4.5 ARMATURE REACTION

In a unloaded d.c machine armature current is vanishingly small and the flux per pole is decided by the field current alone. The uniform distribution of the lines of force get upset when armature too carries current due to loading. In one half of the pole, flux lines are concentrated and in the other half they are rarefied. Qualitatively one can argue that during loading condition flux per pole will remain same as in no load operation because the increase of flux in one half will be balanced by the decrease in the flux in the other half. Since it is the flux per pole which decides the emf generated and the torque produced by the machine, seemingly there will be no effect felt so far as the performance of the machine is concerned due to armature reaction. This in fact is almost true when the machine is lightly or moderately loaded

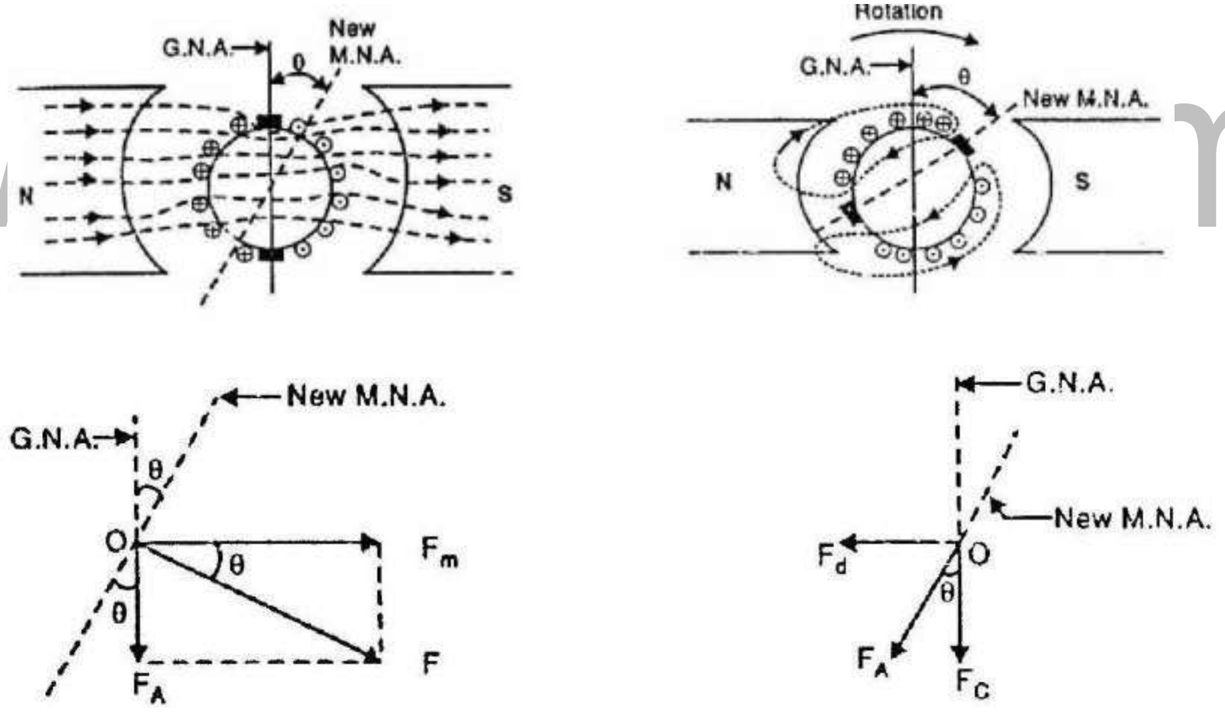


Figure 4.5.1 Armature Reaction

[Source: "“Electric Machinery Fundamentals” by Stephen J. Chapman, *Page: 311]*

However at rated armature current the increase of flux in one half of the pole is rather less than the decrease in the other half due to presence of *saturation*. In other words there will be a net decrease in flux per pole during sufficient loading of the machine. This will have a direct bearing on the emf as well as torque developed affecting the performance of the machine.

Apart from this, due to distortion in the flux distribution, there will be some amount of flux present along the q-axis (brush axis) of the machine. This causes commutation difficult. In the following sections we try to explain armature reaction in somewhat detail considering motor and generator mode separately.

4.8 Generator Characteristics

The three most important characteristics or curves of a D.C generator are:

Open Circuit Characteristic(O.C.C.)

This curve shows the relation between the generated emf. at no-load (E0) and the field current (If) at constant speed. It is also known as magnetic characteristic or no-load saturation curve. Its shape is practically the same for all generatorswhether separately or self-excited. The data for O.C.C. curve are obtained experimentally by operating the generator at no load and constant speed and recording the change in terminal voltage as the field current is varied.

Internal or Total characteristic (E/Ia)

This curve shows the relation between the generated emf. On load (E) and the armature current (Ia). The emf E is less than E0 due to the demagnetizing effect of armature reaction. Therefore, this curve will lie below the open circuit characteristic (O.C.C.)It cannot be obtained directly by experiment. It is because a voltmeter cannot read the emf. Generated on load due to the voltage drop in armature resistance. The internal characteristic can be obtained from external characteristic if winding resistances are known because armature reaction effect is included in both characteristics.

External Characteristic (V/IL)

This curve shows the relation between the terminal voltage (V) and load current (IL). The terminal voltage V will be less than E due to voltage drop in the armature circuit. Therefore, this curve will lie below the internal characteristic. This characteristic is very important in determining the suitability of a generator for a given purpose. It can be obtained by making simultaneous.

No-load Saturation Characteristic (E0/I*f*)

It is also known as magnetic characteristic or open circuit Characteristic (*O.C.C*).It shows the relation between the no-load generated emf in armature, E0 and the field or exciting current I*f* at a given fixed speed.

It is just demagnetization curve for the material of the electromagnets. Its shape is practically the same for all generators whether separately-excited or self-excited.

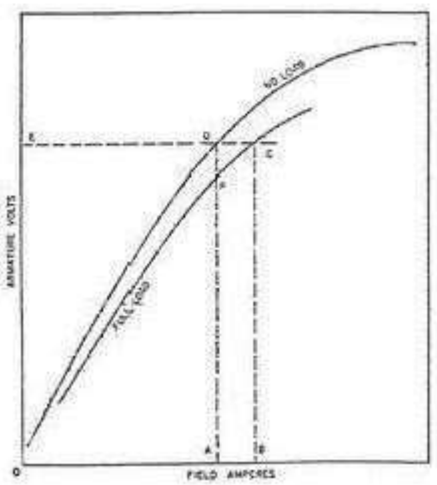


Figure 4.8.1 Field vs Armature

[Source: "'Electric Machinery Fundamentals" by Stephen J. Chapman, *Page: 352]*

A typical no load saturation curve is shown in Figure. It has generator output voltage plotted against field current. The lower straight line portion of the curve represents the air gap because the magnetic parts are not saturated. When the magnetic parts start to saturate, the curve bends over until complete saturation is reached. Then the curve becomes a straight line again.

Separately-Excited Generator

The No-load saturation curve of a separately excited generator will be as shown in the above Figure. It is obvious that when it is increased from its initial small value, the flux and hence generated emf .E.g. increase directly as current so long as the poles are unsaturated. This is represented by straight portion in Figure. But as the flux density increases, the poles become saturated, so a greater increase I*f* is required to produce a given increase in voltage than on the lower part of the curve. That is why the upper portion of the curve bends.

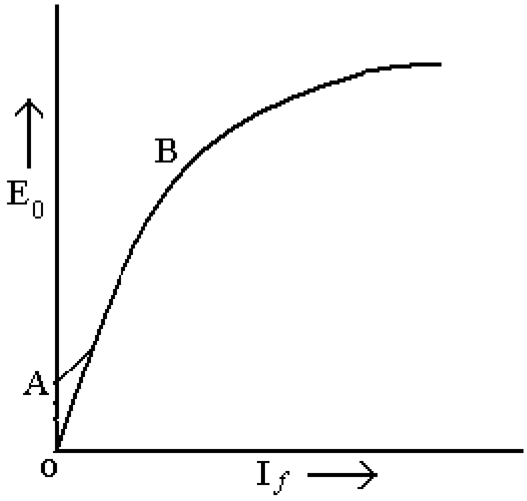


Figure 4.8.2 OCC Curve

[Source: "'Electric Machinery Fundamentals" by Stephen J. Chapman, *Page: 353]*

The O.C.C curve for self-excited generators whether shunt or series wound is shown in above Figure. Due to the residual magnetism in the poles, some emf (=OA) is generated even when I*f* =0.Hence, the curve starts a little way up. The slight curvature at the lower end is due to magnetic inertia. It is seen that the first part of the curve is practically straight. This is due to fact that at low flux densities reluctance of iron path being negligible ,total reluctance is given by the air gap reluctance which is constant. Hence, the flux and consequently, the generated emf is directly proportional to the exciting current .However, at high flux densities, where μ is small ,iron path reluctance becomes appreciable and straight relation between E and If no longer holds good. In other words, after point B, saturation of pole starts. However, the initial slope of the curve is determined by air-gap width. O.C.C for higher speed would lie above this curve and for lower speed, would lie below it. Separately-excited Generator Let we consider a separately-excited generator giving its rated no-load voltage of E0 for a certain constant field current. If there were no armature reaction and armature voltage drop,then this voltage would have remained constant as shown in Figure by the horizontal line 1.

But when the generator is loaded, the voltage falls due to these two causes, there by giving slightly dropping characteristics .If we subtract from E0 the values of voltage drops due to armature reaction for different loads**,** then we get the value of E-the emf actually induced in the armature under load conditions. Curve 2 is plotted in this way and is known as the internal characteristic

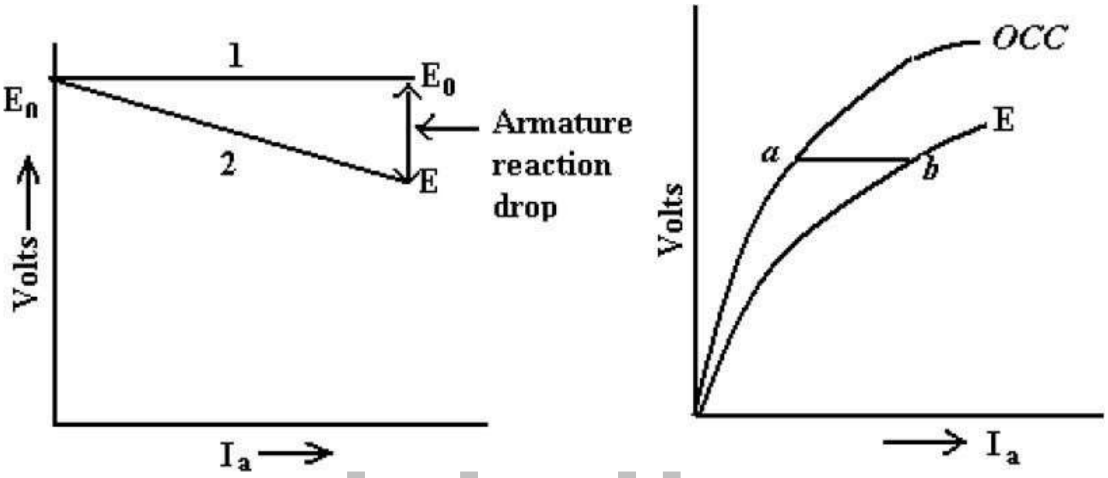


Figure 4.8.3 Current Vs Voltage

[Source: ““Electric Machinery Fundamentals” by Stephen J. Chapman*, Page: 355]*

In this generator, because field windings are in series with the armature, they carry full armature current Ia. As Ia is increased, flux and hence generated emf is also increased as shown by the curve. Curve *Oa*is the *O.C.C.* The extra exciting current necessary to neutralize the weakening effect of armature reaction at full load is given by the horizontal distance *ab*. Hence, point *b* is on the internal characteristic.

External Characteristic (V/I)

It is also referred to as performance characteristic or sometimes voltage-regulating curve. It gives relation between the terminal voltage V and the load current I. This curve lies below the internal characteristic because it takes in to account the voltage drop over the armature circuit resistance. The values of V are obtained by subtracting IaRa from corresponding values of E. This characteristic is of great importance in judging the suitability of a generator for a particular purpose.

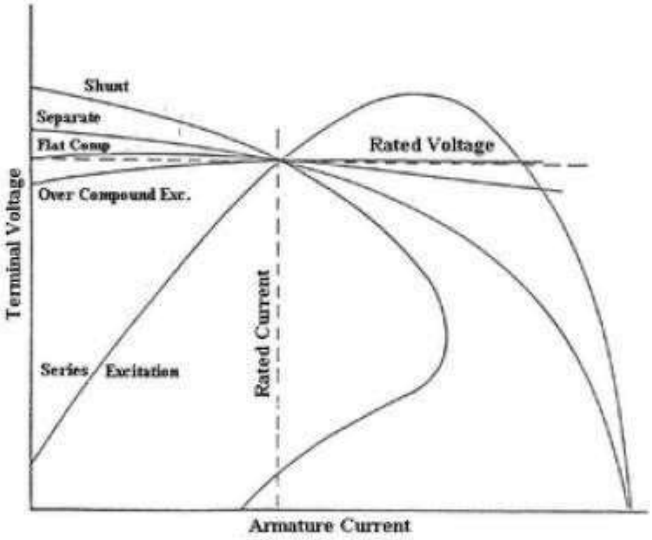


Figure 4.8.4 Armature Current Vs Terminal voltage

[Source: "'Electric Machinery Fundamentals" by Stephen J. Chapman, *Page: 356]*

It may be obtained in two ways Graphically from the *O.C.C* provided the armature and field resistances are known and also if the demagnetizing effect or the armature reaction is known

Figure above shows the external characteristic curves for generators with various types of excitation. If a generator, which is separately excited, is driven at constant speed and has a fixed field current, the output voltage will decrease with increased load current as shown. This decrease is due to the armature resistance and armature reaction effects. If the field flux remained constant, the generated voltage would tend to remain constant and the output voltage would be equal to the generated voltage minus the IR drop of the armature circuit. However, the demagnetizing component of armature reactions tends to decrease the flux, thus adding an additional factor, which decreases the output voltage.

4.7 COMMUTATION AND INTER POLES

In larger machines the commutation process would involve too much sparking, which causes brush wear, noxious gases (ozone) that promote corrosion, etc. In these cases it is common to use separate commutation inter poles. These are separate, usually narrow or seemingly vestigal pole pieces which carry armature current. They are arranged in such a way that the flux from the inter pole drives current in the commutated coil in the proper direction

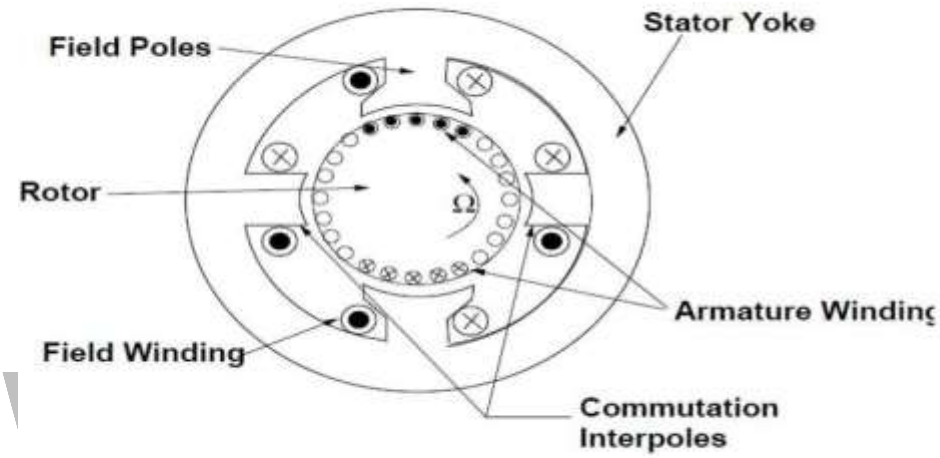


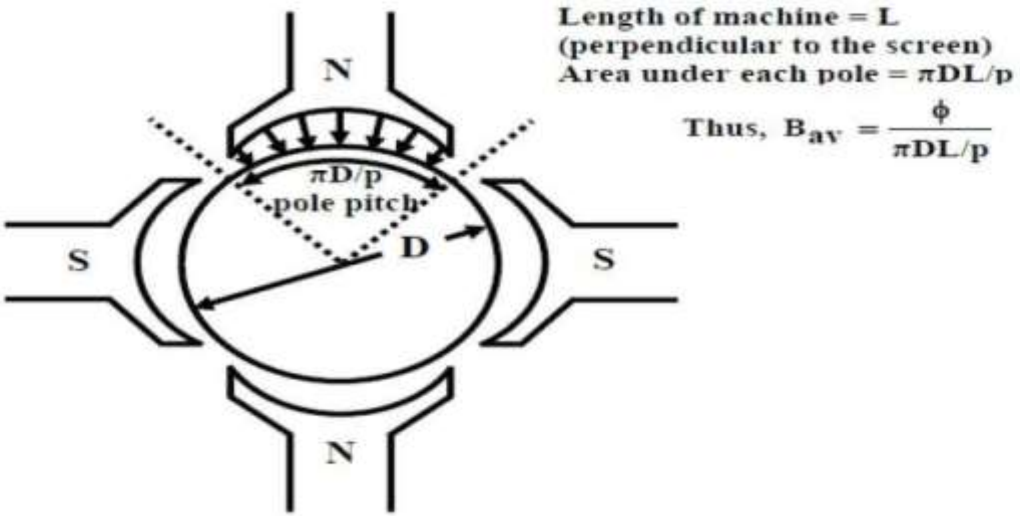
Figure 4.7.1 Inter poles

[Source: "'Electric Machinery Fundamentals" by Stephen J. Chapman, *Page: 341]*

Remember that the coil being commutated is located physically between the active poles and the inter pole is therefore in the right spot to influence commutation. The inter pole is wound with armature current (it is in series with the main brushes). It is easy to see that the inter pole must have a flux density proportional to the current to be commutated. Since the speed with which the coil must be commutated is proportional to rotational velocity and so is the voltage induced by the inter pole, if the right numbers of turns are put around the inter pole, commutation can be made to be quite accurate.

4.4 EMF EQUATION

Consider a D.C generator whose field coil is excited to produce a flux density distribution along the air gap and the armature is driven by a prime mover at constant speed as shown in figure



Length of machine = L
(perpendicular to the screen)
Area under each pole = πDL/p

Thus, $B_{av} = \frac{\phi}{\pi DL/p}$

Figure 4.4.1 Armature of Generator

[Source: "'Electric Machinery Fundamentals" by Stephen J. Chapman, *Page: 307]*

Let us assume a p polar d.c generator is driven (by a prime mover) at n rps. The excitation of the stator field is such that it produces a φ Wb flux per pole. Also let z be the total number of armature conductors and a be the number of parallel paths in the armature circuit. In general, as discussed in the earlier section the magnitude of the voltage from one conductor to another is likely to very since flux density distribution is trapezoidal in nature. Therefore, total average voltage across the brushes is calculated on the basis of average flux density Bav.

. Hence average flux density in the gap is given by

$$E_A = \frac{pz}{a}\phi n$$

4.2 LAP WINDING

This type of winding is used in dc generators designed for high-current applications. The windings are connected to provide several parallel paths for current in the armature. For this reason, lap-wound armatures used in dc generators require several pairs of poles and brushes.

In lap winding, the finishing end of one coil is connected to a commutator segment and to the starting end of the adjacent coil situated under the same pole an so on,till all the coils have been connected. This type of winding derives its name from the fact it doubles or laps back with its succeeding coils. Following points regarding simplex lap winding should be noted:

1. The back and front pitches are odd and of opposite sign. But they can't be equal. They differ by 2 or some multiple thereof.

2. Both YB and YF should be nearly equal to a pole pitch.

3. The average pitch YA = (YB + YF)/2.It equals pole pitch = Z/P.

4. Commutator pitch YC = ±1.

5. Resultant pitch YR is even, being the arithmetical difference of two odd numbers i.e YR = YB - YF.

6. The number of slots for a 2-layer winding is equal to the number of coils. The number of commutator segments is also the same.

7. The number of parallel paths in the armature = mP where 'm' is the multiplicity of the winding and 'P' the number of poles. Taking the first condition, we have YB = YF ± 2m where m=1 fo simplex lap and m =2 for duplex winding etc.

8. If YB > YF i.e YB = YF + 2, then we get a progressive or right-handed winding i.e a winding which progresses in the clockwise direction as seen from the comutator end. In this case YC = +1.

9. If YB < size="1">F i.e YB = YF - 2,then we get a retrogressive or left-handed winding i.e one which advances in the anti-clockwise direction when seen from the commutator side. In this case YC = -1.

10. Hence, it is obvious that for

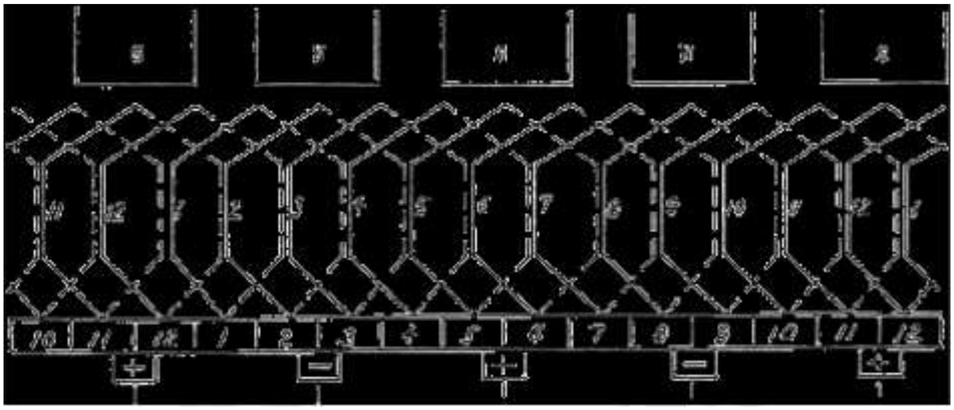


Figure 4.2.1 Lap Winding diagram

[Source: "'Electric Machinery Fundamentals" by Stephen J. Chapman, *Page: 281]*

Progressive winding   Retrogres sive winding

$Y_B = \frac{Z}{} + 1$ $Y_B = \frac{Z}{} \cdot 1$

$'_F \quad \frac{Z}{P} \quad 1$ $Y_F \quad \frac{Z}{P} + 1$

4.6 METHODS OF EXCITATION

Various methods of excitation of the field windings are Separately-excited generators

Self-excited generators: series generators, shunt generators, compound generators With self-excited generators, residual magnetism must be present in the machine iron to get the self-excitation process started.

The relation between the steady-state generated emf Ea and the armature terminal voltageVa is $Va=Ea-IaRa$

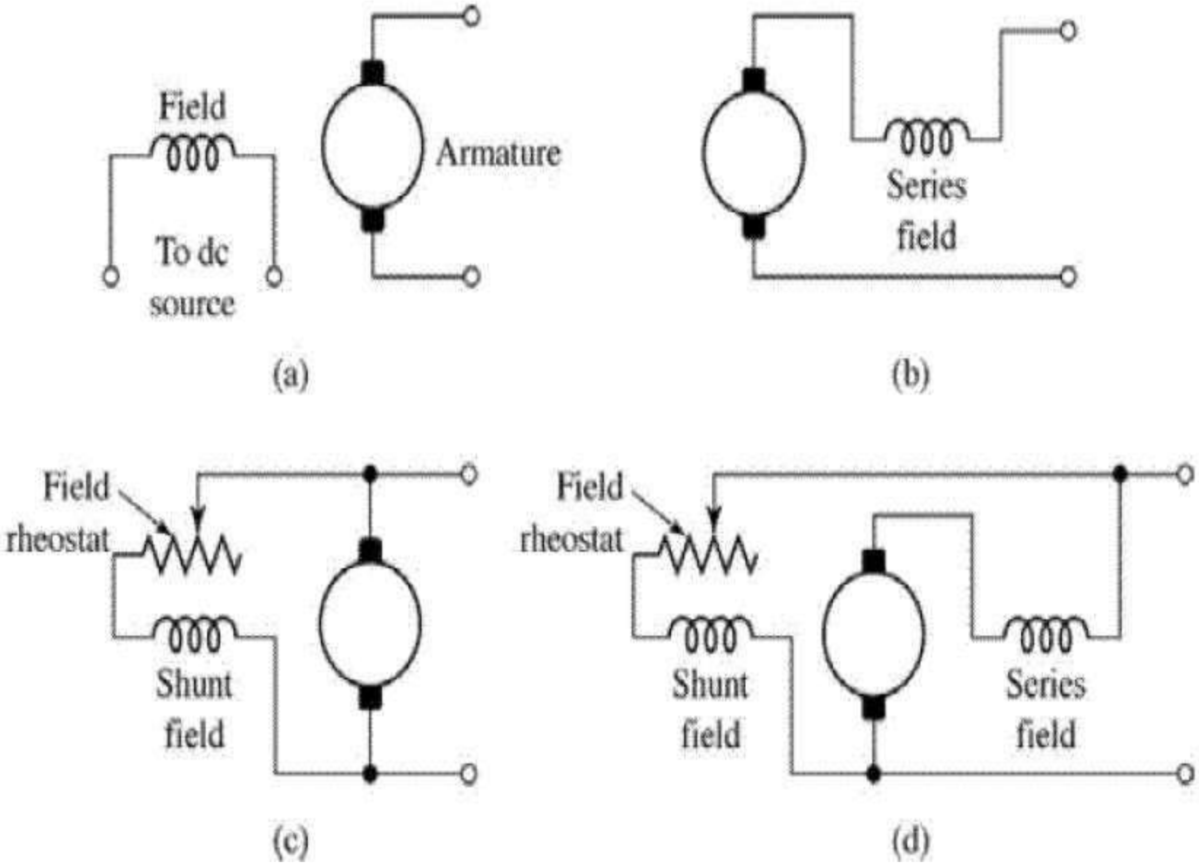


Figure 4.6.1 Method of Excitation

[Source: "'Electric Machinery Fundamentals" by Stephen J. Chapman, *Page: 332]*

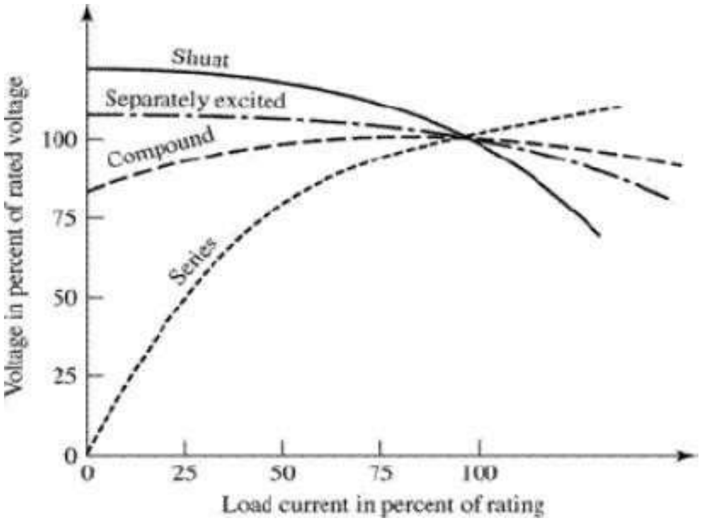


Figure 4.6.2 Load curve

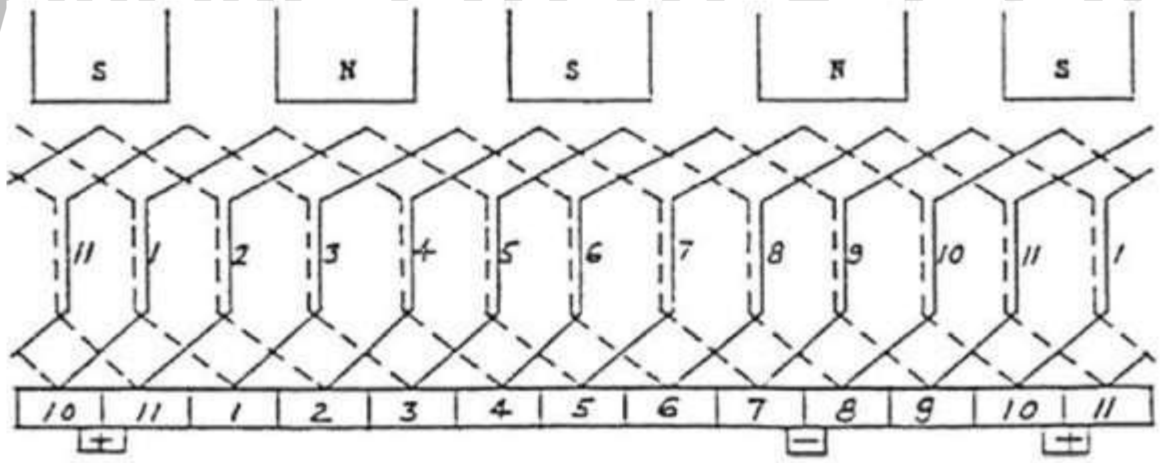
[Source: "'Electric Machinery Fundamentals" by Stephen J. Chapman, *Page: 333]*

Typical steady-state dc-motor speed-torque characteristics are shown in Figure.1.4, in which it is assumed that the motor terminals are supplied from a constant-voltage source.

In a motor the relation between the emf Ea generated in the armature and the armature terminal voltage Va is Va=Ea+IaRa. The application of dc machines lie in the variety of performance characteristics offered by the possibilities of shunt, series, and compound excitation.

4.3 WAVE WINDING

This type of winding is used in dc generators employed in high-voltage applications. Notice that the two ends of each coil are connected to commutator segments separated by the distance between poles. This configuration allows the series addition of the voltages in all the windings between brushes. This type of winding only requires one pair of brushes. In practice, a practical generator may have several pairs to improve commutation. When the end connections of the coils are spread apart as shown in Figure a wave or series winding is formed. In a wave winding there are only two paths regardless of the number of poles. Therefore, this type winding requires only two brushes but can use as many brushes as poles. Because the winding progresses in one direction round the armature in a series of 'waves' it is know as wave winding. If, after passing once round the armature, the winding falls in a slot to the left of its starting point then winding is said to be retrogressive. If, however, it falls one slot to the right, then it is progressive



Figire 4.3.1 Wave winding diagram

[Source: "'Electric Machinery Fundamentals" by Stephen J. Chapman, *Page: 282]*

1. YF are odd and of the same sign.
2. Back and front pitches are nearly equal to the pole pitch and may be equal or differ by 2, in which case, they are respectively one more or one less than the average pitch.
3. Resultant pitch YR = YF + YB.

4. Commutator pitch, YC = YA (in lap winding YC = ±1). Also YC = (No.of commutator bars ± 1) / No.of pair of poles.

5. The average pitch which must be an integer is given by YA = (Z ± 2)/P = (No.of commutator bars ± 1)/No.of pair of poles.

6. The number of coils i.e NC can be found from the relation NC = (PYA ± 2)/2.

7. It is obvious from 5 that for a wave winding, the number of armature conductors with 2 either added or subtracted must be a multiple of the number of poles of the generator. This restriction eliminates many even numbers which are unsuitable for this winding.

8. The number of armature parallel paths = 2m where 'm' is the multiplicity of the winding.

4.1 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.

Construction:

A D.C. machine consists mainly of two part the stationary part called stator and the rotating part called rotor. The stator consists of main poles used to produce magnetic flux ,commutating poles or inter poles in between the main poles to avoid sparking at the Commutator but in the case of small machines sometimes the interpoles are avoided and finally the frame or yoke which forms the supporting structure of the machine. The rotor consist of an armature a cylindrical metallic body or core with slots in it to place armature windings or bars, a Commutator and brush gears The magnetic flux path in a motor or generator is show below and it is called the magnetic structure of generator or motor.

The major parts can be identified as,

1. Frame
2. Yoke
3. Poles Institute of Technology Madras
4. Armature
5. Commutator and brush gear
6. Commutating poles
7. Compensating winding
8. Other mechanical parts

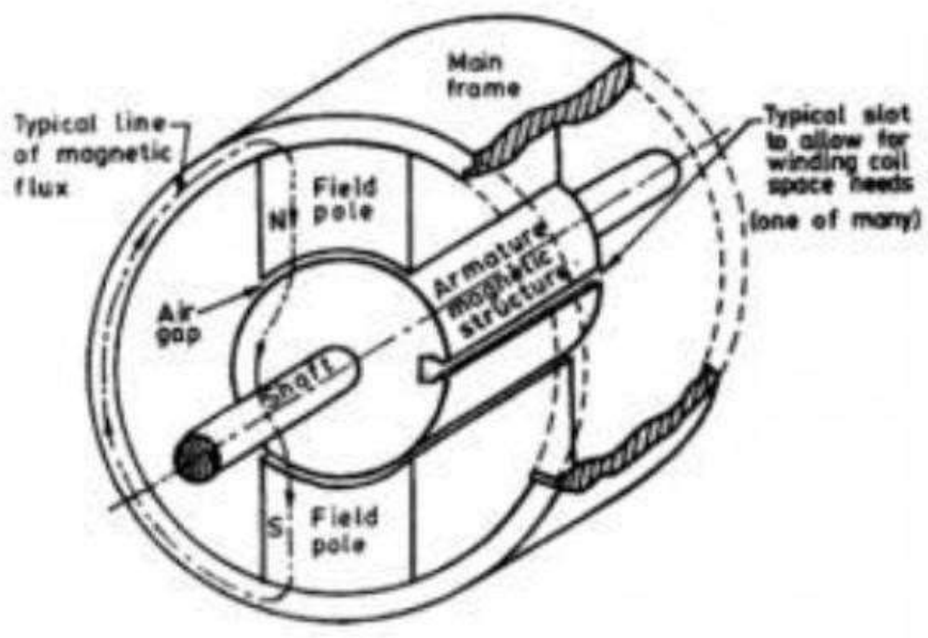


Figure 4.1.1 DC Machines

[Source: "'Electric Machinery Fundamentals" by Stephen J. Chapman, *Page: 273]*

Frame

Frame is the stationary part of a machine on which the main poles and Commutator poles are bolted and it forms the supporting structure by connecting the frame to the bed plate. The ring shaped body portion of the frame which makes the magnetic path for the magnetic fluxes from the main poles and inter poles is called frames.

Yoke.

Yoke was made up of cast iron but now it is replaced by cast steel. This is because cast iron is saturated by a flux density of 0.8 Web/sq.m where as saturation with cast iron steel is about 1.5 Web/sq.m. So for the same magnetic flux density the cross section area needed for cast steel is less than cast iron hence the weight of the machine too. If we use cast iron there may be chances of blow holes in it while casting.so now rolled steels are developed and these have consistent magnetic and mechanical properties.

End Shields or Bearings

If the armature diameter does not exceed 35 to 45 cm then in addition to poles end shields or frame head with bearing are attached to the frame.If the armature diameter is greater than 1m pedestal type bearings are mounted on the machine bed plate outside the frame. These bearings could be ball or roller type but generally plain pedestal bearings are employed. If the diameter of the armature is large a brush holder yoke is generally fixed to the frame

Main poles

Solid poles of fabricated steel with separate/integral pole shoes are fastened to the frame by means of bolts. Pole shoes are generally laminated. Sometimes pole body and pole shoe are formed from the same laminations. The pole shoes are shaped so as to have a slightly increased air gap at the tips. Inter-poles 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 com poles. The width of the tip of the com pole can be about a rotor slot pitch.

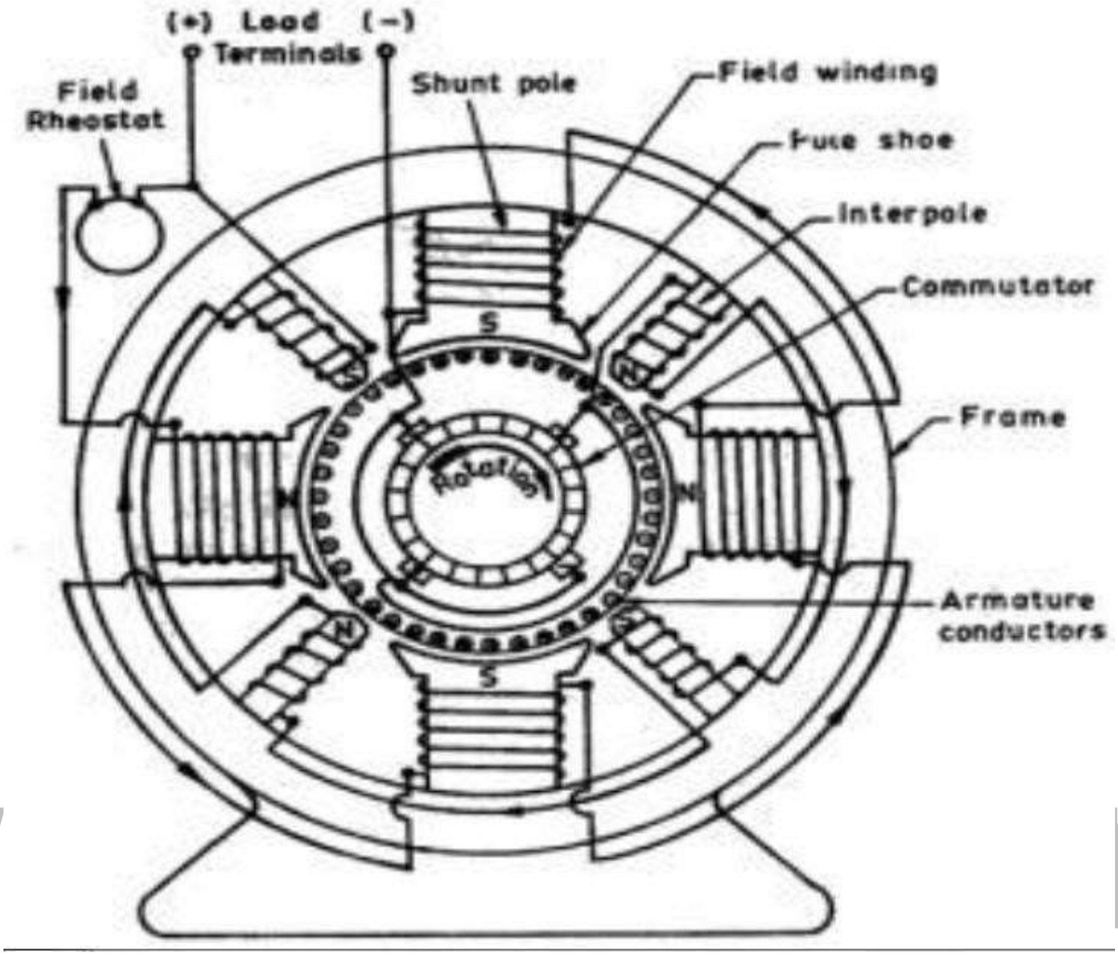


Figure 4.1.2 Parts of DC machines

[Source: "'Electric Machinery Fundamentals" by Stephen J. Chapman, *Page: 275]*

Armature

The armature is where the moving conductors are located. The armature is constructed by stacking laminated sheets of silicon steel. Thickness of this 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 of Technology Madras 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.

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 have 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. 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 Brush holder with a Brush and Positioning of the brush on the Commutator from the brush is taken out by means of flexible pigtail. The brushes are kept pressed on the Commutator with the help of springs. This is to ensure proper contact between the brushes and the Commutator even under high speeds of operation. Jumping of brushes must be avoided to ensure arc free current collection and to keep the brush contact drop low.

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.