Preface

From the great series of experiments, performed by *Michael Faraday*, as far back as 1831, in which he discovered electromagnetic induction, just as from *Moritz Hermann Jacobi* who accomplished the construction of the first real electric motor in May 1834, continuing with *James Clark Maxwell* who summarized, between 1861 – 1864, all the current knowledge of electromagnetism in four fundamental equations which are still valid today and fully describe the theory of electrical engineering, and with *Nikola Tesla* who was the first to work on electric power transmission through a multi-phase alternating current system, and the first to present the principles of a multi-phase induction motor, and let us not forget *Michael Dolivo-Dobrowolsky* who built, in the beginning of 1889, the first simple, practically useful three-phase induction motor with squirrel-cage rotor, just like from many other scientists and inventors, we received a great legacy of knowledge that led to all modern electric motors, generators and transformers, which can be found within many appliances that surrounds us.

As regarding the importance of electric machines in modern life style, it is sufficient to be reminded that a vast amount of electricity is produced by rotating electric generators, the energy distribution systems could not be sustained without the contribution of electric transformers, and above all, over a half of the electric energy is used by electric motors in various applications which cover a wide variety of processes, and the best of all is still to come with the automotives industry trend of replacing, in the near future, the internal combustion engine with traction electric motors, on the background of the environmental threats and the limited oil resources. Therefore, there are plenty of reasons for the electrical engineers to be concerned with designing and building new, more efficient electric machines.

The main objective of this course is to provide basic knowledge to electrical engineering students for understanding the operating principles of most widely used electric machines. Principal laws and basic concepts are presented along with electric transformers, conventional electric machines such as direct current (DC), induction and synchronous motors and generators, and special: brushless DC (BLDC), stepping motors and switch reluctance motors (SRM).

Adrian Munteanu

1. Principal Laws and Basic Concepts

1.1. Introduction

An electric machine can be considered any electro-mechanical energy converter based on a magnetic field action. The reversibility of the energy conversion represents a useful propriety of electric machines which allows operating as electric motors, converting electricity to mechanical power or electric generators, converting mechanical power to electricity. The movement involved in the mechanical power can be rotating or linear.

A transformer is a power converter that transfers alternative current (AC) electrical energy through inductive coupling between electric circuits of the transformer's windings, accomplishing a voltage level change at the same frequency. Although transformers do not contain any moving parts, they can also be considered electric machines due to the same principle of operation.

Understanding the principal laws and basic concepts that govern the fascinating world of electric machines allows us to appreciate their importance and unlimited potential and to imagine ingenious solutions for achieving higher performances and developing new applications. In order to master all that, one has to start from the beginning and defining the fundamental concepts electric machines operate with and reviewing the laws that interfere.

1.2. Electromagnetic Fundamentals

1.2.1. Electromagnetic Field Equations

Maxwell's equations are a set of partial differential equations that, together with the Lorentz force law, form the foundation of classical electrodynamics, classical optics, and electric circuits. Maxwell's equations describe how electric and magnetic fields are generated and altered by each other and by charges and currents. They are named after the Scottish physicist and mathematician James Clerk Maxwell who published an early form of those equations between 1861 and 1862.

The equations have two major variants. The *microscopic* set of Maxwell's equations uses total charge and total current, including the complicated charges and currents in materials at the atomic scale; it has universal applicability, but may be unfeasible to calculate. The *macroscopic* set of Maxwell's equations defines two new auxiliary fields that describe large-scale behavior without having to consider these atomic scale details, but it requires the use of parameters characterizing the electromagnetic properties of the relevant materials.

Maxwell's macroscopic equations, also known as *Maxwell's equations in matter*, can be defined as:

$$\nabla \times H = J + \frac{\partial D}{\partial t}$$

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

$$\nabla \cdot B = 0$$

$$\nabla \cdot D = \rho_v$$

In order to apply Maxwell's macroscopic equations, it is necessary to specify the relations between displacement field *D* and the electric field *E*, as well as the magnetizing field *H* and the magnetic field *B*. The equations specifying this response are called *constitutive relations*. For real-world materials, the constitutive relations are rarely simple, except approximately, and usually determined by experiment. For materials without polarization and magnetization (vacuum), the constitutive relations are:

$$B = \mu_0 \cdot \mu_r \cdot H$$

$$D = \varepsilon_0 \cdot \varepsilon_r \cdot E$$

$$E = \rho \cdot J$$

where:

μ_0 vacuum permeability of the material,

μ_r relative permeability of the material,

ε_0 -permittivity,

ε_r relative permittivity,

ρ electric resistivity
J current density

First Maxwell equation, also known as *Ampère's circuital law,* can be written as:

$$\oint_{\partial\Sigma} H \cdot dl = \iint_{\Sigma} J \cdot dS$$

The second Maxwell equation, named *Faraday's law of induction,* can be expressed as:

$$\oint_{\partial\Sigma} E \cdot dl = -\iint_{\Sigma} \frac{\partial B}{\partial t} \cdot dS$$

The third Maxwell equation, known as *Gauss's law for magnetism* can be formulated as:

$$\oiint_{\Sigma} B \cdot dS = 0$$

1.2.2. Electromotive Force

Faraday's law states that a voltage appears across the terminals of an electric coil when the flux linkages, associated with this, changes. This e*lectromotive force (emf)* is proportional to the rate of change of flux linkages:

$$e = \frac{d\psi}{dt}$$

where ψ is the flux linkages.

In a two-terminal device (such as a coil), the *emf* can be measured as voltage across the two open-circuited terminals. The created electrical potential difference drives current flow if a close circuit is attached. When current flows, however, the voltage across the terminals of the source of *emf* has no longer the open-circuit value, due to voltage drops inside the device due to its internal resistance:

$$u = R \cdot i + \frac{d\psi}{dt}$$

where: *R* is the circuit resistance and *i* the flowing current.

This relation shows a certain application of *Faraday's law of induction*, which is the general principle governing the *emf* in electrical machines.

1.2.3. Magnetomotive Force (mmf)

Similar to the way that electromotive force (emf) drives a current of electrical charge in electrical circuit, *magnetomotive force* (*mmf*) drives magnetic flux through magnetic circuits. In analogy to the definition of emf, the magnetomotive force F around a closed loop is defined as:

$$\mathcal{F} = \oint H \cdot dl$$

An applied *mmf* drives magnetic flux through the magnetic components of the system. This is proportional to the number of magnetic field lines that pass through the cross section area. The direction of the *magnetic field* vector B is by definition from the South to the North pole of a magnet inside the magnet; outside the field lines go from North to South.

The flux through an element of area perpendicular to the direction of magnetic field is given by the product of the magnetic field and the area element. More generally, *magnetic flux* Φ is defined by a scalar product of the magnetic field and the area element vector. Quantitatively, the magnetic flux through a surface S is defined as the integral of the magnetic field over the area of the surface:

$$\Phi = \iint_S B \cdot dS$$

In electronic circuits, *Ohm's law* is an empirical relation between the *emf* applied across an element and the current I through that element.

Hopkinson's law is a counterpart to *Ohm's law* used in magnetic circuits. It states that:

$$\mathcal{F} = \Phi \cdot R_m$$

where R_m is the magnetic reluctance of that element.

Like Ohm's law, Hopkinson's law can be interpreted either as an empirical equation that works for some materials, or it may serve as a definition of reluctance.

Magnetic reluctance, or *magnetic resistance*, is analogous to resistance in an electrical circuit (although it does not dissipate magnetic energy). In likeness to the way an electric field causes an electric current to follow the path of least resistance, a magnetic field causes magnetic flux to follow the path of least magnetic reluctance.

Magnetic flux always forms a closed loop, as described by Maxwell's equations, but the path of the loop depends on the reluctance of the surrounding materials. It is concentrated around the path of least reluctance. Air and vacuum have high reluctance, while easily magnetized materials such as soft iron have low reluctance. The concentration of flux in low-reluctance materials forms strong temporary poles and causes mechanical forces that tend to move the materials towards regions of higher flux so it is always an attractive force (pull).

The inverse of reluctance is called permeance:

$$\lambda = \frac{1}{R_m}$$

Magnetic circuits obey the same laws as electrical circuit.

1.2.4. Production of Induced Force on a Wire

A current carrying conductor present in a uniform magnetic field of flux density *B*, would produce a force to the conductor/wire. Dependent upon the direction of the surrounding magnetic field, the force induced is given by:

$$F = i(l \times B)$$

where: i – represents the current flow in the conductor

l – wire length, with direction of l defined to be in the direction of current flow

B – magnetic field density

The direction of the force is given by the *left-hand rule*. Direction of the force depends on the direction of current flow and the direction of the surrounding magnetic field.

The induced force formula shown earlier is true if the current carrying conductor is perpendicular to the direction of the magnetic field. If the current carrying conductor is position at an angle to the magnetic field, the formula is modified to be as follows:

$$F = i \cdot l \cdot B \cdot \sin\theta$$

where: θ – angle between the conductor and the direction of the magnetic field.

In summary, this phenomenon is the basis of an electric motor where torque or rotational force of the motor is the effect of the stator field current and the magnetic field of the rotor.

1.3. Basic Concepts

1.3.1. Rotation Motion, Newton's Law and Power Relationship

Almost all electric machines rotate about an axis, called the shaft of the machine. Consequence, it is important to have a basic understanding of rotational motion.

Angular position, θ – is the angle at which it is oriented, measured from some arbitrary reference point. Its measurement units are in radians or in degrees, and it is similar to the linear concept of distance along a line.

Angular velocity, ω – defined as the velocity at which the measured point is moving, is similar to the concept of standard velocity:

$$v = \frac{dr}{dt}$$

where: r – distance made by the body
t – time taken to travel the distance r

For a rotating body, angular velocity is formulated as:

$$\omega = \frac{d\theta}{dt}$$

where: θ – angular position/angular distance made by the rotating body

t – time taken for the rotating body to mace the specified distance.

Angular acceleration, α – is defined as the rate of change in angular velocity with respect to time. Its formulation is as shown:

$$\alpha = \frac{d\omega}{dt}$$

Torque, τ [Nm]:

In linear motion, a force applied to an object causes its velocity to change. In the absence of a net force on the object, its velocity is constant. The greater the force applied to the object, the more rapidly its velocity changes.

Similarly, in the concept of rotation, when an object is rotating, its angular velocity is constant unless a torque is present on it. Greater the torque is, rapidly the angular velocity changes.

Torque is known as a rotational force applied to a rotating body giving angular acceleration (twisting force).

Definition: *Torque is the product of force applied to the object and the smallest distance between the line of action of the force and the object's axis of rotation, stated in Nm.*

Work, W – is defined as the application of *Force*, *F* through a distance, stated in *Joules*. Therefore, work may be defined as:

$$W = \int F \cdot dr$$

Assuming that the direction of *F* is collinear (in the same direction) with the direction of motion and constant in magnitude, hence,

$$W = F \cdot r$$

Applying the same concept for rotating bodies,

$$W = \int \tau \cdot d\theta$$

Assuming that τ is constant:

$$W = \tau \cdot \theta$$

Power, P – is defined as rate of doing *Work*, stated in *Watts*. Hence,

$$P = \frac{dW}{dt}$$

Applying this for rotating bodies,

$$P = \frac{d}{dt}(\tau \cdot \theta) = \tau \frac{d\theta}{dt} = \tau \cdot \omega$$

This equation can describe the mechanical power on the shaft of a motor or generator.

Newton's law for objects moving in a straight line gives a relationship between the force applied to the object and the acceleration experience by the object as the result of force applied to it. In general,

$$F = m \cdot a$$

where: *F* – force applied
m – mass of object
a – resultant acceleration of object

Applying these concept for rotating bodies,

$$\tau = J \cdot \alpha$$

where: τ – torque
J – moment of inertia
α – angular acceleration

1.3.2. Magnetic Behavior of Ferromagnetic Materials

Materials which are classified as non-magnetic all show a linear relationship between the flux density *B* and coil current *I*. In other words, they have constant permeability. Thus, for example, in free space, the permeability is constant. But in iron and other ferromagnetic materials it is not constant Fig.1.

For magnetic materials, a much larger value of *B* is produced in these materials than in free space. Therefore, the permeability of magnetic materials is much higher than μ_0. However, the permeability is not linear anymore but does depend on the current over a wide range.

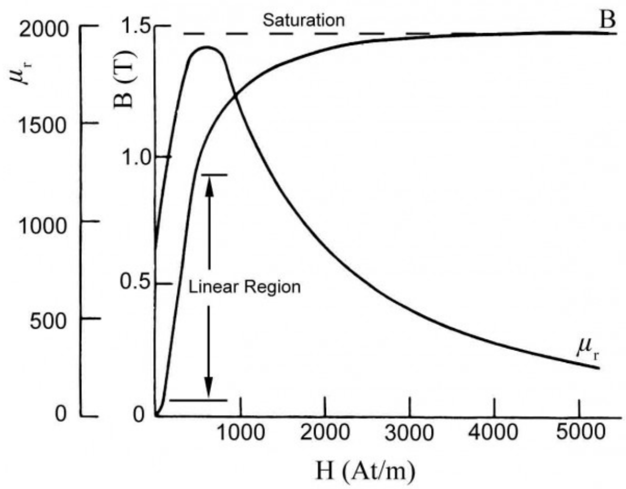


Fig.1 The magnetizing curve of a ferromagnetic core.

Thus, the permeability is the property of a medium that determines its magnetic characteristics. In other words, the concept of magnetic permeability corresponds to the ability of the material to permit the flow of magnetic flux through it.

In electrical machines and electromechanical devices a somewhat linear relationship between B and I is desired, which is normally approached by limiting the current. When the flux produced in the core is plotted versus the mmf producing it, results the so called the saturation curve or the magnetization curve. At first, a small increase in the mmf produces a huge increase in the resulting flux. After a certain point, further increases in the mmf produce relatively smaller increases in the flux. Finally, there will be no change at all as you increase mmf further. The region in which the curve flattens out is called *saturation region*, and the core is said to be saturated. The region where the flux changes rapidly is called the *unsaturated region*. The transition region is called the *knee of the curve*.

Consequence, the magnetizing intensity is directly proportional to mmf and magnetic flux density is directly proportional to flux for any given core.

From relation $B = \mu H$ results that the slope of curve is the permeability of the core at that magnetizing intensity. The permeability is large and relatively constant in the unsaturated region and then gradually drops to a low value as the core become heavily saturated.

The advantage of using a ferromagnetic material for cores in electric machines and transformers is that one gets more flux for a given mmf than with air (free space).

If the resulting flux has to be proportional to the mmf, then the core must be operated in the unsaturated region.

Generators and motors depend on magnetic flux to produce voltage and torque, so they need as much flux as possible. So, they operate near the knee of the magnetization curve (flux not linearly related to the mmf). This non-linearity as a result gives peculiar behaviors to machines.

As magnetizing intensity *H* increased, the relative permeability first increases and then starts to drop off.

1.3.3. Energy Losses in a Ferromagnetic Core

A. Hysteresis Loss

Typical flux behavior (known as *hysteresis loop*) in a ferromagnetic core when applying AC current through a coil is as shown in Fig.2.

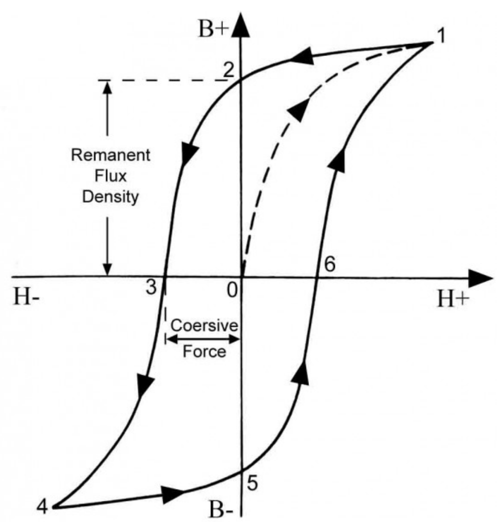


Fig.2 Typical Hysteresis loop when AC current is applied

When applying AC current, assuming the flux in the core is initially zero, the flux traces the path 0-1 (saturation curve), as current increases. When the current decreases, the flux traces out a different path from the one when the current increases 1-2-3-4. When the current increases again, it traces out path 4-5-6-1.

The amount of flux present in the core depends not only on the amount of current applied to the windings of the core, but also on the previous history of the flux in the core.

HYSTERESIS is the dependence on the preceding flux history and the resulting failure to retrace flux paths. When a large mmf is first applied to the core and then removed, the flux path in the core will 0-1-2. When mmf is removed, the flux does not go to zero – *remanent flux*. This is how permanent magnets are produced. To force the flux to zero, an amount of mmf known as *coercive mmf* must be applied in the opposite direction.

To understand hysteresis in a ferromagnetic core, we have to look into the behavior of its atomic structure before, during and after the presence of a magnetic field. The atoms of iron and similar metals (cobalt, nickel, and some of their alloys) tend to have their magnetic fields closely aligned with each other. Within the metal, there is an existence of small regions known as domains where in each domain there is a presence of a small magnetic field which randomly aligned through the metal structure Fig.3.

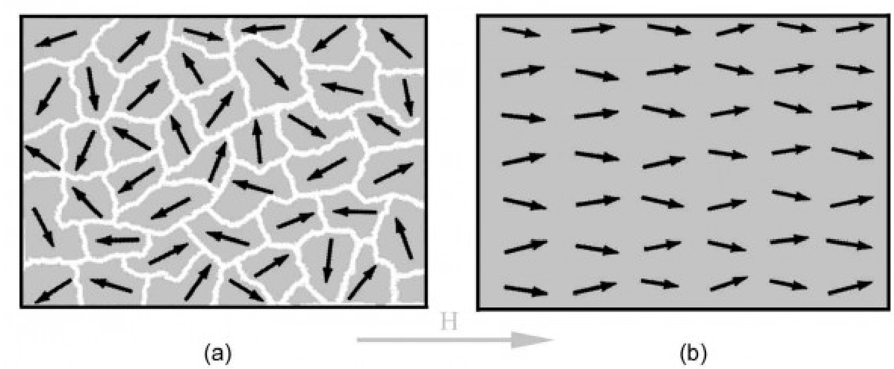


Fig.3 Ferromagnetic material: (a) not magnetized; (b) with an external magnetizing force (H).

Magnetic field direction in each domain is random as such that the net magnetic field is zero. When mmf is applied to the core, each magnetic field will align with respect to the direction of the magnetic field. That explains the exponential increase of magnetic flux during the early stage of magnetization. As more and more domain are aligned to the magnetic field, the total magnetic flux will maintain at a constant level hence as shown in the magnetization curve (saturation).

When mmf is removed, the magnetic field in each domain will try to revert to its random state. However, not all magnetic field domain's would revert to its random state hence it remained in its previous magnetic field position. This is due to the lack of energy required to disturb the magnetic field alignment. Hence the material will retain some of its magnetic properties (permanent magnet) up until an external energy is applied to the material.

Examples of external energy may be in the form of heat or large mechanical shock. That is why a permanent magnet can lose its magnetism if it is dropped, hit with a hammer or heated.

Therefore, in an AC current situation, to realign the magnetic field in each domain during the opposite cycle would require extra mmf (also known as coercive mmf). This extra energy requirement is known as *hysteresis loss*. The larger the material, the more energy is required hence the higher the hysteresis loss.

Area enclosed in the hysteresis loop formed by applying an AC current to the core is directly proportional to the energy lost in a given AC cycle.

B. Eddy Current Loss

A time-changing flux induces voltage within a ferromagnetic core. These voltages cause swirls of current to flow within the core – *eddy currents*. Energy is dissipated (in the form of heat) because these eddy currents are flowing in a resistive material (iron).

The amount of energy lost to eddy currents is proportional to the size of the paths they follow within the core. To reduce energy loss, ferromagnetic core should be broken up into small strips, or laminations, and build the core up out of these strips. An insulating oxide or resin is used between the strips, so that the current paths for eddy currents are limited to small areas Fig.4.

Core losses are extremely important in practice, since it greatly affects operating temperatures, efficiencies, and ratings of magnetic devices.

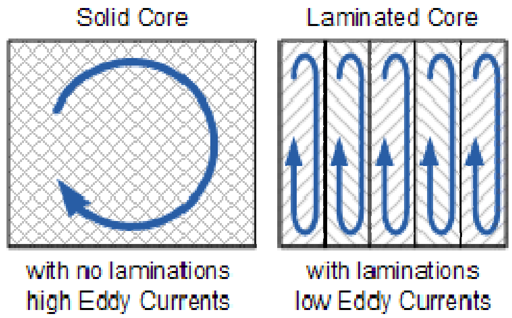


Fig. 4 Path of eddy current

2. Transformers

2.1. Introduction

Michael Faraday propounded the principle of electro-magnetic induction in 1831. It states that a voltage appears across the terminals of an electric coil when the flux linked with the same changes. The magnitude of the induced voltage is proportional to the rate of change of the flux linkages. This finding forms the basis for many magneto electric machines.

The earliest use of this phenomenon was in the development of induction coils. These coils were used to generate high voltage pulses to ignite the explosive charges in the mines. As the d.c. power system was in use at that time, very little of transformer principle was made use of. In the d.c. supply system the generating station and the load center have to be necessarily close to each other due to the requirement of economic transmission of power. Also the d.c. generators cannot be scaled up due to the limitations of the commutation. This made the world look for other efficient methods for bulk power generation and transmission.

During the second half of the 19th century the alternators, transformers and induction motors were invented. These machines work on alternating power supply. The role of the transformers became obvious. The transformer which consisted of two electric circuits linked by a common magnetic circuit helped the voltage and current levels to be changed, keeping the power invariant. The efficiency of such conversion was extremely high. Thus one could choose a moderate voltage for the generation of a.c. power, a high voltage for the transmission of this power over long distances and finally use a small and safe operating voltage at the user end. All these are made possible by *electric transformers*. The a.c. power systems thus got well established.

Transformers can link two or more electric circuits. In its simple form two electric circuits can be linked by a magnetic circuit, one of the electric coils is used for the creation of a time varying magnetic field. The second coil which is made to link this field has an induced voltage in the same. The magnitude of the induced emf is decided by the number of turns used in each coil. Thus the voltage level can be increased or decreased by changing the number of turns. This excitation winding is called a *primary* and the output winding is called a *secondary*.

As a magnetic medium forms the link between the primary and the secondary windings there is no conductive connection between the two electric circuits. *The transformer thus provides an electric isolation between the two circuits*.

The frequency on the two sides will be the same. As there is no change in the nature of the power, the resulting machine is called a '*transformer*' and not a '*converter*'. The electric power at one voltage/current level is only 'transformed' into electric power, at the same frequency, to another voltage/current level.

Even though most of the large-power transformers can be found in the power systems, the use of the transformers is not limited to the power systems.

Transformers can be found operating in the frequency range starting from a few Hertz going up to several mega Hertz.

Power ratings vary from a few mill watts to several hundreds of megawatts. The use of the transformers is so wide spread that it is virtually impossible to think of a large power system without transformers.

Demand on electric power generation doubles every decade in a developing country. For every MVA of generation the installed capacity of transformers grows by about 7MVA. These show the indispensable nature of power transformers.

2.2. Constructional features

Transformers used in practice are of extremely large variety, depending upon the end use. In addition to the transformers used in power systems, in power transmission and distribution, a large number of special transformers are in use in applications like electronic supplies, rectification, furnaces, traction etc. Here, we will focus mainly on power transformers.

The principle of operation of these transformers also is the same but the user requirements differ. Power transformers of smaller sizes could be air cooled while the larger ones are oil cooled. These machines are highly material intensive equipments and are designed to match the applications for best operating conditions. Hence they are ‘tailor made’ to a job. This brings in a very large variety in their constructional features.

Here more common constructional aspects alone are discussed. These can be broadly divided into:

- Core construction
- Winding arrangements
- Insulation
- Cooling aspects

2.2.1. Core Construction

Transformer core for the power frequency application is made of highly permeable material. The high value of permeability helps to give a low reluctance for the path of the flux and the flux lines mostly confine themselves to the iron. Relative permeability μ_r well over 1000 are achieved by the present day materials. Silicon steel in the form of thin laminations is used for the core material. Over the years progressively better magnetic properties are obtained by going in for *hot rolled non-oriented* to *hot rolled grain oriented* steel.

The thickness of the laminations progressively got reduced from over 0.5 mm to the present 0.25 mm per lamination. These laminations are coated with a thin layer of insulating varnish, oxide or phosphate. The magnetic material is required to have a high permeability μ and a high saturation flux density, a very low remanence B_r and a small area under the *B-H* loop to permit high flux density of operation with low magnetizing current and low hysteresis loss.

The resistivity of the iron sheet itself is required to be high to reduce the eddy current losses. The eddy current itself is highly reduced by making the laminations very thin. If the lamination is made too thin then the production cost of steel laminations increases. The steel should not have residual mechanical stresses which reduce their magnetic properties and hence must be annealed after cutting and stacking.

In the case of very small transformers (from a few volt-amperes to a few kilo volt-amperes) hot rolled silicon steel laminations in the form of E & I, E & E, L & L or U & I as shown in Fig. 5 are used and the core cross section would be a square or a rectangle.

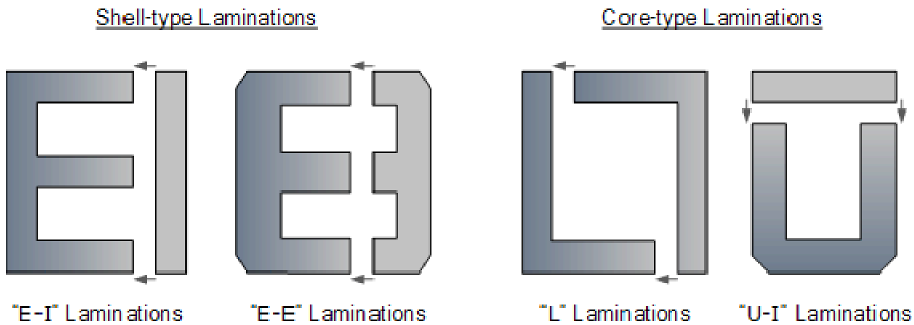


Fig.5: Different lamination types

The percentage of silicon in the steel is about 3.5%. Above this value the steel becomes very brittle and also very hard to cut. The saturation flux density of the present day steel lamination is about 2 Tesla.

Broadly classifying, the core construction can be separated into core type and shell type. In a core type construction the winding surrounds the core. A few examples of single phase and three phase core type constructions are shown in Fig. 6. In a shell type on the other hand the iron surrounds the winding.

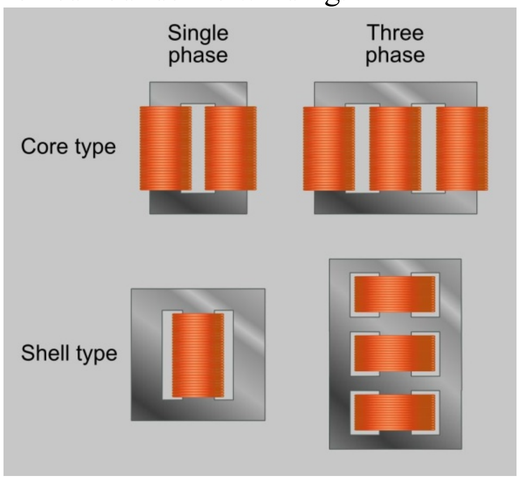


Fig.6: Core and Shell Type Construction

In the case of very small transformers the conductors are very thin and round. These can be easily wound on a former with rectangular or square cross section. Thus no special care is needed for the construction of the core. The cross section of the core also would be square or rectangular. As the rating of the transformer increases the conductor size also increases. Flat conductors are preferred to round ones. To wind such conductor on a rectangular former is not only difficult but introduces stresses in the conductor, at the bends. From the short circuit force with stand capability point of view also this is not desirable. Also, for a given area enclosed the length of the conductor becomes more. Hence it results in more load losses. In order to avoid all these problems the coils are made cylindrical and are wound on formers on heavy duty lathes. Thus the core construction is required to be such as to fill the circular space inside the coil with steel laminations.

Stepped core construction thus becomes mandatory for the core of large transformers. Fig. 7 shows a few typical stepped core constructions.

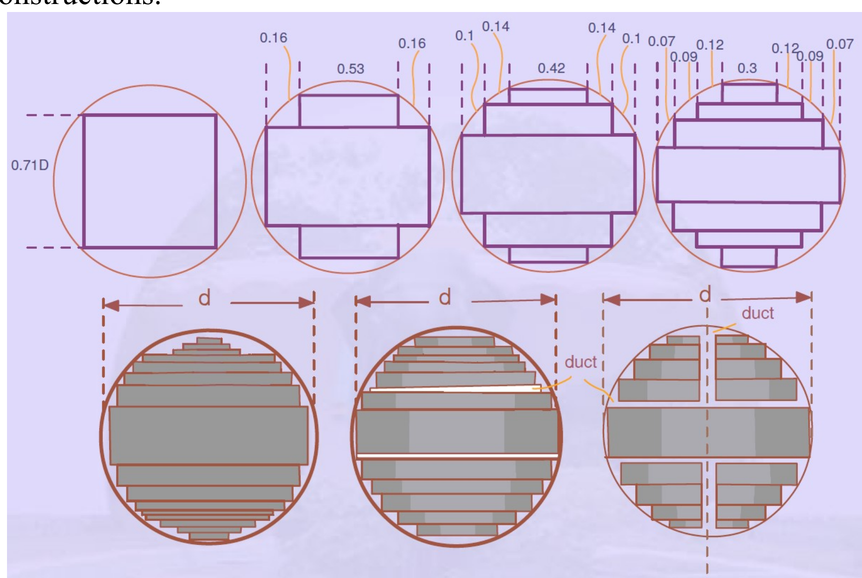


Fig.7: Stepped Core Construction

When the core size increases it becomes extremely difficult to cool the same (Even though the core losses are relatively very small). Cooling ducts have to be provided in the core. The steel laminations are grain oriented exploiting the simple geometry of the transformer to reduce the excitation losses. The iron losses in the lamination, when the flux is oriented in the direction of grain orientation, are about 30% of that in the normal direction.

Another important aspect to be carefully checked and monitored is the air gaps in series in the path of the main flux. As the reluctance of air path is about 1000 times more than that of the steel, an air path of 1 mm will require a mmf needed by a 1 meter path in iron. Hence butt joints between laminations must be avoided. Lap joints are used to provide alternate paths for flux lines thus reducing the reluctance of the flux paths. Some typical constructional details are shown in Fig. 8.

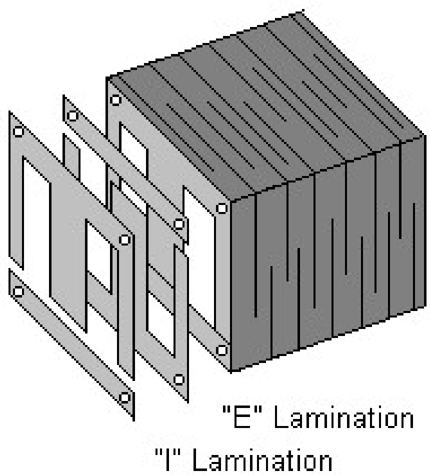


Fig.8: Typical stacked Core

In some power transformers the core is built up by threading a long strip of steel through the coil in the form of a toroid (wound core). This construction is normally followed in instrument transformers to reduce the magnetizing current and hence the errors.

Large cores made up of laminations must be rendered adequately stiff by the provision of stiffening plates usually called as flitch plates. Punched through holes and bolts are progressively being avoided to reduce heating and melting of the through bolts. The whole stack is wrapped up by strong epoxy tapes to give mechanical strength to the core which can stand in upright position. Channels and angles are used for the frame and they hold the bottom yoke rigidly.

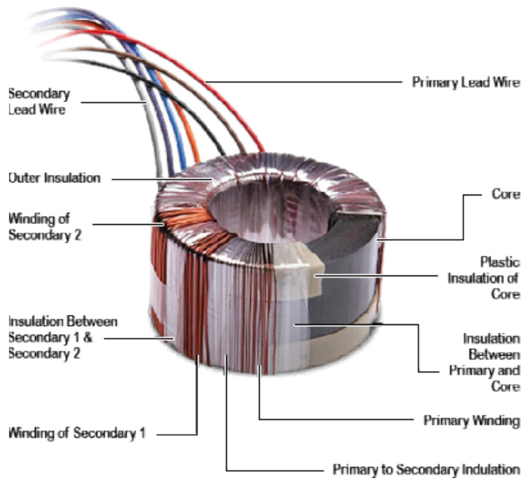


Fig.9: Wound Core Construction

2.2.2. Windings

Windings form another important part of transformers. In a two winding transformer, two windings would be present. The one which is connected to a voltage source and creates the flux is called as a *primary winding*. The second winding where the voltage is induced by induction is called a *secondary*.

If the secondary voltage is less than that of the primary the transformer is called a *step down transformer*. If the secondary voltage is greater than it is a *step up transformer*. A step down transformer can be made a step up transformer by making the low voltage winding its primary. Hence it may be more appropriate to designate the windings as *High Voltage* (HV) and *Low Voltage* (LV) windings. The winding with more number of turns will be a HV winding. The current on the HV side will be lower as V-I product is a constant and given as the VA rating of the machines. Also the HV winding needs to be insulated more to withstand the higher voltage across it. HV also needs more clearance to the core, yoke or the body. These aspects influence the type of the winding used for the HV or LV windings.

Transformer coils can be broadly classified in to *concentric coils* (Fig. 10) and *sandwiched coils* (Fig. 11). The former are very common with core type transformers while the latter one is common with shell type transformers.

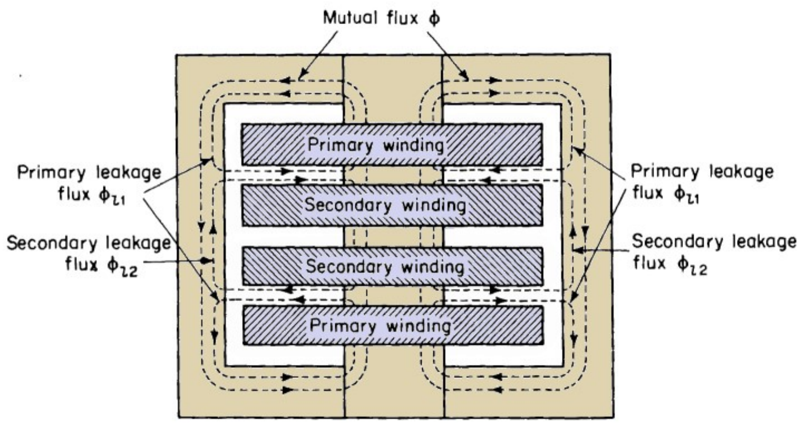


Fig.10: Concentric coils

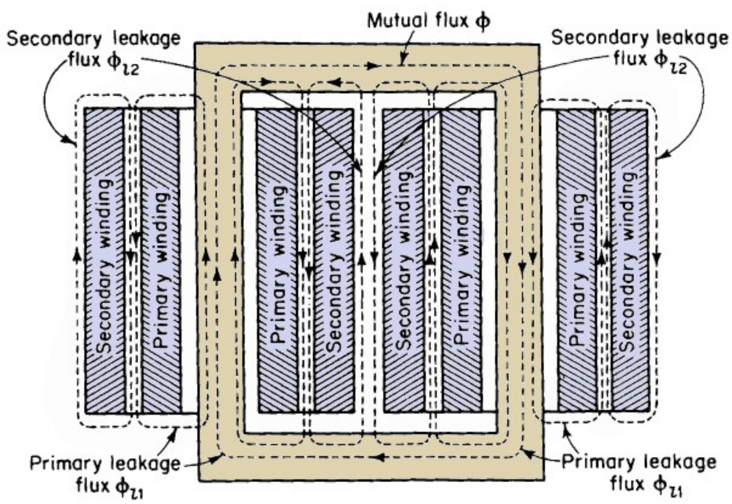


Fig.11: Sandwiched coils

Most common types of coils are:

- *Helical Windings:* One very common cylindrical coil arrangement is the helical winding. This is made up of large cross section rectangular conductor wound on its flat side. The coil progresses as a helix. This is commonly used for LV windings. The insulation requirement also is not too high. Between layers no insulation (other than conductor insulation) is needed as the voltage between layers is low. The complexity of this type of winding rapidly increases as the current to be handled becomes greater. The conductor cross section becomes too large and difficult to handle. The eddy current losses in the conductor rapidly increase. Hence two or more conductors have to be wound and connected in parallel. The parallel circuits bring in problems of current sharing between the circuits. Transpositions of the parallel paths have to be adopted to reduce unequal current distribution. The modern practice is to use continuously transposed and bunched conductors.

- *Cross over coils:* The second popular winding type is the cross over coil. These are made of circular conductors not exceeding 5 to 6 sq mm in cross section. These are used for HV windings of relatively small transformers. These turns are wound in several layers. The length and thickness of each block is made in line with cooling requirements. A number of such blocks can be connected in series, leaving cooling ducts in between the blocks, as required by total voltage requirement.
- *Disc coils*: Disc coils consist of flat conductors wound in a spiral form at the same place spiraling outwards. Alternate discs are made to spiral from outside towards the center. Sectional discs or continuous discs may be used. These have excellent thermal properties and the behavior of the winding is highly predictable. Winding of a continuous disc winding needs specialized skills.
- *Sandwich coils*: Sandwich windings are more common with shell type core construction. They permit easy control over the short circuit impedance of the transformer. By bringing HV and LV coils close on the same magnetic axis the leakage is reduced and the mutual flux is increased. By increasing the number of sandwiched coils the reactance can be substantially reduced.

2.2.3. Insulation

The insulation used in the case of electrical conductors in a transformer is varnish or enamel in dry type of transformers. In larger transformers to improve the heat transfer characteristics the conductors are insulated using un-impregnated paper or cloth and the whole core-winding assembly is immersed in a tank containing transformer oil.

The transformer oil thus has dual role. It is an insulator and also a cooling agent. The porous insulation around the conductor helps the oil to reach the conductor surface and extract the heat. The conductor insulation may be called the minor insulation as the voltage required to be withstood is not high.

The major insulation is between the windings. Annular bakelite cylinders serve this purpose. Oil ducts are also used as part of insulation between windings. The oil used in the transformer tank should be free from moisture or other contamination to be of any use as an insulator.

2.2.4. Cooling Aspects

Scaling advantages make the design of larger and larger unit sizes of transformers economically attractive. This can be explained as below. Consider a transformer of certain rating designed with certain flux density and current density. If now the linear dimensions are made larger by a factor of K keeping the current and flux densities the same the core and conductor areas increase by a factor of K^2. The losses in the machine, which are proportional to the volume of the materials used, increase by a factor of K^3.The rating of the machine increases by a factor of K^4. The surface area however increases by a factor of K2 only. Thus the ratio of loss per surface area goes on increasing by a factor of K. The substantial increase in the output is the major attraction in going in for larger units.

However cooling of the transformer becomes more and more difficult. As the rating increases better cooling techniques are needed. Simple air cooling of the transformers is adopted in dry type transformers. The limit for this is reached by the time the rating is a few kVA. Hence air cooling is used in low voltage machines. This method of cooling is termed as AN (Air Natural). Air Blast (AB) method improves on the above by directing the blast of air at the core and windings. This permits some improvement in the unit sizes.

Substantial improvement is obtained when the transformer is immersed in an oil tank. The oil reaches the conductor surface and extracts the heat and transports the same to the surface of the tank by convection. This is termed as ON (Oil Natural) type of cooling. This method permits the increase in the surface available for the cooling further by the use of ducts, radiators etc.

OB (Oil Blast) method is an improvement over the ON-type and it directs a blast of air on the cooling surface. In the above two cases the flow of oil is by natural convective forces. The rate of circulation of oil can be increased with the help of a pump, with the cooling at the surface remaining natural cooling to air. This is termed as OFN (Oil Forced Natural). If now a forced blast of air is also employed, the cooling method becomes OFB (Oil Forced Blast). A forced circulation of oil through a radiator is done with a blast of air over the radiator surface. Substantial amount of heat can be removed by employing water cooling. Here the hot oil going into the radiator is cooled by a water circuit. Due to the high specific heat of water, heat can be evacuated effectively.

Next in hierarchy comes OFW which is similar to OFB except that instead of blast of air a forced circulation of cool water in the radiator is used in this.

In many large sized transformers the cooling method is matched with the amount of heat that is required to be removed. As the load on the transformer changes the heat generated within also changes. Suitable cooling method can be pressed into service at that time. This gives rise to the concept of mixed cooling technique.

Even though the basic functions of the oil used in transformers are *heat conduction* and *electrical insulation*, there are many other properties which make particular oil eminently suitable. Organic oils of vegetative or animal origin are good insulators but tend to decompose giving rise to acidic by products which attack the paper or cloth insulation around the conductors. Mineral oils are suitable from the point of electrical properties but tend to form sludge.

The properties that are required to be looked into before selecting oil for transformer application are as follows:

- *Insulting property* This is a very important property. However most of the oils naturally fulfil this. Therefore deterioration in insulating property due to moisture or contamination may be more relevant.
- *Viscosity* It is important as it determines the rate of flow of the fluid. Highly viscous fluids need much bigger clearances for adequate heat removal.
- *Purity* The oil must not contain impurities which are corrosive. Sulphur or its compounds as impurities cause formation of sludge and also attack metal parts.
- *Sludge formation* Thickening of oil into a semisolid form is called sludge. Sludge formation properties have to be considered

while choosing the oil as the oil slowly forms semi-solid hydrocarbons. These impede flows and due to the acidic nature, corrode metal parts. Heat in the presence of oxygen is seen to accelerate sludge formation. If the hot oil is prevented from coming into contact with atmospheric air sludge formation can be greatly reduced.

- *Acidity* Oxidized oil normally produces CO_2 and acids. The cellulose which is in the paper insulation contains good amount of moisture. These form corrosive vapors. A good breather can reduce the problems due to the formation of acids.
- *Flash point And Fire point* Flash point of oil is the temperature at which the oil ignites spontaneously. This must be as high as possible (not less than 160◦C from the point of safety). Fire point is the temperature at which the oil flashes and continuously burns. This must be very high for the chosen oil (not less than 200◦C). Inhibited oils and synthetic oils are therefore used in the transformers. Inhibited oils contain additives which slow down the deterioration of properties under heat and moisture and hence the degradation of oil. Synthetic transformer oil like chlorinated biphenyl has excellent properties like chemical stability, non-oxidizing, good dielectric strength, moisture repellant, reduced risk due fire and explosion.

It is therefore necessary to check the quality of the oil periodically and take corrective steps to avoid major break downs in the transformer.

2.3. Ideal Transformer

Earlier it was shown that a voltage is induced in a coil when the flux linkage associated with the same changed. If one can generate a time varying magnetic field any coil placed in the field of influence linking the same experiences an induced emf. A time varying field can be created by passing an alternating current through an electric coil. This is called mutual induction. The medium can even be air. Such an arrangement is called air cored transformer. Indeed such arrangements are used in very high frequency transformers.

Even though the principle of transformer action is not changed, the medium has considerable influence on the working of such devices. These effects can be summarized as the followings:

1. The magnetizing current required to establish the field is very large, as the reluctance of the medium is very high.

2. There is linear relationship between the mmf created and the flux produced.

3. The medium is non-loss and hence no power is wasted in the medium.

4. Substantial amount of leakage flux exists.

5. It is very hard to direct the flux lines as we desire, as the whole medium is homogeneous.

If the secondary is not loaded the energy stored in the magnetic field finds its way back to the source as the flux collapses. If the secondary winding is connected to a load then part of the power from the source is delivered to the load through the magnetic field as a link.

The medium does not absorb and lose any energy. Power is required to create the field and not to maintain the same. As the winding losses can be made very small by proper choice of material, the ideal efficiency of a transformer approaches 100%. The large magnetizing current requirement is a major deterrent.

However if now a piece of magnetic material is introduced to form the magnetic circuit the situation changes dramatically. These can be enumerated as below.

1. Due to the large value for the permeance (μ_r of the order of 1000 as compared to air) the magnetizing current requirement decreases dramatically. This can also be visualized as a dramatic increase in the flux produced for a given value of magnetizing current.

2. The magnetic medium is linear for low values of induction and exhibits saturation type of non-linearity at higher flux densities.

3. The iron also has hysteresis type of non-linearity due to which certain amount of power is lost in the iron (in the form of hysteresis loss), as the B-H characteristic is traversed.

4. Most of the flux lines are confined to iron path and hence the mutual flux is increased very much and leakage flux is greatly reduced.

5. The flux can be easily ‘directed’ as it takes the path through steel which gives great freedom for the designer in physical arrangement of the excitation and output windings.

6. As the medium is made of a conducting material eddy currents are induced in the same and produce losses. These are called ‘eddy current losses’. To minimize the eddy current losses the steel core is required to be in the form of a stack of insulated laminations.

From the above it is seen that the introduction of magnetic core to carry the flux introduced two more losses. Fortunately the losses due hysteresis and eddy current for the available grades of steel are very small at power frequencies. Also the copper losses in the winding due magnetization current are reduced to an almost insignificant fraction of the full load losses. Hence steel core is used in power transformers.

In order to have better understanding of the behavior of the transformer, initially certain idealizations are made and the resulting ‘ideal’ transformer is studied. These idealizations are as follows:

1. Magnetic circuit is linear and has infinite permeability. The consequence is that a vanishingly small current is enough to establish the given flux. Hysteresis loss is negligible.

As all the flux generated confines itself to the iron, there is no leakage flux.

2. Windings do not have resistance. This means that there are no copper losses, nor there is any ohmic drop in the electric circuit.

In fact the practical transformers are very close to this model and hence no major departure is made in making these assumptions.

Fig. 12 shows a two winding ideal transformer. The primary winding has N_1 turns and is connected to a voltage source of V_1 volts. The secondary has N_2 turns. Secondary can be connected to load impedance for loading the transformer. The primary and secondary are shown on the same limb and separately for clarity.

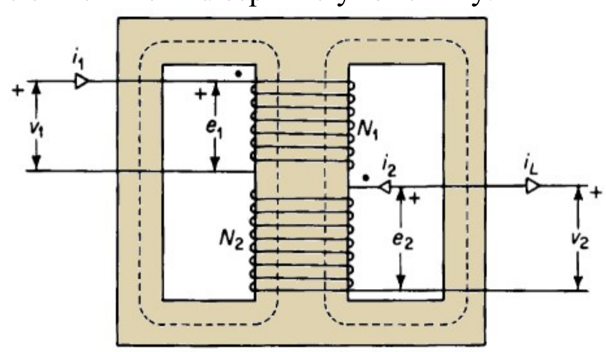


Fig.12: Two winding ideal transformer

As a current I_0 amps is passed through the primary winding of N_1 turns it sets up an mmf of I_0N_1 ampere which is in turn sets up a flux ϕ through the core. Since the reluctance of the iron path given by $R = l/\mu A$ is zero as $\mu \rightarrow \infty$, a vanishingly small value of current I_0 is enough to setup a flux which is finite. As I_0 establishes the field inside the transformer it is called the magnetizing current of the transformer.

This current is the result of a sinusoidal voltage V applied to the primary. As the current through the loop is zero (or vanishingly small), at every instant of time, the sum of the voltages must be zero inside the same. Writing this in terms of instantaneous values we have,

$$v_1 - e_1 = 0$$

where v_1 is the instantaneous value of the applied voltage and e_1 is the induced emf due to Faradays principle. The negative sign is due to the application of the Lenz's law and shows that it is in the form of a voltage drop. Kirchoff's law application to the loop will result in the same thing.

This equation results in $v_1 = e_1$ or the induced emf must be same in magnitude to the applied voltage at every instant of time. Let $v_1 = V_{1peak} \cos \omega t$ where V_{1peak} is the peak value and $\omega = 2\pi f t$, f is the frequency of the supply. As $v_1 = e_1$; $e_1 = d\psi_1/dt$ but $e_1 = E_{1peak} \cos \omega t$ » $E_1 = V_1$. It can be easily seen that the variation of flux linkages can be obtained as $\psi_1 = \psi_{1peak} \sin \omega t$. Here ψ_{1peak} is the peak value of the flux linkages of the primary.

Thus the RMS primary induced emf is

$$e_1 = \frac{d\psi_1}{dt} = \frac{d(\psi_{1peak} \sin \omega t)}{dt}$$

$$E_1 = \frac{\psi_{1peak}\omega}{\sqrt{2}} = \frac{2\pi f N_1 \phi_m}{\sqrt{2}} = 4.44 f \phi_m N_1$$

The same mutual flux links the secondary winding. However the magnitude of the flux linkages will be $\psi_{2peak} = N_2\phi_m$. The induced emf in the secondary can be similarly obtained as,

$$e_2 = \frac{d\psi_2}{dt} = \frac{d(\psi_{2peak} \sin \omega t)}{dt}$$

$$E_2 = \frac{\psi_{2peak}\omega}{\sqrt{2}} = \frac{2\pi f \quad _2\phi_m}{\sqrt{2}} = 4.44 f \phi_m N_2$$

which yields the voltage ratio as

$$\frac{E_1}{E_2} = \frac{N_1}{N_2}$$

The voltages E_1 and E_2 are obtained by the same mutual flux and hence they are in phase. If the winding sense is opposite i.e., if the primary is wound in clockwise sense and the secondary counter clockwise sense then if the top terminal of the first winding is at maximum potential the bottom terminal of the second winding would be at the peak potential. Similar problem arises even when the sense of winding is kept the same, but the two windings are on opposite limbs (due to the change in the direction of flux). Hence in the circuit representation of transformers a dot convention is adopted to indicate the terminals of the windings that go high (or low) together. This can be established experimentally by means of a polarity test on the transformers. At a particular instant of time if the current enters the terminal marked with a dot it magnetizes the core. Similarly a current leaving the terminal with a dot demagnetizes the core.

So far, an unloaded ideal transformer is considered. If now a load impedance Z_L is connected across the terminals of the secondary winding a load current flows. This load current produces a demagnetizing mmf and the flux tends to collapse. However this is detected by the primary immediately as both E_2 and E_1 tend to collapse. The current drawn from supply increases up to a point the flux in the core is restored back to its original value. The demagnetizing mmf produced by the secondary is neutralized by additional magnetizing mmf produces by the primary leaving the mmf and flux in the core as in the case of no-load. Thus the transformer operates under constant induced emf mode.

Thus,

$$i_1N_1 - i_2N_2 = i_0N_1$$

but, $i_0 \to \infty$

$$i_1N_1 = i_2N_2$$

If the reference directions for the two currents are as convention, the above equation can be written in phasor form as,

$$\bar{I}_1N_1 = \bar{I}_2N_2$$

If an impedance of Z_L is connected across the secondary,

$$\bar{I}_2 = \frac{\bar{E}_2}{\bar{Z}_L}$$

The input impedance under such conditions is

$$\bar{Z}_i = \frac{\bar{E}_1}{\bar{I}_1} = \left(\frac{N_1}{N_2}\right)^2 \frac{\bar{E}_2}{\bar{I}_2} = \left(\frac{N_1}{N_2}\right)^2 \bar{Z}_L$$

An impedance of Z_L when viewed 'through' a transformer of turns ratio (N_1/N_2) is seen as $(N_1/N_2)^2\ Z_L$. Transformer thus acts as an impedance converter. The transformer can be interposed in between a source and a load to 'match' the impedance.

Finally, the phasor diagram for the operation of the ideal transformer is shown in Fig. 13 in which θ_1 and θ_2 are power factor angles on the primary and secondary sides. As the transformer itself does not absorb any active or reactive power it is easy to see that $\theta_1 = \theta_2$

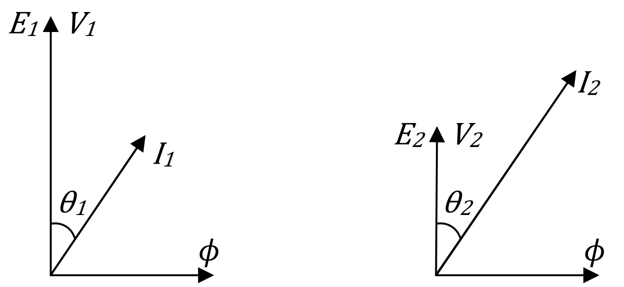


Fig.13: Phasor diagram of Operation of an Ideal Transformer

Thus, from the study of the ideal transformer it is seen that the transformer provides electrical isolation between two coupled electric circuits while maintaining power invariance at its two ends. However, grounding of loads and one terminal of the transformer on the secondary/primary side are followed with the provision of leakage current detection devices to safe guard the persons working with the devices. Even though the isolation aspect is a desirable one its utility cannot be over emphasized. It can be used to step up or step down the voltage/current at constant volt-ampere. Also, the transformer can be used for impedance matching. In the case of an ideal transformer the efficiency is 100% as there are no losses inside the device.

2.4. Practical Transformer

An ideal transformer is useful in understanding the working of a transformer but it cannot be used for the computation of the performance of a practical transformer due to the non-ideal nature of the practical transformer. In a working transformer the performance aspects like magnetizing current, losses, voltage regulation, efficiency etc are important. Hence the effects of the non-idealization like finite permeability, saturation, hysteresis and winding resistances have to be added to an ideal transformer to make it a practical transformer. Conversely, if these effects are removed from a working transformer what is left behind is an ideal transformer.

Finite permeability of the magnetic circuit necessitates a finite value of the current to be drawn from the mains to produce the mmf required to establish the necessary flux. The current and mmf required is proportional to the flux density B that is required to be established in the core.

$$B = \mu H; \quad B = \frac{\phi}{A}$$

where A is the area of cross section of the iron core in m^2. H is the magnetizing force which is given by,

$$H = i\frac{N_1}{l}$$

where l is the length of the magnetic path in m.

It results:

$$\phi = \frac{A\mu i N_1}{l}$$

The magnetizing force and the current vary linearly with the applied voltage as long as the magnetic circuit is not saturated. Once saturation sets in, the current has to vary in a nonlinear manner to establish the flux of sinusoidal shape. This non-linear current can be resolved into fundamental and harmonic currents. This is discussed to some extent under harmonics. At present the effect of this non-linear behavior is neglected as a secondary effect. Hence the current drawn from the mains is assumed to be purely sinusoidal and directly proportional to the flux density of operation. This current can be represented by a current drawn by an inductive reactance in the circuit as the net energy associated with the same over a cycle is zero. The energy absorbed when the current increase is returned to the electric circuit when the current collapses to zero. This current is called the magnetizing current of the transformer. The magnetizing current I_m is given by $I_m = E_1/X_m$ where X_m is called the magnetizing reactance. The magnetic circuit being loss absorbs and dissipates the power depending upon the flux density of operation. These losses arise out of hysteresis, eddy current inside the magnetic core. These are given by the following expressions:

$$P_h \approx B^{1.6} f$$

$$P_e \approx B^2 f^2 t^2$$

P_h - Hysteresis loss, Watts
P_e - Eddy current loss, Watts
B - Flux density of operation Tesla.
f - Frequency of operation, Hz
t - Thickness of the laminations of the core, m.

For a constant voltage, constant frequency operation B is constant and so are these losses. Active power consumption by the no-load current can be represented in the input circuit as a resistance R_c connected in parallel to the magnetizing reactance X_m. Thus the no-load current I_0 may be made up of I_c (loss component) and I_m (magnetizing component):

$$\bar{I}_0 = \bar{I}_c - j\bar{I}_m$$

$I_c^2 R_c$ – gives the total core losses (i.e. hysteresis + eddy current loss)
$I_m^2 X_m$ – reactive volt amperes consumed for establishing the mutual flux.

Finite μ of the magnetic core makes a few lines of flux take to a path through the air. Thus these flux lines do not link the secondary winding. It is called as leakage flux. As the path of the leakage flux is mainly through the air the flux produced varies linearly with the primary current I_1. Even a large value of the current produces a small value of flux. This flux produces a voltage drop opposing its cause, which is the current I_1. Thus this effect of the finite permeability of the magnetic core can be represented as a series inductive element jx_{l1}. This is termed as the reactance due to the primary leakage flux. As this leakage flux varies linearly with I_1, the flux linkages per ampere and the primary leakage inductance are constant (This is normally represented by l_{l1} Henry). The primary leakage reactance therefore becomes

$$X_{l1} = 2\pi f l_{l1}$$

A similar effect takes place on the secondary side when the transformer is loaded. The secondary leakage reactance jX_{l2} arising out of the secondary leakage inductance l_{l2} is given by

$$X_{l2} = 2\pi f l_{l2}$$

Finally, the primary and secondary windings are wound with copper (sometimes aluminum in small transformers) conductors; thus the windings have a finite resistance (though small). This is represented as a series circuit element, as the power lost and the drop produced in the primary and secondary are proportional to the respective currents. These are represented by r_1 and r_2 respectively on primary and secondary side. A practical transformer without these imperfections (taken out and represented explicitly in the electric circuits) is an ideal transformer of turns ratio N_1/N_2 (voltage ratio E_1/E_2).

A practical transformer is presented in Fig. 14 where I_2' represents the primary current component that is required to flow from the mains in the primary N_1 turns to neutralize the demagnetizing secondary current I_2 due to the load in the secondary turns. The total primary current is:

$$\bar{I}_1 = \bar{I}_2' + \bar{I}_0$$

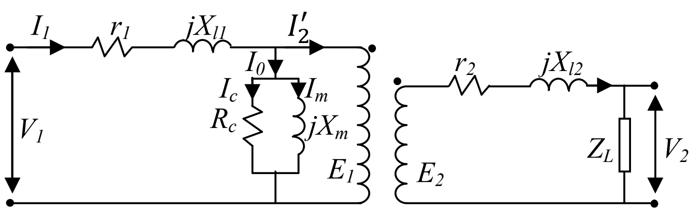


Fig.14: Practical transformer equivalent circuit

By solving this circuit for any load impedance Z_L one can find out the performance of the loaded transformer.

However, it is not very convenient for use due to the presence of the ideal transformer of turns ratio N_1/N_2. If the turns ratio could be made unity by some transformation the circuit becomes very simple to use. This is done here by replacing the secondary by a 'hypothetical' secondary having N_1 turns which is 'equivalent' to the physical secondary. The equivalence implies that the ampere turns, active and reactive power associated with both the circuits must be the same. Then there is no change as far as their effect on the primary is considered. Thus

$$V_2' = aV_2$$

$$I_2' = \frac{I_2}{a}$$

$$r_2' = a^2 r_2$$

$$x_{l2}' = a^2 x_{l2}$$

$$Z_L' = a^2 Z_L$$

where $a = N_1/N_2$ - turns ratio.

This particular equivalent circuit is as seen from the primary side. It is also possible to refer all the primary parameters to secondary by making the hypothetical equivalent primary winding on the input side having the number of turns to be N_2. Such an equivalent circuit having all the parameters referred to the secondary side.

The equivalent circuit can be derived, with equal ease, analytically using the Kirchoff's equations applied to the primary and secondary. Referring to Fig. 14, we have (by neglecting the shunt branch)

$$V_1 = E_1 + I_1(r_1 + jX_{l1})$$

$$E_2 = V_2 + I_2(r_2 + jX_{l2})$$

$$N_1 I_0 = N_1 I_1 + N_2 I_2 \quad or \quad I_1 = -\frac{I_2}{a} + I_0 = -\frac{I_2}{a} + I_c + I_m$$

Multiply both sides of the second equation by 'a' and replacing into the first one the expression of $E_1 = a\,E_2$ we will have:

$$\begin{aligned} V_1 &= aV_2 + aI_2(r_2 + jX_{l2}) + I_1(r_1 + jX_{l1}) \\ &= V_2' + I_1(a^2 r_2 + ja^2 X_{l2}) + I_1(r_1 + jX_{l1}) \\ &= V_2' + I_1(r_1 + r_2' + jX_{l1} + jX_{l2}') \end{aligned}$$

2.5. Phasor diagrams

The resulting equivalent circuit as shown in Fig. 15 is known as the exact equivalent circuit. This circuit can be used for the analysis of the behavior of the transformers.

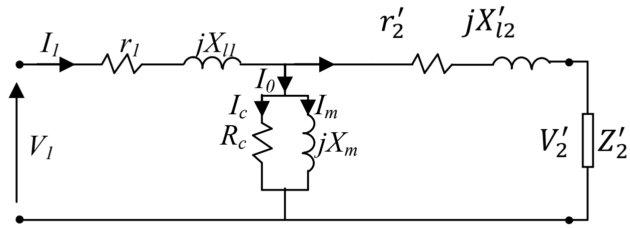


Fig.15: Equivalent circuit

On similar lines to the ideal transformer the phasor diagram of operation can be drawn for a practical transformer also. The positions of the current and induced emf phasor are not known uniquely if we start from the phasor V_1. Hence it is assumed that the phasor ϕ is known. The E_1 and E_2 phasor are then uniquely known. Now, the magnetizing and loss components of the currents can be easily represented. Once I_0 is known, the drop that takes place in the primary resistance and series reactance can be obtained which when added to E_1 gives uniquely the position of V_1 which satisfies all other parameters. This is represented in Fig. 16 as phasor diagram on no-load.

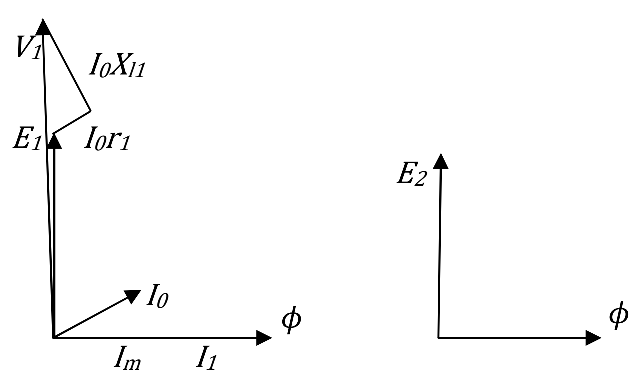


Fig. 16: Phasor Diagram of a Practical Transformer – no load

Next we proceed to draw the phasor diagram corresponding to a loaded transformer. The position of the E_2 vector is known from the flux phasor. Magnitude of I_2 and the load power factor angle θ_2 are assumed to be known. But the angle θ_2 is defined with respect to the terminal voltage V_2 and not E_2. By trial and error the position of I_2 and V_2 are determined. V_2 should also satisfy the Kirchoff's equation for the secondary. Rest of the construction of the phasor diagram then becomes routine. The equivalent primary current I_2' is added vectorially to I_0 to yield I_1. $I_1(r_1+jX_{l1})$is added to E_1 to yield V_1. This is shown in Fig. 17 as phasor diagram for a loaded transformer.

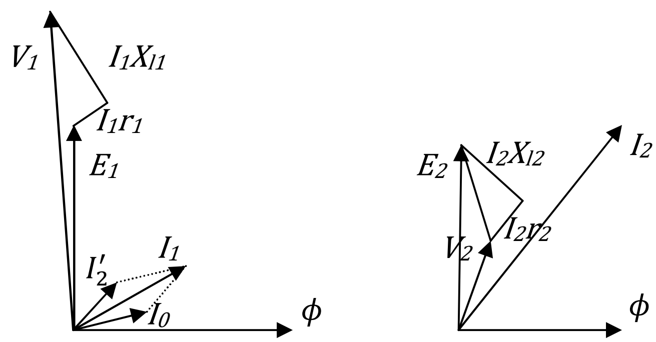


Fig. 17: Phasor Diagram of a Practical Transformer – under load

2.6. Three Phase Transformer

2.6.1. Three Phase Transformer Basics

Thus far we have looked at the construction and operation of the single-phase, two winding voltage transformer which can be used increase or decrease its secondary voltage with respect to the primary supply voltage. But voltage transformers can also be constructed for connection to not only one single phase, but for two-phases, three-phases, six-phases and even elaborate combinations up to 24-phases for some DC rectification transformers.

If we take three single-phase transformers and connect their primary windings to each other and their secondary windings to each other in a fixed configuration, we can use the transformers on a three-phase supply.

Three-phase, also written as 3-phase or 3φ supplies are used for electrical power generation, transmission, and distribution, as well as for all industrial uses. Three-phase supplies have many electrical advantages over single-phase power and when considering three-phase transformers we have to deal with three alternating voltages and currents differing in phase-time by 120 degrees as shown below (Fig.18).

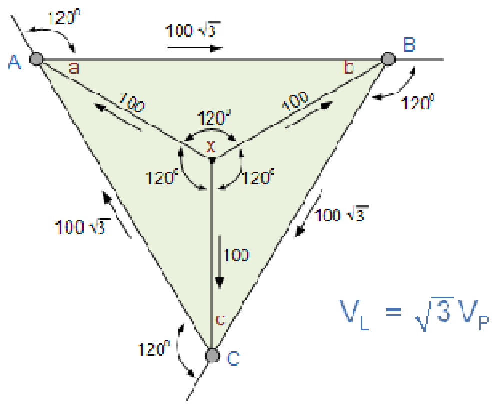


Fig.18: Three-phase voltage system diagram

A transformer cannot act as a phase changing device and change single-phase into three-phase or three-phase into single phase. To make the transformer connections compatible with three-phase supplies we need to connect them together in a particular way to form a *Three Phase Transformer Configuration*.

A three phase transformer or 3φ transformer can be constructed either by *connecting together three single-phase transformers*, thereby forming a so-called *three phase transformer bank*, or by using *one pre-assembled and balanced three phase transformer* which consists of three pairs of single phase windings mounted onto one single laminated core.

The advantages of building a single three phase transformer is that for the same kVA rating it will be smaller, cheaper and lighter than three individual single phase transformers connected together because the copper and iron core are used more effectively. The methods of connecting the primary and secondary windings are the same, whether using just one Three Phase Transformer or three separate Single Phase Transformers. Consider the circuit below:

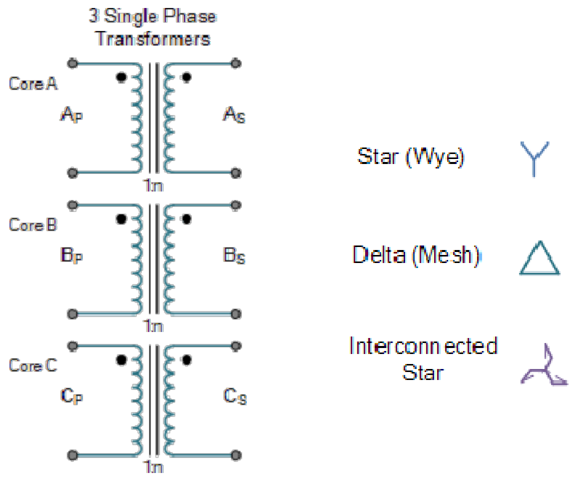


Fig.19: Three phase transformer connections

The primary and secondary windings of a transformer can be connected in different configuration as shown to meet practically any requirement. In the case of three phase transformer windings, three forms of connection are possible: *"star" (wye), "delta" (mesh) and "interconnected-star" (zig-zag)*. The combinations of the three windings may be with the primary delta-connected and the secondary star-connected, or star-delta, star-star or delta-delta, depending on the transformers use. When transformers are used to provide three or more phases they are generally referred to as a *Polyphase Transformer*.

2.6.2. Three Phase Transformer Star and Delta Configurations

But what do we mean by "*star*" and "*delta*" three-phase transformer connection. A three phase transformer has three sets of primary and secondary windings. Depending upon how these sets of windings are interconnected, determines whether the connection is a star or delta configuration. The available voltages which are each displaced from the other by 120 electrical degrees and flow of the transformers currents are also decided by the type of the electrical connection used on both the primary and secondary sides.

With three single-phase transformers connected together, the magnetic flux's in the three transformers differ in phase by 120 time-degrees. With a single the three-phase transformer there are three magnetic flux's in the core differing in time-phase by 120 degrees.

The standard method for marking three phase transformer windings is to label the three primary windings with capital (upper case) letters A, B and C, used to represent the three-phases. The secondary windings are labeled with small (lower case) letters a, b and c. Each winding has two ends normally labeled 1 and 2 so that, for example, the second winding of the primary has ends which will be labeled B1 and B2, while the third winding of the secondary will be labeled c1 and c2 as shown.

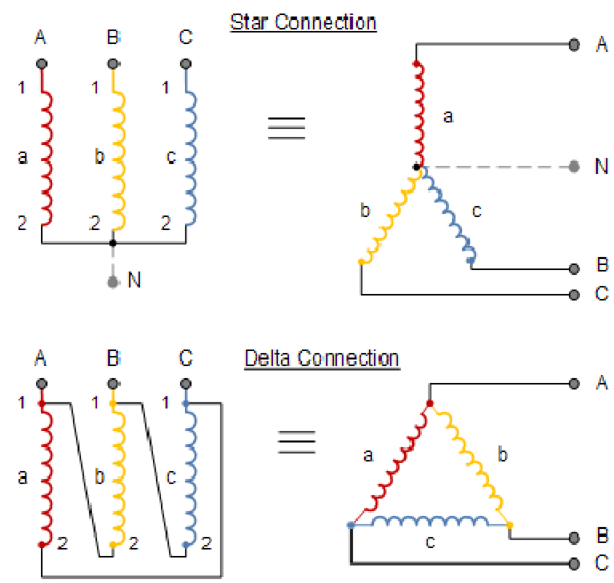


Fig.20: Transformer star and delta configurations

Symbols are generally used on a three phase transformer to indicate the type or types of connections used with upper case Y for star connected, D for delta connected primary windings, with lower case y, d for their respective secondary. Then, star-star would be labeled *Yy*, delta-delta would be labeled *Dd* and so on depending on the types of connected transformers.

2.6.3. Transformer Winding Identification

We now know that there are four ways in which three single-phase transformers may be connected together between primary and secondary three-phase circuits. The configurations are delta-delta, star-star, star-delta, and delta-star. Transformers for high voltage operation with the star connections has the advantage of reducing the voltage on an individual transformer, reducing the number of turns required and an increase in the size of the conductors, making the coil windings easier and cheaper to insulate than delta transformers.

The delta-delta connection nevertheless has one big advantage over the star-delta configuration, in that if one transformer of a group of three should become faulty or disabled, the two remaining ones will continue to deliver three-phase power with a capacity equal to approximately two thirds of the original output from the transformer unit.

In a delta connected (Dd) group of transformers, the line voltage, V_L is equal to the supply voltage, $V_L = V_S$. But the current in each phase winding is given as: $1/\sqrt{3}$ of the line current.

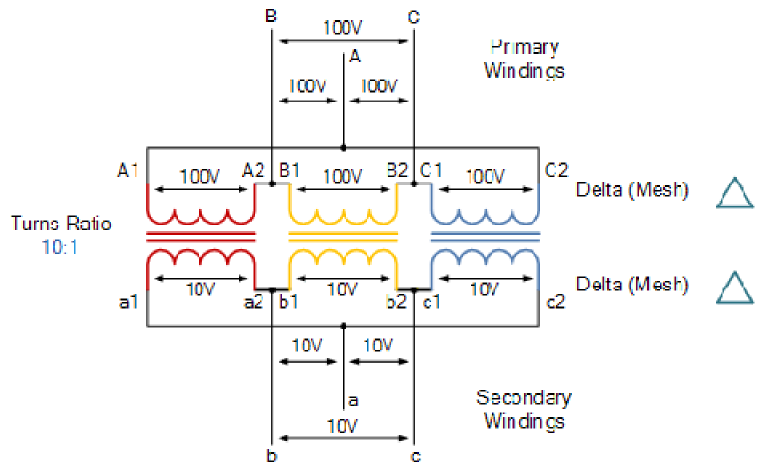


Fig.21: Transformer delta and delta connections

One disadvantage of delta connected three phase transformers is that each transformer must be wound for the full-line voltage, (in our example above 100V) and for 57.7 per cent, line current. The greater number of turns in the winding, together with the insulation between turns, necessitates a larger and more expensive coil than the star connection. Another disadvantage with delta connected three phase transformers is that there is no "neutral" or common connection.

In the star-star arrangement (Yy), (wye-wye), each transformer has one terminal connected to a common junction, or *neutral point* with the three remaining ends of the primary windings connected to the three-phase mains supply. The number of turns in a transformer winding for star connection is 57.7 per cent, of that required for delta connection.

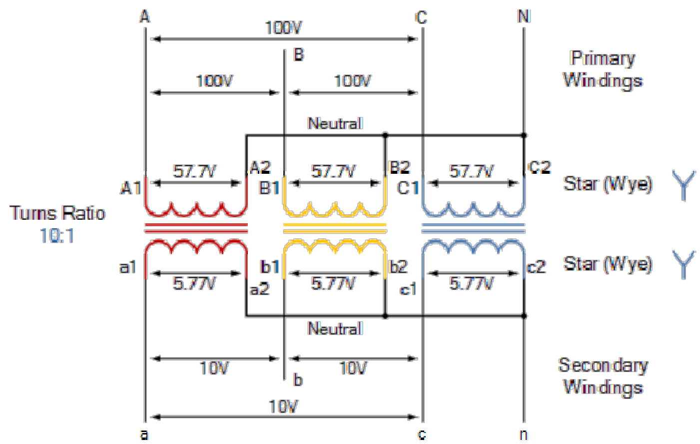


Fig.22: Transformer wye-wye connections

The star connection requires the use of three transformers, and if any one transformer becomes fault or disabled, the whole group might become disabled. Nevertheless, the star connected three phase transformer is especially convenient and economical in electrical power distributing systems, in that a fourth wire may be connected as a neutral point, (n) of the three star connected secondary as shown in Fig.22.

The voltage between any lines of the three-phase transformer is called the "*line voltage*", V_L, while the voltage between any line and the neutral point of a star connected transformer is called the "*phase voltage*", V_P. This phase voltage between the neutral point and any one of the line connections is $1/\sqrt{3}$ of the line voltage. Then above, the primary side phase voltage, V_P is given as.

$$V_P = \frac{1}{\sqrt{3}} V_L$$

The secondary current in each phase of a star-connected group of transformers is the same as that for the line current of the supply, then $I_L = I_S$.

Then the relationship between line and phase voltages and currents in a three-phase system can be summarized as:

Connection	Voltages	Currents
Star	$V_L = \sqrt{3}V_P$	$V_L = V_P$
Delta	$I_L = I_P$	$I_L = \sqrt{3}I_P$

Other possible connections for three phase transformers are star-delta Yd, where the primary winding is star-connected and the secondary is delta-connected or delta-star Dy with a delta-connected primary and a star-connected secondary. Delta-star connected transformers are widely used in low power distribution with the primary windings providing a three-wire balanced load to the utility company while the secondary windings provide the required 4th-wire neutral or earth connection.

When the primary and secondary have different types of winding connections, star or delta, the overall turns ratio of the transformer becomes more complicated. If a three-phase transformer is connected as delta-delta (Dd) or star-star (Yy) then the transformer could potentially have a 1:1 turns ratio. That is the input and output voltages for the windings are the same.

However, if the 3-phase transformer is connected in star–delta, (Yd) each star-connected primary winding will receive the phase voltage, V_P of the supply, which is equal to $1/\sqrt{3} \times V_L$. Then each corresponding secondary winding will then have this same voltage induced in it, and since these windings are delta-connected, the voltage $1/\sqrt{3} \times V_L$ will become the secondary line voltage. Then with a 1:1 turns ratio, a star–delta connected transformer will provide a √3:1 step-down line-voltage ratio.

Then for a star–delta (Yd) connected transformer the turns ratio becomes:

$$\frac{N_P}{N_S} = \frac{V_P}{\sqrt{3}V_S}$$

Likewise, for a delta–star (Dy) connected transformer, with a 1:1 turns ratio, the transformer will provide a 1:√3 step-up line-voltage ratio. Then for a delta-star connected transformer the turns ratio becomes:

$$\frac{N_P}{N_S} = \frac{\sqrt{3}V_P}{V_S}$$

Then for the four basic configurations of a three-phase transformer, we can list the transformers secondary voltages and currents with respect to the primary line voltage, V_L and its primary line current I_L as shown in the following table.

Primary-Secondary Configuration	Line Voltage	Line Current
Delta – Delta	aV_L	$\frac{I_L}{a}$
Delta – Star	$\sqrt{3}aV_L$	$\frac{I_L}{\sqrt{3}a}$
Star – Delta	$\frac{aV_L}{\sqrt{3}}$	$\sqrt{3}\frac{I_L}{a}$
Star – Star	aV_L	$\frac{I_L}{a}$

Where: *a* equals the transformers "turns ratio" of the number of secondary windings N_S, divided by the number of primary windings N_P. (N_S/N_P)

2.7. Special Transformers

2.7.1. Autotransformer

Unlike the usual voltage transformer which has two electrically isolated windings, the primary and the secondary, an *Autotransformer* has only one single voltage winding which is usually "tapped" at various points along it to provide a percentage of the primary voltage supply across its secondary load. The autotransformer has the usual magnetic core but only one winding, which is common to both the primary and secondary circuits.

Therefore in an autotransformer the primary and secondary windings are both linked together electrically and magnetically. This type of transformer design is a lot cheaper but the main disadvantage of an autotransformer is that it does not have the primary/secondary winding isolation of a conventional double wound transformer.

The section of winding designated as the primary part of the winding is connected to the AC power source with the secondary being part of this primary winding. An autotransformer can also be used to step the supply voltage up or down by reversing the connections. If the primary is the total winding and is connected to a supply, and the secondary circuit is connected across only a portion of the winding, then the secondary voltage is "stepped-down" as shown.

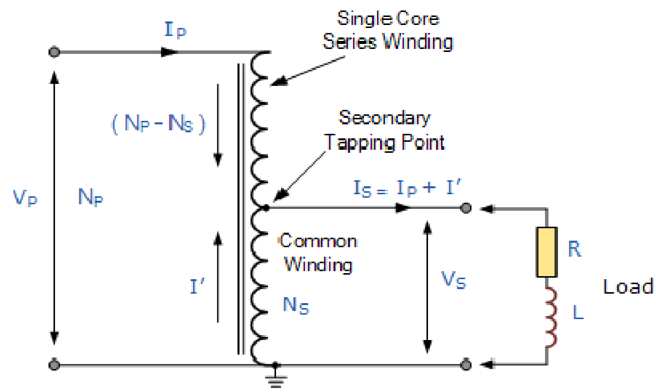


Fig.23: Autotransformer design

When the primary current I_P is flowing through the single winding in the direction of the arrow as shown, the secondary current, I_S, flows in the opposite direction. Therefore, in the portion of the winding that generates the secondary voltage, V_S the current flowing out of the winding is the difference of I_P and I_S.

The Autotransformer can also be constructed with more than one single tapping point. Autotransformers can be used to provide different voltage points along its winding or increase its supply voltage with respect to its supply voltage V_P as shown.

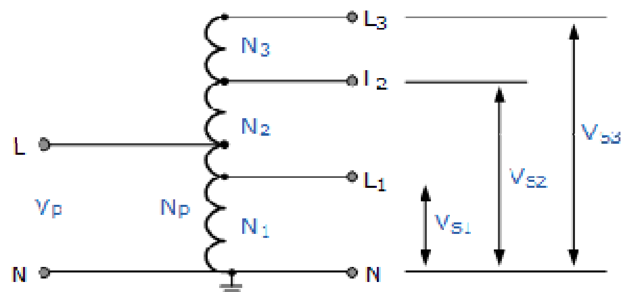


Fig.24: Autotransformer with multiple tapping points

An autotransformer is used mainly for the adjustments of line voltages to either change its value or to keep it constant. If the voltage adjustment is by a small amount, either up or down, then the transformer ratio is small as V_P and V_S are nearly equal. Currents I_P and I_S are also nearly equal.

Therefore, the portion of the winding which carries the difference between the two currents can be made from a much smaller conductor size, since the currents are much smaller saving on the cost of an equivalent double wound transformer. However, the regulation, leakage inductance and physical size (since there is no second winding) of an autotransformer for a given VA or KVA rating are less than for a double wound transformer.

Autotransformers are clearly much cheaper than conventional double wound transformers of the same VA rating. When deciding upon using an autotransformer it is usual to compare its cost with that of an equivalent double wound type. This is done by comparing the amount of copper saved in the winding.

Disadvantages of an autotransformer:

1). The main disadvantage of an autotransformer is that it does not have the primary to secondary winding isolation of a conventional double wound transformer. Then autotransformer's cannot safely be used for stepping down higher voltages to much lower voltages suitable for smaller loads.

2). If the secondary side winding becomes open-circuited, current stops flowing through the primary winding stopping the transformer action resulting in the full primary voltage being applied to the secondary circuit.

3). If the secondary circuit suffers a short-circuit condition, the resulting primary current would be much larger than an equivalent double wound transformer due to the increased flux linkage damaging the autotransformer.

4). Since the neutral connection is common to both the primary and secondary windings, earthling of the secondary winding automatically earths the primary as there is no isolation between the two windings. Double wound transformers are sometimes used to isolate equipment from earth.

The autotransformer has many uses and applications including the starting of induction motors, used to regulate the voltage of transmission lines, and can be used to transform voltages when the primary to secondary ratio is close to unity. An autotransformer can also be made from conventional two-winding transformers by connecting the primary and secondary windings together in series and depending upon how the connection is made, the secondary voltage may add to, or subtract from, the primary voltage.

As well as having a fixed or tapped secondary that produces a voltage output at a specific level, there is another useful application of the auto transformer type of arrangement which can be used to produce a variable AC voltage from a fixed voltage AC supply. This type of *Variable Autotransformer* is generally used in laboratories and science labs in schools and colleges and is known more commonly as the *Variac*.

The construction of a variable autotransformer, or variac, is the same as for the fixed type. A single primary winding wrapped around a laminated magnetic core is used as in the auto transformer but instead of being fixed at some predetermined tapping point, the secondary voltage is tapped by a carbon brush. This carbon brush is rotated or allowed to slide along an exposed section of the primary winding, making contact with it as it moves supplying the required voltage level.

Then a variable autotransformer contains a variable tap in the form of a carbon brush that slides up and down the primary winding which controls the secondary winding length and hence the secondary output voltage is fully variable from the primary supply voltage value to zero volts.

The variable autotransformer is usually designed with a significant number of primary windings to produce a secondary voltage which can be adjusted from a few volts to fractions of a volt per turn. This is achieved because the carbon brush or slider is always in contact with one or more turns of the primary winding. As the primary coil turns are evenly spaced along its length. Then the output voltage becomes proportional to the angular rotation.

We can see that the variac can adjust the voltage to the load smoothly from zero to the rated supply voltage. If the supply voltage was tapped at some point along the primary winding, then potentially the output secondary voltage could be higher than the actual supply voltage. Variable autotransformers can also be used for the dimming of lights and when used in this type of application, they are sometimes called "dimmerstats".

Variacs are also very useful in electrical and electronics workshops and labs as they can be used to provide a variable AC supply. But caution needs to be taken with suitable fuse protection to ensure that the higher supply voltage is not present at the secondary terminals under fault conditions.

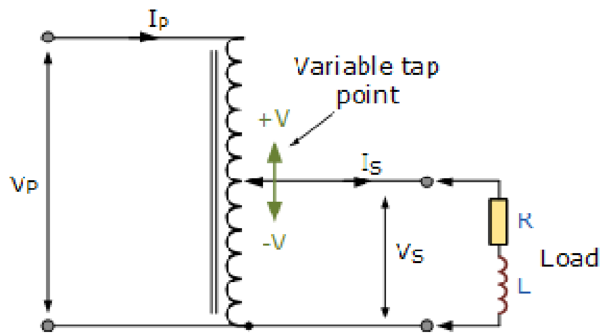


Fig.25: Variable autotransformer

The autotransformer has many advantages over conventional double wound transformers. They are generally more efficient for the same VA rating, are smaller in size, and as they require less copper in their construction, their cost is less compared to double wound transformers of the same VA rating. Also, their core and copper losses, I^2R are lower due to less resistance and leakage reactance giving a superior voltage regulation than the equivalent two winding transformer.

2.7.2. Welding transformers

Most of the supplies available now are a.c. Therefore a transformer for welding is most commonly used as compared to motor-generator set. Moreover motor-generator set has to be kept in running position continuously during the weld is made.

Welding transformer (Fig.26) is a transformer having thin primary windings with a large number of turns, while the secondary has more area of cross-section and less number of turns ensuring less voltage and very high current in the secondary.

One end of the secondary is connected to the welding electrode, whereas the other end is connected to the pieces to be welded. If any high current flows, heat is produced due to the contact resistance between the electrode and the pieces to be welded. The generated heat melts a tip of the electrode and the gap between the two pieces is filled.

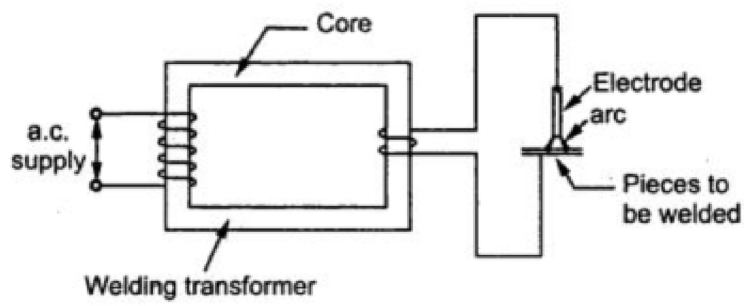


Fig.26 Diagram of a welding transformer

A winding used for the welding transformer is highly reactive or a separate reactor may be added in series with the secondary winding. Volt-ampere characteristics for a welding transformer are shown in the Fig. 27.

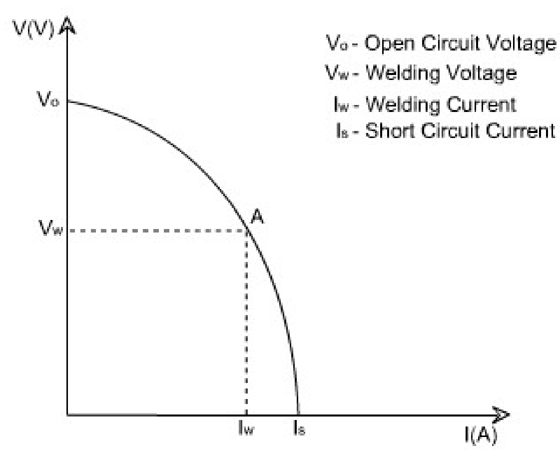


Fig.27: Volt ampere characteristics for a welding transformer

The welding transformer can be used with various reactors for control of arc. The various methods of such control are:

- *Tapped Reactor* (Fig.28): In this, output current is regulated by taps on the reactor. This has limited number of current settings.

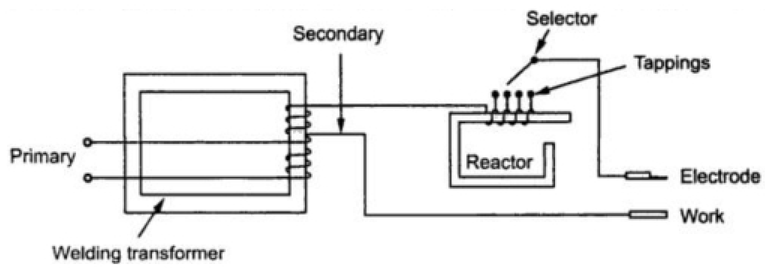


Fig.28: Tapped reactor

- *Moving Coil Reactor* (Fig.29)*:* In this method, the relative distance between primary and the secondary is adjusted. When the distance between the coils is large the current obtained is less.

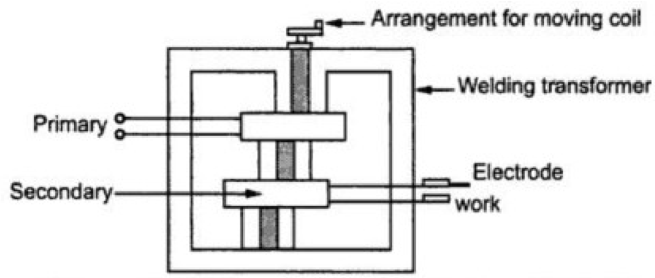


Fig.29: Moving Coil Reactor

- *Magnetic Shunt Reactor* (Fig.30)*:* In this method, position of central magnetic shunt can be adjusted. This adjusts the shunted flux and hence output current gets changed.

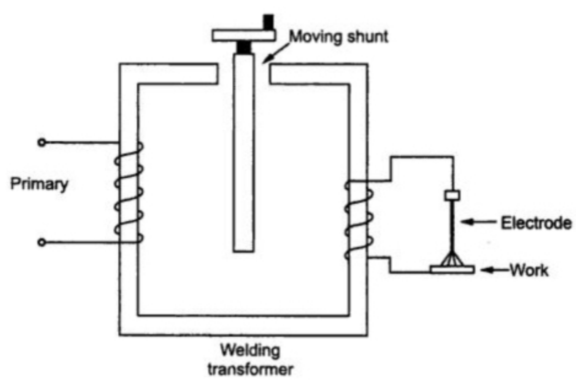


Fig.30: Magnetic Shunt Reactor

- *Continuously Variable Reactor* (Fig.31): The height of the reactor is continuously varied in this method. Greater the core insertion greater is the reactance and less is the output current.

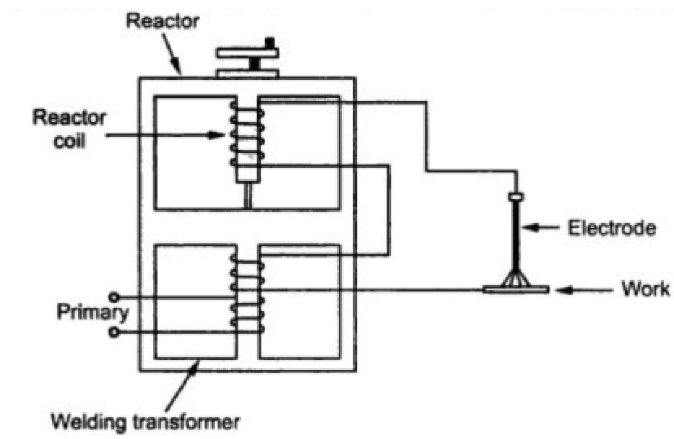


Fig.31: Continuously variable reactor

- *Saturable Reactor* (Fig.32): The reactance of the reactor is adjusted by changing the value of d.c. excitation obtained from d.c. controlled transducer. More the d.c. currents, reactor approaches to saturation. This changes the reactance of reactor and hence changing the current.

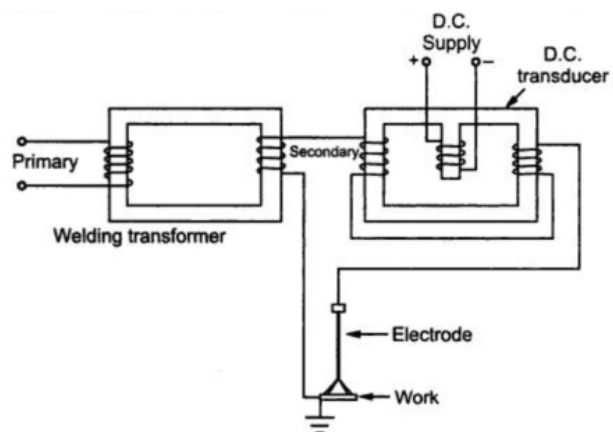


Fig.32: Saturable Reactor

3. D.C Machines

3.1. Introduction

The steam age signaled the beginning of an industrial revolution. The advantages of machines and gadgets in helping mass production and in improving the services spurred the industrial research. Thus a search for new sources of energy and novel gadgets received great attention. By the end of the 18th century the research on electric charges received a great boost with the invention of storage batteries. This enabled the research work on moving charges or currents. It was soon discovered (in 1820) that, these electric currents are also associated with magnetic field like a load stone. This led to the invention of an electromagnet. Hardly a year later, the force exerted on a current carrying conductor placed in the magnetic field was invented. This can be termed as the birth of a motor. A better understanding of the inter relationship between electric and magnetic circuits was obtained with the enumeration of laws of induction by Faraday in 1831. Parallel research was contemporarily being done to invent a source of energy to recharge the batteries in the form of a d.c. source of constant amplitude (or d.c. generator). For about three decades the research on d.c. motors and d.c. generators proceeded on independent paths. During the second half of the 19th century these two paths merged. The invention of a commutator paved the way for the birth of d.c. generators and motors. These inventions generated great interest in the generation and use of electrical energy. Other useful machines like alternators, transformers and induction motors came into existence almost contemporarily. The evolution of these machines was very quick. They rapidly attained the physical configurations that are being used even today. The d.c. power system was poised for a predominant place as a preferred system for use, with the availability of batteries for storage, d.c. generators for conversion of mechanical energy into electrical form and d.c. motors for getting mechanical outputs from electrical energy.

The limitations of the d.c. system however became more and more apparent as the power demand increased. In the case of d.c. systems the generating stations and the load centers have to be near to each other for efficient transmission of energy. The invention of induction machines in the 1880s tilted the scale in favor of a.c. systems mainly due to the advantage offered by transformers, which could step up or step down the a.c.voltage levels at constant power at extremely high efficiency. Thus a.c. system took over as the preferred system for the generation transmission and utilization of electrical energy. The d.c. system, however could not be obliterated due to the support of batteries. Further, d.c. motors have excellent control characteristics. Even today the d.c. motor remains an industry standard as far as the control aspects are concerned. In the lower power levels and also in regenerative systems the d.c. machines still have a major say.

In spite of the apparent diversity in the characteristics, the underlying principles of both a.c. and d.c. machines are the same. They use the electromagnetic principles which can be further simplified at the low frequency levels at which these machines are used.

3.2. Constructional Aspects of D.C. Machines

As mentioned earlier the d.c. machines were invented during the second half of the 19th century. The initial pace of development work was phenomenal. The best configurations stood all the competition and the test of time and were adopted. Less effective options were discarded. The present day d.c. machines contains most, if not all, of the features of the machine developed over a century earlier. To appreciate the working and the characteristics of these machines, it is necessary to know about the different parts of the machine – both electrical and non-electrical. The description would also aid the understanding of the reason for selecting one form of construction or the other. A view of a typical d.c. machine is given in Fig.33.

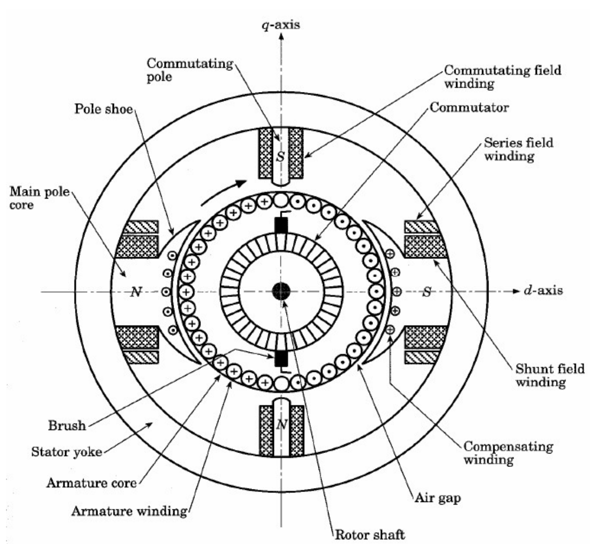


Fig.33: General arrangement of a dc machine

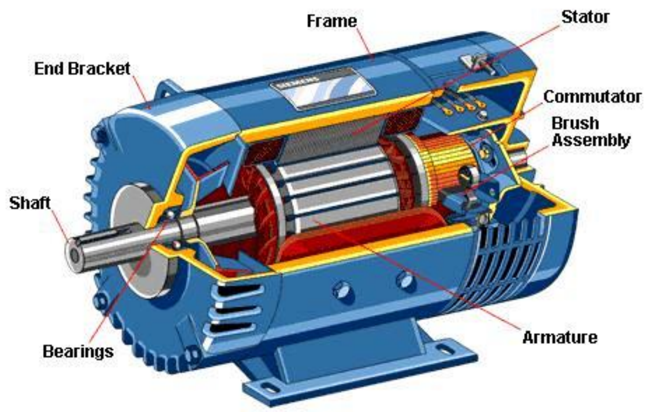


Fig. 34: Main parts of a d.c. machine

The main parts of a d.c. machine as can be seen in Fig.34 are:

- *the body (frame)*

The body constitutes the outer shell within which all the other parts are housed. This will be closed at both the ends by two end covers which also support the bearings required to facilitate the rotation of the rotor and the shaft. Even though for the generation of an emf in a conductor a relative movement between the field and the conductor would be enough, due to practical considerations of commutation, a rotating conductor configuration is selected for d.c. machines. Hence the shell or frame supports the poles and yoke of the magnetic system. In many cases the shell forms part of the magnetic circuit itself. Cast steel is used as a material for the frame and yoke as the flux does not vary in these parts. In large machines these are fabricated by suitably welding the different parts. Those are called as fabricated frames. Fabrication as against casting avoids expensive patterns. In small special machines these could be made of stack of laminations suitably fastened together to form a solid structure.

- *the main poles*

Solid poles of fabricated steel with separate/integral pole shoes are fastened to the frame by means of bolts. Pole shoes are generally laminated. Sometimes pole body and pole shoe are formed from the same laminations. Stiffeners are used on both sides of the laminations. The pole shoes are shaped so as to have a slightly increased air gap at the tips.

- *the inter-poles (commutating poles)*

These are small additional poles located in between the main poles. These can be solid, or laminated just as the main poles. These are also fastened to the yoke by bolts. Sometimes the yoke may be slotted to receive these poles. The inter poles could be of tapered section or of uniform cross section.

These are also called as commutating poles. The width of the tip of the commutating poles can be about a rotor slot pitch.

- *the armature*

The armature is where the moving conductors are located. The armature is constructed by stacking laminated sheets of silicon steel. Thickness of these lamination is kept low to reduce eddy current losses. As the laminations carry alternating flux the choice of suitable material, insulation coating on the laminations, stacking it etc are to be done more carefully. The core is divided into packets to facilitate ventilation. The winding cannot be placed on the surface of the rotor due to the mechanical forces coming on the same. Open parallel sided equally spaced slots are normally punched in the rotor laminations. These slots house the armature winding. Large sized machines employ a spider on which the laminations are stacked in segments. End plates are suitably shaped so as to serve as 'Winding supporters'. Armature construction process must ensure provision of sufficient axial and radial ducts to facilitate easy removal of heat from the armature winding.

- *the field windings*

In the case of wound field machines (as against permanent magnet excited machines) the field winding takes the form of a concentric coil wound around the main poles. These carry the excitation current and produce the main field in the machine. Thus the poles are created electromagnetically. Two types of windings are generally employed. In shunt winding large number of turns of small section copper conductor is used. The resistance of such winding would be an order of magnitude larger than the armature winding resistance. In the case of series winding a few turns of heavy cross section conductor is used. The resistance of such windings is low and is comparable to armature resistance. Some machines may have both the windings on the poles. The total ampere turns required to establish the necessary flux under the poles is calculated from the magnetic circuit calculations. The total mmf required is divided equally between north and south poles as the poles are produced in pairs. The mmf required to be shared between shunt and series windings are apportioned as per the design requirements. As these work on the same magnetic system they are in the form of concentric coils. Mmf 'per pole' is normally used in these calculations.

- *the armature winding*

As mentioned earlier, if the armature coils are wound on the surface of the armature, such construction becomes mechanically weak. The conductors may fly away when the armature starts rotating. Hence the armature windings are in general pre-formed, taped and lowered into the open slots on the armature. In the case of small machines, they can be hand wound. The coils are prevented from flying out due to the centrifugal forces by means of bands of steel wire on the surface of the rotor in small groves cut into it. In the case of large machines slot wedges are additionally used to restrain the coils from flying away. The end portion of the windings are taped at the free end and bound to the winding carrier ring of the armature at the commutator end. The armature must be dynamically balanced to reduce the centrifugal forces at the operating speeds.

- *the compensating winding*

One may find a bar winding housed in the slots on the pole shoes. This is mostly found in d.c. machines of very large rating. Such winding is called compensating winding. In smaller machines, they may be absent. The function and the need of such windings will be discussed later on.

- *the commutator*

Commutator is the key element which made the d.c. machine of the present day possible. It consists of copper segments tightly fastened together with mica/micanite insulating separators on an insulated base. The whole commutator forms a rigid and solid assembly of insulated copper strips and can rotate at high speeds. Each commutator segment is provided with a 'riser' where the ends of the armature coils get connected. The surface of the commutator is machined and surface is made concentric with the shaft and the current collecting brushes rest on the same. Under-cutting the mica insulators that are between these commutator segments has to be done periodically to avoid fouling of the surface of the commutator by mica when the commutator gets worn out.

- *the brush and the brush holders*

Brushes rest on the surface of the commutator. Normally electro-graphite is used as brush material. The actual composition of the brush depends on the peripheral speed of the commutator and the working voltage. The hardness of the graphite brush is selected to be lower than that of the commutator. When the brush wears out the graphite works as a solid lubricant reducing frictional coefficient. More number of relatively smaller width brushes are preferred in place of large broad brushes. The brush holders provide slots for the brushes to be placed. The connection from the brush is taken out by means of flexible pigtail. The brushes are kept pressed on the commutator with the help of springs. This is to ensure proper contact between the brushes and the commutator even under high speeds of operation. Jumping of brushes must be avoided to ensure arc free current collection and to keep the brush contact drop low. Radial positioning of the brushes helps in providing similar current collection conditions for both direction of rotation. For unidirectional drives trailing brush arrangement or reaction arrangement may be used. Reaction arrangement is preferred as it results in zero side thrust on brush box and the brush can slide down or up freely. Also staggering of the brushes along the length of the commutator is adopted to avoid formation of

’tracks’ on the commutator. This is especially true if the machine is operating in a dusty environment like the one found in cement plants.

- *other mechanical parts*

End covers, fan and shaft bearings form other important mechanical parts. End covers are completely solid or have opening for ventilation. They support the bearings which are on the shaft. Proper machining is to be ensured for easy assembly. Fans can be external or internal. In most machines the fan is on the non-commutator end sucking the air from the commutator end and throwing the same out. Adequate quantity of hot air removal has to be ensured.

- *bearings*

Small machines employ ball bearings at both ends. For larger machines roller bearings are used especially at the driving end. The bearings are mounted press-fit on the shaft. They are housed inside the end shield in such a manner that it is not necessary to remove the bearings from the shaft for dismantling. The bearings must be kept in closed housing with suitable lubricant keeping dust and other foreign materials away. Thrust bearings, roller bearings, pedestal bearings etc are used under special cases. Care must be taken to see that there are no bearing currents or axial forces on the shaft both of which destroy the bearings.

3.3. Armature Windings

Armature windings, along with the commutator, form the heart of the d.c. machine. This is where the emf is induced and hence its effective deployment enhances the output of the machine. There are two different types of armature windings: *ring winding* and *drum winding*.

The *ring winding* has only one conductor in a turn working as an active conductor. The second conductor is used simply to complete the electrical connections. Thus the effectiveness of the electric circuit is only 50 percent. Looking at it differently, half of the magnetic flux per pole links with each coil. Also, the return conductor has to be wound inside the bore of the rotor, and hence the rotor diameter is larger and mounting of the rotor on the shaft is made difficult.

In a *drum winding* both forward and return conductors are housed in slots cut on the armature (or drum). Both the conductors have emf induced in them. Looking at it differently the total flux of a pole is linked with a turn inducing much larger voltage induced in the same. The rotor is mechanically robust with more area being available for carrying the flux. There is no necessity for a rotor bore. The rotor diameters are smaller. Mechanical problems that existed in ring winding are no longer there with drum windings. The coils could be made of single conductors (single turn coils) or more number of conductors in series (multi turn coils). These coils are in turn connected to form a closed winding. The two sides of the coil lie under two poles one north and the other south, so that the induced emf in them are always additive by virtue of the end connection. Even though the total winding is a closed one the sum of the emf would be zero at all times. Thus there is no circulating current when the armature is not loaded. The two sides of the coil, if left on the surface, will fly away due to centrifugal forces. Hence slots are made on the surface and the conductors are placed in these slots and fastened by steel wires to keep them in position. Each armature slot is partitioned into two layers, a top layer and a bottom layer Fig.35.

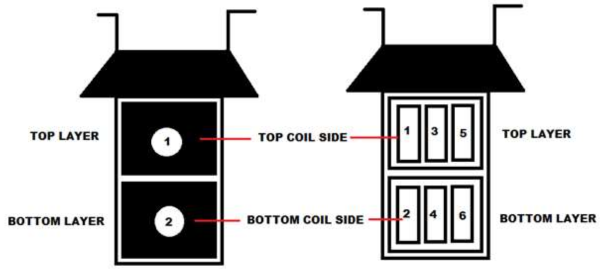


Fig.35: Double layer winding

The winding is called as a double layer winding. This is a direct consequence of the symmetry consideration. The distance, measured along the periphery of the armature from any point under a pole to a similar point under the neighboring pole is termed as a *pole pitch*. The forward conductor is housed in the top layer of a slot and the return conductor is housed in the bottom layer of a slot which is displaced by about one pole pitch. The junction of two coils is terminated on a commutator segment. Thus there are as many commutator segments as the number of coils. In a double layer winding in S slots there are 2S layers. Two layers are occupied by a coil and hence totally there are S coils. The S junctions of these S coils are terminated on S commutator segments. The brushes are placed in such a manner that a maximum voltage appears across them. While the number of parallel circuits in the case of ring winding is equal to the number of poles, in the case of drum winding a wide variety of windings are possible.

The number of brushes and parallel paths thus vary considerably. The number of turns in a coil can be one (single turn coils) or more (multi turn coils). As seen earlier the sum of the instantaneous emfs appears across the brushes. This sum gets altered by the voltage of a coil that is being switched from one circuit to the other or which is being commutated. As this coil in general lies in the magnetic neutral axis it has a small value of voltage induced in it. This change in the sum expressed as the fraction of the total induced voltage is called as the *ripple*. In order to reduce the ripple, one can increase the number of coils coming in series between the brushes. As the number of coils is the same as the number of slots in an armature with two coil sides per slot one is forced to increase the number of slots. However increasing the slot number makes the tooth width too narrow and makes them mechanically weak.

In a drum winding, the coils span a pole pitch where ever possible. Such coils are called *'full pitched'* coils. The emf induced in the two active conductors of such coils have identical emfs with opposite signs at all instants of time. If the span is more than or less than the full pitch then the coil is said to be '*chorded*'. In chorded coils the induced emfs of the two conductor may be of the same sign and hence oppose each other (for brief intervals of time). Slight short chording of the coil reduces overhang length and saves copper and also improves commutation. Hence when the pole pitch becomes fractional number, the smaller whole number may be selected discarding the fractional part.

Similar to the pitch of a coil one can define the *winding pitch* and *commutator pitch*. In a d.c. winding the end of one coil is connected to the beginning of another coil (not necessarily the next), this being symmetrically followed to include all the coils on the armature. Winding pitch provides a means of indicating this. Similarly the commutator pitch provides the information regarding the commutators to which the beginning and the end of a coil are connected. Commutator pitch is the number of 'micas' between the ends of a coil. For all these information to be simple and useful the numbering scheme of the coils and commutator segments becomes important. One simple method is to number only the top coil side of the coils in sequence. The return conductor does not need be numbered. As a double layer is being used the bottom coil side is placed in a slot displaced by one coil span from the top coil side. Sometimes the coils are numbered as $1 - 1'$, $2 - 2'$ etc. indicating the second sides by $1'$, $2'$ etc. The numbering of commutators segments are done similarly. The commutator segment connected to top coil side of coil 1 is numbered 1. This method of numbering is simple and easy to follow. It should be noted that changing of the pitch of a coil slightly changes the induced emf in the same. The pitch of the winding however substantially alters the nature of the winding.

The armature windings are classified into two families based on this. They are called *lap winding* and *wave winding*. They can be simply stated in terms of the commutator pitch used for the winding.

3.3.1. Lap winding

The commutator pitch for the lap windings is given by $y_c = \pm m$, m = 1, 2, 3... where y_c is the commutator pitch, *m* is the order of the winding.

For $m = 1$ we get a *simple lap winding*, $m = 2$ gives *duplex lap winding* etc. $y_c = m$ gives a *multiplex lap winding* of order *m* (Fig.36).

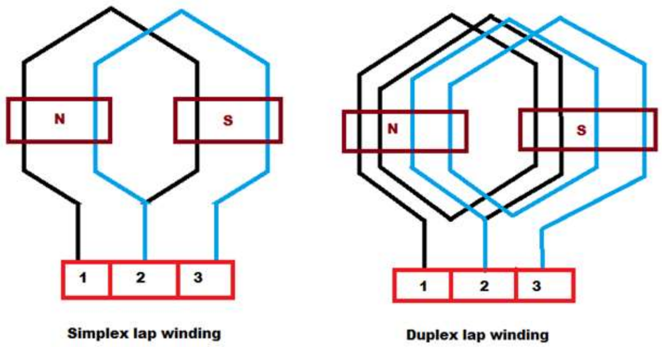


Fig.36: Simplex and duplex lap winding

The sign refers to the direction of progression of the winding. Positive sign is used for '*progressive*' winding and the negative sign for the '*retrogressive*' winding. Fig. 37 shows one coil as per progressive and retrogressive lap winding arrangements.

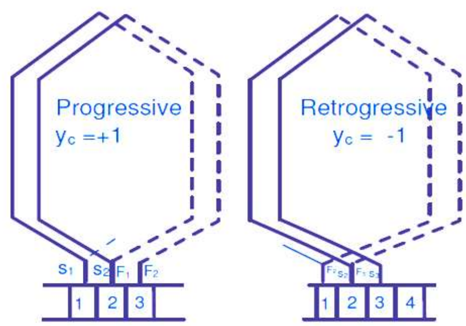


Fig.37: Progressive and retrogressive lap winding

Fig. 38 shows a developed view of a simple lap winding for a 4-pole armature in 12 slots. The connections of the coils to the commutator segments are also shown. The position of the armature is below the poles and the conductors move from left to right as indicated. The position and polarity of the brushes are also indicated. Single turn coils with $y_c = 1$ are shown here. The number of parallel paths formed by the winding equals the number of poles. The number of conductors that are connected in series between the brushes therefore becomes equal to *Z/2b*. Thus the lap winding is well suited for high current generators. In a symmetrical winding the parallel paths share the total line current equally.

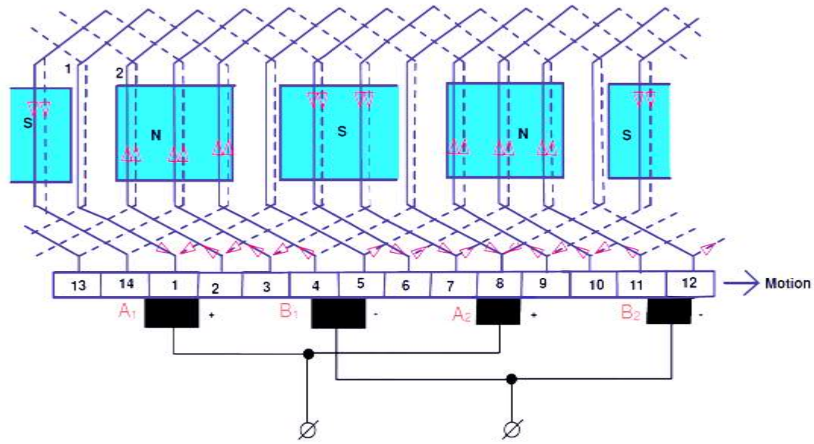


Fig. 38: Developed view of a retrogressive Lap winding

The increase in the number of parallel paths in the armature winding brings about a problem of circulating current. The induced emfs in the different paths tend to differ slightly due to the non-uniformities in the magnetic circuit. This will be more with the increase in the number of poles in the machine. If this is left uncorrected, circulating currents appear in these closed parallel paths. This circulating current wastes power produces heat and over loads the brushes under loaded conditions. One method commonly adopted in d.c. machines to reduce this problem is to provide equalizer connections. As the name suggests these connections identify similar potential points of the different parallel paths and connect them together to equalize the potentials. Any difference in the potential generates a local circulating current and the voltages get equalized. Also, the circulating current does not flow through the brushes loading them. The number of such equalizer connections, the cross section for the conductor used for the equalizer etc are decided by the designer.

3.3.2. Wave windings

In wave windings the coils carrying emf in the same direction at a time are all grouped together and connected in series. Hence in a simple wave winding there are only two paths between the brushes, the number of conductors in each path being 50 percent of the total conductors. To implement a wave winding one should select the commutator pitch as

$$y_c = \frac{C \pm 1}{p}$$

where C is the total segments on the commutator. y_c should be an integer number; C and p should satisfy this relation correctly. Here also the positive sign refers to the progressive winding and the negative sign yields a retrogressive winding. $y_c = (C \pm m)/p$ yields a multiplex wave winding of order m. A simple wave winding for 4 poles in 21 slots is illustrated in Fig. 39.

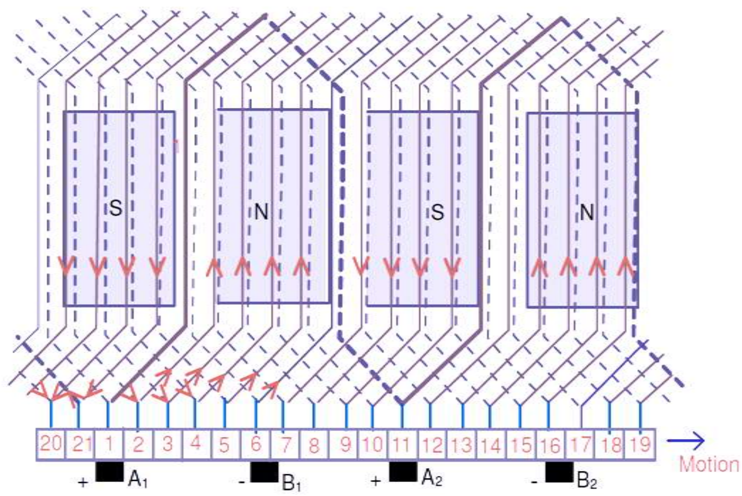


Fig.39: Wave winding sample

As could be seen from the figure, the connection to the next (or previous) adjacent coil is reached after p coils are connected in series. The winding closes on itself after all the coils are connected in series. The position for the brushes is indicated in the diagram.

It is seen from the formula for the commutator pitch, the choice of commutator segments for wave winding is restricted. The number of commutator segments can only be one more or one less than some multiple of pole pairs. As the number of parallel circuits is 2 for a simple wave winding irrespective of the pole numbers it is preferred in multi polar machine of lower power levels.

As mentioned earlier the simple wave winding forms two parallel paths, duplex wave winding has 2x2=4 etc. The coils under all the north poles are grouped together in one circuit and the other circuit collects all the coils that are under all the south poles. Two brush sets are therefore adequate. Occasionally people employ brush sets equal to the number of poles. This arrangement does not increase the number of parallel circuits but reduces the current to be collected by each brush set. This can be illustrated by an example. A 4-pole wave connected winding with 21 commutator segments is taken. $y_c = (21-1)/2 = 10$. A retrogressive wave winding results. The total string of connection can be laid out as shown below. If coil number 1 is assumed to be in the neutral axis then other neutral axis coils are a pole pitch apart i.e. coils 6, 11, 16.

If the brushes are kept at commutator segment 1 and 6, nearly half the number of coils come under each circuit. The polarity of the brushes are positive and negative alternately. Or, one could have two brushes at 11 and 16 or any two adjacent poles. By having four brushes at 1, 6, 11 and 16 and connecting 1,11 and 6,16 still only two parallel circuits are obtained. The brush currents however are halved. This method permits the use of commutator of shorter length as lesser current is to be collected by each brush and thus saving on the cost of the commutator.

Multiplex windings of order *m* have *m* times the circuits compared to a simplex winding and so also more restriction on the choice of the slots, coil sides, commutator and brushes. Hence windings beyond duplex are very uncommon even though theoretically possible. The duplex windings are used under very special circumstances when the number of parallel paths had to be doubled.

3.4. Armature Reaction

When working under load, the armature conductors carry currents and produce a field of their own. The interaction between the fields therefore must be properly understood in order to comprehend the behavior of the loaded machine. As the magnetic structure is complex and as we are interested in the flux cut by the conductors, we primarily focus our attention on the surface of the armature. A sign convention is required for mmf as the armature and field mmf are on two different members of the machine. The convention used here is that the mmf acting across the air gap and the flux density in the air gap are shown as positive when they act in a direction from the field system to the armature. A flux line is taken and the value of the current enclosed is determined. As the magnetic circuit is non-linear, the field mmf and armature mmf are separately computed and added at each point on the surface of the armature. The actual flux produced is proportional to the total mmf and the permeance. The flux produced by field and that produced by armature could be added to get the total flux only in the case of a linear magnetic circuit. The mmf distribution due to the poles and armature are discussed now in sequence.

3.4.1. MMF Distribution Due to the Field Coils Acting Alone

Fig.40 shows the exciter field in the cross section through a dc machine.

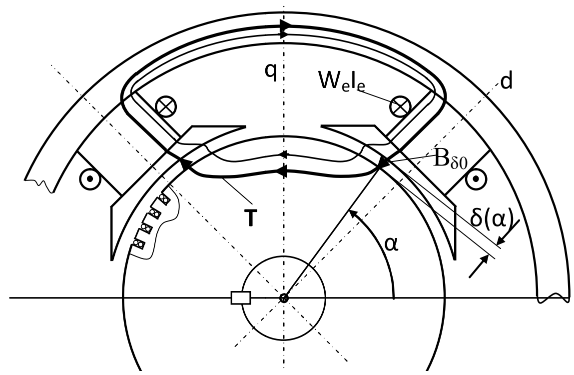


Fig.40: Exciter field

Fig. 41 shows the distribution of mmf due to field coils over two pole pitches. It is a step curve with the width being equal to the pole arc. The permeance variation at the surface is given assuming the air gap under the pole to be uniform and neglecting the slotting of the armature. The no-load flux density curve can be obtained by multiplying mmf and permeance.

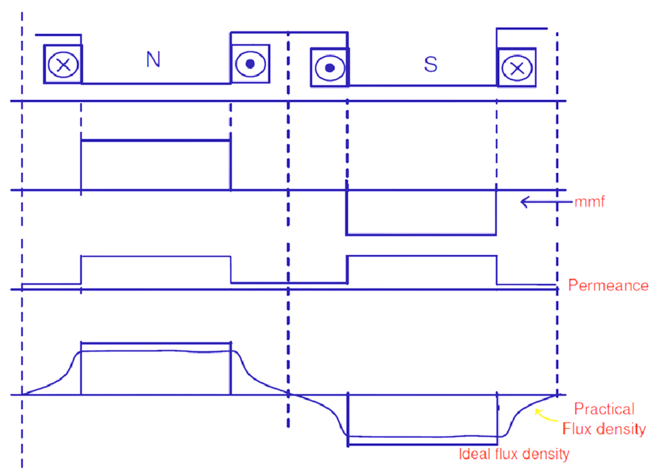


Fig. 41 Mmf distribution of the field coils

3.4.2. MMF Distribution Due to Armature Conductors Alone Carrying Currents

Fig.42 shows the armature field alone under carrying currents in the cross section through a dc machine.

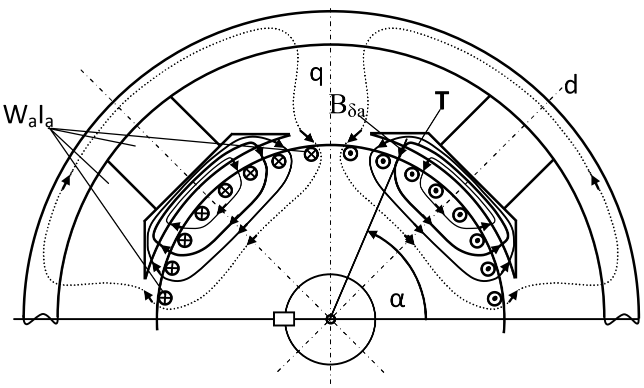


Fig.42: Armature field alone under carrying currents

The armature has a distributed winding, as against the field coils which are concentrated and concentric. The mmf of each coil is shifted in space by the number of slots. For a full pitched coil, each coil produces a rectangular mmf distribution. The sum of the mmf due to all coils would result in a stepped triangular wave form. If we neglect slotting and have uniformly spaced coils on the surface, then the mmf distribution due to the armature working alone would be a triangular distribution in space since all the conductors carry equal currents. MMF distribution is the integral of the ampere conductor distribution.

This is depicted in Fig. 43. This armature mmf per pole is given by

$$F_a = \frac{1}{2}\frac{I_c Z}{2p}$$

where I_c is the conductor current and Z is total number of conductors on the armature. This peak value of the mmf occurs at the inter polar area, shifted from the main pole axis by half the pole pitch when the brushes are kept in the magnetic neutral axis of the main poles.

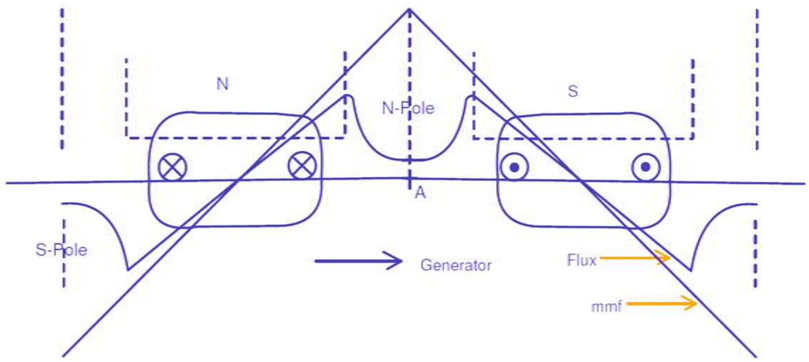


Fig.43: Mmf and flux distribution under the action of armature alone carrying current

3.4.3. Total Mmf and Flux of a Loaded Machine

The mmf of field coils and armature coils are added up and the resultant mmf distribution is obtained as shown in Fig. 44.

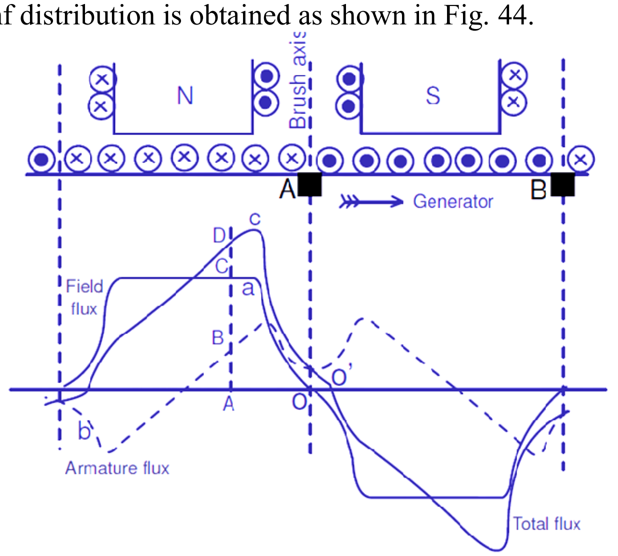


Fig.44: Flux distribution in a loaded generator without brush shift

This shows the decrease in the mmf at one tip of a pole and a substantial rise at the other tip. If the machine has a pole arc to pole pitch ratio of 0.7 then 70% of the armature reaction mmf gets added at this tip leading to considerable amount of saturation under full load conditions. This is obtained by multiplying mmf and permeance waves point by point in space. Actual flux distribution differs from this slightly due to fringing. As seen from the figure, the flux in the inter polar region is substantially lower due to the high reluctance of the medium. The air gaps under the pole tips are also increased in practice to reduce excessive saturation of this part. The advantage of the salient pole field construction is thus obvious. It greatly mitigates the effect of the armature reaction. Also, the coils undergoing commutation have very little emf induced in them and hence better commutation is achieved. Even though the armature reaction produced a cross magnetizing effect, the net flux per pole gets slightly reduced, on load, due to the saturation under one tip of the pole. This is more so in modern d.c. machines where the normal excitation of the field makes the machine works under some level of saturation.

3.4.4. Effect of Brush Shift

In some small d.c. machines the brushes are shifted from the position of the magnetic neutral axis in order to improve the commutation. This is especially true of machines with unidirectional operation and uni-modal (either as a generator or as a motor) operation. Such a shift in the direction of rotation is termed 'lead' (or forward lead). Shift of brushes in the opposite to the direction of rotation is called 'backward lead'. This lead is expressed in terms of the number of commutator segments or in terms of the electrical angle. A pole pitch corresponds to an electrical angle of 180 degrees.

Fig. 45 shows the effect of a forward brush lead on the armature reaction. The magnetization action due to the armature is no longer entirely cross magnetizing. Some component of the same goes to demagnetize the main field and the net useful flux gets reduced. This may be seen as the price we pay for improving the commutation. Knowing the pole arc to pole pitch ratio one can determine the total mmf at the leading and trailing edges of a pole without shift in the brushes.

$$F_{min} = F_f - \alpha F_a$$

$$F_{max} = F_f + \alpha F_a$$

where F_f is the field mmf, F_a is armature reaction mmf per pole, and α is the pole arc to pole pitch ratio.

The net flux per pole decreases due to saturation at the trailing edge and hence additional ampere turns are needed on the pole to compensate this effect. This may be to the tune of 20 percent in the modern d.c. machines. The brush shift gives rise to a shift in the axis of the mmf of the armature reaction. This can be resolved into two components, one in the quadrature axis and second along the pole axis as shown in Fig.45(b). The demagnetizing and cross magnetizing component of the armature ampere turn per pole can be written as

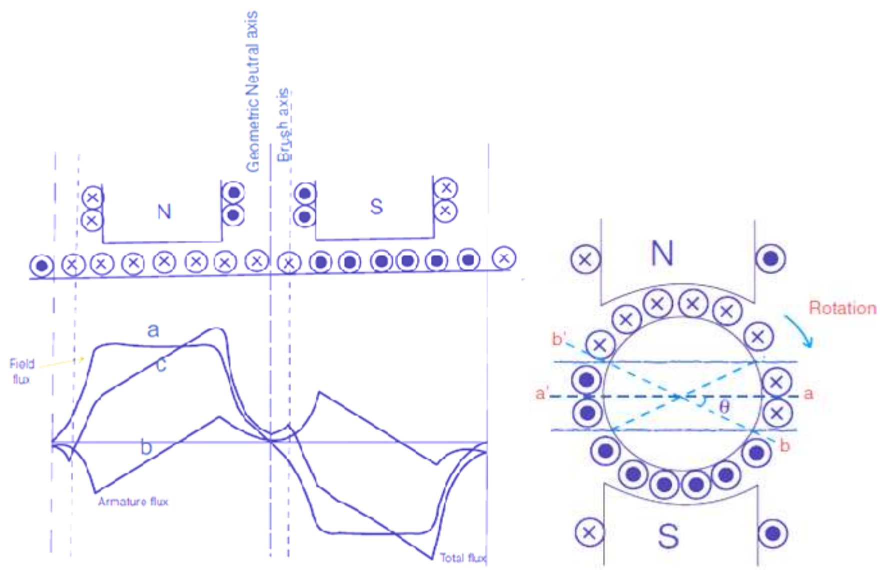
$$F_d = \frac{2\theta}{\pi} F_a$$

$$F_d = \left(1 - \frac{2\theta}{\pi}\right) F_a$$

where θ is the angle of lead. In terms of the number of commutator segments they are

$$F_d = \frac{C_l}{\frac{C}{4p}} \frac{I_c Z}{4p} = \frac{C_l}{C} I_c Z$$

where, C_l is the brush lead expressed in number of commutator segments.



(a) (b)

Fig.45: Effect of brush shift on armature reaction

3.4.5. Armature Reaction in Motors

As discussed earlier, for a given polarity of the field and sense of rotation, the motoring and generating modes differ only in the direction of the armature current. Alternatively, for a given sense of armature current, the direction of rotation would be opposite for the two modes. The leading and trailing edges of the poles change positions if direction of rotation is made opposite. Similarly when the brush leads are considered, a forward lead given to a generator gives rise to weakening of the generator field but strengthens the motor field and vice-versa. Hence it is highly desirable, even in the case of non-reversing drives, to keep the brush position at the geometrical neutral axis if the machine goes through both motoring and generating modes.

The second effect of the armature reaction in the case of motors as well as generators is that the induced emf in the coils under the pole tips gets increased when a pole tip has higher flux density. This increases the stress on the ‘mica’ (micanite) insulation used for the commutator, thus resulting in increased chance of breakdown of these insulating sheets. To avoid this effect the flux density distribution under the poles must be prevented from getting distorted and peaky.

The third effect of the armature reaction mmf distorting the flux density is that the armature teeth experience a heavy degree of saturation in this region. This increases the iron losses occurring in the armature in that region. The saturation of the teeth may be too great as to have some flux lines to link the thick end plates used for strengthening the armature. The increase in iron loss could be as high as 50 percent more at full load compared to its no-load value.

The above two effects can be reduced by providing a ’compensating’ mmf at the same spatial rate as the armature mmf. This is provided by having a compensating winding housed on the pole shoe which carries currents that are directly proportional to the armature current. The ampere conductors per unit length are maintained identical to that of the armature. The sign of the ampere conductors is made opposite to the armature. This is illustrated in Fig. 46 and Fig. 47.

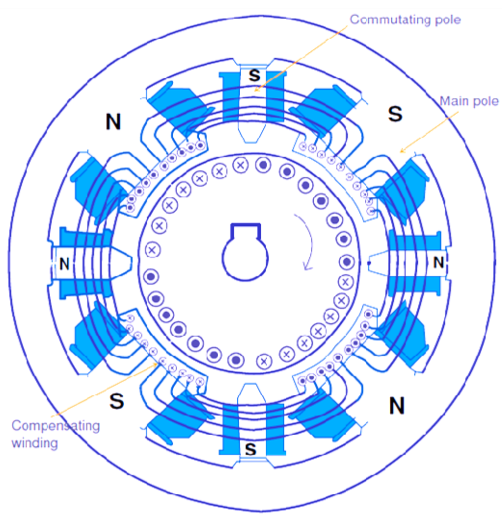


Fig.46: Compensating winding

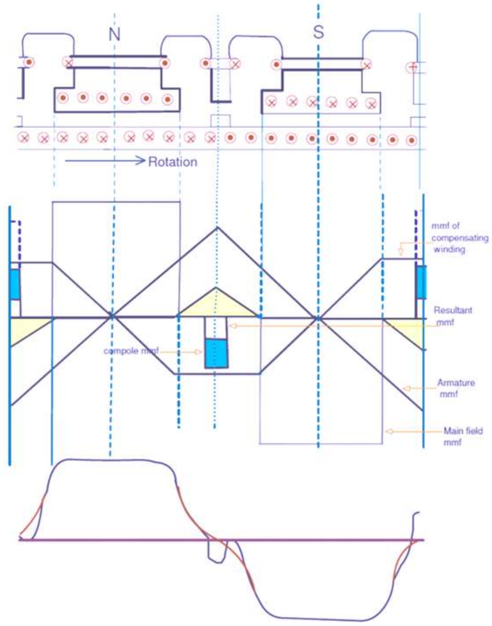


Fig.47: Armature reaction with Compensating winding

Since the compensating winding is connected in series with the armature, the relationship between armature mmf and the mmf due to compensating winding remains proper for all modes of working of the machine. The mmf required to be setup by the compensating winding can be found out to be

$$F_c = \frac{I_c Z}{4p} \frac{polearc}{polepitch}$$

Under these circumstances the flux density curve remains unaltered under the poles between no-load and full load.

The axis of the mmf due to armature and the compensating winding being the same and the signs of mmf being opposite to each other the flux density in the region of geometric neutral axis gets reduced thus improving the conditions for commutation. One can design the compensating winding to completely neutralize the armature reaction mmf. Such a design results in overcompensation under the poles. Improvement in commutation condition may be achieved simply by providing a commutating pole which sets up a local field of proper polarity. It is better not to depend on the compensating winding for improving commutation.

Compensating windings are commonly used in large generators and motors operating on weak field working at high loads.

From the analysis of the phenomenon of armature reaction that takes place in a d.c. machine it can be inferred that the equivalent circuit of the machine need not be modified to include the armature reaction. The machine can simply be modeled as a voltage source of internal resistance equal to the armature circuit resistance and a series voltage drop equal to the brush contact drop, under steady state. With this circuit model one can arrive at the external characteristics of the d.c. machine under different modes of operation.

3.5. Commutation

As seen earlier, in an armature conductor of a heteropolar machine a.c. voltages are induced as the conductor moves under north and south pole polarities alternately. The frequency of this induced emf is given by the product of the pole-pairs and the speed in revolutions per second. The induced emf in a full pitch coil changes sign as the coil crosses magnetic neutral axis. In order to get maximum d.c. voltage in the external circuit the coil should be shifted to the negative group. This process of switching is called commutation (Fig.48).

During a short interval when the two adjacent commutator segments get bridged by the brush the coils connected in series between these two segments get short circuited. Thus in the case of ring winding and simple lap winding 2p coils get short circuited. In a simple wave winding in a 2p pole machine 2 coils get short circuited. The current in these coils become zero and get reversed as the brush moves over to the next commutator segment. Thus brush and commutator play an important role in commutation.

Commutation is the key process which converts the induced a.c. voltages in the conductors into d.c.

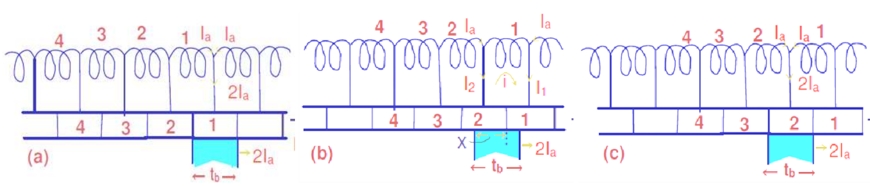


Fig.48: Commutation process

3.6. Principles of D.C. Machines

D.C. machines are the electro mechanical energy converters which work from a d.c. source and generate mechanical power or convert mechanical power into a d.c. power. These machines can be broadly classified into two types, on the basis of their magnetic structure.

They are,

1. Homopolar machines
2. Hetero-polar machines.

These are discussed in sequence below.

3.6.1. Homopolar Machines

Even though the magnetic poles occur in pairs, in a homopolar generator the conductors are arranged in such a manner that they always move under one polarity. Either north pole or south pole could be used for this purpose. Since the conductor encounters the magnetic flux of the same polarity every where it is called a homopolar generator. A cylindrically symmetric geometry is chosen. The conductor can be situated on the surface of the rotor with one slip-ring at each end of the conductor. A simple structure where there is only one cylindrical conductor with ring brushes situated at the ends is shown in Fig. 49. The excitation coil produces a field which enters the inner member from outside all along the periphery. The conductor thus sees only one pole polarity or the flux directed in one sense. A steady voltage now appears across the brushes at any given speed of rotation. The polarity of the induced voltage can be reversed by reversing either the excitation or the direction of rotation but not both. The voltage induced would be very low but the currents of very large amplitudes can be supplied by such machines. Such sources are used in some applications like pulse-current and MHD generators, liquid metal pumps or plasma rockets. The steady field can also be produced using a permanent magnet of ring shape which is radially magnetized. If higher voltages are required one is forced to connect many conductors in series. This series connection has to be done externally. Many conductors must be situated on the rotating structure each connected to a pair of slip rings. However, this modification introduces parasitic air-gaps and makes the mechanical structure very complex.

The voltage drops at the brushes become very significant at this level bringing down the efficiency of power conversion. Even though homopolar machines are d.c. generators in a strict sense that they 'generate' steady voltages, they are not quite useful for day to day use.

A more practical converters can be found in the d.c. machine family called "hetero-polar" machines.

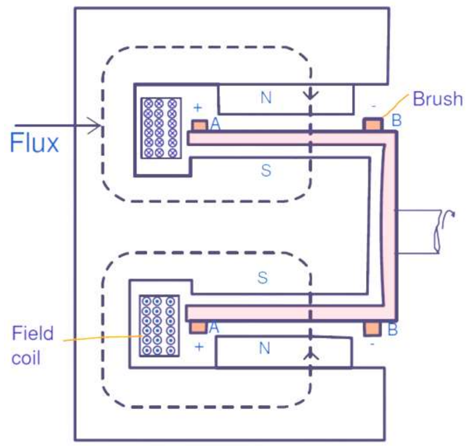


Fig.49: Homopolar generator

3.6.2. Hetero-polar D.C. Machines

In the case of a hetero-polar generator the induced emf in a conductor goes through a cyclic change in voltage as it passes under north and south pole polarity alternately. The induced emf in the conductor therefore is not a constant but alternates in magnitude. For a constant velocity of sweep the induced emf is directly proportional to the flux density under which it is moving. If the flux density variation is sinusoidal in space, then a sine wave voltage is generated. This principle is used in the a.c generators. In the case of d.c. generators our aim is to get a steady d.c. voltage at the terminals of the winding and not the shape of the emf in the conductors. This is achieved by employing an external element, which is called a commutator, with the winding.

Fig. 50 shows an elementary hetero-polar, 2-pole machine and one-coil armature. The ends of the coil are connected to a split ring which acts like a commutator. As the polarity of the induced voltages changes the connection to the brush also gets switched so that the voltage seen at the brushes has a unidirectional polarity. This idea is further developed in the modern day machines with the use of commutators. The brushes are placed on the commutator. Connection to the winding is made through the commutator only. The idea of a commutator is an ingenious one. Even though the instantaneous value of the induced emf in each conductor varies as a function of the flux density under which it is moving, the value of this emf is a constant at any given position of the conductor as the field is stationary. Similarly the sum of a set of coils also remains a constant. This thought is the one which gave birth to the commutator. The coils connected between the two brushes must be ”similarly located” with respect to the poles irrespective of the actual position of the rotor.

This can be termed as the condition of symmetry. If a winding satisfies this condition then it is suitable for use as an armature winding of a d.c. machine. The ring winding due to Gramme is one such. It is easy to follow the action of the d.c. machine using a ring winding, hence it is taken up here for explanation.

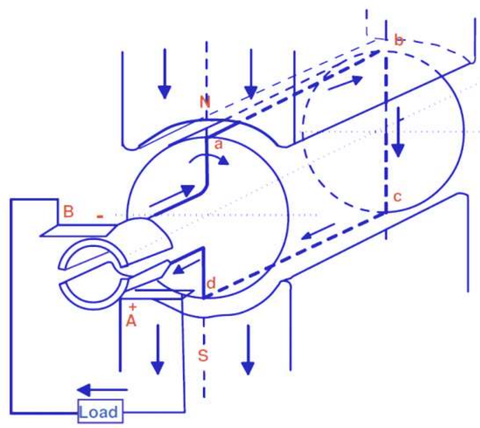


Fig.50: Hetero-polar d.c. generator

Fig. 51 shows a 2-pole, 12 coil, ring wound armature of a machine. The 12 coils are placed at uniform spacing around the rotor. The junction of each coil with its neighbor is connected to a commutator segment. Each commutator segment is insulated from its neighbor by a mica separator. Two brushes A and B are placed on the commutator which looks like a cylinder. If one traces the connection from brush A to brush B one finds that there are two paths. In each path a set of voltages get added up. The sum of the emfs is constant (nearly). The constancy of this magnitude is altered by a small value corresponding to the coil short circuited by the brush. As we wish to have a maximum value for the output voltage, the choice of position for the brushes would be at the neutral axis of the field. If the armature is turned by a distance of one slot pitch the sum of emfs is seen to be constant even though a different set of coils participate in the addition. The coil which gets short circuited has nearly zero voltage induced in the same and hence the sum does not change substantially. This variation in the output voltage is called the ’ripple’. More the number of coils participating in the sum lesser would be the ’percentage’ ripple.

Another important observation from the working principle of a heterogeneous generator is that the actual shape of the flux density curve does not matter as long as the integral of the flux entering the rotor is held constant; which means that for a given flux per pole the voltage will be constant even if the shape of this flux density curve changes (speed and other conditions remaining unaltered). This is one reason why an average flux density over the entire pole pitch is taken and flux density curve is assumed to be rectangular.

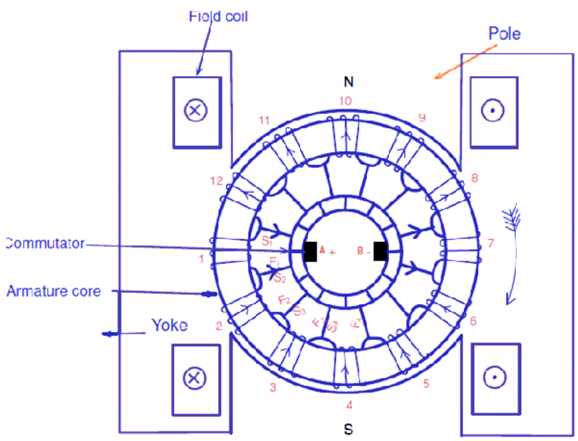


Fig.51: Two pole machine -With Gramme ring type armature

A rectangular flux density wave form has some advantages in the derivation of the voltage between the brushes. Due to this form of the flux density curve, the induced emf in each turn of the armature becomes constant and equal to each other. With this back ground the emf induced between the brushes can be derived. The value of the induced in one conductor is given by

$$E_c = B_{av} l v$$

where

B_{av} - Average flux density over a pole pitch, Tesla.

L - Length of the 'active' conductor, m.

V - Velocity of sweep of conductor, m/sec.

If there are Z conductors on the armature and they form b pairs of parallel circuits between the brushes by virtue of their connections, then number of conductors in a series path is $Z/2b$.

The induced emf between the brushes is

$$E = E_c \frac{Z}{2b} = \frac{\phi p Z n}{b}$$

The number of pairs of parallel paths is a function of the type of the winding chosen. This will be discussed later under the section on the armature windings.

The above principles can easily be extended to the case of motoring mode of operation also. This will be discussed next in the section on motoring operation of d.c. machines.

In the motoring operation the d.c. machine is made to work from a d.c. source and absorb electrical power. This power is converted into the mechanical form. This is briefly discussed here. If the armature of the d.c. machine which is at rest is connected to a d.c. source then, a current flows into the armature conductors. If the field is already excited then these current carrying conductors experience a force as per the law of interaction discussed above and the armature experiences a torque. If the restraining torque could be neglected the armature starts rotating in the direction of the force. The conductors now move under the field and cut the magnetic flux and hence an induced emf appears in them. The polarity of the induced emf is such as to oppose the cause of the current which in the present case is the applied voltage. Thus a 'back emf' appears and tries to reduce the current. As the induced emf and the current act in opposing sense the machine acts like a sink to the electrical power which the source supplies. This absorbed electrical power gets converted into mechanical form. Thus the same electrical machine works as a generator of electrical power or the absorber of electrical power depending upon the operating condition. The absorbed power gets converted into electrical or mechanical power.

3.7. Methods of Excitation

It is seen already that the equivalent circuit model of a d.c. machine becomes very simple in view of the fact that the armature reaction is cross magnetizing. Also, the axis of compensating mmf and mmf of commutating poles act in quadrature to the main field. Thus flux under the pole shoe gets distorted but not diminished (in case the field is not saturated). The relative connections of armature, compole and compensating winding are unaltered whether the machine is working as a generator or as a motor; whether the load is on the machine or not. Hence all these are connected permanently inside the machine. The terminals reflect only the additional ohmic drops due to the compole and compensating windings. Thus commutating pole winding and compensating winding add to the resistance of the armature circuit and can be considered a part of the same. The armature circuit can be simply modelled by a voltage source of internal resistance equal to the armature resistance + compole resistance + compensating winding resistance. The brushes behave like non-linear resistance; and their effect may be shown separately as an additional constant voltage drop equal to the brush drop.

3.7.1. Excitation Circuit

The excitation for establishing the required field can be of two types

a) Permanent magnet excitation (PM)

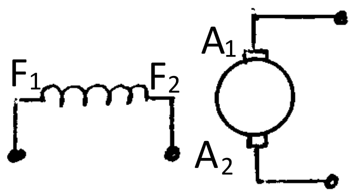
b) Electromagnetic excitation.

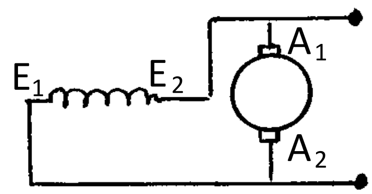
Permanent magnet excitation is employed only in extremely small machines where providing a field coil becomes infeasible. Also, permanent magnet excited fields cannot be varied for control purposes. Permanent magnets for large machines are either not available or expensive. However, an advantage of permanent magnet is that there are no losses associated with the establishment of the field.

Electromagnetic excitation is universally used. Even though certain amount of energy is lost in establishing the field it has the advantages like lesser cost, ease of control. The required ampere turns for establishing the desired flux per pole may be computed by doing the magnetic circuit calculations. MMF required for the poles, air gap, armature teeth, armature core and stator yoke are computed and added.

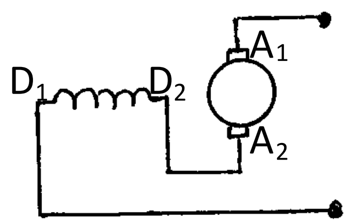
A flux loop traverses a stator yoke, armature yoke, and two numbers each of poles, air gap, armature teeth in its path. It is convenient to think of mmf per pole which is nothing but the ampere turns required to be produced by a coil wound around one pole. In the case of small machines all this mmf is produced by a coil wound around one pole. The second pole is obtained by induction. This procedure saves cost as only one coil need be wound for getting a pair of poles. This produces an unsymmetrical flux distribution in the machine and hence is not used in larger machines. In large machines, half of total mmf is assigned to each pole as the mmf per pole. The total mmf required can be produced by a coil having large number of turns but taking asmall current. Such winding has a high value of resistance and hence a large ohmic drop. It can be connected across a voltage source and hence called a shunt winding. Such method of excitation is termed as shunt excitation. On the other hand, one could have a few turns of large cross section wire carrying heavy current to produce the required ampere turns. These windings have extremely small resistance and can be connected in series with a large current path such as an armature. Such a winding is called a series winding and the method of excitation, series excitation. A d.c. machine can have either of these or both these types of excitation.

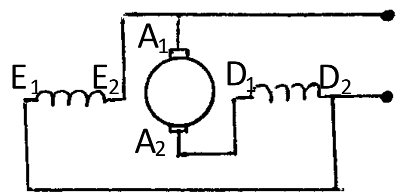
These are shown in Fig. 52. When both shunt winding and series winding are present, it is called compound excitation. The mmf of the two windings could be arranged to aid each other or oppose each other. Accordingly they are called cumulative compounding and differential compounding. If the shunt winding is excited by a separate voltage source then it is called separate excitation. If the excitation power comes from the same machine, then it is called self excitation. Series generators can also be separately excited or self excited. The characteristics of these generators are discussed now in sequence.





(a)Separate excitation (b) Shount excitation





(c)Series excitation (d)Compound excitation

Fig.52: D.C generator connections

3.7.2. Separately Excited Shunt Generators

Fig. 53 shows a shunt generator with its field connected to a voltage source V_f through a regulating resistor in potential divider form. The current drawn by the field winding can be regulated from zero to the maximum value. If the change in the excitation required is small, simple series connection of a field regulating resistance can be used. In all these cases the presence of a prime mover rotating the armature is assumed. A separate excitation is normally used for testing of d.c. generators to determine their open circuit or magnetization characteristic. The excitation current is increased monotonically to a maximum value and then decreased in the same manner, while noting the terminal voltage of the armature. The load current is kept zero. The speed of the generator is held at a constant value. The graph showing the nature of variation of the induced emf as a function of the excitation current is called as open circuit characteristic (occ), or no-load magnetization curve or no-load saturation characteristic. Fig. 30(b) shows an example. The magnetization characteristic exhibits saturation at large values of excitation current. Due to the hysteresis exhibited by the iron in the magnetic structure, the induced emf does not become zero when the excitation current is reduced to zero. This is because of the remnant field in the iron. This residual voltage is about 2 to 5 percent in modern machines. Separate excitation is advantageous as the exciting current is independent of the terminal voltage and load current and satisfactory operation is possible over the entire voltage range of the machine starting from zero.

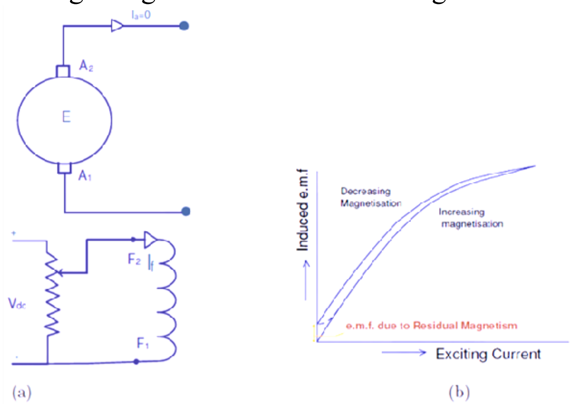


Fig.53: Shunt generator

3.7.3. Shunt Self Excitation Generator

In a self excited machine, there is no external source for providing excitation current. The shunt field is connected across the armature. For series machines there is no change in connection. The series field continues to be in series with the armature.

Self excitation is now discussed with the help of Fig. 54(a). The process of self excitation in a shunt generator takes place in the following manner. When the armature is rotated a feeble induced emf of 2 to 5 percent appears across the brushes depending upon the speed of rotation and the residual magnetism that is present. This voltage gets applied across the shunt field winding and produces a small mmf. If this mmf is such as to aid the residual field then it gets strengthened and produces larger voltage across the brushes. It is like a positive feedback. The induced emf gradually increases till the voltage induced in the armature is just enough to meet the ohmic drop inside the field circuit. Under such situation there is no further increase in the field mmf and the buildup of emf also stops.

If the voltage build up is ‘substantial’, then the machine is said to have ‘self excited’.

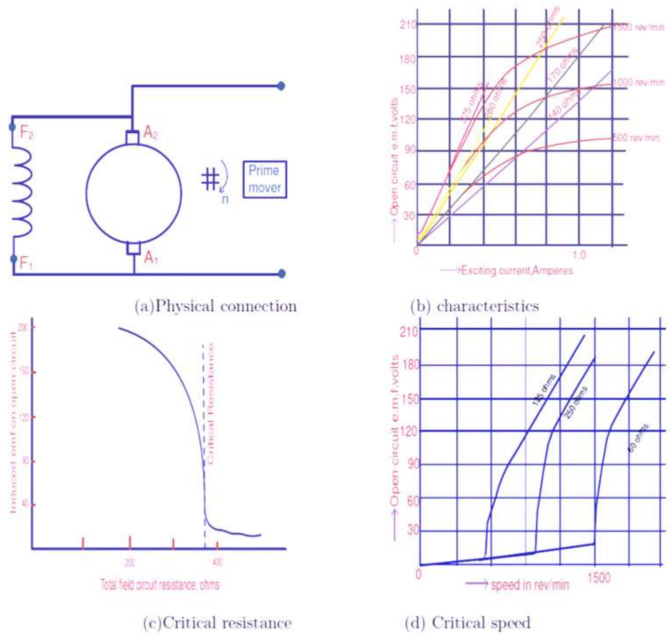


Fig.54: Shunt self excitation generator

Fig. 54(b) shows the magnetization curve of a shunt generator. The field resistance line is also shown by a straight line OC. The point of intersection of the open circuit characteristic (OCC) with the field resistance line, in this case C, represents the voltage build up on self excitation. If the field resistance is increased, at one point the resistance line becomes a tangent to the OCC. This value of the resistance is called the critical resistance. At this value of the field circuit resistance the self excitation suddenly collapses. See Fig. 54(c). Instead of increasing the field resistance if the speed of the machine is reduced then the same resistance line becomes a critical resistance at a new speed and the self excitation collapses at that speed. In this case, as the speed is taken as the variable, the speed is called the critical speed. In the linear portion of the OCC the ordinates are proportional to the speed of operation; hence the critical resistance increases as a function of speed Fig. 54(b) and (d).

The conditions for self excitation can be listed as below:

1. Residual field must be present.
2. The polarity of excitation must aid the residual magnetism.
3. The field circuit resistance must be below the critical value.
4. The speed of operation of the machine must be above the critical speed.
5. The load resistance must be very large.

Remedial measures to be taken if the machine fails to self excite are briefly discussed below.

1. The residual field will be absent in a brand new, unexcited, machine. The field may be connected to a battery in such cases for a few seconds to create a residual field.

2. The polarity of connections has to be set right. The polarity may become wrong either by reversed connections or reversed direction of rotation. If the generator had been working with armature rotating in clockwise direction before stopping and if one tries to self excite the same with counter clockwise direction then the induced emf opposes residual field, changing the polarity of connections of the field with respect to armature is normally sufficient for this problem.

3. Field circuit resistance implies all the resistances coming in series with the field winding like regulating resistance, contact resistance, drop at the brushes, and the armature resistance. Brush contact resistance is normally high at small currents. The dirt on the commutator due to dust or worn out mica insulator can increase the total circuit resistance enormously. The speed itself might be too low so that the normal field resistance itself is very much more than the critical value. So ensuring good speed, clean commutator and good connections should normally be sufficient to overcome this problem.

4. Speed must be increased sufficiently to a high value to be above the critical speed.

5. The load switch must be opened or the load resistance is made very high.

3.7.4. Self Excitation of Series Generators

The conditions for self excitation of a series generator remain similar to that of a shunt machine. In this case the field circuit resistance is the same as the load circuit resistance and hence it must be made very low to help self excitation. To control the field mmf a small resistance called diverter is normally connected across the series field. To help in the creation of maximum mmf during self excitation any field diverter if present must be open circuited. In a series generator load current being the field current of the machine the self excitation characteristic or one and the same. This is shown in Fig. 55.

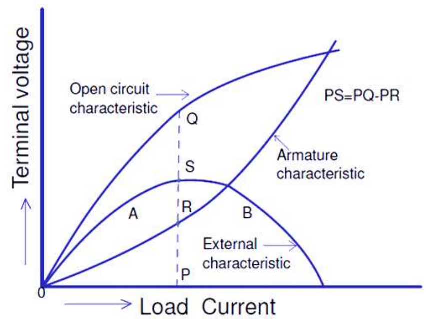


Fig.55: External characteristics of a series generator

3.7.5. Self Excitation of Compound Generators

Most of the compound machines are basically shunt machines with the series winding doing the act of strengthening/weakening the field on load, depending up on the connections. In cumulatively compounded machines the mmf of the two fields aid each other and in a differentially compounded machine they oppose each other. Due to the presence of the shunt winding, the self excitation can proceed as in a shunt machine. A small difference exists however depending up on the way the shunt winding is connected to the armature. It can be a short shunt connection or a long shunt connection. In long shunt connection the shunt field current passes through the series winding also. But it does not affect the process of self excitation as the mmf contribution from the series field is negligible.

Both series field winding and shunt field winding are wound around the main poles. If there is any need, for some control purposes, to have more excitation windings of one type or the other they will also find their place on the main poles. The designed field windings must cater to the full range of operation of the machine at nominal armature current. As the armature current is cross magnetizing the demagnetization mmf due to pole tip saturation alone need be compensated by producing additional mmf by the field.

The d.c. machines give rise to a variety of external characteristics with considerable ease. The external characteristics are of great importance in meeting the requirements of different types of loads and in parallel operation. The external characteristics, also known as load characteristics, of these machines are discussed next.

3.8. Load Characteristics of D.C. Generators

Load characteristics are also known as the external characteristics. External characteristics expresses the manner in which the output voltage of the generator varies as a function of the load current, when the speed and excitation current are held constant. If they are not held constant then there is further change in the terminal voltage. The terminal voltage V can be expressed in terms of the induced voltage E and armature circuit drop as

$$V = E - I_a R_a - V_b$$

V_b - brush contact drop, V
I_a - armature current, A
R_a - armature resistance + inter pole winding resistance+ series winding resistance + compensating winding resistance.

As seen from the equation E being function of speed and flux per pole it will also change when these are not held constant. Experimentally the external characteristics can be determined by conducting a load test. If the external characteristic is obtained by subtracting the armature drop from the no-load terminal voltage, it is found to depart from the one obtained from the load test. This departure is due to the armature reaction which causes saturation at one tip of each pole. Modern machines are operated under certain degree of saturation of the magnetic path. Hence the reduction in the flux per pole with load is obvious. The armature drop is an electrical drop and can be found out even when the machine is stationary and the field poles are unexcited. Thus there is some slight drop in the external characteristics, which is good for parallel operation of the generators.

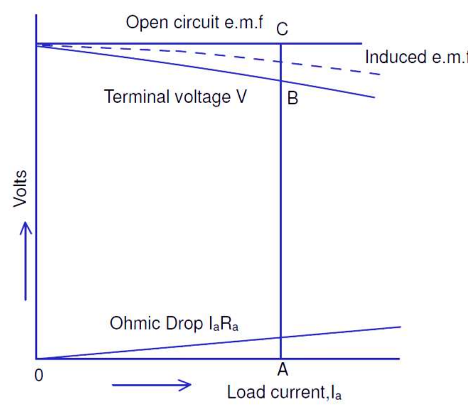


Fig.56: External characteristics of a separately excited shunt generator

One could easily guess that the self excited machines have slightly higher droop in the external characteristic as the induced emf *E* drops also due to the reduction in the applied voltage to the field. If output voltage has to be held constant then the excitation current or the speed can be increased. The former is preferred due to the ease with which it can be implemented. As seen earlier, a brush lead gives rise to a load current dependent mmf along the pole axis. The value of this mmf magnetizes/demagnetizes the field depending on whether the lead is backward or forward.

3.8.1. External Characteristics of a Shunt Generator

For a given no-load voltage a self excited machine will have more voltage drop at the terminals than a separately excited machine, as the load is increased. This is due to the dependence of the excitation current also on the terminal voltage. After certain load current the terminal voltage decreases rapidly along with the terminal current, even when load impedance is reduced. The terminal voltage reaches an unstable condition. Also, in a self excited generator the no-load terminal voltage itself is very sensitive to the point of intersection of the magnetizing characteristics and field resistance line. The determination of the external characteristics of a shunt generator forms an interesting study. If one determines the load magnetization curves at different load currents then the external characteristics can be easily determined. Load magnetization curve is a plot showing the variation of the terminal voltage as a function of the excitation current keeping the speed and armature current constant. If such curves are determined for different load currents then by determining the intersection points of these curves with field resistance line one can get the external characteristics of a shunt generator. Load saturation curve can be generated from no-load saturation curve /OCC by subtracting the armature drop at each excitation point. Thus it is seen that these family of curves are nothing but OCC shifted downwards by armature drop. Determining their intercepts with the field resistance line gives us the requisite result. Instead of shifting the OCC downwards, the x axis and the field resistance line is shifted 'upwards' corresponding to the drops at the different currents, and their intercepts with OCC are found. These ordinates are then plotted on the original plot. This is shown clearly in Fig. 57. The same procedure can be repeated with different field circuit resistance to yield external characteristics with different values of field resistance. The points of operation up to the maximum current represent a stable region of operation. The second region is unstable. The decrease in the load resistance decreases the terminal voltage in this region.

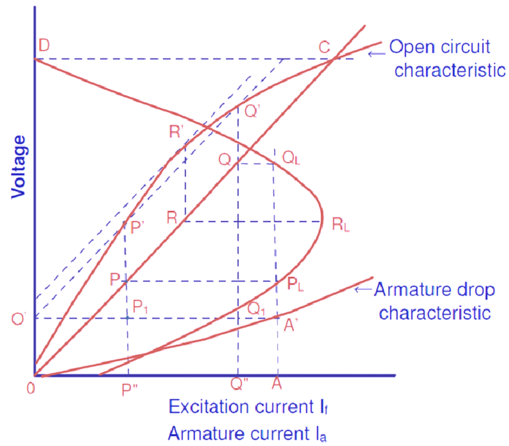


Fig.57: External characteristics of a self excited of a shunt generator

3.8.2. External Characteristics of Series Generators

In the case of series generators also, the procedure for the determination of the external characteristic is the same. From the occ obtained by running the machine as a separately excited one, the armature drops are deducted to yield external /load characteristics.

The armature drop characteristics can be obtained by a short circuit test as before. Fig. 55 shows the load characteristics of a series generator. The first half of the curve is unstable for constant resistance load. The second half is the region where series generator connected to a constant resistance load could work stably. The load characteristics in the first half however are useful for operating the series generator as a booster. In a booster the current through the machine is decided by the external circuit and the voltage injected into that circuit is decided by the series generator. This is shown in Fig. 58.

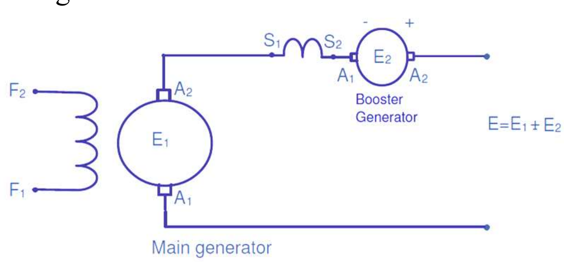


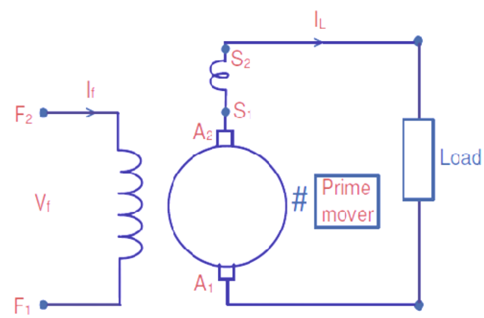
Fig.58: Series generator used as Booster

3.8.3. Load characteristics of compound generators

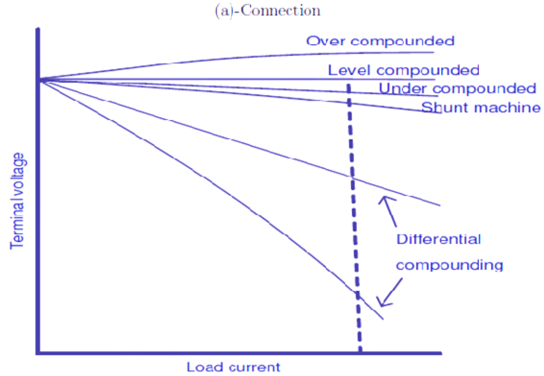
In the case of compound generators the external characteristics resemble those of shunt generators at low loads. The load current flowing through the series winding aids or opposes the shunt field ampere turns depending upon whether cumulative or differential compounding is used. This increases /decreases the flux per pole and the induced emf *E*.

Thus a load current dependant variation in the characteristic occurs. If this increased emf cancels out the armature drop the terminal voltage remains practically same between no load and full load. This is called as level compounding. Any cumulative compounding below this value is called under compounding and those above are termed over- compounding.

These are shown in Fig. 59. The characteristics corresponding to all levels of differential compounding lie below that of a pure shunt machine as the series field mmf opposes that of the shunt field.



(a)-Connection



(b)-Characteristics

Fig.59: External characteristic of Compound Generator

External characteristics for other voltages of operation can be similarly derived by changing the speed or the field excitation or both.

3.9. D.C. Motors

D.C. motors have a place of pride as far as electrical drives are considered. The simplicity and linearity of the control method makes them highly preferred machines in precision drives. In spite of the great advancements in a.c. drives these machines are still sought after by the industries. Apart from high precision application they are preferred in standalone systems working on batteries and high speed drives off constant voltage mains.

After the field is excited if we pass a current through the armature the rotor experiences a torque and starts rotating. The direction of the torque can be readily obtained from the law of interaction. These moving conductors cut the field and induce emf, usually called the 'back emf' according to Lenz's law and act as a sink of electrical power from the electrical source. This absorbed power appears as mechanical power. The converted mechanical power should overcome the frictional and iron losses before useful work could be done by the same.

The connections to the supply of a d.c. shunt motor are given in Fig.60.

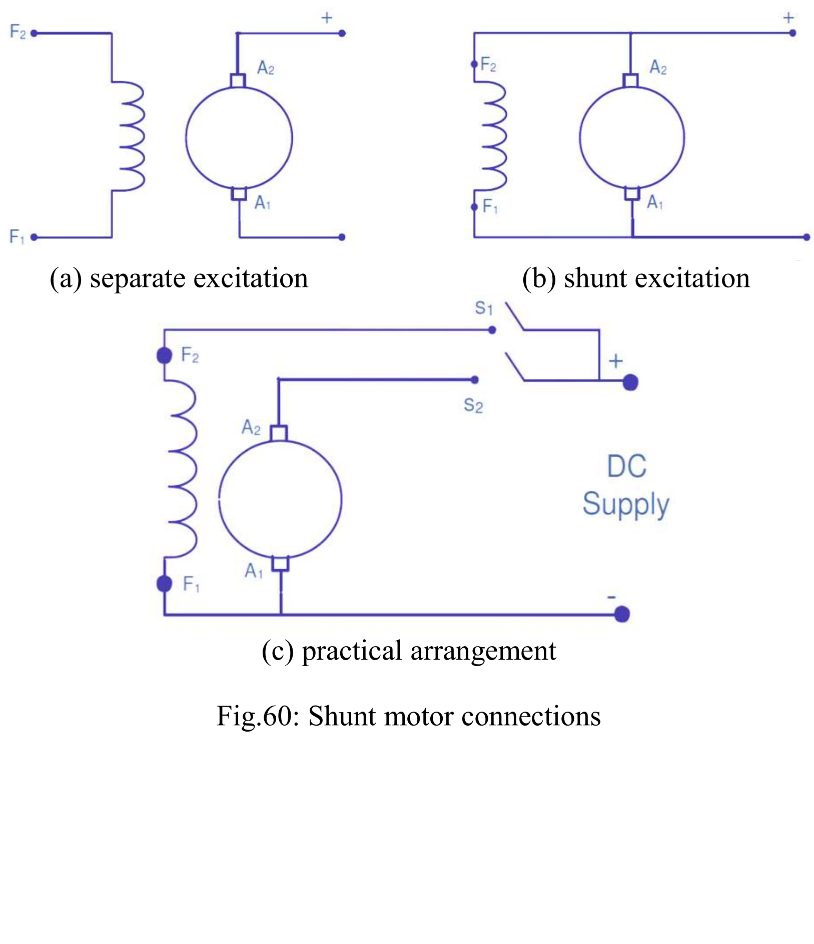


Fig.60: Shunt motor connections

Commonly used connection is where in both the field and the armature are energized simultaneously Fig. 60(b). As the field has higher inductance and time constant torque takes some time to reach the full value corresponding to a given armature current.

In Fig. 60(c), the switch S_1 is closed a few seconds prior to switch S_2. By then the field current would have reached the steady value. So the torque per ampere is high in this case.

The only difference in the second connection Fig. 60(a) is that the shunt field winding is connected to a separate source. This connection is used when the armature and field voltage are different as is common in high voltage d.c. machines. The field voltage is kept low in such cases for the sake of control purposes. Here again the field circuit must be energized prior to the armature. Suitable interlock should be provided to prevent the armature switch being closed prior to / without closing of field circuit as the armature currents reach very large values still not producing any torque or rotation. The relevant equations for the motoring operation can be written as below

$$V - E - I_a R_a - V_b = 0 \qquad or \qquad E = V - I_a R_a - V_b$$

$$E = \frac{p\phi Z n}{b} = K_e \phi n \qquad where \qquad K_e = \frac{pZ}{b}$$

$$T_M = \frac{1}{2\pi}\frac{p\phi Z I_a}{b} = K_t \phi I_a \qquad where \qquad K_t = \frac{1}{2\pi}\frac{pZ}{b}$$

$$\text{and} \quad T_M - T_L = J\frac{d\omega}{dt}$$

where:
T_L - Load torque
T_M - Motor torque
J - polar moment of inertia.
ω - angular velocity

The first one is an electrical equation, the second and the third are electromechanical in nature and the last equation is the mechanical equation of motion. K_e and K_t are normally termed as back emf constant and torque constant respectively. Under steady speed of operation the fourth equation is not required. Using these equations one can determine the torque speed characteristics of the machine for a given applied voltage.

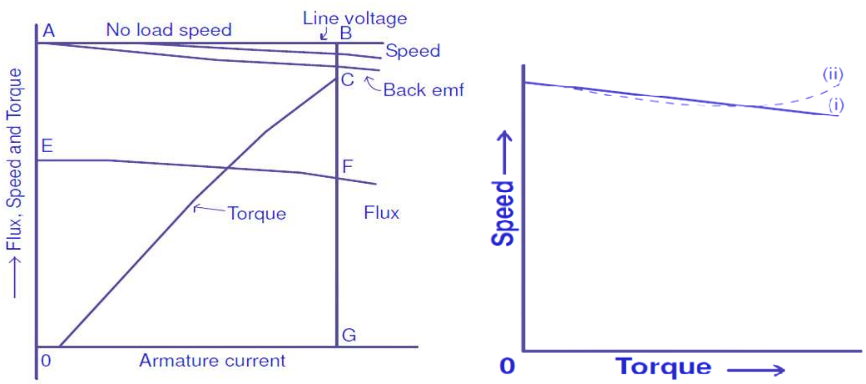
These characteristics are similar to the external characteristics for a generator. Here the torque on the machine is assumed to be varying and the corresponding speed of operation is determined. This is termed as the torque speed characteristic of the motor.

3.9.1 Torque speed characteristics of a shunt motor

A constant applied voltage V is assumed across the armature. As the armature current I_a, varies the armature drop varies proportionally and one can plot the variation of the induced emf E. The mmf of the field is assumed to be constant. The flux inside the machine however slightly falls due to the effect of saturation and due to armature reaction.

The variation of these parameters are shown in Fig. 61. Knowing the value of E and flux one can determine the value of the speed. Also knowing the armature current and the flux, the value of the torque is found out. This procedure is repeated for different values of the assumed armature currents and the values are plotted as in Fig. 61(a). From these graphs, a graph indicating speed as a function of torque or the torque-speed characteristics is plotted Fig. 61(b).

As seen from the figure the fall in the flux due to load increases the speed due to the fact that the induced emf depends on the product of speed and flux. Thus the speed of the machine remains more or less constant with load. With highly saturated machines the on-load speed may even slightly increase at over load conditions. This effects gets more pronounced if the machine is designed to have its normal field ampere turns much less than the armature ampere turns. This type of external characteristics introduces instability during operation Fig. 61(b) and hence must be avoided. This may be simply achieved by providing a series stability winding which aids the shunt field mmf.



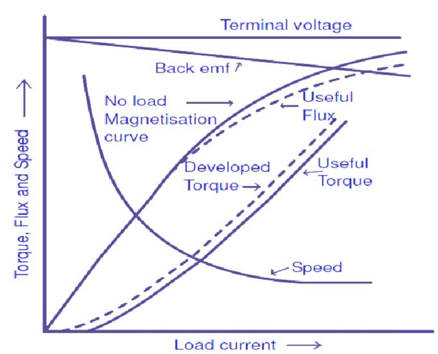
(a) Load characteristics (b) Torque speed characteristics

Fig. 61: DC Shunt motor characteristics

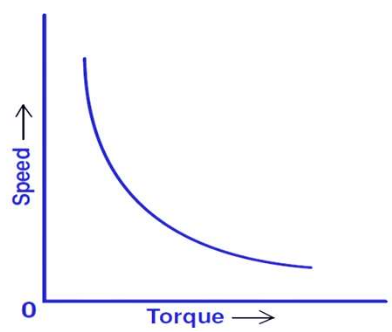
3.9.2. Load characteristics of a series motor

Following the procedure described earlier under shunt motor, the torque speed characteristics of a series motor can also be determined. The armature current also happens to be the excitation current of the series field and hence the flux variation resembles the magnetization curve of the machine. At large value of the armature currents the useful flux would be less than the no-load magnetization curve for the machine. Similarly for small values of the load currents the torque varies as a square of the armature currents as the flux is proportional to armature current in this region. As the magnetic circuit becomes more and more saturated the torque becomes proportional to Ia as flux variation becomes small.

Fig. 62(a) shows the variation of E_1, flux, torque and speed following the above procedure from which the torque-speed characteristics of the series motor for a given applied voltage V can be plotted as shown in Fig. 62(b) The initial portion of this torque-speed curve is seen to be a rectangular hyperbola and the final portion is nearly a straight line. The speed under light load conditions is many times more than the rated speed of the motor. Such high speeds are unsafe, as the centrifugal forces acting on the armature and commutator can destroy them giving rise to a catastrophic break down. Hence series motors are not recommended for use where there is a possibility of the load becoming zero. In order to safeguard the motor and personnel, in the modern machines, a 'weak' shunt field is provided on series motors to ensure a definite, though small, value of flux even when the armature current is nearly zero. This way the no-load speed is limited to a safe maximum speed. It is needless to say, this field should be connected so as to aid the series field.



(a) Load characteristics



(b) Torque speed characteristics

Fig. 62: DC Series motor characteristics

3.9.3. Load characteristics of a compound motor

Two situations arise in the case of compound motors. The mmf of the shunt field and series field may oppose each other or they may aid each other. The first configuration is called differential compounding and is rarely used. They lead to unstable operation of the machine unless the armature mmf is small and there is no magnetic saturation. This mode may sometimes result due to the motoring operation of a level-compounded generator, say by the failure of the prime mover. Also, differential compounding may result in large negative mmf under overload/starting condition and the machine may start in the reverse direction. In motors intended for constant speed operation the level of compounding is very low as not to cause any problem.

Cumulatively compounded motors are very widely used for industrial drives. High degree of compounding will make the machine approach a series machine like characteristics but with a safe no-load speed. The major benefit of the compounding is that the field is strengthened on load. Thus the torque per ampere of the armature current is made high. This feature makes a cumulatively compounded machine well suited for intermittent peak loads. Due to the large speed variation between light load and peak load conditions, a fly wheel can be used with such motors with advantage. Due to the reasons provided under shunt and series motors for the provision of an additional series/shunt winding, it can be seen that all modern machines are compound machines. The difference between them is only in the level of compounding.

3.10. Application of d.c. motors

Some elementary principles of application alone are dealt with here. The focus is on the mechanical equation of dynamics which is reproduced here once again.

$$T_M - T_L = J\frac{d\omega}{dt}$$

Here T_M and T_L are the motor torque and the load torques respectively which are expressed as functions of ω. Under steady state operation dω/dt will be zero. The application of motors mainly looks at three aspects of operation.

1. Starting
2. Speed control
3. Braking

The speed of the machine has to be increased from zero and brought to the operating speed. This is called starting of the motor. The operating speed itself should be varied as per the requirements of the load. This is called speed control. Finally, the running machine has to be brought to rest, by decelerating the same. This is called braking. The torque speed characteristics of the machine is modified to achieve these as it is assumed that the variation in the characteristics of the load is either not feasible or desirable. Hence the methods that are available for modifying the torque speed characteristics and the actual variations in the performance that these methods bring about are of great importance. When more than one method is available for achieving the same objective then other criteria like, initial cost, running cost, efficiency and ease operation are also applied for the evaluation of the methods. Due to the absence of equipment like transformer, d.c. machine operation in general is assumed to be off a constant voltage d.c. supply.

The relevant expressions may be written as,

$$n = \frac{E}{K_e \phi} = \frac{V - I_a R_a - V_b}{pZ \, {}^{\phi}/_{b}}$$

$$T_M = K_t \phi I_a = \frac{1}{2\pi} \frac{pZ}{b} \phi I_a$$

$$T_M - T_L = J \frac{d\omega}{dt}$$

As can be seen, speed is a function of E and ϕ and T is a function of ϕ and I_a. Using these equations, the methods for starting , speed control and braking can be discussed.

3.10.1 Starting of d.c. machines

For the machine to start, the torque developed by the motor at zero speed must exceed that demanded by the load. Then $T_M - T_L$ will be positive so also is $d\omega/dt$, and the machine accelerates. The induced emf at starting point is zero as the $\omega = 0$ The armature current with rated applied voltage is given by V/R_a where R_a is armature circuit resistance.

Normally the armature resistance of a d.c. machine is such as to cause 1 to 5 percent drop at full load current. Hence the starting current tends to rise to several times the full load current. The same can be told of the torque if full flux is already established. The machine instantly picks up the speed. As the speed increases the induced emf appears across the terminals opposing the applied voltage. The current drawn from the mains thus decreases, so also the torque. This continues till the load torque and the motor torque are equal to each other. Machine tends to run continuously at this speed as the acceleration is zero at this point of operation.

The starting is now discussed with respect to specific machines.

If armature and field of d.c. shunt motor are energized together, large current is drawn at start but the torque builds up gradually as the field flux increases gradually. To improve the torque per ampere of line current drawn it is advisable to energize the field first. The starting current is given by V/R_a and hence to reduce the starting current to a safe value, the voltage V can be reduced or armature circuit resistance Ra can be increased.

Variable voltage V can be obtained from a motor generator set. This arrangement is called Ward-Leonard arrangement. A schematic diagram of Ward-Leonard arrangement is shown in Fig. 63. By controlling the field of the Ward-Leonard generator one can get a variable voltage at its terminals which is used for starting the motor.

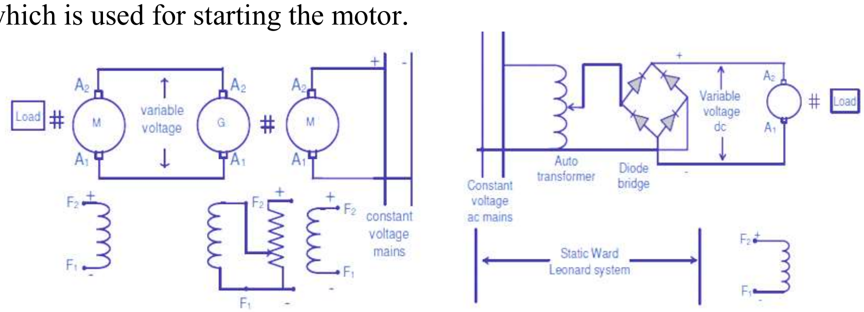


Fig.63: Ward-Leonard arrangement

The second method of starting with increased armature circuit resistance can be obtained by adding additional resistances in series with the armature, at start. The current and the torque get reduced. The torque speed curve under these conditions is shown in Fig. 64(a). It can be readily seen from this graph that the unloaded machine reaches its final speed but a loaded machine may crawl at a speed much below the normal speed. Also, the starting resistance wastes large amount of power. Hence the starting resistance must be reduced to zero at the end of the starting process. This has to be done progressively, making sure that the current does not jump up to large values. Starting of series motor and compound motors are similar to the shunt motor. Better starting torques are obtained for compound motors as the torque per ampere is more. Characteristics for series motors are given in Fig. 65.

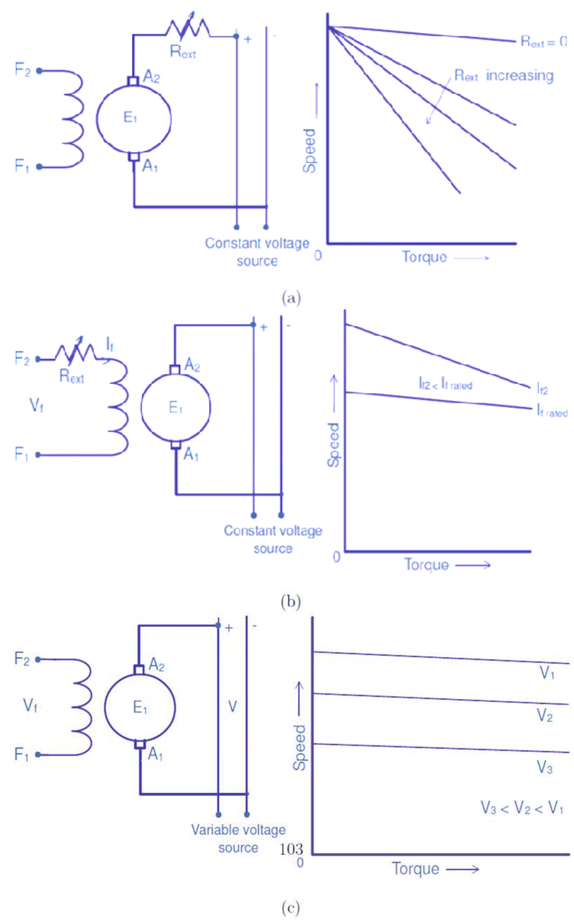


Fig.64: Shunt Motor characteristics

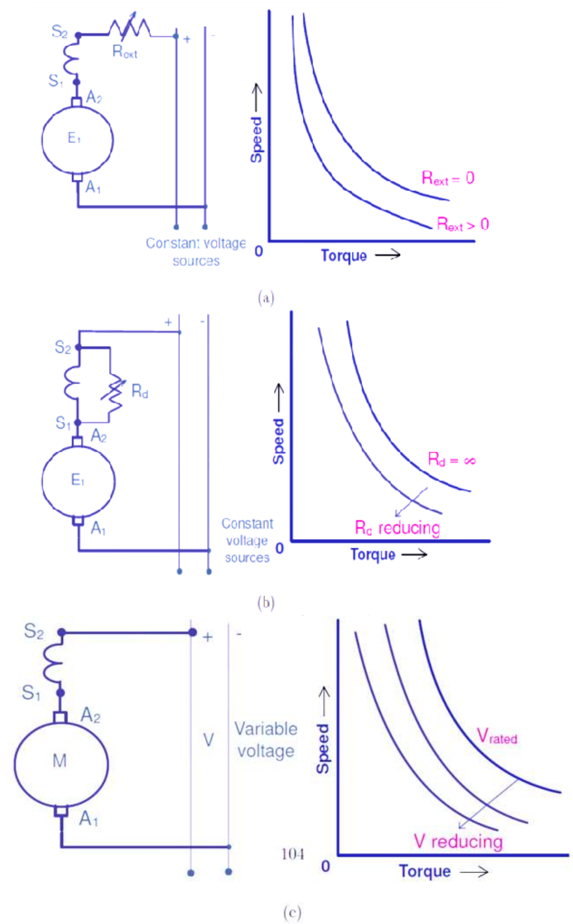


Fig.65: Series motor control

3.10.2. Speed control of d.c. motors

In the case of speed control, armature voltage control and flux control methods are available. The voltage control can be from a variable voltage source like Ward-Leonard arrangement or by the use of series armature resistance. Unlike the starting conditions the series resistance has to be in the circuit throughout in the case of speed control. That means considerable energy is lost in these resistors. Further these resistors must be adequately cooled for continuous operation. The variable voltage source on the other hand gives the motor the voltage just needed by it and the losses in the control gear is a minimum. This method is commonly used when the speed ratio required is large, as also the power rating.

Field control or flux control is also used for speed control purposes. Normally field weakening is used. This causes operation at higher speeds than the nominal speed.

Strengthening the field has little scope for speed control as the machines are already in a state of saturation and large field mmf is needed for small increase in the flux. Even though flux weakening gives higher speeds of operation it reduces the torque produced by the machine for a given armature current and hence the power delivered does not increase at any armature current. The machine is said to be in constant power mode under field weakening mode of control. Above the nominal speed of operation, constant flux mode with increased applied voltage can be used; but this is never done as the stress on the commutator insulation increases.

Thus operation below nominal speed is done by voltage control. Above the nominal speed field weakening is adopted. For weakening the field, series resistances are used for shunt as well as compound motors. In the case of series motors however field weakening is done by the use of 'diverters' . Diverters are resistances that are connected in parallel to the series winding to reduce the field current without affecting the armature current.

3.10.3. Braking the d.c. motors

When a motor is switched off it 'coasts' to rest under the action of frictional forces.

Braking is employed when rapid stopping is required. In many cases mechanical braking is adopted. The electric braking may be done for various reasons such as those mentioned below:

1. To augment the brake power of the mechanical brakes.
2. To save the life of the mechanical brakes.
3. To regenerate the electrical power and improve the energy efficiency.
4. In the case of emergencies to step the machine instantly.
5. To improve the through put in many production process by reducing the stopping time.

In many cases electric braking makes more brake power available to the braking process where mechanical brakes are applied. This reduces the wear and tear of the mechanical brakes and reduces the frequency of the replacement of these parts. By recovering the mechanical energy stored in the rotating parts and pumping it into the supply lines the overall energy efficiency is improved. This is called regeneration. Where the safety of the personnel or the equipment is at stake the machine may be required to stop instantly. Extremely large brake power is needed under those conditions.

Electric braking can help in these situations also. In processes where frequent starting and stopping is involved the process time requirement can be reduced if braking time is reduced. The reduction of the process time improves the throughput.

Basically the electric braking involved is fairly simple. The electric motor can be made to work as a generator by suitable terminal conditions and absorb mechanical energy. This converted mechanical power is dissipated/used on the electrical network suitably.

Braking can be broadly classified into:

1. Dynamic
2. Regenerative
3. Reverse voltage braking or plugging

These are now explained briefly with reference to shunt, series and compound motors.

Dynamic braking

• Shunt machine

In dynamic braking the motor is disconnected from the supply and connected to a dynamic braking resistance. The supply to the field should not be removed. Due to the rotation of the armature during motoring mode and due to the inertia, the armature continues to rotate. An emf is induced due to the presence of the field and the rotation. This voltage drives a current through the braking resistance. The direction of this current is opposite to the one which was flowing before change in the connection. Therefore, torque developed also gets reversed. The machine acts like a brake.

• Series machine

In the case of a series machine the excitation current becomes zero as soon as the armature is disconnected from the mains and hence the induced emf also vanishes. In order to achieve dynamic braking the series field must be isolated and connected to a low voltage high current source to provide the field. Rather, the motor is made to work like a separately excited machine. When several machines are available at any spot, as in railway locomotives, dynamic braking is feasible. Series connection of all the series fields with parallel connection of all the armatures connected across a single dynamic braking resistor is used in that case.

• Compound generators

In the case of compound machine, the situation is like in a shunt machine. A separately excited shunt field and the armature connected across the braking resistance are used. A cumulatively connected motor becomes differentially compounded generator and the braking torque generated comes down. It is therefore necessary to reverse the series field if large braking torques are desired.

Regenerative braking

In regenerative braking as the name suggests the energy recovered from the rotating masses is fed back into the d.c. power source. Thus this type of braking improves the energy efficiency of the machine. The armature current can be made to reverse for a constant voltage operation by increase in speed/excitation only. Increase in speed does not result in braking and the increase in excitation is feasible only over a small range, which may be of the order of 10 to 15%. Hence the best method for obtaining the regenerative braking is to operate, the machine on a variable voltage supply. As the voltage is continuously pulled below the value of the induced emf the speed steadily comes down. The field current is held constant by means of separate excitation. The variable d.c. supply voltage can be obtained by Ward-Leonard arrangement. Braking torque can be obtained right up to zero speed. In modern times static Ward-Leonard scheme is used for getting the variable d.c. voltage. This has many advantages over its rotating machine counterpart. Static set is compact, has higher efficiency, and requires lesser space and silent in operation; however it suffers from drawbacks like large ripple at low voltage levels, unidirectional power flow and low over load capacity. Bidirectional power flow capacity is a must if regenerative braking is required. Series motors cannot be regeneratively braked as the characteristics do not extend to the second quadrant.

Plugging

The third method for braking is by plugging. Initially the machine is connected to the supply with a switch. If now the switch is moved to the other position, then a reverse voltage is applied across the armature. The induced armature voltage *E* and supply voltage V aid each other and a large reverse current flows through the armature. This produces a large negative torque or braking torque. Hence plugging is also termed as reverse voltage braking. The machine instantly comes to rest. If the motor is not switched off at this instant the direction of rotation reverses and the motor starts rotating the reverse direction. Plugging is a convenient mode for quick reversal of direction of rotation in reversible drives. Just as in starting, during plugging also it is necessary to limit the current and thus the torque, to reduce the stress on the mechanical system and the commutator. This is done by adding additional resistance in series with the armature during plugging.

4. Alterative Current (A.C.) Machines

AC motors are used worldwide in many applications to transform electrical energy into mechanical energy. There are many types of AC motors, but AC induction motors are the most common type of motor used in industrial applications.

4.1. AC Induction Motor Construction

Three-phase AC induction motors are commonly used in industrial applications. This type of motor has three main parts, rotor, stator, and enclosure. The stator and rotor do the work, and the enclosure protects the stator and rotor.

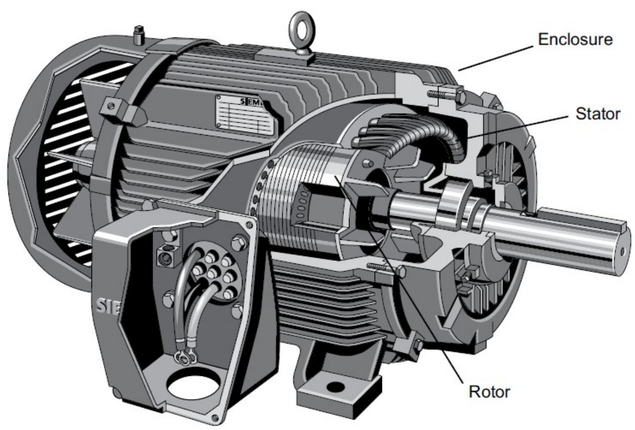


Fig.66: Induction motor construction

The stator is the stationary part of the motor's electromagnetic circuit. The stator core is made up of many thin metal sheets, called laminations. Laminations are used to reduce energy loses that would result if a solid core were used.

Stator laminations are stacked together forming a hollow cylinder. Coils of insulated wire are inserted into slots of the stator core.

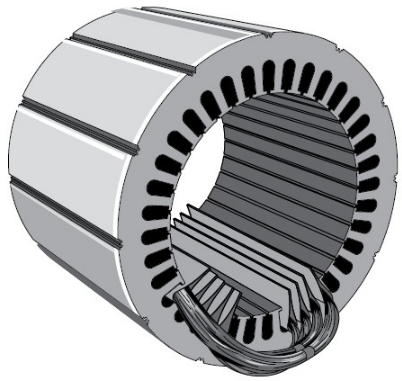


Fig.67: Stator core and windings

When the assembled motor is in operation, the stator windings are connected directly to the power source. Each grouping of coils, together with the steel core it surrounds, becomes an electromagnet when current is applied. Electromagnetism is the basic principle behind motor operation.

The rotor is the rotating part of the motor's electromagnetic circuit. The most common type of rotor used in a three-phase induction motor is a squirrel cage rotor. The squirrel cage rotor is so called because its construction is reminiscent of the rotating exercise wheels found in some pet cages. Another type of three-phase induction motor is the wound rotor motor. A major difference between the wound rotor motor and the squirrel cage rotor is that the conductors of the wound rotor consist of wound coils instead of bars. These coils are connected through slip rings and brushes to external variable resistors.

Both squirrel cage and wound rotors are made by stacking thin steel laminations to form a cylinder.

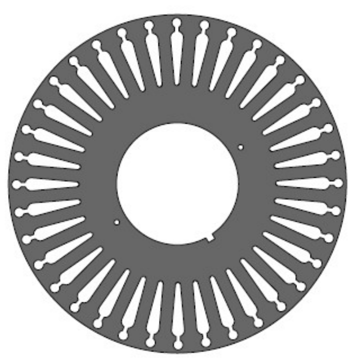


Fig.68: Rotor laminations

Rather than using coils of wire as conductors, in wound rotor case, conductor bars are die cast into the slots evenly spaced around the cylinder in squirrel cage rotors. After die casting, rotor conductor bars are mechanically and electrically connected with end rings. The rotor is then pressed onto a steel shaft to form a rotor assembly.

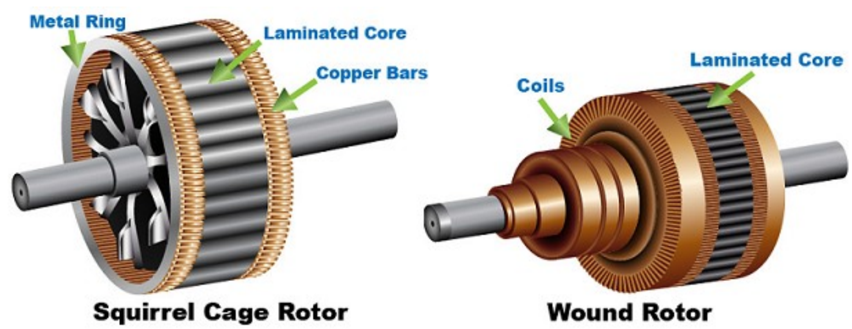


Fig.69: Induction motor rotor types

The enclosure consists of a frame (or yoke) and two end brackets (or bearing housings). The stator is mounted inside the frame. The rotor fits inside the stator with a slight air gap separating it from the stator. There is no direct physical connection between the rotor and the stator. The enclosure protects the internal parts of the motor from water and other environmental elements. The degree of protection depends upon the type of enclosure.

Bearings, mounted on the shaft, support the rotor and allow it to turn. Some motors use a fan, also mounted on the rotor shaft, to cool the motor when the shaft is rotating.

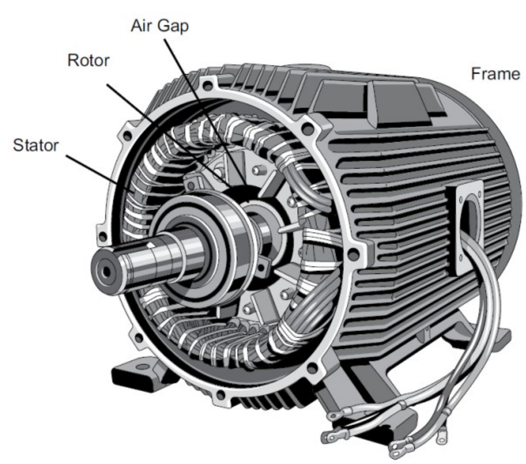


Fig.70: Induction motor assemble

4.2. Developing a Rotating Magnetic Field

The principles of electromagnetism explain the shaft rotation of an AC motor. Recall that the stator of an AC motor is a hollow cylinder in which coils of insulated wire are inserted. The following diagram shows the electrical configuration of stator windings. In this example, six windings are used, two for each of the three phases. The coils are wound around the soft iron core material of the stator. When current is applied, each winding becomes an electromagnet, with the two windings for each phase operating as the opposite ends of one magnet.

In other words, the coils for each phase are wound in such a way that, when current is flowing, one winding is a north pole and the other is a south pole. For example, when A1 is a north pole, A2 is a south pole and, when current reverses direction, the polarities of the windings also reverse.

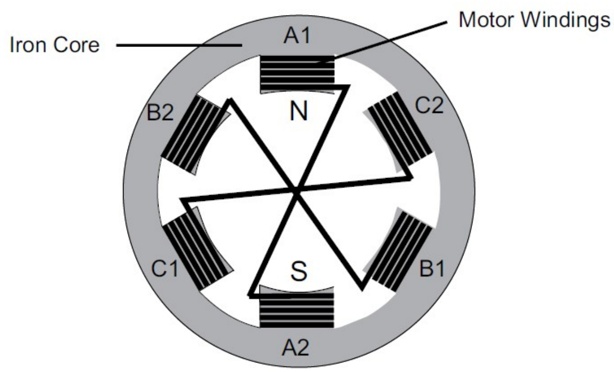


Fig.71: Stator winding configuration

The stator is connected to a three-phase AC power source. Fig. 72 shows windings A1 and A2 connected to phase A of the power supply. When the connections are completed, B1 and B2 will be connected to phase B, and C1 and C2 will be connected to phase C.

As Fig. 73 shows, coils A1, B1, and C1 are 120° apart. Note that windings A2, B2, and C2 also are 120° apart. This corresponds to the 120° separation between each electrical phase. Because each phase winding has two poles, this is called a two-pole stator.

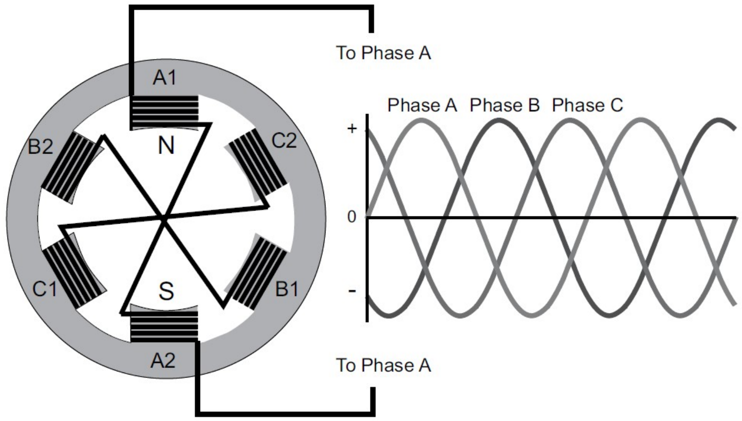


Fig.72: Stator winding connected to a three-phase AC power source

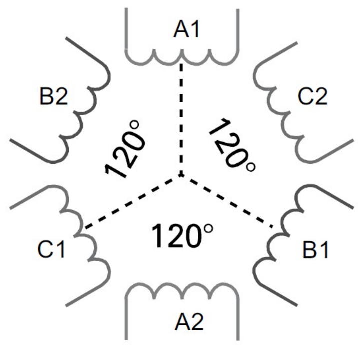


Fig.73: One pole-pair stator winding (two poles)

When AC voltage is applied to the stator, the magnetic field developed in a set of phase coils depends on the direction of current flow. Refer to the following chart as you read the explanation of how a rotating magnetic field is developed. This chart assumes that a positive current flow in the A1, B1 or C1 windings results in a north pole.

Winding	Current Flow Direction	
	Positive	**Negative**
A1	North	South
A2	South	North
B1	North	South
B2	South	North
C1	North	South
C2	South	North

In the following illustration, a start time has been selected during which phase A has no current flow and its associated coils have no magnetic field. Phase B has current flow in the negative direction and phase C has current flow in the positive direction. Based on the previous chart, B1 and C2 are south poles and B2 and C1 are north poles. Magnetic lines of flux leave the B2 north pole and enter the nearest south pole, C2. Magnetic lines of flux also leave the C1 north pole and enter the nearest south pole, B1. The vector sum of the magnetic fields is indicated by the arrow

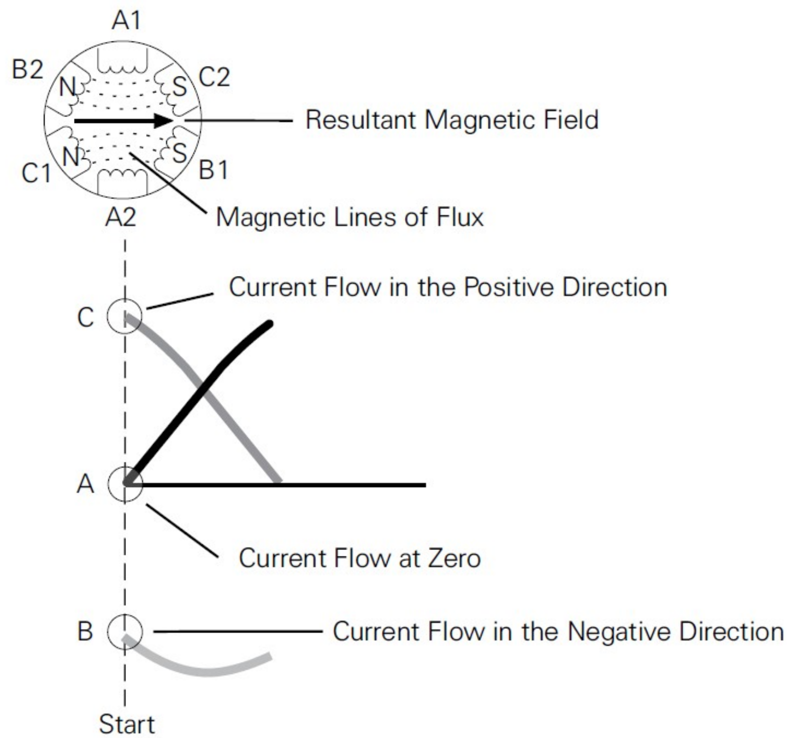


Fig.74: Stator field at start time

The following chart shows the progress of the magnetic field vector as each phase has advanced 60°. Note that at time 1 phase C has no current flow and no magnetic field is developed in C1 and C2. Phase A has current flow in the positive direction and phase B has current flow in the negative direction. As the previous chart shows, windings A1 and B2 are north poles and windings A2 and B1 are south poles. The resultant magnetic field vector has rotated 60° in the clockwise direction.

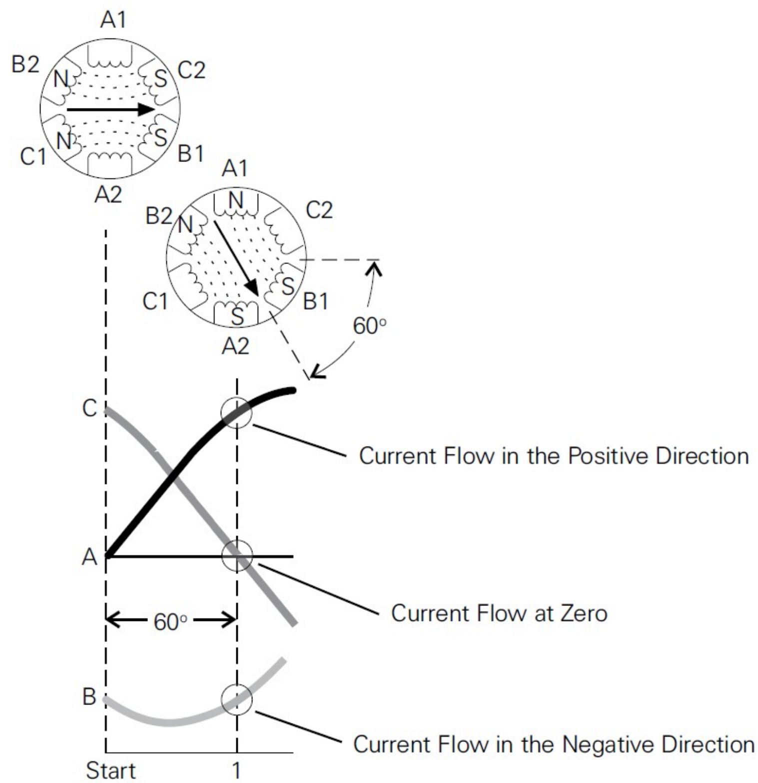


Fig.75: Stator field at time 1 (after 60º)

At time 2, phase B has no current flow and windings B1 and B2 have no magnetic field. Current in phase A is flowing in the positive direction, but phase C current is now flowing in the negative direction. The resultant magnetic field vector has rotated another 60°.

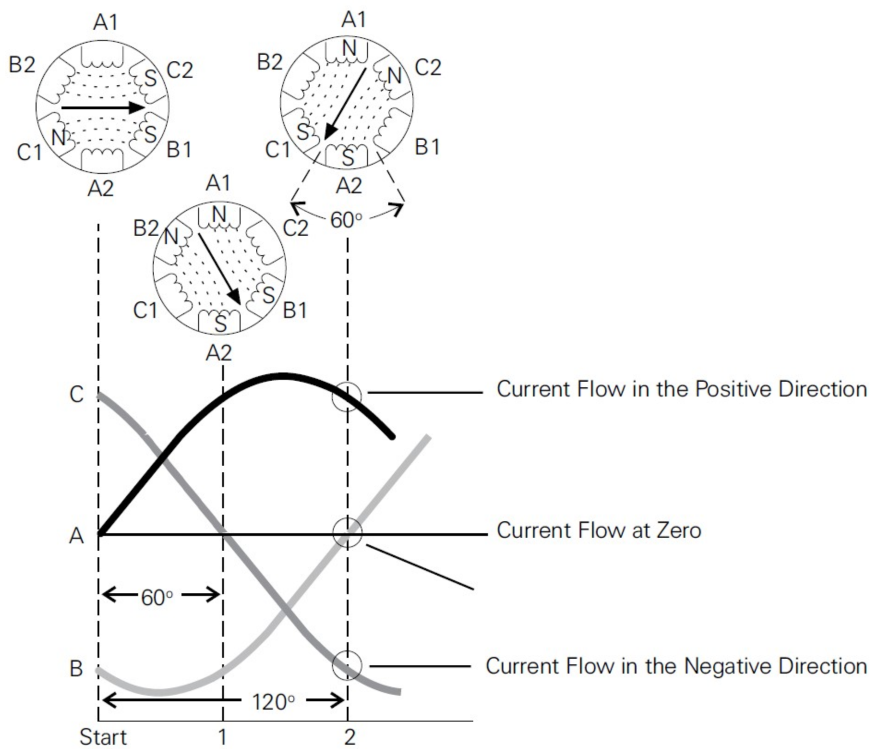


Fig.76: Stator field at time 2 (after 120º)

At the end of six such time intervals, the magnetic field will have rotated one full revolution or 360°. This process repeats 50 times a second for a 50 Hz power source.

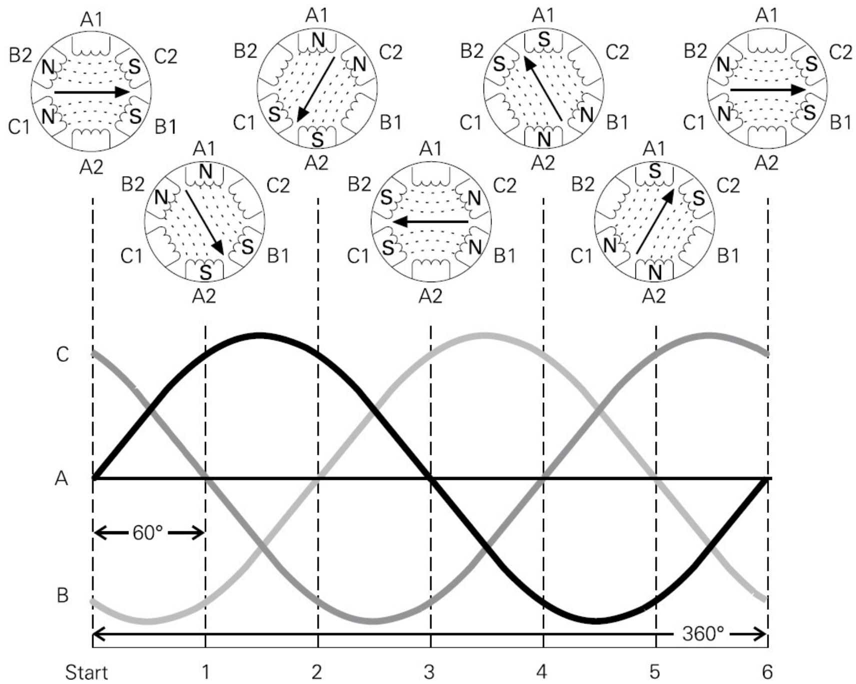


Fig.76: Stator field full cycle (360º)

The speed of the rotating magnetic field is referred to as the synchronous speed (n_S) of the motor. Synchronous speed is equal to 50 times the frequency (f), divided by the number of motor pole-pairs (p).

$$n_s = \frac{50f}{p}$$

The synchronous speed for a two-pole motor operated at 50 Hz, for example, is 3000 rpm.

Synchronous speed decreases as the number of poles increases. The following table shows the synchronous speed at 50 Hz for several different pole-pairs numbers.

pole-pair no.	synchronous speed
1	3000
2	1500
3	1000
4	750

The rotor speed is different to the synchronous speed. To see how a rotor works, a magnet mounted on a shaft can be substituted for the squirrel cage rotor. When the stator windings are energized, a rotating magnetic field is established. The magnet has its own magnetic field that interacts with the rotating magnetic field of the stator. The north pole of the rotating magnetic field attracts the south pole of the magnet, and the south pole of the rotating magnetic field attracts the north pole of the magnet. As the magnetic field rotates, it pulls the magnet along. AC motors that use a permanent magnet or a rotor are referred to as permanent magnet synchronous motors. The term synchronous means that the rotors rotation is synchronized with the magnetic field and the rotor's speed is the same as the motor's synchronous speed.

Instead of a permanent magnet rotor, a squirrel cage induction motor induces a current in its rotor, creating an electromagnet. As the following illustration shows, when current is flowing in a stator winding, the electromagnetic field created cuts across the nearest rotor bars.

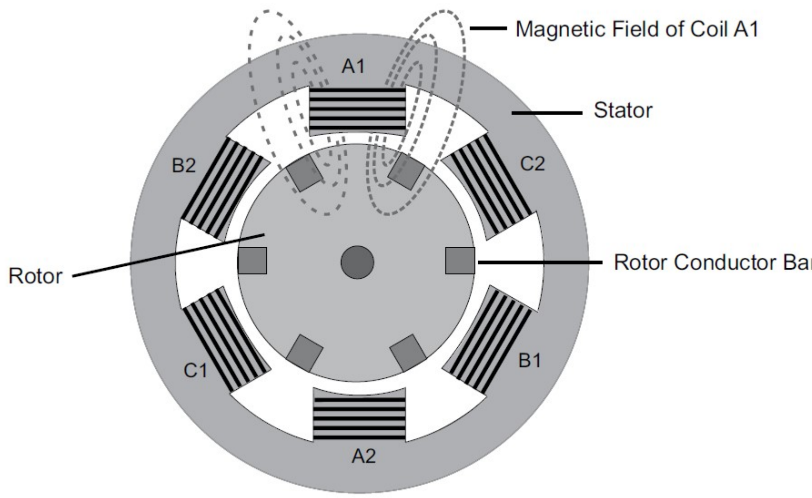


Fig.77: Stator magnetic field

When a conductor, such as a rotor bar, passes through a magnetic field, a voltage (emf) is induced in the conductor. The induced voltage causes current flow in the conductor. In a squirrel cage rotor, current flows through the rotor bars and around the end ring and produces a magnetic field around each rotor bar.

Because the stator windings are connected to an AC source, the current induced in the rotor bars continuously changes and the squirrel cage rotor becomes an electromagnet with alternating north and south poles.

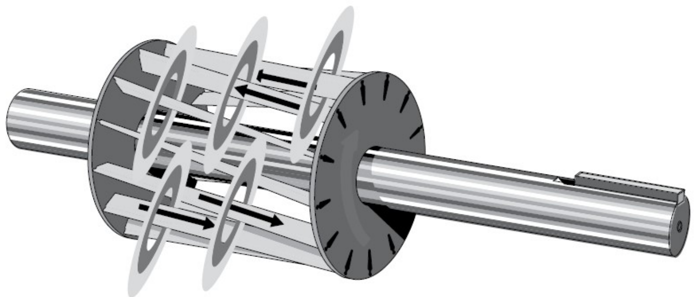


Fig.78: Rotor bars magnetic field

The following illustration shows an instant when winding A1 is a north pole and its field strength is increasing. The expanding field cuts across an adjacent rotor bar, inducing a voltage. The resultant current flow in one rotor bar produces a south pole. This causes the motor to rotate towards the A1 winding. At any given point in time, the magnetic fields for the stator windings are exerting forces of attraction and repulsion against the various rotor bars. This causes the rotor to rotate, but not exactly at the motor's synchronous speed.

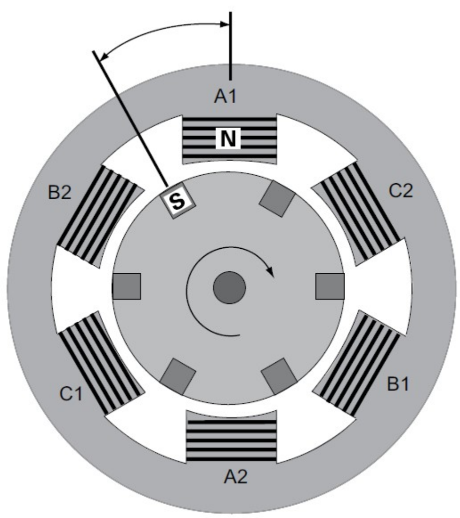


Fig.79: Magnetic fields interaction

For a three-phase AC induction motor, the rotating magnetic field must rotate faster than the rotor to induce current in the rotor. When power is first applied to the motor with the rotor stopped, this difference in speed is at its maximum and a large amount of current is induced in the rotor.

After the motor has been running long enough to get up to operating speed, the difference between the synchronous speed of the rotating magnetic field and the rotor speed is much smaller. This speed difference is called slip.

Slip is necessary to produce torque. Slip is also dependent on load. An increase in load causes the rotor to slow down, increasing slip. A decrease in load causes the rotor to speed up, decreasing slip. Slip is expressed as a percentage and can be calculated using the following formula.

$$s[\%] = \frac{n_s - n_r}{n_s}\, 100$$

4.3. Operating Characteristics of Induction Motors

4.3.1. Methods of Starting Cage Motors

Direct Starting – Problems

Our everyday domestic experience is likely to lead us to believe that there is nothing more to starting a motor than closing a switch, and indeed for most low-power machines (say up to a few kW) – of whatever type – that is indeed the case. By simply connecting the motor to the supply we set in train a sequence of events which sees the motor draw power from the supply while it accelerates to its target speed. When it has absorbed and converted sufficient energy from electrical to kinetic form, the speed stabilizes and the power drawn falls to a low level until the motor is required to do useful mechanical work. In these low-power applications acceleration to full speed may take less than a second, and we are seldom aware of the fact that the current drawn during the acceleration phase is often higher than the continuous rated current.

For motors over a few kW, however, it is necessary to assess the effect on the supply system before deciding whether or not the motor can be started simply by switching directly onto the supply. If supply systems were ideal (i.e. the supply voltage remained unaffected regardless of how much current was drawn) there would be no problem starting any induction motor, no matter how large. The problem is that the heavy current drawn while the motor is running up to speed may cause a large drop in the supply system voltage, annoying other customers on the same supply and perhaps taking it outside statutory limits.

It is worthwhile reminding ourselves about the influence of supply impedance at this point, as this is at the root of the matter, so we begin by noting that any supply system, no matter how complicated, can be modeled by means of the delightfully simple The equivalent circuit is shown in Fig.80 (We here assume a balanced 3-phase operation, so a 1-phase equivalent circuit will suffice.)

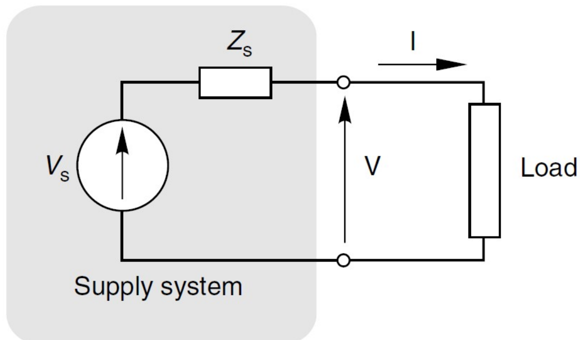


Fig.80: Equivalent circuit of supply system

The supply is represented by an ideal voltage source (V_s) in series with the supply impedance Z_s. When no load is connected to the supply, and the current is zero, the terminal voltage is V_s; but as soon as a load is connected the load current (I) flowing through the source impedance results in a volt drop, and the output voltage falls from V_s to V, where

$$V = V_s - IZ_s$$

For most industrial supplies the source impedance is predominantly inductive, so that Z_s is simply an inductive reactance, X_s. Typical phasor diagrams relating to a supply with a purely inductive reactance are shown in Fig.81: in (a) the load is also taken to be purely reactive, while the load current in (b) has the same magnitude as in (a) but the load is resistive. The output (terminal) voltage in each case is represented by the phasor labeled V.

For the inductive load (a) the current lags the terminal voltage by 90° while for the resistive load (b) the current is in phase with the terminal voltage. In both cases the volt drop across the supply reactance (IX_s) leads the current by 90°.

The first point to note is that, for a given magnitude of load current, the volt drop is in phase with V_s when the load is inductive, whereas with a resistive load the volt drop is almost at 90° to V_s. These results in a much greater fall in the magnitude of the output voltage when the load is inductive than when it is resistive. The second, obvious, point is that the larger the current, the more the drop in voltage.

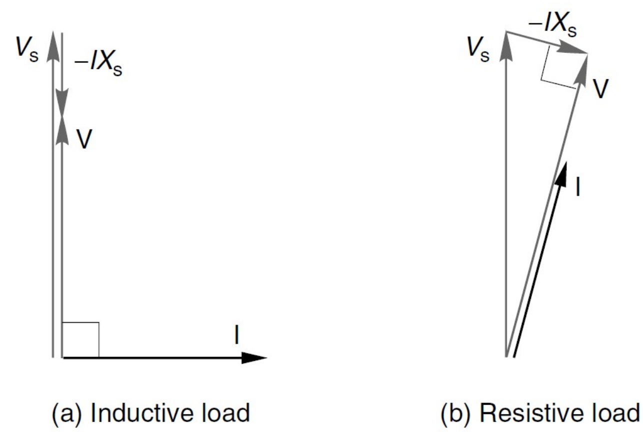


Fig.81: Phasor diagrams showing the effect of supply-system impedance on the output voltage with (a) inductive load and (b) resistive load

Unfortunately, when we try to start a large cage induction motor we face a double-whammy because not only is the starting current typically five or six times rated current, but it is also at a low-power factor, i.e. the motor looks predominantly inductive when the slip is high. (In contrast, when the machine is up to speed and fully loaded, it's current is perhaps only one fifth of its starting current and it presents a predominantly resistive appearance as seen by the supply. Under these conditions the supply voltage is hardly any different from at no-load.)

Since the drop in voltage is attributable to the supply impedance, if we want to be able to draw a large starting current without upsetting other consumers it would be clearly best for the supply impedance to be as low as possible, and preferably zero. But from the supply authority viewpoint very low supply impedance brings the problem of how to scope in the event of an accidental short-circuit across the terminals. The short-circuit current is inversely proportional to the supply impedance, and tends to infinity as Z_s approaches zero. The cost of providing the switch-gear to clear such a large fault current would be prohibitive, so a compromise always has to be reached, with values of supply impedances being set by the supply authority to suit the anticipated demands.

Systems with low internal impedance are known as 'stiff' supplies, because the voltage is almost constant regardless of the current drawn.

(An alternative way of specifying the nature of the supply is to consider the fault current that would flow if the terminals were short-circuited: a system with low impedance would have a high fault current or 'fault level'.) Starting on a stiff supply requires no special arrangements and the three motor leads are simply switched directly onto the mains. This is known as ‘direct-on-line’ (DOL) or ‘direct-to-line’ (DTL) starting. The switching will usually be done by means of a relay or contactor, incorporating fuses and other overload protection devices, and operated manually by local or remote pushbuttons, or interfaced to permit operation from a programmable controller or computer.

In contrast, if the supply impedance is high (i.e. a low-fault level) an appreciable volt drop will occur every time the motor is started, causing lights to dim and interfering with other apparatus on the same supply. With this ‘weak’ supply, some form of starter is called for to limit the current at starting and during the run-up phase, thereby reducing the magnitude of the volt drop imposed on the supply system. As the motor picks up speed, the current falls, so the starter is removed as the motor approaches full speed. Naturally enough the price to be paid for the reduction in current is a lower starting torque, and a longer run-up time.

Whether or not a starter is required depends on the size of the motor in relation to the capacity or fault level of the supply, the prevailing regulations imposed by the supply authority, and the nature of the load.

The references above to ‘low’ and ‘high’ supply impedances must therefore be interpreted in relation to the impedance of the motor when it is stationary. A large (and therefore low impedance) motor could well be started quite happily DOL in a major industrial plant, where the supply is ‘stiff’, i.e. the supply impedance is very much less than the motor impedance.

But the same motor would need a starter when used in a rural setting remote from the main power system, and fed by a relatively high impedance or ‘weak’ supply. Needless to say, the stricter the rules governing permissible volt drop, the more likely it is that a starter will be needed.

Motors which start without significant load torque or inertia can accelerate very quickly, so the high starting current is only drawn for a short period. A 10 kW motor would be up to speed in a second or so, and the volt drop may therefore be judged as acceptable. Clutches are sometimes fitted to permit ‘off-load’ starting; the load being applied after the motor has reached full speed. Conversely, if the load torque and/or inertia are high, the run-up may take many seconds, in which case a starter may prove essential. No strict rules can be laid down, but obviously the bigger the motor, the more likely it is to require a starter.

Star/delta (wye/mesh) starter

This is the simplest and most widely used method of starting. It provides for the windings of the motor to be connected in star (wye) to begin with, thereby reducing the voltage applied to each phase to 58% ($1/\sqrt{3}$) of its

DOL value. Then, when the motor speed approaches its running value, the windings are switched to delta (mesh) connection. The main advantage of the method is its simplicity, while its main drawbacks are that the starting torque is reduced (see below), and the sudden transition from star to delta gives rise to a second shock – albeit of lesser severity – to the supply system and to the load. For star/delta switching to be possible both ends of each phase of the motor windings must be brought out to the terminal box. This requirement is met in the majority of motors, except small ones which are usually permanently connected in delta.

With a star/delta starter the current drawn from the supply is approximately one third of that drawn in a DOL start, which is very welcome, but at the same time the starting torque is also reduced to one third of its DOL value. Naturally we need to ensure that the reduced torque will be sufficient to accelerate the load, and bring it up to a speed at which it can be switched to delta without an excessive jump in the current.

Various methods are used to detect when to switch from star to delta.

In manual starters, the changeover is determined by the operator watching the ammeter until the current has dropped to a low level, or listening to the sound of the motor until the speed becomes steady. Automatic versions are similar in that they detect either falling current or speed rising to a threshold level, or else they operate after a preset time.

Autotransformer starter

A 3-phase autotransformer is usually used where star/delta starting provides insufficient starting torque. Each phase of an autotransformer consists of a single winding on a laminated core. The mains supply is connected across the ends of the coils, and one or more tapping points (or a sliding contact) provide a reduced voltage output, as shown in Fig.82.

The motor is first connected to the reduced voltage output, and when the current has fallen to the running value, the motor leads are switched over to the full voltage.

If the reduced voltage is chosen so that a fraction α of the line voltage is used to start the motor, the starting torque is reduced to approximately α^2 times its DOL value, and the current drawn from the mains is also reduced to α^2 times its direct value. As with the star/delta starter, the torque per ampere of supply current is the same as for a direct start.

The switch over from the starting tap to the full voltage inevitably results in mechanical and electrical shocks to the motor. In large motors the transient over voltages caused by switching can be enough to damage the insulation, and where this is likely to pose a problem a modified procedure known as the Korndorfer method is used. A smoother changeover is achieved by leaving part of the winding of the autotransformer in series with the motor winding all the time.

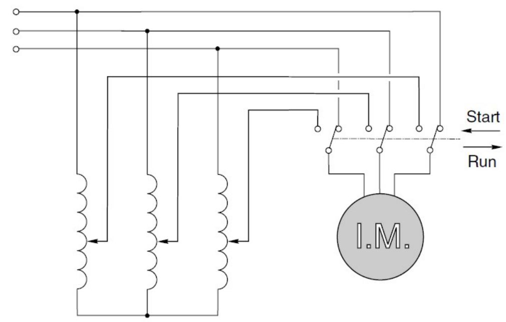


Fig.82: Autotransformer starter for cage induction motor

Resistance or reactance starter

By inserting three resistors or inductors of appropriate value in series with the motor, the starting current can be reduced by any desired extent, but only at the expense of a disproportionate reduction in starting torque.

For example, if the current is reduced to half its DOL value, the motor voltage will be halved, so the torque (which is proportional to the square of the voltage – see later) will be reduced to only 25% of its DOL value.

This approach is thus less attractive in terms of torque per ampere of supply current than the star/delta method. One attractive feature, however, is that as the motor speed increases and its effective impedance rises, the volt drop across the extra impedance reduces, so the motor voltage rises progressively with the speed, thereby giving more torque.

When the motor is up to speed, the added impedance is shorted-out by means of a contactor. Variable-resistance starters (manually or motor operated) are sometimes used with small motors where a smooth jerk-free start is required, for example in film or textile lines.

Solid-state soft starting

This method is now the most widely used. It provides a smooth build-up of current and torque, the maximum current and acceleration time are easily adjusted, and it is particularly valuable where the load must not be subjected to sudden jerks. The only real drawback over conventional starters is that the mains currents during run-up are not sinusoidal, which can lead to interference with other equipment on the same supply.

The most widely used arrangement comprises three pairs of back-to-back thyristors connected in series with three supply lines, as shown in Fig.83(a).

Each thyristor is fired once per half-cycle, the firing being synchronized with the mains and the firing angle being variable so that each pair conducts for a varying proportion of a cycle. Typical current waveforms are shown in Fig. 83(b): they are clearly not sinusoidal but the motor will tolerate them quite happily.

A wide variety of control philosophies can be found, with the degree of complexity and sophistication being reflected in the price. The cheapest open-loop systems simply alter the firing angle linearly with time, so that the voltage applied to the motor increases as it accelerates. The 'ramp-time' can be set by trial and error to give an acceptable start, i.e. one in which the maximum allowable current from the supply is not exceeded at any stage. This approach is reasonably satisfactory when the load remains the same, but requires resetting each time the load changes.

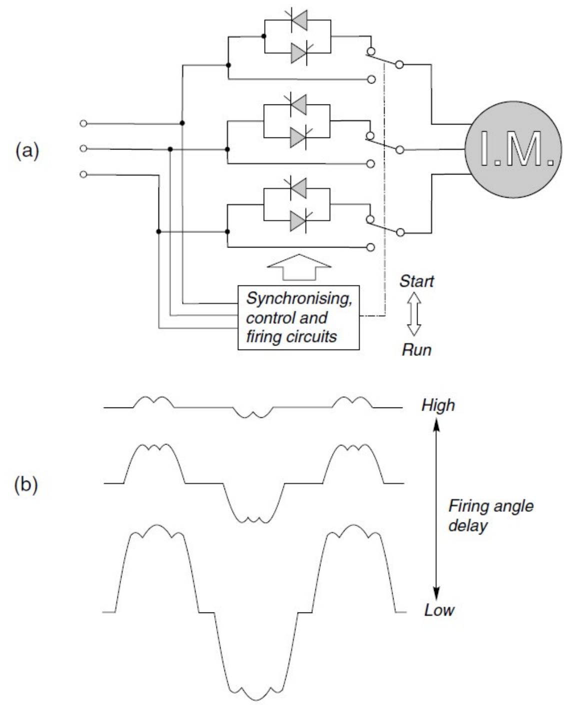


Fig.83: (a) Thyristor soft-starter, (b) typical motor current waveforms

Loads with high static friction are a problem because nothing happens for the first part of the ramp, during which time the motor torque is insufficient to move the load. When the load finally moves, its acceleration is often too rapid. The more advanced open-loop versions allow the level of current at the start of the ramp to be chosen, and this is helpful with 'sticky' loads.

More sophisticated systems – usually with on-board digital controllers – provide for tighter control over the acceleration profile by incorporating closed-loop current feedback. After an initial ramping up to the start level (over the first few cycles), the current is held constant at the desired level throughout the accelerating period, the firing angle of the thyristors being continually adjusted to compensate for the changing effective impedance of the motor. By keeping the current at the maximum value, which the supply can tolerate the run-up time, is minimized

Alternatively, if a slow run-up is desirable, a lower accelerating current can be selected.

As with the open-loop systems the velocity–time profile is not necessarily ideal, since with constant current the motor torque exhibits a very sharp rise as the pullout slip is reached, resulting in a sudden surge in speed.

Prospective users need to be wary of some of the promotional literature, where naturally enough the virtues are highlighted while the shortcomings are played down. Claims are sometimes made that massive reductions in starting current can be achieved without corresponding reductions in starting torque. This is nonsense: the current can certainly be limited, but as far as torque per line amp is concerned soft-start systems are no better than series reactor systems, and not as good as the autotransformer and star/delta methods.

Starting using a variable-frequency inverter

Operation of induction motors from variable-frequency inverters will be described later, but it is appropriate to mention here that one of the advantages of inverter-fed operation is that starting is not a problem because it is usually possible to obtain at least rated torque at zero speed without drawing an excessive current from the mains supply.

None of the other starting methods we have looked at have this ability, so in some applications it may be that the comparatively high cost of the inverter is justified solely on the grounds of its starting and run-up potential.

4.3.2. Run-Up and Stable Operating Regions

In addition to having sufficient torque to start the load it is obviously necessary for the motor to bring the load up to full speed. To predict how the speed will rise after switching on we need the torque–speed curves of the motor and the load, and the total inertia.

By way of example, we can look at the case of a motor with two different loads (see Fig.84). The solid line is the torque–speed curve of the motor, while the dotted lines represent two different load characteristics.

Load (A) is typical of a simple hoist, which applies constant torque to the motor at all speeds, while load (B) might represent a fan.

For the sake of simplicity, we will assume that the load inertias (as seen at the motor shaft) are the same.

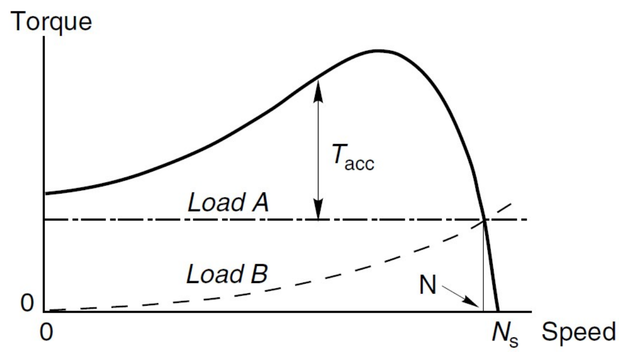


Fig.84: Typical torque–speed curve showing two different loads which have the same steady running speed

The speed–time curves for run-up are shown in Fig.85. Note that the gradient of the speed–time curve (i.e. the acceleration) is obtained by dividing the accelerating torque T_{acc} (which is the difference between the torque developed by the motor and the torque required to run the load at that speed) by the total inertia.

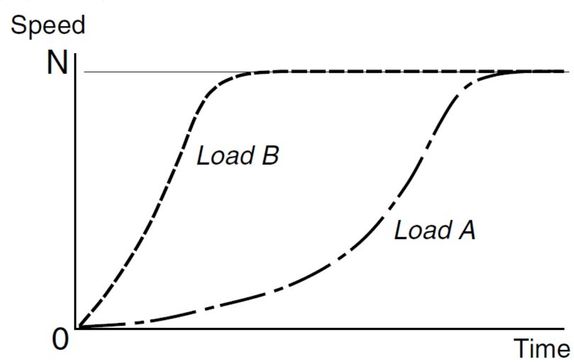


Fig.85: Speed–time curves during run-up, for motor and loads

In this example, both loads ultimately reach the same steady speed, (i.e. the speed at which motor torque equals load torque), but B reaches full speed much more quickly because the accelerating torque is higher during most of the run-up. Load A picks up speed slowly at first, but then accelerates hard (often with a characteristic ‘whoosh’ produced by the ventilating fan) as it passes through the peak torque–speed and approaches equilibrium conditions.

It should be clear that the higher the total inertia, the slower the acceleration and vice versa. The total inertia means the inertia as seen at the motor shaft.

An important qualification ought to be mentioned in the context of the motor torque–speed curves shown by the solid line in Fig.84.

This is that curves like this represent the torque developed by the motor when it has settled down at the speed in question, i.e. they are the true steady-state curves. In reality, a motor will generally only be in a steady-state condition when it settles at its normal running speed, so for most of the speed range the motor will be accelerating. In particular, when the motor is first switched on, there will be a transient period of a few cycles as the three currents gradually move towards a balanced 3-phase pattern.

During this period the torque can fluctuate wildly and the motor can pick up significant speed, so the actual torque may be very different from that shown by the steady-state curve, and as a result the instantaneous speeds can fluctuate about the mean value. Fortunately, the average torque during run-up can be fairly reliably obtained from the steady-state curves, particularly if the inertia is high and the motor takes many cycles to reach full speed, in which case we would consider the torque–speed curve as being ‘quasi-steady state’.

Harmonic effects – skewing

A further cautionary note in connection with the torque–speed curves shown in this and most other books relate to the effects of harmonic airgap fields. Despite the limitations imposed by slotting, the stator winding magnetic flux (MMF) is remarkably close to the ideal of a pure sinusoid. Unfortunately, because it is not a perfect sinusoid, Fourier analysis reveals that in addition to the predominant fundamental component, there are always additional unwanted ‘space harmonic’ fields. These harmonic fields have synchronous speeds that are inversely proportional to their order. For example a 4-pole, 50 Hz motor will have a main field rotating at 1500 rev/min, but in addition there may be a fifth harmonic (20-pole) field rotating in the reverse direction at 300 rev/min, a seventh harmonic (28-pole) field rotating forwards at 214 rev/min, etc. These space harmonics are minimized by stator winding design, but can seldom be eliminated.

If the rotor has a very large number of bars it will react to the harmonic field in much the same way as to the fundamental, producing additional induction motor torques centered on the synchronous speed of the harmonic, and leading to unwanted dips in the torque speed, typically as shown in Figure 86.

Users should not be too alarmed as in most cases the motor will ride through the harmonic during acceleration, but in extreme cases a motor might, for example, stabilize on the seventh harmonic, and 'crawl' at about 214 rev/min, rather than running up to 4-pole speed (1500 rev/min at 50 Hz), as shown by the dot in Figure 86.

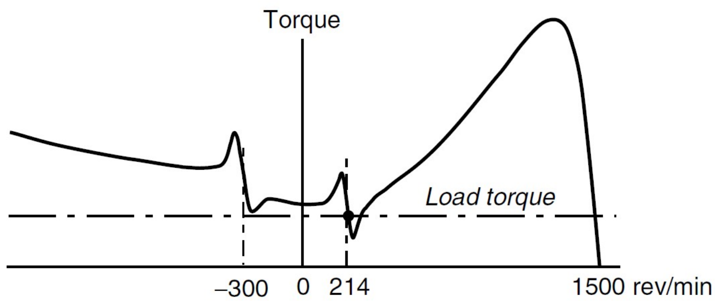


Fig.86: Torque–speed curve showing the effect of space harmonics, and illustrating the possibility of a motor 'crawling' on the seventh harmonic

To minimize the undesirable effects of space harmonics the rotor bars in the majority of induction motors are not parallel to the axis of rotation, but instead they are skewed (typically by around one or two slot pitches) along the rotor length. This has very little effect as far as the fundamental field is concerned, but can greatly reduce the response of the rotor to harmonic fields.

Because the overall influence of the harmonics on the steady-state curve is barely noticeable, and their presence might worry users, they are rarely shown, the accepted custom being that 'the' torque–speed curve represents the behavior due to the fundamental component only.

High inertia loads – overheating

Apart from accelerating slowly, high inertia loads pose a particular problem of rotor heating, which can easily be overlooked by the unwary user. Every time an induction motor is started from rest and brought up to speed, the total energy dissipated as heat in the motor windings is equal to the stored kinetic energy of the motor plus load. Hence with high inertia loads, very large amounts of energy are released as heat in the windings during run-up, even if the load torque is negligible when the motor is up to speed. With totally enclosed motors the heat ultimately has to find its way to the finned outer casing of the motor, which is cooled by air from the shaft-mounted external fan. Cooling of the rotor is therefore usually much worse than the stator, and the rotor is thus most likely to overheat during high inertia run-ups.

No hard and fast rules can be laid down, but manufacturers usually work to standards which specify how many starts per hour can be tolerated. Actually, this information is useless unless coupled with reference to the total inertia, since doubling the inertia makes the problem twice as bad. However, it is usually assumed that the total inertia is not likely to be more than twice the motor inertia, and this is certainly the case for most loads. If in doubt, the user should consult the manufacturer who may recommend a larger motor than might seem necessary simply to supply the full-load power requirements.

Steady-state rotor losses and efficiency

The discussion above is a special case, which highlights one of the less attractive features of induction machines. This is that it is never possible for all the power crossing the air-gap from the stator to be converted to mechanical output, because some is always lost as heat in the rotor circuit resistance. In fact, it turns out that at slip s the total power (P_r) crossing the air-gap always divides so that a fraction $s\ P_r$ is lost as heat, while the remainder (1 - s) P_r is converted to useful mechanical output.

Hence, when the motor is operating in the steady state the energy conversion efficiency of the rotor is given by

$$\eta_r = \frac{\text{Mechanical output power}}{\text{Rated power input to rotor}} = (1 - s)$$

This result is very important, and shows us immediately why operating at small values of slip is desirable. With a slip of 5% (or 0.05), for example, 95% of the air-gap power is put to good use. But if the motor was run at half the synchronous speed (s = 0.5), 50% of the airgap power would be wasted as heat in the rotor.

We can also see that the overall efficiency of the motor must always be significantly less than (1 - s), because in addition to the rotor copper losses there are stator copper losses, iron losses and winding and friction losses. This fact is sometimes forgotten, leading to conflicting claims such as ‘full-load slip = 5%, overall efficiency = 96%’, which is clearly impossible.

Steady-state stability – pullout torque and stalling

We can check stability by asking what happens if the load torque suddenly changes for some reason. The load torque shown by the dotted line in Fig.87 is stable at speed X, for example: if the load torque increased from T_a to T_b, the load torque would be greater than the motor torque, so the motor torque would decelerate. As the speed dropped, the motor torque would rise, until a new equilibrium was reached, at the slightly lower speed (Y). The converse would happen if the load torque were reduced, leading to a higher stable running speed.

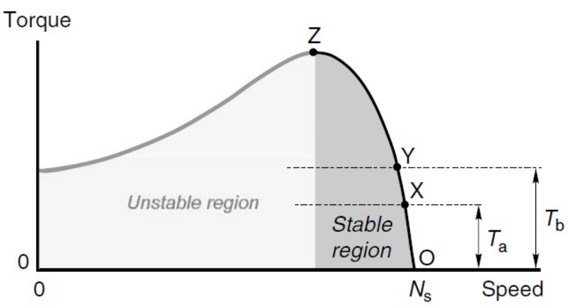


Fig.87: Torque–speed curve illustrating stable operating region (0XYZ)

But what happens if the load torque is increased more and more? We can see that as the load torque increases, beginning at point X, we eventually reach point Z, at which the motor develops its maximum torque. Quite apart from the fact that the motor is now well into its overload region, and will be in danger of overheating, it has also reached the limit of stable operation. If the load torque is further increased, the speed falls (because the load torque is more than the motor torque), and as it does so the shortfall between motor torque and load torque becomes greater and greater. The speed therefore falls faster and faster, and the motor is said to be 'stalling'. With loads such as machine tools (a drilling machine, for example), as soon as the maximum or 'pullout' torque is exceeded, the motor rapidly comes to a halt, making an angry humming sound. With a hoist, however, the excess load would cause the rotor to be accelerated in the reverse direction, unless it was prevented from doing so by a mechanical brake.

4.3.3. Torque–Speed Curves - Influence of Rotor Parameters

We saw earlier that the rotor resistance and reactance influenced the shape of the torque–speed curve. The designer can vary both of these parameters, and we will explore the pros and cons of the various alternatives. To limit the mathematics the discussion will be mainly qualitative, but it is worth mentioning that the whole matter can be dealt rigorously using the equivalent circuit approach.

We will deal with the cage rotor first because it is the most important, but the wound rotor allows a wider variation of resistance to be obtained, so it is discussed later.

Cage rotor

For small values of slip, i.e. in the normal running region, the lower we make the rotor resistance the steeper the slope of the torque–speed curve becomes, as shown in Fig.88. We can see that at the rated torque (shown by the horizontal dotted line in Fig.88) the full-load slip of the low-resistance cage is much lower than that of the high-resistance cage. But we saw earlier that the rotor efficiency is equal to (1 - s), where s is the slip. So, we conclude that the low-resistance rotor not only gives better speed holding, but is also much more efficient. There is of course a limit to how low we can make the resistance: copper allows us to achieve a lower resistance than aluminum, but we can't do anything better than fill the slots with solid copper bars.

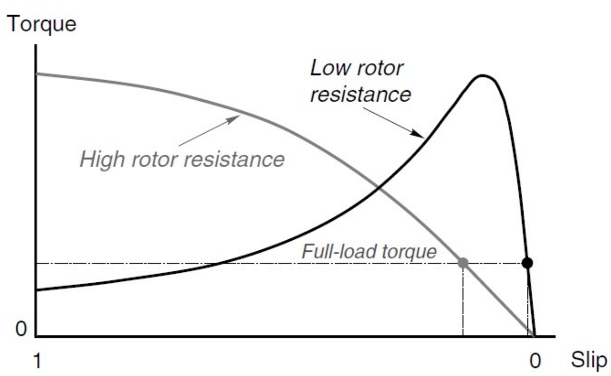


Fig.88: Influence of rotor resistance on torque–speed curve of cage motor. The full-load running speeds are indicated by the vertical dotted lines

As we might expect there are drawbacks with a low-resistance rotor. The starting torque is reduced (see Fig.88), and worse still the starting current is increased. The lower starting torque may prove insufficient to accelerate the load, while increased starting current may lead to unacceptable volt drops in the supply.

Altering the rotor resistance has little or no effect on the value of the peak (pullout) torque, but the slip at which the peak torque occurs is directly proportional to the rotor resistance. By opting for a high enough resistance (by making the cage from bronze, brass or other relatively high resistivity material) we can if we wish to arrange for the peak torque to occur at or close to starting, as shown in Fig.88. The snag in doing this is that the full-load efficiency is inevitably low because the full-load slip will be high (see Fig.88).

There are some applications for which high-resistance motors are well suited, an example being for metal punching presses, where the motor accelerates a flywheel, which is used to store energy. To release a significant amount of energy, the flywheel slows down appreciably during impact, and the motor then has to accelerate it back up to full speed. The motor needs a high torque over a comparatively wide speed range, and does most of its work during acceleration. Once up to speed the motor is effectively running light, so its low efficiency is of little consequence. High-resistance motors are also used for speed control of fan-type loads.

To sum up, a high-rotor resistance is desirable when starting and at low speeds, while a low resistance is preferred under normal running conditions. To get the best of both worlds, we need to be able to alter the resistance from a high value at starting to a lower value at full speed.

Obviously we cannot change the actual resistance of the cage once it has been manufactured, but it is possible to achieve the desired effect with either a ‘double cage’ or a ‘deep bar’ rotor. Manufacturers normally offer a range of designs, which reflect these trade-offs, and the user then selects the one which best meets his particular requirements.

Double cage rotors

Double cage rotors have an outer cage made up of relatively high resistivity material such as bronze, and an inner cage of low resistivity, usually copper, as shown in Fig.89.

The inner cage is sunk deep into the rotor, so that it is almost completely surrounded by iron. This causes the inner bars to have a much higher leakage inductance than if they were near the rotor surface, so that under starting conditions (when the induced rotor frequency is high) their inductive reactance is very high and little current flows in them. In contrast, the bars of the outer cage are placed so that their leakage fluxes face a much higher reluctance path, leading to a low-leakage inductance. Hence, under starting conditions, rotor current is concentrated in the outer cage, which, because of its high resistance, produces a high starting torque.

At the normal running speed the roles are reversed. The rotor frequency is low, so both cages have low reactance and most of the current therefore flows in the low-resistance inner cage. The torque–speed curve is therefore steep, and the efficiency is high.

Considerable variation in detailed design is possible to shape the torque–speed curve to particular requirements. In comparison with a single-cage rotor, the double cage gives much higher starting torque, substantially less starting current, and marginally worse running performance.

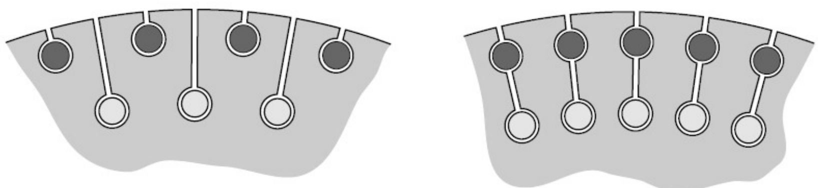


Fig.89: Alternative arrangements of double cage rotors.

Deep bar rotors

The deep bar rotor has a single cage, usually of copper, formed in slots which are deeper and narrower than in a conventional single-cage design. Construction is simpler and therefore cheaper than in a double cage rotor, as shown in Fig.90.

The deep bar approach ingeniously exploits the fact that the effective resistance of a conductor is higher under a.c. conditions than under d.c. conditions. With a typical copper bar of the size used in an induction motor rotor, the difference in effective resistance between d.c. and say 50 or 60 Hz (the so-called ‘skin-effect’) would be negligible if the conductor was entirely surrounded by air. But when it is almost completely surrounded by iron, as in the rotor slots, its effective resistance at mains frequency may be two or three times its d.c. value.

Under starting conditions, when the rotor frequency is equal to the supply frequency, the skin effect is very pronounced, and the rotor current is concentrated towards the top of the slots. The effective resistance is therefore increased, resulting in a high-starting torque from a low-starting current. When the speed rises and the rotor frequency falls, the effective resistance reduces towards its d.c. value, and the current distributes itself more uniformly across the cross section of the bars. The normal running performance thus approaches that of a low-resistance single-cage rotor, giving a high efficiency and stiff torque–speed curve. The pullout torque is, however, somewhat lower than for an equivalent single-cage motor because of the rather higher leakage reactance.

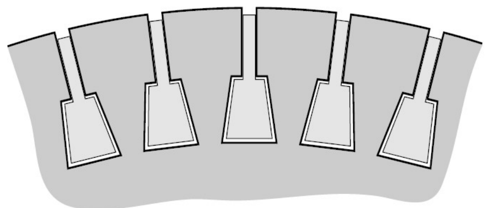


Fig.90: Typical deep-bar rotor construction

Most small and medium motors are designed to exploit the deep bar effect to some extent, reflecting the view that for most applications the slightly inferior running performance is more than outweighed by the much better starting behavior. A typical torque–speed curve for a general-purpose medium-size (55 kW) motor is shown in Fig.91.

Such motors are unlikely to be described by the maker specifically as ‘deep-bar’ but they nevertheless incorporate a measure of the skin effect and consequently achieve the ‘good’ torque–speed characteristic shown by the solid line in Fig.91.

The current–speed relationship is shown by the dotted line in Fig.91, both torque and current scales being expressed in per unit (p.u.).

This notation is widely used as shorthand, with 1 p.u. (or 100%) representing rated value. For example, a torque of 1.5 p.u. simply means one and a half times rated value, while a current of 400% means a current of four times rated value.

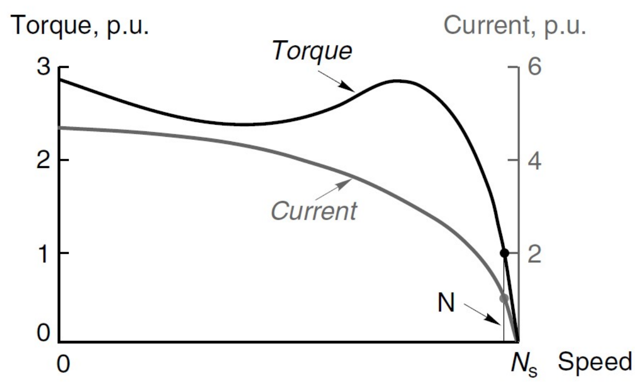


Fig.91: Typical torque–speed and current–speed curves for a general-purpose industrial cage motor

Starting and run-up of slipring motors

By adding external resistance in series with the rotor windings the starting current can be kept low but at the same time the starting torque is high. This is the major advantage of the wound-rotor or slipring motor, and makes it well suited for loads with heavy starting duties such as stone-crushers, cranes and conveyor drives.

The influence of rotor resistance is shown by the set of torque–speed curves in Fig.92. The curve on the right corresponds to no added rotor resistance, with the other six curves showing the influence of progressively increasing the external resistance.

A high-rotor resistance is used when the motor is first switched on, and depending on the value chosen any torque up to the pullout value (perhaps twice full load) can be obtained. Typically, the resistance will be selected to give full-load torque at starting, together with rated current from the mains. The starting torque is then as indicated by point A in Fig.92.

As the speed rises, the torque would fall more or less linearly if the resistance remained constant, so to keep close to full-load torque the resistance is gradually reduced, either in steps, in which case the trajectory ABC etc. is followed (see Fig.92), or continuously so that maximum torque is obtained throughout. Ultimately the external resistance is made zero by shorting-out the sliprings, and thereafter the motor behaves like a low-resistance cage motor, with a high running efficiency.

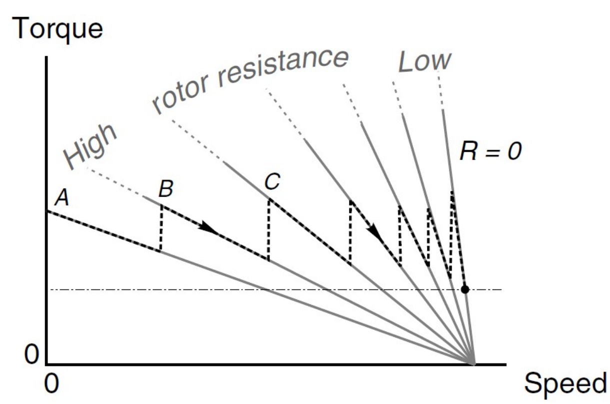


Fig.92: Torque–speed curves for a wound-rotor (slipring) motor showing how the external rotor-circuit resistance (R) can be varied in steps to provide an approximately constant torque during acceleration

As mentioned earlier, the total energy dissipated in the rotor circuit during run-up is equal to the final stored kinetic energy of the motor and load. In a cage motor this energy ends up in the rotor, and can cause overheating. In the slipring motor, however, most of the energy goes into the external resistance. This is a good thing from the motor point of view, but means that the external resistance has to absorb the thermal energy without overheating.

Fan-cooled grid resistors are often used, with tapings at various resistance values. These are progressively shorted-out during run-up, either by a manual or motor-driven drum-type controller, or with a series of timed contactors. Alternatively, where stepless variation of resistance is required, a liquid resistance controller is often employed.

It consists of a tank of electrolyte (typically caustic soda) into which three electrodes can be raised or lowered. The resistance between the electrodes depends on how far they are immersed in the liquid.

The electrolyte acts as an excellent short-term reservoir for the heat released, and by arranging for convection to take place via a cooling radiator, the equipment can also be used continuously for speed control (see later).

Attempts have been made to vary the effective rotor circuit resistance by means of a fixed external resistance and a set of series connected thyristors, but this approach has not gained wide acceptance.

4.3.4. Influence of Supply Voltage on Torque–Speed Curve

We established earlier that at any given slip, the air-gap flux density is proportional to the applied voltage, and the induced current in the rotor is proportional to the flux density. The torque, which depends on the product of the flux and the rotor current, therefore depends on the square of the applied voltage. This means that a comparatively modest fall in the voltage will result in a much larger reduction in torque capability, with adverse effects which may not be apparent to the unwary until too late.

To illustrate the problem, consider the torque–speed curves for a cage motor shown in Fig.93. The curves (which have been expanded to focus attention on the low-slip region) are drawn for full voltage (100%), and for a modestly reduced voltage of 90%. With full voltage and full load torque the motor will run at point X, with a slip of say 5%. Since this is the normal full-load condition, the rotor and stator currents will be at their rated values.

Now suppose that the voltage falls to 90%. The load torque is assumed to be constant so the new operating point will be at Y. Since the air-gap flux density is now only 0.9 of its rated value, the rotor current will have to be about 1.1 times rated value to develop the same torque, so the rotor e.m.f. is required to increase by 10%. But the flux density has fallen by 10%, so an increase in slip of 20% is called for. The new slip is therefore 6%.

The drop in speed from 95% of synchronous to 94% may well not be noticed, and the motor will apparently continue to operate quite happily.

But the rotor current is now 10% above its rated value, so the rotor heating will be 21% more than is allowable for continuous running.

The stator current will also be above rated value, so if the motor is allowed to run continuously, it will overheat. This is one reason why all large motors are fitted with protection, which is triggered by over temperature.

Many small and medium motors do not have such protection, so it is important to guard against the possibility of under voltage operation.

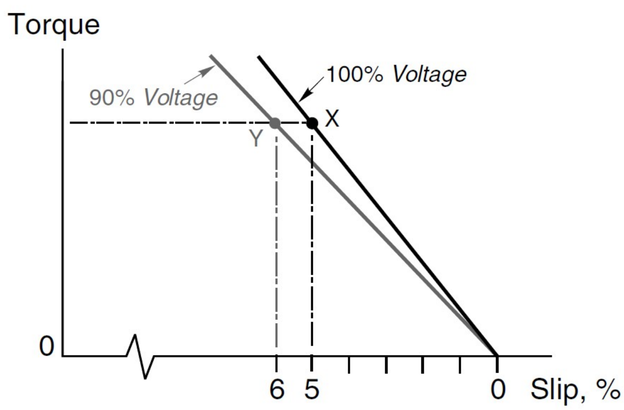


Fig.93: Influence of stator supply voltage on torque–speed curves

4.4. Generating and Braking

Having explored the torque–speed curve for the normal motoring region, where the speed lies between zero and just below synchronous, we must ask what happens if the speed is above the synchronous speed, or is negative.

A typical torque–speed curve for a cage motor covering the full range of speeds, which are likely to be encountered in practice, is shown in Fig.94. We can see that the decisive factor as far as the direction of the torque is concerned is the slip, rather than the speed.

When the slip is positive the torque is positive, and vice versa. The torque therefore always acts so as to urge the rotor to run at zero slip, i.e. at the synchronous speed. If the rotor is tempted to run faster than the field it will be slowed down, whilst if it is running below synchronous speed it will be urged to accelerate forwards. In particular, we note that for slips greater than 1, i.e. when the rotor is running backwards (i.e. in the opposite direction to the field), the torque will remain positive, so that if the rotor is unrestrained it will first slow down and then change direction and accelerate in the direction of the field.

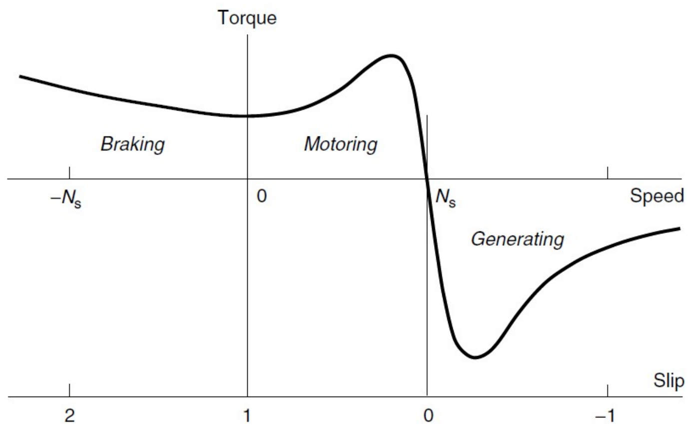


Fig.94: Torque–speed curve over motoring region (slip between 0 and 1), braking region (slip greater than 1) and generating region (negative slip)

4.4.1. Generating Region – Overhauling Loads

For negative slips, i.e. when the rotor is turning in the same direction, but at a higher speed than the travelling field, the 'motor' torque is in fact negative. In other words the machine develops a torque that which opposes the rotation, which can therefore only be maintained by applying a driving torque to the shaft. In this region the machine acts as an induction generator, converting mechanical power from the shaft into electrical power into the supply system. Many cage induction machines are used in this way in wind power generation schemes because their inherently robust construction leads to low maintenance.

It is worth stressing that, just as with the d.c. machine, we do not have to make any changes to an induction motor to turn it into an induction generator. All that is needed is a source of mechanical power to turn the rotor faster than the synchronous speed. On the other hand, we should be clear that the machine can only generate when it is connected to the supply.

If we disconnect an induction motor from the mains and try to make it generate simply by turning the rotor we will not get any output because there is nothing to set up the working flux: the flux (excitation) is not present until the motor is supplied with magnetizing current from the supply.

There are comparatively few applications in which mains-fed motors find themselves in the generating region, though as we will see later it is quite common in inverter-fed drives. We will, however, look at one example of a mains-fed motor in the so-called 'regenerative' mode to underline the value of the motor's inherent ability to switch from motoring to generating automatically, without the need for any external intervention.

Consider a cage motor driving a simple hoist through a reduction gearbox, and suppose that the hook (unloaded) is to be lowered.

Because of the static friction in the system, the hook will not descend on its own, even after the brake is lifted, so on pressing the 'down' button the brake is lifted and power is applied to the motor so that it rotates in the lowering direction. The motor quickly reaches full speed and the hook descends. As more and more rope winds off the drum, a point is reached where the lowering torque exerted by the hook and rope is greater than the running friction, and a restraining torque is then needed to prevent a runaway. The necessary stabilizing torque is automatically provided by the motor acting as a generator as soon as the synchronous speed is exceeded, as shown in Fig.94. The speed will therefore be held at just above the synchronous speed, provided of course that the peak generating torque (see Fig.94) is not exceeded.

4.4.2. Plug reversal and plug braking

Because the rotor always tries to catch up with the rotating field, it can be reversed rapidly simply by interchanging any two of the supply leads.

The changeover is usually obtained by having two separate 3-pole contactors, one for forward and one for reverse. This procedure is known as *plug reversal* or *plugging*, and is illustrated in Fig.95.

The motor is initially assumed to be running light (and therefore with a very small positive slip) as indicated by point A on the dotted torque–speed curve in Fig.95(a). Two of the supply leads are then reversed, thereby reversing the direction of the field, and bringing the mirror-image torque–speed curve shown by the solid line into play. The slip of the motor immediately after reversal is approximately 2, as shown by point B on the solid curve. The torque is thus negative, and the motor decelerates, the speed passing through zero at point C and then rising in the reverse direction before settling at point D, just below the synchronous speed.

The speed–time curve is shown in Fig.95(b). We can see that the deceleration (i.e. the gradient of the speed–time graph) reaches a maximum as the motor passes through the peak torque (pullout) point, but thereafter the final speed is approached gradually, as the torque tapers down to point D.

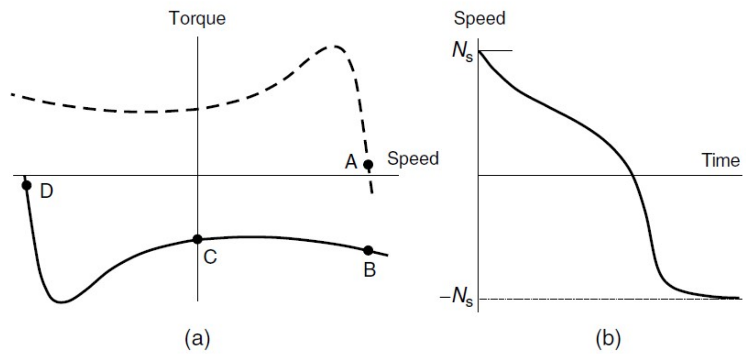


Fig.95: Torque–speed and speed–time curves for plug reversal of cage motor

Very rapid reversal is possible using plugging; for example a 1 kW motor will typically reverse from full speed in under 1 s. But large cage motors can only be plugged if the supply can withstand the very high currents involved, which are even larger than when starting from rest. Frequent plugging will also cause serious overheating, because each reversal involves the 'dumping' of four times the stored kinetic energy as heat in the windings.

Plugging can also be used to stop the rotor quickly, but obviously it is then necessary to disconnect the supply when the rotor comes to rest, otherwise it will run-up to speed in reverse. A shaft-mounted reverse rotation detector is therefore used to trip out the reverse contactor when the speed reaches zero.

We should note that, whereas, in the regenerative mode, the slip was negative, allowing mechanical energy from the load to be converted to electrical energy and fed back to the mains, plugging is a wholly dissipative process in which all the kinetic energy ends up as heat in the motor.

4.4.3. Injection Braking

This is the most widely used method of electrical braking. When the 'stop' button is pressed, the 3-phase supply is interrupted, and a d.c. current is fed into the stator via two of its terminals. The d.c. supply is usually obtained from a rectifier fed via a low-voltage high-current transformer.

We saw earlier that the speed of rotation of the air-gap field is directly proportional to the supply frequency, so it should be clear that since d.c. is effectively zero frequency, the air-gap field will be stationary. We also saw that the rotor always tries to run at the same speed as the field. So, if the field is stationary, and the rotor is not, a braking torque will be exerted. A typical torque–speed curve for braking a cage motor is shown in Fig.96, from which we see that the braking (negative) torque falls to zero as the rotor comes to rest.

This is in line with what we would expect, since there will be induced currents in the rotor (and hence torque) only when the rotor is 'cutting' the flux. As with plugging, injection (or dynamic) braking is a dissipative process, all the kinetic energy being turned into heat inside the motor.

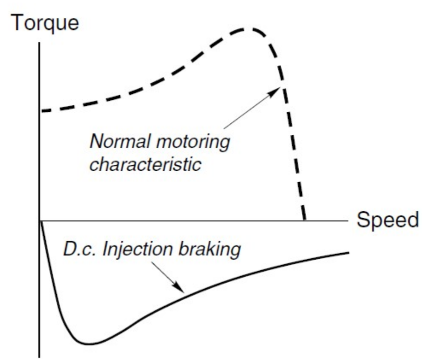


Fig.96: Torque–speed curve for d.c. injection braking of cage motor

4.5. Speed Control

We have seen that to operate efficiently an induction motor must run with a small slip. It follows that any efficient method of speed control must be based on varying the synchronous speed of the field, rather than the slip. The two factors that determine the speed of the field, are the supply frequency and the pole number.

The pole number has to be an even integer, so where continuously adjustable speeds control over a wide range is called for; the best approach is to provide a variable-frequency supply.

4.5.1. Variable-Frequency Speed Control

The best method of speed control must provide continuous smooth variation of the synchronous speed, which in turn calls for variation of the supply frequency. This is achieved using an inverter to supply the motor. The function of the converter is to draw power from the fixed-frequency constant-voltage mains, and convert it to variable frequency, variable voltage for driving the induction motor.

Variable frequency inverter-fed induction motor drives are used in ratings up to hundreds of kilowatts. Standard 50 Hz or 60 Hz motors are often used (though as we will see later this limits performance), and the inverter output frequency typically covers the range from around 5–10 Hz up to perhaps 400 Hz. This is sufficient to give a large speed range.

The majority of inverters are 3-phase input and 3-phase output, but single-phase input versions are available up to about 5 kW, and some very small inverters (usually less than 1 kW) are specifically intended for use with single-phase motors.

The majority of inverters used in motor drives are voltage source inverters (VSI), in which the output voltage to the motor is controlled to suit the operating conditions of the motor. Current source inverters (CSI) are used, particularly for large applications.

Three simple relationships need to be borne in mind to simplify understanding of how the inverter-fed induction motor behaves. Firstly, we established that for a given induction motor, the torque developed depends on the strength of the rotating flux density wave, and on the slip speed of the rotor, i.e. on the relative velocity of the rotor with respect to the flux wave. Secondly, the strength or amplitude of the flux wave depends directly on the supply voltage to the stator windings, and inversely on the supply frequency. And thirdly, the absolute speed of the flux wave depends directly on the supply frequency.

Recalling that the motor can only operate efficiently when the slip is small, we see that the basic method of speed control rests on the control of the speed of rotation of the flux wave (i.e. the synchronous speed), by control of the supply frequency. If the motor is a 4-pole one, for example, the synchronous speed will be 1500 rev/min when supplied at 50 Hz, 1200 rev/min at 40 Hz, 750 rev/min at 25 Hz and so on. The no-load speed will therefore be almost exactly proportional to the supply frequency, because the torque at no load is small and the corresponding slip is also very small.

Turning now to what happens on load, we know that when a load is applied the rotor slows down, the slip increases, more current is induced in the rotor, and more torque is produced. When the speed has reduced to the point where the motor torque equals the load torque, the speed becomes steady. We normally want the drop in speed with load to be as small as possible, not only to minimize the drop in speed with load, but also to maximize efficiency: in short, we want to minimize the slip for a given load.

The slip for a given torque depends on the amplitude of the rotating flux wave: the higher the flux, the smaller the slip needed for a given torque. It follows that having set the desired speed of rotation of the flux wave by controlling the output frequency of the inverter we must also ensure that the magnitude of the flux is adjusted so that it is at its full (rated) value, regardless of the speed of rotation. This is achieved by making the output voltage from the inverter vary in the appropriate way in relation to the frequency.

We recall that the amplitude of the flux wave is proportional to the supply voltage and inversely proportional to the frequency, so if we arrange that the voltage supplied by the inverter vary in direct proportion to the frequency, the flux wave will have constant amplitude. This philosophy is at the heart of most inverter-fed drive systems: there are variations, as we will see, but in the majority of cases the internal control of the inverter will be designed so that the output voltage to frequency ratio (V/f) is automatically kept constant, at least up to the 'base' (50 Hz or 60 Hz) frequency.

Many inverters are designed for direct connection to the mains supply, without a transformer, and as a result the maximum inverter output voltage is limited to a value similar to that of the mains. With a 415 V supply, for example, the maximum inverter output voltage will be perhaps 450 V. Since the inverter will normally be used to supply a standard induction motor designed for say 415 V, 50 Hz operation, it is obvious that when the inverter is set to deliver 50 Hz, the voltage should be 415 V, which is within the inverter's voltage range. But when the frequency was raised to say 100 Hz, the voltage should – ideally – be increased to 830 V in order to obtain full flux. The inverter cannot supply voltages above 450 V, and it follows that in this case full flux can only be maintained up to speeds a little above base speed. (It should be noted that even if the inverter could provide higher voltages, they could not be applied to a standard motor because the winding insulation will have been designed to withstand not more than the rated voltage.)

Established practice is for the inverter to be capable of maintaining the V/f ratio constant up to the base speed (50 Hz or 60 Hz), but to accept that at all higher frequencies the voltage will be constant at its maximum value. This means that the flux is maintained constant at speeds up to base speed, but beyond that the flux reduces inversely with frequency. Needless to say the performance above base speed is adversely affected, as we will see.

Users are sometimes alarmed to discover that both voltage and frequency change when a new speed is demanded. Particular concern is expressed when the voltage is seen to reduce when a lower speed is called for. Surely, it is argued, it can't be right to operate say a 400 V induction motor at anything less than 400 V. The fallacy in this view should now be apparent: the figure of 400 V is simply the correct voltage for the motor when run directly from the mains, at say 50 Hz. If this full voltage was applied when the frequency was reduced to say 25 Hz, the implication would be that the flux would have to rise to twice its rated value.

This would greatly overload the magnetic circuit of the machine, giving rise to excessive saturation of the iron, an enormous magnetizing current and wholly unacceptable iron and copper losses. To prevent this from happening, and keep the flux at its rated value, it is essential to reduce the voltage in proportion to frequency. In the case above, for example, the correct voltage at 25 Hz would be 200 V.

Torque–speed characteristics – constant V/f operation

When the voltage at each frequency is adjusted so that the ratio V/f is kept constant up to base speed, and full voltage is applied thereafter, a family of torque–speed curves as shown in Fig.97 is obtained. These curves are typical for a standard induction motor of several kW output.

As expected, the no-load speeds are directly proportional to the frequency, and if the frequency is held constant, e.g. at 25 Hz, the speed drops only modestly from no-load (point a) to full-load (point b). These are therefore good open-loop characteristics, because the speed is held fairly well from no-load to full-load. If the application calls for the speed to be held precisely, this can clearly be achieved (with the aid of closed-loop speed control) by raising the frequency so that the full-load operating point moves to point (c).

We also note that the pull-out torque and the torque stiffness (i.e. the slope of the torque–speed curve in the normal operating region) is more or less the same at all points below base speed, except at low frequencies where the effect of stator resistance in reducing the flux becomes very pronounced.

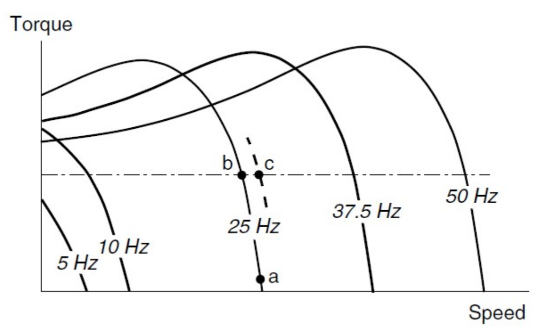


Fig.97: Torque–speed curves for inverter-fed induction motor with constant voltage–frequency ratio

It is clear from Fig.97 that the starting torque at the minimum frequency is much less than the pullout torque at higher frequencies, and this could be a problem for loads which require a high starting torque.

The low-frequency performance can be improved by increasing the V/f ratio at low frequencies in order to restore full flux, a technique which is referred to as ‘low-speed voltage boosting’. Most drives incorporate provision for some form of voltage boost, either by way of a single adjustment to allow the user to set the desired starting torque, or by means of more complex provision for varying the V/f ratio over a range of frequencies. A typical set of torque–speed curves for a drive with the improved low-speed torque characteristics obtained with voltage boost is shown in Fig.98.

The curves in Fig.98 have an obvious appeal because they indicate that the motor is capable of producing practically the same maximum torque at all speeds from zero up to the base (50 Hz or 60 Hz) speed.

This region of the characteristics is known as the ‘constant torque’ region, which means that for frequencies up to base speed, the maximum possible torque which the motor can deliver is independent of the set speed. Continuous operation at peak torque will not be allowable because the motor will overheat, so an upper limit will be imposed by the controller, as discussed shortly. With this imposed limit, operation below base speed corresponds to the armature-voltage control region of a d.c. drive.

We should note that the availability of high torque at low speeds (especially at zero speed) means that we can avoid all the ‘starting’ problems associated with fixed-frequency operation.

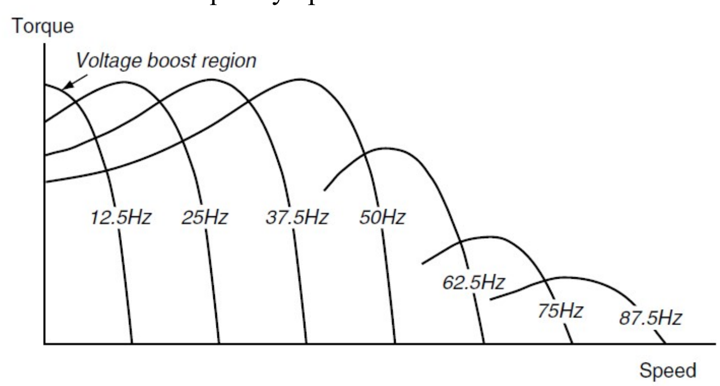


Fig.98: Typical torque–speed curves for inverter-fed induction motor with low-speed voltage boost, constant voltage–frequency ratio from low speed up to base speed, and constant voltage above base speed

By starting off with a low frequency which is then gradually raised the slip speed of the rotor is always small, i.e. the rotor operates in the optimum condition for torque production all the time, thereby avoiding all the disadvantages of high-slip (low torque and high current) that are associated with mains-frequency starting. This means that not only can the inverter-fed motor provide rated torque at low speeds, but – perhaps more importantly – it does so without drawing any more current from the mains than under full-load conditions, which means that we can safely operate from a weak supply without causing excessive voltage dips. For some essentially fixed-speed applications, the superior starting ability of the inverter-fed system alone may justify its cost.

Beyond the base frequency, the V/f ratio reduces because V remains constant. The amplitude of the flux wave therefore reduces inversely with the frequency. The pull-out torque always occurs at the same absolute value of slip speed, and that the peak torque is proportional to the square of the flux density. Hence in the constant voltage region the peak torque reduces inversely with the square of the frequency and the torque–speed curve becomes less steep, as shown in Fig.98. Although the curves in Fig.98 show what torque the motor can produce for each frequency and speed, they give no indication of whether continuous operation is possible at each point, yet this matter is of course extremely important from the user's viewpoint.

Limitations imposed by the inverter – constant power and constant torque regions

The main concern in the inverter is to limit the currents to a safe value as far as the main switching devices are concerned. The current limit will be at least equal to the rated current of the motor, and the inverter control circuits will be arranged so that no matter what the user does the output current cannot exceed a safe value.

The current limit feature imposes an upper limit on the permissible torque in the region below base speed. This will normally correspond to the rated torque of the motor, which is typically about half the pull-out torque, as indicated by the shaded region in Fig.99.

In the region below base speed, the motor can therefore develop any torque up to rated value at any speed (but not necessarily for prolonged periods, as discussed below). This region is therefore known as the 'constant torque' region, and it corresponds to the armature voltage control region of a d.c. drive.

Above base speed of the flux is reduced inversely with the frequency; because the stator (and therefore rotor) currents are limited, the maximum permissible torque also reduces inversely with the speed, as shown in Fig.99. This region is therefore known as the ‘constant power’ region. There is of course a close parallel with the d.c. drive here, both systems operating with reduced or weak Weld in the constant power region. The region of constant power normally extends to somewhere around twice base speed, and because the flux is reduced the motor has to operate with higher slips than below base speed to develop the full rotor current and torque.

At the upper limit of the constant power region, the current limit coincides with the pull-out torque limit. Operation at still higher speeds is sometimes provided, but constant power is no longer available because the maximum torque is limited to the pull-out value, which reduces inversely with the square of the frequency. In this high-speed motoring region (Fig.99), the limiting torque–speed relationship is similar to that of a series d.c. motor.

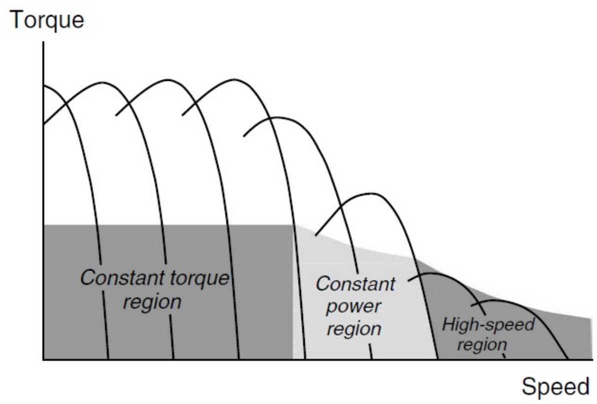


Fig.99: Constant torque, constant power and high-speed motoring regions

4.5.2. Pole-changing motors

For some applications continuous speed control may be an unnecessary luxury, and it may be sufficient to be able to run at two discrete speeds.

Among many instances where this can be acceptable and economic are pumps, lifts and hoists, fans and some machine tool drives.

We established that the pole number of the field was determined by the layout and interconnection of the stator coils, and that once the winding has been designed, and the frequency specified, the synchronous speed of the field is fixed. If we wanted to make a motor, that could run at either of two different speeds, we could construct it with two separate stator windings (say 4-pole and 6-pole), and energize the appropriate one. There is no need to change the cage rotor since the pattern of induced currents can readily adapt to suit the stator pole number. Early 2-speed motors did have 2 distinct stator windings, but were bulky and inefficient. It was soon realized that if half of the phase belts within each phase winding could be reversed in polarity, the effective pole number could be halved. For example, a 4-pole MMF pattern (N-S-N-S) would become (N-N-S-S), i.e. effectively a 2-pole pattern with one large N pole and one large S pole. By bringing out six leads instead of three, and providing switching contactors to effect the reversal, two discrete speeds in the ratio 2:1 are therefore possible from a single winding. The performance at the high (e.g. 2-pole) speed is relatively poor, which is not surprising in view of the fact that the winding was originally optimized for 4-pole operation.

It was not until the advent of the more sophisticated pole amplitude modulation (PAM) method in the 1960s that 2-speed single-winding high-performance motors with more or less any ratio of speeds became available from manufacturers. This subtle technique allows close ratios such as 4/6, 6/8, 8/10 or wide ratios such as 2/24 to be achieved. Close ratios are used in pumps and fans, while wide ratios are used for example in washing machines where a fast spin is called for.

The beauty of the PAM method is that it is not expensive. The stator winding has more leads brought out, and the coils are connected to form non-uniform phase belts, but otherwise construction is the same as for a single-speed motor. Typically six leads will be needed, three of which are supplied for one speed, and three for the other, the switching being done by contactors. The method of connection (star or delta) and the number of parallel paths within the winding are arranged so that the air-gap flux at each speed matches the load requirement. For example, if constant torque is needed at both speeds, the flux needs to be made the same, whereas if reduced torque is acceptable at the higher speed the flux can obviously be lower.

4.5.3. Voltage control of high-resistance cage motors

Where efficiency is not of paramount importance, the torque (and hence the running speed) of a cage motor can be controlled simply by altering the supply voltage. The torque at any slip is approximately proportional to the square of the voltage, so we can reduce the speed of the load by reducing the voltage. The method is not suitable for standard low-resistance cage motors, because their stable operating speed range is very restricted, as shown in Fig.100(a). But if special high-rotor resistance motors are used, the slope of the torque–speed curve in the stable region is much less, and a rather wider range of steady-state operating speeds is available, as shown in Fig.100(b).

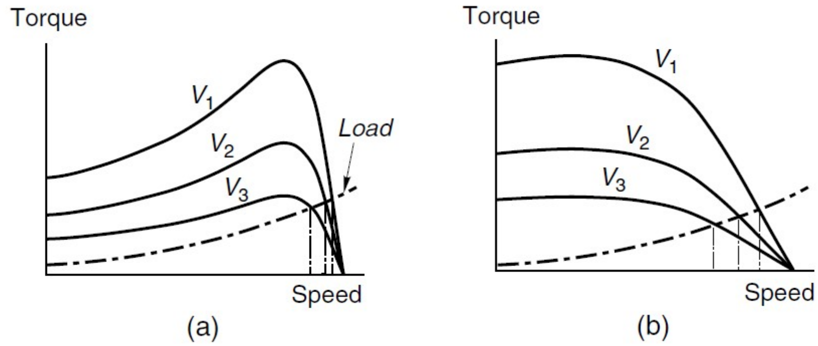


Fig.100: Speed control of cage motor by stator voltage variation; (a) low-resistance rotor, (b) high-resistance rotor

The most unattractive feature of this method is the low efficiency, which is inherent in any form of slip control. We recall that the rotor efficiency at slip s is (1 - s), so if we run at say 70% of synchronous speed (i.e. s = 0:3), 30% of the power crossing the air-gap is wasted as heat in the rotor conductors. The approach is therefore only practicable where the load torque is low at low speeds, so that at high slips the heat in the rotor is tolerable. A fan-type characteristic is suitable, as shown in Fig.100(b), and many ventilating systems therefore use voltage control.

Voltage control became feasible only when relatively cheap thyristor a.c. voltage regulators arrived on the scene during the 1970s. Previously the cost of autotransformers or induction regulators to obtain the variable voltage supply was simply too high. The thyristor hardware required is essentially the same as discussed earlier for soft starting, and a single piece of kit can therefore serve for both starting and speed control.

Where accurate speed control is needed, a tachogenerator must be fitted to the motor to provide a speed feedback signal, and this naturally increases the cost significantly.

Applications are numerous, mainly in the range 0.5–10 kW, with most motor manufacturers offering high-resistance motors specifically for use with thyristor regulators.

4.5.4. Speed control of wound-rotor motors

The fact that the rotor resistance can be varied easily allows us to control the slip from the rotor side, with the stator supply voltage and frequency constant. Although the method is inherently inefficient it is still used in many medium and large drives such as hoists, conveyors and crushers because of its simplicity and comparatively low cost.

A set of torque–speed characteristics is shown in Fig.101, from which it should be clear that by appropriate selection of the rotor circuit resistance, any torque up to typically 1.5 times full-load torque can be achieved at any speed.

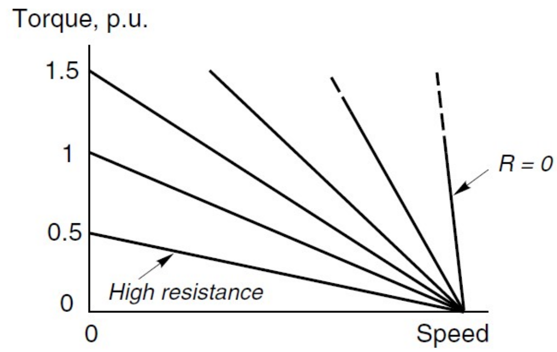


Fig.101: Influence of external rotor resistance (R) on torque–speed curve of wound-rotor motor

4.6. Single-Phase Induction Motors

Single-phase induction motors are simple, robust and reliable, and are used in enormous numbers especially in domestic and commercial applications where 3-phase supplies are not available. Although outputs of up to a few kW are possible, the majority are below 0.5 kW, and are used in applications such as refrigeration compressors, washing machines and dryers, pumps and fans, small machine tools, tape decks, printing machines, etc.

4.6.1. Principle of operation

If one of the leads of a 3-phase motor is disconnected while it is running light, it will continue to run with a barely perceptible drop in speed, and a somewhat louder hum. With only two leads remaining there can only be one current, so the motor must be operating as a single-phase machine. If load is applied the slip increases more quickly than under 3-phase operation, and the stall torque is much less, perhaps one third.

When the motor stalls and comes to rest it will not restart if the load is removed, but remains at rest drawing a heavy current and emitting an angry hum. It will burn out if not disconnected rapidly.

It is not surprising that a truly single-phase cage induction motor will not start from rest, because as we saw before the single winding, fed with a.c., simply produces a pulsating flux in the air-gap, without any suggestion of rotation. It is, however, surprising to find that if the motor is given a push in either direction it will pick up speed, slowly at first but then with more vigor, until it settles with a small slip, ready to take-up load. Once turning, a rotating field is evidently brought into play to continue propelling the rotor.

We can understand how this comes about by first picturing the pulsating MMF set up by the current in the stator winding as being the resultant of two identical travelling waves of MMF, one in the forward direction and the other in reverse. (This equivalence is not self-evident but is easily proved; the phenomenon is often discussed in physics textbooks under the heading of standing waves.) When the rotor is stationary, it reacts equally to both travelling waves, and no torque is developed. When the rotor is turning, however, the induced rotor currents are such that their MMF opposes the reverse stator MMF to a greater extent than they oppose the forward stator MMF. The result is that the forward flux wave (which is what develops the forward torque) is bigger than the reverse flux wave (which exerts a drag). The difference widens as the speed increases, the forward flux wave becoming progressively bigger as the speed rises while the reverse flux wave simultaneously reduces. This ‘positive feedback’ effect explains why the speed builds slowly at first, but later zooms up to just below synchronous speed. At the normal running speed (i.e. small slip), the forward flux is many times larger than the backward flux, and the drag torque is only a small percentage of the forward torque.

As far as normal running is concerned, a single winding is therefore sufficient. But all motors must be able to self-start, so some mechanism has to be provided to produce a rotating field even when the rotor is at rest.

Several methods are employed, all of them using an additional winding.

The second winding usually has less copper than the main winding, and is located in the slots which are not occupied by the main winding, so that its MMF is displaced in space relative to that of the main winding. The current in the second winding is supplied from the same single-phase source as the main winding current, but is caused to have a phase-lag, by various means which are discussed later. The combination of a space displacement between the two windings together with a time displacement between the currents produces a 2-phase machine. If the two windings were identical, displaced by 90°, and fed with currents with 90° phase-shift, an ideal rotating field would be produced. In practice we can never achieve a 90° phase-shift between the currents, and it turns out to be more economic not to make the windings identical. Nevertheless, a decent rotating field is set up, and entirely satisfactory starting torque can be obtained. Reversal is simply a matter of reversing the polarity of one of the windings, and performance is identical in both directions.

The most widely used methods are described below. At one time it was common practice for the second or auxiliary winding to be energized only during start and run-up, and for it to be disconnected by means of a centrifugal switch mounted on the rotor, or sometimes by a time switch. This practice gave rise to the term 'starting winding'. Nowadays it is more common to find both windings in use all the time.

4.6.2. Capacitor-run motors

A capacitor is used in series with the auxiliary winding (see Fig.102) to provide a phase-shift between the main and auxiliary winding currents. The capacitor (usually of a few μF, and with a voltage rating which may well be higher than the mains voltage) may be mounted piggyback fashion on the motor, or located elsewhere. Its value represents a compromise between the conflicting requirements of high starting torque and good running performance.

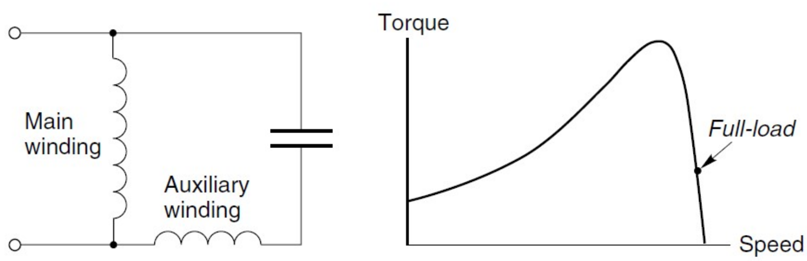


Fig.102: Single-phase capacitor-run induction motor

A typical torque–speed curve is also shown in Fig.102; the modest starting torque indicates that the capacitor-run motors are generally best suited to fan-type loads. Where higher starting torque is needed, two capacitors can be used, one being switched out when the motor is up to speed.

As mentioned above, the practice of switching out the starting winding altogether is no longer favored for new machines, but many old ones remain, and where a capacitor is used they are known as 'capacitor start' motors.

4.6.3. Split-phase motors

The main winding is of thick wire, with a low resistance and high reactance; while the auxiliary winding is made of fewer turns of thinner wire with a higher resistance and lower reactance (see Fig.103). The inherent difference in impedance is sufficient to give the required phase-shift between the two currents without needing any external elements in series. Starting torque is good at typically 1.5 times full-load torque, as also shown in Fig.103. As with the capacitor type, reversal is accomplished by changing the connections to one of the windings.

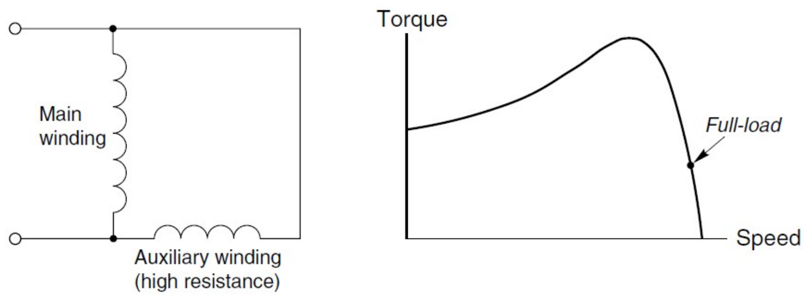


Fig.103: Single-phase split-phase induction motor

4.6.4. Shaded-pole motors

There are several variants of this extremely simple, robust and reliable cage motor, which predominate for low-power applications such as hairdryers, oven fans, tape decks, office equipment, display drives, etc. A 2-pole version from the cheap end of the market is shown in Fig.104.

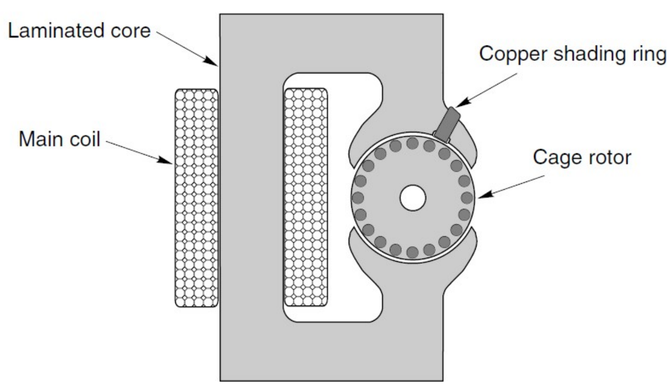


Fig.104: Shaded-pole induction motor

The rotor, typically between 1 and 4 cm diameter, has a die-cast aluminum cage, while the stator winding is a simple concentrated coil wound round the laminated core. The stator pole is slotted to receive the ‘shading ring’, which is a single short-circuited turn of thick copper or aluminum.

Most of the pulsating flux produced by the stator winding bypasses the shading ring and crosses the air-gap to the rotor. But some of the flux passes through the shading ring, and because it is alternating it induces an e.m.f. and current in the ring. The opposing MMF of the ring current diminishes and retards the phase of the flux through the ring, so that the flux through the ring reaches a peak after the main flux, thereby giving what amounts to a rotation of the flux across the face of the pole.

This far from perfect travelling wave of flux produces the motor torque by interaction with the rotor cage. Efficiencies are low because of the rather poor magnetic circuit and the losses caused by the induced currents in the shading ring, but this is generally acceptable when the aim is to minimize first cost. Series resistance can be used to obtain a crude speed control, but this is only suitable for fan-type loads. The direction of rotation depends on whether the shading ring is located on the right or left side of the pole, so shaded pole motors are only suitable for unidirectional loads.