TTE Training Ltd.

Phase 2
Electrical Course Notes

E2-CN-009

Induction Motors

Star Delta Starting
Variable Speed Control
Circuit / Motor Protection

<u>PRINCIPLE OF OPERATION OF THE INDUCTION MOTOR</u>

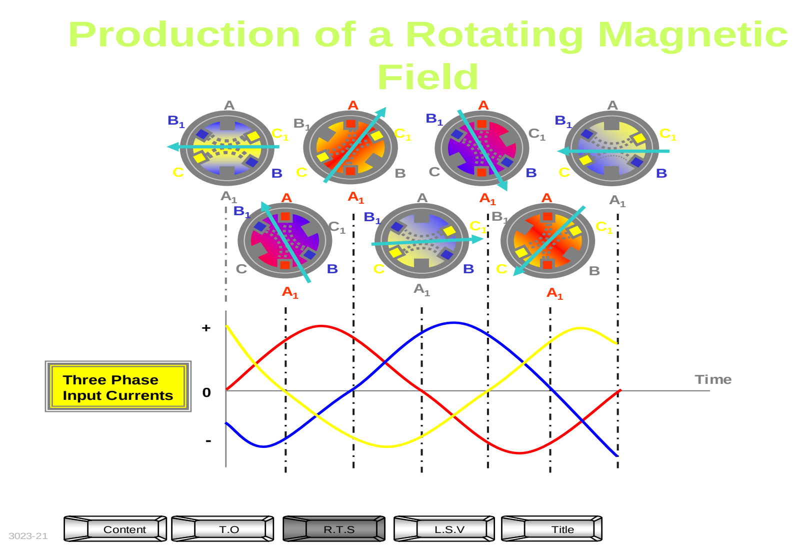
THE SQUIRREL CAGE INDUCTION MOTOR

The normal induction motor operates only on a three-phase supply. It consists of a Stator wound with a three-phase winding in slots on the inside of the yoke. The windings are distributed around the Stator, so that in a so called 2 Pole motor the axes are spaced 120 degrees apart.

Each winding end is brought out to a terminal box. The windings will then be either connected in Star or in Delta. This is usually achieved using connecting links between the relevant terminals.

Most motors that are in TTE, workshop 13 are of the dual voltage type. This means that the motor windings are connected in Delta when running on a 230 Volt, three phase supply such as would be found in different countries, or Star connected when running on a 400 Volt three-phase supply as would be used in the UK. This information can be found on the metal rating plate attached to the motor. Induction motors that you will be dealing with on site will no doubt be a lot larger than the ones here at TTE and will be designed to run on the standard UK three-phase supply.

If a three-phase supply is connected to the Stator terminals, such an arrangement gives rise to a rotating magnetic field. This completes one revolution in one cycle of the supply; with a 50 Hz system frequency the field rotates at 50 revolutions per second. This is called the 'Synchronous Speed'

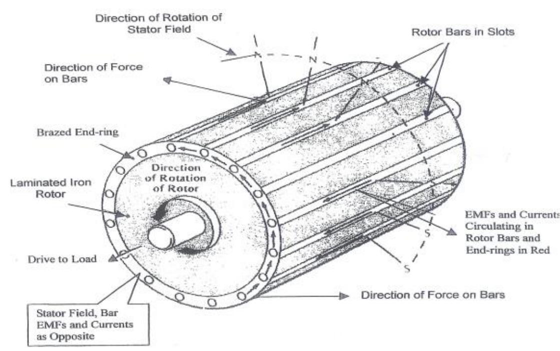


Inside the Stator is a Rotor which is free to rotate and has no electrical connections to it, i.e. no brush gear. The Rotor is built up using many iron laminations and fitted with uninsulated aluminum bars on slots around its outer edge, the bars are short circuited at both ends by cast metal rings.

The bars and rings form a cage like assembly, and this form of motor, by far the most common, is called a ‘Squirrel cage induction motor’.

While the Rotor is at rest and therefore stationary, the rotating field from the Stator passes through the all Rotor conductors in turn generating emf’s in them by Faradays Law of induction. Because all the Rotor bars are short circuited, the emf’s cause current to flow through the bars and the end rings as indicated below. The direction of the currents will change as the passing field changes from North to South and back again.

The current in the Rotor bars will also produce a magnetic field. This magnetic field is guided or concentrated around the Rotor by means of the iron laminations fitted around the Rotor bars. The iron laminations form an easy path for the magnetism to flow through. Laminations are used as opposed to a solid block of iron to reduce the effect of Eddy currents. Eddy currents are formed because iron is a conductor of electricity, thus the magnetic field flowing in the iron will form a current. Consequently, this current will also produce a magnetic field which will react with the magnetic fields in both the Rotor and Stator windings and effectively reduce the overall running efficiency of the motor. To reduce the problem of Eddy currents iron laminations are used. In fact, any electrical equipment that relies upon the effect of magnetic fields will use iron laminations e.g. Relays, Solenoids, Contactors, Transformers and Generators.



MAGNETIC FIELD, EMFs AND CURRENTS in ROTOR

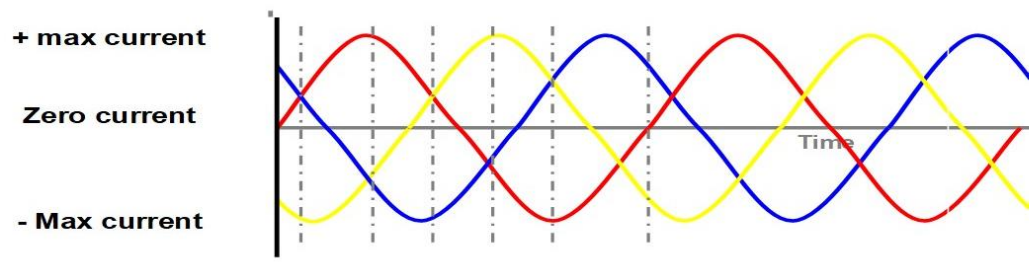
The Rotor bar currents react with magnetic field surrounding them to produce a sideways mechanical force on each other bar. By Flemmings left hand rule these forces act on all bars in the same direction and produce a combined torque on the Rotor in the direction of field rotation. This causes the Rotor to accelerate from rest.

In more simple terms the Rotor can be considered as being ‘Dragged Around’ by the rotating magnetic field.

Although the Rotor is pulled around by the effect of the rotating magnetic field it cannot run at the same speed otherwise there will not be any induced emf in the Rotor conductors.

The difference between the Rotor speed and the Stator speed is called the ‘Slip Speed’.

WINDING CONFIGURATIONS No Neutral required; Insulation & Balance Tests



Three Phase Currents

Before the installation of an induction motor and as part of fault diagnosis procedure, insulation and balance tests are carried out.

The insulation test, is to ensure there is no breakdown in insulation between any of the windings and the conductive parts of the motor i.e. the metal casing etc.

The balance test of the windings to carried out to ensure that the resistance of all Stator windings is the same within a tolerance of 10%, plus or minus. This ensures that the current drawn by all three phases and Stator windings is the same.

By examining the above current waveforms of a balanced motor i.e. all Stator winding resistances in balance, then the currents will be equal in all three windings. If the instantaneous values are added up together at any instance of time on the graph, then the total sum is always zero. Therefore, there is no separate return current because the three currents always balance out. A neutral connection on the motor and a neutral cable is not required.

You can prove this by placing all three supply cables to a running motor into the jaws of a current clamp meter and you will see that it reads zero. Placing the leads individually into the current meter a reading of current is observed.

WINDING CONFIGURATIONS

The Three Phase Motor

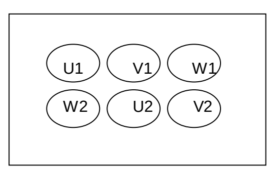
There are three windings in the common three-phase induction motor. The winding ends are brought out to the motor terminal block. The normal terminal box contains the six ends of the three windings (in some special cases, only three windings are brought out to the terminal block, in this case the winding connections are connected internally; these motors are generally of a smaller rating)

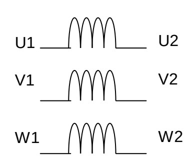
The terminated ends of the windings are identified in various ways: -

Colour Code – (Red, Yellow, Blue) or (Brown, Black, Grey)

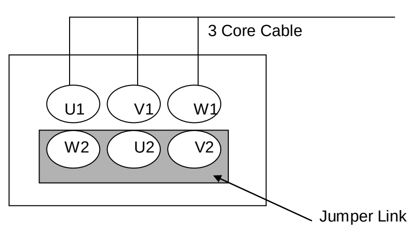
Letter Code: To identify winding ends and their placement within the motor Stator. Older motors are identified by the letter code, A1, A2; B1, B2; C1, C2; More modern motors are identified in the European code (BS 4999), U1, U2; V1, V2; W1, W2.

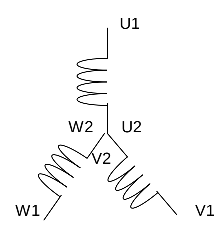
Normal Terminal Block





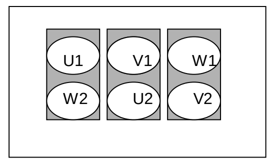
Motor Connections

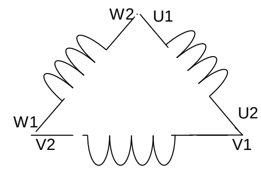




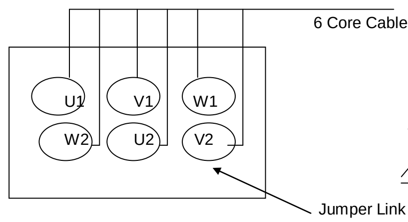
Star Connected Motor Connections

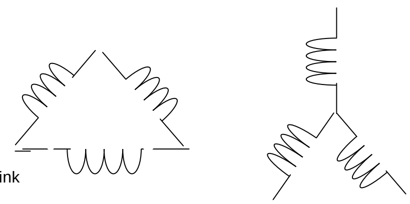
Delta Connected Terminal Block





Motor Connections





Star / Delta Connected Terminal Block

Methods of Motor Protection

High Rupture Capacity Fuses

As covered in earlier training, Induction motor circuits are fed from the three-phase supply via HRC fuses. These fuses are designed to withstand the initial high starting currents of induction motors. In addition to give a more immediate protection of the motor, Current Transformers, Overload units and Thermistors are also used.

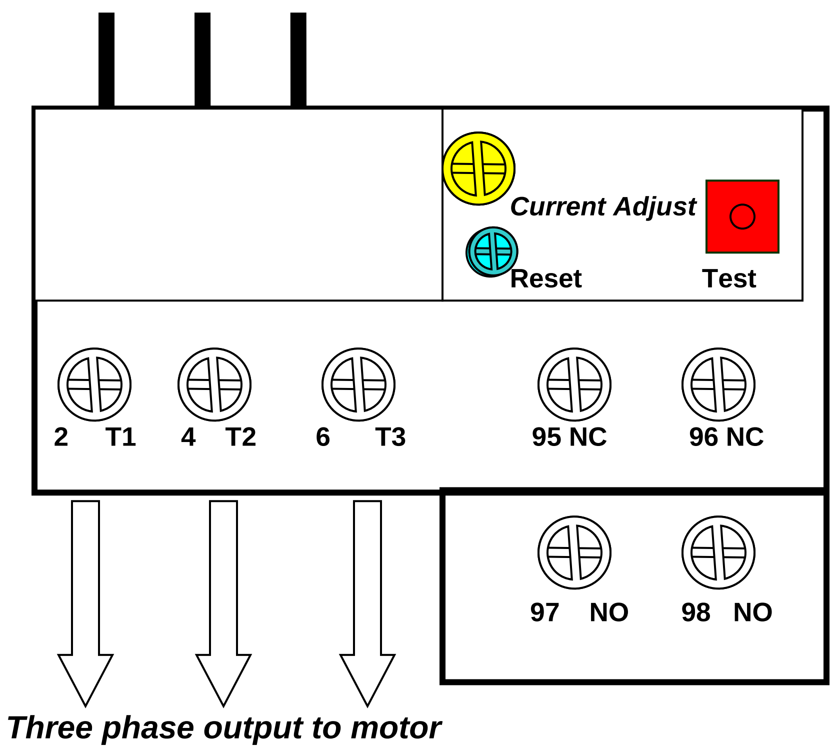
Current Transformers

The operation of Current Transformers has also been covered in earlier training. However, when a motor is operated via an Inverter, Current Transformers are usually included within the Inverter to monitor the current drawn by the motor. If the current becomes excessive or there is an imbalance between supply phases this can be sensed by the Current Transformer which can then shut down the Inverter to protect the motor and Inverter from any damage until the fault has been rectified.

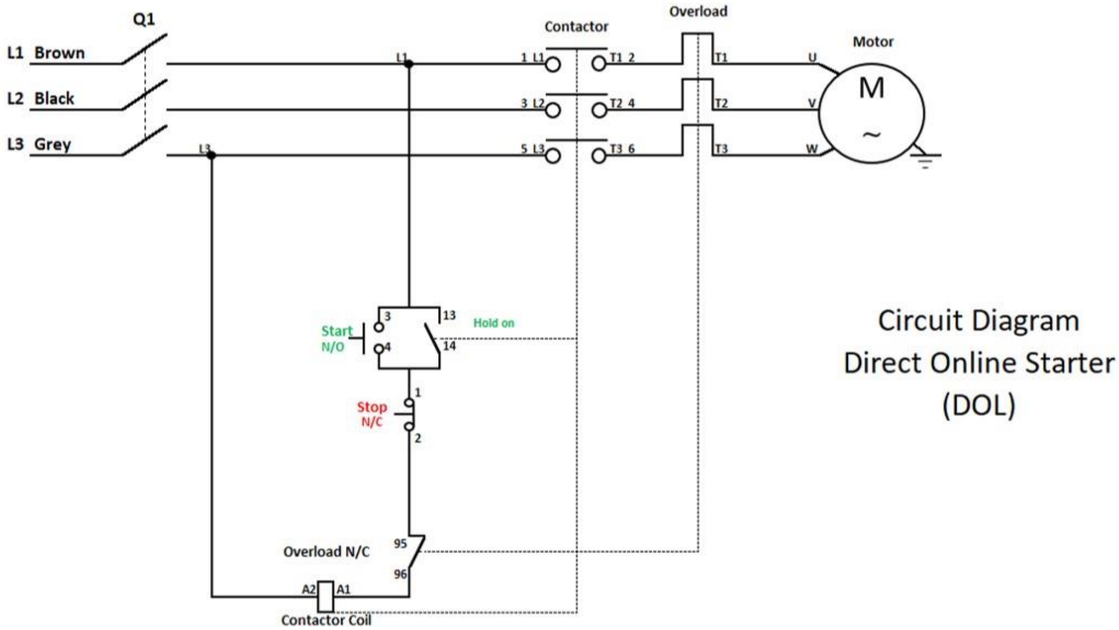
Overload Units

An overload unit can be designed to fit directly onto the motor contactor. Inside the overload unit are three bi-metallic strips, which carry the motor current. If the current exceeds a predetermined level, then the bi-metallic strips will heat and bend to operate a built-in switch which has one Normally Closed and one Normally Open contact. The Normally Closed switch (usually designated terminals 95 & 96) is wired into the motor start circuit. The Normally Open contacts (usually designated terminals 97 & 98) can be connected to an indicator light situated in the Distribution Room or to the Process Operator. If there is a fault condition and the bi-metallic strips become distorted, then the NO contacts will break the control circuit to de-energise the contactor thus isolating the motor. It must be remembered that the bi-metallic strips on their own, do not isolate the motor. The NC contacts must be wired into the motor control circuit
Also incorporated is a red test button which can be operated to test the operation of the unit. In some instances, the test button is also used as the Stop Button in small Direct On-Line circuits where the stop button on the panel is a simple plunger that operates the button.

<u>Typical Overload Unit</u>



Basic Direct On-Line Circuit Diagram

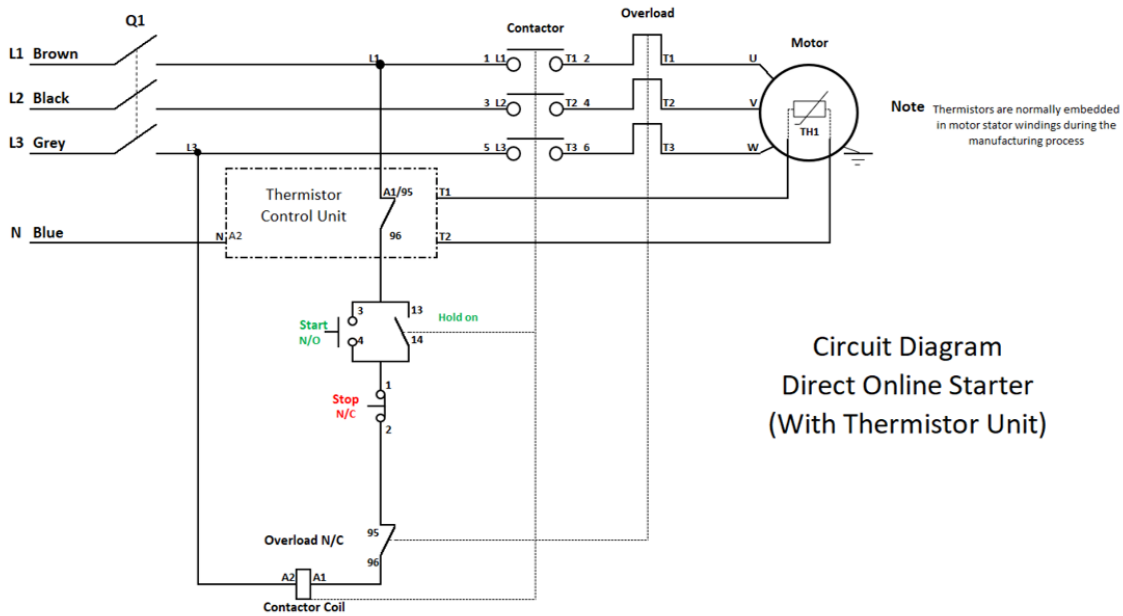


Thermistor Protection

Thermistors are Semiconductors which exhibit significant changes in resistance with change in temperature, i.e., they are thermally sensitive devices. They are formulated to produce negligible change in resistance with change in temperature until a designed critical point at which point the resistance changes rapidly. This characteristic is used to operate as a protective device. Thermistors can be formulated to be either positive or negative temperature coefficient.
For positive temperature coefficient (PTC) the thermistor normally has a very low resistance until the critical point when the resistance rapidly rises i.e., rises as the temperature rises to a formulated critical point. For negative temperature coefficient (NTC) the Thermistors operate in the reverse i.e. a normally high resistance until the temperature rises to a formulated critical point at which point the resistance rapidly falls to a low value. Essentially a Thermistor is a temperature operated solid state switch.

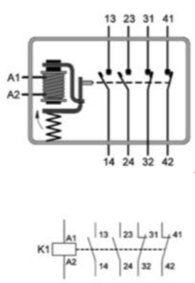
Thermistors can be housed in the Stator windings of the motor at points which can be considered ‘hot spots’ i.e., the highest temperature point for an excessive overload current or failure of the cooling system. Thermistors offer better protection than other single systems because they directly measure the temperature of the Stator windings. But the disadvantage is that they must be embedded in the winding which can introduce a weakness into the insulation system. For this reason, they are restricted to the rather more expensive motors and those critical to plant operation.

Thermistors are wired back to a separate electronic unit located with the motor start circuit. The electronic unit will detect changes in thermistors resistance i.e., the motor is drawing an excessive overload current or overheating and will then operate a Normally Closed contact to break the motor start circuit and isolate the motor in the same way as the Overload unit. Normally Open contacts will then close to operate a warning circuit or light.



Relays

Relays are basically electrically operated switches that utilise an electromagnetic coil to change over different sets of normally open and or normally closed contacts to switch circuits in and out at the same or different times based on the type of relay being used. Just like contactors they have different operating parameters and voltages for the coils and common values are 230VAC, 110VAC AND 24VDC. Some are quite simple and employ just one of each N/O or N/C, as in the overload relay that protects motors from excessive mechanical loading, some can be quite complicated incorporating time delays in seconds minutes and even hours and days, these are called multifunction timer relays. See examples of some symbols and types below.

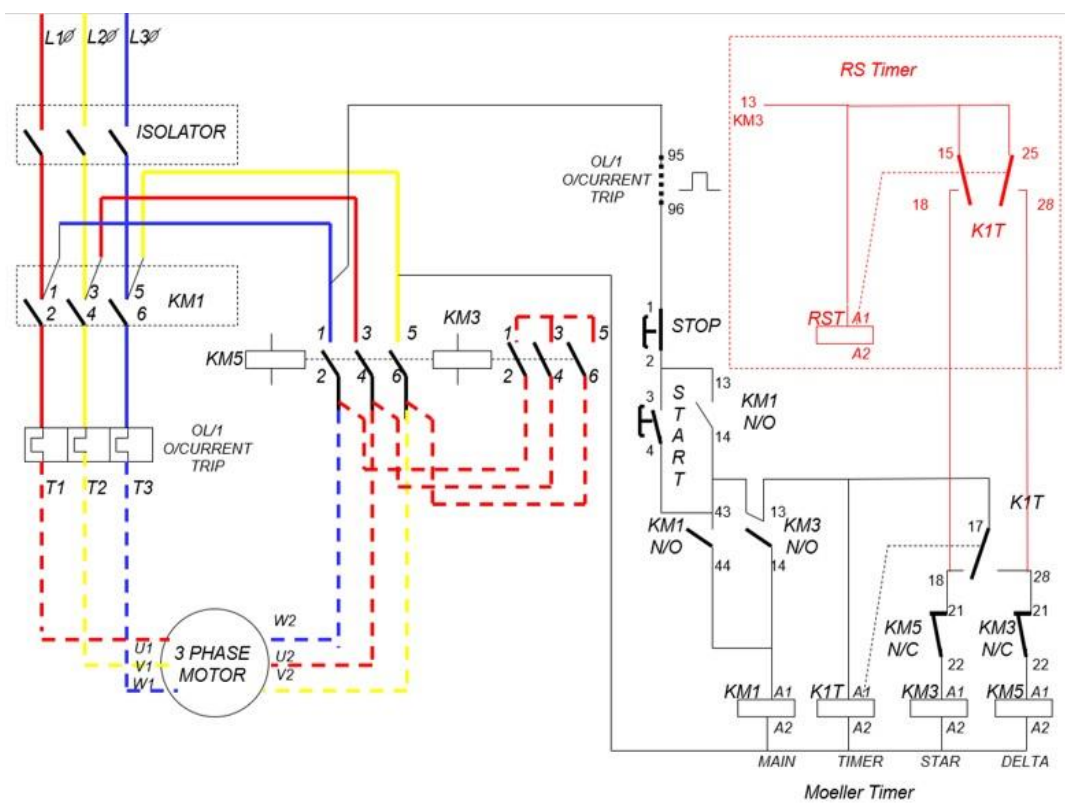


Star / Delta Starting

All induction motors on start up draw as much as 8 times the supply current. Although this is only an initial surge lasting for a few milli-seconds the motor will very quickly settle down and draw its normal supply current. For many larger induction motors, direct online starting is not feasible due to this high starting current. For, instance, it may be necessary to have to upgrade all power and distribution equipment to cater for large starting currents which would be uneconomical or impracticable considering the number of times a motor is started say over one shift period.

A simple solution is to start a motor with its windings connected initially in Star and then connecting the windings in Delta after the motor has drawn the initial surge of current. For a motor to be operated in Star/Delta, the ends of each winding are brought out to the motor terminal box and routed up to the motor start circuit using a six-core cable.

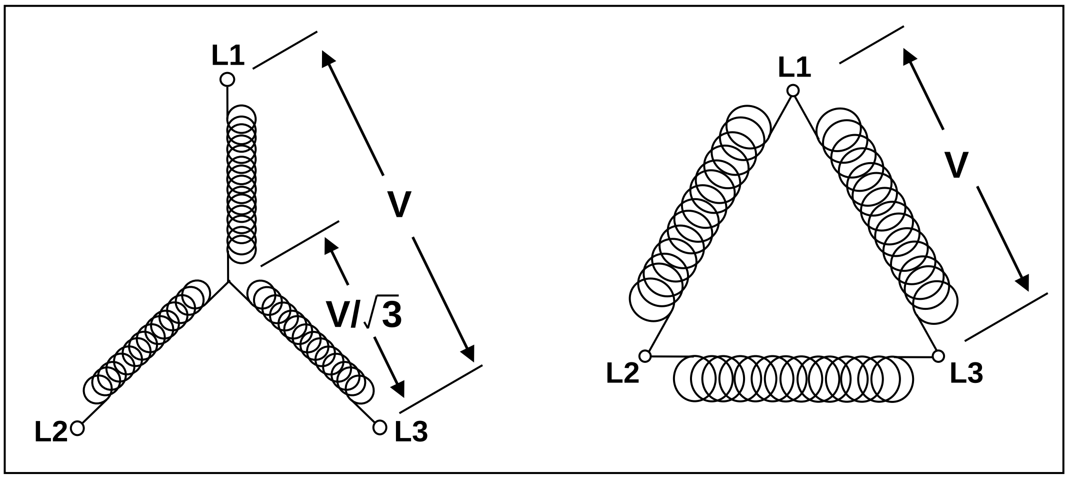
Referring to the circuit diagram below, contactor KM1 connects the three-phase supply to the motor in the same way as a Direct On-Line starter. Contactor KM5 connects the motor windings in Delta and Contactor KM3 connects the motor windings in Star. An adjustable electronic timer K1T controls the length of time that the motor can run in Star,



(NB old pre-harmonised wiring colours are used above for clarity)

When the motor is started the windings are connected in Star. In effect the supply voltage is now connected across two Stator windings so that each winding receives approximately 58% of the supply voltage. As a result, the motor start current is also reduced by approximately 1/3 of the current. As there is a direct relationship between the current drawn by the motor and the torque produced by the motor it may be necessary to run the motor initially off load and connecting the load when the motor is running in Delta.

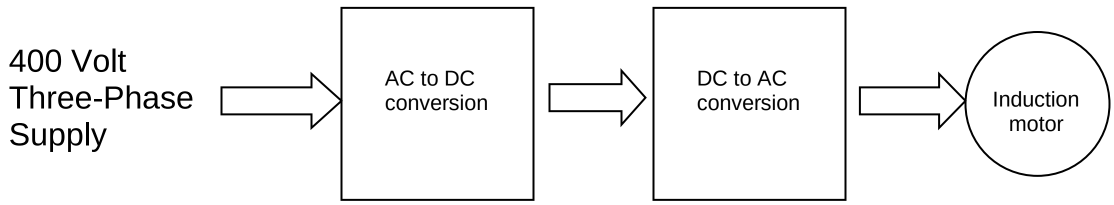
As the motor accelerates the timer will switch the winding connections over by energising the Delta contactor. Each phase will then receive the full supply voltage hence develop full torque and the motor accelerates to full speed.



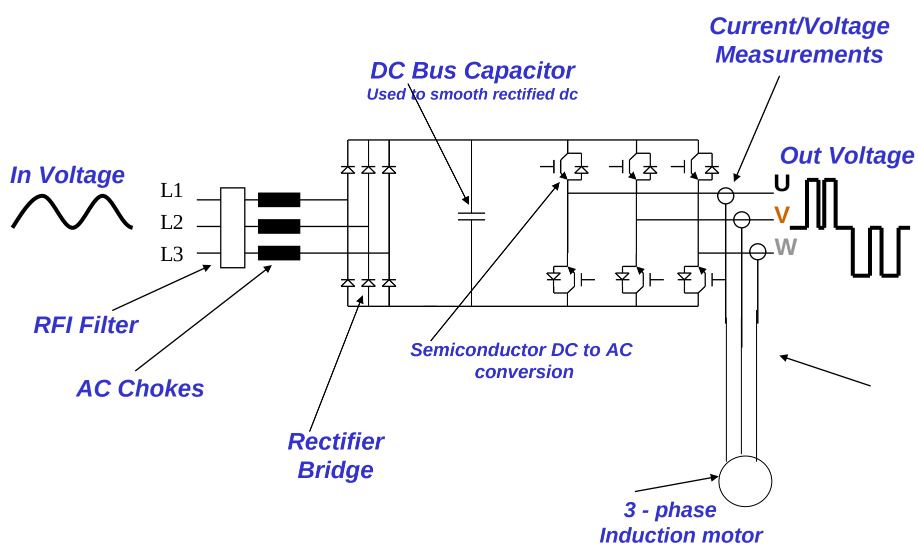
Speed Control of an Induction Motor

Although induction motors are normally the preferred option in industry due to their simplicity of construction and reliability, the one major disadvantage until recently is the inability to easily vary the Rotor speed. As previously described the motor operates due to the rotating magnetic field created by the three-phase supply. The speed of rotation of this magnetic field is dependant upon two factors, the number of pole pairs per phase and the supply frequency. Typically, there is one pair of poles for each winding, i.e., one pair of poles per phase but two poles a North and a South. So, for a three-phase motor there are three pairs of poles but only one pair for each phase, so it is called a two-pole motor. It is possible to half the speed of the rotating magnetic field by doubling the number of poles i.e., a motor with two pairs of poles (four pole motor). This will in effect reduce the speed of the rotating magnetic field by one half. In theory you could further increase the number of pairs of poles but that would make the construction of the Stator windings very difficult, so motors are limited to, two, four or six poles.

This will give you three speeds from the motor and by including a gearbox more speed selection can be obtained. This can often be used in practiced on machine tools e.g., milling and drilling machines and lathes. As can be seen this will only give you fixed speeds and no possibility of varying the speed in between the fixed output from the gearbox. The other option is to vary the supply frequency, this is set at 50 Hz or 50 cycles per second in the UK. This is achieved by fitting a unit known as an Inverter between the supply voltage and the motor. The Inverter converts the three-phase supply from AC to DC and then reconverts it to AC at a frequency dependant upon the speed requirement of the motor. As shown in the following block diagram and simplified circuit diagrams.

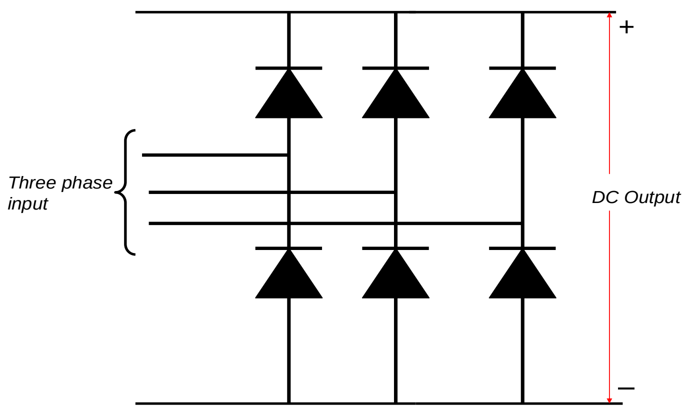


AC Drive Main Circuit



AC to DC Conversion

Conversion of the three-phase AC supply to DC is achieved by use of Diodes that act as one-way valves in that they will only allow the current to flow in one direction.



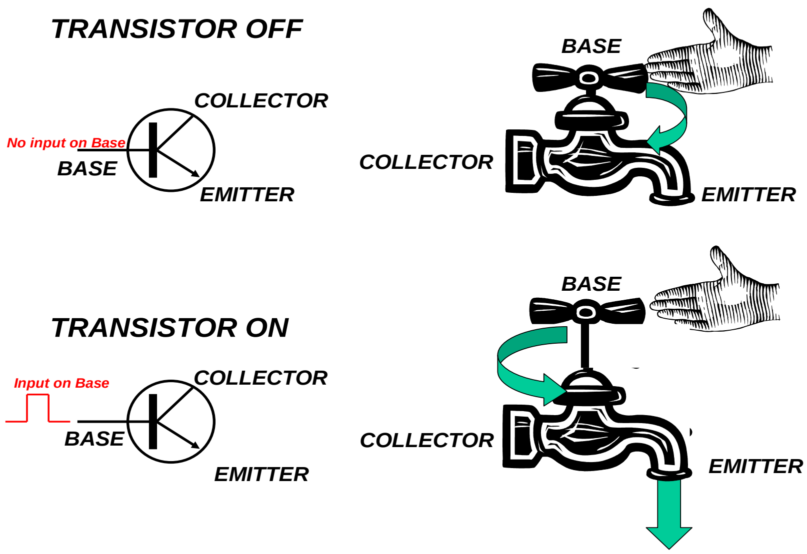
Conversion of 3 phase AC into DC

After rectification of the AC supply to DC, the DC is in effect converted back into AC again, but this time the frequency can be varied dependant on the speed requirements of the operation that the motor is driving. The various speed requirements can then be programmed into the Inverter electronics via a keypad or laptop or PC. Many types of Inverter use a Windows based software program. The control and programming of the frequency/speed requirements of the motor is achieved by a microprocessor-controlled computer built into the Inverter and is beyond the scope of this training.

However, the switching of the DC into an AC is achieved by the built-in computer controlling the operation of semiconductor devices that can handle very high currents and can switch on and off instantaneously at very high frequencies. Several different types of semiconductor devices can be used for this purpose but in general it could be Transistors or thyristors being used.

A simple explanation of the operation of a Transistor

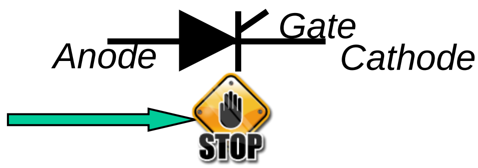
The Transistor is the electronic equivalent of a tap. The Transistor has three terminals known as the Base, Collector, and the Emitter. We can control the current flowing through the Collector and Emitter by switching a very small electrical signal on to the Base. If there is no signal on the Base, then there is a very high resistance between the Collector and Emitter and no current flows between the Collector and Emitter In other words the tap is turned off. If a small signal is put on the Base, then the resistance between Collector and Emitter falls to a very low value allowing current to flow i.e., the tap is turned on. We can vary or control the amount of current flowing between the Collector and Emitter by varying the controlling signal on the Base – just as you control the amount of water coming out of a tap by varying the amount of travel on the tap handle.



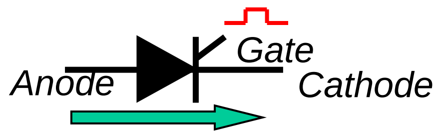
In the application of an Inverter the Transistors are used as switches. The electronics inside the Inverter will switch on the Transistors by applying an electronic pulse to the Base so that maximum current flows from the Collector to the Emitter, or there is no input to the Base, so the Transistor is in effect switched off.

A simple explanation of the operation of a Thyristor

The circuit symbol is very similar to that of a Diode which has been covered in Phase 1. However, there is an extra terminal known as the Gate. Again, as with a Diode current will pass through the Diode from Anode to Cathode (i.e., conduct) when the Anode is more positive than the Cathode. But in the case of the Thyristor, it will only conduct this time when a small electrical signal is fed to the Gate. In other words, the Gate must be opened before the Thyristor can conduct.



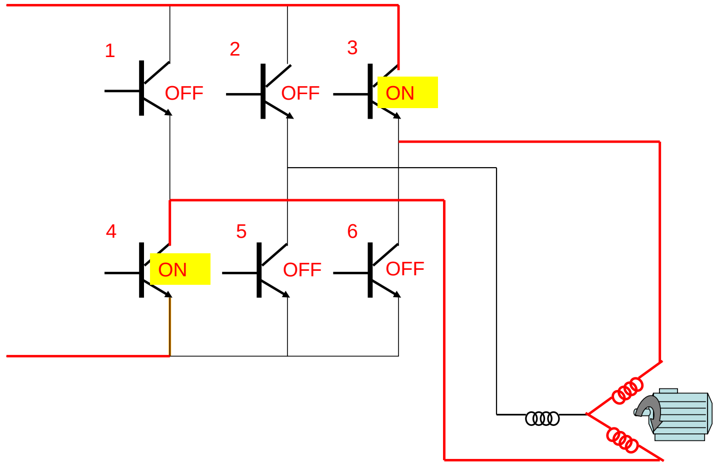
No input on Gate Thyristor will not conduct when voltage is applied to Anode



Input on Gate Thyristor conducts When voltage applied to Anode

DC to AC Conversion

Conversion of the DC back into AC is achieved by means of either six Transistors or six Thyristors using the circuits as shown below. In these examples' Transistors have been used but for this simplified explanation Thyristors could also be substituted. The resulting AC as a result of the Transistors/Thyristors switching, producing a series of square waves and not a sine wave as the original supply voltage. An Induction Motor will run quite happily with either a sine wave or a square wave input. You may notice that the motor will emit a rather high-pitched noise when being supplied via an Inverter. This is perfectly normal and is due to the shape of the magnetic fields
The diagrams below show the sequence of Transistor/Thyristor switching used to produce an AC input into a three-phase motor.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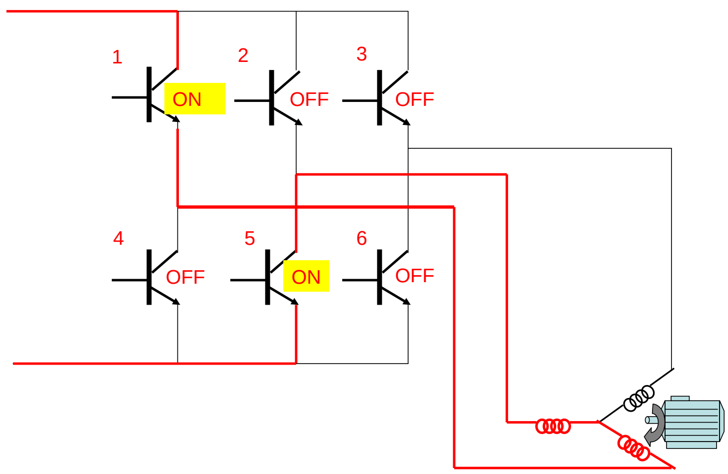
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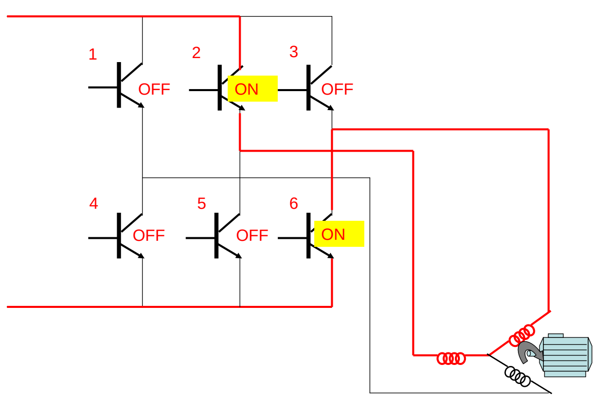
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Elimination of Contactors

Change of direction of rotation.

The direction of rotation of the motor is controlled by the sequence of the Transistor switching. To change the direction of rotation of the motor, the electronics in the Inverter will change the sequence of Transistor switching. This facility then eliminates the need to have forward and reverse contactors and associated control and interlock circuits.

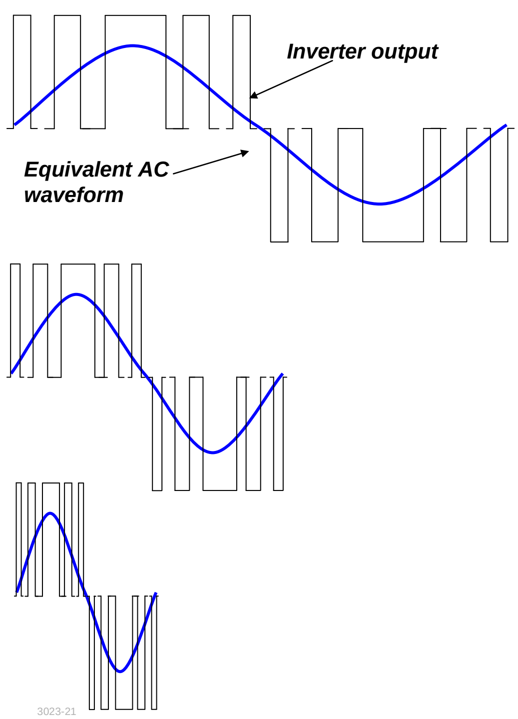
Star Delta

The installation and programming of an Inverter can also do away with the need where required for a Star/Delta start circuit. The Inverter can be programmed to slowly pulse in the starting current to a motor. This is often referred to as a **Soft Start.**

However due to their relative cheapness compared to the cost of an Inverter, Forward and Reverse contactor switching, and Star Delta start circuits are still used for many situations.

Relationship of input frequency to speed

The following diagrams illustrate how the DC to AC conversion by the Inverter electronics uses the switching frequency to vary the speed of the motor.



Low frequency pulses For low speed

Medium frequency pulses For low medium speed

High frequency pulses For high speed