**Armature Reaction:** The effect of magnetic field set up by armature current on the distribution of flux under main poles of a generator. The armature magnetic field has two effects:

(i) It demagnetises or weakens the main flux and

(ii) It cross-magnetises or distorts it. Fig 1 shows the flux distribution of a bipolar generator when there is no current in the armature conductors. The brushes are touching the armature conductors directly, although in practice, they touch commutator segments, it is seen that: (a) the flux is distributed symmetrically with respect to the polar axis, which is the line joining the centres of NS poles. (b) The magnetic neutral axis (M.N.A.) coincides with the geometrical neutral axis (G.N.A.). Magnetic neutral axis may be defined as the axis along which no emf is produced in the armature conductors because they move parallel to the lines of flux. Or M.N.A. is the axis which is perpendicular to the flux passing through the armature.

Brushes are always placed along M.N.A. Hence, M.N.A. is also called ‘axis of commutation’ because reversal of current in armature conductors takes place across this axis. Vector OFm which represents, both magnitude and direction, the mmf of producing the main flux. Fig 2 shows the field (or flux) set up by the armature conductors alone when carrying current, the field coils being unexcited. The current direction is downwards in conductors under N-pole and upwards in those under S-pole.
The armature mmf (depending on the strength of the armature current) is shown separately both in magnitude and direction by the vector OFA. Under actual load conditions, the two mmf exist simultaneously in the generator as shown in Fig. 3. It is seen that the flux through the armature is no longer uniform and symmetrical about the pole axis, rather it has been distorted. The flux is seen to be crowded at the trailing pole tips but weakened or thinned out at the leading pole tips (the pole tip which is first met during rotation by armature conductors is known as the leading pole tip and the other as trailing pole tip). The strengthening and weakening of flux is separately shown for a four-pole machine in Fig. 4.
In Fig. 3 is shown the resultant mmf $OF$ (The new position of M.N.A.) which is found by vectorially combining $OF_m$ and $OFA$. And the new position of M.N.A which is always perpendicular to the resultant mmf vector $OF$, is also shown in the figure. With the shift of M.N.A., say through an angle $\theta$ brushes are also shifted so as to lie along the new position of M.N.A. Due to this brush shift, the armature conductors and hence armature current is redistributed. All conductors to the left of new position of M.N.A. but between the two brushes, carry current downwards and those to the right carry current upwards. The armature mmf is found to lie in the direction of the new position of M.N.A. (or brush axis). The armature mmf is now represented by the vector $OFA$. $OFA$ can now be resolved into two rectangular components, $OF_d$ parallel to polar axis and $OF_c$ perpendicular to this axis. We find that:

(i) Component $OF_c$ is at right angles to the vector $OF_m$ representing the main mmf. It produces distortion in the main field and is hence called the cross-magnetising or distorting component of the armature reaction.

(ii) The component $OF_d$ is in direct opposition of $OF_m$ which represents the main mmf. It exerts a demagnetising influence on the main pole flux. Hence, it is called the demagnetising or weakening component of the armature reaction.

It should be noted that both distorting and demagnetising effects will increase with increase in the armature current.
Demagnetising and Cross-magnetising Conductors: All conductors lying within angles $AOC = BOD = 2\theta$ at the top and bottom of the armature, are carrying current in such a direction as to send the flux through the armature from right to left. It is these conductors which act in direct opposition to the main field and are hence called the demagnetising armature conductors.

Now consider the remaining armature conductors lying between angles $AOD$ and $COB$. These conductors carry current in such a direction as to produce a flux at right angles to the main flux. This results in distortion of the main field. Hence, these conductors are known as cross-magnetising conductors and constitute distorting ampere-conductors. Since armature demagnetising ampere-turns are neutralized by adding extra ampere-turns to the main field winding, it is essential to calculate their number. But before proceeding further, it should be remembered that the number of turns is equal to half the number of conductors because two conductors constitute one turn.

Let $Z =$ total number of armature conductors

$I =$ current in each armature conductor

$= Ia/2$ ... for simplex wave winding

$= Ia/P$ ... for simplex lap winding

$\theta_m =$ forward lead in mechanical or geometrical or angular degrees.

Total number of armature conductors in angles $AOC$ and $BOD$ is $\frac{4\theta_m}{360} \times Z$. As two conductors constitute one turn,
\[
\text{Total number of turns in these angles} = \frac{2\theta_m}{360} \times Z
\]

\[
\text{Demagnetising amp – turns per pair of pole} = \frac{2\theta_m}{360} \times ZI
\]

\[
\text{AT}_d \text{ per pole} = \frac{\theta_m}{360} \times ZI
\]

The conductors lying between angles AOD and BOC constitute what are known as distorting or cross-magnetising conductors. Their number is found as under:

\[
\text{Total armature-conductors/pole both cross and demagnetising} = \frac{Z}{P}
\]

\[
\text{Cross-magnetising conductors/pole} = \frac{Z}{P} - \frac{Z \times 2\theta_m}{360} = Z \left(\frac{1}{p} - \frac{2\theta_m}{360}\right)
\]

\[
\text{Cross-magnetising amp-conductors/pole} = ZI \left(\frac{1}{p} - \frac{2\theta_m}{360}\right)
\]

\[
\text{Cross-magnetising amp-turns/pole} = ZI \left(\frac{1}{2p} - \frac{\theta_m}{360}\right)
\]

\[
\text{ATc/pole} = ZI \left(\frac{1}{2p} - \frac{\theta_m}{360}\right)
\]

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

\[
\text{No. of extra turns/pole} = \frac{AT_d}{I_f}
\]

\[
I_f \text{ – field current}
\]

If the leakage coefficient \( \lambda \) is given, then multiply each of the above expressions by it.

If lead angle is given in electrical degrees, it should be converted into mechanical degrees by the following relation:

\[
\theta_m = \frac{\theta_e}{p/2} = \frac{2\theta_e}{p}
\]

**Compensating Windings:** These are used for large direct current machines which are subjected to large fluctuations in load i.e. rolling mill motors and turbo-generators etc. Their function is to neutralize the cross magnetizing effect of armature reaction. In the absence of compensating windings, the flux will be suddenly shifting backward and forward with every change in load. This shifting of flux will induce statically induced emf in the armature coils. The magnitude of this emf will depend upon the rapidity of changes in load and the amount of change. It may be so high as to strike an arc between
the consecutive commutator segments across the top of the mica sheets separating them. This may further develop into a flashover around the whole commutator thereby shortcircuiting the whole armature. These windings are embedded in slots in the pole shoes and are connected in series with armature in such a way that the current in them flows in opposite direction to that flowing in armature conductors directly below the pole shoes.

Compensating winding must provide sufficient m.m.f so as to counterbalance the armature mmf Let

\[ Z_c = \text{No. of compensating conductors/pole face} \]

\[ Z_a = \text{No. of active armature conductors/pole}, \]

Ia = Total armature current

Ia/A = current of armature conductor

\[ \therefore Z_c I_a = Z_a A \]

No. of armature conductors/pole = \( Z / P \)

No. of armature turns/pole = \( Z / 2P \)

\[ \therefore \text{No. of armature-turns immediately under one pole} = \frac{Z}{2P} \times \frac{\text{pole arc}}{\text{pole pitch}} = 0.7 \times \frac{Z}{2p} \]

(approximately)
\[ \text{No. of armature amp-turns/pole for compensating winding} = 0.7 \times \frac{Z}{2p} = 0.7 \times \text{armature amp-turns/pole} \]

**Commutation:** The currents induced in armature conductors of a d.c. generator are alternating. These currents flow in one direction when armature conductors are under N-pole and in the opposite direction when they are under S-pole. As conductors pass out of the influence of a N-pole and enter that of S-pole, the current in them is reversed. This reversal of current takes place along magnetic neutral axis or brush axis i.e. when the brush spans and hence shortcircuits that particular coil undergoing reversal of current through it. This process by which current in the short-circuited coil is reversed while it crosses the M.N.A. is called commutation. The brief period during which coil remains short-circuited is known as commutation period \( T_c \). If the current reversal i.e. the change from \( + I \) to zero and then to \( -I \) is completed by the end of short circuit or commutation period, then the commutation is ideal. If current reversal is not complete by that time, then sparking is produced between the brush and the commutator which results in progressive damage to both. The brush width is equal to the width of one commutator segment and one mica insulation. In Fig (a) coil B is about to be short circuited because brush is about to come in touch with commutator segment ‘a’. It is assumed that each coil carries 20 A, so that brush current is 40 A. Prior to the beginning of short circuit, coil B belongs to the group of coils lying to the left of the brush and carries 20 A from left to right. In Fig (b) the current through coil B has reduced down from 20 A to 10 A. As area of contact of the brush is more with segment ‘b’ than with segment ‘a’, it receives 30 A from the former, the total again being 40 A. Fig (c) shows the coil B in the middle of its short-circuit period, the brush contact areas with the two segments ‘b’ and ‘a’ are equal. The current through it has decreased to zero. The two currents of value 20 A each, pass to the brush directly from coil A and C.
In Fig (d), coil B has become part of the group of coils lying to the right of the brush. Coil B now carries 10 A in the reverse direction which combines with 20 A supplied by coil A to make up 30 A that passes from segment ‘a’ to the brush. The other 10 A is supplied by coil C and passes from segment ‘b’ to the brush, again giving a total of 40 A at the brush. Fig (e) depicts the moment when coil B is almost at the end of commutation or short circuit period. For ideal commutation, current through it should have reversed but it is carrying 15 A only instead of 20 A. If the current varies at a uniform rate i.e. if BC is a straight line, then it is referred to as linear commutation. However, due to the production of self-induced emf in the coil the variations follow the dotted curve. It is seen that, in that case, current in coil B has reached only a value of KF = 15 A in the reversed direction, hence the difference of 5 A (20-15 A) passes as a spark. So, we conclude that sparking at the brushes, which results in poor commutation is due to the inability of the current in the short-circuited coil to reverse completely by the end of short-circuit period (which is usually of the order of 1/500 second). The main cause which retards or delays this quick reversal is the production of self-induced emf in the coil undergoing commutation. It may be pointed out that the coil possesses appreciable amount of self inductance because it lies embedded in the armature which is
built up of a material of high magnetic permeability. This self-induced emf is known as reactance voltage.

**Methods of Improving Commutation:** There are two practical ways of improving commutation i.e. of making current reversal in the short-circuited coil as sparkless as possible. These methods are known as (i) resistance commutation and (ii) emf. commutation (which is done with the help of either brush lead or interpoles, usually the later).

**Resistance Commutation:** This method of improving commutation consists of replacing low-resistance Cu brushes by comparatively high-resistance carbon brushes. When current I from coil C reaches the commutator segment b, it has two parallel paths open to it. The first part is straight from bar ‘b’ to the brush and the other parallel path is via the short-circuited coil B to bar ‘a’ and then to the brush. If the Cu brushes are used, then there is no inducement for the current to follow the second longer path, it would preferably follow the first path. But when carbon brushes having high resistance are used, then current I coming from C will prefer to pass through the second path. The additional advantages of carbon brushes are that (i) they are to some degree self-lubricating and polish the commutator and (ii) should sparking occur, they would damage the commutator less than when Cu brushes are used. But some of their minor disadvantages are: (i) Due to their high contact resistance (which is beneficial to sparkless commutation) a loss of approximately 2 volt is caused. Hence, they are not much suitable for small machines where this voltage forms an appreciable percentage loss. (ii) Owing to this large loss, the commutator has to be made some what larger than with Cu brushes in order to dissipate heat efficiently without greater rise of temperature. (iii) because of their lower current density (about 7-8 A/cm² as compared to 25-30 A/cm² for Cu brushes) they need larger brush holders.
**EMF Commutation:** In this method, arrangement is made to neutralize the reactance voltage by producing a reversing emf in the short-circuited coil under commutation. This reversing emf, as the name shows, is an emf in opposition to the reactance voltage and if its value is made equal to the latter, it will completely wipe it off, thereby producing quick reversal of current in the short-circuited coil which will result in sparkless commutation. The reversing emf may be produced in two ways: (i) either by giving the brushes a forward lead sufficient enough to bring the short-circuited coil under the influence of next pole of opposite polarity or (ii) by using interpoles. The first method was used in the early machines but has now been abandoned due to many other difficulties it brings along with.

**Interpoles of Compoles:** These are small poles fixed to the yoke and spaced in between the main poles. They are wound with comparatively few heavy gauge Cu wire turns and are connected in series with the armature so that they carry full armature current. Their polarity, in the case of a generator, is the same as that of the main pole ahead in the direction of rotation. The function of interpoles is two-fold: (i) As their polarity is the same as that of the main pole ahead, they induce an emf in the coil (under commutation) which helps the reversal of current. The emf induced by the compoles is known as commutating or reversing emf. The commutating emf neutralizes the reactance emf thereby making commutation sparkless. With interpoles, sparkless commutation can be obtained up to 20 to 30% overload with fixed brush position. In fact, interpoles raise sparking limit of a machine to almost the same value as heating.
limit. Hence, for a given output, an interpole machine can be made smaller and, therefore, cheaper than a non-interpolar machine.

As interpoles carry armature current, their commutating emf is proportional to the armature current. This ensures automatic neutralization of reactance voltage which is also due to armature current.

(ii) Another function of the interpoles is to neutralize the cross-magnetising effect of armature reaction. Hence, brushes are not to be shifted from the original position.

![Diagram of machine with main poles and interpoles](image1.png)

OF as before, represents the mmf due to main poles. OA represents the cross-magnetising mmf due to armature. BC which represents mmf due to interpoles, is obviously in opposition to OA, hence they cancel each other out. This cancellation of crossmagnetisation is automatic and for all loads because both are produced by the same armature current. The distinction between the interpoles and compensating windings should be clearly understood. Both are connected in series and thier m.m.fs. are such as to neutralize armature reaction. But compoles additionally supply mmf for counteracting the reactance voltage induced in the coil undergoing commutation. Moreover, the action of the compoles is localized; they have negligible effect on the armature reaction occurring on the remainder of the armature periphery.
**Characteristics of D.C. Generators:** Following are the three most important characteristics or curves of a d.c. generator:

1. No-load saturation Characteristic \((E_0/If)\): It is also known as Magnetic Characteristic or Open-circuit Characteristic (O.C.C.). It shows the relation between the no-load generated mmf in armature, \(E_0\) and the field or exciting current \(I_f\) at a given fixed speed. It is just the magnetisation curve for the material of the electromagnets. Its shape is practically the same for all generators whether separately-excited or self-excited.

2. Internal or Total Characteristic \((E/I_a)\): It gives the relation between the mmf \(E\) actually induces in the armature (after allowing for the demagnetising effect of armature reaction) and the armature current \(I_a\). This characteristic is of interest mainly to the designer.

3. External Characteristic \((V/I)\): It is also referred to as performance characteristic or sometimes voltage-regulating curve. It gives relation between that terminal voltage \(V\) and the load current \(I\). This curve lies below the internal characteristic because it takes into account the voltage drop over the armature circuit resistance. The values of \(V\) are obtained by subtracting \(I_aR_a\) from corresponding values of \(E\). This characteristic is of great importance in judging the suitability of a generator for a particular purpose. It may be obtained in two ways (i) by making simultaneous measurements with a suitable voltmeter and an ammeter on a loaded generator or (ii) graphically from the O.C.C.
provided the armature and field resistances are known and also if the demagnetising effect (under rated load conditions) or the armature reaction (from the short-circuit test) is known.

**Separately-excited Generator:**

(a) No-load Saturation Characteristic \((E_0/I_f)\): the voltage equation of a d.c. generator is,

\[
E_g = \frac{\phi Z N}{60} \times \left( \frac{P}{A} \right) \text{ volt}
\]

Hence, if speed is constant, the above relation becomes \(E = k\phi\)

It is obvious that when \(I_f\) is increased from its initial small value, the flux \(\phi\) and hence generated mmf \(E_g\) increase directly as current so long as the poles are unsaturated. This is represented by the straight portion Od. But as the flux density increases, the poles become saturated, so a greater increase in \(I_f\) is required to produce a given increase in voltage than on the lower part of the curve. That is why the upper portion db of the curve Odb bends over as shown.

(b) Internal and External Characteristics: Let us consider a separately-excited generator giving its rated no-load voltage of \(E_0\) for a certain constant field current (line I). But when the generator is loaded, the voltage falls due to armature reaction and armature voltage drop, thereby giving slightly dropping characteristics. If we subtract from \(E_0\) 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 II is plotted in this way and is known as the internal characteristic. The straight line Oa
represents the $I_aR_a$ drops corresponding to different armature currents. If we subtract from $E$ the armature drop $I_aR_a$, we get terminal voltage $V$. Curve III represents the external characteristic and is obtained by subtracting ordinates the line $Oa$ from those of curve II.

![Graph showing armature characteristics and no-load curve](image)

**No-load Curve for Self-excited Generator:** The O.C.C. or no-load saturated curves for self-excited generators whether shunt or series connected, are obtained in a similar way. The field winding of the generator (whether shunt or series wound) is disconnected from the machine and connected to an external source of direct current. The field or exciting current $I_f$ is increased by suitable steps (starting from zero) and the corresponding values of $E_0$ are measured. On plotting the relation between $I_f$ and $E_0$, a curve of this form is obtained. Due to residual magnetism in the poles, some emf (= OA) is generated even when $I_f = 0$. Hence, the curve starts a little way up. It is seen that the first part of the curve is practically straight. This is due to the fact that the flux and consequently, the generated emf is directly proportional to the exciting current. However, at high flux densities saturation of poles starts, and straight relation between $E$ and $I_f$ no longer holds good. It should be noted that O.C.C. for a higher speed would lie above this curve and for a lower speed, would lie below it.
**Voltage Built up and Critical Resistance for Shunt Generator:** For shunt generator, due to residual magnetism in the poles, some emf and hence current, would be generated. This current while passing through the field coils will strengthen the magnetism of the poles (provided field coils are properly connected as regards polarity). This will increase the pole flux which will further increase the generated mmf. Increased mmf means more current which further increases the flux and so on. This mutual reinforcement of mmf and flux proceeds on till equilibrium is reached at some point like P. The point lies on the resistance line OA of the field winding. Let R be the resistance of the field winding. Line OA is drawn such that its slope equals the field winding resistance i.e. every point on this curve is such that volt/ampere = R. The voltage OL corresponding to point P represents the maximum voltage to which the machine will build up with R as field resistance. OB represents smaller resistance and the corresponding voltage OM is slightly greater than OL. If field resistance is increased, then slope of the resistance line increased, and hence the maximum voltage to which the generator will build up at a given speed, decreases. If R is increased so much that the resistance line does not cut the O.C.C. at all (like OI), then obviously the machine will fail to excite i.e. there will be no ‘build up’ of the voltage. If the resistance line just lies along the slope, then with that value of field resistance, the machine will just excite. The value of the resistance represented by the tangent to the curve, is known as critical resistance $R_c$ for a given speed.
**How to Find Critical Resistance \( R_c \):** First, O.C.C. is plotted from the given data. Then, tangent is drawn to its initial portion. The slope of this curve gives the critical resistance for the speed at which the data was obtained.

**How to Draw O.C.C. at Different Speeds:** Suppose we are given the data for O.C.C. of a generator run at a fixed speed, say, \( N_1 \). It will be given that O.C.C. at any other constant speed \( N_2 \) can be deduced from the O.C.C. for \( N_1 \). If the O.C.C. for speed \( N_1 \) is given, since \( E \propto N \) for any fixed excitation, then \( \frac{E_2}{E_1} = \frac{N_2}{N_1} \) or \( E_2 = E_1 \times \frac{N_2}{N_1} \). As seen, for \( I_f = OH \), \( E_1 = HC \). The value of new voltage for the same \( I_f \) but at \( N_2 \): \( E_2 = HC \times \frac{N_2}{N_1} = HD \). In this way, point D is located. In a similar way, other such points can be found and the new O.C.C. at \( N_2 \) drawn.
Critical Speed \( N_c \): Critical speed of a shunt generator is that speed for which the given shunt field resistance represents critical resistance. Curve 2 corresponds to critical speed because \( R_{sh} \) line is tangential to it. Obviously

\[
\frac{BC}{AC} = \frac{N_c}{\text{Full Speed}} = \frac{N_c}{N} \quad \therefore \quad N_c = \frac{AC}{BC} \times \text{Full speed}(N)
\]

Conditions for Build-up of a Shunt Generator: We may summarize the conditions necessary for the build-up of a (self-excited) short generator as follows:

1. There must be some residual magnetism in the generator poles.
2. For the given direction of rotation, the shunt field coils should be correctly connected to the armature i.e. they should be so connected that the induced current reinforces the mmf produced initially due to residual magnetism.

3. If excited on open circuit, its shunt field resistance should be less than the critical resistance (which can be found from its O.C.C.)

4. If excited on load, then its load resistance should be more than a certain minimum value of resistance which is given by internal characteristic

**External Characteristic:** It is found that if after building up, a shunt generator is loaded, then its terminal voltage $V$ drops with increase in load current. Such a drop in voltage is undesirable especially when the generator is supplying current for light and power for which purpose it is desirable that $V$ should remain practically constant and independent of the load. This condition of constant voltage is almost impossible to be fulfilled with a shunt generator unless the field current is being automatically adjusted by an automatic regulator. Without such regulation terminal voltage drops considerably as the load on the generator is increased. These are three main reasons for the drop in terminal voltage of a shunt generator when under load.

(i) Armature resistance drop: As the load current increases, more and more voltage is consumed in the ohmic resistance of the armature circuit. Hence, the terminal voltage $V = E - I_a R_a$ is decreased where $E$ is the induced mmf in the armature under load condition.

(ii) Armature reaction drop: Due to the demagnetising effect of armature reaction, pole flux is weakened and so the induced mmf in the armature is decreased.

(iii) The drop in terminal voltage $V$ due to (i) and (ii) results in a decreased field current $I_f$ which further reduces the induced mmf. For obtaining the relation between the terminal voltage and load current, the generator is connected as shown below. The shunt generator is first excited on no-load so that it gives its full open circuit voltage = $Oa$. Then, the load is gradually applied and, at suitable intervals, the terminal voltage $V$ and the load current $I$ are noted. The field current as recorded by ammeter $A1$ is kept constant by a rheostat (because during the test, due to heating, shunt field resistance is
increased). By plotting these readings, the external characteristic is obtained. The portion ab is the working part of this curve. Over this part, if the load resistance is decreased, load current is increased as usual, although this results in a comparatively small additional drop in voltage. These conditions hold good till point b is reached. This point is known as breakdown point. It is found that beyond this point (where load is maximum = OB) any effort to increase load current by further decreasing load resistance results in decreased load current (like OA) due to a very rapid decrease in terminal voltage.

Voltage Regulation: By voltage regulation of a generator is meant the change in its terminal voltage with the change in load current when it is running at a constant speed. If the change in voltage between no-load and full load is small, then the generator is said to have good regulation but if the change in voltage is large, then it has poor regulation. The voltage regulation of a d.c. generator is the change in voltage when the load is reduced from rated value to zero, expressed as percentage of the rated load voltage. If no-load voltage of a certain generator is 240 V and rated-load voltage is 220 V, then, regulation = (240-220)/220 = 0.091 or 9.1 %

Internal or Total Characteristic: Internal characteristic gives the relation between $E$ and $I_a$. Hence, $E/I_a$ curve can be obtained from $V/I$ curve. In this figure, ab represents the external characteristic as discussed above. The field resistance line OB is drawn as usual. The horizontal distances from OY line to the line OB give the values of field currents for different terminal voltages. If we add these distances horizontally to the external characteristic ab, then we get the curve for the total armature current i.e. dotted
curve ac. For example, point d on ac is obtained by making gd = ef. The armature resistance drop line Or is then plotted as usual. If brush contact resistance is assumed constant, then armature voltage drop is proportional to the armature current. For any armature current = OK, armature voltage drop I_aR_a = mK. If we add these drops to the ordinates of curve ac, we get the internal characteristic. For example, St = mK. The point t lies on the internal characteristic. Other points like t can be found similarly at different armature currents as the total characteristic can be drawn. It may be noted here, in passing, that product EI_a gives the total power developed within the armature. Some of this power goes to meet I^2R losses in armature and shunt field windings and the rest appears as output. If load resistance is decreased, the armature current increases up to a certain load current value. After that, any decrease in load resistance is not accompanied by increase in load current. Rather, it is decreased and the curve turns back. If the load resistance is too small, then the generator is short-circuited and there is no generated mmf due to heavy demagnetisation of main poles. Line OP is tangential to the internal characteristic MB and its slope gives the value of the minimum resistance with which the generator will excite if excited on load.

**Series Generator:** In this generator, because field windings are in series with the armature [Fig.(a)], they carry full armature current I_a. As I_a is increased, flux and hence
generated mmf 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. If the ordinate bc = gh = armature voltage drop, then point c lies on the external characteristic [Fig (b)]. It will be noticed that a series generator has rising voltage characteristic i.e. with increase in load; its voltage is also increased. But it is seen that at high loads, the voltage starts decreasing due to excessive demagnetising effects of armature reaction. In fact, terminal voltage starts decreasing as load current is increased as shown by the dotted curve. For a load current OC’, the terminal voltage is reduced to zero as shown.

**Compound-wound Generator:** A shunt generator is unsuitable where constancy of terminal voltage is essential, because its terminal voltage decreases as the load on it increases. This decrease in V is particularly objectionable for lighting circuit where even slight change in the voltage makes an appreciable change in the candle power of the incandescent lamps. A shunt generator may be made to supply substantially constant voltage (or even a rise in voltage as the load increases) by adding to it a few turns joined in series with either the armature or the load. These turns are so connected as to aid to shunt turns when the generator supplies load. As the load current increases, the current through the series windings also increase thereby increasing the flux. Due to the
increase in flux, induced mmf is also increased. By adjusting the number of series turns (or series amp-turns), this increase in mmf can be made to balance the combined voltage drop in the generator due to armature reaction and the armature drop. Hence, V remains practically constant which means that field current is also almost unchanged.

We have already discussed the three causes which decrease the terminal voltage of a shunt generator. Out of these three, the first two are neutralized by the series field amp-turns and the third one, therefore, does not occur. If the series field amp-turns are such as to produce the same voltage at rated load as at no-load, then the generator is flat-compounded. It should be noted, however, that even in the case of a flat-compounded generator, the voltage is not constant from no-load to rated load. At half the load, the voltage is actually greater than the rated voltage. If the series field amp-turns are such that the rated-load voltage is greater than the no-load voltage, then generator is over-compounded. If rated-load voltage is less than the no-load voltage, then the generator is under-compounded but such generators are seldom used. For short distances such as in hotels and office buildings, flat-compound generators are used because the loss of voltage over small lengths of the feeder is negligible. But when it is necessary to maintain a constant voltage then an over compounded generator, which combines the functions of a generator and a booster, is invariably used.
How to Calculate Required Series Turns: Consider a 110-V, 250-ampere generator. Suppose it gives its rated no-load voltage with a field current of 5.8 A. If, now, the series windings are disconnected and the shunt field rheostat is left unchanged then the machine will act as shunt generator, hence its voltage will fall with increase in load current. Further, supply that the field current has to be increased to 6.3 A in order to maintain the rated terminal voltage at full load. If the number of turns of the shunt field winding is 2000, then \(2000 \times (6.3 - 5.8) = 1000\) amp-turns represent the additional excitation that has to be supplied by the series windings. As series turns will be carrying a full load current of 250 A, hence number of series turns = \(1000/250 = 4\).

In general, let

\[\Delta I_{sh}\] = increase in shunt field current required to keep voltage constant from no-load to full load.

\[N_{sh}\] = No. of shunt field turns per pole (or the total number of turns)

\[N_{se}\] = No. of series turns per pole (or the total number of turns)

\[I_{se}\] = current through series winding

= armature current \(I_a\) —for long-shunt

= load current \(I\) —for short-shunt

It is seen that while running as a simple generator, the increase in shunt field ampere-turns necessary for keeping its voltage constant from no-load to full-load is \(N_{sh} \cdot \Delta I_{sh}\).

This increase in field excitation can be alternatively achieved by adding a few series turns to the shunt generator [Fig. (a)] thereby converting it into a compound generator.

\[\therefore N_{sh} \cdot \Delta I_{sh} = N_{se} I_{se}\]

If other things are known, \(N_{se}\) may be found from the above equation. In practice, a few extra series amp-turns are taken in order to allow for the drop in armature. Any surplus amp-turns can be changed with the help of a divertor across the series winding as shown in Fig. (b). As said above, the degree of compounding can be adjusted with the help of a variable-resistance, divertor as shown in Fig. (b). If \(I_d\) is the current through the divertor of resistance \(R_d\), then remembering that series windings and divertor are in parallel,

\[\therefore I_{se} R_{se} = I_d R_d\] or \(R_d = I_{se} R_{se}/I_d\)

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Uses of D.C. Generators:

1. Shunt generators with field regulators are used for ordinary lighting and power supply purposes. They are also used for charging batteries because their terminal voltages are almost constant or can be kept constant.

2. Series generators are not used for power supply because of their rising characteristics. However, their rising characteristic makes them suitable for being used as boosters in certain types of distribution systems particularly in railway service.

3. Compound generators: The cumulatively-compound generator is the most widely used d.c. generator because its external characteristic can be adjusted for compensating the voltage drop in the line resistance. Hence, such generators are used for motor driving which require d.c. supply at constant voltage, for lamp loads and for heavy power service such as electric railways. The differential-compound generator has an external characteristic similar to that of a shunt generator but with large demagnetization armature reaction. Hence, it is widely used in arc welding where larger voltage drop is desirable with increase in current.

End of Part (2)