UNIVERSITY OF DIYALA

COLLEGE OF ENGINEERING

DEPARTMENT OF THE ELECTRICAL POWER AND MACHINES ENGINEERING

Second Stage

ELECTRICAL MACHINES

Lecture: 3

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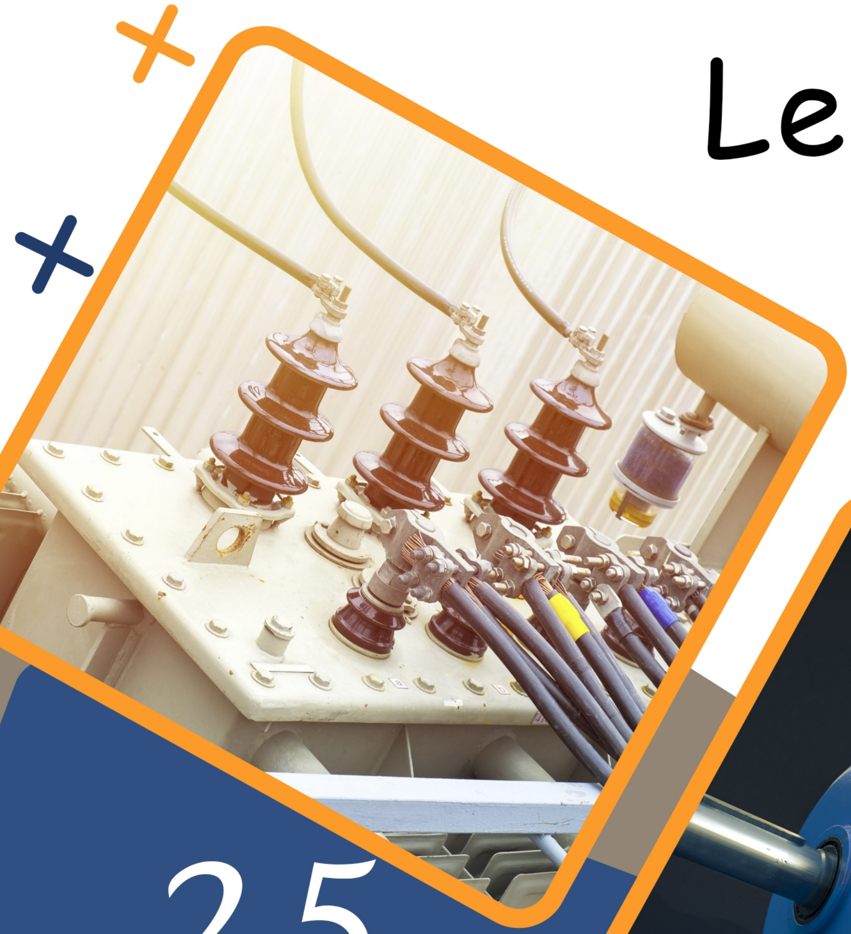

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Armature Reaction:

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

(*i*) It demagnetises or weakens the main flux.

(*ii*) It cross-magnetises or distorts it.

Figure (1) shows the flux distribution of a bipolar generator when there is no current in the armature conductors. For convenience, only two poles have been considered, though the following remarks apply to multipolar fields as well. Moreover, the brushes are shown touching the armature conductors directly, although in practice, they touch commutator segments, It is seen that,

(a) The flux is distributed symmetrically with respect to the polar axis, which is the line joining the centres of NS poles.

(b) The magnetic neutral axis or plane $(M.N.A.)$ coincides with the geometrical neutral axis or plane $(G.N.A.)$.

Magnetic neutral axis may be defined as the axis along which no e.m.f. is produced in the armature conductors because they then move parallel to the lines of flux.

Or $M.N.A.$ is the axis which is perpendicular to the flux passing through the armature.

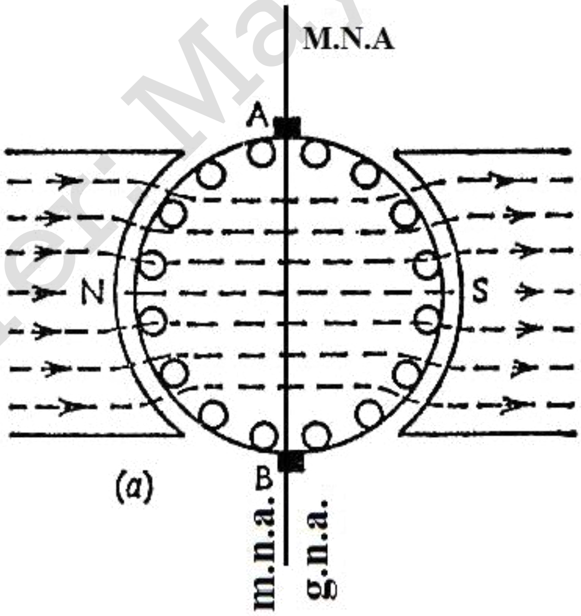


Figure (1)

Note: Brushes are always placed along $M.N.A.$ Hence, $M.N.A.$ is also called ‘axis of commutation’ because reversal of current in armature conductors takes place across this axis.

In Figure (2) is shown the field (or flux) set up by the armature conductors *alone* when carrying current, the field coils being unexcited.

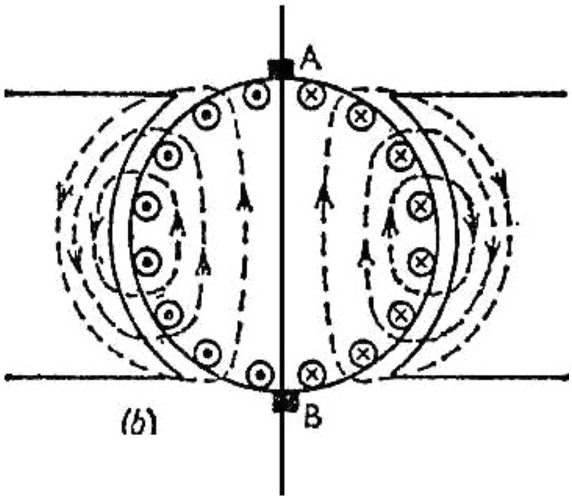


Figure (2)

The direction of the armature current is the same as it would actually be when the generator is loaded. It may even be found by applying Fleming's Right-hand Rule. The current direction is downwards in conductors under $N - pole$ and upwards in those under $S - pole$. The downward flow is represented by crosses and upward flow by dots.

Figure (3) shows the effect of armature magnetic field and its effect on the main poles magnetic field. It is seen that the flux through the armature is no longer uniform and symmetrical about the pole axis, rather it has been distorted. The flux is seen to be crowded at the trailing pole tips but weakened at the leading pole tips.

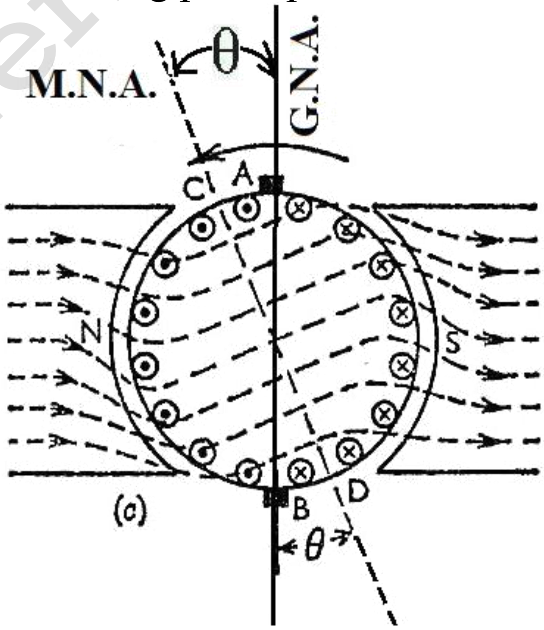


Figure (3)

Compensating Windings:

These are used for large direct current machines which are subjected to large fluctuations in load $i.e.$ rolling mill motors and turbo-generators etc. Their function is to neutralize the cross-magnetizing effect of armature reaction.
These windings are embedded in slots in the pole shoes and are connected in series with armature in such a way that the current in them flows in opposite direction to that flowing in armature conductors directly below the pole shoes. An elementary scheme of compensating winding is shown in Figure (4).

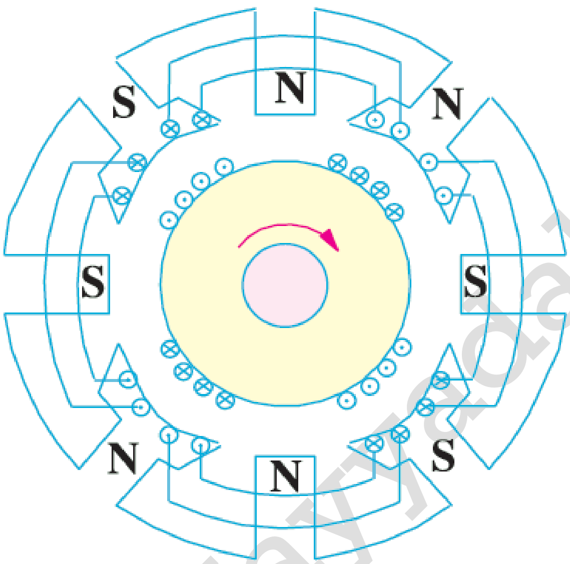


Figure (4)

It should be carefully noted that compensating winding must provide sufficient m.m.f so as to counterbalance the armature m.m.f.

Owing to their cost and the room taken up by them, the compensating windings are used in the case of large machines which are subject to violent fluctuations in load and also for generators which have to deliver their full-load output at considerable low induced voltage as in the Ward-Leonard set.

Parallel Operation of Shunt Generators:

Power plants, whether in D.C. or A.C. stations, will be generally found to have several smaller generators running in parallel rather than large single units capable of supplying the maximum peak load. These smaller units can be run single or in various parallel combinations to suit the actual load demand. Such practice is considered extremely desirable for the following reasons:

(*i*) Continuity of Service:

Continuity of service is one of the most important requirements of any electrical apparatus. This would be impossible if the power plant consisted only of a single unit, because in the event of break- down of the prime mover or the generator itself, the entire station will be shut down. In recent years, the requirement of uninterrupted service has become so important especially in factories etc. that it is now recognized as an economic necessity.

(ii) Efficiency:

Usually, the load on the electrical power plant fluctuates between its peak value sometimes during the day and its minimum value during the late night hours. Since generators operate most efficiently when delivering full load, it is economical to use a single small unit when the load is light. Then, as the load demand increases, a larger generator can be substituted for the smaller one or another smaller unit can be connected to run in parallel with the one already in operation.

(iii) Maintenance and Repair:

It is considered a good practice to inspect generators carefully and periodically to forestall any possibility of failure or breakdown. This is possible only when the generator is at rest which means that there must be other generators to take care of the load. Moreover, when the generator does actually breakdown, it can be repaired with more care and not in a rush, provided there are other generators available to maintain service.

(iv) Additions to Plant:

Additions to power plants are frequently made in order to deliver increasingly greater loads. Provision for future extension is, in fact, made by the design engineers fight from the beginning. It becomes easy to add other generators for parallel operation as the load demand increases.

Load Sharing:

Let:

E_1, E_2 = no-load voltages of the two generators

R_1, R_2 = their armature resistances

V = common terminal voltage

Then,

$$I_1 = \frac{E_1 - V}{R_1} \quad \text{and} \quad I_2 = \frac{E_2 - V}{R_2}$$

$$\therefore \quad \frac{I_2}{I_1} = \frac{E_2 - V}{E_1 - V} \times \frac{R_1}{R_2} = \frac{K_2 N_2 \Phi_2 - V}{K_1 N_1 \Phi_1 - V} \times \frac{R_1}{R_2}$$

(*i*) Two parallel shunt generators having equal no-load voltages share the load in such a ratio that the load current of each machine produces the same drop in each generator.
(*ii*) In the case of two parallel generators having unequal no-load voltages, the load currents produce sufficient voltage drops in each so as to keep their terminal voltage the same.
(*iii*) The generator with the least drop assumes greater share of the change in bus load.
(*iv*) Paralleled generators with different power ratings but the same voltage regulation will divide any oncoming bus load in direct proportion to their respective power ratings.

Connecting Shunt Generators in Parallel:

The generators in a power plant are connected in parallel through bus-bars. The bus-bars are heavy thick copper bars and they act as $+v_e$ and $-v_e$ terminals. The positive terminals of the generators are. connected to the $+v_e$ side of bus-bars and negative terminals to the negative side of bus-bars. Figure (5). below shows shunt generator 1 connected to the bus-bars and supplying load. When the load on the power plant increases beyond the capacity of this generator, the second shunt generator 2 is connected in parallel with the first to meet the increased load demand. The procedure for paralleling generator 2 with generator 1 is as under

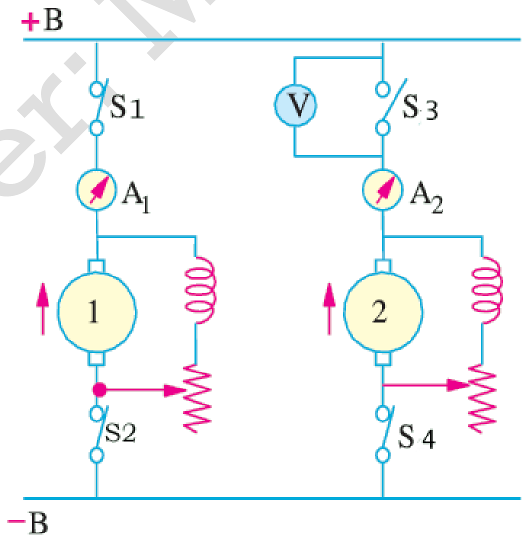


Figure (5)

(*i*) The prime mover of generator 2 is brought up to the rated speed. Now switch *S*4 in the field circuit of the generator 2 is closed.
(*ii*) Next the excitation of generator 2 is adjusted till it generates voltage equal to the bus-bars voltage. This is indicated by voltmeter V_2.

(*iii*) Now the generator 2 is ready to be paralleled with generator 1. The main switch S3 is closed, thus putting generator 2 in parallel with generator 1. Note that generator 2 is not supplying any load because its generated emf is equal to bus-bars voltage. The generator is said to be "floating" ($i.e.$ not supplying any load) on the bus-bars.

(*iv*) If generator 2 is to deliver any current, then its generated voltage E should be greater than the bus-bars voltage V. In that case, current supplied by it is $I = (E - V)/R_a$ where R_a is the resistance of the armature circuit. By increasing the field current (and hence induced emf E), the generator 2 can be made to supply proper amount of load.

(*v*) The load may be shifted from one shunt generator to another merely by adjusting the field excitation. Thus if generator 1 is to be shut down, the whole load can be shifted onto generator 2 provided it has the capacity to supply that load. In that case, reduce the current supplied by generator 1 to zero (This will be indicated by ammeter A1) open the main switch S1.

Example 1: Two 220V, D.C. generators, each having linear external characteristics, operate in parallel. One machine has a terminal voltage of 270V on no-load and 220V at a load current of 35A, while the other has a voltage of 280V at no-load and 220V at 50A. Calculate the output current of each machine and the bus-bar voltage when the total load is 60A. What is the kW output of each machine under this condition?

Solution:

Generator No. 1:

Voltage drop for 35A = 270 − 220 = 50V

$\therefore$ Voltage drop/ampere $= \frac{50}{35} = \frac{10}{7}$ V/A

Generator No. 2:

Voltage drop/ampere $= \frac{(280-220)}{50} = 1.2$ V/A

Let: V = bus-bar voltage
I_1 = current output of generator No.1
I_2 = current output of generator No.2

Then, $V = 270 - \left(\frac{10}{7}\right) I_1$ for generator No. 1

$V = 280 - 1.2 I_2$ for generator No. 2

Since bus-bar voltage is the same.

$\therefore \quad 270 - \frac{10}{7} I_1 = 280 - 1.2 I_2$ or $4.2 I_2 - 5 I_1 = 35$ (*i*)

Also $I_1 + I_2 = 60$ (*ii*)

Solving the two equations, we get

$I_1 = 23.6\text{A}$
$I_2 = 36.4\text{A}$

Now $V = 280 - 1.2I_2 = 280 - (1.2 \times 36.4)$
$\cong 236.3\text{V}$

Output of 1st machine $= \frac{236.3 \times 23.6}{1{,}000}$
$\cong 5.577\text{kW}$

Output of 2nd machine $= \frac{236.3 \times 36.4}{1{,}000}$
$\cong 8.602\text{kW}$

Example 2: Two shunt generators each with an armature resistance of 0.01Ω and field resistance of 20Ω run in parallel and supply a total load of 4,000A. The e.m.f.s are respectively 210V and 220V. Calculate the bus-bar voltage and output of each machine.

Solution:

Generators are shown in Figure (6).

Let:

V = bus-bar voltage
I_1 = output current of G_1
I_2 = output current of G_2

Now, $I_1 + I_2 = 4{,}000\text{A}$, $I_{sh} = \frac{V}{20}$.

$I_{a1} = \left(I_1 + \frac{V}{20}\right)$; $I_{a2} = \left(I_2 + \frac{V}{20}\right)$

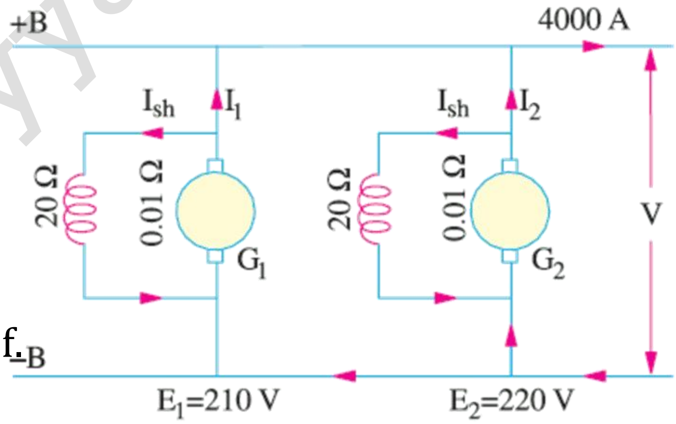


Figure (6)

In each machine,

V + armature drop = induced e.m.f.

$\therefore \quad V + I_{a1}R_a = E_1$

Or $V + \left(I_1 + \frac{V}{20}\right) \times 0.01$
$= 210$ 1st machine

Also $V + I_{a2}R_a = E_2$

Or $V + \left(I_2 + \frac{V}{20}\right) \times 0.01 = 220$ 2nd machine

Subtracting, we have $0.01\,(I_1 - I_2) = 10$ or $I_1 - I_2 = 1{,}000$

Also, $I_1 + I_2 = 4{,}000\text{A}$ $\therefore$ $I_1 = 2{,}500\text{A}$; $I_2 = 1{,}500\text{A}$

Substituting the value of I_1 above, we get

$V + \left(2{,}500 + \frac{V}{20}\right) \times 0.01 = 210 \quad \therefore \quad V = 184.9\text{V}$

Output of 1st generator

$= 184.9 \times \frac{2{,}500}{1{,}000} = 462.25\text{kW}$

Output of 2nd generator

$$= 184.9 \times \frac{1{,}500}{1{,}000} = 277.35\text{kW}$$

Characteristics of D.C. Generators:

The D.C. generator has following characteristics in general:

1. No-Load (or Magnetization) Characteristic.
2. Load Characteristic, which is subdivided into:

(i) Internal Characteristic (ii) External Characteristic

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. Its shape is practically the same for all generators whether separately-excited or self-excited.

In general,

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

At no load, $E_0 \propto \Phi$, with $\left(\frac{ZN}{60}\frac{P}{A}\right)$ are constant

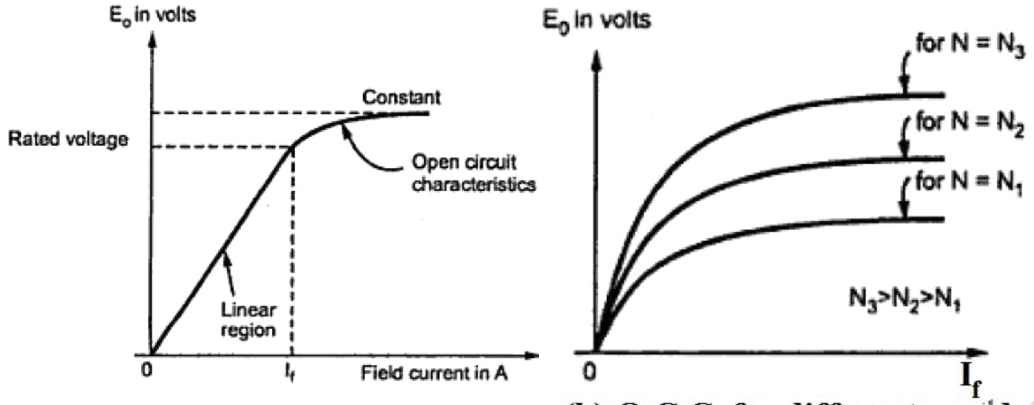
$$E_0 \propto I_f \quad \text{as} \quad \Phi \propto I_f$$

Thus induced e.m.f. increases directly as I_f increases. But after certain If core gets saturated and flux Φ also remains constant though I_f increases. Hence after saturation, voltage also remains constant.

Note: Thus characteristics is linear till saturation and after that bends such that voltage remains constant though I_f increases. The characteristics is shown in the Figure (7-a).

Now the induced e.m.f. also varies with speed. Actually, $E_0 \propto N\Phi$

So if magnetization characteristics for various speeds are plotted we will get family of parallel characteristics as shown in the Figure (7-b). For lower speeds, generated voltages are less so characteristics for lower speeds are below the characteristics for higher speeds.



(a) open circuit characteristic (b) O.C.C. for different speeds

Figure (7)

2. Load Characteristic:

(*i*) Internal or Total Characteristic (E/I_a):

It is the relation between the e.m.f. E actually induces in the armature (after allowing for the demagnetizing effect of armature reaction) and the armature current I_a.

(*ii*) External Characteristic (V/I_L):

It is also referred to as *performance characteristic* or sometimes *voltage-regulating curve*. It gives relation between the terminal voltage V and the load current (I_L). 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.

It may be obtained in two ways:
(a) By making simultaneous measurements with a suitable voltmeter and an ammeter on a loaded generator.
(b) Graphically from the $O.C.C.$ provided the armature and field resistances are known and also if the demagnetizing effect (under rated load conditions) or the armature reaction (from the short-circuit test) is known.

Separately-excited Generator:

No-load Saturation Characteristic (E_0/I_f):

Connect the circuit shown in Figure (8).

(*i*) The voltmeter reads the no-load voltage E_0 and the ammeter reads the field current I_f.

(*ii*) When switch S_1 is open, $I_f = 0$ & $E_0 = 0$.

(*iii*) Close switch S_1 & (S_2 is still open), then adjust the value of rheostat (or variable resistor) at maximum value and read the values of I_f & E_0.

(*iv*) Reduce the value of rheostat gradually (means increasing I_f gradually) and reads the value of I_f & E_0 at each value of rheostat.

Now, the voltage equation of a D.C. generator is, $E_g = \frac{\Phi ZN}{60} \frac{P}{A}$ volt

Hence, if speed is constant, the above relation becomes $E_g = K\Phi$

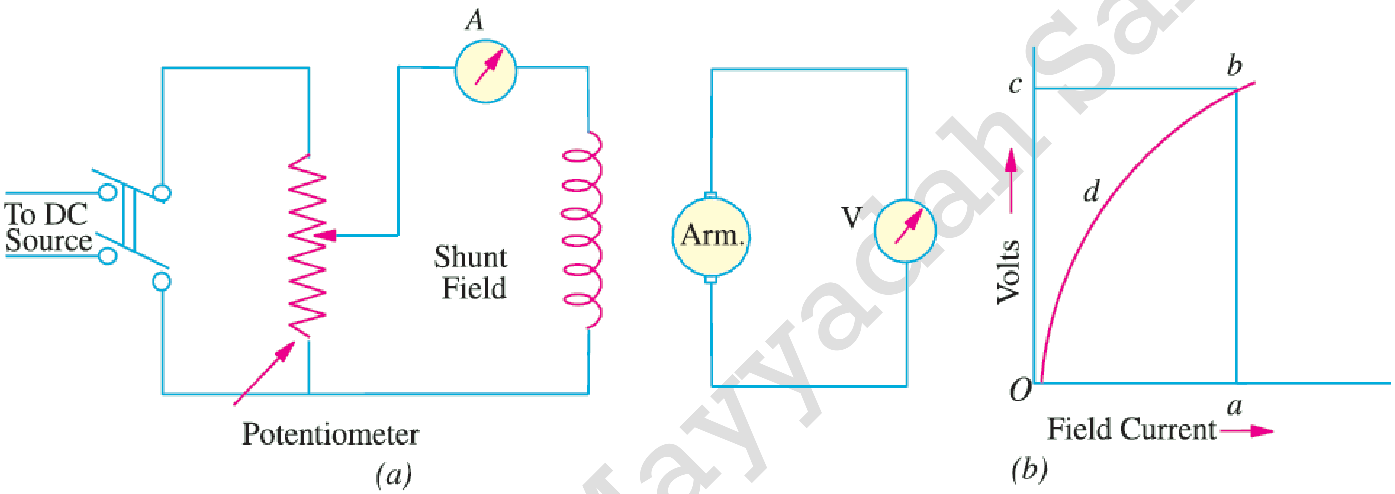


Figure (8)

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 Figure (2-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.

Note: Under no-load condition, armature reaction and armature voltage drop are neglected because armature current equal zero.

Critical Resistance for Shunt Generator:

Line OA is drawn such that its slope equals the field winding resistance $i.e.$ every point on this curve is such that $\frac{E_0}{I_f} = R_f$.

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_f 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.

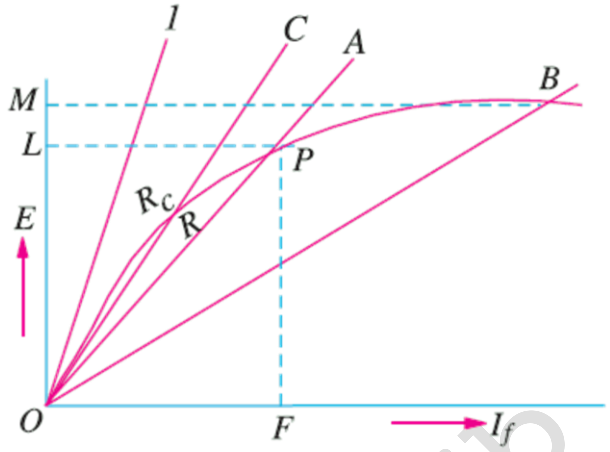


Figure (9)

The value of the resistance represented by the tangent to the curve, is known as *critical resistance* R_c for a given speed. *Critical resistance* can be defined as the maximum value of field resistance at which the generator voltage will build up.

How to Find Critical Resistance R_c?

First, $O.C.C.$ is plotted from the given data. Then, tangent is drawn to its initial portion. The slope of this curve gives the critical resistance for the speed at which the data was obtained.

How to Draw $O.C.C.$ at Different Speeds?

Suppose we are given the data for $O.C.C.$ of a generator run at a fixed speed, say, N_1. It will be shown that $O.C.C.$ at any other constant speed N_2 can be deduced from the $O.C.C.$ for N_1. In Figure (10) the $O.C.C.$ for speed N_1 is shown.

Since $E \propto N$ for any fixed excitation, hence $\frac{E_2}{E_1} = \frac{N_2}{N_1}$ or $E_2 = E_1 \times \frac{N_2}{N_1}$

As seen, for $I_f = OH$, $E_1 = HC$. The value of new voltage for the same I_f but at N_2.

$$E_2 = HC \times \frac{N_2}{N_1} = HD$$

In this way, point D is located. In a similar way, other such points can be found and the new $O.C.C.$ at N_2 drawn.

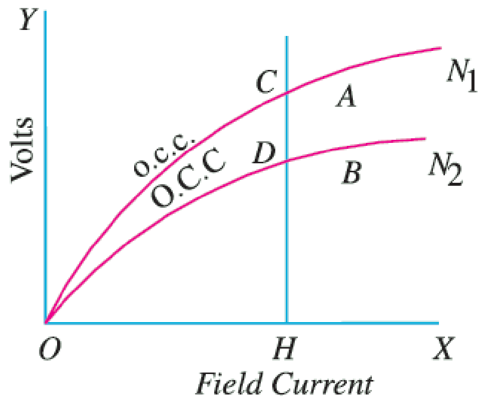


Figure (10)

Critical Speed N_c:

Critical speed of a shunt generator is that speed for which the given shunt field resistance represents critical resistance. In Figure (11) , curve 2 corresponds to critical speed because R_{sh} line is tangential to it. Obviously

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

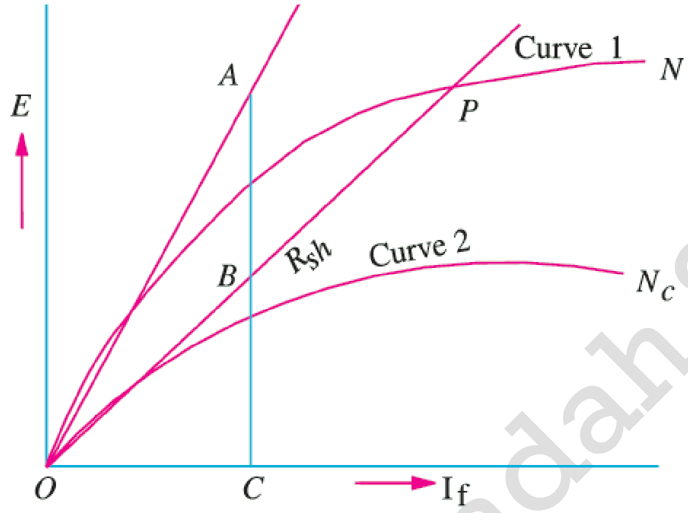


Figure (11)

Example 3: The magnetization curve of a D.C. shunt generator at 1,500 $r.p.m.$ 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 100Ω (*ii*) the critical field resistance at 1,500 $r.p.m.$ and (*iii*) the magnetization curve at 1,200 $r.p.m.$ and therefrom the open-circuit voltage for a field resistance of 100Ω.

Solution:

(*i*) The magnetization curve at 1,500 $r.p.m.$ is plotted from the given data.
The 100Ω resistance line OA is obtained by joining the origin (0,0) with the point (1A, 100V), this point is chosen because $R_{sh} = \frac{E_0}{I_f} = \frac{100\text{V}}{1\text{A}} = 100\Omega$.

The voltage corresponding to point A is 227.5V. Hence, no-load voltage to which the generator will build-up is 227.5V.

(*ii*) The tangent OT represents the critical resistance at 1,500 $r.p.m.$ considering point B, $R_c = \frac{225}{1.5} = 150\Omega$.

(iii) $E_{01} = \frac{\Phi Z N_1}{60} \frac{P}{A}$; $E_{02} = \frac{\Phi Z N_2}{60} \frac{P}{A}$

$$\frac{E_{02}}{E_{01}} = \frac{\frac{\Phi Z N_2 P}{60 \quad A}}{\frac{\Phi Z N_1 P}{60 \quad A}} \Rightarrow\Rightarrow \frac{E_{02}}{E_{01}} = \frac{N_2}{N_1},$$

Φ is constant because we take the same field current values.

$$\therefore \quad E_{02} = E_{01} \times \frac{N_2}{N_1}$$

For 1,200 $r.p.m.$, the induced voltages for different field currents would be $\left(\frac{1200}{1500}\right) = 0.8$ of those for 1,500 $r.p.m.$ (multiply each value of induced voltage by 0.8 to get the new values of induced voltage).

The values of these voltages are tabulated below:

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 magnetization curve is also plotted in Figure (12). The 100Ω line cuts the curve at point C which corresponds to an induced voltage of 166V.

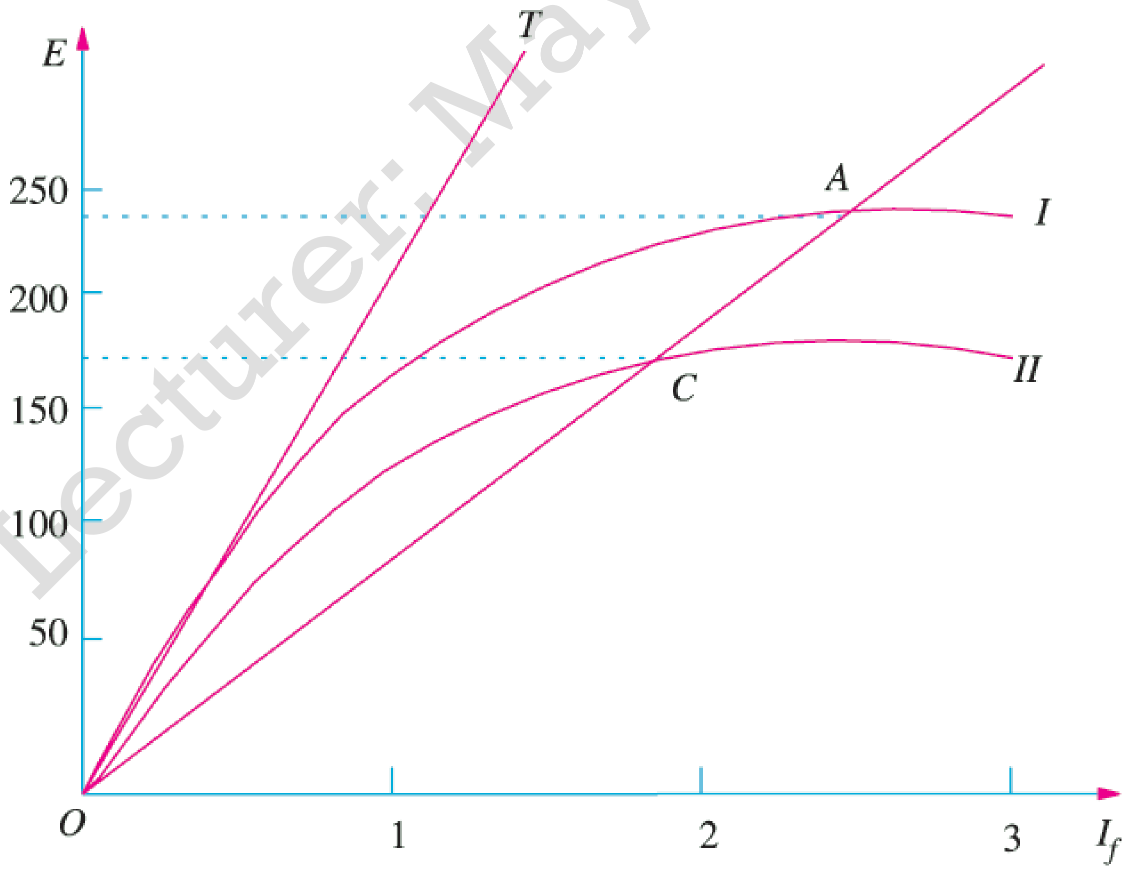


Figure (12)

Example 4: The data for open circuit characteristics of a D.C. shunt generator driven at rated speed is given as,

I_f (A):	0.5	1.0	1.5	2.0	2.5	3.0	3.5
E_0 (V):	60	120	138	145	149	151	152

If resistance of field circuit is adjusted to 53Ω calculate the open circuit voltage and load current when the terminal voltage is 100V. Neglect the armature reaction and assume $R_a = 0.1\Omega$. Use graph paper.

Solution:

Draw the open circuit characteristics on the graph paper from the given data.

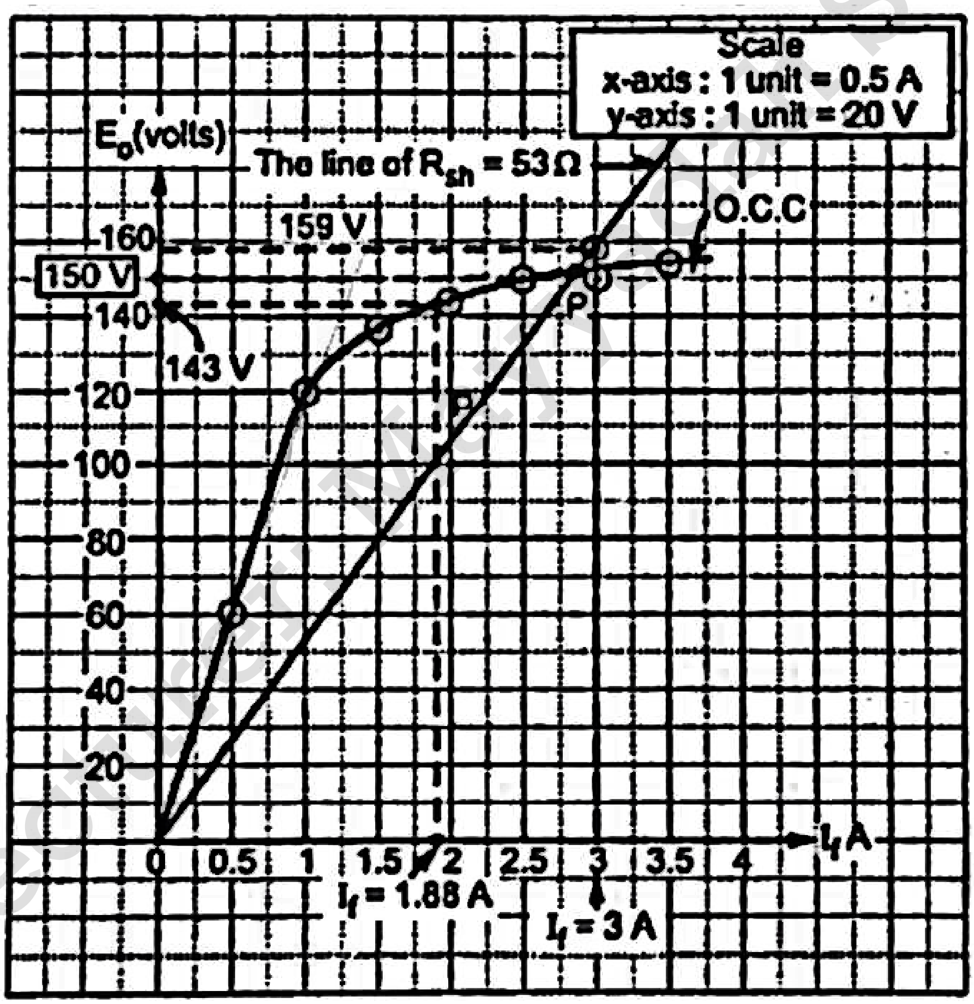


Figure (13)

Draw the line corresponding to $R_{sh} = 53\Omega$. To draw this line, consider an equation of line $y = \text{m}x$ which passes through origin.

Now, $y = E_0$; $x = I_f$ and $m = \text{slope} = R_{sh}$

$\therefore \quad E_0 = R_{sh} I_f$

One point on this line is (0,0).
For second point on line consider $I_f = 3\text{A}$ say, then

$$E_0 = R_{sh} \times 3 = 53 \times 3 = 159\text{V}$$

So second point is (3,159).
Draw the line on graph paper passing through (0,0) and (3,159), till it intersects $O.C.C.$ at P, as shown. The induced e.m.f. corresponding to point P is 150V. Thus machine has open circuit voltage of 150V. The terminal voltage $V_t = 100\text{V}$.
For a shunt generator,

$$I_{sh} = V_t/R_{sh} = \frac{100}{53} = 1.8867\text{A} = I_f$$

And $E_0 = V_t + I_a R_a$
From graph, $E_0 = 143\text{V}$ for $I_{sh} = I_f = 1.8867\text{A}$

$\therefore \quad 143 = 100 + (I_a \times 0.1)$

$\therefore \quad I_a = 430\text{A}$

Now, $I_a = I_L + I_{sh}$ ...For shunt generator

$\therefore \quad I_L = I_a - I_{sh} = 430 - 1.8867 = 428.1133\text{A}$

This is the load current when $V = 100\text{V}$.

Example 5: The open-circuit characteristic of a separately-excited D.C. generator driven at 1,000 $r.p.m.$ 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 100Ω, find (a) open-circuit voltage and exciting current (b) the critical resistance and (c) resistance to induce 115V on open circuit.
Solution:
The $O.C.C.$ has been plotted in Figure (14). The shunt resistance line OA is drawn as usual.
(a) $O.C.$ voltage = 100V ; Exciting current = 1A
(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 $\frac{90}{0.6} = 150\Omega$.
(c) Line OB represents shunt resistance for getting 115V on open-circuit. Its resistance $= \frac{115}{1.4} = 82.1\Omega$.

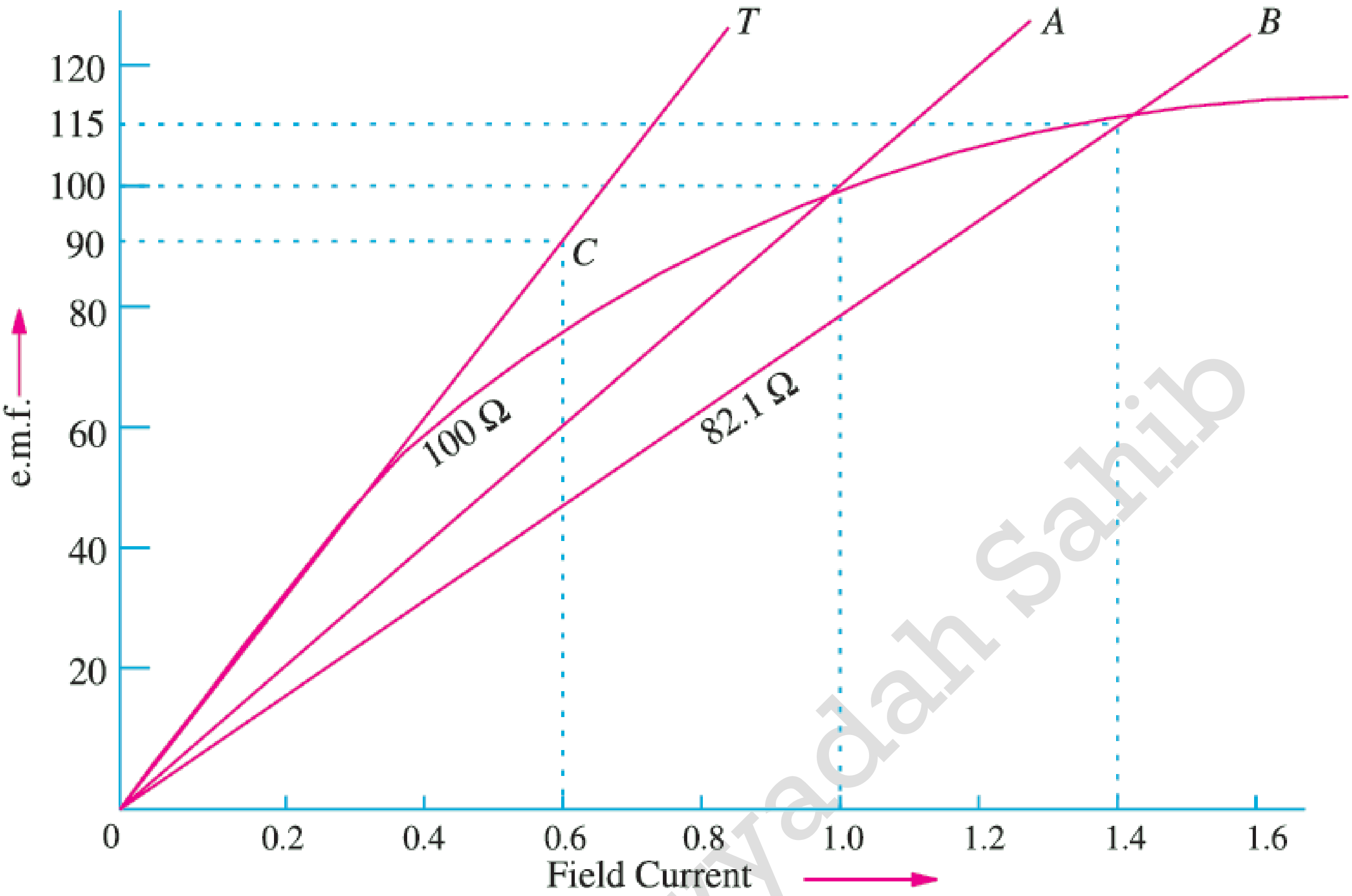


Figure (14)

Example 6: The magnetization characteristic for a 4-pole, 110V, 1,000 $r.p.m.$ shunt generator is as follows:

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

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

Solution: In Figure (15), OA represents the 45Ω line which is drawn as usual.

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

(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 110V and 1.1A respectively.

$$\therefore \quad R_c = \frac{110}{1.1} = 100\Omega$$

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

$$\frac{CD}{BD} = \frac{N_c}{1{,}000} \Rightarrow\Rightarrow \frac{49}{100} = \frac{N_c}{1{,}000}$$

$\therefore \quad N_c = 490\ r.p.m.$

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

$$\therefore \quad 5 = \frac{\Phi \times 144 \times 1{,}000}{60}\left(\frac{4}{4}\right) \Rightarrow\Rightarrow \Phi = 2.083\text{mWb}$$

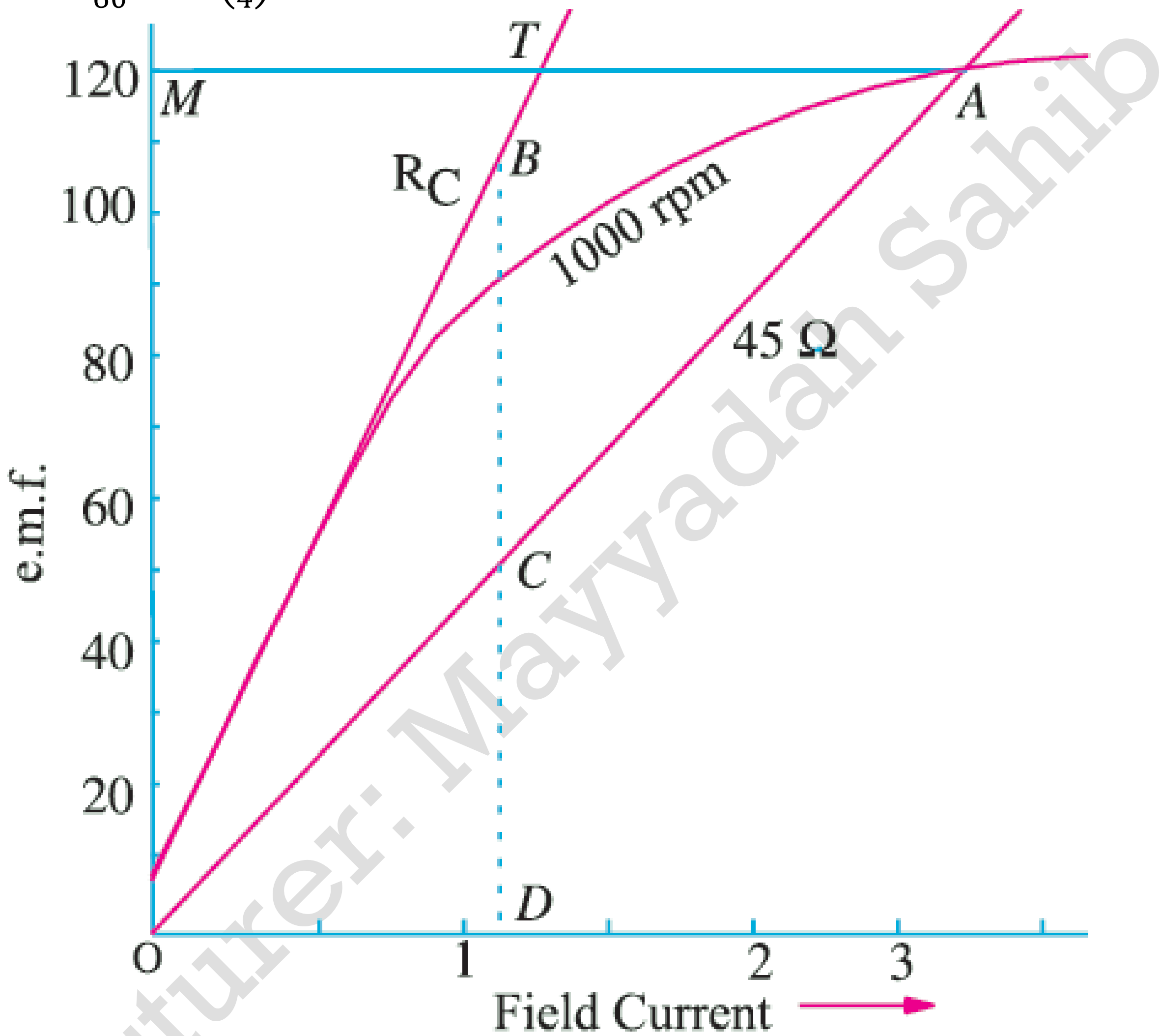


Figure (15)