

1.1 Introduction

The law of conservation of energy states that the energy can neither be created nor be destroyed but it can be converted from one form to other. An electrical energy does not occur naturally and also cannot be stored. Still, it is the most popular form of Energy, since it can be transported at remote Load-locations for optimum utilization of resources. Hence the efforts are made to generate it continuously to meet the large demands. But to generate an electrical energy means to convert some other form of energy into an electrical form, according to law of conservation of energy.

Converters that are used to continuously translate electrical input to mechanical output or vice versa are called electric machines. The process of translation is known as electromechanical energy conversion. An electric machine is therefore a link between an electrical system and a mechanical system. In these machines the conversion is reversible. If the conversion is from mechanical to electrical energy, the machine is said to act as a **generator**. If the conversion is from electrical to mechanical energy, the machine is said to act as a **motor**.

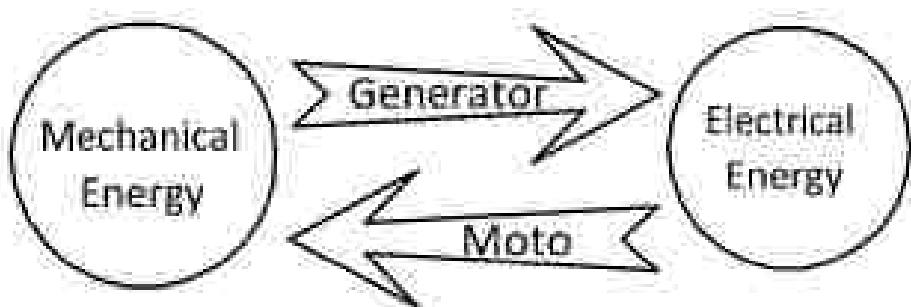


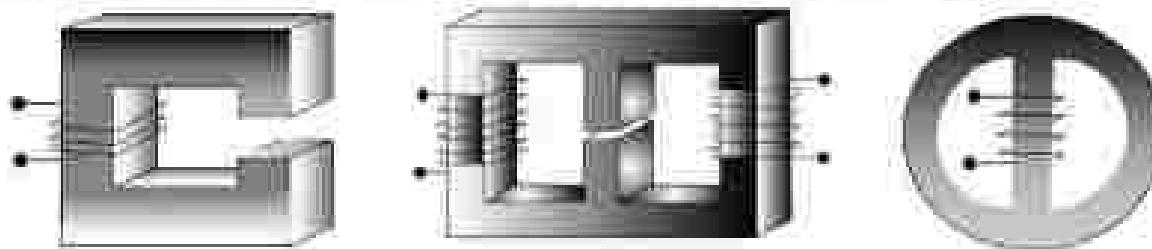
Fig. 1.1 The Energy directions in generator and motor actions.

1.2 Magnetic Circuits

In this lesson, we shall acquaint with the basic concepts of magnetic circuit and methods of solving n. Biot-Savart law for calculating magnetic field due to a known current distribution although fundamental and general in nature.

In a magnetic circuit, the magnetic lines of force leaves the north pole passes through the entire circuit and return the starting point. A magnetic circuit usually consists of materials having high permeability such as iron, soft steel etc. These materials offer very small opposition to the flow of magnetic flux.

Before really starting, let us look at some magnetic circuits shown in the following figures.



The above figures have a magnetic material of regular geometric shape called core. A coil having a number of turns (= N) of conducting material (say copper) are wound over the core. This coil is called the **exciting coil**. When no current flows through the coil, we don't expect any magnetic field or lines of forces to be present inside the core. However in presence of current in the coil, magnetic flux ϕ will be produced within the core. The strength of the flux depends on the product of number of turns (N) of the coil and the current it carries. The quantity 'NI' called **mf** (magneto-motive force) can be thought as the cause in order to produce an effect in the form of flux ϕ within the core. It is somewhat similar to an electrical circuit problem where a voltage (emf) is applied (cause) and a current is produced (effect) in the circuit. Hence the term **magnetic circuit** is used in relation to producing flux in the core by applying **mf** (= NI).

At this point it may just note that a magnetic circuit may be as simple as shown in figure 1.1 with a single core and a single coil or as complex as having different core materials, air gap and multiple exciting coils as in figure 1.2.

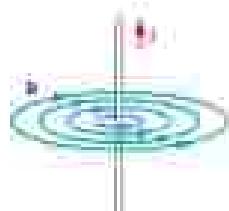
1.3 Definitions and laws for calculating magnetic field

Magnetic fields are the fundamental mechanism by which energy is converted from one form to another in motors, generators and transformers.

We know that any **current carrying conductor produces a magnetic field**. A magnetic field is characterised either by, the **magnetic field intensity** (\vec{H}) or by, the **magnetic flux density** (\vec{B}) vector.

These two vectors are connected by a rather simple relation: $\vec{B} = \mu_0 \mu_r \vec{H}$

Where $\mu_0 = 4\pi \times 10^{-7} \text{ Vs/A}$ is called the absolute permeability of free space and μ_r , a dimensionless quantity called the relative permeability of a medium (or a material). For example the value of μ_r is 1 for free space or could be several thousands in case of ferrimagnetic materials.



The quantity of the magnetic field is proportion to the current. The direction of the magnetic field is found by right hand rule or Maxwell's corkscrew rule.

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.

Magnetic field strength (H): This is also known as field intensity, magnetic intensity or magnetic field, and is represented by the letter H. Its unit is ampere turns per meter.

$$H = \frac{Ni}{l}$$

Flux density (B): The total number of lines of force per square meter of the cross-sectional area of the magnetic core is called flux density, and is represented by the symbol B. Its SI unit is tesla (weber per meter square).

$$\vec{B} = \mu_0 \mu_r \vec{H}$$

The flux density B of a sample is a nonlinear function of H, given by the **magnetisation curve**. Worse than this, the flux density depends on what has happened in the past, as well as to the current value of H.

Magneto-Motive Force (MMF): The amount of flux density setup in the core is dependent upon five factors - the current, number of turns, material of the magnetic core, length of core and the cross-sectional area of the core. More current and the more turns of wire we use, the greater will be the magnetizing effect. We call this product of the turns and current the magneto-motive force (mmf), similar to the electromotive force (emf).

$$MMF = NI \text{ ampere-turns}$$

Magnetic flux (ϕ): Flux is another manifestation of the magnetic field, defined by its ability to induce an electric field when it changes. The Magnetic Lines of Force produced by a magnet is called magnetic flux. It is denoted by ϕ and its unit is *Weber*.

$$\mathcal{Q} = BA$$

$$\begin{aligned} &= \mu_0 \mu_r H A \\ &= \mu_0 \mu_r \left(\frac{NI}{l} \right) A \\ &= \frac{NI}{\frac{l}{\mu_0 \mu_r A}} \\ \mathcal{Q} &= \frac{NI}{R} = \frac{\text{emf}}{\text{Reluctance}} = \frac{NI}{\frac{l}{\mu_0 \mu_r A}} \end{aligned}$$

Magnetic Reluctance (R):

The obstruction offered by a magnetic circuit to the magnetic flux is known as **reluctance**. Magnetic reluctance, or magnetic resistance, is a measurement used in the analysis of magnetic circuits. It is like resistance in an electrical circuit, but rather than dissipating magnetic energy it stores magnetic energy. As 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. It is a scalar, extensive quantity, like electrical resistance.

$$Rel. S = \frac{1}{\mu_0 \mu_r A}$$

The conductivity of a conductor is practically constant, independent of the current. The permeability of iron is by no means constant so as the Reluctance.

Permeance: The inverse of electrical resistance is conductance which is a measure of conductivity of a material. Hence the inverse of reluctance is known as **permance**, P where μ represents the degree at which the material permits the flow of magnetic flux.

$$P = \frac{1}{R} \quad P = \frac{\mu A}{l}$$

Residual Magnetism: It is the magnetism which remains in a material when the effective magnetizing force has been reduced to zero.

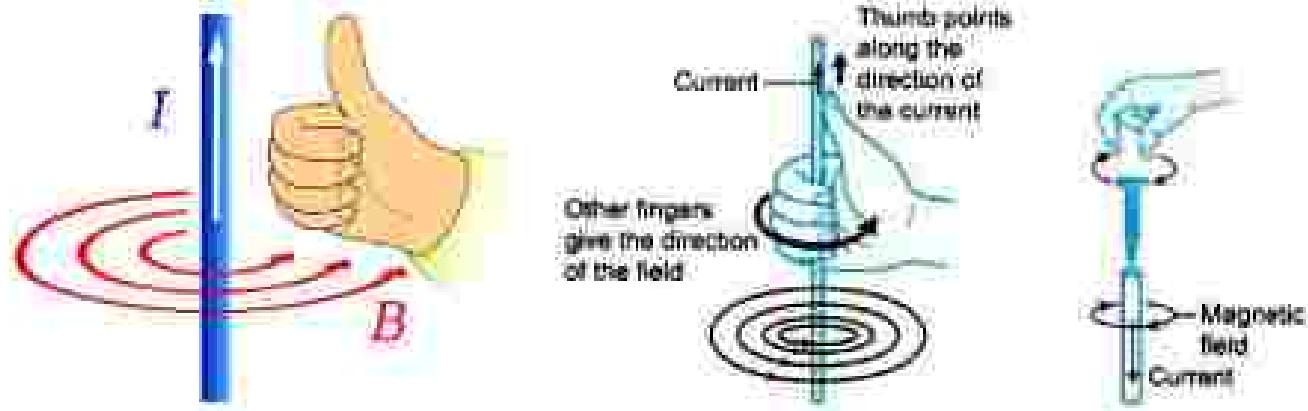
Magnetic Saturation: The limit beyond which the strength of a magnet cannot be increased is called magnetic saturation.

1.4 Basic principles:

Electric machines can be broadly classified into electrostatic machines and electromagnetic machines. The electrostatic principles do not yield practical machines for commercial electric power generation. The present day machines are based on the electromagnetic principles. Though one sees a variety of electrical machines in the market, the basic underlying principles of all these are the same. To understand, design and use these machines the following laws must be studied.

Maxwell's Cotescrew rule/ Right Hand Thumb Rule:

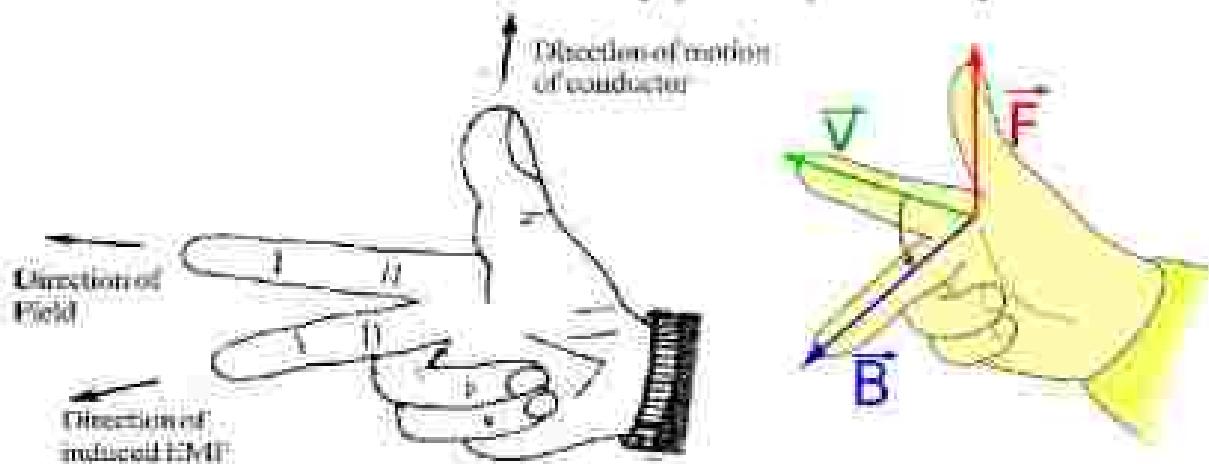
This rule is used to find the direction of field produced by a conductor or coil. According to this rule "If we hold a current carrying conductor such that thumb representing the direction of current flow, then rotation of rest of the fingers represent the direction of flux.", or "If rotation of rest of the fingers represent the current in a coil, then the thumb will represent the direction of flux."



Fleming's Right-Hand Rule:

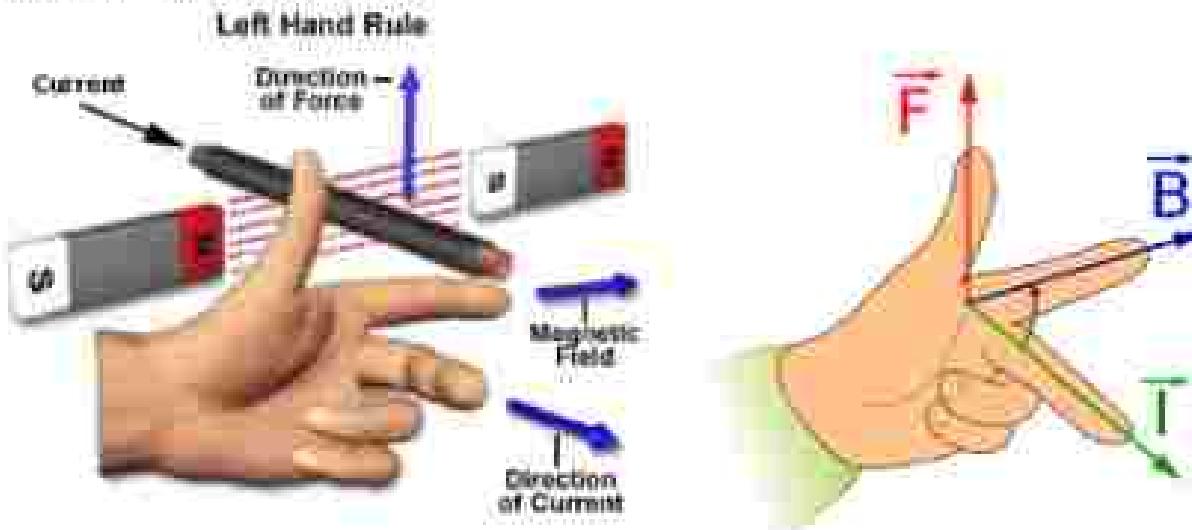
"Hold out your right hand with forefinger, second finger, and thumb at right angles to one another. If the forefinger represents the direction of the field, and the thumb represents the direction of the motion then, the second finger represents the direction of the induced emf in the coil".

- This rule is used to find out the *direction of dynamically induced emf*.



Fleming's Left Hand Rule:

"Hold out your left hand with forefinger, second finger and thumb at right angles to one another. If the forefinger represents the direction of the field, and the second finger that of the current, then thumb gives the direction of the motion or force."



Faraday's Laws of Electro Magnetic Induction:

Faraday proposed this law of Induction in 1831. It states that "If the magnetic flux lines linking a coil changes, then an emf is induced in the coil. This emf is proportional to the rate of change of these flux linkages". This can be expressed mathematically,

$$\epsilon = -\frac{d\psi}{dt} = -N \frac{d\phi}{dt}$$

Where $\psi = N\phi$ \pm flux linkage, N =No. of turns in the coil, ϕ =flux lines linking all these turns (in weber).

The direction of the induced emf can be determined by the application of Lenz's law.

Note the negative sign at the equation above which is in accordance to Lenz' Law which states:

Lenz's Law:

It states that "the direction of the induced emf is such as to produce an effect to oppose this change in flux linkages" i.e. if the coils were short circuited, it would produce current that would cause a flux opposing the original flux change. It is analogous to the inertia in the mechanical systems.

Biot-Savart law (Law of electromagnetic interaction)

Biot-Savart law is of fundamental in nature and tells us how to calculate $d\vec{B}$ or $d\vec{H}$ at a given point with position vector , due to an elemental current and is given by,

$$d\vec{B} = \frac{\mu_0 \mu_r}{4\pi} \frac{Id\vec{l} \times \vec{r}}{r^3}$$

If the shape and dimensions of the conductor carrying current is known then field at given point can be calculated by integrating the RHS of the above equation.

$$\vec{B} = \frac{\mu_0 I}{4\pi} \int_{\text{length}} \frac{d\vec{l} \times \hat{r}}{r^3}$$

where, length indicates that the integration is to be carried out over the length of the conductor. However, it is often not easy to evaluate the integral for calculating field at any point due to any arbitrary shaped conductor. One gets a nice closed form solution for few cases such as:

1. Straight conductor carries current and to calculate field at a distance d from the conductor.
2. Circular coil carries current and to calculate field at a point situated on the axis of the coil.

Ampere's circuital law:

The relation between the magnetic field and the electric current can be most compactly expressed by Ampere's Law, which states that line integral of the magnetic field (\vec{H}) along any arbitrary closed path is equal to the current enclosed by the path. Mathematically,

$$\oint \vec{H} \cdot d\vec{l} = I$$

The value of this line integral is called the *magnetic motive force*, or mmf around the curve.

For certain problems particularly in magnetic circuit problems Ampere's circuital law is used to calculate field instead of the more fundamental Biot-Savart law.

Consider an infinite straight conductor carrying current i and we want to calculate field at a point situated at a distance d from the conductor. Now take the closed path to be a circle of radius d . At any point on the circle the magnitude of field strength will be constant and direction of the field will be tangential.

Thus LHS of the above equation simply becomes $H \times 2\pi d$. So field strength is $H = \frac{i}{2\pi d} A/m$.

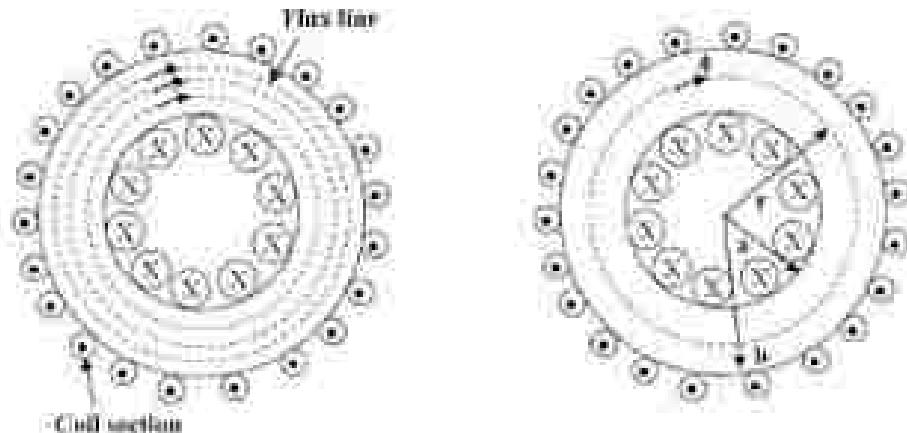
It should be noted that in arriving at the final result no integration is required and it is obtained rather quickly. However, one has to choose a suitable path looking at the distribution of the current and arguing that the magnitude of the field remains constant throughout the path before applying the law with advantage.

Application of Ampere's circuital law in magnetic circuit

Ampere's circuital law is quite handy in determining field strength within a core of a magnetic material. Due to application of mmf, the many dipole magnets of the core are aligned one after the other in a somewhat disciplined manner. The contour of the lines of force resembles the shape the material. The situation is somewhat similar to flow of water through an arbitrary shaped pipe. Flow path is constrained to be the shape of the bent pipe. For an example, look at the sectional view of a toroidal magnetic circuit with N number of turns wound uniformly as shown below. When the coil carries a current i , magnetic lines of forces will be created and they will be confined within the core as the permeability of the core is many (order of thousands) times more than air.

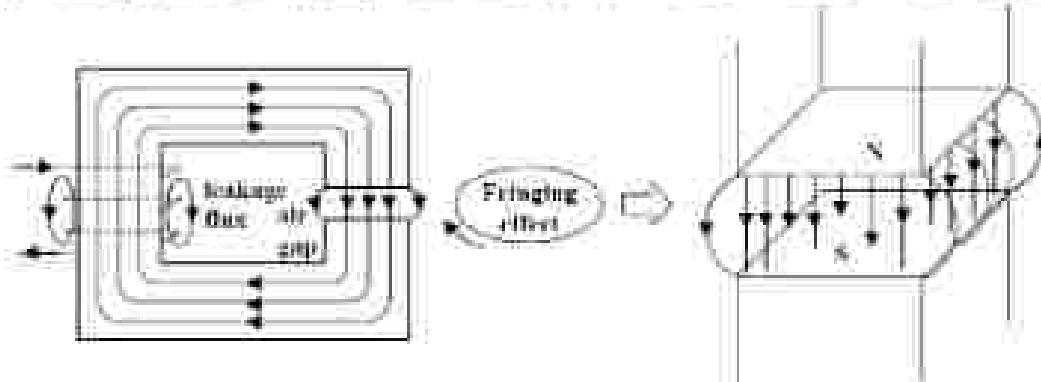
Take the chosen path to be a circle of radius r . Note that the value of ii will remain same at any point on this path and directions will be always tangential to the path. Hence by applying Ampere's circuital law to

the path we get the value of H to be $\frac{NI}{2\pi r}$. If r is increased from a to be b the value of H decreases with r . a and b are respectively the inner and outer radius of the toroidal core.



1.4.1 Assumptions

- Leakage flux & fringing effect: Strictly speaking all the flux produced by the coils will not be confined to the core. There will be some flux lines which will complete their paths largely through the air. Since the reluctance (discussed in the following section) of air is much higher compared to the reluctance offered by the core, the leakage flux produced is rather small. In our discussion here, we shall neglect leakage flux and assume all the flux produced will be confined to the core only.



In the magnetic circuit of figure as shown above has an air gap. For an exciting current, the flux lines produced are shown. These flux lines cross the air gap from the top surface of the core to the bottom surface of the core. So the upper surface behaves like a north pole and the bottom surface like a south pole. Thus all the flux lines will not be vertical and confined to the core face area alone. Some lines of force in fact will reach the bottom surface via bulged out curved paths outside the face area of the core. These flux which follow these curved paths are called fringing flux and the phenomenon is called fringing effect. Obviously the effect of fringing will be smaller if the air gap is quite small. Effect of fringing will be appreciable if the air gap length is more. In short the effect of fringing is to make flux density in the air gap a bit less than in the core as in the air same amount of flux is spread over an area which is greater than the core sectional area. Unless otherwise specified, we shall neglect the fringing effect in our following discussions. Effect of fringing sometimes taken into account by considering the effective area in air to be about 10 to 12% higher than the core area.

2. In the practical magnetic circuit, the thickness (α , over which the lines of forces are spread = $b - a$) are much smaller compared to the overall dimensions (a or b) of the core. Under this condition, we shall not make great mistake if we calculate H at $r_m = \frac{(b-a)}{2}$ and take this to be H everywhere within the core. The length of the flux path corresponding to the mean radius i.e., $l_m = 2\pi r_m$ is called the mean length. This assumption allows us

- Calculate the mean length l_m of the flux path from the given geometry of the magnetic circuit.
- Apply Ampere's circuital law to calculate $H = \frac{NI}{l_m}$
- Note, this H may be assumed to be same everywhere in the core.
- Calculate the magnitude of the flux density B from the relation $B = \mu_0 H M$
- Total flux within the core is $\phi = BA$, where A is the cross sectional area of the core.

1.4.2 Magnetic Material

Magnetic materials are classified based on the property called permeability as

1. Dia Magnetic Materials
2. Para Magnetic Materials
3. Ferro Magnetic Materials

1. Dia-Magnetic Materials:

The materials whose permeability is below unity are called Dia magnetic materials. They are repelled by magnet.

Ex: Lead, gold, copper, glass, mercury

2. Para Magnetic Materials:

The materials with permeability above unity are called Para magnetic materials. The force of attraction by a magnet towards these materials is low.

Ex: Copper Sulphate, Oxygen, Platinum, Aluminum.

3. Ferro Magnetic Materials:

The materials with permeability thousands of times more than that of paramagnetic materials are called Ferro magnetic materials. They are very much attracted by the magnet.

Ex: Iron, Cobalt, Nickel.

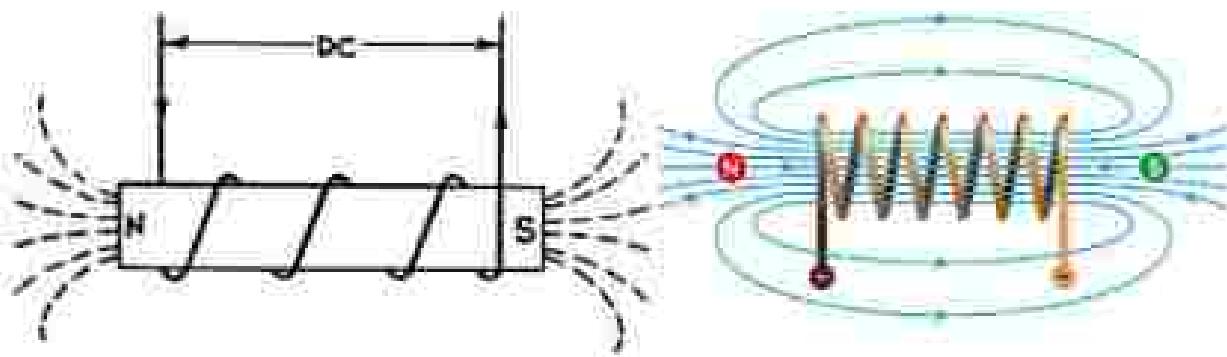
Permanent Magnet

Permanent magnet means, the magnetic materials which will retain the magnetic property permanently. This type of magnets are manufactured by aluminum, nickel, iron, cobalt steel (ALNICO).

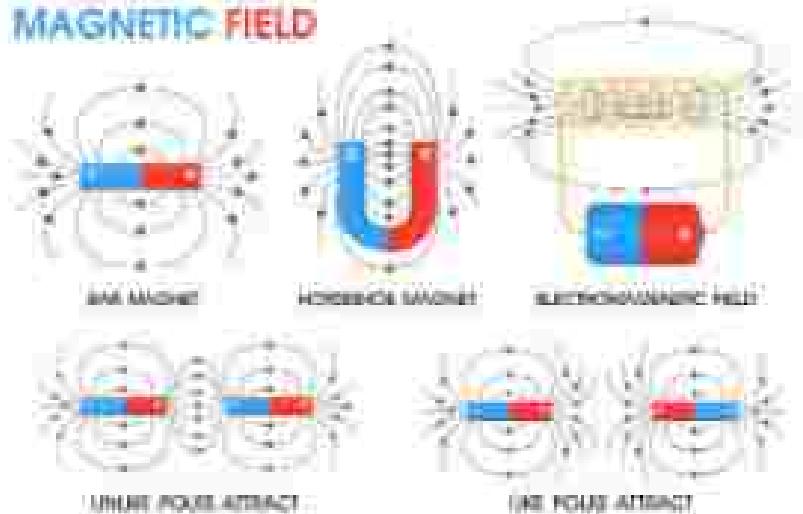
Electro Magnet

Insulated wire wound on a bobbin in many turns and layers in which current is flowing and a soft iron piece placed in the bobbin is called electromagnet.

This is used in all electrical machines, transformers, electric bells. It is also used in a machine used by doctors to pull out iron filing from eyes, etc.



MAGNETIC FIELD



Magnetic Hysteresis

It may be defined as the lagging of magnetization or induction flux density (B) behind the magnetizing force (H). It may also be defined as a quality of a magnetic substance due to which energy is dissipated in it on the reversal of its magnetism.

1.5 B-H Characteristics

A magnetic material is identified and characterized by its B-H characteristic. Materials which are classified as non-magnetic all show a linear relationship between the flux density B and coil current I or H . In other words, they have constant permeability. Thus, for example, in free space, the permeability is constant and $\mu = \mu_0$. But in iron and other ferromagnetic materials it is not constant as shown in figure.

Apply AC current. Assume flux in the core is initially zero. As current increases, the flux traces the path abc (saturation curve). When the current decreases, the flux traces out a different path "bcd" from the one when the current increases. When the current increases again, it traces out path cde . 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.

The initial portion of the B-H curve is nearly a straight line and called linear zone. After this zone the curve gradually starts deviating from a straight line and enters into the nonlinear zone. The slope of the

curve $\delta B / \Delta H$ starts gradually decreasing after the linear zone. A time comes when there is practically no increase in B in spite of the fact that H is further increased. The material is then said to be saturated. The rise in the value of B in the linear zone is much more than in the nonlinear or saturation zone for same ΔH . This can be ascertained from the $B-H$ curve by noting $\Delta B_1 > \Delta B_2$ for same ΔH .

As magnetizing intensity H increases, the relative permeability first increases and then starts to drop off. Hence reluctance remains constant initially (Linear Zone), then starts increasing and finally becomes infinitely large (Saturation Zone).

The point from which the curve starts bending or the linear zone ends is known as *Knee point*. In actual magnetic materials, the flux does not drop to zero when the mmf returns to zero, but there is a *remanent/ Residual flux*. To reduce the flux to zero, an mmf in the reverse direction called the *coercive force* must be applied.

Generators and motors depend on magnetic flux to produce voltage and torque, as 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 behaviours to machines.

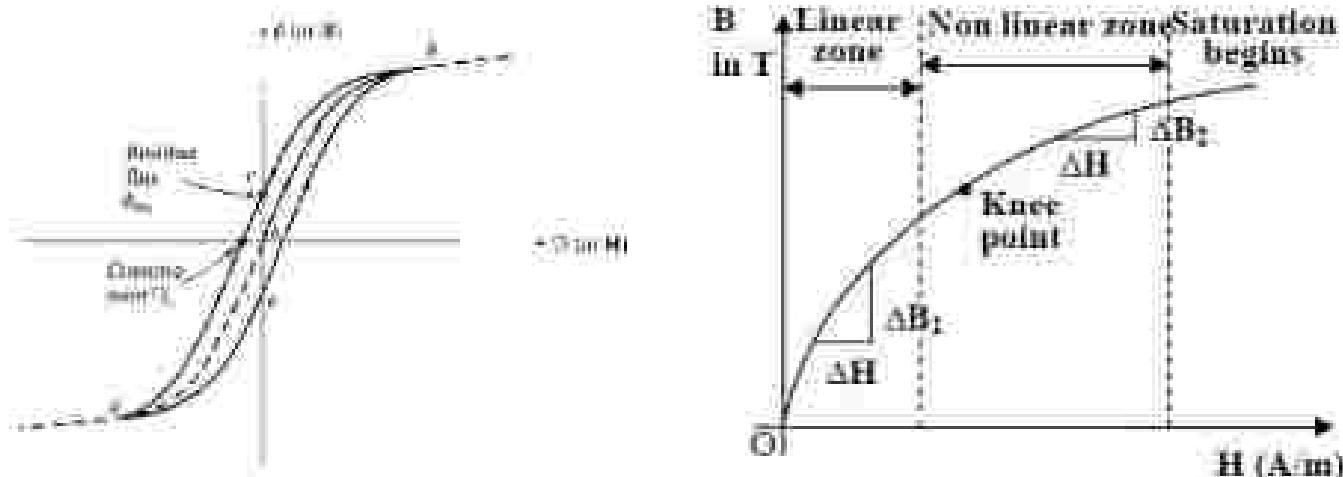
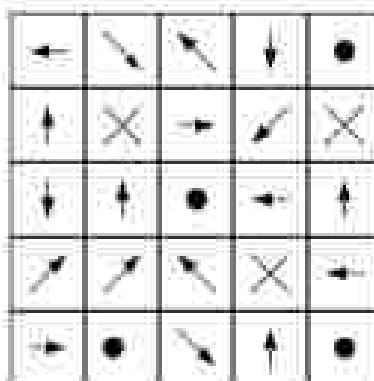


Figure 1.71: A typical $B-H$ curve.

Typical Hysteresis loop when no current is applied.

In a ferrimagnetic material, very large numbers of tiny magnets (magnetic dipoles) are present at the atomic/molecular level. The material however does not show any net magnetic property due to random distribution of the dipoles and eventual cancellation of their effects and the net magnetic field is zero.

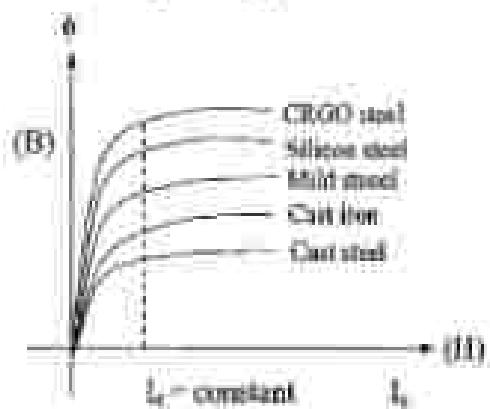


Magnetic domain orientation in a initial structure before the presence of a magnetic field.

In presence of an external field H , these dipoles start aligning themselves along the direction of the applied field. Thus the more and more dipoles get aligned (resulting into more B) as the H i.e., current in the exciting coil is increased. At the initial phase, increase in B is practically proportional to H . However rate of this alignment gets reduced after a definite value of H as number of randomly distributed dipoles decreases. This is reflected in the nonlinear zone as shown in figure. Obviously if we further increase H , a time will come when almost all the dipoles will get aligned. Under such circumstances we should not expect any rise in B even if H is increased and the core is said to be saturated. At the saturation zone, the characteristic becomes almost parallel to the H axis.

Different materials will have different B - H curves and if the characteristics are plotted on same graph paper, one can readily decides which of them is better than the other. One can easily conclude that CRGO steel is better over the other, as flux produced in CRGO steels the highest for same applied field H .

From the above discussion it can be said that there is no point in operating a magnetic circuit deep into saturation zone as because large exciting current will put extra overhead on the source supplying power to the coil. Also any desire to increase B by even a small amount in this zone will call for large increase in the value of the current. In case of transformer and rotating machines operating point is chosen close to the knee point of the B - H characteristic in order to use the magnetic material to its true potential. To design a constant value of inductance, the operating point should be chosen in the linear zone.



1.6 Basic Requirement for production of induced emf:

All the generators work on the principle of dynamically induced emf.

$$\text{i.e., } e = \frac{d\psi}{dt} = N \frac{d\phi}{dt}$$

Where $\psi = N\phi$ = Flux linkage.

The change in flux associated with the conductor can exist only when there exists a relative motion between the conductor and the flux.

So, a generating action requires the following basic components to exist.

1. Magnetic field
2. Set of conductors
3. A relative speed between the above two. (To achieve a time rate of change of flux across the set of conductors.)

The relative motion can be achieved by three different ways:

1. Either the field or the conductor will be stationary and other will rotate in space.
 - e.g. DC Machine, Synchronous Machine.
2. Both will stationary but the nature of flux will be time varying.
 - e.g. Transformer
3. Either the field or the conductor will rotate and nature of flux will be time varying.
 - e.g. Induction Machine.

If the emf is induced by 2nd method, it is known as *statically induced emf*, whereas the others are known as *dynamically induced emf*.

1.6.1 Statically Induced Emf

Statically Induced emf is of two types. They are

1. Self induced emf
2. Mutually induced emf.

Self Induced emf

Self induction is that phenomenon where by a change in the current in a conductor induces an emf in the conductor itself i.e. when a conductor is given current, flux will be produced, and if the current is changed the flux also changes, as per Faraday's law when there is a change of flux, an emf will be induced. This is called self induction. The induced emf will be always opposite in direction to the applied emf. The opposing emf thus produced is called the counter emf of self induction.

Uses of Self induction

1. In the fluorescent tubes for starting purpose.
2. In lightning arrester.
3. In auto-transformers.
4. In smooth choke which is used in welding plant.

Mutually Induced EMF

It is the electromagnetic induction produced by one circuit in the nearby second circuits due to the variable flux of the first circuit cutting the conductor of the second circuit, that means when two coils or

circuits are kept near to each other and if current is given to one circuit and it is changed, the flux produced due to that current which is linking both the coils or circuits cuts both the coils, an emf will be produced in both the circuits. The production of emf in second coil is due to the variation of current in first coil known as mutual induction.

Uses:

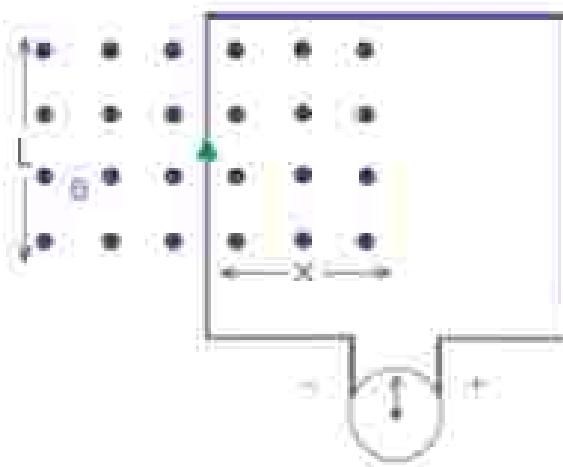
1. It is used in ignition coil which is used in motor car.
2. It is also used in inductance furnace.
3. It is used for the principle of transformer.

1.6.21 Dynamically induced EMF

Dynamically induced emf means an emf induced in a conductor when the conductor moves across a magnetic field. The Figure shows when a conductor with the length ' l ' moves at a linear speed ' v ' in a magnetic field ' B ' Wb/m^2 , the induced voltage in the conductor can be obtained with the help of Faraday's law as shown in the following equation:

$$e = \frac{dy}{dt} = N \frac{d\phi}{dt}$$

where B , l , and v are mutually perpendicular. The polarity (Direction) of the induced voltage can be determined from the so-called *Fleming's Right-Hand Rule*. Assuming the number of turns ($=N$) to be unity,



$$\begin{aligned} e &= \frac{d\phi}{dt} = \frac{d(BA)}{dt} \\ &= B \frac{dA}{dt} = B \frac{d(lx)}{dt} = Bl \frac{dx}{dt} \\ &= Blv \end{aligned}$$

In the example shown above, only one conductor is taken and the flux 'cut' by the same in the normal direction is used for the computation of the emf. The second conductor of the arm may be assumed to be far away or immoving. This greatly simplifies the computation of the induced voltage. For a conductor moving at a constant velocity v the induced emf becomes just proportional to the uniform flux density. This type of voltage is called *speed emf (or rotational emf)*.

If the conductor, field and motion are not normal to each other then the mutually normal components are to be taken for the computation of the voltage. Hence a more complete formula will be as follows:

$$e_m = (v \times B)l \cos\theta$$

Where; θ - angle between the conductor and the direction of ($v \times B$)

The induction of voltages in a wire moving in a magnetic field is fundamental to the operation of all types of generators.

1.7 Electromagnetic Force (F)

A current carrying conductor present in an uniform magnetic field of flux density B, would produce a force to the conductor/ wire (known as *Lorenz force*). 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 - Length of wire, with direction of l defined to be in the direction of current flow

B - Magnetic field density

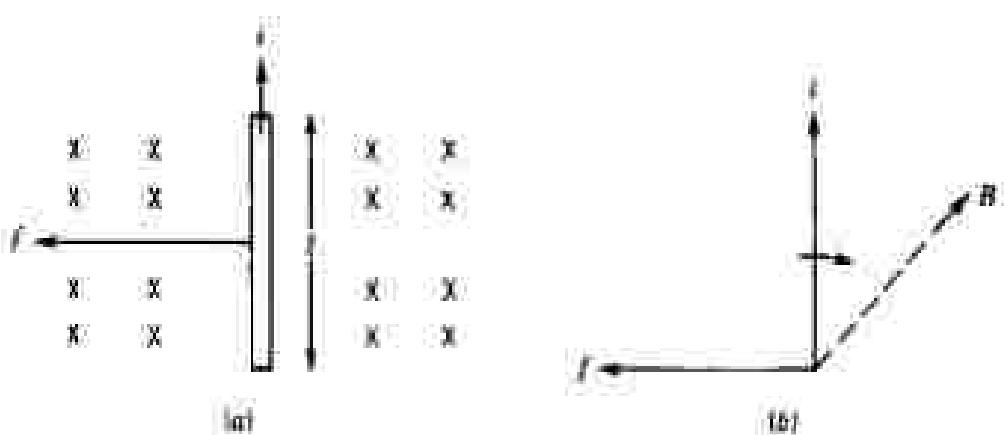
Where, B, l and i are mutually perpendicular. The direction of the force can be determined by using the *Fleming's Left Hand Rule*.

If the current carrying conductor is position at an angle to the magnetic field, the formula is modified to be as follows:

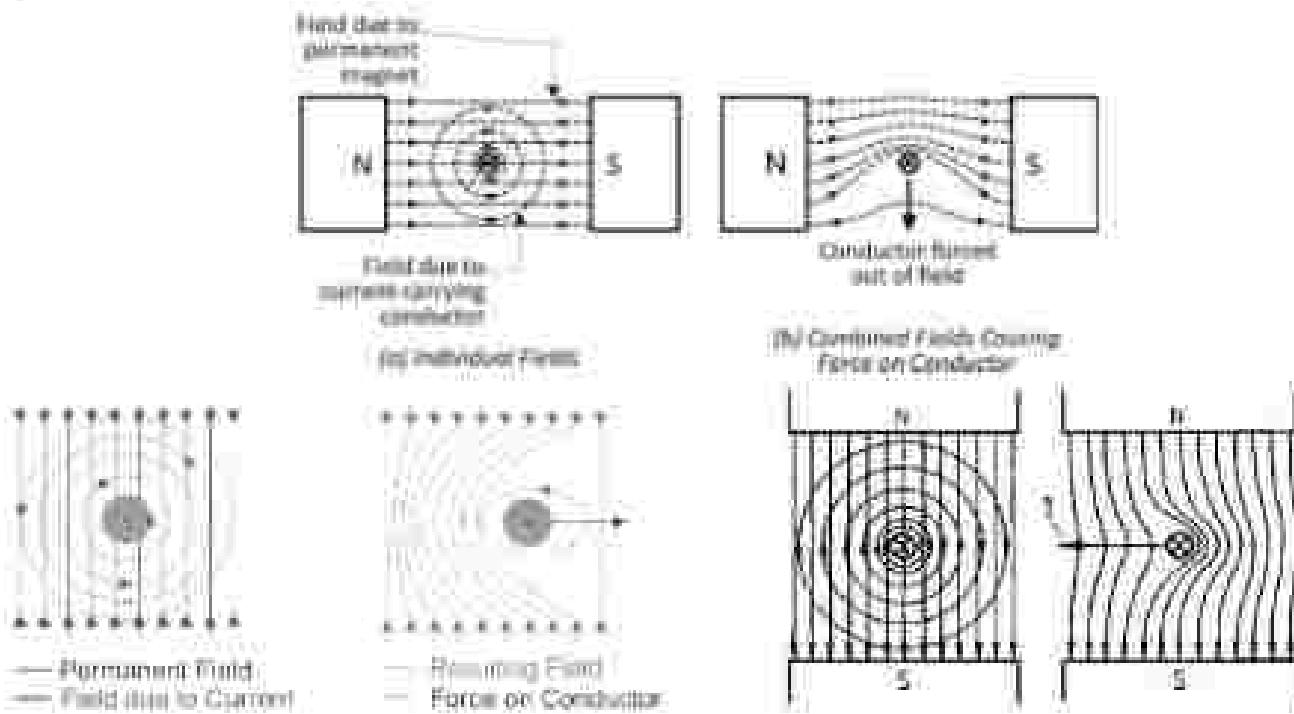
$$F = ilB \sin\theta$$

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.



Electromagnetic force. (a) Current-carrying conductor moving in a magnetic field. (b) Force direction.



From the above figures it can be concluded that, the direction of force produced can be reversed by reversing the current direction flow or field, but not both.

D.C Machines

2.1 Introduction

The steam age signaled the beginning of an industrial revolution. 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 was the force exerted on a current carrying conductor placed in the magnetic field 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 enunciation of laws of induction by Faraday in 1831.

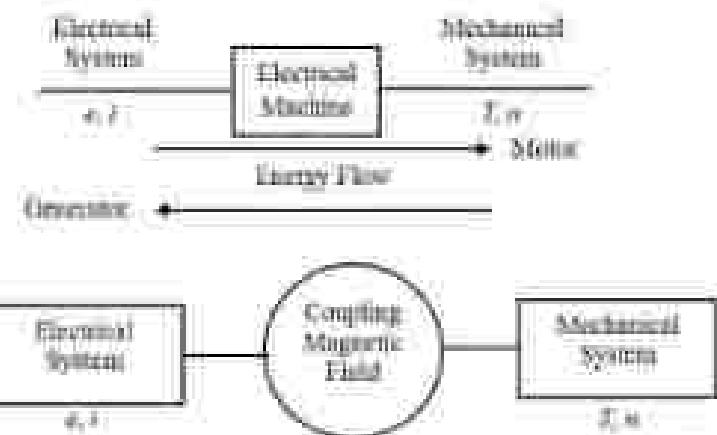
Parallel research was contemporarily being done to invent a source of energy to recharge the batteries in the form of a.c. source of constant amplitude (or d.c. generator). For about three decades the research on d.c. motors and d.c. generators proceeded on independent paths. During the second half of 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. 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 output 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 able 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.

When a conductor moves in a magnetic field, voltage is induced in the conductor (Generator action). When a current carrying conductor is placed in a magnetic field, the conductor experiences a mechanical force (Motor action). The above two operation takes place simultaneously irrespective of the type of machine. Hence motoring and generating action is like two sides of a coin i.e., the same machine can operate in both mode.



The DC machine can operate both as a generator and as a motor. When it operates as a generator, the input to the machine is mechanical power and the output is electrical power. A prime mover rotates the armature of the DC machine, and DC power is generated in the machine. The prime mover can be a gas turbine, a diesel engine, or an electrical motor. When the DC machine operates as a motor, the input to the machine is electrical power and the output is mechanical power. If the armature is connected to a DC supply, the motor will develop mechanical torque and power. In fact, the DC machine is used more as a motor than as a generator.

2.2 General Concepts of Rotating Machines:

There are various kinds of rotating electrical machines such as D.C machines, Induction machines, Synchronous machines etc. and they can run either as motor or as a generator. Although mode of excitation may vary in the above types of machines and constructionally they may be different, however these machines work on the basis of common underlying principles.

When a generator or a motor runs at a constant speed, we can say with conviction (from Newton's laws of rotational motion) that the *Driving torque* and the *Opposing torque* must be numerically equal and acting in opposite directions.

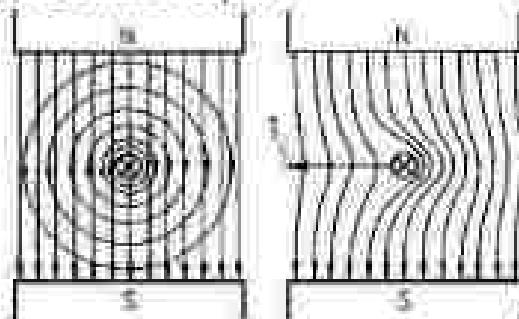
2.2.1 Types of Torque:

With respect to electrical Machine generally there are two types of torque known as,

1. Electromagnetic Torque/Interaction torque
2. Reluctance Torque.

Electromagnetic Torque: The interaction of two sets of magnets/ magnetic field one produced by stator winding currents and the other by rotor winding currents are responsible for production of electromagnetic torque in a rotating machine.

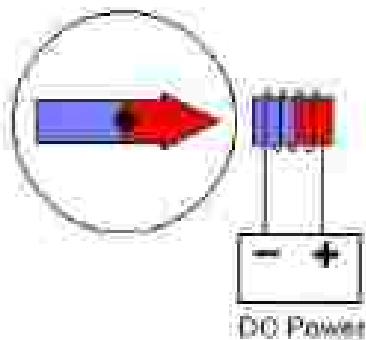
Most of the rotating machines are based on this torque.



Reluctance Torque: This torque produced due to the presence of variable reluctance in the path. Reluctance torque or alignment torque is experienced by a ferromagnetic object placed in an external magnetic field, which causes the object to line up with the external magnetic field.

An external magnetic field induces an internal magnetic field in the object and because of this torque is produced. The torque is exerted on the object so that it tries to position itself to give minimum reluctance for the magnetic flux. It is also known as Saliency torque because it causes due to the saliency of the machine.

Example Reluctance motor:



2.2.2 Generator mode

In case of generator mode, the driving torque is obtained by *prime movers*. A diesel engine or water turbine or steam turbine could be selected as prime movers. In laboratory, servos are used as prime movers. The direction of rotation of the generator is same as the direction of the prime-mover torque.

A loaded electrical rotating machine always produces electromagnetic torque T_e due to the interaction of stator field and armature current. T_e together with small frictional torque is the opposing torque in generator mode. This opposing torque is called the *load torque*, T_L .

If one wants to draw more electrical power out of the generator, T_e (hence T_L) increases due to more armature current. Therefore, prime mover torque must increase to balance T_L for steady speed operation with more fuel intake.

2.2.3 Motor mode

In case of motor mode, the driving torque is the electromagnetic torque, T_e and direction of rotation will be along the direction of T_e . Here the opposing torque will be due to mechanical load (such as pumps, lift, crane, blower etc.) put on the shaft and small frictional torque. In this case also the opposing torque is called the load torque T_L . For steady speed operation, $T_e = T_L$ numerically and acts in opposite direction. To summarize,

- If it is acting as a motor, electromagnetic torque T_e acts along the direction of the rotor rotation and the load torque T_L acts in the opposite direction of rotation. If

$T_e = T_L$, motor runs steadily at constant speed.

$T_e > T_L$, motor will accelerate and

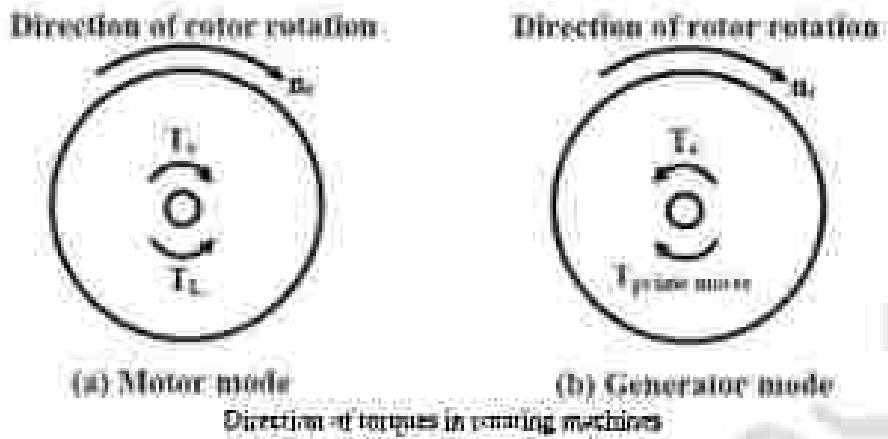
$T_e < T_L$, motor will decelerate.

- On the other hand, if the machine is acting as a generator, the prime mover torque T_{pm} acts along the direction of rotation while the electromagnetic torque, T_e acts in the opposite direction of rotation. Here also during transient operation if

$T_{pm} = T_e$, the generator runs steadily at constant

$T_{pm} > T_e$, the generator will accelerate and

$T_{pm} < T_e$, the generator will decelerate.



2.3 Common underlying principles of rotating machines

Electromagnetic torque in any rotating machine is produced due to interaction of stator and rotor magnetic poles. It is shown that the number of poles of stator and rotor must be equal and the relative speed between the two sets of field must be zero. Stator and rotor poles are created bypassing currents through the stator coils and the rotor coils.

Above two are essentially common to all rotating machines such as D.C. machine, induction machine and synchronous machine.

Explanation:

The production of electromagnetic torque can be considered to be interaction between two sets of magnets, one produced due to current in the stator windings and the other produced due to rotor winding. The rotor being free to rotate, it can only move along the direction of the resultant torque.

Let us first assume that windings are so wound that both stator and rotor produces same number of poles when they carry current. As shown below both stator and rotor produces 4 number of poles each. It can easily be seen that rotor pole N_{R1} is repelled by N_{S1} and attracted by S_{S2} . These two forces being additive produces torque in the clockwise direction. In the same way other rotor poles experience torque along the same clockwise direction confirming that a resultant torque is produced.

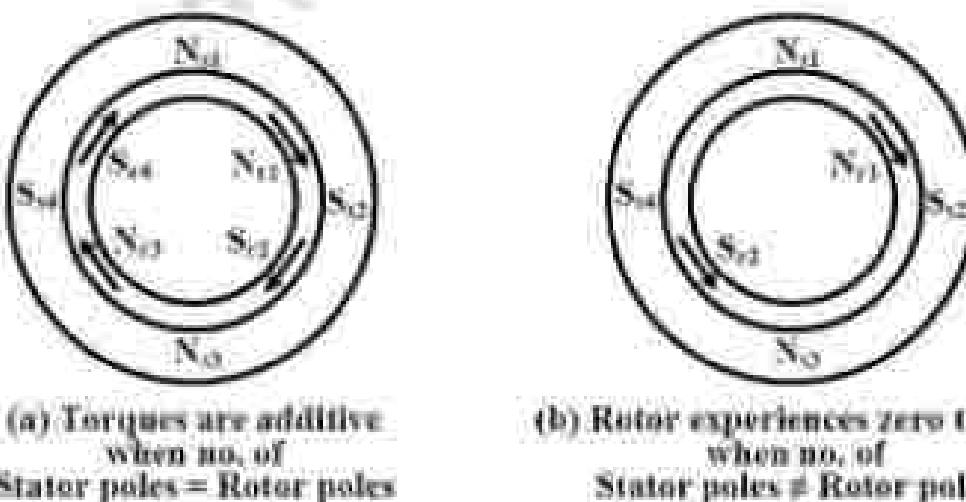


Figure 1: Direction of torques in rotating machines

However, if stator winding produces 4 poles and rotor winding produces 2 poles, the resultant torque experienced by rotor will be zero as shown above. Here N_{R1} is repelled by N_{S1} and attracted by S_{S2} trying to

produce torque in the clockwise direction; while S_2 is attracted by N_2 and repelled by S_1 trying to produce torque in the counter clockwise direction. So net torque is zero.

So a rotating electrical machine cannot work with different numbers of poles in stator and rotor. The condition that stator number of poles should be equal to the rotor number of poles is actually a necessary condition for production of steady electromagnetic torque.

What is the sufficient condition then?

When stator and rotor number of poles are same and equal to 4. Suppose the relative position of the poles shown, is at a particular instant of time say t. We can easily recognize the factors on which the magnitude of the torque produced will depend at this instant. Strength of stator & rotor poles is definitely one factor and the other factor is the relative position of stator and rotor poles (which essentially means the distance between the interacting poles). If the machine has to produce a definite amount of torque for all time to come for sustained operation, the relative position of the stator and rotor field patterns must remain same and should not alter with time. Alternative way of expressing this is to say the relative speed between the stator and rotor fields should be zero with respect to a stationary observer.

Summarizing the above we can conclude that a rotating electrical machine can produce steady electromagnetic torque only when the following two conditions are satisfied.

- Stator and rotor number of poles must be same.
- There should not be a relative speed existing between the two fields with respect to a stationary observer.

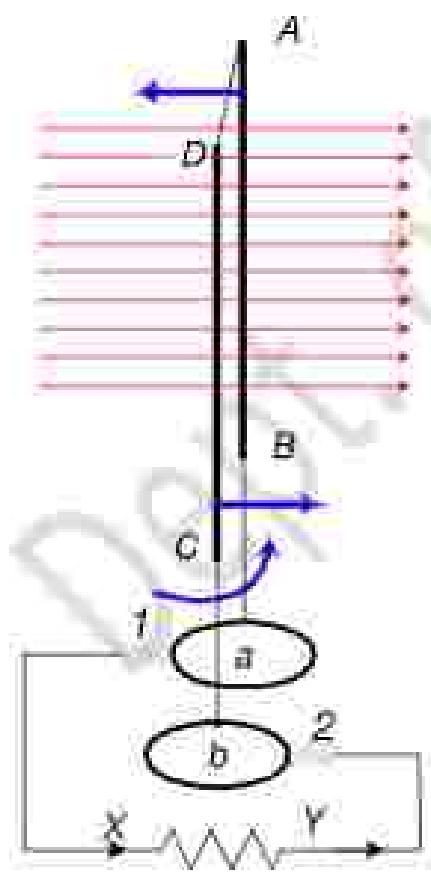
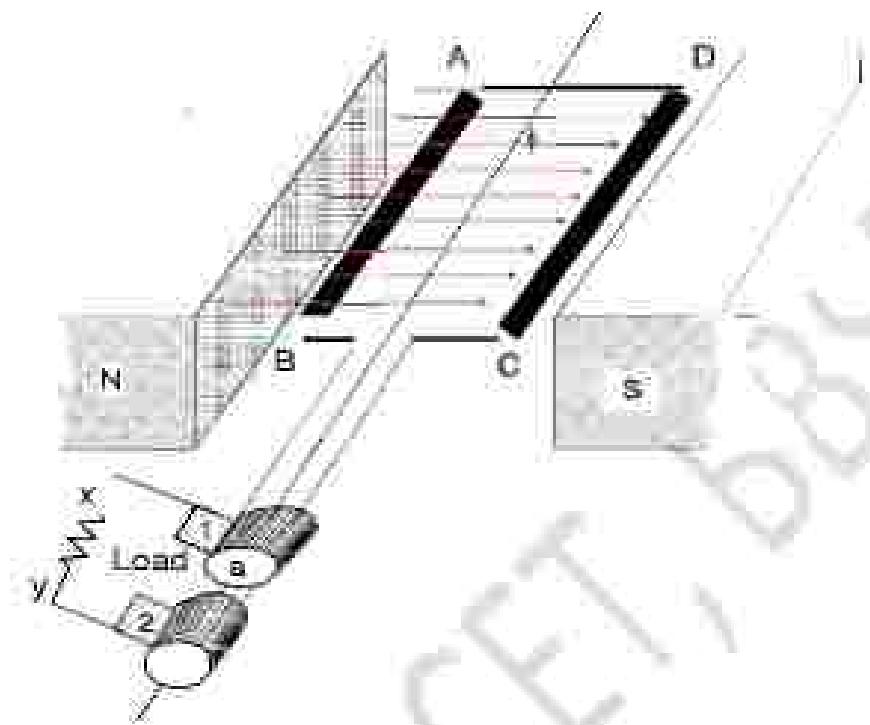
2.4 Simple loop generator and AC to DC

Let us consider a single turn rectangular copper coil ABCD moving about its own axis, a magnetic field provided by the permanent magnets or electromagnets. The two ends of the coil are joined to two slip rings or discs 'a' and 'b' which are insulated from each other and from the central shaft. Two collecting brushes (of carbon or copper) press against the slip rings to collect the current induced in the coil and convey it to the external load resistance R .

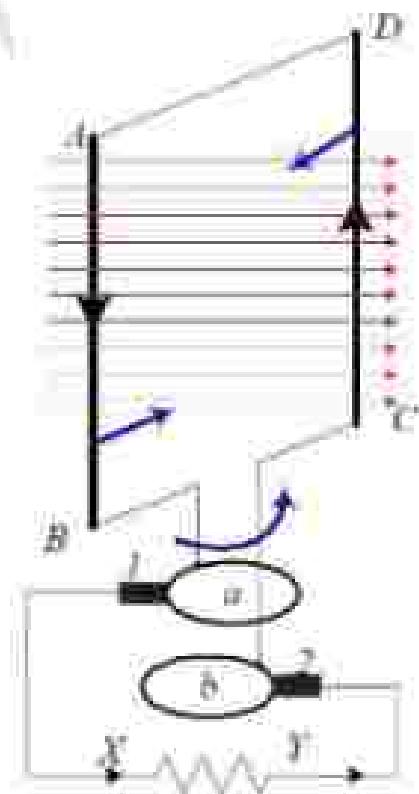
Imagine the coil to be rotating in clockwise direction. As the coil assumes successive positions in the field,

the flux linked with changes. Hence, an EMF induced in it which is proportional to the rate of change of flux linkage, $e = -N \frac{d\Phi}{dt}$.

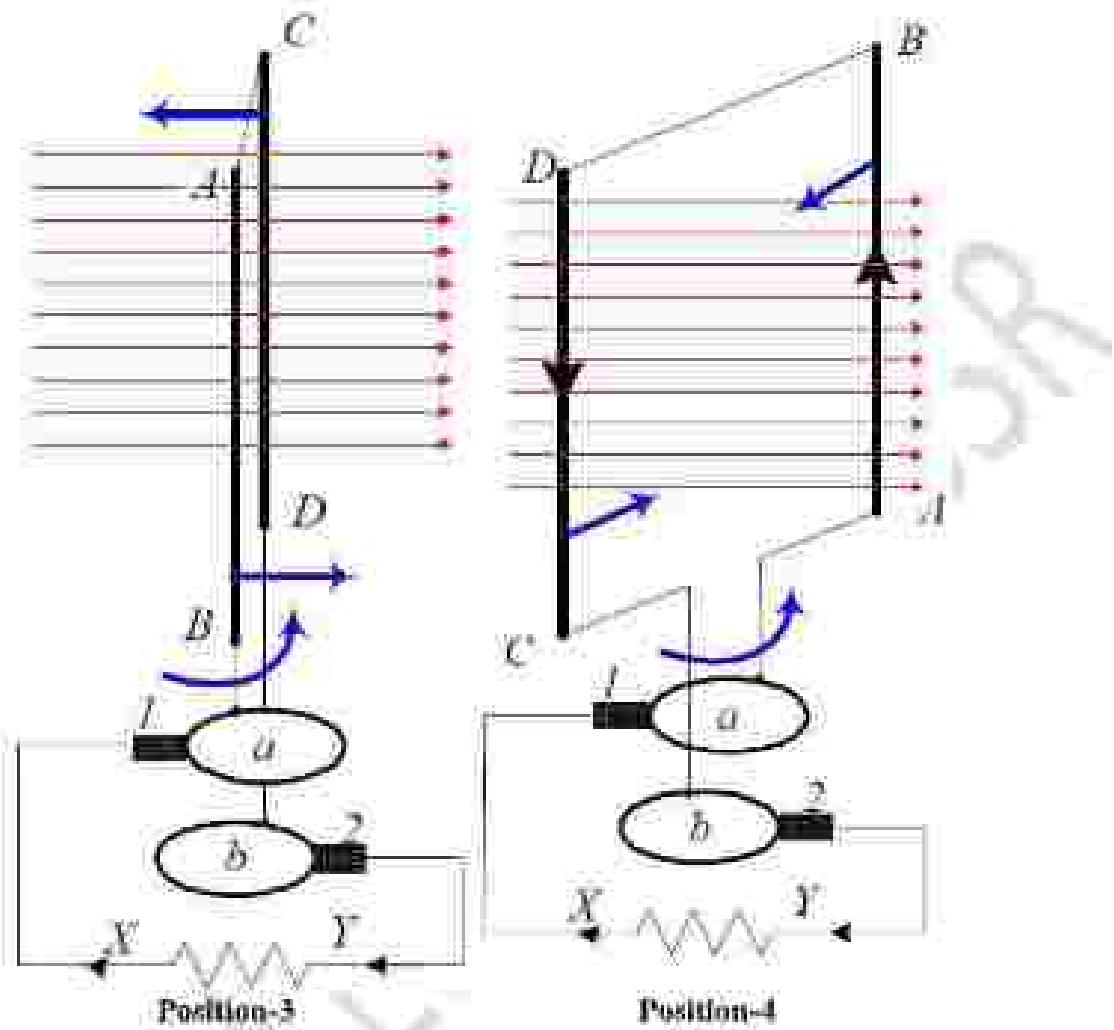
When the plane of the coil is at right angles to the lines of flux, then, the direction of velocity of both sides of the coil is parallel to the direction of the field lines so, there is no cutting for the field lines. Then flux linkages with the coil are minimum. Hence, there is no induced EMF in the coil. Let us take this no emf or vertical position of the coil as the starting position. The angle of rotation or time will be measured from this position so we can determine the first point ($\text{ang} = 0^\circ$).



Position-1



Position-2



As the coil continues rotating further, the rate of change of flux linkages (and hence induced EMF in it) increases, until position 2, is reached at 90 degrees. Here the coil plane is horizontal i.e. parallel to the lines of flux. As seen, the *rate of change of flux linkages is maximum*. Hence, maximum EMF induced in the coil at 90 degrees and the direction of current flow is ABXYCD as shown in Fig.

In the next quarter revolution i.e. from 90° to 180°, the rate of change of flux linkages *decreases*. Hence, the induced EMF decreases gradually till in position 3 of the coil, it reduced to zero value.

In the next half revolution i.e. from 180° to 360°, the variations in the magnitude of EMF are similar to those in the first half revolution but it found that the direction of the induced current is from D to C and B to A. Hence, the path of current flow is along DCYXBA which is just the reverse of the previous direction of flow. Therefore, we find that the current in the resistive load, R that we obtain from such a simple generator reverses its direction after every half revolution as shown in Fig. Such a current undergoing periodic reversals is known as alternating current.

It is, obviously, different from a direct current which continuously flows in one and the same direction which we need to generate from the DC generator. So, we should make some modification to get unidirectional current in the load. It should be noted that alternating current not only reverses its direction, it

does not even keep its magnitude constant while flowing in any one direction.

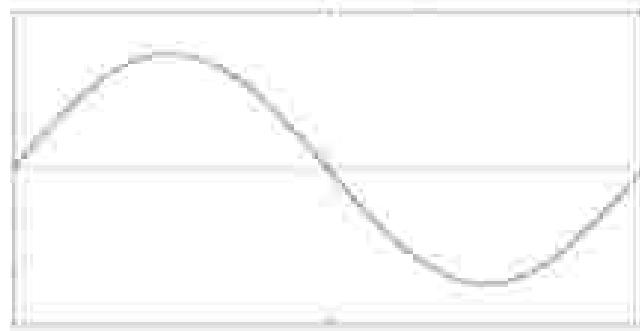
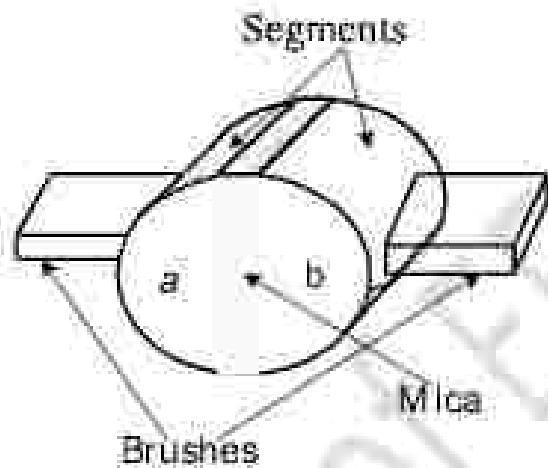


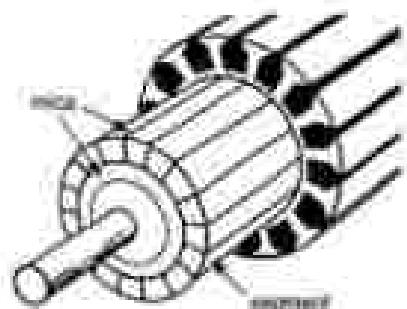
Fig. 3.6

2.4.1 Conversion from AC to DC:

For making the flow of current unidirectional in the external circuit, the slip rings are replaced by split rings which shown in Fig. 3.7. The cylinders are made out of a conducting cylinder which is cut into two halves or segments insulated from each other by a thin sheet of mica or some other insulating material. As before, the coil ends are joined to these segments on which rest the carbon or copper brushes.

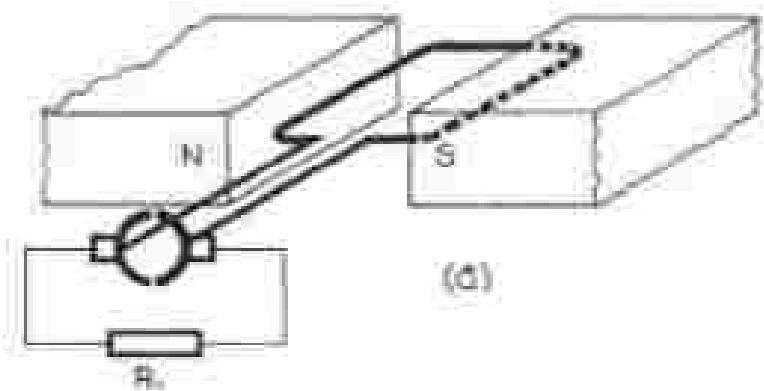


Two segments split rings in simple generator loop.



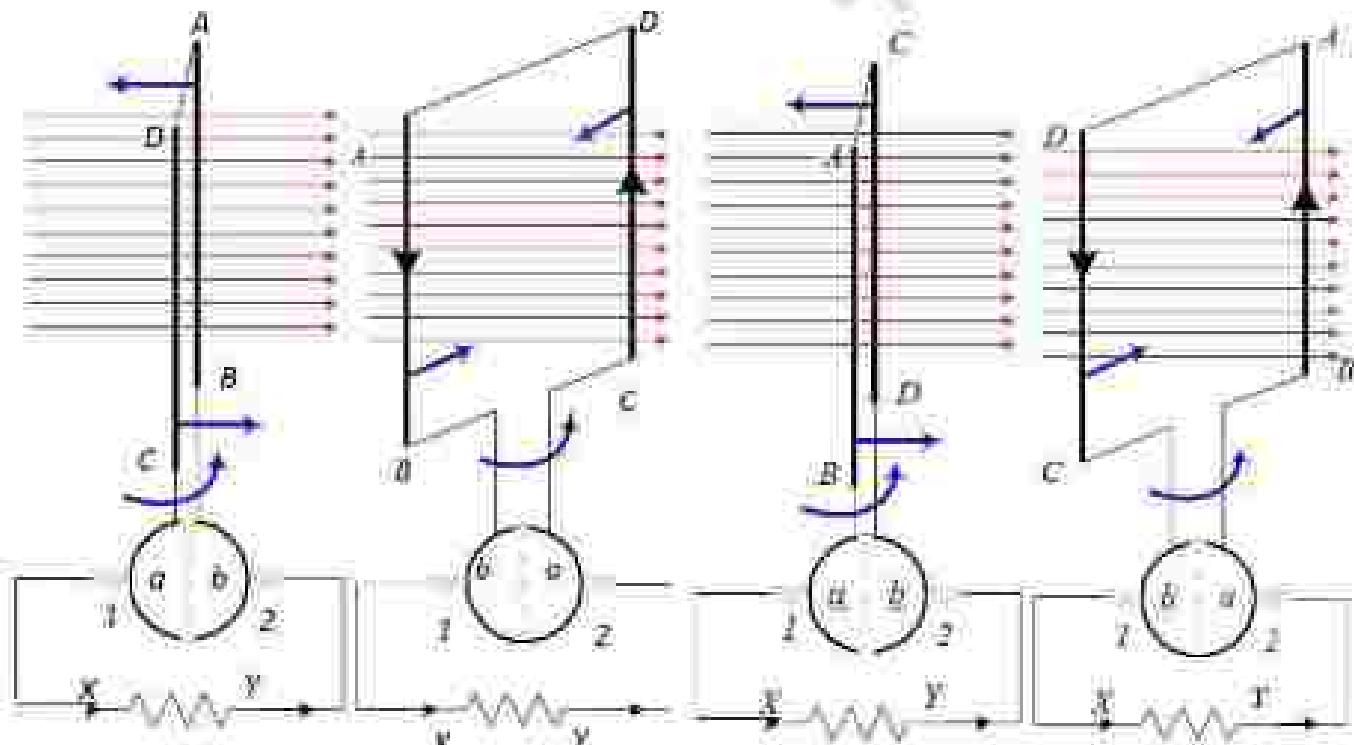
Many segments split rings in Practical generator loop.

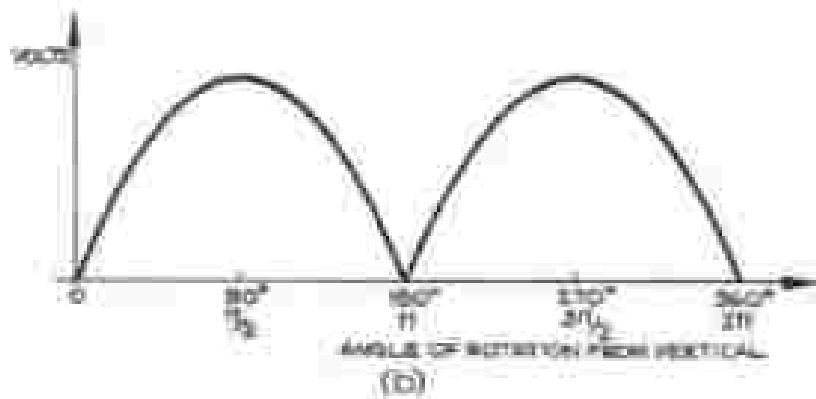
It is seen that in the first half revolution current flows along ABXYCD i.e. the brush No. 1 in contact with segment *a* acts as the positive end of the supply and *b* as the negative end. In the next half revolution, the direction of the induced current in the coil has reversed. But at the same time, the positions of segments *a* and *b* have also reversed with the result that brush No. 1 comes in touch with that segment which is positive (segment *b* in this case). Hence, the current in the load resistance again flows from X to Y. The waveform of the current through the external circuit. This current is unidirectional but not continuous like pure direct current.



(a)

It should be noted that the position of brushes is so arranged that the change-over of segments *a* and *b* from one brush to the other takes place when the plane of the rotating coil is at right angles to the plane of the flux lines. It is so because in that position, the induced EMF in the coil is zero.





2.4.2 Conclusions

- Irrespective of the Type of Generator, the nature of induced emf is always A.C.
- Frequency of the induced emf is given by: $f = \frac{PN}{120}$

$$\text{Cycles / Rev} = \frac{P}{2}$$

$$\text{Rev / Sec} = \frac{N}{60}$$

$$\Rightarrow (\text{Cycles / Rev}) \cdot (\text{Rev / Sec}) = \frac{P}{2} \cdot \frac{N}{60}$$

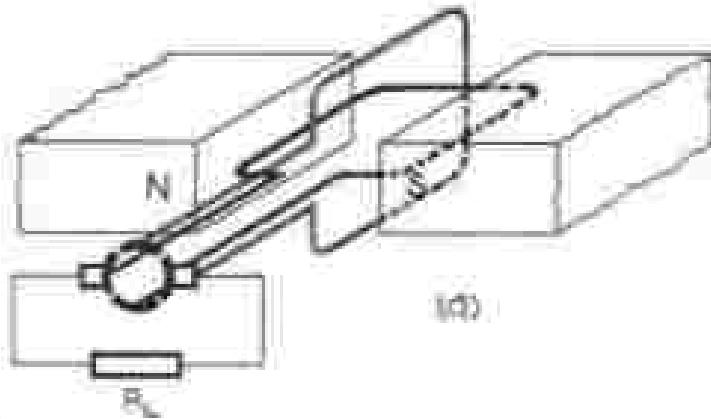
$$\Rightarrow \text{Cycles / Sec} = \frac{PN}{120}$$

$$\Rightarrow f = \frac{PN}{120}$$

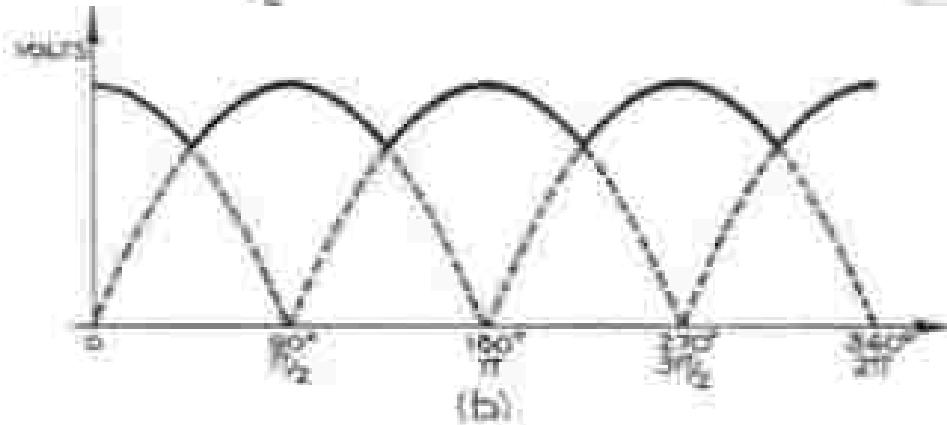
- The value of induced emf is always A.C., whereas it can be converted to D.C. in the output circuit by some mechanical arrangement known as commutator.

AC Generator + Commutator=DC Generator

- The direction of current/ induced emf in the conductors under each pole remain same. It reverses when it changes from one pole to another, for which it is known as pseudo-stationary coil.
- Although the output waveform is unidirectional, it is still pulsating. Let us consider how we can more closely approximate to a d.c. waveform. Using two coils connected to four sections that rotate in the magnetic field as shown. As the coils rotate, the e.m.f. that is produced across the load is as shown in fig below. This waveform approximates more closely to a direct constant voltage.



(a)



(b)

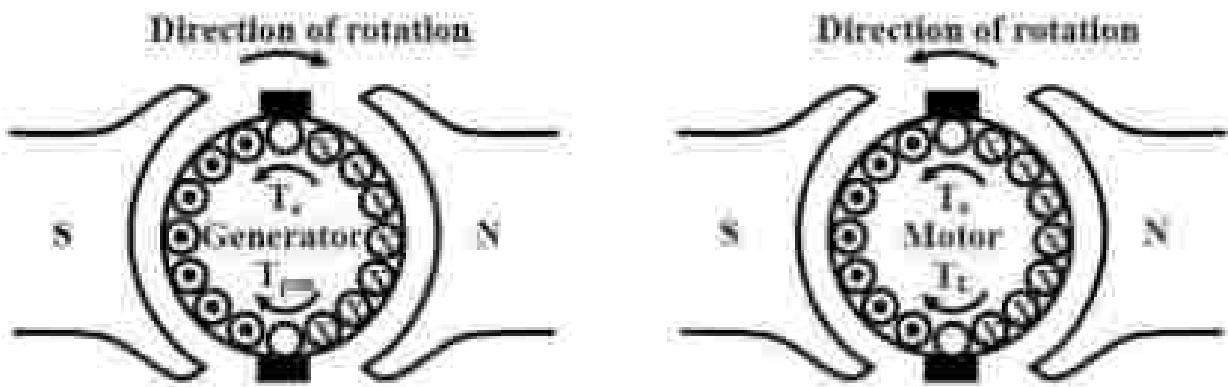
Cells connected to a four-section commutator and the waveform

2.5 Generating and Motoring Action:

2.5.1 D.C generator:

All Generators are based on the same principle of Faraday's Law of Electromagnetic Induction. Let the armature of a DC Generator driven by a prime mover in the clockwise direction and the stator field is excited to produce the major poles as shown. There will be induced voltage in each armature conductor. The direction of the induced voltage can be ascertained by applying Fleming's right hand rule. All the conductors under the influence of North Pole have \odot directed induced voltage, while the conductors under the influence of South Pole have \circlearrowleft induced voltage in them. For a loaded generator the direction of the armature current will be same as that of the induced voltages. Thus, \odot and \circlearrowleft also represent the direction of the currents in the conductors.

We know a current carrying conductor placed in a magnetic field experiences force, the direction of which can be obtained by applying Fleming's left hand rule. Applying this rule to the armature conductors, we note that rotor experiences a torque (T_r) in the counter-clockwise direction (i.e., opposite to the direction of rotation) for which it is known as *counter torque*. As discussed earlier, for steady speed operation $T_{em} = T_r$.



2.5.2 D.C motor:

An Electric motor is one which converts electric energy into mechanical energy. Its action is based on the principle that when a current-carrying conductor is placed in a magnetic field, it experiences a mechanical force whose direction is given by Fleming's Left-hand Rule and whose magnitude is given by $F = BId$ Newton.

Let the external supply is given to a DC motor in such a manner that the conductors under the influence of North Pole have current in \textcirclearrowleft direction, while the conductors under the influence of South Pole have current in \textcirclearrowright direction. The direction of force experienced by each conductor can be found out by applying *Fleming's left hand rule*. As a result, the conductors start moving in counter clockwise direction.

We know when a conductor revolves around a magnetic field an emf is induced, which can be found out by applying *Fleming's right hand rule*. Applying this rule to the armature conductors, it is found that the induced emf acts in opposite direction of the supply voltage, for which it is known as counter or back emf.

2.6 Mechanical & Electrical Degrees

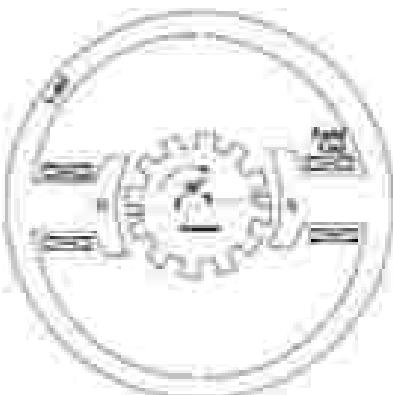
If a rectangular coil rotated relative to a magnetic field, alternating voltage will induce in the coil. Let us consider the first figure, where the rectangular coils is rotated in a magnetic field created by 2-pole. For one complete rotation of 360° the coil will link North Pole flux and then south pole flux and process repeats. Therefore, one cycle of emf will be induce when the coil makes one complete rotation (i.e., moves by 360°). To have maximum voltage induced in the coil, the coil span should be 180° meaning that when one coil side will be under the center of the North Pole, the other coil side should be under the center of the South Pole. This ensures maximum induced voltage in the coil.

Now consider the second generator having 4 poles as shown in figure 8. In this case obviously coil span should not be made 180° mechanical as the induced voltage across the coil will be zero. For maximum induced voltage, coil span should be 90° mechanical, which ensure that when one coil side will be under the center of the North Pole, the other coil side should be under the center of the South Pole.

Also note for this 4-pole machine, two cycles of emf will be generate when the coil makes 360° mechanical movement (one complete rotation). The distance between the center of the North Pole and the consecutive South Pole is defined as 180° electrical. Hence the coil span should be 180° electrical and one cycle of emf will be induced when the coil moves by 360° electrical. Let θ_e and θ_m denote electrical and mechanical degrees respectively and n_e and n_m denote electrical and mechanical speeds respectively then the relationship between the electrical and mechanical degrees and between the electrical and mechanical speeds are:

$$\theta_{el} = \frac{P}{2} \theta_{mech}, \text{ where } P = \text{No. of Poles}$$

It is interesting to note that, whatever is happening under a pair of pole, same thing happens under other pair of poles as well. Thus in general for a P pole machine, it is sufficient to analyze the machine based on a pair of pole.



A 2-pole generator.



A 4-pole generator.

Q. Someone has manufactured a machine such that stator winding produces 6 poles and the rotor winding produces 4 poles. Can this machine work?

Solution: No steady torque can be produced since numbers of poles are different for stator and rotor. The machine will not work.

Q. In a rotating machine, stator produces 2 poles and is found to rotate at a speed of 3000 rpm with respect to a stationary observer while the rotor also produces 2 poles and is found to rotate at a speed of 1500 rpm with respect to a stationary observer in the same direction as that of the stator field. Can this machine produce a steady electromagnetic torque?

Solution: Relative speed between the two fields is $3000 - 1500 = 1500$ rpm, hence no steady torque is possible.

Q. In a rotating machine, stator produces 4 poles and is found to rotate at a speed of 3000 rpm with respect to a stationary observer while the rotor also produces 4 poles and is found to rotate at a speed of 3000 rpm with respect to a stationary observer in the same direction as that of the stator field. Can this machine produce a steady electromagnetic torque?

Solution: Yes it will, since number of poles are same and the relative speed between the fields is also zero.

Q. In a rotating machine, stator produces 4 poles and is found to rotate at a speed of 3000 rpm with respect to a stationary observer while the rotor also produces 4 poles and is found to rotate at a speed of 3000 rpm with respect to a stationary observer in the opposite direction as that of the stator field. Can this machine produce a steady electromagnetic torque?

Solution: No, since the relative speed between the two fields is 6000 rpm.

3. Construction of DC Machines

As discussed earlier DC machine is based on production of dynamically induced emf, so to achieve relative velocity between the flux and set of conductors, one is stationary and other is rotating. The two major parts are:

1. Stationary part: It is designed mainly for producing a magnetic flux.
2. Rotating part: It is called the armature, where all the energy conversion takes place.

The stationary parts and rotating parts are separated from each other by an air gap of length around 2–6 mm.

- 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/armature configuration is selected for D.C. machines.
- To have a large voltage output, a number of conductors are connected together in a specific manner to form a winding. The winding is called *armature winding* of a dc machine and the part on which this winding is kept is called armature of the machine. It is the one where all the energy conversion takes place.
- The rating of a Machine is the rating of its armature.
- The magnetic field is produced by a current carrying winding which is called field winding.
- The rating of the field winding is around 0.5 to 2% of its armature rating as its function is only to produce the necessary flux in space.
- The conductors placed on the armature are rotated with the help of some external device. Such an external device is called a prime mover. The commonly used prime movers are diesel engines, steam engines, steam turbines, water turbines etc.

3.1 The major parts can be identified as:

- (i) Magnetic Frame or Yoke
- (ii) Pole-cores and Pole-shoes
- (iii) Field Coils
- (iv) Armature Core
- (v) Armature Windings
- (vi) Commutator
- (vii) Brushes and Bearings

Of these, the yoke, the pole cores, the armature core and air gaps between the poles and the armature core form the magnetic circuit whereas the rest form the electrical circuit.

A sectional view of a 4-pole D.C. machine is shown in figure 3.1. The length of the machine is perpendicular to the paper. Stator has got 4 numbers of projected poles with coils wound over it.

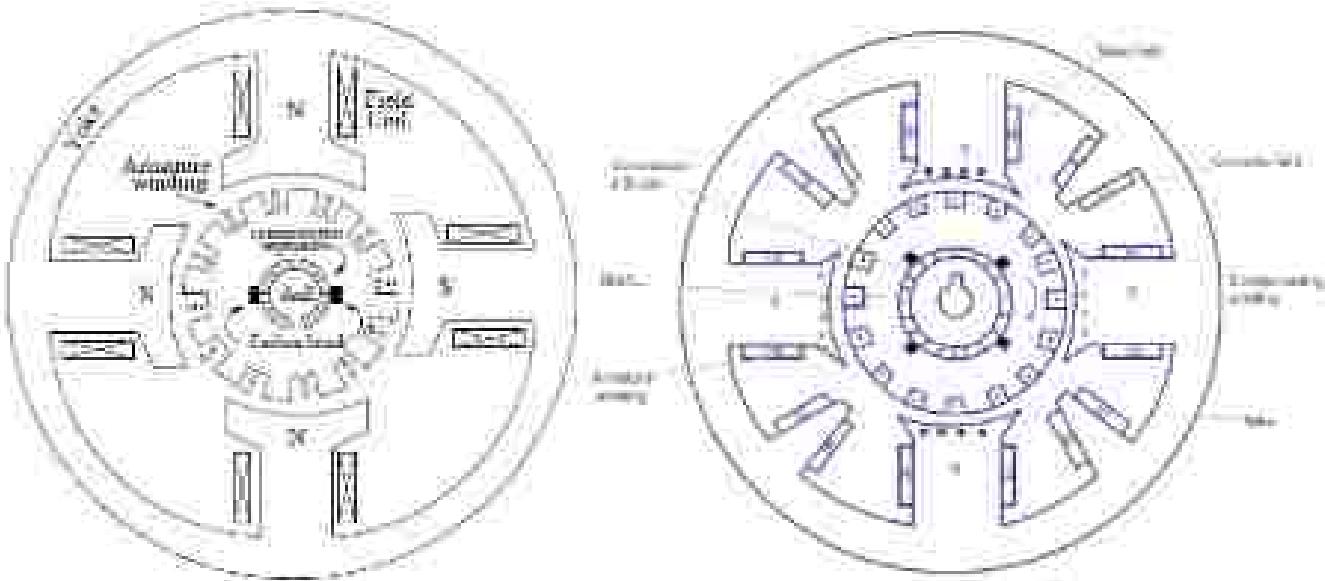


Figure 3.1: Sectional view of D.C. machine.

3.1.1 Frame/Yoke:

Frame is a hollow cylindrical un-laminated solid structure on which the main poles and interpoles are bolted and it forms the supporting structure by connecting the frame to the bed plate. It protects the machine from atmospheric elements and provides the necessary mechanical strength. It provides a low reluctance magnetic path for flux from the main poles and interpoles.

To provide low reluctance path, it must be made up of some ferromagnetic material. It is prepared by using cast iron because it is the cheapest. For large machines milled steel or cast steel is used which provides high permeability i.e., low reluctance and gives good mechanical strength.

Cast iron is saturated by a flux density of 0.8 Web/m^2 , whereas saturation with cast steel is about 1.5 Web/m^2 . So for the same magnetic flux density the cross section area needed for cast steel is less than cast iron hence the weight of the machine too.

3.1.2 Main poles:

It has two major parts:

1. Pole core/ Pole body
2. Pole shoe

Pole core/ Pole body: Solid poles of fabricated steel are fastened to the frame by means of bolts. Generally pole body is not laminated whereas Pole shoes are laminated. Sometimes pole body and pole shoe are formed from the same laminations. Pole core basically houses the field winding.

Pole shoe:

- These are formed by stacking thin steel sheets of thickness 1 to 1.5 mm to reduce eddy current loss.
- The width of Pole shoe is larger than the pole core to increase the cross-section area by reducing the reluctance of the magnetic path, so that the flux/pole will be more and to support the exciting coils (or field coils).

- The pole shoes are chamfered so as to have a slightly increased air gap (about 50% more) at the tips to reduce the effect of armature reaction.
- The pole faces of the machine are curved to provide a uniform air gap width and to give a uniform flux density everywhere under the faces and to maintain a trapezoidal flux distribution in space.
- Each pole behaves like a magnetized 'N' or 'S' pole, when excited.

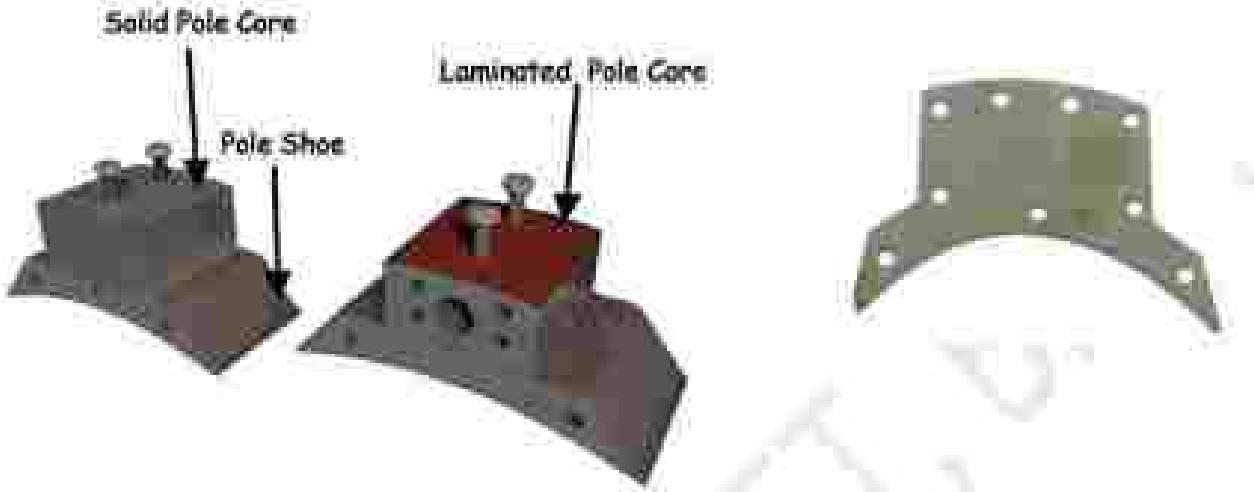
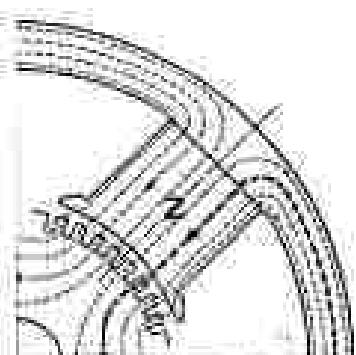


Figure 3.2: Field Poles.

Q. Why there is loss due to eddy current in pole shoe whereas not in pole core?

Ans: As shown in figure, the armature surface is not a smooth one, rather continuous slots and teethes are there which results in variable reluctance path to the field flux.

With the change in position of slots w.r.t. the pole shoe due to its rotation, the reluctance seen by a particular position varies. As the field lines tries to follow low reluctance path, the flux density in the pole varies, which results an emf to induce there. As a result a current starts to circulate, known as eddy current. So to reduce its effect these are laminated.



3.1.3 Field windings:

For machine rated below 500W, permanent magnet as pole are preferred, whereas in the case of wound field 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 like a heteropolar structure. Thus the poles are created electromagnetically.

For the 4-pole machine we shall have 4 coils. These coils can be connected in series and ultimately two terminals marked with F_1 and F_2 can be brought out. When these coils will carry some D.C current, alternate North and South Pole will be created.

In shunt winding large number of turns of small cross section copper conductor is used. 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.

These coils may be connected in series in order that consecutive poles produce opposite polarities (i.e., N-S-N-S) when excited from a source.

Magnetic Circuit of 4 pole DC machine is shown in fig. below

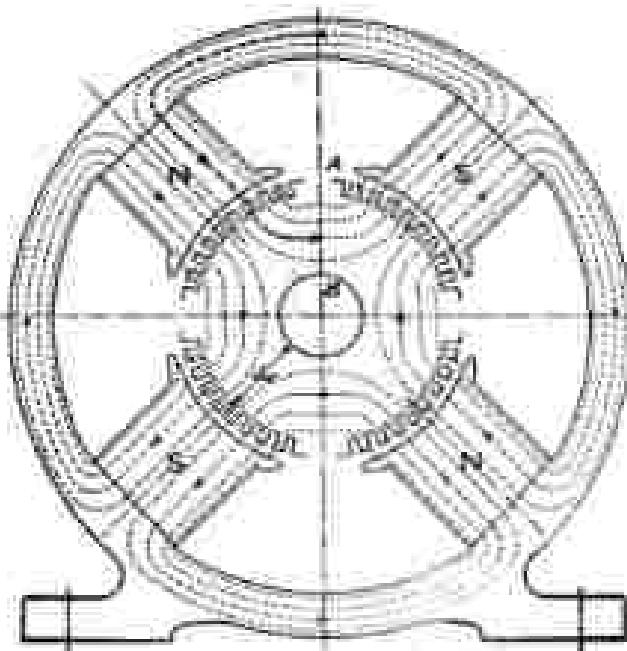


Figure 3.3 Magnetic circuit of a 4-pole Machine

3.1.4 Inter-poles:

These are small additional poles located in between the main poles fastened to the yoke by bolts. These can be solid, or laminated just as the main poles. The width of the tip of the inter-pole can be about a rotor slot pitch. The inter-poles could be of tapered section or of uniform cross section.

3.1.5 Armature cores:

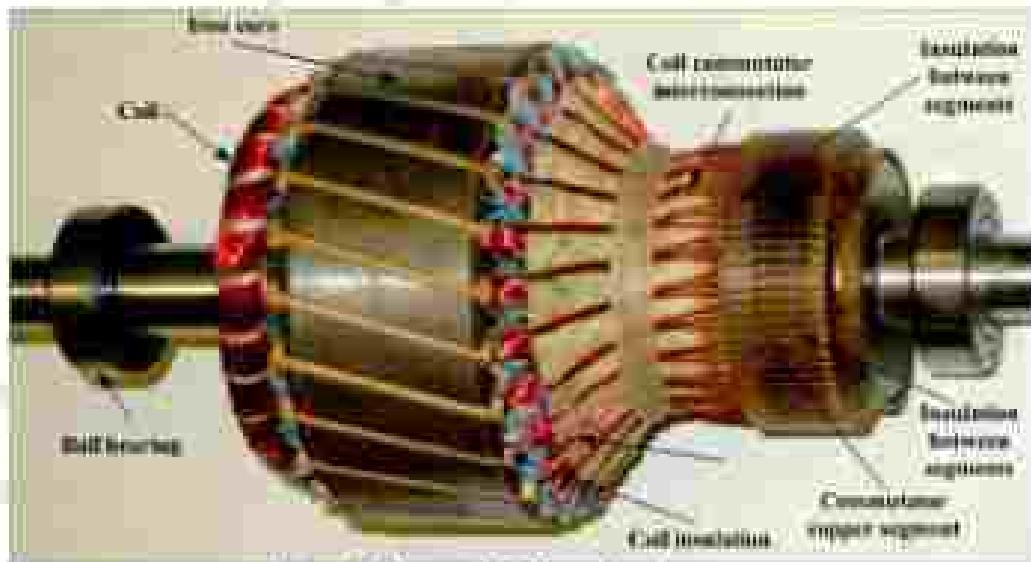


Figure 3.4: practical D.C. machine Armature.

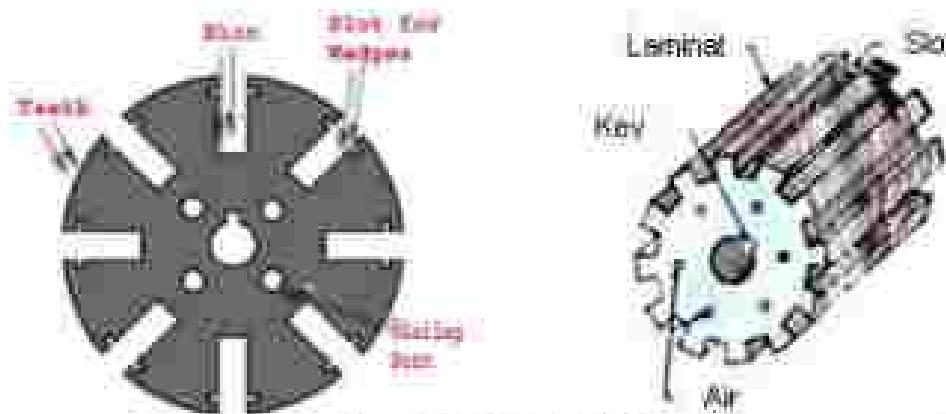


Figure 3.4: Armature Core

- Rotating member of the machine where the conductors are located is called the armature.
- It is solid cylindrical or drum-shaped and built up of several thin circular silicon steel plates of thickness about 0.3 to 0.6 mm with number of slits and teeth punched to form the core.
- These slots house the armature winding.
- It also provides a low reluctance path to the flux from N-pole to S-pole, for which high permeable material is chosen.
- Circular plates are insulated from each other by the varnish coating to reduce eddy current losses.
- Armature core is provided with axial ducts of dia 5mm to 10 mm with an interval of 5cm to 10cm to facilitate easy removal of heat from the armature winding.
- Generally open slots are used and they are skewed to avoid vibration.

3.1.6 Commutator:

It is a form of rotating switch placed between armature and brush. The function of the commutator is to facilitate collection of current from the armature conductors; it acts as an interface between the machine and external circuit. It is of cylindrical structure and is built up of wedge-shaped segments of high-conductivity hard-drawn or drop forged copper.

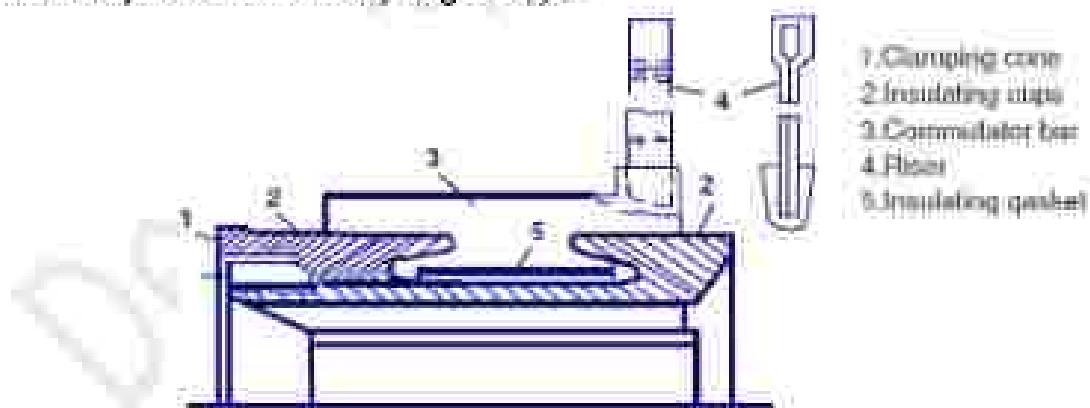


Figure 3.5: Commutator Segment

It consists of copper segments tightly fastened together with mica/mica-micahite insulating separators of thickness 0.8mm and dielectric strength of 30V-40V on an insulated base, such that each copper segment has its own electrical identity. 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 'rise' where the ends of the armature coils get connected. Current collecting brushes rest on the surface of commutator.

The number of segments is equal to the number of armature coils. Each commutator segment is connected to the armature conductor by means of a copper lug or strip (or tiger). To prevent them from flying out under the action of centrifugal forces, the segments have V-grooves, these grooves being insulated by conical micaite rings.

In generator it acts as a mechanical rectifier which converts the inherently A.C voltage in the armature coils, to D.C voltage. Whereas in a motor it acts as a mechanical inverter which converts the applied DC to AC for the armature coils.

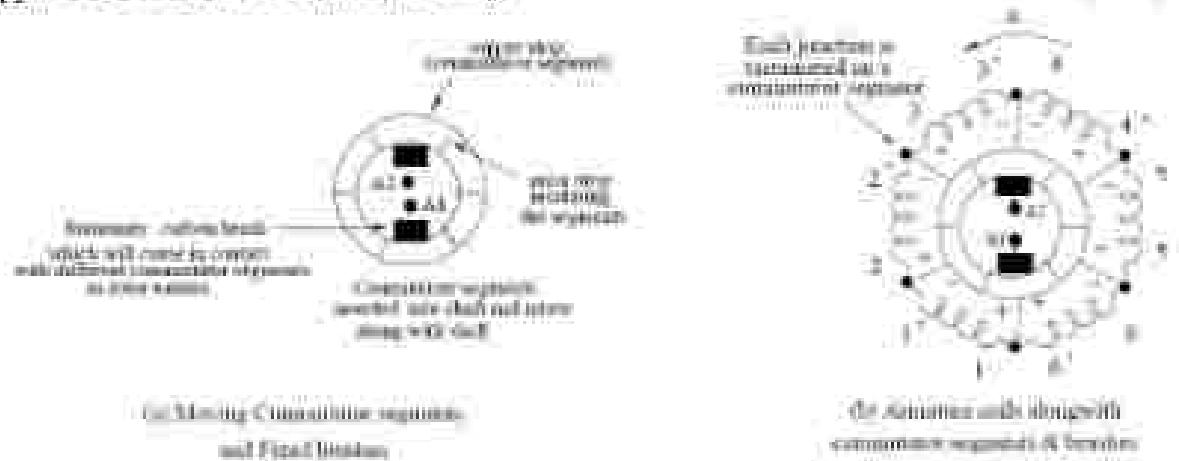


Figure 3.6: Armature showing commutator, brushes & armature terminals

3.1.7 Brush and brush holders

The function of Brushes is to collect current from commutator, is usually made of carbon or graphite and is in the shape of a rectangular block.

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/ current. The hardness of the graphite brush is selected to be lower than that of the Commutator. Graphite brush works as a solid lubricant reducing frictional coefficient. More number of relatively smaller width brushes is preferred in place of large broad brushes.

The brush holders provide slots for the brushes to be placed. The connection Brush holder with a Brush and Positioning of the brush on the Commutator 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.



Figure 3.7: Bearing and Brush Holder

Other mechanical parts End covers, fan and shaft bearings form other important mechanical parts. 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.

3.1.2 Armature winding:

Two types of windings mostly employed for the armatures of DC machines are known as *Lap Winding* and *Wave Winding*. The difference between the two is merely due to the different arrangement of the coil connections at the front or commutator end of armature. The following rules, however, apply to both types of the winding:

Double layer lap or wave windings are generally used for armature. Essentially all the armature coils are connected in series forming a closed armature circuit. However as the coils are distributed, the resultant voltage acting in the closed path is zero thereby ensuring no circulating current in the armature. The junctions of two consecutive coils are terminated on to the commutator segments. Stationary carbon brushes are placed physically under the center of the stator poles touching the rotating commutator segments.

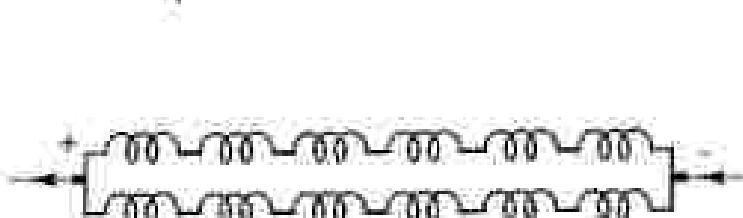
Number of parallel paths in armature, $n = P$, for LAP winding
and $n = 2$, for WAVE winding.

Lap Winding	Wave Winding
Number of parallel paths (n) = poles (P)	Number of parallel paths (n) = 2 (always)
Number of brush sets required is equal to number of poles	Number of brush sets required is always equal to two
Preferable for high current, low voltage capacity generators	Preferable for high current, low current capacity generators
Normally used for generators of capacity more than 500 A	Preferred for generator of capacity less than 500 A

3.2 Key Points:

- In DC machine all the armature coils are connected in series, for which it is known as series or close winding.
- It is the brush, whose presence divides the coil into multiple parallel paths. So for a wave winding always 2 brushes are used, whereas in Lap winding no. of brushes are same as that of the no. of poles. Hence, the no. of parallel paths is equal to the no. of brushes.
- No. of coils in a parallel path are always same, whereas the coils changes their position from one parallel path to other.
- Direction of current in a coil gets reversed when it passes a brush.
- Direction of current in a conductor also gets reversed as it moves from one pole to another, for which in circuit representation brushes are placed in the inter-polar region.
- Average value of voltage in each coil irrespective of the parallel path remaining same. Whereas the instantaneous voltage in a coil depends on its current position w.r.t a pole.

- The magnitude of current in each parallel path is same, but the magnitude of voltage is different in each coil, depending on its position.
- For simplex wave winding always there are 2 brushes, whereas for simplex lap winding it is the no. of poles.



Coil arrangement in wave winding.



Coil arrangement in lap winding.

- Armature winding is so designed that, when current circulates, it produces same number of poles as in field.

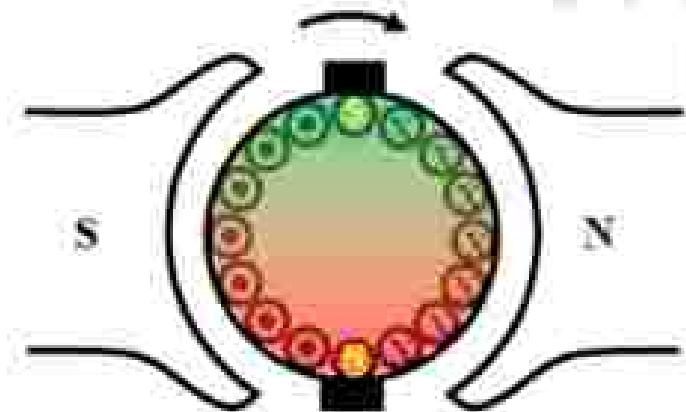


Figure 3.8: A 2-pole DC Machine

- An armature winding designed for 2 poles cannot be used in a 4-pole machine.
- In general a large number of armature coils are used and the armature is in motion. Therefore, if we take a snap shot of the armature at any arbitrary time, we would expect half of the coil sides will be under the North Pole and remaining half will be under South Pole. So distribution of emfs and their polarities in space will remain unchanged. However, positions of the coils will change as armature is rotating. Stationary observers at positions A₁ and A₂ will always conclude -ve polarity at A₁ and +ve polarity at A₂, no matter which junctions are passing through A₁ and A₂.

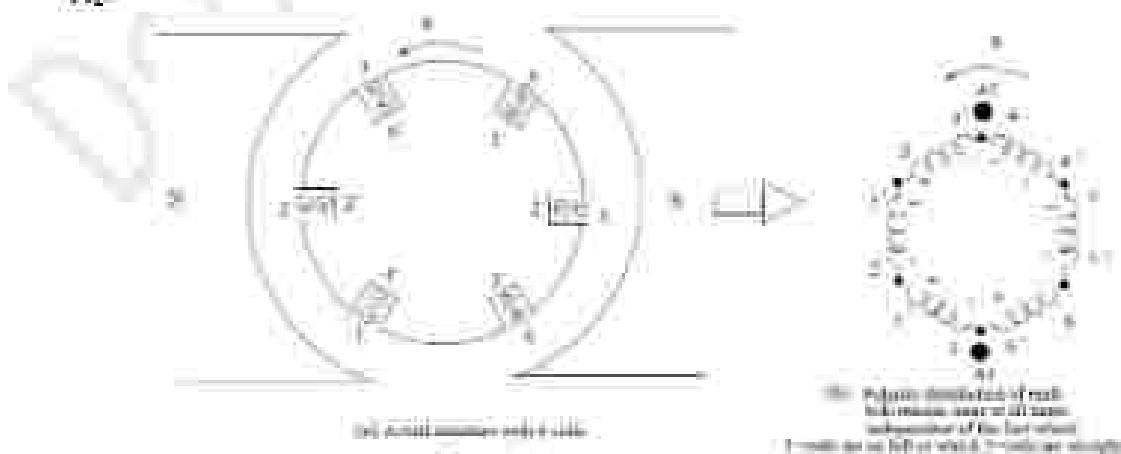


Figure 3.9: Armature having six slots

4. D.C machine Armature Winding

Armature winding of a D.C machine is always closed and of double layer type. Closed winding essentially means that all the coils are connected in series forming a closed circuit. The junctions of the consecutive coils are terminated on copper bars called commutator segments. Each commutator segment is insulated from the adjacent segments by mica insulation.

4.1 Terminologies in Armature Winding:

For reasonable understanding of armature winding, let us first get acquainted with the following terminologies.

Conductor: Active length of winding wire or strip in slot, which take part in energy conversion.

Turn: Two consecutive series conductors form a turn. The two turns placed inside separate slots on the armature periphery approximately a pole pitch apart. These conductors be under opposite poles so that emf induced in them is additive.

Coil: It is a set/bunch of turns placed in two specific slots.

Coil-side: Set of conductors from a single coil placed in a slot.

- A coil consists of two coil sides, upper or lower coil sides placed in two different slots, approximately a pole pitch apart (180° electrical) two maximize induced voltage.
- This essentially means if at a given time one coil side is under the center of the North Pole, the other coil side should be under the center of the South Pole.

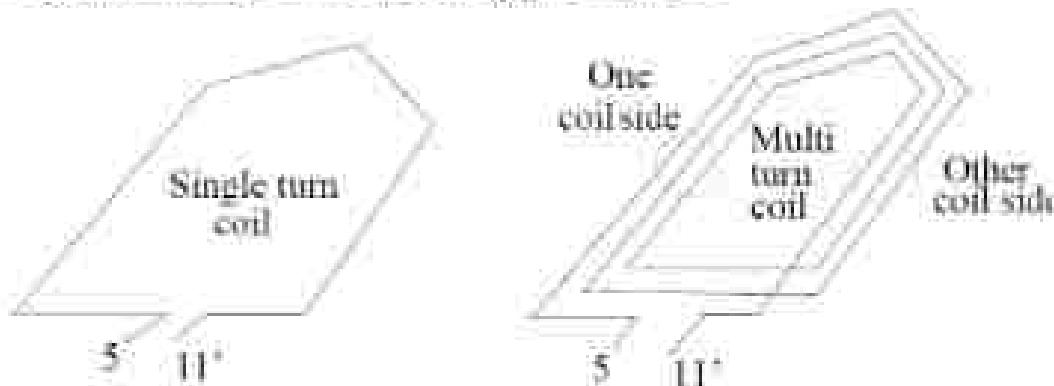


Figure 4.1: Single turn & Multi turn coil.

Coil span: It is the spacing between the two coil sides of a coil.

- The spacing is expressed in terms of number of slots between the sides.
- If 'S' is the total number of slots and 'P' is the total number of poles then, coil span is S/P .
- For 20 slots, 4 poles winding, coil span is 5. Let the slots be numbered serially as 1, 2, ..., 20. If one coil side is placed in slot number 3, the other coil side of the coil must occupy slot number 8 ($= 3 + 5$).

Over-hang: End portion of coil connecting the two conductors or coil sides is called overhang winding.

- No emfs induced in this part, it only allow the current to flow from one conductor to another.

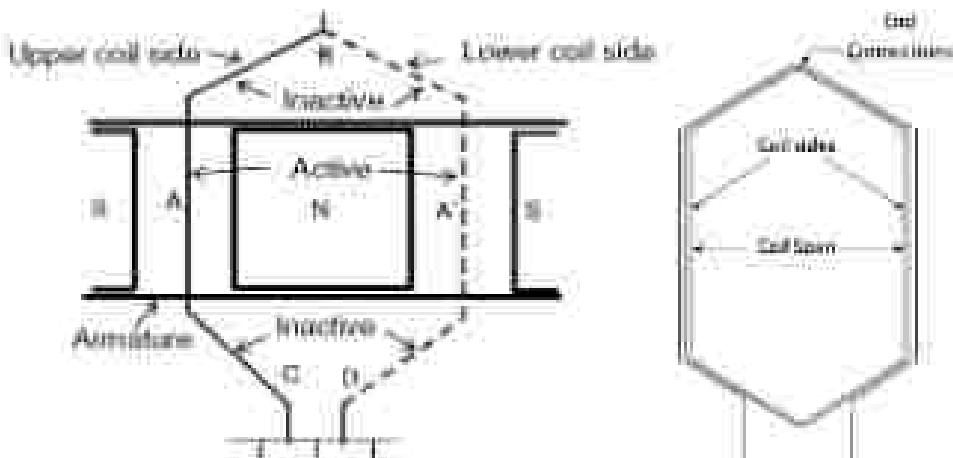


Figure 4.2: Armature coil

Pole-pitch: It is the peripheral distance between two adjacent poles of a machine. Generally, it is measured in terms of number of armature slots per pole. If there are 40 slots and 4 poles, then pole pitch is $40/4 = 10$ slots. It is always 180° electrical.

Length of machine = L ,
perpendicular to the screen.
Arc under each pole = $\pi RL/p$

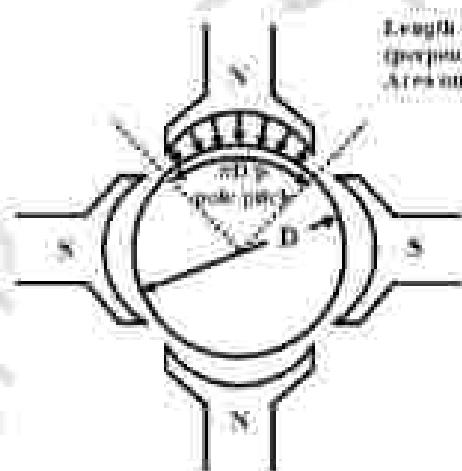


Figure 4.3: 4-Pole Armature

Full Pitch Coil: if the coil span is exactly equal to a pole pitch (=slots/pole) then it is full pitched coil. For a full pitch coil if one coil side is under 'N' pole other has to be under 'S' pole always.

Short Pitched coil/Chorded coil: If the coil span is not equal to a pole pitch (usually less only) then it is called Short pitched coil.

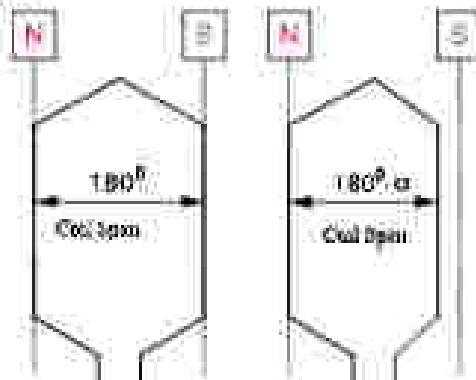


Figure 4.4: Full pitched and short pitched coil

Developed diagram:

Instead of dealing with circular disposition of the slots, it is always advantageous to work with the developed diagram of the armature slots and the commutator segments. As shown in figure 7, imagine the structure to be cut radially along the line XX'0 and unfolded along the directions shown, the resulting figure is known as developed diagram.

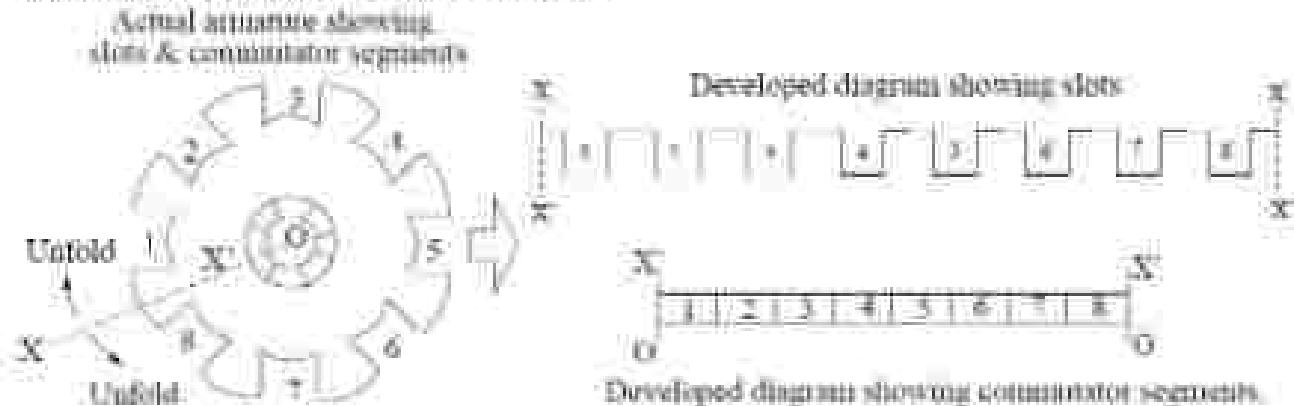


Figure 4.5: Actual and developed diagram of armature and commutator segments.

Concentrated coil: In this type of coil, all the turns belong to the coil placed in same location or in two slots only. DC Machine field winding, Transformer coils are example of this type of winding.

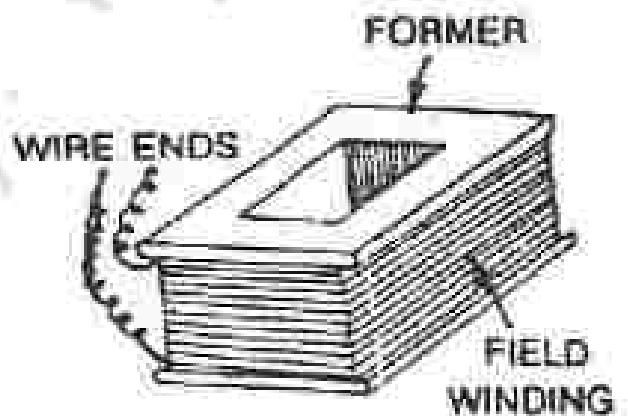


Figure 4.6: Concentrated Coil

Distributed Coil: The turns of the coil are uniformly distributed over the entire circumference, and also uniformly in all the slots. All Armature windings are distributed in nature.



Figure 4.7: Distributed Coil

Single-Layerwinding: Winding having one coil side in each slot.

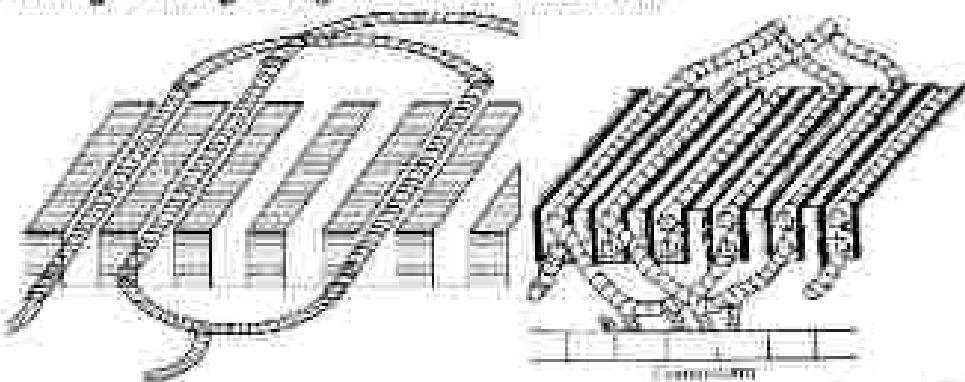


Figure 4.8: Single layer coil & Double layer coil

Double layer winding: Winding in which each slot houses two coil sides belonging to two different coils known as double layer winding.

- Physically one coil side is placed in the lower portion of the slot while the other is placed above it, to bring more mechanical strength to machine.
- In the n^{th} slot, coil side in the upper deck is numbered as ' n ' and the coil side in the lower deck is numbered as ' n' . In the 5th slot upper coil side is numbered as 5 and the lower coil side is numbered 5.
- In the winding diagram, upper coil side is shown with firm line while the lower coil side is shown with dashed line.
- If 'S' is the no. of slots in a machine then number of coils is $\frac{S}{2}$ for single layer winding, whereas it is S for double layer winding.
- In the developed diagram the upper coil side present in slot number x is shown by firm line and named x while lower coil side is shown by a dashed line (just beside the upper coil side) and named as x' .

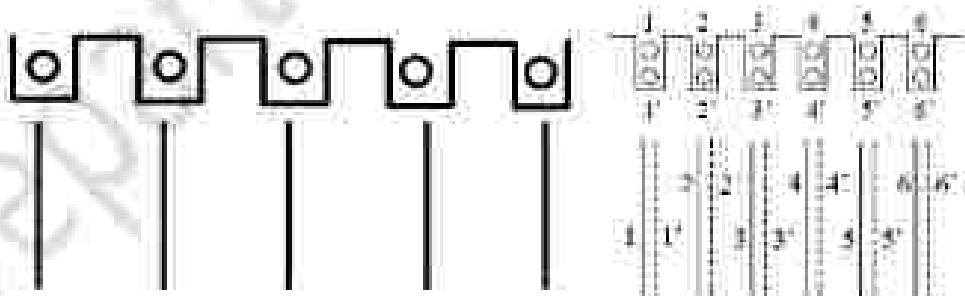


Figure 4.9: Front and Top view of single & Double Layer Coil

Numbering a coil: For a double layer winding if one coil side will be in the upper deck then the other side will be in the lower deck. Suppose $S = 20$ and $P = 4$, then coil span is 5.

Let the upper coil side of this coil be placed in slot number 6, the other coil side must be in the lower deck of slot number 11. The coil should now be identified as (3-11'). In other words coil sides of a coil are numbered depending on the slot numbers in which these are placed.

Slot angle/ Slot Pitch: Angular distance covered by a slot is slot angle. It is measured in electrical degrees.

$$\text{slot angle}(\gamma) = \frac{\text{Total electrical angle}}{\text{No. of slots}} = \frac{\frac{P}{2} \times 360^\circ}{S}$$

$$\text{No. of slots per pole} = \frac{S}{p}$$

$$\text{Cover } 180^\circ \text{ electrical, hence slot angle}(\gamma) = \frac{180^\circ}{\frac{S}{p}}$$

Simplex and Multiplex Winding:

In DC Machine armature windings, there are several sets of completely closed and independent windings. If there is only one set of closed winding, it is called simplex winding. If there are two such windings on the same armature, it is called duplex winding and so on. The multiplicity affects the number of parallel paths in the armature. For a given number of armature slots and coils, as the multiplicity increases, the number of parallel paths in the armature increases thereby increasing the current rating but decreasing the voltage rating.

In simplex lap winding, the number of parallel paths is equal to the pole. In duplex lap winding the pole is twice to that of a parallel path. In general numbers of parallel paths are

$$A = m * 2; \text{ for Wave winding}$$

$$= m * p; \text{ for Lap Winding}$$

Where, m=Multiplexing

Commutator pitch: As discussed earlier, the free ends of the coil sides of a coil (say S-11') are to be terminated on to two specific commutator segments. The separation of coil sides of a coil in terms of number of commutator segments is called the commutator pitch (y_c). In fact the value of y_c decides the types of winding (lap or wave) which will result.

In case of lap winding $y_c = \pm m$

$$\text{Wave winding, } y_c = \frac{2(s+m)}{p}, m = 1, 2, 3, 4, \dots$$

Where; y_c is the commutator pitch, m is the order of the winding.

For m = 1 we get a simplex winding.

m = 2 gives duplex winding etc.

$y_c = m$, gives a multiplex winding of order m.

The sign refers to the direction of progression of the winding. Positive sign is used for 'progressive' winding and the negative sign for the 'regressive' winding.

- On a Commutator segment, two coil sides (belonging to two different coils) terminate. As being the total number of coil sides, number of commutator segments must be equal to S, is equal to number of slots. Commutator segments can also be numbered as 1, 2, ..., 20 in order to identify them clearly.
- The commutator segment to which one coil terminated, the next coil start from that commutator segment.

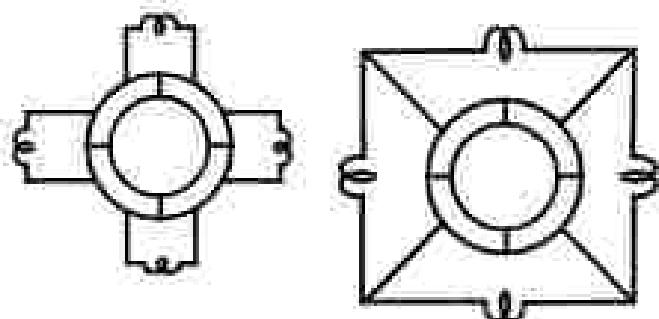


Figure 4.10: Commutator Segment

Progressive Winding: If the starting end of the loop is connected to the first commutator segment and ending end is connected to that commutator segment that is located next to the previous one, then it is progressive winding.

Retrogressive Winding: If the ending end is connected to the commutator segment that is behind the previous one, then this is retrogressive winding.

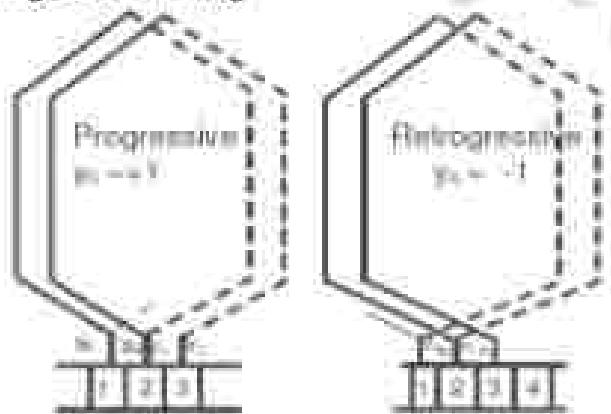


Figure 4.11: Progressive & Retrogressive Coil

Back pitch (Y_b): Distance between two coil sides of the coil at the back of the commutator is called back pitch. It is equal to the number difference of the conductors connected to a given segment of the commutator.

Front pitch (Y_f): Distance between finish of a coil and the starting of next coil, which are connected to same commutator segment, is called Front pitch.

Resultant pitch: Distance between starting of two consecutive coils is called resultant pitch (Y_r).

$$\text{For Lap Winding: } Y_r = Y_b - Y_f$$

$$\text{For Wave Winding: } Y_r = Y_b + Y_f$$

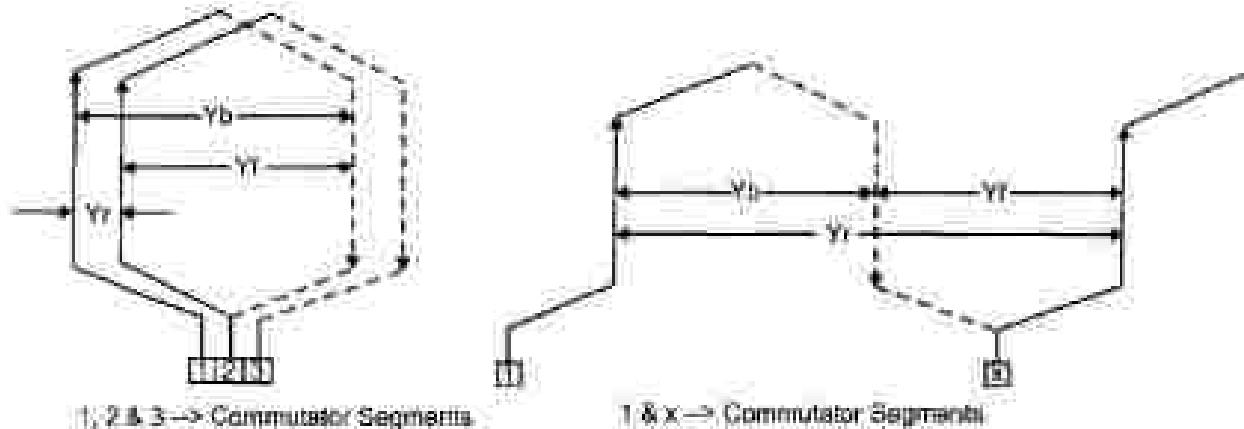


Figure 4.12: Front and Back Pitch

4.2 Armature winding: General procedure

1. Type of winding (lap or wave), total number of slots S and total number of poles P will be given.

2. Calculate coil span ($= S/P$).

3. Calculate commutator pitch y_c . For lap winding $y_c = \pm 1$

$$\text{and for wave winding } y_c = \frac{2(P+1)}{P}.$$

4. We have to complete the windings showing the positions of coil sides in slots, interconnection of the coils through commutator segments using appropriate numbering of slots, coil sides and commutator segments.

5. Finally to decide and place the stationary brushes on the correct commutator segments.

4.2.1 Lap winding

Let, the total number of slots = S

The total number of poles = P

- Total no. of commutator segments = S .

Total no. of coils = S (double layer winding)

Commutator Pitch $y_c = +1$ (simplex lap winding)

Example:

Suppose we want to make a lap winding for a 4 pole D.C. machine having a total number slots $S = 16$.

- So coil span is $16/4 = 4$.
- Commutator pitch of a progressive lap winding is $y_c = +1$.
- As the coil span is 4, the first coil has sides 1 and 5' ($= 1+4$) and the identification of the coil can be expressed as $(1 - 5')$.
- Let us terminate coil side 1 on commutator segment 1. The question now is where to terminate coil side 5' ? Since the commutator pitch y_c is +1, 5' to be terminated on commutator segment 2 ($= y_c+1$).

- In DC armature winding all coils are to be connected in series. So naturally next coil (2-6') should start from commutator segment 2 and the coil side 6' terminated on segment 3.
- It can be seen that the second coil 2-6' is in the lap of the first coil 1-5', hence the winding is called lap winding.
- The winding proceeds from left to right due to our assumption that $y_r = +1$. Such a winding is called progressive simplex lap winding. It can be easily shown that if y_r is chosen to be -1, the winding would have proceeded from right to left giving rise to a retrogressive lap winding.
- One can make first a winding table and then go for actual winding.

Winding Table

Coids	Commutator segment where coils to terminate
1-5'	1,2
2-6'	2,3
3-7'	3,4
4-8'	4,5
5-9'	5,6
6-10'	6,7
7-11'	7,8
8-12'	8,9
9-13'	9,10
10-14'	10,11
11-15'	11,12
12-16'	12,13
13-1'	13,14
14-2'	14,15
15-3'	15,16
16-4'	16,1

- The developed diagram of complete 16 slots with the commutator segments is given below.

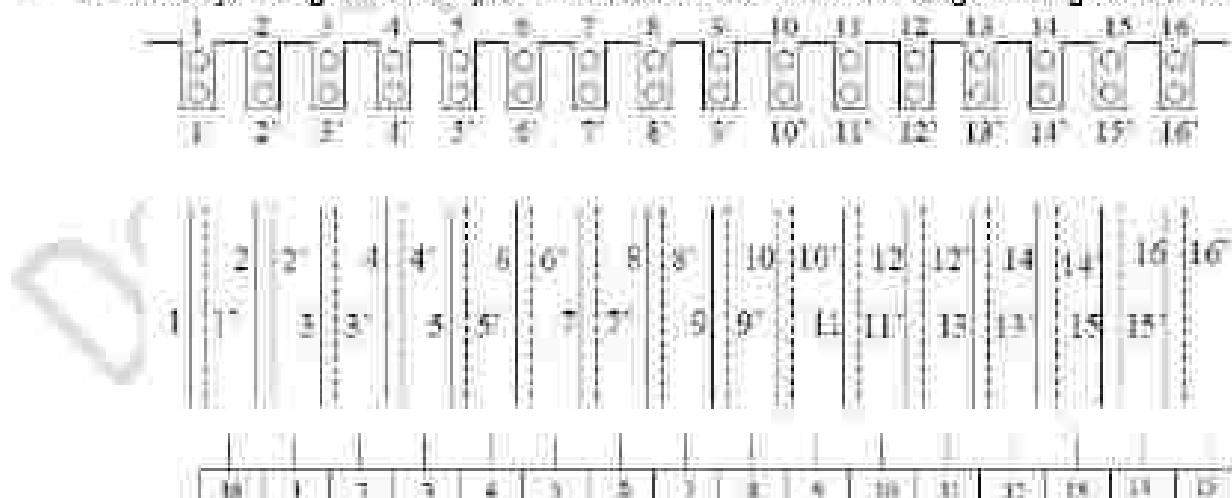


Figure 4.13: Developed diagram of the armature showing slots, coil sides & commutator segments.

- As explain above to start with the coil (1-5) will start from commutator segment 1 and terminate at 2, the second coil (2-6) will start from commutator segment 2 and terminate at 3 as shown in fig. below.

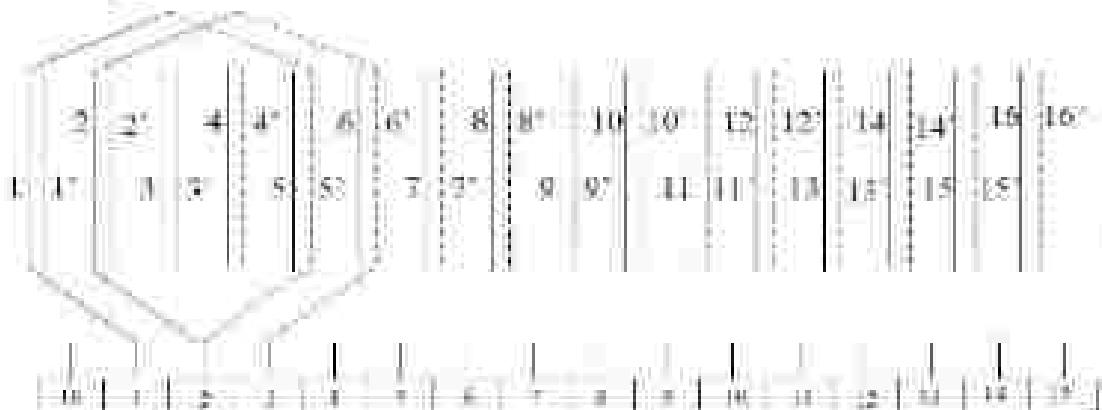


Figure 4.14: Starting a Lap winding.

The complete progressive lap winding refer to the winding table 14 shown in figure 4.15.

- To fix up the position of the brushes, let us assume the instant when slots 1,2,3 and 4 are under the influence of the North Pole which obviously means slots 5 to 8 are under South Pole, slots 9 to 12 are under North Pole and slots 13 to 16 under South Pole. The poles are shown with shaded areas above the active length (hs) (coil sides) of the coils.
- Considering generator mode of action and direction of motion from left to right (i.e., in clockwise direction of rotation of the actual cylindrical armature), we can apply right hand rule to show the directions of emf in each coil side by arrows as shown in figure 4.15.
- The emfs in the first four coils (1-5', 2-6', 3-7' and 4-8') are in the clockwise directions with coil side 8'-ve and 1 -ve. In the same way, 5 is +ve, 12 is -ve; 16 is +ve and 9 is -ve; 13 is +ve and 4 is -ve.

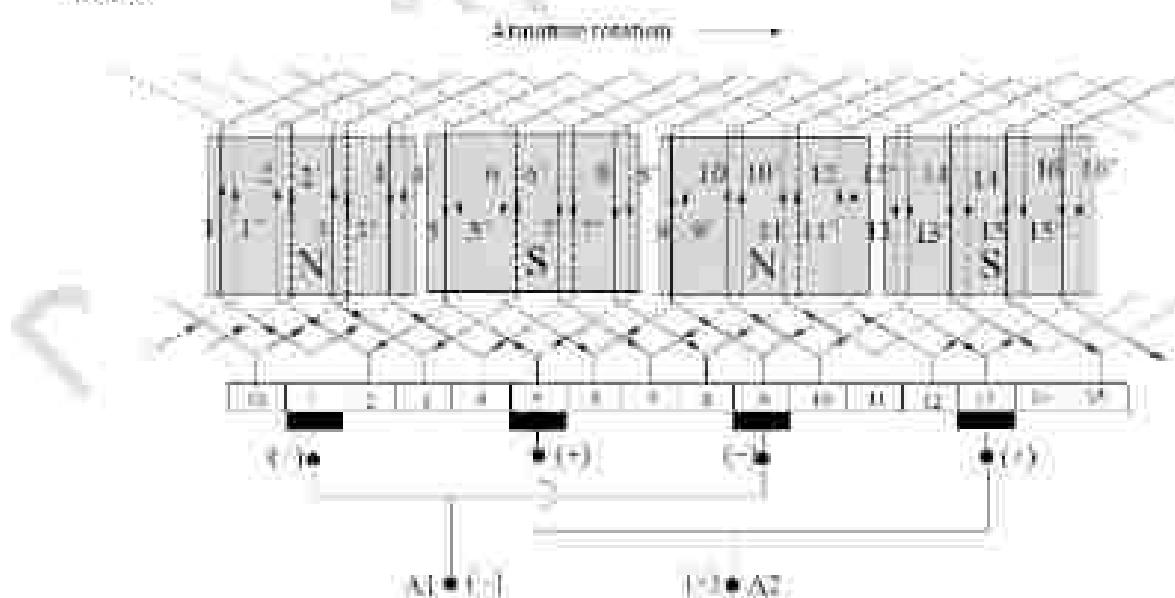


Figure 4.15: Complete simplex progressive lap winding.

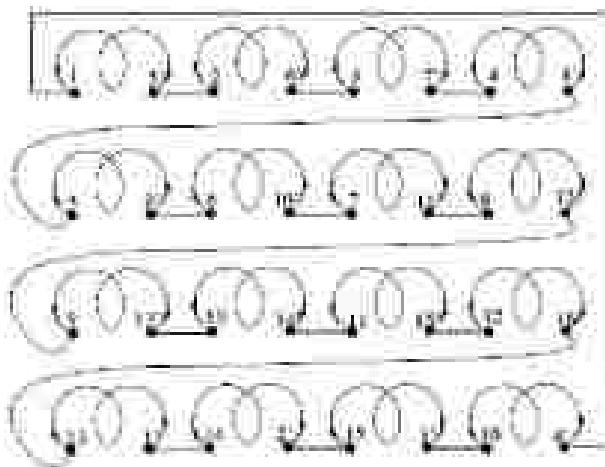


Figure 4.15. coil connections.

- Therefore, two +ve brushes may be placed on the commutator segment numbers 5 and 13; Two number of -ve brushes may be placed on commutator segment numbers 1 and 9. Two armature terminals A2 and A1 are brought out after shorting the +ve brushes together and the -ve brushes together respectively.
- Thus in the armature 4 parallel paths exist across A2 and A1. Careful look at the winding shows that physical positions of the brushes are just below the center of the poles. Also, worthwhile to note that the separation between the consecutive +ve and the -ve brushes is one pole pitch ($16/4 = 4$) in terms of commutator segments.
- In fact for a P polar machine using lap winding, number of parallel paths $x = P$. Therefore, in a lap winding number of brushes will always be equal to the number of poles.

4.2.2 Wave winding:

In this winding the coil sides of a coil is not terminated in adjacent commutator segments, i.e., $y_c \neq 1$. Instead y_c is selected to be closely equal to two pole pitch in terms of commutator segments.

Mathematically, $y_c = \frac{12}{P}$.

Let us attempt to make a wave winding with the specifications $S = 16$ and $P = 4$. Obviously, coil span is 4 and $y_c = 3$. The first coil is (1-3) and is terminated on commutator segments 1 and 9. The second coil (9-13) is to be connected in series with the first and to be terminated on commutator segments 9 and 1 (i.e. 17). Thus we find the winding gets closed just after traversing only two coils which is not possible to carry on with the winding. Our inability to complete the wave winding will persist if S receives a multiple of P . It is because of this reason expression for commutator pitch y_c is modified to $y_c = \frac{3(2t+1)}{P}$.

In other words, number of slots, should be such that $\frac{2t+1}{P}$ should be multiple of P . It can be shown that if +ve sign is taken the result will be a progressive wave winding and if -ve sign is taken the result will be retrogressive wave winding.

Example

We have seen that for 4-pole wave winding, choice of $S = 16$ is no good. Let us choose number of slots to be 17 and proceed as follows:

No. of poles, $P = 4$

No. of slots, $S = 17$

Winding pitch, $y_c = \frac{16(2+1)}{4}$ (choosing +1 for progressive winding)

$$\therefore y_c = 2(17 + 1)/4 = 9$$

Coil span = S/D = 4

Winding table	
Coils	Commutator segment where coils to terminate
1-5	1, 10
10-14	10, 2
2-6	2, 11
11-15	11, 3
3-7	3, 12
12-16	12, 4
4-8	4, 13
13-17	13, 5
5-9	5, 14
14-1	14, 6
6-10	6, 15
15-2	15, 7
7-11	7, 16
16-3	16, 8
8-12	8, 17
17-4	17, 9
9-13	9, 1

- Following similar procedure as Lap winding, the coil (1-5) will start from commutator segment 1 and terminate at 10, the second coil (10-14) will start from commutator segment 10 and terminate at 2 as shown in fig. 4.17 below. A look at those two coils suggests that the winding progresses like a wave - hence the name wave winding.

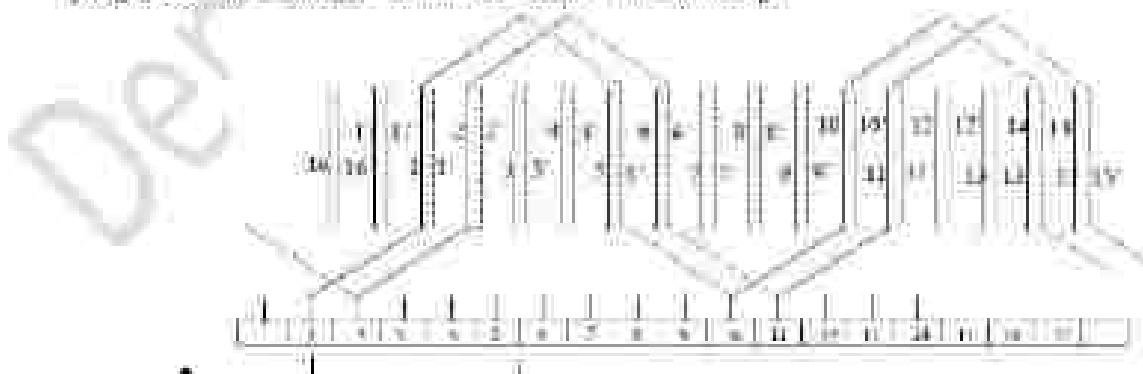


Figure 4.17: Starting a simplex progressive wave winding.

The complete progressive wave winding refer to the winding table is shown in figure 4.18.

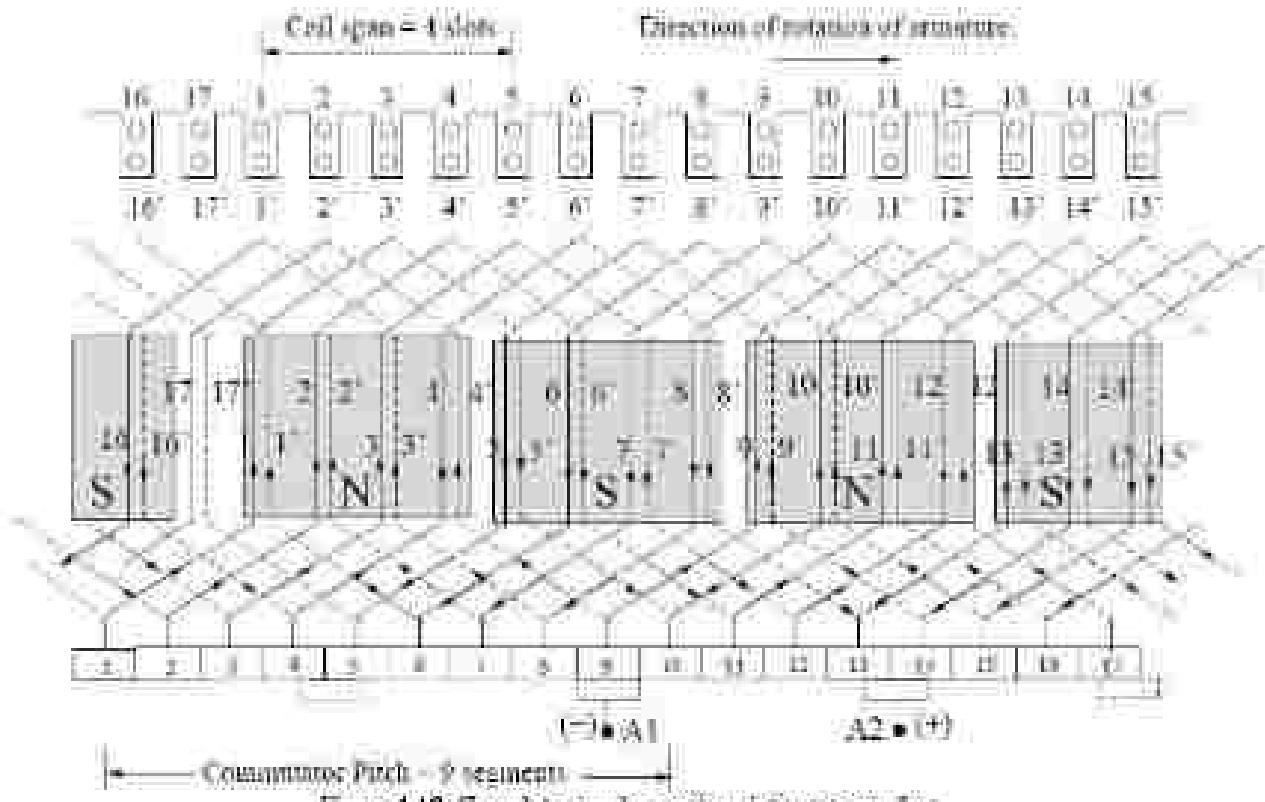


Figure 4.18: Complete simplex progressive wave winding.

- To fix up the position of the brushes, assuming slots 1 to 4 and 9 to 12 to be under North Pole; slots 5 to 8 and 13 to 16 to be under South Pole. Since S/P is not an integer slot 17 has been assumed to be in the neutral zone. It is interesting to note that polarity of the induced emf reverses after nearly half of coils are traversed. So numbers of armature circuit parallel paths are two only.
- As a pair of brush divides the armature into two parallel paths. From the direction of emfs - ve brush can be placed on commutator segment 9 and the +ve brush can be positioned touching commutator segments 13 and 14.

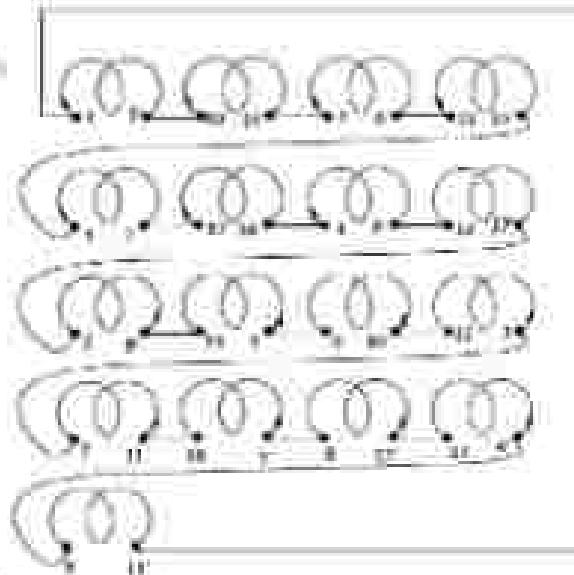


Figure 4.18: Wave winding coil connections.

- In a wave winding since number of parallel paths are 2, theoretically a pair of brushes is sufficient for armature independent of the number of poles of the machine. However, for relatively large armature current one can put additional brushes such that total numbers of brushes are equal to P thereby reducing the size of the brushes. For the 4 pole winding that we are considering, additional +ve brush can be placed over commutator segments 4 & 5 and another -ve brush can be placed over commutator segments 17 & 1 as shown with dotted boxes in figure 16.
- Series connection of all the coils is also shown in figure 4.19.

4.3 Equalizing Connections/Equalizer Ring:

We know that the armature circuit in lap winding of a multi-polar machine has as many parallel paths as the number of poles. Because of wear in the bearings, vibration and/or other reasons, the air gap in a generator become unequal and, therefore, the flux per pole becomes unequal. This causes the voltages of the different paths to be unequal. With unequal voltages in these parallel paths, circulating current will flow even if no current is supplied to an external load. If these currents are large, some of the brushes will be required to carry a greater current at full load than they were designed to carry and this will cause sparking.

To relieve the brushes of these circulating currents, points on the armature that are at the same potential are connected together by means of *copper bars called equalizer rings*.

Thus referring to Fig. 4.20, the coil 1-8 and 13-20 occupies the same position relative to the poles; therefore the two coils are connected to the same equalizer ring. The equalizers provide a low resistance path for the circulating current. As a result, the circulating current due to the slight differences in the voltages of the various parallel paths passes through the equalizer rings instead of passing through the brushes.

This reduces sparking. Equalizer rings should be used only on windings in which the number of coils is a multiple of the number of poles.

Note: Equalizer rings are not used in wave winding because there is no imbalance in the voltages of the two parallel paths. This is due to the fact that conductors in each of the two paths pass under all N and S poles successively (unlike a lap winding where all conductors in any parallel path lie under one pair of poles).

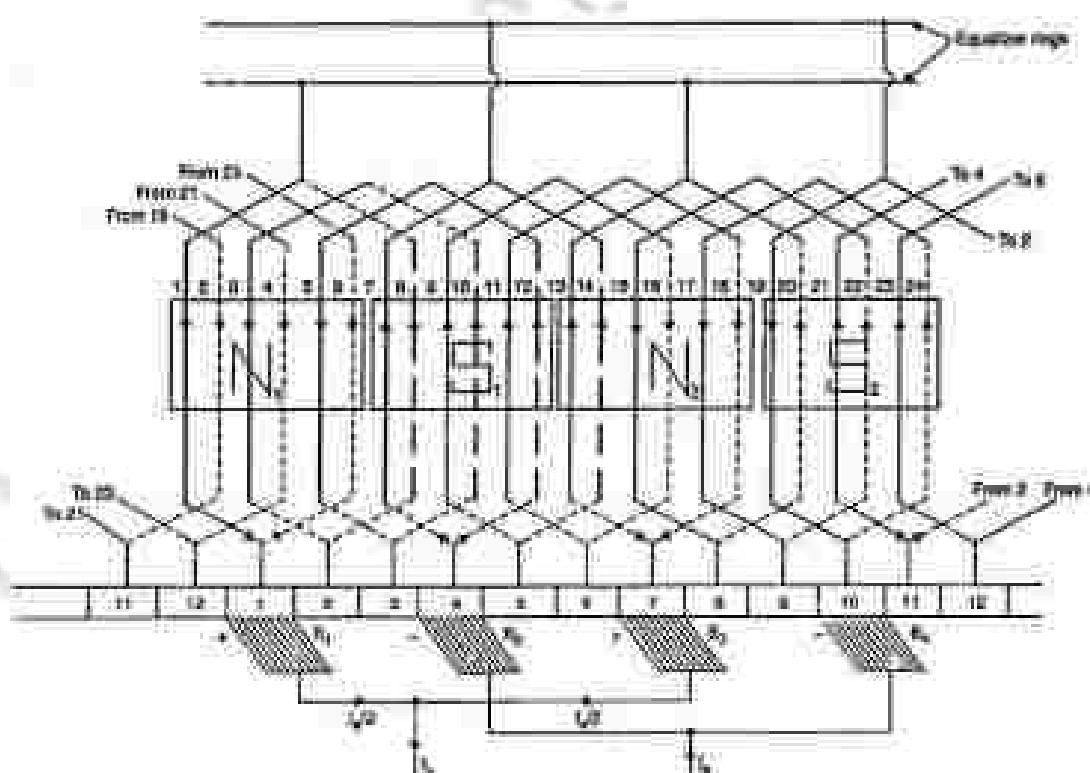


Figure 4.20 Armature winding with Equalizer Ring

4.4 Dummy coils and dummy commutator segments:

Due to the restrictions posed by lap and wave windings on the choice of number of slots and commutator segments a practical difficulty arises. Each machine with a certain pole number, voltage and power ratings may require a particular number of slots and commutator segments for a proper design. Thus each machine may be tailor made for a given specification. This will require stocking and handling many sizes of armature and commutator.

Sometimes due to the non-availability of a suitable slot number or commutator, one is forced to design the winding in an armature readily available in stock. Such designs, obviously, violate the symmetry conditions as armature slots and commutator segment may not match. If one is satisfied with approximate solutions then the designer can omit the surplus coil or surplus commutator segment and complete the design. This is called the use of a "dummy". All the coils are placed in the armature slots. The surplus coil is electrically isolated and taped. It serves to provide mechanical balance against centrifugal forces. Similarly, in the case of surplus commutator segment two adjacent commutator segments are connected together and treated as a single segment. These are called dummy coils and dummy commutator segments.



Figure 4.21: Dummy Coil

5.1 EMF Equation

Let us consider a D C generator whose field coil is excited to produce a flux density distribution along the air gap and the armature is driven by a prime mover at constant speed.

Let us assume:

- P: No of poles
- N: Speed at which driven in rpm
- Φ : flux per pole in wb.
- Z: Total number of armature conductors
= No. of slots × No. of conductors/slot
- A: The number of parallel paths in the armature circuit
- D: Diameter of the machine in meters
- L: length of the machine in meters
- E_s = e.m.f induced in any parallel path in armature

In general, the magnitude of the voltage from one conductor to another is likely to vary as flux density distribution is trapezoidal in nature. Therefore, total average voltage across the brushes is calculated on the basis of average flux density B_{av} .

5.1.1 Method-I: (Using BLV Concept)

$$\text{Average flux density } B_{av} = \frac{\text{total flux}}{\text{total area}} = \frac{\Phi}{\pi D L}$$

$$\text{The tangential velocity, } v = \frac{\pi D N}{60}$$

$$\text{Induced voltage in a single conductor (} E_{\text{single}}\text{)} = B_{av} I v = \frac{\Phi}{\pi D L} \cdot \frac{Z}{A} \cdot \frac{\pi D N}{60} = \frac{\Phi Z N}{60 A}$$

$$\text{Number of conductors present in each parallel path} = \frac{Z}{A}$$

Generated e.m.f. E_A = e.m.f. generated in any one of the parallel paths i.e. E_s

$$\text{Therefore, total voltage appearing across the brushes } E_s = \frac{\Phi Z N}{60 A} \left(\frac{Z}{A} \right)$$

$$\text{Thus voltage induced across the armature, } E_s = \frac{\Phi Z N}{60} \left(\frac{Z}{A} \right) = K_e \Phi N$$

$$\text{Where } K_e \text{ is known as anti-cuonstant of a D C machine and given by } K_e = \frac{Z I}{60 A}$$

Across the armature, a voltage will be generate so long there exist some flux per pole and the machine runs with some speed. Therefore irrespective of the fact that the machine is operating as generator or as motor, armature has an induced voltage in it given by, $\frac{\Phi Z N}{60} \left(\frac{Z}{A} \right)$. This emf is called back emf for motor operation.

5.1.2 Method-II:

$$\text{Average e.m.f. generated by conductor} = \frac{d\phi}{dt} \text{ Volt.} (\because n = 1)$$

Now, flux linkage per conductor in one revolution $\Phi = \Phi \text{ Wb}$

No. of revolutions/second = $N/60$

Hence, Time for one revolution, $dt = \frac{60}{N}$ second

Hence, according to Faraday's Laws of Electromagnetic Induction

$$\text{Induced voltage in a single conductor (E_{per conductor})} = \frac{d\Phi}{dt} = \frac{\Phi N}{60}$$

Number of conductors present in each parallel path = $\frac{Z}{A}$

Generated e.m.f. E_g = e.m.f. generated in any one of the parallel paths i.e. E

$$\text{Therefore, total voltage appearing across the brushes } E_g = \frac{\Phi N}{60} \left(\frac{Z}{A} \right)$$

$$\text{Thus voltage induced across the armature, } E_A = \frac{\Phi N}{60} \left(\frac{Z}{A} \right) = K_A \Phi N$$

For a simplex wave-wound generator:

No. of parallel paths = 2

No. of conductors (in series) in one path = $Z/2$.

$$\text{E.M.F. generated in any one of the parallel paths i.e. } E = \frac{\Phi N}{60} \left(\frac{Z}{2} \right) = \frac{\Phi N Z}{120}$$

For a simplex Lap-wound generator:

No. of parallel paths = P

No. of conductors (in series) in one path = Z/P

$$\text{E.M.F. generated in any one of the parallel paths i.e. } E = \frac{\Phi N}{60} \left(\frac{Z}{P} \right) = \frac{\Phi N Z}{60P}$$

In general:

$$E_A = \frac{\Phi N}{60} \left(\frac{Z}{A} \right)$$

Where A=2, for Wave Winding

=P, for Lap Winding

$$\text{EMF} = \frac{\Phi N}{60} \left(\frac{Z}{A} \right) = K_A \Phi N$$

$$\text{Where } K_A = \frac{Z}{60A}$$

per/pole

Therefore,

$$E_1 = K_1 N_1 \phi$$

$$E_2 = K_2 N_2 \phi_2$$

For constant field excitation, $I_{F1} = I_{F2} \Rightarrow \phi = \phi_1$

$$\frac{E_1}{E_2} = \frac{K_1 N_1 \phi_1}{K_2 N_2 \phi_1} = \frac{N_1}{N_2}$$

For constant speed operation, $N_1 = N_2$

$$\frac{E_1}{E_2} = \frac{K_1 N_1 \phi_1}{K_2 N_2 \phi_2} = \frac{I_{F1}}{I_{F2}}$$

5.1.3 Brush Contact Drop (V_b):

It is the voltage drop over the brush contact resistance when current passes from commutator segments to brushes. Its value depends on the amount of current and the value of contact resistance. This drop is usually small and includes brushes of both polarities. However, in practice, the brush contact drop is assumed to have following constant values for all loads:

- 0.5 V for metal-graphite brushes.
- 2 V for carbon brushes.

5.2 Classification of DC Machine:

The field circuit and the armature circuit can be interconnected in various ways to provide a wide variety of performance characteristics, which is an outstanding advantage of DC machines.

DC Machines are usually classified according to the way in which their fields are excited. It may be divided into

- (a) separately-excited generators and
- (b) Self-excited generators.

(a) In a separately excited generator field winding is energized from a separate voltage source in order to produce flux in the machine. So long the machine operates in unsaturated condition the flux produced will be proportional to the field current.

Field excitation may also be provided by *permanent magnet*. This may be considered as a form of separately excited machine, the permanent magnet providing the separate but constant excitation.

A separately excited dc motor is a motor whose field circuit is supplied from a separate constant-voltage power supply, while a shunt dc motor is a motor whose field circuit gets its power directly across the armature terminals of the motor.

When the supply voltage to a motor is assumed constant, there is no practical difference in behavior between these two machines. Unless otherwise specified, whenever the behavior of a shunt motor is described, the separately excited motor is included too.

(b) Self-excited: Machines are those whose field coils are energized by the current produced by the machine themselves. There are three types of self-excited generators named according to the manner in which their field coils (or windings) are connected to the armature.

(i) Shunt field coil has large number of turns, small cross sectional area and connected in parallel across the armature, hence the name shunt winding. Due to large number of turns, small cross sectional area it has high resistance so, it takes only a small current (less than 5% of the rated armature current).

(ii) Series field coil has low resistance, fewer numbers of turns with large cross sectional area and connected either in series with the armature or the line. It is meant to be connected in series with the armature and naturally to be designed for rated armature current.

At no load Field current is very small; however, field gets strengthened as load is connected. Variation in load causes the armature/field current to vary.

(iii) In compound machine the field poles are excited by two coils, both series field coil and shunt field. If the shunt winding is connected across the armature, it is known as *short-shunt* machine. In an alternative connection, the shunt winding is connected across the series connection of armature and series winding and the machine is known as *long-shunt* machine. There is no significant difference between these two connections. If series coil is left alone without any connection, then it becomes a shunt machine.

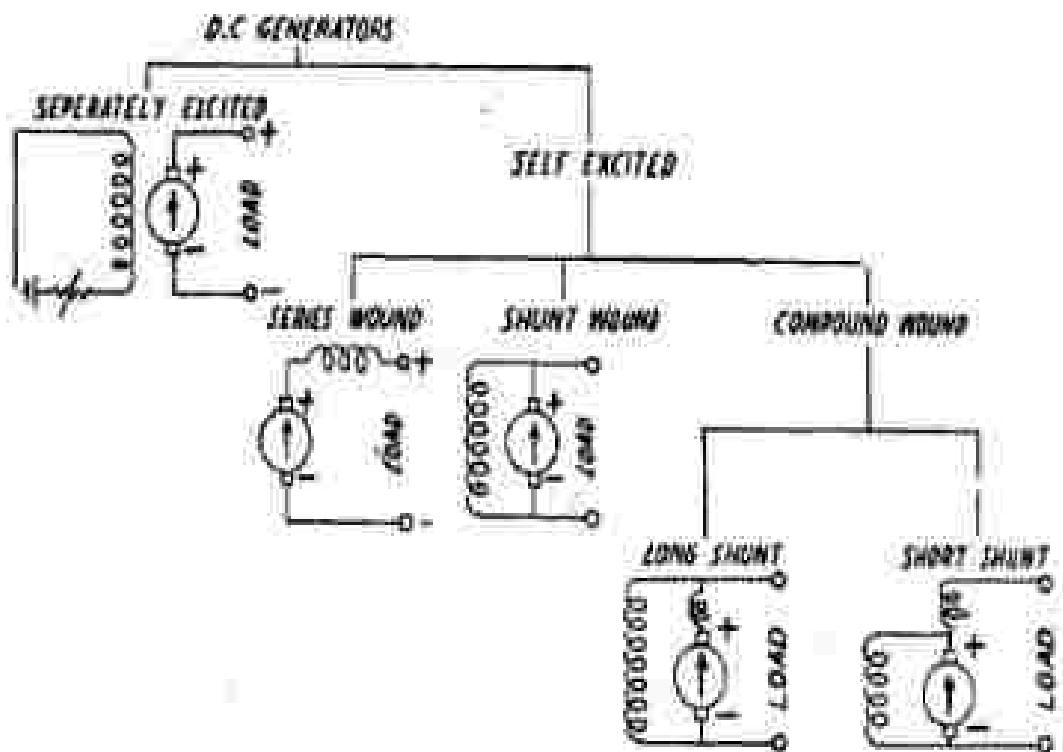
In a compound machine, the shunt field is stronger than the series field. Series field coil may be connected in such a way that the mmf produced by it aids the shunt field mmf – then the machine is said to be *cumulative compound* machine, otherwise if the series field mmf acts in opposition with the shunt field mmf – then the machine is said to be *differential compound* machine.

Based on degree of compounding again cumulative compound machine machines can be classified as

1. Over Compounding ($V_{no-load} > V_{no-load}$)
2. Flat Compounding ($V_{no-load} = V_{no-load}$)
3. Under Compounding ($V_{no-load} < V_{no-load}$)

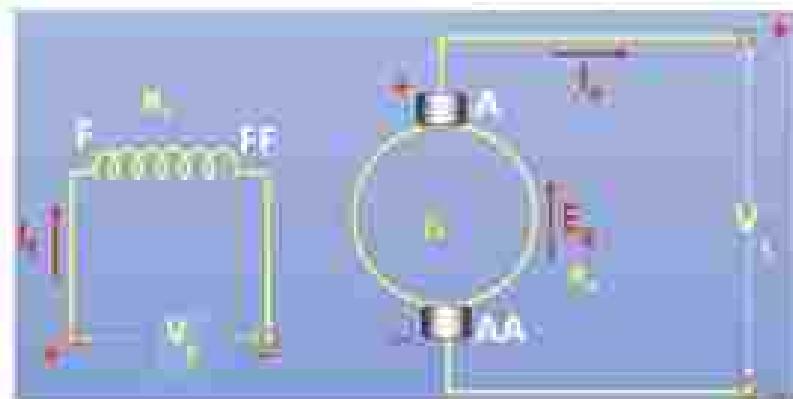


A rheostat is normally included in the circuit of the shunt winding to control the field current and thereby to vary the field mmf.



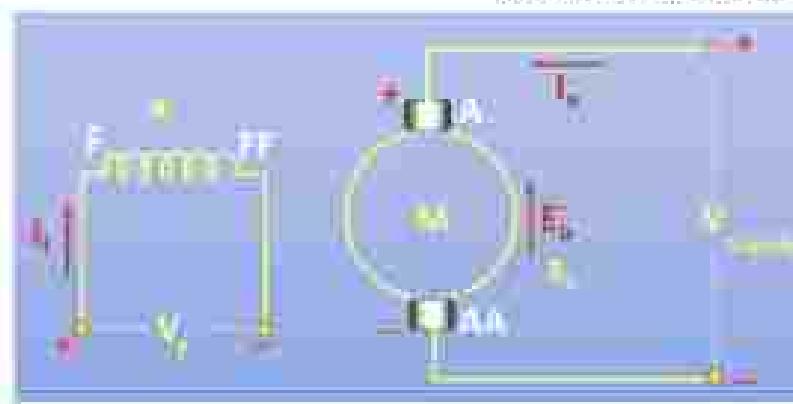
5.3 KVI. Equation of DC Machine:

Separately Excited Generator



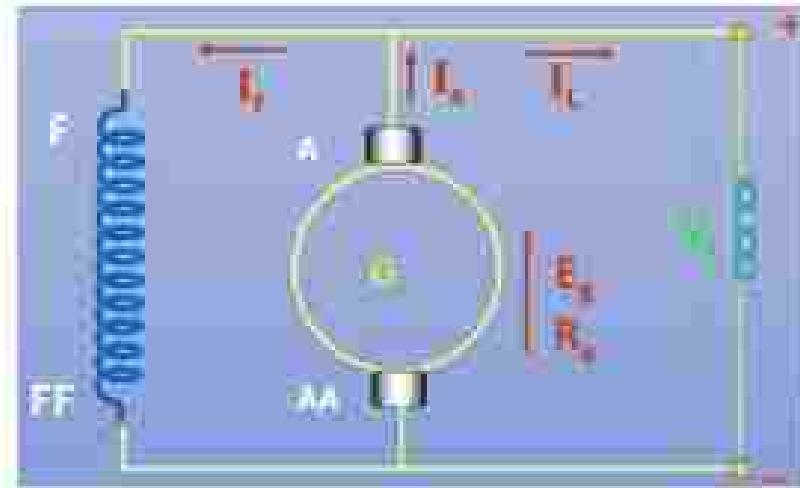
$$\begin{aligned}
 I_a &= I_L \\
 I_L &= \frac{V}{R_L} \\
 E_a - I_a R_a - V_s &= V_i \\
 \Rightarrow I_a E_a - I_a^2 R_a - I_a V_s &= V_i I_a \\
 \Rightarrow E_a I_a - V_s I_a + (I_a^2 R_a + I_a V_s) &= V_i I_a \\
 P_{in} = E_a I_a ; P_{loss} = V_s I_a ; P_{loss} &= I_a^2 R_a + I_a V_s
 \end{aligned}$$

Separately Excited Motor



$$\begin{aligned}
 I_a &= I_L \\
 E_a &= V_i - I_a R_a - V_s \\
 \Rightarrow I_a E_a &= V_i I_a - I_a^2 R_a - I_a V_s \\
 \Rightarrow V_i I_a &= E_a I_a + (I_a^2 R_a + I_a V_s) \\
 P_{in} = P_{mechanical} &= E_a I_a ; P_{in} = V_i I_a \\
 P_{loss} &= I_a^2 R_a + I_a V_s
 \end{aligned}$$

Shunt Generator



$$I_a = I_L + I_s$$

$$I_L = \frac{V_i}{R_L}, I_s = \frac{V_i}{R_s}$$

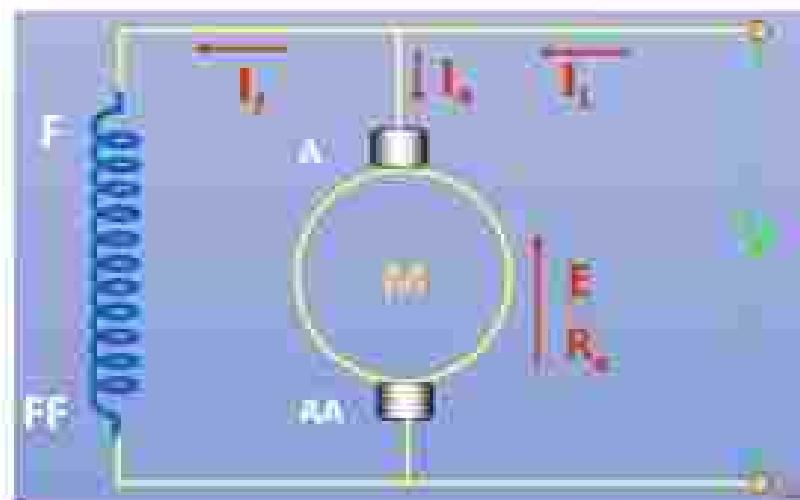
$$E_g - I_s R_s - V_b = V_i$$

$$\Rightarrow I_s E_g - I_s^2 R_s - I_s V_b = V_i I_s$$

$$\Rightarrow E_g I_s = V_i I_s + (I_s^2 R_s + I_s V_b)$$

$$P_{loss} = E_g I_s, P_{out} = V_i I_s, P_{gen} = I_s^2 R_s + I_s V_b$$

Shunt Motor



$$I_L = I_s + I_a$$

$$I_s = \frac{V_i}{R_s}$$

$$E_m = V_i - I_s R_s - V_a$$

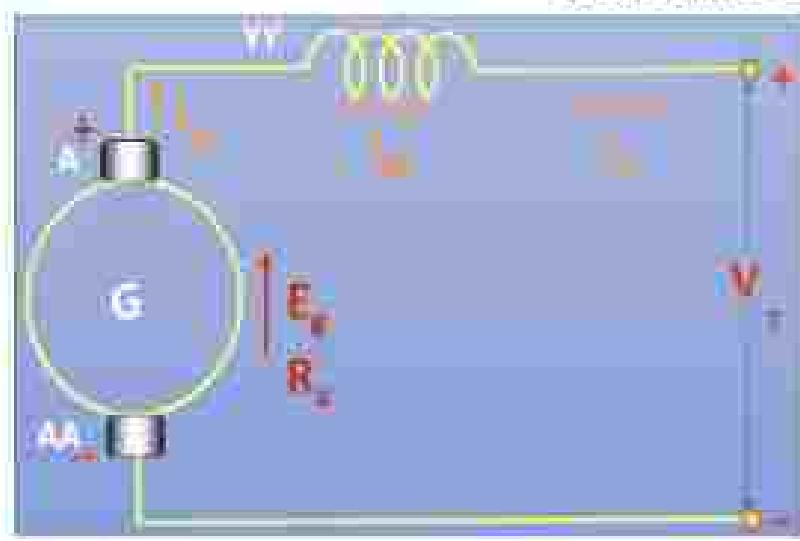
$$\Rightarrow I_a E_m = V_i I_a - I_a^2 R_s - I_a V_a$$

$$\Rightarrow V_a I_a = E_m I_a + (I_a^2 R_s + I_a V_i)$$

$$P_{loss} = P_{internal\ loss} = E_m I_a, P_{in} = V_i I_a$$

$$P_{load} = I_a^2 R_s + I_a V_i$$

Series Generator



$$I_s = I_L = I_a$$

$$I_L = \frac{V_i}{R_L}$$

$$E_g - I_a (R_s + R_w) - V_b = V_i$$

$$\Rightarrow I_a E_g - I_a^2 (R_s + R_w) - I_a V_b = V_i I_a$$

$$\Rightarrow E_g I_a = V_i I_a + I_a^2 (R_s + R_w) + I_a V_b$$

Series Motor



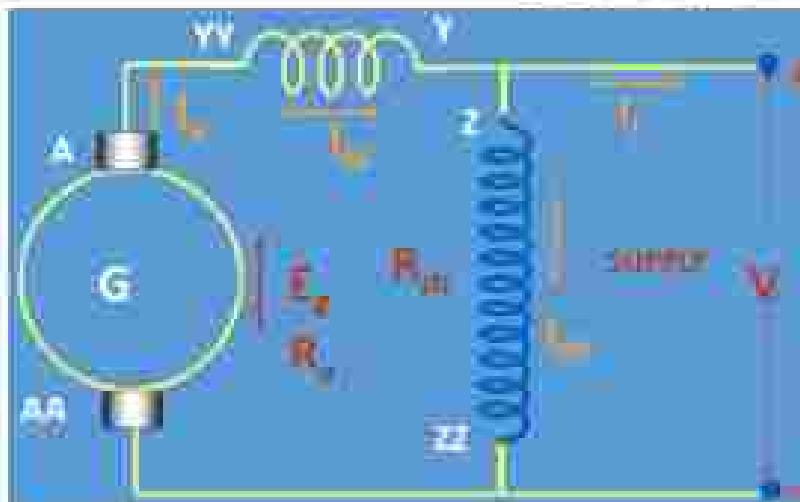
$$I_s = I_L = I_a$$

$$E_b = V_i - I_s(R_s + R_a) - V_b$$

$$\Rightarrow I_s E_b = V_i I_s - I_s^2(R_s + R_a) - I_s V_b$$

$$\Rightarrow V_i I_s = E_b I_s + I_s^2(R_s + R_a) + I_s V_b$$

Long Shunt Generator



$$I_s = I_L + I_a$$

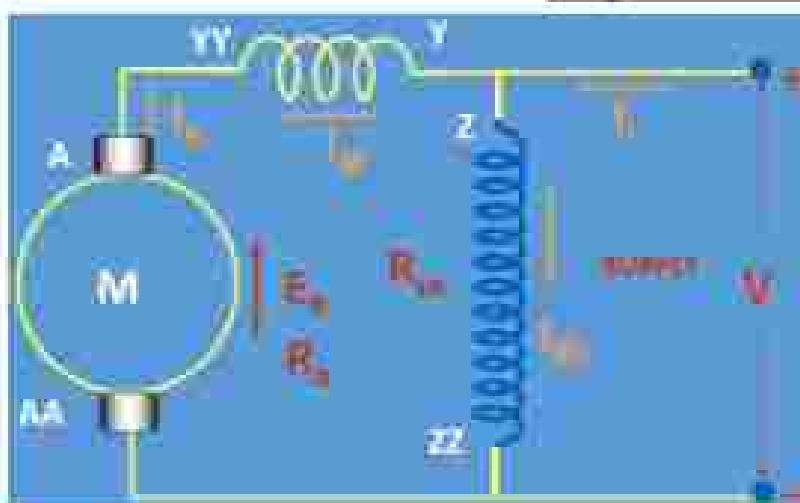
$$I_L = \frac{V}{R_L}, I_a = \frac{V}{R_a}$$

$$E_g = I_a(R_a + R_s) - V_b = V_i$$

$$\Rightarrow I_s E_g - I_s^2(R_a + R_s) - I_s V_b = V_i I_s$$

$$\Rightarrow E_g I_s = V_i I_s + I_s^2(R_a + R_s) + I_s V_b$$

Long Shunt Motor



$$I_L = I_s + I_a$$

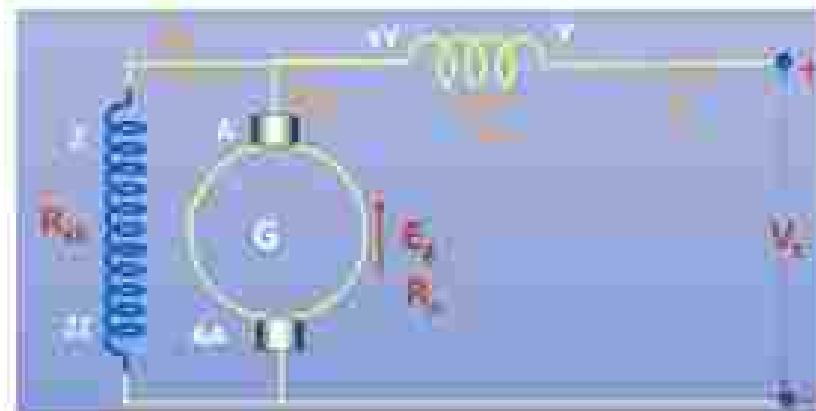
$$I_a = \frac{V}{R_a}$$

$$E_g = V_i - I_s(R_s + R_a) - V_b$$

$$\Rightarrow I_s E_g = V_i I_s - I_s^2(R_s + R_a) - I_s V_b$$

$$\Rightarrow V_i I_s = E_g I_s + I_s^2(R_s + R_a) + I_s V_b$$

Short Shunt Generator



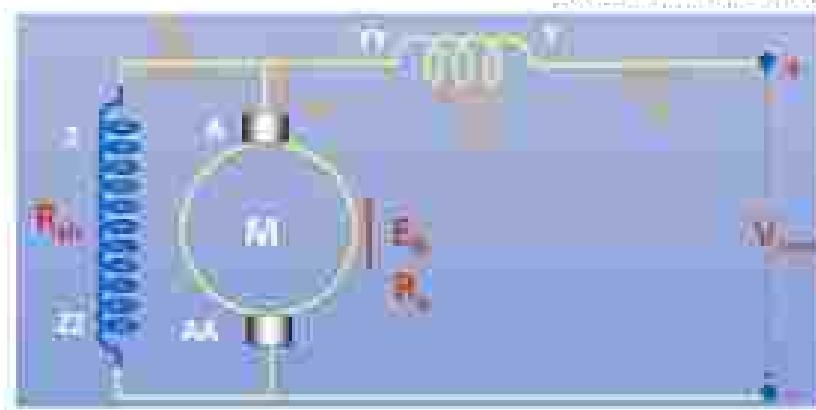
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$$I_L = \frac{V_o}{R_o}$$

$$E_a - I_a R_a - I_b R_b = V_b$$

$$I_s = \frac{V_s + I_s R_s}{R_{in}} = \frac{E_s - I_s R_s - V_s}{R_{in}}$$

Short Shunt Motor



$$G_1 = G_0 + \epsilon$$

$$E_i = V_i - I_i R_i - I_o R_o - V_o$$

$$I_{AB} = \frac{V_i - I_A R_o}{R_B} = \frac{E_F + I_A R_o - V_A}{R_B}$$

3.4 Condition for Maximum Power

Thus mechanical power developed by a motor is maximum when back *EMF* (E_b) is equal to half the applied voltage. This condition is, however, not realized in practice, because in that case current would be much beyond the normal current of the motor. Moreover, half the input would be wasted in the form of heat and taking other losses (mechanical and magnetic) into consideration, the motor efficiency will be well below 50 percent.

5.4.1 Generating Mode of Operation

$$\Rightarrow E_1 = \gamma^{\ast} R = E_1$$

$$\Rightarrow P_{\text{in}} = E_{\text{in}} - I^{\text{in}} R_{\text{in}}$$

Differentiating the above equation with respect to t , and equating to zero, we get

$$\frac{\delta P_{\text{ext}}}{\delta I} = E_1 - 2I_1 R = 0$$

$$\Theta_1 = \frac{E_1}{2E_2}$$

Replacing λ in equation (1), we get

$$E_s - \frac{R_s}{2R} R_o = V_t$$

$$\Rightarrow E_s - \frac{E_t}{2} = V_t$$

$$\Rightarrow \frac{E_t}{2} = V_t$$

$$\boxed{\frac{E_t}{2} = V_t} \Rightarrow \text{Condition for Maximum Power}$$

5.4.3 Motoring Mode of Operation:

$$E_s = V_t - I_s R_s \quad (\text{Neglecting } V_d) \quad (2)$$

$$\Rightarrow I_s E_s = V_t I_s - I_s^2 R_s$$

$$\Rightarrow P_{\text{max}} = V_t I_s - I_s^2 R_s$$

Differentiating the above equation with respect to I_s and equating to zero, we get

$$\frac{\delta P_{\text{max}}}{\delta I_s} = V_t - 2I_s R_s = 0$$

$$\Rightarrow I_s = \frac{V_t}{2R_s}$$

Replacing I_s in equation (2), we get

$$E_s = V_t - \frac{V_t}{2R_s} R_s$$

$$\Rightarrow E_s = V_t - \frac{V_t}{2}$$

$$\Rightarrow E_s = \frac{V_t}{2}$$

$$\boxed{E_s = \frac{V_t}{2}} \Rightarrow \text{Condition for Maximum Power}$$

Efficiency during Maximum power:

$$P_{\text{max-power}} = \frac{V_t^2}{4R_s}; \quad \because E_s I_s = \frac{V_t}{2} \times \frac{V_t}{2R_s}$$

$$P_s = V_t I_s = \frac{V_t^2}{2R_s}$$

$$\eta = \frac{P_{\text{max-power}}}{P_s} \times 100\% = 50\%$$

Hence machines are never operated at maximum output power condition as it is only 50%, and other half is loss.

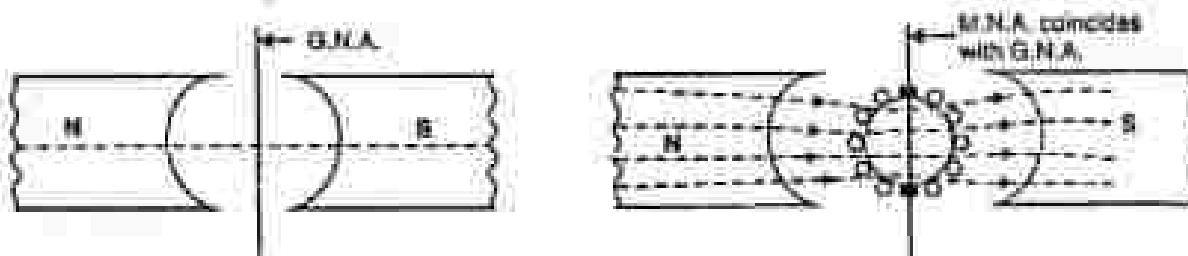
All the machines are designed to operate nearly at rated condition with better efficiency.

Polar axis: It is the line joining the centres of N-S poles

Magnetic neutral axis (M.N.A.) is defined as the "axis along which no emf is produced in the armature conductors" because they move parallel to the lines of flux. Or "it is the axis which is perpendicular to the resultant flux passing through the armature".

The magnetic neutral plane can also be defined as "the plane within the machine where the velocity of the rotor wires is exactly parallel to the magnetic flux lines", so that emf induced in the conductors in the plane is exactly zero.

Geometric neutral axis (G.N.A.): It is the axis which is placed geometrically or physically in the mid-way between two adjacent main poles. With no current in the armature conductors, at no load, the M.N.A. coincides with G.N.A.



Brush axis: It is an imaginary axis along which the brushes are placed. Brushes are so placed that the coil undergoing commutation/ passing the brush should along the magnetic neutral plane.

Armature reaction:

In an unloaded d.c. machine armature current is vanishingly small and the flux per in the machine is established by the mmf produced by the field current alone. The uniform distribution of the lines of force gets upset when armature too carries current due to loading.

It is defined as "The effect of magnetic field set up by armature current on the main field flux distribution is known as Armature Reaction".

The armature magnetic field has two effects:

- a) It demagnetizes or weakens the main flux and
- b) It cross-magnetizes or distorts the main field distribution.

Case-I: No Load operation

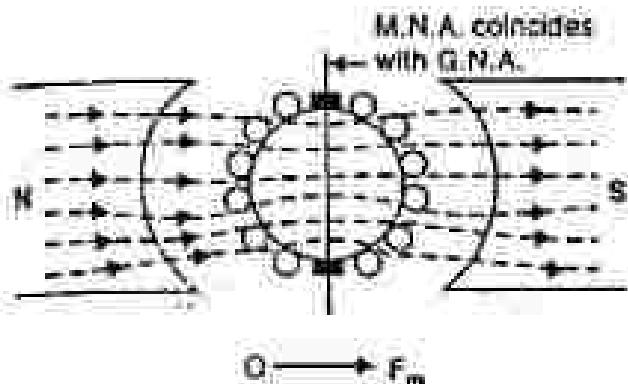
When a d.c. machine operates absolutely under no load condition, armature current is zero. Under such a condition T_f developed is zero and runs at constant no load speed. In absence of armature current (I_a), the flux per pole ϕ , inside the machine is solely decided by the field current and lines of force are uniformly distributed under a pole as shown in figure. The neutral plane in this machine is exactly vertical.

It is seen that:

(a) The flux is distributed symmetrically with respect to the polar axis.

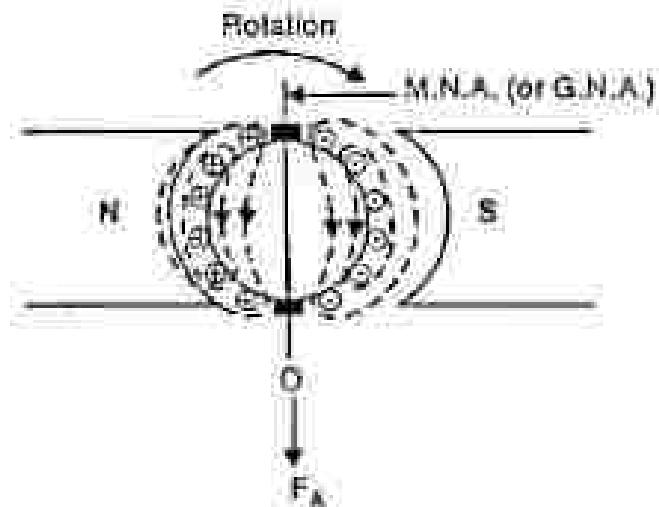
(b) The magnetic neutral axis (M.N.A.) coincides with the geometrical neutral axis (G.N.A.)

Brushes are always placed along M.N.A. Hence, M.N.A. is also called 'axis of commutation' or 'brush axis' because reversal of current in armature conductors takes place across this axis. Vector F_a , which represents both magnitude and direction, the mmf producing the main flux, which is orthogonal to G.N.A.

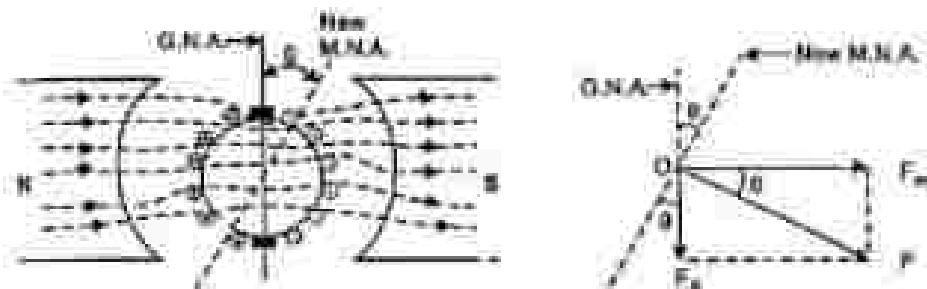


Case-II: Considering Armature flux alone.

Fig below shows the field (or flux) set up by the armature conductors alone when carrying current, the field coils being unexcited. Let the current direction is downwards " \odot " in conductors under N-pole and upwards " \odot " in those under S-pole. The armature mmf (depending on the strength of the armature current) is shown separately both in magnitude and direction by the vector F_A , which is parallel to the brush axis.



Case-III: Loaded operation

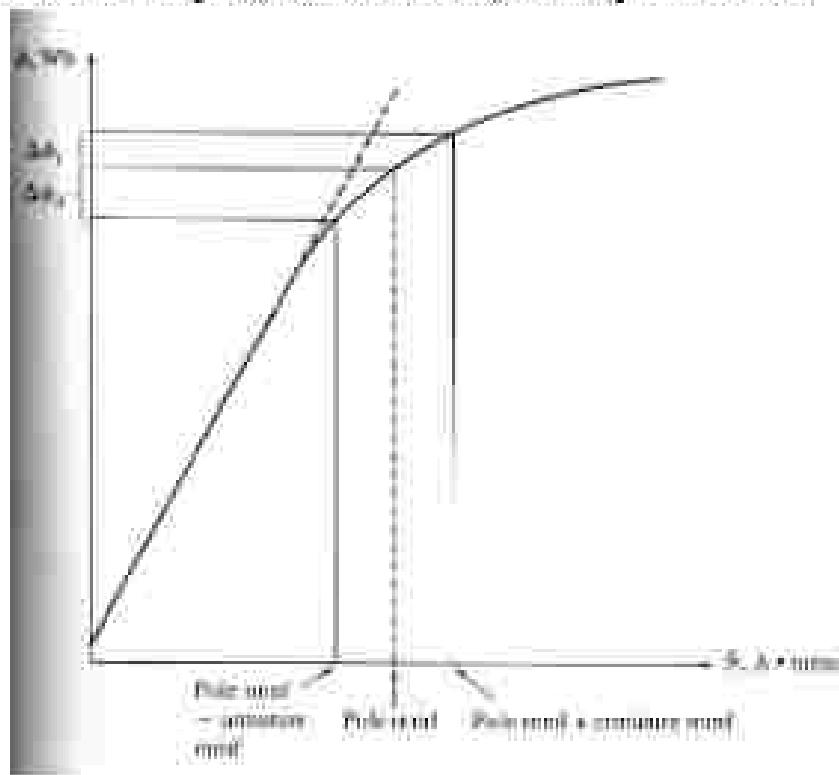


Under actual load conditions, the two mmf exist simultaneously in the generator. It is seen that the flux through the armature is no longer uniform and symmetrical about the pole axis, rather it has been distorted. The flux per pole ϕ , developed in the machine is decided not only by the mmf of the field winding alone but the armature mmf as soon as the armature starts carrying current. By superposing the no load, field lines (F_m) and the armature field lines (F_A) we can get the resultant field

lines pattern and the new position of M.N.A which is always perpendicular to the resultant mmf vector as shown above.

In general, the neutral-plane shifts in the direction of motion for generator and opposite to the direction of motion for a motor. Furthermore, the amount of the shift depends on the amount of rotor current and hence on the load of the machine.

As the machine is loaded, the neutral-plane shifts, and the coils undergoing commutation have a voltage across them. This result in circulating current to flow between the shifted segments and large sparks at the brushes. The end result is arcing and sparking at the brushes, which is cross magnetizing effect. This is a very serious problem, since it leads to drastically reduced brush life, pitting of the commutator segments, and higher maintenance costs. Notice that this problem cannot be fixed even by placing the brushes over the full-load neutral plane, because then they would spark at no load.



The flux seen to be crowded at the trailing pole tips but weakened or thinned out at the leading pole tips (the pole tip, which is first met during rotation by armature conductors, is known as the leading pole tip and the other as trailing pole tip). Consequently, flux density under the pole increases in one half of the pole and decreases under the other half of the pole. If the increased flux density causes magnetic saturation, the net effect is a reduction of flux per pole.

Most machines operate at flux densities near the knee point. Therefore, at locations on the pole surfaces where the rotor mmf adds to the pole mmf, only a small increase in flux occurs. But at locations on the pole surfaces where the rotor mmf subtracts from the pole mmf, there is a larger decrease in flux. The net result is that the total average flux under the entire pole face is decreased.

The flux weakening causes problems in both generators and motors. In generators, the effect of flux weakening is simply to reduce the voltage supplied by the generator for any given load. In motors,

the effect can be more serious. When the flux in a motor is decreased, its speed increases. But increasing the speed of a motor can increase its load, resulting in more flux weakening.

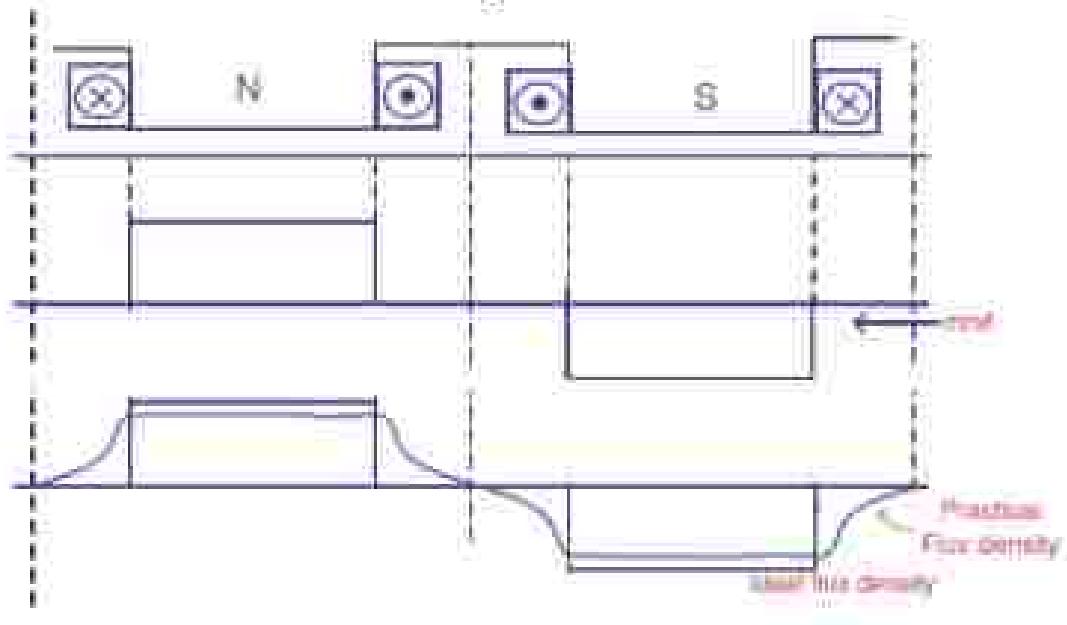
Determinant effect of Armature reaction:

- Since it is the flux per pole which decides the emf generated and the torque produced by the machine, there will be no effect felt so far as the performance of the machine is concerned due to armature reaction, when the machine is lightly or moderately loaded. However at rated armature current the core gets saturated. In other words there will be a net decrease in flux per pole (About 1–5%), this will *reduce the emf as well as torque* developed affecting the performance of the machine.
- Apart from this, due to distortion in the flux distribution, there will be some amount of flux present along the q-axis (brush axis) of the machine. This causes *commutation difficulty*. In extreme cases, the neutral-plane shift can even lead to *flashover in the commutator segments* near the brushes. The air near the brushes in a machine is normally ionized as a result of the sparking on the brushes. Flashover occurs when the voltage of adjacent commutator segments gets large enough to sustain an arc in the ionized air above them. If flashover occurs, the resulting arc can even melt the commutator's surface.
- However, the net flux reduces but the maximum value of the flux density (B_{max}) increases, which increases the iron loss, as iron loss proportional to B^2_{max} .



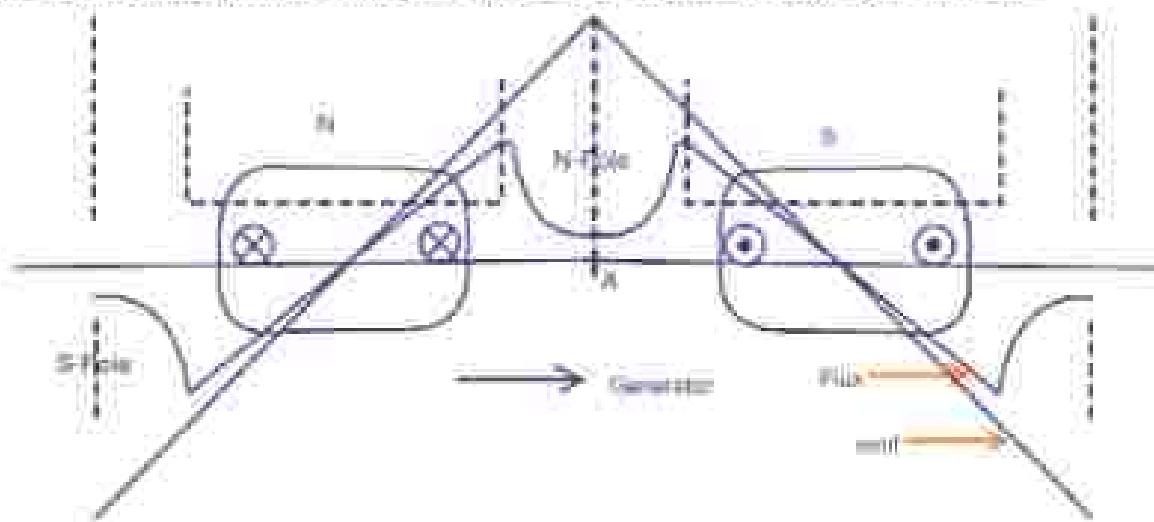
- As the flux density increases at the trailing pole tip, if the two sides of a coil undergo these points an emf induces which may large than 30–40 V (dielectric strength of commutator segment insulation). This may cause a flashover in commutator.
- To compensate the reduction in flux due to de-magnetization additional turns are provided in the field winding which increases the weight and cost of the machine.

MMF distribution due to the field coils acting alone

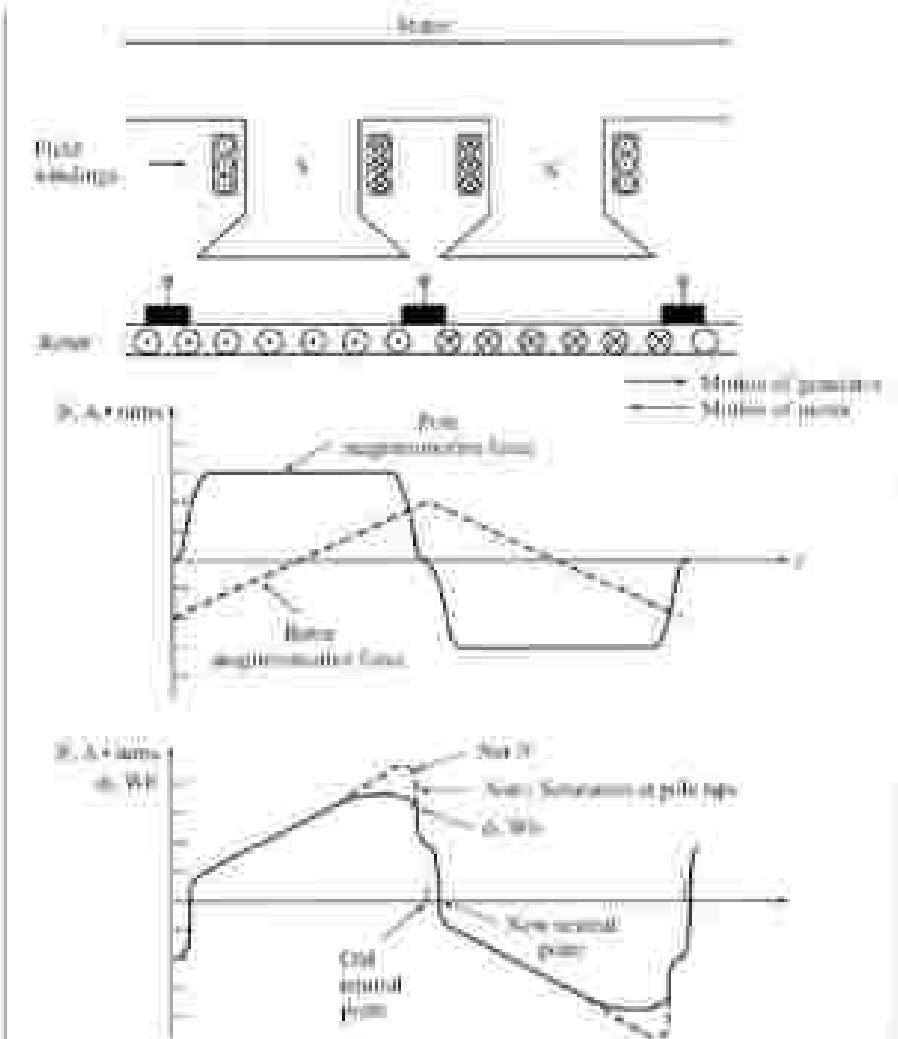


MMF distribution due to armature conductors alone carrying currents

The armature has a distributed winding. 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.



Total mmf and flux of a loaded machine:



In this figure note that the armature mmf distribution is triangular in nature and the flux density distribution due to armature current is obtained by dividing armature mmf with the reluctance of the air gap. The reluctance is constant and small at the polar region. This means that the armature flux density will simply follow the armature mmf pattern. However, the reluctance in the q-axis/inter pole region is quite large giving rise to small resultant flux of polarity same as the main pole behind in the q-axis.

Point to be noted here is that the lines of forces gets concentrated near the leading pole tip and rarefied near the trailing pole. Also note the presence of some flux in the q-axis with a polarity same as main pole ahead.

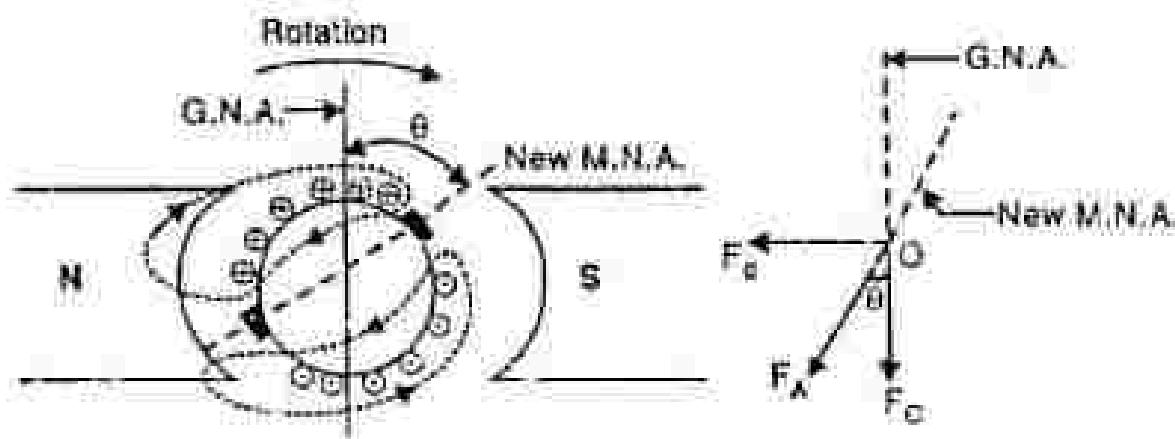
Process of reducing Armature Reaction:

For small machines (up to few kilo watts) no special care is taken to avoid the armature reaction effects. However for large machines, to get rid of the ill effects of armature reaction one can use compensating winding, inter poles, or both.

Effect of Brush Shift:

The first approach taken by machine designers was simple. If the neutral plane of the machine shifts, why not shift the brushes with it in order to stop the sparking. This method is good but there are several problems:

- The neutral plane moves with every change in load, and the shift direction reverses when the machine goes from motor operation to generator operation. Therefore, someone has to adjust the brushes every time the load changes.
- Although this method may have stopped the brush sparking, it actually aggravated the flux-weakening effect of the armature reaction in the machine.



With the shift of M.N.A., say through an angle θ brushes are also shifted to lay along the new position of M.N.A. Due to this brush shift, the armature conductors and hence armature current is re-distributed. All conductors to the left of new position of M.N.A. but between the two brushes carry current downwards and those to the right carry current upwards. The armature mmf is found to lie in the direction of the new position of M.N.A. (or brush axis). The armature mmf is now represented by the vector F_A . F_A can now be resolved into two rectangular components: F_B parallel to polar axis and F_C perpendicular to this axis. We find that:

- i) Component F_C is at right angles to the vector F_A representing the main mmf. It produces distortion in the main field and is hence called the cross-magnetising or distorting component.
- ii) The component F_B is in direct opposition of F_A which represents the main mmf. It exerts a demagnetising influence on the main pole flux. Hence, it is called the demagnetising or weakening component.

It should be noted that both distorting and demagnetising effects will increase with increase in the armature current.

For generators, the brushes are shifted in the direction of rotation. For motors, the brushes are shifted against the direction of rotation.

As soon as the brushes are moved, the commutation improves, meaning there is less sparking. However, if the load fluctuates, the armature mmf rises and falls and so the neutral zone shifts back and forth between the no load and full load positions. We would therefore have to move the brushes back

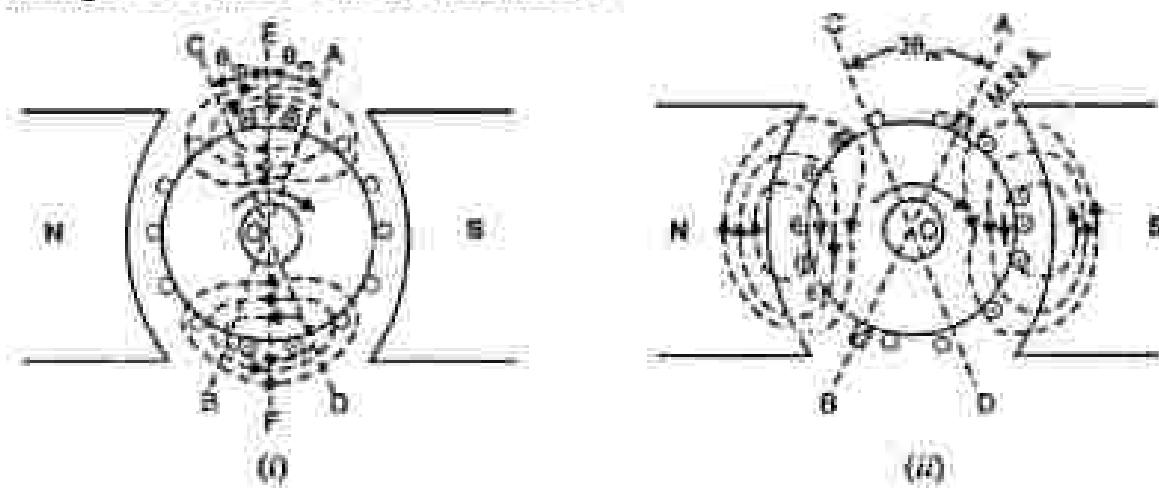
and forth to obtain a sparks commutation. This procedure is not practical and other means are used to resolve the problem. For small DC machines, however, the brushes are set in an intermediate position to ensure reasonably good commutation at all loads.

Cross magnetising & demagnetizing AT/pole:

All conductors lying within angles $\angle AOC = \angle BOD = 2\theta$ at the top and bottom of the armature, are carrying current in such a direction as to send the flux through the armature from right to left. It is these conductors which act in direct opposition to the main field and are hence called the demagnetizing armature conductors.

Now consider the remaining armature conductors lying between angles $\angle AOD$ and $\angle COB$. These conductors carry current in such a direction as to produce a flux at right angles to the main flux. This results in distortion of the main field. Hence, these conductors are known as cross-magnetising conductors and contribute distorting ampere-conductors.

Since armature demagnetizing ampere-turns are neutralized by adding extra ampere-turns to the main field winding, it is essential to calculate their number.



$$F_d + \frac{\theta}{2} \rightarrow F_m \quad \begin{matrix} \theta \\ \downarrow \\ F_c \end{matrix}$$

Let Z = total number of armature conductors

I_a = current in each armature conductor

$$I_a = \frac{I_a}{2} \text{ For Wave wound Machine}$$

$$I_a = \frac{I_a}{p} \text{ For Lap wound Machine}$$

θ_m = forward lead in mechanical or geometrical or angular degrees

$$\text{Total number of armature conductors in angles } \angle AOC \text{ and } \angle BOD \text{ is } \frac{4\theta_m}{360} \times Z$$

$$\text{Total number of armature turns in these angles is } \frac{4\theta_m}{360} \times \frac{Z}{2} = \frac{2\theta_m}{360} \times Z$$

$$\text{Demagnetizing Turns per Pole: } \frac{\theta_m}{360} \times Z$$

$$\text{Demagnetising turns per pole} = \frac{\theta_a}{360} \times ZI$$

$$AT_{\text{per pole}} = \frac{\theta_a}{360} \times ZI_c = \frac{\theta_a}{360} \times \frac{ZI}{A}$$

The conductors lying between angles $\angle AOD$ and $\angle COB$ are known as cross-magnetizing conductors. Their number is found as:

$$\text{Total armature-conductors/pole (Both cross and demagnetizing)} = \frac{Z}{p}$$

$$\text{Total armature-turns/pole (Both cross and demagnetizing)} = \frac{I}{2p}$$

$$\text{Cross-magnetizing turns/pole} = \frac{Z}{2p} \cdot \frac{\theta_a}{360} \times Z = Z \left(\frac{1}{2p} - \frac{\theta_a}{360} \right)$$

$$\text{Cross-magnetizing Ampere-turns/pole} = AT_{\text{per pole}} = ZI \left(\frac{1}{2p} - \frac{\theta_a}{360} \right)$$

For neutralizing the demagnetizing effect of armature-reaction, an extra number of turns may be put on each pole.

$$\text{No. of extra turns/pole} = \frac{AT_e}{I_f} / \text{Field Current},$$

- If the leakage coefficient λ is given, then multiply each of the above expressions by it.
- If lead angle is given in electrical degrees, it should be converted into mechanical degrees by the following relation: $\theta_x = \frac{2}{p} \theta_e$

Commutating Poles (Interpoles):

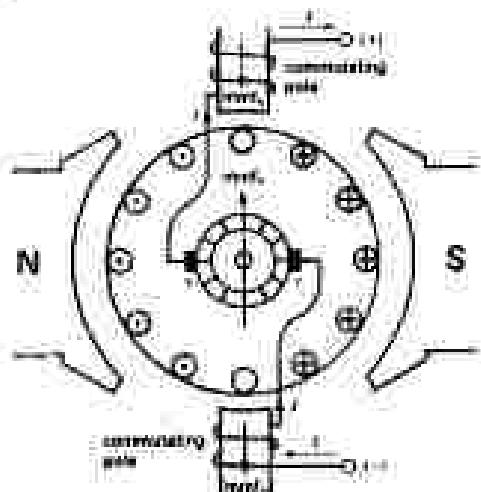
The basic idea here is that if the voltage in the wires undergoing commutation can be made to zero, then there will be no sparking at the brushes. Additional small poles called *inter poles* or *commutating poles* are provided in between two main poles in medium and large machines to get rid of the commutation problem arising out of armature reaction.

These narrow poles carry windings that are connected in series with the armature. The number of turns on the windings is so designed that these poles develop a magneto-motive force *mmf*, equal and opposite to the magneto-motive force *mmf_a* of the armature in the inter-polar region. If the cancellation is exact, then there will be no sparking at the brushes. As the load current varies, the two magneto-motive forces rise and fall together, exactly opposing each other at all times. By nullifying the armature *mmf* in this way, the flux in inter polar region is always zero and so we no longer have to shift the brushes. In practice, the *mmf* of the commutating poles is made slightly greater than the armature *mmf*. This creates a small flux in the neutral zone, which aids the commutation process.

Careful inspection of the figures mentioned reveal that the polarity of the inter pole should be same as that of the main pole ahead in case of generator and should be same as that of main pole behind in case of motor.

Fig. shows how the commutating poles of a 2-pole machine. Clearly, the direction of the current flowing through the windings indicates that the *mmf* of the commutating poles acts opposite to the *mmf*

of the armature and, therefore, neutralizes its effect. However, the neutralization is restricted to inter-polar zone only where commutation takes place. The distorted flux distribution under the main poles, unfortunately, remains the same.



Interpole produces an mmf that opposes the mmf of the armature.

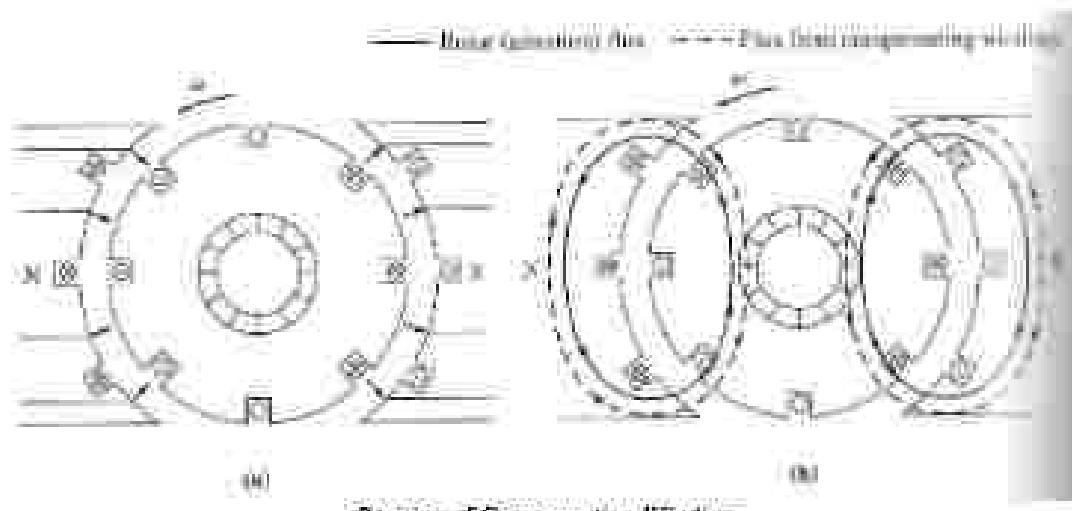
Compensating Windings:

These are used for large direct current machines which are subjected to large fluctuations of load i.e. rolling mill motors and turbo-generators etc. Their function is to neutralize the cross-magnetizing effect of armature reaction under the polar region.

The basic idea of nullifying armature mmf is based on a very simple fact. We know that a magnetic field is produced in the vicinity when a conductor carries current. Naturally another conductor carrying same current but in the opposite direction if placed in close proximity of the first conductor, the resultant field in the vicinity will be close to zero. Additional winding called compensating winding is placed on the pole faces of the machine and connected in series with the armature circuit in such a way that the direction of current in compensating winding is opposite to that in the armature conductor directly below the pole shoes.

In the absence of compensating windings, the flux will be suddenly shifting backward and forward with every change in load. This shifting of flux will induce statically induced EMF in the armature coils. The magnitude of this EMF will depend upon the rate of changes in load and the amount of change. It may be so high as to strike an arc between the consecutive commutator segments across the top of the mica sheets separating them. This may further develop into a flash-over around the whole commutator thereby shortcircuiting the whole armature.

Owing to their cost and the room taken up by them, the compensating windings are used in the case of large machines which are subject to violent fluctuations in load and also for generators which have to deliver their full-load output at considerably low induced voltages.



Position of Compensating Winding

No. of Compensating Windings Turns

$$\text{No. of armature conductors/pole} = \frac{z}{p}$$

$$\text{No. of armature turns/pole} = \frac{z}{zp}$$

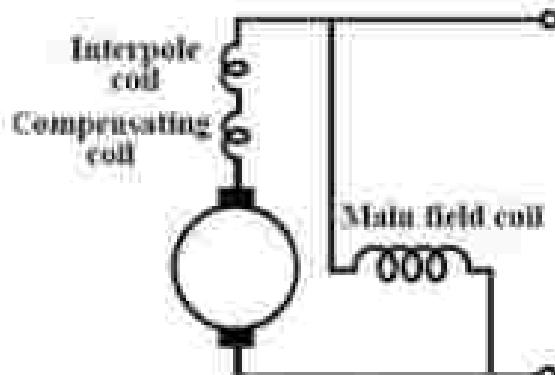
$$\text{Then, No. of armature turns immediately under one pole} = \frac{z}{zp} \cdot \frac{\text{Pole arc}}{\text{Pole pitch}} = 0.7 \cdot \frac{z}{2p}$$

I_c = current in each armature conductor

$$I_a = \frac{I_c}{2} \quad \text{For Wave wound Machine}$$

$$I_a = \frac{I_c}{p} \quad \text{For Lap wound Machine}$$

$$\text{Then, No. of armature amp-turns/pole for compensating winding} = 0.7 \text{ amp-turns/pole} = 0.7 \cdot \frac{2I_a}{2p}$$

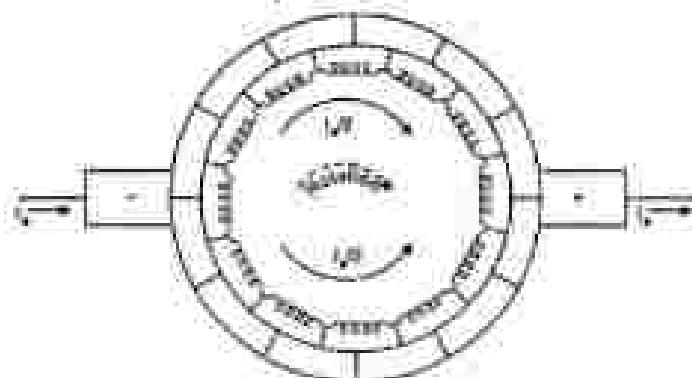


Interpole & compensating coil connection.

Commutation:

If we concentrate our attention to a single conductor, we immediately recognize that the direction of current reverses as it moves from the influence of one pole to the influence of the next opposite pole. This reversal of current in the conductor is called *commutation*.

The currents in the coils connected to a brush are either all towards the brush (positive brush) or all directed away from the brush (negative brush). Therefore, current in a coil will reverse as the coil passes a brush. This reversal of current as the coil passes a brush or brush axis is called *commutation*.



During no load operation when the conductor reaches the magnetic neutral axis or the q-axis, the induced voltage in it is zero as there is no flux present in the q-axis. Also any coil present in this position and undergoing commutation will get short circuited by the commutator segments and brushes. In other words we see that every coil will be short circuited whenever it undergoes commutation and fortunately at that time induced emf in the coil being zero, no circulating current will be present at least during no-load condition. But as discussed earlier, flux in the quadrature axis will never be zero when the machine is loaded. Hence coil undergoing commutation will have circulating current causing problem.

The brush width is equal to the width of one commutator segment and one mica insulation.

The brief period during which coil remains short-circuited is known as *commutation period* (T_c).

If the current reversal i.e. the change from + I to zero and then to -I is completed by the end of short circuit or commutation period, then the *commutation is ideal*. If current reversal is not complete by that time, then sparking is produced between the brush and the commutator which results in progressive damage to both and known as *poor commutation*.

In Fig (a) coil B is about to be shortcircuited because brush is about to come in touch with commutator segment 'a'. It is assumed that each coil carries 20 A, so that brush current is 40 A. Prior to the beginning of short circuit, coil B belongs to the group of coils lying to the left of the brush and carries 20 A from left to right.

In Fig (b) the current through coil B has reduced downfrom 20 A to 10 A. As area of contact of the brush is more with segment 'b' than with segment 'a', it receives 30 A from the former, the total again being 40 A.

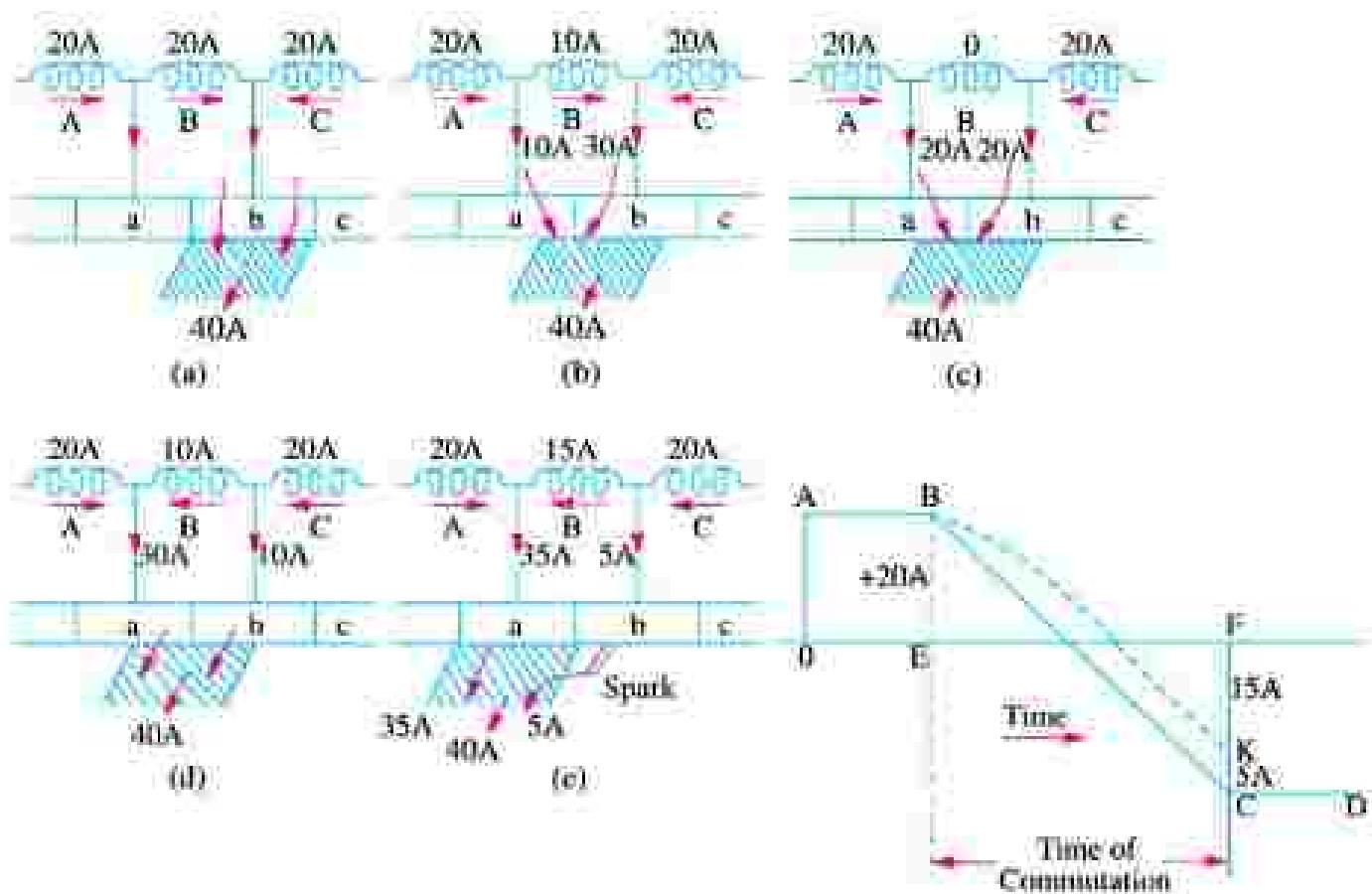
Fig (c) shows the coil B in the middle of its short-circuit period, the brush contact areas with the two segments 'b' and 'a' are equal. The current through it has decreased to zero. The two currents of value 20 A each pass to the brush directly from coil A and C.

In Fig (d), coil B has become part of the group of coils lying to the right of the brush. Coil B now carries 10 A in the reverse direction which combines with 20 A supplied by coil A to make up 30 A that passes from segment 'a' to the brush. The other 10 A is supplied by coil C and passes from segment 'b' to the brush, again giving a total of 40 A at the brush.

Fig (e) depicts the moment when coil B is almost at the end of commutation or short circuit period. For ideal commutation, current through it has reversed and carrying 20 A in opposite direction. As the current varies at a uniform rate i.e. if BC is a straight line, then it is referred to as linear commutation.

However, in actual practice it may so happen, the coil will carry 15 A only (say) instead of 20 A, due to the production of self-induced emf in the coil, which is known as reactance voltage. This reactance voltage opposes the change of current in the coil undergoing commutation. The result is that the change of current in the coil occurs more slowly than it would be under ideal commutation.

The curve BK (dotted curve) represents the change in current when self-inductance of the coil is taken into account. It is seen that, in that case, current in coil B has reached only a value of $KF = 15$ A in the reversed direction, hence the difference of 5 A (20-15 A) passes as a spark. So, we conclude that sparking at the brushes, which results in poor commutations due to the inability of the current in the short-circuited coil to reverse completely by the end of short-circuit period (which is usually of the order of 1/500 second).



Calculation of Reactance Voltage:

Reactance voltage = Coefficient of self-inductance * Rate of change of current.

The time of short circuit (or commutation period T_c) is equal to the time required by the commutator to move a distance equal to the circumferential thickness of the brush minus the thickness of one insulating strip of mica.

Let W_b = brush width in cm;

W_m = mica thickness in cm

v = peripheral speed of commutator in cm/s

Commutation period, $T_c = \frac{W_b - W_m}{v}$ second

Let the current in the coil undergoing commutation change from +I to -I (Amperes) during the commutation. If 'L' is the inductance of the coil, then reactance voltage is given by:

$$\text{Reactance voltage, } E_r = L \cdot \frac{di}{dt} = L \cdot \frac{2I}{T_c} \text{ Volt}$$

Characteristics of D.C. Generators:

Various Characteristics of a DC generator are given as:

i. Open Circuit Characteristic (OCC) (E_o/I_o)

It is also known as magnetic characteristic or no-load characteristics. It shows the relation between the no-load armature e.m.f. E_o and the field or exciting current I_o at a fixed speed.

ii. Internal or Total Characteristic (E_i/I_o)

It gives the relation between the *actually induced* e.m.f. E_i in the armature and the armature current I_a .

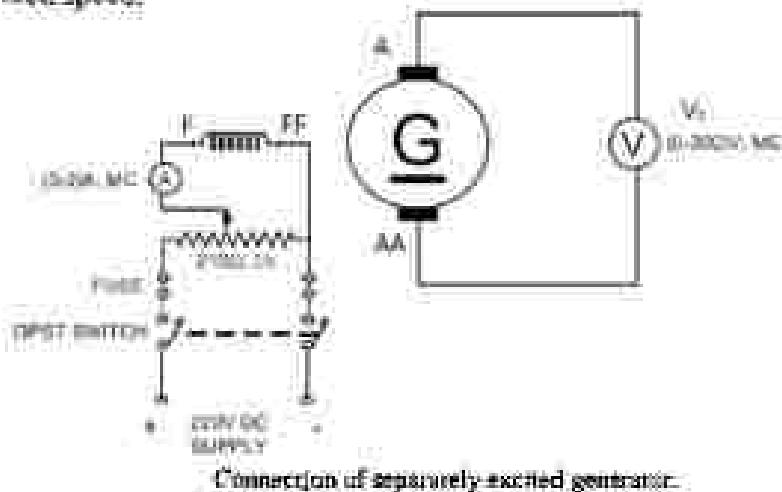
iii. External Characteristic (V/I_o)

It is also known as performance characteristic or sometimes voltage-regulating curve. It gives relation between the terminal voltage V and the load current I_L .

Characteristics of a separately excited generator:

No load or Open circuit characteristic (OCC)/ No-load saturation Characteristic:

It shows the relation between the no-load generated emf in armature, E_0 and the field or exciting current I_o at a given fixed speed.



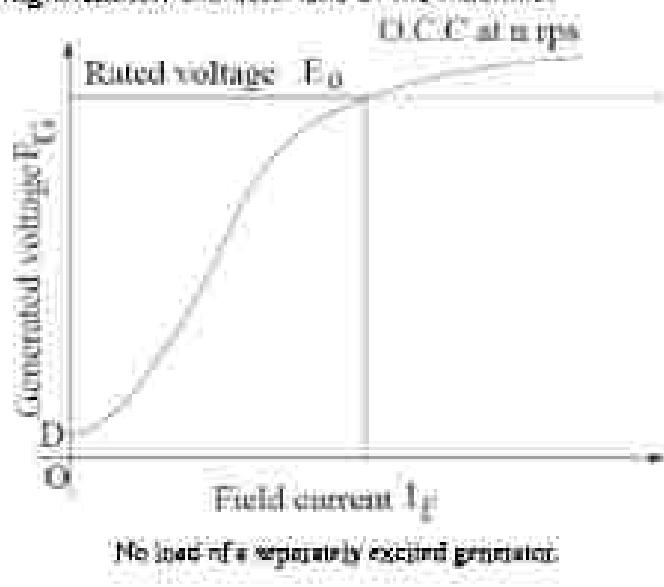
Connection of separately excited generator.

In this type of generator field winding is excited from a separate source, hence field current is independent of armature terminal voltage. The generator is driven by a prime mover at rated speed, say "N" rpm. With switch 'S' in opened condition, field is excited via a potential divider connection from a separate d.c. source and field current is gradually increased. The field current will establish the flux (ϕ) per pole. The voltmeter V connected across the armature terminals of the machine will record the generated emf $E = \frac{\phi \cdot N}{R_A} (Z_A)$. Let us gradually raise the exciting current I_o so that the *mf* of the field increases, which increases the flux.

It may be noted that even when there is no field current, a small voltage (OD), about 2 to 5% of rated value is generated due to residual flux. When the exciting (field) current is relatively small, the flux is small and the iron in the machine is unsaturated. Very little *mf* is needed to establish the flux in the core, as the permeability of air is constant, the flux increases in direct proportion to the exciting current, so the O.C.C follows a straight line.

However, as we continue to raise the exciting current, the iron in the field and the armature begins to saturate. A large increase in the *mf* is now required to produce a small increase in flux. The

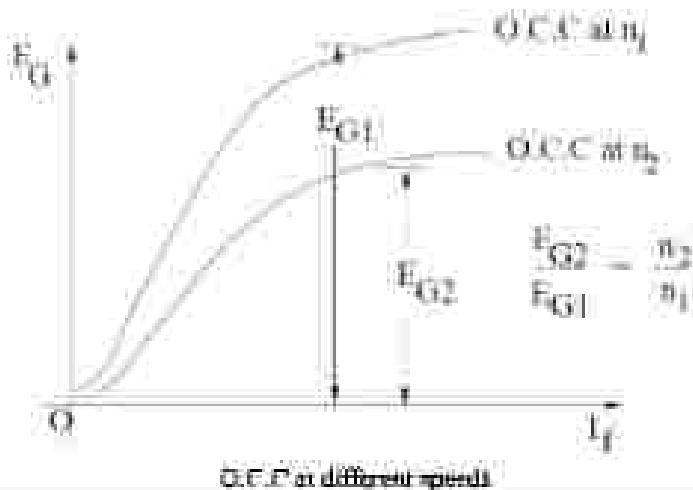
machine is now said to be saturated. When saturation sets in, ϕ practically becomes constant and hence E_g too becomes constant. In other words, O.C.C follows the $B-H$ characteristic, hence this characteristic is sometimes also called the magnetisation characteristic of the machine.



It is important to note that if O.C.C is known at a certain speed N_1 , O.C.C at another speed N_2 can easily be predicted. It is because for a constant field current, ratio of the generated voltages becomes the ratio of the speeds as shown below.

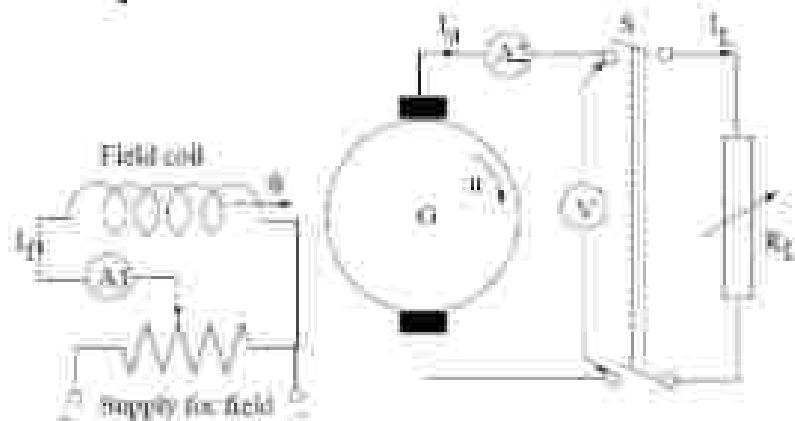
$$\begin{aligned} \frac{E_{g2}}{E_{g1}} &= \frac{\text{Induced emf at } N_2}{\text{Induced emf at } N_1} \\ &= \frac{\frac{\phi N_2}{\theta N_1}}{\frac{\phi N_1}{\theta N_2}} \quad (\text{At constant field}) \\ \frac{E_{g2}}{E_{g1}} &= \frac{N_2}{N_1} \quad I_f = \text{const.} \\ \text{or, } E_{g2} &= \frac{N_2}{N_1} E_{g1} \end{aligned}$$

Therefore points on O.C.C at n_2 can be obtained by multiplying ordinates of O.C.C at n_1 with the ratio $\frac{n_2}{n_1}$. It should be noted that O.C.C. for a higher speed would lie above this curve and for a lower speed would lie below it.



Internal and External Characteristics of separately excited generator

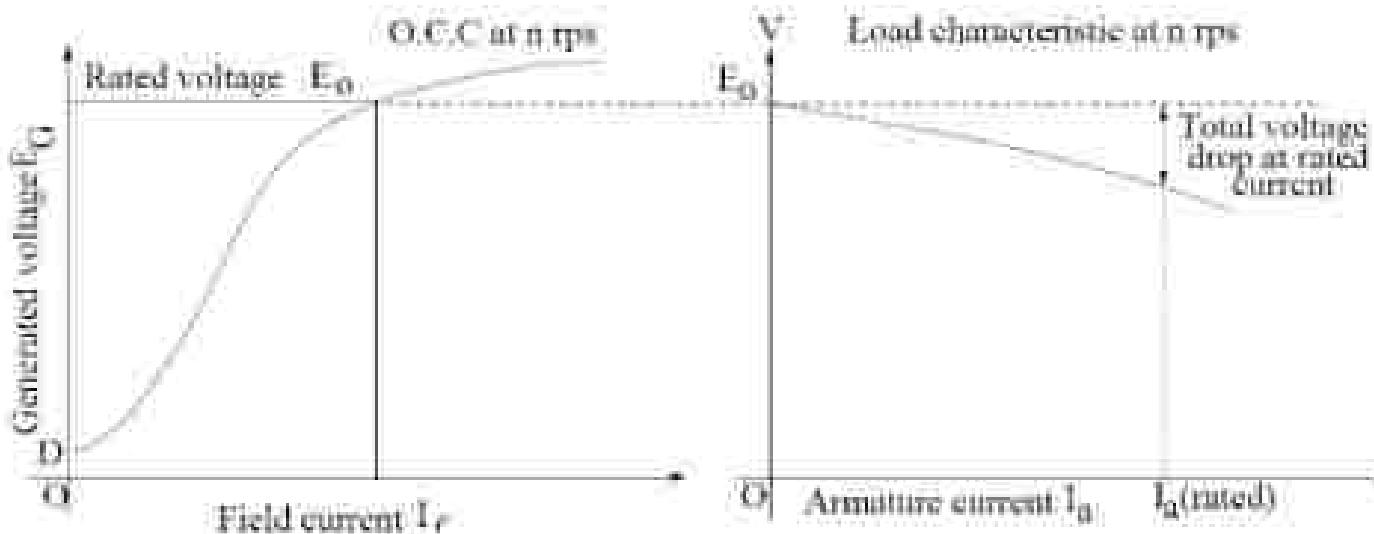
External characteristic essentially describes how the terminal voltage of a generator changes for varying Load current I_L at a constant speed.



Let us consider a separately excited generator that is driven at constant speed and whose field is excited to produce the resultant flux. The induced voltage E_a is generated across the armature terminals with no load resistance connected across it (i.e., with S opened).

So for $I_L = 0$, $V = E_a$ should be the first point on the load characteristic. Now with ' S ' is closed and by decreasing R_L from infinitely large value, we can increase the load so as the armature/load current I_L gradually and note the voltmeter reading. Voltmeter reads the terminal voltage and is expected to decrease due to various drops such as armature resistance drop and brush voltage drop. In an un-compensated generator, the induced voltage E_a also decreases slightly with increasing load, because pole-tip saturation tends to decrease the field flux. While noting down the readings of the ammeter 'A2' and the voltmeter 'V', one must see that the speed remains constant at rated value. Hence the load characteristic will be *drooping* in nature.

If we subtract from E_a the values of voltage drops due to armature reaction for different loads, then we get the value of E -the emf actually induced in the armature under load conditions. The variation of actual induced emf with load is known as the *internal characteristic*.



Characteristics of a shunt generator:

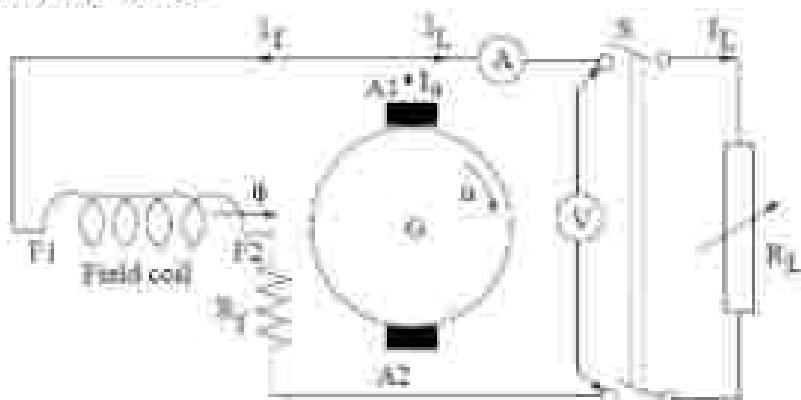
No-load Curve for Self-excited Generator:

The O.C.C. or no-load saturated curves for self-excited generators whether shunt or series connected, are obtained in a similar way. The field winding of the generator (whether shunt or series wound) is disconnected from the machine and connected to an external source of direct current.

The field or exciting current I_f is increased by suitable steps (starting from zero) and the corresponding values of E_g are measured.

Voltage builds up:

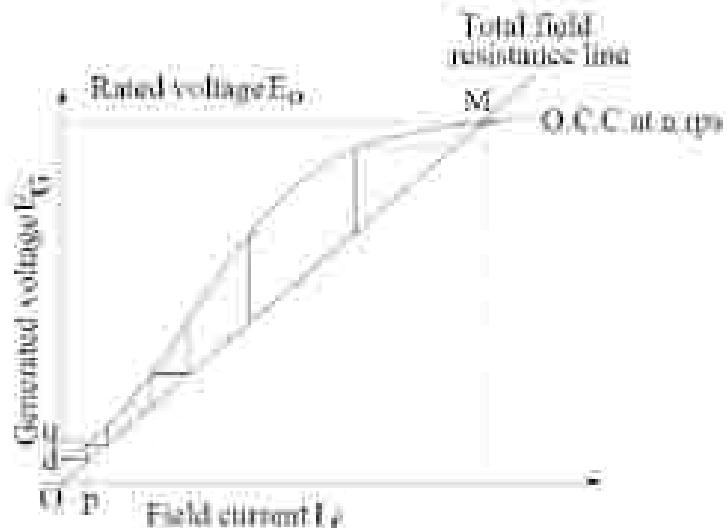
Before loading a shunt generator, it is allowed to build up its voltage. Let us discuss how a DC shunt generator adjust itself to reach the rated voltage, and what are the other factors that influence it's the process of building up of the voltage.



Suppose there exist some residual field. Therefore, if the generator is driven at rated speed, we should expect a small voltage $\frac{2\pi f \mu M}{4\pi} (e)$ to be induced across the armature. As this small voltage will be directly applied across the field circuit as it is connected in parallel with the armature, a small field current will circulate which results an additional flux. If it so happens that this additional flux aids the already existing residual flux, total flux now becomes more generating more voltage. This more voltage will drive more field current generating more voltage. Both field current and armature generated voltage grow *cumulatively*.

This growth of voltage and the final value to which it will settle down can be understood by the two plots shown. One corresponds to the O.C.C at rated speed and obtained by connecting the generator in separately excited fashion. The other one is the V-I characteristic of the field circuit which is a straight line passing through origin and its slope represents the total field circuit resistance.

Initially voltage induced due to residual flux is obtained from O.C.C and given by ' od '. The field current thus produced can be obtained from field circuit resistance line and given by ' op '. In this way voltage build up process continues along the air gap. The final stable operating point (M) will be the point of intersection between the O.C.C and the field resistance line.

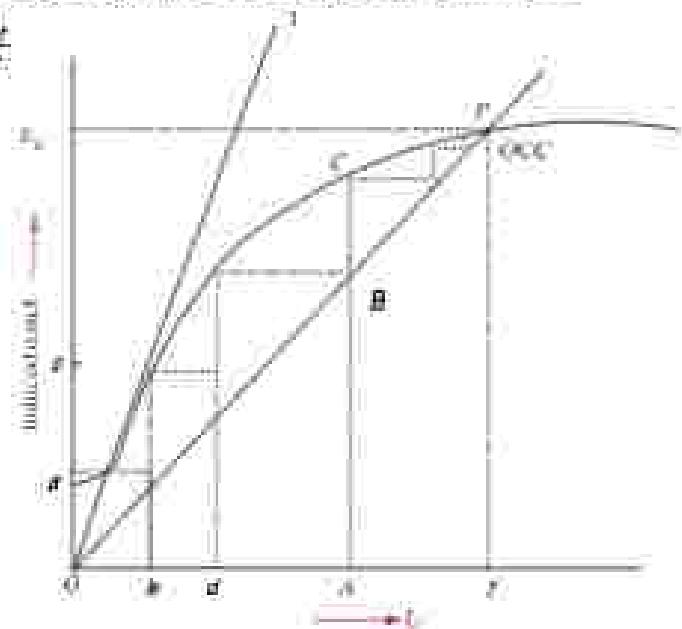


Why point 'M' is the stable point to which the machine builds up?

During this process of voltage build up field current continuously increases, so $\frac{di_f}{dt} \neq 0$. Now, the generated e.m.f. in the armature has to supply the ohmic drop $i_f R_{sh}$ in the winding and to overcome the opposing self-induced e.m.f. in the field coil, i.e. $L \frac{di_f}{dt}$, as field coils have appreciable self-inductance.

$$E_g = i_f R_{sh} + L \frac{di_f}{dt}$$

If the generated e.m.f. is in excess of the ohmic drop $i_f R_{sh}$, energy would continue being stored in the field poles. For example, corresponding to field current OA , the generated e.m.f. is AC . Out of this, AB goes to supply ohmic drop $i_f R_{sh}$ and BC goes to overcome self-induced e.m.f. in the coil. Corresponding to $i_f = OF$, whole of the generated e.m.f. is used to overcome the ohmic drop. None is left to overcome $L \frac{di_f}{dt}$. Hence no energy is stored in the pole fields. Consequently, there is no further increase in pole flux and the generated e.m.f.



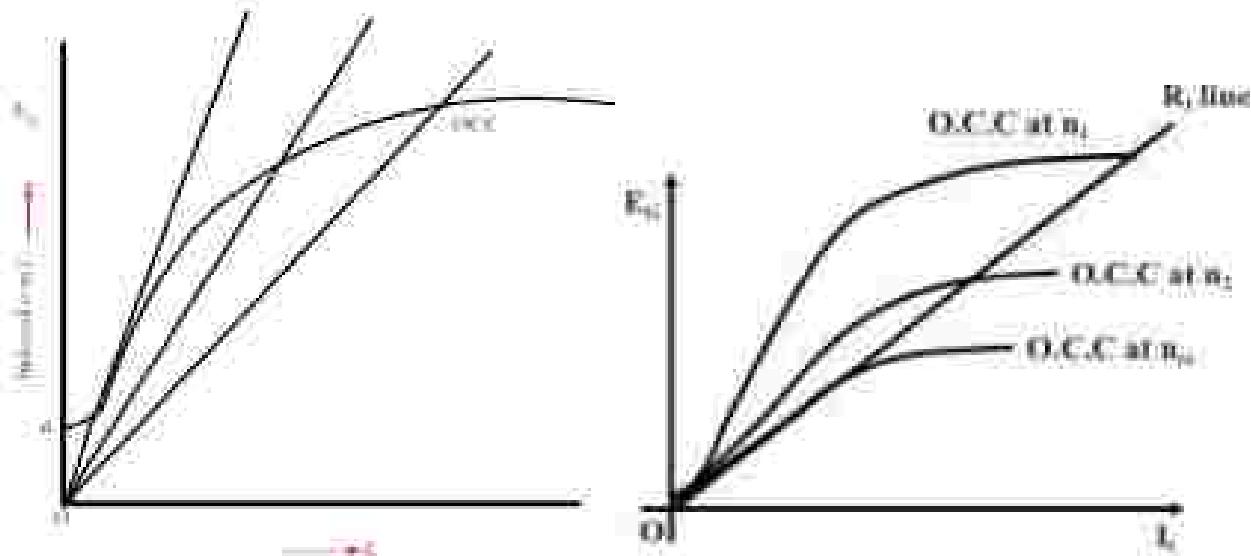
Effects of Variation of speed on voltage build up:

Suppose a shunt generator has built up voltage at a certain speed. Now if the speed of the prime mover is reduced without changing field resistance (R_f), the developed voltage will be less as because the O.C.C. at lower speed will come down. As a result the voltage to which the machine builds up reduces, due to the point of intersection. If speed is further reduced to a certain critical speed (N_c), the present field resistance line will become tangential to the O.C.C. at N_c . For any speed below N_c , no voltage build up is possible in a shunt generator.

Effects of Variation of field resistance on voltage build up:

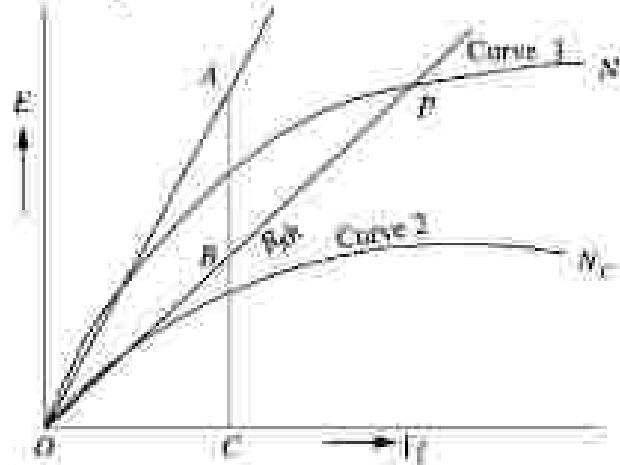
If field circuit resistance is increased, final voltage decreases as the point of intersection shifts toward left. If the field resistance is increased further the V-I line intersect the O.C.C. at starting point, hence the machine fails to buildup. The field circuit resistance line which is tangential to the O.C.C. is

called the *critical* field resistance. If the field circuit resistance is more than the critical value, the machine will fail to excite and no voltage will be induced. The reason being no point of intersection is possible in this case.



How to Find Critical Resistance (R_c): First, O.C.C. is plotted from the given data. Then, a tangent is drawn to its initial portion. The slope of this curve gives the critical resistance for the speed at which the data was obtained.

How to Find Critical Speed (N_c): O.C.C. is plotted from the given data. Then, a tangent is drawn to its initial portion. Draw a line corresponds to shunt field resistance R_s .



Obviously

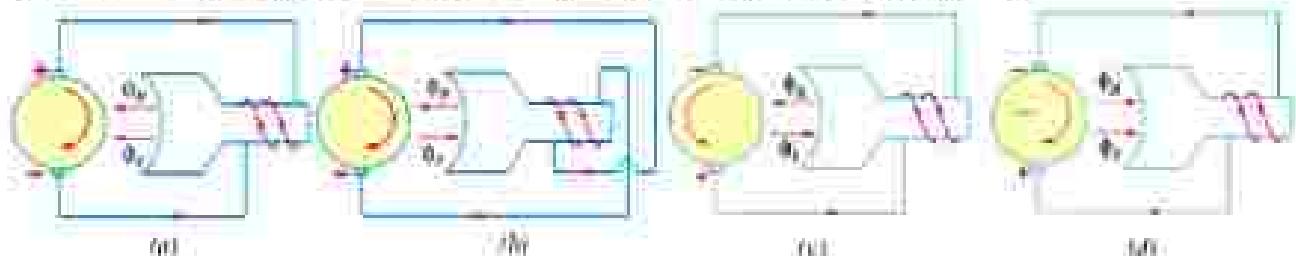
$$\frac{BC}{AC} = \frac{N_c}{\text{Fullspeed}(N)} : N_c = \frac{BC}{AC} \times \text{Fullspeed}(N)$$

A shunt generator driven by a prime mover cannot build up voltage if it fails to comply any of the conditions listed below.

1. The machine must have some *residual* field. (If not then one can excite the field separately with some constant current or a spark/arc can be created across the field terminals. Now removal of this current will leave some amount of residual field.)

- For the given direction of rotation, Field winding connection should be such that the residual flux is strengthened by the field current in the coil. (If due to this, no voltage is being built up, reverse the field terminal connection.)*
- The speed of operation of the machine must be above the critical speed.
- If excited at no load, then total field circuit resistance must be less than the critical field resistance.
- If excited on load, then its load resistance should be more than a certain minimum value of resistance which is given by internal characteristic.

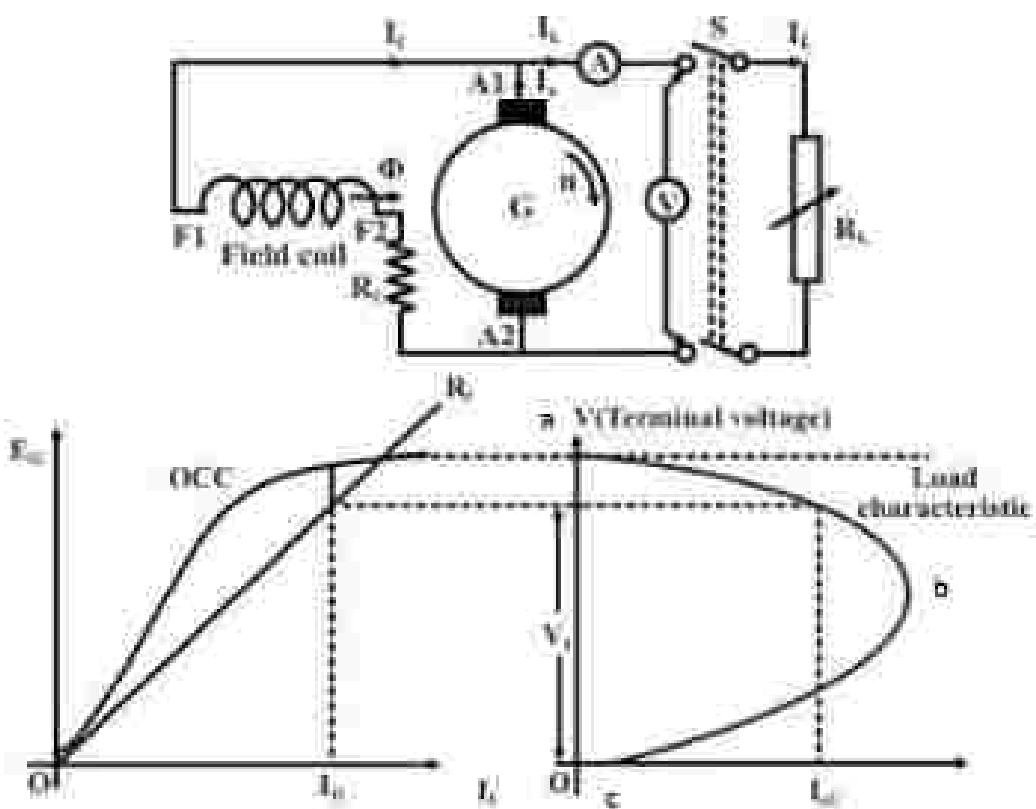
*Note: If the field connection is reversed it may wipe off the residual magnetism.



Internal and External Characteristics of shunt generator

External characteristic essentially describes how the terminal voltage of a generator changes for varying load current I_L at a constant speed.

Let us consider a shunt generator driven at constant speed and whose excitation is adjusted to produce the resultant flux so as the rated induced emf. The induced voltage E_a is generated across the armature terminals with no load resistance connected across it (i.e., with 'S' opened).



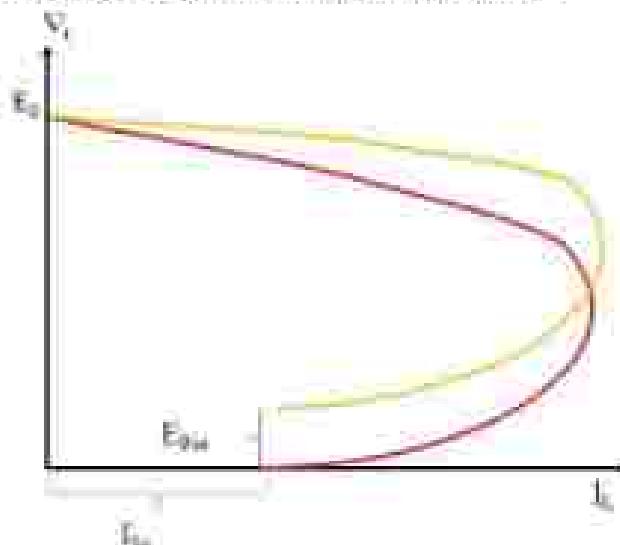
With switch 'S' in open condition, the generator is practically under no load condition and field current is pretty small. The voltmeter reading will be *no load induced emf* E_0 or E_a . In other words, E_a and $I_L = 0$ is the first point in the load characteristic.

To load the machine 'S' is closed and the load resistances decreased so that it delivers load current I_L . Unlike separately excited motor, here $I_L \neq I_a$. In fact, for shunt generator, $I_b = I_a + I_L$. So increase of I_L will mean increase of I_a as well. The drop in the terminal voltage will be caused by,

- (i) The usual $I_a R_a$ drop and brush voltage drop
- (ii) Due to the demagnetizing effect of armature reaction armature.
- (iii) Apart from these, in shunt generator, field current is decided by the terminal voltage by virtue of its parallel connection. As terminal voltage decreases, field current hence I_a also decreases causing additional drop in terminal voltage.

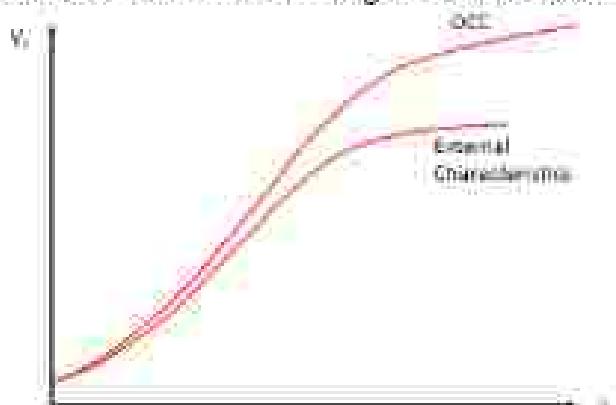
Over the portion 'ab', where the load current is comparatively small, when external load resistance is decreased, it results in increased load current as expected according to Ohm's law. These conditions hold good till point b is reached. This point is known as breakdown point. However, due to increase in load current, V is also decreased due to the cause (iii) as mention above. But after the portion 'ab', If load resistance is decreased then, the current is *increased* momentarily. But due to the severe armature reaction for this heavy current and increased $I_a R_a$ drop, the terminal voltage V drastically reduces. The effect of this drastic reduction in V results in less load current. In other words, after breakdown point, the terminal voltage V decreases more rapidly than the load resistance. Hence, any further decrease in load resistance actually causes a *decrease* in load current. As load resistance is decreased beyond point b, the curve turns back till when the generator is actually short-circuited, it cuts the current axis at point c. Here, terminal voltage V is reduced to zero, though there would be some value of E due to residual magnetism.

Internal Characteristic: Internal characteristic gives the relation between E_a and I_L . Hence, this curve can be obtained from external characteristics curve. If brush contact resistance is assumed to be constant, then armature voltage drop is proportional to the armature current. If we add the armature voltage drops to the terminal voltage we get the internal characteristic.

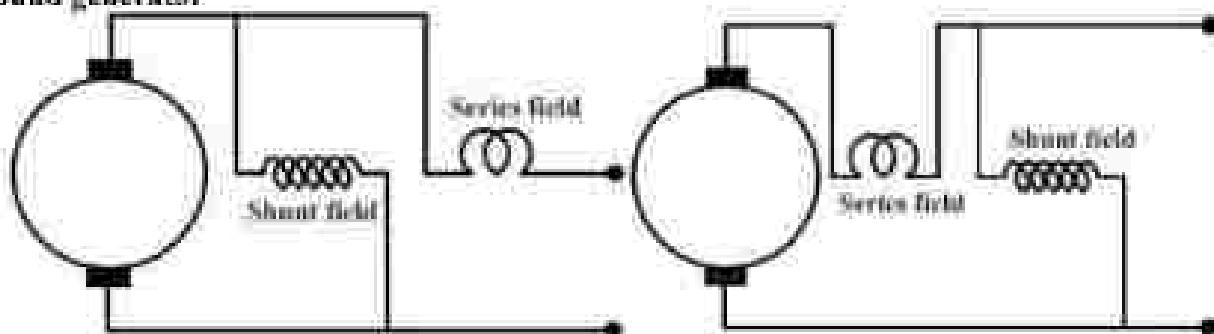


External Characteristics of series Generator:

In this generator, as the field winding is in series with the armature, it carry full armature current. As I_A is increased, flux and hence generated e.m.f. also increased. It will be noticed that a series generator has rising voltage characteristic i.e. with increase in load, its voltage is also increased. But it is seen that at high loads, the voltage starts decreasing due to excessive de-magnetising effects of armature reaction. In fact, terminal voltage starts decreasing as load current is increased as shown by the dotted curve. For a load current O.C.C. the terminal voltage is reduced to zero as shown.



Compound generator



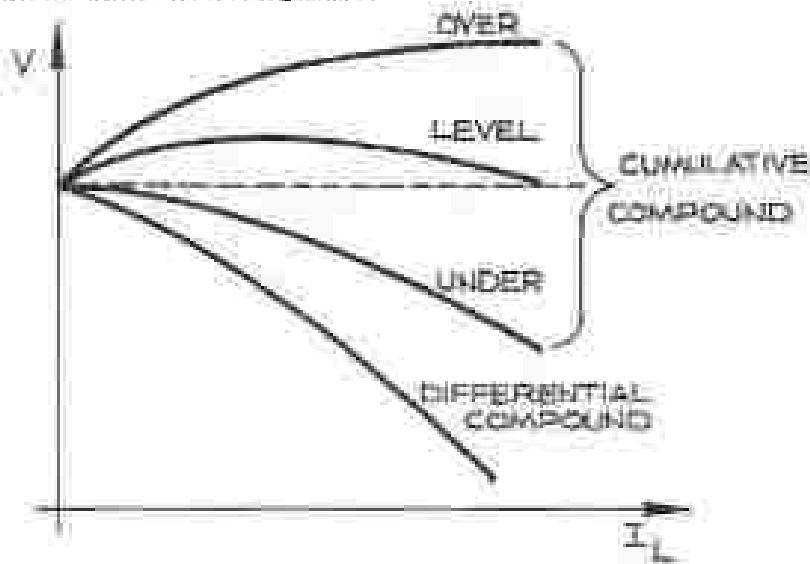
The compound generator was developed to prevent the terminal voltage of a D.C. generator from decreasing with increasing load.

In a compound generator, series field coil current is load dependent. Therefore, for a cumulatively compound generator, with the increase in load, flux per pole increases. This increases the generated emf and terminal voltage. Unlike a shunt motor, depending on the strength of the series field mmf, terminal voltage at full load current may be same or more than the no load voltage. When the terminal voltage at rated current is same that at no load condition, then it is called a level compound generator. If however, terminal voltage at rated current is more than the voltage at no load, it is called a over compound generator. The load characteristic of a cumulative compound generator will naturally be above the load characteristic of a shunt generator. At load current higher than the rated current, terminal voltage starts decreasing due to saturation, armature reaction effect and more drop in armature and series field resistances.

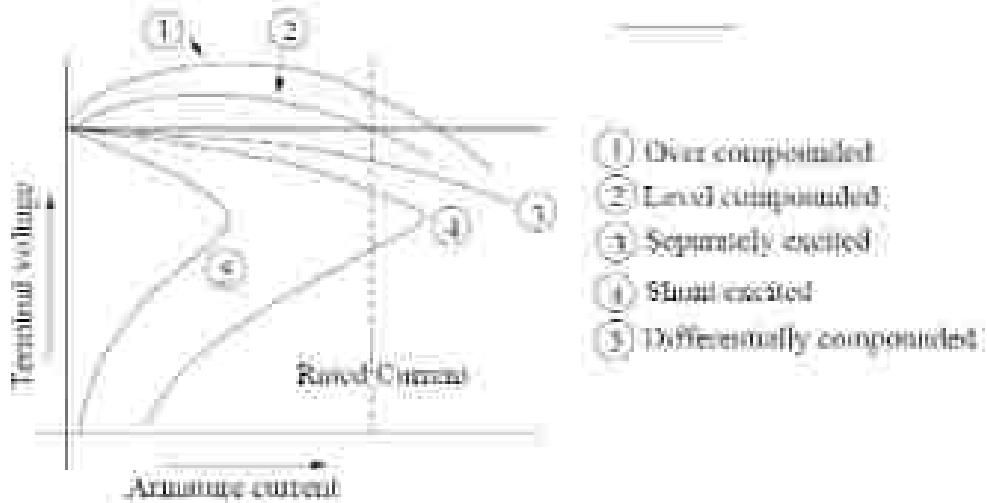
To understand the usefulness of the series coil in a compound machine let us undertake the following simple calculations. Suppose as a shunt generator (series coil not connected) 300 AT/pole is necessary to get no load terminal voltage of 220 V. Let the terminal voltage becomes 210 V at rated armature current of 20 A. To restore the terminal voltage to 220 V, shunt excitation needs to be raised such that AT/pole required is 380 at 20 A of rated current. As a level compound generator, the extra AT

$(380-300 = 80)$ will be provided by series field. Therefore, number of series turns per pole will be $80/20 = 4$. Thus in a compound generator series field will automatically provide the extra AT to arrest the drop in terminal voltage which otherwise is inevitable for a shunt generator.

In a differential compound generator the *north* of the series field acts opposite to the shunt field. As a result, the terminal voltage falls drastically with increasing load. Differential compound generators were formerly used in DC arc welders, because they tended to limit the short-circuit current and to stabilize the arc during the welding process.



Range of load characteristics for a compound-wound d.c. generator



Voltage Regulation:

Voltage regulation of a generator is defined as the change in terminal voltage between no-load and full load, expressed as percentage of the rated load voltage.

If it is small, then the generator is said to have good regulation but if the change in voltage is large, then it has poor regulation.

Application of D.C. Generators:

1. Shunt generators with field regulators are used for ordinary lighting and power supply purposes. They are also used for charging batteries because their terminal voltages are almost constant or can be kept constant.
2. Series generators are not used for power supply because of their rising characteristics. However, their rising characteristic makes them suitable for being used as boosters in certain types of distribution systems particularly in railway service.
3. Compound generators: The cumulatively-compound generator is the most widely used d.c. generator because its external characteristic can be adjusted for compensating the voltage drop in the line resistance. Hence, such generators are used for motor driving which require d.c. supply at constant voltage, for lamp loads and for heavy power service such as electric railways. The differentially-compound generator has an external characteristic similar to that of a shunt generator but with large demagnetization armature reaction. Hence, it is widely used in arc welding where larger voltage drop is desirable with increase in current.

DC Motor:

D.C. Motor Principle:

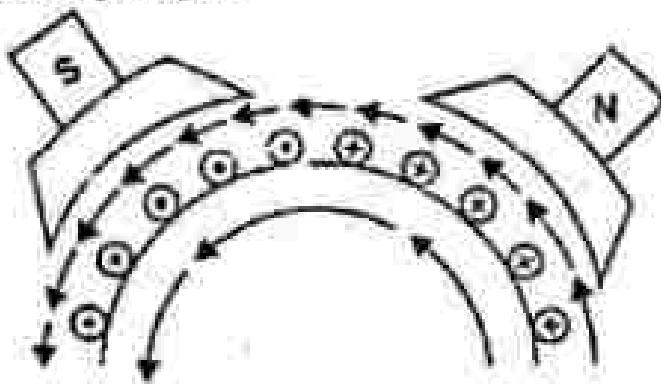
A machine that converts d.c. electrical power into mechanical power is known as a d.c. motor. Its operation is based on the principle that when a current carrying conductor is placed in a magnetic field, the conductor experiences a mechanical force. The direction of this force is given by Fleming's left hand rule and magnitude is given by, $F = BiL$ Newtons.

Basically, there is no constructional difference between a d.c. motor and a d.c. generator. The same d.c. machine can be run as a generator or motor.

Working of D.C. Motor

When the terminals of the motor are connected to an external source of d.c. supply:

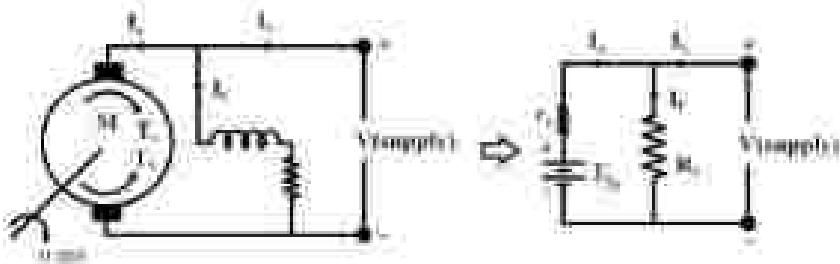
- i. the field magnets are excited developing alternate N and S poles;
- ii. The armature conductors carry currents.



All conductors under N-pole carry currents in one direction while all the conductors under S-pole carry currents in the opposite direction. Suppose the conductors under N-pole carry currents into the plane of the paper and those under S-pole carry currents out of the plane of the paper. Since each armature conductor is carrying current and is placed in the magnetic field, mechanical force acts on it.

Applying Fleming's left hand rule, it is clear that force on each conductor is tending to rotate the armature in anticlockwise direction. All these forces add together to produce a driving torque which sets the armature rotating. When the conductor moves from one side of a brush to the other, the current in that conductor is reversed and at the same time it comes under the influence of next pole which is of opposite polarity. Consequently, the direction of force on the conductor remains the same.

As soon as the armature starts rotating, dynamically (or motinally) induced e.m.f. is produced in the armature conductors. The direction of this induced e.m.f. can be found by Fleming's Right-hand Rule, i.e. outwards i.e., in direct opposition to the applied voltage. This is why it is known as back e.m.f. "E_b" or counter e.m.f. Its value is the same as for the motinally induced e.m.f. in the generator i.e. $E_b = \frac{\phi \omega}{R} \left(\frac{2}{\pi} \right)$ volt. The applied voltage V has to be force current through the armature conductors against this back e.m.f. "E_b". The electric work done in overcoming this opposition is converted into mechanical energy developed in the armature ($E_b I_a = \omega T_s$).



The armature and field coils are connected in parallel in a d.c. shunt motor and the parallel combination is supplied with voltage V . I_a , I_f and I_s are respectively the current drawn from supply, the armature current and the field current respectively. The following equations can be written by applying KCL and KVL in the field circuit and KVL in the armature circuit.

$$I_s = I_f + I_a \text{ (applying KCL)}$$

$$I_f = \frac{V}{R_f} \text{ (from KVL in field circuit)}$$

$$I_a = \frac{V - I_f R_a}{R_a} \text{ (from KVL in the armature circuit)}$$

$$= \frac{V - I_s R_a}{R_a}$$

How motor moves from one steady state operating point to another steady operating point?
How the motor is self regulating in nature?

Qualitative Analysis:

Let us assume the motor is absolutely under no-load condition which essentially means $T_L = 0$ and there is friction present. Thus when supply is switched on, both $I_a (= \frac{V}{R_a})$ and ϕ will be established developing T_f . As $T_f > 0$, motor should pick up speed due to acceleration. As motor speed increases, armature current decreases since back emf E_a rises. The value of T_f also progressively decreases. But so long T_f is present, acceleration will continue, increasing speed and back emf. A time will come when supply voltage and E_a will be same making armature current I_a zero. Now T_f becomes zero and acceleration stops and motor continues to run steadily at constant speed given by $N = \frac{V}{k_B \phi}$ and drawing no armature current. Note that input power to the armature is zero and mechanical output power is zero as well.

Let us bring a little reality to the previous discussion. Let us not neglect frictional torque during acceleration period from rest. Let us also assume frictional torque to be constant and equal to T_{fr} . How the final operating point will be decided in this case? When supply will be switched on T_f will be developed and machine will accelerate if $T_f > T_{fr}$. With time T_f will decrease as I_a decreases. Eventually, a time will come when T_f becomes equal to T_{fr} and motor will continue to run at constant steady no load speed N_0 . The motor in the final steady state however will continue to draw a definite amount of armature current which will produce T_f just enough to balance T_{fr} .

Suppose, the motor is running steadily at no load speed N_0 , drawing no load armature I_{a0} and producing torque $T_{f0} (= T_{fr})$. Now imagine, a constant load torque is suddenly imposed on the shaft of the motor at $t = 0$. Since speed cannot change instantaneously, at $t = 0^+$, $I_a(t = 0^+) = I_{a0}$ and $T_f(t = 0^+) =$

T_m . Thus, at $t = 0^+$, opposing torque is $(T_b + T_{load}) < T_m$. Therefore, the motor should start decelerating drawing more armature current and developing more torque T_e . Final steady operating point will be reached when, $T_e = T_{load} + T_b$ and motor will run at a new speed lower than no load speed N_0 but drawing I_a greater than the no load current I_{a0} .

Quantitative Analysis:

Suppose that the load on the shaft of a shunt motor is increased. Then the load torque T_{load} will exceed the induced torque T_{ind} in the machine, and the motor will start to slow down. When the motor slows down, its induced emf back emf ($E_b = K\phi N$) reduces, so the armature current ($\uparrow I_a = \frac{E_b - E_b}{R_a}$) in the motor increases. As the armature current rises, the induced torque in the motor increases ($\uparrow T_{ind} = K\phi I_a$) and finally the induced torque will equal the load torque at a lower mechanical speed of rotation.

Torque equation:

By the term torque is meant the turning or twisting moment of a force about an axis. It is measured by the product of the force and the radius at which this force acts.

Whenever armature carries current in presence of flux, conductor experiences force which gives rise to the electromagnetic torque T_e . Obviously T_e will be developed both in motor and generator mode of operation. It may be noted that the direction of conductor currents reverses as we move from one pole to the other. This ensures unidirectional torque to be produced.

Let Armature current = I_a

Current flowing through each conductor $I_c = \frac{I_a}{4}$

Average flux density $B_{av} = \frac{\text{total flux}}{\text{total area}} = \frac{\mu\Phi}{\pi D L}$

Force on a single conductor $= B_{av} * I_c * L = \frac{\mu\Phi}{\pi D L} * \frac{I_a}{4} * L = \frac{\mu\Phi I_a}{4\pi D L}$

Torque on a single conductor $= \frac{\mu\Phi I_a}{4\pi D L} * \frac{D}{2} = \frac{\mu}{2\pi A} \Phi I_a$

Total electromagnetic torque developed, $T_e = \frac{\mu}{2\pi A} \Phi I_a * z = \frac{\mu z}{2\pi A} \Phi I_a$

$$T_e = K_t \Phi I_a$$

Where, K_t is known as torque constant and given by $\frac{\mu z}{2\pi A}$.

For a shunt machine, as the flux almost remain constant $T_e \propto I_a$

For a series machine the flux is directly proportional to armature current so,

$$T_e \propto I_a \quad \text{If the core is saturated}$$

$$T_e \propto I_a^2 \quad \text{If the core is unsaturated}$$

Thus we see that the above equation is once again applicable both for motor and generator mode of operation. The direction of the electromagnetic torque, T_e will be along the direction of rotation in case of motor operation and opposite to the direction of rotation in case of generator operation.

As we know, $E_b = \frac{\mu \Phi N}{60} \left(\frac{2}{\pi} \right)$, dividing this equation with the torque equation we will get

$$\frac{T_e}{E_b} = \frac{\frac{P_2}{2\pi A} \Phi I_a}{\frac{p \Phi N}{60} \left(\frac{2}{A} \right)}$$

$$\Rightarrow \frac{T_e}{E_b} = \frac{60}{2\pi N} I_a$$

$$\Rightarrow \frac{T_e}{E_b} = \frac{I_a}{N} \left(A \times \omega = \frac{2\pi N}{60} \right)$$

$$or, \quad \frac{T_e}{E_b} = \frac{9.55}{N} I_a$$

$$T_e = \frac{T_e}{E_b} = 9.55 \frac{E_b I_a}{N}$$

$$T_e = 9.55 \frac{P_{out}}{N}$$

Shaft Torque

The total gross torque, as calculated above, is not available at the output for doing useful work, because a certain amount is utilized for supplying iron and friction losses in the motor. The torque which is available for doing useful work is known as shaft torque T_A . It is so called because it is available at the shaft. The difference $T_e - T_A$ is known as lost torque.

$$P_{out} = \omega T_A$$

$$or, T_A = \frac{P_{out}}{\omega}$$

Speed Equation:

The voltage equation of Dc-motor is given by:

$$E_b = \frac{p \Phi N}{60} \left(\frac{2}{A} \right)$$

$$E_b = K_c \Phi N$$

And

$$E_b = V_t - I_a R_b$$

Combining above equations:

$$V_t - I_a R_b = K_c \Phi N$$

$$\therefore N = \frac{V_t - I_a R_b}{K_c \Phi}$$

Let the machine is operating at constant load and excitation, if the load on the machine now changes, the above equations can be written as:

$$\frac{N_1}{N_2} = \frac{E_{b1}}{E_{b2}} \cdot \frac{\Phi_1}{\Phi_2} = \frac{E_{b1}}{E_{b2}} \cdot \frac{I_{r1}}{I_{r2}}$$

$$and \quad \frac{I_r}{I_2} = \frac{\Phi_1}{\Phi_2} \cdot \frac{I_{r1}}{I_{r2}}$$

For a shunt and separately excited motor:

$$\frac{N_2}{N_1} = \frac{E_{b1}}{E_{b2}}$$

and $\frac{T_2}{T_1} = \frac{i_{a1}}{i_{a2}}$

As the flux almost remains constant, if not changed intentionally or by de-magnetization.

For series Motor:

As the field and armature current are the same, $\Phi \propto I_a$

$$\frac{N_1}{N_2} = \frac{E_{b1}}{E_{b2}} \cdot \frac{\Phi_2}{\Phi_1} = \frac{E_{b1}}{E_{b2}} \cdot \frac{i_{a2}}{i_{a1}}$$

and $\frac{T_1}{T_2} = \frac{i_{a1}}{i_{a2}} \cdot \frac{i_{a1}}{i_{a2}} = \frac{i_{a1}^2}{i_{a2}^2}$

Speed Regulation:

The term speed regulation refers to the change in speed of a motor with change in applied load torque, other conditions remaining constant.

The speed regulation is defined as "the change in speed from no load to rated load, expressed as percent of the rated load speed".

$$\% \text{ speed regulation} = \frac{\text{N.L. speed} - \text{F.L. speed}}{\text{F.L. speed}} \times 100 \%$$