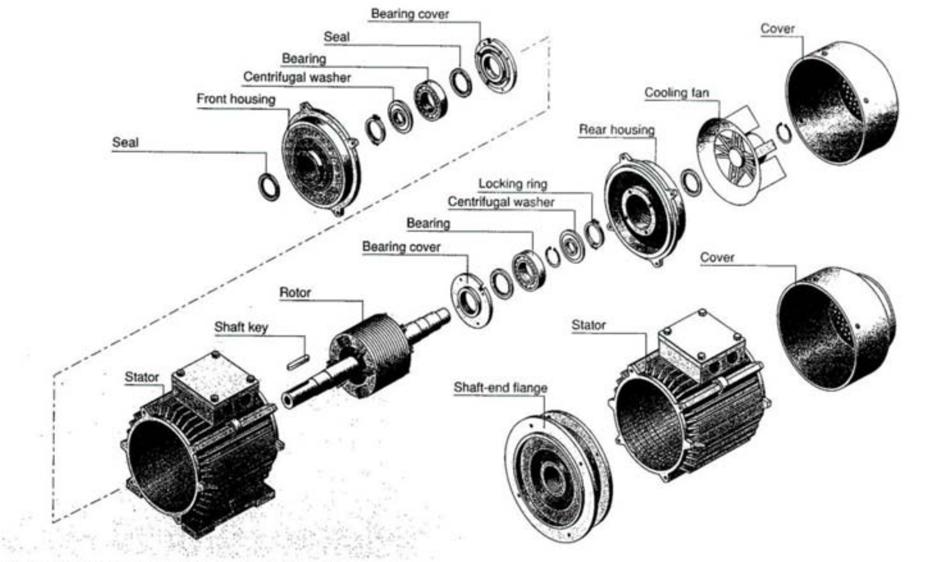
Electric Motors

This bulletin has been updated to describe how to commission various motor starter systems (this should be valuable information for all site engineers) and to incorporate the section previously distributed as an addendum. Other sections have also been updated and expanded to give further details on common use on modern refrigeration plant.

1.0 Introduction

From the wide variety of motor types available we almost invariably use a 3-phase, alternating current, induction motors, because they are relatively cheap, convenient and robust in comparison to the alternatives, e.g. single phase, DC.

A 3-phase AC motor comprises a stator (the stationary part) and a rotor. Usually the stator is a cylindrical casing of slotted steel laminations with copper windings held in the slots and the rotor, a barrel of copper conductors on a shaft, sits inside the casing (Fig 1). When alternating current flows in the stator a magnetic field is induced (hence “induction” motor), which tends to rotate the shaft proving the required motion.



3-phase asynchronous squirrel-cage motor (exploded view)

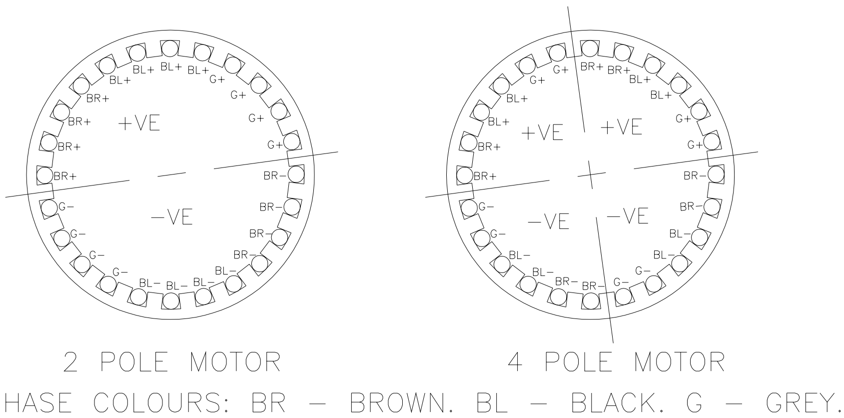


FIGURE 2 ARRANGEMENT OF MOTOR PHASES

The way in which the windings are connected will determine the speed at which the shaft rotates. The simplest (and fastest) induction motor has only one pair of magnetic poles per phase and rotates once for every cycle of mains voltage. Hence, on a 50Hz supply it will run at just below 3000 rpm. Note that if the windings are connected to give a greater number of pole pairs, the motor will run more slowly but there are just as many windings (Fig 2).

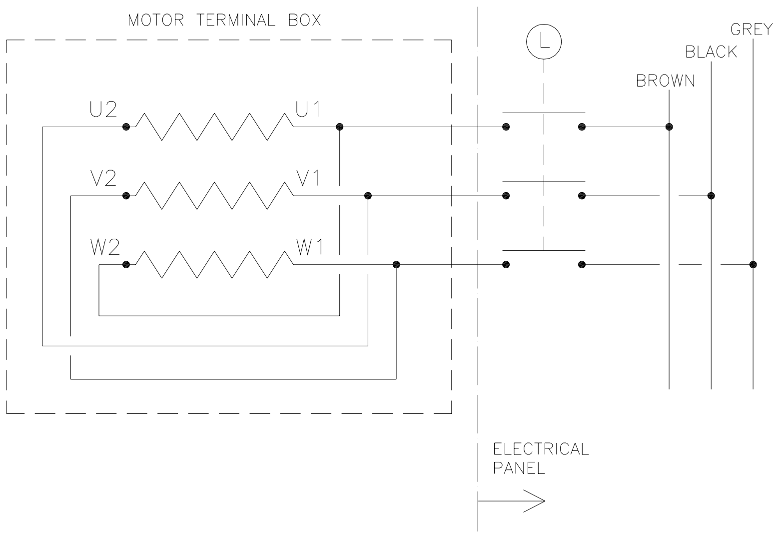


FIGURE 3 DOL MOTOR STARTER

Torque is only transmitted to the rotor if the copper bars cut through the lines of magnetic flux generated. Hence, for the motor to provide useful power output it must run slightly slower than the rotation of the magnetic field. If the field rotates at 3000 rpm, the motor will most likely rotate at 2900 rpm – 2980 rpm. The speed difference is known as slip, and for small slip it is proportional to the load on the motor. If, however, the load was too great, the motor would stall. In practice, the overload would trip before this due to excessive current drawn by the motor.

The motor may also be protected from over-current using thermistors embedded in the windings during manufacture. The thermistors detect increases in winding temperature and are wired to a cut-out which will stop the motor. Single speed motors require three thermistors and for dual wound two-speed motors it is necessary to use six. Thermistors, if fitted, are used in addition to thermal overloads in the control panel. Star use thermistors (in addition to thermal overloads) where the motor is dependent on external cooling, for example a semi-hermetic compressor motor or a water cooled motor and where the motor is >30kW and is inverter driven or operates with a voltage >1000V.

1.1 Selecting the Right Option

Motors must be selected

- to give the correct power output at rated conditions
- to run at the right speed
- to provide sufficient protection against solids, moisture and gases, and
- to deliver sufficient torque to start and accelerate the load from rest

1.1.1 Motor Power

Motor power output is quoted in kW shaft power, i.e. the amount of power transmitted to the load. The input power will be higher due to the motor efficiency. When selecting a motor for a low temperature compressor it is important to consider the “pull-down” load when the power requirement may be higher than the normal running condition. However, motors should not be grossly oversized as the efficiency and power factory can be very poor on part load.

1.1.2 Motor Speed

As mentioned previously, motor speed is directly related to the number of pole pairs in the motor. With a 50Hz supply a 2-pole motor runs at 3000 rpm, 4-pole at 1500 rpm, 6-pole at 1000 rpm and so on. Direct drive compressors usually use 2-pole (screw compressors) or 4-pole and 6-pole (reciprocating compressors) motors. Belt-driven compressors use a 4-pole motor with a pulley ratio to slow down (or occasionally speed up) the compressor to the required speed. Actual running speed is about 3%-5% slower than synchronous speed to provide the motor driving force.

Multi-speed motors can be designed in a variety of ways. The most common types are dual-wound and Dahlander. The dual-wound motor has two sets of windings to allow the pole configuration to be changed, and matching the winding design to the power requirement on each speed. Typically a motor will run at full or half speed, e.g. 2/4 pole, although other splits (within the constraints of pole configuration), e.g. 8/12 pole, are also possible. Dahlander motors use additional tappings to reconstruct the windings in a different manner. This makes the motor smaller and cheaper than a dual-wound type, but as the windings cannot always be matched to the load the efficiency is impaired.

1.1.3 Degrees of Protection

Technical Bulletin No 81 gives details of the international numbering system (IEC ratings) for electrical apparatus. For outdoor applications, e.g. condenser fan, pump, etc, we require a minimum of IP55. Indoor applications in a wet or possibly wet environment, e.g. a brine pump or oil pump, will also be IP55. If a large motor is to be installed in a dry area the degree of protection can be reduced to IP23 (drip-proof). For small motors, e.g. less than 15kW, where the cost is negligible, IP55 should be used. IP55 motors are also referred to as totally enclosed, fan ventilated (TEFV) or totally enclosed, fan cooled (TEFC).

In a potentially explosive atmosphere the motor must also provide protection against ingress of explosive gases. ATEX certified motors will be required for potentially explosive atmospheres where the zone rating, category, gas or dust group and maximum surface temperature as well as any special customer requirements will have to be checked.

1.1.4 Rated Voltage

The main considerations in selecting high motor voltages are the starting and running currents which result. As the cable size required to feed a motor depends on the current drawn, there is an economic balance point where the additional costs of HV motors and switchgear are matched by the reduced cabling cost. When an LV motor would require significant refurbishment of the infrastructure, this point will be at a relatively small motor rating. Usually motors above the 450kW – 500kW range should be high voltage. 3.3kV is the norm. As for higher voltages than this, the motor costs are expensive. Note electrical engineers will refer to voltages between 600V and 15kV as medium voltage (and low voltage as up to 600V ac), although this is not uniformly defined.

High voltage motors are almost always started DOL (Direct on Line) because the additional current drawn during starting is small in comparison to other loads on the HV supply. For example, a 250kW motor will have typical starting and running currents of 950A and 430A respectively when started Star-Delta on a 415V supply. Using DOL starting at 3.3kV will reduce these to 325A and 54A respectively.

1.1.5 Star Refrigeration Requirements for Compressor Drives

1.1.5.1 Reciprocating Compressors

We require a minimum starting torque in Star of 60%. Any variation below this must be agreed with the Technical Department. This must be specified in the order.

On direct drive compressor units we specify ball bearings at the motor drive and non-drive ends. Belt drive motors require roller bearings at the drive end. The casing should be cast-iron to absorb high vibration levels from the compressor. Usually IP23 protection is adequate, but this should be checked with the customer.

1.1.5.2 Screw Compressors

Starting torque requirements are similar to reciprocating compressors, provided the compressor can start on minimum load. The requirement for loaded start is much higher and must be checked carefully. Ball bearings at both ends are acceptable and there is less need to use cast iron, so lighter steel or aluminium alternatives can be considered. The noise should also be checked carefully.

2.0 Starting Characteristics

A typical motor will only deliver about 35% - 45% of full load torque (FLT) when starting from rest by Star-Delta starting. This is because the motor windings have only 240V instead of 415V across them. As the torque varies with the voltage squared, the starting torque will be one-third of the locked rotor torque (LRT) which typically is 140% of FLT. This is fine for starting light "self-loading" loads like fans and centrifugal pumps, but is not sufficient for screw or reciprocating compressors. The high "breakaway" torque in a compressor plus the initial pressure difference which may exist mean that a starting torque of 60% is required. This can be achieved by winding the stator to give a higher than normal LRT (say 180%), and hence higher starting torque. Once the load has started to rotate the difference between motor torque and load torque requirement is available to accelerate the load up to running speed. If there is no difference, the motor will stall. If the difference is too small, the compressor will not reach full speed quickly enough and may suffer lubrication problems and cause power supply overload problems.

Although high torque is required, the starting current must be kept to a minimum as all cables, switchgear, circuit breakers, etc must be sized for the starting current. The locked rotor current is about six times full load current so DOL starting is not used for medium to large motors. Instead there are a number of techniques which reduce the initial voltage. As with torque, the current-voltage relationship follows a square law.

2.1 Types of Starter

The selection of starting method, as with voltage selection, is based on a balance of economic factors. These include the cost of the starter and additional cost of the motor set against savings in wiring and switchgear.

2.1.1 Direct On Line (DOL)

With DOL starting a 3-phase contactor connects the load directly to the main supply (Fig 3). This allows the motor to develop full locked rotor torque (typically 110%-120% FLT) but can result in a current in-rush of up to 6-7 times FLC. Switchgear is cheap, small and simple. This type of starter can usually be used for direct (not belt) drive motors up to 15kW.

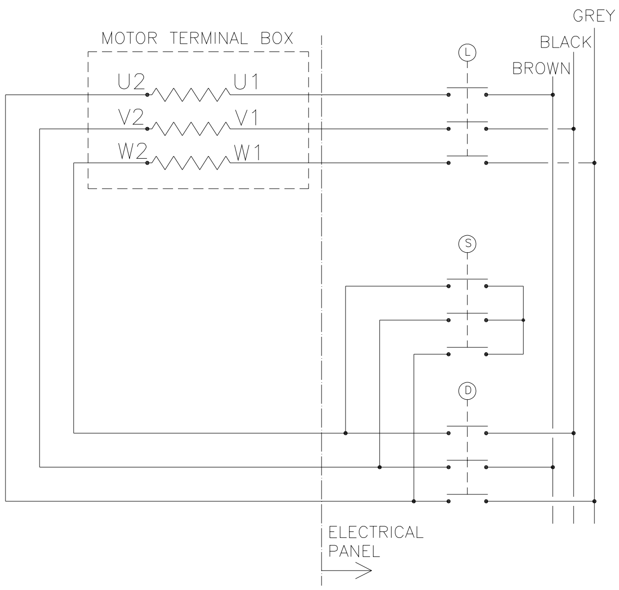


FIGURE 4 STAR DELTA STARTER

2.1.2 Star-Delta Starting

A Star-Delta starter uses three contactors (Star, Delta and Line) instead of the one which would be required for DOL, and hence is roughly three times the price (Fig 4). The motor windings for each phase are initially connected to a common node, resulting in line voltage (240V) instead of phase voltage (415V) across each winding. Starting current and starting torque are reduced to one-third of their DOL values. There is a second current spike when the starter switches from Star to Delta where each winding is connected across two adjacent phases. A mechanical interlock between the Star and Delta contactors is required to prevent the two contactors being closed at the same time. A time delay of approximately 150ms is also used between the Star contactor opening and the Delta contactor closing to ensure there is no possibility of short circuit between the phases. A compressor running at 1450 rpm turns one revolution every 40ms, so this delay can result in significant drop in speed for a reciprocating compressor, making the second current spike quite large and often worse than the initial current surge.

2.1.3 Closed Transition Starting

The problem of secondary current spikes can be removed by including a switched bank of resistors in the starter. These are connected in series with the motor windings until after the change from Star to Delta, protecting against a short circuit between phases and allowing the Star and Delta contactors to be switched simultaneously. There is no loss of speed and consequently no secondary spike in the current. The resistors are obviously large and add significantly to the cost and size of the starter. This system is no longer in common use and shall not be used on new plant without the agreement of the Technical Department.

2.1.4 Auto Transformer Starters

In an auto transformer, the starting current is reduced by using a step down transformer to supply the initial voltage and the motor is started DOL. Auto transformers are supplied with multiple tappings so that the starting voltage can be varied to suit site conditions. Typical tappings are 55%, 65%, 75% and 85% of line voltage. These would result in starting currents and torques of approximately 30%, 42%, 56% and 72% of locked rotor values respectively. When the motor reaches full speed, the transformer is bypassed, bringing the supply up to full phase voltage and removing the transformer losses. There is a danger that the transformer inductance may interact with the capacitors in power factor correction systems so PFC must always be isolated until the transformer has been bypassed. In addition the motor and starter characteristics should be carefully matched. This system is no longer in common use and shall not be used on new plant without agreement of the Technical Department.

2.1.5 Electronic Soft Start

There are a number of ways in which the voltage can be reduced using power electronics. In every case, however, the reduction in starting torque and current is proportional to the square of the voltage ratio so it is not usually possible to achieve the necessary high starting torque required for compressors without relatively high starting currents. Most soft start units allow the user to set a current limit or a ramp time but in some cases these need to be set to such a high limit or short time to achieve the necessary torque that the starting current can be 3-4 times FLC, i.e. worse than the Star-Delta starting. However soft starters avoid the need for 6 motor cables (found with Star-Delta starting) allow the motor torque to exceed 1/3 rd of the DOL value (found with Star-Delta starting) and avoid the transition spike (again as found with Star-Delta starting) so are common on 400V motors above 400kW, and smaller if the customer prefers. As with auto transformer starting, interaction with PFC capacitors may cause high frequency harmonics and consequently excessive currents so must be avoided.

2.1.6 Part Winding Motor Starting

This type of motor has a starter winding composed of two parallel windings with 6 terminals (effectively 2 sets of 3 windings already partially connected) or with 12 terminals (effectively 2 sets of 3 windings with each end of each winding taken to an individual terminal). When the first winding is connected to the supply the "half motor" starts directly on the full voltage of the supply. This divides the normal starting current and torque by two. The second set of windings is connected to the supply when the motor reaches full speed.

This type of starting is common on semi-hermetic compressors where the reduced current surge compared to DOL starting but higher torque than Star-Delta starting are a good compromise. Motors can even have an un-equal split in which case the electrical specification must carefully note this.

3.0 Variable Speed Drives

In certain fan, pump and compressor applications it is advantageous to vary the speed of the motor, for example, to give control of head pressure in air cooled or evaporative condensers or to control the flow rate of pumped fluid. They are particularly suitable for achieving energy savings and close control on pumps and fans.

A frequency inverter converts the 50Hz supply voltage to DC using a standard bridge rectifier and smoothing capacitor circuit, and then uses the DC to create alternating current at the required frequency. Drives up to 250kW are available from a number of suppliers and special drives up to 500kW can be supplied. The frequency can be varied from 0Hz to over 80Hz in some cases. There are principally two types of inverter available.

3.1 Voltage Fed Inverters

The voltage fed inverter uses pulse width modulation to modify the output voltage and frequency. An adverse effect of using voltage control is that high frequency current harmonics are induced on the current signal. This can cause overload trips and fuse failures and can interfere with other adjacent plant in extreme cases. The harmonics can also cause overheating in the drive motor. For this reason, PWM drives can only be used up to maximum of 150kW (usually much less), with the motor oversized to compensate. An advantage of PWM drives is that the power factor on full speed and full load is very high, although it falls to about 0.3 at 10% speed.

3.2 Current Fed Inverters

Current fed inverters (also known as Current Source Inverters, CSI) control the current output instead of the voltage. This removes the problem of high frequency current harmonics, although the voltage form is subject to ‘spikes’. CSI drives are most effective in larger sizes, although they are very expensive. They are available in two types – 6 pulse and 12 pulse. 12 pulse inverters are usually used to limit the harmonics that the inverter causes in the mains supply. Always consult the Technical Department if the motors to be driven by inverters on one site exceed 300kW total power. 6 pulse inverters are cheaper and simpler but do not provide such a smooth output. An advantage of CSI is that the drive will fail-safe in the event of a short circuit.

WEG and some other manufacturers now have a twin 6 pulse drive arrangement that has a similar effect to 12 pulse drives but is much cheaper.

3.3 Precautions

Care must be taken to ensure that motors do not draw excessive current when operating close to full speed and that the motor does not overheat at low speed due to the loss of cooling effect from the motor fan. Some loads, particularly reciprocating machines and gear drives, can be susceptible to resonant vibration at certain speed within the operating range. Compressor lubrication may be inadequate at low speed in reciprocating machines and leakage past the rotors may be excessive at low speed in a screw, leading to very poor volumetric efficiency.

It is sometimes necessary to oversize motors when they are to be used with a variable speed drive. Motors may also need ceramic bearings to avoid arcing in the bearings. Motor manufacturers must always be consulted if a VSD is proposed and the motor order shall state that the motor is for inverter operation and state the speed range that will be required.

4.0 Useful Notes and Formulae

These notes are only intended as a guide. If in doubt about any calculation, check with a qualified electrical engineer.

4.1 Nomenclature

V	Voltage	N	Motor speed (rpm)
I	Current (amps)	Ns	Synchronous speed (rpm)
η	efficiency (fraction)		
cos Φ	power factor (fraction)		
P	power (kilowatts, kW)		
T	torque (Nm)		
s	slip (fraction)		
R	winding resistance (ohms Ω)	X	winding reactance (ohms Ω)

4.2 Motor Input Power

$$P_I = \frac{\sqrt{3}VI\eta\cos\Phi}{1000}$$

where P_I is the motor input (electrical power) V is three-phase voltage (typically 415V)

4.3 Shaft Power Output

$$P_S = \frac{\sqrt{3}VI\eta\cos\Phi}{1000}$$

4.4 Motor Current

$$I = \frac{1000P_S}{\sqrt{3}VI\eta\cos\Phi}$$

4.5 Slip

$$s = \frac{N_s - N}{N_s}$$

4.6 Power Factor

$$\cos\Phi = \frac{\sqrt{3}VI}{1000P_I}$$

This can be thought of as the ratio of useful power to apparent power. Low power factor values are a disadvantage as they mean the current and therefore the transmission losses are higher for a given power.

4.7 Running Torque

$$T = \frac{60{,}000P_S}{2\pi N}$$

$$P_S = \frac{2\pi NT}{60{,}000}$$

5.0 Minimising Transition Spikes in Star-Delta Starters

In any three phase supply the voltage between each phase and neutral is “out of step” with the inter-phase voltage. When this is represented graphically the phase angle is found to be 30°. In a Star-Delta starter this phase angle can lead to an unnecessarily high current spike when the starter changes from Star to Delta. Old wire colours are noted in brackets following the corresponding new wire colours.

By convention the phases are labelled brown (red), black (yellow) and grey (blue), with the brown (red) phase 120° ahead of the black (yellow), and the black (yellow) phase 120° ahead of the grey (blue). The voltage difference from brown (red) to black (yellow) is 30° ahead of the difference between brown (red) and neutral, and the difference from brown (red) to grey (blue) is 30° behind the difference between brown (red) and neutral.

When the motor runs with the windings Star connected, the driving voltages in the windings are in phase with the line voltages. During the gap between disconnecting from the Star configuration and reconnecting in the Delta configuration a derived voltage is created in the rotor windings because the motor is still spinning. The derived voltage is initially in phase with the line voltages, but as the motor slows down while disconnected, the derived voltage frequency will reduce, tending to shift the phase angle between the derived voltage and the phase voltage.

This means that when the Delta contactor pulls in there will be a brief current surge while the phase difference is eliminated. Depending upon the phase rotation this surge may be slight or it may be significant.

This leads to two significant details for commissioning and servicing plant with Star-Delta starters.

Firstly the starter should be wired so that the brown (red) phase connects through to grey (blue), the grey (blue) phase connects through to black (yellow) and the black (yellow) phase connects through to brown (red). In other words if the brown (red) phase from the line contactor is connected to terminal U1 then the grey (blue) phase from the Delta contactor should connect to U2. Likewise, if the grey (blue) phase from the line contactor feeds V1 then the black (yellow) phase from the Delta contactor should connect to V2, and so on. This will mean that the phase shift between the derived voltage at transition and the relevant phase voltage will reduce. If on the other hand the phases are wired brown (red) to black (yellow), black (yellow) to grey (blue) and grey (blue) to brown (red) then the effect is reversed and the transition spike will be larger than necessary.

Secondly, if the phases are wired correctly to minimise the transition spike, but the motor runs in the wrong direction, it is necessary to change the wires at the motor to correct the direction of rotation. It is frequently said that it is simply necessary to swap two of the phases in the panel, but obviously this would result in the previously described phenomenon of large transitions spikes. Therefore to avoid this it is instead necessary to disconnect four terminals in the motor terminal box and swap the wires.

The procedure for checking that the phase connections are correct is to trace each phase from the line contactor to the motor, and from the motor to the Delta contactor.

Line Contactor	Motor	Delta Contactor
Brown (Red)	U1 – U2	Grey (Blue)
Black (Yellow)	V1 – V2	Brown (Red)
Grey (Blue)	W1 – W2	Black (Yellow)

If this produces the wrong direction of rotation then exchange the wires on U1 and V1 and on U2 and V2. This will then give the following connections:

Line Contactor	Motor	Delta Contactor
Brown (Red)	V1 – V2	Grey (Blue)
Black (Yellow)	U1 – U2	Brown (Red)
Grey (Blue)	W1 – W2	Black (Yellow)

If the phase connections are not correct then the motor will start satisfactorily and will run in the correct direction, but the plant may occasionally suffer from nuisance trips of MCBs or blown fuses for no apparent reason.

6.0 Commissioning Motor Starters

Most motor starter systems will need some degree of commissioning to ensure they work properly.

6.1 Direct On Line

Apart from correctly setting the overload (to the FLC value on the motor rating plate) the only other commissioning required is to check that the direction of rotation is correct and that the running current is acceptable.

6.2 Star-Delta Starting

As well as the items described above it is essential that the Star-Delta changeover timer is set correctly.

The timer shall always be set so that the motor reaches full speed before the change to Delta. This can be determined from the sound of the motor and machine, and from the current draw. The motor current will fall away from the characteristic high starting current (typically 2 to 3 times the FLC) down to the current corresponding to full speed – usually less than the FLC when the motor reaches full speed. This is best viewed on an analogue ammeter as the values will change very quickly. The change to Delta should occur soon after the motor reaches full speed particularly for machines such as water pumps that do not start unloaded. Compressors have a variable start time but as large machines start unloaded running in Star for 2 or 3 seconds after reaching full speed will not cause a problem. In this case the changeover timer should be set to ensure the compressor reaches full speed before the change to Delta when the discharge pressure is high before the compressor starts. Contact the Technical Department if the compressor doesn't reach full speed within 8 seconds.

6.3 Closed Transition Starting

The Star-Delta timer should be set exactly as above.

6.4 Auto Transformer Starters

Again the motor should be allowed to reach full speed before the change over from the first step (Star and line contactors closed) to the second step (Star contactor opened). The time between opening the Star contactor and closing the bypass contactor is normally very short (fraction of a second) as it is mainly intended just to damp the electrical transition. The two line contactors are normally opened immediately the bypass contactor closes.

6.5 Electronic Soft Start

The starter should be set to a relatively high current threshold for starting compressors, 3.5 times the FLC is a good value for the first attempt. The compressor should normally reach full speed within 10 seconds and it should be noted that slowing down the acceleration can increase the starting current required as the oil separator pressure can build up before the compressor reaches full speed. The bypass contactor should close 2 to 4 seconds after full speed is reached.

6.6 Variable Speed Drives

Inverters are very good at limiting the starting current however it is better for compressors to limit the time required to reach the minimum allowable continuous speed to 10 seconds to minimise vibration, lubrication and (in screw compressors) oil logging.

The maximum and minimum allowable compressor speeds should be set in the inverter itself (not the PLC or other control system) before commissioning starts to protect the compressor from operator or control system error.

Lastly, the inverter may need to be set with bands of speed where the compressor is not allowed to run continuously due to excessive vibration. These speeds should be programmed in the inverter itself. If in doubt contact the Technical Department.

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