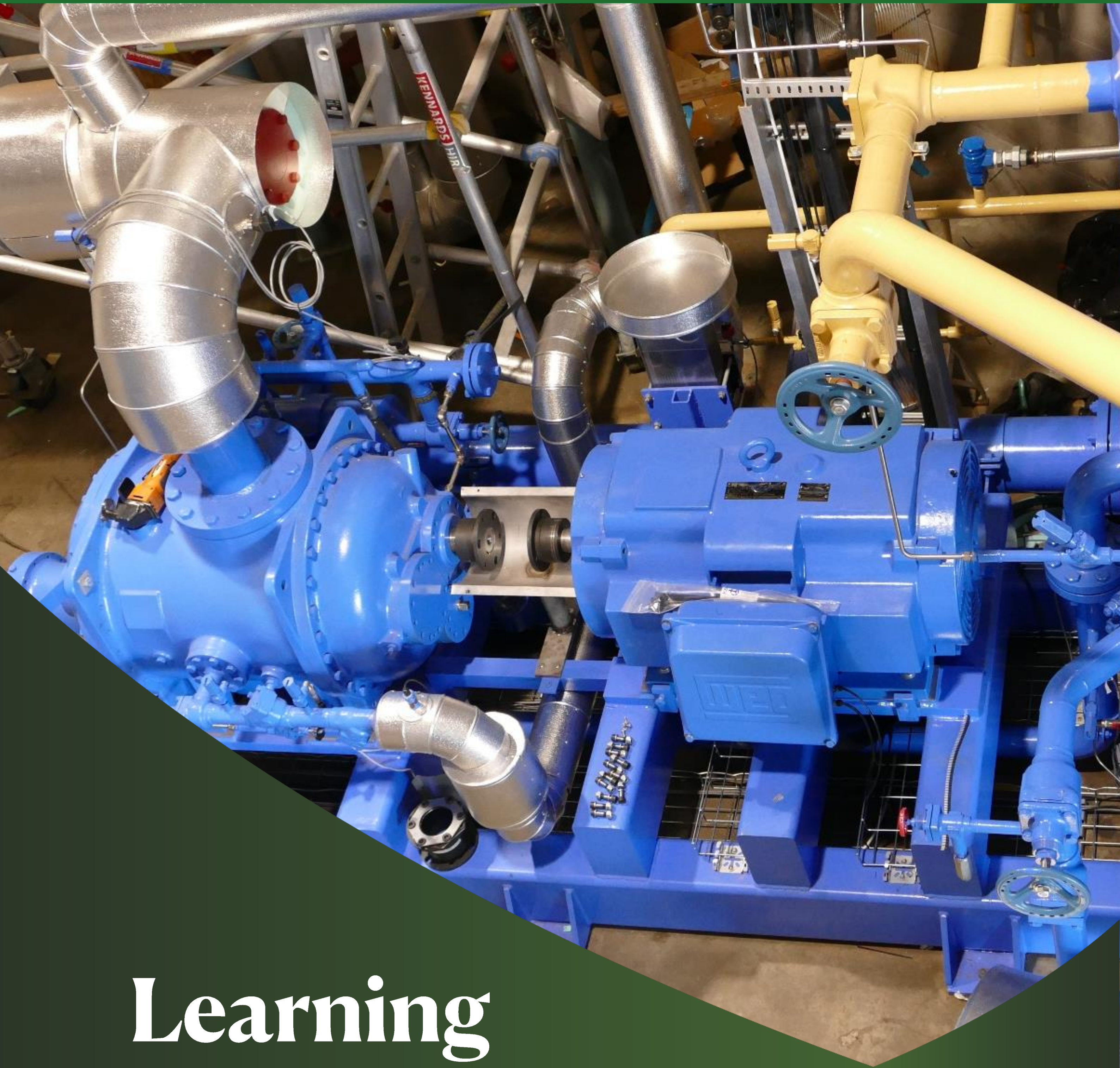


Learning resource

Demonstrate and apply knowledge AC electric motor control and installation

Level 4 | Credits 5

Te Pūkenga

Contents

Using this resource

The following information boxes may be found in this resource.

If there is an important note, or a key idea – they may be written into a box like this.

Definition

Word	Meaning of word

Formula

If there is an important formula, it may appear in a box like this.

$$I = \frac{V}{R}$$

Introduction

This unit standard covers the starting, speed control, installation and commissioning of alternating current (AC) electric motors. It will specifically address the following areas:

- motor starters;
- motor speed controllers;
- connect and test three-phase induction motor starters;
- connect and test motor speed controllers; and
- install and commission induction motors.

Starting methods

There are a variety of ways to start electric motors. In this resource, we will look at some methods of motor starting and why those starters are used.

Motor Starting Current (In-rush current)

Whenever an electric motor is started there is a large “in-rush” of current which can cause problems in the electrical supply system, especially with large motors.

Depending on the motor type, size and amount of load it is starting, the starting in-rush current can be anywhere between 5 to 10 times the full load current.

The large spike in current can cause the supply voltage to “dip”. This dip in supply voltage can be experienced by others on the network and, in some cases, cause problems such as electronic equipment (e.g. the switch mode power supplies found in computers) detecting the fall in voltage and shutting down to protect themselves.

The in-rush current can also introduce voltage transients into the supply system that cause problems, especially for electronic equipment.

Example

If an 11KW electric motor was started direct-on-line it has a full load current of 21A at 415V AC. Multiply this by 10 as above, means that at start-up this machine can potentially draw a current of 210A.

This sudden, large amount of current draw will cause supply issues. This problem has led to lines companies imposing rules around large motors and how they are connected and started.

One example, prior to 2011, Orion (a lines company in Christchurch) had a policy that any motor above 10KW would require a reduced voltage starter. This was because at that point they had a very highly reinforced mesh network. Post the event of February 2011, this limit was reduced to 4KW as the network was not as strong.

A reduced voltage starter will reduce the starting voltage which, will in turn reduce the starting current and therefore reduce the fall in supply voltage and transients.

Methods of Starting AC Motors

There are a variety of motor starters that are available for starting motors. These can start a motor more gently than letting a motor rip into it direct-on-line (DOL).

Some examples of motor starting methods are:

- Direct-On-Line
- Star-Delta starting
- Series inductance starting
- Auto-transformer starting
- Series resistance starting
- Solid state soft-starting
- Rotor resistance starting

Most of these motor starting techniques reduce the voltage at the motor stator terminals, which effectively reduces the starting current as well as the starting torque.

During motor starting, both the stator current and output torque are proportional to the square of the voltage. During star-delta starting, the voltage is reduced to 0.58 of its normal value and this results in the current and torque being reduced to 0.33 of the direct-on-line values.

$$I_{start} \quad \alpha \quad (\text{Voltage})^2$$

$$T_{start} \quad \alpha \quad (\text{Voltage})^2$$

An example of a solid-state motor control device is a Variable Frequency Drive (VFD) A.K.A. Variable Speed Drive (VSD). They are very versatile electronic motor speed controllers with the ability to manage the start-up of electric motors as well. They are now the most common motor start control devices used in industry.

Photo by Graeme Jeffrey

Direct-On-Line (DOL) starting

Direct-On-Line (DOL) starting is the simplest and most economical method of starting an electric motor. This is because it is simply connecting the motor to the supply without reducing the supply voltage or current.

A suitably rated contactor is used to connect the motor directly to the power supply. While this method is simple and produces a reasonable level of starting torque (full motor starting torque), and is often used for smaller motors, there are several disadvantages.

The starting current is high (between 5 to 10 times full load current) and there is also a mechanical shock to the motor due to the full torque being applied instantly.

Because the starting current is so high, depending on the size of the motor, this can result in voltage drops in the power system. This can affect the owner's supply and other consumers on the same network.

The instant full start up torque can eventually damage the drive system, particularly with material handling equipment such as conveyors.

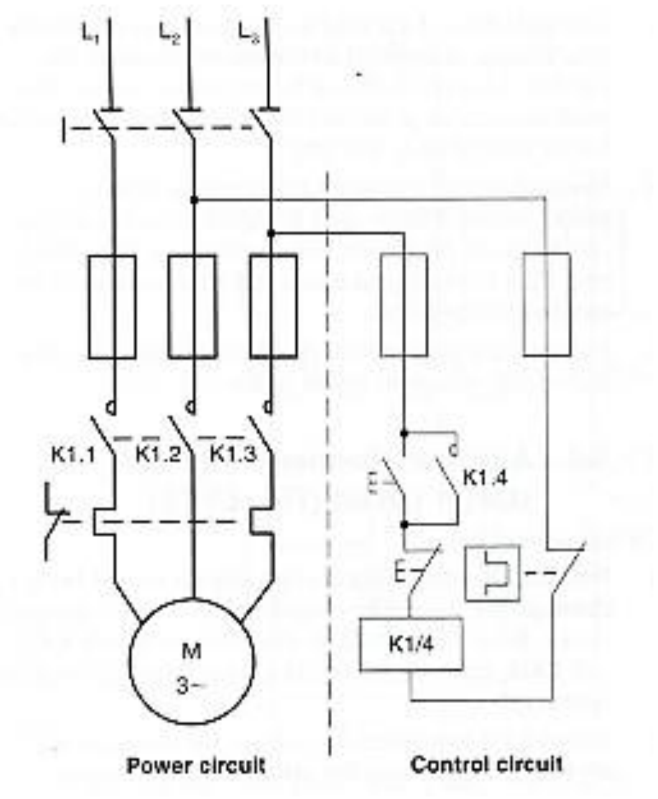
An example of a DOL motor control circuit is shown here.

Obviously, there are many variations possible with any control circuits.

The one shown here is supplied from two of the three phases and so has a circuit voltage of 400V.

In your work you may come across a variety of different ways of doing the same thing, that is a good thing and will make you more versatile.

The important thing is that you can look at any circuit diagram and be able to understand how the circuit works.



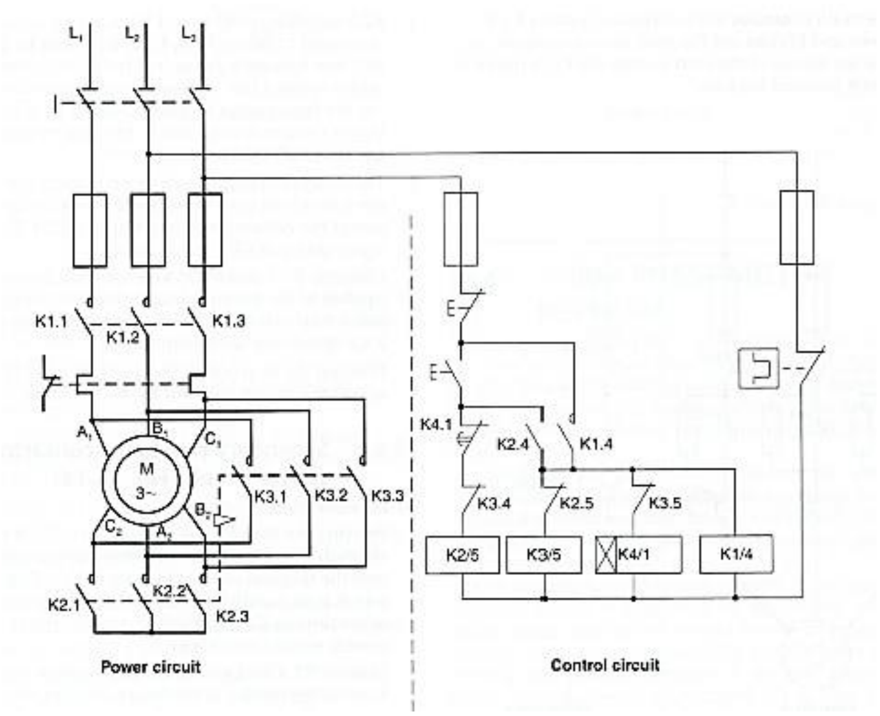
Circuit diagram of a DOL starter and motor

Star/Delta Starters

A Star/Delta starter is a two-position method of starting induction motors.

Firstly, the Star/Delta starter will connect the motor windings in a star formation to reduce the start voltage and to reduce some of the aggression of the starting motor. This produces a gentler acceleration of the motor from standstill and lower starting current.

When the windings are connected in Star, the voltage applied to each winding is reduced to 58% of the line voltage. The starting torque available is one third of the full starting torque. With a Star/Delta starter, there is no variation available to the torque produced at starting as it is fixed by the Star connection.



Circuit diagram of star-delta starter and motor

After the motor reaches a steady speed on the Star connection, the contactor is switched into the Delta position - this changeover is sometimes carried out manually (by hand) or automatically by a timing device.

When the starter is switched to the second position the windings are connected directly across the supply in Delta format to produce full torque for running. This method of starting requires the six ends of the motor windings to be brought out to a terminal block in the starter.

The nature of the resulting motor torque makes it suitable for light starting loads that require heavy running torques. An example would be a large boiler stoking fan that is easier to spin at start-up but requires a lot more motor drive torque as it speeds up and moves more air.

Advantages:

- simple and inexpensive

Disadvantages:

- low starting torque
- no possible adjustment in starting torque
- six motor winding end terminals required at the motor
- a short break in line supply to the motor when changing from Star to Delta

Applications:

- machine starting on no-load or light loads e.g. centrifugal pumps and fans.

It is important that the correct phase sequence is followed when connecting the conductors to the motor and starter. If done incorrectly, it can lead to very high current peaks during the Star/Delta switch-over. These peaks can damage the motor windings and stress the control gear unnecessarily.

The small pause in time between connection in Star and Delta, needs to be long enough to allow the opening contact arcs to safely extinguish before connecting in Delta, but still as fast as possible to not lose too much motor speed. If too fast, an electrical short can happen in the contactors caused through arcing.

Typical Star-Delta motor starter problems

1. Motor starts in Star but stops in Delta - check motor lead connections to the starter as it is most likely that they have been wrongly connected.
2. Motor will not start in Star - check motor connections, or the load may be too great for the torque developed in Star.
3. Contacts on Star contactor welded or badly burnt - this is a sure sign that the Star contactor is breaking a load far in excess of its rated capacity.
4. Motor starts in Star, but all contactors drop out when changing to Delta - check control circuit wiring, especially any external circuitry and all auxiliary contacts.

Auto Transformer Starting

This is another method of starting squirrel cage motors with reduced voltage and can be used where the Star/Delta method does not produce enough starting torque.

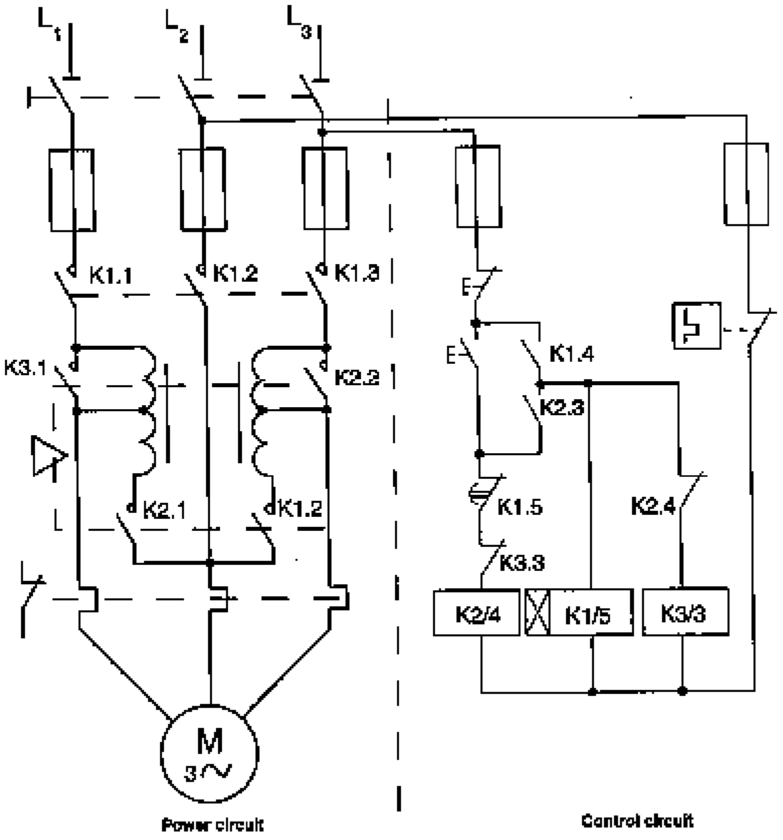
The motor will only need three terminals in its connector block for this starter. This method of starting is not suitable for starting a motor against very heavy loads.

These starters are suitable for most applications such as pumps, blowers, conveyors, compressors, fans and other machines where it is necessary to maintain maximum starting torque with a minimum of current drawn from the line.

The auto-transformer starter consists of a Star-connected auto-transformer with a six-pole switch arranged as three double-pole switches. A choice of tapping voltage is available for supplying the motor stator windings at start.

The common tappings are 40%, 60% and 75% of the supply voltage.

For these particular tappings, the line current and the starting torque are reduced to about 16%, 36% and 56% respectively of the direct-on-line starting values.



Autotransformer Control Circuit

Because of the tappings available, this method of starting is adaptable for different types of starting torque conditions.

The choice of a particular tapping depends on whether the motor is to be started on no-load or medium load.

Auto transformers can be arranged to give the Korndorfer system of switching. This is where a section of the transformer is left in the circuit during the transition period (from start to run) to maintain a motoring torque.

Most contactor-type auto-transformer starters are designed to give Korndorfer switching.

Advantages of the auto transformer starter

1. Good torque/current ratio.
2. Adjustable starting values are available.
3. Only 3 wires and three connections to the motor are required.
4. Starter size is relatively smaller.
5. Lower cost.

Disadvantages of the auto transformer starter

1. The autotransformer connection is not available with certain three-phase connections.
2. Higher (and possibly more damaging) short-circuit currents can result from a lower series impedance.
3. There is no isolation of the high and low voltage ends of the auto transformer winding. Any noise or other voltage anomaly coming in on one side is passed through to the other.
4. If the auto transformer fails, the full supply voltage can be delivered to the motor on start up.

Primary Resistance Starting

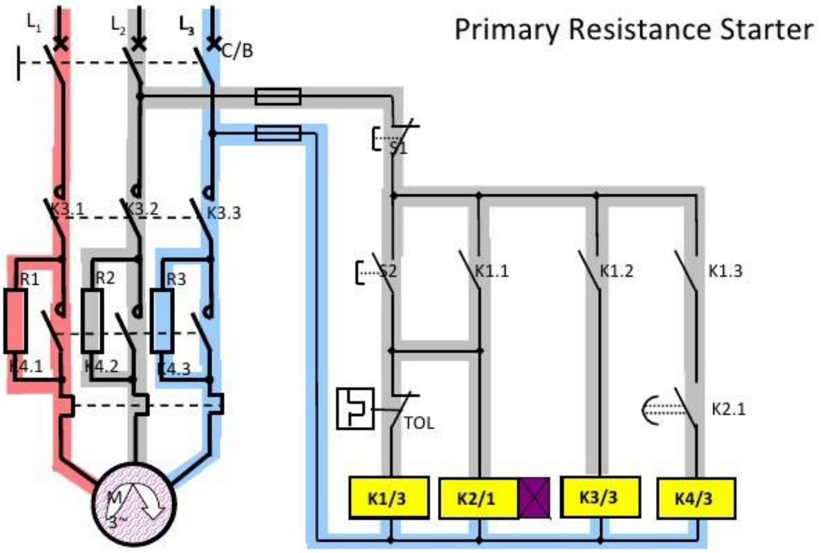
This method is suitable for starting squirrel cage motors under no-load or light-load conditions.

Primary resistance starting is a variable-stage starting method in which variable resistances are connected in series with the motor windings during the main period of acceleration, after which the resistors are short circuited.

Depending on the types of resistors used, the starting torques available are in the region of 25% and 65% of the direct-on-line value.

The torque available at start-up can be adjusted by varying the value of resistance.

As with other forms of two-stage starting, a time delay device is incorporated in the circuit to prevent premature changeover.



Advantages	smooth starting with possible adjustments in the starting values
Disadvantages	costly, and requires large resistors that cause power loss during starting
	heat is generated in the resistances

Applications

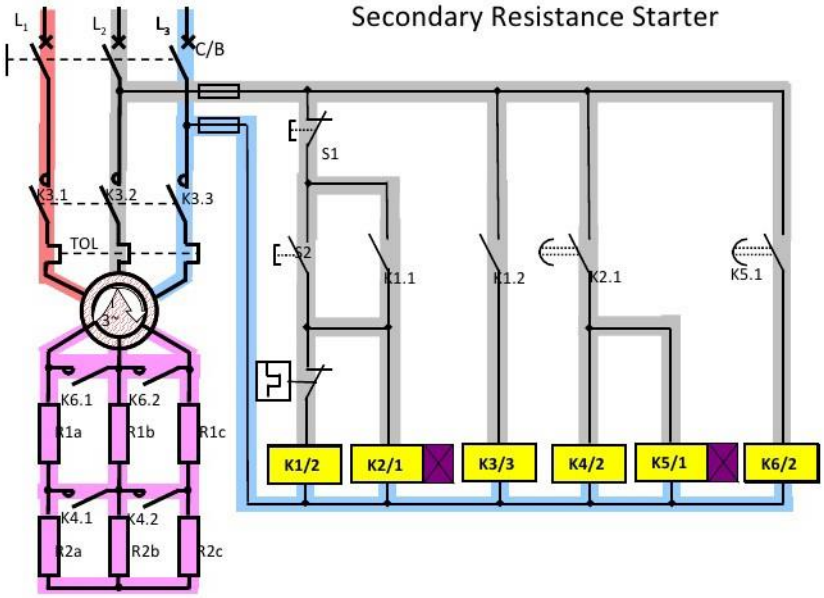
Primary resistance starting is particularly suitable for fans, blowers, centrifugal pumps, line shafting and general-purpose applications where smooth acceleration is desirable, together with a constantly increasing torque as the motor accelerates.

This type of starter provides a simple solution where a smooth start is required to prevent mechanical damage to couplings etc. from a motor with too much starting torque.

This resistance is sometimes left in circuit permanently on small motors with a short duration load cycle.

Secondary resistance starting

Secondary resistance starters have external resistors connected to the rotor circuit of wound rotor induction machines via the slip-rings for starting and for speed control.



At starting, with the rotor stationary, the frequency of the rotor supply will equal the line frequency which causes an increase in the inductive reactance of the rotor circuit.

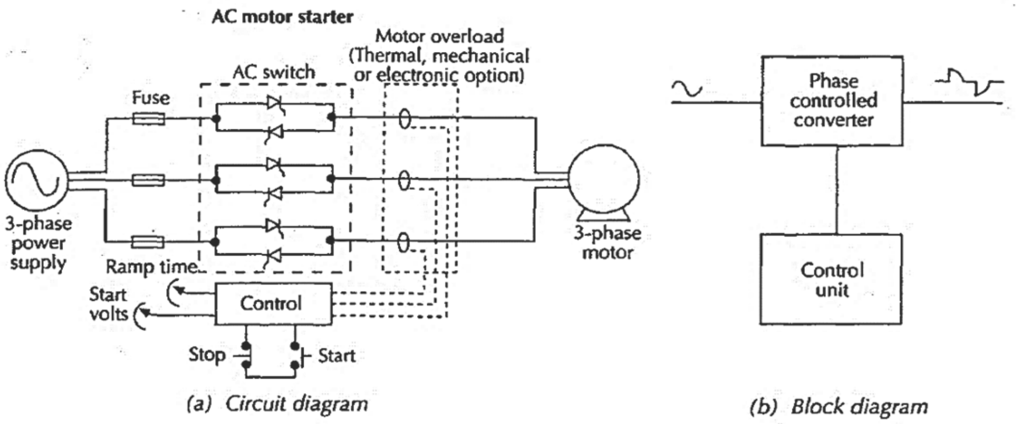
The introduction of this external resistance into the AC wound rotor circuit means that, the rotor and impedance values can now be adjusted to produce the maximum starting torque, and at the same time reduce the starting currents.

The speed and torque of an induction motor depends largely on the relative proportion of the resistance and reactance.

Solid State (Soft) Starters

Solid-state soft starters use electronic AC switches to adjust the motor starting torque. The AC switches used are either triacs, reverse parallel connected SCR/diodes or SCR/SCR circuits.

The start voltage to the motor is controlled by chopping part of the supply wave off using the SCRs or triacs. The amount chopped off can be controlled and the soft starter is used to “softly” start the motor and then ramp its speed and torque up until full speed.



Simplified diagram of a solid-state soft starter

The following are some advantages of an electronic starter:

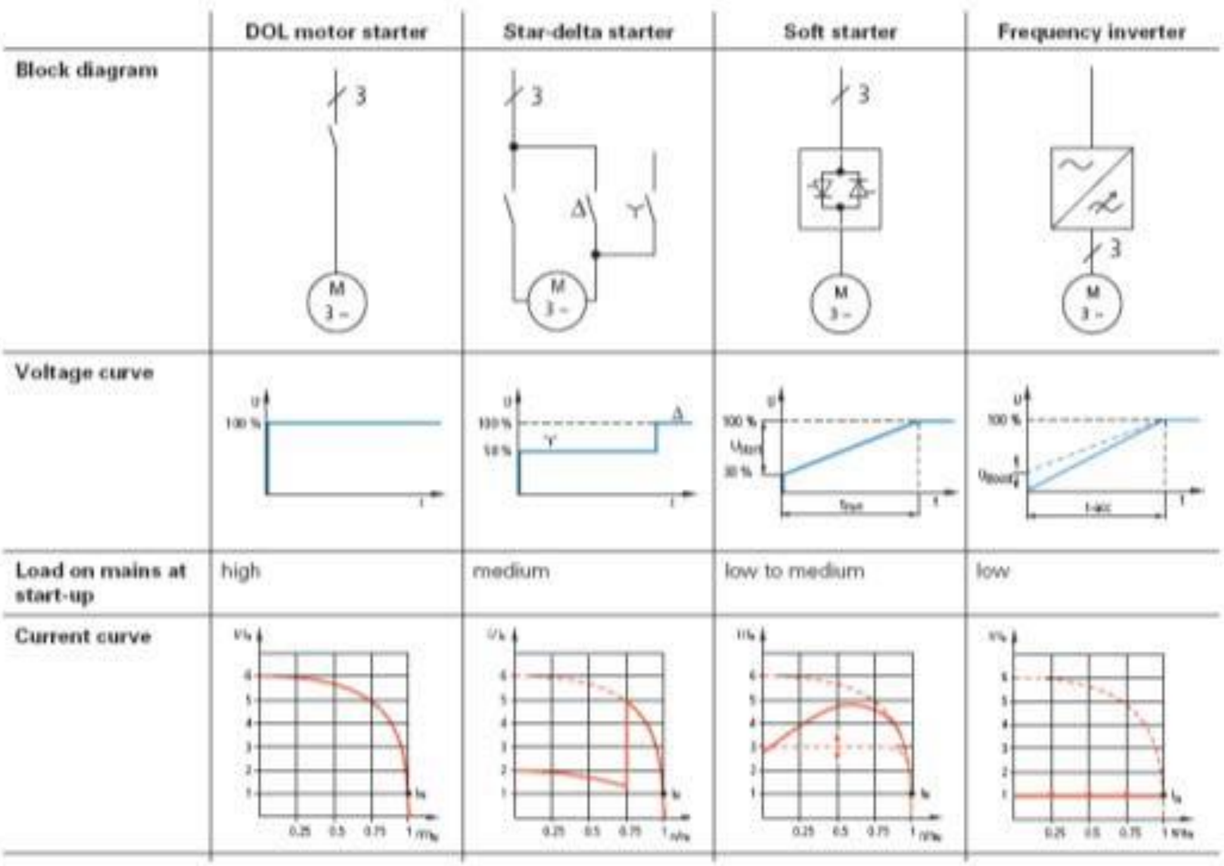
1. They are very efficient, much more efficient than a primary-resistance starter for example.
2. Starting is softer and so there is reduced shock loading during starting.
3. They have start ramp-up and stop ramp-down time control that may be programmed to suit the application.
4. They have a range of protection facilities built in such as single-phasing, phase failure and overload protection. Thyristors are protected by special fuses and snubbers.

Note: Low voltage control wires should be wired in screened cable and, power factor capacitors should not be connected to the motor side of the starter because of the non-sinusoidal voltages being applied to the motor.

Comparison of Motor Starter Characteristics

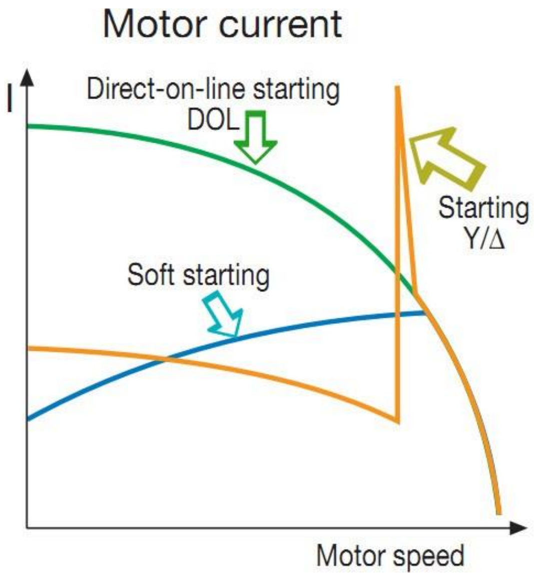
Starting method	Starting current %IFL	Starting torque %TFL	Full Load Current	Full Load Torque	Relative Cost	Example loads	General comments
Direct online	700%	150%	Light inertia loads (14% I_{Start})	Low	Low	Centrifugal pumps, lathes	Starling torque greater than full-load torque
Primary resistance	300%	40%	Almost no load (33% I_{Start})	Low	Average	Fans, small bores	Poor starting torque ($T \infty V^2$)
Star-Delta	200%	33%	Light loads (50% I_{Start})	Medium	Average	Motor-generator units	Starting torque % full load torque
Auto transformer	300%	80%	Substantial proportion of full load (33% I_{Start})	High	High	Hydraulic pumps, conveyors	Starting torque slightly less than full-load torque
Secondary resistance	100%	100%	High inertia loads (100% I_{Start})	High	Average	Shock loads such as presses, shears	Rotor resistance adjusted to give starting T_s = FLT
Electronic controlled starters	Controll-able	Controll-able	Controll-able	Controll-able	High	Machine planers, printing presses, high speed tools	Starter programmed to suit application

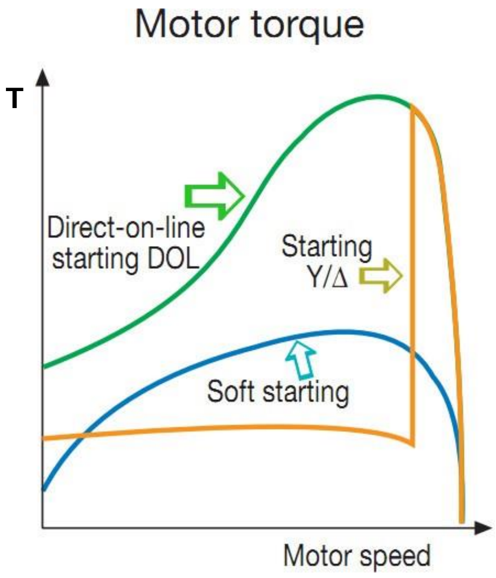
Common motor starting methods comparison



	DOL motor starter	Star-delta starter	Soft starter	Frequency inverter
Block diagram				
Voltage curve				
Load on mains at start-up	high	medium	low to medium	low
Current curve				

Comparison between soft starter, Star Delta and direct online starting





Motor Speed Controllers

Motor speed controllers are different to motor starters, although generally motor speed controllers do both jobs.

Photo by Graeme Jeffrey

The key difference between a VFD/VSD and a soft starter

With both a VFD/VSD and a soft starter, the acceleration and deceleration times for a motor and its load can be programmed.

Where a VFD and soft starter differ, is that once at speed, the soft starter switches into bypass mode and no longer controls the motor speed.

It stays this way until the operator selects stop. The soft starter will now take back control of the motor speed and will ramp down the motor and load to a stop in accordance with its programmed deceleration settings.

The key difference is that a VFD continues to control the speed of the motor and load while the motor is running.

Although generally VFDs have become the preferred solution, some applications still lend themselves more to the use of a soft starter which can be a cheaper solution if run speed control is not required.

Operational Requirements

The operational requirements of motor speed controllers are that they need to be step-less (continuous control), have minimum losses, cause minimum harmonics and radio-frequency interference.

Ideally, motors suitable for speed control are the ones designed for varying speeds and have adequate cooling systems, especially for low speed running.

Motors used with speed controllers can have problems if they are not designed to be speed controlled. If they are running at low speeds, they may overheat quickly. The motor may need to be de-rated so that it does not heat up as much at slow speeds, or, extra cooling needs to be provided in addition to the shaft fan.

Motor Speed

For a squirrel cage induction motor to produce torque, the rotor speed needs to “slip” behind the (synchronous) speed of the motors rotating magnetic field. You can calculate the synchronous speed of the rotating field (synchronous speed of the motor) using the following formula:

$f(x)$

Formula

$$\mathrm{N} = \frac{60\ x\ F}{P} = \mathrm{RPM}$$

Where P = Pair of poles

F = frequency

There are two possible variables as seen in the speed equation. The frequency and number of poles. If you vary either of these, you can vary the speed of the motor.

There are some different ways of going about speed control, depending on the size, type and application of the motor being controlled.

Pole Changing

Normally, a motor is selected for its speed by its number of poles.

Probably the most common motor has four poles and a full load speed of approximately 1460 rpm. This is a synchronous speed of 1500rpm with a rotor speed slip of 40rpm.

Increasing the number of poles reduces the running speed in large steps. This gives us good torque speed control, but it is not continuous (is in large steps), and the change between speeds is not smooth.

In fact, switching from two-pole to four-pole causes a speed change of nearly 1400 rpm, as a 2-pole motor nominally rotates around 2850 rpm.

Although there are special designs of induction motors whose speed can be changed in one or more steps by changing the number of poles, it is impractical to continuously vary the number of poles to try and achieve smooth speed control.

Characteristic	Pole Changing
Efficiency	High
Smoothness	Poor
Torque	Good
Continuous Control	No
Relative cost	High

Also, a pole change motor is more complex and has a high relative cost compared to a standard motor, because of the cost of the extra sets of windings.

Increasing the number of poles also increases the physical size of the machine and further increases costs. However, this system has a high efficiency.

Variable Frequency Electronic Speed Control

Another way of controlling some motors is the Variable Frequency Drive (VFD) A.K.A. Variable Speed Drive (VSD)

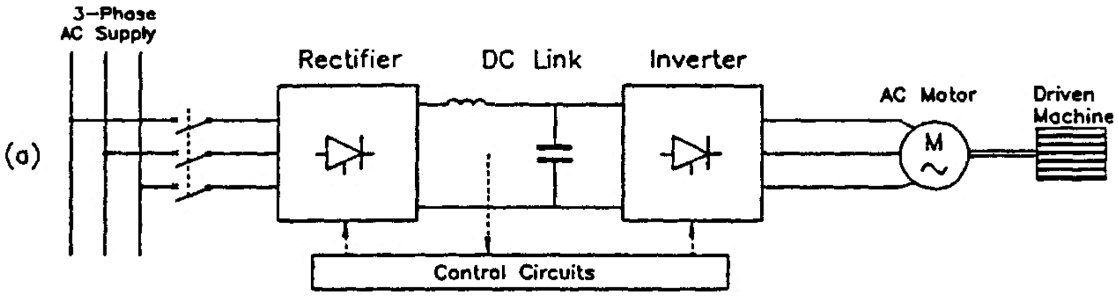
This type of speed controller is able to vary the frequency (and voltage) applied to a motor by electronic means, to produce a step-less speed control.

As the speed of a motor is proportional to the supply frequency, its speed can be decreased by reducing the supply frequency, or, increased by increasing the supply frequency.

In order to keep the torque constant, the voltage will also have to be changed to keep the voltage/frequency ratio constant. Conversely, if the motor torque needs to be changed, it can be controlled by controlling this ratio.

In a Variable Frequency Drive the incoming AC is rectified, filtered and smoothed to become DC. The DC is then inverted back to produce switched AC of varying frequency and voltage using thyristors or IGBT’s.

This variable frequency can be fed to the motor to produce a variable speed.



Main Components of a Variable Frequency Drive

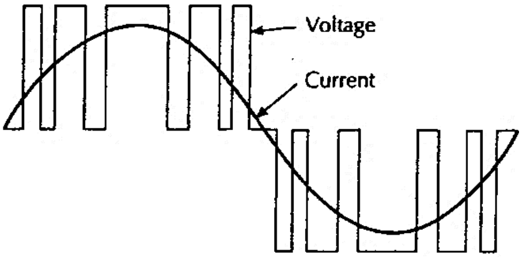
Note: A VFD/VSD takes the normal 50Hz AC supply voltage and produces its own AC output. The output can be produced at any frequency required to cause a motor to run at any speed (within reasonable parameters). The output can be varied at any time to ramp the motor speed up or down.

How a VFD varies frequency and voltage

A VFD converter uses pulse-width modulation (PWM) to control both the frequency and the effective voltage of its output.

Pulse-width modulation supplies an alternating voltage, which is made up from a series of rectangular pulses.

The Figure below shows that the voltage supply is switched on and off a number of times in each cycle. At the start of the cycle, voltage is switched on for a brief moment and then off. Switching then occurs for a slightly longer time, and so on. This averages out to produce the equivalent of a sinusoidal output.



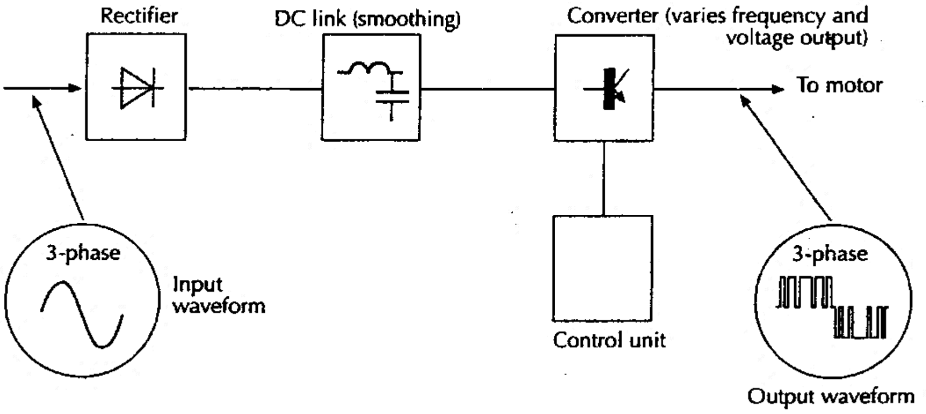
Pulse-width modulation

The output voltage is controlled so that the ratio between voltage and frequency remains constant to avoid over-fluxing the motor.

If the motor supply frequency is varied from 0 to 50 Hz in a step-less manner, the speed of the motor will vary in an extremely smooth step-less manner as well. That is, the speed of a four-pole machine can be continuously controlled from 0 to nearly 1500 rpm.

The AC motor is able to provide its rated torque over the speed range up to 50 Hz without a significant increase in losses.

It is even possible to increase the speed of an induction motor to above its normal base speed by raising the supplied frequency above 50 Hz up to 100 Hz and sometimes more.



Block diagram of a Variable-frequency drive


Photo by Graeme Jeffrey

Care must be taken when increasing the speed of a motor above its rated speed, the torque must be reduced so that the power supplied by the motor does not exceed its rated value.

While more speed may be desirable, it does come at a cost to torque. There is a point where a motor may be going fast but does not produce enough torque to be useful.

The motor bearings need to be able to cope with higher speeds, and the higher supply frequency can have some side effects too.

The limitations are small when compared to the advantages offered by electronic frequency-speed control.

The efficiency of electronic control is good, but there are losses associated with switching and controlling the supply. VFDs have more losses compared to pole changing which has a higher efficiency because there is no manipulation of the supply.

The initial cost of electronic speed control is relatively high, but they have become the industry norm and prices are reducing.

Characteristic	**Electronic speed control**
Efficiency	Good
Smoothness	Excellent
Torque	Controllable
Continuous Control	Yes
Relative cost	High

Using Secondary Resistance as Speed Control

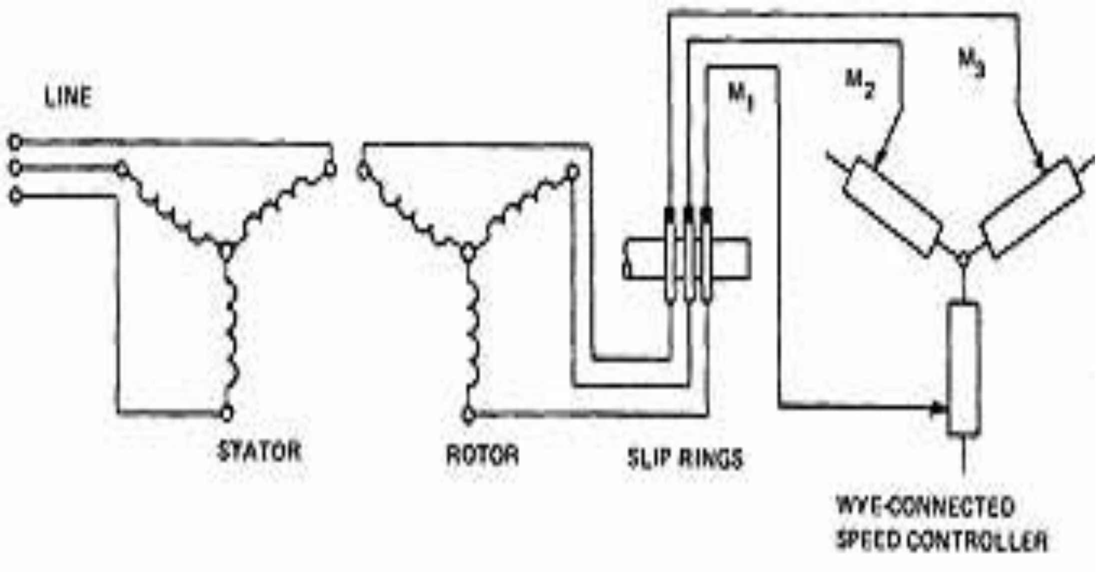
This type of speed controller is able to introduce resistance into the rotor to firstly, control the starting of the motor and then also to change the speed of the motor once running.

Increasing the resistance in the rotor will slow the motor down. Full speed is achieved once all of the resistance is removed.

This method can provide high torque and continuous smooth control by adjusting the resistance.

Its cost is average when compared to the relatively high cost of both pole changing and electronic speed control, but its efficiency is relatively poor.

Characteristic	Secondary Resistance
Efficiency	Poor
Smoothness	Good
Torque	High
Continuous Control	Yes
Relative cost	Average



Common Motor Faults

There are many causes of excessive current draw in motors, the following list mentions a few of the more common causes.

- locked rotor
- under or over voltage
- too frequent starting
- single phasing
- high ambient temperature
- impaired ventilation
- excessive run up time
- sustained overload
- unsuitable duty cycle

Over-current

If the motor draws excessive current, the windings of the motor will start to get hot quickly. If this is not detected and stopped the winding's insulation can burn off and break down. Overload can be effectively detected by using a thermal overload incorporating a bi-metallic strip.

The excessive current drawn by the motor will also flow in the coil around the bimetallic strip of the thermal overload.

This will cause the strip to start to bend. If this excess current continues to flow the bimetallic strip would bend sufficiently to open a contact and break the feed circuit to the contactor coil. The motor would then stop.

There are electronic versions of thermal overloads that monitor for overcurrent as well. They look similar to thermal overloads and do a similar job.

For more complex scenarios a current sensing transformer can be used, it feeds back to a controller which monitors the current on each phase. When this exceeds a pre-set value on any phase, the controller instructs the contactor to open and thereby stops the motor.

Thermistor Protection

Temperature sensing devices embedded in the motor winding are a great way of detecting temperature rise in motor windings for any reason. Thermistor is a brand name for some of these devices.

The thermistor material exhibits a sudden increase or decrease in resistance at a definite temperature. This change in resistance is used to actuate a tripping circuit to stop the motor when the cut-off temperature is reached.

Thermistors are inserted in the end windings when the motor is being wound, as this is the most effective position.

No-voltage or under voltage protection

No voltage protection devices release due to low voltage or power failure. The device will then require manual resetting. This prevents motors restarting when the power supply returns to normal.

There are two reasons for this. Under voltage causes a motor to slow down and this may cause the motor to overheat. If the voltage drops, we want to stop the motor.

And also, importantly, the no voltage release will prevent a motor automatically restarting after a power failure. This is to prevent injury from the surprise unsafe automatic restarting of a motor after a power outage.

Phase reversal

A phase reversal relay detects if the phase sequence to a three-phase motor changes and if it does, it will prevent the motor from starting.

This protects against the motor running backwards (due to the phase sequence changing for some reason) which could result in damage to the auxiliary equipment (i.e. gears, chain-drives, etc.), catastrophic damage to the machine and/or danger to people.

Photo by Graeme Jeffrey

Phase failure

This is when, during normal operation of a three-phase motor, a phase is lost. In this case the phase failure relay will trip and ‘tell’ the controlling platform or device (e.g. PLC) to shut down the motor.

Mechanical stress

This can manifest itself as heating of windings, shaft breakage, bearing failure, fan failure, shaft misalignment, vibration etc.

Many motors now come with thermistors embedded into the stator windings, and these along with monitoring bearing temperatures, are commonly used on medium to large motors to indicate mechanical stress.

If the attached protective devices pick up symptoms of a fault, then they can be set to intervene. This will result in the motor being stopped.

Mechanical stress can also be caused on start-up, where the motor suddenly and rapidly tries to come up to full speed against a heavy load, or when the load is brought to a stop too quickly.

There are various electronic sensor systems and motor condition monitoring programs available to measure vibrations, noise, heat and even smoke - the tell-tale signs that a machine has mechanical stress.

A history of current draw, vibration, noise, temperature and other machine vitals can be recorded and monitored for indications of trouble and changes over time.

This can help with planning preventative maintenance programmes and assist with decisions about how urgent an issue is.

Photo by Graeme Jeffrey

Te Pūkenga

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