D.C Machines

1 Introduction

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

The limitations of the d.c. system however became more and more apparent as the power demand increased. In the case of d.c. systems the generating stations and the load centers have to be near to each other for efficient transmission of energy. The invention of induction machines in the 1880s tilted the scale in favor of a.c. systems mainly due to the advantage offered by transformers, which could step up or step down the a.c.voltage levels at constant power at extremely high efficiency. Thus a.c. system took over as the preferred system for the generation transmission and utilization of electrical energy. The d.c. system, however could not be obliterated due to the 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. These basic principles are discussed at first.

1.1 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 electro-magnetic 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.

1. Electric circuit laws - $Kirchoff's \;\; Laws$
2. Magnetic circuit law - $Ampere's \;\; Law$
3. Law of electromagnetic induction - $Faraday's \;\; Law$
4. Law of electromagnetic interaction -$BiotSavart's \;\; Law$

Most of the present day machines have one or two electric circuits linking a common magnetic circuit. In subsequent discussions the knowledge of electric and magnetic circuit laws is assumed. The attention is focused on the Faraday's law and Biot Savart's law in the present study of the electrical machines.

1.1.1 Law of electro magnetic induction

Faraday proposed this law of Induction in 1831. It states that if the magnetic flux lines linking a closed electric 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,

$$e \propto \frac{d\psi}{dt} \tag{1}$$

where ψ is the flux linkages given by the product of flux lines in weber that are linked and N the number of turns of the coil. This can be expressed as,

$$e \propto N\frac{d\Phi}{dt} \tag{2}$$

Here N is the number of turns of the coil, and Φ is the flux lines in weber linking all these turns. The direction of the induced emf can be determined by the application of Lenz's law. Lenz's law states that the direction of the induced emf is such as to produce an effect to oppose this change in flux linkages. It is analogous to the inertia in the mechanical systems.

The changes in the flux linkages associated with a turn can be brought about by

(i) changing the magnitude of the flux linking a static coil

(ii) moving the turn outside the region of a steady field

(iii) moving the turn and changing the flux simultaneously

These may be termed as Case(i), Case(ii), and Case(iii) respectively.

This is now explained with the help of a simple geometry. Fig. 1 shows a rectangular loop of one turn (or N=1). Conductor 1 is placed over a region with a uniform flux density of B Tesla. The flux lines, the conductor and the motion are in mutually perpendicular directions. The flux linkages of the loop is BLN weber turns. If the flux is unchanging and conductor stationary, no emf will be seen at the terminals of the loop. If now the flux alone changes with time such that $B = B_m.\cos\omega t$, as in Case(i), an emf given by

$$\begin{aligned} e = \frac{d}{dt}(B_m.L.N\cos\omega t) &= -(B_m.L.N\omega).\sin\omega t. \\ &= -jB_m.L.N\omega.\cos\omega t \qquad \text{volt} \end{aligned} \tag{3}$$

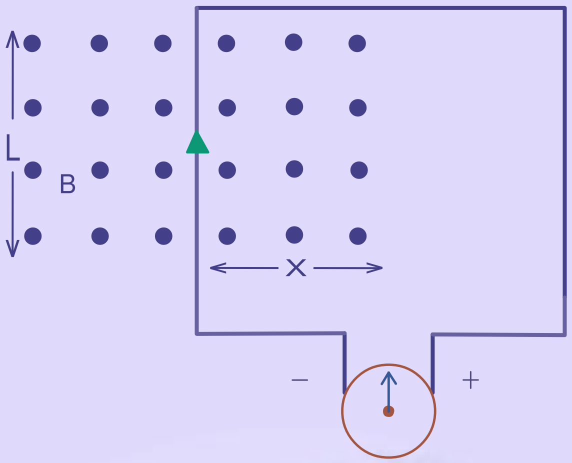


Figure 1: Faraday's law of Induction

appears across the terminals. This is termed as a "transformer" emf.

If flux remains constant at B_m but the conductor moves with a velocity v, as in Case(ii), then the induced emf is

$$e = \frac{d\psi}{dt} = \frac{d(B_m.L.N)}{dt} = B_m.L.N\frac{dX}{dt} \quad \text{volts} \tag{4}$$

but

$$\frac{dX}{dt} = v \quad \therefore e = B_m.L.N.v \quad \text{volts} \tag{5}$$

The emf induced in the loop is directly proportional to the uniform flux density under which it is moving with a velocity v. This type of voltage is called speed emf (or rotational emf). The Case(iii) refers to the situation where B is changing with time and so also is X. Then the change in flux linkage and hence the value of e is given by

$$e = \frac{d\psi}{dt} = \frac{d(B_m.L.X.N.\cos\omega t)}{dt} = B_m.\cos\omega t.L.N.\frac{dX}{dt} - B_m.L.X.N.\omega.\sin\omega t. \tag{6}$$

In this case both transformer emf and speed emf are present.

The Case(i) has no mechanical energy associated with it. This is the principle used in transformers. One coil carrying time varying current produces the time varying field and a second coil kept in the vicinity of the same has an emf induced in it. The induced emf of this variety is often termed as the transformer emf.

The Case(ii) is the one which is employed in d.c. machines and alternators. A static magnetic field is produced by a permanent magnet or by a coil carrying a d.c. current. A coil is moved under this field to produce the change in the flux linkages and induce an emf in the same. In order to produce the emf on a continuous manner a cylindrical geometry is chosen for the machines. The direction of the field, the direction of the conductor of the coil and the direction of movement are mutually perpendicular as mentioned above in the example taken.

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 turn may be assumed to be far away or unmoving. This greatly simplifies the computation of the induced voltage as the determination of flux linkages and finding its rate of change are dispensed with. For a conductor moving at a constant velocity v the induced emf becomes just proportional to the uniform flux density of the magnetic field where the conductor is situated. 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. The induced emf of this type is usually referred to as a rotational emf (due to the geometry).

Application of Faradays law according to Case(iii) above for electro mechanical energy conversion results in the generation of both transformer and rotational emf to be present in the coil moving under a changing field. This principle is utilized in the induction machines and a.c. commutator machines. The direction of the induced emf is

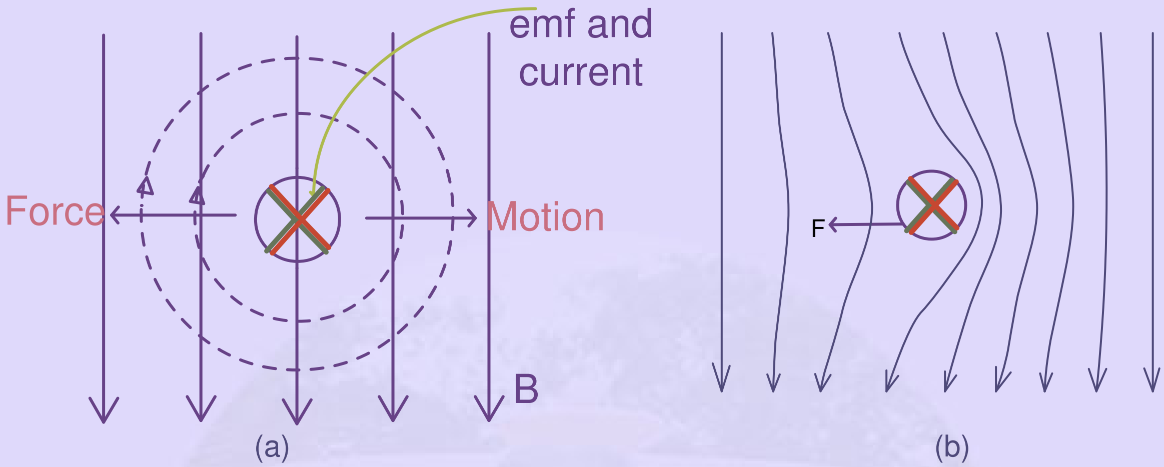


Figure 2: Law of induction-Generator action

decided next. This can be obtained by the application of the Lenz's law and the law of interaction. This is illustrated in Fig. 3.

In Case(i), the induced emf will be in such a direction as to cause a opposing mmf if the circuit is closed. Thus, it opposes the cause of the emf which is change in ψ and hence ϕ. Also the coil experiences a compressive force when the flux tries to increase and a tensile force when the flux decays. If the coil is rigid, these forces are absorbed by the supporting structure.

In Case(ii), the direction of the induced emf is as shown. Here again one could derive the same from the application of the Lenz's law. The changes in the flux linkages is

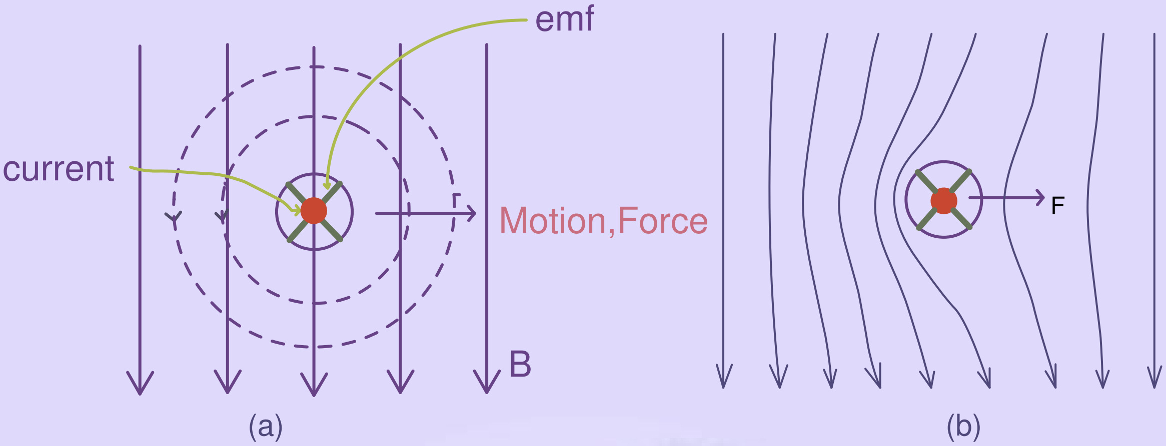


Figure 3: Law of interaction- Motor action

brought about by the sweep or movement of the conductor. The induced emf, if permitted to drive a current which produces an opposing force, is as shown in the figure. If one looks closely at the field around the conductor under these conditions it is as shown in Fig. 2(a)and (b). The flux lines are more on one side of the conductor than the other. These lines seem to urge the conductor to the left with a force F. As F opposes v and the applied force, mechanical energy gets absorbed in this case and the machine works as a generator. This force is due to electro magnetic interaction and is proportional to the current and the flux swept. Fig. 3(a)and (b) similarly explain the d.c.motor operation. The current carrying conductor reacts with the field to develop a force which urges the conductor to the right. The induced emf and the current are seen to act in opposite direction resulting in the absorption of electric energy which gets converted into the mechanical form.

In Case (iii) also the direction of the induced emf can be determined in a similar manner. However, it is going to be more complex due to the presence of transformer emf and rotational emf which have phase difference between them.

Putting mathematically, in the present study of d.c.machines,

$$F = B.L.I \quad \text{Newton}$$

When the generated voltage drives a current, it produces a reaction force on the mechanical system which absorbs the mechanical energy. This absorbed mechanical energy is the one which results in the electric current and the appearance of electrical energy in the electrical circuit. The converse happens in the case of the motor. If we force a current against an induced emf then the electrical power is absorbed by the same and it appears as the mechanical torque on the shaft. Thus, it is seen that the motoring and generating actions are easily changeable with the help of the terminal conditions.

2 Principles of d.c. machines

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

1. Homopolar machines
2. Heteropolar machines.

These are discussed in sequence below.

2.1 Homopolar machines

Homopolar generators

Even though the magnetic poles occur in pairs, in a homopolar generator the conductors are arranged in such a manner that they always move under one polarity. Either north pole or south pole could be used for this purpose. Since the conductor encounters the magnetic flux of the same polarity every where it is called a homopolar generator. A cylindrically symmetric geometry is chosen. The conductor can be situated on the surface of the rotor with one slip-ring at each end of the conductor. A simple structure where there is only one cylindrical conductor with ring brushes situated at the ends is shown in Fig. 4. The excitation coil produces a field which enters the inner member from outside all along the periphery. The conductor thus sees only one pole polarity or the flux directed in one sense. A steady voltage now appears across the brushes at any given speed of rotation. The polarity of the induced voltage can be reversed by reversing either the excitation or the direction of

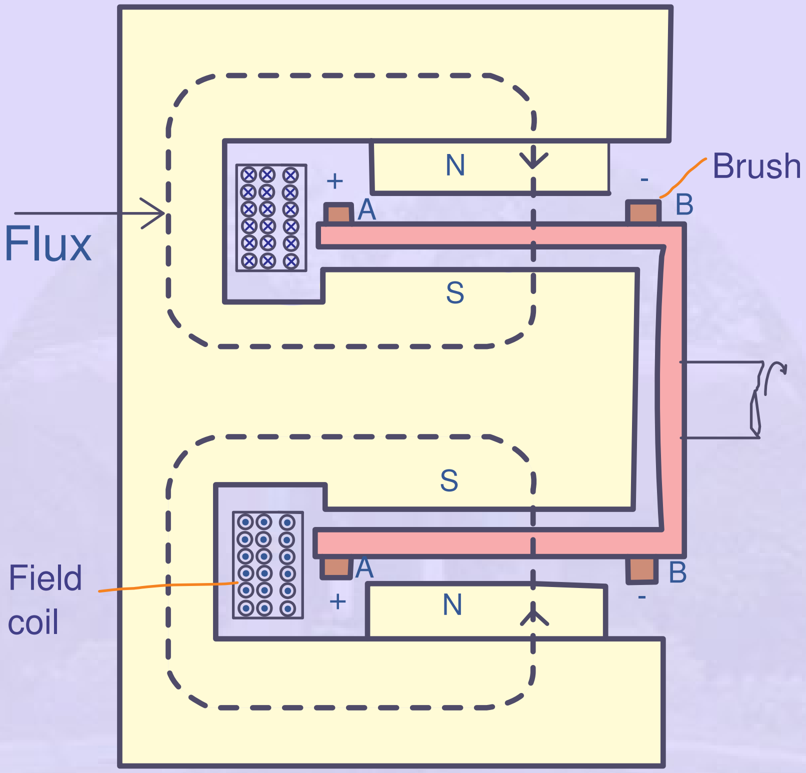


Figure 4: Homopolar Generator

rotation but not both. The voltage induced would be very low but the currents of very large amplitudes can be supplied by such machines. Such sources are used in some applications like pulse-current and MHD generators, liquid metal pumps or plasma rockets. The steady field can also be produced using a permanent magnet of ring shape which is radially magnetized. If higher voltages are required one is forced to connect many conductors in series. This series connection has to be done externally. Many conductors must be situated on the rotating structure each connected to a pair of slip rings. However, this modification introduces parasitic air-gaps and makes the mechanical structure very complex. The magnitude of the induced emf in a conductor 10 cm long kept on a rotor of 10 cm radius rotating at 3000 rpm, with the field flux density being 1 Tesla every where in the air gap, is given by

$$
\begin{aligned}
e &= BLv \\
&= 1 * 0.1 * 2\pi * 0.1 * \frac{3000}{60} = 3.14 \quad \text{volt}
\end{aligned}
$$

The voltage drops at the brushes become very significant at this level bringing down the efficiency of power conversion. Even though homopolar machines are d.c. generators in a strict sense that they 'generate' steady voltages, they are not quite useful for day to day use. A more practical converters can be found in the d.c. machine family called "hetero-polar" machines.

2.2 Hetero-polar d.c. generators

In the case of a hetero-polar generator the induced emf in a conductor goes through a cyclic change in voltage as it passes under north and south pole polarity alternately. The induced emf in the conductor therefore is not a constant but alternates in magnitude. For

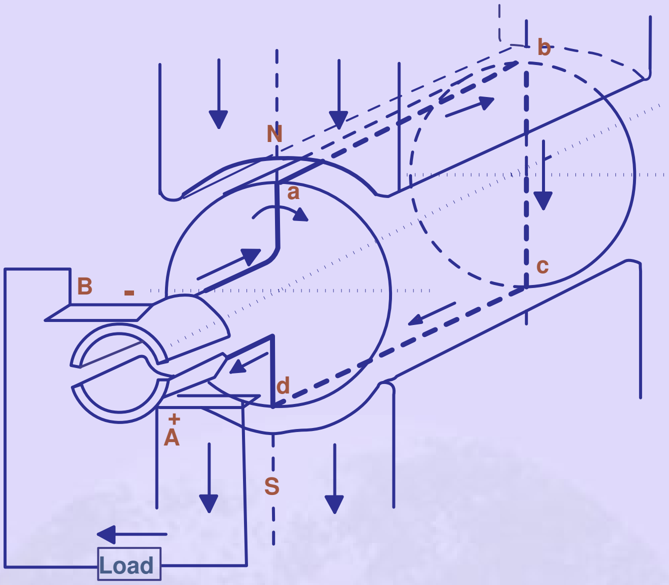


Figure 5: Elementary hetro-polar machine

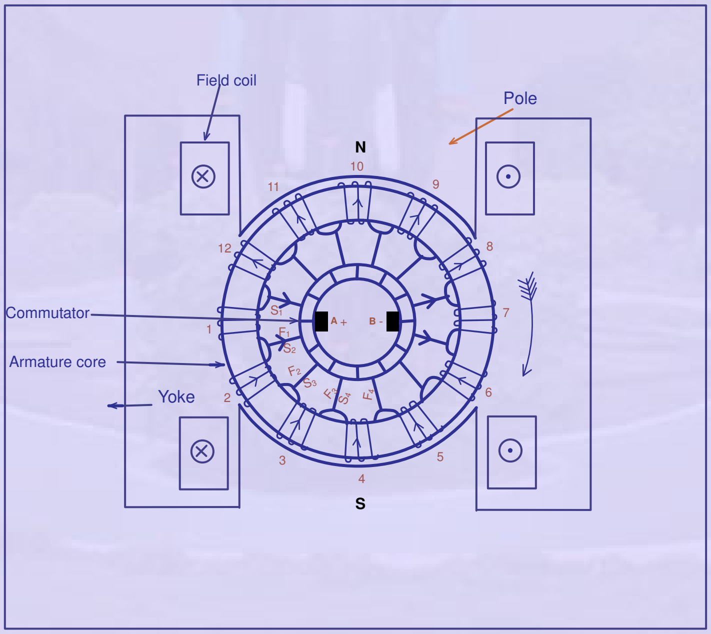


Figure 6: Two pole machine -With Gramme ring type armature

a constant velocity of sweep the induced emf is directly proportional to the flux density under which it is moving. If the flux density variation is sinusoidal in space, then a sine wave voltage is generated. This principle is used in the a.c generators. In the case of d.c. generators our aim is to get a steady d.c. voltage at the terminals of the winding and not the shape of the emf in the conductors. This is achieved by employing an external element, which is called a commutator, with the winding.

Fig. 5 shows an elementary hetero-polar, 2-pole machine and one-coil armature. The ends of the coil are connected to a split ring which acts like a commutator. As the polarity of the induced voltages changes the connection to the brush also gets switched so that the voltage seen at the brushes has a unidirectional polarity. This idea is further developed in the modern day machines with the use of commutators. The brushes are placed on the commutator. Connection to the winding is made through the commutator only. The idea of a commutator is an ingenious one. Even though the instantaneous value of the induced emf in each conductor varies as a function of the flux density under which it is moving, the value of this emf is a constant at any given position of the conductor as the field is stationary. Similarly the sum of a set of coils also remains a constant. This thought is the one which gave birth to the commutator. The coils connected between the two brushes must be "similarly located" with respect to the poles irrespective of the actual position of the rotor. This can be termed as the condition of symmetry. If a winding satisfies this condition then it is suitable for use as an armature winding of a d.c. machine. The ring winding due to Gramme is one such. It is easy to follow the action of the d.c. machine using a ring winding, hence it is taken up here for explanation.

Fig. 6 shows a 2-pole, 12 coil, ring wound armature of a machine. The 12 coils are placed at uniform spacing around the rotor. The junction of each coil with its neighbor is connected to a commutator segment. Each commutator segment is insulated from its neighbor by a mica separator. Two brushes A and B are placed on the commutator which looks like a cylinder. If one traces the connection from brush A to brush B one finds that there are two paths. In each path a set of voltages get added up. The sum of the emfs is constant(nearly). The constancy of this magnitude is altered by a small value corresponding to the coil short circuited by the brush. As we wish to have a maximum value for the output voltage, the choice of position for the brushes would be at the neutral axis of the field. If the armature is turned by a distance of one slot pitch the sum of emfs is seen to be constant even though a different set of coils participate in the addition. The coil which gets short circuited has nearly zero voltage induced in the same and hence the sum does not change substantially. This variation in the output voltage is called the 'ripple'. More the number of coils participating in the sum lesser would be the 'percentage' ripple.

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

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

$$E_c = B_{av}.L.v \quad \text{Volt} \tag{7}$$

where

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

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

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

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

The induced emf between the brushes is

$$E = E_c.\frac{Z}{2b} \tag{8}$$

$$E = B_{av}.L.v.\frac{Z}{2b} \quad \text{Volts} \tag{9}$$

But $v = (2p).Y.n$ where p is the pairs of poles Y is the pole pitch, in meters, and n is the number of revolutions made by the armature per second.

Also B_{av} can be written in terms of pole pitch Y, core length L, and flux per pole ϕ as

$$B_{av} = \frac{\phi}{(L.Y)} \quad \text{Tesla} \tag{10}$$

Substituting in equation Eqn. 9,

$$E = \frac{\phi}{(L.Y)}.L.(2p.Y.n).\frac{Z}{2b} \quad = \frac{\phi p Z n}{b} \quad \text{volts} \tag{11}$$

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

2.2.1 Torque production

When the armature is loaded, the armature conductors carry currents. These current carrying conductors interact with the field and experience force acting on the same. This force is in such a direction as to oppose their cause which in the present case is the relative movement between the conductors and the field. Thus the force directly opposes the motion. Hence it absorbs mechanical energy. This absorbed mechanical power manifests itself as the converted electrical power. The electrical power generated by an armature delivering a current of I_a to the load at an induced emf of E is EI_a Watts. Equating the mechanical and electrical power we have

$$2\pi n T = EI_a \tag{12}$$

where T is the torque in Nm. Substituting for E from Eqn. 11, we get

$$2\pi n T = \frac{p.\phi.Z.n}{b}.I_a \tag{13}$$

which gives torque T as

$$T = \frac{1}{2\pi}.p.\phi.(\frac{I_a}{b})Z \quad \text{Nm} \tag{14}$$

This shows that the torque generated is not a function of the speed. Also, it is proportional to 'total flux' and 'Total ampere conductors' on the armature, knowing that $I_a/2b$ is I_c the conductor current on the armature. The expression for the torque generated can also be derived from the first principles by the application of the law of interaction. The law of interaction states that the force experienced by a conductor of length L kept in a uniform field of flux density B carrying a current I_c is proportional to B,L and I_c. Force on a single conductor F_c is given by,

$$F_c = B.L.I_c \quad \text{Newton} \tag{15}$$

The total work done by an armature with Z conductors in one revolution is given by,

$$W_a = B_{av}.L.I_c.Z.(2p.Y) \quad \text{Joules} \quad = \frac{\phi}{L.Y}.L.I_c.Z.2p.Y \quad \text{Joules} \tag{16}$$

The work done per second or the power converted by the armature is,

$$P_{conv} = \phi.2p.Z.I_c.n \quad \text{watts} \tag{17}$$

$$AsI_c = \frac{I_a}{2b} \tag{18}$$

$$= \phi.p.Z.n.\frac{I_a}{b} \tag{19}$$

which is nothing but EI_a.

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

2.2.2 Motoring operation of a d.c. machine

In the motoring operation the d.c. machine is made to work from a d.c. source and absorb electrical power. This power is converted into the mechanical form. This is briefly discussed here. If the armature of the d.c. machine which is at rest is connected to a d.c. source then, a current flows into the armature conductors. If the field is already excited then these current carrying conductors experience a force as per the law of interaction discussed above and the armature experiences a torque. If the restraining torque could be neglected the armature starts rotating in the direction of the force. The conductors now move under the field and cut the magnetic flux and hence an induced emf appears in them. The polarity of the induced emf is such as to oppose the cause of the current which in the present case is the applied voltage. Thus a 'back emf' appears and tries to reduce the current. As the induced emf and the current act in opposing sense the machine acts like a sink to the electrical power which the source supplies. This absorbed electrical power gets converted into mechanical form. Thus the same electrical machine works as a generator of electrical power or the absorber of electrical power depending upon the operating condition. The absorbed power gets converted into electrical or mechanical power. This is briefly explained earlier with the help of Figure 3(a) and 3(b). These aspects would be discussed in detail at a later stage.

3 Constructional aspects of d.c. machines

As mentioned earlier the d.c. machines were invented during the second half of the 19th century. The initial pace of development work was phenomenal. The best configurations stood all the competition and the test of time and were adopted. Less effective options were discarded. The present day d.c. generator contains most, if not all, of the features of the machine developed over a century earlier. To appreciate the working and the characteristics of these machines, it is necessary to know about the different parts of the machine - both electrical and non-electrical. The description would also aid the understanding of the reason for selecting one form of construction or the other. An exploded view of a small d.c. machine is shown in Fig. 7.

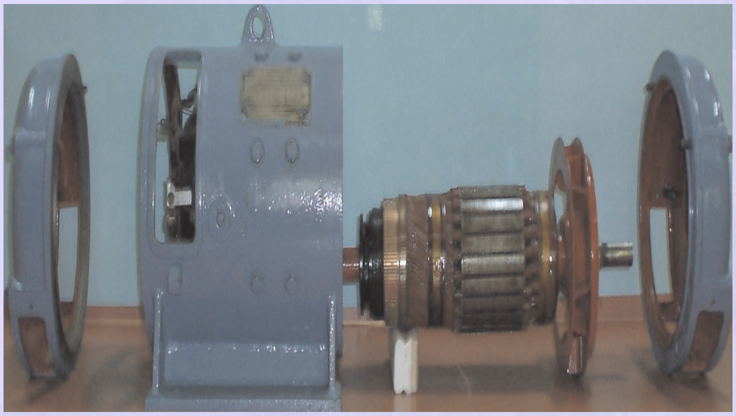


Figure 7: Exploded view of D.C.Machine

Click here to see the assembling of the parts.

The major parts can be identified as,

1. Body
2. Poles

3. Armature
4. Commutator and brush gear
5. Commutating poles
6. Compensating winding
7. Other mechanical parts

The constructional aspects relating to these parts are now discussed briefly in sequence.

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

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

Inter-poles These are small additional poles located in between the main poles. These can be solid, or laminated just as the main poles. These are also fastened to the yoke by bolts. Sometimes the yoke may be slotted to receive these poles. The inter poles could be of tapered section or of uniform cross section. These are also called as commutating poles or compoles. The width of the tip of the compole can be about a rotor slot pitch.

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

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

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

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

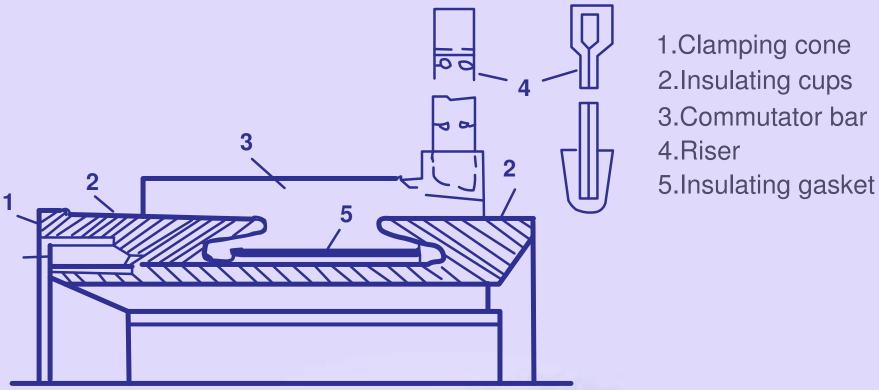
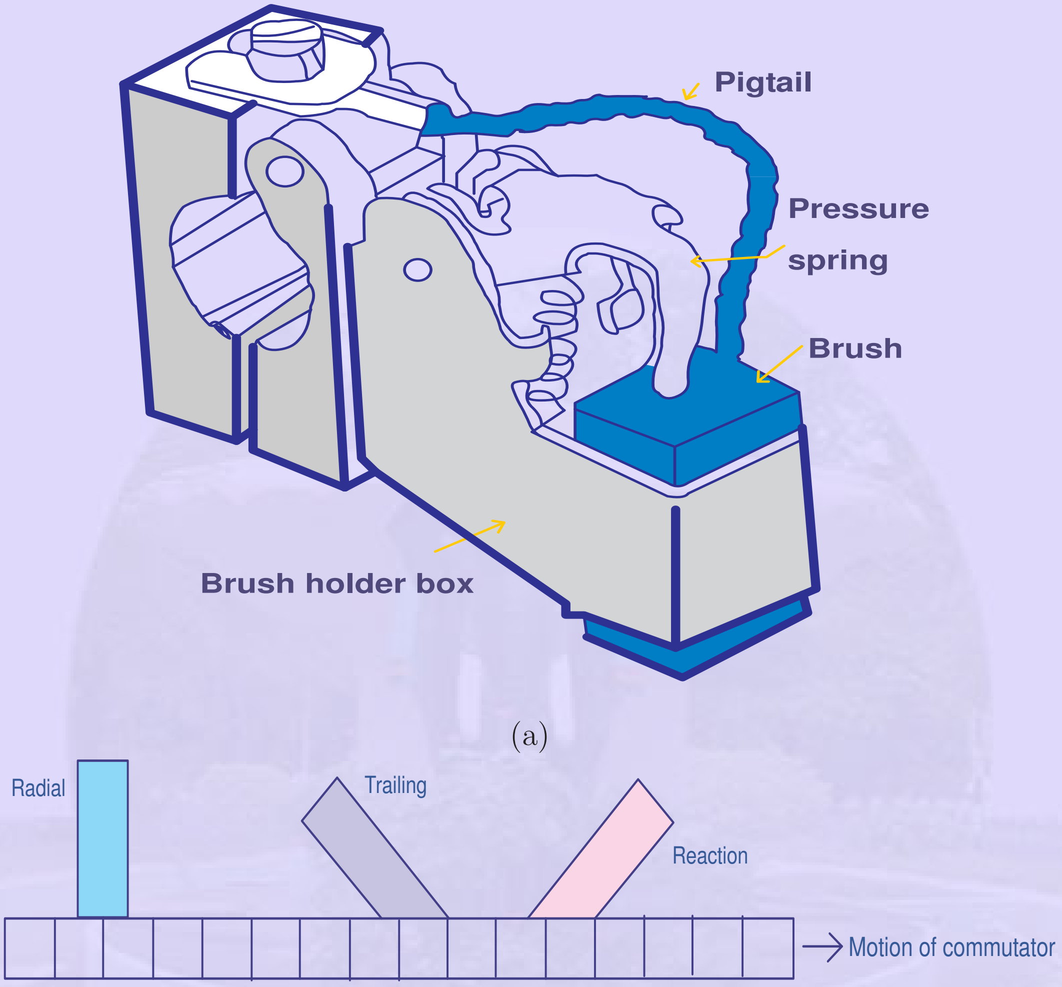


Figure 8: Cylindrical type commutator-a longitudinal section

Commutator Commutator is the key element which made the d.c. machine of the present day possible. It consists of copper segments tightly fastened together with mica/micanite insulating separators on an insulated base. The whole commutator forms a rigid and solid assembly of insulated copper strips and can rotate at high speeds. Each commutator segment is provided with a 'riser' where the ends of the armature coils get connected. The surface of the commutator is machined and surface is made concentric with the shaft and the current collecting brushes rest on the same. Under-cutting the mica insulators that are between these commutator segments has to be done periodically to avoid fouling of the surface of the commutator by mica when the commutator gets worn out. Some details of the construction of the commutator are seen in Fig. 8.

Brush and brush holders Brushes rest on the surface of the commutator. Normally electro-graphite is used as brush material. The actual composition of the brush depends on the peripheral speed of the commutator and the working voltage. The hardness of the graphite brush is selected to be lower than that of the commutator. When the brush wears out the graphite works as a solid lubricant reducing frictional coefficient. More number of relatively smaller width brushes are preferred in place of large broad brushes. The brush holders provide slots for the brushes to be placed. The connection from the brush is taken out by means of flexible pigtail. The brushes are kept pressed on the commutator with the help of springs. This is to ensure proper contact between



(a)

(b)

Figure 9: Brush holder with a Brush and Positioning of the brush on the commutator

the brushes and the commutator even under high speeds of operation. Jumping of brushes must be avoided to ensure arc free current collection and to keep the brush contact drop low. Fig. 9 shows a brush holder arrangement. Radial positioning of the brushes helps in providing similar current collection conditions for both direction of rotation. For unidirectional drives trailing brush arrangement or reaction arrangement may be used in Fig. 9-(b) Reaction arrangement is preferred as it results in zero side thrust on brush box and the brush can slide down or up freely. Also staggering of the brushes along the length of the commutator is adopted to avoid formation of 'tracks' on the commutator. This is especially true if the machine is operating in a dusty environment like the one found in cement plants.

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

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

4 Armature Windings

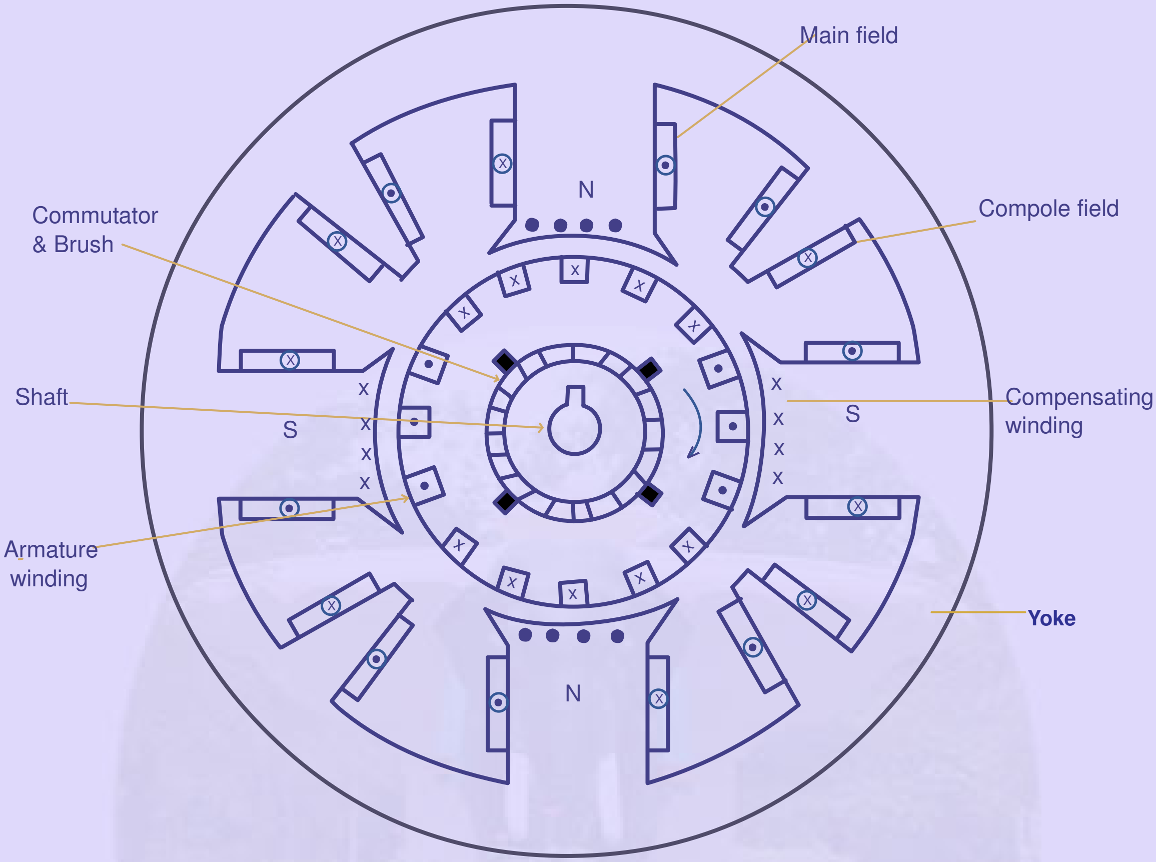


Figure 10: Cross sectional view

Fig. 10 gives the cross sectional view of a modern d.c. machine showing all the salient parts. Armature windings, along with the commutators, form the heart of the d.c. machine. This is where the emf is induced and hence its effective deployment enhances the output of the machine. Fig. 11(a) shows one coil of an armature of Gramme ring arrangement and Fig. 11(b) shows one coil as per drum winding arrangement. Earlier, a simple form of this winding in the form of Gramme ring winding was presented for easy understanding. The Gramme ring winding is now obsolete as a better armature winding has

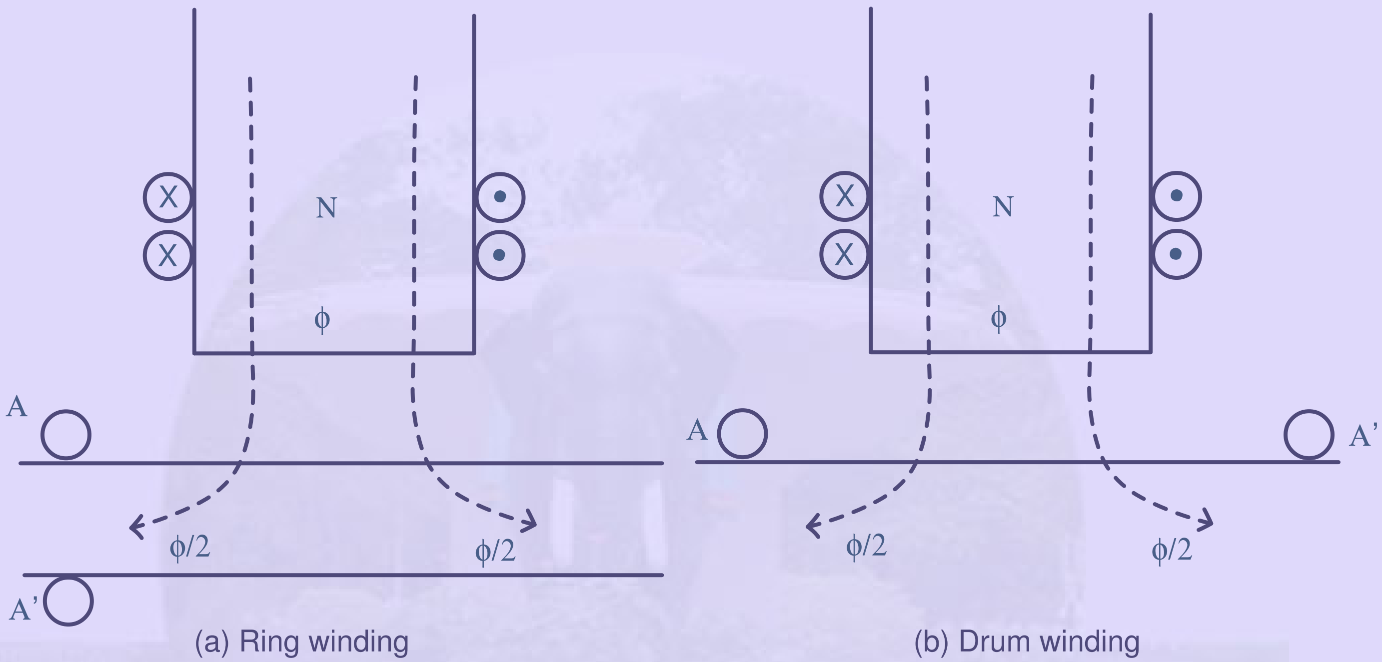
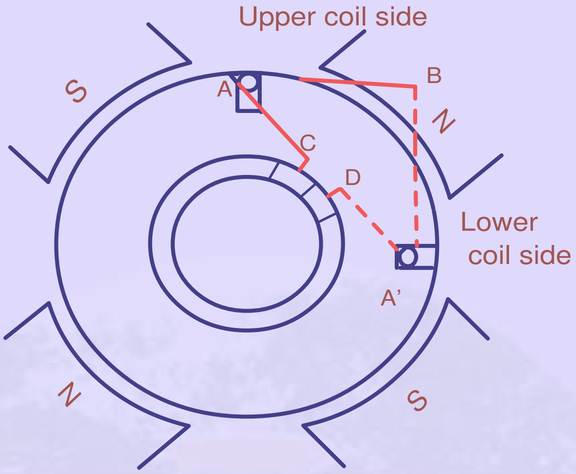


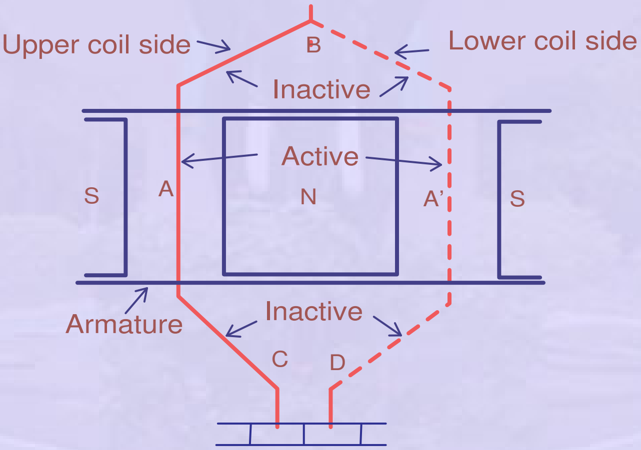
Figure 11: Ring winding and drum winding

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

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



(a) End view



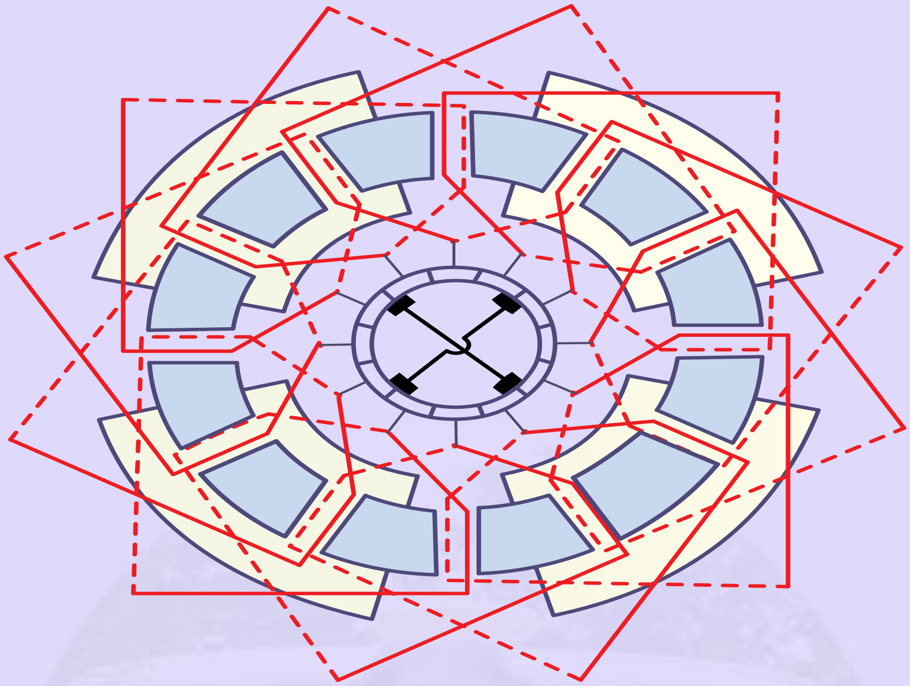
(b) Developed view

Figure 12: Arrangement of a single coil of a drum winding

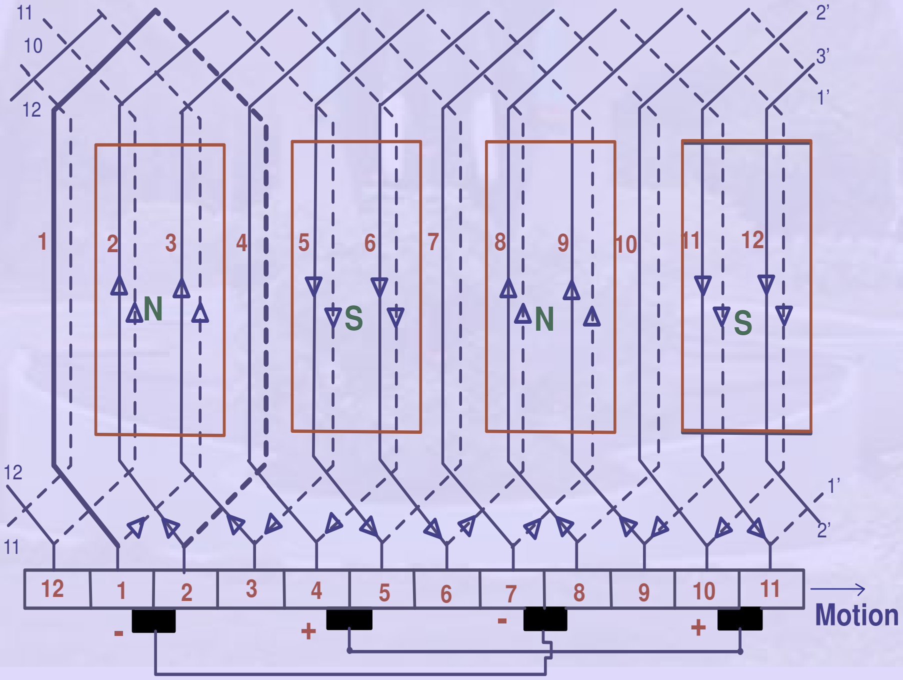
of a slot which is displaced by about one pole pitch. The junction of two coils is terminated on a commutator segment. Thus there are as many commutator segments as the number of coils. In a double layer winding in S slots there are 2S layers. Two layers are occupied by a coil and hence totally there are S coils. The S junctions of these S coils are terminated on S commutator segments. The brushes are placed in such a manner that a maximum voltage appears across them. While the number of parallel circuits in the case of ring winding is equal to the number of poles, in the case of drum winding a wide variety of windings are possible. The number of brushes and parallel paths thus vary considerably. The physical arrangement of a single coil is shown in Fig. 12 to illustrate its location and connection to the commutators.

Fig. 13 shows the axial side view while Fig. 13-(b) shows the cut and spread view of the machine. The number of turns in a coil can be one (single turn coils) or more (multi turn coils). As seen earlier the sum of the instantaneous emfs appears across the brushes. This sum gets altered by the voltage of a coil that is being switched from one circuit to the other or which is being commutated. As this coil in general lies in the magnetic neutral axis it has a small value of voltage induced in it. This change in the sum expressed as the fraction of the total induced voltage is called as the ripple. In order to reduce the ripple, one can increase the number of coils coming in series between the brushes. As the number of coils is the same as the number of slots in an armature with two coil sides per slot one is forced to increase the number of slots. However increasing the slot number makes the tooth width too narrow and makes them mechanically weak.

To solve this problem the slots are partitioned vertically to increase the number of coil sides. This is shown in Fig. 14. In the figure, the conductors a, b and c belong to a coil. Such 2/3 coils occupy the 2/3 top coil sides of the slot. In the present case the number of coils in the armature is 2S/3S.

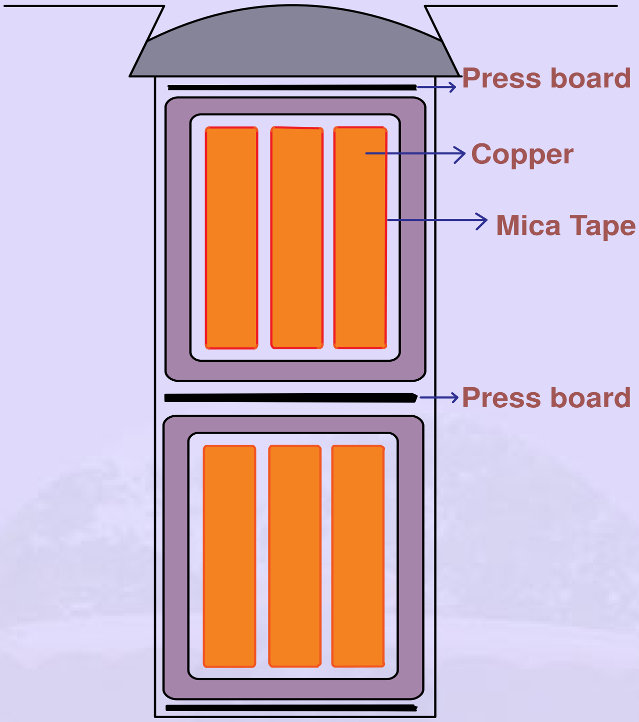


(a)End view

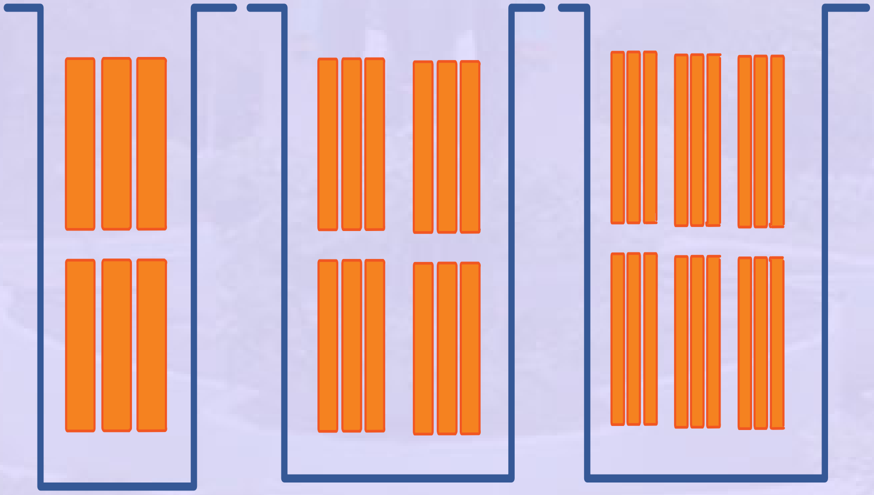


(b)Developed view

Figure 13: Lap Winding



(a) Single coil-side perlayer



(b) More coil sides perlayer

Figure 14: Partitioning of slots

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

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

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

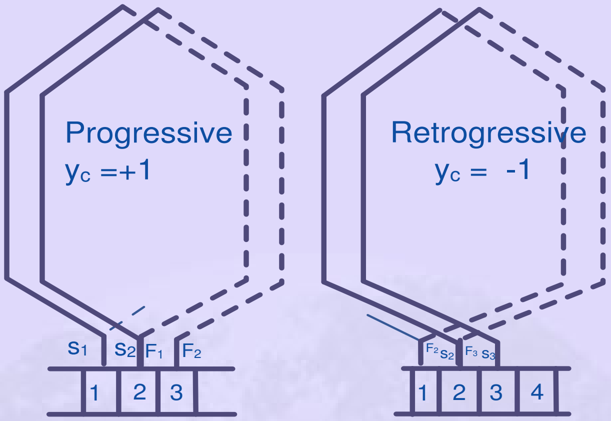
4.1 Lap winding

The commutator pitch for the lap windings is given by

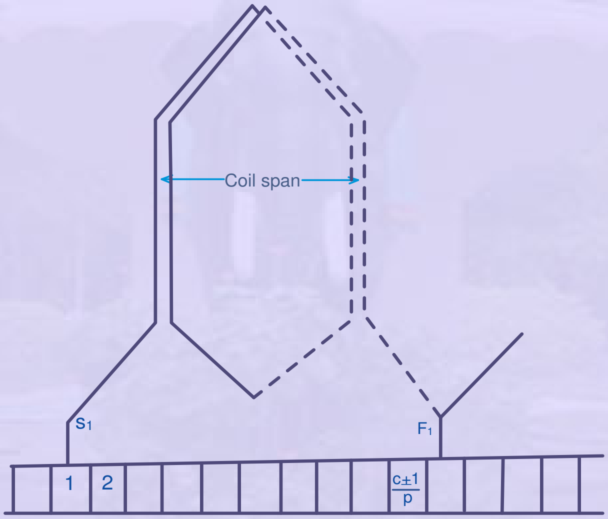
$$y_c = \pm m, \quad m = 1, 2, 3... \tag{20}$$

where y_c is the commutator pitch, m is the order of the winding.

For $m = 1$ we get a simple lap winding, $m = 2$ gives duplex lap winding etc. $y_c = m$ gives a multiplex lap winding of order m. The sign refers to the direction of progression of the winding. Positive sign is used for 'progressive' winding and the negative sign for the 'retrogressive' winding. Fig. 15 shows one coil as per progressive and retrogressive lap winding arrangements. Fig. 16 shows a developed view of a simple lap winding for a 4-pole armature in 12 slots. The connections of the coils to the commutator segments are also shown. The position of the armature is below the poles and the conductors move from left to right as indicated. The position and polarity of the brushes are also indicated. Single turn coils with $y_c = 1$ are shown here. The number of parallel paths formed by the winding equals the number of poles. The number of conductors that are connected in series between the brushes therefore becomes equal to $Z/2b$. Thus the lap winding is well suited for high current generators. In a symmetrical winding the parallel paths share the total line current



(a) Lap winding



(b) Wave winding

Figure 15: Typical end connections of a coil and commutator

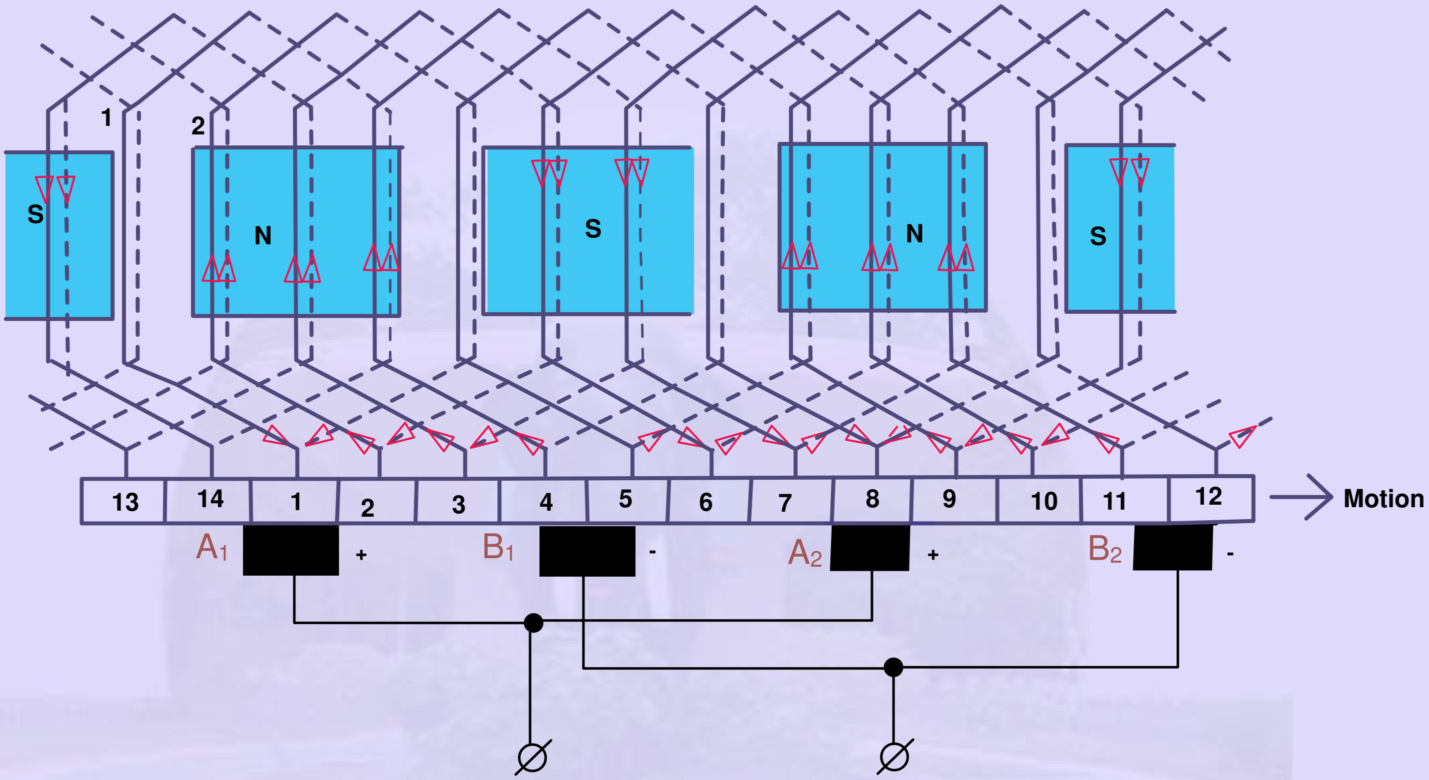
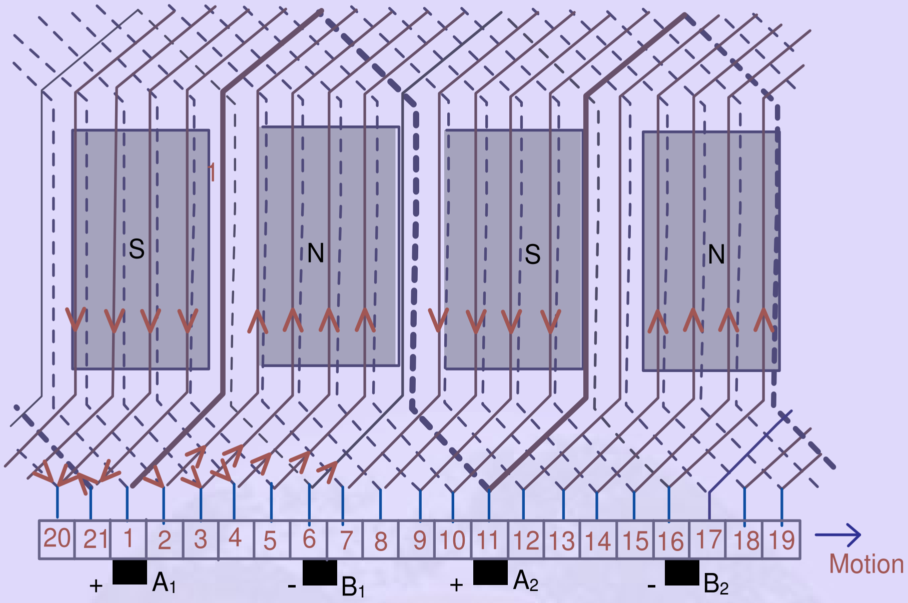


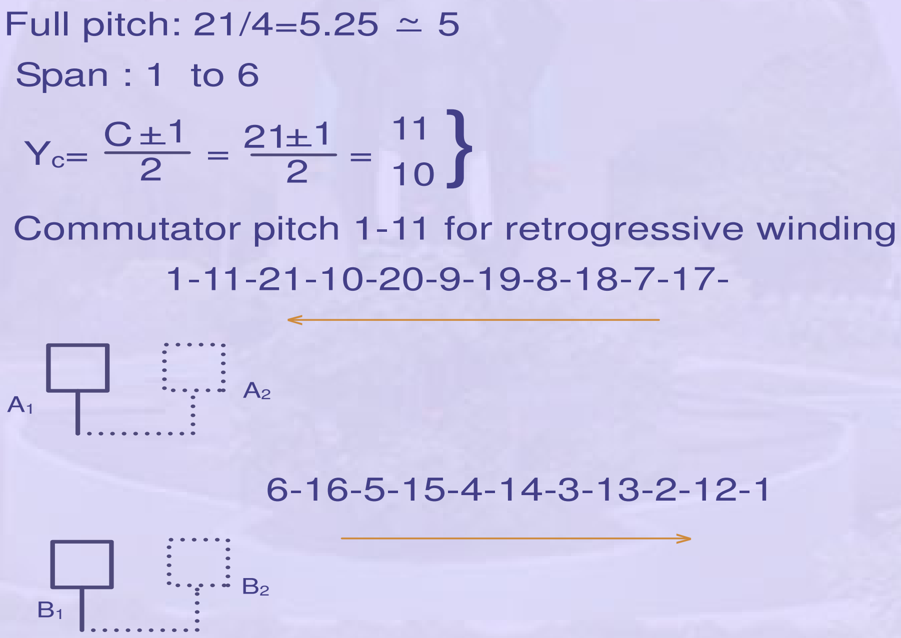
Figure 16: Developed view of a retrogressive Lap winding

equally.

The increase in the number of parallel paths in the armature winding brings about a problem of circulating current. The induced emfs in the different paths tend to differ slightly due to the non-uniformities in the magnetic circuit. This will be more with the increase in the number of poles in the machine. If this is left uncorrected, circulating currents appear in these closed parallel paths. This circulating current wastes power, produces heat and over loads the brushes under loaded conditions. One method commonly adopted in d.c. machines to reduce this problem is to provide equalizer connections. As the name suggests these connections identify similar potential points of the different parallel paths and connect them together to equalize the potentials. Any difference in the potential generates a local circulating current and the voltages get equalized. Also, the circulating current does not flow through the brushes loading them. The number of such equalizer connections, the cross section for the conductor used for the equalizer etc are decided by the designer. An example of equalizer connection is discussed now with the help of a 6-pole armature having 150 commutator segments. The coil numbers 1, 51 and 101 are identically placed under the poles of same polarity as they are one pole-pair apart. There are 50 groups like that. In order to limit the number of links to 5(say), the following connections are chosen. Then 1,11,21,31, and 41 are the coils under the first pair of poles. These are connected to their counter parts displaced by 50 and 100 to yield 5 equalizer connections. There are 10 coils connected in series between any two successive links. The wave windings shall be examined next.



(a)Winding layout


Full pitch: 21/4=5.25 ≃ 5

Span : 1 to 6

$$Y_c = \frac{C \pm 1}{2} = \frac{21 \pm 1}{2} = \left.\begin{matrix} 11 \\ 10 \end{matrix}\right\}$$

Commutator pitch 1-11 for retrogressive winding

1-11-21-10-20-9-19-8-18-7-17-

6-16-5-15-4-14-3-13-2-12-1

(b)Parallel paths

Figure 17: Developed view of a Retrogressive Wave winding

4.2 Wave windings

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

$$y_c = \frac{C \pm 1}{p} \tag{21}$$

where C is the total segments on the commutator. y_c should be an integer number; C and p should satisfy this relation correctly. Here also the positive sign refers to the progressive winding and the negative sign yields a retrogressive winding. $y_c = (C \pm m)/p$ yields a multiplex wave winding of order m. A simple wave winding for 4 poles in 21 slots is illustrated in Fig. 17. As could be seen from the figure, the connection to the next (or previous) adjacent coil is reached after p coils are connected in series. The winding closes on itself after all the coils are connected in series. The position for the brushes is indicated in the diagram.

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

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

If the brushes are kept at commutator segment 1 and 6, nearly half the number of coils come under each circuit. The polarity of the brushes are positive and negative alternately. Or, one could have two brushes at 11 and 16 or any two adjacent poles. By having four brushes at 1, 6, 11 and 16 and connecting 1,11 and 6,16 still only two parallel circuits are obtained. The brush currents however are halved. This method permits the use of commutator of shorter length as lesser current is to be collected by each brush and thus saving on the cost of the commutator. Fig. 17(b) illustrates this brush arrangement with respect to a 21 slot 4 pole machine. Similarly proceeding, in a 6-pole winding 2,4 or 6 brush sets may be used.

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

4.3 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. As mentioned earlier this approach must be avoided as far as possible by going in for proper slot numbers and commutator. Slightly un-symmetric winding may be tolerable in machines of smaller rating with very few poles.

5 Armature reaction

Earlier, an expression was derived for the induced emf at the terminals of the armature winding under the influence of motion of the conductors under the field established by field poles. But if the generator is to be of some use it should deliver electrical output to a load. In such a case the armature conductors also carry currents and produce a field of their own. The interaction between the fields must therefore must be properly understood in order to understand the behavior of the loaded machine. As the magnetic structure is complex and as we are interested in the flux cut by the conductors, we primarily focus our attention on the surface of the armature. A sign convention is required for mmf as the armature and field mmf are on two different members of the machine. The convention used here is that the mmf acting across the air gap and the flux density in the air gap are shown as positive when they act in a direction from the field system to the armature. A flux line is taken and the value of the current enclosed is determined. As the magnetic circuit is non-linear, the field mmf and armature mmf are separately computed and added at each point on the surface of the armature. The actual flux produced is proportional to the total mmf and the permeance. The flux produced by field and that produced by armature could be added to get the total flux only in the case of a linear magnetic circuit. The mmf distribution due to the poles and armature are discussed now in sequence.

5.0.1 MMF distribution due to the field coils acting alone

Fig. 18 shows the distribution of mmf due to field coils over two pole pitches. It is a step curve with the width being equal to the pole arc. The permeance variation at the surface is given by Fig. 18 assuming the air gap under the pole to be uniform and neglecting

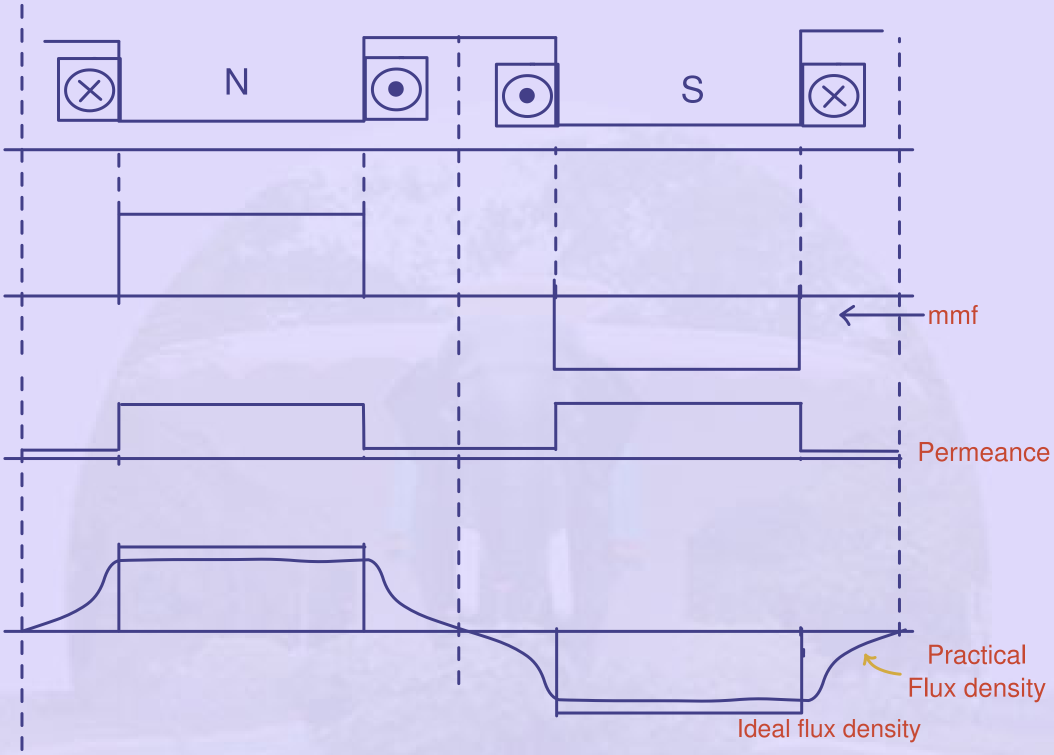


Figure 18: Mmf and flux variation in an unloaded machine

the slotting of the armature. The no-load flux density curve can be obtained by multiplying mmf and permeance. Allowing for the fringing of the flux, the actual flux density curve would be as shown under Fig. 18.

5.0.2 MMF distribution due to armature conductors alone carrying currents

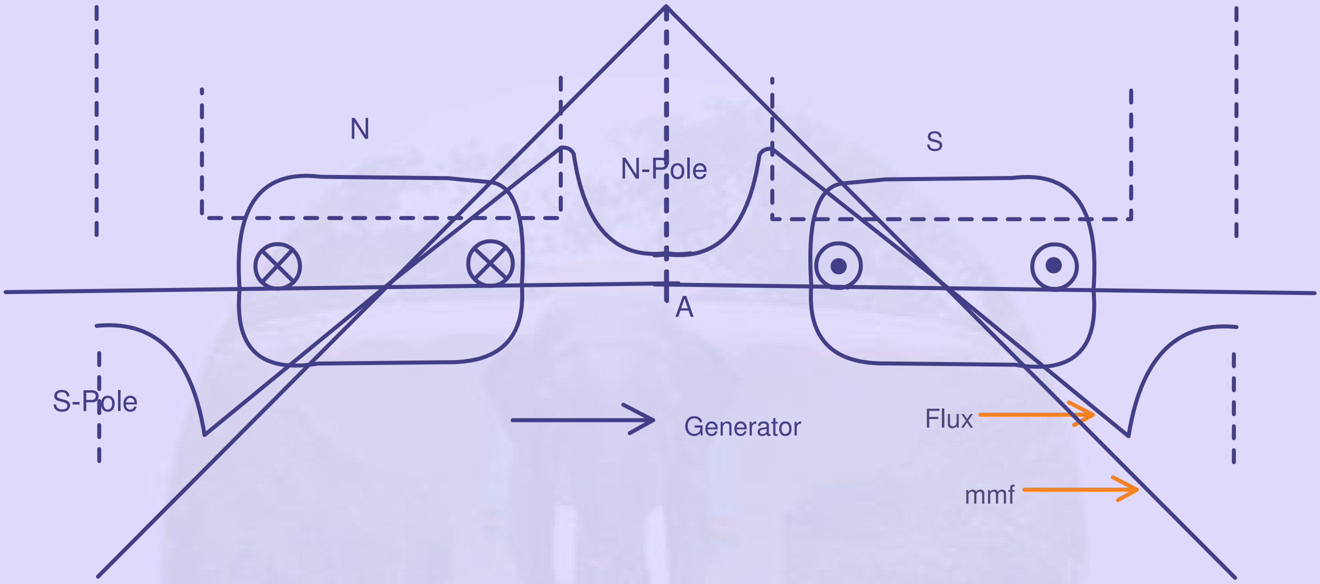


Figure 19: Mmf and flux distribution under the action of armature alone carrying current

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

This is depicted in Fig. 19. This armature mmf per pole is given by

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

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

5.0.3 Total mmf and flux of a loaded machine

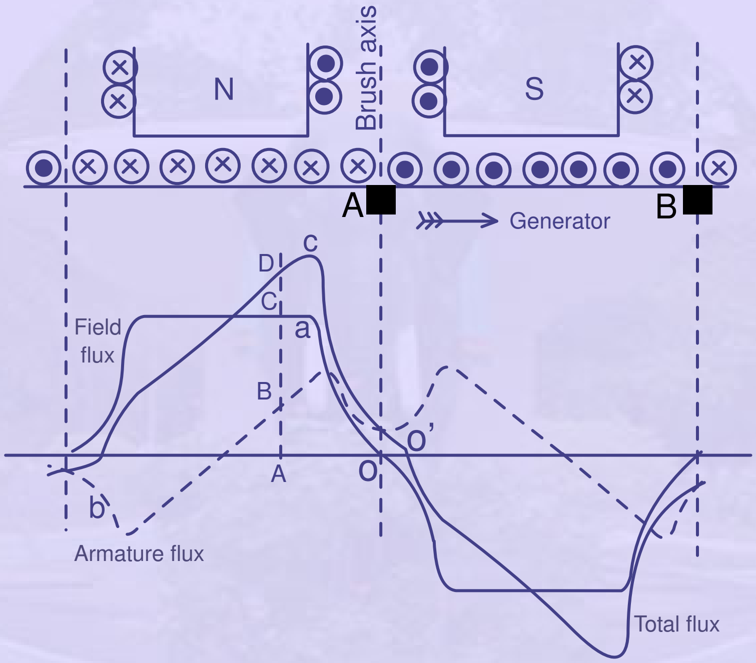


Figure 20: Flux distribution in a loaded generator without brush shift

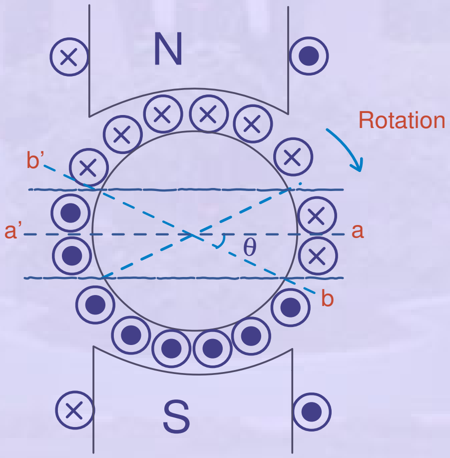
The mmf of field coils and armature coils are added up and the resultant mmf distribution is obtained as shown in Fig. 20.

This shows the decrease in the mmf at one tip of a pole and a substantial rise at the other tip. If the machine has a pole arc to pole pitch ratio of 0.7 then 70% of the armature reaction mmf gets added at this tip leading to considerable amount of saturation under full load conditions. The flux distribution also is shown in Fig. 20. This is obtained by multiplying mmf and permeance waves point by point in space. Actual flux distribution differs from this slightly due to fringing. As seen from the figure, the flux in the inter polar region is substantially lower due to the high reluctance of the medium. The air gaps under the pole tips are also increased in practice to reduce excessive saturation of this part. The advantage of the salient pole field construction is thus obvious. It greatly mitigates the effect of the armature reaction. Also, the coils under going commutation have very little emf induced in them and hence better commutation is achieved. Even though the armature reaction produced a cross magnetizing effect, the net flux per pole gets slightly reduced, on load, due to the saturation under one tip of the pole. This is more so in modern d.c. machines where the normal excitation of the field makes the machine work under some level of saturation.

5.0.4 Effect of brush shift

In some small d.c. machines the brushes are shifted from the position of the magnetic neutral axis in order to improve the commutation. This is especially true of machines with unidirectional operation and uni-modal (either as a generator or as a motor) operation. Such a shift in the direction of rotation is termed ‘lead’ (or forward lead). Shift of brushes in the opposite to the direction of rotation is called ‘backward lead’. This lead is expressed in terms of the number of commutator segments or in terms of the electrical angle. A pole pitch corresponds to an electrical angle of 180 degrees. Fig. 21 shows the effect of a forward

(a)Armature reaction with brush shift



(b)Calculation of demagnetizing mmf per pole

Figure 21: Effect of brush shift on armature reaction

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

$$F_{min} = F_f - \alpha.F_a \tag{22}$$

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

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

$$F_a = \frac{1}{2}\frac{Z.I_c}{2p}. \tag{23}$$

The net flux per pole decreases due to saturation at the trailing edge and hence additional ampere turns are needed on the pole to compensate this effect. This may be to the tune of 20 percent in the modern d.c. machines.

The brush shift gives rise to a shift in the axis of the mmf of the armature reaction. This can be resolved into two components, one in the quadrature axis and second along the pole axis as shown in Fig. 21.(b) The demagnetizing and cross magnetizing component of the armature ampere turn per pole can be written as

$$F_d = \frac{2\theta}{\pi}.F_a \tag{24}$$

$$F_q = (1 - \frac{2\theta}{\pi}).F_a \tag{25}$$

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

$$F_d = \frac{C_l}{\frac{C}{4p}}.\frac{I_c Z}{4p} \quad \text{or} \quad \frac{C_l}{C}.I_c.Z \tag{26}$$

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

5.0.5 Armature reaction in motors

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

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

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

The above two effects can be reduced by providing a 'compensating' mmf at

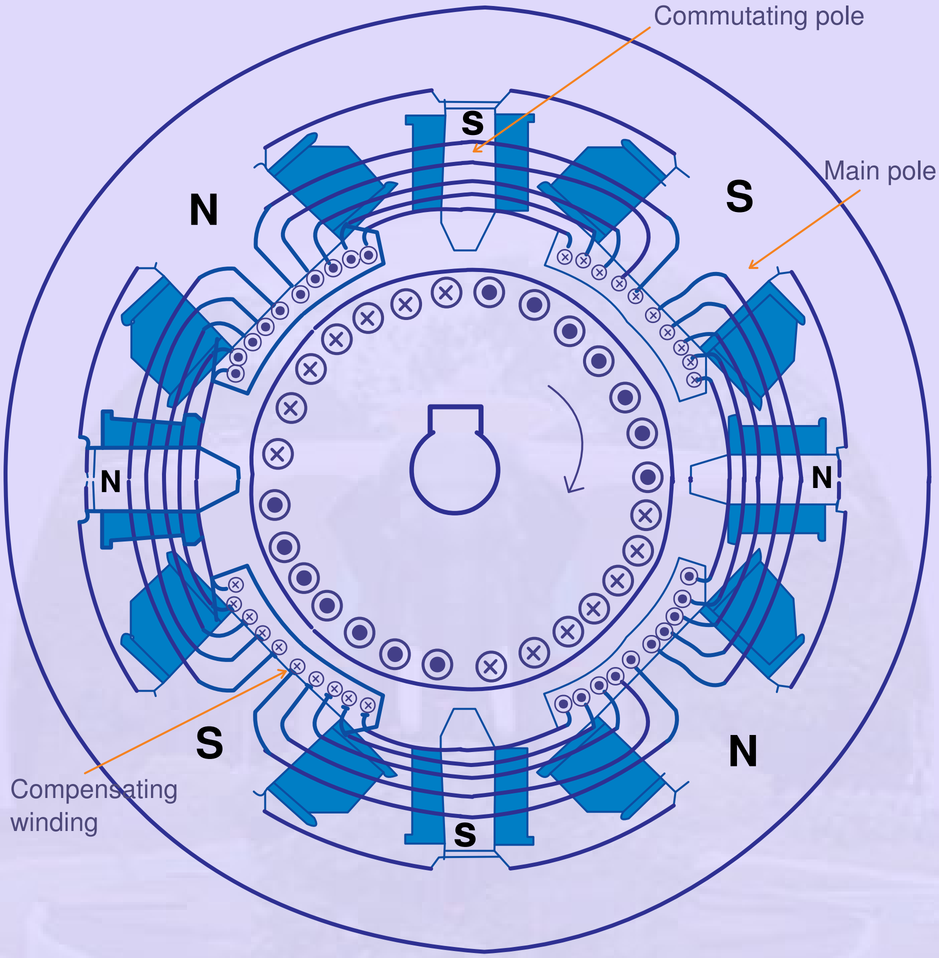


Figure 22: Compensating winding

the *same spatial* rate as the armature mmf. This is provided by having a compensating winding housed on the pole shoe which carries currents that are directly proportional to the armature current. The ampere conductors per unit length is maintained identical to that of

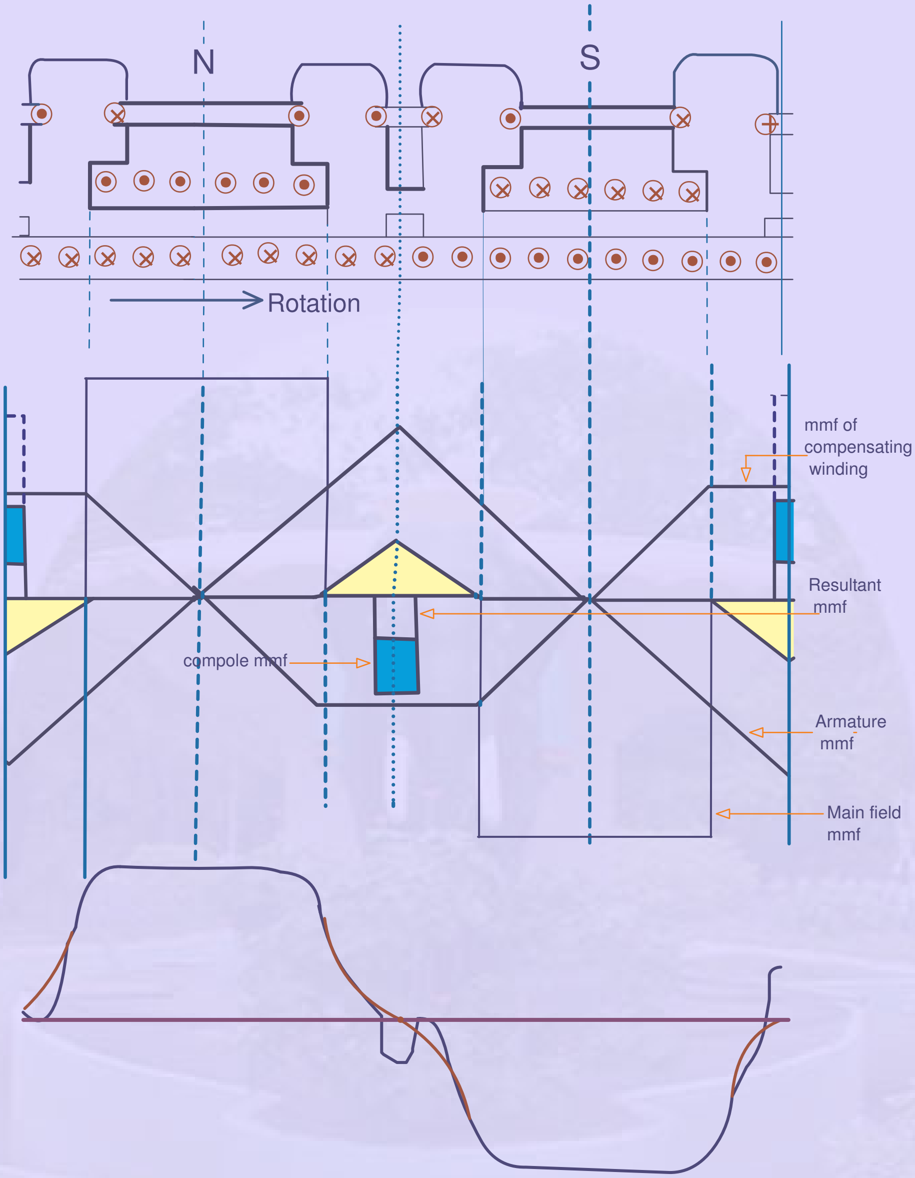


Figure 23: Armature reaction with Compensating winding

the armature. The sign of the ampere conductors is made opposite to the armature. This is illustrated in Fig. 22 and Fig. 23 . Since the compensating winding is connected in series with the armature, the relationship between armature mmf and the mmf due to compensating winding remains proper for all modes of working of the machine. The mmf required to be setup by the compensating winding can be found out to be

$$F_c = \frac{I_c.Z}{4p}.\frac{polearc}{polepitch} \tag{27}$$

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

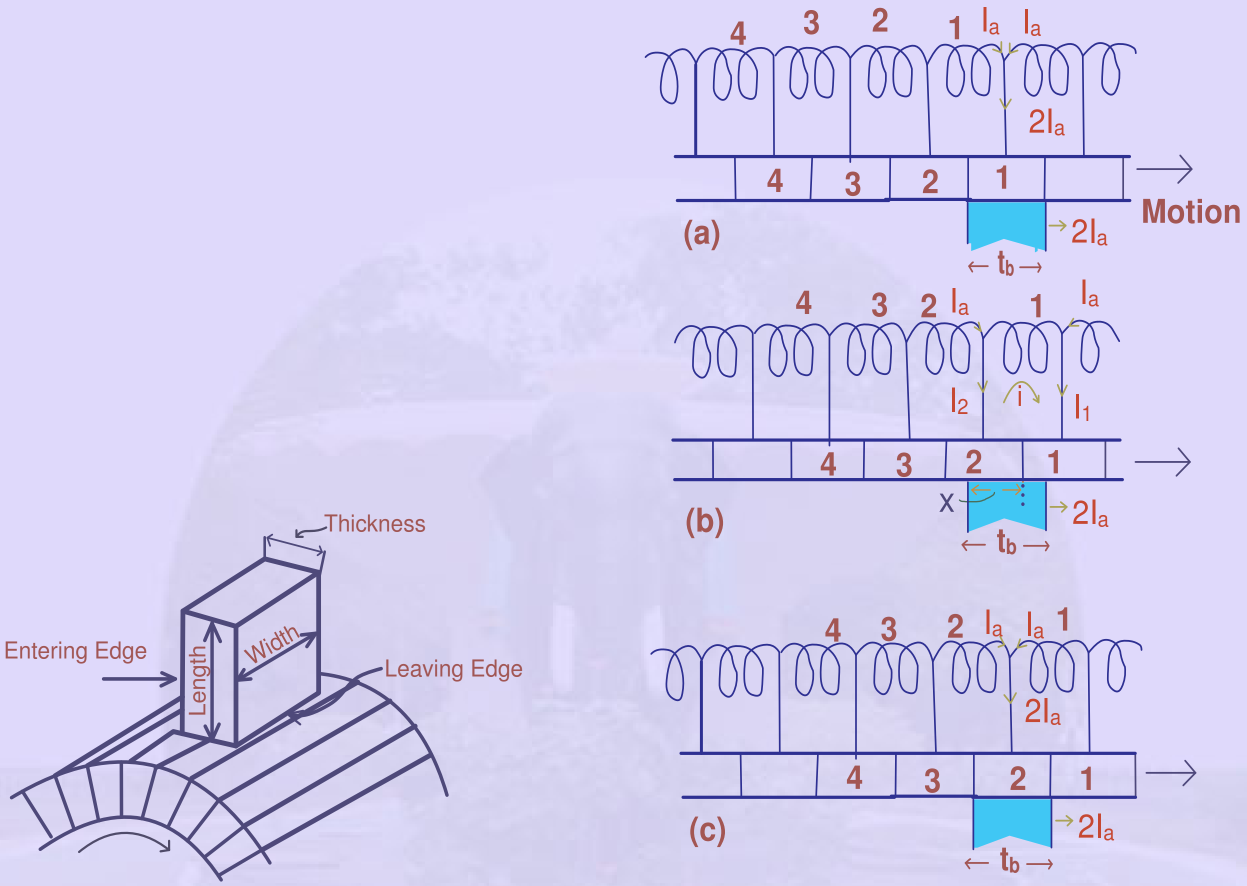
The axis of the mmf due to armature and the compensating winding being the same and the signs of mmf being opposite to each other the flux density in the region of geometric neutral axis gets reduced thus improving the conditions for commutation. One can design the compensating winding to completely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

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

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

5.1 Commutation

As seen earlier, in an armature conductor of a heteropolar machine a.c. voltages are induced as the conductor moves under north and south pole polarities alternately. The frequency of this induced emf is given by the product of the pole-pairs and the speed in revolutions per second. The induced emf in a full pitch coil changes sign as the coil crosses magnetic neutral axis. In order to get maximum d.c. voltage in the external circuit the coil should be shifted to the negative group. This process of switching is called commutation. During a short interval when the two adjacent commutator segments get bridged by the brush the coils connected in series between these two segments get short circuited. Thus in the case of ring winding and simple lap winding 2p coils get short circuited. In a simple wave winding in a 2p pole machine 2 coils get short circuited. The current in these coils become zero and get reversed as the brush moves over to the next commutator segment. Thus brush and commutator play an important role in commutation. Commutation is the key process which converts the induced a.c. voltages in the conductors into d.c. It is important to learn about the working of the same in order to ensure a smooth and trouble free operation of the machine.



(a)Location of Brush (b)Process of commutation

Figure 24: Location of the brush and Commutation process

5.1.1 Brushes

Brush forms an important component in the process of commutation. The coil resistance is normally very small compared to the brush contact resistance. Further this brush contact resistance is not a constant. With the brushes commonly used, an increase in the current density of the brushes by 100 percent increases the brush drop by about 10 to 15 percent. Brush contact drop is influenced by the major factors like speed of operation, pressure on the brushes, and to a smaller extent the direction of current flow.

Major change in contact resistance is brought about by the composition of the brush. Soft graphite brushes working at a current density of about $10A/cm^2$ produce a drop of 1.6V (at the positive and negative brushes put together) while copper-carbon brush working at $15A/cm^2$ produces a drop of about 0.3V. The coefficient of friction for these brushes are 0.12 and 0.16 respectively. The attention is focussed next on the process of commutation.

5.1.2 Linear Commutation

If the current density under the brush is assumed to be constant through out the commutation interval, a simple model for commutation is obtained. For simplicity, the brush thickness is made equal to thickness of one commutator segment. In Fig. 24(b), the brush is initially solely resting on segment number 1. The total current of $2I_a$ is collected by the brush as shown. As the commutator moves relative to the brush position, the brush position starts to overlap with that of segment 2. As the current density is assumed to be constant, the current from each side of the winding is proportional to the area shared on the two segments. Segment 1 current uniformly comes down with segment 2 current increasing uniformly keeping the total current in the brush constant. The currents I_1 and I_2 in brush segments 1 and 2 are given by

$$I_1 = 2I_a(1 - \frac{x}{t_b}) \quad \text{and} \qquad I_2 = 2I_a\frac{x}{t_b} \tag{28}$$

giving $I_1 + I_2$ to be 2 I_a.

Here 'x' is the width of the brush overlapping on segment 2. The process of commutation would be over when the current through segment number 1 becomes zero. The current in the coil undergoing commutation is

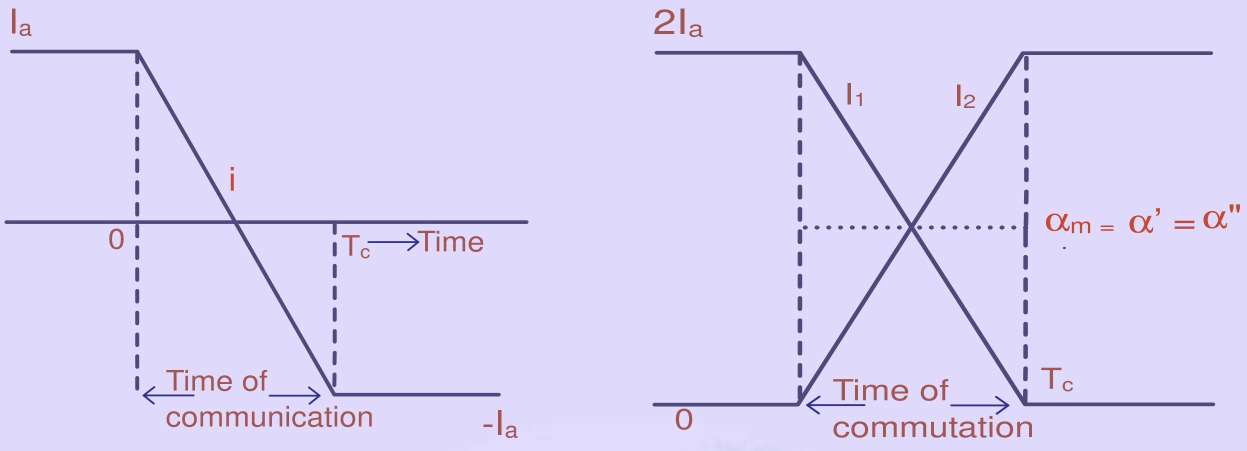
$$i = I_1 - I_a = I_a - I_2 = \frac{(I_1 - I_2)}{2} = I_a(1 - \frac{2x}{t_b}) \tag{29}$$

The time required to complete this commutation is

$$T_c = \frac{t_b}{v_c} \tag{30}$$

where v_c is the velocity of the commutator. This type of linear commutation is very close to the ideal method of commutation. The time variation of current in the coil undergoing commutation is shown in Fig. 25.(a). Fig. 25.(b) also shows the timing diagram for the currents I_1 and I_2 and the current densities in entering edge α_e, leaving edge α_l and also the mean current density α_m in the brush. Machines having very low coil inductances, operating at low load currents, and low speeds, come close to this method of linear commutation.

In general commutation will not be linear due to the presence of emf of self induction and induced rotational emf in the coil. These result in retarded and accelerated commutation and are discussed in sequence.



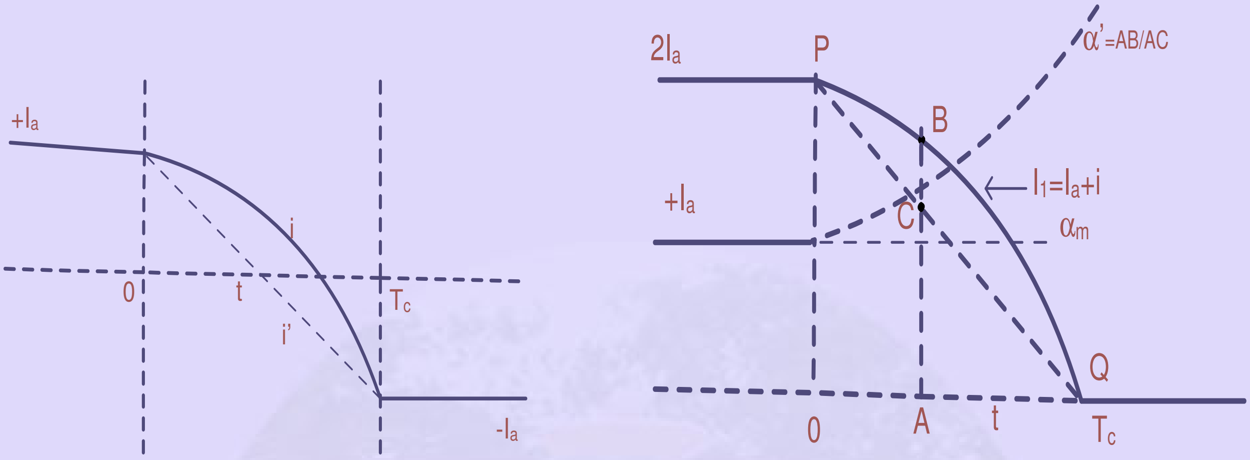
(a) (b)

Figure 25: Linear commutation

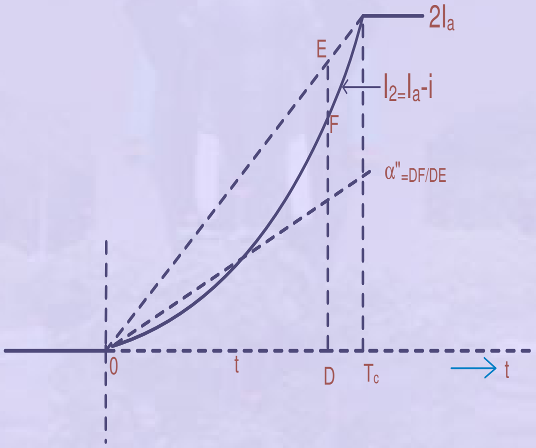
5.1.3 Retarded commutation

Retarded commutation is mainly due to emf of self induction in the coil. Here the current transfer from 1 to 2 gets retarded as the name suggests. This is best explained with the help of time diagrams as shown in Fig. 26.(a). The variation of i is the change in the current of the coil undergoing commutation, while i' is that during linear commutation. Fig. 26(b) shows the variation of I_1 and current density in the brush at the leaving edge and Fig. 26.(c) shows the same phenomenon with respect to I_2 at entering edge. The value of current in the coil is given by i undergoing commutation. α_m is the mean current density in the brush given by total current divided by brush area of cross section. α_l and α_e are the current density under leaving and entering edges of the brush. As before,

$$I_1 = I_a + i \qquad \text{and} \qquad I_2 = I_a - i \tag{31}$$



(a) commutation (b) Leaving edge density



(c)Entry edge density

Figure 26: Diagrams for Retarded commutation

The variation of densities at leaving and entering edges are given as

$$\alpha_l = \frac{AB}{AC}.\alpha_m \tag{32}$$

$$\alpha_e = \frac{DF}{DE}.\alpha_m \tag{33}$$

At the very end of commutation, the current density

$$\begin{aligned} \alpha_e &= \alpha_m.\frac{di}{dt}/\frac{di^{'}}{dt} \\ &= \alpha_m.\frac{di}{dt}/\frac{2I_a}{T_c} \end{aligned} \tag{34}$$

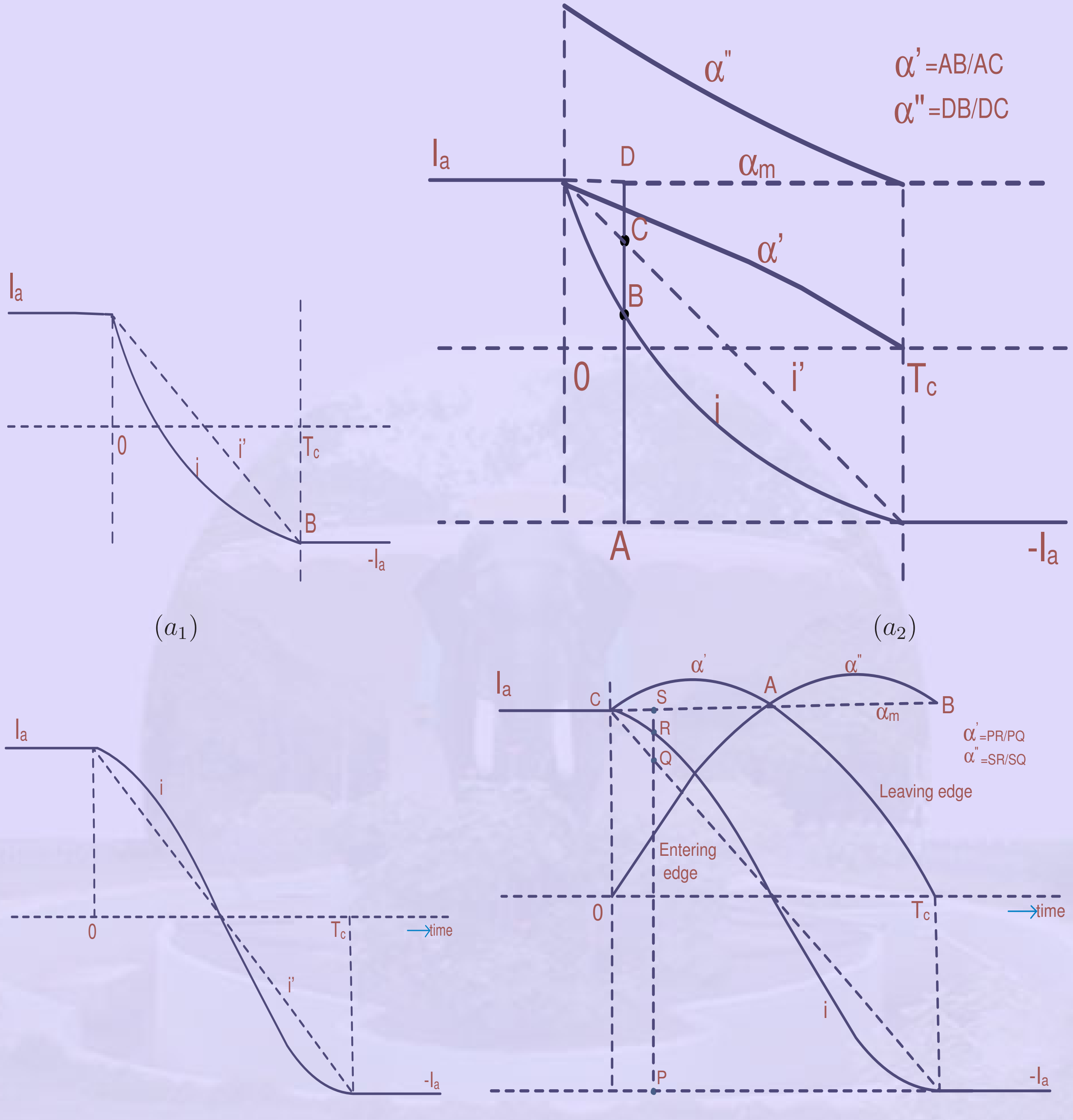
If at this point $di/dt = 0$ the possibility of sudden breaking of the current and hence the creation of an arc is removed .

Similarly at the entering edge at the end of accelerated commutation, shown in Fig. 27.(b).

$$\alpha_e = \alpha_m.\frac{di}{dt}/\frac{2I_a}{T_c} \tag{35}$$

Thus retarded communication results in $di/dt = 0$ at the beginning of commutation (at entering edge) and accelerated communication results in the same at the end of commutation (at leaving edge). Hence it is very advantageous to have retarded commutation at the entry time and accelerated commutation in the second half. This is depicted in Fig. 27.(b_1). It is termed as sinusoidal commutation.

Retarded commutation at entry edge is ensured by the emf of self induction which is always present. To obtain an accelerated commutation, the coil undergoing commutation must have in it an induced emf of such a polarity as that under the pole towards which it is moving. Therefore the accelerated commutation can be obtained by i) a forward



(a_1) (a_2)

(b_1) (b_2)

Figure 27: Accelerated and Sinusoidal commutation

lead given to the brushes or by ii) having the field of suitable polarity at the position of the brush with the help of a small pole called a commutating pole. In a non-inter pole machine the brush shift must be changed from forward lead to backward lead depending upon generating or motoring operation. As the disadvantages of this brush shifts are to be avoided, it is preferable to leave the brushes at geometric neutral axis and provide commutating poles of suitable polarity (for a generator the polarity of the pole is the one towards which the conductors are moving). The condition of commutation will be worse if commutating poles are provided and not excited or they are excited but wrongly.

The action of the commutating pole is local to the coil undergoing commutation. It does not disturb the main field distribution. The commutating pole winding overpowers the armature mmf locally and establishes the flux of suitable polarity. The commutating pole windings are connected in series with the armature of a d.c. machine to get a load dependent compensation of armature reaction mmf.

The commutating pole are also known as compole or inter pole. The air gap under compole is made large and the width of compole small. The mmf required to be produced by compole is obtained by adding to the armature reaction mmf per pole F_a the mmf to establish a flux density of required polarity in the air gap under the compole F_{cp} .This would ensure straight line commutation. If sinusoidal commutation is required then the second component F_{cp} is increased by 30 to 50 percent of the value required for straight line commutation.

The compole mmf in the presence of a compensating winding on the poles will be reduced by Fa * pole arc/pole pitch. This could have been predicted as the axis of the compensating winding and armature winding is one and the same. Further, the mmf of compensating winding opposes that of the armature reaction.

5.2 Methods of excitation

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

5.2.1 Excitation circuit

The excitation for establishing the required field can be of two types a) Permanent magnet excitation(PM) b) Electro magnetic excitation. Permanent magnet excitation is

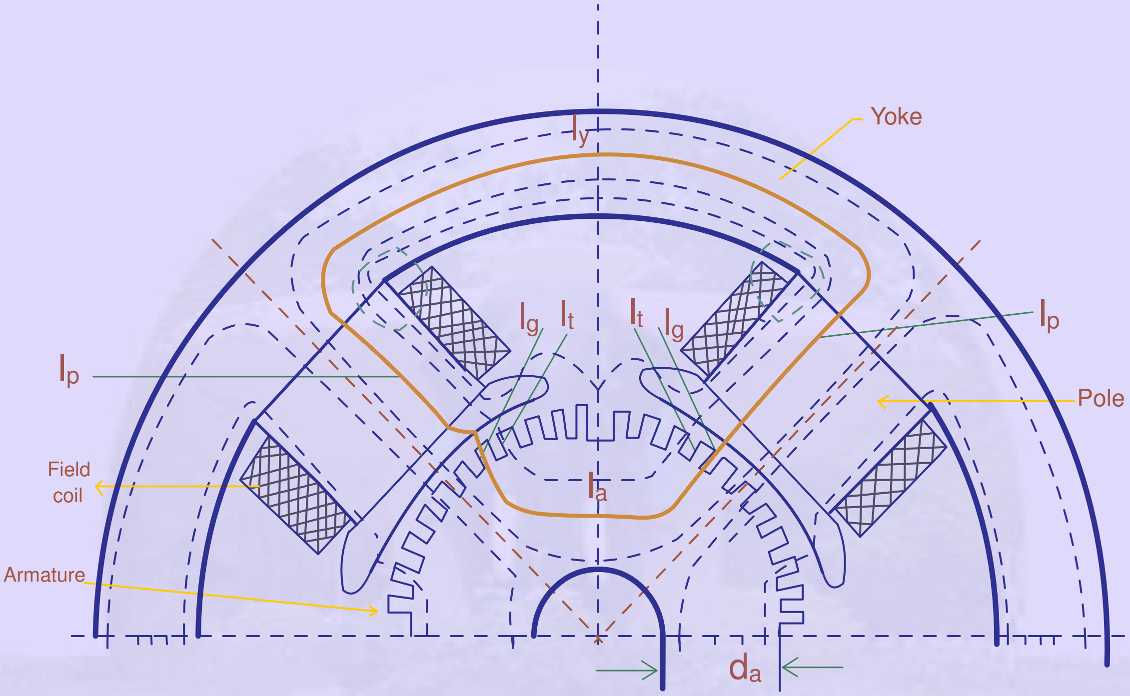


Figure 28: Magnetization of a DC machine

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

Electromagnetic excitation is universally used. Even though certain amount of energy is lost in establishing the field it has the advantages like lesser cost, ease of control.

The required ampere turns for establishing the desired flux per pole may be computed by doing the magnetic circuit calculations. MMF required for the poles, air gap, armature teeth, armature core and stator yoke are computed and added. Fig. 28 shows two poles of a 4-pole machine with the flux paths marked on it. Considering one complete flux loop, the permeance of the different segments can be computed as,

$$P = A.\mu/l$$

Where P- permeance

A- Area of cross section of the part

mu- permeability of the medium

l- Length of the part

A flux loop traverses a stator yoke, armature yoke, and two numbers each of poles, air gap, armature teeth in its path. For an assumed flux density B_g in the pole region the flux crossing each of the above regions is calculated. The mmf requirement for establishing this flux in that region is computed by the expressions

$$\begin{aligned}\text{Flux} &= \text{mmf . permeance}\\ &= B.A\end{aligned}$$

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

These are shown in Fig. 29. When both shunt winding and series winding are present, it is called compound excitation. The mmf of the two windings could be arranged to aid each other or oppose each other. Accordingly they are called cumulative compounding and differential compounding. If the shunt winding is excited by a separate voltage source

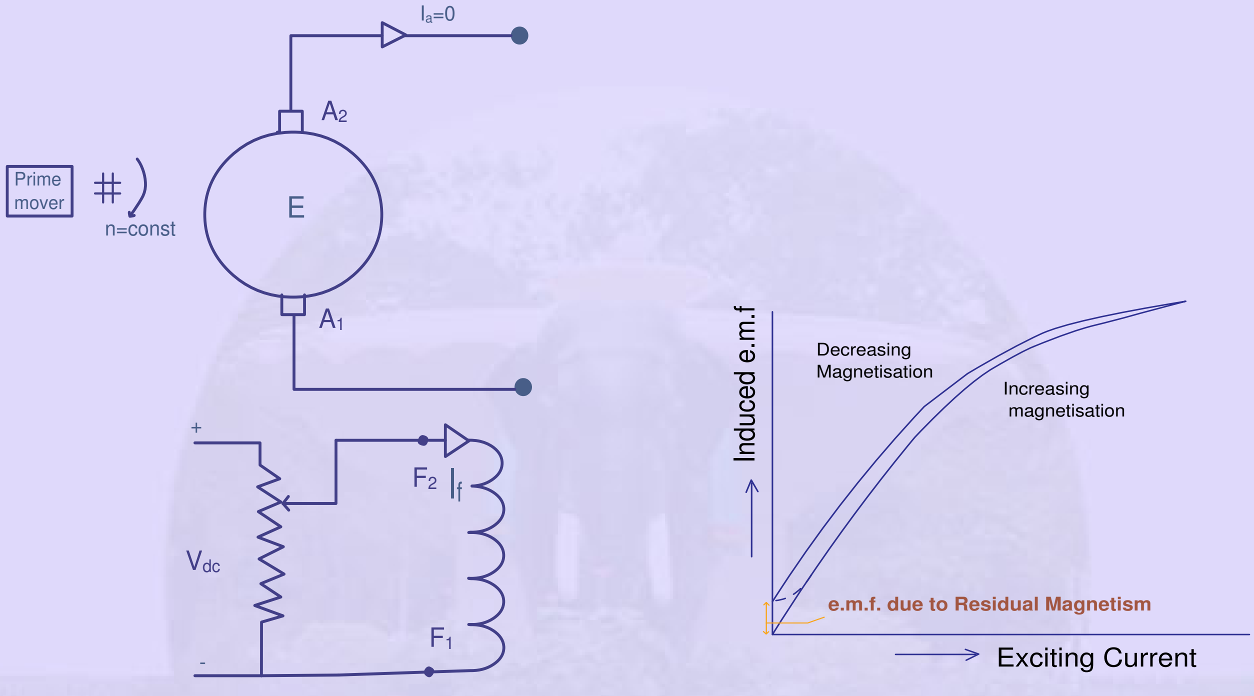
(a)Separate excitation (b) Self excitation

(c)Series excitation (d)Compound excitation

Figure 29: D.C generator connections

then it is called separate excitation. If the excitation power comes from the same machine, then it is called self excitation. Series generators can also be separately excited or self excited. The characteristics of these generators are discussed now in sequence.

5.2.2 Separately excited shunt generators



(a) (b)

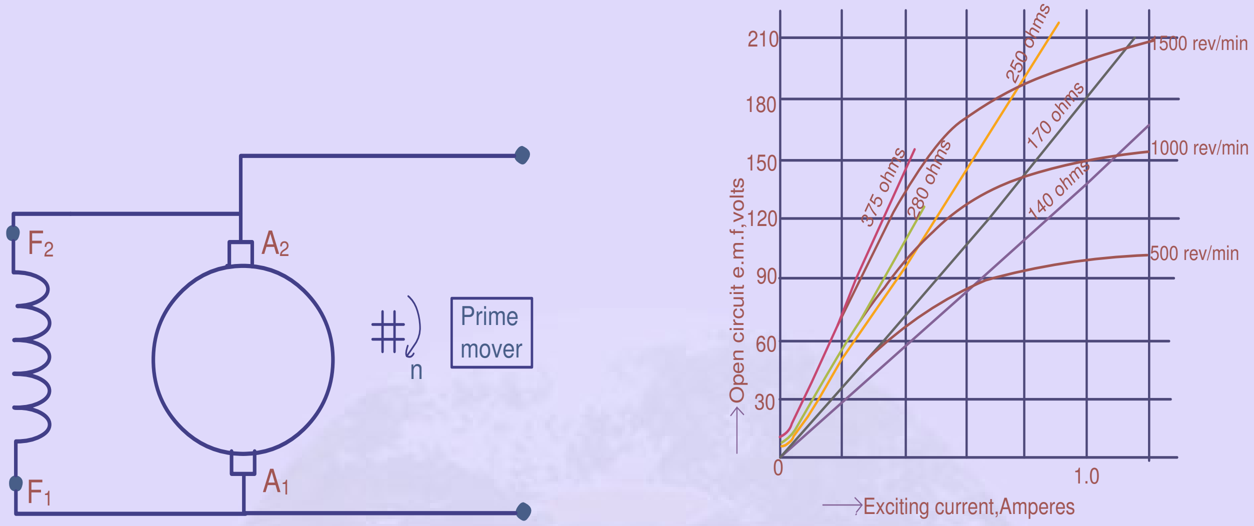
Figure 30: Magnetization characteristics

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

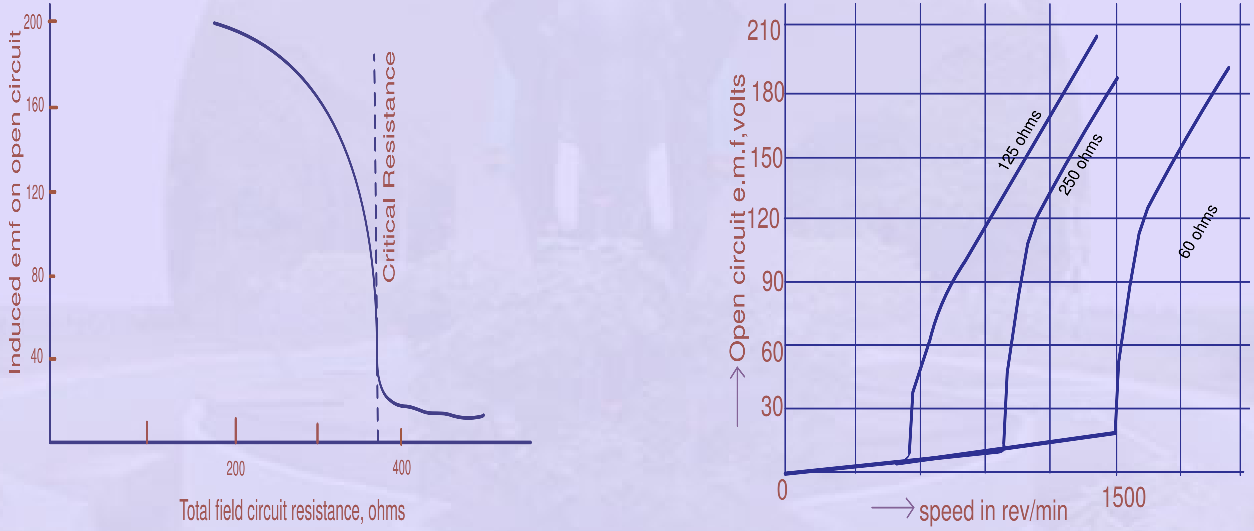
5.2.3 Self excitation

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

Self excitation is now discussed with the help of Fig. 31.(a) The process of self excitation in a shunt generator takes place in the following manner. When the armature is rotated a feeble induced emf of 2 to 5 percent appears across the brushes depending upon the speed of rotation and the residual magnetism that is present. This voltage



(a)Physical connection (b) characteristics



(c)Critical resistance (d) Critical speed

Figure 31: Self excitation

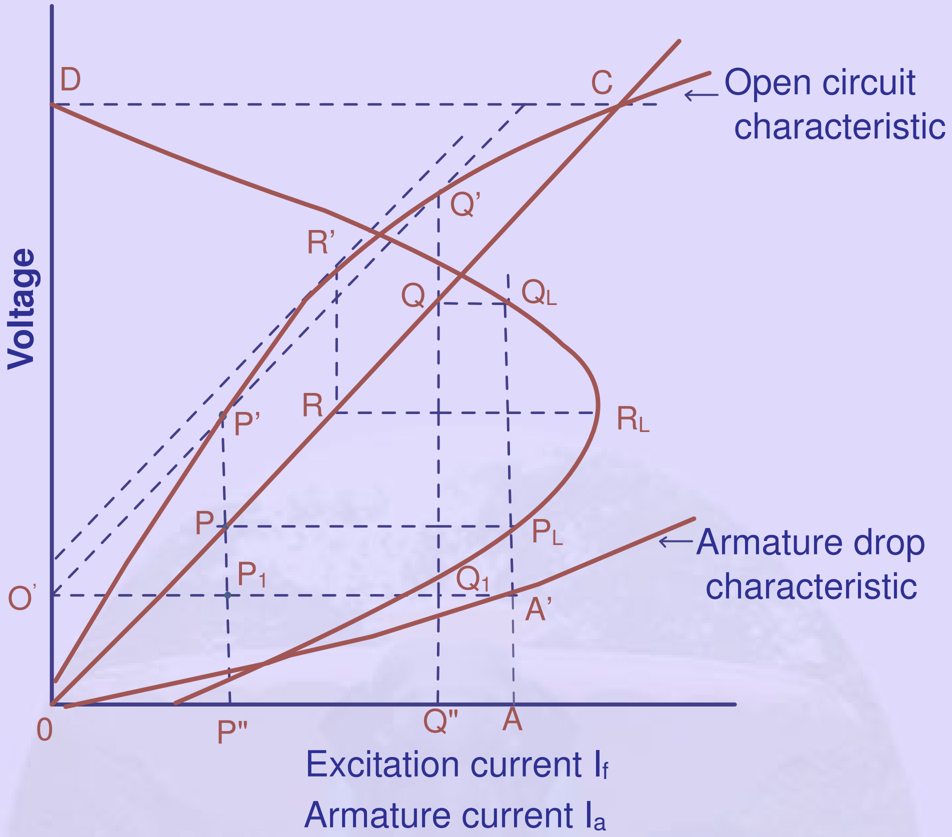


Figure 32: External characteristics of a self excited of a shunt generator

gets applied across the shunt field winding and produces a small mmf. If this mmf is such as to aid the residual field then it gets strengthened and produces larger voltage across the brushes. It is like a positive feed back. The induced emf gradually increases till the voltage induced in the armature is just enough to meet the ohmic drop inside the field circuit. Under such situation there is no further increase in the field mmf and the build up of emf also stops. If the voltage build up is 'substantial', then the machine is said to have 'self excited'.

Fig. 31(b) shows the magnetization curve of a shunt generator. The field resistance line is also shown by a straight line OC. The point of intersection of the open circuit characteristic (OCC) with the field resistance line, in this case C, represents the voltage build up on self excitation. If the field resistance is increased, at one point the resistance line becomes a tangent to the OCC. This value of the resistance is called the critical resistance. At this value of the field circuit resistance the self excitation suddenly collapses. See Fig. 31(c). Instead of increasing the field resistance if the speed of the machine is reduced then the same resistance line becomes a critical resistance at a new speed and the self excitation collapses at that speed. In this case, as the speed is taken as the variable, the speed is called the critical speed. In the linear portion of the OCC the ordinates are proportional to the speed of operation, hence the critical resistance increases as a function of speed Fig. 31.(b) and (d).

The conditions for self excitation can be listed as below.

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

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

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

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

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

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

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

5.2.4 Self excitation of series generators

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

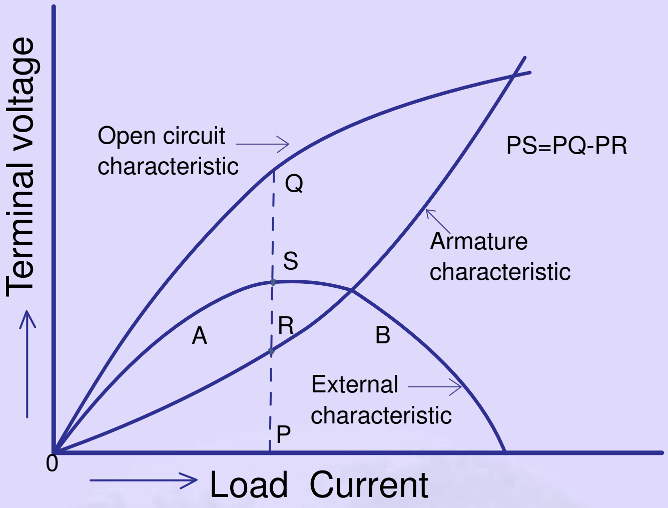


Figure 33: External characteristics of a Series Generator

open circuited.In a series generator load current being the field current of the machine the self excitation characteristic or one and the same. This is shown in Fig. 33

5.2.5 Self excitation of compound generators

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

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

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

5.3 Load characteristics of d.c. generators

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

$$V = E - I_a R_a - V_b \tag{36}$$

V_b - brush contact drop, V

I_a - armature current, A

R_a - armature resistance + inter pole winding resistance+ series winding resistance + com-

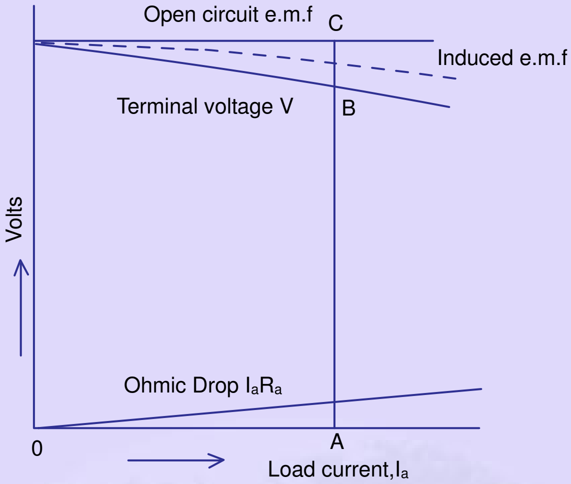


Figure 34: External characteristics of a separately excited shunt generator

pensating winding resistance.

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

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

5.4 External characteristics of a shunt generator

For a given no-load voltage a self excited machine will have more voltage drop at the terminals than a separately excited machine, as the load is increased. This is due to the dependence of the excitation current also on the terminal voltage. After certain load current the terminal voltage decreases rapidly along with the terminal current, even when load impedance is reduced. The terminal voltage reaches an unstable condition. Also, in a self excited generator the no-load terminal voltage itself is very sensitive to the point of intersection of the magnetizing characteristics and field resistance line. The determination of the external characteristics of a shunt generator forms an interesting study. If one determines the load magnetization curves at different load currents then the external characteristics can be easily determined. Load magnetization curve is a plot showing the variation of the terminal voltage as a function of the excitation current keeping the speed and armature current constant. If such curves are determined for different load currents then by determining the intersection points of these curves with field resistance line one can get the external characteristics of a shunt generator. Load saturation curve can be generated from no-load saturation curve /OCC by subtracting the armature drop at each excitation point. Thus it is seen that these family of curves are nothing but OCC shifted downwards by armature drop. Determining their intercepts with the field resistance line gives us the requisite result. Instead of shifting the OCC downwards, the x axis and the field resistance line is shifted 'upwards' corresponding to the drops at the different currents, and their intercepts with OCC are found. These ordinates are then plotted on the original plot. This is shown clearly in Fig. 32. The same procedure can be repeated with different field circuit resistance to yield external characteristics with different values of field resistance. The points of operation up to the maximum current represent a stable region of operation. The second region is unstable. The decrease in the load resistance decreases the terminal voltage in this region.

5.4.1 External characteristics of series generators

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

Fig. 33 shows the load characteristics of a series generator. The first half of the curve is unstable for constant resistance load. The second half is the region where series generator connected to a constant resistance load could work stably. The load characteristics in the first half however is useful for operating the series generator as a booster. In a booster the current through the machine is decided by the external circuit and the voltage injected into that circuit is decided by the series generator. This is shown in Fig. 35

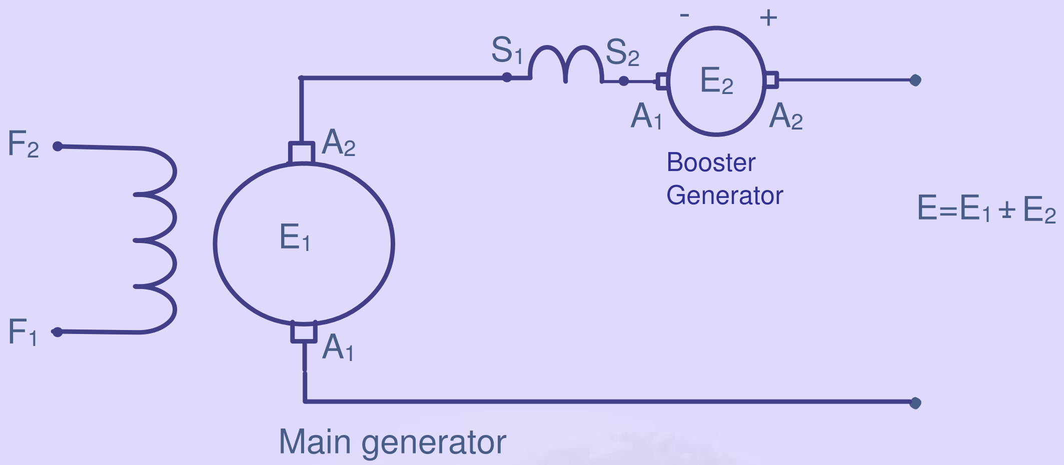
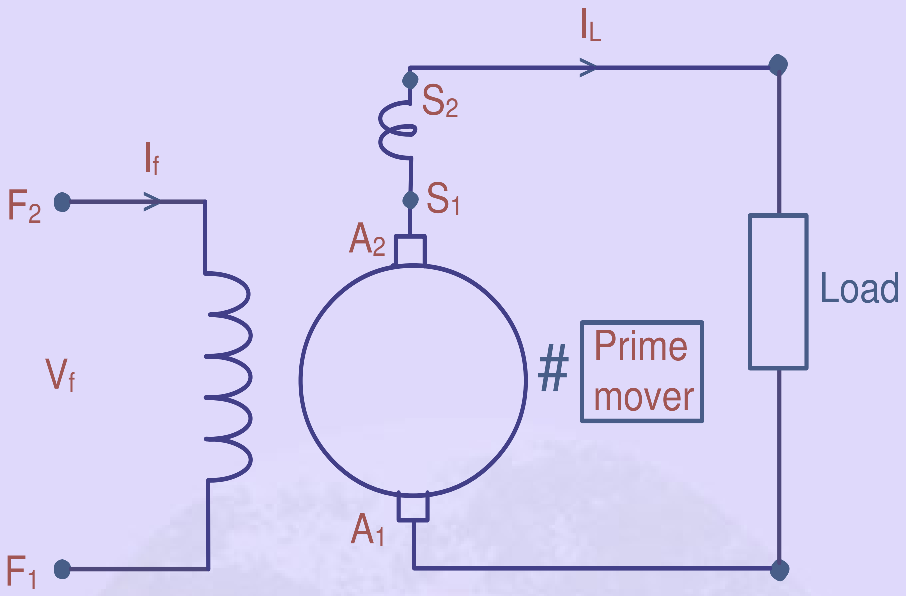


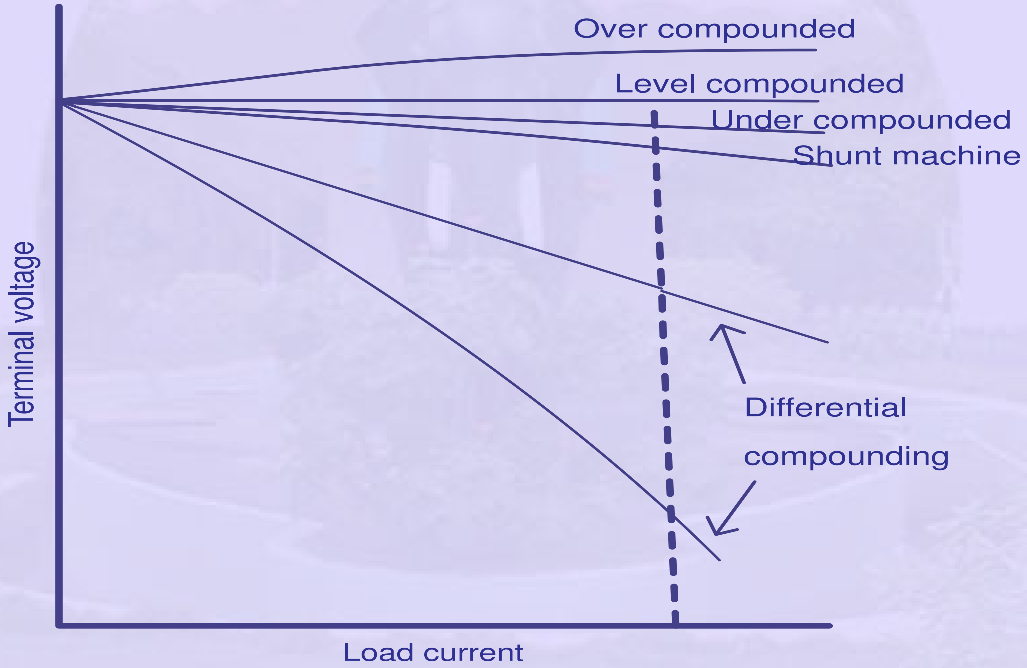
Figure 35: Series generator used as Booster

5.4.2 Load characteristics of compound generators

In the case of compound generators the external characteristics resemble those of shunt generators at low loads. The load current flowing through the series winding aids or opposes the shunt field ampere turns depending upon whether cumulative or differential compounding is used. This increases /decreases the flux per pole and the induced emf E. Thus a load current dependant variation in the characteristic occurs. If this increased emf cancels out the armature drop the terminal voltage remains practically same between no load and full load. This is called as level compounding. Any cumulative compounding below this value is called under compounding and those above are termed over- compounding. These are shown in Fig. 36. The characteristics corresponding to all levels of differential compounding lie below that of a pure shunt machine as the series field mmf opposes that of the shunt field.



(a)-Connection



(b)-Characteristics

Figure 36: External characteristic of Compound Generator

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

5.5 Parallel operation of generators

D.C. generators are required to operate in parallel supplying a common load when the load is larger than the capacity of any one machine. In situations where the load is small but becomes high occasionally, it may be a good idea to press a second machine into operation only as the demand increases. This approach reduces the spare capacity requirement and its cost. In cases where one machine is taken out for repair or maintenance, the other machine can operate with reduced load. In all these cases two or more machines are connected to operate in parallel.

5.5.1 Shunt Generators

Parallel operation of two shunt generators is similar to the operation of two storage batteries in parallel. In the case of generators we can alter the external characteristics easily while it is not possible with batteries. Before connecting the two machines the voltages of the two machines are made equal and opposing inside the loop formed by the two machines. This avoids a circulating current between the machines. The circulating current produces power loss even when the load is not connected. In the case of the loaded machine the difference in the induced emf makes the load sharing unequal.

Fig. 37 shows two generators connected in parallel. The no load emfs are made equal to $E_1 = E_2 = E$ on no load; the current delivered by each machine is zero. As the load is gradually applied a total load current of I ampere is drawn by the load. The load voltage

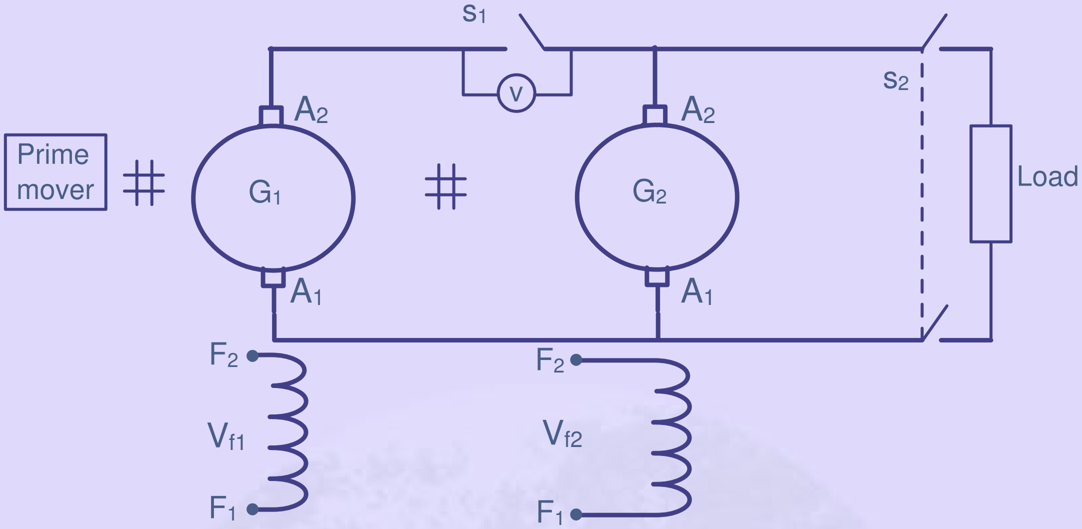


Figure 37: Connection of two shunt generators in Parallel

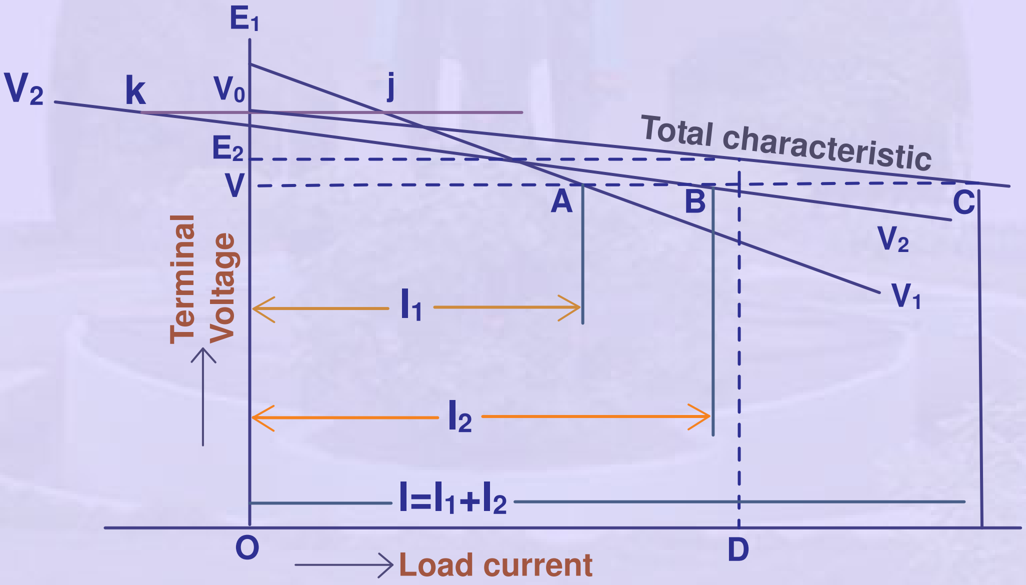


Figure 38: Characteristics of two shunt generators in Parallel

under these conditions is V volt. Each machines will share this total current by delivering currents of I_1 and I_2 ampere such that $I_1 + I_2 = I$.

Also terminal voltage of the two machines must also be V volt. This is dictated by the internal drop in each machine given by equations

$$V = E_1 - I_1 R_{a1} = E_2 - I_2 R_{a2} \tag{37}$$

where R_{a1} and R_{a2} are the armature circuit resistances. If load resistance R_L is known these equations can be solved analytically to determine I_1 and I_2 and hence the manner in which to total output power is shared. If R_L is not known then an iterative procedure has to be adopted. A graphical method can be used with advantage when only the total load current is known and not the value of R_L or V. This is based on the fact that the two machines have a common terminal voltage when connected in parallel. In Fig. 38 the external characteristics of the two machines are first drawn as I and II . For any common voltage the intercepts OA and OB are measured and added and plotted as point at C. Here OC = OA + OB . Thus a third characteristics where terminal voltage is function of the load current is obtained. This can be called as the resultant or total external characteristics of the two machines put together. With this, it is easy to determine the current shared by each machine at any total load current I.

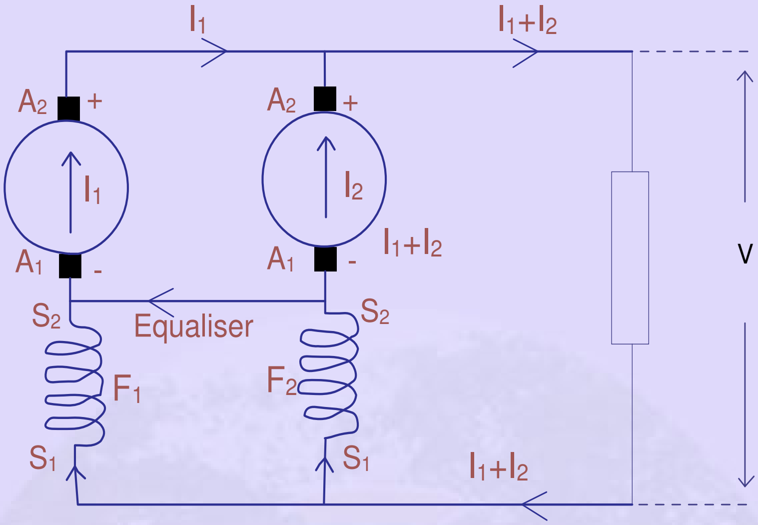
The above procedure can be used even when the two voltages of the machines at no load are different. At no load the total current I is zero ie $I_1 + I_2 = 0$ or $I_1 = -I_2$. Machine I gives out electrical power and machine II receives the same. Looking at the voltage equations, the no load terminal equation V_o becomes

$$V_o = E_1 - I_{1nl} R_{a1} = E_2 + I_{2nl} R_{a2} \tag{38}$$

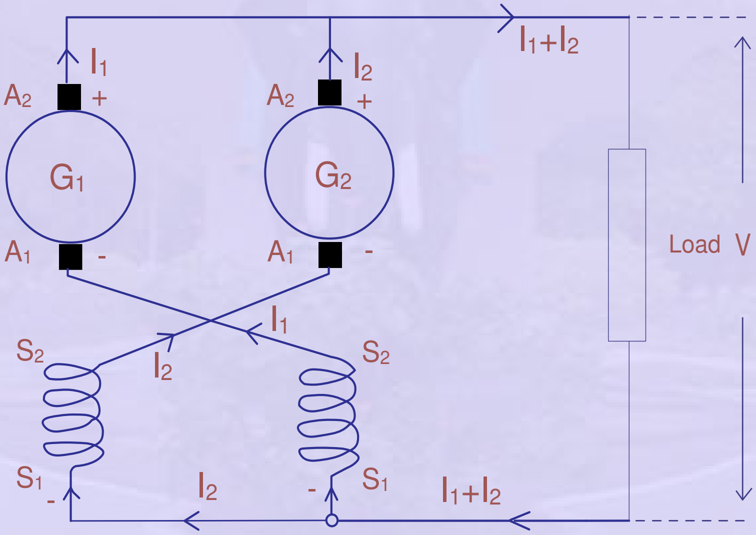
As can be seen larger the values of R_{a1} and R_{a2} larger is the tolerance for the error between the voltages E_1 and E_2. The converse is also true. When R_{a1} and R_{a2} are nearly zero implying an almost flat external characteristic, the parallel operation is extremely difficult.

5.5.2 Series generators

Series generators are rarely used in industry for supplying loads. Some applications like electric braking may employ them and operate two or more series generates in parallel. Fig. 39 shows two series generators connected in parallel supplying load current of I_1 and I_2. If now due to some disturbance E_1 becomes $E_1 + \Delta E_1$ then the excitation of the machine I increases, increasing the load current delivered. As the total current is I the current supplied by machine II reduces, so also its excitation and induced emf. Thus machine I takes greater and greater fraction of the load current with machine II shedding its load. Ultimately the current of machine II becomes negative and it also loads the first machine. Virtually there is a short circuit of the two sources, the whole process is thus highly unstable. One remedy is for a problem as this is to make the two fields immune to the circulating current between the machines. This is done by connecting an equalizer between the fields as shown in Fig. 39-a . With the equalizer present, a momentary disturbance does not put the two machines out of action. A better solution for such problems is to cross connect the two fields as shown in Fig. 39-b. A tendency to supply a larger current by a machine strengthens the field of the next machine and increases its induced emf . This brings in stable conditions for operation rapidly.

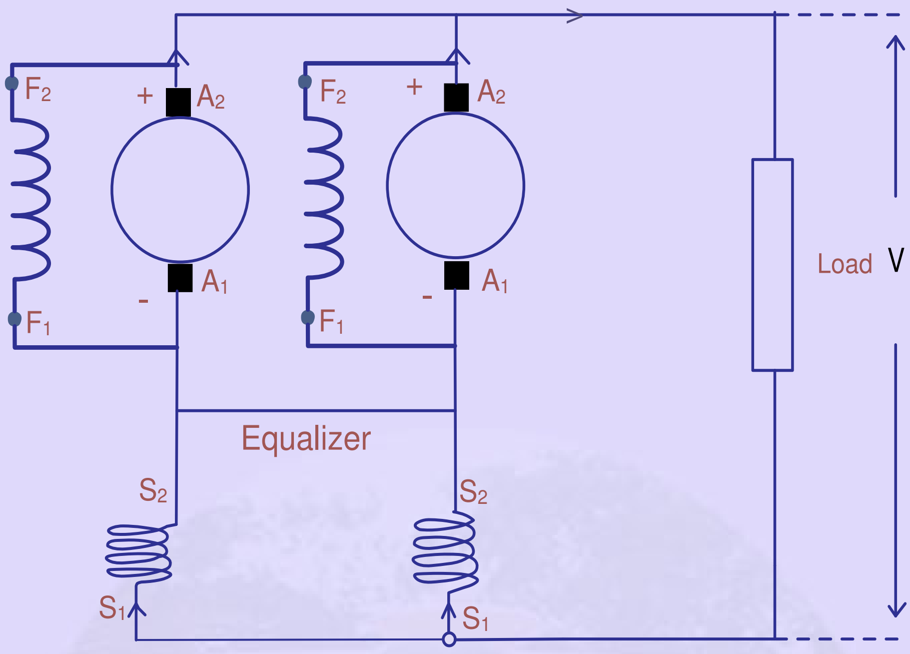


(a)Equalizer connection

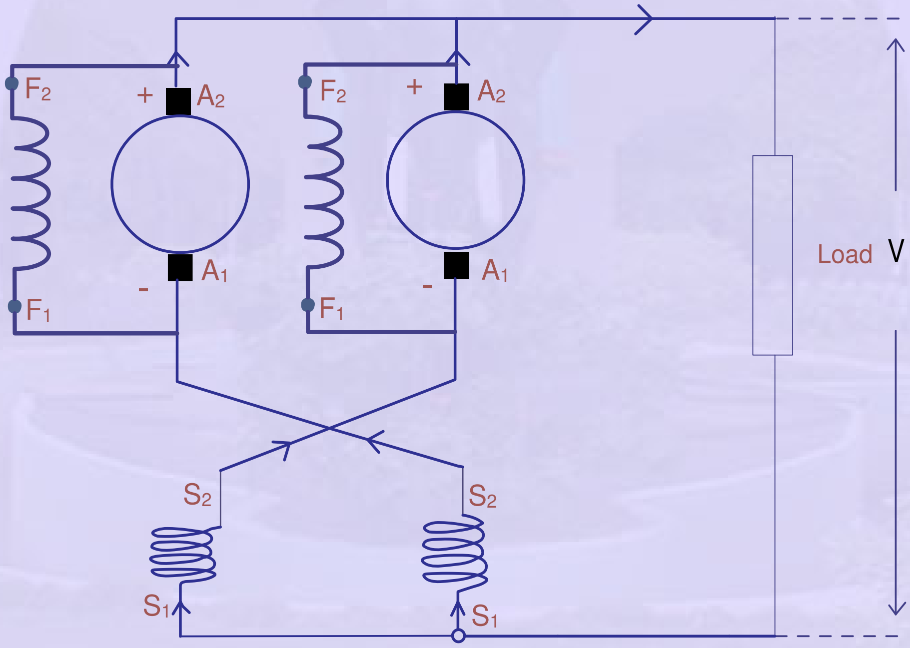


(b)Cross connection of fields

Figure 39: Series Generator working in parallel



(a)Equalizer connection



(b)Cross connection of series fields

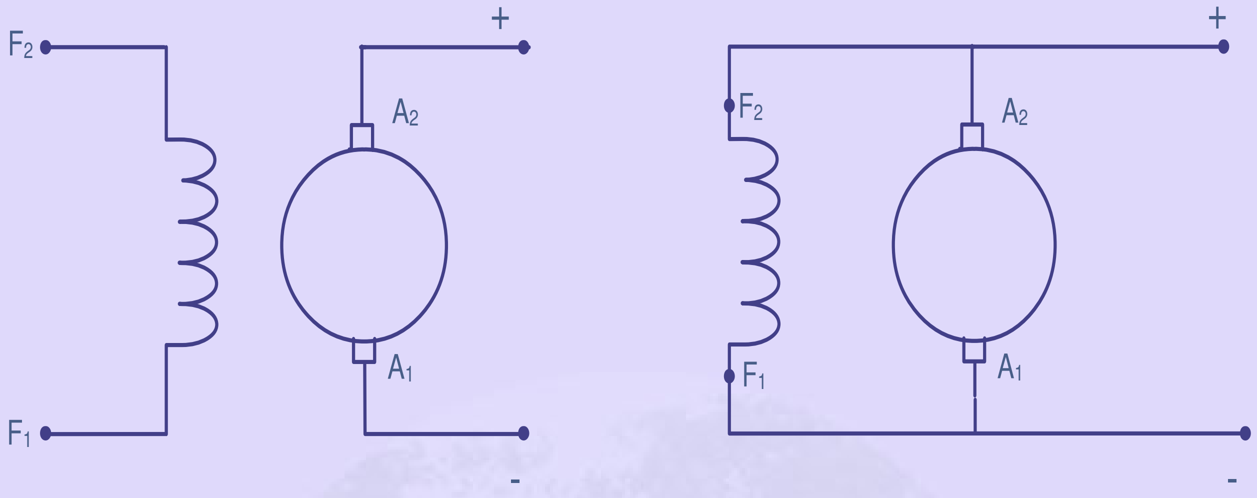
Figure 40: Compound generators operating in parallel

5.5.3 Compound Generators

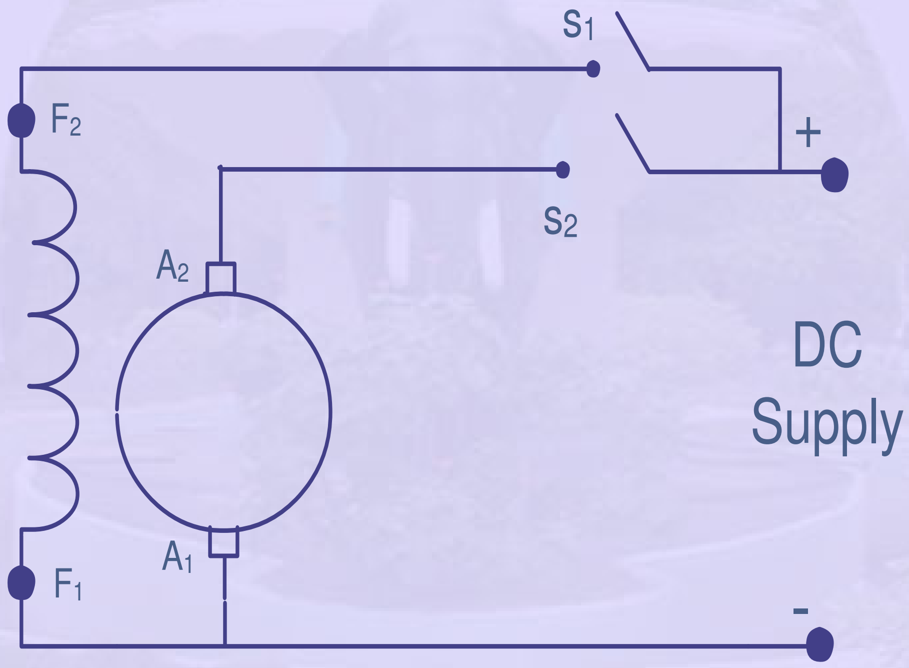
The parallel operation of compound machines is similar to shunt generators. Differential compounding would produce a drooping external characteristics and satisfactory parallel operation is made easy. But most of the generators are used in the cumulatively compounded mode. In such cases the external characteristics will be nearly flat making the parallel operation more difficult. By employing equalizer connection for the series windings this problem can be mitigated. Fig. 40 shows the connection diagram for parallel operation of two compound generators.

5.6 D.C. motors

D.C. motors have a place of pride as far as electrical drives are considered. The simplicity, and linearity of the control method makes them highly preferred machines in precision drives. In spite of the great advancements in a.c. drives these machines are still sought after by the industries. Apart from high precision application they are preferred in stand alone systems working on batteries and high speed drives off constant voltage mains. After the field is excited if we pass a current through the armature the rotor experiences a torque and starts rotating. The direction of the torque can be readily obtained from the law of interaction. These moving conductors cut the field and induce emf, usually called the 'back emf' according to Lenz's law and act as a sink of electrical power from the electrical source. This absorbed power appears as mechanical power. The converted mechanical power should overcome the frictional and iron losses before useful work could be done by the same. The connections to the supply of a d.c. shunt motor are given in Fig. 41.



(a)Separate excitation (b) Shunt excitation



(c)Practical arrangement

Figure 41: Shunt motor connections

Commonly used connection is where in both the field and the armature are energized simultaneously Fig. 41(b). As the field has higher inductance and time constant torque takes some time to reach the full value corresponding to a given armature current. In Fig. 41.(c), the switch S_1 is closed a few seconds prior to switch S_2 . By then the field current would have reached the steady value. So the torque per ampere is high in this case.

The only difference in the second connection Fig. 41.(a) is that the shunt field winding is connected to a separate source. This connection is used when the armature and field voltage are different as is common in high voltage d.c. machines. The field voltage is kept low in such cases for the sake of control purposes. Here again the field circuit must be energized prior to the armature. Suitable interlock should be provided to prevent the armature switch being closed prior to / without closing of field circuit as the armature currents reach very large values still not producing any torque or rotation. The relevant equations for the motoring operation can be written as below

$$V - E - I_aR_a - V_b = 0 \quad \text{or} \quad E = V - I_aR_a - V_b \tag{39}$$

$$E = \frac{p.\phi.Z.n}{b} = K_e\phi.n \quad \text{where} \quad K_e = \frac{pZ}{b} \tag{40}$$

$$T_M = \frac{1}{2\pi}.\frac{p.\phi.ZI_a}{b} = K_t\phi I_a \quad \text{where} \quad K_t = \frac{1}{2\pi}.\frac{pZ}{b} \tag{41}$$

$$\text{and } T_M - T_L = J\frac{dw}{dt} \tag{42}$$

where

T_L- Load torque

T_M- Motor torque

J - polar moment of inertia.

w - angular velocity $= 2\pi.n$

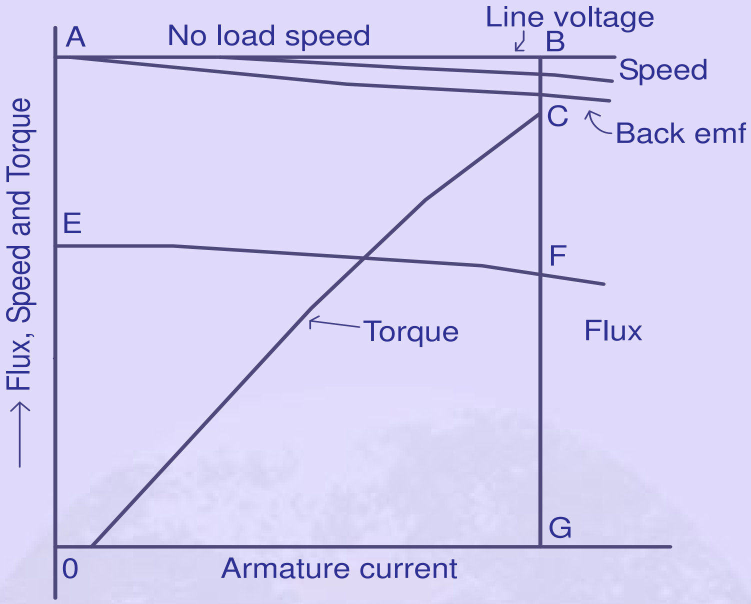
The first one is an electrical equation, the second and the third are electro mechanical in nature and the last equation is the mechanical equation of motion. K_e and K_t are normally termed as back emf constant and torque constant respectively. Under steady speed of operation the fourth equation is not required. Using these equations one can determine the torque speed characteristics of the machine for a given applied voltage. These characteristics are similar to the external characteristics for a generator. Here the torque on the machine is assumed to be varying and the corresponding speed of operation is determined. This is termed as the torque speed characteristic of the motor.

5.7 Torque speed characteristics of a shunt motor

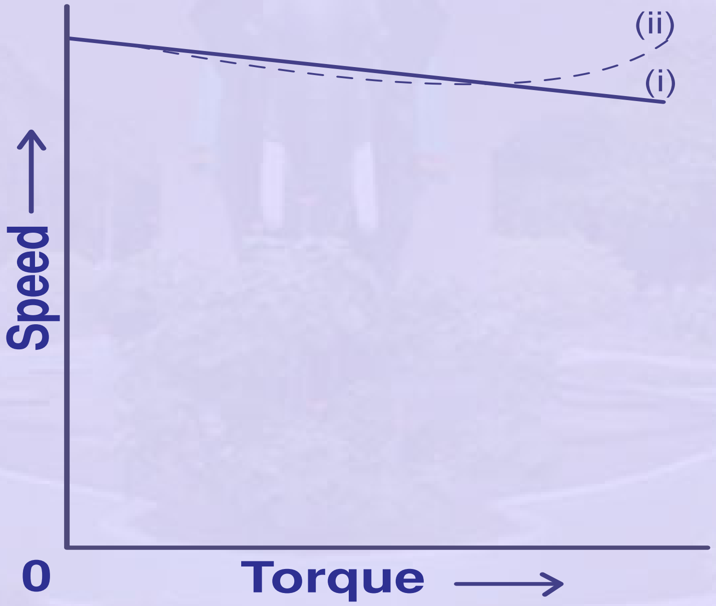
A constant applied voltage V is assumed across the armature. As the armature current I_a, varies the armature drop varies proportionally and one can plot the variation of the induced emf E. The mmf of the field is assumed to be constant. The flux inside the machine however slightly falls due to the effect of saturation and due to armature reaction. The variation of these parameters are shown in Fig. 42.

Knowing the value of E and flux one can determine the value of the speed. Also knowing the armature current and the flux, the value of the torque is found out. This procedure is repeated for different values of the assumed armature currents and the values are plotted as in Fig. 42-(a). From these graphs, a graph indicating speed as a function of torque or the torque-speed characteristics is plotted Fig. 42-(b)(i).

As seen from the figure the fall in the flux due to load increases the speed due to the fact that the induced emf depends on the product of speed and flux. Thus the speed



(a)Load characteristics



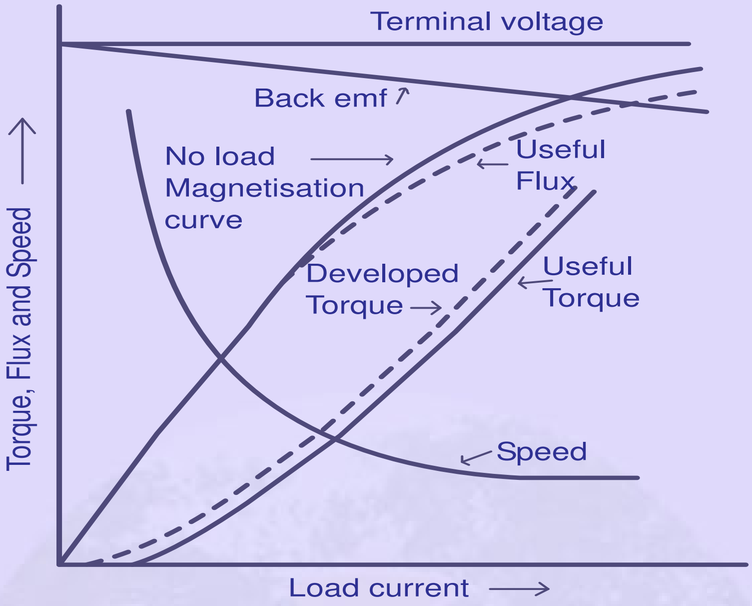
(b)Torque speed curve

Figure 42: DC Shunt motor characteristics

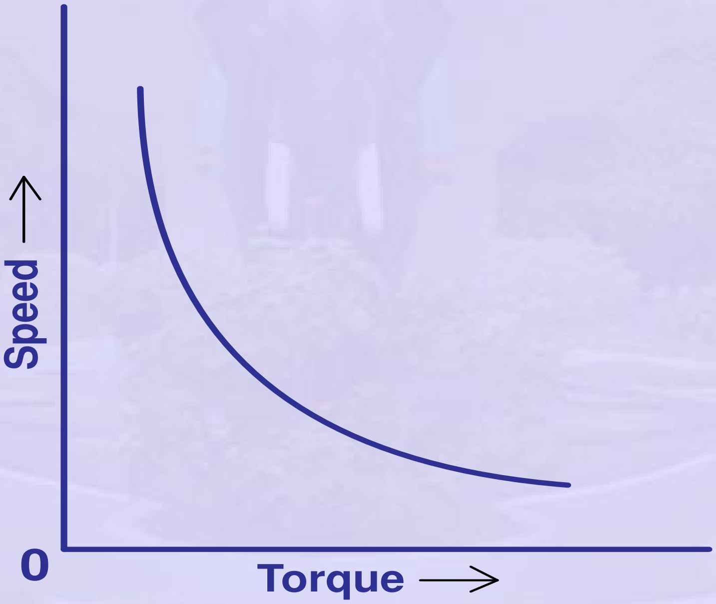
of the machine remains more or less constant with load. With highly saturated machines the on-load speed may even slightly increase at over load conditions. This effects gets more pronounced if the machine is designed to have its normal field ampere turns much less than the armature ampere turns. This type of external characteristics introduces instability during operation Fig. 42(b)(ii) and hence must be avoided. This may be simply achieved by providing a series stability winding which aids the shunt field mmf.

5.8 Load characteristics of a series motor

Following the procedure described earlier under shunt motor, the torque speed characteristics of a series motor can also be determined. The armature current also happens to be the excitation current of the series field and hence the flux variation resembles the magnetization curve of the machine. At large value of the armature currents the useful flux would be less than the no-load magnetization curve for the machine. Similarly for small values of the load currents the torque varies as a square of the armature currents as the flux is proportional to armature current in this region. As the magnetic circuit becomes more and more saturated the torque becomes proportional to I_a as flux variation becomes small. Fig. 43(a) shows the variation of E_1, flux , torque and speed following the above procedure from which the torque-speed characteristics of the series motor for a given applied voltage V can be plotted as shown in Fig. 43.(b) The initial portion of this torque-speed curve is seen to be a rectangular hyperbola and the final portion is nearly a straight line. The speed under light load conditions is many times more than the rated speed of the motor. Such high speeds are unsafe, as the centrifugal forces acting on the armature and commutator can destroy them giving rise to a catastrophic break down. Hence series motors are not recommended for use where there is a possibility of the load becoming zero. In order to



(a)Load characteristics



(b)-Torque speed curve

Figure 43: Load characteristics of a Series Motor

safeguard the motor and personnel, in the modern machines, a 'weak' shunt field is provided on series motors to ensure a definite, though small, value of flux even when the armature current is nearly zero. This way the no-load speed is limited to a safe maximum speed. It is needless to say, this field should be connected so as to aid the series field.

5.9 Load characteristics of a compound motor

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

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

6 Parallel operation of d.c. motors

As in the case of generators motors may also be required to operate in parallel driving a common load. The benefits as well as the problems in both the cases are similar. As the two machines are coupled to a common load the speed of the load is the common parameter in the torque speed plane. The torque shared by each machine depends on the intersection of the torque speed curves. If the torque speed lines are drooping the point of intersection remains reasonably unaltered for small changes in the characteristics due to temperature and excitation effects. However if these curves are flat then great changes occur in torque shared by each machine. The machine with flatter curve shares a larger portion of the torque demand. Thus parallel operation of two shunt motors is considerably more difficult compared to the operation of the same machines as generators. The operation of level compounded generators is much more difficult compared to the same machines working as cumulative compounded motor. On a similar count parallel operation of cumulative compounded motors is easier than shunt motors. Series motors are, with their highly falling speed with the load torque, are ideal as far as the parallel operation is considered. Considerable differences in their characteristics still do not affect adversely their parallel operation. One application where several series motors operate in parallel is in electric locomotives. Due to the uneven wear and tear of the wheels of the locomotive the speeds of the rotation of these motors can be different to have the same common linear velocity of the locomotive. The torque developed by each machine remains close to the other and there is no tendency for derailment.The torque speed curves for parallel operation of series motors are given in Fig. 44

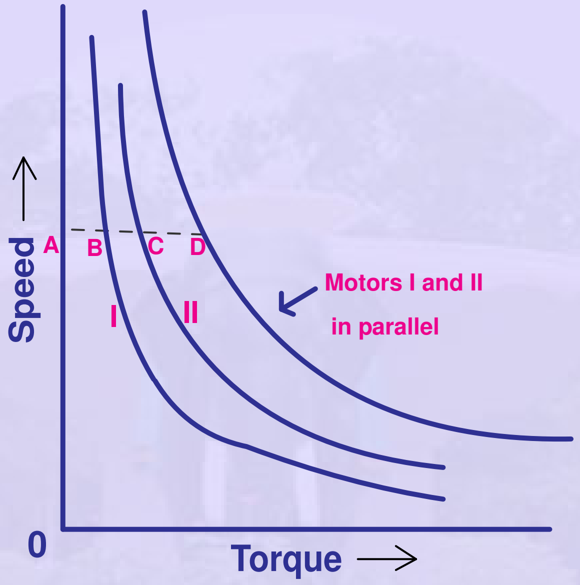


Figure 44: Parallel operation of Series motors

7 Series operation of motors

In the case of series operation the motors shafts of the two machines are connected to the same load and also the two armatures are series connected. This forces a common armature current through both the machines and the torques developed by the machines are proportional to the flux in each machine. Series operation of series motors is adopted during starting to improve the energy efficiency. This method is ideally suited for shunt and compound machines with nearly flat torque speed characteristics. Such machines can go through high amount of dynamics without the fear of becoming unstable. This configuration is used in steel mills. Having two smaller machines connected to the shaft is preferred over there in place of one large machine as the moment of inertia of the motors is much reduced, thus improving the dynamics.

8 Application of d.c. motors

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

$$T_M - T_L = J\frac{dw}{dt} \tag{43}$$

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

1. Starting
2. Speed control
3. Braking

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

The relevant expressions may be written as,

$$n = \frac{E}{K_e\phi} = \frac{V - I_aR_a - V_b}{pZ\phi/b} \tag{44}$$

$$T_M = K_t.\phi.I_a = \frac{1}{2\pi}.\frac{p.Z}{b}.\phi I_a \tag{45}$$

$$T_M - T_L = J\frac{d\omega}{dt} \tag{46}$$

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

8.1 Starting of d.c. machines

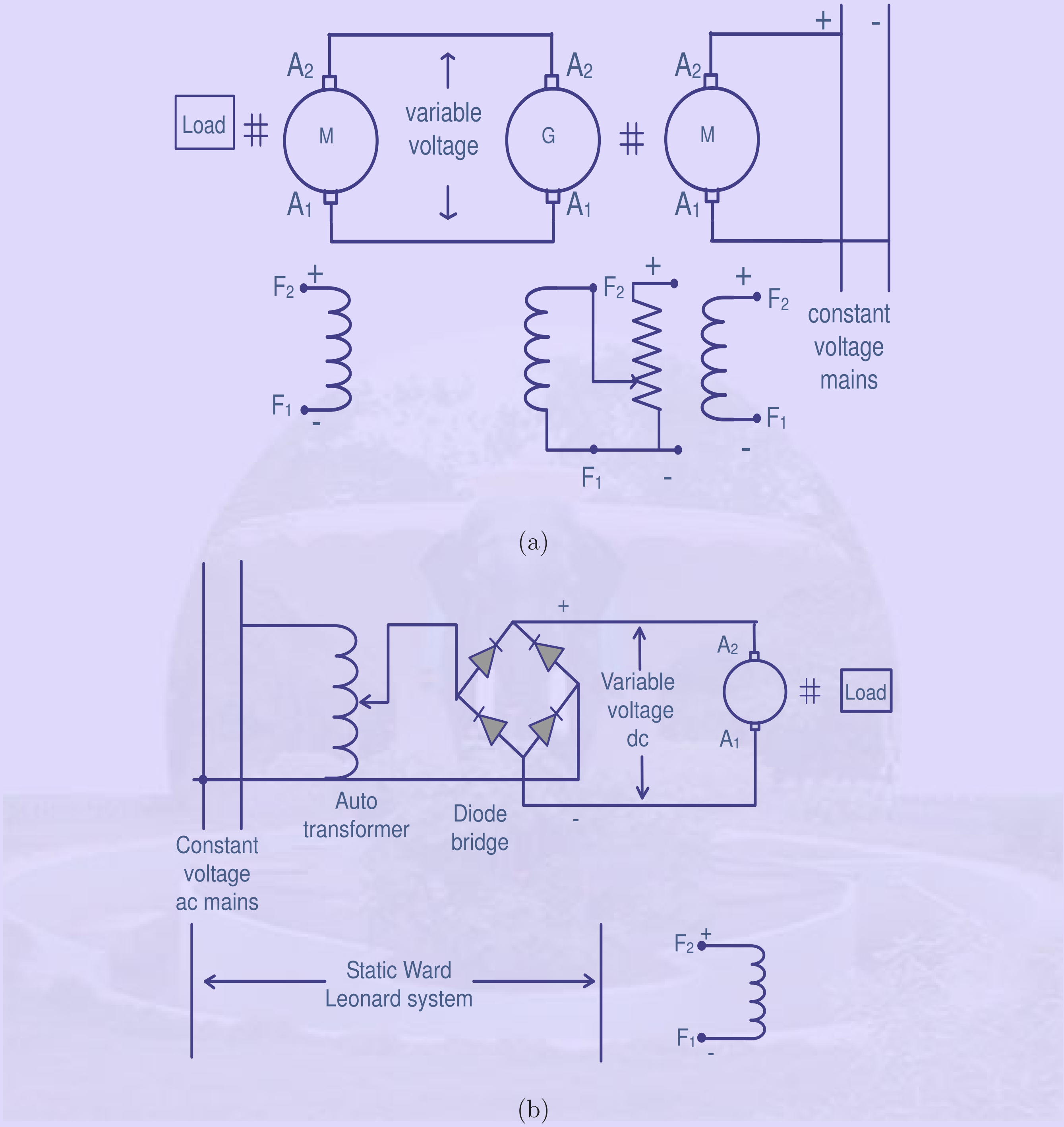
For the machine to start, the torque developed by the motor at zero speed must exceed that demanded by the load. Then $T_M - T_L$ will be positive so also is $d\omega/dt$, and the machine accelerates. The induced emf at starting point is zero as the $\omega = 0$ The armature current with rated applied voltage is given by V/R_a where R_a is armature circuit resistance. Normally the armature resistance of a d.c. machine is such as to cause 1 to 5 percent drop at full load current. Hence the starting current tends to rise to several times the full load current. The same can be told of the torque if full flux is already established. The machine instantly picks up the speed. As the speed increases the induced emf appears across the terminals opposing the applied voltage. The current drawn from the mains thus decreases, so also the torque. This continues till the load torque and the motor torque are equal to each other. Machine tends to run continuously at this speed as the acceleration is zero at this point of operation.

The starting is now discussed with respect to specific machines.

8.1.1 DC shunt motor

If armature and field of d.c. shunt motor are energized together, large current is drawn at start but the torque builds up gradually as the field flux increases gradually. To improve the torque per ampere of line current drawn it is advisable to energize the field first. The starting current is given by V/R_a and hence to reduce the starting current to a safe value, the voltage V can be reduced or armature circuit resistance R_a can be increased. Variable voltage V can be obtained from a motor generator set. This arrangement is called Ward-Leonard arrangement. A schematic diagram of Ward-Leonard arrangement is shown in Fig. 45. By controlling the field of the Ward-Leonard generator one can get a variable voltage at its terminals which is used for starting the motor.

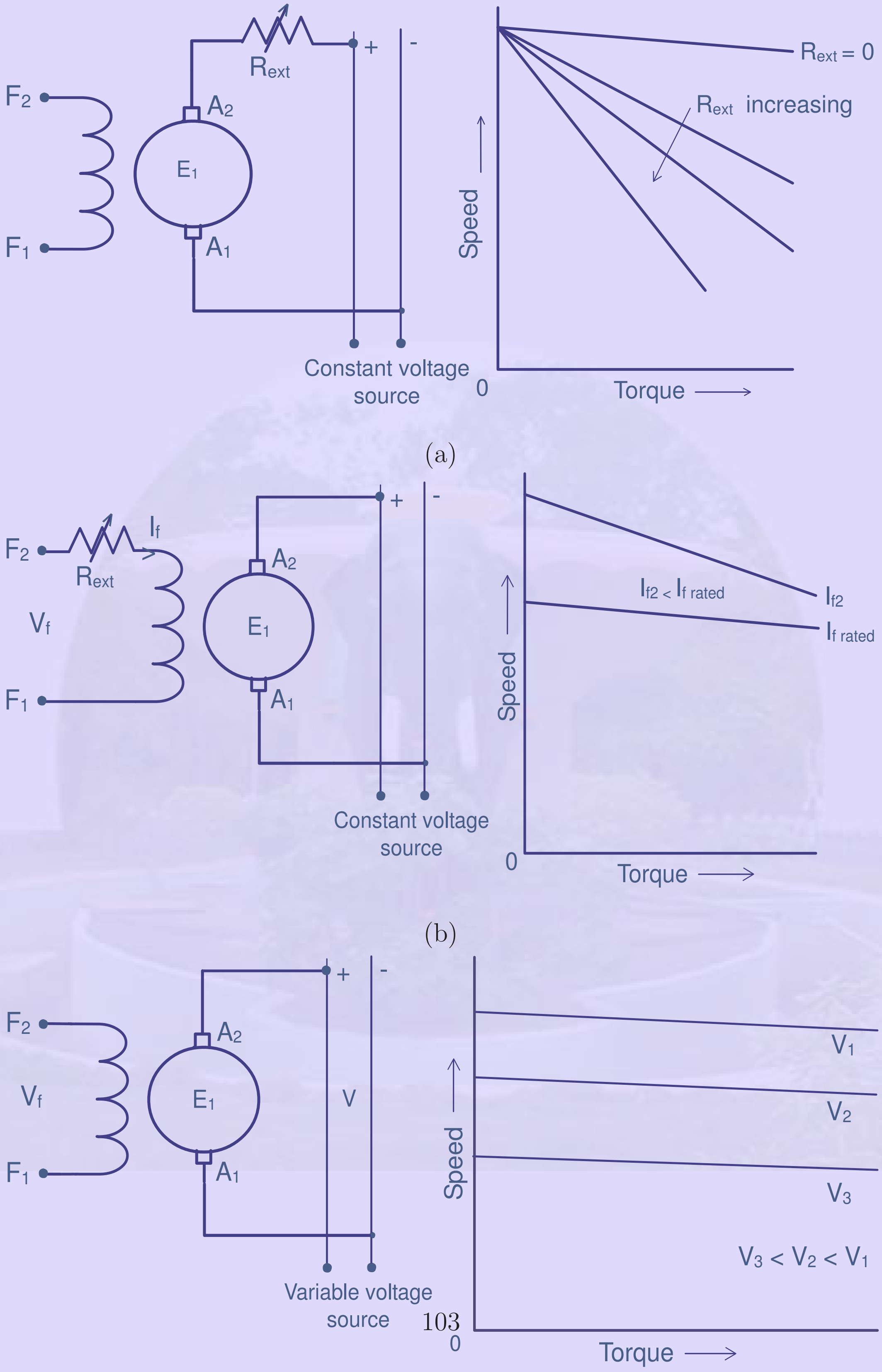
The second method of starting with increased armature circuit resistance can be obtained by adding additional resistances in series with the armature, at start. The current and the torque get reduced. The torque speed curve under these conditions is shown in Fig. 46(a) . It can be readily seen from this graph that the unloaded machine reaches its final speed but a loaded machine may crawl at a speed much below the normal speed. Also, the starting resistance wastes large amount of power. Hence the starting resistance must be reduced to zero at the end of the starting process. This has to be done progressively, making sure that the current does not jump up to large values. Starting of series motor and compound motors are similar to the shunt motor. Better starting torques are obtained for compound motors as the torque per ampere is more. Characteristics for series motors are given in fig. 47.



(a)

(b)

Figure 45: Ward-Leonard arrangement



(a)

(b)

(c)

Figure 46: Shunt Motor characteristics

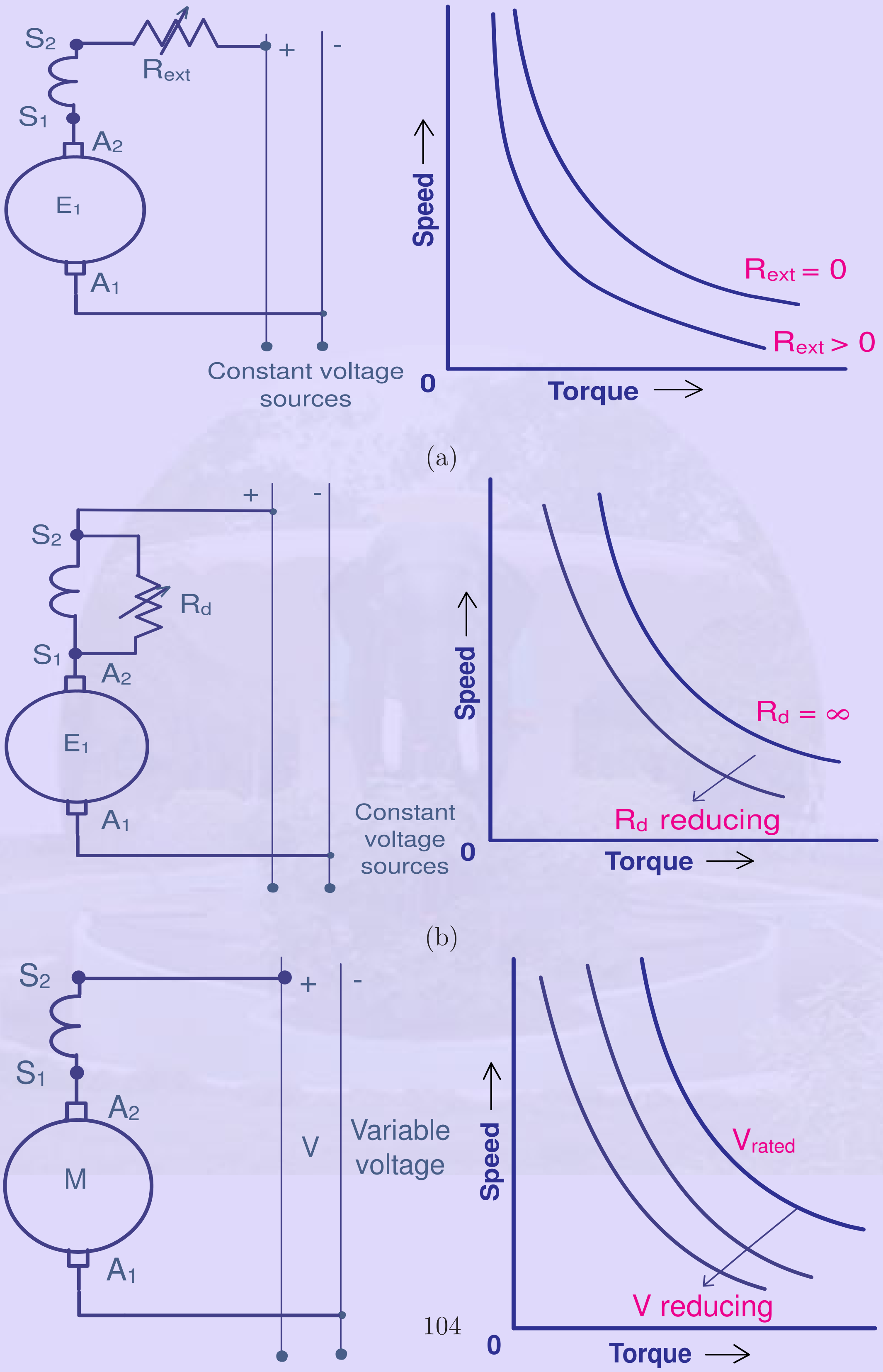
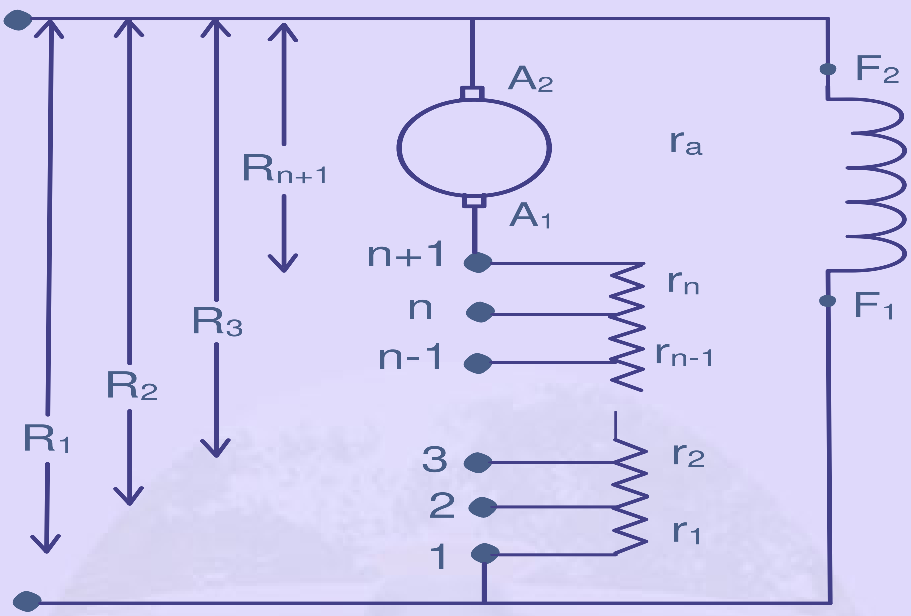
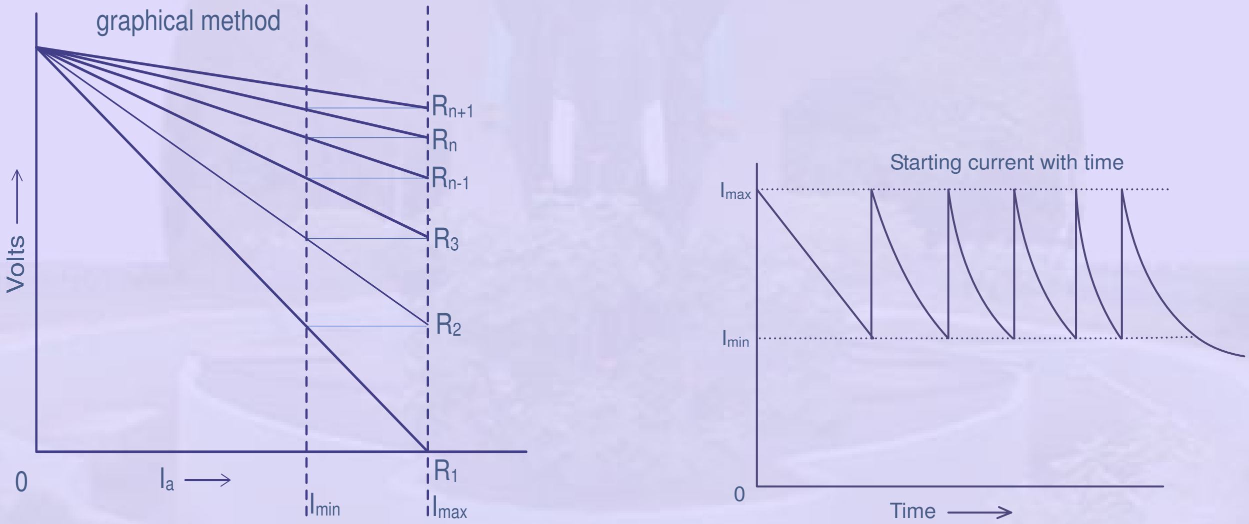


Figure 47: Series motor control



(a)Physical connection



(b) Characteristics (c) Time-current plot

Figure 48: Calculation of starter resistance steps

8.1.2 Grading of starting resistance for a shunt motor

If the starting resistor is reduced in uniform steps then the current peaks reached as we cut down the resistances progressively increase. To ascertain that at no step does the current jump to a large value non-uniform reduction of resistances must be assorted to. This use of a non-uniform resistance step is called 'grading' of the resistors. The calculations for a starter resistance of a shunt motor are shown below with the help of Fig. 48. In the figure an n element or n+1 step starter is shown. The armature resistance when all the external resistances are cut off is r_a. The total armature circuit resistance at step 1 is $R_1 = (r_1 + r_2 + ... + r_n) + r_a$. The field winding is connected across the supply. The starting current reaches a maximum value I_max when we move on to a step. One resistance element is cut from the circuit when the current falls down to I_min . During the instant when the element is cut the speed and hence the induced emf does not change but the current jumps back to I_max . Thus during the starting the current changes between two limits I_max and I_min. Writing the expression for the current before and after the resistance is changed on step R_i and R_{i+1}, we have

$$I_min = \frac{V-E}{R_i} \qquad I_max = \frac{V-E}{R_{i+1}} \qquad \text{or} \qquad \frac{I_max}{I_min} = \frac{R_i}{R_{i+1}} \tag{47}$$

Proceeding this way for all the steps

$$\frac{I_max}{I_min} = \frac{R_1}{R_2} = \frac{R_2}{R_3} = ... = \frac{R_{n-1}}{R_n} = \frac{R_n}{R_{n+1}} = k(say) \tag{48}$$

$$k^n = \frac{R_1}{R_2} * \frac{R_2}{R_3} * ... * \frac{R_n}{R_{n+1}} = \frac{R_1}{R_{n+1}} = \frac{R_1}{r_a} \qquad k = \sqrt[n]{\frac{R_1}{r_a}} \tag{49}$$

Sometimes the ratio k may be required to be fixed. Then the number of steps required can be calculated as

$$n \log k = \log \frac{R_1}{r_a} \quad , n = \frac{\log \frac{R_1}{r_a}}{\log k} \tag{50}$$
$$\frac{\log R_1 - \log R_n}{\log k}$$

Also,

$$R = \sqrt[n]{\frac{V}{I_1 r_a}} = \sqrt[n]{\frac{V}{R I_2 r_a}} = \sqrt[n+1]{\frac{V}{I_2 r_a}} \tag{51}$$

From these expressions it is seen that to have the ratio k to be unity, the number of steps should be infinity. Smaller the number of steps larger is the ratio of maximum to minimum current. Also, it is not possible to choose n and k independently. I_max is set by the maximum possible starting current from the point of view of commutation. I_min is found from the minimum torque against which the starting is required to be performed. Similar method exists in the case of series motors and compound motors. In these cases the ratio of currents and the ratio of fluxes are needed. The equation becomes non-linear and a graphical method is normally adopted for the design of the resistances in those cases.

Resistance method of starting is cheaper and simple and hence is used universally. But it wastes energy in the starting resistor. Hence this method is not advised when frequent starting of the motor is required. Ward-Leonard method gives a energy efficient method of starting. With the help of a auto transformer and rectifier set one can get variable voltage d.c. supply from a constant voltage a.c power source. This is some times called a static Ward-Leonard arrangement. This method is becoming more popular over the rotating machine counter part.

8.2 Speed control of d.c. motors

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

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

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

8.3 Braking the d.c. motors

When a motor is switched off it ‘coasts’ to rest under the action of frictional forces. Braking is employed when rapid stopping is required. In many cases mechanical braking is adopted. The electric braking may be done for various reasons such as those mentioned below:

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

In many cases electric braking makes more brake power available to the braking process where mechanical brakes are applied. This reduces the wear and tear of the mechanical brakes and reduces the frequency of the replacement of these parts. By recovering the mechanical energy stored in the rotating parts and pumping it into the supply lines the overall energy efficiency is improved. This is called regeneration. Where the safety of the personnel or the equipment is at stake the machine may be required to stop instantly. Extremely large brake power is needed under those conditions. Electric braking can help in these situations also. In processes where frequent starting and stopping is involved the process time requirement can be reduced if braking time is reduced. The reduction of the process time improves the throughput.

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

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

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

8.3.1 Dynamic braking

- Shunt machine

  In dynamic braking the motor is disconnected from the supply and connected to a dynamic braking resistance R_{DB}. In and Fig. 49 this is done by changing the switch from position 1 to 2 . The supply to the field should not be removed. Due to the rotation of the armature during motoring mode and due to the inertia, the armature continues to rotate. An emf is induced due to the presence of the field and the rotation. This voltage drives a current through the braking resistance. The direction of this current is opposite to the one which was flowing before change in the connection. Therefore, torque developed also gets reversed. The machine acts like a brake. The torque speed characteristics separate by excited shunt of the machine under dynamic braking mode is as shown in Fig. 49(b) for a particular value of R_{DB}. The positive torque corresponds to the motoring operation. Fig. 50 shows the dynamic braking of a shunt excited motor and the corresponding torque-speed curve. Here the machine behaves as a self excited generator.

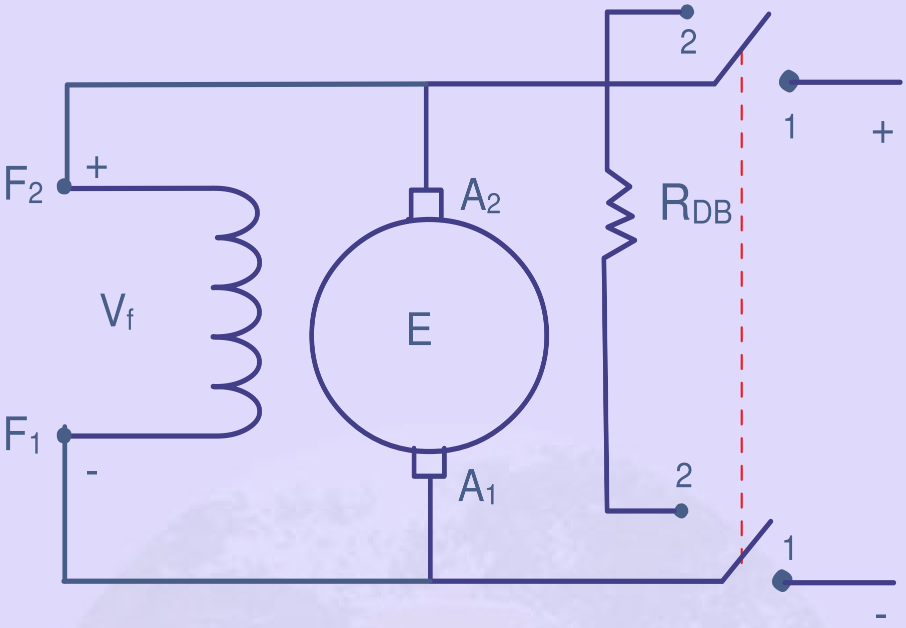
Below a certain speed the self-excitation collapses and the braking action becomes Zero.

- Series machine

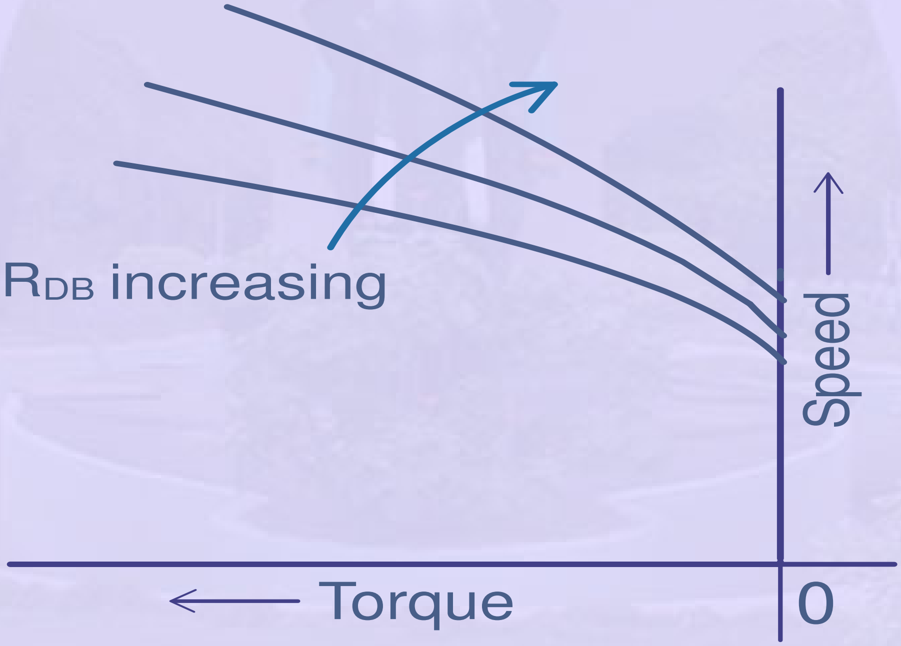
  In the case of a series machine the excitation current becomes zero as soon as the armature is disconnected from the mains and hence the induced emf also vanishes. In order to achieve dynamic braking the series field must be isolated and connected to a low voltage high current source to provide the field.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

- Compound generators

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

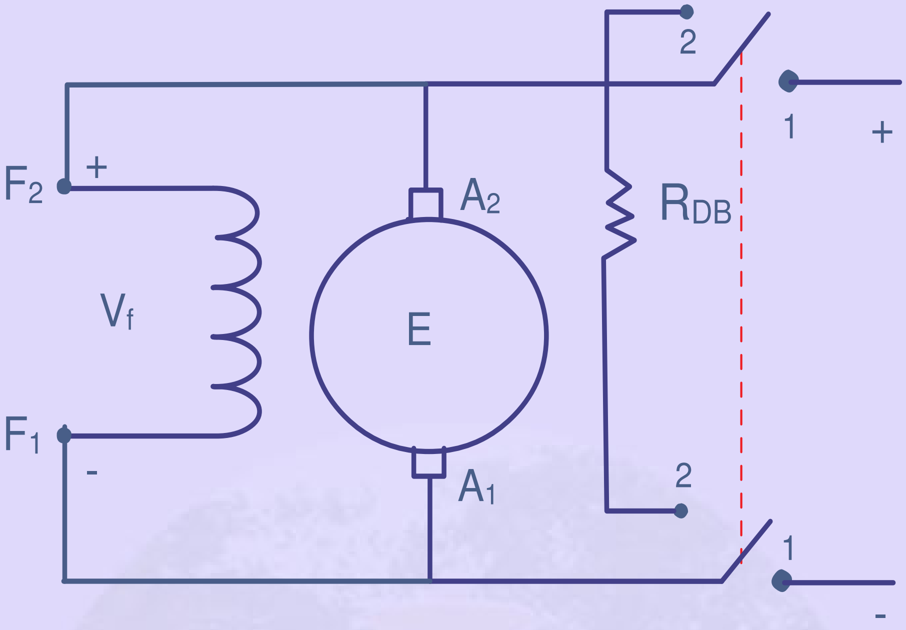


(a)Connections

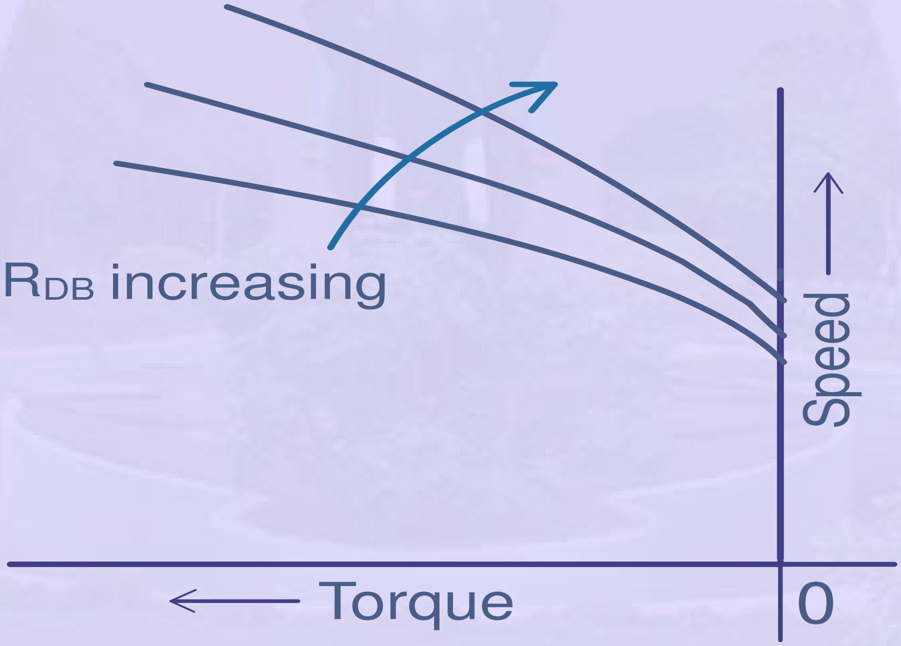


(b)Characteristics

Figure 49: Dynamic Braking of a shunt motor



(a)Connections



(b)Characteristics

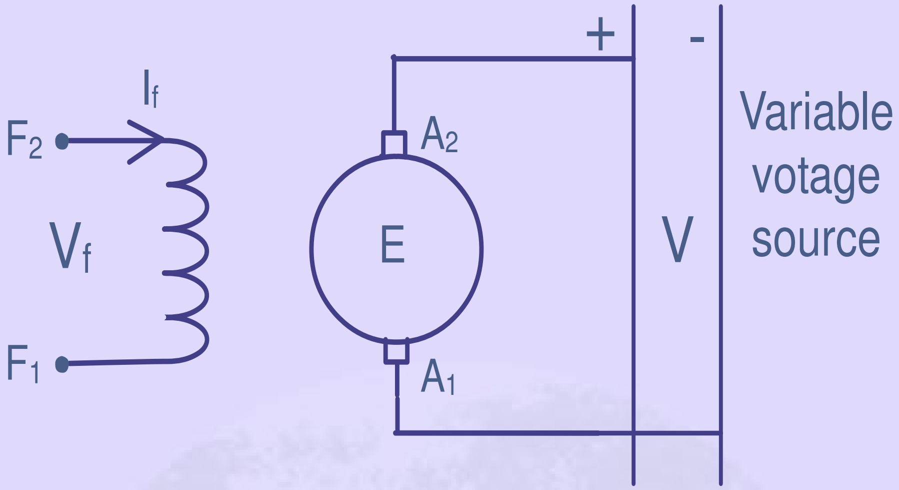
Figure 50: Dynamic braking of shunt excited shunt machine

8.3.2 Regenerative braking

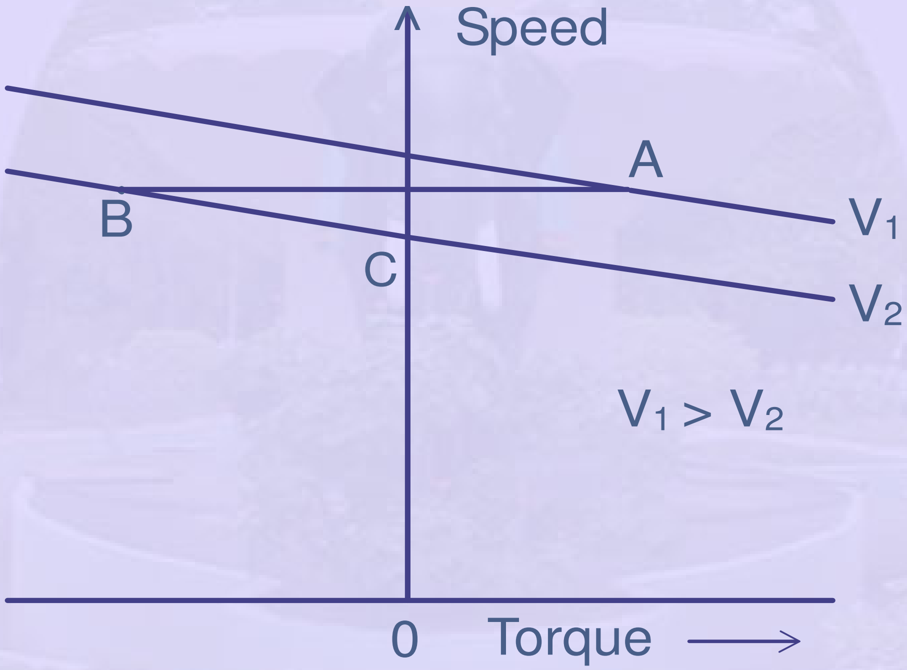
In regenerative braking as the name suggests the energy recovered from the rotating masses is fed back into the d.c. power source. Thus this type of braking improves the energy efficiency of the machine. The armature current can be made to reverse for a constant voltage operation by increase in speed/excitation only. Increase in speed does not result in braking and the increase in excitation is feasible only over a small range, which may be of the order of 10 to 15%. Hence the best method for obtaining the regenerative braking is to operate, the machine on a variable voltage supply. As the voltage is continuously pulled below the value of the induced emf the speed steadily comes down. The field current is held constant by means of separate excitation. The variable d.c. supply voltage can be obtained by Ward-Leonard arrangement, shown schematically in Fig. 51. Braking torque can be obtained right up to zero speed. In modern times static Ward-Leonard scheme is used for getting the variable d.c. voltage. This has many advantages over its rotating machine counter part. Static set is compact, has higher efficiency, requires lesser space, and silent in operation; however it suffers from drawbacks like large ripple at low voltage levels, unidirectional power flow and low over load capacity. Bidirectional power flow capacity is a must if regenerative braking is required. Series motors cannot be regeneratively braked as the characteristics do not extend to the second quadrant.

8.3.3 Plugging

The third method for braking is by plugging.Fig. 52 shows the method of connection for the plugging of a shunt motor. Initially the machine is connected to the supply with the switch S in position number 1. If now the switch is moved to position 2, then a reverse voltage is applied across the armature. The induced armature voltage E and supply voltage

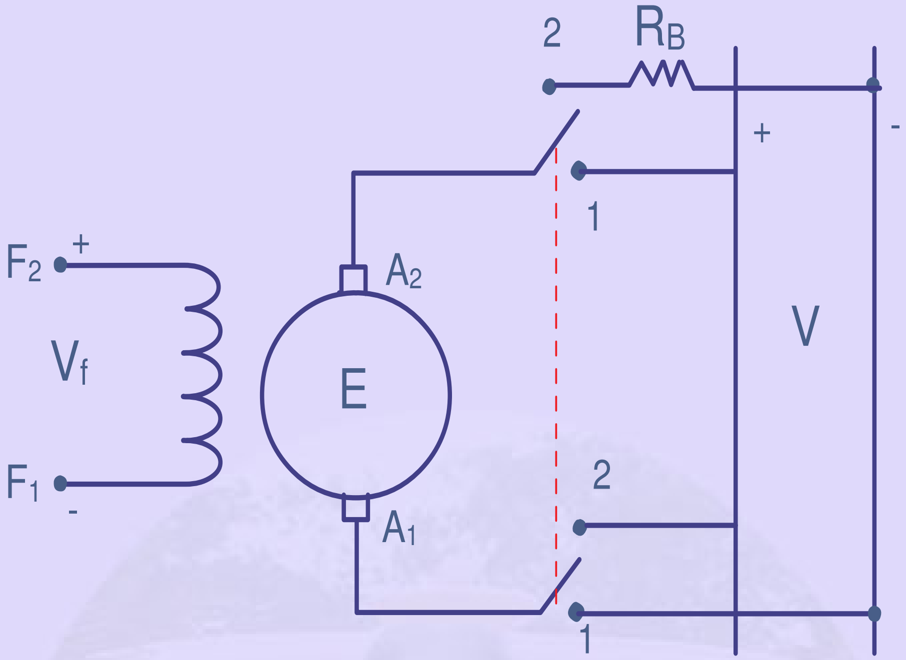


(a)Physical connection

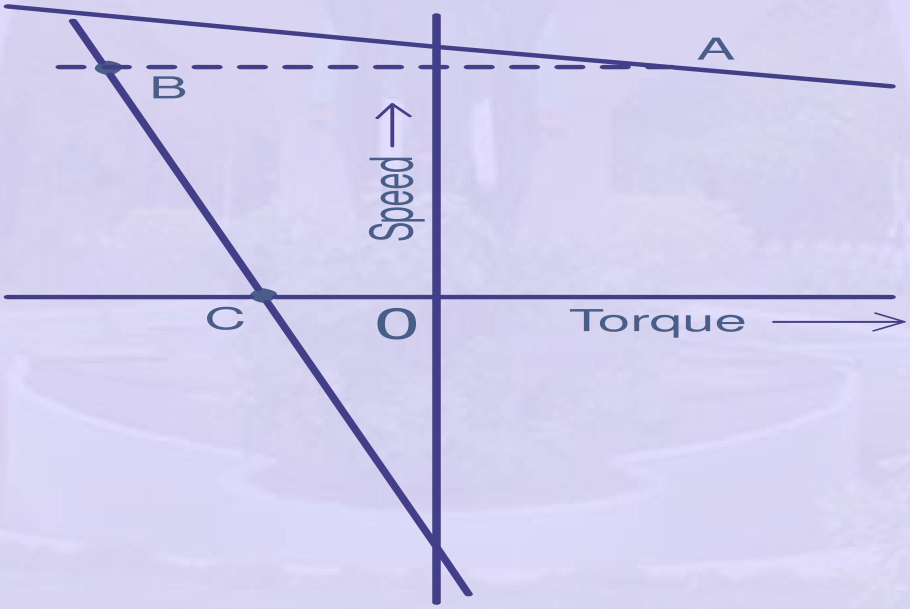


(b)Characteristics

Figure 51: Regenerative braking of a shunt machine



(a)Physical connection



(b)Characteristics

Figure 52: Plugging or reverse voltage braking of a shunt motor

V aid each other and a large reverse current flows through the armature. This produces a large negative torque or braking torque. Hence plugging is also termed as reverse voltage braking. The machine instantly comes to rest. If the motor is not switched off at this instant the direction of rotation reverses and the motor starts rotating the reverse direction. This type of braking therefore has two modes viz. 1) plug to reverse and 2) plug to stop. If we need the plugging only for bringing the speed to zero, then we have to open the switch S at zero speed. If nothing is done it is plug to reverse mode. Plugging is a convenient mode for quick reversal of direction of rotation in reversible drives. Just as in starting, during plugging also it is necessary to limit the current and thus the torque, to reduce the stress on the mechanical system and the commutator. This is done by adding additional resistance in series with the armature during plugging.

- Series motors

  In the case of series motors plugging cannot be employed as the field current too gets reversed when reverse voltage is applied across the machine. This keeps the direction of the torque produced unchanged. This fact is used with advantage, in operating a d.c. series motor on d.c. or a.c. supply. Series motors thus qualify to be called as ‘Universal motors’.

- Compound motors

  Plugging of compound motors proceeds on similar lines as the shunt motors. However some precautions have to be observed due to the presence of series field winding. A cumulatively compounded motor becomes differentially compounded on plugging. The mmf due to the series field can ’over power’ the shunt field forcing the flux to low values or even reverse the net field. This decreases the braking torque, and increases the duration of the large braking current. To avoid this it may be advisable to deactivate the series field at the time of braking by short circuiting the same. In such cases the braking proceeds just as in a shunt motor. If plugging is done to operate the motor in the negative direction of rotation as well, then the series field has to be reversed and connected for getting the proper mmf. Unlike dynamic braking and regenerative braking where the motor is made to work as a generator during braking period, plugging makes the motor work on reverse motoring mode.

8.4 Application of d.c motors and generators

It is seen from the earlier sections that the d.c.machine is capable of having variety of torque-speed characteristics depending on the circuit conditions. The need for generating these characteristics will be clear only when they are seen along with the characteristics of the loads that they operate with. Even though a detailed treatment of motor load systems is outside the scope here, it may be useful to look into the typical torque-speed characteristics of some of the common loads.

Loads are broadly divided into,

(a) Passive loads

(b) Active loads

They may be unidirectional in operation or work in either direction (Reversible loads).

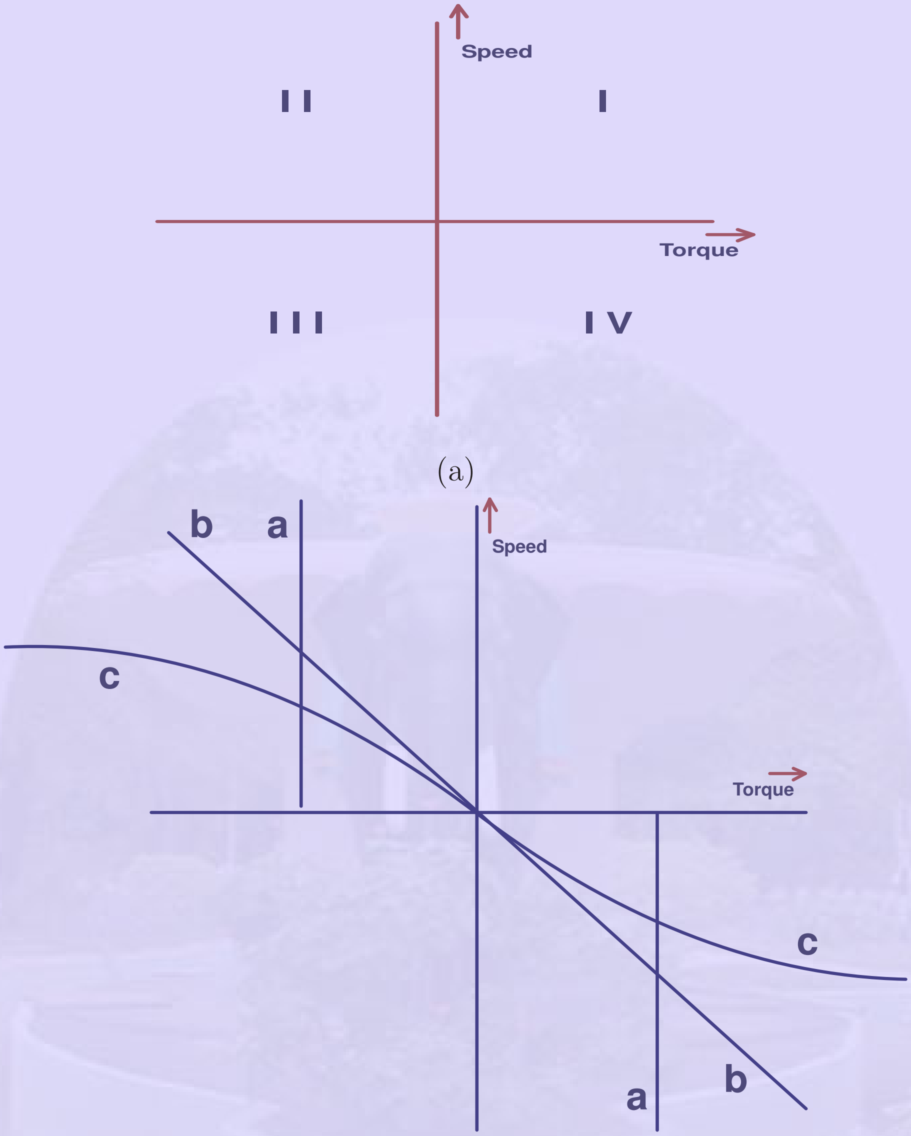
Passive loads absorb the mechanical energy developed by the motors while active loads are capable of working as both sinks and sources for mechanical energy. The direction of rotation may be taken to be clockwise/counter clockwise rotation. Normally the direction in which the load operates most of the time, is taken as the positive direction of rotation. Any torque which accelerates the motor load system in the positive direction of rotation is termed as a positive toque. With this rotation torques of motors, generators or loads can be represented graphically on a four quadrantal diagram. The torque being taken as an independent variable, is represented along the x-axis. Y-axis represents the speed. Quadrants. I and III in Fig. 53(a) represent 'forward motoring' and 'reverse motoring' operation respectively. Quadrants II and IV similarly represent generating/braking quadrants as they absorb mechanical power and cause braking action.

Fig. 53(b) shows a few typical load characteristics on a four quadrantal diagram.

The characteristics a, b,and c correspond to frictional torque, cutting torque and fan torque respectively. While the frictional torque is not a function of speed, the cutting toque is proportional to the speed and the fan torque varies as the square of the speed. These can only absorb mechanical power and hence are represented in quadrantal II for positive direction of rotation. Similar loads produce characteristics in quadrant IV for negative direction of rotation.

Fig. 54 shows a typical behaviour of an active load. Here an elevator is taken as an example. Here the counter weight is assumed to be heavier than the cage and similarly the loaded cage in assumed to be heavier than the counter weight. As seen from the Fig. 54 the torque is constant and depends on the difference in the weight of the case and the counter weight, and the radius of the drum. The characteristics of the load exists in all the four quadrants and is capable of delivering as well as absorbing mechanical power. Hence it is called as an active load. The governing equation when the motor and a load are connected together is

$$T_M(w) - T_L(w) = J\frac{dw}{dt} \tag{52}$$



(a)

(b)

Figure 53: Typical load characteristics on a four quadrantal diagram

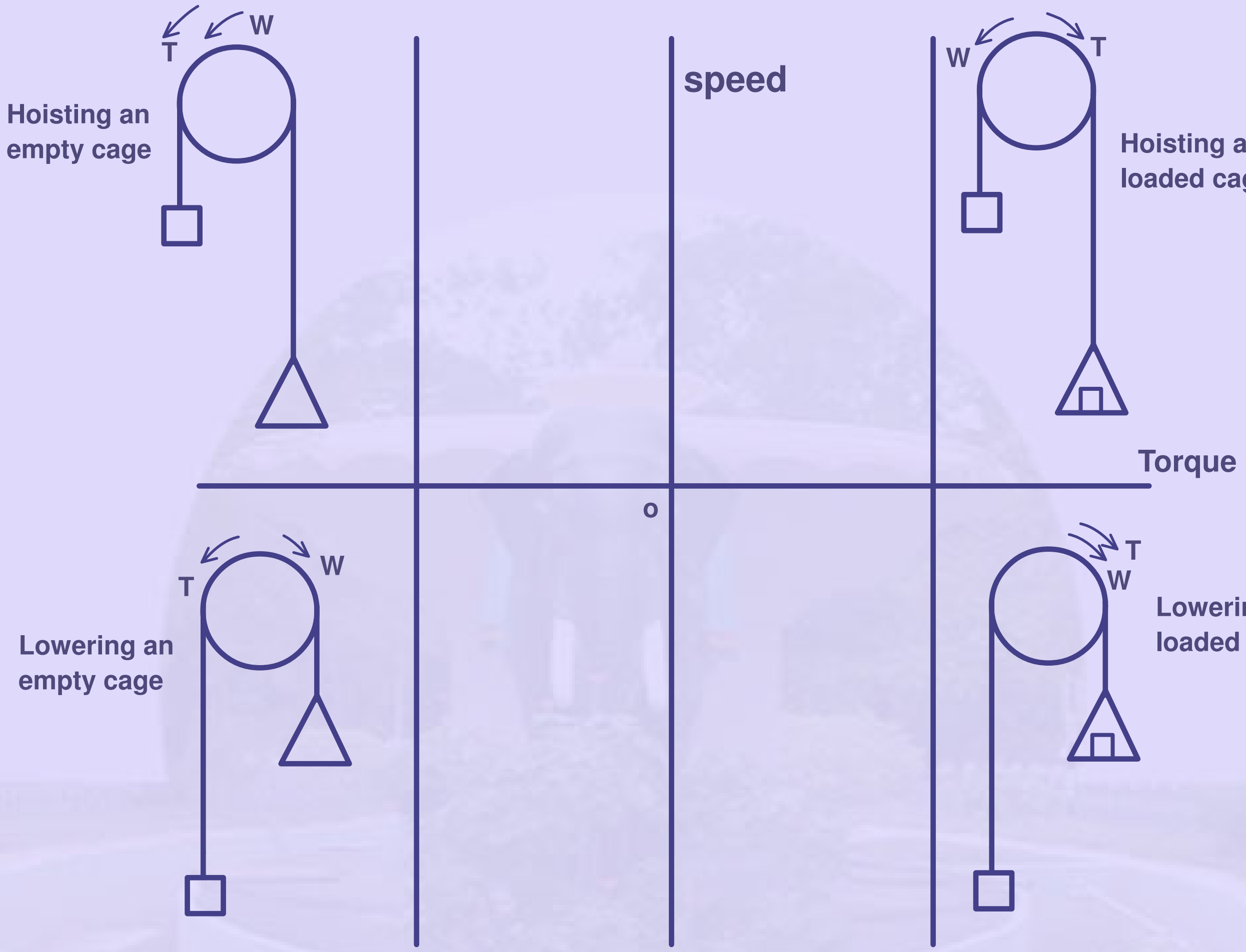


Figure 54: Four quadrantal diagram

where $T_M(w)$ and $T_M(w)$ are motor and load torques respectively. J is the polar moment of inertia of the motor and load put together at the motor shaft. $\frac{dw}{dt}$ is made positive when the speed has to be increased in the positive direction and negative when reducing the speed. Under steady operation $T_M(w) - T_L(W) = 0$. Both motor and load torques are expressed as functions of the speed. The speed at which motor and load torques are equal and opposite is the steady state operating speed. By varying the characteristics of the motor (or the load), this speed can be changed to suit our requirements. Normally the torque speed characteristics of a load cannot be changed easily. Thus most speed control methods adopt, varying the motor characteristics to achieve speed control. Some typical loads and the motors commonly used to drive the same are tabulated in Table.

d.c. shunt motor	lathes,fans,pumps disc and band saw drive requiring moderate torques.
d.c. series motor	Electric traction, high speed tools
d.c. compound motor	Rolling mills and other loads requiring large momentary toques.

9 Testing of d.c. machines

A d.c. machine has to be tested for proper fabrication and trouble free operation. From the tests one can determine the external characteristics needed for application of these machines. Also, one can find the efficiency, rating and temperature rise of the machine. Some of the tests are discussed in sequence now.

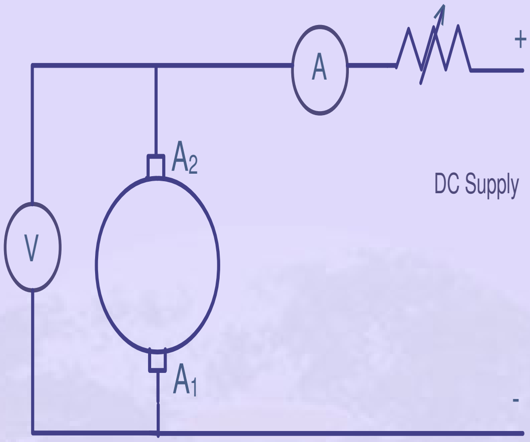
9.1 Measurement of armature resistance

Measurement of winding resistances of field windings and armature winding are performed by v-i method. Field is not excited during this test.

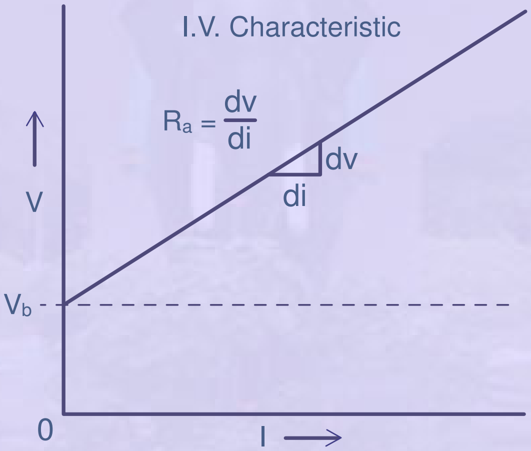
Even though any value of applied voltage can be used, the highest permissible voltage/current is chosen during the test to minimize the errors. The armature circuit consists of two resistances in series. They are armature winding resistance and resistance due to the brushes and the brush drop. The brush contact drop behaves like a non-linear resistance. To separate this from the armature circuit resistance and brush resistance a number of v-i readings are taken. An equation of $V = V_b + IR_a$ form is fitted through these test points shown graphically in Fig. 55. For large values of I the equivalent armature resistance is taken to be V/I ohm. If the value of brush drop V_b can be neglected then the armature resistance $R_a = V/I$ ohm.

9.2 Open Circuit Characteristic (OCC)

The OCC is of great value as it shows the mmf and hence the field current required to generate a given voltage at any speed, on no load. It is a graph showing the variation



(a)Physical connection



(b)Characteristics

Figure 55: Measurement of Armature resistance and Brush drop

of the induced emf as a function of excitation current, when the speed is held constant, with the load current being zero. It is also called the no-load saturation curve or no load magnetization characteristic. This is experimentally determined by running the machine as a separately excited generator on no-load at a constant speed and noting the terminal voltage as a function of the excitation current. This curve can be used to find the OCC at other speeds and also the self excited voltage when the machine works as a shunt generator.

9.3 Short circuit characteristics:(SCC)

In the case of short circuit test the armature is kept short circuited through an ammeter. The machine is demagnetized and an extremely small field current is passed through the field. The variation of the short circuit current as a function of excitation current is plotted as the SCC. The speed is to be held constant during this test also. The short circuit test gives an idea of the armature drop at any load current.

9.4 Load test

To assess the rating of a machine a load test has to be conducted. When the machine is loaded, certain fraction of the input is lost inside the machine and appears as heat, increasing the temperature of the machine. If the temperature rise is excessive then it affects the insulations, ultimately leading to the breakdown of the insulation and the machine. The load test gives the information about the efficiency of a given machine at any load condition. Also, it gives the temperature rise of the machine. If the temperature rise is below the permissible value for the insulation then the machine can be safely operated at that load, else the load has to be reduced. The maximum continuous load that can be delivered by the machine without exceeding the temperature rise for the insulation used, is termed as the continuous rating of the machine. Thus the load test alone can give us the proper information of the rating and also can help in the direct measurement of the efficiency.

9.5 Measurement of rotor inertia

The moment of inertia value is very important for the selection of a proper motor for drives involving many starts and stops or requiring very good speed control characteristics. The inertia can be determined by a retardation test.

The test works on the principle that when a motor is switched off from the mains it decelerates and comes to rest. The angular retardation at any speed is proportional to the retarding torque and is inversely proportional to the inertia. The torque lost at any speed is calculated by running the motor at that speed steadily on no load and noting the power input.From this power the losses that takes place in the armature and field are deducted to get the power converted into mechanical form. All this power is spent in over coming the mechanical losses at that speed. This can be repeated at any defined speed to get the lost power (P_L) and torque lost (T_{lost}) due to mechanical losses. In a retardation test the motor speed is taken to some high value and the power to the motor is switched off. The torque required by the losses is supplied by the energy stored in the motor inertia. The lost torque at any speed can be written as

$$\begin{aligned} P_L &= T_{lost}.\omega \qquad (53) \\ T_{lost} &= P_L/w = J\frac{dw}{dt} \end{aligned}$$

Here the $\frac{dw}{dt}$ is the slope of the retardation curve and the (T_{lost}) is the torque required to be met at the given speed. From these values the moment of inertia can be computed as

$$J = \frac{T_{lost}}{\frac{dw}{dt}} = \frac{P_L}{w.\frac{dw}{dt}} kgm^2 \tag{54}$$

9.6 Efficiency of a d.c. machine

A machine when loaded yields an output. The input to the machine is measured at that operating point. The the efficiency in per unit is given as the ratio of output power to input power.

$$\begin{aligned} \eta &= \frac{output\ power}{input\ power} \\ &= \frac{Input\ power - power\ lost\ inside\ the\ machine}{input\ power} \\ &= \frac{output\ power}{output\ power + power\ lost\ inside\ the\ machine} \end{aligned} \tag{55}$$

The first definition is used in the direct estimation of the efficiency . The other two definitions are known as determination of efficiency using the loss segregation. For the segregation of losses one must know the losses that take place inside a d.c. machine. The losses that take place inside a d.c. machine can be listed as below.

1. Armature copper loss.
2. Brush and brush contact loss.
3. Shunt field loss
4. Series field loss
5. Commutating pole loss

6. Compensating winding loss
7. Mechanical losses
8. Iron losses
9. Stray load losses

Out of these items 1,2,7,8 and 9 will be present in all the d.c. machines. Out of the remaining one or more may be present depending on which winding is present. These losses change with temperature of operation. Mechanical losses vary with variation in speed. Iron losses change with the degree of saturation and distortion of the shape of the field flux distribution under the poles.

When a d.c. machine is loaded using a suitable load the output delivered by the machine increases. The input requirement also increases along with the output. The difference between the input and output powers is the power lost inside the machine as loss. The efficiency of power conversion is given by the ratio of output power to input power. Putting in mathematical form for a motor,

$$\eta = \frac{VI - losses}{VI} \tag{56}$$

for constant speed operation, the speed dependant losses remain constant. The load dependant losses form the variable losses. While the loss that takes place in the brush drop in the brushes is proportional to the load current, the loss that takes place in the resistance of the armature is proportional to the square of the load current. Even though the loss that takes place in a field winding is proportional to the square of the current through that winding, it is classified under constant losses as the excitation current is held constant during loading.

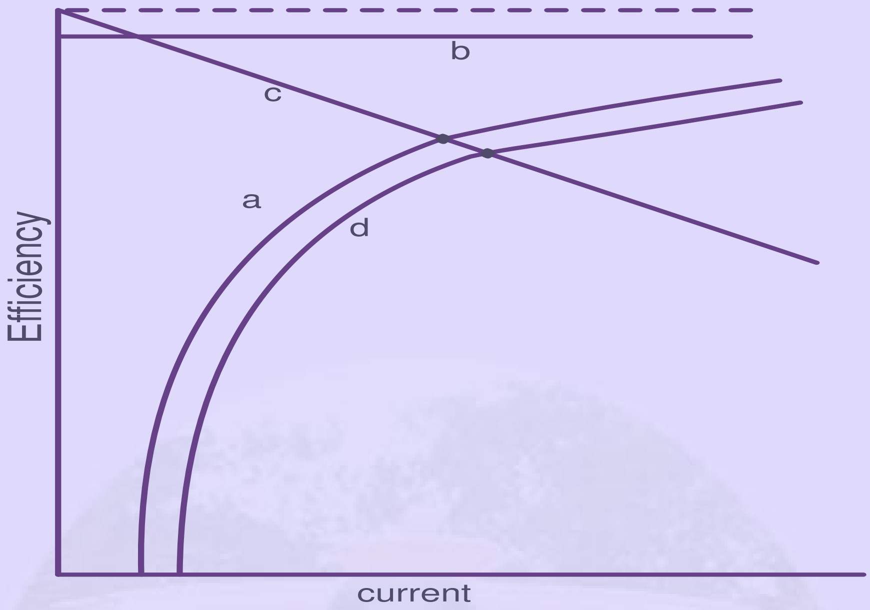
Thus the total losses in a d.c. motor can be expressed in the form

$$P_L = a + bI + cI^2 \tag{57}$$

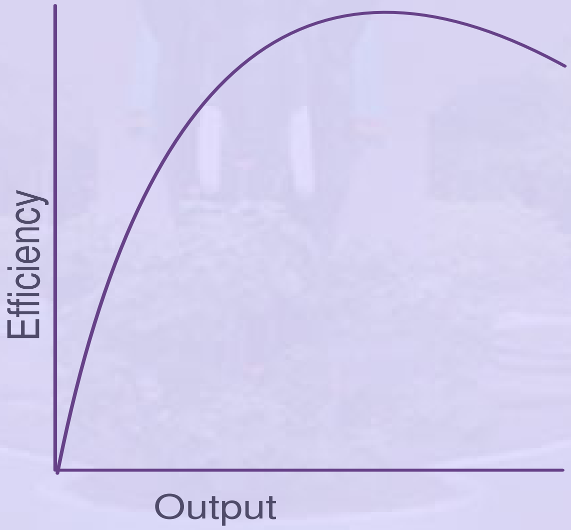
$$\eta = \frac{VI - P_L}{VI} = 1 - (\frac{A}{I} + B + CI) \tag{58}$$

When $A = \frac{a}{V}, B = \frac{b}{V}$ and $C = cV$.

The term inside the brackets is sometimes referred to as the deficiency. For a typical d.c.motor these are plotted in Fig. 56(a) as a function of the load current. The curves a,b,c in the figure represent the efficiency curve taking one component of the loss at a time. The curve d is the efficiency curve with all three components taken together. The resultant curve exhibits a maximum. This can be easily seen from the graph that this maximum occurs when constant losses equal the variable losses.$\frac{A}{I} = CI$ or $A = CI^2$. Fig. 56(b) depicts a typical output vs η curve of a d.c.machine.



(a)Efficiency Vs Load current



(b)Output Vs Efficiency

Figure 56: Efficiency of a D.C.machine