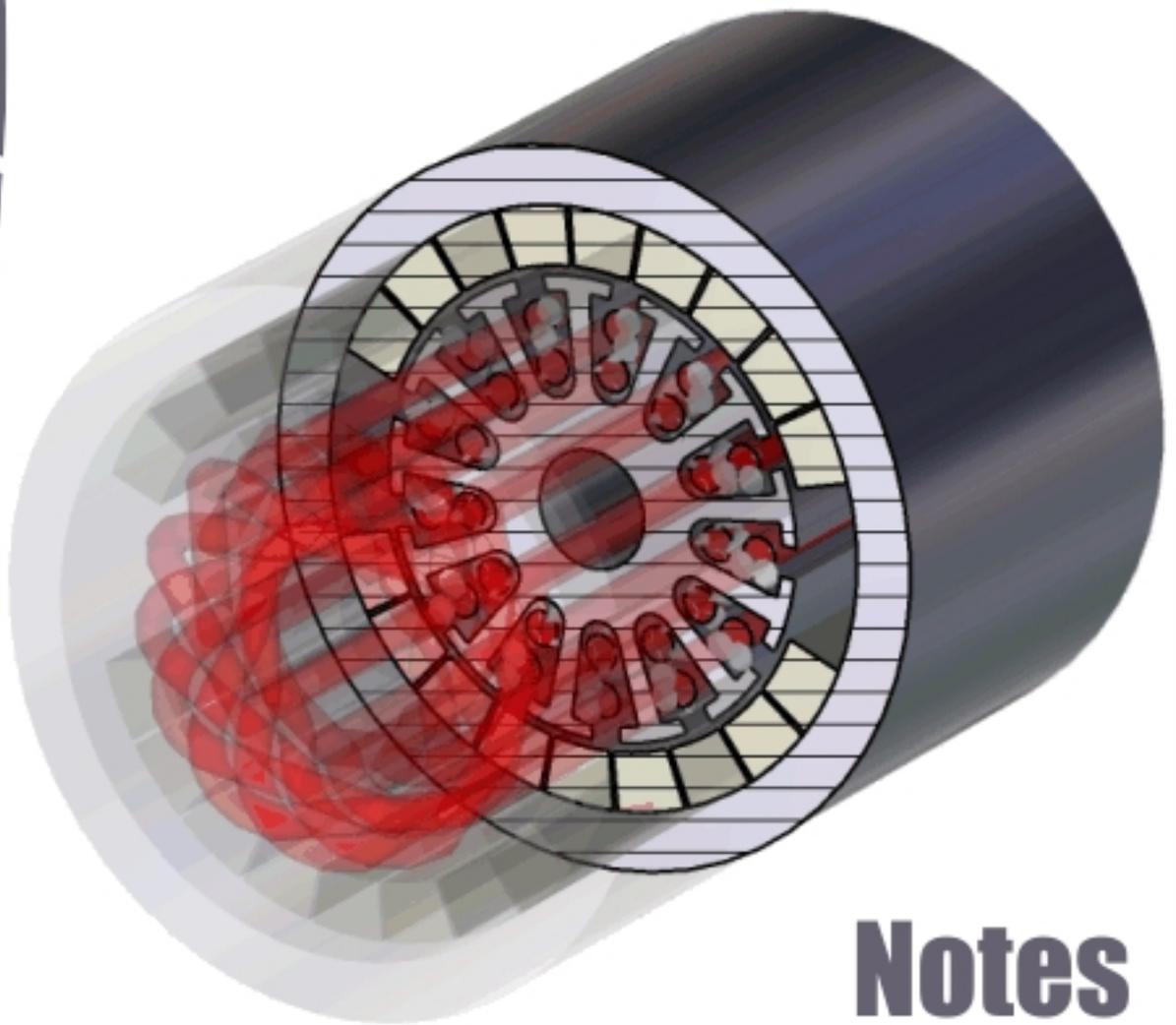# DC Machines and Synchronous Machines

**Notes**

# UNIT 1

## CLASSIFICATION OF DC MACHINES

**METHODS OF EXCITATION**: depending on the type of excitation of field winding, there are two basic types of DC machine.

1. Separately excited machine: In this type of machines the field flux is produced by connecting the field winding to an external source.
2. Self excited machine: The field flux is produced by connecting the field winding with the armature in this type. A self excited machine requires residual magnetism for operation.

Depending on the type of field winding connection DC machines can be further classified as:

1. Shunt machine: The field winding consisting of large number of turns of thin wire is usually excited in parallel with armature circuit and hence the nameshunt field winding. This winding will be having more resistance and hence carries less current.
2. Series machine: The field winding has a few turns of thick wire and is connected in series with armature.
3. Compound machine: Compound wound machine comprises of both series and shunt windings and can be either short shunt or long shunt, cumulative, differential or flat compounded.
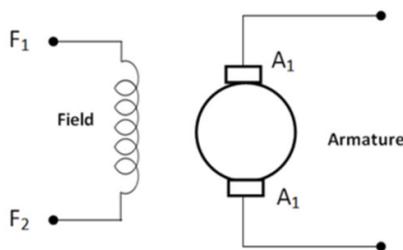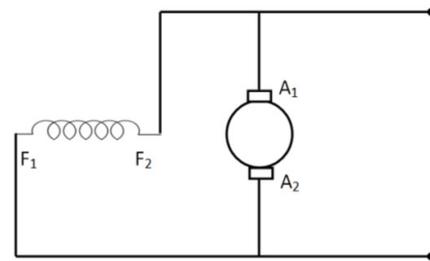


Figure 1.1 Separately Excited Machine
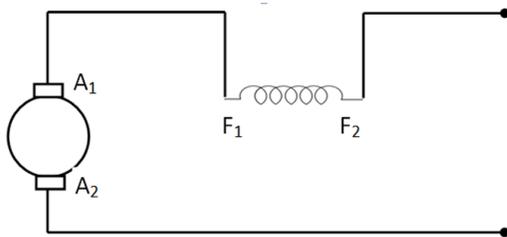


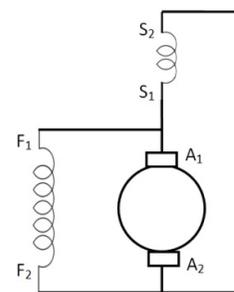Figure 1.2 Self Excited Machine



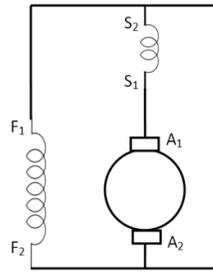Figure 1.3 Series Wound Machine



Figure 1.4 Short Shunt Compound Machine

Figure 1.5 Long Shunt Compound Machine

In separate excited DC machine, the field winding is connected to a separate DC source. This type of machine is most flexible as full and independent control of both armature and field circuit is possible. Figure 1.1 shows separately excited DC generator. Permanent magnet machines also fall in this category.

A self excited DC generator could be excited by its armature voltage as shown in figure 1.2 (i.e., shunt excitation) or by its armature current as shown in figure 1.3 (series excitation). Compound wound generator comprises of both series and shunt windings and can be either short shunt (figure 1.4) or long shunt (figure 1.5), cumulative or differential or flat compounded.

# ARMATURE WINDINGS

Armature winding is an arrangement of conductors distributed in slots provided on the periphery of the armature. Depending on the way in which the coils are interconnected at the commutator end of the armature, the windings can be classified as lap and wave windings. Further they can be classified as simplex and multiplex. The important terms used in armature windings are given below:
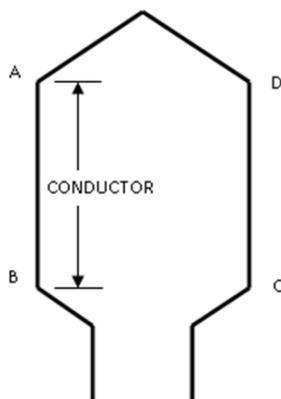


Representation of a Single Turn coil

Figure 1.6

**COIL PITCH/COIL SPAN**: represents the span of the coil. It can be represented in terms of electrical degrees, slots or conductor. For full pitched winding, the span is $180^0$ electrical or number of slots per pole. A full pitched coil leads to maximum voltage per coil.

**BACK PITCH/COIL SPAN($Y_b$)**: is the distance measured in between the two coil sides of the same coil at the back end of the armature, the commutator end being the front end of armature. It can be represented in terms of number of slots or coil sides. Back pitch also represents the span of coil.

**FRONT PITCH$(Y_f)$:** is the distance between the two coil sides of two different coils connected in series at the front end of the armature.
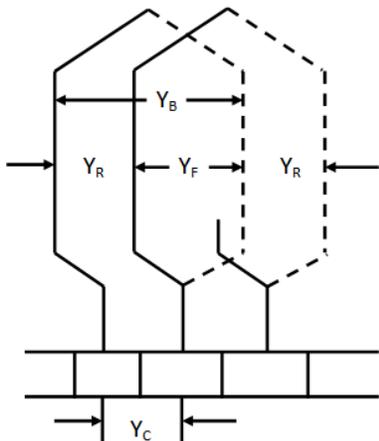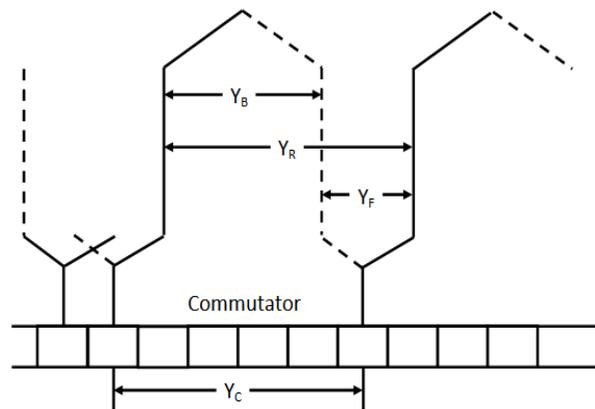


|     Figure 1.7     |     Figure 1.8     |

**COMMUTATOR PITCH ($Y_C$):** is measured in terms of commutator segments between the two coil ends of a coil.

**SINGLE LAYER WINDING:** In this winding one coil is placed in each slot.

**DOUBLE LAYER WINDING:** In this winding two or multiples of coil sides are arranged in two layers in each slot.

Front pitch, back pitch and commutator pitch are shown in figures 1.7 and 1.8 for lap and wave windings respectively.

**SALIENT FEATURES OF LAP AND WAVE WINDING**

1. Armature winding is a closed winding. Depending on the type of winding, the closed path gets divided into number of parallel paths and is available between the positive and negative brushes.
2. Wave winding is used for high voltage low current machines.
3. Equalizing rings are not required in wave winding where as there are used in lap winding.
4. Lap winding is suitable for low voltage high current machines because of more number of parallel paths.

In case of lap winding, the number of parallel path (A) = number of poles (P)

In case of wave winding, the number of parallel path (A) = 2 irrespective of number of poles.

Each path will have $\frac{Z}{A}$ conductors connected in series.

**EQUATION FOR INDUCED EMF:**

Let $\Phi$= flux per pole in weber

$Z$ = number of armature conductors = Number of slots X conductors per slot.

$P$ = Number of poles; $A$= Number of parallel paths in armature.

$A$= P for lap wound armature; $A$=2 for wave wound armature

$N$ = speed of armature in rpm; $E$ = induced emf in each parallel path.

Average emf generated/conductor in one revolution $= \dfrac{d\Phi}{dt}$

Flux cut by a conductor in one revolution $=d\Phi = P\Phi$ weber.

Since Number of revolutions/second $= \dfrac{N}{60}$ ; Time taken for one revolution $= dt = \dfrac{60}{N}$ seconds.

EMF generated/conductor $= \dfrac{d\Phi}{dt} = \dfrac{\Phi P}{\frac{60}{N}} = \dfrac{\Phi PN}{60}$ volts.

Since each path has $\dfrac{Z}{A}$ conductors in series,

EMF generated in each path is E $= \dfrac{\Phi PN}{60} \ X \ \dfrac{z}{A}$ volts $= \dfrac{\Phi ZPN}{60A}$ volts…………… 1

Also,   for a shunt generator, from figure 1.2, E=$V + I_a r_a + BCD$……………2

For a series generator, from figure 1.3, E=$V + I_a(r_a + r_{se}) + BCD$……3

For a short shunt compound generator, from figure 1.4, E= $V + I_a r_a + I_{se} r_{se} + BCD$…..4

For a long shunt compound generator, from figure 1.5, E= $V + I_a r_a + I_a r_{se} + BCD$……5

Where V=Terminal voltage

$I_a$=Armature current;   $r_a$=Armature resistance

$r_{se}$=Series field resistance; BCD=brush contact drop

**PROBLEMS**

1. The armature of a 4 pole wave wound DC shunt generator has 144 slots and 3 conductors per slot. If armature is rotated with a speed of 1200 rpm in a field of 0.025 wb/pole, calculate the EMF generated.

    **SOLUTION**: Z = 144 X 3 = 432; $E = \frac{\Phi ZNP}{60A} = 432 \ volts$.

2. An 8 pole DC generator has 960 conductors and a flux/pole of 20 m wb. Calculate the EMF generated when running at 500 rpm for (i) A lap connected armature winding and (ii) A wave connected armature winding.

    **SOLUTION:** (i) Lap winding $E = \frac{\Phi ZNP}{60 \ A} = 160 \ V$

    (ii) Wave winding $E = \frac{\Phi ZNP}{120} = 640 \ V$

3. An 8 pole DC shunt generator with 778 conductors wave connected and running at 500 rpm supplies a load of 12.5 Ω resistance at terminal voltage of 250 V, the armature resistance is 0.24Ω and the field resistance is 250 Ω. Find the armature current, induced emf and Φ/pole.

    **SOLUTION:**$I_L = \frac{V}{R} = \frac{250}{12.5} = 20 \ A$ $\qquad\qquad E = 250 + (21 \ X \ 0.24) = 255.04 \ V$

    $I_{sh} = \frac{250}{250} = 1 \ A$ $\qquad\qquad\qquad\qquad E = \frac{\Phi ZNP}{60A}$ $\quad$ Φ = 9.83 m wb.

    $I_a = 20 + 1 = 21 \ A$

4. A 4 pole long shunt lap wound generator supplies 25 kW at a terminal voltage of 500 V. The armature resistance is 0.03 Ω. Series field resistance is 0.04Ω and shunt field resistance is 200 Ω. The brush drop may be taken as 1.0 V. Determine the emf generated. Calculate also the number of conductors if the speed is 1200 rpm and Φ/pole is 0.02 wb. Neglect armature reaction.

    **SOLUTION:**$I = \frac{25X1000}{500} = 50A; \quad I_{sh} = \frac{500}{200} = 2.5 \ A$

    $I_a = I + I_{sh} = 50 + 2.5 = 52.5 \ A$

    Series field drop = 52.5 x 0.04 = 2.1 V

    Armature drop$I_a r_a = 52.5 \ X \ 0.3 = 1.575 \ V$

    Brush drop = 2 x 1 = 2V

    $E = 500 + 1.575 + 2.1 + 2 = 505.67 \ V$

    $E = \frac{\Phi ZNP}{60A}; \ Z = 1264$

## CHARACTERISTICS OF D.C GENERATORS

**The three important characteristics of DC generator are**

**1.  Open circuit characteristic or Magnetization curve or No – load saturation Curve**

Open circuit characteristic is the relation between the No-load generated emf in the armature, and the field exciting current at a fixed speed. It is the magnetization curve for the material of electro-magnets. It is same for separately excited or self excited machine.

**2.  Internal or total characteristic**

This characteristic curve gives the relation between the emf generated in the armature and the armature current.

**3.  External characteristic**

This gives the relation between the terminal voltage and the load current. This characteristic takes into account the voltage drop due to armature circuit resistance and the effect of armature reaction. This characteristic is of importance in judging the suitability of generator for a particular purpose. This characteristic is also referred to as performance characteristics or voltage regulating curve.

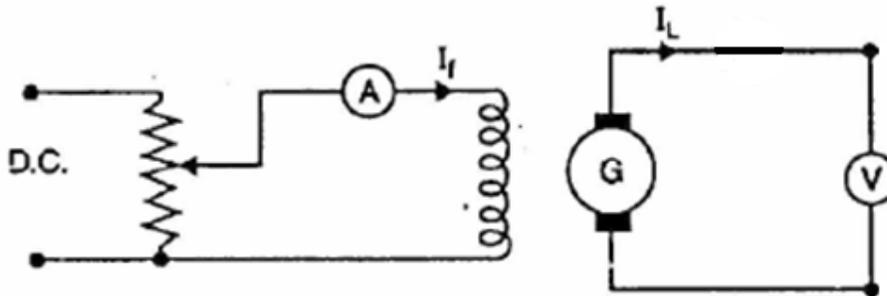1.  open circuit characteristics $\left(\dfrac{E}{I_f}\right)$



**Figure 1.9**

The circuit diagram for obtaining the OCC is shown in figure 1.9. Irrespective of the type of the DC machine, namely, shunt, series, compound, the shunt field winding is disconnected and excited from an external source.

Induced emf $E = \dfrac{\Phi ZNP}{60\,A}$

If the speed is constant, then $E = K\,\Phi$        where K is a constant.

As iron is unsaturated under low excitation current condition, emf increases as flux increases with increase in excitation current. As the field current increases further the iron starts saturating, the emf will not increase proportionately as the flux is not varying proportionately with the current. This is shown by the knee 'pq' of the characteristic curve shown in figure 1.10. A further increase in field current leads to saturation of iron and the flux remains almost constant and hence the induced emf will also remain constant. This is shown by the region 'qr' in the figure1.10.
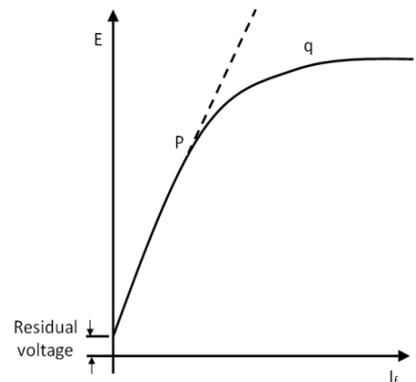
Figure 1.10

## CRITICAL RESISTANCE FOR SHUNT GENERATOR

When the armature is rotating with armature open circuited, an emf is induced in the armature because of the residual flux. When the field winding is connected with the armature, a current flows through the field winding ( in case of shunt field winding, field current flows even on No-load and in case of series field winding only with load) and produces additional flux. This additional flux along with the residual flux generates higher voltage. This higher voltage circulates more current to generate further higher voltage. This is a cumulative process till the saturation is attained. The voltage to which it builds is decided by the resistance of the field winding as shown in the figure 1.11. If field circuit resistance is increased such that the resistance line does not cut OCC like 'om' in the figure 1.11, then the machine will fail to build up voltage to the rated value. The slope of the air gap line drawn as a tangent to the initial linear portion of the curve represents the maximum

Figure 1.11

resistance that the field circuit can have beyond which the machine fails to build up voltage. This value of field circuit resistance is called critical field resistance. The field circuit is generally designed to have a resistance value less than this so that the machine builds up the voltage to the rated value.
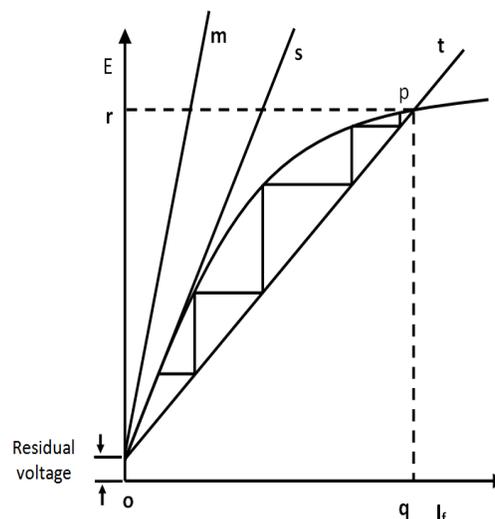
**CONDITIONS FOR VOLTAGE BUILD UP OF A GENERATOR**

Following are the conditions necessary for the voltage build up of a self excited generator.

(i)      Residual magnetism must be present.

(ii)      For the given direction of rotation, the field coils must be properly connected to the armature so that the flux produced by the field current reinforces the residual flux.

(iii)    Its field resistance must be less than the critical field resistance.

**CRITICAL SPEED**

Critical speed of a generator is that speed for which the field circuit resistance becomes the critical field resistance.

From the figure 1.12 $\dfrac{BC}{AC} = \dfrac{N_C}{N}$

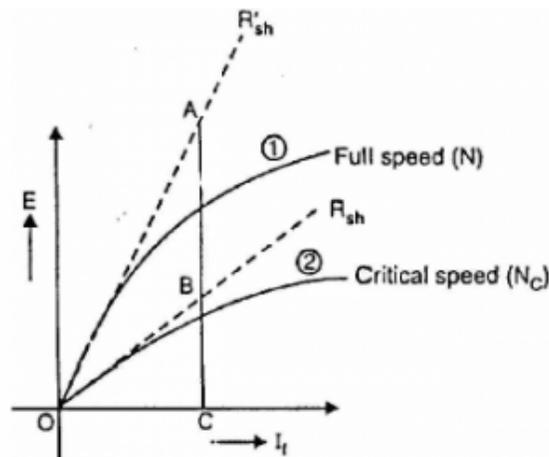Critical speed $N_c = \dfrac{BC}{AC} \times N$     where N is the full speed



Figure 1.12

Relation between induced emf and terminal voltage will provide an insight into the performance of the machine. The terminal voltage of the machine under loaded condition reduces from the no-load induced emf value because of the armature circuit voltage drop and armature reaction. Further the contact drop of the brushes will have to be taken into account. Usually a brush contact drop of 1volt is considered for a brush. This will be constant throughout the operating range of the machine.

# ARMATURE REACTION

The action of magnetic field set up by armature current on the distribution of flux under main poles of a DC machine is called the armature reaction.

When the armature of a DC machines carries current, the distributed armature winding produces its own mmf. The machine air gap is now acted upon by the resultant mmf distribution caused by the interaction of field ampere turns ($AT_f$) and armature ampere turns ($AT_a$). As a result the air gap flux density gets distorted.
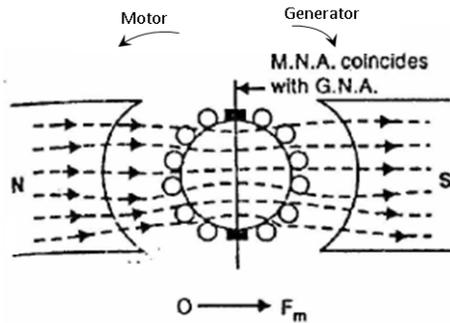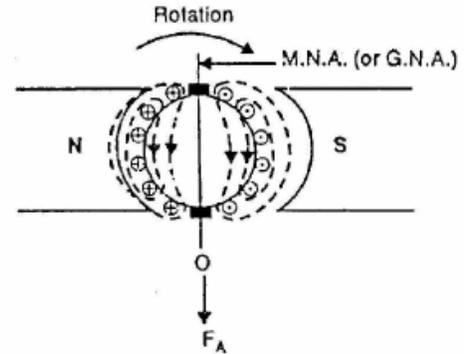


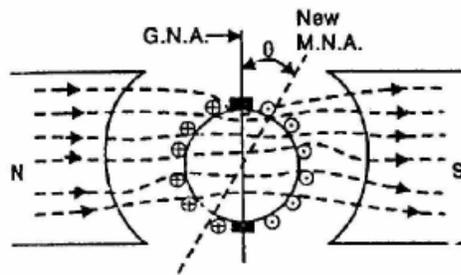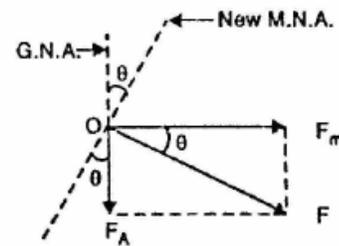**Figure 1.13**



**Figure 1.14**



**Figure 1.15**



**Figure 1.16**

Figure 1.13 shows a two pole machine with single equivalent conductor in each slot and the main field mmf ($F_m$) acting alone. The axis of the main poles is called the direct axis (d-axis) and the interpolar axis is called quadrature axis (q-axis). It can be seen from the Figure 1.14 that $AT_a$ is along the interpolar axis as shown. $AT_a$ which is at $90^0$ to the main field axis is known as cross magnetizing mmf. Figure 1.14 shows the armature mmf ($F_A$) acting alone.

Figure 1.15 shows the practical condition in which a DC machine operates. Both the main flux i.e., $AT_f$(Field mmf) and $AT_a$ (armature mmf) are existing. Because of both mmf acting simultaneously,

there is a shift in brush axis and crowding of flux lines at the trailing pole tip and flux lines are weakened or thinned at the leading pole tip. (The pole tip which is first met in the direction of rotation by the armature conductor is leading pole tip and the other is trailing pole tip)

If the iron in the magnetic circuit is assumed unsaturated, the net flux/pole remains unaffected by the armature reaction though the air gap flux density distribution gets distorted. If the main pole excitation is such that the iron is in the saturated region of magnetization (practical case) the increase in flux density at one end of the poles caused by armature reaction is less than the decrease at the other end, so that there is a net reduction in the flux/pole. This is called the demagnetizing effect. Thus it can be summarized that the nature of armature reaction in a DC machine is

(i)     Cross magnetizing with its axis along the q-axis.

(ii)    It causes no change in flux/pole if the iron is unsaturated but causes reduction in flux/pole in the presence of iron saturation. This is termed as demagnetizing effect.

The resultant mmf 'F' is shown in figure 1.16

Graphical picture of flux density distribution is shown in figure 1.17

(a) Layout of armature and field of 2-poles of a DC machine.
(b) Armature mmf and flux density distribution (brushes in geometrical neutral axis)
(c) Main field and resultant flux density distribution – shift (θ) in Magnetic neutral axis.

The cross magnetizing effect of the armature reaction can be reduced by making the main field ampere-turns larger compared to the armature ampere-turns such that the main field mmf exerts predominantcontrol over the air gap. This is achieved by

(i)     Introducing saturation in the teeth and pole shoe.

(ii)    By chamfering the pole shoes which increases the air gap at the pole tips. This increases the reluctance to the path of main flux but its influence on the cross-flux is much greater.

(iii)   The best and most expensive method is to compensate the armature reaction mmf by a compensating winding located in the pole-shoes and carrying a suitable current.
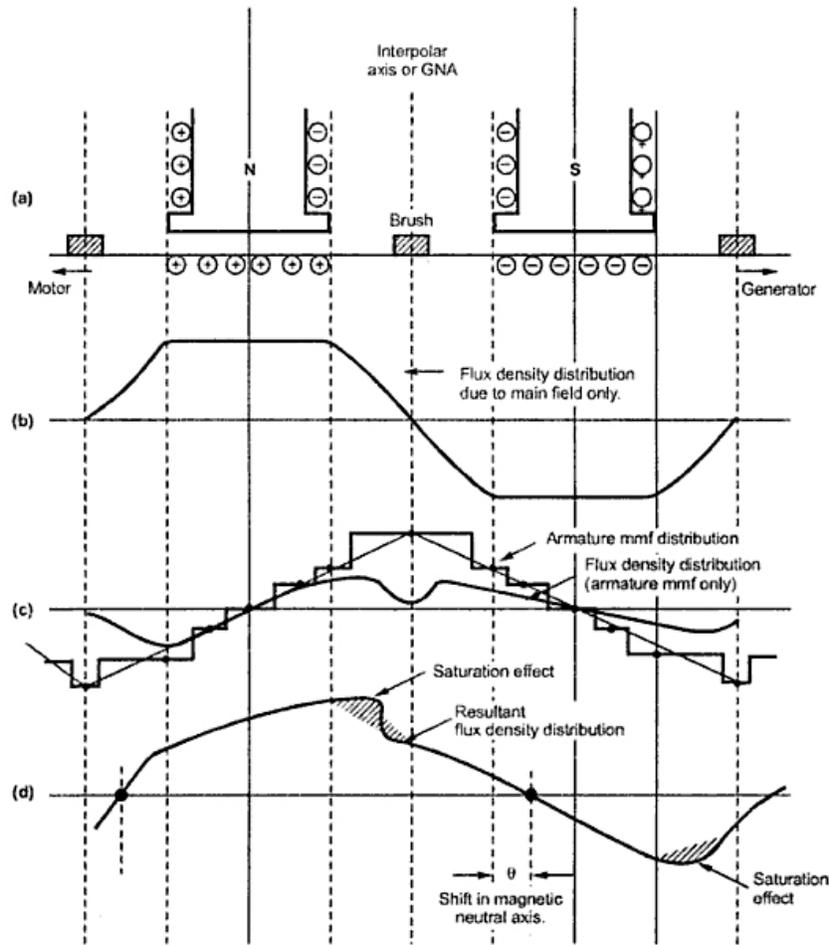
Figure 1.17

**COMPENSATING WINDINGS:** the armature reaction causes the flux density wave to be so badly distorted that when a coil is passing through the region of peak flux densities, the emf induced in it exceeds the average coil voltage. If this emf is higher than the breakdown voltage across adjacent segments, a spark over could result which can easily spread over the whole commutator, resulting in the complete short circuit of the armature. Another factor which can cause severe over voltages to appear between commutator segments is the time variation of armature reaction and its associated flux due to sudden changes in machine load. If the load on the machine undergoes fast changes, the armature current $I_a$ and armature flux/pole $\Phi_a$ changes accordingly resulting in statically induced emf in the coil proportional to $d\Phi_a/dt$. This voltage along with dynamically induced emf worsens the conditions if both are additive. i.e., if the load is dropped from a generator or added to a motor.

The remedy for the above situation is to neutralize the armature reaction ampere-turns by compensating winding placed in the slots cut out in pole face such that the axis of the winding coincides with the brush axis as shown in figure 1.18 and 1.19.
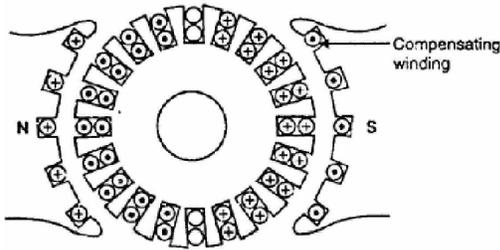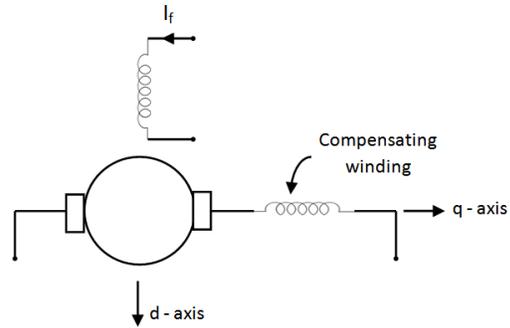


Figure 1.18                                    Figure 1.19

The compensating windings neutralize the armature mmf directly under the pole which is the major portion because in the interpole region the air gap will be large. The remaining small portion of armature mmf in the interpole region is neutralized by the interpole windings. The number of ampere-turns required in the compensating windings is given by

$$AT_{cw}/Pole = AT_a(peak)X\left(\frac{polearc}{polepitch}\right)$$

$$= \frac{IZ}{2AP} X \left(\frac{Polearc}{PolePitch}\right)\ldots\ldots\ldots.6$$

Compensating windings though expensive, must be provided in machines where heavy overloads are expected or the load fluctuates rapidly.Ex. Motors driving steel mills.

**DEMAGNETISING AMPERE TURN/POLE:**

The exact conductors which produce demagnetizing effect are shown in Fig 1.20,Where the brush axis is given a forward lead of θ so as to lie along the new axis of M.N.A. The flux produced by the current carrying conductors lying in between the angles AOC and BOD is such that, it opposes the main flux and hence they are called as demagnetizing armature conductors.
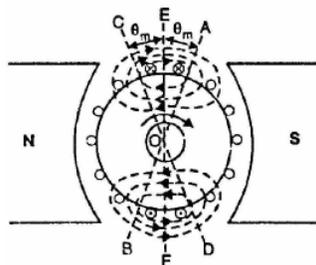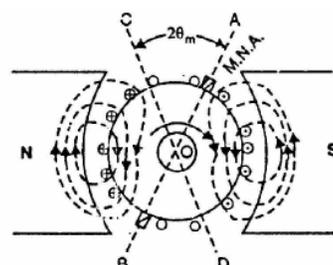


**Figure 1.20**                                    **Figure 1.21**

Z= total no of armature conductors

I = current in each armature conductors

$= \frac{I_a}{2}$ for wave winding

$= \frac{I_a}{P}$ for lap winding

$\Phi_m$= forward lead in mechanical or angular deg.

Total no of armature conductors in between angles AOC & BOD $= \frac{4\theta_m}{360} XZ$

2Z=1turn, total no of turns in these angles $= \frac{2\theta_m}{360} XZ$

Demagnetizing amp turns/pair of poles $= \frac{2\theta_m}{360} XZXI$

Therefore AT$_d$/pole$= \frac{\theta_m}{360} XZI$……..7

## CROSS MAGNETIZING AT/POLE

In the figure 1.21 Conductors lying in between the angles BOC and DOA are carrying the current in such a way that the direction of the flux is downwards i.e., at right angles to the main flux. This results is the distortion in the main flux. Hence, these conductors are called cross magnetizing or distorting ampere conductors.

Total armature conductors/pole$= \frac{Z}{P}$

Demagnetizing conductors / pole $= Z \frac{2\theta_m}{360}$

Therefore cross magnetizing conductors/pole$= \frac{Z}{P} - Z \frac{2\theta_m}{360}$

Cross magnetizing ampere conductors/pole$= Z \left( \frac{1}{P} - \frac{2\theta_m}{360} \right)$

Cross magnetizing ampere turns/pole = AT$_c$/pole$= ZI \left( \frac{1}{2P} - \frac{\theta_m}{360} \right)$………8

For neutralizing the demagnetizing effect number of extra turns required:

Number of extra turns/pole$= \frac{AT_d}{I_{sh}}$ for shunt generator …….9

$\qquad\qquad = \frac{AT_d}{I_a}$ for series generator ………10

$Note: \theta_{mechanical} = \frac{2\theta_{electrical}}{P}$

When a DC generator is loaded, voltage drop occurs due to

1. The armature reaction - which causes the voltage drop because of demagnetization.
2. Armature circuit resistance - causes voltage drop in the armature.

Hence the terminal voltage of the DC generator will be less than the No-load induced emf.

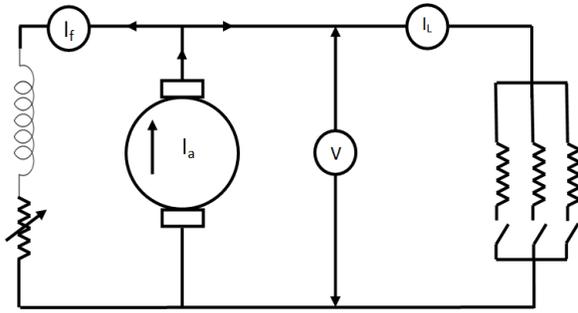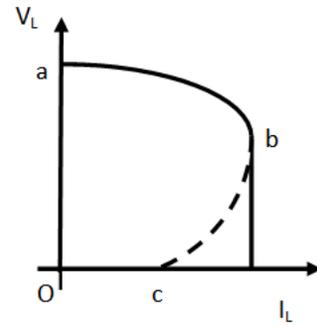## LOAD CHARACTERISTICS or EXTERNAL CHARACTERISTICS



Figure 1.22



Figure 1.23

The circuit diagram for obtaining the load characteristics is shown in figure 1.22.

The generator is brought to its rated speed and rated voltage is built up and loaded gradually. The plot of terminal voltage vs load current gives the external characteristic which is shown in the figure 1.23. There are three reasons for the drop in voltage ('ab' in figure 1.23) as the load increases.

1) Armature resistance drop
2) Armature reaction drop
3) Drop in terminal voltage due to 1 and 2 results in decreased field current which further reduces the induced emf.

The portion 'ab' on the external characteristic curve is the working part of the generator. If the load current is increased further, it is found that the terminal voltage rapidly decreases and comes to zero which is nothing but short circuit. The drastic decrease in terminal voltage 'bc' is due to the severe armature reaction for the large load current and increased armature resistance drop. Thus any increase in load current beyond the point 'b' results in terminal voltage drastically reducing though there would be some induced emf due to residual magnetism.
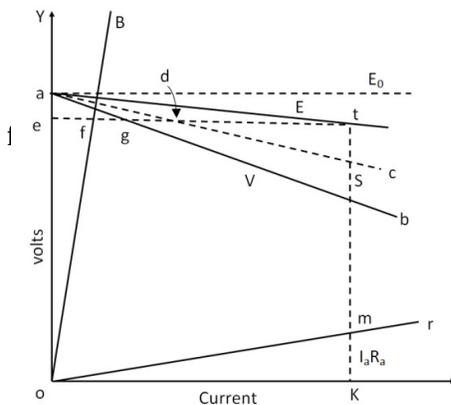
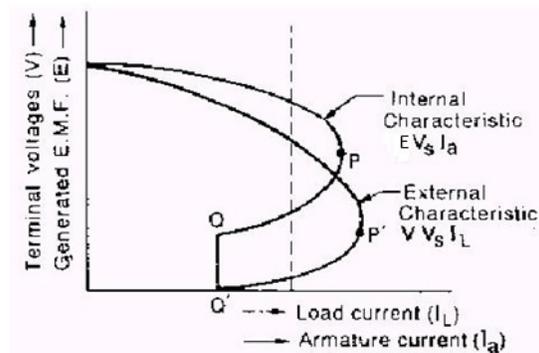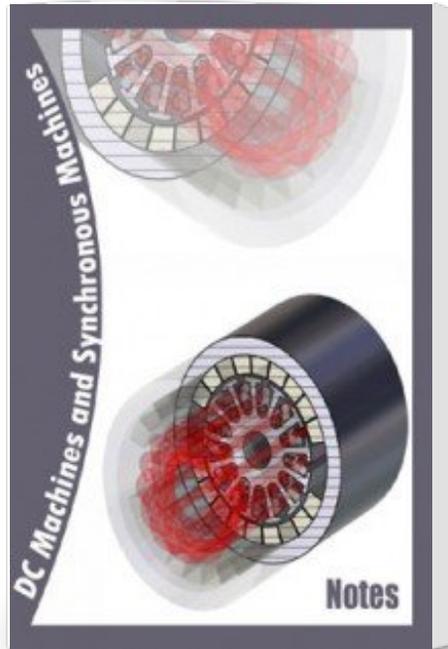## INTERNAL OR TOTAL CHARACTERISTICS



Figure 1.24



Figure 1.25

# DC Machines and Synchronous Machines Notes eBook



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