Introduction To Industrial Motors

Lesson 3 – Basic Theory

Introduction to Industrial Motors
Lesson 1 - Basic Theory

Goal	IMO internal and external sales staff will have a basic introduction to electric motors.
Objectives	• Lesson 1 is intended to provide the participant with fundamental knowledge of AC and DC motors, and should be attempted following successful completion of courses: *Introduction to electrical power* (lesson 1) – Basic theory, and *Introduction to low voltage AC power systems* (lesson 2) – Basic theory. • This lesson introduces AC and DC machines common in industry and a basic knowledge of how they work. Also covered is a brief look at different types of loads. • This lesson further prepares the participant for dealing with simple electrical engineering and automation questions from customers. • To widen the knowledge and awareness of the delegate as to what happens 'down-stream' of IMO products in a process.
Length	This lesson is intended to take approximately 2 hours +
Content outline	***1.*** **Getting Started** *(same as general course pattern)* **2. Overview** **3. DC motors, AC motors, Loads, Other motors**
Learning Activities	Delegates will engage in the following activities at the end of this lesson • Quiz • Test at later date
Evaluation Strategy	Delegates may be deemed to have an appropriate understanding of this course by obtaining at least 80% in the test.

Industrial Electric Motors

Electric motors were invented well over 100 years ago and have remained one of the most important factors in the growth of industry and manufacturing worldwide. This lesson concentrates on the most popular types, the dc motor and the ac motor, but mentions other types of motor also. We will also take a brief look at the characteristics of some common loads that motors can be asked to drive. Industrial motors come in all shapes and sizes, from the most minute of barely a few Watts, to gigantic machines rated at one Megawatt or more. It is a fact that around 80% of the total power generated in the UK is used by electric motors, and from this figure it follows that there are many millions of motors in everyday use. Every different motor application will be best suited to one of a variety of designs and types, each one having very different characteristics.

Fans, conveyors, mixers, crushers, pumps, lifts, elevators, extruders, cranes, hoists, compressors, air conditioning, and robots, all use electric motors to function. They may be installed on ships, aircraft, trains, trams, oil rigs, etc and at some point in the near future cars will be propelled by motors also.

Motors are used to convert electrical energy into mechanical force and movement so they are able to do work directly, or via some form of pulley arrangement or gearbox.
Below we will describe the operating principles of the two most widely used motor types.

DC motors – As the name implies these motors work on DC current only. There are several different winding configurations possible – series wound, shunt wound, series-shunt, compound, etc, each giving the dc machine a different torque and speed performance. DC motors are the oldest type of motors, and for decades provided us with most industrial solutions, having inherently high output torque right across their speed range and even at zero speed will have full torque at the output shaft. A dc motor consists of a rotor with a coil(s) wound onto it known as the **Armature**. The ends of the armature windings are terminated at a special area of the rotor called the **Commutator**.
This is constructed of many copper segments formed over a tube, each segment separated from the next and previous segments by mica insulation. Each end of the armature coil(s) is soldered onto its own segment.

The second major part of the dc motor is the fixed winding known as the **Field** coil, embedded into the motor frame. Spring loaded soft carbon **brushes** always make contact with the armature, and carry the dc current directly to and from the armature.

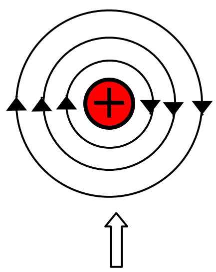
The whole rotor assembly is held in position by bearings at either end of the shaft, and large permanent magnets fixed into the walls of the machine provide the required excitation.

Electronic speed control is possible by using a DC **drive** to adjust the amount of dc voltage and current fed to the dc motor. By this method the speed of the motor is proportional to the voltage applied to the armature, and torque is proportional to armature current. DC motors are usually supplied with a tacho-generator mounted on the end of the rotor to give a feedback signal to the dc drive, for closed loop speed control.DC motors are also fitted with a large separately excited blower, to ensure the machine does not over heat when the speed is low or at standstill, and current and torque are high.

The biggest problem with dc motors is their relatively high maintenance costs. The brush gear and commutator face has to be inspected regularly for excessive wear, and brushes changed periodically. Of course this means that the machine has to be stopped and taken out of service which can interrupt production, etc. Compared to ac motors, dc machines of the same power output are also much more expensive to buy as new and repair later. Although still reasonably popular in some applications, by and large we are seeing the dc market shrink as modern ac speed control methods allow ac induction motors to perform with similar dynamics to their dc rivals. At very small powers, the dc motor will always remain dominant, especially in the domestic power tool and hair dryer type applications.

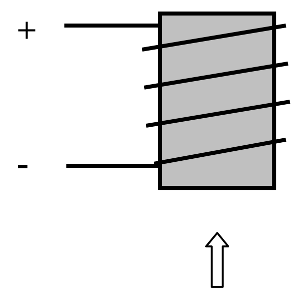
DC motor basic principles

Fig 1



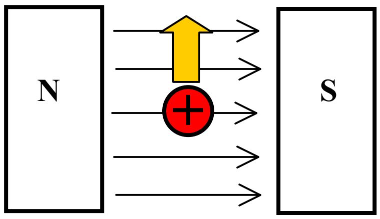
Passing a current through a conductor generates a field around it

Fig 2



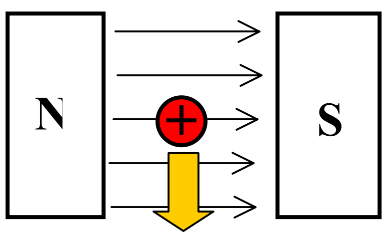
Winding the conductor around an iron core gives a much greater field

Fig 3



If you move a conductor through a field an emf will be induced along it

Fig 4



If you pass a current through the conductor the fields will interact and make it move

Fig 5

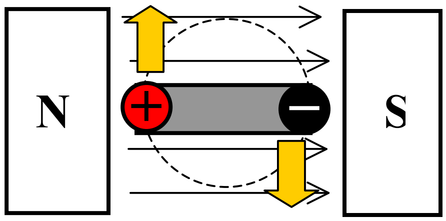
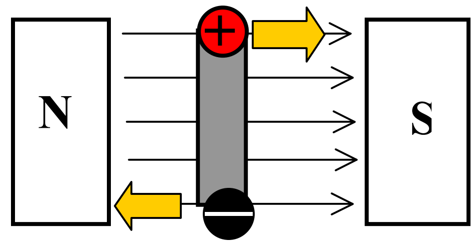
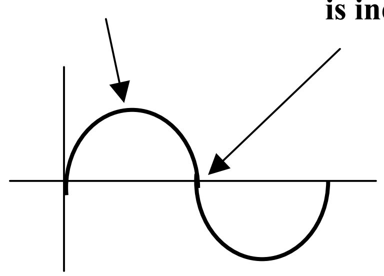


Fig 6



Loop horizontal – the red side of the loop is moving up and cutting flux. An emf is induced in it. The black side is moving down and cutting flux, an emf is also induced.

Loop vertical – both sides are moving parallel to the flux lines. **Neither side is cutting flux. No emf is induced.**



Magnets – Magnetic lines of force come out of the North Pole and go into the South Pole. The magnetic field strength is proportional to the number of lines per unit area. Passing a current through a conductor generates a magnetic field around it. The field strength is proportional to the current, greatest near the conductor. Winding the conductor into a loop concentrates the flux in the centre. The practical unit of field strength is known as the Ampere-turn. Iron offers less opposition (Reluctance) to the flux than air, and an iron core in a coil greatly increases the field strength.

Generator action – A voltage is induced in a conductor moved at right angles to a field. As the conductor moves it ‘cuts’ the lines of flux. The cutting rate is proportional to its velocity and the field strength. The voltage is proportional to the cutting rate and the length of the conductor. This is a generator action see figure 3 and 4.

Motor action – The flux around a conductor carrying current and at right angles to a magnetic field adds to the main flux on one side and subtracts from it on the other. A force is exerted in the direction of reduced flux. The force is proportional to the main field strength, the current and the length. This is motor action and is what makes a dc motor generate **torque** and rotate. Motoring and generating are complementary. A motor is a generator is a motor see figures 5 and 6.

Simple alternator – The coil is rotated clockwise, connections are made by slip rings and brushes.

In Figure 5 the red end of the loop is moving up and is cutting the flux lines. A voltage is induced along it as shown. The black end is moving down and is cutting flux lines, and a voltage is induced as shown. The induced voltages are in series. A meter connected to the slip rings will register a current flow.

In Figure 6 the red end is moving to the right and the black end is moving to the left. Both sides are moving parallel to the flux lines so no cutting action is taking place. No voltage is induced along the wire and no current flows in the meter. This is called the neutral position because there is no output. Although not shown in a diagram, the next stage would be the red end moving down and the black end moving up, so both cutting flux lines again. The meter would show current flowing again but in the opposite direction. The output is proportional to the vertical component of velocity. If the loop were rotated constantly the output would be sinusoidal. There would be one cycle of output per complete revolution of the loop.

Simple DC generator – If you cut a slip ring in half, insulate the two halves from each other and connect the loop to the two halves and arrange for the brushes to contact first one half then the other, you will have made a commutator. The commutator swaps the connections to the loop every half revolution. This process is called commutation. Current still alternates in the loop but is unidirectional in the external circuit. The output is two positive half cycles per revolution. The output has a large ripple – it varies from zero to maximum. In a practical generator there are many loops so its output has much less ripple.

Simple DC motor – This arrangement is also a dc motor. If you apply a voltage to the commutator brushes, current will flow in the loop. The current in the loop generates a magnetic field around the conductor. This field interacts with the main magnetic field. Each half of the loop experiences a force at right angles to the main field and to the direction of the current. The currents in the two halves of the loop are flowing in the opposite directions so the forces on the two halves are in opposite directions. The result is a torque which makes the loop rotate.

When the loop is vertical the force is at right angles to the direction of motion so the torque is zero. As the loop passes through the vertical the commutator reverses the connections. The direction of the current in each half of the loop reverses, so the direction of the forces also reverse. So torque is always generated in the same sense (clockwise). The torque is maximum when the loop is horizontal. The torque goes to zero every time the loop passes through the vertical. This is called **torque ripple** In a practical motor there are many loops so there is much less torque ripple.

SIMPLE DC MOTOR / GENERATOR

[DC armature current]

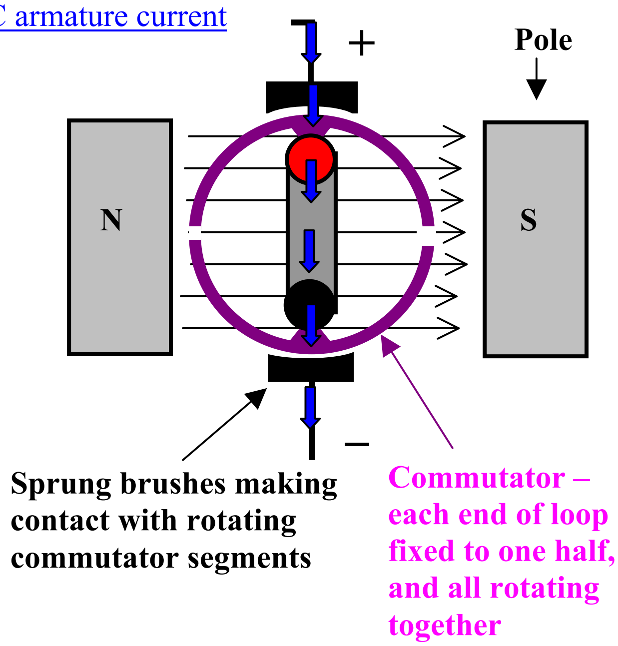


Figure 7

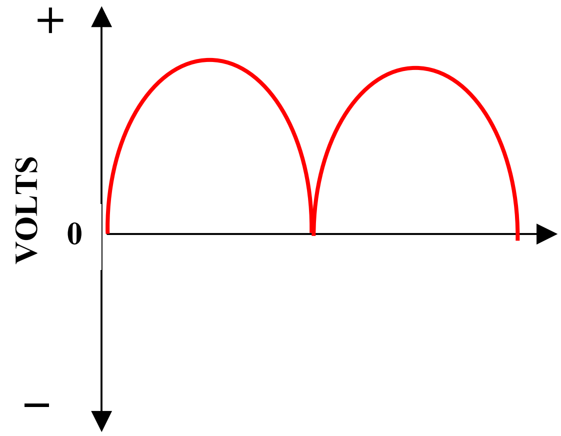


Figure 8

A dc motor is a generator. As the motor rotates it generates a voltage, just as before. This voltage is called the **counter emf** and it always opposes the applied voltage. The difference is the net voltage causing current to flow in the loop. The faster the loop rotates the greater the counter emf, so there is less voltage left over to make current flow in the loop and so less torque. This is what limits the speed of a dc motor.

A real DC motor / generator – The torque generated by the motor is proportional to the strength of the main field. In an industrial size motor it is difficult to get a strong field using permanent magnets so we use a wound field as shown. The field windings use a large number of turns of relatively fine wire and are located in slots in the surface of laminated field poles. The magnetic circuit is completed by the laminated steel motor frame. See Figure 9 on the next page.

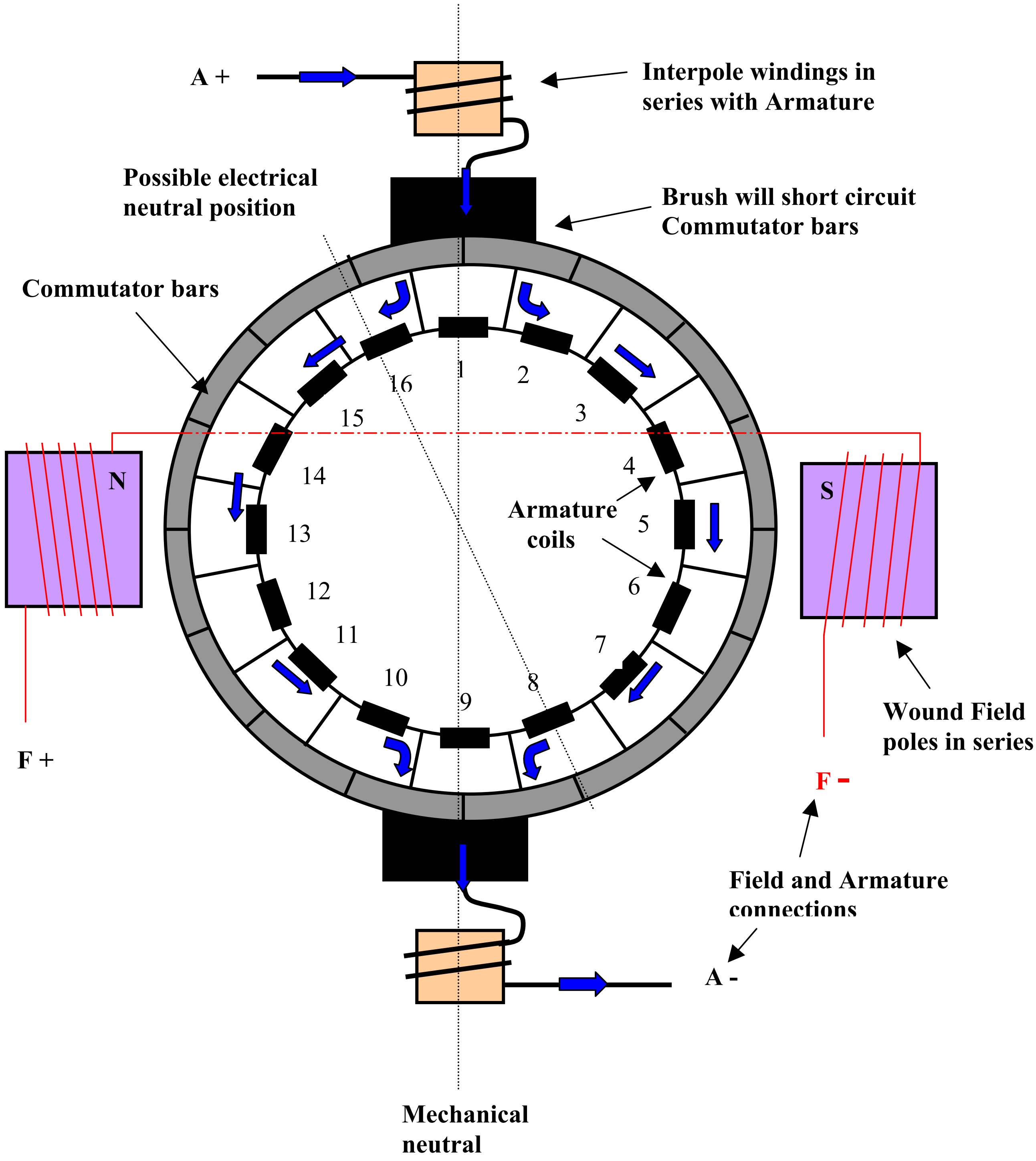


Figure 9. A real DC motor (end view diagram)

The motor has 16 armature coils. The coils lie in slots in the surface of the armature core. The core is a stack of punched laminated steel sheets. Steel has much less reluctance than air, so the flux density produced by armature current is much larger, so the motor can generate much more torque for the same current. Steel is a conductor so as the core rotates currents are induced along it, just as they are in the armature windings. These induced currents are known as **eddy currents**. These eddy currents are wasteful; they just heat up the core. The steel laminations in the core are thin, insulated from each other, and parallel to the main flux to minimise the eddy currents. Coils 2 – 8 are in series, coils 10 – 16 are in series, and the two sets of coils are in parallel. Armature current flows through the two sets of coils.

Motor action – Coils 5 and 13 are moving perpendicular to the main field and generate maximum torque. Coils 1 and 9 are moving parallel to the main field so they generate no torque. The coils in intermediate positions generate intermediate quantities of torque. There will be much less torque ripple than in the simple motor.

Generator action – Coils 5 and 13 are moving perpendicular to the main field and generate maximum voltage. Coils 1 and 9 are moving parallel to the main field so they generate no voltage. The coils in intermediate positions generate intermediate voltage. There will be much less voltage ripple than in the simple motor.

As a commutator segment passes under a brush the direction of current flow in its coil must reverse. Coils 1 and 9 are parallel to the main flux so they have zero volts. They can be safely shorted by the brush without sparking or arcing which would damage the commutator. This is why the brushes are in the position shown. This position is the mechanical neutral of the machine – perpendicular to the main flux.

Interpoles – There is a problem. The only reason why the motor works at all is that the field produced by the current in the armature windings interacts with the main field to produce torque. The interaction distorts the magnetic flux in the motor and rotates it in the same direction as the motor is turning. This effect is known as **armature reaction**. The angle of rotation is proportional to armature current and could be as much as 90º at maximum armature current. Coils 1 and 9 are no longer moving parallel to the field because the field has moved, so the brushes will arc and spark and damage will be caused to the brushes and commutator. You could compensate by physically moving the brushes, say to coil positions 8 and 16, but they will only ever be right for a particular value of armature current.

The solution is to fit extra magnetic poles called **interpoles** between the main field poles, and to connect these in series with the armature current. The field produced by these poles compensates for the flux distortion and moves the magnetic neutral position back to where it should be. Because the interpole current is the same as the armature current (they are in series) the compensation always exactly matches the distortion. Problem solved!

Equations – When the motor is running the difference between the voltage applied to the armature terminals and the back emf is available to drive current through the armature resistance.

Voltage equation

Terminal volts = Back EMF + volts dropped across armature resistance.
The back emf is proportional to the flux and the speed.

$\mathbf{V_{TOTAL} = V_b + (I_a \times R_a)}$ Where: $\mathbf{I_a}$ = **Armature current** and $\mathbf{R_a}$ = **Armature resistance**

$\mathbf{V_b = K \times Flux \times N}$ Where: **K** is a constant and **N** = **speed**

so

$$\boxed{\mathbf{V_{TOTAL} = K \times Flux \times N + (I_a \times R_a)}}$$

Torque equation

The torque developed is proportional to the flux of the main field and the armature current.

$$\boxed{\textbf{Torque = constant x Flux x Armature current}}$$

Torque = $\mathbf{K.Flux.I_a}$

The constant K takes account of the radius of the armature, the number, length, and arrangement of the conductors, and the number of poles.

»»

If the motor is operated from a suitable DC power supply, starting current must be limited. If you connect the field then apply volts to the armature there will be a rush of current through the armature. The armature is stationary so there is no back emf. The full value of the applied voltage is available to drive current through the armature. This starting current must be limited or the motor will be damaged. One method is to progressively switch out a number of starter resistors connected in series with the armature supply.

The torque generated depends only upon the flux and the armature current. In the simplest arrangement the field is powered from a fixed supply, so the torque depends only on the armature current. So if we limit our starting current to 100% then we get 100% starting torque. This is the principle advantage of a dc motor.

IT ACCELERATES UNTIL DEVELOPED TORQUE = LOAD TORQUE

With 100% starting torque the motor will accelerate rapidly. As it accelerates the counter emf increases, reducing the voltage available to drive current through the armature. The current, torque and acceleration rate drop off. The speed will continue to increase until a steady state condition is reached where the counter emf limits the current to the value where the torque developed exactly matches the load torque, and that is the final speed it runs at.

THE SPEED VARIES TO MATCH THE LOAD TORQUE

If the load increases the motor will be generating less torque than the load requires at that speed, so it slows down. The back emf decreases so the armature current increases which generates more torque. The speed drops until the torque developed matches that required by the load. If the load decreases the motor will be generating more torque than it needs, so it speeds up until the increased back emf reduces the armature current and torque to match the new load. Look at the voltage equation. If the load (I_a x R_a) and the Flux stay the same then the speed varies directly with the applied volts.

TORQUE IS PROPORTIONAL TO ARMATURE CURRENT.
&
SPEED IS PROPORTIONAL ARMATURE VOLTS

WEAKER FIELD, MORE SPEED, LESS MAXIMUM TORQUE

$$\mathbf{V_T = K \times Flux \times N + (I_a \times R_a)}$$

$$\mathbf{T = K.Flux.I_a}$$

If the applied voltage and armature current are constant then reducing the flux increases the speed. This is called **field weakening.** Look at the torque equation. Decreasing the flux reduces the maximum available torque. This can be done using a variable resistance or an electronic controller (drive).

Reversing – There are two ways to reverse the direction of a DC motor – reverse the direction of armature current or reverse the direction of field current. In practice you can do either with a contactor. Do both and nothing happens.

Dynamic braking – Imagine a dc motor driving a flywheel at high speed. What happens if we reduce the applied terminal volts? A motor is a generator is a motor. The motor will be going faster than the applied voltage says it should, and the inertia (stored energy) in the flywheel will keep it going. The motor will be doing more generating than motoring – the back emf will be greater than the applied voltage. The motor will convert **kinetic** (rotational) energy in the flywheel into electrical energy and supply it back to whatever is connected across the armature. This is called **regeneration**. If you switch in a resistor across the armature while this is happening it will load the generator (ie, the motor), absorb energy from it, and slow it down. The more current you take out the greater the braking effect. This is called **dynamic braking**.

Torque-speed curve – The motor rating plate specifies a **base** speed and a maximum speed. We have seen that 100% torque is available from zero speed upwards. The mechanical power produced by the motor is the product of the torque it is producing and the speed it is rotating at. The electrical power being absorbed by the motor is the product of the armature volts and the armature current. Ignoring losses the mechanical and electrical powers are the same. The base speed is the maximum speed at which the motor can generate 100% torque without being overloaded. A motor generating 100% torque at its base speed has maximum armature volts, maximum armature current and is producing its maximum power.

The motor can run above its base speed, but the power must never exceed 100%. This can be achieved by field weakening. Reducing the field flux increases the speed for a given armature volts. Reducing the field flux also reduces the maximum torque available proportionally, so the power remains constant. For a DC machine the maximum speed is typically 3 or 4 times base speed.

FROM ZERO SPEED TO BASE SPEED THE MOTOR CAN GENERATE CONSTANT 100% TORQUE.

FROM BASE SPEED TO MAXIMUM SPEED THE MOTOR CAN GENERATE CONSTANT 100% POWER

See Figure 10 on the next page .

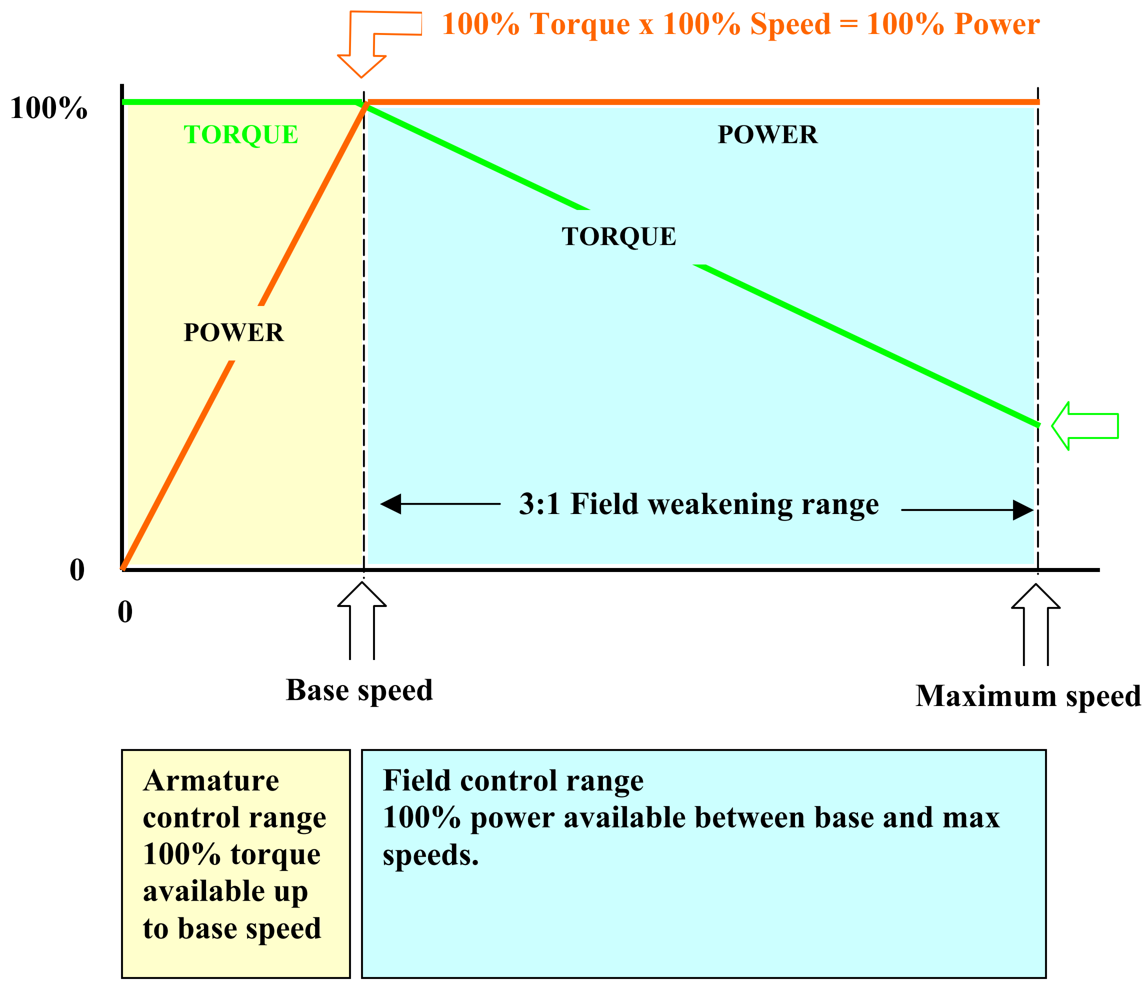


Figure 10. DC Motor torque / speed curve

AC motors – There are many types of AC motor, and for general purposes can be wound for single or three phase supply voltages. Industrial AC motors are nearly always of the 3-phase type as the single phase types are limited to a few kilowatts of power output and have other disadvantages. By far the most popular AC machine in use is the called the **Induction motor** or **Asynchronous motor.** The induction motor is inherently a single speed machine, running speed governed by the frequency of the supply voltage. The induction motor has however many advantages over the DC motor. The main ones being lower initial cost, lower cost of ownership, less maintenance, more robust, and is readily available as an 'off-the-shelf' solution in standard power ratings. See Figure 11.

0.25kW	**0.37 / 0.4kW**	**0.55kW**	**0.75kW**	**1.1kW**
1.5kW	**2.2kW**	**3kW**	**3.7 / 4kW**	**5.5kW**
7.5kW	**11kW**	**15kW**	**18.5kW**	**22kW**
30kW	**37kW**	**45kW**	**55kW**	**75kW**
90kW	**110kW**	**132kW**	**160kW**	**185kW**
200kW	**220kW**	**250kW**	**280kW**	**315kW**

Figure 11. Standard Induction motor power ratings available for 380 – 440V 50/60Hz 3-phase supplies

For many years the induction motor struggled to make an impact in the market place because of its inability to run at different speeds other than rated. The number of magnetic poles ordered for a specific machine allowed some fixed flexibility of operating speed, but for process and manufacturing industries, the lack of infinite controllability other than stop/start and forward reverse operations limited widespread use in favour of the easily controlled DC machine.

In the early 1970's, the first true variable speed controllers for induction motors were manufactured. In the 1980's, with the rapid development of digital electronics, microprocessors and high power semi-conductors, ac speed control was fast becoming state of the art, and the DC markets began to decline. In the 1990's to date, the advance of AC technology has meant that the DC machine no longer has any real dominance apart from a few specialist applications. It is usually possible to retrofit a suitable induction motor and electronic ac speed controller, either in open or closed loop control depending upon the application, in place of an existing DC motor arrangement, with all the advantages included.

The AC induction motor works in an entirely different way to the DC motor as we shall see, although some theory and first principles are common to both. The main difference is that AC motor has no brushes or physical or electrical connection between the rotor and the stator like the DC machine – the rotor receiving power from the stator by the induction principal.

AC motor basic principles

The Stator – The Stator and the Rotor are the two main parts of an induction motor.
The stator is the fixed part of the motor. In the stator housing there is a laminated iron core consisting of thin sheets of 0.3 to 0.5mm thick. The stator core has slots machined into the internal faces which contain the three phase windings. The phase windings and the stator core must produce a magnetic field in a number of pole pairs. It is the number of pole pairs which determine the speed of the rotating magnetic field. When an asynchronous induction motor is operated at rated frequency, the speed of the magnetic field is called the **synchronous speed** of the motor, $\mathbf{n_0}$.

Pole number	2	4	6	8	12
n_0 (rpm)	3000	1500	1000	750	500

Figure 12. The pole numbers of the motor versus synchronous speed at 50Hz supply volltage

The phase windings consist of several coils. The actual number is determined by the required pairs of poles. For example, in a 2-pole motor one coil covers:-

$$\frac{360^o}{\text{number of poles}} = \frac{360^o}{2} = \mathbf{180^o}$$

The interval between the starting points of the coils is:-

$$\frac{360^o}{\text{number of phase windings}} = \frac{360^o}{3} = \mathbf{120^o}$$

In 4-pole motors we have $\frac{360^o}{4} = \mathbf{90^o}$ and $\frac{360^o}{3 \times 2} = \mathbf{60^o}$

The Magnetic field – The field rotates in the air gap between the stator and the rotor. A magnetic field is induced when one of the phase windings is connected to one of the phases of the supply voltage.

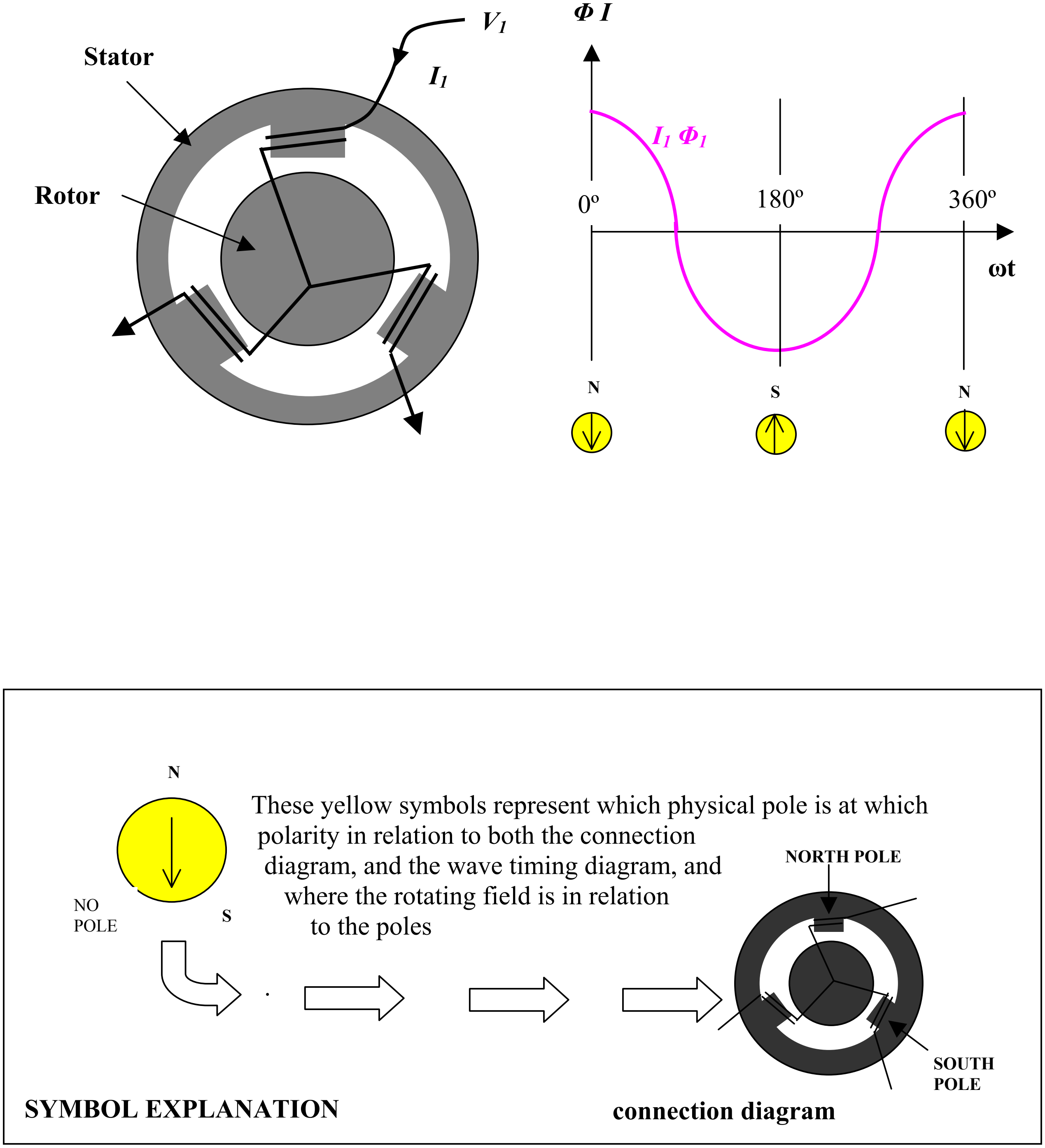


Figure 13. Connecting one phase gives an alternating magnetic field $I_1\ \Phi_1$

Two magnetic fields are produced in the stator core when two phase windings are connected to two phases of the supply voltage at the same time. In a 2-pole machine there is 120º displacement between the two fields, and there is also a time interval between the maximum values of the two fields. This is how a magnetic field is created which rotates in the stator.

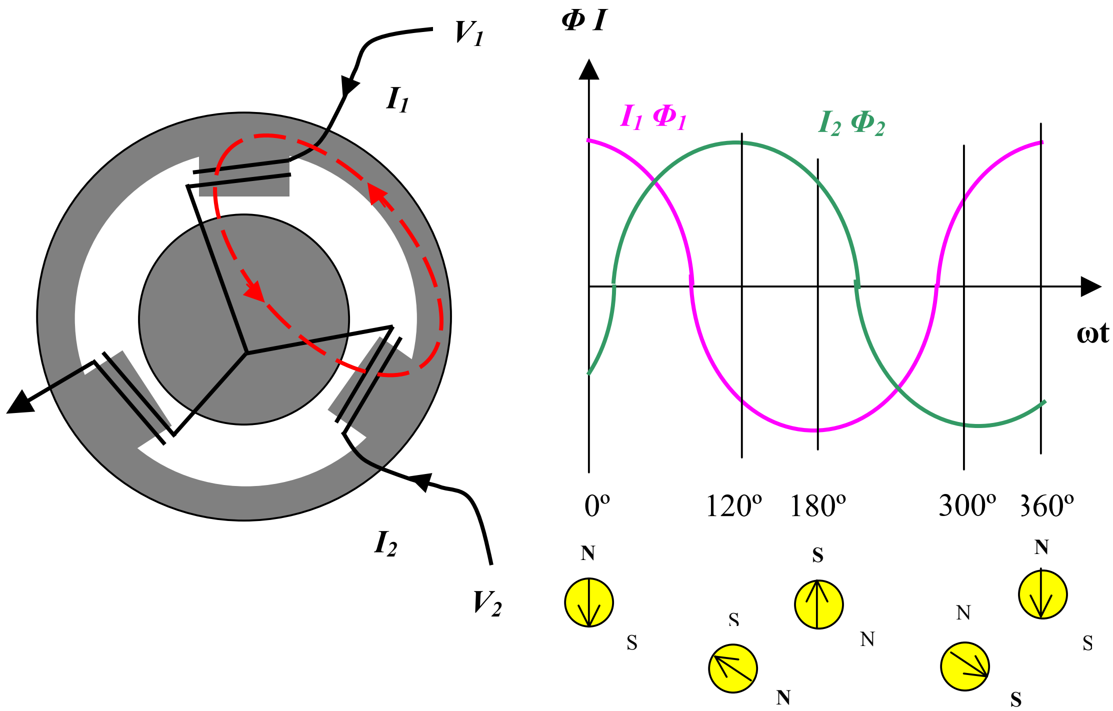


Figure 14. Connecting two phases gives an asymmetrical rotating field

However, the field is very asymmetrical until the third phase is connected. When the third phase is connected, there are three magnetic fields rotating in the stator core. There is 120º displacement between the three phases.

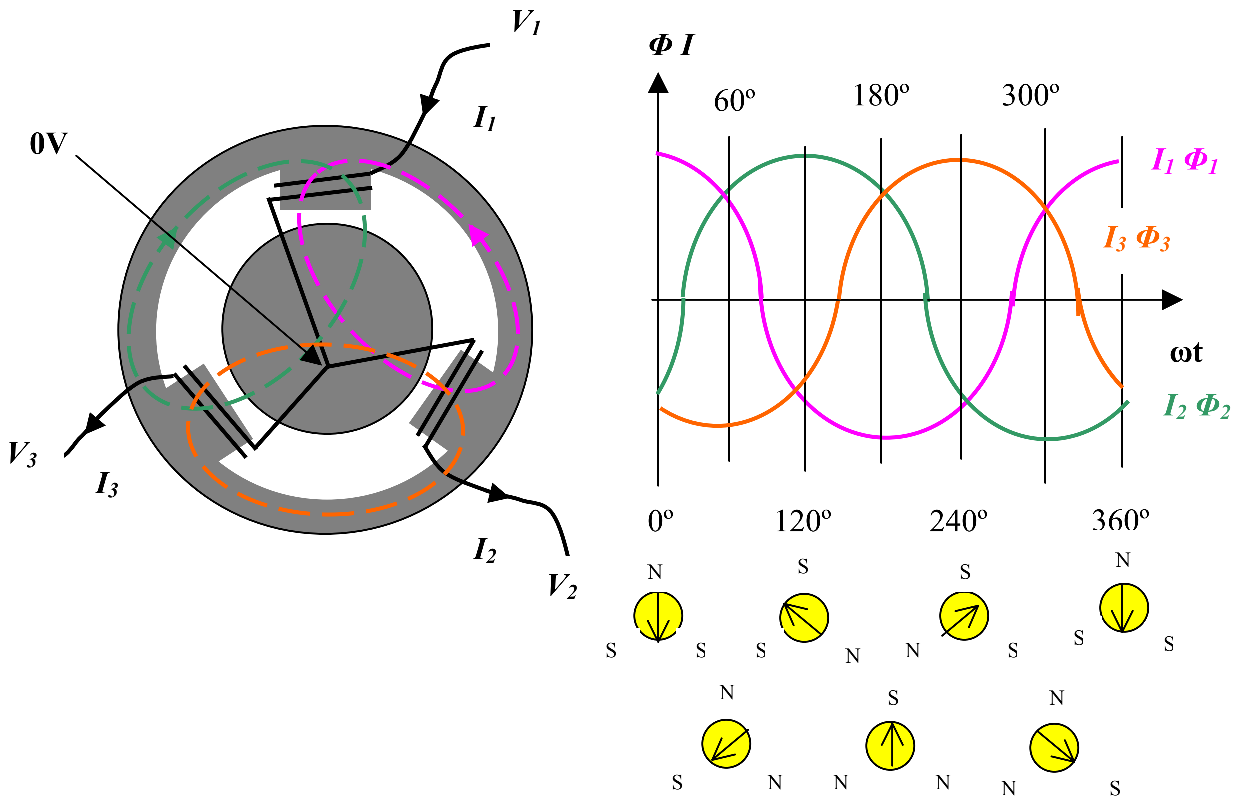


Figure 15. Connecting all three phases gives a symmetrical rotating field

The stator has now been connected to the 3-phase supply voltage. The magnetic fields of the individual phase windings make up a symmetrically rotating magnetic field.
The amplitude of the rotating field is constant and equal to 1.5 times the maximum value of the alternating fields. The speed of rotation is given by:-

$$\mathbf{n_0 = \frac{f \times 60}{p}}$$

Where **p** = **number of pole pairs**

The speed is thus dependant on the number of poles in the motor and the frequency of the supply voltage.

The Rotor – The rotor is mounted on the motor shaft (see figure 16). The rotor, like the stator is made up of thin laminated iron or steel with slots machined into them. The most usual type of rotor is called a **'Squirrel cage'** because it resembles a kind of hamster wheel. It has aluminium rods cast into the slots, and at both ends of the rotor they are all short circuited by an aluminium ring.

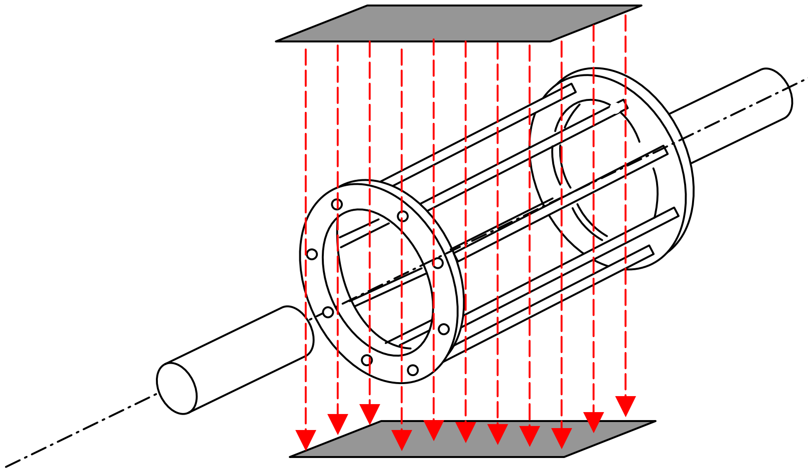
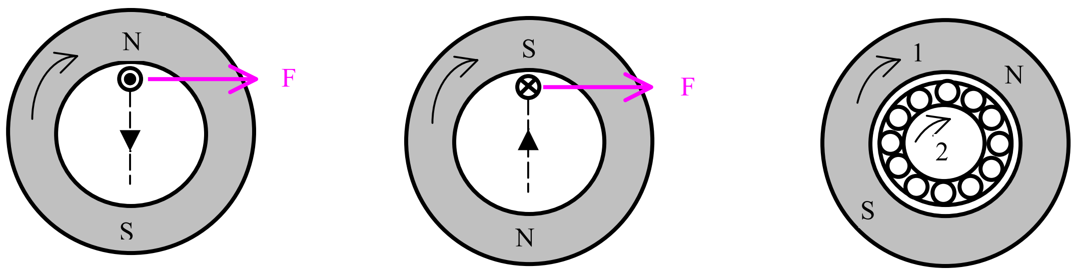


Figure 16. Operational field and Squirrel cage rotor, showing aluminium rods and shorting rings at both ends. Shaft is shown cut away inside rotor for clarity.

This type of rotor is the most common type, replacing older types with wound rotors and slip-rings. If a rotor bar is placed in the rotating field, it is passed by a magnetic pole. The magnetic field of the pole induces an emf along the rotor bar. Because the rod is short circuited by the aluminium rings at either end, a current also flows in the bar. The bar is thus influenced by force F. The next pole passing the bar is of the opposite polarity. It induces a current in the opposite direction of the first one. However, as the direction of the magnetic field has changed the force is still affecting the bar in the same direction.

If the whole rotor is placed in the rotating field all the rotor bars are thus influenced by forces making the rotor rotate. The rotor speed (2) will not reach the speed of the rotational field (1), as no currents will be induced in the rotor bars where the speeds are the same. See Figure 17 on the next page.



Key to symbols

$\odot$ **Current flowing towards you in rotor bar**

$\otimes$ **Current flowing away from you in rotor bar**

Figure 17. Induction in the Rotor bars

Torque, Slip and Speed

Normally the rotor speed $\mathbf{n_n}$ is a little lower than the speed of the rotational field $\mathbf{n_0}$.

$$\mathbf{n_n = \frac{f \times 60}{p} \times (1 - s)}$$

s, which is the difference between the speed of the rotating field and the speed of the rotor is called the **Slip**. $\mathbf{s = n_0 - n_n}$.
The slip is often indicated as a percentage of the synchronous speed:-

$$\mathbf{s = \frac{n_0 - n_n}{n_0} \times 100\%}$$

Normally the slip is between 2 and 8 per cent.
The force acting upon a conductor is proportional with the magnetic field $\mathbf{\Phi}$ and the current **I** in the conductor. In the rotor bars voltage is induced through the magnetic field. Because of this voltage a current **I** can flow in the short-circuited rotor bars.
The various forces make up torque **T** on the motor shaft.

As the magnetic field can be considered to be constant the torque is directly proportional to the current in the rotor and there is **<u>direct proportionality between the torque output and the slip of the motor.</u>**

This is because the torque output is very much dependant on the resistance of the rotor. The bigger the resistance, the less the output torque, and the current heat losses increase with the square of the slip.

The motor slip can be calculated, since the motor nameplate gives the rated speed and frequency. These two items indicate the pole number of the motor.

Example
Calculate the percentage slip of a 50Hz, 960 RPM motor.

From the expression:- $n_0 = \dfrac{f \times 60}{p}$ Where p = number of pole pairs

we can judge the motor to to be a 6 pole machine i.e. the synchronous speed will be (50 x 60) ÷ 3 = 1000RPM. (3 is the closest to number of pole pairs to get 960 RPM at the shaft).
The slip speed $\mathbf{n_S}$ = 1000 – 960 = 40 RPM

The slip is normally stated as a percentage:- $\mathbf{s} = \dfrac{\mathbf{n_S}}{\mathbf{n_0}} = \dfrac{40}{1000} = 0.04 = \mathbf{4\%}$

Figure 18 shows the relationship between the motor torque and the speed. The actual characteristic would be dependent on the design of the rotor slots.

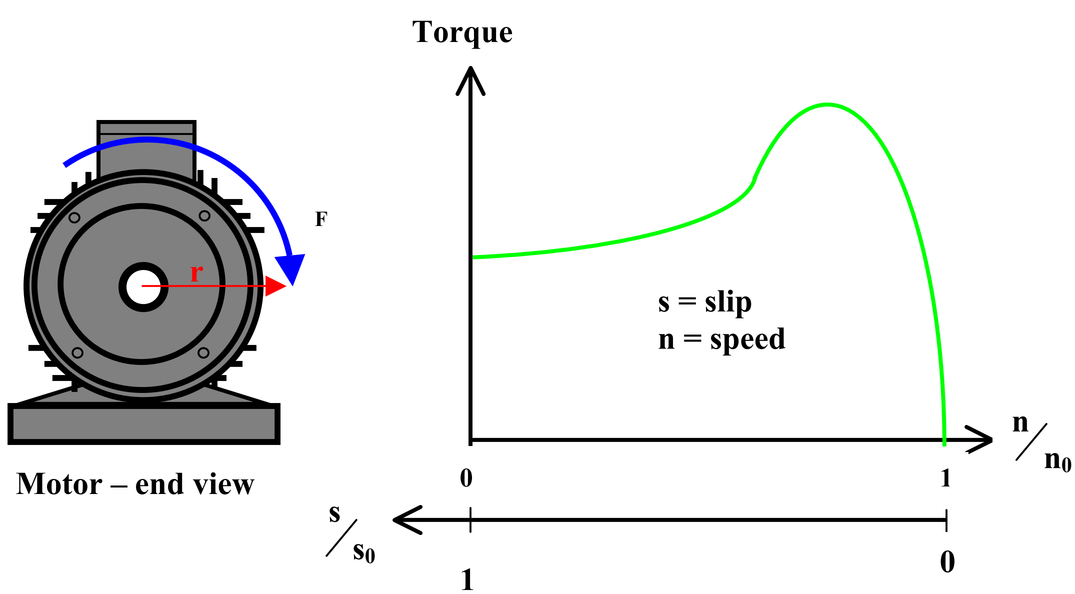


Figure 18. The motor torque is equal to Force 'F' x Radius 'r'

The motor **torque** expresses the force or the "twist" arrising on the motor shaft. The force could for example arise on the flywheel mounted on the shaft. 'F' represents the force and 'r' the radius of the flywheel. The motor torque is **T = F x r**. The work **W** done by the motor can be calculated as follows:- **W = F x d**.

d is the distance moved for a given load and **n** the number of revolutions:-

$$\mathbf{d} = \mathbf{n} \times \mathbf{2} \times \boldsymbol{\pi} \times \mathbf{r}$$

The work can also be expressed as the power multiplied by the period where the power is active:-

$$\mathbf{W} = \mathbf{P} \times \mathbf{t}$$

From these two equations we can derive the following equation for output torque:-

$$\text{Torque, } \mathbf{T} = \frac{\mathbf{P \times 9.55}}{\mathbf{n}}$$

This formula clearly shows the inter-relationship between the motor output power '**P**' expressed in Watts, the shaft speed '**n**' in RPM, and the torque '**T**' in Newton metres (Nm). 9.55 is a constant. If power P is expressed in kW's, change 9.55 to 9550.

Example.

Calculate the shaft output torque of a 4pole, 415V, 50Hz, 7.5kW motor at rated speed.

The motor is 50Hz, 4 pole, so $\mathbf{n_0} = \frac{\mathbf{f \times 60}}{\mathbf{p}} = \frac{50 \times 60}{2} = 1500$ RPM

Slip s is normally between 2 and 8%, so at 5%; slip = 1500 x 0.5 = 75 RPM

Shaft speed at 50Hz = 1500 – 75 = 1425 RPM

so $T = \frac{7{,}500 \times 9.55}{1425} = \mathbf{50Nm}$

Apart from the normal operating range the motor has two braking ranges.

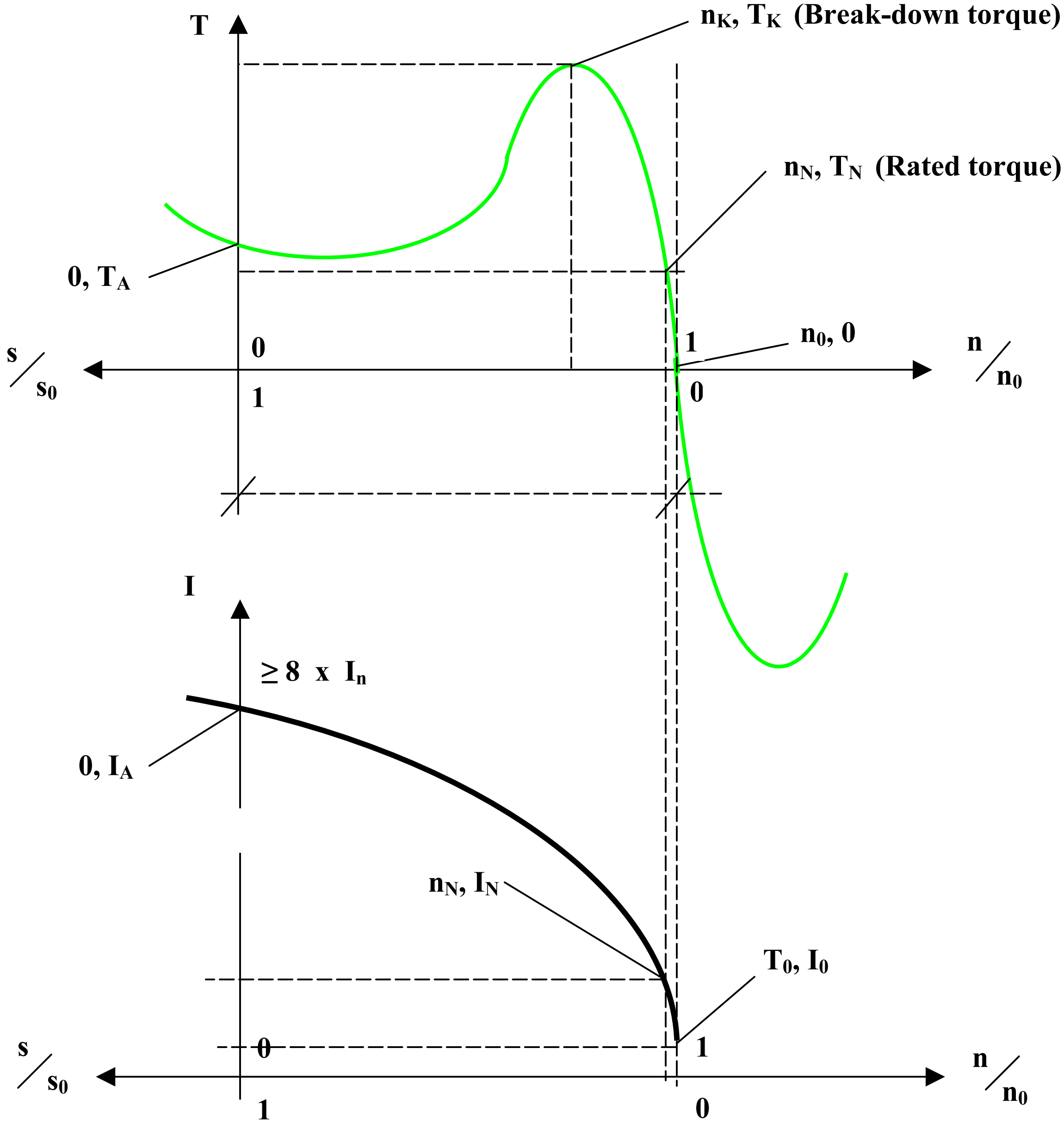


Figure 19. Current and load characteristics of the induction motor

In the range $\frac{n}{n_0} > 1$, the motor will act like a generator.

The flywheel (or whatever mechanical load is connected to the shaft) is pulling the motor over synchronous speed. In this range the motor yields a counter torque and power is transferred back to the mains.

In the range $\frac{n}{n_0} < 0$, braking is called counter current braking.

If two phases to a motor are suddenly swapped over the rotating field changes direction of rotation. Immediately after the rotational speed slip ratio $\frac{n}{n_0}$ will be equal to **1**.

The motor which was loaded with the torque **T** will now brake with a braking torque. This action is known as **'Plug braking'.** If the motor is not disconnected when n = 0 it will accelerate in the new rotational direction of the magnetic field.

In the range $0 < \frac{n}{n_0} < 1$ the motor will be operating in its normal working range.

The operational range can be split up into two ranges:

the **acceleration** range $0 < \frac{n}{n_0} < \frac{n_k}{n_0}$ and

the **operational** range $\frac{n_k}{n_0} < \frac{n}{n_0} < 1$

The important points of the working range are:

T_a is the **starting torque** of the motor. It is the torque which builds up the motor power when it is connected to rated voltage and rated frequency at standstill.

T_k is called the **stall torque** or **maximum torque** of the motor. This is the absolute highest torque that the motor can yield, when it is connected to the nominal voltage and frequency.

T_n is the nominal torque of the motor. The nominal values of the motor are the mechanical and electrical values for which the motor was designed in accordance with the **IEC 34** standard. These can be seen on the motor rating plate or nameplate attached to the motor body.

Efficiency and losses

The motor consumes electrical power from the power supply. At a constant load, the input is larger than the mechanical output than the motor is able to provide, due to losses – or inefficiencies, in the motor. The relationship between the input and output is the motor efficiency **Eff.**

$$\text{Eff} = \frac{P_2}{P_1} = \frac{\text{Output power}}{\text{Input power}}$$

The typical efficiency of a motor is between 0.7 and 0.9 depending on the size of the motor and the number of poles. As a general rule the the larger the motor the better the efficiency. Also, efficiency improves as the motor load torque increases.
Modern high efficiency motors – EFF1 types, can even reach 95% at the higher power ranges of 75 to 90kW.

The efficiency of a motor can be determined by the ratio between its power rating and the electrical input power.

$$\text{Eff.} = \frac{P}{\sqrt{3} \times V \times I \times \cos\varphi}$$

Example
Find the efficiency of a 5.5kW, 415V, 12.5A motor, with power factor of 0.81.

$$\text{Eff.} = \frac{5500}{\sqrt{3} \times 415 \times 12.5 \times 0.81} = \frac{5500}{7277.9} = \mathbf{75.6\%}$$

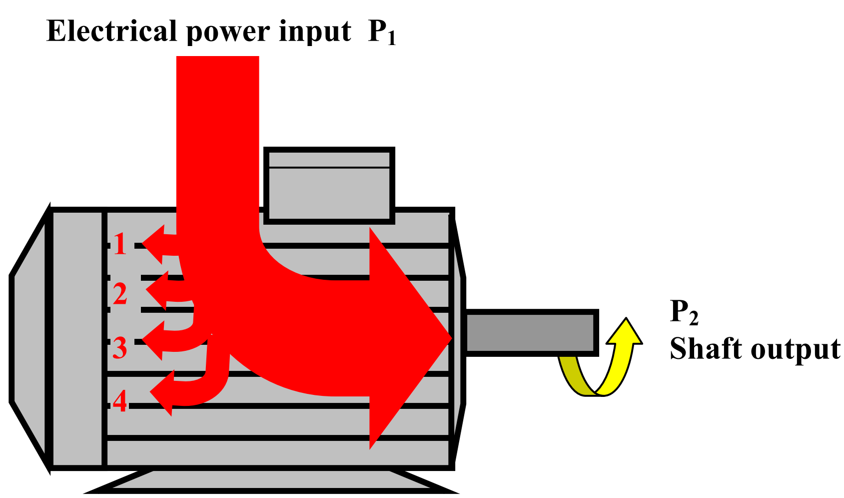


Figure 20. Losses in the motor

There are four main causes of losses in the motor:

1. Copper losses
2. Iron losses
3. Fan losses
4. Friction losses

Copper losses – occur due to current flowing in the resistances of the stator windings and rotor assembly. These are heat losses, and cause the motor to get hot.

Iron losses – consist of hysterisis losses and eddy current losses. Hysterisis losses occur when the iron is magnetized by an ac current and must be de-magnetized at a 50Hz supply voltage at 100 times per second. Both magnetizing and de-magnetizing requires energy. The motor takes excess power from the supply in order to cover the hysterisis losses which increase with frequency and the magnetic induction.

Eddy current losses occur because the magnetic fields induce electric voltage in the iron core and the wire. These voltages result in currents which lead to heat losses and move in circles around the magnetic fields.

By splitting the iron core up into thin sheets, the eddy currents are forced to circulate in much reduced areas hence losses are drastically reduced.

Fan losses - the motor cooling fan mounted on the non – drive end (NDE) of the shaft, will incur losses as it becomes loaded by the air which it is pushing over the cooling fins.

Friction losses – these are caused by the friction in the bearings that hold the shaft in place inside of the motor body.

The friction losses and the wind resistance of the cooling fan are the main reasons why the rotor speed can never match the synchronous field. Of course, if it were able to, the flux lines would no longer be cut by the rotor bars, no torque would be produced, and the motor would stall.

Magnetic field

The motor is designed for a fixed voltage and frequency and the magnetization of the motor depends upon the voltage and the frequency. If the voltage to frequency **V/F** ratio increases the motor is over-magnetized, if it decreases the motor is under magnetized.
The magnetic field of an under-magnetized motor is weakened, and the torque which the motor is able to produce is reduced. This could mean that the motor fails to start or accelerate to rated speed. Alternatively, the accelerating time may be extended leading to motor overload.

An over-magnetized motor is overloaded during operation. The power for this extra magnetization is also converted into heat in the motor and may damage the insulation on stator windings. However, three-phase AC motors and in particular asynchronous motors are very robust, so the problem of faulty magnetization leading to damage will only occur in continuous operation.

The way the motor runs indicates whether the magnetizing conditions are poor. Signs to be aware of are declining speed at varying load and unstable or jerky operation of the motor.

Starting the AC motor

Smaller three-phase motors can be started by using a magnetic contactor **(such as IMO's MC series)** to physically connect the three phases to the power supply in a single switching operation. This type of switching is known as the **direct on line** or **DOL** method. When an induction motor is switched directly to line in this way, the starting currents can be 7 or 8 times that of the rated current of the motor. This current falls to nominal value as the motor develops sufficient torque to accelerate the load to the running speed. A thermal overload **(such as IMO's MC0R series)** must be used in series with the contactor to protect the motor from sustained overload conditions. The current feeding the motor is routed through heater elements in the overload unit. In the event of a sustained overload, the elements overheat and the bi-metal strips carrying the contact faces will bend in such a way that the current carrying contacts separate and break the circuit. Usually a manual or automatic reset can be selected and can be activated when the elements have cooled and the bi-metals have returned to their original shape and proximity to the heaters.

When the high starting current is not acceptable, for example if the motor is large and/or the supply is not able to deliver such current, another common form of starting is known as **star-delta** starting.

Connections

Some motors are wound in such a way that the stator windings can be connected to suit different voltage levels, for example 3-phase 230V or 3-phase 400V. The different connection methods are possible by connecting the six ends of the 3-stator windings into either of two different configurations inside the motor terminal box. The two methods are known as the **star** connection and the **delta** connection.

<u>Reversing any two of the three input wires will change the direction of rotation.</u>

Example

Let us look at a typical motor nameplate that would be fixed to the body of a motor.

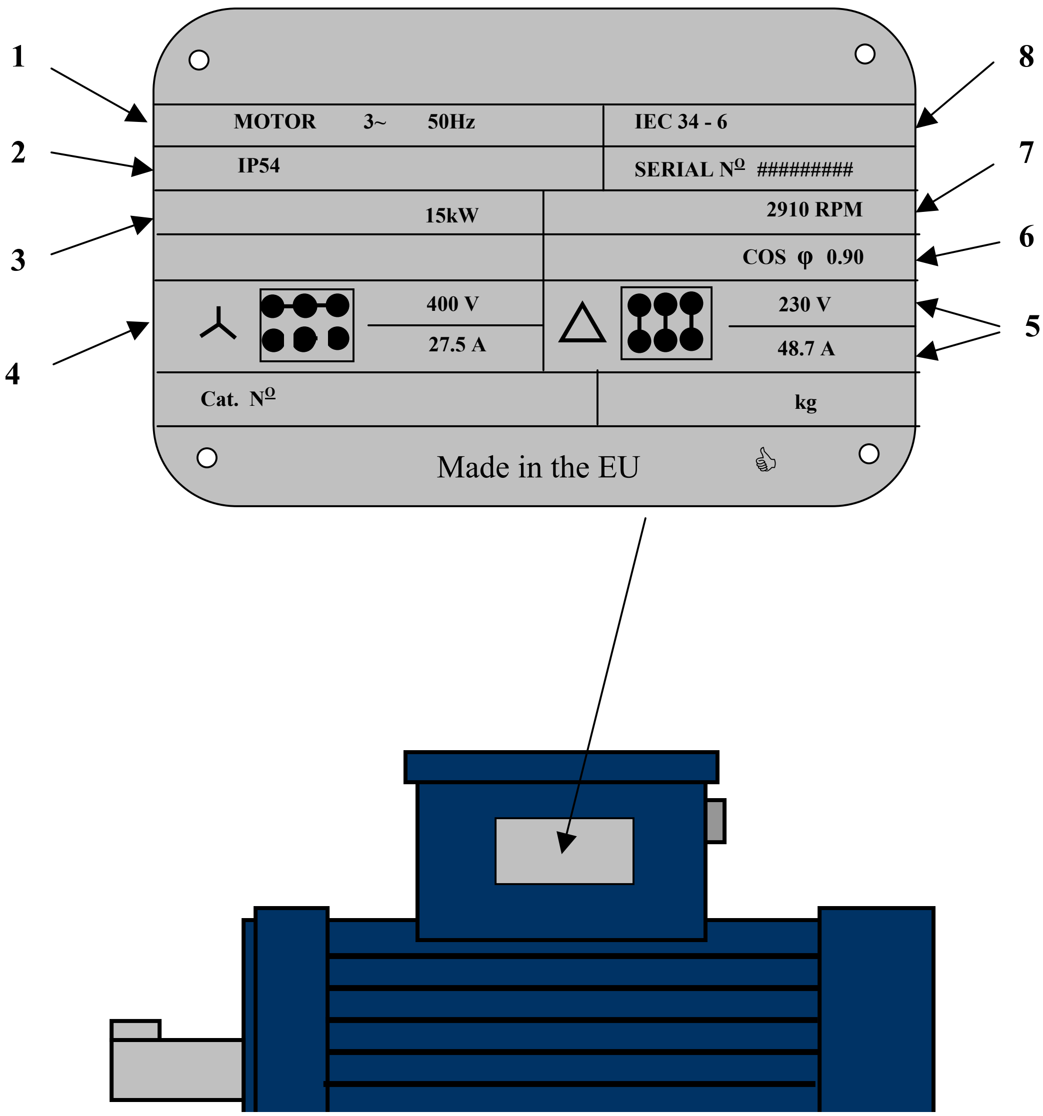


Figure 21. The motor nameplate or rating plate.

The nameplate for a typical 15kW motor as Figure 21 may have the following data: -

1. The motor has three phases and is for a mains supply with a frequency of 50Hz.

2. The motor protection rating indicates the degree of protection provided by the motor enclosure against the penetration of liquids and foreign bodies.

3. The rated output of the motor is 15kW, i.e. the motor is able to supply a shaft output of at least 15kW if connected to the mains supply as indicated. Horsepower (HP) is not now a commonly used unit for measuring motor output (except in the USA / N. America where it is still used). Motors that display their rated output power in HP can easily be interpreted as kW by using the formula **1HP = 0.736kW**.

4/5. The stator windings can be connected in a star or delta formation. If the mains voltage is 400V (380-415V) the winding must be connected in a star format. The motor current is then 27.5A per phase. If the mains voltage is 230V, the windings must be connected in a delta formation. The motor current then increases to 48.7A per phase.

At start-up, when the current up to 8 times higher than the rated current, the mains supply may be overloaded. This has led to supply companies to issue regulations ordering the start-up current of large motors to be reduced. This can be achieved electronically by using a **Soft-Start** controller **(such as the Saftronics Softdrive KSD30/400/20, available to IMO)** or having the motor start-up in a star connection and subsequently switching to a delta connection. This can be achieved by using the **IMO MC-Y** range of star-delta contactors.

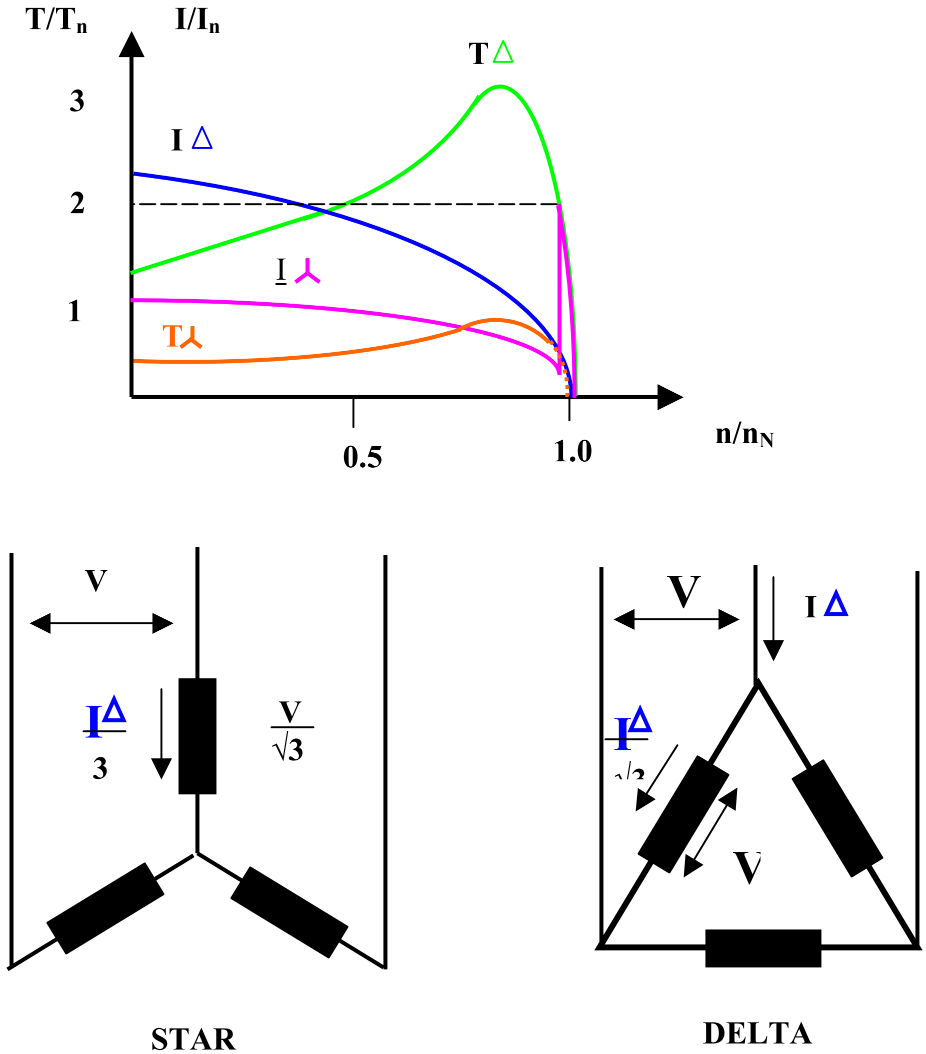


Figure 22. Motor torque and current, star and delta connection

With the star connection power and torque are reduced to ⅓ rd, and the motor cannot start at full load. A motor designed for star connection will be overloaded if there is no switch over to star for full load operation.

6. The rated current, $\mathbf{I_S}$, which the motor takes is called apparent current and can be divided into two: an active current $\mathbf{I_W}$ and a reactive current $\mathbf{I_B}$. Cos φ indicates the share of the active current as a percentage of the motor current at rated operation. The active current is converted into shaft output power (kW) while reactive current indicates the power required to build up the magnetic field. When the magnetic field is suddenly removed, the magnetizing power will be fed back to the mains supply.

   The word "reactive" indicates that the current moves in and out of the motor without contributing to the shaft output.

   The apparent current input to the motor from the mains is not determined by simply adding the active current to the reactive current; this is because these to currents are displaced in time. The size of this displacement depends upon the frequency of the supply network. At a frequency of 50Hz, the displacement between the two currents is 5 milliseconds.
   A geometrical summation is thus required:- $\mathbf{I_S = \sqrt{(I_W^2 + I_B^2)}}$

   The currents can be seen as sides of a right-angled triangle, where the long side equals the square root of the sum of the squares of the other two sides, following Pythagoras's theorem.

   φ is the angle between the apparent current $\mathbf{I_S}$ and the active current $\mathbf{I_W}$.

   Cos φ is the ratio between the size of the two currents: $\mathbf{\cos\varphi = \frac{I_W}{I_S}}$

   Cos φ can also be shown as the ratio actual output **P** and the apparent output **S**.

   $\mathbf{\cos\varphi = \frac{P}{S}}$

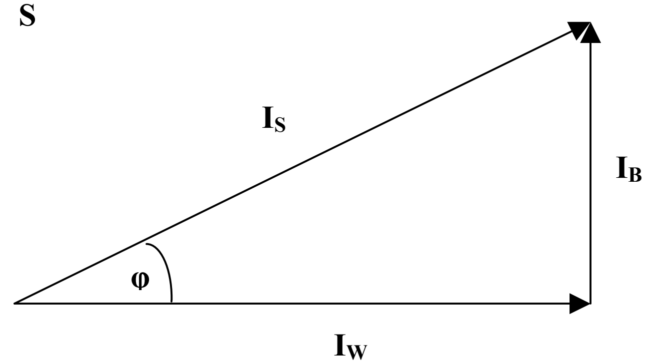


Figure 23. Connection between apparent, reactive and active currents

The phrase " apparent power" means that only part of the apparent current generates power, i.e. the part named $\mathbf{I_W}$, the active current.

7. The rated speed of the motor is the shaft speed at rated voltage, rated frequency, and rated load.

8. Electric motors are designed for different types of cooling.
   Normally the cooling method is stated in accordance with IEC Publication 34-6.

Types of load

When the motor torque output is equal to the load torque we have a stationary load. In such cases the torque and the speed are constant.

The characteristics for the motor and machine are stated as the ratio between speed and torque or output. The torque, speed and power characteristics of machine loads can be divided into four groups.

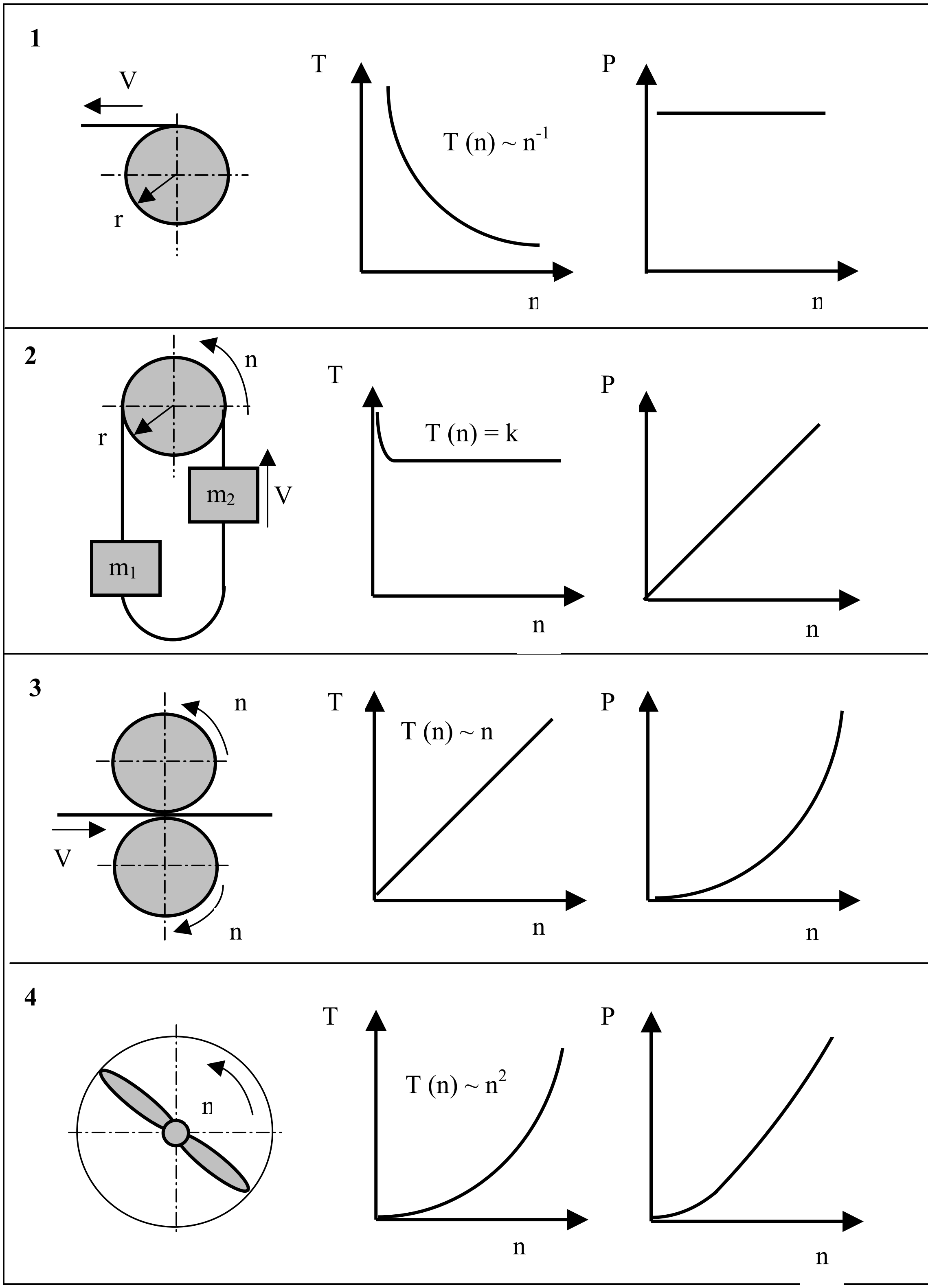


Figure 23a. Typical load characteristics. Note: T = Torque, P = Power, n = Speed

Group 1 consists of machines for winding material under tension. This group for example includes coil winding, veneer cutting machines and machine tools.
This group is known as the **constant power** group **(CP).**

Group 2 consists of conveyors, cranes, lifts, positive displacement pumps, screw feeders and mixers, etc. This group is known as **constant torque (CT).**

Group 3 is mainly machines containing rollers.

Group 4 are machines that use centrifugal forces such as fans, centrifugal pumps and oil/water separators (centrifuges). This group is known as **variable torque (VT).**

The stationary state occurs when motor and machine torque are identical. See Figure 23b. The graphs cross each other at point **B**.
When a motor is sized for a given operating machine, the intersection point should be as close as possible to a point **N** for the rated motor data.
A surplus torque should be made available throughout the range from standstill to the intersection point. If that is not the case, operation becomes unstable and the stationary state may change if the speed is too low. One of the reasons for this is that the surplus torque is required for acceleration.

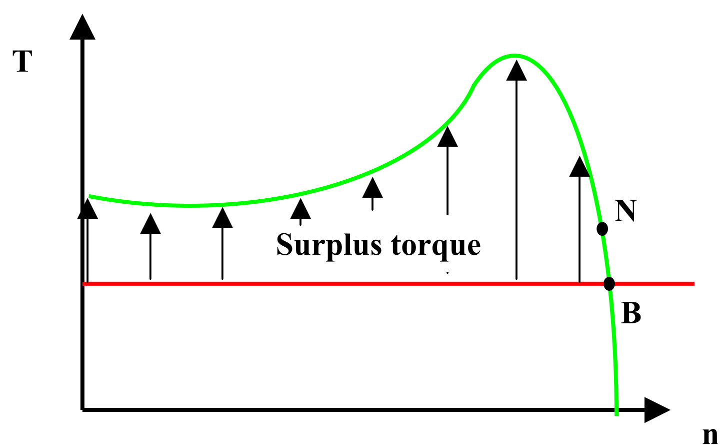


Figure 23b. The motor needs a surplus torque for acceleration

In particular for machines in groups 1 and 2, it is necessary to take account of this starting condition. These types of load may have an initial starting torque which is the same size as the starting torque of the motor. When the starting torque of the load is higher than the starting torque of the motor, the motor cannot start. See Figure 23c.

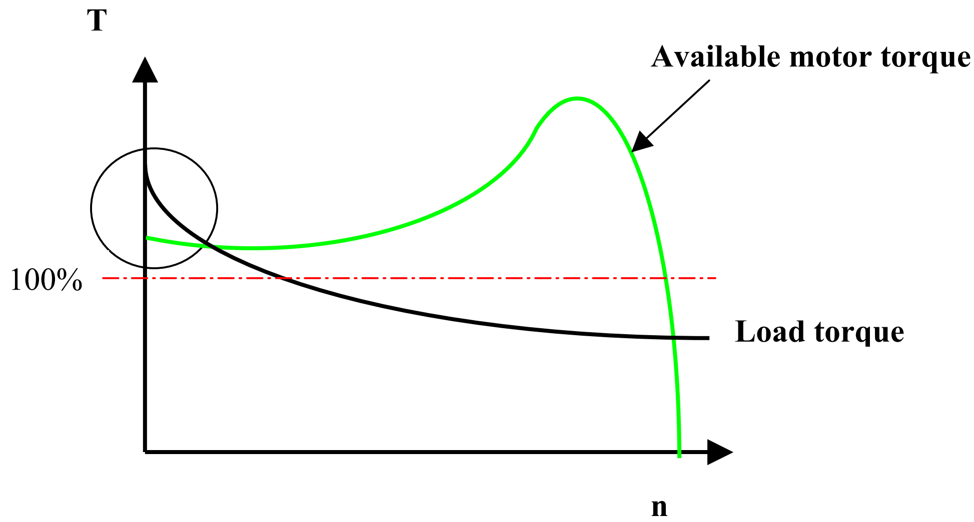


Figure 23c. The starting state may call for a particularly high torque

Other types of motors

Up until now we have only discussed the fundamentals of the DC motor and the 3-phase AC induction motor. This is because they are the most commonly used general purpose motors in industry, and an understanding of how they operate will give useful knowledge for future lessons. However, there are many other types of electric motor available. Below are listed just a few.

Synchronous motor – This is a 3-phase AC machine similar to the asynchronous (induction) motor. The main difference is that the rotor is designed to operate at the same speed as the rotating magnetic field. The rotor has salient magnetic poles made from either permanent magnets for small motors or electro-magnets for large powers.

A synchronous motor is unable to start by its self like the induction motor, and it needs to be started by separate start-up windings called damping windings-which allow starting as the induction motor. These then have to be switched out as the rotor accelerates. Larger motors require another motor called a **pony** motor that is fixed to the shaft of the synchronous motor. This is used to accelerate the shaft up to speed before being electrically disconnected.

Synchronous motors have a constant speed which is independent of load. The motor will not tolerate a higher load than the starting power between the rotor and magnetic field.
If the load exceeds this power the synchronism is interrupted and it stalls.

Reluctance motors – three phases AC reluctance motors are also similar to induction machines in as much that they start the same way but then become synchronous. In operation they then behave in a similar way to the synchronous motor – there is little overload capability, and it will readily stall if the load is too high. Since reluctance motors have a squirrel cage type rotor, they are sturdy, relatively inexpensive, reliable and maintenance free. The main disadvantages are that they are inefficient, and they have a very poor power factor of only 0.4 or 0.5.

Single-phase AC induction motors – These are similar to 3-phase induction motors but are wound for a 1-phase supply. They are only available in small power ratings, say 4kW at 230V/50Hz because the current required from the single-phase supply would be too high at larger powers. Again, this type of motor cannot start without assistance from a capacitor and a start winding. The capacitor start is the most usual method, splitting the phase between the run winding and the start winding, to create a second rotating field. This enables the motor to develop sufficient torque to accelerate. When the motor is up to rated speed the capacitor and its series winding can be switched out by a centrifugal switch, or left in depending on the design.

These motors are not suited to applications that require speed control by electronic methods, as the capacitor will be damaged by high frequency waveforms from the drive.

AC and DC Servo motors - Servo motors are not general-purpose motors, they are special devices used where extremely accurate speed, torque and position control are required, with a high dynamic response. They are always used closed loop in association with a multi-axis servo amplifier to perform precision operations, for example-accelerate-hold-accelerate- hold-stop-home. This cycle may be required to be repeatable every second or so with stopping accuracy less than ±1mm, under full load conditions. Because of the accuracy required, the servo motor will be supplied fitted with a **resolver.** This is a feedback device that gives a unique output at every angular position of the shaft, representative of direction and magnitude so that the amplifier can resolve the signal into co-ordinate data.

The motors will always be constructed in such a way that the inertia of the shaft is low, i.e. the permanent magnet rotor will be much longer and of smaller radius than an induction motor of the same power rating. This is to aid dynamic response.

Servo systems are expensive by comparison, but are designed to do a specific range of duties that would be out of range of standard ac or dc motors.

Quiz 1

1. What names are given to the two windings in a DC motor?

2. What do we call the opposition to magnetic flux?

3. What is the difference between a DC motor and a DC generator?

4. Maximum torque is induced in a dc current carrying loop when it is moving at right angles to the lines of flux. True or False?

5. What do we call the currents that circulate in the iron core?

6. What part of the dc motor eliminates armature reaction?

7. In a DC motor, what two quantities is torque proportional to?

8. A DC motor will accelerate until which two properties are equal?

9. What is speed proportional to in a DC motor?

10. What is the name given to the method of increasing the speed of a DC motor by reducing magnetic field flux?

11. How is the direction of rotation changed in a DC motor?

12. What kind of energy is stored in a rotating mass?

13. When a DC motor is being driven by its load, i.e. going faster than the applied voltage directs that it should, it is said to be doing what?

14. If the excess energy is removed from a motor operating as in Q13 above, by connecting a resistor across the armature, the process is called what?

15. What is 'Base speed'?

16. The typical maximum speed for a DC motor is what?

Quiz 2

1. What are the two main parts of the induction motor?

2. The speed of the rotating field in the induction motor is known as?

3. Write the formula for synchronous speed, n_0?

4. The rotor of the induction motor is sometimes called a 'Hamster wheel'. True or False?

5. What is slip?

6. What is torque?

7. To calculate motor torque what two other values must be known?

8. The ratio of a motors input power to its output power is known as?

9. High efficiency (EFF 1) motors can typically reach what % efficiency?

10. Name any two losses that occur in an AC motor?

11. What is the ultimate consequence of under-magnetizing an induction motor?

12. If an 11kW, 400V, 21 Amp induction motor were to be started DOL, what would be the typical starting current?

13. How is the direction of rotation changed in an ac motor?

14. Convert 20 Horsepower (HP) to kilowatts (kW)

15. What kind of load is a Fan?

16. What kind of load is a conveyor?