GENERATOR CHARACTERISTICS

Ç Generator characteristics gives the relation between terminal voltage and load current. It is of great importance in judging the suitability of a generator for a particular purpose

28.1. 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/I_f)

It is also known as Magnetic Characteristic or Open-circuit Characteristic (*O.C.C.*). It shows the relation between the no-load generated e.m.f. 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 e.m.f. *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 and can be obtained as explained in Art. 28.12.

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 $I_a R_a$ 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 (Art. 28.10) 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.

28.2. Separately-excited Generator

(*a*) (*i*) No-load Saturation Characteristic (E_0/I_f)

The arrangement for obtaining the necessary data to plot this curve is shown in Fig. 28.1. The exciting or field current I_f is obtained from an external independent d.c. source. It can be varied from zero upwards by a potentiometer and its value read by an ammeter *A* connected in the field circuit as shown.

Now, the voltage equation of a d.c. generator is, $E_g = \dfrac{\Phi\, ZN}{60} \times \left(\dfrac{P}{A}\right)$ volt
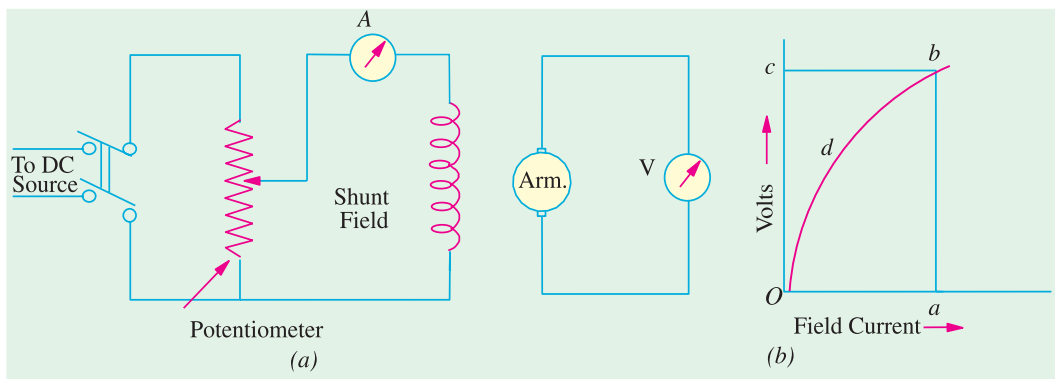

Fig. 28.1

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 Φ and hence generated e.m.f. E_g increase directly as current so long as the poles are unsaturated. This is represented by the straight portion *Od* in Fig. 28.1 (*b*). 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.

(ii) Load Saturation Curve (V/I_f)

The curve showing relation between the terminal voltage V and field current I_f when the generator is loaded, is known as Load Saturation Curve.

The curve can be deduced from the no-load saturation curve provided the values of armature reaction and armature resistance are known. While considering this curve, account is taken of the
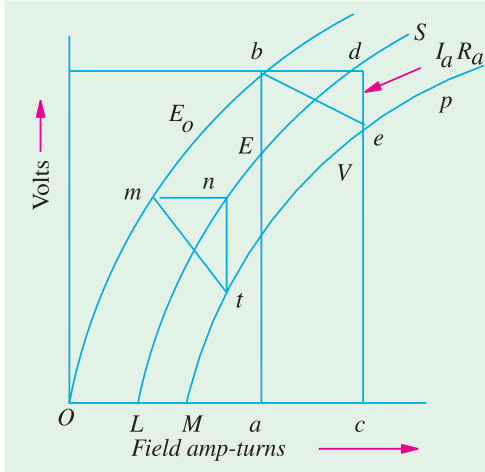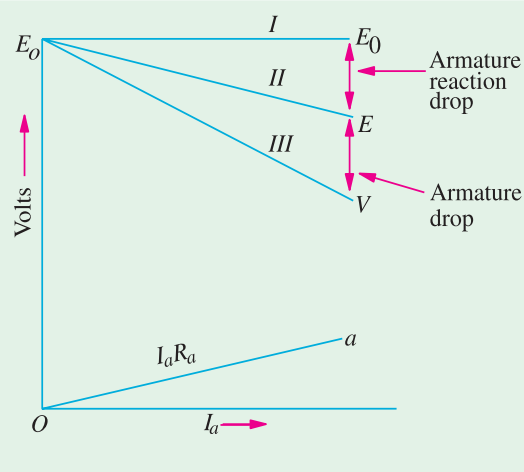

| Fig. 28.2 | Fig. 28.3 |

demagnetising effect of armature reaction and the voltage drop in armature which are practically absent under no-load conditions. The no-load saturation curve of Fig. 28.1 has been repeated in Fig. 28.2 on a base of field amp-turns (and not current) and it is seen that at no-load, the field amp-turns required for rated no-load voltage are given by Oa. Under load conditions, the voltage will decrease due to demagnetising effect of armature reaction. This decrease can be made up by suitably increasing the field amp-turns. Let ac represent the equivalent demagnetising amp-turns per pole. Then, it means that in order to generate the same e.m.f. on load as at no-load, the field amp-turns/pole must be increased by an amount $ac = bd$. The point d lies on the curve LS which shows relation between the voltage E generated under *load* conditions and the field amp-turns. The curve LS is practically parallel to curve Ob. The terminal voltage V will be less than this generated voltage E by an amount $= I_a R_a$ where R_a is the resistance of the armature circuit. From point d, a vertical line $de = I_a R_a$ is drawn. The point e lies on the full-load saturation curve for the generator. Similarly, other points are obtained in the same manner and the full-load saturation curve Mp is drawn. The right-angled triangle bde is known as **drop reaction triangle**. Load saturation curve for half-load can be obtained by joining the mid-points of such lines as mn and bd etc. In the case of self-excited generators, load saturation curves are obtained in a similar way.

(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. If there were no armature reaction and armature voltage drop, then this voltage would have remained constant as shown in Fig. 28.3. by the dotted horizontal line *I*. But when the generator is loaded, the voltage falls due to these two causes, 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 e.m.f. *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 $I_a R_a$ drops corresponding to different armature currents. If we subtract from E the armature drop $I_a R_a$, 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.

28.3. 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.
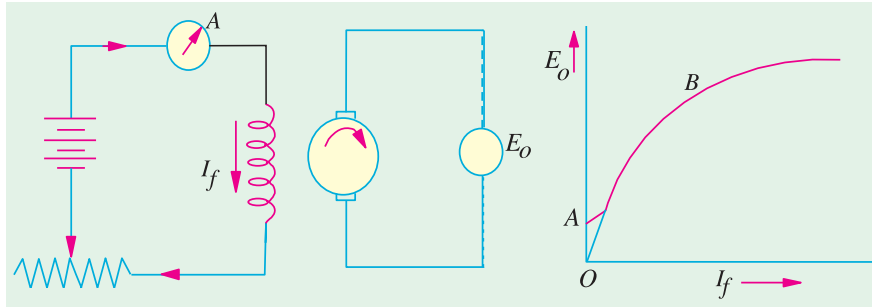

Fig. 28.4   **Fig. 28.5**

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 as shown in Fig. 28.4. The field or exciting current I_f is varied rheostatically and its value read on the ammeter A. The machine is drived at constant speed by the

Self Excited Generator

prime mover and the generated e.m.f. on on-load is measured by the voltmeter connected across the armature. 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 shown in Fig. 28.5 is obtained.

Due to residual magnetism in the poles, some e.m.f. (= OA) is generated even when $I_f = 0$. Hence, the curve starts a little way up. The slight curvature at the lower end is due to magnetic inertia. It is seen that the first part of the curve is practically straight. This is due to the fact that at low flux densities, reluctance of iron path being negligible (due to high permeability), total reluctance is given by the air-gap reluctance which is constant. Hence, the flux and consequently, the generated e.m.f. is directly proportional to the exciting current. However, at high flux densities, – where μ is small, iron path reluctance becomes appreciable and straight relation between E and I_f no longer holds good. In other words, after point B, saturation of poles starts. However, the initial slope of the curve is determined by air-gap width.

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.

It should also be noted and the load-saturation curve for a shunt generator is similar to the one shown in Fig. 28.2.

Critical Resistance for Shunt Generator

Now, connect the field windings back to the armature and run the machine as a shunt generator. Due to residual magnetism in the poles, some e.m.f. 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 e.m.f. Increased e.m.f. means more current which further increases the flux and so on. This mutual reinforcement of e.m.f. and flux proceeds on till equilibrium is reached at some point like P (Fig. 28.6). 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 *OT*), then obviously the machine will fail to excite *i.e.* there will be no 'build up' of the voltage. If the resistance line

Fig. 28.6

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*.
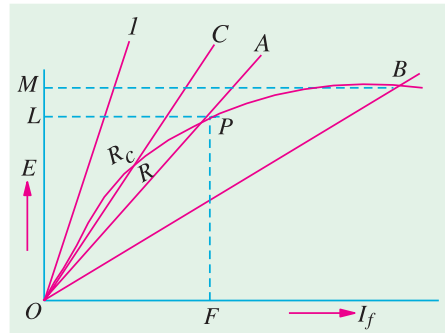
28.4 How to Find Critical Resistance R_c ?

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.

28.5 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 shown that *O.C.C.* at any other constant speed N_2 can be deduced from the *O.C.C.* for N_1. In Fig. 28.7 the *O.C.C.* for speed N_1 is shown.

Fig. 28.7   **Fig. 28.8**
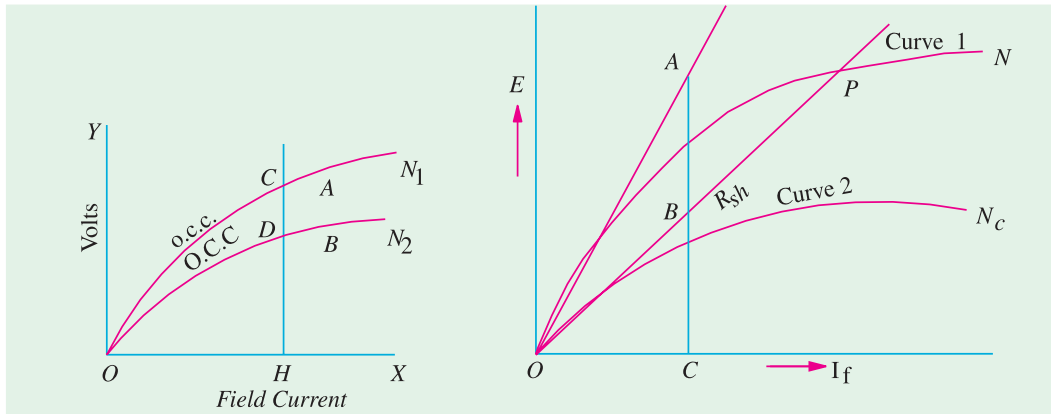
Since $E \propto N$ for any fixed excitation, hence $\dfrac{E_2}{E_1} = \dfrac{N_2}{N_1}$ or $E_2 = E_1 \times \dfrac{N_2}{N_1}$

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.

28.6. Critical Speed N_c

Critical speed of a shunt generator is that speed for which the given shunt field resistance represents critical resistance. In Fig. 28.8, curve 2 corresponds to critical speed because R_{sh} line is tangential to it. Obviously

$$\frac{BC}{AC} = \frac{N_c}{\text{Full Speed}} = \frac{N_c}{N} \quad \therefore \quad N_c = \frac{BC}{AC} \times \text{Full speed } N$$

Example 28.1. *The magnetization curve of a d.c. shunt generator at 1500 r.p.m. is :*

I_f (A) :	0	0.4	0.8	1.2	1.6	2.0	2.4	2.8	3.0
E_0 (V) :	6	60	120	172.5	202.5	221	231	237	240

For this generator find **(i)** *no load e.m.f. for a total shunt field resistance of 100 Ω* **(ii)** *the critical field resistance at 1500 r.p.m. and* **(iii)** *the magnetization curve at 1200 r.p.m. and therefrom the open-circuit voltage for a field resistance of 100 Ω.*

(b) *A long shunt, compound generator fitted with interpoles is cummutatively-compounded. With the supply terminals unchanged, the machine is now run as compound motor. Is the motor differentially or cumulatively compounded ? Explain.* **(Elect, Machines, A.M.I.E. Sec. B, 1990)**

Solution. The magnetisation curve at 1500 r.p.m. is plotted in Fig. 28.9 from the given data. The 100 Ω resistance line *OA* is obtained by joining the origin (0, 0) with the point (1A, 100 V). The voltage corresponding to point *A* is 227.5 V. Hence, no-load voltage to which the generator will build-up is 227.5 V.

The tangent *OT* represents the critical resistance at 1500 r.p.m. considering point *B*, $R_c = 225/1.5 = 150$ Ω.

For 1200 r.p.m., the induced voltages for different field currents would be (1200/1500) = 0.8 of those for 1500 r.p.m. The values of these voltages are tabulated below :

Fig. 28.9

I_f (A) :	0	0.4	0.8	1.2	1.6	2.0	2.4	2.8	3.0
E_0 (V) :	4.8	48	96	138	162	176.8	184.8	189.6	192

The new magnetisation curve is also plotted in Fig. 28.9. The 100 Ω line cuts the curve at point *C* which corresponds to an induced voltage of 166 V.

Example 28.2. *A shunt generator is to be converted into a level compounded generator by the addition of a series field winding. From a test on the machine with shunt excitation only, it is found that the shunt current is 3.1 A to give 400 V on no load and 4.8 A to give the same voltage when the machine is supplying its full load of 200 A. The shunt winding has 1200 turns per pole. Find the number of series turns required per pole.* **(Elect. Machines, A.M.I.E. Sec. B, 1989)**
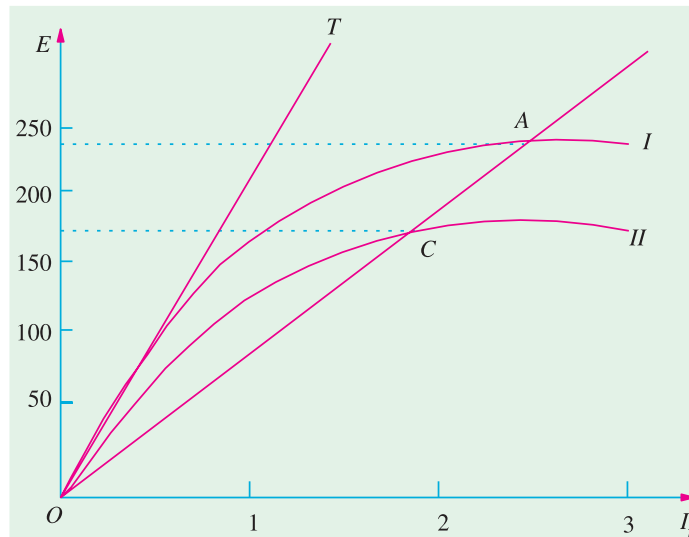
Solution. At no-load the ampere turns required to produce 400 V = $3.1 \times 1200 = 3720$

On full-load ampere turns required to produce the same voltage = $4.8 \times 1200 = 5760$

Additional ampere turns required due to de-magnetising effect of load current = $5760 - 3720 = 2040$.

If N is a number of series turns required when load current is 200 A, then

$$N \times 200 = 2040, N = 10.2$$

Example 28.3. *The open-circuit characteristic of a d.c. shunt generator driven at rated speed is as follows :*

Field Amperes :	0.5	1.0	1.5	2.0	2.5	3.0	3.5 A
Induced Voltage :	60	120	138	145	149	151	152 V

If resistance of field circuit is adjusted to 53 Ω, calculate the open circuit voltage and load current when the terminal voltage is 100 V. Neglect armature reaction and assume an armature resistance of 0.1 Ω.   **(Electrical Technology Punjab Univ. Dec. 1989)**

Solution. Take $I_f = 3$ A, $R_{sh} = 53$ Ω,

Point A is (3A, 159V) point. Line OA is the 53 Ω line in Fig. 28.10. It cuts drop = $3 \times 53 = 159$ V. *O.C.C.* at B. Line BM is drawn parallel to the base. OM represents the *O.C.* voltage which equals **150 V.**
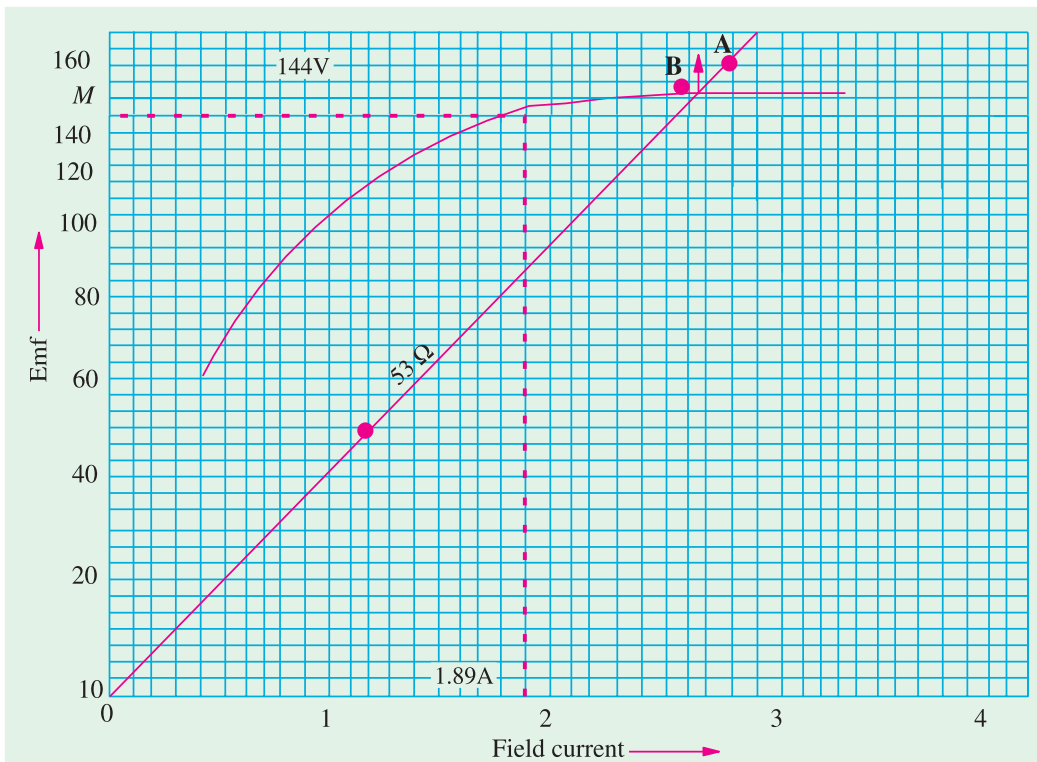

Fig. 28.10

Now, when $V = 100$ V, $I_{sh} = I_f = 100/53 = 1.89$ A

Generated or *O.C.* voltage corresponding to this exciting current as seen from graph of Fig. 26.10 is 144 V.

Now $E = V + I_a R_a$ or $I_a R_a = 144 - 100 = 44$ V

∴ $0.1 I_a = 44$ or $I_a = 44/0.1 = $ **440 A**

Example 28.4. *The following figures give the O.C.C. of a d.c. shunt generator at 300 r.p.m.*

Field amperes :	0	2	3	4	5	6	7
Armature volt :	7.5	92	132	162	183	190	212

Plot the O.C.C. for 375 r.p.m. and determine the voltage to which the machine will excite if field circuit resistance is 40 Ω.

(*a*) *What additional resistance would have to be inserted in the field circuit to reduce the voltage to 200 volts at 375 r.p.m.?*

(*b*) *Without this additional resistance, determine the load current supplied by the generator, when its terminal voltage is 200 V. Ignore armature reaction and assume speed to be constant. Armature resistance is 0.4 Ω.* **(Elect. Machines - I, South Gujarat Univ. 1986)**

Solution. The e.m.f. induced at 375 r.p.m. would be increased in the ratio 375/300 corresponding to different shunt field current values. A new table is given with the voltages multiplied by the above ratio.

Field amperes :	0	2	3	4	5	6	7
Armature volt :	9.4	115	165	202.5	228.8	248.8	265

The new *O.C.C.* at 375 r.p.m. is shown in Fig. 26.11. Line *OA* represents 40-Ω line.

The voltage corresponding to point *A* is 260 V. Hence machine will excite to 260 volt with 40 Ω shunt field resistance.

Fig. 28.11

(*a*) From Fig. 28.11, it is clear that for exciting the generator to 200 V, exciting current should be 3.8 A.

∴ Field circuit resistance = 200/3.8 = 52.6 Ω

∴ Additional resistance required = 52.6 − 40

= **12.6 Ω**

(*b*) In this case, shunt field resistance = 40 Ω ...(as above)

Terminal voltage = 200 V ∴ Field current = 200/40 = 5 A

Generated e.m.f. for exciting current of 5 A = 228.8 V

For a generator $E = V + I_a R_a$ ∴ $I_a R_a = E − V$ or $0.4\, I_a = 228.8 − 20 = 28.8$

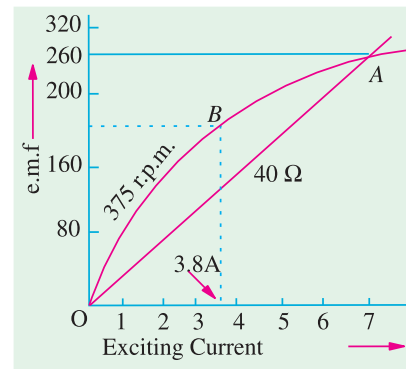∴ $I_a = 28.8/0.4 = 72$ A ∴ Load current $I = 72 − 5 = $ **67 A**

Example 28.5. *The open-circuit characteristic of a separately-excited d.c. generator driven at 1000 r.p.m. is as follows :*

Field current :	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6
E.M.F. volts :	30.0	55.0	75.0	90.0	100.0	110.0	115.0	120.0

If the machine is connected as shunt generator and driven at 1,000 r.p.m. and has a field resistance of 100 Ω, find (*a*) *open-circuit voltage and exciting current* (*b*) *the critical resistance and* (*c*) *resistance to induce 115 volts on open circuit.*

(Elect. Machines, Nagpur, Univ. 1993)

Solution. The *O.C.C.* has been plotted in Fig. 28.12. The shunt resistance line *OA* is drawn as usual.

(*a*) *O.C.* voltage = **100 V**; Exciting current = **1 A**

(*b*) Line *OT* is tangent to the initial part of the *O.C.C.* It represents critical resistance. As seen from point *C*, value of critical resistance is 90/0.6 = **150 Ω.**
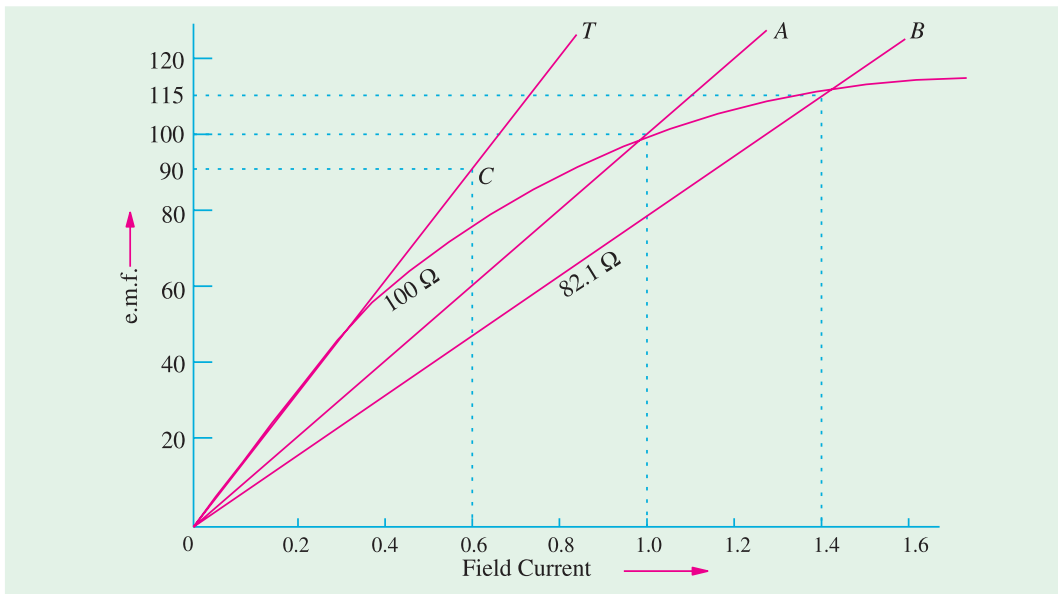
Fig. 28.12

(*c*) Line *OB* represents shunt resistance for getting 115 V on open-circuit. Its resistance = 115/1.4 = **82.1 Ω.**

Example 28.6. *A d.c. generator has the following magnetisation characteristics.*

Field current (A) :	1	2	3	4	5	6	7	8
Generated e.m.f. (V) :	23	45	67	85	100	112	121	126

If the generator is shunt excited, determine the load current.

(*a*) *when terminal p.d. is 120 V, the field resistance is 15 Ω at a speed of 600 r.p.m. And*

(*b*) *when terminal p.d. is 144 V, the field resistance is 18 Ω at a speed of 700 r.p.m.*

Solution. (*a*) When terminal p.d. = 120 V, then field current $I_f = V/R_{sh}$ = 120/15 = 8 Ω

From the given data, it is seen that the generated e.m.f. = 126 V[*]

Voltage drop = 126 − 120 = 6 V

Since drop due to armature reaction is neglected, this represents the armature drop.

∴　　　　　$I_a R_a$ = 6　or　I_a = 6/0.02 = 300 A　　　　Load current = 300 − 8 = **292 A**

(*b*) The *O.C.* data at 700 r.p.m. can be obtained by multiplying the given values of generated e.m.f. by a factor of 700/600 = 7/6. Hence, the new data is :

Field current (A)	:	1	2	3	4	5	6	7	8
Generated e.m.f. (V)	:	26.8	52.5	78.2	99.2	116.6	131	141	146

When　　　　　　　　　V = 144 V and R_{sh} = 18 Ω, field current = 144/18 = 8 A

From the given data, the corresponding generated e.m.f. is 146 V.

Voltage drop　　　　$I_a R_a$ = 146 − 144 = 2V

∴　　　　　　　　　I_a = 2/0.02 = 100 A　　　∴ Load current = 100 − 8 = **92 A**

Example 28.7. *The O.C.C. of a d.c. generator driven at 400 rev/min is as follows :*

Field current (A)	:	2	3	4	5	6	7	8	9
Terminal volts	:	110	155	186	212	230	246	260	271

---

[*]　　We need not plot the *O.C.C.* in this particular case.

Find :

(*a*) *voltage to which the machine will excite when run as a shunt generator at 400 rev/min with shunt field resistance equal to 34 Ω.*

(*b*) *resistance of shunt circuit to reduce the O.C. voltage to 220 V.*

(*c*) *critical value of the shunt field circuit resistance.*

(*d*) *the critical speed when the field circuit resistance is 34 Ω.*

(*e*) *lowest possible speed at which an O.C. voltage of 225 V can be obtained.*

(Electrical Technology, Bombay Univ. 1987)

Solution. The *O.C.C.* as plotted from the given data is shown in Fig. 28.13. The 34-Ω line *OA* is drawn as usual.

(*a*) The voltage to which machine will excite = *OM* = **255 V.**

(*b*) The horizontal line from *N* (220 V) is drawn which cuts the *O.C.C.* at point *B*. Resistance represented by line *OB* = 220/5.4 = **40.7 Ω.**

(*c*) Line *OC* has been drawn which is tangential at the origin to the *O.C.C.* This represents the value of critical resistance = 140/2.25 = **62.2 Ω.**

(*d*) Take any convenient point *D* and erect a perpendicular which cuts both *OA* and *OC*.

$$\frac{DE}{DF} = \frac{N_C}{400} \quad \text{or} \quad \frac{110}{202} = \frac{N_C}{202}, N_C = \textbf{218 r.p.m.}$$

(*e*) From point *P* (225 V) drawn a horizontal line cutting *OA* at point *G*. From *G*, draw a perpendicular line *GK* cutting the *O.C.C.* at point *H*. If *N'* is the lowest speed possible for getting 225 volt with 34 Ω shunt circuit resistance, then

$$\frac{GK}{HK} = \frac{N'}{400} \quad \text{or} \quad \frac{225}{241} \text{ or } N' = \textbf{375 r.p.m.}$$
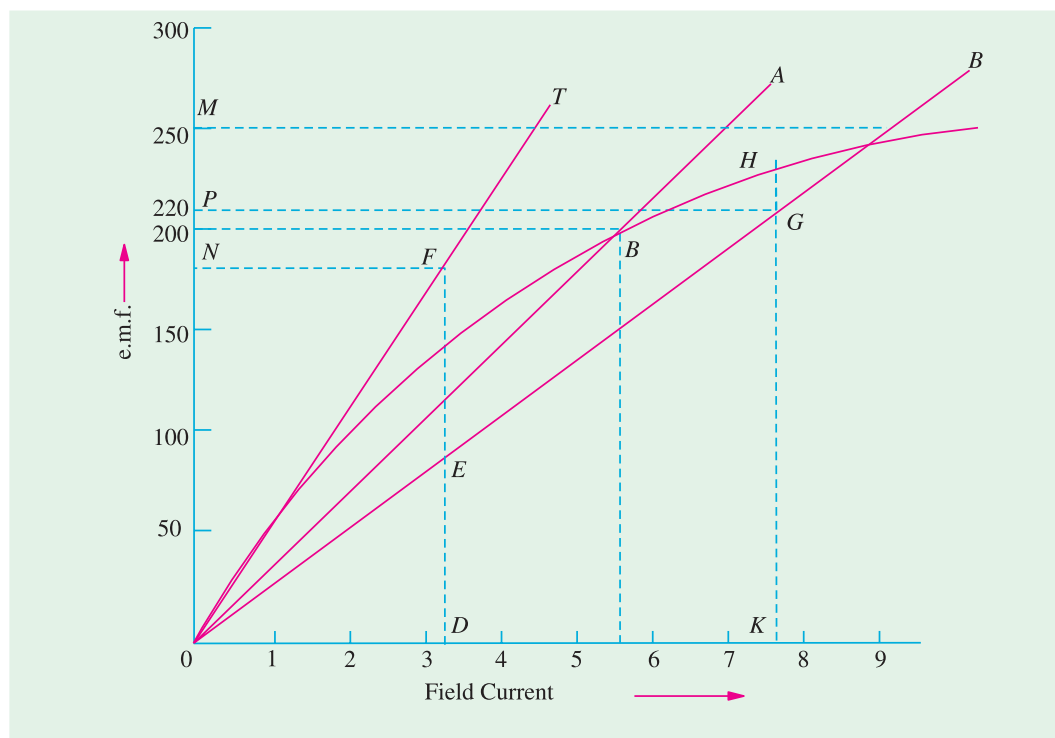

Fig. 28.13

Example 28.8. *The magnetization characteristic for a 4-pole, 110-V, 1000 r.p.m. shunt generator is as follows :*

Field current	0	0.5	1	1.5	2	2.5	3 A
O.C. voltage	5	50	85	102	112	116	120 V

Armature is lap-connected with 144 conductors. Field resistance is 45 ohms. Determine

  (i) *voltage the machine will build up at no-load.*

  (ii) *the critical resistance.*

  (iii) *the speed at which the machine just fails to excite.*

  (iv) *residual flux per pole.*

(Electrical Machinery- I, Mysore Unit. 1988)

Fig. 28.14

Solution. In Fig. 28.14, *OA* represents the 45-Ω line which is drawn as usual.

  (i) The voltage to which machine will build up = *OM* = **118 V.**

  (ii) *OT* is tangent to the initial part of the O.C.C. It represents critical resistance. Take point *B* lying on this line. Voltage and exciting current corresponding to this point are 110 V and 1.1 A respectively.

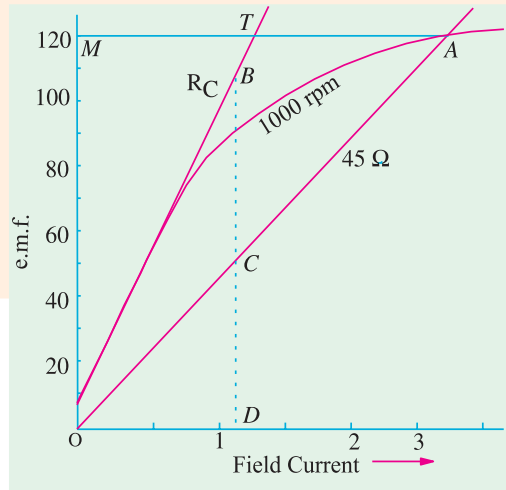$$\therefore \qquad\qquad R_c \ = \ 110/1.1 = \mathbf{100\ \Omega}$$

  (iii) From any point on *OT*, say point *B*, drop the perpendicular *BD* on *X*-axis.

$$\frac{CD}{BD} \ = \ \frac{N_c}{1000} \quad \text{or} \quad \frac{49}{110} = \frac{N_c}{1000}$$

$$\therefore \qquad\qquad N_c \ = \ \mathbf{445\ r.p.m.}$$

  (iv) As given in the table, induced e.m.f. due to residual flux (*i.e.* when there is no exciting current) is 5 V.

$$\therefore \qquad\qquad 5 \ = \ \frac{\Phi \times 144 \times 1000}{60}\left(\frac{4}{4}\right) \qquad \therefore \ \ \Phi = \mathbf{2.08\ mWb.}$$

Example 28.9. *A shunt generator gave the following results in the O.C.C. test at a speed of r.p.m.*

Field current (A) :	1	2	3	4	6	8	10
E.M.F. (volt) :	90	185	251	290	324	345	360

The field resistance is adjusted to 50 Ω and the terminal is 300 V on load. Armature resistance is 0.1 Ω and assuming that the flux is reduced by 5% due to armature reaction, find the load supplied by the generator. **(Electromechanic, Allahabad Univ.; 1992)**

Solution. When the terminal voltage is 300 V and R_{sh} = 50 Ω, then field current is

$$= \ 300/40 = 6\ A$$

With this shunt current, the induced e.m.f. as seen from the given table (we need not draw the O.C.C.) is 324 V.

Due to armature reaction, the flux and hence the induced e.m.f. is reduced to 0.95 of its no-load value.

Hence, induced e.m.f. when generator is no load = 324 × 0.95 = 307.8 V

Armature drop at the given load = 307.8 − 300 = 7.8 V

$$I_a R_a = 7.8, \quad I_a = 7.8/0.1 = 78 \text{ A}$$

Load current = 78 − 6 = 72 A ; Generator output = 72 × 300/1000 = **21.6 kW**

Example 28.10. *A shunt generator gave the following open-circuit characteristic :*

Field current :	0.5	1.0	1.5	2.0	2.5	3.0	3.5 A
O.C. e.m.f. :	54	107	152	185	210	230	245 V

The armature and field resistances are 0.1 Ω and 80 Ω respectively. Calculate (a) the voltage to which the machine will excite when run as a shunt generator at the same speed.

(b) The volts lost due to armature reaction when 100 A are passing in the armature at a terminal voltage of 175 V.

(c) The percentage reduction in speed for the machine to fail to excite on open circuit.

(Electrical Machines-I, Bombay Univ. 1988)

Solution. (*a*) O.C.C. is shown in Fig. 28.15. *OA* represents 80 Ω line. The maximum voltage to which the generator will build up is given by *OM* = **222 V.**

Fig. 28.15

(*b*) With 175 V terminal p.d. on load

$$I_{sh} = 175/80 = 2.2 \text{ A}$$

Voltage corresponding to this field current is given by *OC* = 195 V.

Voltage lost due to armature reaction and armature drop = 195 − 175 = 20 V.

Now, armature drop = 0.1 × 100 = 10 V

Let '*x*' be the volts lost due to armature reaction.

Then 10 + *x* = 20   ∴   *x* = **10 V**

(*c*) Line *OT* is drawn tangential to the curve. *DFG* is perpendicular to the base line.

$$\frac{N_c}{N} = \frac{FG}{DG} = \frac{160}{220} \quad \text{or} \quad \frac{N_e - N}{N} = \frac{-60}{220}$$

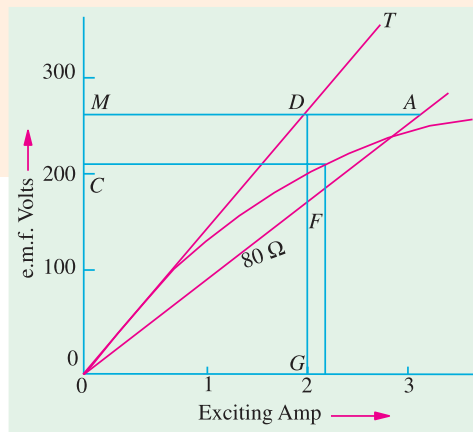Percentage reduction in speed = $\frac{-60}{220} \times 100$ = **– 27.3 %**

Example 28.11. *The O.C.C. of a shunt generator running at 800 r.p.m. is as follows :*

Field current (amp.)	:	1	2	3	4	5	6
Induced e.m.f. (volt).	:	82.5	180	225	252	273	282

If the shunt field resistance is 60 Ω, find

(i) the voltage to which the machine will build up running at the same speed (ii) the value of field regulating resistance if the machine is to build up to 120 V when its field coils are grouped in two parallel circuits and generator is runing at half the speed.

(Electrical Technology, Hyderabad Univ. 1991)

Solution. O.C.C. is drawn from the given data and is shown in Fig. 28.16. *OA* represents 60 Ω. The voltage corresponding to point *A* is *OM* = 260 V.

(*i*) Generator will build up to **260 volts.**

(*ii*) Lower curve represents the induced e.m.f. for different exciting current values at 400 r.p.m. From point *B* which represents 120 V, draw *BC*. From *C* draw a perpendicular *CD* which gives the

exciting current of 3.6 A. It means that current through *each* parallel path of shunt field coils is 3.6 A. Total current which passes through the field regulator resistance is $3.6 \times 2 = 7.2$ A because it is in series with the field coils.

Hence, total shunt field resistance = $120/7.2 = 16.67$ Ω

Now, resistance of each shunt parallel path = $60/2 = 30$ Ω

Joint resistance of two parallel paths = $30/2 = 15$ Ω

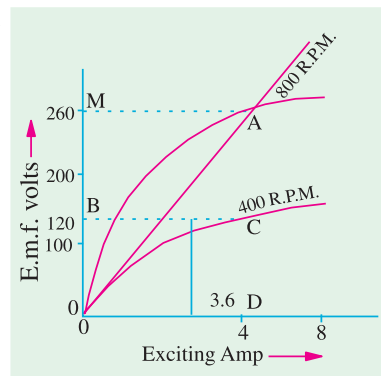∴   Shunt field regulator resistance = $16.67 - 15 = $ **1.67 Ω**

Fig. 28.16

28.7. Voltage Build up of a Shunt Generator

Before loading a shunt generator, it is allowed to build up its voltage. Usually, there is always present some residual magnetism in the poles, hence a small e.m.f. is produced initially. This e.m.f. circulates a small current in the field circuit which increases the pole flux (provided field circuit is properly connected to armature, otherwise this current may wipe off the residual magnetism). When flux is increased, generated e.m.f. is increased which further increases the flux and so on. As shown in Fig. 28.17, *Oa* is the induced e.m.f. due to residual magnetism which appears across the field circuit and causes a field current *Ob* to flow. This current aids residual flux and hence produces, a larger induced e.m.f. *Oc*. In turn, this increased e.m.f. *Oc* causes an even larger current *Od* which creates more flux for a still larger e.m.f. and so on.

Now, the generated e.m.f. in the armature has

(*a*)   to supply the ohmic drop $I_f R_{sh}$ in the winding and (*b*) to overcome the opposing self-induced e.m.f. in the field coil *i.e. L. (d I_f/ dt)*because field coils have appreciable self-inductance.

$$e_g = I_f R_{sh} + L \cdot d I_f/dt$$

If (and so long as), the generated e.m.f. is in excess of the ohmic drop $I_f R_{sh}$, energy would continue being stored in the pole fields. For example, as shown in Fig. 28.17, corresponding to field current *OA*, the generated e.m.f. is *AC*. Out of this, *AB* goes to supply ohmic drop $I_f R_{sh}$ and *BC* goes to overcome self-induced e.m.f. in the coil. Corresponding to $I_f = OF$, whole of the generated e.m.f. is used to overcome the ohmic drop. None is left to overcome $L.dI_f/dt$. Hence no energy is stored in the pole fields. Consequently, there is no further increase in pole flux and the generated e.m.f. With the given shunt field resistance represented by line *OP*, the maximum voltage to which the machine will build up is *OE*. If resistance is decreased, it will built up to a somewhat higher voltage. *OR* represents the resistance known as *critical resistance*. If shunt field resistance is greater than this value, the generator will fail to excite.
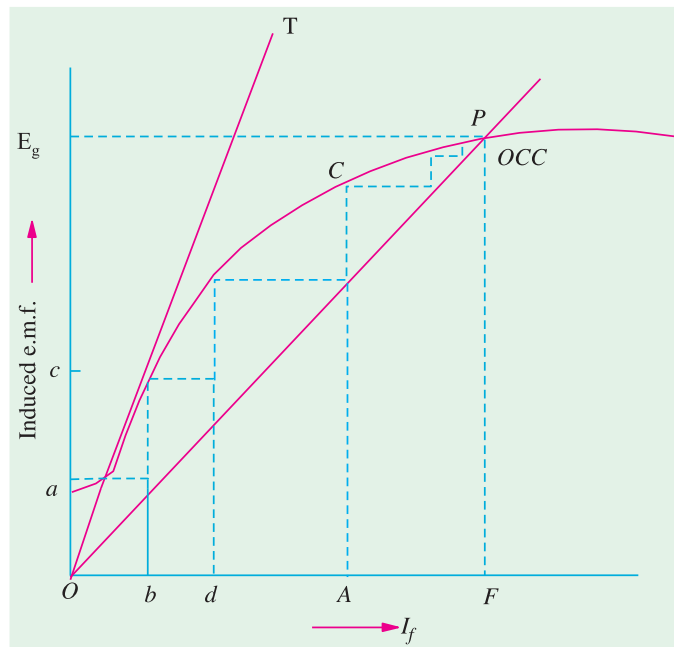

Fig. 28.17

28.8.   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 e.m.f. 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.)

Fig. 28.18

4.   If excited on load, then its shunt field resistance should be more than a certain minimum value of resistance which is given by internal characteristic (Art 28.11).
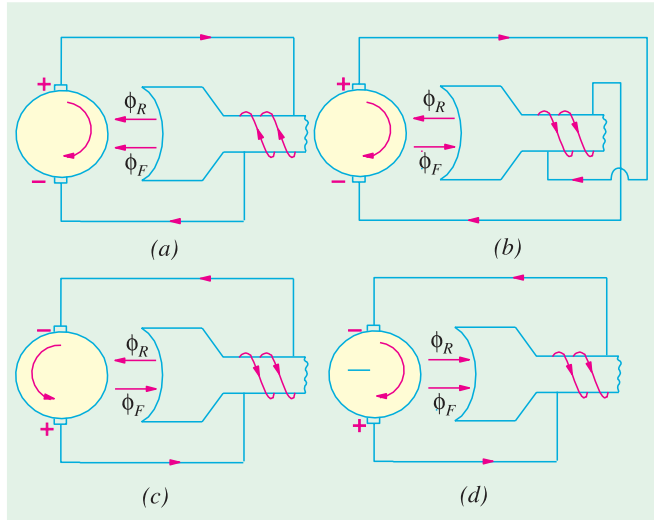
28.9.   Other Factors Affecting Voltage Building of a DC Generator

In addition to the factors mentioned above, there are some other factors which affect the voltage building of a self-excited d.c. generator. These factors are (*i*) reversed shunt field connection (*ii*) reversed rotation and (*iii*) reversed residual magnetism. These adverse effects would be explained with the help of Fig. 28.18 and the right-hand rule for finding the direction of the coil flux. For the sake of simplicity, only one field pole has been shown in the Fig. 28.18.

Fig. 28.18 (*a*) represents the normal operation, the prime mover rotation is clockwise and both the residual flux Φ_R and the field flux Φ_F are directed to the left.

Fig. 28.18 (*b*) shows reversed connection of the field circuit which causes Φ_F to oppose Φ_R. Consequently, the generator voltage builds down from its original residual value.

In Fig. 28.18 (*c*), reversed armature rotation causes the reversal of the voltage produced by the residual magnetism. Even though the field coil connections are correct, the reversed field current flow causes Φ_F to oppose Φ_R so that the voltage builds down from its original residual value.

Fig. 28.18 (*d*) shows the case when due to some reason the residual magnetism gets reversed. Hence, the armature voltage is also reversed which further reverses the field current. Consequently, both Φ_F and Φ_R are reversed but are directed to the right as shown. Under this condition, the voltage buildup is in the reversed direction. Obviously, the generator will operate at rated voltage but with reversed polarity.

If desired, the reversed polarity can be corrected by using an external d.c. source to remagnetise the field poles in the correct direction. This procedure is known as field flashing.

Example 28.12. *The O.C.C. of a generator is given by the following :*

Field current :	1.5	3.5	4.5	6	7.5	9	10.5
E.M.F. :		168	330	450	490	600	645	675

The speed at which data is obtained is 1000 r.p.m. Find the value of the shunt field resistance that will give a p.d. of 600 V with an armature current of 300 A at the same speed. Due to armature

reaction, the shunt field current is given by I_{sh} (eff.) = I_{sh} – 0.003 I_a. Armature resistance, including brush contact resistance, is 0.1 Ω. What will be the p.d. on open circuit at the same speed ?

Solution. As shown in Fig. 28.19, the *O.C.C.* has been plotted from the given data.

Voltage drop due to armature resistance = 300 × 0.1 = 30 V.

Reduction of field current due to armature reaction = 0.003 × 300 = 0.9 A.

Any point *A* is taken on the *O.C.C.* A vertical distance *AB* = 30 V is taken and then the horizontal line *BC* = 0.9 A is drawn thus completing triangle *ABC* which is known as drop reaction triangle. Then, point *C* lies on the 300 ampere load saturation curve. This curve can be drawn by finding such similar points like *C′* etc.

Fig. 28.19

From point *L* representing 600 V, a horizontal line is drawn cutting the load saturation curve at *D*. Join *OD*. Current corresponding to point *D* is 9.4 A. The slope of I_f the line *OD* gives the value of shunt resistance to give 600 V with 300 amperes of armature current.

∴ R_{sh} = 600/9.4 = **63.8 Ω**
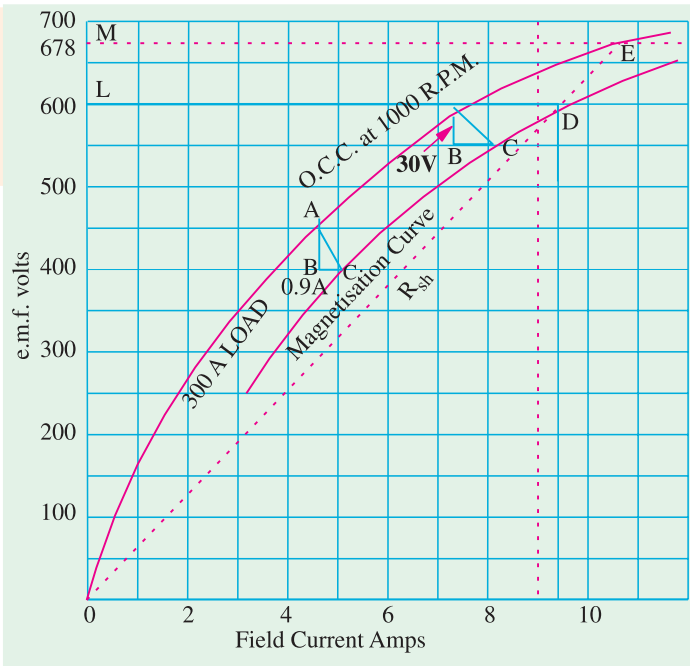
It is seen that e.m.f. on open circuit is **678 V.**

28.10. External Characteristic

After becoming familiar with the no-load characteristic of a shunt generator, we will now proceed to find its external characteristic (*V/I*) when loaded. 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 e.m.f. 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 e.m.f. 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 e.m.f.

For obtaining the relation between the terminal voltage and load current, the generator is connected as shown in Fig. 28.20 (*a*).
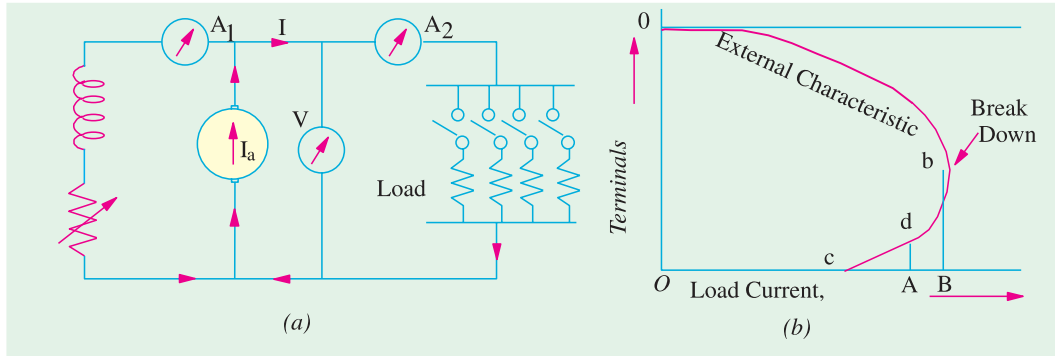

Fig. 28.20

The shunt generator is first excited on no-load so that it gives its full open circuit voltage = *Oa* [Fig. 28.20 (*b*)]. Then, the load is gradually applied and, at suitable intervals, the terminal voltage *V* (as read by the voltmeter) and the load current *I* (as read by the ammeter A_2) are noted. The field current as recorded by ammeter A_1 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 of Fig. 28.20 (*b*) 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 effect 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.*

We will discuss the reason for this unusual behaviour of the generator in more details. Over the earlier portion *ab* [Fig. 28.20 (*b*)] where the load current is comparatively small, when external load resistance is decreased, it results in increased load current as might be expected keeping Ohm's law in mind. It should not, however, be forgotten that due to increase in load current, *V* is also decreased somewhat due to the cause (*iii*) given above. But over the portion *ab*, the effect of decrease in load resistance predominates the effect of decrease in *V* because load current is relatively small.

At point *b*, generator is delivering a very large current *i.e.* current which is many times greater than its normal current. If load resistance is decreased at this point so as to be able to draw a load current greater than *OB*, the current is *increased* momentarily. But due to the severe armature reaction for this heavy current and increased $I_a R_a$ drop, the terminal voltage *V* is drastically reduced. The effect of this drastic reduction in *V* results in less load current (= *OA*). In other words, over the portion *bdc* of the curve, the terminal voltage *V* decreases more rapidly than the load resistance. Hence, any, further decrease in load resistance actually causes a *decrease* in load current (it may seem to contravene Ohm's law but this law is not applicable, here since *V* is not constant). As load resistance is decreased beyond point *b*, the curve turns back till when the generator is actually short-circuited, it cuts the current axis at point *c*. Here, terminal voltage *V* is reduced to zero, though there would be some value of *E* due to residual magnetism (Fig. 28.22).

28.11. 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,   regn. $= (240 - 220)/220 = 0.091$ or 9.1 %

28.12. Internal or Total Characteristic

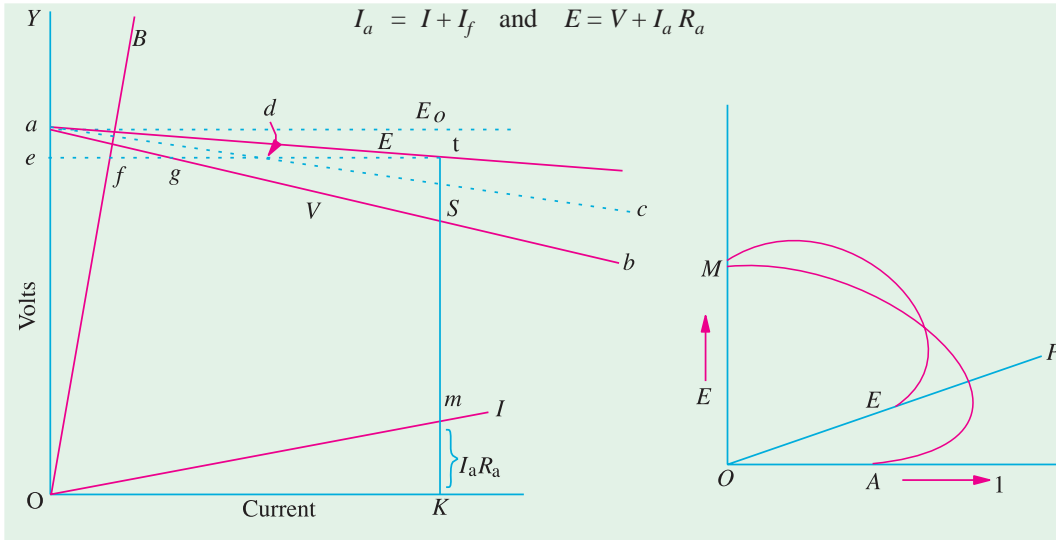As defined before, internal characteristic gives the relation between E and I_a. Now in a shunt generator

$$I_a = I + I_f \quad \text{and} \quad E = V + I_a R_a$$

Fig. 28.21   Fig. 28.22

Hence, E/I_a curve can be obtained from V/I curve as shown in Fig. 28.21. 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 $I_a R_a = mK$. 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 $I^2 R$ losses in armature and shunt field windings and the rest appears as output.

As explained in Art 28.10 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 as shown in Fig. 28.22. If the load resistance is too small, then the generator is short-circuited and there is no generated e.m.f. 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.*

28.13. Series Generator

Series generator

In this generator, because field windings are in series with the armature [Fig. 28.23 (*a*)], they carry full armature current I_a. As I_a is increased, flux and hence generated e.m.f. 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. 28.23 (*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.

Example 28.13. *In a 220 V supply system, a series generator, working on a linear portion of its magnetisation characteristic is employed as a booster. The generator characteristic is such that induced e.m.f. increases by 1 volt for every increase of 6 amperes of load current through the generator. The total armature resistance of the generator is 0.02 Ω. If supply voltage remains constant, find the voltage supplied to the consumer at a load current of 96 A. Calculate also the power supplied by the booster itself.*
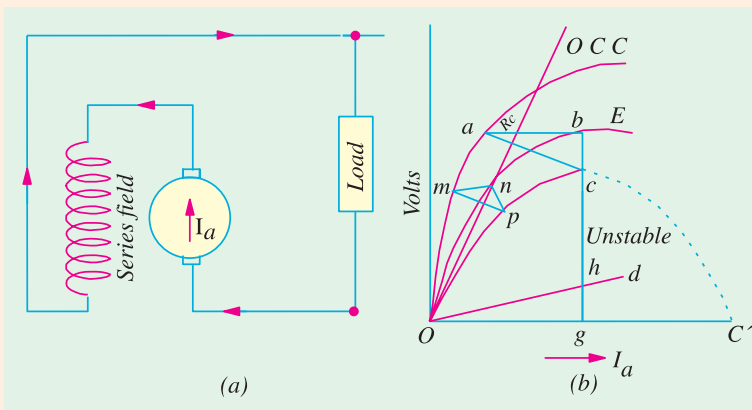

Fig. 28.23

Solution.

Voltage increase for 6 amperes	=	1 V ∴ Voltage increase for 96 A = 96/6 = 16 V
Voltage drop in series coils	=	96 × 0.02 = 1.9 V
Net Voltage rise due to booster	=	16 − 1.9 = 14.1 V
Voltage at consumer end	=	220 + 14.1 = **234.1 V**
Power supplied by booster itself	=	14.1 × 96 = 1354 W = **1.354 kW**

Example 28.14. *A d.c. series generator, having an external characteristic which is a straight line through zero to 50 V at 200 A is connected as a booster between a station bus bar and a feeder of 0.3 ohm resistance. Calculate the voltage difference between the station bus-bar and the far end of the feeder at a current of (i) 200 A and (ii) 50 A.*

(AIME Sec. B Elect. Machine Summer 1991)

Solution. (*i*)   Voltage drop   =   200 × 0.3 = 60 V

Booster voltage provided by series generator for 200 A current as given = 50 V.

∴   Net voltage decrease   = $60 - 50 = 10$ V

(*ii*)   Feeder drop   = $50 \times 0.3 = 15$ V

Booster voltage provided by series generator (by proportion) is

$$= 50 \times 50/200 = 12.5 \text{ V}$$

∴   Net decrease in voltage   = $15 - 12.5 = 2.5$ V

28.14. 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 (Fig. 28.24). 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 e.m.f. is also increased. By adjusting the number of series turns (or series amp-turns), this increase in e.m.f. 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 (Art 28.10). Out of these three, the first two are neutralized by the series field amp-turns and the third one, therefore, does not occur.

Series Generator   Shunt Generator

Compound-wound generator
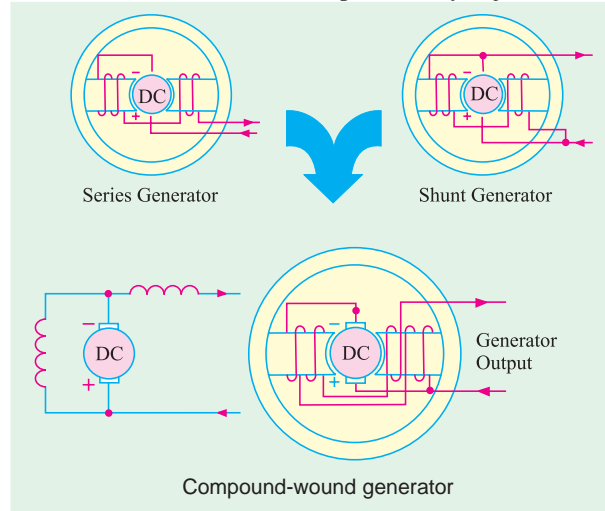
If the series field amp-turns are such as to produce the same voltage at rated load as at no-load, then the generator is *flat-compounded*. It should be noted, however, that even in the case of a flat-compounded generator, the voltage is not constant from no-load to rated-load. At half the load, the voltage is actually greater than the rated voltage as seen from Fig. 28.24.

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.
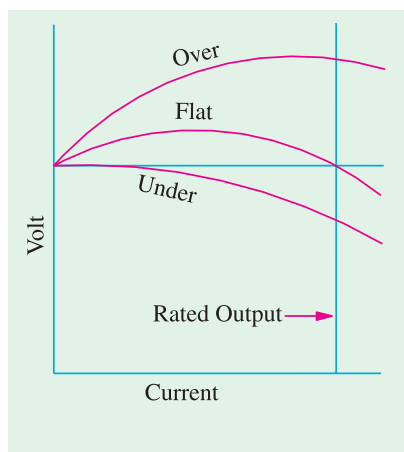

Fig. 28.24

28.15. 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

Fig. 28.25

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 $= 1000/250 = 4$.
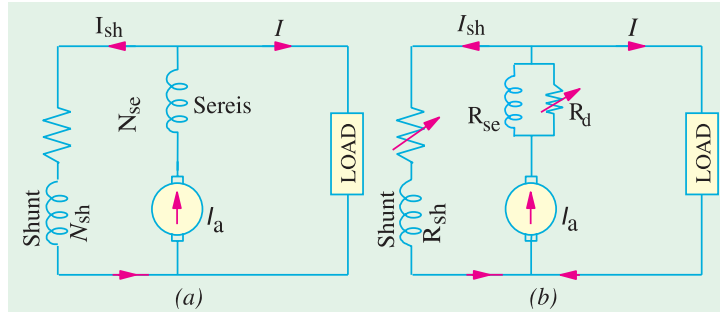
In general, let

ΔI_{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 $N_{sh} \cdot \Delta_{sh}$. This increase in field excitation can be alternatively achieved by adding a few series turns to the shunt generator [Fig. 28.25 (a)] thereby converting it into a compound generator.

∴ $N_{sh} \cdot \Delta I_{sh} = N_{se} I_{se}$

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. 28.25 (b).

As said above, the degree of compounding can be adjusted with the help of a variable-resistance, divertor as shown in Fig. 28.25 (b). If I_d is the current through the divertor of resistance R_d, then remembering that series windings and divertor are in parallel,

∴ $I_{se} \cdot R_{se} = I_d R_d$ or $R_d = I_{se} R_{se}/I_d$

Example 28.15. *A shunt generator is converted into a compound generator by addition of a series field winding. From the test on the machine with shunt excitation only, it is found that a field current of 5 A gives 440 V on no-load and that 6 A gives 440 V at full load current of 200 A. The shunt winding has 1600 turns per pole. Find the number of series turns required.*

(Elect. Machines, A.M.I.E., Sec., B, 1991)

Solution. It would be assumed that shunt generator is converted into a short shunt compound generator. It is given that for keeping the voltage of shunt generator constant at 440 V both at no-load and full-load, shunt field ampere-turns per pole have to be increased from $1600 \times 5 = 8000$ to

$(1600 \times 6) = 9600$ *i.e.* an increase of $(9600 - 8000) = 1600\ AT$. The same increase in field AT can be brought about by adding a few series turns.

Let n be the number of series turns required per pole. Since they carry 200 A,

$\therefore$ $\qquad n \times 200 = 1600; n =$ **8 turns/pole**

Example 28.16. *A long shunt compound generator has a shunt field winding of 1000 turns per pole and series field winding of 4 turns per pole and resistance 0.05 Ω. In order to obtain the rated voltage both at no-load and full-load for operation as shunt generator, it is necessary to increase field current by 0.2 A. The full-load armature current of the compound generator is 80 A. Calculate the divertor resistance connected in parallel with series field to obtain flat compound operation.*

(Elect. Machines A.M.I.E. Sec. B, 1993)

Solution.

Additional AT required to maintain rated voltage both at no-load and full-load (Fig. 28.26) $= 1000 \times 0.2 = 200$

No. of series turns/pole $= 4$

Current required to produce 200 AT by the series field $= 200/4 = 50$ A.

Since $\qquad I_a = 80$ A, the balance of 30 A must pass through the parallel divertor resistance.

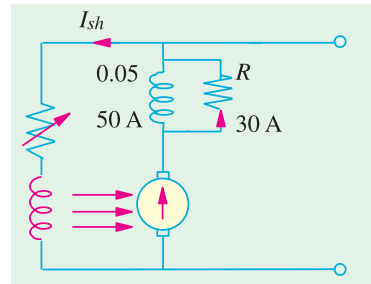$\therefore$ $\qquad 30\,R = 50 \times 0.05, R = 0.0833\ \Omega$

Fig. 28.26

Example 28.17. *A 220-V compound generator is supplying a load of 100 A at 220 V. The resistances of its armature, shunt and series windings are 0.1 Ω, 50 Ω and 0.06 Ω respectively. Find the induced e.m.f. and the armature current when the machine is connected (a) short shunt (b) long shunt (c) how will the series amp-turns be changed in (b) if a divertor of 0.14 Ω is connected in parallel with the series windings ? Neglect armature reaction and brush contact drop.*

Solution. (*a*) **Short-shunt** (Fig. 28.27).

$\qquad$ Voltage drop in series $= 100 \times 0.06 = 6$ V; $I_{sh} = 220/50 = 4.4$ A.

$\therefore$ $\qquad I_a = 100 + 4.4 =$ **104.4**

$\qquad$ Armature drop $= 104.4 \times 0.1 = 10.4$ V

$\therefore$ $\qquad$ Induced e.m.f. $= 220 + 6 + 10.5 =$ **236.4 V**

(*b*) **Long-shunt** (Fig. 28.28)

$\qquad I_{sh} = 220/50 = 4.4$ A $\quad \therefore \quad I_a = 100 + 4.4 =$ **104.4 A**

Voltage drop over armature and series field winding $= 104.4 \times 0.16 = 16.7$ V

$\therefore$ $\qquad$ Induced e.m.f. $= 200 + 16.7 =$ **216.7 V**
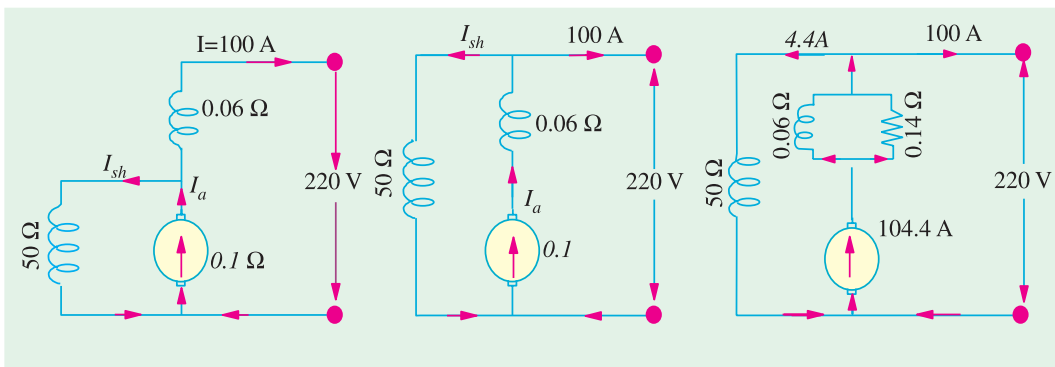

Fig. 28.27 $\qquad\qquad$ **Fig. 28.28** $\qquad\qquad$ **Fig. 28.29**

(*c*) As shown in Fig. 28.29, a divertor of resistance 0.14 Ω is connected in parallel with the series field winding. Let *n* be the number of series turns.

Number of series amp-turns without divertor = $n \times 104.4 = 104.4\,n$

When divertor is applied, then current through series field is

$$= \frac{104.4 \times 0.14}{(0.14 + 0.06)} = 73.8\ A$$

∴   Series amp-turns = $73.8 \times n$ ∴ Series amp-turns are reduced to $\dfrac{73.8\,n}{104.4\,n} \times 100 =$ **70 %**

Example 28.18. *A 250-kW, 240-V generator is to be compounded such that its voltage rises from 220 volts at no-load to 240 V at full load. When series field is cut out and shunt field is excited from an external source, then from the load test it is found that this rise in voltage can be obtained by increasing the exciting current from 7 A at no-load to 12 A at full-load. Given shunt turns/pole = 650, series turns/pole = 4 and resistance of series winding, 0.006 Ω. If the machine is connected long-shunt, find the resistance of the series amp-turns at no-load and drop in series winding resistance at full-load.*

Solution.   Full-load current $= 250 \times 10^3/240$

$\qquad\qquad\qquad\qquad\quad = 1042\ A$

Increase in shunt field ampere-turns to over-compound the shunt generator

$\qquad = 650\,(12 - 7) = 3,250.$ As seen from Fig. 28.30

$\qquad 4 \times I_{se} = 3250$

$\qquad\qquad I_{se} = 3250/4 = 812.5\ A$

∴ $\qquad I_d = 1042 - 812.5 = 229.5\ A$

It is so because no-load shunt current being negligible, $I_a = I = 1042\ A$.

Fig. 28.30

Since series winding and divertor are in parallel, $I_d\,R_d = I_{se}\,R_{se}$ or $229.5\,R_d = 812.5 \times 0.006$

∴ $\qquad R_d = $ **0.0212 Ω**

Example 28.19. *A 60-kW d.c. shunt generator has 1600 turns/pole in its shunt winding. A shunt field current of 1.25 A is required to generate 125 V at no-load and 1.75 A to generate 150 V at full load. Calculate*

 (*i*) *the minimum number of series turns/pole needed to produce the required no-load and full-load voltages as a short-shunt compound generator.*

(*ii*) *if the generator is equipped with 3 series turns/pole having a resistance of 0.02 Ω, calculate divertor resistance required to produce the desired compounding.*

(*iii*) *voltage regulation of the compound generator.*

Solution. (*i*) Extra excitation ampere-turns required = $1600\,(1.75 - 1.25) = 800$

$\qquad\qquad I_{se} = I = 60,000/150 = 400\ A$

∴   No. of series turns/pole required = $800/400 =$ **2**

Hence, minimum number of series turns/pole required for producing the desired compound generator terminal voltage is **2**.

(*ii*) Now, actual No. of series turns/pole is 3. Hence, current passing through it can be found from

$\qquad\qquad 3 \times I_{se} = 800;\ I_{se} = 800/3\ A$

As shown in Fig. 28.31, $I_d = 400 - (800/3) = 400/3\ A$

Also $(800/3) \times 0.02 = (400/3) \times R_d;\quad R_d = $ **0.04 Ω**

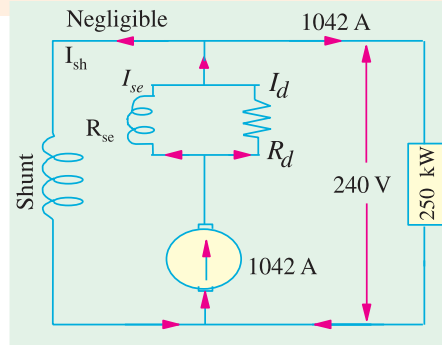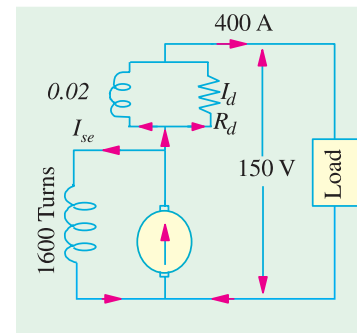(*iii*)$\qquad$ % regn. = $(125 - 150) \times 100/150 = $ **– 16.7%**

Fig. 28.31

Example 28.20. *A D.C. generator having an external characteristics which is a straight line through zero to 50 V at 200 Amp, is connected as a booster between a station bus-bar and a feeder of 0.3 ohm resistance. Calculate the voltage between the far end of the feeder and the bus-bar at a current of (i) 160 A, (ii) 50 A.*   **(Manomaniam Surdaranar Univ. Nov. 1998)**

Solution. Due to the feeder resistance of 0.3 ohm there is a voltage drop of 1×0.3 volts in the direction of current, where I refers to the current flowing. Due to booster, there is a rise in voltage given by $I \times (50/200)$ according to the *V-I* characteristic given for the series generator. As a sum total of these two, the net feeder drop will be $I \times (0.3 - 0.25)$ or I volts, and that represents the voltage between far end of the feeder and the bus-bar.

(*i*)   **At 160 A,** the net voltage drop in feeder = 160×0.05 or $48 - 40 = 9$ volts.

Since 48 volts drop is partially compensated by 40 volts boosted up.

(*ii*)   **At 50 A,** the required answer = (15 volts drop 12.5 volts boosted up) = 2.5 volts drop.
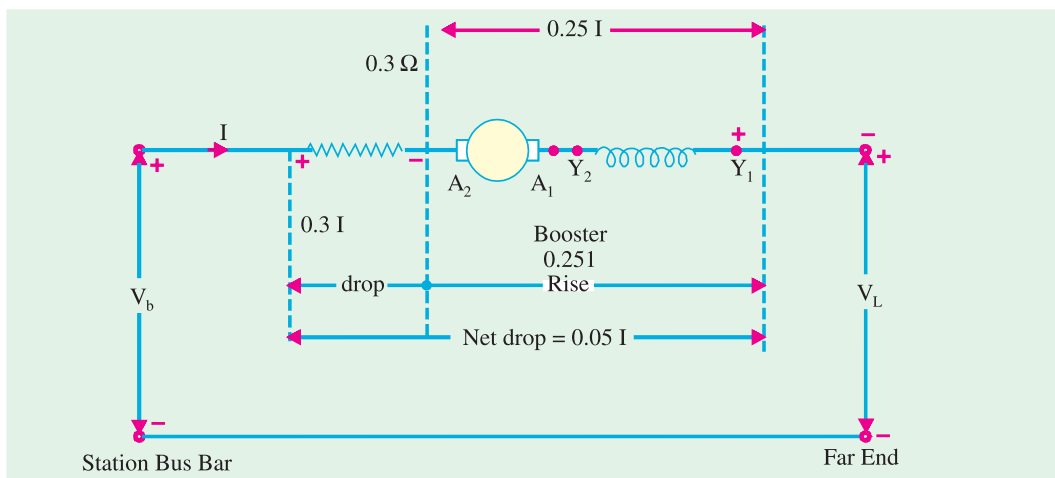
Fig. 28.32. Feeder and Booster

28.16. 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 (Ex. 28.15) 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

Compound generators are used in electric railways

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.

Tutorial Problem in 28.1

1. The *OC* curve of a d.c. shunt generator for a speed of 1000 r.p.m. is given by the following table.

Field current :	2.0	3.0	4.0	5.0	6.0	7.0
E.M.F. volts :	102	150	188	215	232	245

The shunt has a resistance of 37 Ω. Find the speed at which excitation may be expected to build up.

The aramture resistance of 0.04 Ω. Neglecting the effects of brush drop and armature reaction, estimate the p.d. when the speed is 1000 r.p.m. and the armature delivers a current of 100 A.   **(725 r.p.m.; 231 V)**

2. A d.c. shunt generator running at 850 r.p.m. gave the followig *O.C.C.* data :

Field current (A)	:	0	0.5	1	2	3	4	5
E.M.F. (V)	:	10	60	120	199	232	248	258

If the resistance of the shunt field is 50 Ω, determine the additional resistance required in the shunt field circuit to give 240 V at a speed of 1000 r.p.m.   **[64.3 Ω)**

3. Sketch the load characteristic of a d.c. generator with (*i*) shunt (*ii*) series excitation. Give reasons for the particular shape in each case.

The *O.C.C.* at 700 r.p.m. of a series generator with separately-excited field is as follows :

Field current (A)	:	20	40	50	60	75
Armature e.m.f. (V)	:	190	360	410	450	480

Determine the current and terminal voltage as a self-excited series machine when running at 600 r.p.m. with a load of 6 Ω connected to the terminal. Resistance of armature and series winding is 0.3Ω. Ignore effect of armature reaction.   **[369 V; 61.5 A]**

4. The *O.C.C.* data for separately-excited generator when run at 130 r.p.m. on open circuit is

E.M.F. (V)	:	12	44	73	98	113	122	127
Exciting current	:	0	0.2	0.4	0.6	0.8	1.0	1.2

Deduce the curve of e.m.f. and excitation when the generator is running separately-excited at 1000 r.p.m. To what voltage will the generator build up on no-load when running at 1000 r.p.m.? To what voltage will the generator build up on no-load when running at 100 r.p.m. if the total field resistance is 100 Ω ?   **[91 V]**

5. The following figures give the *O.C.C.* of d.c. Shunt generator driven at a constant speed of 700 r.p.m.

Terminal voltage (V):	10	20	40	80	120	160	200	240	260
Field Current (A) :	0	0.1	0.24	0.5	0.77	1.2	1.92	3.43	5.2

Determine the critical resistance at (*a*) 700 r.p.m. (*b*) 850 r.p.m. If resistance of field coils is 50 Ω, find the range of the field rheostat required to vary the voltage between the limits of 180 V and 250 V on open circuit at a speed of 700 r.p.m.   **[160 Ω ; 194 Ω; 70 Ω to 10 Ω]**

6. The *O.C.C.* of a shunt generator when separately-excited and running at 1000 r.p.m. is given by :

O.C.C. volt :	56	112	150	180	200	216	230
Field amp. :	0.5	1.0	1.5	2.0	2.5	3.0	3.5

If the generator is shunt-connected and runs at 1100 r.p.m. with a total field resistance of 80 Ω, determine

(*a*) no-load e.m.f.

(*b*) the output when the terminal voltage is 200 V if the armature resistance is 0.1 Ω.

(*c*) the terminal voltage of the generator when giving the maximum output current.

Neglect the effect of armature reaction and of brush contact drop.

[236 V; 200 V; 460 V; 150 V (approx.)]

7. A long-shunt compound d.c. generator with armature, series field and shunt field resistance of 0.5, 0.4 and 250 Ω respectively gave the following readings when run at constant speed :

Load current (A)	:	0	10	20	30	40
Terminal p.d. (V)	:	480	478	475	471	467

Plot the curve of internal generated e.m.f. against load current. Explain fully the steps by which this curve is obtained and tabulate the values from which it is plotted.   **[For 40 A; E = 504.7 V (approx.)]**

8. A shunt generator has the following open-circuit characteristic at 800 r.p.m.

Field amperes	:	0.5	1.0	1.5	2.0	2.5	3.0	3.5
E.M.F. Volt	:	54	107	152	185	210	230	245

Armature and shunt field resistances are respectively 0.1 Ω and 80 Ω. The terminal p.d. falls to 175 V when the armature current is 100 A. Find the O.C. volts and the volts lost due to (*i*) reduction in the field current (*ii*) armature resistance (*iii*) armature reaction.   **[220 V (*i*) 27 V (*ii*) 120 V (*iii*) 8 V]**

9. The open-circuit characteristic of a shunt generator when driven at normal speed is as follows :

Field current	:	0.5	1.0	1.5	2.0	2.5	3.0	3.5 A
O.C. volts	:	54	107	152	185	210	230	240 V

The resistance of armature circuit is 0.1 Ω. Due to armature reaction the effective field current is given by the relation I_{sh} (eff.) $= I_{sh} - 0.003\,I_a$. Find the shunt field circuit resistance that will give a terminal voltage of 220 V with normal speed (*a*) on open circuit (*b*) at a load current of 100 A. Also find (*c*) number of series turns for level compounding at 220 V with 100 A armature current ; take number of shunt turns per pole as 1200 and (*d*) No. of series turns for over-compounding giving a terminal voltage of 220 V at no-load and 230 V with 100 A armature current.   **[(*a*) 80 Ω (*b*) 66 Ω (*c*) 6.8 Ω (*d*) 9.1 turns]**

10. Find how many series turns per pole are needed on a 500-kW compound generator required to give 450 V on no-load and 500 V on full-load, the requisite number of ampere-turns per pole being 9,000 and 6,500 respectively. The shunt winding is designed to give 450 V at no-load when its temperature is 20°C. The final temperature is 60°C. Take $\alpha_0 = 1/234.5$ per °C.

[2.76] (Electrical Technology, Allahabad Univ. 1977)

OBJECTIVE TESTS – 28

1. The external characteristic of a shunt generator can be obtained directly from its —— characteristic.
(*a*) internal
(*b*) open-circuit
(*c*) load-saturation
(*d*) performance

2. Load saturation characteristic of a d.c. generator gives relation between
(*a*) V and I_a
(*b*) E and I_a
(*c*) E_0 and I_f
(*d*) V and I_f

3. The slight curvature at the lower end of the *O.C.C.* of a self-excited d.c. generator is due to
(*a*) residual pole flux
(*b*) high armature speed
(*c*) magnetic inertia
(*d*) high field circuit resistance.

4. For the voltage built-up of a self-excited d.c. generator, which of the following is not an essential condition ?
(*a*) There must be some residual flux
(*b*) Field winding mmf must aid the residual flux
(*c*) Total field circuit resistance must be less than the critical value
(*d*) Armature speed must be very high.

5. The voltage build-up process of a d.c. generator is
(*a*) difficult
(*b*) delayed
(*c*) cumulative
(*d*) infinite

6. Which of the following d.c. generator cannot build up on open-circuit ?

(*a*) shunt
(*b*) series
(*c*) short shunt
(*d*) long shunt

7. If a self-excited d.c. generator after being installed, fails to build up on its first trial run, the first thing to do is to
(*a*) increase the field resistance
(*b*) check armature insulation
(*c*) reverse field connections
(*d*) increase the speed of prime mover.

8. If residual magnetism of a shunt generator is destroyed accidentally, it may be restored by connecting its shunt field
(*a*) to earth
(*b*) to an a.c. source
(*b*) in reverse
(*d*) to a d.c. source.

9. The three factors which cause decrease in the terminal voltage of a shunt generator are
(*a*) armature reactances
(*b*) armature resistance
(*c*) armature leakages
(*d*) armature reaction
(*e*) reduction in field current

10. If field resistance of a d.c. shunt generator is increased beyond its critical value, the generator
(*a*) output voltage will exceed its name-plate rating
(*b*) will not build up

(c) may burn out if loaded to its name-plate rating

(d) power output may exceed its name-plate rating

11. An ideal d.c. generator is one that has .... voltage regulation.
(a) low   (b) zero
(c) positive   (d) negative

12. The .... generator has poorest voltage regulation.
(a) series   (b) shunt
(c) compound   (d) high

13. The voltage regulation of an overcompound d.c. generator is always ....

(a) positive
(b) negative
(c) zero
(d) high

14. Most commercial compound d.c. generator are normally supplied by the manufacturers as over compound machines because
(a) they are ideally suited for transmission of d.c. energy to remotely-located loads
(b) degree of compounding can be adjusted by using a divertor across series field
(c) they are more cost effective than shunt generators
(d) they have zero percent regulation.

ANSWERS

1. (b) **2.** (d) **3.** (c) **4.** (d) **5.** (c) **6.** (b) **7.** (c) **8.** (d) **9.** (b,d,e) **10.** (b) **11.** (b) **12.** (a) **13.** (b) **14.** (b).

QUESTIONS AND ANSWERS ON D.C. GENERATORS

Q. 1. How may the number of parallel paths in an armature be increased ?
Ans. By increasing the number of magnetic poles.
Q. 2. How are brushes connected in a d.c. generator ?
Ans. Usually, all positive brushes are connected together and all the negative brushes together (Fig. 28.33).
Q. 3. What is meant by armature reaction ?
Ans. It is the effect of armature magnetic field 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.
Q. 4. What is the effect of this distortion on the operation of the machine ?
Ans. It acts as a magnetic drag on the armature which consequently requires more power to turn it.
Q. 5. How can field distortion be remedied ?
Ans. By using compensating windings which are embed-

Fig. 28.33

ded in the slots in the pole-shoe and are connected in series with the armature.
Q. 6. What is meant by normal neutral plane ?
Ans. It is a plane which passes through the axis of the armature perpendicular to the magnetic field of the generator when there is no flow of current through the armature.
Q. 7. What is the importance of this plane in the working of the machine ?
Ans. It gives the position where brushes would be placed to prevent sparking during the operation of the generator where the main pole field not distorted by armature field and were there no self-induction in the coils.
Q. 8. How do you differentiate between normal neutral plane ?
Ans. The *NNP* is the position of zero induction and hence minimum sparking assuming no field distortion *i.e.* on no-load. It is perpendicular to magnetic axis. *NA* is the position of zero induction and hence minimum sparking with distorted field *i.e. when generator is on load.*
Q. 9. How do you define 'commutating plane' ?
Ans. It is the plane which passes through the axis of the armature and through centre of contact of the brushes as shown in Fig. 28.34.
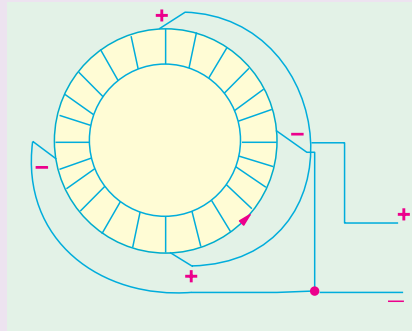
Q. 10. **What is the angle of lead ?**
 Ans. It is the angle between the *NNP* and the commutating plane.
Q. 11. **What affects this angle ?**
 Ans. For sparkless commutation, the angle of lead varies directly with load. Its value can be kept small by making main pole field considerably more powerful than the armature field.
Q. 12. **What is the best way of minimizing eddy currents in an armature ?**
 Ans. Lamination.
Q. 13. **How should the armature be laminated for the purpose ?**
 Ans. It should be laminated at right angle to its axis.
Q. 14. **How does field distortion affect communication ?**
 Ans. The neutral plane no longer coincides with the normal neutral plane but is advanced by a certain angle in the direction of rotation of the armature.

Fig. 28.34

Q. 15. **Should the brushes of a loaded generator be placed in the neutral plane ?**
 Ans. No.
Q. 16. **Why not ?**
 Ans. The brushes must be advanced by a certain angle (called brush lead) beyond the neutral plane to prevent sparking.
Q. 17. **What causes sparking at the brushes ?**
 Ans. It is due to the self-induction of the coil undergoing commutation.
Q. 18. **What is the standard direction of rotation of the d.c. generators ?**
 Ans. Clockwise when viewed from the end opposite to the driven end.
Q. 19. **What is meant by build-up of a generator ?**
 Ans. It means the gradual increase in the generator voltage to its maximum value after the generator is started from rest.
Q. 20. **How should a generator be started ?**
 Ans. It is usually brought up to speed with the help of the driving engine called prime-mover.
Q. 21. **How should a shunt or compound generator be started ?**
 Ans. Such machines excite best when all switches controlling the external circuit are open.
Q. 22. **How about a series generator ?**
 Ans. In this case, the external circuit must be closed otherwise the generator will not build-up.
Q. 23. **What is the procedure for shunting down a generator ?**
 Ans. First, the load should be gradually reduced, if possible, by easing down the driving engine, then when the generator is supplying little or no current, the main switch should be opened. When the voltmeter reads almost zero, then brushes should be raised from the commutator.
**Q. 24.** **What are the indications and causes of an overloaded generator ?**
 Ans. A generator is said to be overloaded if a greater output is taken from it that it can safely carry. Overloading is indicated by (***i***) excessive sparking at brushes and (***ii***) overheating of the armature and other parts of the generator. Most likely causes of overloading are :
   1. Excessive voltage-as indicated by the voltmeter or the increased brilliancy of the pilot lamp. This could be due to over-excitation of field magnets or too high speed of the engine.
   2. Excessive current–which could be due to bad feeding of the load.
   3. Reversal of polarity–this happens occasionally when the series or compound-wound generators are running in parallel. Polarity reversal occurs during stopping by the current from the machines at work.
   4. Short-circuit or ground in the generator itself or in the external circuit.
Q. 25. **Mention and explain the various causes for the failure of the generator to build up.**
 Ans. Principal causes due to which a generator may fail to excite are :
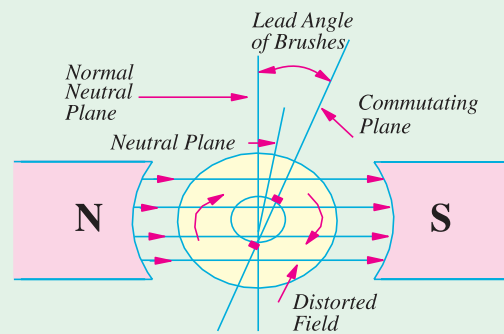
1. Brushes not properly adjusted–if brushes are not in their proper positions, then whole of the armature voltage will not be utilized and so would be insufficient to excite the machine.
2. Defective contacts-unclean contacts may interpose large resistance in the path of the exciting current and reduce it to such a small value that it fails to excite the machine.
3. Incorrect adjustment of regulators–in the case of shunt and compound generators, it is possibly that the resistance of field regulator may be too high to permit the passage of sufficient current through the field windings.
4. Speed too low–in the case of shunt–and compound-wound generators, there is certain critical armature speed below which they will not excite.
5. Open-circuit–in the case of series machines.
6. Short-circuit–in the generator of external circuit.
7. Reversed field polarity–usually caused by the reversed connections of the field coils.
8. Insufficient residual magnetism–The trouble normally occurs when the generator is new. It can be remedied by passing a strong direct current through the field coils.

Q. 26. **How do we conclude that connections between field coils and armature are correct ?**

Ans. If the generator builds up when brought to full speed. If it does not, then connections are reversed.

Q. 27. **When a generator loses its residual magnetism either due to lighting or short circuit, how can it be made to build up ?**

Ans. By temporarily magnetisng the main poles with the help of current from an external battery.

Q. 28. **Can a generator be reversed by reversing the connections between the armature and field coils ?**

Ans. No, because if these connections are reversed, the generator will not build up at all.

Q. 29. **Will a generator build up if it becomes reversed ?**

Ans. Yes.

Q. 30. **Then, what is the objection to a reversed generator ?**

Ans. Since the current of such a reversed generator is also reversed, serious trouble can occur if attempt is made to connect it in parallel with other machines which are not reversed.

Q. 31. **What are the two kinds of sparking produced in a generator ?**

Ans. One kind of sparking is due to bad adjustment of brushes and the other due to bad condition of the commutator. The sparking of the first are bluish whereas those of the other are reddish in colour.

Q. 32. **What is the probable reason if sparking does not disappear in any position when brushes are rocked around the commutator ?**

Ans. (*i*) The brushes may not be separated at correct distance.
(*ii*) The neutral plane may not be situated in the true theoretical position on the commutator due to faulty winding.

Q. 33. **What is the permissible rise of temperature in a well-designed generator ?**

Ans. 27°C above the surrounding air.

Q. 34. **What are the causes of hot bearings ?**

Ans. (*i*) lack of oil (*ii*) belt too tight (*iii*) armature not centered with respect of pole pieces (*iv*) bearing too tight or not in line.

Q. 35. **What causes heating of armature ?**

Ans. 1. Eddy currents.
2. Moisture which almost short-circuits the armature.
3. Unequal strength of magnetic poles.
4. Operation above rated voltage and below normal speed.

Q. 36. **What is the commutator pitch of a 4-pole d.c. armature having 49 commutator bars?**

Ans. $Y_c = (49 \pm 1)/2 = 24$ or 25.

Q. 37. **Will it make any difference if lower figure of 24 is selected in preference to other.**

Ans. Yes. Direction of armature rotation would be reversed.