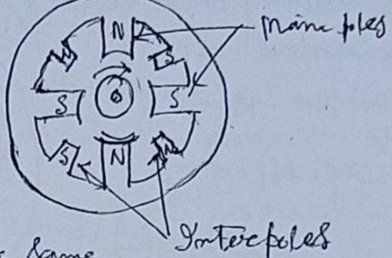
Interpoles or Compoles :-

These are small poles fixed to the yoke and spaced in between the main poles. These 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.



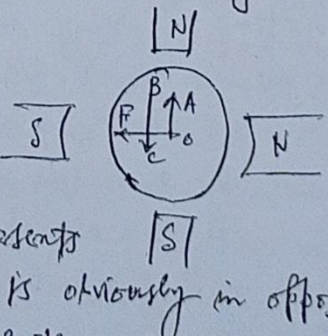
The functions of interpoles are -

(i) As their polarity is the same as that of the main pole ahead, they induce an e.m.f. in the coil (under commutation) which helps the reversal of current. The e.m.f. induced by the interpoles is known as commutating or reversing e.m.f.. The commutating e.m.f. neutralises the reactance e.m.f., thereby making commutation sparkless.

As interpoles carry armature current, their commutating e.m.f. is proportional to the armature current. This ensures automatic neutralisation of reactance voltage which is also due to armature current.

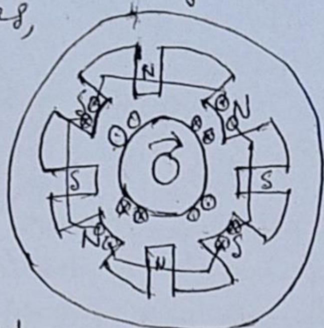
(ii) Another function of interpoles is to neutralise the cross-magnetising effect of armature reaction. Hence, brushes are not to be shifted from the original position.

In the figure shown -



OF - represents m.m.f. due to main poles. OA - represents the cross-magnetising m.m.f. due to armature. BC - which represents the m.m.f. due to interpoles, is obviously in opposition to OA, hence, they cancel each other out. This cancellation of cross-magnetisation is automatic and for all loads because both are produced by the same armature current.

Compensating Windings:- These are used for large d.c. machines which are subjected to large fluctuation in load i.e., rolling mill motors, turbo-generators etc..



Their function is to neutralise the cross-magnetising 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 e.m.f. 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 in to a flash-over around the whole commutator thereby short-circuiting 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 m.m.f..

Let, Z_c = No. of compensating conductors/pole face.

Z_a = No. of active armature conductors/pole

I_a = Total armature current

I_a/A = Current per armature conductor.

$$\therefore \; Z_c I_a = Z_a \cdot \frac{I_a}{A}$$

$$\Rightarrow Z_c = \frac{Z_a}{A}.$$

No. of compensating windings :-

No. of armature conductors / pole = $\frac{Z}{P}$.

No. of armature turns / pole = $\frac{Z}{2P}$.

$\therefore$ No. of armature turns immediately under one pole

$$= \frac{Z}{2P} \times \frac{\text{Pole arc}}{\text{Pole pitch}} = 0.7 \frac{Z}{2P} \text{ (approx.)}$$

$\therefore$ No. of armature ampere-turns / pole for compensating winding $= 0.7 \times \frac{ZI}{2P}$

$= 0.7 \times$ armature ampere turns / pole.

D.C. generator characteristics :-

There are mainly two types of characteristics —

① open circuit characteristics (O.C.C.) and

② Load characteristics.

① open circuit characteristics :- O.C.C. gives the relation between the induced e.m.f. E_0 in the ~~generator~~ generator and the field current I_f, when the generator is driven at constant speed (generally the rated speed) with the armature circuit kept open. This has the shape of the magnetisation or saturation characteristic.

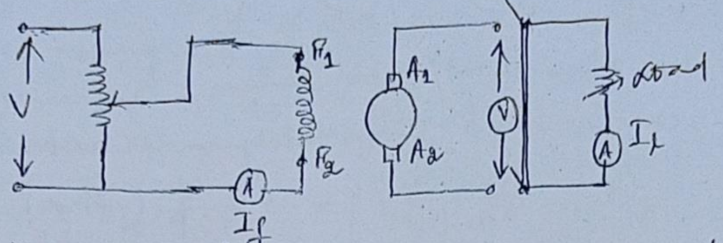
② Load characteristics :- The load characteristics can be classified as internal and external load characteristics. The external load characteristics gives the relation between the terminal voltage V and the load current I_L for a given speed of the generator at a given field current.

The internal load characteristics gives the relation between the on-load induced e.m.f. V_g and ~~load~~ ~~current I_L~~ the armature current I_a at a given speed of the generator and at constant field current. * in the armature circuit.

Generally, as the load is increased, the terminal voltage V. tends to fall due to the following causes —

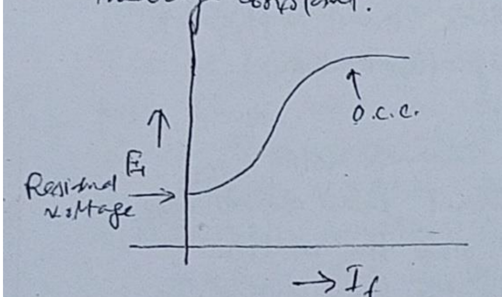
(i) the reduction in the useful flux per pole on account of armature reaction effect and (ii) the internal voltage drop in the resistance of the windings at

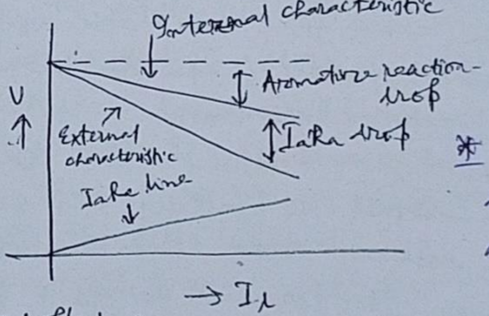
Separately excited generator :-



The circuit diagram for getting the o.c.c. and load-characteristics of separately excited D.c. generator is shown in the figure.

The o.c.c. is obtained by varying the field current and plotting the respective induced e.m.f. across the armature, keeping the load circuit open. The characteristic is plotted at the rated speed of the generator. As the induced e.m.f. at a constant speed is proportional to the flux, the characteristic becomes linear at low value of field current. At higher field currents, due to the saturation of field poles, the curve departs from linearity and the induced e.m.f. becomes nearly constant.





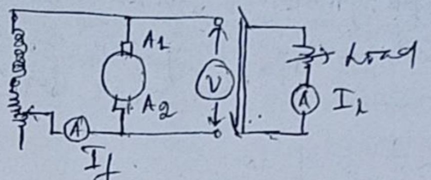
* a slight drooping curve as load current is increased.

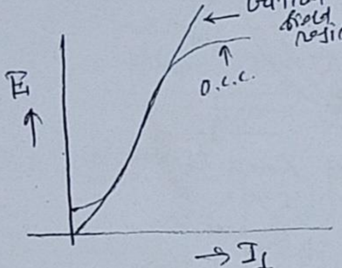
The following procedure is adopted to get the load characteristics. The d.c. generator is driven at rated speed and keeping the load circuit opened, the field current is adjusted to get the rated terminal voltage. Then, the load circuit is closed and the load current is increased gradually. The corresponding terminal voltage is noted and plotted against the armature current, and this gives the external load characteristics. To this armature resistance drop is added to get the internal load characteristics. Due to the effect of armature reaction, the internal load characteristic is showing *

Applications:- Separately excited generators are used for controlling speeds of d.c.-motors over a large range and in other applications, where a wide range of terminal voltage is required.

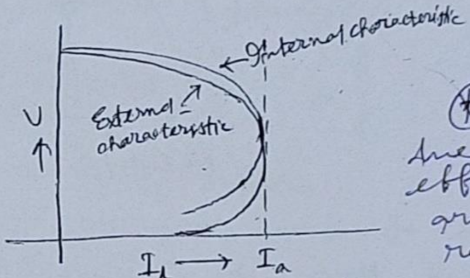
Shunt generator:-

Unlike the separately excited generator, the field in this case is connected in parallel with the armature. Otherwise, the experimental procedure for getting the o.c.c. is the same as described for separately excited generator.





(a) O.C.C.



(b) Load characteristics

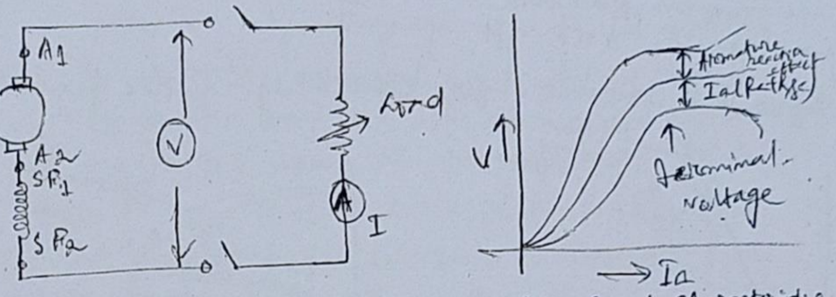
Fig.(a)- shows the o.c.c. of a d.c. shunt generator. The slope drawn for the initial part of the o.c.c. gives the critical field resistance. Unless the resistance of the shunt field is less than the critical resistance, the shunt generator would not build up e.m.f. In addition to this, there should be some residual magnetism in field poles so that initially there can be an induced emf. across the armature terminals. It is also necessary that this field flux produced aids the residual flux. If not, the residual flux will be wiped-off and the machine will not build-up e.m.f.

Load characteristics:- Fig.(b) shows the internal and external load characteristics. As the load current is increased, the terminal voltage decreases which reduces the shunt field current. This in turn reduces the induced emf. and thereby the terminal voltage. (*)

(*) In addition, due to the effect of armature-reaction, there is a further decrease in field flux and hence, the induced e.m.f.. These reasons cause ~~the~~ a cumulative decrease in the terminal voltage. Due to the above phenomena, the external and internal characteristics of the shunt generator have such a drooping shape.

Applications:- Shunt generators are used for battery charging. They are used as exciters for synchronous machines and for separately excited d.c. generators.

Series generator:-



(a) Circuit connection (b) Load characteristics

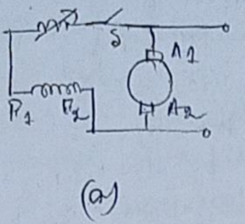
In case of series generators, the o.c.c. can not be obtained. However the magnetisation curve can be plotted by exciting the field separately. The load characteristics are obtained in the usual manner.

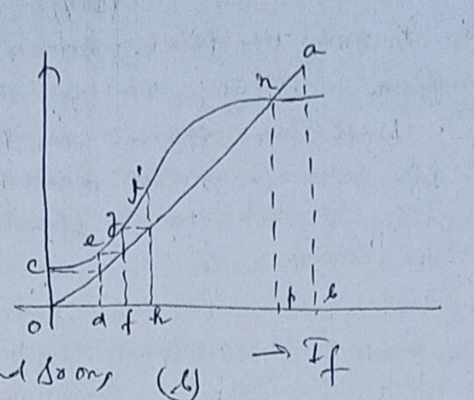
Applications:- As the series generator output voltage is directly dependent upon the load current, they are used as boosters for injecting voltage in long feeders to compensate for resistance drop of the line. In such cases, it is placed in series with the feeder.

Voltage build up of a shunt generator:- In fig.(b), Oa is the graphical plot of ohms law for the field circuit.

$\therefore$ Slope of line Oa = field resistance, R_f.

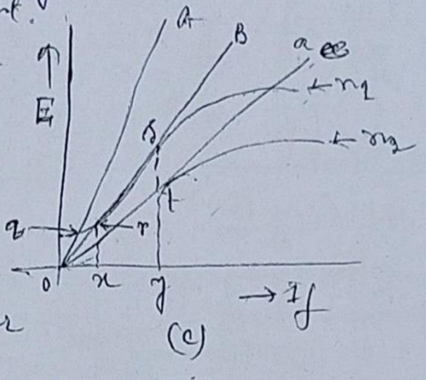
When the armature is driven at a speed for which the magnetisation curve is given, the residual pole flux generates a small voltage Oc, with switch S open. When S is closed, residual flux voltage Oc produces a small field current Od, which in turn raises the generated voltage to de. This voltage raises the field current to of which further raises the





generated e.m.f. to fg and so on, till stable point n is reached.

Beyond the point n, the generated e.m.f. given by the magnetisation curve is less than that required to maintain the corresponding field current, therefore point n is the stable point.



If shunt field resistance is increased to OA, then the field resistance line and the magnetisation curve intersect at point q, therefore, the voltage will not build up further than point q.

If OB represents the field resistance line, then the intersection may be anywhere between points r and s. The generated voltage will vary between rx and sy, resulting in unstable conditions. So, field resistance represented by the line OB, is called the critical field resistance at a given speed.

Conditions for build-up of a shunt generator:-

(i) There must be some residual magnetism in the generator poles.

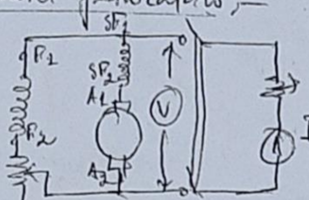
(ii) The small voltage due to residual magnetism should circulate currents in the field coils in such a direction as to produce flux lines aiding the residual flux. If the field connections are reversed the flux produced by the small field currents opposes the residual flux and the generated voltage decreases to zero. In such a case, only field * connections should be reversed

(iii) In case the field resistance is more than the critical field resistance, voltage will not build up.

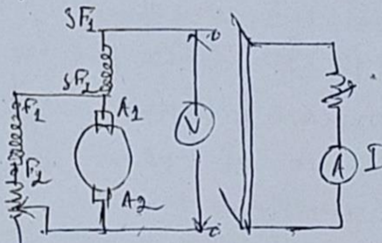
(iv) With no external resistance in the field circuit if self ~~&~~ excited generator fails to build up, it may be due to the armature speed being less than the critical speed.

Critical speed:– In fig. (c), suppose the line O_a represents the field resistance line with zero external resistance in the field circuit. If speed is reduced from n_1 to n_2, O_a becomes tangent to the magnetisation curve at n_2, then speed n_2 is called the critical speed.

Compound generators:–



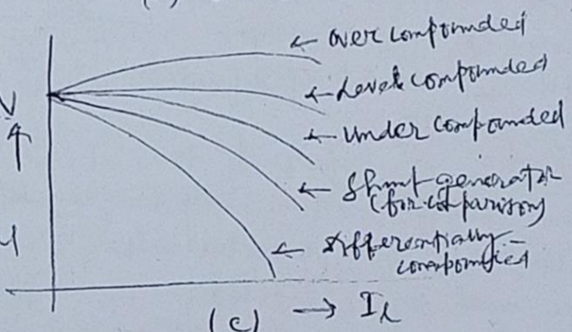
(a) Long shunt



(b) Short shunt

These generators may be either (i) cumulatively compounded or (ii) differentially compounded machines.

The shunt generator gives a drooping external characteristic, whereas the series generator



(c)

yields a rising characteristic, therefore, if a machine is excited by both shunt and series field windings, the drop in the terminal voltage of the generator can be compensated either in part or in full. Depending upon the requirements and by choosing different ratios of shunt field and series turns, different load characteristics can be obtained.

Applications:– Compound generators are used wherever constant terminal voltages have to be maintained for different loading conditions.

Parallel operation of D.C. generators :-

In most power plants, it is necessary or at least desireable, that the power be supplied by several small units rather than by a single large unit. The reasons are—

(i) Several small units are more reliable than a single large unit, ~~for~~ because if one of the small units is disabled, the entire power supply is not cut-off.

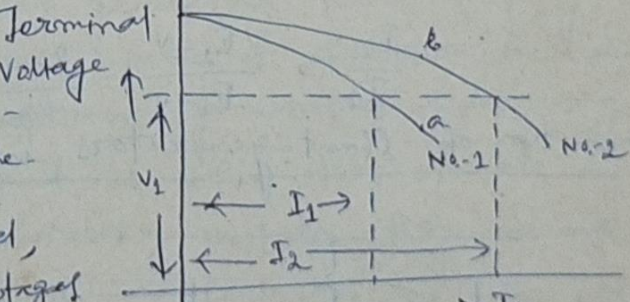
(ii) The units may be connected in service and taken out of service to correspond with the load on the station. This keeps the units loaded up to their rated capacity and increases the efficiency of operation.

(iii) A unit can be repaired more readily if there are several in the station.

(iv) Additional units may be installed to correspond with the growth of station load.

(v) The station load may exceed the capacity of any single avialable unit.

Shunt generators, because of their drooping characteristic, are particularly well suited for parallel operation.



It is seen that generator-1 has the more-drooping characteristic. If the two generators are connected in parallel, their terminal voltages must be same. Therefore, for a common terminal voltage V_1, generator-1 delivers I_1 A. and generator-2 delivers I_2 A. That is, the generator with the more drooping characteristic, carries the smaller load.

Assume that some condition arises which temporarily causes generator-1 to take more than its share of the load. If the increased current persisted after normal condition were restored, generator-1 would tend to operate at some point 'a' on its characteristics. This results in a drop in its terminal voltage, which tends to make it take less load. So, generator-2 must take less load, the total load remaining constant and accordingly generator-2 will tend to operate at some point 'b' on its characteristics. This will raise its terminal voltage and cause it to take more load. Therefore, any tendency of one generator to take more than its share of load results in changes of voltage in the system which oppose this tendency. Hence, shunt generators in parallel may be said to be in stable equilibrium.

Let us discuss load sharing of two generators which have unequal no-load voltages.

Let, E_1, E_2 = No-load voltages of the two generators

R_1, R_2 = their armature resistances

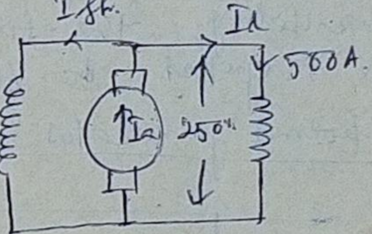
V = common terminal voltage

$$\therefore \quad I_1 = \frac{E_1 - V}{R_1}, \quad I_2 = \frac{E_2 - V}{R_2}.$$

$$\therefore \quad \frac{I_2}{I_1} = \frac{E_2 - V}{E_1 - V} \cdot \frac{R_1}{R_2}.$$

Problems:- ① The out put of a shunt generator is 500A. at a terminal voltage of 250V. If the armature resistance is 0.04 Ω and shunt field resistance is 50 Ω, what is the generated emf?

Soln:- Current through shunt field winding,



$$I_{sh.} = \frac{250}{50} = 5\text{ A.}$$

Load current, $I_L = 500$A.

∴ Armature current, $I_a = I_L + I_{sh}$

$= 500 + 5 = 505$ A.

∴ Armature voltage drop $= I_a R_a$

$= 505 \times 0.04 = 20.2$ V.

∴ E.m.f. generated, $E_a = V + I_a R_a$

$= 250 + 20.2 = 270.2$ V.

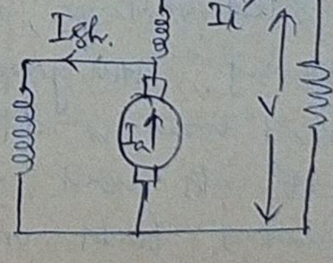
*② A 20-kW compound generator works on full-load with a terminal voltage of 250 V. The armature, series and shunt windings have resistances of 0.05, 0.025 and 100 Ω respectively. Calculate the total e.m.f. generated in the armature when the machine is connected as short shunt.

Soln:- Here, V = 250V

$R_a = 0.05\ \Omega$

$R_{se} = 0.025\ \Omega$

$R_{sh.} = 100\ \Omega$



$\therefore$ Load current, $I_L = \dfrac{20\times 1000}{250} = 80A.$

Voltage drop in series winding

$= 80\times 0.025 = 2V.$

$\therefore$ Voltage across shunt field winding

$= 250 + 2 = 252 V.$

$\therefore$ Shunt field current, $I_{sh.} = \dfrac{252}{100} = 2.52 A.$

$\therefore$ $I_a = I_{sh.} + I_L = 2.52 + 80 = 82.52$ A.

$\therefore$ Armature resistance drop, $I_aR_a = 82.52\times 0.05$

$= 4.126 V.$

$\therefore$ generated e.m.f, $E_a = 250 + 2 + 4.126$

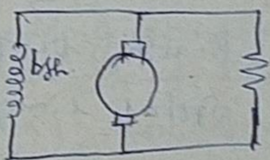
$= 256.126$ V.

* (3) A 4-pole, wave wound, 750 r.p.m shunt generator has armature and field resistances of 0.4 Ω and 200 Ω ~~resist~~ respectively. The armature has 720 conductors and the flux per pole is 2.895 mega lines. If load resistance is 10 Ω, determine the terminal voltage of the machine.

Soln :- Here, $P = 4$,

$A = 2$, $Z = 720$

$N = 750$ r.p.m.



$\phi = 2.895\times 10^6$ lines

$= 2.895\times 10^6 \times 10^{-8}$ wb.

$= 2.895\times 10^{-2}$ wb.

$\therefore$ Induced e.m.f., $E = \dfrac{\phi Z N P}{60\times A}$

$= \dfrac{2.895\times 10^{-2}\times 720\times 750\times 4}{60\times 2} = 521$ V.

Equivalent resistance of shunt field resistance and load resistance in parallel

$= \dfrac{200\times 10}{200+10} = \dfrac{200}{21}\ \Omega$

$\therefore$ Total resistance $= 0.4 + \dfrac{200}{21} = \dfrac{208.4}{21}\ \Omega$

$\therefore$ Armature current, $I_a = \dfrac{521}{208.4/21} = 52.5 A.$

∴ Armature voltage drop = $I_a R_a$

$= 52.5 \times 0.4 = 21$ V.

∴ Terminal voltage $= 521 - 21 = 500$ V.

(4) A 4-pole shunt generator delivers a current of 42 A. at 220 V. The armature resistance is 0.1 Ω and field resistance is 110 Ω. Calculate: (i) the current in each conductor of the armature if it is lap wound and (ii) the e.m.f. generated. Contact drop per brush may be taken as 1 volt.

Soln:- Load current, $I_L = 42$ A.

∴ Shunt field current, $I_{sh} = \frac{220}{110} = 2$ A.

∴ Armature current, $I_a = I_L + I_{sh}$

$= 42 + 2 = 44$ A.

(i) Current in each conductor,

$$I_c = \frac{I_a}{A} = \frac{44}{4} = 11 \text{ A.}$$

(ii) Armature voltage drop $= I_a R_a$

$= 44 \times 0.1 = 4.4$ V.

Brush drop $= 2 \times 1 = 2$ V.

∴ Total e.m.f. generated

$= 220 + 4.4 + 2 = 226.4$ V.

*(5) A shunt generator has a full load current of 196 A. at 220 V. The stray losses are 720 W. and the shunt resistance is 55 Ω. It has a full-load efficiency of 88%, find the armature resistance. Also, find the current corresponding to maximum efficiency.

Soln:- Output $= 220 \times 196 = 43120$ W.

Electrical input $= \frac{\text{output}}{\text{efficiency}}$

$$= \frac{43120}{0.88} = 49000 \text{ W.}$$

$\therefore$ Total losses = 49,000 − 43,120 = 5880 W.

Shunt field current, $I_{sh} = \frac{220}{55} = 4$ A.

$\therefore$ Armature current, $I_a = 196 + 4 = 200$ A.

Shunt field copper loss = 220 × 4 = 880 W.

Stray losses = 720 W.

$\therefore$ Constant losses = 880 + 720 = 1600 W

$\therefore$ Armature copper loss = 5880 − 1600 = 4280 W.

$\therefore I_a^2 R_a = 4280$

$\Rightarrow R_a = \frac{4280}{(200)^2} = 0.107\ \Omega.$

For maximum efficiency,

$I_a^2 R_a$ = constant losses = 1600 W.

$\therefore I_a = \sqrt{\frac{1600}{0.107}} = 122.3$ A.

(6) A separately excited generator gave the following data for open-circuit characteristic at 1000 r.p.m.

I_f	0	0.2	0.4	0.6	0.8	1.0	1.2	1.4
E_a	5	50	100	140	170	190	200	205

The armature resistance, including brushes is 0.5 Ω. If the generator is now shunt connected and is driven at 1100 r.p.m., then for a total shunt field resistance of 180 Ω, calculate — (i) no-load e.m.f. and (ii) the output current and shunt field current for a terminal voltage of 190 V.. (Neglect armature reaction).

Soln:- (i) Induced e.m.f. at 1100 r.p.m.,

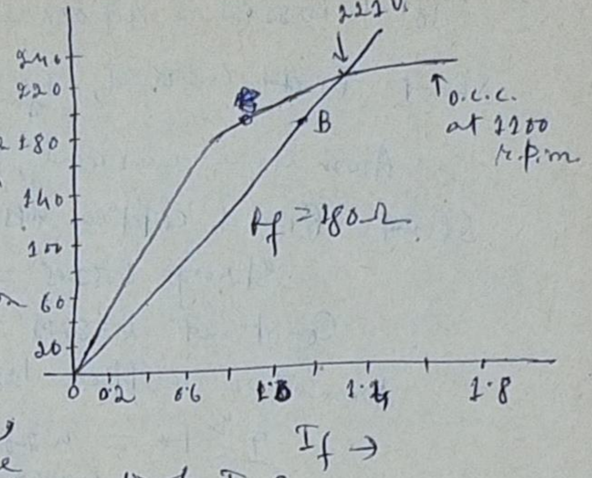
$E_{1(1100)} = E_{1(1000)} \times \frac{1100}{1000}$

So, the magnetization curve is given by the table below—

I_f (A)	0	0.2	0.4	0.6	0.8	1.0	1.2	1.4
E_a (V)	5.5	55	110	154	187	209	220	225.5

The curve is plotted in the figure. The field resistance line 180 Ω is drawn. It is seen to meet the saturation curve at 221 V., which is the no-load induced e.m.f.

(vi) Terminal voltage of 190 V is indicated by the point B on the field resistance line. The vertical difference between the magnetisation curve and the field resistance line at the point B is 22.5 V, which is equal to the total armature resistance drop $I_a R_a$.



$$\therefore \quad I_a = \frac{22.5}{0.5} = 45\text{ A}.$$

I_{sh} corresponding to terminal voltage 190 V.

$$= \frac{190}{180} = 1.06\text{ A}.$$

$\therefore$ Output current $= 45 - 1.06 = 43.94$ A.

(7) A 250 V, 500 kW, 8 pole d.c. generator has a lap wound armature with 480 conductors. Calculate the demagnetising and a cross-magnetising ampere turns per pole at full load. If the brushes are given a forward lead of 7.5° (mechanical).

Soln:- Brush lead in degrees electrical,

$$\beta = 7.5 \times \frac{P}{2} = 7.5 \times \frac{8}{2} = 30°.$$

Full load armature current,

$$I_a = \frac{500 \times 1000}{250} = 2000\text{ A}.$$

$\therefore$ Armature current through each conductor

$$= \frac{I_a}{8} = \frac{2000}{8} = 250\text{ A}.$$

$\therefore$ Demagnetising ampere-turns per pole

$$= \frac{ZI}{P} \times \frac{\beta}{180} = \frac{480 \times 250}{8} \times \frac{30}{180}$$

$$= 2500\text{ A.T.}$$

$\therefore$ cross magnetising ampere turns / pole

$$= \frac{ZI}{P}\left[\frac{1}{2} - \frac{\theta}{180}\right]$$

$$= \frac{480 \times 250}{8}\left[\frac{1}{2} - \frac{30}{180}\right]$$

$$= 5000 \text{ A.T.}$$

(8) The terminal voltage of a shunt generator decreases linearly from 250V to 225 V. when its load current is increased from 0 to 100A. This generator is operated in parallel with another generator whose terminal voltage falls uniformly from 260V to 230V when loaded to 150A. Find the load currents supplied by each generator (i) when the terminal voltage is 240V. and (ii) when the total load current is 200A.

Soln:- (i) For a fall in terminal voltage of 25V. (i.e, 250−225), the load current is 100A. For a fall of 10 V. (i.e, 250−240), its load current $= \frac{10}{25} \times 100 = 40$A.

Similarly the load current of the second generator for a fall of 20V in its terminal voltage $= \frac{20}{30} \times 150 = 100$A.

(ii) When the load current is 200A, let the current supplied by the first generator $= I_1$ A., so, current from the second generator $= (200 - I_1)$ A.

$\therefore$ Terminal voltage of the first generator

$$= \left[250 - \frac{25}{100} \times I_1\right] \text{V} \quad \text{—— (1)}$$

and that of second generator

$$= \left[260 - \frac{30}{150}(200 - I_1)\right] \text{V.} \quad \text{—— (2)}$$

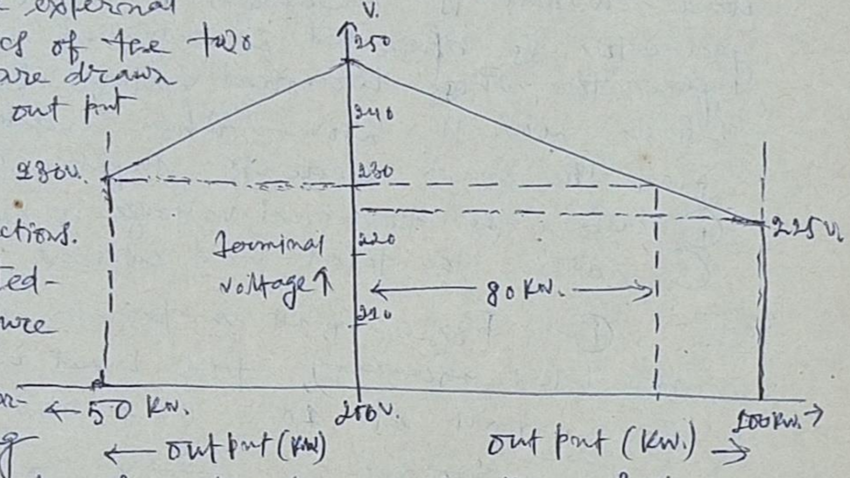
As the generators are in parallel, their terminal voltages must be the same.

$\therefore$ Equating (1) and (2), and solving, $I_1 = 66.67$

$\therefore$ Current supplied by generator-2 $= 200 - 66.67$
$= 133.33$ A.

(9) Two d.c. Shunt generators of ratings 100 kW. and 50 kW. respectively are operated in parallel. The 100 kW. machine has a voltage regulation of 10% varying linearly from no-load to full-load, whereas that of the other generator is 8%. Find the maximum load that can be carried by them, when in parallel, without exceeding the rating of either machines, if the no-load terminal voltage of each machine is 250V.

Soln:- The external characteristics of the two generators are drawn with their out put powers plotted in opposite directions. It can be noted from the figure that the 50 kW. generator will be having



full load on it when the terminal voltage falls to 230V, whereas the 100 kW. machine reaches full load only at 225 V. Therefore when the load is increased, the 50-kW. generator attains full load first.

When 50-kW load is taken by the smaller machine, its terminal voltage is 230V, and at this voltage, it can be seen from the graph that the larger generator supplies 80-kW.

∴ The maximum load that can be supplied without over-loading either machine

$$= 50 + 80 = 130 \text{ kW}.$$

D.C. Motor:—

Motor principle:— An electric motor converts electric energy into mechanical energy. Its action is based on the principle that when a current carrying conductor is placed in a magnetic field, it experiences a mechanical force whose direction is given by Fleming's left hand rule and whose magnitude is given by $F = BIl$ ~~...~~ newton.

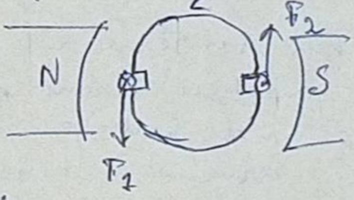
B = flux density in Wb/m^2

l = length of conductor in meter

I = current through the conductor in Amp.

Constructionally there is no basic difference between a d.c. generator and a d.c. motor. The same machine may be used either as motor or generator. D.C. motors are also like generators, shunt wound, or series wound or compound wound.

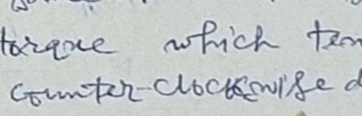
Figure (a) shows a rectangular coil of a single turn whose plane lies parallel to a magnetic field.



(a)

As the current in each conductor is the same and they lie in the same magnetic field, each conductor develops same force F. The conductor on the left hand side moves downward with a force F and the right hand side conductor moves upward with the same force F. Both forces act to develop a torque which tends to turn the coil in a counter-clockwise direction.

Fig. (b) shows a part of a multipolar d.c. motor.



(b)

When its field magnets are excited and its armature conductors are supplied with current from the supply mains, they experience a force tending to rotate the armature.

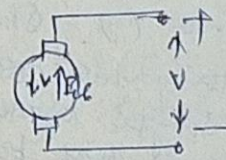
Armature conductors under N-pole are assumed to carry current downwards and those under S pole, to carry currents upward. It will be seen that each conductor experiences a force F which tends to rotate the armature in anti-clockwise direction. These forces collectively produce a driving torque which sets the armature rotating.

The function of a commutator in the motor is same as in a generator.

Counter e.m.f., Torque speed and torque equation :-

When the motor armature rotates, the conductors also rotate and hence, cut the flux. In accordance with the laws of electromagnetic induction, e.m.f. is induced in them whose direction, as found by Fleming's right hand rule, is in opposition to the applied voltage. Because of this opposing direction, it is referred to as counter e.m.f. or back e.m.f., E_b.

As this counter e.m.f E_b opposes the applied terminal voltage V, the net voltage acting in the armature circuit $= V - E_b$.



$$\therefore \quad I_a R_a = V - E_b$$

$$\Rightarrow \quad E_b = V - I_a R_a \quad \text{--- (1)}$$

We know, $E_b = \dfrac{\phi Z N P}{60 \times A}$ Volts,

$$\therefore \quad \frac{\phi Z N P}{60 \times A} = V - I_a R_a$$

$$\therefore \quad N = \frac{(V - I_a R_a) \times 60 \times A}{\phi Z P} \quad \text{r.p.m.}$$

$$\therefore \quad N = \frac{K(V - I_a R_a)}{\phi} \quad \text{r.p.m.} \quad \text{--- (2)}$$

where, $K = \dfrac{60 A}{Z P}$.

For large machines, generally, $I_a R_a << V$,

$$\therefore \quad \boxed{N = \frac{KV}{\phi}} \quad \text{--- (3)}$$

So speed of a d.c. motor is directly proportional to the applied voltage and inversely proportional to the flux per pole.

The torque developed by the motor armature of a motor can be obtained by equating the mechanical power developed by the motor and the corresponding electrical input supplied to it. Let, the armature draws a current of I_a amp. for an applied voltage V.

$\therefore$ Input to motor $= VI_a$

Armature copper loss $= I_a^2 R_a$

$\therefore$ Power developed by the armature,

$$P_m = VI_a - I_a^2 R_a$$
$$= I_a(V - I_a R_a)$$
$$= E_b I_a \text{ watts.}$$

If T is the torque developed by the motor in N-m. and ω is the angular velocity in rad./sec,

then $T.\omega = E_b I_a$

Now, $E_b = \frac{\phi Z N P}{60 \times A}$ and $\omega = \frac{2\pi N}{60}$

$$\therefore T \times \frac{2\pi N}{60} = \frac{\phi Z N P}{60 \times A} \times I_a$$

$$\boxed{\begin{aligned} \therefore T &= \frac{1}{2\pi} \times \frac{\phi Z P}{A} I_a \text{ N-m} \\ &= 0.159 \left(\frac{\phi Z P}{A}\right) I_a \text{ N-m.} \end{aligned}}$$

For a given d.c motor, as Z, P and A are fixed, the torque developed is proportional to the product of ϕ and I_a, that is,

$$\boxed{T \propto \phi I_a}$$

Shaft torque (T_{sh}) :- The whole of the armature torque is not available for doing useful work, because a certain percentage of it is required for supplying iron and friction losses in the motor.

The torque which is available for doing useful work is known as shaft torque (T_{sh}).

$\therefore$ Output $= T_{sh} \times 2\pi \frac{N}{60}$ watts.

$$\therefore \boxed{\begin{aligned} T_{sh} &= \frac{60}{2\pi} \times \frac{\text{Out put}}{N} \\ &= 9.55 \times \frac{\text{Out put}}{N} \quad N\text{-m.} \end{aligned}}$$

Condition for maximum power:-

Mechanical power developed by a motor,

$$P_m = VI_a - I_a^2 R_a$$

For maximum value of P_m,

$$\frac{dP_m}{dI_a} = 0 \Rightarrow V - 2 I_a R_a = 0$$

$$\Rightarrow I_a R_a = \frac{V}{2}$$

$$\Rightarrow V - E_b = \frac{V}{2} \Rightarrow \boxed{E_b = \frac{V}{2}}$$

So, mechanical power developed by a motor is maximum when back e.m.f. is equal to half the applied voltage.

Speed Regulation:- The speed regulation is defined as the change in speed when the load on the motor is reduced from rated value to zero, expressed as percent of the rated full load speed.

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

Load characteristics of d.c. motor:-

The important characteristics in motor are — (i) Speed - current (ii) torque - current and (iii) Speed - torque.

The speed torque is also called as mechanical characteristics as both the quantities involved are mechanical.

(1) Shunt motor:-

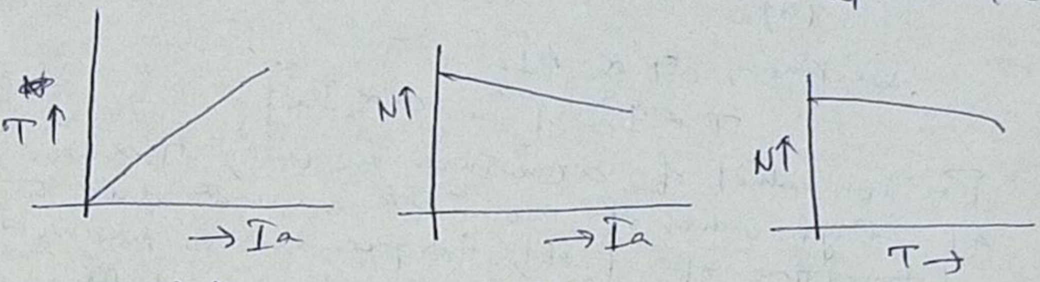
Speed of a motor, $N = \frac{K(V - I_a R_a)}{\phi}$

As the flux is constant in a shunt motor,

$$N = K_1 (V - I_a R_a).$$

So speed-current relation is a straight line with a negative slope $K_1 R_a$.

Hence, as the load is increased, the speed decreases to about 3 to 6% of the no-load speed. But, the armature reaction weakens the field to a small extent and so the speed increases slightly. With the result, the net decrease in speed due to increase of load is limited to about 5%. Hence, the shunt motor is considered almost a constant speed motor.



(a) (b) (c)

$T \propto \phi I_a$

So, $T \propto I_a$, as $\phi \rightarrow$ constant.

Speed-torque relation of a shunt motor can be obtained from fig.(a) and fig.(b).

Applications:- Shunt motors are used for driving centrifugal pumps, light machine-tools and in other applications, where practically constant speed is required.

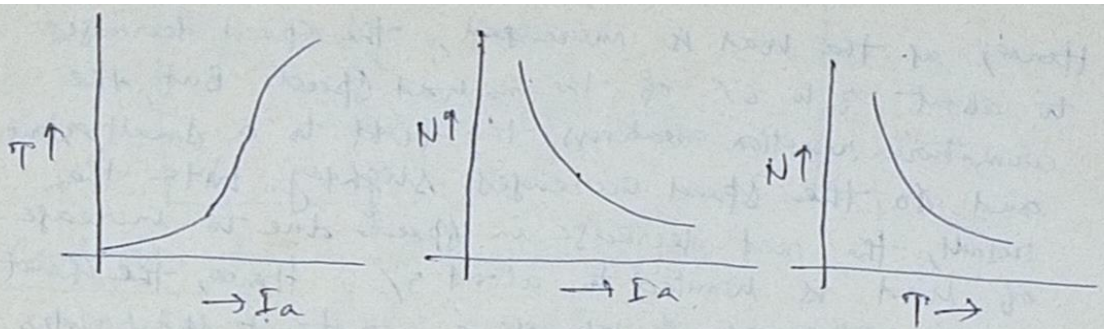
Series motor:-

Speed, $N = \frac{K(V - I_a R_a)}{\phi}$.

Under light load conditions, the speed is inversely proportional to armature current, hence the speed-current curve is hyperbolic.

When the load is heavy, I_a is large. Hence, speed is low. This decreases E_b and allows more armature current to flow.

But when load current and hence I_a falls to a small value, speed becomes dangerously high. Hence a series motor should never be started without some mechanical load.



(a) (b) (c)

. We know, $T \propto \phi I_a$

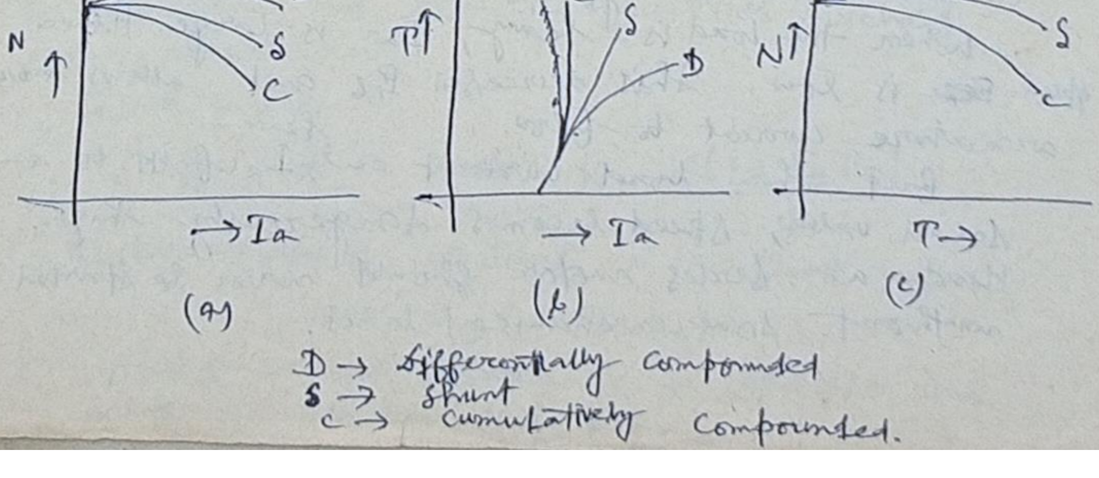
$\therefore \quad T \propto I_a^2 \quad [\because \phi \propto I_a]$.

For low values of armature current, $T \propto I_a^2$.
At high values of armature current, due to saturation of field, torque becomes linear with I_a.

Speed – torque relation is obtained from fig. (a) and fig. (b). It is seen that the series motor has a high starting torque.

__Applications:__– The series motor is used extensively for traction, in cranes and other applications like lifts, where a high starting torque is required.

(3) __Compound motor:__– These motors have both series and shunt windings. If series excitation helps the shunt excitation, then the motor is said to be cumulatively compounded. If series field opposes the shunt field, then the motor is said to be differentially compounded.



(a) (b) (c)

D → differentially compounded
S → shunt
C → cumulatively compounded.