EDEXCEL NATIONAL CERTIFICATE/DIPLOMA

UNIT 67 - FURTHER ELECTRICAL PRINCIPLES

NQF LEVEL 3

OUTCOME 4 - 3 PHASE POWER

Unit content

4. Understand three-phase alternating current (AC) theory
***Three-phase AC theory*:** principles of single-phase and three-phase supplies e.g. rotation of a single coil in a magnetic field, rotation of three identical coils fixed 120° apart in a magnetic field; star and delta methods of connection for power distribution systems; three and four wire systems; voltage relationships for star and delta connections under balanced conditions of load; calculation of power in balanced and unbalanced three-phase loads e.g. $P = 3\sqrt{}V_L I_L \cos\theta$, $P = 3I_p^2 R_p$

Power measurements in a three-phase AC system: e.g. delta system — one wattmeter method, star system - two wattmeter method

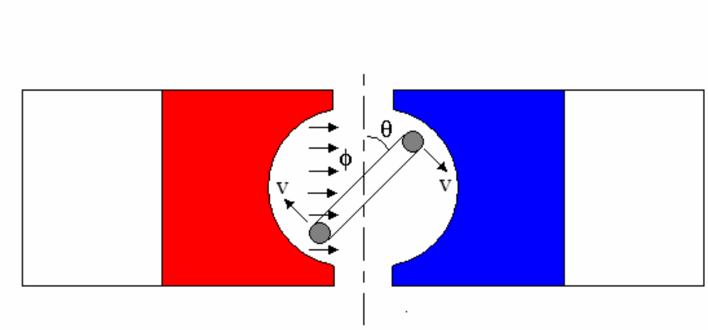
***Three-phase AC induction motor*:** construction e.g. stator, rotor, poles; principle of operation e.g. production of torque, synchronous speed, number of poles, starting methods, characteristics (speed/torque/efficiency versus current curves); concept of a rotating magnetic field e.g. application of a three-phase supply to the stator windings, flux generated by each phase of the stator winding

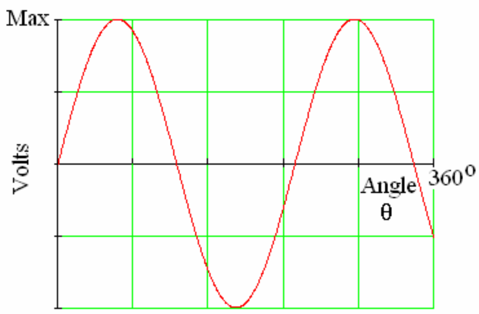
It assumed that the student has studied the Electrical and Electronic principles module.

SINGLE PHASE GENERATION - REVISION

Consider a very simple generator consisting of a loop rotating in a uniform magnetic field. The e.m.f. generated in the conductor is obtained from the basic equation **e = B ℓ v.** In this equation v is the velocity of the conductor at right angles to the flux and clearly when the loop is horizontal in the diagram this is the velocity of the conductor. When the loop is in the vertical plane the velocity is parallel to the flux and no e.m.f. is produced. At any other position the velocity is found by resolving v in the vertical direction. v(vertical) = v sin θ

Hence **E = B ℓ v Sin** θ and this gives a sinusoidal alternating voltage.

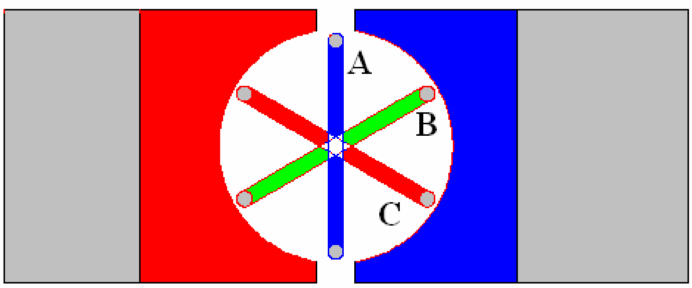


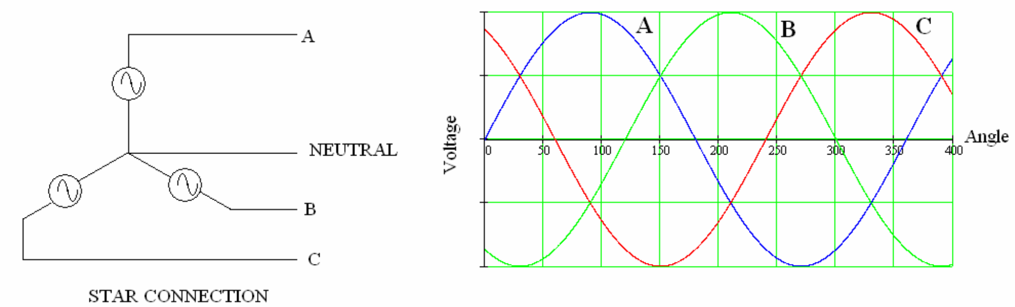


In a practical a.c. generator the loop would have more turns to increase the effective length and slip rings would be used to connect the loop to the external system.

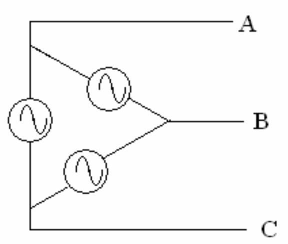
THREE PHASE GENERATION

Suppose we use three loops A B and C instead of one spaced at 120° as shown. Each loop has two ends and if we want to measure the voltages relative to ground zero then we would have to connect one end of all three together and ground it. We have in affect three generators producing an e.m.f with the peaks spaced 120° apart as shown. This is 3 phase a.c.





This form of connection is called **STAR.** We would need three slip rings to connect the loops to the external system and another for the common connection. Notice that the voltage difference between any two lines can be greater at a given instance than the voltage relative to ground. The current owing in any loop is the same as the current flowing in the lines A, B and C. It is possible to connect the loops in a triangular configuration so that the common wire is not needed. When connected as shown it is called a **DELTA** formation. In this case, we have no ground. The current flowing in any loop is not the same as the current flowing in the lines A, B and C. We can still use a ground zero to measure the voltages relative to ground.



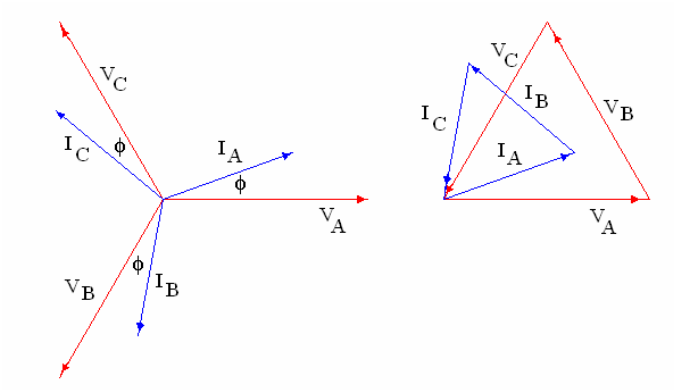
DELTA CONNECTION

We will not discuss here the way that large 3 phase generators are constructed but the principles explained here apply. We must now consider that the 3 phases are supplied to the users by a grid system. At the users end you might be connected between a single phase and neutral to get single phase electricity (domestic users). To help balance the load in each phase domestic suppliers in different areas are connected to different phases. Industrial users will be connected to all three phases and may use the full 3 phase system or single phases. The loads used are usually single and 3 phase motors as well as other inductive devices so they need to apply power factor correction to each phase to reduce the phase angle between current and voltage.

BALANCED LOADS

Electricity suppliers like to keep current and voltage the same in each phase. This is called a balanced load. Ideally the phase angle ϕ between voltage and current would be zero and this would be the case if the load connected at the user end of the system was purely resistive. If not, then power factor correction should be used to keep it to a minimum. The diagram shows the phasors for voltage and current spaced by 120^o with the same phase angle for each.

If we add the phasors as shown we get a closed triangle showing the resultant voltage and current is zero. This means that the current in the neutral or ground line is zero and so the fourth wire is not really needed. For simplicity, in all the following work it will be assumed that the loads are balanced.



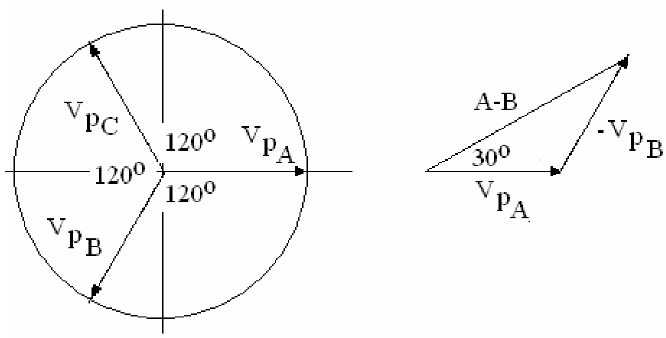
PHASE AND LINE VOLTAGE AND CURRENT

The voltage difference between a phase and neutral is designated Vp (Phase voltage)
The voltage difference between any two phases is denoted V_L (Line voltage)
The current difference between a phase and neutral is designated Ip (Phase current)
The current difference between any two phases is denoted I_L (Line current)

If you study the graph of voltage against angle, you will see that the voltage difference between any two phases (V_L) at certain angles is bigger than the voltage between that phase and neutral (Vp). If V is the maximum phase voltage, then we can express the three phase voltages as:

$V_{pA} = V \sin(\theta)$
$V_{pB} = V \sin(\theta + 120^o)$ or $V_B = V \sin(\theta + 2\pi/3)$ in radian
$V_{pC} = V \sin(\theta + 240^o)$ or $V_C = V \sin(\theta + 4\pi/3)$ in radian

The line voltage between A and B is: $V_L = Vp \sin(\theta) - V \sin(\theta + 2\pi/3) = V \{\sin(\theta) - \sin(\theta + 2\pi/3)\}$
This is best solved using phasors. First consider the phasor diagram for the line voltage. The equal voltages A, B and C are 120^o apart with A in the reference direction. The vector for A - B is shown.
Solving by trigonometry:
$V_{(A-B)} = V_L = 2V\cos(30^o)$
It can be shown that $2\cos(30)^o = 1.732 = \sqrt{3}$



$$\mathbf{V_L = \sqrt{3}\ Vp}$$

If we apply the same logic to the current, then we have a current in each winding which we call the phase current (I_p) and a current in each line called the line current (I_L). If we draw the phasor diagram we will find

$$\mathbf{I_L = \sqrt{3}\, I_p}$$

If the current drawn by each phase is equal then the power for each phase is P = $V_P I_P \cos(\phi)$
Since there are three phases the total power is P = 3 $V_P I_P \cos(\phi)$

$$P = 3\frac{V_L I_p cos(\phi)}{\sqrt{3}} = \sqrt{3}\, V_L I_p cos(\phi)$$

3 phase power is	$P = \sqrt{3}\, V_L I_P \cos(\phi)$
The Apparent power is	$S = \sqrt{3}\, V_L I_P$
The reactive power is	$Q = \sqrt{3}\, V_L I_P \sin(\phi)$

Note - confusion arises when some text state that the line current in a star connection is the same as the phase current. The definition used here for line current is the difference in current as measured between lines so in the above equations strictly only use phase current.

If the power in each phase is balanced and used by a purely resistive load R, then the power in each is I^2R and the total is $3\, I^2R$.

WORKED EXAMPLE No.1

A three phase system with a line voltage of 400V r.m.s and frequency 50 Hz is supplied to a balanced load. The phase angle between the voltage and current is -37^o. The current supplied to each phase is 80 A. Calculate the phase voltage and power supplied.

SOLUTION

$V_p = V_L/\sqrt{3} = 400/1.732 = 231$ V
$P = \sqrt{3}V_L I_P \cos(\phi) = \sqrt{3}(400)(80)\cos(30) = 55.425$ kW

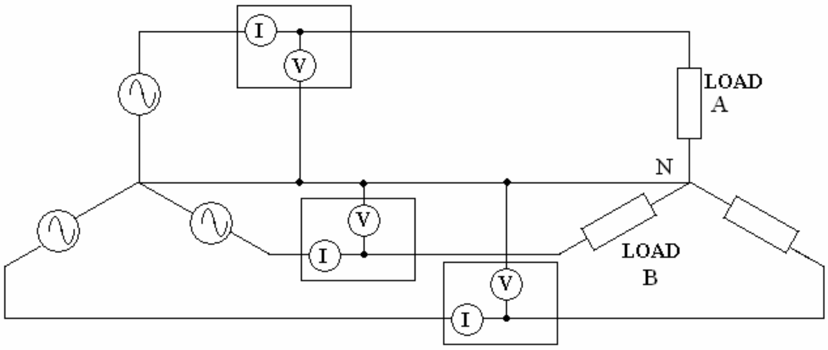
SELF ASSESSMENT EXERCISE No. 1

1. A three phase system with a line voltage of 315 V r.m.s. and frequency 60 Hz is supplied to a balanced load. The phase angle between the voltage and current is -20^o. The current to each phase is 150 A. Calculate the phase voltage and power supplied.
(Answers 181.9 V and 76.9 kW)

2. A 3 phase system uses a line voltage of 415 V rms and maximum line current of 200 A rms. What are the corresponding phase voltages and currents? 239.6 V and 115.5 A
If the phase angle is -8^o calculate:
i. the three phase power. 142361 W
ii. the reactive power. -20007 W
iii. the apparent power. 143760 W

MEASURING 3 PHASE POWER

We might think that the simplest way to measure three phase power is to use 3 Watt meters, one on each phase. Remember that a Watt meter must measure current and voltage so it has three terminals. The diagram shows 3 meters in use with the star formation. Each meter is inserted into a line with one connection to neutral. The total power is the sum of the three meters.

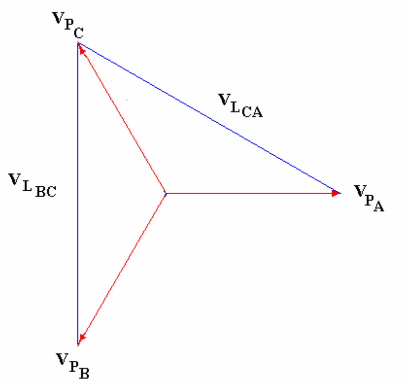


If the system is balanced then the power would be the same for each phase so one meter could be used and the figure tripled.

When the Delta connection is used there is no neutral wire so we have a problem. Fortunately we can measure the total power with only two Watt meters. Here is a bit of theory from Blondel. The total power is as before:

$$\Sigma P = V_{PA} I_{PA} + V_{PB} I_{PB} + V_{PC} I_{PC}$$

Now consider the voltage phasor diagram.



The phase voltage V_{PA} is the vector sum of the line voltage and V_{LCA} and the phase voltage V_{PC}

$V_{PA} = V_{LCA} + V_{PC}$

Similarly $V_{PB} = V_{LBC} + V_{PC}$

The total power can be written as:

$\Sigma P (=V_{LCA} + V_{PC}) I_{PA} + (V_{LBC} + V_{PC}) I_{PB} + V_{PC} I_{PC}$

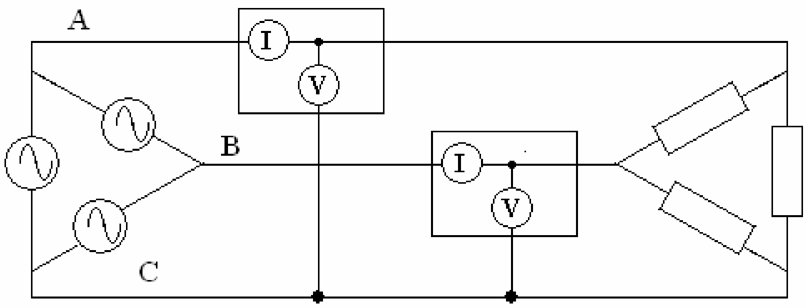
$\Sigma P = V_{LCA} I_{PA} + V_{PC} I_{PA} + V_{LBC} I_{PB} + V_{PC} I_{PB} + V_{PC} I_{PC}$

$\Sigma P = V_{LCA} I_{PA} + V_{LBC} I_{PB} + V_{PC} (I_{PA} + I_{PB} + I_{PC})$

It was shown earlier that for a balanced system, the total current is zero hence:

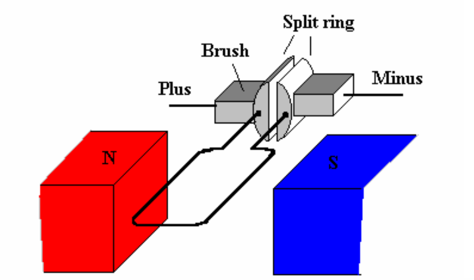
$\Sigma P = V_{LCA} I_{PA} + V_{LBC} I_{PB}$

This means that the total power can be measured with two Watt meters connected as shown in the diagram. This can be used with star or delta and the diagram shows the delta connection.

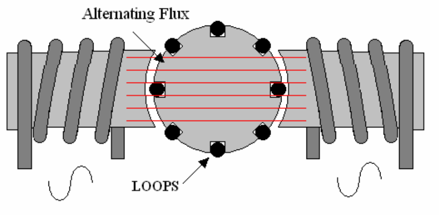


INDUCTION MOTORS

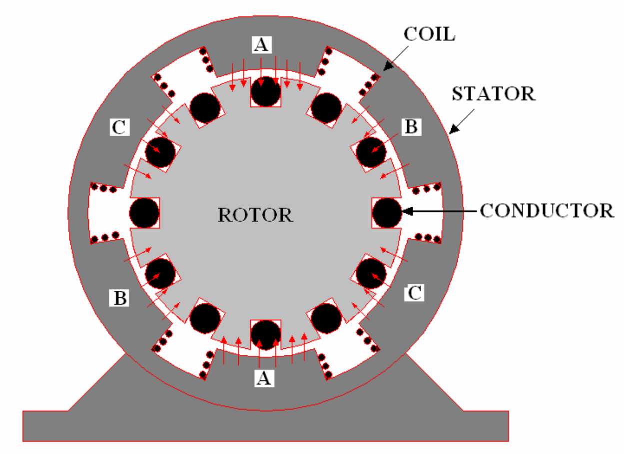
In a DC motor the current is applied to the conductors on the rotor so that the magnetic field interacts with the constant flux. (Covered in Outcome 1).



The main difference between an AC and DC motor is that the magnetic flux is produced by AC in the coils and an alternating magnetic flux produced. The loops on the rotor are shorted and a current is induced in them by the changing flux. This will produce a circular magnetic field around the conductor and this interacts with the varying magnetic field to produce a force on the conductor. This principle is used in induction motors. The design of single phase induction motors is a bit more complicated than this in order to make them work.

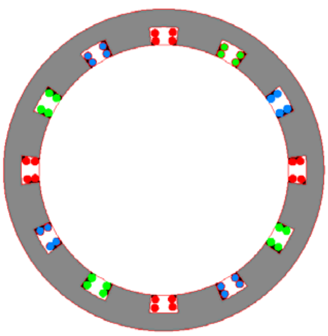


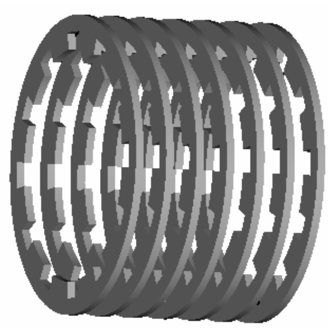
Three phase induction motors use the same principle but there are three set of coils shown as A, B and C. Each one is connected to a phase.
This results in a magnetic flux that varies from maximum to minimum at any point and the point of maximum flux moves around the stator. In other words a rotating magnetic flux is produced.



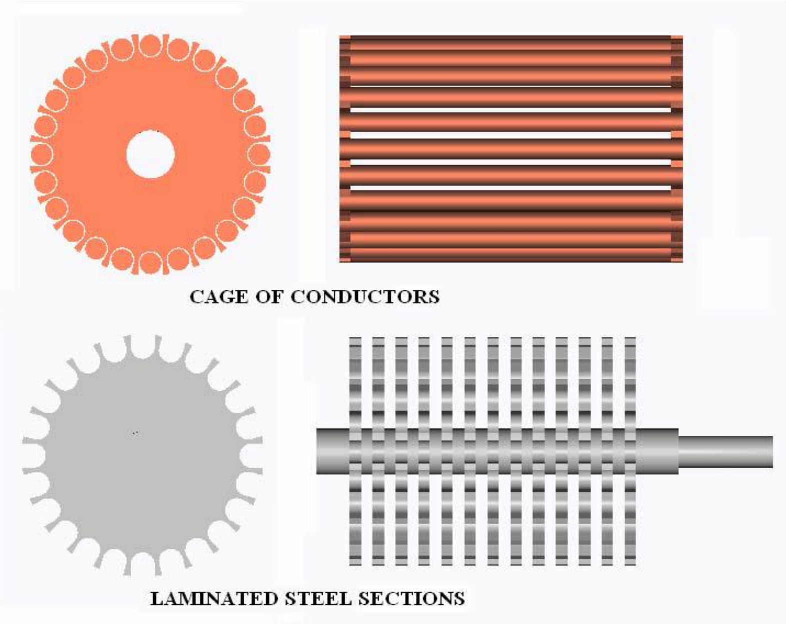
The current and flux induced in the rotor conductors reacts with the rotating field and the rotor is dragged around with the flux. The speed of rotation of the magnetic field is known as the synchronous speed and this depends on the frequency of the power supply. In the UK this is normally 50 Hz and the synchronous speed is 3000 rev/min. When the motor is initially switched on and the rotor is stationary, the effect is at its strongest. This gives it an advantage over other types because it has a high starting torque. The rotor can never rotate at the synchronous speed because there would be no relative motion between the magnetic field and the rotor windings and no current could be induced.

In reality, the coils in the stator overlap and are not spaced as shown previously. This diagram shows the three colours representing three overlapping poles. The stator is made from soft iron laminations as shown to prevent eddy currents being generated in the iron and causing losses.





In the three phase induction motor, the conductors on the rotor are essentially short circuits. Most commonly they are arranged like a cage called a Squirrel Cage for obvious reasons. These slot into the rotor which is made up of laminated iron sections to reduce losses.
In squirrel cage motors, the motor speed is determined by the load it drives and by the number of poles generating a magnetic field in the stator.



SYNCHRONOUS MOTORS

Three-phase synchronous motors have an additional coil on the rotor that is supplied with Direct Current. This produces a constant magnetic field. The motor accelerates to the synchronous speed because the north and south poles of the rotor magnet locks to the south and north poles of the rotating stator field.

The rotor of a synchronous motor will usually include a squirrel cage winding which is used to start the motor rotation and then the DC coil is connected to lock it at the synchronous speed. The squirrel cage has no effect at synchronous speeds as no induction takes place.

NOTES ON SINGLE PHASE MOTOR

Single phase induction and synchronous motors, used in most domestic situations; operate on principles similar to those explained for three phase motors. However, various modifications have to be made in order to generate starting torques, since the single phase will not generate a rotating magnetic field alone. Consequently, split phase, capacitor, or shaded pole designs are used in induction motors. Synchronous single phase motors, used for timers, clocks, tape recorders etc., rely on the reluctance or hysteresis designs. You will need to look elsewhere for details of these designs.
The advantages of 3 Phase motors over single phase are:

More Compact
More Efficient
High starting Torque
Less costly
Smoother running

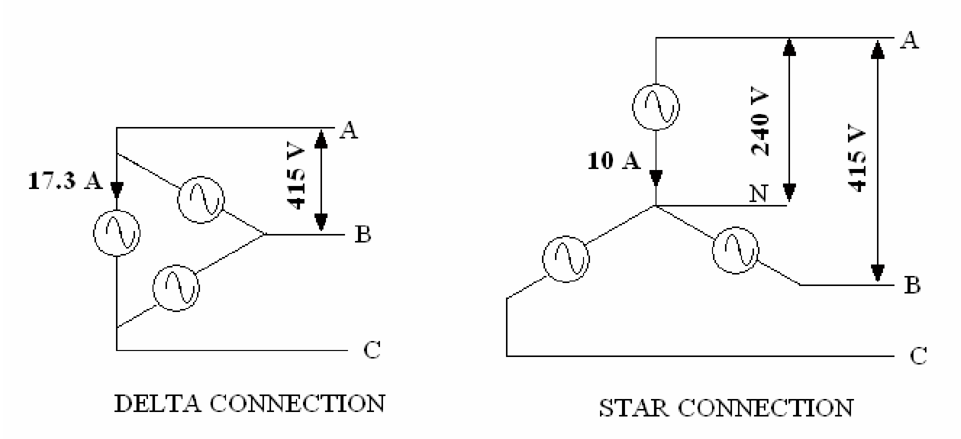
One disadvantage is that when starting large motors, very high currents are drawn in the windings so various methods of starting theme used and you need to study the STAR – DELTA method

STAR - DELTA STARTING

It was shown earlier that the line current is related to phase current by the formula $I_L = \sqrt{3}I_p$

If the coils are connected in a star formation, the current flowing through them is the phase current. If the coils are connected in the delta formation, the current flowing through them is the line current.

Suppose we had a 3 phase motor supplied with 415 V and 17.3 A (Line values). If the motor is connected in delta formation we have 17.3 A in each coil and 415 V over each.
If we connect it in star formation we get 17.3/√3 = 10 A in each coil and √3 x 415 = 240 V over each.



3 Phase motors running normally have their field coils connected in the DELTA fashion. Because of the high currents drawn on starting when the induction effect is greatest, the coils are connected in the star formation and then changed to the delta formation when it has accelerated close to its running speed. Note that the starting torque is also reduced in star formation but this is usually sufficient to run the motor up to speed.

The change from Star to Delta is normally achieved by external switching and this is commonly referred to as a soft starter or a Star Delta starter. This is simply a number of contactors (switches) that connect the different leads together to form the required connection, i.e. Star or Delta. These use a specific starting sequence with timers to switch between Star and Delta.

The starting components need extensive protection involving the monitoring of time, current, voltage and motor speed. The cost of the soft starter depends on the frequency of starting/stopping the motor and the motor rating (size and duty).

When switching is done, large transients occur in the voltage and currents. It is important that a short pause occurs during switchover so that the star contactors can have reliable arc quenching.
This pause must not be so long that the motor decelerates.

SELF ASSESSMENT EXERCISE No. 2

1. Describe the differences between the 3 phase induction motor and the 3 phase synchronous motor.

2. What are the advantages of using 3 phase motors compared to single phase motors?

3. Describe the construction of a 3 phase synchronous motor.

4. Explain the reasons for using Star Delta connections to start 3 phase motors and discuss the advantages and disadvantages.

5. Explain with the aid of a diagram how a rotating magnetic filed is produced in the stator of a 3 phase motor.

6. Explain with the aid of a circuit diagram how you would measure the power supplied to 3 phase induction motor when it is connected in the Star formation with only one Watt meter.

7. Explain with the aid of a circuit diagram how you would measure the power supplied to 3 phase induction motor when it is connected in the Delta formation.