Modern electrical motors are available in many different forms, such as single phase motors, three-phase motors, brake motors, synchronous motors, asynchronous motors, special customised motors, two speed motors, three speed motors, and so on, all with their own performance and characteristics.

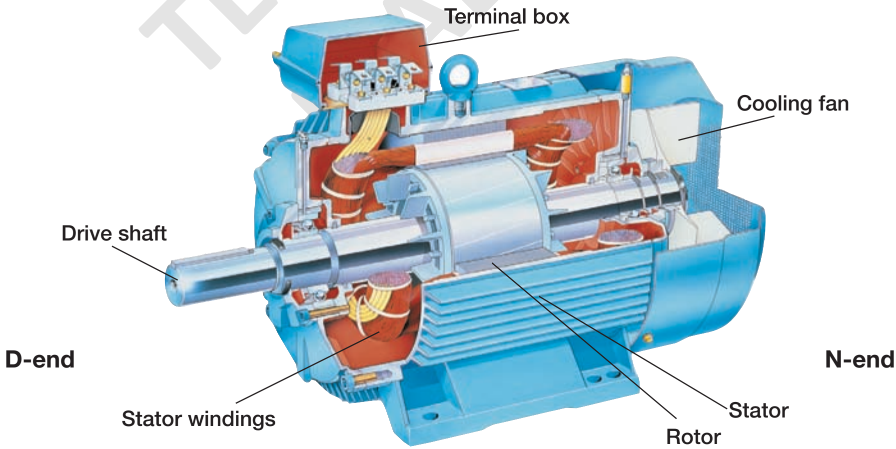
For each type of motor there are many different mounting arrangements, for example foot mounting, flange mounting or combined foot and flange mounting. The cooling method can also differ very much, from the simplest motor with free self-circulation of air to a more complex motor with totally enclosed air-water cooling with an interchangeable cassette type of cooler.

To ensure a long lifetime for the motor it is important to keep it with the correct degree of protection when under heavy-duty conditions in a servere environment. The two letters IP (International Protection) state the degree of protection followed by two digits, the first of which indicates the degree of protection against contact and penetration of solid objects, whereas the second states the motor's degree of protection against water.

The end of the motor is defined in the IEC-standard as follows:

- The D-end is normally the drive end of the motor.
- The N-end is normally the non-drive end of the motor.

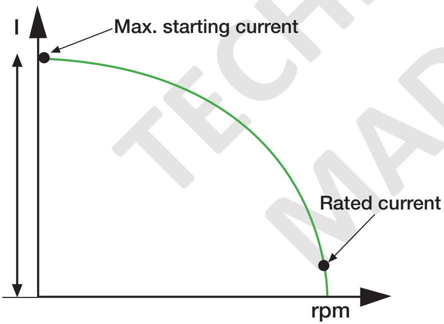
Note that in this handbook we will focus on asynchronous motors only.



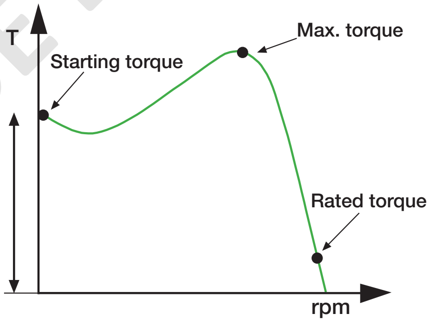
Squirrel cage motors

In this book the focus has been placed on the squirrel cage motor, the most common type of motor on the market. It is relatively cheap and the maintenance cost is normally low. There are many different manufacturers represented on the market, selling at various prices. Not all motors have the same performance and quality as for example motors from ABB. High efficiency enables significant savings in energy costs during the motor's normal endurance. The low level of noise is something else that is of interest today, as is the ability to withstand severe environments.

There are also other parameters that differ. The design of the rotor affects the starting current and torque and the variation can be really large between different manufacturers for the same power rating. When using a softstarter it is good if the motor has a high starting torque at Direct-on-line (D.O.L) start. When these motors are used together with a softstarter it is possible to reduce the starting current further when compared to motors with low starting torque. The number of poles also affects the technical data. A motor with two poles often has a lower starting torque than motors with four or more poles.



Current diagram for typical sqirrel cage motor



Torque diagram for a typical squirrel cage motor

Voltage

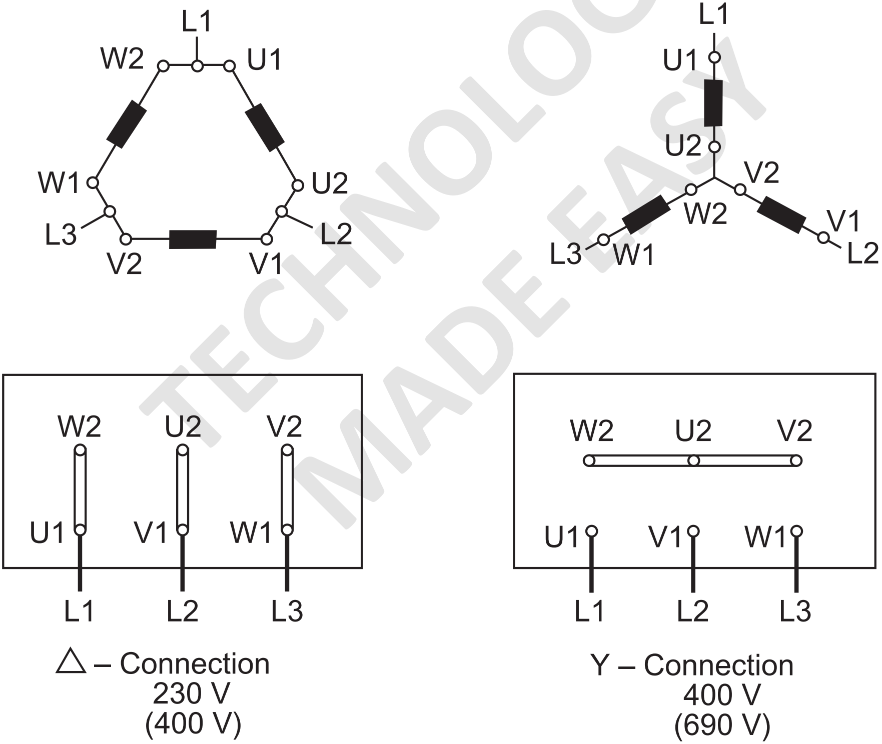
Three-phase single speed motors can normally be connected for two different voltage levels. The three stator windings are connected in star (Y) or delta (D).

The windings can also be connected in series or parallel, Y or YY for instance. If the rating plate on a squirrel cage motor indicates voltages for both the star and delta connection, it is possible to use the motor for both 230 V, and 400 V as an example.

The winding is delta connected at 230 V and if the main voltage is 400 V, the Y-connection is used.

When changing the main voltage it is important to remember that for the same power rating the rated motor current will change depending on the voltage level.

The method for connecting the motor to the terminal blocks for star or delta connection is shown in the picture below.



Wiring diagram for Y- and Delta connection

Power factor

A motor always consumes active power, which it converts into mechanical action. Reactive power is also required for the magnetisation of the motor but it doesn't perform any action. In the diagram below the active and reactive power is represented by P and Q, which together give the power S.

The ratio between the active power (kW) and the reactive power (kVA) is known as the power factor, and is often designated as the cos φ. A normal value is between 0.7 and 0.9, when running where the lower value is for small motors and the higher for large ones.

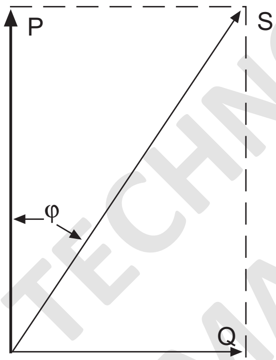


Diagram indicating P, Q, S and Cos φ

Speed

The speed of an AC motor depends on two things: the number of poles of the stator winding and the main frequency. At 50 Hz, a motor will run at a speed related to a constant of 6000 divided by the number of poles and for a 60 Hz motor the constant is 7200 rpm.

To calculate the speed of a motor, the following formula can be used:

$$n = \frac{2 \times f \times 60}{p}$$

n = speed
f = net frequency
p = number of poles

Example:

4-pole motor running at 50 Hz

$$n = \frac{2 \times 50 \times 60}{4} = 1500 \text{ rpm}$$

This speed is the synchronous speed and a squirrel-cage or a slip-ring motor can never reach it. At unloaded condition the speed will be very close to synchronous speed and will then drop when the motor is loaded.

The difference between the synchronous and asynchronous speed also named rated speed is "the slip" and it is possible to calculate this by using the following formula:

$$s = \frac{n_1 - n}{n_1}$$

s = slip (a normal value is between 1 and 3 %)

n_1 = synchronous speed

n = asynchronous speed (rated speed)

Table for synchronous speed at different number of poles and frequency:

No. of poles	50 Hz	60 Hz
2	3000	3600
4	1500	1800
6	1000	1200
8	750	900
10	600	720
12	500	600
16	375	450
20	300	360

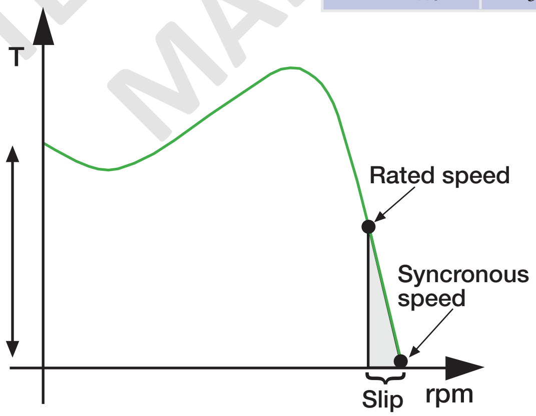


Diagram showing syncronous speed vs.rated speed

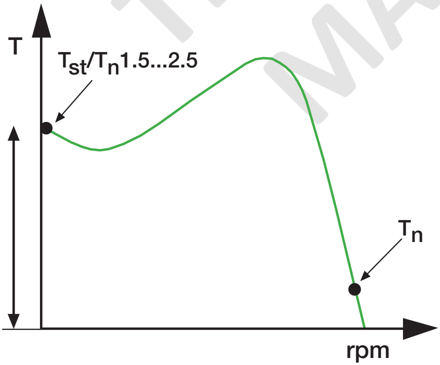
Torque

The starting torque for a motor differs significantly depending on the size of the motor. A small motor, e.g. ≤ 30 kW, normally has a value of between 2.5 and 3 times the rated torque, and for a medium size motor, say up to 250 kW, a typical value is between 2 to 2.5 times the rated torque. Really big motors have a tendency to have a very low starting torque, sometimes even lower than the rated torque. It is not possible to start such a motor fully loaded not even at D.O.L start.

The rated torque of a motor can be calculated using the following formula:

$$M_r = \frac{9550 \text{ x } P_r}{n_r}$$

M_r = Rated torque (Nm)
P_r = Rated motor power (kW)
n_r = Rated motor speed (rpm)



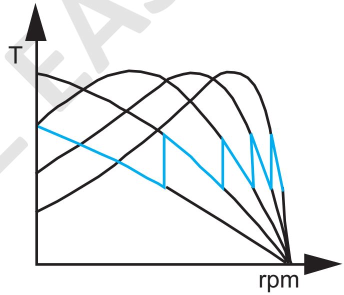
Torque diagram for a typical squirrel cage motor

Slip-ring motors

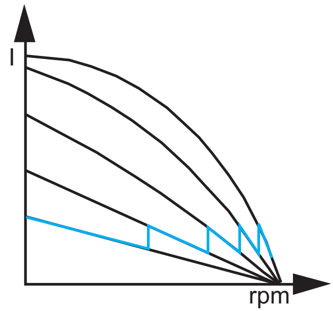
In some cases when a D.O.L start is not permitted due to the high starting current, or when starting with a star-delta starter will give too low starting torque, a slip-ring motor is used. The motor is started by changing the rotor resistance and when speeding up the resistance is gradually removed until the rated speed is achieved and the motor is working at the equivalent rate of a standard squirrel-cage motor.

The advantage of a slip-ring motor is that the starting current will be lower and it is possible to adjust the starting torque up to the maximum torque.

In general, if a softstarter is going to be used for this application you also need to replace the motor.



Torque diagram for a slip-ring motor



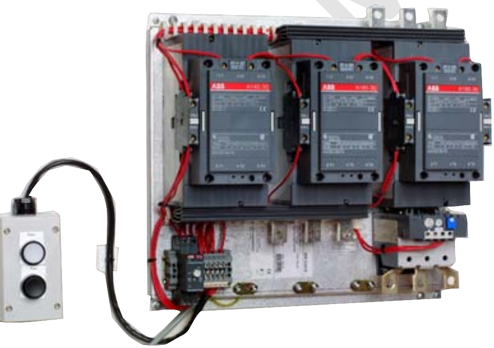
Current diagram for a slip-ring motor

The following is a short description of the most common starting methods for squirrel cage motors.
An overview of common problems when starting and stopping a motor with different starting methods, see page *14*

Direct-on-line start (D.O.L)

Frequency converter

Start-delta start



Softstarter

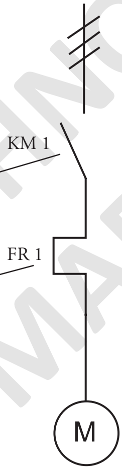
Direct-on-line start (D.O.L)

This is by far the most common starting method available on the market. The starting equipment consists of only a main contactor and thermal or electronic overload relay. The disadvantage with this method is that it gives the highest possible starting current. A normal value is between 6 to 7 times the rated motor current but values of up to 9 or 10 times the rated current exist. Besides the starting current there also exists a current peak that can rise up to 14 times the rated current since the motor is not energised from the the first moment when starting.

The values are dependent on the design and size of the motor, but in general, a smaller motor gives higher values than a larger one.

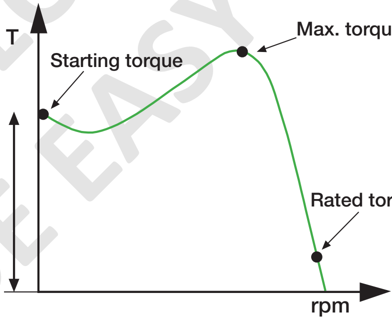
During a direct-on-line start, the starting torque is also very high, and is higher than necessary for most applications. The torque is the same as the force, and an unnecessary high force gives unnecessary high stresses on couplings and the driven application. Naturally, there are cases where this starting method works perfectly and in some cases also the only starting method that works.

D.O.L. starter with contactor and O/L relay

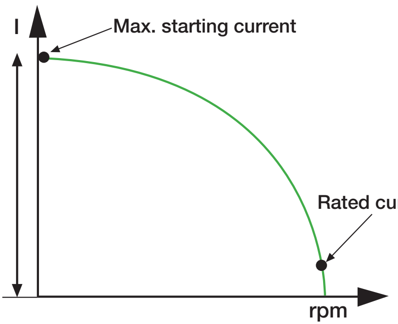


Single line diagram for a D.O.L.

KM 1 Main contactor
FR 1 Overload relay



Torque/speed curve att D.O.L start



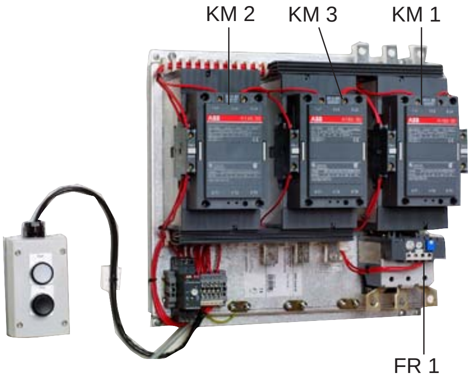
Current curve at D.O.L start

Star-delta start

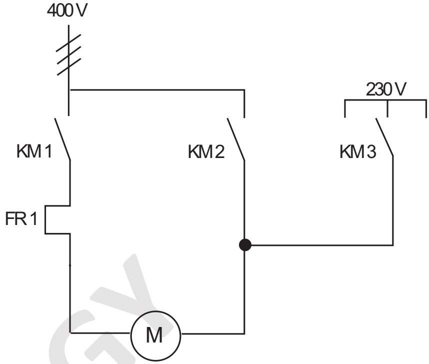
This is a starting method that reduces the starting current and starting torque. The device normally consists of three contactors, an overload relay and a timer for setting the time in the star-position (starting position). The motor must be delta connected during a normal run, in order to be able to use this starting method.

The received starting current is about 30 % of the starting current during direct on line start and the starting torque is reduced to about 25 % of the torque available at a D.O.L start. This starting method only works when the application is light loaded during the start. If the motor is too heavily loaded, there will not be enough torque to accelerate the motor up to speed before switching over to the delta position.

When starting up pumps and fans for example, the load torque is low at the beginning of the start and increases with the square of the speed. When reaching approx. 80-85 % of the motor rated speed the load torque is equal to the motor torque and the acceleration ceases. To reach the rated speed, a switch over to delta position is necessary, and this will very often result in high transmission and current peaks. In some cases the current peak can reach a value that is even bigger than for a D.O.L start. Applications with a load torque higher than 50 % of the motor rated torque will not be able to start using the start-delta starter.

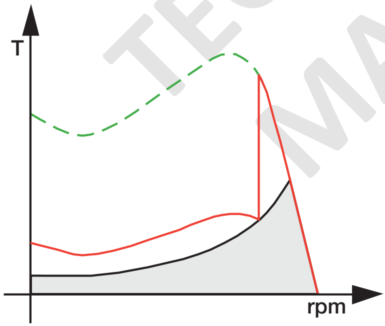


Star-delta starter with contactors and O/L relay

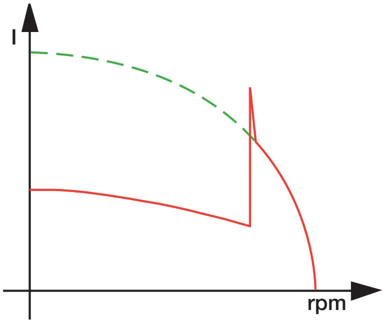


Single line diagram for a Star-delta starter

KM 1 Main contactor
KM 2 Delta contactor
KM 3 Star contactor
FR 1 Overload relay



Torque/speed curve at Star-Delta start



Current curve at Star-Delta start

Frequency converter

The frequency converter is sometimes also called VSD (Variable Speed Drive), VFD (Variable Frequency Drive) or simply Drives, which is probably the most common name.

The drive consists primarily of two parts, one which converts AC (50 or 60 Hz) to DC and the second part which converts the DC back to AC, but now with a variable frequency of 0-250 Hz. As the speed of the motor depends on the frequency this makes it possible to control the speed of the motor by changing the output frequency from the drive and this is a big advantage if there is a need for speed regulation during a continuous run.

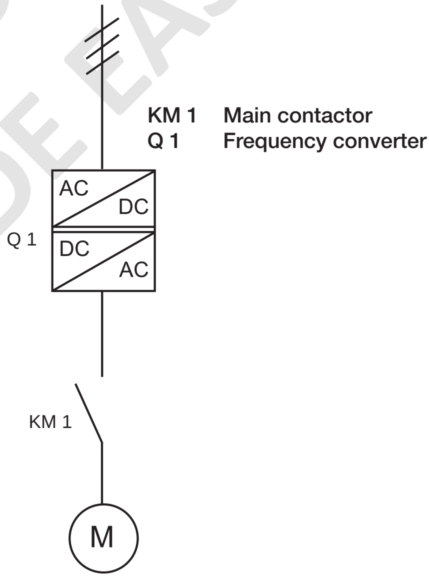
In many applications a drive is still only used for starting and stopping the motor, despite the fact that there is no need for speed regulation during a normal run. Of course this will create a need for much more expensive starting equipment than necessary.

By controlling the frequency, the rated motor torque is available at a low speed and the starting current is low, between 0.5 and 1.0 times the rated motor current, maximum 1.5 x I_n.

Another available feature is softstop, which is very useful, for example when stopping pumps where the problem is water hammering in the pipe systems at direct stop. The softstop function is also useful when stopping conveyor belts from transporting fragile material that can be damaged when the belts stop too quickly.

It is very common to install a filter together with the drive in order to reduce the levels of emission and harmonics generated.

Frequency converter



Single line diagram for a frequency converter

Softstarter

A softstarter has different characteristics to the other starting methods. It has thyristors in the main circuit, and the motor voltage is regulated with a printed circuit board. The softstarter makes use of the fact that when the motor voltage is low during start, the starting current and starting torque is also low.

During the first part of the start the voltage to the motor is so low that it is only able to adjust the play between the gear wheels or stretching driving belts or chains etc. In other words, eliminating unnecessary jerks during the start.

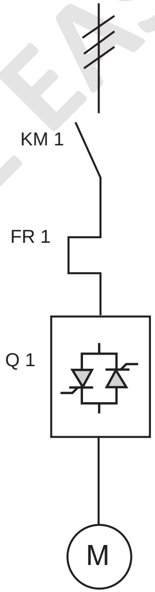
Gradually, the voltage and the torque increase so that the machinery starts to accelerate.

One of the benefits with this starting method is the possibility to adjust the torque to the exact need, whether the application is loaded or not. In principle the full starting torque is available, but with the big difference that the starting procedure is much more forgiving to the driven machinery, with lower maintenance costs as a result.

Another feature of the softstarter is the softstop function, which is very useful when stopping pumps where the problem is water hammering in the pipe system at direct stop as for star-delta starter and direct-on-line starter.

The softstop function can also be used when stopping conveyor belts to prevent material from damage when the belts stop too quickly.

Softstarter



KM 1 Main contactor
FR 1 Overload relay
Q 1 Softstarter

Single line diagram for a softstarter

Common problems when starting and stopping motors with different starting methods

Type of problem Type of starting method

	Direct-on-line	Star-delta start	Drives	Softstarter
Slipping belts and heavy wear on bearings	Yes	Medium	No	No
High inrush current	Yes	No	No	No
Heavy wear and tear on gear boxes	Yes	Yes (loaded start)	No	No
Damaged goods / products during stop	Yes	Yes	No	No
Water hammering in pipe system when stopping	Yes	Yes	Best solution	Reduced
Transmission peaks	Yes	Yes	No	No

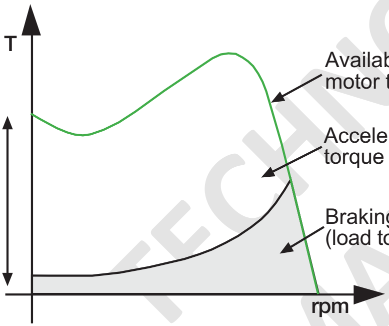
Auto transformer start and start of a part winding motor have similar problems to the star-delta start.

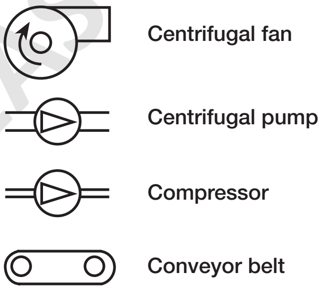
All motors are used for starting and running different applications. This chapter covers the most common ones. The different applications will also result in different load conditions for the motor. There are two factors to consider:

1. **Braking load torque, a direct braking force on the motor shaft. To be able to accelerate, the motor has to be stronger than the load. The accelerating torque is the difference between the available motor torque and the load toque.**

   Accelerating torque = Available motor torque – load torque

2. **Involved moment of inertia or flywheel mass will also affect the start. The bigger inertia the longer starting time for the same motor.**



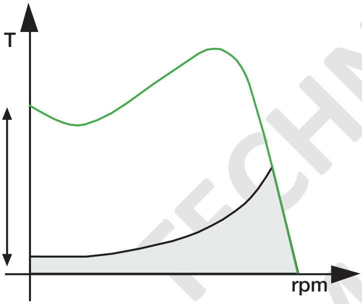


For some applications the motor is started with reduced load torque, i.e. unloaded start. Big centrifugal fans are often started with a closed damper and this will make the start easier (shorter) but since the moment of inertia is still present the starting time might be quite long anyway.

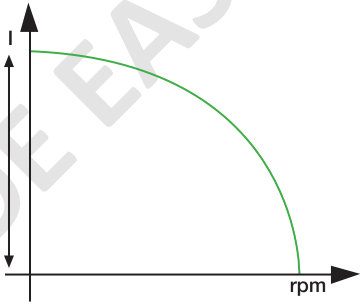
Direct-on-line start

Centrifugal fans are very often driven by one or more drive belts. During a D.O.L start these belts have a tendency to slip. The reason is that these types of fans always have a more or less high moment of inertia (big flywheel). So even if the fan is started unloaded, the flywheel is still there.

The belts slip depending on whether the starting torque from the motor is too high during the start sequence and the belts are not able to transfer these forces. This typical problem gives high maintenance costs but also production losses when you need to stop production to change belts and bearings.



Torque/speed curve at D.O.L start



Current curve at D.O.L start

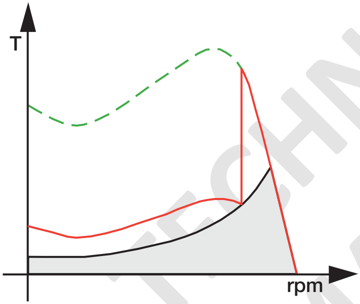
Star-delta starter (Y-D)

The star-delta starter gives lower starting torque but depending on the fact that the load torque increases with the square of the speed, the motor torque will not be high enough in the star position to accelerate the fan to the rated speed.

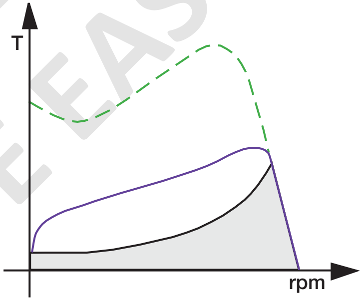
When switching over to delta position it will be both a high transmission and current peak, often equal to values when making a D.O.L start or even higher, with a slipping belt as a result. It is possible to reduce the slip by stretching the belts very hard. This gives high mechanical stresses on bearings both in the motor and the fan with high maintenance costs as result.

Softstarter

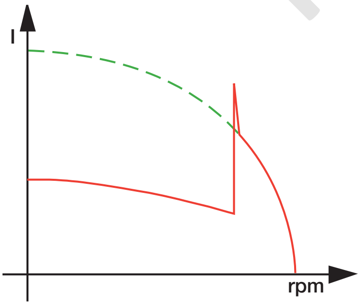
The key to solve these problems is to reduce the starting torque from the motor during start. By using an ABB softstarter the voltage is decreased to a low value at the beginning of the start, low enough to avoid slip but high enough to start up the fan. The softstarter provides the ability to adjust to fit any starting condition, both unloaded and fully loaded starts.



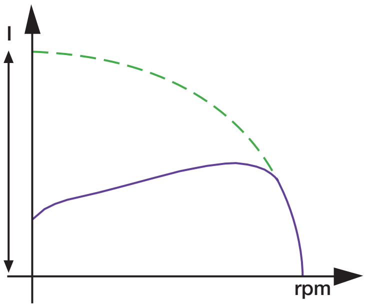
Torque/speed curve at Star-Delta start



Torque/speed curve when using a softstarter



Current curve at Star-Delta start

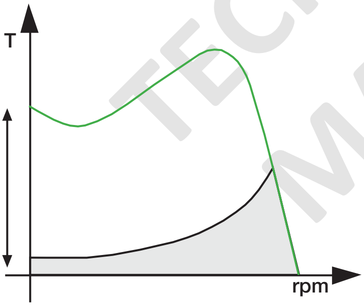


Current curve when using a softstarter

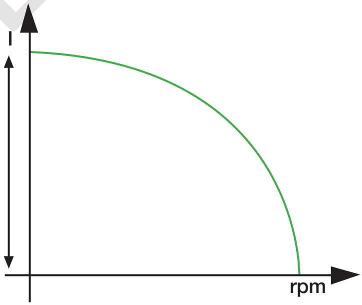
There are a lot of different types of pumps; like piston pumps, centrifugal pumps, screw pumps etc. But the most common version is the centrifugal pump and we have selected this one to describe.

Direct-on-line start

Starting up a pump is normally not a problem for a squirrel cage motor. The problem is the wear and tear depending on pressure waves in the pipe system created when the motor starts and stops too quickly. During a D.O.L start the motor gives much too high starting torque with the result that the motor accelerates and reaches nominal speed too quickly. The reason is that the braking load torque is low for a pump during start. This starting method also gives maximum possible starting current.



Torque/speed curve at D.O.L start



Current curve at D.O.L start

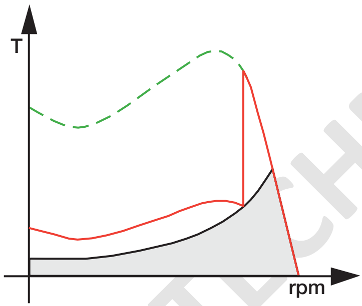
Star-delta starter (Y-D)

By using a star-delta starter it is possible to reduce the starting torque. The motor torque in the star position is too weak to be able to complete the start and reach the rated speed.

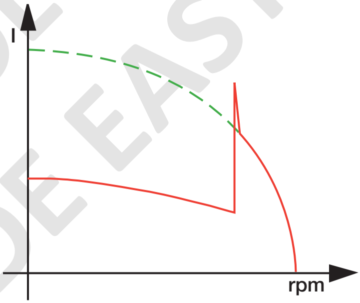
The quadratic load torque will become too high for the motor when reaching approx. 80-85 % of the rated speed and the switch over to the delta position will give both high transmission and current peaks with pressure waves as a result. The current peaks can be equally high as at a D.O.L start or even higher.

When stopping a pump

During stop it is also normal to have problems. When making a direct stop by disconnecting the main supply the motor stops too quickly. Depending on high mass flow in the pipe system the water will continue with the same speed for a short period and then come back again, backwards in the pipe system. This creates high pressure shocks on valves and gives high mechanical stresses on the pipe system.



Torque/speed curve at Star-Delta start



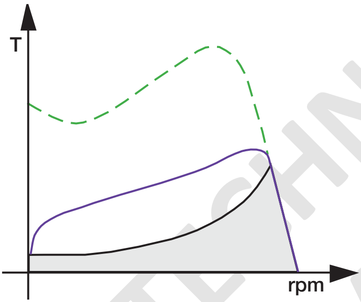
Current curve at Star-Delta start

Softstarter

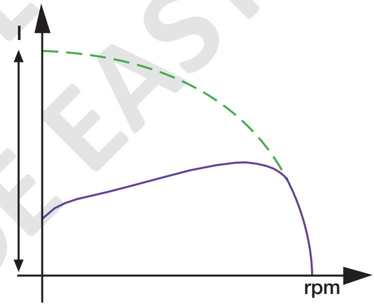
By using an ABB softstarter the voltage is reduced during the start sequence with the result that the motor torque is reduced. During the start sequence the softstarter increases the voltage so that the motor will be strong enough to accelerate the pump to the nominal speed without any torque or current peaks. A normal starting current with a softstarter when starting a fully loaded centrifugal pump is approx. 4 times rated motor current.

Also during the stop sequence the softstarter is the solution. The softstarter reduces the voltage during stop via a voltage ramp and the motor becomes weaker and weaker. Because of this the water speed slows down very smoothly without creating any pressure waves.

A special function on the softstarter is sometimes available, called "step-down voltage",which ensures an optimum setting to the actual need for any pipe system.



Torque/speed curve when using a softstarter

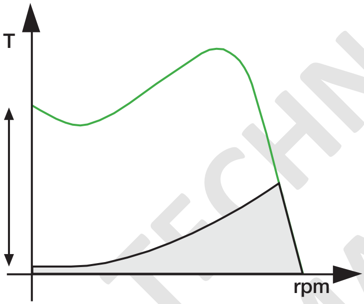


Current curve when using a softstarter

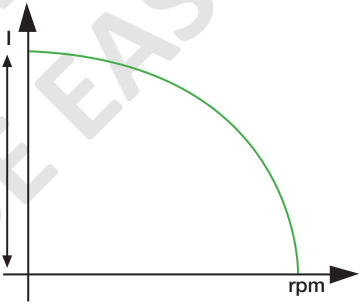
Smaller compressors are often of piston type and the load torque increases linearly with the speed. Screw compressors are often used when there is a bigger need for air flow and this type has a load torque increasing with the square of the speed. Drive belts are often used between motor and compressor but direct connections via some type of toothed couplings are also common. Some compressors are started with reduced load.

Direct-on-line start (D.O.L)

Compressors started direct-on-line are exposed to high mechanical stresses on the compressor itself, but also on drive belts and couplings. The result is shortened endurance. In cases where the drive belts are used the belts very often slip during start. The high starting torque received during starting with this method is the source of the problems. The starting current is always high at D.O.L start. A normal value can be approx. 7 times rated motor current.



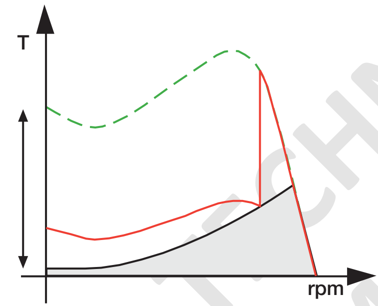
Torque/speed curve at D.O.L start



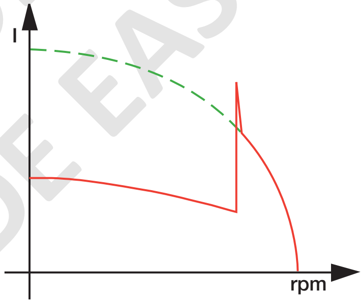
Current curve at D.O.L start

Star-delta starter (Y-D)

Star-delta start gives a lower starting torque and starting current but the motor is too weak during the start up to be able to accelerate the motor up to nominal speed. When switching to the delta position both current and torque peaks will occur with high mechanical stresses as a result. Compressors are very often running at no load condition for longer periods when the pressure in the system is high. A motor running under these circumstances always has a poor power factor and low efficiency. Some times the value is so low that it must be compensated.



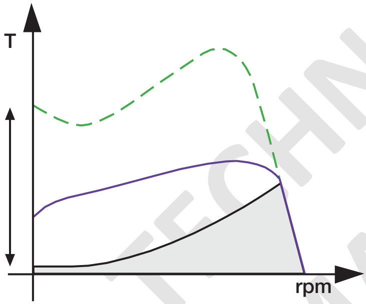
Torque/speed curve at Star-delta start



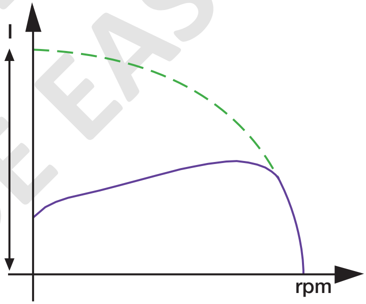
Current curve at Star-delta start

Softstarter

By using an ABB softstarter it is possible to limit the starting torque to a level suitable for all different applications. The result is less stress on couplings, bearings and no slipping belts during start. The maintenance cost will be reduced to a minimum. When using a softstarter the starting current received is approx. 3 to 4 times the rated motor current.



Torque/speed curve when using a softstarter



Current curve when using a softstarter

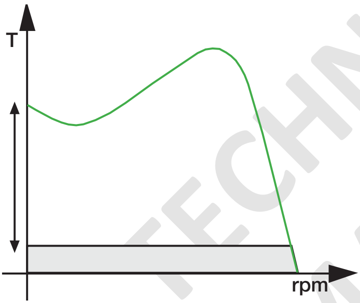
Conveyor belts can have a lot of different looks and directions of use. It is a typical constant torque load with low to high braking torque depending on how heavy it is loaded.

Direct-on-line start (D.O.L)

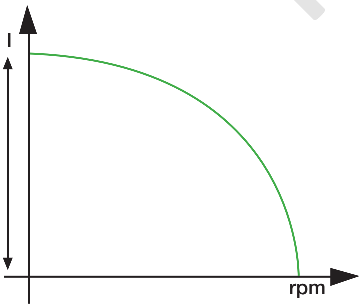
Conveyor belts often need a starting torque very near or just above the rated torque of the motor. A direct-on-line start with a normal squirrel cage motor gives approx. 1.5 to 2.5 times rated torque of the motor depending on motor size, type etc. When making a direct-on-line start there is a very high risk of slipping between the belt and the driving role depending on this high starting torque.

Gearboxes and couplings are also exposed to high mechanical stresses. This result is considerable wear and tear and often high maintenance costs. Sometimes fluid couplings are used to reduce the transferred torque. This method is expensive and requires a lot of maintenance.

Low braking torque

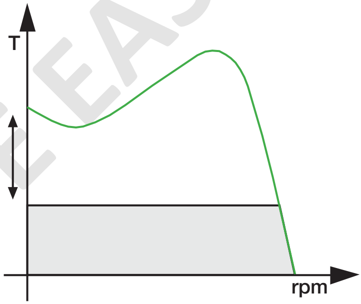


Torque/speed curve at D.O.L start

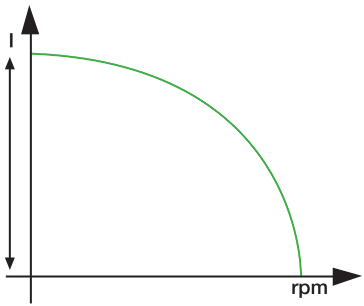


Current curve at D.O.L start

High braking torque



Torque/speed curve at D.O.L start

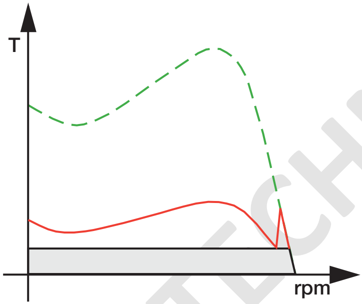


Current curve at D.O.L start

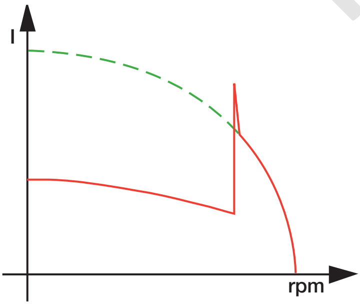
Star-delta start

It is not possible to use this starting method when the load torque is close to the rated motor torque during start (see figure below, High braking torque).

Low braking torque

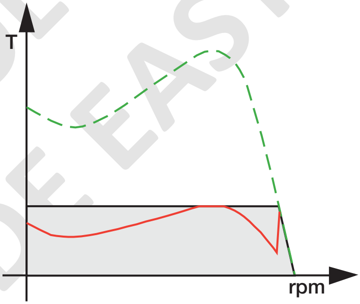


Torque/speed curve at Star-delta start

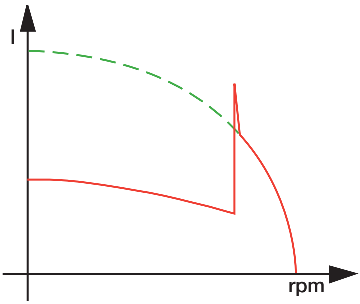


Current curve at Star-delta start

High braking torque



Torque/speed curve at Star-delta start

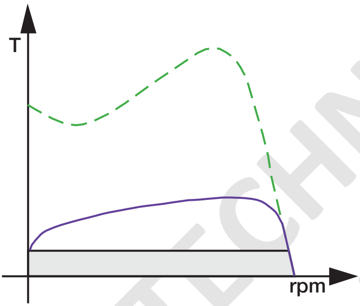


Current curve at Star-delta start

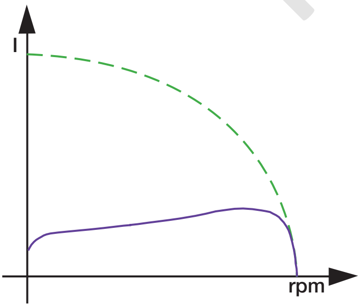
Softstarter

By using an ABB softstarter the starting torque can be reduced to a minimum value still able to start up the conveyor belt. The setting possibility of the softstarter makes it possible to adjust the torque to exactly the level that is necessary for the start. The result is the least possible stress on gearboxes and couplings and no slipping belts during start. This will reduce the maintenance cost to a minimum. When using a softstarter you will receive approx. 3 to 4 times rated motor current during start.

Low braking torque

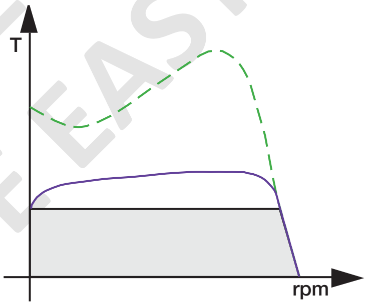


Torque/speed curve when using a softstarter

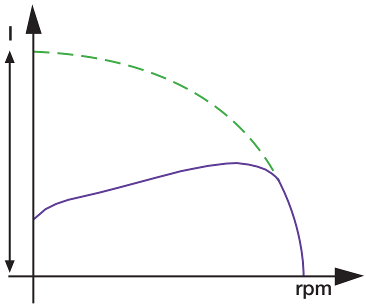


Current curve when using a softstarter

High braking torque



Torque/speed curve when using a softstarter



Current curve when using a softstarter