Learning resource

Demonstrate and apply knowledge AC electric motor control and installation (level 4, credits 5)

Trainee Name: ____

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

$f(x)$

Formula

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

$I = \sqrt{I} \div R$

Introduction

This unit standard covers the starting, speed control, and 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

An induction motor has a full load running current which is stated on the nameplate, but this is not the current that would be drawn from the supply on starting. Before we look at why that is, let's review some motor basics.

An AC electric motor contains a stator with windings, and a rotor which has no windings but contains laminations with slots (sometimes skewed for smoother starting) on a squirrel cage frame (hence the other common industry name – squirrel cage rotor induction motor).

The other type of motor in common use is a wound rotor induction motor. This type of motor has a series of windings formed onto the rotor – hence its name wound rotor. This type of machine is more common with generators, as the addition of some DC to the rotor via slip rings and brushes allows a stronger electromagnetic force to be built up in the rotor and hence higher voltage can be obtained for its size from the stator. Remember when generating, a prime mover (water, steam, etc.) is used to drive the generator which generates power from the stator. In a motor the power is in the stator and the rotor gets out of the way by rotating and driving a load.

By way of a reminder the term synchronous speed refers to when the incoming machine is synchronised to the power grid and is then rotating at the same speed or frequency as the power grid.

The table below shows the difference between the relative speeds of synchronous machines or motors and some typical normal motors at 50 Hz.

Number of Poles	**Motor/Generator**	
	(at 50Hz)	(in rpm)
	Synchronous speeds	Typical Motor speeds
2	3000	2850
4	1500	1450
6	1000	960
8	750	730

You will notice that the synchronous speeds are higher than the normal motor speeds. This is because of slip. Most AC motors rely on this slip to produce torque. This difference in speed is because the electromagnetic field in the stator of a motor rotates at a faster speed than in the rotor. The synchronous motor is the exception. It will run at synchronous speed.

Motor Starting Current (In-rush current)

Whenever an electric motor is started, there is a large in-rush current as the stator magnetises up or fluxes up. The level of this in-rush current can vary depending on whether the motor is starting under no load, light load or full load. Consequently, the magnitude of the in-rush current can likewise vary but typically most texts take the size of the in-rush current as being somewhere between 5 to 10 times the full load current

This large in-rush current causes a dip in the supply voltage that will be experienced not only by the motor operator's supply but other on the network. In some cases, electronic equipment on the network will detect the fall in voltage and shutdown to protect themselves. The in-rush current can also introduce voltage transients into the supply system that cause problems, especially for electronic equipment.

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.

Example

If for example, a 11KW electric motor were to start directly onto the network, this would have an effect on the electricity network.

The full load current of a motor this size is 21A at 415V AC. Multiply this by 10 as above, means that upon start-up this machine will potentially draw a current of 210A. As you will be aware from previous material there is a relationship between voltage and current (Ohms law V = I.R and the power law P = V.I.Cos φ). So, if the current increases, and then resistance is held the same (as the winding resistance in the motor can't change) then the applied voltage must fall in order for the power to remain the same.

The result of this is that those consumers or other users nearby to this 11KW motor, when it starts up are also going to see a dip in the supply voltage available to their devices, and in many cases these electronic devices (e.g. the switch mode power supplies found in computers and most modern electronic devices) will detect a fall in voltage and shutdown to protect themselves.

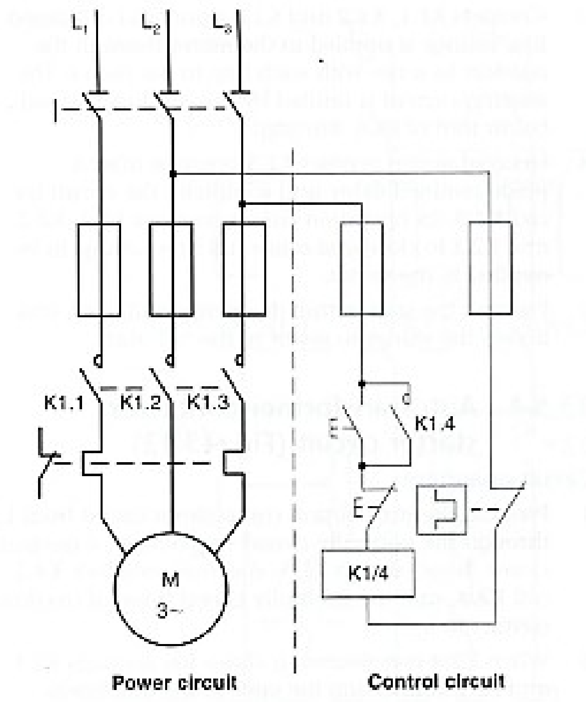
This has led to lines companies imposing several rules and criteria around what can and cannot be connected to their network. For example, prior to 2011, Orion (a lines company in Christchurch) had a policy that anything above 10KW would require a reduced voltage starter. This was because at that point 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.

Methods of Starting AC Motors

Direct on Line (DOL) starting

Direct-On-Line (DOL) starting is the simplest and most economical method of starting an AC squirrel cage induction motor. A suitably rated contactor is used to connect the stator windings of the motor directly to the three-phase power supply. While this method is simple and produces a reasonable level of starting torque, there are several disadvantages:

- The starting current is very high - between 5 to 10 times the full load current. Depending on the size of the motor, this can result in voltage drops in the power system. This will affect the owner's supply and others on the same network.
- The full torque is applied instantly at starting and the mechanical shock can eventually damage the drive system, particularly with materials handling equipment such as conveyors.
- In spite of high starting current, for some applications the starting torque may be relatively low - only 1.0 to 2.5 times full load torque.



Circuit diagram of star-delta starter and motor

To overcome these problems, other methods of starting are often used. Some common examples are as follows:

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

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

From the equivalent circuits and formulae for AC induction motors covered earlier, the following conclusions can be drawn about reduced voltage starting:

Both the stator current and output torque during starting are proportional to the square of the voltage. During star-delta starting, the voltage is reduced to 0.58 of its rated value. The current and torque are reduced to 0.33 of prospective value.

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

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

Star/Delta Starters

There are many methods by which a motor can be started using a reduced voltage. The star/delta method is a two-position method of starting induction motors. Firstly, the windings are connected in star formation to accelerate the motor from standstill. The second position connects the windings in delta (direct across the supply) for running. This method of starting requires the six ends of the motor windings to be brought out to a terminal block.

When the windings are connected in star, the voltage applied to each winding is reduced to 58% of the line voltage. The starting current is correspondingly reduced to 58% of the normal phase current at start (i.e. one third of line current or typically 2 to 2.5xI_e). The starting torque available is one third of the full voltage (direct switching) torque.

After the motor has reached a certain steady speed on star connection, the contactor is switched into the delta position - this changeover being carried by hand or automatically by a timing device. The nature of the start is suitable for drives with light loadings, but require heavy running torques. There is no variation available to the torque produced at starting as it is fixed by the star connection.

Advantages:

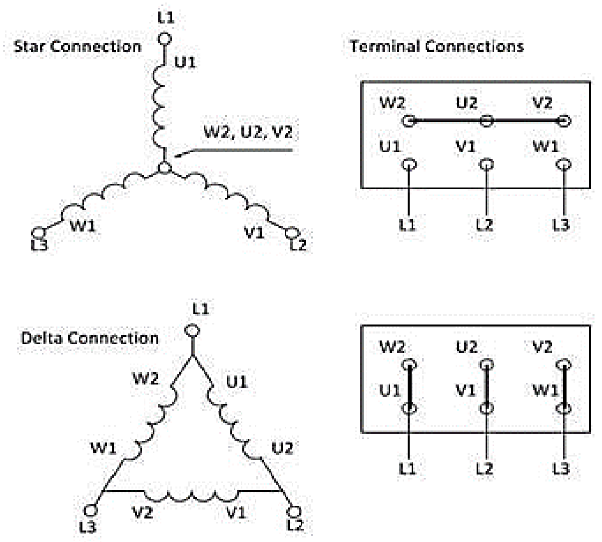
- simple and inexpensive

Disadvantages:

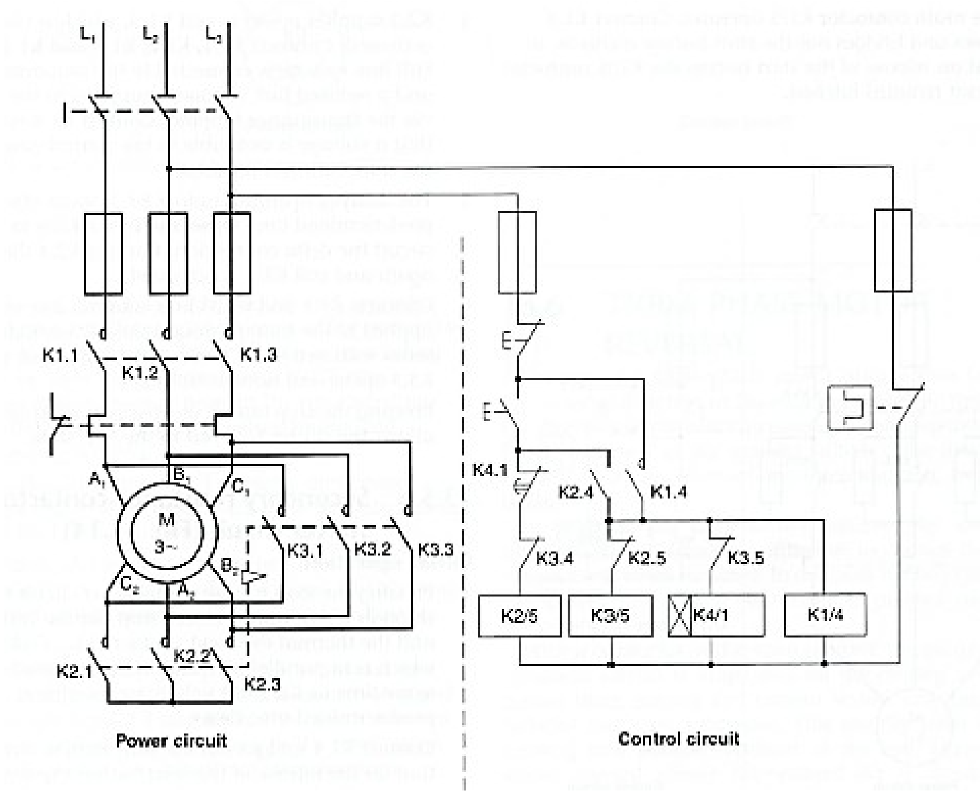
- low starting torque
- no adjustment in starting possible
- six terminals required at the motor
- break in line supply when changing from star to delta

Applications:

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



Termination of the six winding ends



Circuit diagram of star-delta starter and motor

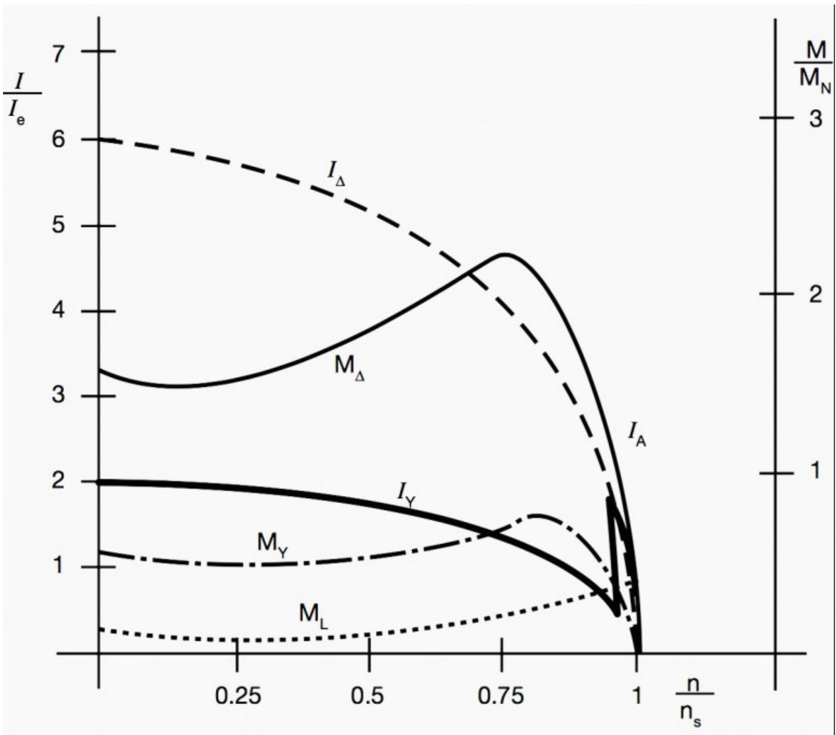
Typical Star-Delta motor starter problems

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 load can be too great for developed torque in Star.
3. Contacts on Star contactor weld 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 contactor drop out when changing to Delta - check control circuit wiring, especially any external circuitry and all auxiliary contacts.

In summary

Star-Delta is a starting method that reduces the starting current and starting torque. The components normally consist 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 normal running 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 starting and the starting torque is reduced to about 25% of the torque available as a DOL start. This starting method only works when the application is lightly 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, the load torque is low at the beginning of the start and increases with the square of the speed.

A typical torque curve for a normal Star-Delta starter is shown below.



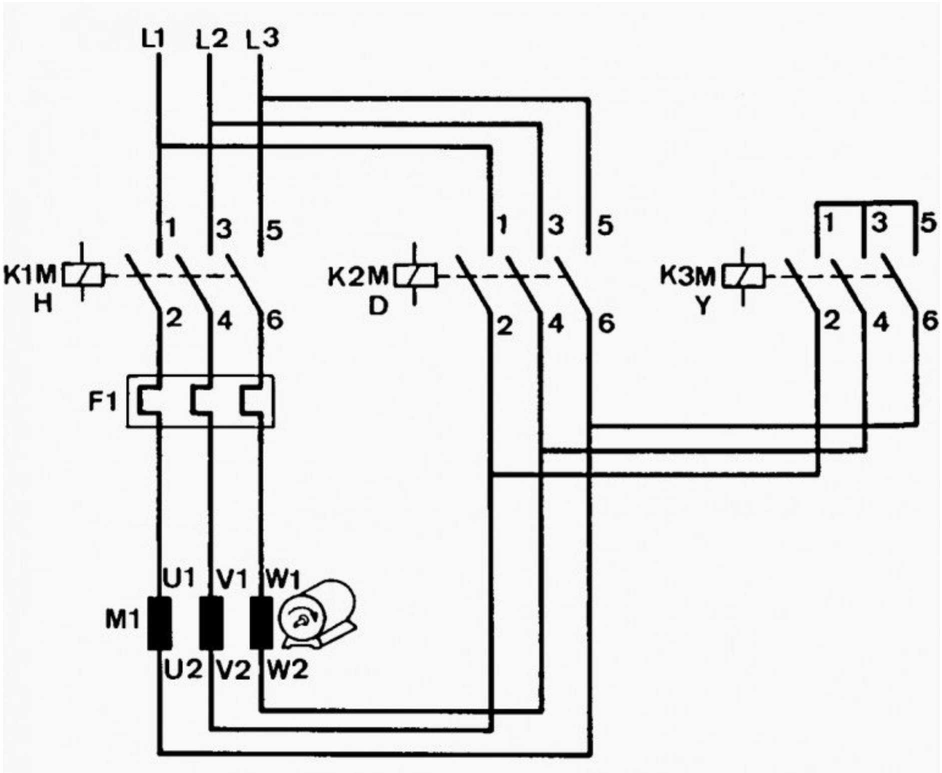
Where:

- **I** – Motor current
- **I_e** – Rated operating current of motor
- **M_Δ** – Torque for delta connection
- **M_E** – Rated operating torque of motor
- **n** – Speed
- **n_s** – Synchronous speed
- **M_L** – Load torque
- **I_Y** – Current in star connection
- **I_Δ** – Current in delta connection
- **I_A** – Current curve for Star-Delta start

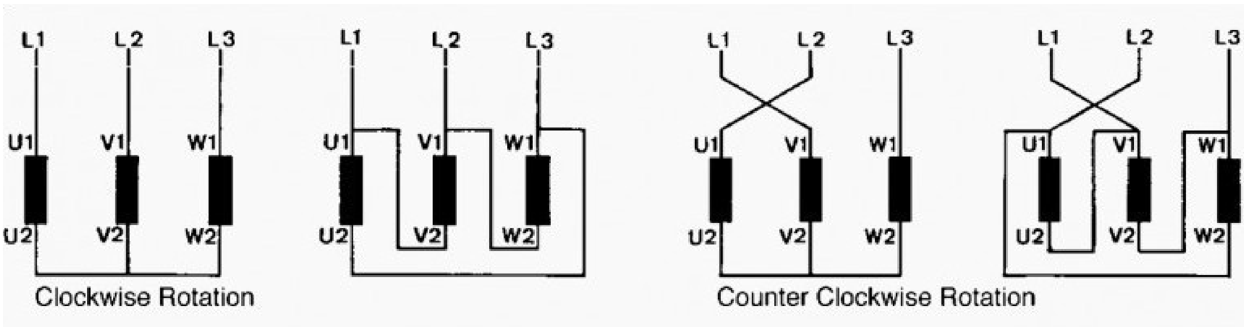
When reaching approximately 80-85% of the motor rated speed, the load torque is equal to the motor torque and the acceleration ceases. To reach the rated speed, a switch over to delta position is necessary, and this will very often result in high transmission and current spike or peak. In some cases, the current peak can reach a value that is even bigger than for a DOL start. Applications with a load torque higher than 50% of the motor rated torque will not be able to start using the Star-Delta starter.

When changing from star to delta, attention must be paid to the correct phase sequence, i.e. the correct connection of the conductors to motor and starter. Incorrect phase sequence can lead to very high current peaks during the cold switch-over pause, due to the easy torque reduction following re-start. These peaks can damage the motor windings and stress the control gear unnecessarily.

Sufficient time has to be maintained between the star contactor's de-energisation and the energisation of the delta contactor, in order to safely extinguish the star contactor's disconnecting arc before the delta contactor is energised. During a switch-over which is too fast, a short circuit may develop via the disconnecting arc. The switch over time period, however, should be just long enough for an arc disconnection, so that the speed decreases as little as possible. Special timing relays for a Star-Delta switch over fulfil these requirements.

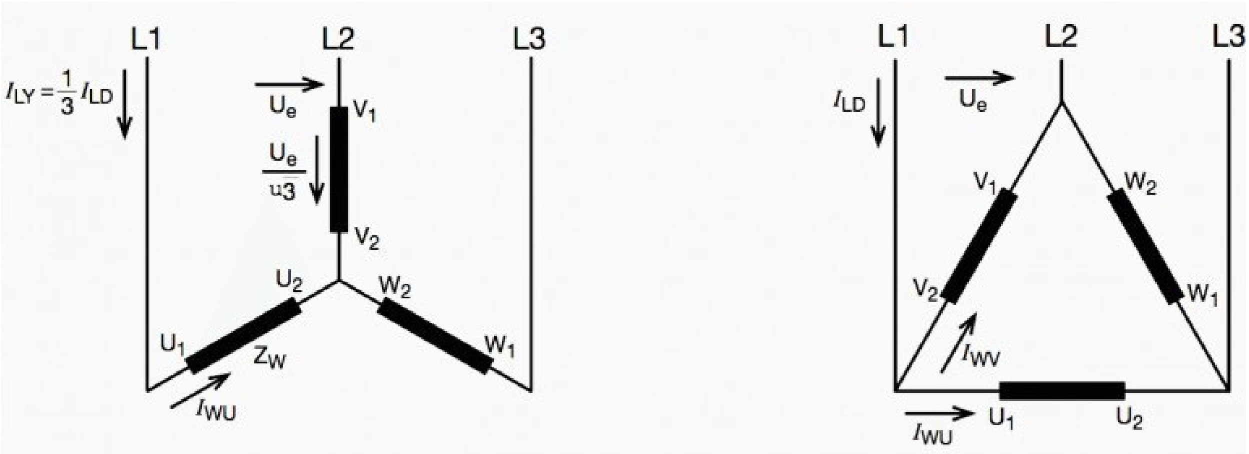


Switch over from Star to Delta by means of Contactor



Correct Motor Connection

Star and Delta connections



Star and Delta Connections – Left and Right respectively

Current ratios for star and delta connections:

- I_{LY} – Supply current for star connection
- I_{LD} – Supply current for delta connection
- I_W – Winding current
- U_e – Mains voltage between lines
- Z_W – Winding impedance

$$I_{LY} = I_{WU} = \frac{U_e}{\sqrt{3}\, Z_W}$$

$$\overrightarrow{I_{L1D}} = \overrightarrow{I_{WU}} + \overrightarrow{I_{WV}}$$

$$I_{LD} = I_W \sqrt{3} = \frac{U_e}{Z_W}\sqrt{3} = 3\, I_{LY}$$

$$I_{LY} = \frac{1}{3}\, I_{LD}$$

Motor Protection of Star-Delta starters

For Motor Protection and Contactor Sizing, the overload relay is situated in the motor line.

Therefore, the current to be adjusted is lower than the motor's rated current by a factor of $1/\sqrt{3}$ = 0.58.

Due to the third harmonics currents circulating in the motor windings, a higher setting of the overload relay may be required. This may only be carried out on the basis of utilising a measuring device which records the correct rms value. Conductor cross-sectional areas must be of a suitable size in order that they will be protected against temperature rises resulting from overload conditions. Therefore, the conductor size selected must be in accordance with the protective device(s) rating.

For motor protection by means of power circuit breakers with motor protection characteristics, the power circuit breaker is switched into the network supply lines, as it also carries out short circuit protection of starter and lines. In this case, the current is set to the rated motor current. A correction of the set value because of the third harmonics is irrelevant under these circumstances. The lines are to be thermally proportioned depending on the power circuit breakers setting.

For normal Star-Delta starting, the control gear must be sized in accordance with the following currents:

- Main contactor K1M 0.58 I_e
- Delta contactor K2M 0.58 I_e
- Star contactor K3M 0.34 I_e

For starting times exceeding approximately 15 seconds, a bigger star contactor has to be selected. If the star contactor is equal to the main contactor, start times of up to approximately one minute are permissible.

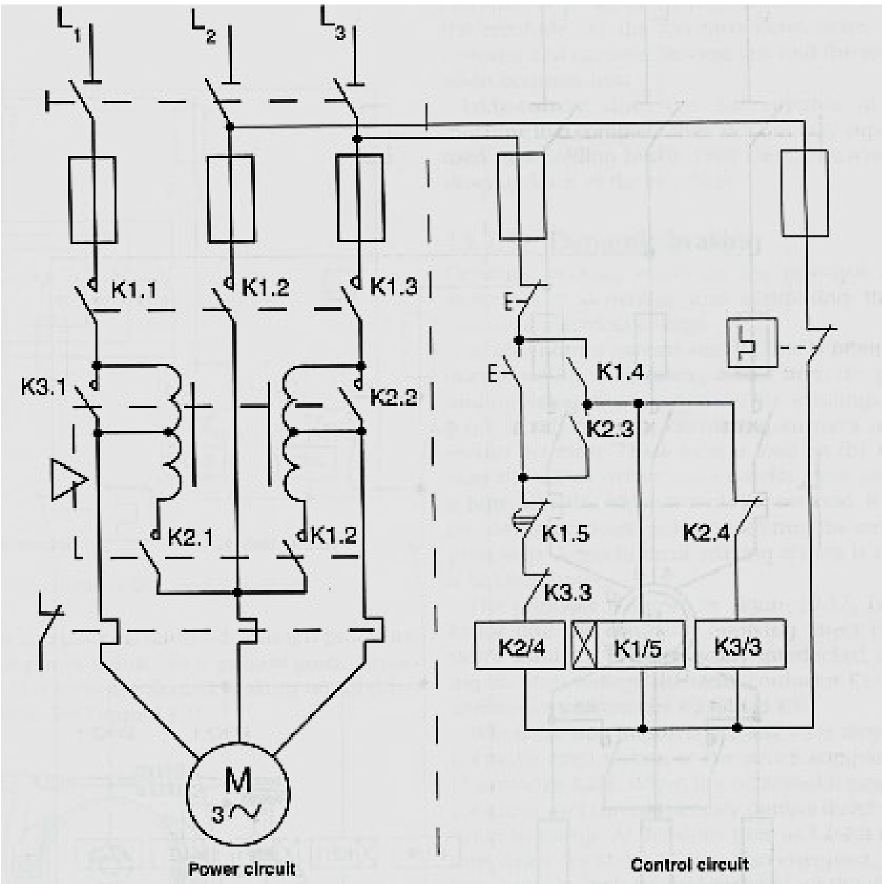
Auto Transformer Starting

This is another method of starting squirrel cage motors with reduced voltage. Basically, it is a two-stage method and is used where the reduction in the starting torque available with the Star- Delta method is not sufficiently high, or because the motor available has only three terminals in its connector block.

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 voltages 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.

The choice of a particular tapping depends on whether the motor is to be started on no-load or medium load. Since the starting torque must be sufficient to accelerate the motor at a satisfactory rate (this method of starting is not suitable for starting a motor against heavy loads). Auto transformers can be arranged to give the Korndorfer system of switching 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.

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



Autotransformer Control Circuit

Advantages of the autotransformer

1. Good torque/current ratio.
2. Adjustable starting values are available.
3. Only 3 wires and three connections to the motor are required.
4. There are considerable savings in size and weight.
5. There are decreased losses for a given KVA capacity.
6. Using an autotransformer connection, provides an opportunity for achieving lower series impedances and better regulation. Its efficiency is more when compared with the conventional one.
7. Its size is relatively smaller.
8. Voltage regulation of autotransformer is much better.
9. Lower cost.
10. Low requirements of excitation current.
11. Less copper is used in its design and construction.
12. In a conventional transformer the voltage step-up or step-down value is fixed while in an autotransformer, we can vary the output voltage as per out requirements and can smoothly increase or decrease its value as per our requirement.

Disadvantages of the autotransformer

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. Short circuits can impress voltages significantly higher than operating voltages across the windings of an autotransformer.
4. For the same voltage surge at the line terminals, the impressed and induced voltages are greater for an autotransformer than for a two-winding transformer.
5. Autotransformer consists of a single winding around an iron core, which creates a change in voltage from one end to the other. In other words, the self-inductance of the winding around the core changes the voltage potential, but there is no isolation of the high and low voltage ends of the winding. So, any noise or other voltage anomaly coming in on one side is passed through to the other. For that reason, Autotransformers are typically only used where there is already some sort of filtering or conditioning ahead of it, as in electronic applications, or the downstream device is unaffected by those anomalies, such as an AC motor during starting.

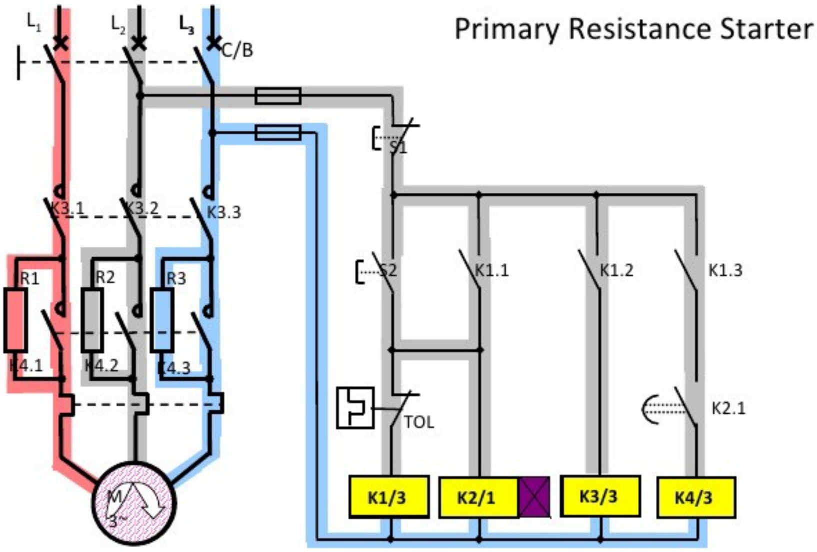
Applications

- Used in both Synchronous motors and induction motors.
- Used in electrical apparatus testing labs since the voltage can be smoothly and continuously varied.
- They find application as boosters in AC feeders to increase the voltage levels.

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 and power losses drawn from the line. They are designed for general purpose industrial applications where heavy duty reliable starting equipment is very important.

Primary Resistance Starting

This method is suitable for starting squirrel cage motors on no-load or light-load conditions. It is a variable-stage 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 is in the region of 25% and 65% of the direct-on-line value (the torque available at starting 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 change over.



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

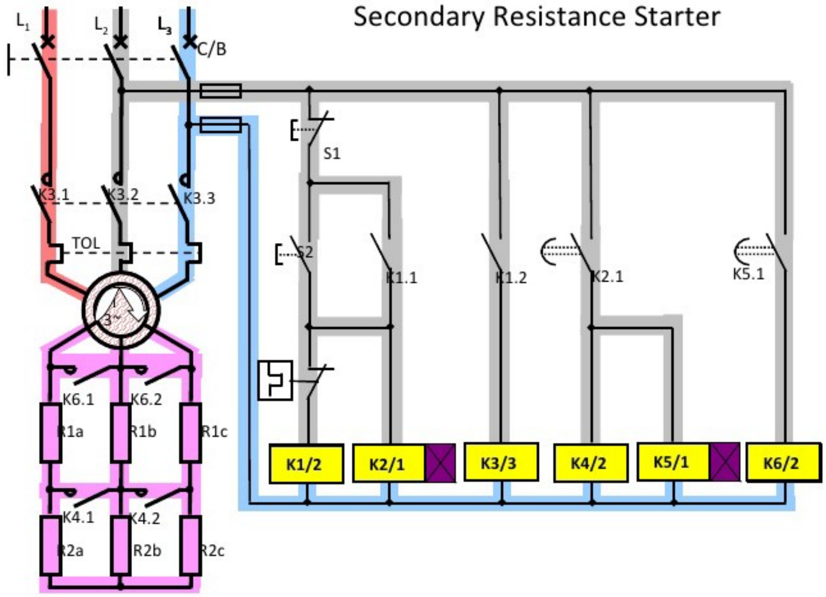
Applications

Application 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. As with Star-Delta starting, care should be taken that initial low starting torque is satisfactory, as some of the above applications can, because of their size, weight and high inertia, require a large starting torque.

Where a smooth start is required to prevent mechanical damage to couplings etc from a motor with too much starting torque, this type of primary resistance may often provide a simple solution. This resistance is sometimes left in circuit permanently on small motors with a short duration of load cycle.

Secondary resistance starting

Wound rotor induction machines have external resistors connected to the rotor circuit in the form of slip-rings for starting and speed control. When the motor is called to start and whilst the rotor is stationary, the frequency of the rotor 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 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 Starters (Soft Starters)

The solid-state soft starter is similar to the primary resistance starter that controls the voltage, applied to the motor windings by means of an impedance in series with each phase connected to the motor. The solid-state soft starter uses solid state AC switches instead of fixed or liquid resistors. The AC switches are either triacs, reverse parallel connected SCR/diode or SCR/SCR circuits. The voltage is controlled by variation in the conduction angle of the SCRs or triacs. The triac and SCR/SCR are both symmetric controllers resulting in odd order harmonic generation.

The asymmetric control of the SCR-diode AC switch causes even order harmonic currents to flow in the motor and the supply. The even harmonics are undesirable for motor control because of the increased losses and heating induced in the motor and supply transformers. The AC switch has a very low power dissipation compared to the traditional primary resistors and is controllable to give a motor voltage from zero to full line voltage without any steps or transients. Solid state soft starters are available in two control formats:

Open Loop Controllers

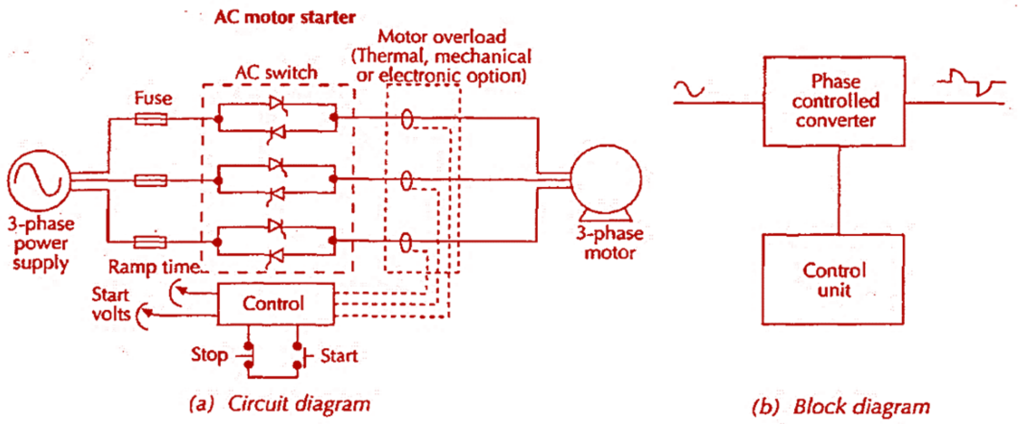
Like traditional electromechanical starters, these operate following a preset timed sequence. The most common open loop system is the Tuned Voltage Ramp where the voltage begins initially at a preset 'start voltage' and increases to line voltage at a preset 'ramp rate'.

Common closed loop controllers are Constant current; Current ramp and Constant acceleration.

Closed Loop Controllers

Monitor one or more parameters during the start period and modify the motor voltage in a manner to control the starting characteristics.

Solid state starters can be designed to give greater starting duties than most motors, and because of their linear voltage control do not cause current or torque steps or transients. Solid state soft starters are transition-less.



Simplified diagram of variable frequency drive

The following are some advantages of the electronic starter:

1. They are very efficient and are much more efficient than the primary-resistance starter.
2. Starting is softer because of the reduced shock loading during starting.
3. They have ramp-up and ramp-down time control and the length of starting run-up (starting) and ramp down (stopping) may be adjusted.
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 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.

Applications

Rock crushing machines need voltage control because of the very heavy crusher or grinding wheels. This kind of load needs slow acceleration coupled with an increase in torque as speed increases.

Centrifugal pumps and fans need little starting torque, but their torque requirements increase as speed increases. The electronic-voltage controller suits this application well because as voltage is increased, torque and speed increase. Some air and refrigeration compressors have similar speed/torque needs.

Bottle conveyors need long ramp-up and ramp-down times which can easily be met by the electronic controller.

Motor Speed Controllers

Operational Requirements

In an ideal world, motor speed controllers would be able to produce infinite speeds that were step-less (continuous control), have minimum losses, and have minimum harmonics and radio-frequency interference. In order to use a motor on the speed controller it must be designed for varying speeds and have adequate cooling systems for low speed running. Motors running at very low speeds can overheat very quickly and so this needs to be accommodated. This may require cooling in addition to the shaft fan.

Synchronous Speed

The speed of the squirrel cage induction motor is slightly less than the synchronous speed of the rotating field. You can calculate the synchronous speed using the following formula:

$f(x)$

Formula

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

Where P = Pair of poles

F = frequency

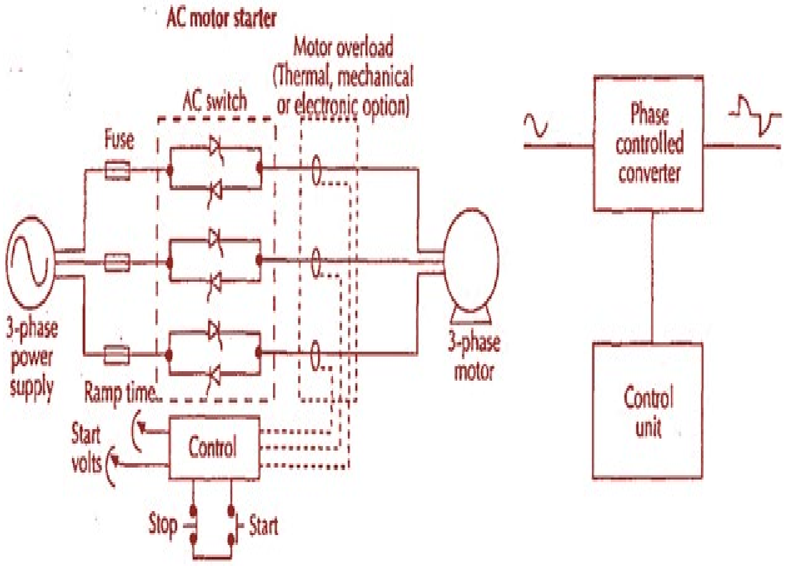
There are two variables: frequency and number of poles. Normally, a motor is selected by its speed as determined by the number of poles. Probably the most common motor has four poles and a full load speed of approximately 1460 rpm. This equates to a slip of 40rpm from the synchronous speed of 1500rpm (60*50/2 = 1500rpm synchronous speed).

Pole Changing

Increasing the number of poles reduces the running speed in large spaced speed steps. This gives us good torque speed control, but it is not continuous, and the smoothness of change is very poor. In fact, switching from two-pole to four-pole operation for example, causes a speed change of nearly 1400 rpm. (A 2-pole motor nominally rotates at 2850 rpm and a 4 pole is nominally 1460rpm which equates to about a 1400rpm speed change). Also, a pole change motor is more complex and has a high relative cost compared to other speed controllers because of the extra cost of two 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.

Electronic Variable Frequency Speed Control

This type of speed controller is able to vary the frequency and voltage applied to a motor by electronic means, to produce step-less speed control. As the speed is proportional to frequency, the speed can be decreased by reducing the frequency and increased by increasing the frequency. In order to keep the torque constant, the voltage will also have to be changed to keep the voltage/frequency ratio constant. Conversely, the torque can be controlled by controlling this ratio.



(a) Circuit diagram (b) Block diagram

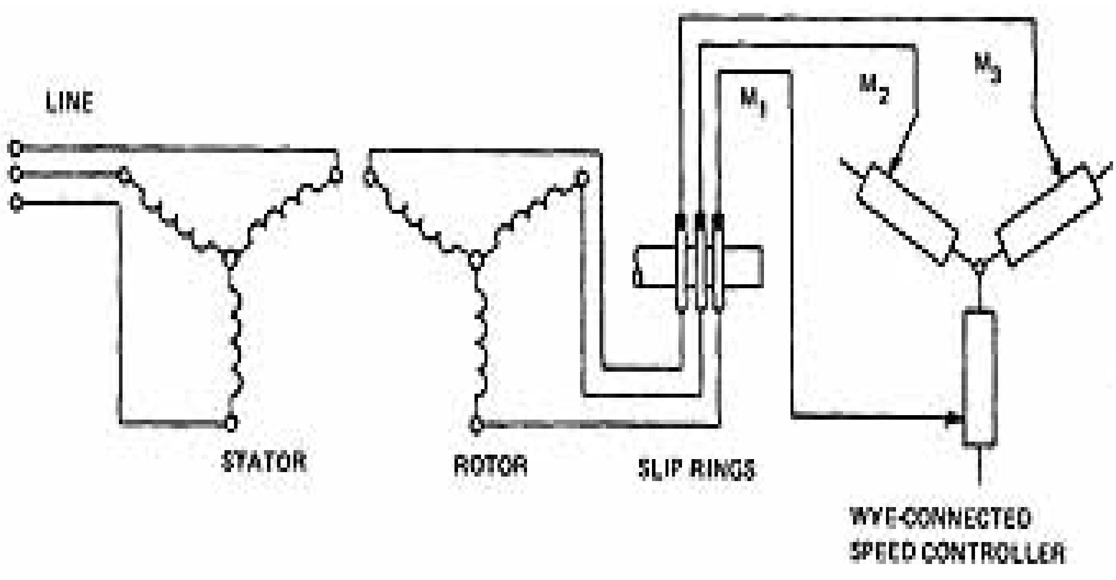
If the frequency is varied from 0 to 50 Hz in a step-less manner, the speed will vary in an extremely smooth step-less manner. That is, the speed of a four-pole machine can be continuously controlled from 0 to nearly 1500 rpm. It is possible to increase the speed of an induction motor to above its normal base speed by raising the supplied frequency above 50 Hz up to 100 Hz. There are no limitations to over- speed operations, the torque must be reduced so that the power supplied by the motor does not exceed its rated value. Care is also needed regarding the suitability of the bearings for this elevated speed.

Slow-speed running has the disadvantage that motor cooling is reduced and so extended slow- speed running will call for larger motors to reduce the heating. These 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 when compared to pole changing which has a higher efficiency as there are no losses, because there is no manipulation of the supply. The initial cost of electronic speed control is relatively high but as they become the industry norm, prices are reducing.

Using Secondary Resistance as Speed Control

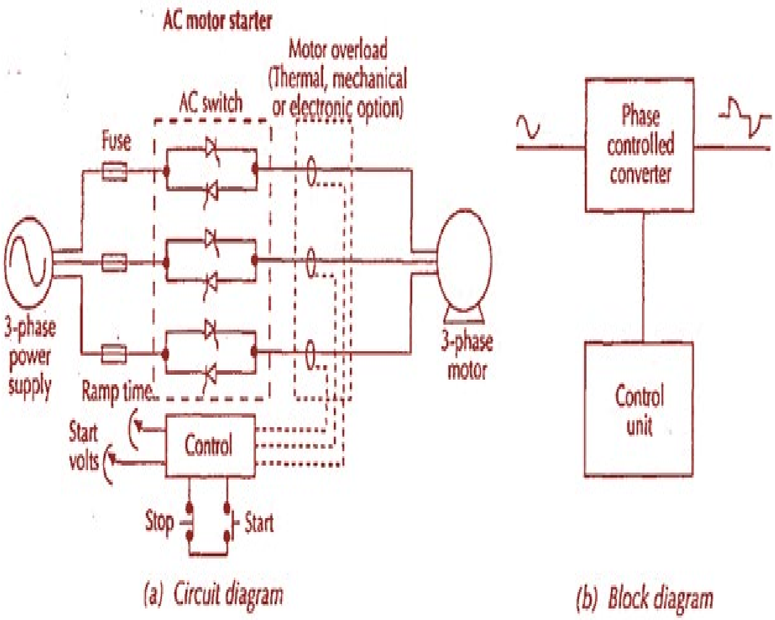
This type of speed controller is able to introduce resistance into the rotor to initially control the starting of the motor, but then to give us continuous speed control once running. Increasing the resistance in the rotor will slow the motor down. Full speed is achieved once the total resistance is removed.

This method can provide a high torque and good smooth continuous 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.



Variable Frequency Drives

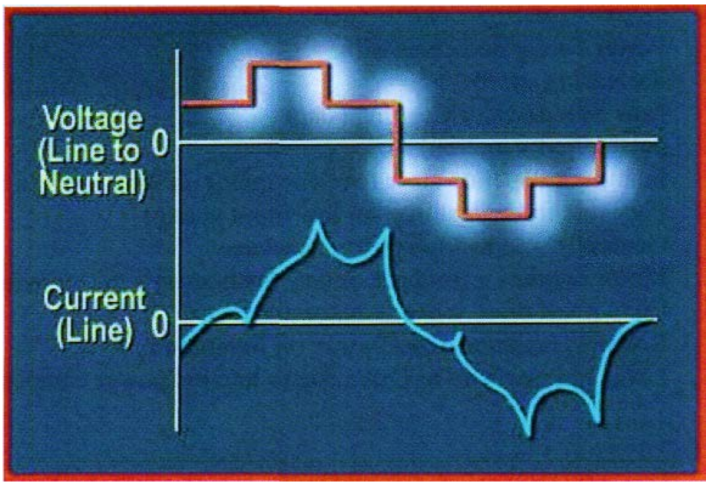
In a Variable Frequency Drive the incoming AC is rectified, filtered and smoothed becoming DC. This is then inverted to produce switched AC of varying frequency and voltage using thyristors or IGBT's. This variable frequency can be fed to the motor to produce a variable speed. Remember speed is inversely proportional to frequency.



There are various methods of producing this speed control:

Variable Voltage Input (VVI)

The VVI is the oldest AC drive technology and was the first AC drive to gain acceptance in the industrial market.



The VVI is sometimes called a "six-step drive" due to the shape of the voltage waveform it sends to the motor.

VVI drives are fairly economical between 25 and 150 horsepower for ranges of speed reduction from 15 to 100% (about 10 to 60 Hertz).

These drives are also used widely on specialty high speed applications (400 to 3000 Hertz).

Advantages:

- Good speed range
- Multiple motor control from one-unit Simple control regulator

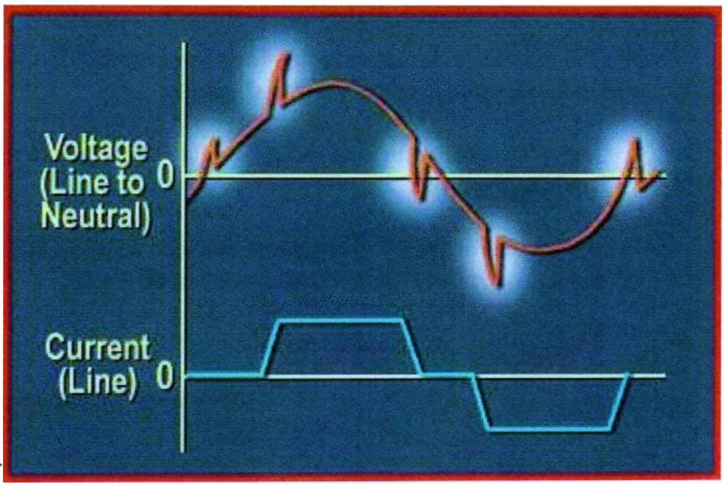
Disadvantages:

- Power Factor decreases with decreasing speed
- Poor ride through ability for low input voltage
- Generates significant output
- Harmonics
- Low Speed Motor Cogging (shaft pulsing/jerky motion)
- Requires Isolation Transformer on Input Side
- During low speed operation (below 15-20 Hz) cogging can be a problem. The jerky motion of the motor shaft can create problems for bearings, gears, or gear reducers.

Current Source Input (CSI)

The CSI is very similar to the VVI except that it is more sensitive to current as opposed to a VVI drive which is more sensitive to voltage.

CSI drives are usually lower cost above 50 horsepower than VVI drives for pumps and fan applications.



The efficiency of a CSI drive may not be as high as a VVI drive and may not provide a total energy saving package compared to other drives.

Due to the current characteristics produced by the CSI, cogging can be a problem at low speeds similar to the VVI.

The voltage output is somewhat closer to the regular sine wave expected by the motor except for the sharp spikes and sags.

Advantages:

- High Efficiency
- Optional Regeneration
- Capability
- Inherent Short Circuit Protection
- Capable of bringing other motors on Line at full voltage

Disadvantages:

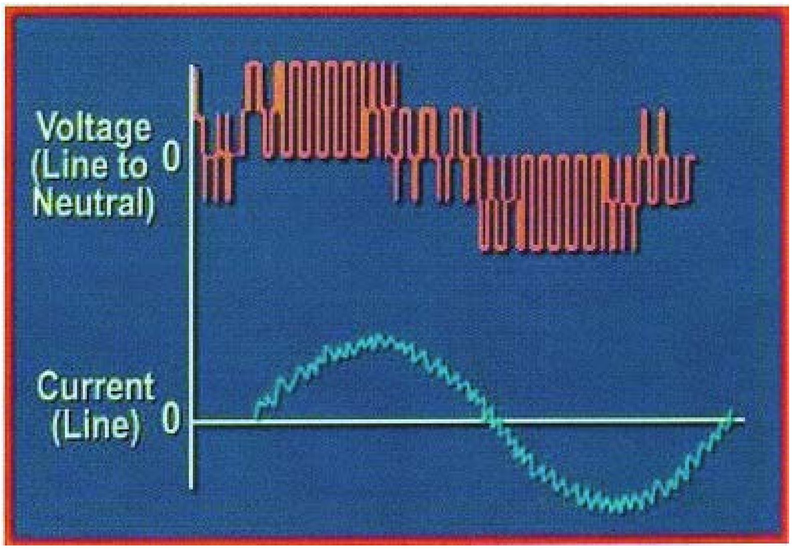
- Power Factor decreases with decreasing speed.
- Low Speed Motor Cogging (shaft pulsing/jerky motion)
- Inability to operate more than one motor on the drive at a time
- Poor ride through ability for low input voltage
- Generally sold as Motor/Drive package.
- Motor requires a feedback device (tachometer, etc.) to work with the drive
- Cannot test drive without motor connected
- Requires Isolation Transformer on Input Side

  Large physical size of Drive due to internal power components.

Pulse Width Modulated (PWM)

These drives are the newest technology and use sophisticated power electronics to accomplish the same frequency and voltage control.

- They provide good efficiency with very little motor heating associated with the other types of drives.
- Pulse Width Modulated or PWM drives provide the best output current to operate the motor and are becoming very popular for adjustable speed applications.
- The current supplied to the motor has no notching to any great degree and is representative of what the motor expects.



Advantages:

- High Efficiency
- Wide controllable speed range
- Ride through capability
- Open Circuit Protection for ride through capability
- Constant Power Factor regardless of speed
- Multi motor operation from one drive
- No cogging problems.
- Competitive Price.

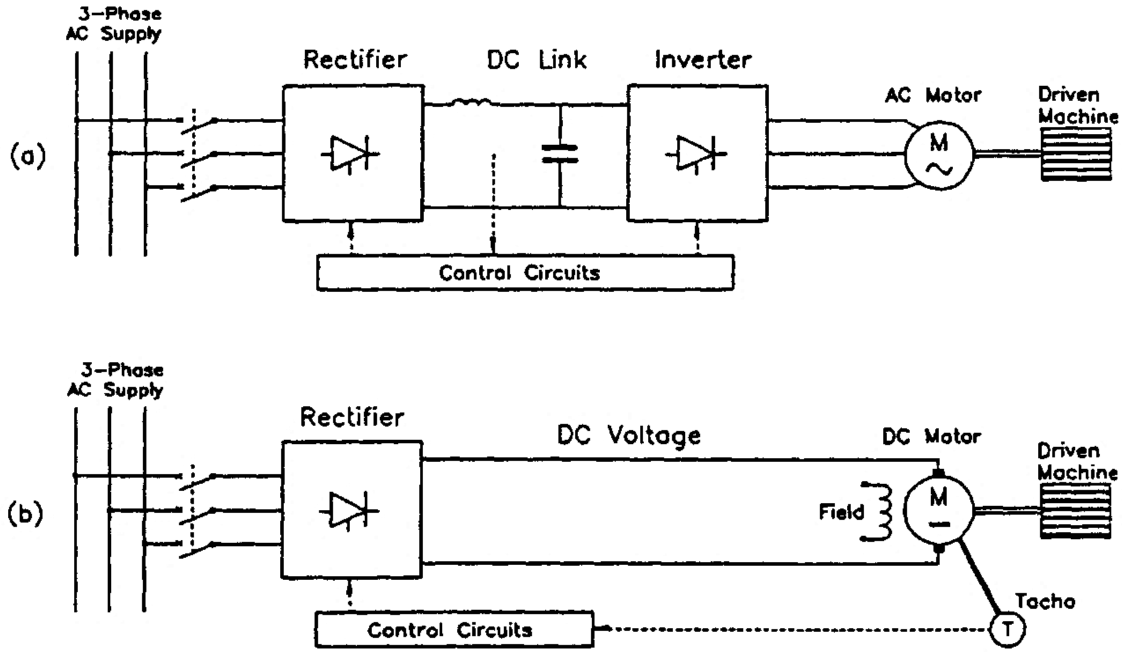
Disadvantages:

- Extra Hardware required for line regenerative capability.
- Complexity of equipment is high compared to VVI and CSI.
- Some PWM drives produce significant audible noise.

Modern VSDs

Since the 1980s the popularity of AC variable speed drives has grown rapidly, mainly due to advances in power electronics and digital control technology affecting both the cost and performance of this type of VSD. The main attraction of the AC VSDs is the rugged reliability and low cost of the squirrel cage AC induction motor. On the other hand, the main difficulty has always been the complexity, cost and reliability of the AC frequency converter.

The main differences between an AC drive and a DC drive are illustrated below. The AC/AC converter is more complex and more expensive than an AC/DC converter because it requires an additional inverter to provide the variable frequency output voltage.



Main Components of (a) AC Variable Speed Drive & (b) DC Variable Speed Drive

Frequency control, as a method of changing the speed of AC motors, has been a well-known technique for some time but it has only recently become an economical and technically viable method of variable speed drive control.

DC motors were used in most variable speed drive applications despite the complexity, high cost and high maintenance requirements of the DC motors. Even today, DC drives are still often used for the more demanding variable speed drive applications. Examples of this are the sectional drives for paper machines, which require separate control of speed and torque.

In comparison to DC drives, AC drives have become a more cost-effective method of speed control for most variable speed drive applications up to 1000 kW. It is also the technically preferred solution for many industrial environments where reliability and low maintenance associated with the AC squirrel cage induction motor are important. Developments in power electronics over the last 10 to 15 years have made it possible to control not only the speed of AC induction motors but also the torque.

Modern AC variable speed drives with *vector control* can achieve, and in some cases exceed, the performance of DC variable speed drives as they allow the delivery of the motors full torque at zero rpm – naturally the motor will require forced fan cooling if it is to survive in this environment for any length of time.

The speed (n) of the motor can be controlled either by adjusting the supply frequency (f) or the number of poles (p). In an AC induction motor, the synchronous speed that is the speed at which the stator field rotates, is governed by the simple formula:

Synchronous Speed

The following formula determines the synchronous speed:

$f(x)$ **Formula**

NS = 60 f / p

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 affect smooth speed control. Consequently, the fundamental principle of modern AC variable speed drives is that the speed of a fixed pole AC induction motor is proportional to the frequency of the AC voltage connected to it.

In practice, the actual speed of the rotor shaft is slower than the synchronous speed of the rotating stator field, due to the slip between the stator field and the rotor.

Actual Speed

$f(x)$ **Formula**

n = (n_s - slip) rev/min

The slip between the synchronous rotating field and the rotor depends on a number of factors, being the stator voltage, the rotor current and the mechanical load on the shaft. Consequently, the speed of an AC induction motor can also be adjusted by controlling the slip of the rotor relative to the stator field.

Unlike a shunt wound DC Motor, the stator field flux in an induction motor is also derived from the supply voltage, and the flux density in the air gap will be affected by changes in the frequency of the supply voltage. The air-gap flux (ϕ) of an AC induction motor is directly proportional to the magnitude of the supply voltage (V) and inversely proportional to the frequency (f).

Air-gap Flux

Formula

$f(x)$ $$\emptyset \propto \frac{VV}{11}$$

To maintain a constant field flux density in the metal parts during speed control, the stator voltage must be adjusted in proportion to the frequency. If not and the flux density is permitted to rise too high, saturation of the iron parts of the motor will result in high excitation currents, which will cause excessive losses and heating. If the flux density is permitted to fall too low, the output torque will drop and affect the performance of the AC drive. Air-gap flux density is dependent on both the frequency and the magnitude of the supply voltage.

So, the speed control of AC motors is complicated by the fact that both voltage and frequency need to be controlled simultaneously, therefore the name variable voltage, variable frequency (VVVF) converter.

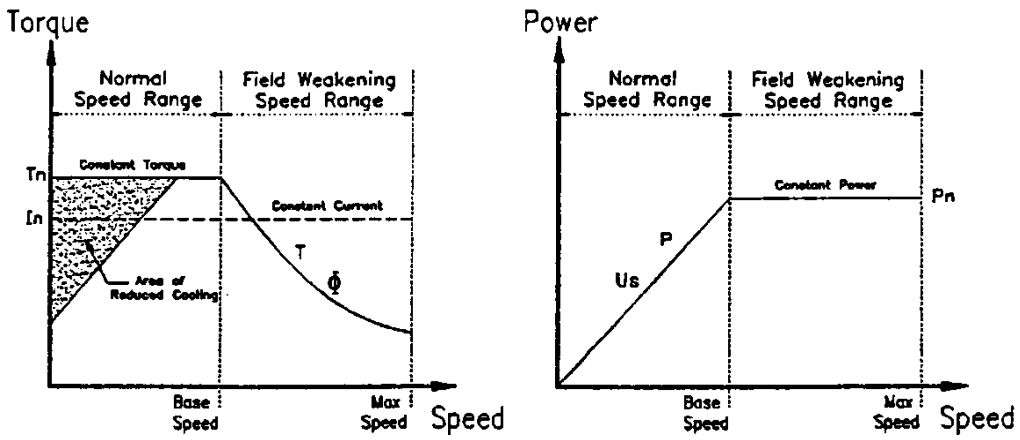
In a similar way to the DC motor, the output torque of the AC motor depends on the product of the air-gap flux density and the rotor current IR. So, to maintain constant motor output torque, the flux density must be kept constant which means that the ratio U/f must be kept constant.

Output Torque: T α ϕ I_R (in Nm)

The direction of rotation of the AC motor can be reversed by changing the firing sequence power electronic valves of the inverter stage. This is simply done through the electronic control circuit.

The output power of the AC Motor is proportional to the product of Torque & Speed.

Output Power: P α Tn (in kW)



Torque & Power of an AC drive over the SPEED RANGE

Remember that reduced power = reduced energy use = energy savings

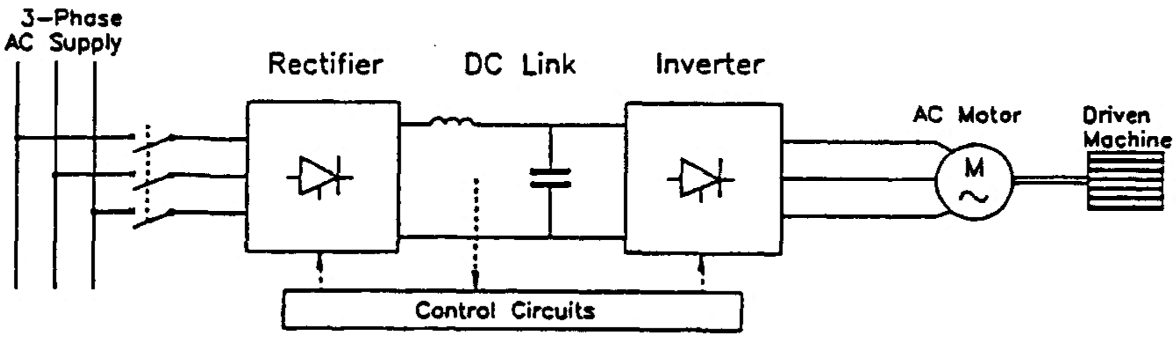
From these equations, the following deductions can be made about an AC motor drive:

- The speed of an AC induction motor can be controlled by adjusting the frequency and magnitude of the stator voltage. Motor speed is proportional to frequency.
- The AC motor can develop its full torque over the normal speed range, if the flux is kept constant - provided the V/f ratio is kept constant. A standard AC motor reaches its rated speed, when the frequency has been increased to rated frequency (50 Hz) and stator voltage V has reached its rated magnitude.
- The speed of an AC induction motor can be increased above its nominal rating by increasing the frequency above 50 Hz, but the V/f ratio will fall because the stator voltage cannot be increased any further. This results in a fall of the air-gap flux and a reduction in output torque. As with the DC motor, this is known as the field weakening range. The performance of the AC motor in the field weakening range is similar to that of the DC motor and is characterised by constant power, reduced torque.
- The output power is zero at zero speed. In the normal speed range and at constant torque, the output power increases in proportion to the speed.
- In the field weakening range, the motor torque falls in proportion to the speed and the output power of the AC motor remains constant.

One of the main advantages of this VVVF speed control system is that, while the controls are necessarily complex, the motors themselves can be of squirrel cage construction and that is probably the most robust and maintenance free form of electric motor yet devised. This is particularly useful where the motors are mounted in hazardous locations or in an inaccessible position, making routine cleaning and maintenance difficult. Where a machine needs to be built into a flameproof, or even waterproof enclosure, this can be done more cheaply with a squirrel cage AC induction motor than for a DC motor.

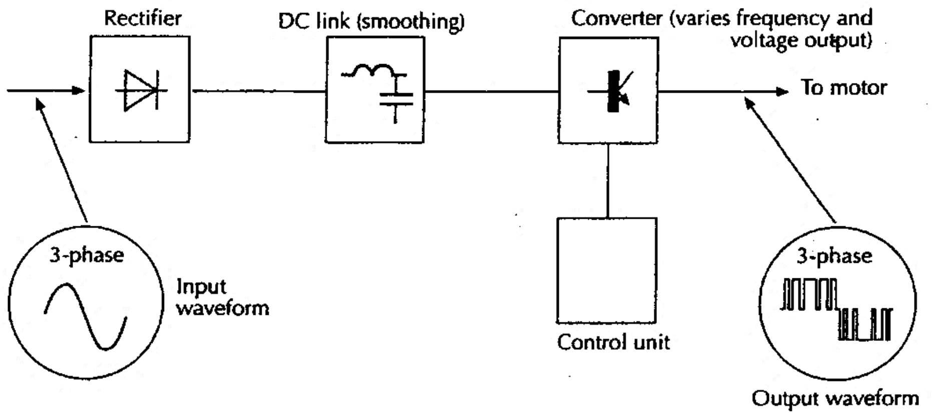
On the other hand, an additional problem with standard AC squirrel cage motors when used for variable speed applications, is that they are cooled by means of a shaft mounted fan. At low speeds, cooling is reduced, which affects the loadability of the drive. The continuous output torque of the drive must be derated for lower speeds, unless a separately powered auxiliary fan is used to cool the motor. This is similar to the cooling requirements of DC motors which require a separately powered auxiliary cooling fan.

The basic construction of an AC frequency converter is shown below:



Main components of a typical VVVF AC variable speed drive

The mains AC supply voltage is converted into a DC voltage and current through a rectifier. The DC voltage and current are filtered to smooth out the peaks before being fed into an inverter, where they are converted into an AC voltage and current with variable frequency. The output



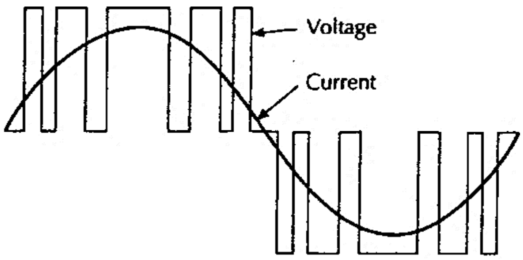
voltage is controlled so that the ratio between voltage and frequency remains constant to avoid over-fluxing the motor. The AC motor is able to provide its rated torque over the speed range up to 50 Hz without a significant increase in losses. The motor can be run at speeds above rated frequency, but with reduced output torque.

Variable-frequency controller

How the converter varies frequency and voltage

A 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.



Pulse-width modulation

A converter that carries out the switching is required to produce a PWM voltage. The circuit formed by the six transistors may also be referred to as a full wave inverter circuit. The emitter and collector of each transistor may be considered as the two terminals of a simple on/off switch. The base connection controls its 'on' or 'off' state.

Selection of AC Converters of VSDs

a) Nature of the application (what are you trying to achieve?)

b) Maximum torque and power requirements (check that safety margin is built into mechanical section)

c) What are the starting torque requirements? (self-start etc.)

d) Acceleration and deceleration requirements (slow - fast)

e) Is braking required and if so, what type?

f) Compatibility with mains supply (phases and voltages)

g) Environmental conditions (ambient temperature, altitude, humidity, water, dust etc).

h) Ventilation & cooling for motor and converter (do we need external cooling etc?)

i) Direction (uni or bidirectional?)

j) Accuracy of speed control

k) Dynamic responses (speed and torque responses)

l) Speed regulation (requirements for changes in load, voltage & temperature)

m) Duty cycle (number of starts and stops per hour)

n) Power factor of drive and its effect on the supply system

o) EMI and harmonics

p) Will EMI (Electromagnetic Inference) filters be required?

q) Earthing, shielding and surge protection requirements

r) Control methods (manual, automatic)

s) Control & communications interfaces and if any indication is required

t) Reliability requirements (is a dedicated standby unit required?)

u) Protection requirements

v) Maintenance requirements

Other requirements could be:

- Noise
- Resonance
- Cost of alternative systems
- Power and control cable requirements.

Guidelines for VFDs & Harmonics

A VFD alters the waveform of the incoming sine wave by rectifying it to DC and then coupling it to an inverter stage via an inductor and capacitor. This process has some limitations. One of these limitations is that this DC bus voltage must be limited to around 500-550V DC so as not to cause any damage to the inverters, rectifiers and inductor capacitor network.

When the drive instructs the motor to decelerate or stop if the load is large enough it may cause the motor to generate electricity back into the VFD. For this reason, many drive manufacturers now include a dummy resistive load which connects across the LC stage, and effectively limits the regenerated voltage and protects the components by limiting the voltage at this stage. Some drive manufacturers will also allow their DC stages to be connected together to form a ‘super DC drive bus’ which means that as one drive is stopping the load it re-generates voltage which can then be picked up by other drives connected to the same DC bus.

The inverter stage – this can be a series of Triacs or nowadays more likely to be IGBT’s (Integrated Gate Bipolar Transistors) will be configured into either a 6 pulse, 12 or 18 pulse configuration. Remember that every time we switch an AC waveform, we will generate a sharp fronted square wave. This square wave forms part of the pulse width modulated waveform discussed previously, but the size of the step is the frequency and the amplitude of the square wave is the voltage. The point here is that this rapid switching of the waveform will generate harmonics. The older VFDs used to emit third and fifth harmonics (150Hz and 250Hz respectively).

Harmonics are multiples of the fundamental frequency which is 50Hz in this case.

For instance, a third harmonic is 3 x 50 = 150 Hz and a fifth is 5 x 50 = 250 Hz and so on.

This level or frequency caused major issues for lines and network power companies as many of them use ripple control injection plants to control the hot water cylinders of customers as part of their load management schemes.

Later or newer drives where the 6-pulse inverter stage has been retained, emit seventh and eleventh harmonic’s, which are still an issue for the network power and lines companies especially where long spur lines are utilised.

Regulations have also been introduced to try and reduce the level of VFD harmonic distortion, with many lines’ companies requiring verification that any new VFD drive installation meets certain minimum harmonic levels before allowing it to be connected to the network.

Another problem has also arisen with the ‘sharp fronted waveform’ and that is the electromagnetic discharge (EMD), which manifests itself as premature bearing failure. After much investigation it is thought that the sharp fronted waveform has a component which is too high in voltage and is causing the insulation to break down as this ‘spike’ exceeds the breakdown voltage rating of the insulation material used by the motor manufacturers. However, the actual cause is still under investigation. This issue has manifested itself in larger motors (those in excess of 50KW) and in some smaller motors where the author has been involved.

Some types of inverter or VFD also seem more prone to causing this issue than others.

There have been several different solutions offered and adopted some of which are listed below:

- Exchange the roller bearings for pin bearings – this lessens or changes the surface area or point of contact of the electromagnetic or electric charge.
- Use insulated bearings at the drive and or non-drive end of the motor.
- Install a brush on the drive end motor output shaft which is then tied to ground.
- Use a shielded power cable to connect the motor and the VFD together and then ground both ends of the shielded cable. (To many of us who have also worked in the instrumentation and controls industries, this is counter intuitive as in this industry one only earths one end of the instrumentation cables shield and it is usually done at the control panel/PLC interface, as this normally has a better low impedance ground than would be found possible in the field).
- Any combination of the above.

Some manufacturers of motors have taken a proactive approach to the problem and as part of their drive to improve motor efficiency have made changes to the construction of the motor and its windings adding more steel to the framework of the motor and increasing the level of insulation of the materials used in the construction of their motors. This has led to some motors costing more than others.

Returning to the 6, 12 or 18 pulse inverters for a moment – the 6-pulse inverter takes the form of two side by side 'Hs' and is commonly called and H bridge even if it resembles more like two H's side by side, e.g. HH. There is an IGBT/Triac or similar switching device in each of these legs of the H. 6-pulse means 6 switching devices, 12 means more H's or 12 switching devices, 18 means 18 switching devices, etc.

The more switching device used, the purer the AC waveform generated and the fewer and lower level of harmonics generated. However, the cost of the drive increases steadily with the introduction of more switching devices. Some drive manufacturers have therefore elected to promote 12 or 18 pulse VFDs whilst other drive manufacturers have elected to stay with the 6-pulse inverter and add a harmonic filter to the incoming mains supply in order to filter out these harmonics using an EMC filter.

This is basically a 'lump of laminated steel or iron' which is tuned to the harmonics being generated by the drive and designed to filter this out of the supply. Some of these now in larger VFDs are called active front ends and designed to filter out a broader spectrum of harmonics.

Initially, VFDs were very expensive and restricted to three phase applications only, however as mass production has taken over, the cost of the three-phase inverter has fallen from around NZD$3000.00 to $1000.00 for the same size and type.

Further improvements in technology have seen the advent of the single-phase inverter. This takes a single-phase waveform, rectifies it to DC, then inverts it back into 3 phase AC but at a lower level as the energy generated cannot exceed that from which it is derived. In other words, 230V AC 50Hz incoming results in 3 phase nominally 210-220VAC at a variable frequency.

What this means is that a normal 3-phase motor with star and delta windings can be configured in delta (230VAC) mode and then connected to the single-phase inverter supply. There are some limitations but generally a small 3-phase electric motor with star and delta windings can be connected to a single-phase supply.

With the mass production of this type of VFD, the cost has fallen dramatically, and it is not un-common for a 0.75KW 1phase VFD to cost between $350 to $600 (October 2017) depending on options, connectivity and whether the overload is integrated within the VFD or an extra cost.

Many VFDs now include some additional feature like I/O (inputs and outputs) which allow the drive to act in many cases like a basic PLC. Typically, on the more basic drives there are 5 inputs, 2 outputs, 2 analogue inputs and 1 analogue output plus a variety of communications modules which can plug in – e.g. Ethernet IP, Devicenet, Profibus, Fieldbus, etc

This I/O is designed to give the operator some flexibility but once again whether it is used or required really comes back to the application. For example, with the 5 inputs, these can mostly be used for a remote start/stop station. This could comprise of an emergency stop, remote start, remote stop, forward/reverse, auto/manual etc.

A manual 5Kohm potentiometer could also be configured such that in manual, the potentiometer determined the speed of the motor and the second analogue input would be configured to receive say a 4-20mA signal from a PLC control loop, etc. The outputs could be configured to provide feedback to the PLC/operator that the VFD was at speed or had faulted, etc.

The limitations

It is worth remembering that soft-starters are all part of the family of reduced voltage starters. This means that the VFD or soft-starter is only capable of supplying 200% of its nameplate rating for 90 seconds and 150% for a little over 2 minutes.

Example

By way of an example, let's say that the mechanical engineer has sized a conveyor application to that requiring a 37KW, 4 pole motor, on a 3-phase supply. This would give a torque of around 239Nm and a FLC of 65.6A.

Now normally if this was going to be started DOL it would draw a current of nominally eight times, this on start-up (524.8 or 525A), which would indicate some form of reduced voltage starter is required. In this case the engineer selected a 37KW VFD. Whilst this worked well initially with an empty conveyor and the VFD was capable of moving the product 'dumped or placed on it' things went wrong when someone tripped the emergency stop conveyor pull cord with a full conveyor.

In this case the motor and VFD were not able to re-start the conveyor with product up to a metre deep on the conveyor. The solution, in this case was to call as many staff as were on shift and equip them with shovels, i.e. the customer had to empty the conveyor by hand until sufficient weight had been removed to allow the VFD to move the motor and conveyor.

Now obviously there were a few more things involved but simply put; when sizing a conveyor always allow for the worst-case scenario and if you are not sure then increase the size of the motor by one or two steps (in this case a 45KW motor would have sufficed). The next important point is not to size the VFD based on the motor size but to increase the size by one or two – in this case the VFD should have been sized at 45KW minimum for a 37KW but 55KW optimally – this is two steps up.

Whilst some suppliers will allow the motor size and VFD to be more closely matched, this is not the case with all suppliers, and it is always best to err on the side of caution.

The reason for this is to allow for more 'head room' with the currents and in so doing allow the VFD to start the load.

Some suppliers will correctly comment that in following this principle of 'up-sizing' it will also reduce the efficiency of the VFD and its operation, especially if pump curves and fan speed optimisation is being used but it would be minimal.

In today's world any energy savings should be taken advantage of but always look closely at the application:

If the load can be safely started with a smaller VFD and motor combination, then certainly make use of this feature and save the money, but if the load is a sudden heavy shock load which must be started in a full condition then increase the motor and VFD size.

Next rule of thumb

With early VFDs 20-60Hz, supply from the VFD was considered to be constant torque. Outside of this, it was considered the torque fell off very rapidly. With the more modern VFD this has been extended to 15-75Hz which is now roughly constant torque with anything outside that either stalling the motor (low speed) or providing high speed with no torque which ultimately may stall the motor.

Secondly, any operation under load below 30Hz will require force fan cooling of the motor as the motors own fan is not operating at its optimal speed and therefore unable to pass sufficient air over the cooling fins on the motor allowing the build-up of heat in the stator of the motor.

For prolonged operation at high speeds, say above 55 Hz, the shaft mounted fan works well but may make excessive noise. Again, it may be advisable to fit a separately powered cooling fan.

Lastly, with a single phase VFD there is a 10A limitation based normally around the socket or household wiring and fuse protection circuit.

Some typical VFD nameplate ratings are shown above.

> **Note:** Most motors of larger size nowadays incorporate a thermistor in the windings. This can be used to provide the VSD with the temperature of the windings and may be configured such that when the motor exceeds a pre-determined temperature the VSD will stop the operation of the motor and safely shut-down the motor until the latter cools sufficiently.

The key difference between a VFD and a soft-starter

With a VFD and with a soft-starter the acceleration and deceleration times for the motor and its load can be programmed. But where a VFD and soft-starter differ, is that once at speed, the soft- starter switches in a contactor and switches itself into bypass mode. In this case when the operator selects stop, then the soft-starter switches out the contactor and will bring the motor and load to a stop in accordance with the deceleration settings as programmed in, much like a VFD.

The key difference is that when the motor and load are at speed, then the VFD is still controlling the load and the operator can still vary the speed of the motor and load, whereas with a soft-starter this is not the case as the motor and load are being driven by the contactor at this point.

Although the VFD is the preferred solution, today many applications lend themselves more to the use of a soft-starter which is also a cheaper solution in many instances.

DC braking

Both the soft-starter and VFD feature the ability to have DC braking enabled. This feature will allow the motor to be brought to a stop (deceleration time) then a DC voltage will be applied to one winding of the motor for a pre-configured time. This is a holding brake. In other words, it is designed to hold the rotor electrically until a mechanical brake locks onto the rotor.

The brake from a VFD is ONLY ever a DC HOLDING brake. If the load is critical (e.g. a lift or hoist or a conveyor with an incline) then it is important that a mechanical brake also be applied to lock onto or engage with the rotor shaft preventing this from moving. The DC holding brake offered by the VFD has a time function attached with its operation and is designed to allow sufficient time for the mechanical brakes electromagnetic field to flux up and lock onto the rotor or for the electro-magnetic flux to collapse – depending on the type of brake.

Harmonics

Harmonics can also be created by VFD's as has already been mentioned. If a harmonic occurs in a motor, it establishes a counter rotating or retarding electro-magnetic field which will add to the slip figure for the motor and which adds to the lost energy for the motor – i.e. it manifests itself as heat in the windings (stator) of the motor.

Each odd pair of harmonics created by a 6-pulse VFD will create a counter rotating electro-magnetic field, namely the 5^{th}, 7^{th}, 11^{th}, 13^{th}, 17^{th} and 19^{th} harmonic. On this basis the harmonic mitigation techniques should be employed, i.e. the requirement to restrict the operating speed range of the motor enforced within the controls of the VFD and the requirement for keeping the motor fins clean.

Last but by no means least, when braking a motor or bringing a motor to a stop, the motor can regenerate energy back into the power system. If a VFD or soft-starter is connected then this 'surplus energy' can be captured and if the VFD or soft-starter is a four-quadrant drive, then this will allow the energy to be fed back in to the grid in a safe manner.

Most VFD's and soft-starters are not of this type though and so require a 'dump resistor' to be fitted or installed. The function of this dump resistor is to limit the DC voltage on the DC bus to around 500-550VDC and thereby prevent damage from occurring to the rectifier and inverter stages as a result of these excessive voltages.

Protective features of motor starters

When using a motor and a reduced voltage starter, additional protective measures as may be appropriate will be required. The scope of these additional protective measures and the number and type of protective measures deployed will to a large extent depend on the value of the investment in the associated plant and equipment, and in how much time is lost in sourcing a replacement. For example, if the motor is a 250kW one, the cost or investment outlay for the motor is considerable and the level and type of protective measures and system employed to protect this motor will by its very nature be more comprehensive, than if the motor were perhaps a 1KW motor.

The value placed on the type of protection system deployed for each motor therefore increases with the cost of each motor, and also, the cost of lost production to the process when the motor fails and has to be replaced. In its simplest form, a small motor (anything up to 1kW) will require some form of protection. In this simple case some form of overload and fusing protection would be appropriate as would the expenditure.

However, as the motor size increases, the motor cost increases, the availability of replacement decreases and the level of inconvenience and cost to the process by way of a lost production increases. For this case, not only will there be fusing, protection and a VFD (for starting and stopping and changing the process speed) or a soft-starter (for start-up or slow down), but phase rotation, phase failure, zero speed sensing and or thermistor protection (for heat in the windings), vibration monitoring, bearing temperature monitoring, diagnostic monitoring, to name a few of the techniques commonly used.

With all but the electronic type of reduced voltage and current starters additional protective devices or equipment will be required, e.g. phase failure relay for protection against the loss of a phase, reversal of the motor is more difficult to achieve as it involves a physical wiring change or additional relay/contactor, over current protection being provided by additional upstream fuses or the contractors own thermal overload, etc.

The advent of soft-starters and VFDs has seen many of these separate protective features being integrated within the electronic controllers and now only require the user to configure or enable them. Some features though such as the effects of mechanical stress, must still rely on the common sense of the user e.g. shaft alignment and vibration.

Common Faults

Over-current

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

The excessive current drawn by the motor will also flow in a 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.

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

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

(a) locked rotor

(b) under or over voltage

(c) too frequent starting

(d) single phasing

(e) high ambient temperature

(f) impaired ventilation

(g) excessive run up time

(h) sustained overload

(i) unsuitable duty cycle

No-voltage or under voltage protection

This no voltage release will prevent automatic restarting after a stoppage due to a drop in voltage or power failure, where restarting could cause injury or where a motor could restart direct-on-line. Under voltage also causes a motor to slow down and this prevents proper cooling causing the motor to overheat. If the voltage drops, we want to stop the motor.

Phase reversal

A phase reversal relay would detect a phase reversal and stop the motor. This protects against the motor going into reverse due to phase changing within the system which could result in damage to the auxiliary equipment (i.e: gears, chain-drives, etc.).

Thermistor Protection

When subjected to a severe over-current, a motor winding will rapidly increase in temperature which, if sustained, could cause the motor to burn out. However, the overload relays in the starter normally protect the motor windings from sustained heavy over current.

Temperature sensing devices embedded in the motor winding give a greater sensitive protection. These devices are called thermistors**.** The positive-temperature-coefficient (PTC) thermistor material consists of barium titanate with modifiers. The thermistor material exhibits a sudden increase in resistance at a definite temperature, and this change in resistance is used to actuate a tripping circuit when the cut-off temperature is reached.

When the motor is being wound the thermistors are inserted in the end windings as this is the most effective position.

Phase failure

This is when during normal operation a phase is lost. In this case the phase failure relay will trip and ‘tell’ the controlling platform or device (e.g. PLC) via an auxiliary contact, that there has been a loss of phase and to initiate tripping or turning off the connected load.

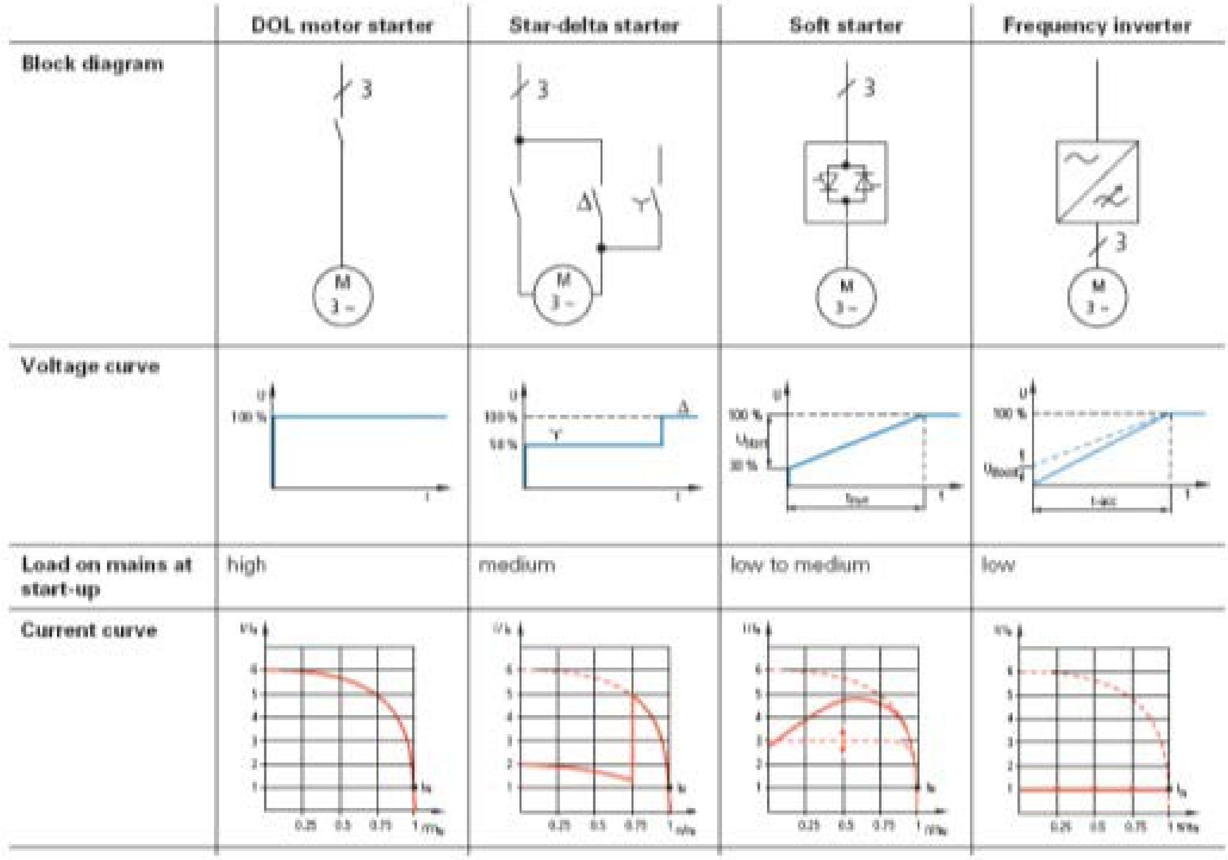
Mechanical stress

This can manifest itself as heat into the windings, shaft breakage, bearing failure, fan failure, shaft misalignment, vibration, etc. Many motors now come with thermistors embedded into the stator windings and this along with perhaps bearing temperatures, are commonly used on medium to large motors. If the attached protective device picks up a fault, then it will intervene. This will result in the motor being stopped and isolated quickly. 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

Comparison of Motor Starter Characteristics

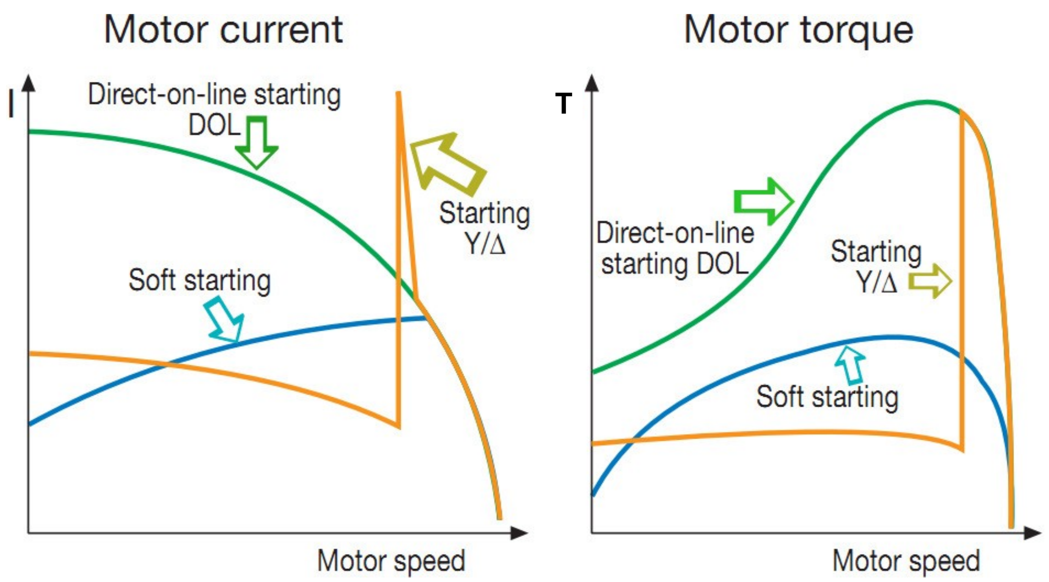
Starting method	Starting current %IFL	Starting torque %TFL	Full Load Current	Full Load Torque	Relative Cost	Example loads	General comments
Direct online	700%	150%	Light inertia loads (14% I_{Start})	Low	Low	Centrifugal pumps, lathes	Starling torque greater than full-load torque
Primary resistance	300%	40%	Almost no load (33% I_{Start})	Low	Average	Fans, small bores	Poor starting torque ($T \propto V^2$)
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



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