Chapter Three

DC GENERATORS

Learning Outcomes:

After the ending of the lesson, students will be able to know about

- the operating principle of a DC generator.
- Classification and generated voltage of a dc generator.
- Characteristics of different types dc generator
- Solution problems of dc generators

Principle of Operation of a D.C. Generator

All the generators work on a principle of dynamically induced e.m.f. This principle nothing but the Faraday's law of electromagnetism induction. It states that, 'whenever the number of magnetic lines of force i.e., flux linking with a conductor or a coil changes, an electromotive force is set up in that conductor or coil.' The change in flux associated with the conductor can exist only when there exists a relative motion between a conductor and the flux. The relative motion can be achieved by rotating conductor with respect to flux or by rotating flux with respect to a conductor. So, a voltage gets generated in a conductor, as long as there exists a relative motion between conductor and the flux. Such an induced e.m.f. which is due to the physical movement of coil or conductor with respect to flux or movement of flux with respect to coil or conductor is called dynamically induced e.m.f.

Key Point:

So, a generating action requires following basic components to exist,

- The conductor or a coil
- The relative motion between conductor and flux.

In a particular generator, the conductors are rotated to cut the magnetic flux, keeping flux stationary. To have a large voltage as the output, the number of conductors is connected together in a specific manner, to form a winding. This winding is called armature winding of a d.c. machine. The part on which this winding is kept is called armature of a d.c. machine. To have the rotation of conductors, the conductors placed on the armature are rotated with the help of some external device. Such an external device is called a prime mover. The commonly used prime movers are diesel engines, steam engines, steam turbines, water turbines etc. The necessary magnetic flux is produced by current carrying winding which is called field winding. The direction of the induced e.m.f. can be obtained by using Fleming's right-hand role.

Conditions to build up voltage in shunt generator

- The shunt winding should have residual magnetic field.
- The direction of shunt winding and armature winding should be in such a way that flux generated by them should aid together.
- The shunt winding should have critical winding resistance**.**

Process of voltage build up

When the armature is rotated, the residual flux in field winding will induce small voltage in armature. The induced voltage in armature generates a flux and it will aid(add) with field flux and the net flux will increase further. This process will be repeating until the actual terminal voltage is reached. Once the terminal voltage is reached then the winding will get saturated and hence there won't be any further increase in flux, also the voltage gets constant.

Emf Equation of a DC Generator

As the armature rotates, a voltage is generated in its coils. In the case of a generator, the emf of rotation is called the Generated emf or Armature emf and is denoted as Er = Eg. In the case of a motor, the emf of rotation is known as Back emf or Counter emf and represented as Er = Eb. The expression for emf is same for both the operations. I.e., for Generator as well as for Motor.

Derivation of EMF Equation of a DC Machine – Generator and Motor

Let,

- **P** – Number of poles of the machine
- **ϕ** – Flux per pole in Weber.
- **Z** – Total number of armature conductors.
- **N** – Speed of armature in revolution per minute (r.p.m).
- **A** – Number of parallel paths in the armature winding.

In one revolution of the armature, the flux cut by one conductor is given as

$$\text{Flux cut by one conductor} = P\varphi \quad \text{wb} \ldots\ldots(1)$$

Time taken to complete one revolution is given as

$$t = \frac{60}{N} \quad \text{seconds} \quad \ldots \ldots . . (2)$$

Therefore, the average induced e.m.f in one conductor will be

$$e = \frac{P\varphi}{t} \quad \ldots \ldots . . (3)$$

Putting the value of (t) from Equation (2) in the equation (3) we will get

$$e = \frac{P\varphi}{60/N} = \frac{P\varphi N}{60} \quad \text{volts} \quad \ldots \ldots . . (4)$$

The number of conductors connected in series in each parallel path = Z/A.

Therefore, the average induced e.m.f across each parallel path or the armature terminals is given by the equation shown below.

$$E = \frac{P\varphi N}{60} \times \frac{Z}{A} = \frac{PZ\varphi N}{60\,A} \quad \text{volts} \quad \text{or}$$

$$E = \frac{PZ\varphi n}{A} \quad \ldots \ldots . (5)$$

Where n is the speed in revolution per second (r.p.s) and given as

$$n = \frac{N}{60}$$

For a given machine, the number of poles and the number of conductors per parallel path (Z/A) are constant. Hence, the equation (5) can be written as

$$E = K\varphi n$$

Where, K is a constant and given as

$$K = \frac{PZ}{A}$$

Therefore, the average induced emf equation can also be written as

$$E \propto \varphi n \quad \text{or}$$

$$E = K_1 \varphi N$$

Where K_1 is another constant and hence induced emf equation can be written as

$$E \propto \varphi N \quad \text{or}$$

$$E \propto \varphi \omega$$

Where ω is the angular velocity in radians/second is represented as

$$\omega = \frac{2\pi N}{60}$$

Thus, it is clear that the induced emf is directly proportional to the speed and flux per pole. The polarity of induced emf depends upon the direction of the magnetic field and the direction of rotation. If either of the two is reverse the polarity changes, but if two are reversed the polarity remains unchanged. This induced emf is a fundamental phenomenon for all the DC Machines whether they are working as a generator or motor. If the machine DC Machine is working as a Generator, the induced emf is given by the equation shown below.

$$E_g = \frac{PZ\,\varphi\,N}{60\,A} \quad \text{volts}$$

Where $\mathbf{E_g}$ is the **Generated Emf**

If the machine DC Machine is working as a Motor, the induced emf is given by the equation shown below.

$$E_b = \frac{PZ\,\varphi\,N}{60\,A} \quad \text{volts}$$

In a motor, the induced emf is called **Back Emf (E_b)** because it acts opposite to the supply voltage.

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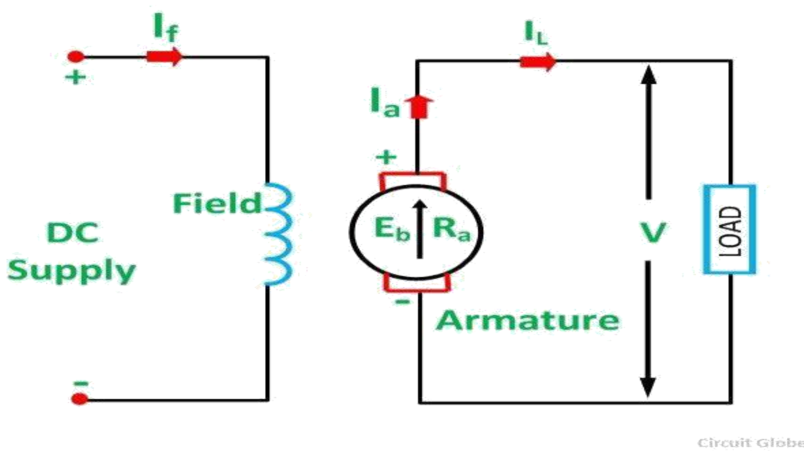
Separately Excited DC Generator

A DC generator whose field winding or coil is energized by a separate or external DC source is called a separately excited DC Generator. The flux produced by the poles depends upon the field current with the unsaturated region of magnetic material of the poles. i.e. flux is directly proportional to the field current. But in the saturated region, the flux remains constant.

The figure of self-excited DC Generator is shown below.



Here,

$I_a = I_L$ where I_a is the armature current and I_L is the line current.

Terminal voltage is given as

$$V = E_g - I_aR_a \quad \ldots\ldots(1)$$

If the contact brush drop is known, then the equation (1) is written as

$$V = E_g - I_aR_a - 2v_b \quad \ldots\ldots(2)$$

The power developed is given by the equation shown below.

$$\text{Power developed} = E_gI_a \quad \ldots\ldots\ldots(3)$$

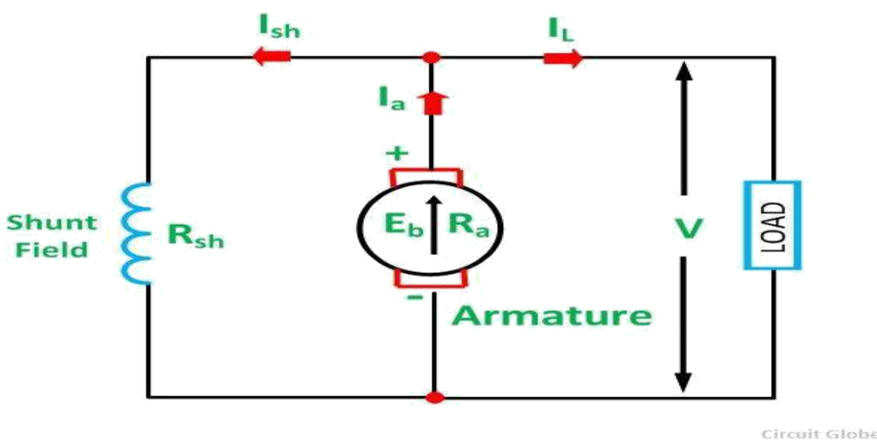
$$\text{Power output} = VI_L = VI_a \quad \ldots\ldots\ldots(4)$$

The self-excited DC Generator is further classified as

1. Shunt Wound Generator
2. Series Wound Generator
3. Compound Wound Generator

In a **shunt wound generator,** the field winding is connected across the armature winding forming a parallel or shunt circuit. Therefore, full terminal voltage is applied across it. A very small field current I_{sh}, flows through it because this winding has many turns of fine wire having very high resistance R_{sh} of the order of 100 ohms.

The connection diagram of shunt wound generator is shown below.



Shunt field current is given as

$$I_{sh} = \frac{V}{R_{sh}}$$

Where R_{sh} is the shunt field winding resistance.

The current field I_{sh} is practically constant at all loads. Therefore, the DC shunt machine is considered to be a constant flux machine.

Armature current is given as $$I_a = I_L + I_{sh}$$

Terminal voltage is given by the equation shown below.

$$V = E_g - I_a R_a$$

If the brush contact drop is included, the equation of the terminal voltage becomes

$$V = E_g - I_a R_a - 2v_b$$

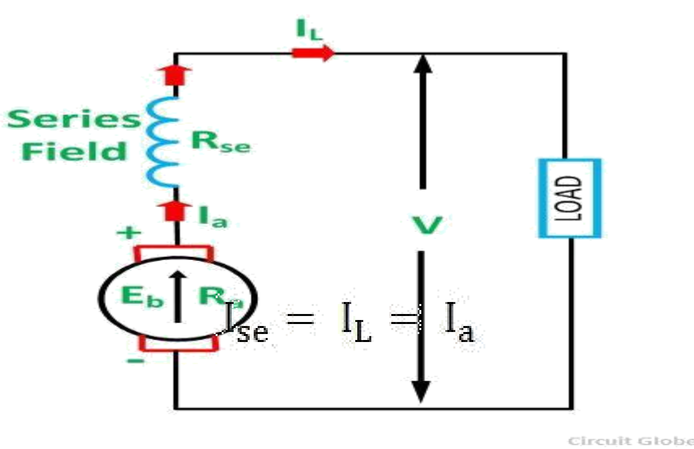
$$\text{Power developed} = E_g I_a$$

$$\text{Power output} = V I_L$$

- ## Series Wound Generator

A **series-wound generator** the field coils are connected in series with the armature winding. The series field winding carries the armature current. The series field winding consists of a few turns of wire of thick wire of larger cross-sectional area and having low resistance usually of the order of less than 1 ohm because the armature current has a very large value.

Its convectional diagram is shown below.



$$I_{se} = I_L = I_a$$

Series field current is given as

R_{se} is known as the series field winding resistance.

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Terminal voltage is given as

$$V = E_g - I_a R_a - I_{se} R_{se}$$

$$V = E_g - I_a (R_a + R_{se})$$

If the brush contact drop is included, the terminal voltage equation is written as

$$V = E_g - I_a (R_a + R_{se}) - 2V_b$$

$$\text{Power developed} = E_g I_a$$

$$\text{Power output} = VI_L = VI_a$$

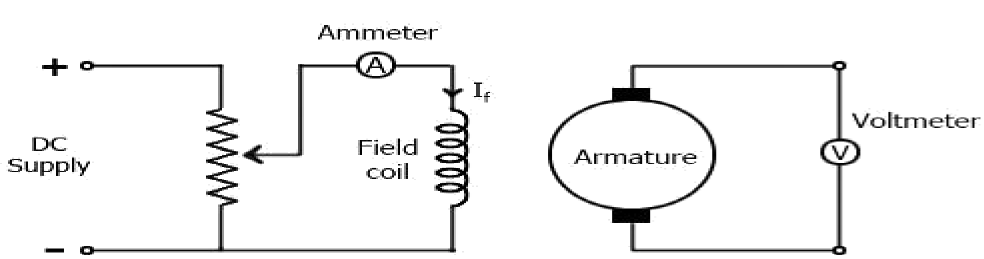
The flux developed by the series field winding is directly proportional to the current flowing through it. But it is only true before magnetic saturation after the saturation flux becomes constant even if the current flowing through it is increased.

Characteristics of DC Generators

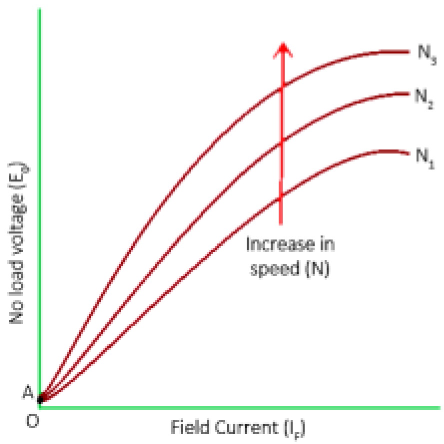
Generally, following three characteristics of DC generators are taken into considerations: (i) Open Circuit Characteristic (O.C.C.), (ii) Internal or Total Characteristic and (iii) External Characteristic. These characteristics of DC generators are explained below.

- **Open Circuit Characteristic (O.C.C.) (E_0/I_f)**

Open circuit characteristic is also known as magnetic characteristic or no-load saturation characteristic. This characteristic shows the relation between generated emf at no load (E_0) and the field current (I_f) at a given fixed speed. The O.C.C. curve is just the magnetization curve and it is practically similar for all type of generators. The data for O.C.C. curve is obtained by operating the generator at no load and keeping a constant speed. Field current is gradually increased and the corresponding terminal voltage is recorded. The connection arrangement to obtain O.C.C. curve is as shown in the figure below. For shunt or series excited generators, the field winding is disconnected from the machine and connected across an external supply.



Now, from the emf equation of dc generator, we know that Eg = kϕ. Hence, the generated emf should be directly proportional to field flux (and hence, also directly proportional to the field current). However, even when the field current is zero, some amount of emf is generated (represented by OA in the figure below). This initially induced emf is due to the fact that there exists some residual magnetism in the field poles. Due to the residual magnetism, a small initial emf is induced in the armature. This initially induced emf aids the existing residual flux, and hence, increasing the overall field flux. This consequently increases the induced emf. Thus, O.C.C. follows a straight line. However, as the flux density increases, the poles get saturated and the ϕ becomes practically constant. Thus, even we increase the If further, ϕ remains constant and hence, Eg also remains constant. Hence, the O.C.C. curve looks like the B-H characteristic.



Open Circuit Characteristic (O.C.C.)

The above figure shows a typical no-load saturation curve or open circuit characteristics for all types of DC generators.

Internal or Total Characteristic (E/I_a)

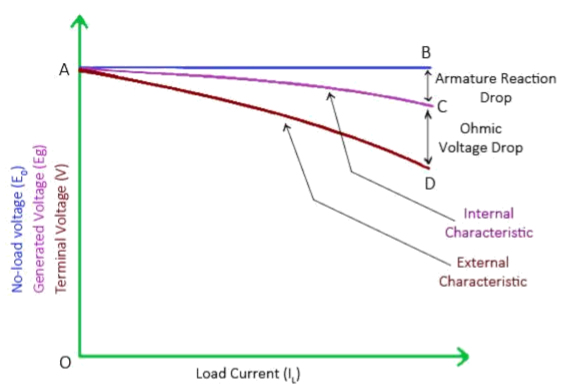
An internal characteristic curve shows the relation between the on-load generated emf (Eg) and the armature current (Ia). The on-load generated emf Eg is always less than E0 due to the armature reaction. Eg can be determined by subtracting the drop due to demagnetizing effect of armature reaction from no-load voltage E0. Therefore, internal characteristic curve lies below the O.C.C. curve.

External Characteristic (V/I_L)

An external characteristic curve shows the relation between terminal voltage (V) and the load current (I_L). Terminal voltage V is less than the generated emf Eg due to voltage drop in the armature circuit. Therefore, external characteristic curve lies below the internal characteristic curve. External characteristics are very important to determine the suitability of a generator for a given purpose. Therefore, this type of characteristic is sometimes also called as performance characteristic or load characteristic.

Internal and external characteristic curves are shown below for each type of generator.

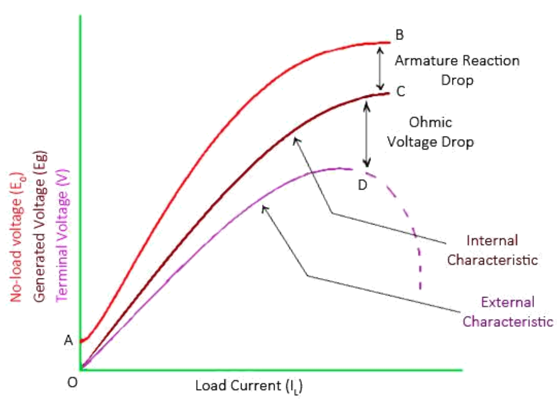
❖ Characteristics of Separately Excited DC Generator:



Characteristics of separately excited DC generator

If there is no armature reaction and armature voltage drop, the voltage will remain constant for any load current. Thus, the straight-line AB in above figure represents the no-load voltage vs. load current IL. Due to the demagnetizing effect of armature reaction, the on-load generated emf is less than the no-load voltage. The curve AC represents the on-load generated emf Eg vs. load current IL i.e., Internal characteristic (as Ia = IL for a separately excited dc generator). Also, the terminal voltage is lesser due to ohmic drop occurring in the armature and brushes. The curve AD represents the terminal voltage vs. load current i.e., external characteristic.

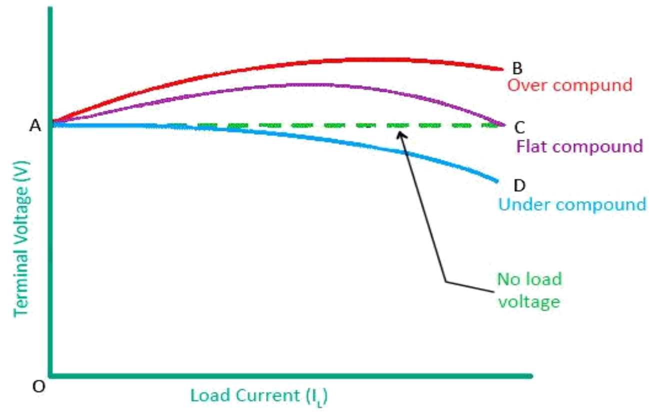
❖ Characteristics of DC Series Generator



Characteristics of DC series generator

The curve AB in above figure identical to open circuit characteristic (O.C.C.) curve. This is because in DC series generators field winding is connected in series with armature and load. Hence, here load current is similar to field current (i.e. IL=If). The curve OC and OD represent internal and external characteristic respectively. In a DC series generator, terminal voltage increases with the load current. This is because, as the load current increases, field current also increases. However, beyond a certain limit, terminal voltage starts decreasing with increase in load. This is due to excessive demagnetizing effects of the armature reaction.

❖ Characteristics Of DC Compound Generator



External characteristic of DC compound generator

The above figure shows the external characteristics of DC compound generators. If series winding amp-turns are adjusted so that, increase in load current causes increase in terminal voltage then the generator is called to be over compounded. The external characteristic for over compounded generator is shown by the curve AB in above figure.

If series winding amp-turns are adjusted so that, the terminal voltage remains constant even the load current is increased, then the generator is called to be flat compounded. The external characteristic for a flat compounded generator is shown by the curve AC.

If the series winding has lesser number of turns than that would be required to be flat compounded, then the generator is called to be under compounded. The external characteristics for an under compounded generator are shown by the curve AD.

Math Problems

Example 2.11. *A 6-pole lap-wound d.c. generator has 600 conductors on its armature. The flux per pole is 0.02 Wb. Calculate (i) the speed at which the generator must be run to generate 300 V. (ii) What would be the speed if the generator were wave-wound ?*

Solution.

(*i*) **Lap wound** $$E_g = \frac{P\phi Z N}{60 A}$$

$$\therefore \quad N = \frac{E_g \times 60 A}{P\phi Z} = \frac{300 \times 60 \times 6}{6 \times 0.02 \times 600} = \textbf{1500 r.p.m.}$$

(*ii*) **Wave wound** $$N = \frac{E_g \times 60 A}{P\phi Z} = \frac{300 \times 60 \times 2}{6 \times 0.02 \times 600} = \textbf{500 r.p.m.}$$

Example 2.12. *An 8-pole, lap-wound armature rotated at 350 r.p.m. is required to generate 260 V. The useful flux per pole is 0·05 Wb. If the armature has 120 slots, calculate the number of conductors per slot.*

Solution. $$E_g = \frac{P\phi Z N}{60 A}$$

$$\therefore \quad Z = \frac{E_g \times 60 A}{P\phi N} = \frac{260 \times 60 \times 8}{8 \times 0.05 \times 350} = 890$$

$\therefore$ No. of conductors/slot = $890/120 = 7.41$

This value must be an even number.

Hence, conductors/slot = **8**

Example 2.13. *The armature of a 6-pole, 600 r.p.m. lap-wound generator has 90 slots. If each coil has 4 turns, calculate the flux per pole required to generate an e.m.f. of 288 volts.*

Solution. Each turn has two active conductors and 90 coils are required to fill 90 slots.

$$\therefore \quad Z = 90 \times 4 \times 2 = 720$$

$$E_g = \frac{P\phi Z N}{60 A}$$

or $$\phi = \frac{E_g \times 60 A}{P Z N} = \frac{288 \times 60 \times 6}{6 \times 720 \times 600} = \textbf{0·04 Wb}$$

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Example 2.23. *A 100 kW, 240 V shunt generator has a field resistance of 55 Ω and armature resistance of 0·067 Ω. Find the full-load generated voltage.*

Solution. Fig. 2.42 shows the shunt generator circuit.

$$I_L = \frac{100 \times 10^3}{240} = 416{\cdot}7 \text{ A}$$

$$I_{sh} = 240/55 = 4.36 \text{ A}$$

$$I_a = I_L + I_{sh}$$
$$= 416{\cdot}7 + 4{\cdot}36 = 421{\cdot}1 \text{ A}$$

$$E_g = V + I_a R_a$$
$$= 240 + 421{\cdot}1 \times 0{\cdot}067 = \mathbf{268{\cdot}2\ V}$$

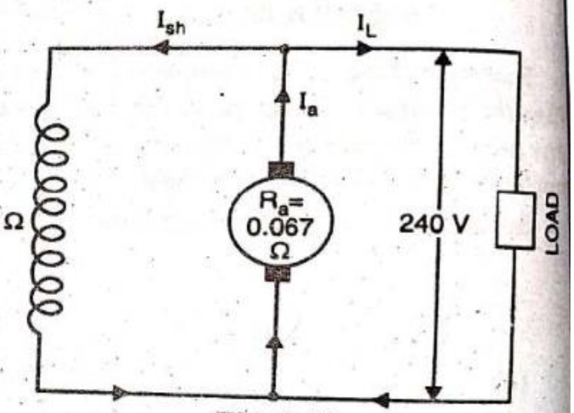

Fig. 2.42

Example 2.42. *A shunt generator supplies 96 A at a terminal voltage of 200 volts. The armature and shunt field resistances are 0·1 Ω and 50 Ω respectively. The iron and frictional losses are 2500 W. Find (i) e.m.f. generated (ii) copper losses (iii) commercial efficiency.*

Solution. Fig. 2.58 shows the connections of shunt generator.

(*i*)
$$I_{sh} = 200/50 = 4 \text{ A}$$
$$I_a = I_L + I_{sh} = 96 + 4 = 100 \text{ A}$$
$$E_g = V + I_a R_a$$
$$= 200 + 100 \times 0{\cdot}1 = \mathbf{210\ V}$$

(*ii*)
$$\text{Armature Cu loss} = I_a^2 R_a = (100)^2 \times 0.1$$
$$= 1000 \text{ W}$$
$$\text{Shunt Cu loss} = I_{sh}^2 R_{sh} = (4)^2 \times 50 = 800 \text{ W}$$
$$\text{Total Cu loss} = 1000 + 800 = \mathbf{1800\ W}$$

(*iii*)
$$\text{Total losses} = \text{Rotational losses} + \text{Cu losses}$$
$$= 2500 + 1800 = 4300 \text{ W}$$
$$\text{Output power} = 96 \times 200 = 19200 \text{ W}$$
$$\text{Input power} = 19200 + 4300 = 23500 \text{ W}$$
$$\therefore \quad \eta_c = \frac{19200}{23500} \times 100 = \mathbf{81.7\%}$$

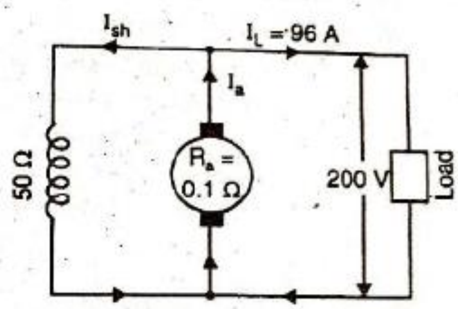

Fig. 2.58

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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.

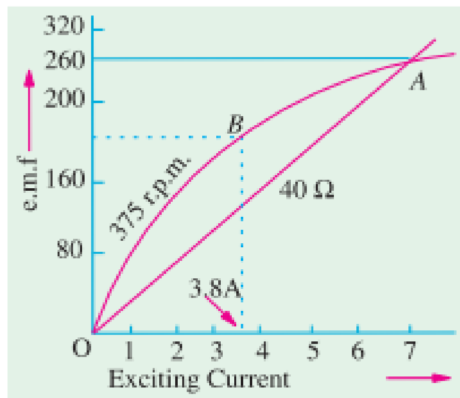

Fig. 28.11

(*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**

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OBE Based Questions (for practice)

Q.1. The open circuit characteristics of a shunt excited dc generator at 1000 rpm speed is given in Table 1. The armature resistance is 0.05 ohm. The generator is driven by a prime-mover at 1000 rpm and running at no load.

If(A)	0.2	0.4	0.6	0.8	1	1.2	1.4	1.52	1.54	1.6	2	2.4
Ea(V)	20	40	60	79	93	103	110	113.5	113.9	115	120	122.4

The operator adjusts the field resistance to 60-ohm. Ignoring armature voltage drop (except in Q(c))

a) What is the EMF induced in armature?
b) What is the field current?
c) What is the voltage drop in armature windings?
d) If the operator increases the field resistance up to 93-ohm, what is the terminal voltage?
e) What is the critical resistance? What will happen if the field resistance is increased to a value greater than the field resistance?