⇒ Fig. 36).

There is also a power surge due to oscillation in the power inductor/capacitor circuit.

The electronic ballast (⇒ Fig. 37), first introduced in the 1980s, does away with these disadvantages.

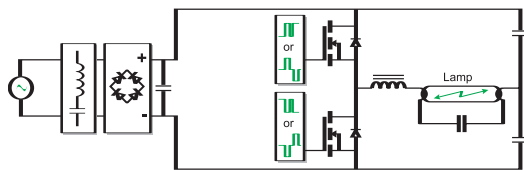
The electronic ballast works by powering the lamp arc by an electronic device generating a rectangular alternating voltage.

There are low frequency or hybrid devices, with frequency ranging from 50 to 500Hz, and high frequency devices with frequency ranging from 20 to 60kHz. The arc is powered by high frequency voltage which completely eliminates flickering and strobe effects.

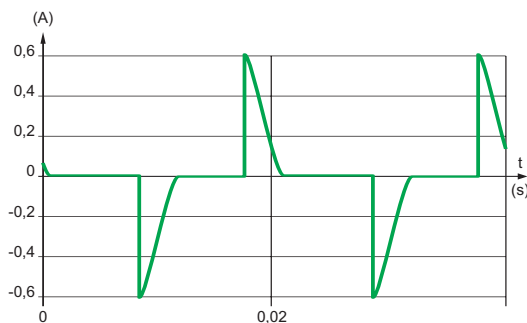
3. Motors and loads

3.7 Types of loads

3.8 Valves and electric jacks



↑ Fig. 38 Electronic ballast schematics



↑ Fig. 39 Current waveform of an electronic ballast

The electronic ballast is totally silent. When a discharge lamp is heating up, it supplies it with increasing voltage while maintaining a virtually constant current. At continuous rating, it regulates the voltage applied to the lamp independently of fluctuations in the mains voltage.

As the arc is powered in optimal voltage conditions, 5-10% of power is saved and the lifetime of the lamp is increased. Furthermore, the output of an electronic ballast can exceed 93%, whereas that of a magnetic device is on average only 85%. The power factor is high (> 0.9).

An electronic ballast does however have some constraints with regard to the layout used ($\Rightarrow$ Fig. 38), since a diode bridge combined with capacitors leads to a power surge when the device is switched on. In operation, the absorbed current is high in third harmonic ($\Rightarrow$ Fig. 39), resulting in a poor power factor of around 55%.

The third harmonic overloads in the neutral conductor. For more information, see *Cahier Technique 202: The singularities of the third harmonic*.

Electronic ballasts usually have capacitors between the power conductors and the earth. These anti-interference capacitors induce a constant leakage current of about 0.5-1mA per ballast.

This limits the number of ballasts that can be powered when a residual current device (RCD) is installed (see the *Cahier Technique 114 Residual current device in LV*).

3.8 Valves and electric jacks

■ Forward

To complete the view of industrial loads that can be linked to automation systems, we should include a brief description of some commonly used devices: electrically-controlled screwjacks and valves.

Processes require loads to be positioned and moved. This function is ensured by pneumatic and hydraulic screwjacks, but can also be controlled by electromechanical ones. These can be built into motor starter units or linked to regulating devices for, e.g. positioning control. The following pages give short description of these positioning devices.

There is a very large market in valves to control fluid flow. These are used to:

- arrest fluid flow (stop valves),
- change the fluid circuit (3-channel valves),
- blend products (mixer valves),
- control flow (regulation valves).

Fluids can be liquids or gases (ventilation or chemical industry).

■ Electric screwjacks

Linearly driven applications require heavy-duty electric screwjacks that are powerful, fast, long-lived and reliable.

Manufacturers offer wide ranges of electric screwjacks for practically all requirements.

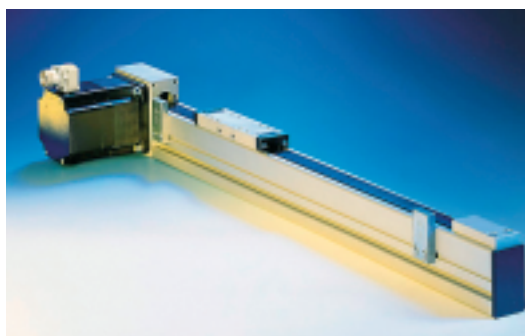
□ Structure of an electric screwjack

Electric screwjacks ($\Rightarrow$ Fig. 40) comprise a control shaft or driving member, a guide unit and an electric motor.

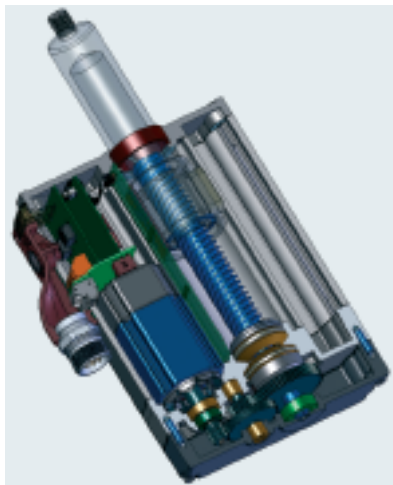
The photo shows an electric screwjack for linear movement.

The movement of the driving member can be linear, for travel, or rotational. For linear movement, a screw nut system makes the driving member travel in a line.

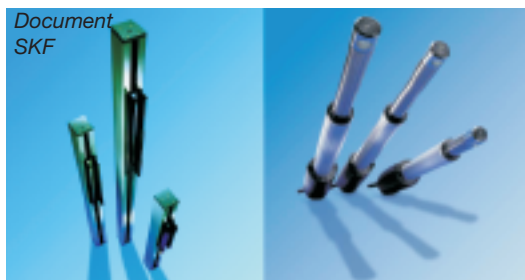
Two of the most common systems are the ball screw and the acme screw. The acme screw is made of rolled steel and the nut is made of plastic.



↑ Fig. 40 Electric screwjacks



↑ Fig. 41 High performance electric screwjack



↑ Fig. 42 Electrical screwjacks from SKF

This is a fairly cost-effective design with useful properties: plastic and metal can work together well without catching.

The acme screw works quietly, so it is suitable for offices, hospitals, etc.

Another of its assets is its high friction coefficient. This design is particularly well suited to screwjacks used in applications where they must be self-locking, i.e. with no recoil against the mass of the load. For instance, when a screwjack is used to adjust the height of a table, one with an acme screw enables the table to withstand heavy loads without altering its vertical position. This means that no brake or other locking mechanism is required to maintain the load in place when it is idle.

The ball screw system is used for high performance purposes (⇒ Fig.41).

The ball screws in the screwjack are made of steel and have a row of ball bearings in a closed system between the nut and the screw.

This design gives a very low friction coefficient between the nut and the screw due to the rolling contact between the ball bearings, nut and tracks.

Wear is low compared to an acme screw, so the ball screw has a lifetime 10 times longer in identical operating conditions. This lifetime also implies that a ball screw can withstand heavy loads and long operating cycles.

Its low friction coefficient makes the ball screw especially efficient because it does not overheat.

The ball screw is therefore highly suited for situations requiring lengthy operation at high speed.

A screwjack with a ball screw system has very little play, so its precision is significantly better in applications where position and precision are crucial.

□ Product family

Electric screwjacks can be made in many different shapes and sizes to fit easily into machines. Manufacturers also offer control units to make it easier to operate them.

The photo (⇒ Fig.42) gives a view of some products offered by one manufacturer (SKF).

□ Selection guide

Choosing the right electric screwjack often requires detailed knowledge of the application and some calculation.

However, manufacturers' catalogues can help in making the initial choice of screwjacks meeting the basic criteria such as load and speed.

□ Screwjack drives and parts

Drives offered by manufacturers.

Electric screwjacks can be driven by:

- direct current motors,
- asynchronous alternating motors,
- brushless synchronous motors,
- stepper motors.

Direct current motors are usually low voltage (12 or 24 volts) for average forces (approx. 4000N) and medium performance (approx. 50mm/s). These screwjacks are used on mobile standalone battery-operated devices.

An asynchronous motor drive considerably increases performance up to 50,000N and 80mm/s. These screwjacks are mostly fitted to immobile machines.

Brushless drives are used for high dynamic performance (approx. 750mm/s) for forces up to about 30,000N.

Stepper motor drives are used for precision positioning of the load without recoil.

□ Parts and variants

- **Built-in controller**

Some electric screwjacks have a built-in control device. This is especially the case in some types of screwjack with a brushless motor drive. These include a speed controller which can be connected to the automation system by a field bus.

- **Potentiometer**

The potentiometer is a movement sensor. This device is used to ascertain the position of a moving part and align it with precision.

- **Thermal protection device**

This protects drives and control units from overheating.

- **Encoder**

This is a sensor which, when it is connected to a control unit, is used to give the position of the screwjack.

- **Stress limiters**

Some types of screwjack are fitted with a mechanical safety device similar to a friction clutch to protect the motor and the reduction unit from damage.

- **Limit switches**

These are switches which limit movement in a given direction in mechanical devices by opening and closing an electrical contact. Limit switches comes in all shapes and sizes and can be fitted on the inside or outside of the screwjack.

These safety devices are part of the control system and it is important to be aware of them when using screwjacks in an automation system or any other system.

- **Mechanical jamming control**

This safety device makes the screwjack to stop in case of an excessive resisting force. It is provided to protect persons from injuries.

- **Electrical jamming control**

This is a safety option on some electric screwjacks.

It cuts the power to the motor when external stress is applied in the opposite direction to screwjack movement.

■ Valves

Valve operating systems do not enter into the scope of this guide. That said, as valves can be part of industrial control systems such as regulation loops or speed controllers, it is useful to have some idea of their structure and what happens when they work.

□ Valve structure

A valve ($\Rightarrow$ Fig. 43) consists of a body and a throttle which presses against a seat. Fluid movement is controlled by an operating rod. This rod is actuated by electric or pneumatic devices.

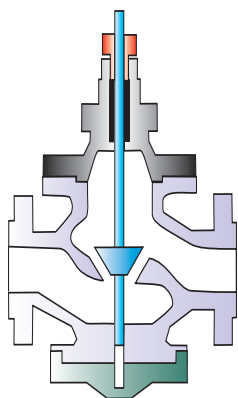
Many valves are pneumatically controlled, others are electrically controlled (solenoid valves).

There are many different valve designs (butterfly, spherical, diaphragm, etc.) for different types of use, fluid and progression rates (output in relation to the position of the throttle or the control signal in regulation valves).

The throttle usually has a specific shape to prevent or mitigate any unwanted effects such as water hammer or cavitation.

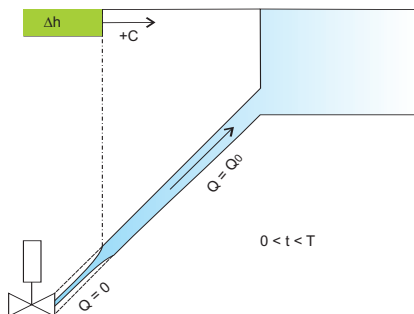
- **Water hammer**

This can occur in hydraulic pipes when the valve is closed. The flow through the pipe is suddenly stopped and causes this phenomenon known as water hammer.

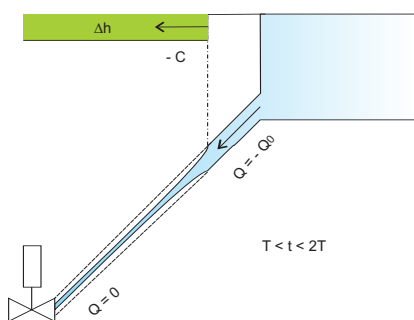


↑ Fig. 43

Cross view of a valve



↑ Fig. 44a Water hammer (start)



↑ Fig. 44b Water hammer

As an example ($\Rightarrow$ fig. 44a et 44b)), here is a description of a pumping station feeding a reservoir above the feed pump.

When the emptying valve is closed, the water drained from the reservoir via the pump below the fluid column tends to pursue its movement while there is no more output from the pump.

This movement causes elastic deformation of the pipe which contracts at a point near the valve.

This phenomenon makes the mass of fluid temporarily available and maintains it in movement.

Depression occurs and spreads throughout the pipe at the speed of elastic waves C until the entire pipe is affected by it, i.e. after a time $T=L/c$, where L is the length of the pipe between the valve and the outlet.

The result is that the pressure where the pipe goes into the reservoir is lower than the pressure in the reservoir and causes backflow. The wave spreads from the reservoir to the pumping station and reaches the valve throttle after a time $2T$ from the start of the phenomenon.

The fluid column continues its descent and hits the closed valve again, causing the pipe to swell and reversing the movement of the fluid.

Water hammer would occur indefinitely if the effects of load loss, depression and overpressure are not gradually damped.

To overcome this potentially destructive phenomenon, valve closing can be controlled by a system based on a slow closing law to keep overpressure and depression within reasonable limits.

Another procedure involves gradually slackening the speed of the feed pump to enable the valve to close the pipe.

In the case of pumps running at constant speed, the most suitable device is a soft start device such as Altistart by Telemecanique or Altivar for speed-controlled pumps.

• Cavitation

Closing a valve results in restricting the section available for fluid flow ($\Rightarrow$ Fig. 45). Applying the Bernoulli theorem, restricting the flow section left by the valve accelerates the flow and lowers static pressure at that point.

The amount of static pressure drop depends on:

- the internal geometry of the valve,
- the amount of static pressure downstream of the valve.

The pressure when the valve is open is shown on ($\Rightarrow$ curve 1).

Flow is restricted at the point of the closing valve throttle, causing a drop in pressure and accelerated flow (Venturi effect);

When the throttle closes, the Venturi effect increases and curve 1 is gradually deformed ($\Rightarrow$ curve 2).

When the static pressure in the fluid vein reaches the value of the vapour tension at the flow temperature, vapour bubbles form in the immediate vicinity of the restricted flow.

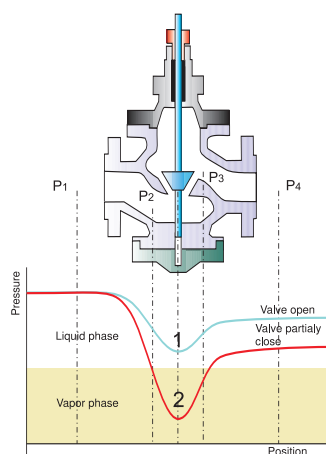
When the static pressure rises again downstream of the valve (pressure P_2), the vapour bubbles condense and implode.

Cavitation has the following undesirable effects:

- unacceptably loud noise, rather like pebbles rattling in the pipes,
- vibrations at high frequencies which loosen the valve nuts and other parts,
- rapid destruction of the throttle, seat and body by removal of metal particles. Surfaces subject to cavitation are grainy,
- the flow through the valve is related to valve opening.

Regulation valves are often required to operate for a long time in conditions where cavitation can occur and their lifetime will be seriously affected by it.

Ways of limiting or preventing cavitation do not enter into the scope of this guide.



↑ Fig. 45 Cavitation phenomenon