DC Machines

Construction and Working of DC Generator

Prof. Sidhartha Panda
Department of Electrical Engineering
VSSUT, Burla

Overview of DC Machines

- DC machine is one of the most commonly used machine for electro-mechanical energy conversion.
- DC machines are classified into two types such as (i) DC generators, and (ii) DC motors.

(i) DC generator

- The machine which produces DC electrical power is known as DC generator.
- An electric generator is a machine which converts mechanical energy/power into electrical energy/power.
- It works on the principle of Faraday's laws of electromagnetic induction, which states that "whenever a conductor cuts the magnetic flux, an e.m.f. induced in it

- **Applications:** DC generators are suitable for many applications – including general lighting, battery charging, giving excitation to the alternators, series arc lighting etc.

(ii) DC Motor

- The machine which produces mechanical power is known as DC motor.
- An electrical motor is a machine which converts electrical energy/power into mechanical energy/power.
- It works on the principle of Lorentz Law, which states that "the current carrying conductor placed in a magnetic and electric field experience a force"

- **Applications:** DC motors are suitable for many applications – including conveyors, turntables, trolleys, underground subway cars etc.
- Any DC machine can act either as a generator or a motor
- A DC machine works as a DC generator when it is driven by a prime mover.
- The same machine works as a DC motor when electrical energy is supplied to it.
- Therefore, the constructional features of a DC generator and DC motor are the same.

Construction of a DC Machine

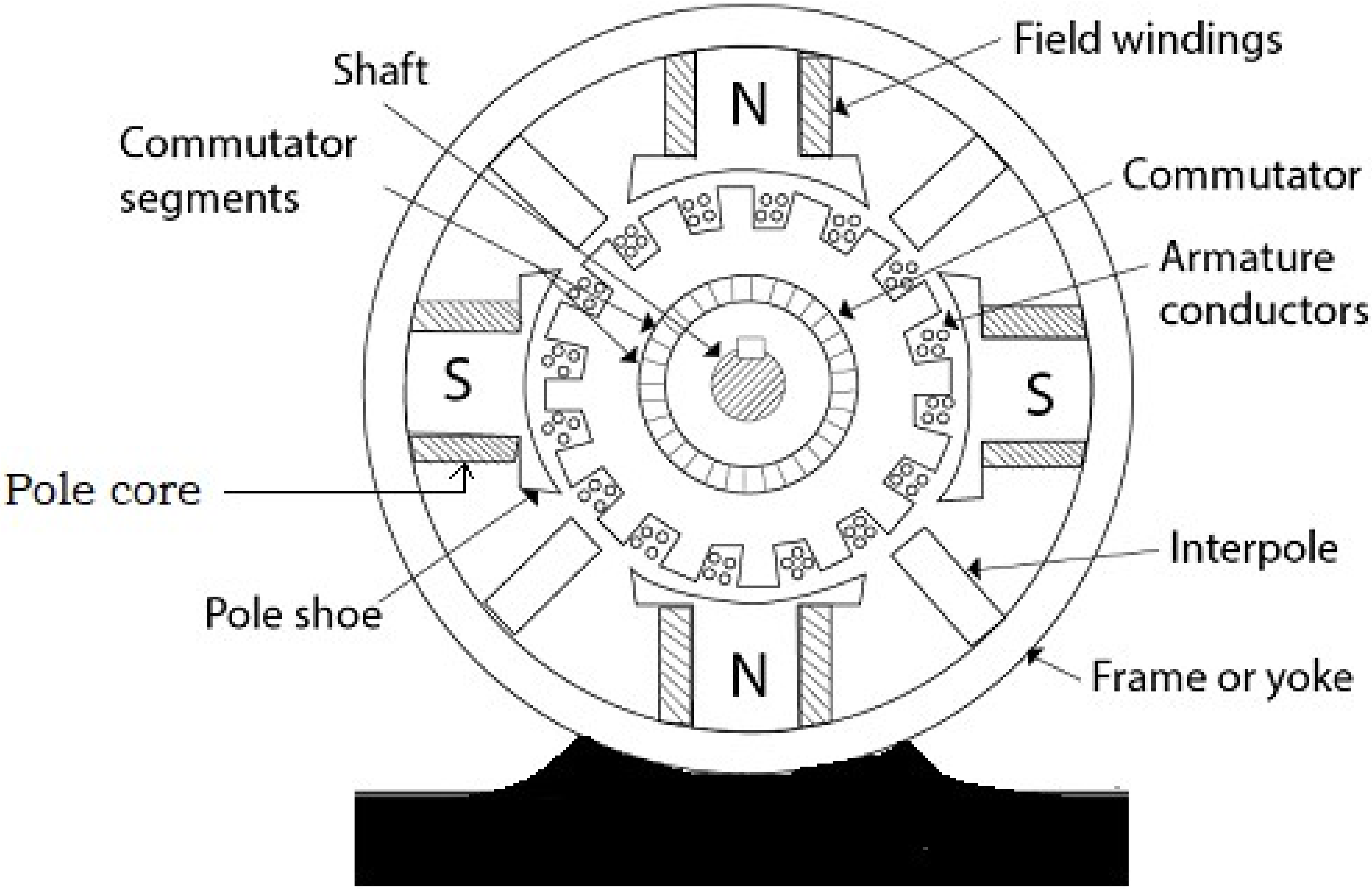


Figure (1.1): *Schematic diagram of a 4-pole DC Machine*

❖ DC machine consists the following main parts.

- Yoke or magnetic frame
- Armature core or stack
- Armature winding
- Pole consists of pole core and pole shoe
- Field winding
- Commutator
- Brushes and Brush holder
- Inter poles
- Shaft and Bearings

(i) Magnetic Frame or Yoke

- Outermost protecting cover for the DC machine.
- Circular steel ring, provides protection to all parts of the machine from moisture, dust etc.
- Provides mechanical support to the field poles and necessary magnetic path between the poles.
- Made up of with cast iron, cast steel, silicon steel, rolled steel etc.

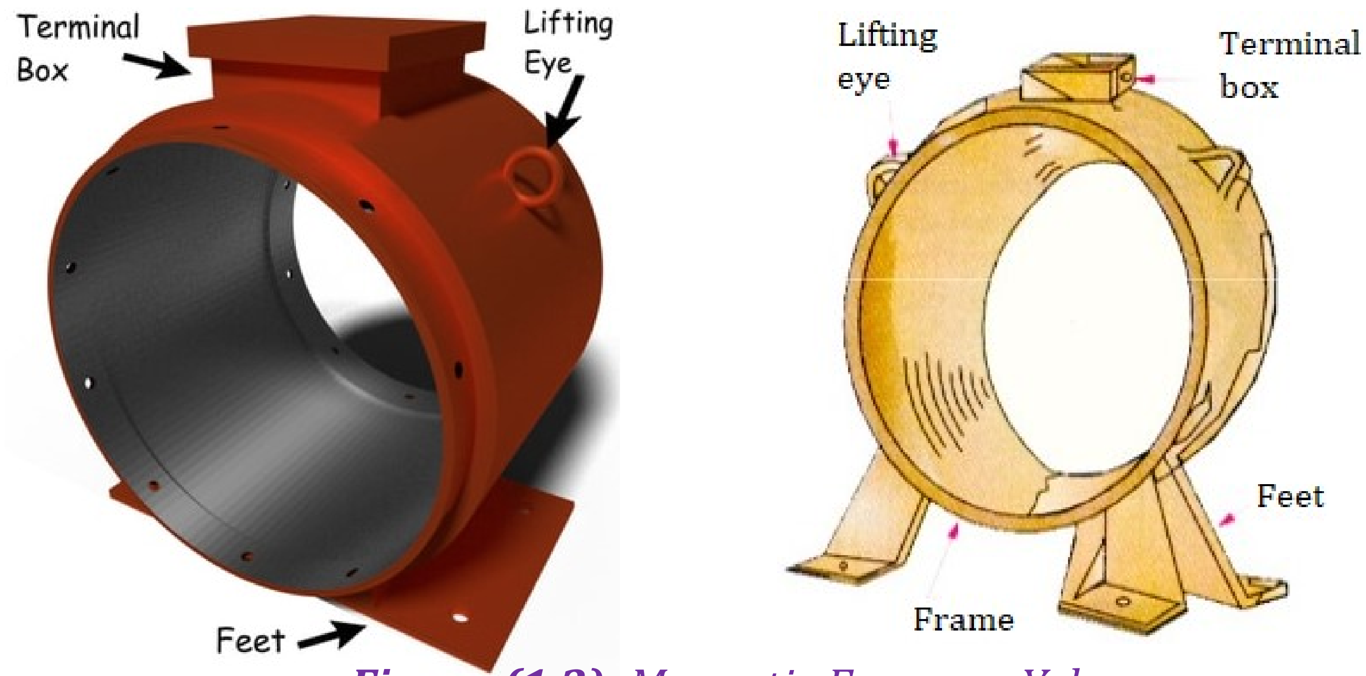


Figure (1.2): *Magnetic Frame or Yoke*

(ii) Armature core or Stack

- Rotating part (rotor) of the DC machine and is mounted on the shaft.
- Cylindrical in shape with slots to carry armature winding.
- Made up of silicon steel laminations in order to reduce the eddy current losses.
- Provided with air ducts for cooling purposes.

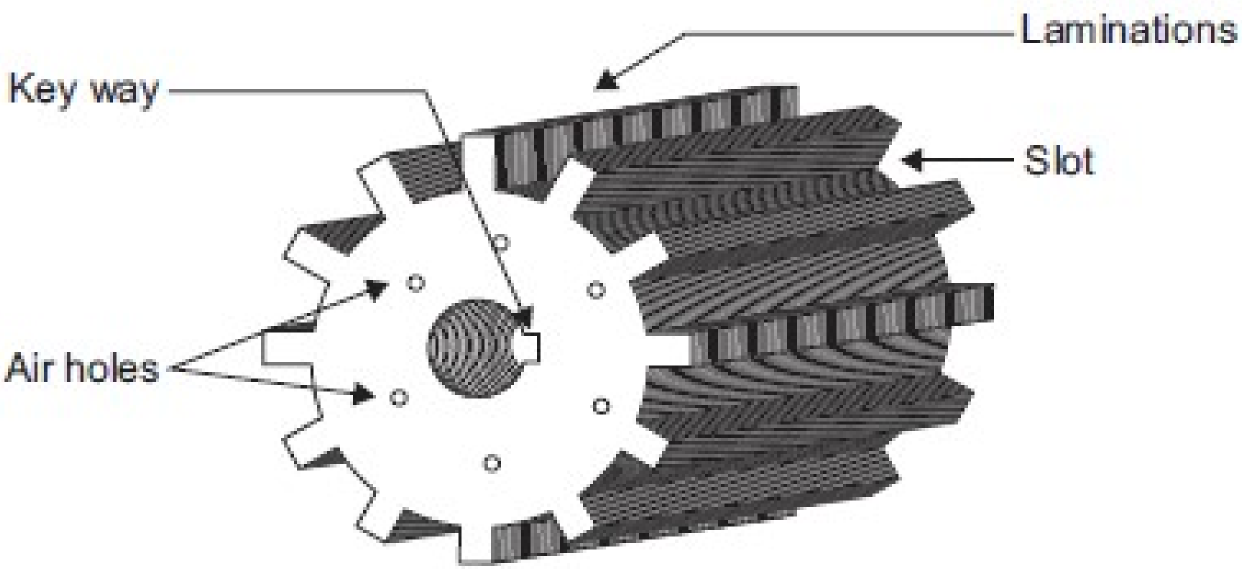


Figure (1.3): *Armature Core*

(iii) Armature winding

- Formed by placing copper coil/conductor in armature slots.
- Armature conductors are insulated from each other and also from the armature core.
- Armature winding can be wound by one of the two methods; lap winding or wave winding.

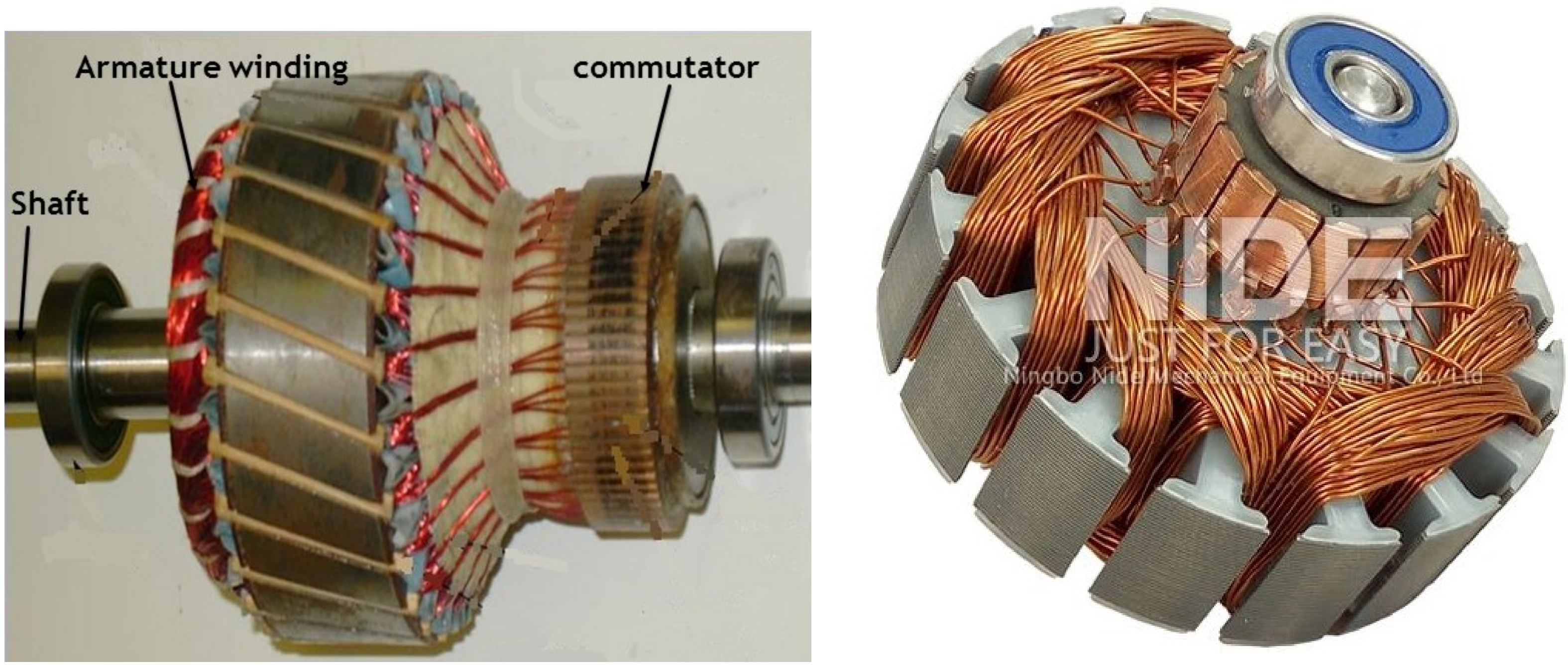


Figure (1.4): *Armature Winding*

- It either generates or receives the voltage depending on whether the unit is a generator or a motor.
- Made-up of with conducting materials like copper.

(iv) Poles and pole shoes

- Poles produce the magnetic flux when the field winding is excited.

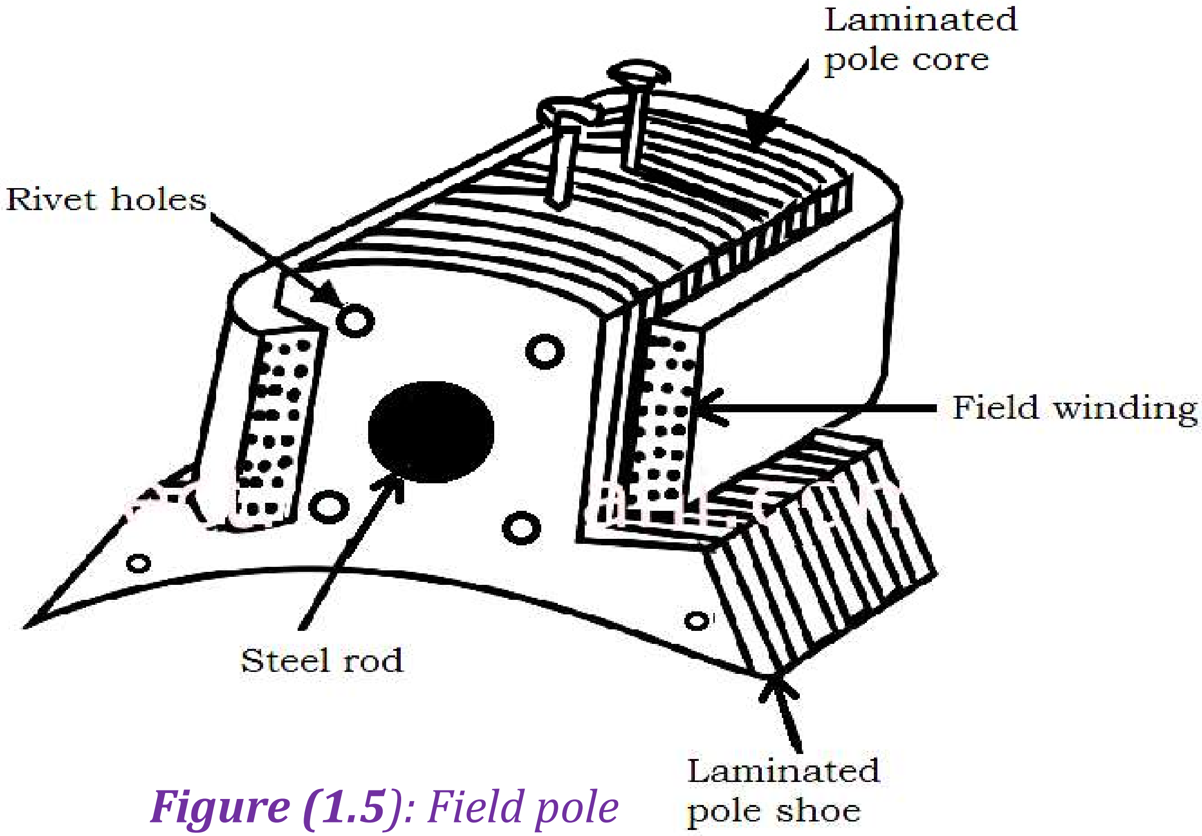


***Figure (1.5)**: Field pole*

- Each pole is divided into two parts namely pole core and pole shoe.
- Pole core is a part on which field winding is wound over.
- Pole shoe serves the following two functions:

  (i) Distributes the magnetic flux uniformly in the air gap.

  (ii) Supports the field winding.
- Poles are joined to the yoke with the help of bolts or welding
- In modern design the pole is made-up of with thin laminations of cast steel or cast iron.

(v) Field winding

- Field coils or field windings are located on the pole core of the machine.

- When the field winding excited, i.e. when the current is passed through the field winding in a specific direction, it sets up magnetic field (i.e. magnetize the poles) in the machine.
- The field coils may be either shunt windings (in parallel with the armature winding) or series windings (in series with the armature winding) or a combination of both.
- Made up of with conducting materials like aluminum, copper etc.

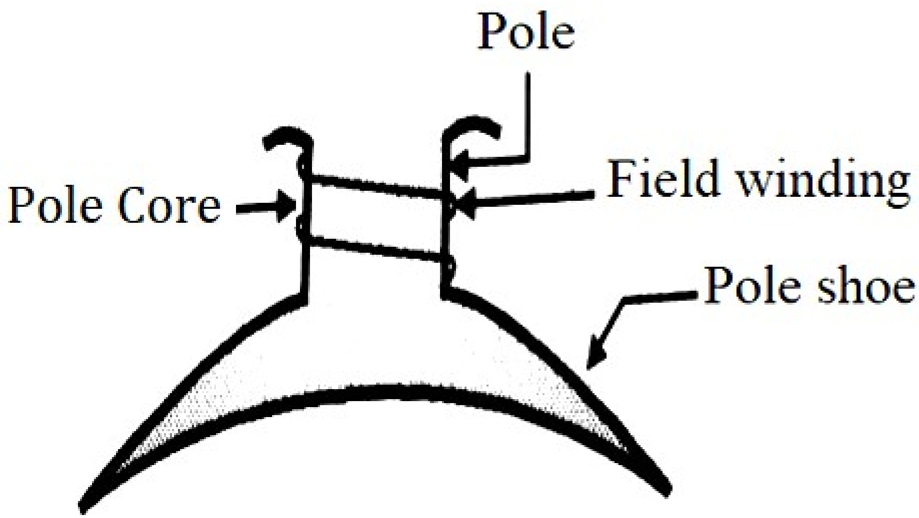


Figure (1.6): *Field winding*

(vi) Commutator

- Commutator is a mechanical rectifier, which converts AC voltage of the rotating conductors to DC voltage.
- Collects the current from the armature conductors and passes it to the external load via brush.
- Cylindrical in structure and is made-up of copper or bronze.

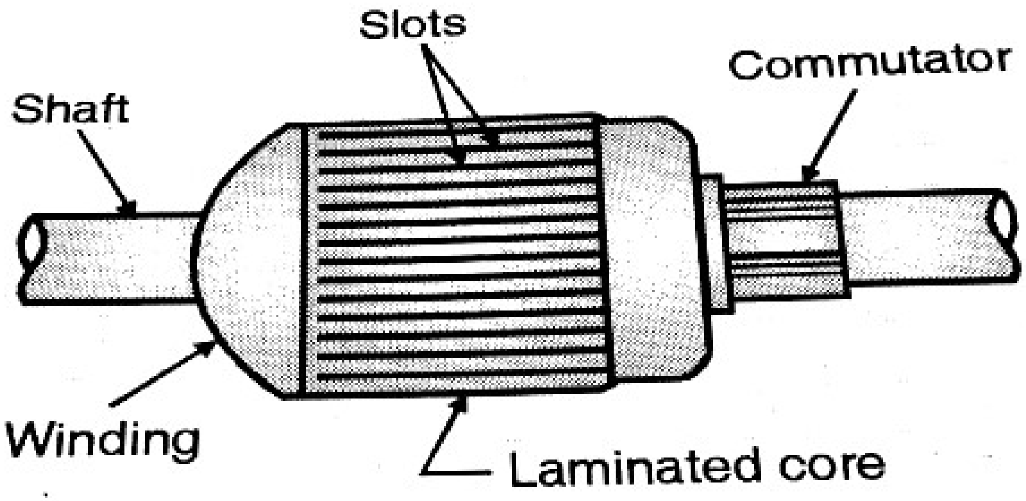


Figure (1.7): *Fully Assembled Commutator*

(vii) Brushes and brush holder

- Brushes conduct the current from the commutator to the external circuit.
- Made-up of with material like carbon, graphite etc.
- A brush holder is usually a metal box that is rectangular in shape.
- The brush holder has a spring that holds the brush in contact with the commutator.

(viii) Inter poles

- Inter poles are similar to the main poles.
- These are connected between the yoke and main field poles.
- They have windings in series with the armature winding.
- Inter poles have the function of reducing the armature reaction effect in the commutating zone.

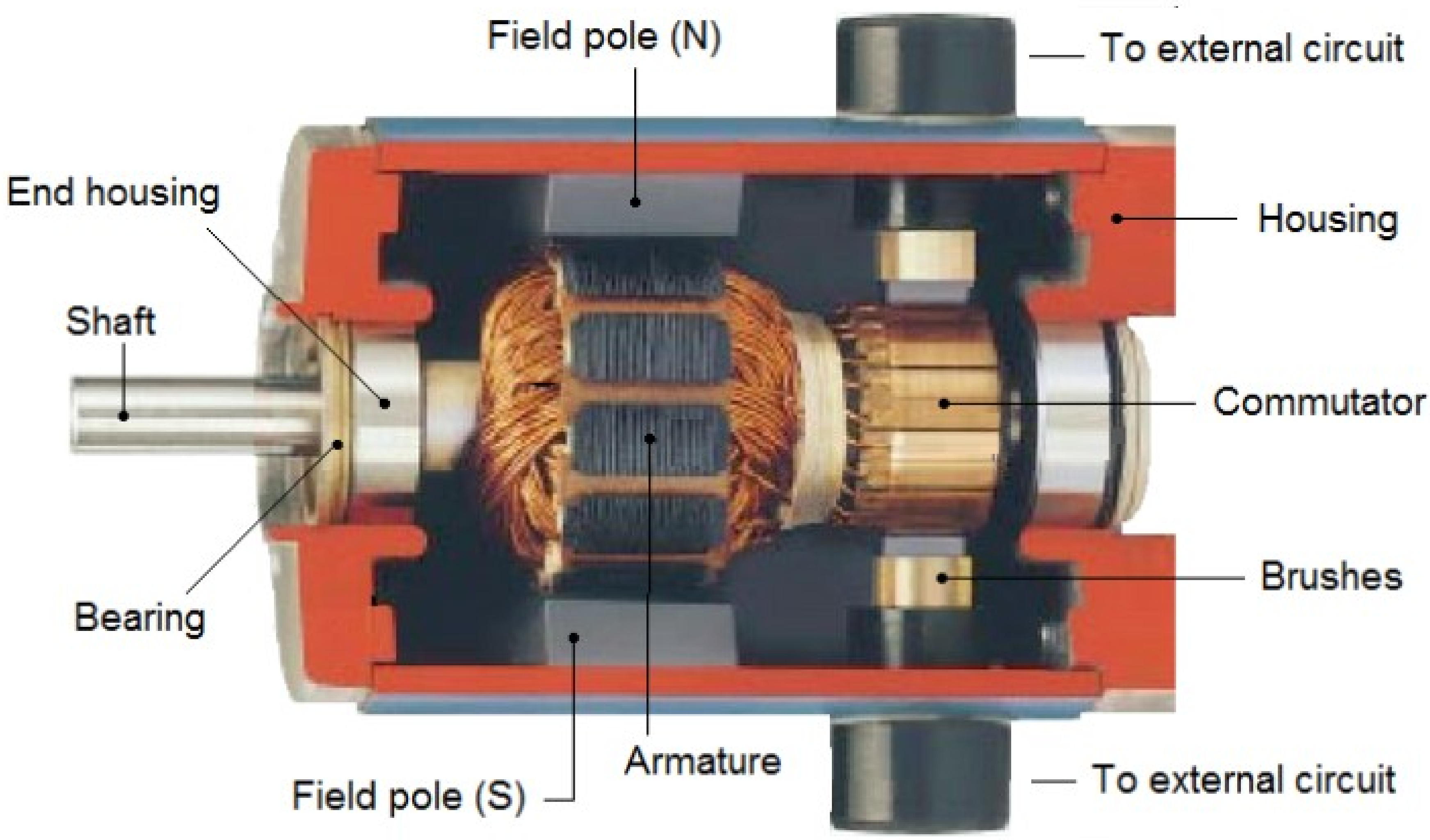


Figure (1.8): *Cut View of DC Machine*

(ix) Shaft and Bearings

- Shaft is made of mild steel with a maximum breaking strength.
- Shaft is used to transfer mechanical power from or to the machine.
- These are normally lubricated by grease or oil.
- The armature is mounted on a steel shaft, which is supported between the two bearings.
- The bearings are either ball or roller type and are fitted in the end housings.
- The function of the bearings is to reduce friction between the rotating and stationary parts of the machine.
- Mostly high carbon steel is used for the construction of bearings.

Working principle of a DC generator

- An electric generator is a machine which converts mechanical energy into electrical energy.
- All the generators work on a principle of dynamically induced e.m.f. i.e. Faraday's law of electromagnetism induction.
- It states that, whenever a conductor cuts the magnetic flux, an e.m.f. induced; which will cause a current to flow if the conductor circuit is closed.
- The direction of induced e.m.f and hence current is given by Fleming's right hand rule.
- Therefore, the essential components of a generator are: (i) a magnetic field, (ii) conductor or a group of conductors, and (iii) motion of the conductor w.r.t. magnetic field.
- Figure (1.9) shows a single loop rectangular copper coil (ABCD) rotating about its own axis in a magnetic field provided by either permanent magnets or electromagnets.

Working principle of a DC generator

- The two ends of the coil are joined to two slip-rings which are insulated from each other and from the central shaft.
- Two collecting brushes (carbon or copper) press against the slip-rings; their function is to collect the current induced in the coil to external load resistance.
- The rotating coil may be called armature and the magnets as field system.

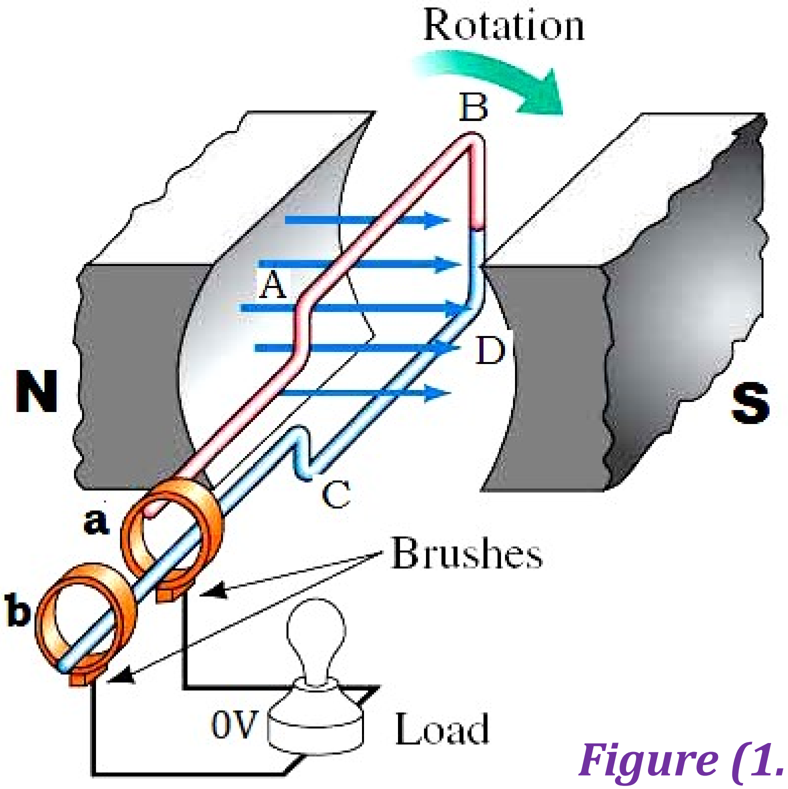


Figure (1.9)

Working principle of a DC generator

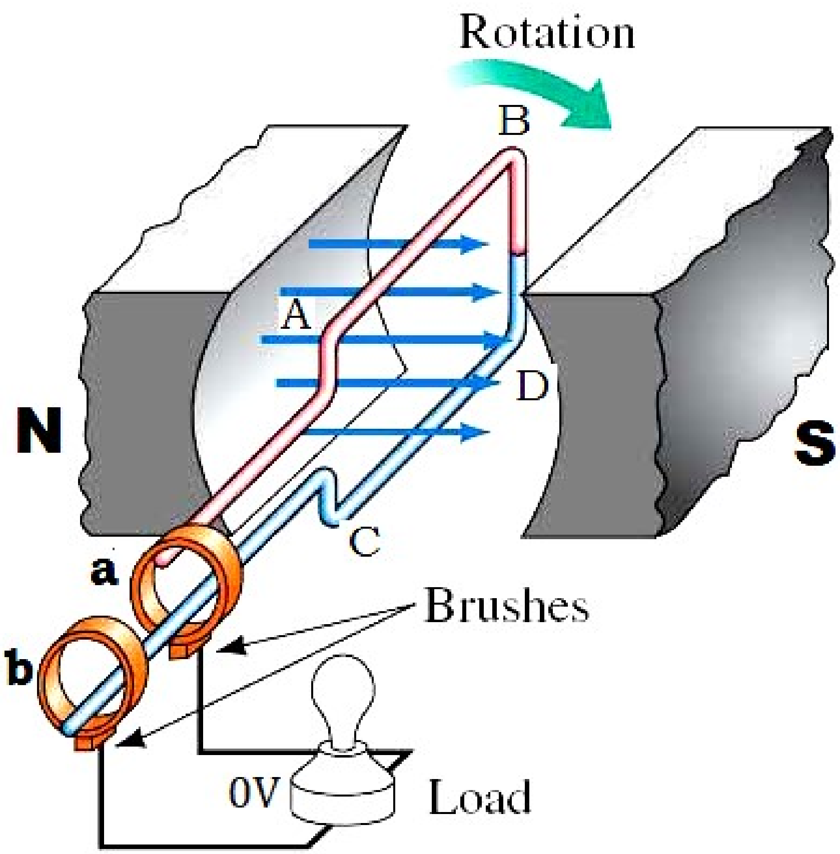


__Figure (1.10):__ Conductor moving parallel to the direction of flux (0^0 position)

- Figure (1.10) shows a single loop coil forming two sides AB and CD able to rotate between north pole 'N' and south pole 'S' of a permanent magnet. Assume this as the starting point and fixing the direction of rotation as clock-wise.
- In this position the conductor coil sides 'AB' and 'CD' are parallel to the magnetic flux and therefore does not cut the magnetic flux and the induced voltage at this instant is zero

Working principle of a DC generator

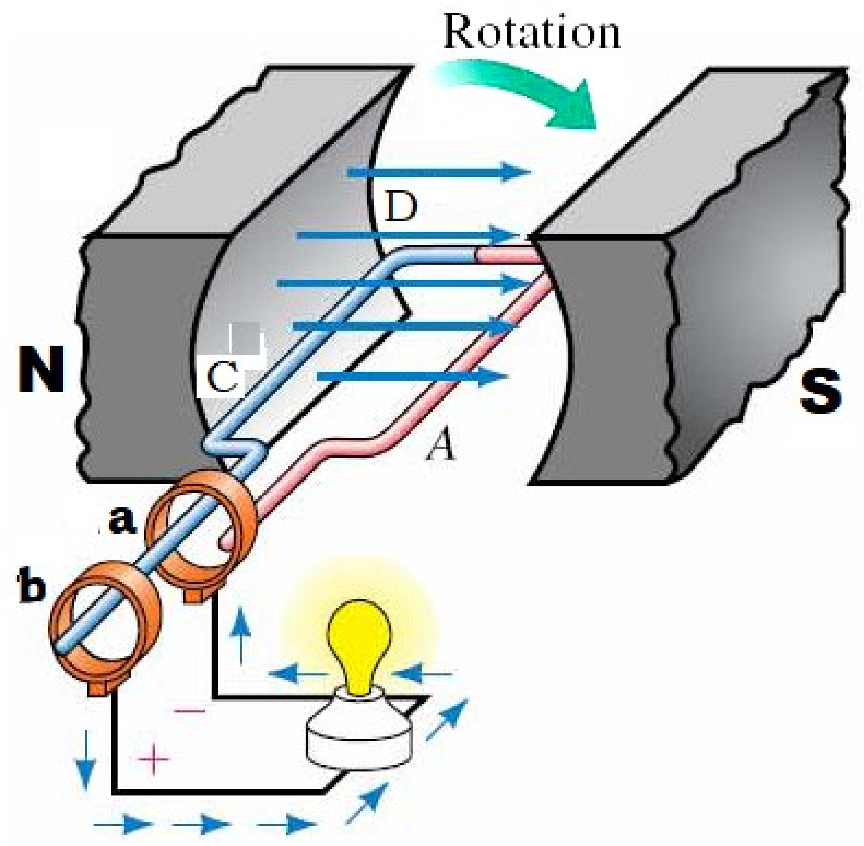


Figure (1.11): Conductor moving perpendicular to the direction of flux (90^0 position)

- As the coil rotates from the 0^0 position to 90^0 in clockwise, the coil sides begin to cut the magnetic flux at a gradually increasing rate and conductor comes to the position as shown in figure (1.11).

- Hence the magnitude of induced e.m.f. also gradually increases and becomes maximum when the coil rotates by an angle 90^0.

Working principle of a DC generator

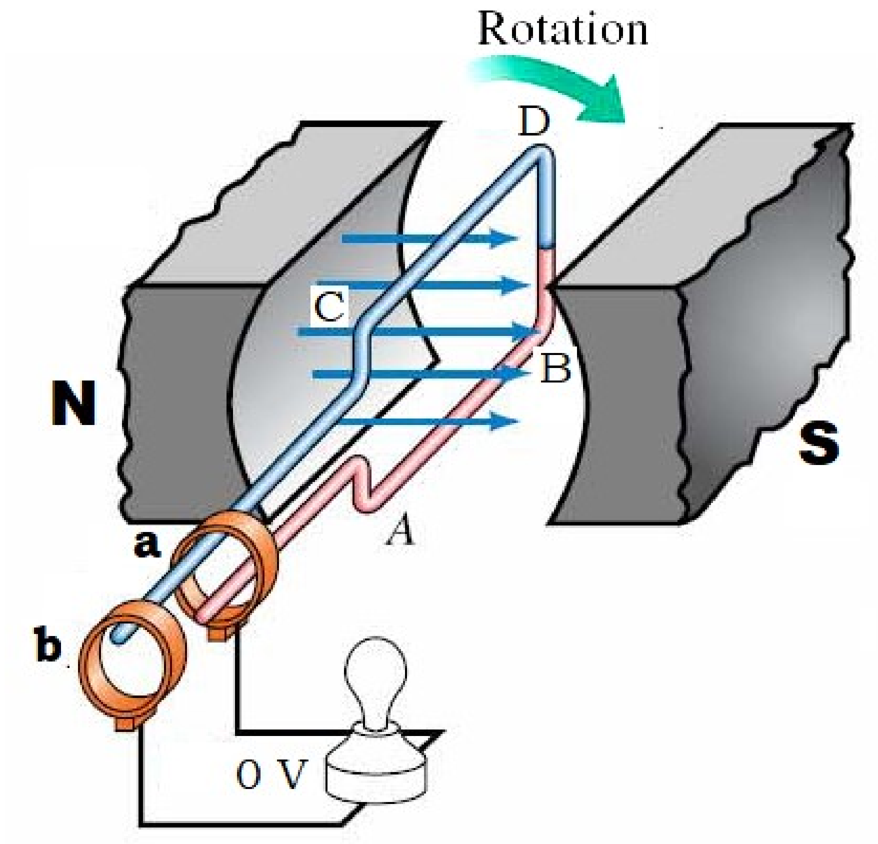


Figure (1.12): Conductor moving parallel to the direction of flux (180^0 position)

- As the coil rotates from the 90^0 position to 180^0, again the coil sides AB and CD are parallel to the flux lines as shown in figure (1.12).
- Under this condition the flux linkage is gradually decreases and hence the induced e.m.f. also gradually decrease and becomes zero at 180^0.
- At this point, the coil has gone through a half-revolution.

Working principle of a DC generator

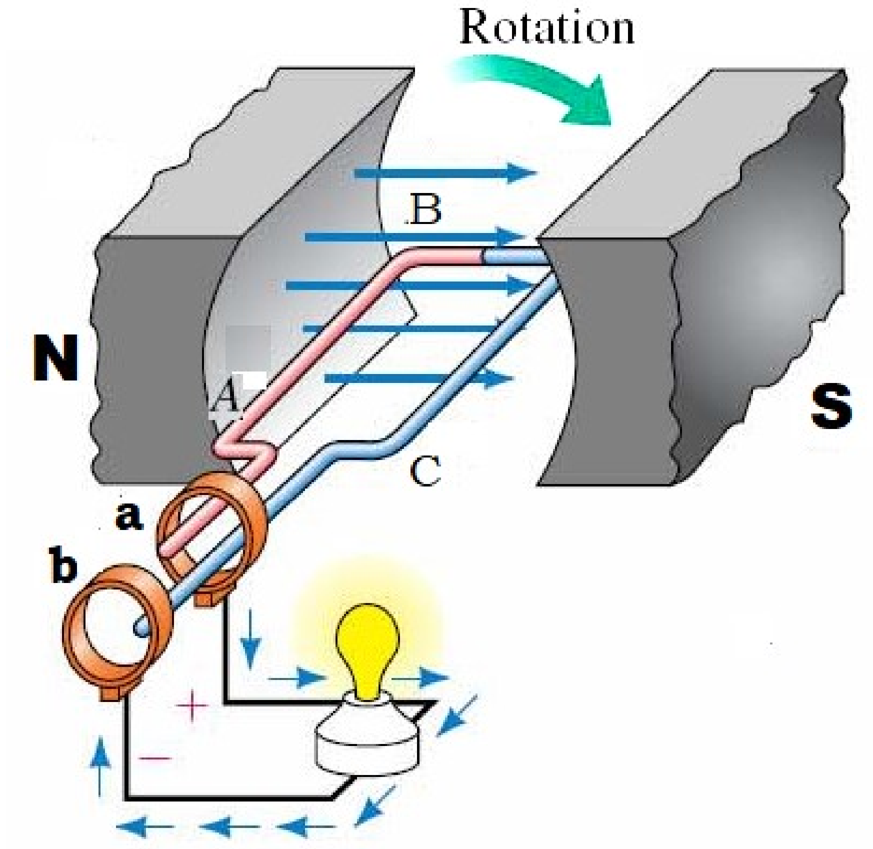


Figure (1.13): Conductor moving perpendicular to the direction of flux (270^0 position)

- Again, as the coil rotates from position 180^0 to 270^0 as shown in figure (1.13), the induced e.m.f. starts increasing from zero to maximum and attains maximum value at 270^0, but in opposite direction.

Working principle of a DC generator

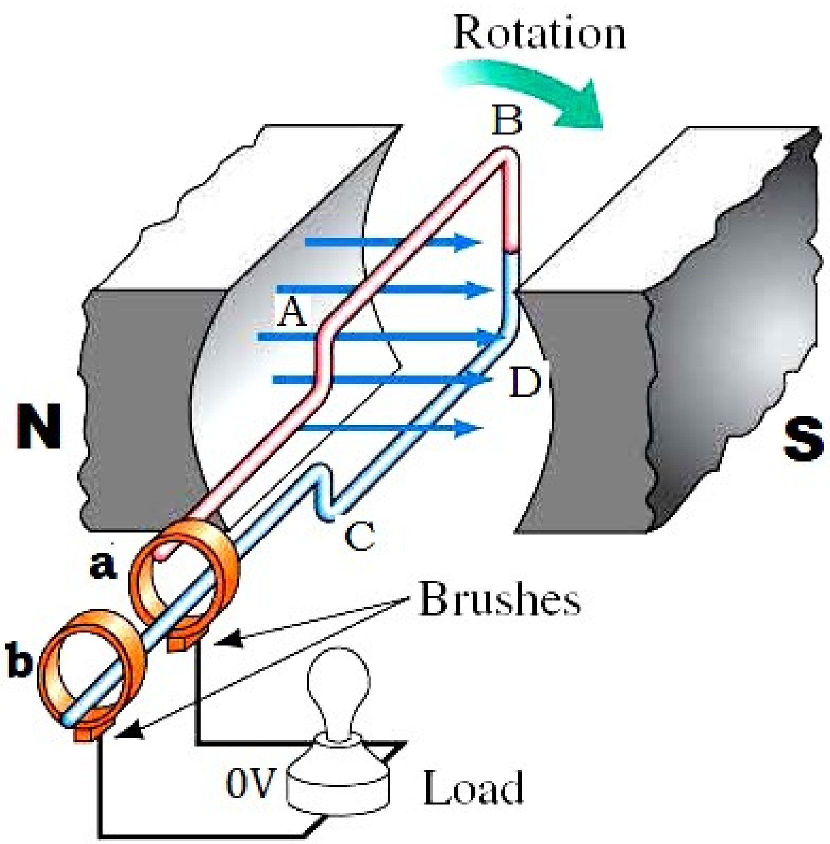


Figure (1.14): Conductor moving parallel to the direction of flux (360^0 position)

- As the coil again moves from 270^0 to 360^0 as shown in figure (1.14), the induced e.m.f. starts decreasing from its maximum value and reaches to zero again.
- So it completes the second half revolution.
- Thus, during the second half-revolution, coil sides cut flux in directions opposite to that which they did in the first half revolution, hence, the polarity of the induced voltage reverses.

Working principle of a DC generator

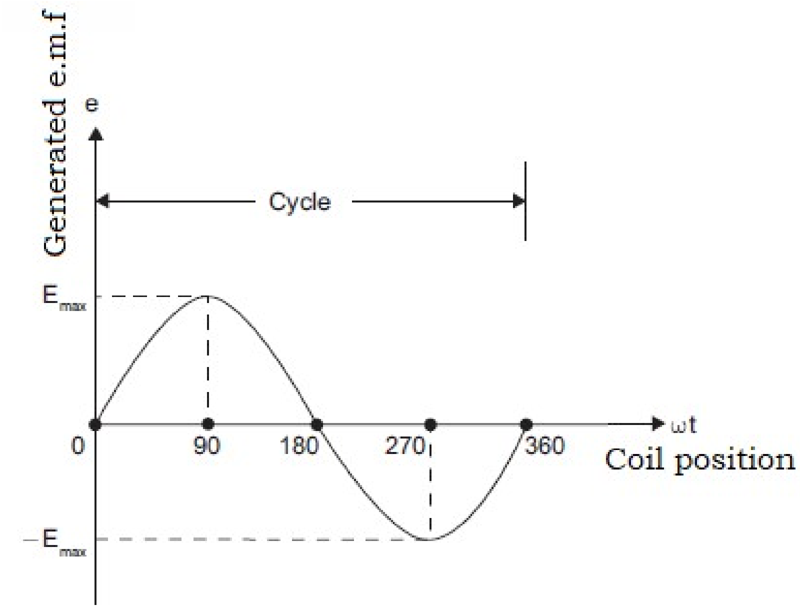


Figure (1.15): Sinusoidal wave form of induced e.m.f.

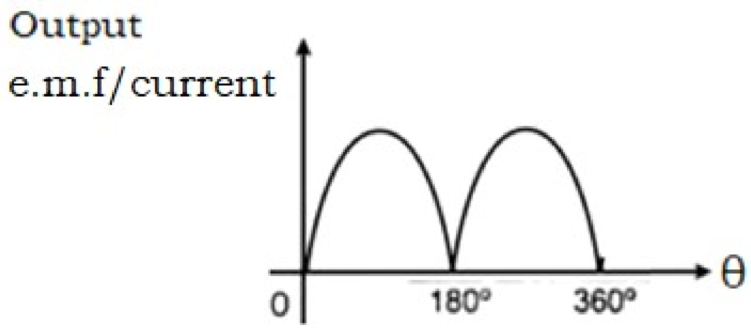


Figure (16): Wave form of unidirectional current at the load

- So from the above discussion, it can be concluded that the e.m.f. induced in the armature conductor of a DC generator is alternating in nature as shown in figure (1.15).

- It is seen that, the e.m.f. induced in the conductors is always sinusoidal and split ring commutator converts this sinusoidal e.m.f. into unidirectional e.m.f. as shown in fig.(1.16)

Fleming's Right Hand Rule:

If the right hand is held with the thumb, fore finger and middle finger mutually at right angles, as shown in the figure (1.17), then

- The Thumb represents the direction of motion of the conductor (F).
- The Fore finger represents the direction of Magnetic field (B).
- The Middle finger represents the direction of induced or generated e.m.f/current (V or I).

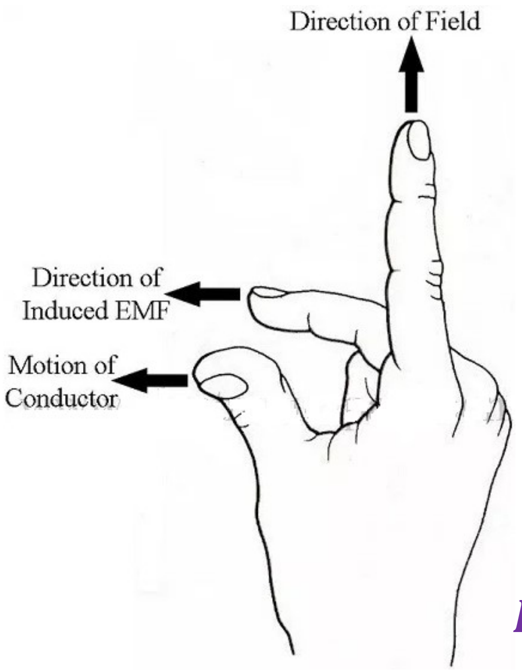


Figure (1.17): *Fleming's right hand rule*

DC Machines
EMF Equation & Types

Prof. Sidhartha Panda
Department of Electrical Engineering
VSSUT, Burla

EMF Equation of a DC Generator

- Let Φ = flux per pole in Weber

  Z = total number of armature conductors

  = number of slots × number of conductors per slot

  N = speed of the armature in rpm

  A = number of parallel paths in the armature winding

  P = number of poles of the generator

- According to Faraday's law of electromagnetic induction, average e.m.f. induced per conductor, $e = \frac{d\Phi}{dt}$

- Total Flux= Flux produced by each pole × No. of poles

  $d\Phi = \Phi \times P = P\Phi$ Webers

- Time taken by a conductor for completing one revolution

  dt =60/N sec

$$\therefore e = \frac{d\Phi}{dt} = \frac{P\Phi}{60/N} = \frac{P\Phi N}{60}$$

- We know that here ‘Z’ conductors are distributed in ‘A’ parallel paths. So effectively (Z/A) conductors need to be multiplied with e.m.f induced in one conductor
- Total e.m.f generated between the armature terminals is given by,
- E_g = average e.m.f. generated per conductor × no. of conductors in each parallel path $= \frac{P\Phi N}{60} \times \frac{Z}{A} = \frac{\Phi ZN}{60} \times \left(\frac{P}{A}\right)$

$$\therefore E_g = \frac{\Phi ZN}{60} \times \left(\frac{P}{A}\right)$$

- For lap winding, A=P
- For wave winding, A=2
- For a given DC generator, Z, P & A are constants and hence generated e.m.f is $E_g \propto \Phi N = k\Phi N;\ where\ k\ is\ a\ const.$

Solved Problem-1: *A 4-pole DC generator having wave wound armature winding has 51 slots, each slot containing 20 conductors. Find the generated voltage in the machine when speed is 1500 rpm and flux per pole is 60 mWb.*

Solution: Given that

No. of poles, P = 4, No. of slots = 51

No. of conductors/slot = 20

Total no. of conductors, Z = 51 x 20 = 1020

Speed, N = 1500 rpm

Flux per pole, Φ=60 mWb

No. of parallel paths, A= 2 (for wave wound)

$$E_g = \frac{\Phi Z N}{60} \times \left(\frac{P}{A}\right) = \frac{60 \times 10^{-3} \times 1020 \times 1500 \times 4}{60 \times 2} = 3060\,V$$

⇒ ***Solved Problem-2:*** *An 8-pole DC generator has per pole flux of 40 mWb and winding is connected in lap with 960 conductors. Calculate the generated e.m.f on open circuit when it runs at 400 rpm. If the armature is wave wound, at what speed must the machine be driven to generate the same voltage.*

Solution: Given that

P=8, Φ=40mWb, Z =960, A=P =8 for lap wound, N= 400rpm

Generated e.m.f., $$E_g = \frac{\Phi Z N}{60} \times \left(\frac{P}{A}\right) = \frac{40 \times 10^{-3} \times 960 \times 400}{60} \times \frac{8}{8} = 256\,V$$

If the armature is wave wound, A=2, P=8

$$E_g = \frac{\Phi Z N}{60} \times \left(\frac{P}{A}\right)$$

$$\Rightarrow N = E_g \times \frac{60A}{\Phi Z P} = 256 \times \frac{60}{40 \times 10^{-3} \times 960} \times \frac{2}{8} = 100 rpm$$

⇒ ***Solved Problem-3:*** *A DC generator has armature e.m.f. of 100V when flux per pole is 20 mWb and speed is 900rpm. Calculate e.m.f. generated when (i) speed is 1000 rpm with same flux, and (ii) speed is 900 rpm but flux is 23 mWb*

Solution: Given that

$$E_{g1} = 100V \text{ , } \Phi_1 = 20 \times 10^{-3} Wb \text{ , } N_1 = 900 rpm$$

We have the relation as

$$E_g \propto \Phi N$$

(i) Speed is 1000 rpm with same flux

$$\frac{E_{g1}}{E_{g2}} = \frac{\Phi_1}{\Phi_2} \times \frac{N_1}{N_2}$$

$$\Rightarrow \quad \frac{100}{E_{g2}} = \frac{\Phi_1}{\Phi_1} \times \frac{900}{1000} \qquad (\because \text{same flux})$$

$$\Rightarrow E_{g2} = 111.11V$$

(ii) Speed is 900 rpm but flux is 23 mWb

$$N_2 = 900\,rpm\,; \;\; \Phi_2 = 23 \times 10^{-3}\,Wb$$

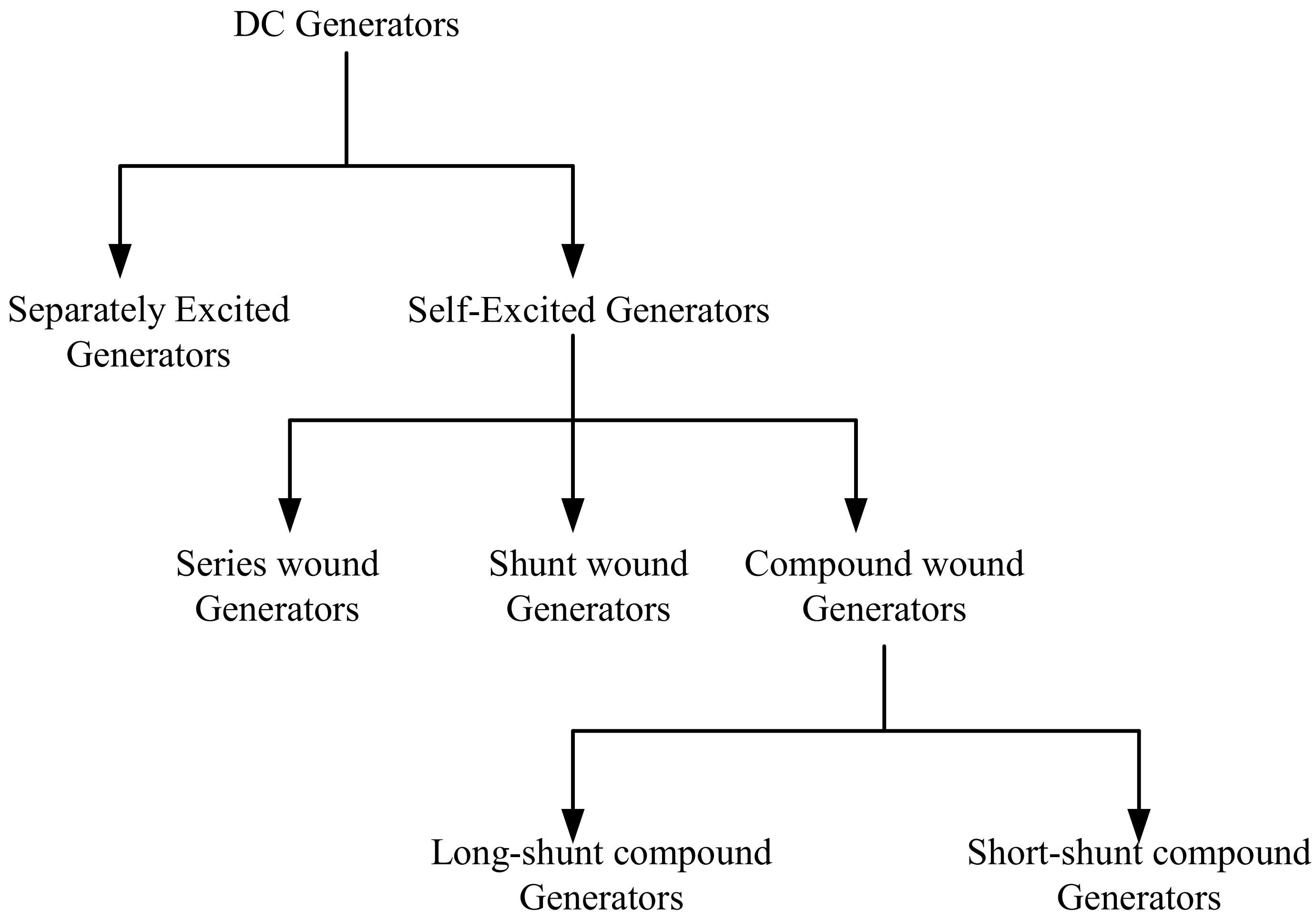
$$\frac{E_{g1}}{E_{g2}} = \frac{\Phi_1}{\Phi_2} \times \frac{N_1}{N_2}$$

$$\frac{100}{E_{g2}} = \frac{20 \times 10^{-3}}{23 \times 10^{-3}} \times \frac{900}{900}$$

$$\Rightarrow E_{g2} = 115V$$

Types of DC Generators

- DC generators are generally classified into the following types according to the methods of their field excitation.



(1) Separately Excited Generators

- ❖ Separately excited generators are those, whose field magnets are energized from an external DC source as shown in figure (1.18).

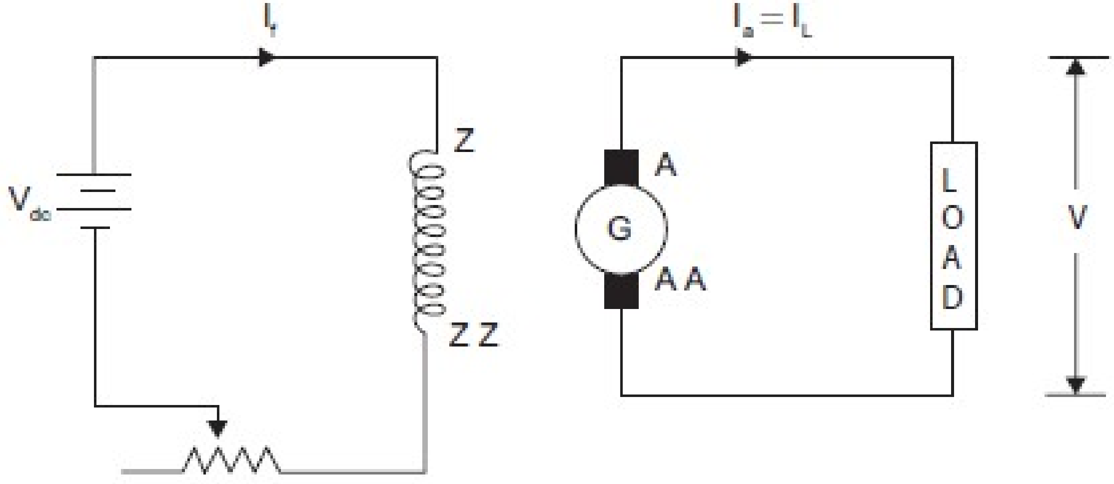


Figure (1.18): *Separately excited generator*

- ❖ **Important relations:**

  Armature current, $I_a = I_L$

  Generated voltage, $E_g = V + I_aR_a + BCD$

  Power developed in the armature, $P_g = E_gI_a$

  Power delivered to load, $P_L = VI_L$

Note: BCD= Brush contact drop, generally 1V per brush

(2) Self-excited Generators

- Self-excited generators are those, whose field magnets are energized by the current produced by the generators themselves.
- Self-excited generators are classified according to the type of field connection they use.
- There are three general types of field connections: series-wound, shunt-wound (parallel), and compound-wound.
- Compound-wound generators are further classified as long-shunt compound and short-shunt compound.

(i) Series-wound Generator

❖ In the series-wound generator, shown in figure (1.19), the field windings are connected in series with the armature. .

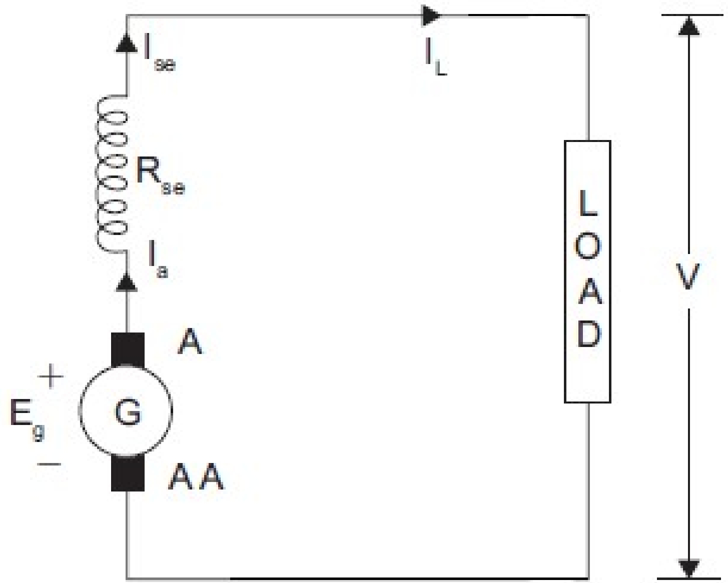


Figure (1.19): *Series wound generator*

❖ **Important relations:**

Armature current, $I_a = I_{se} = I_L$

Generated voltage, $E_g = V + I_a R_a + I_{se} R_{se} + BCD$

Power developed in the armature, $P_g = E_g \, I_a$

Power delivered to load, $P_L = V I_L$

(ii) Shunt-wound Generators

- In a shunt-wound generator as shown in figure (1.20), the field coils consist of many turns of small wire. They are connected in parallel with the load. In other words, they are connected across the output voltage of the armature.

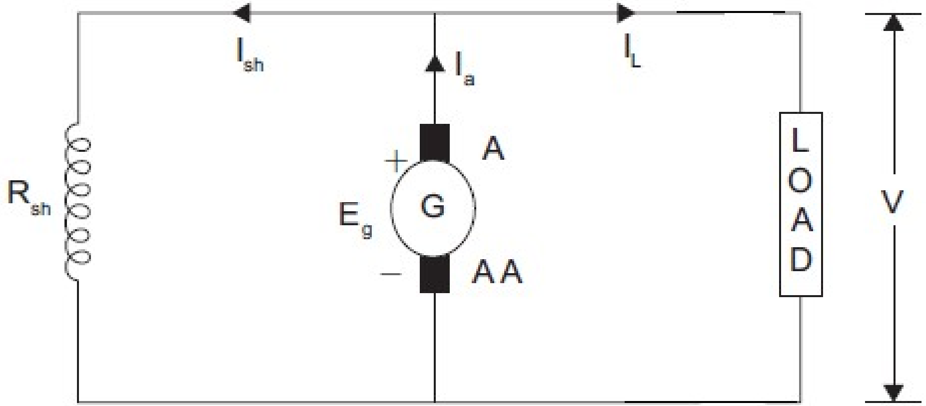


Figure (1.20): *Shunt wound generator*

- **Important relations:**

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

Shunt field current, $I_{sh}= V/R_{sh}$

Generated voltage, $E_g = V+I_aR_a+$ BCD

Power developed in the armature, $P_g= E_gI_a$

Power delivered to load, $P_L= VI_L$

(iii) Compound-Wound Generators

(a) Long-shunt Compound Generators

❖ In which the shunt field winding is in parallel with both armature and series field windings

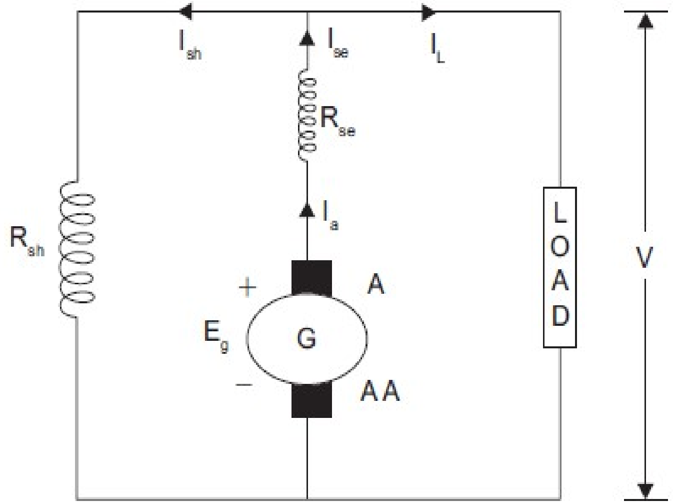


Figure (1.21): Short-shunt compound wound generator

❖ **Important relations:**

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

Shunt field current, $I_{sh} = V/R_{sh}$

Generated voltage, $E_g = V + I_a R_a + I_{se} R_{se} + BCD$

Power developed in the armature, $P_g = E_g I_a$

Power delivered to load, $P_L = VI_L$

(b) Short shunt Compound-wound Generators

- In which only shunt field winding is in parallel with armature winding.

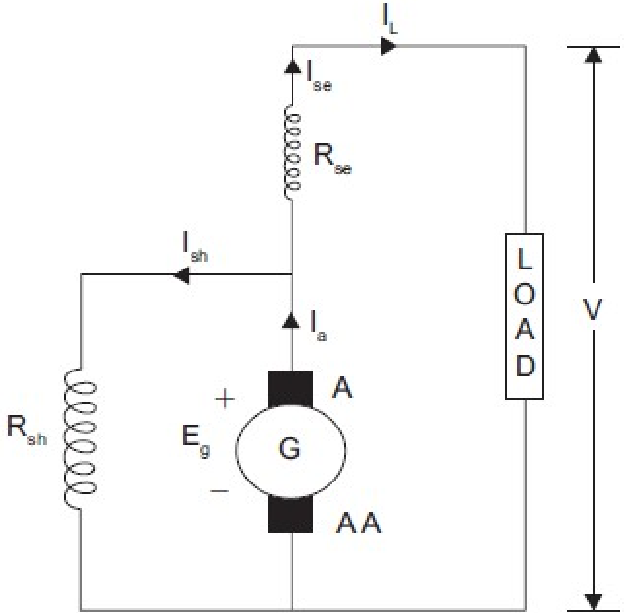


Figure (1.22): *Short-shunt compound wound generator*

- **Important relations:**

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

Series field current, $I_{se} = I_L$

Generated voltage,, $E_g = V + I_aR_a + I_{se}R_{se} + BCD$

Power developed in the armature, $P_g = E_gI_a$

Power delivered to load, $P_L = VI_L$

Solved Problem-4: *A 4-pole DC shunt generator with wave connect armature has armature and field resistance of 0.4Ω and 50Ω respectively and supplied to 50 lamps of 60W, 250V each. Calculate the (i) armature current, (ii) current per path, and (iii) generated e.m.f.*

Solution: Given that

No. of poles, P =4

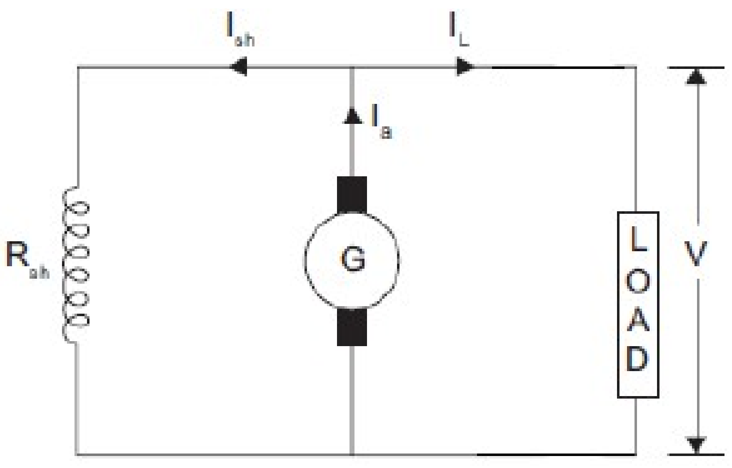
No. of parallel path , A =Z (wave wound)

Armature resistance, $R_a = 0.4\Omega$

Field resistance, $R_{sh} = 50\Omega$

Terminal voltage, V = 250V

Total lamp load, $P_L = 60 \times 50 = 3000\text{W}$



$$I_L = \frac{P_L}{V} = \frac{3000}{250} = 12\text{A}$$

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

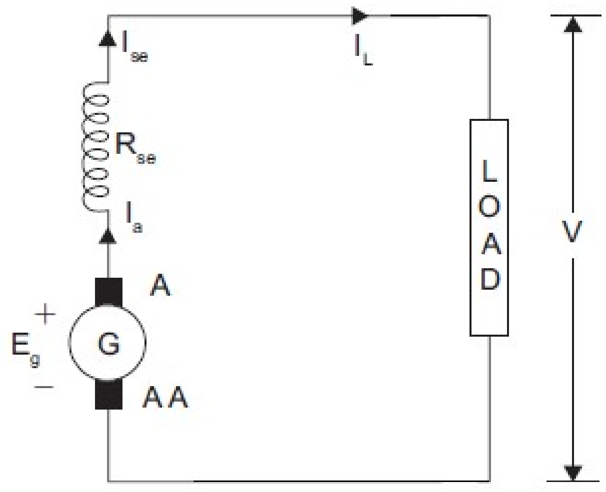
(i) Total armature current, $I_a = I_L + I_{sh} = 12+5 = 17A$

(ii) Current per path $= \frac{I_a}{A} = \frac{17}{2} = 8.5\,A$

(iii) Generated e.m.f., $E_g = V + I_a R_a = 250 + 17 \times 0.4 = 257.8V$

Solved Problem-5: *A series DC generator delivers a current of 150 A at 230V. Its armature and series field resistances are 0.2Ω and 0.06Ω respectively. Find (i) armature current, and (ii) generated e.m.f.*

Solution: Given that



Load current, $I_L = 150A$

Terminal voltage, V =230V

Series field resistance, $R_{se} = 0.06\ \Omega$

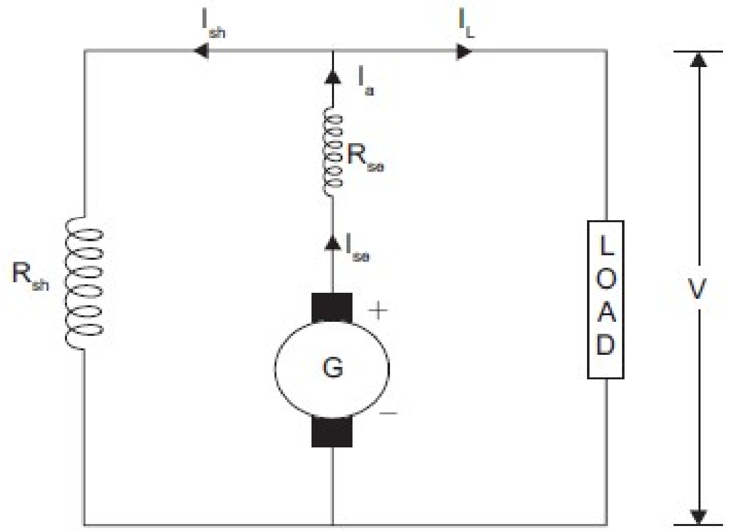
Armature resistance, $R_a = 0.2\Omega$

(i) Armature current, $I_a = I_L = 150A$

(ii) Generated e.m.f., $E_g = V + I_a R_a + I_{se}R_{se} = 230 + 150 \times 0.2 + 150 \times 0.06 = 269V$

Solved Problem-6: *A long shunt compound generator delivers a load current of 50A at 500V and has armature, series field and shunt field resistances of 0.05Ω, 0.03Ω and 250 Ω respectively. Calculate the generated voltage and the armature current? Allow 1V per brush for contact drop.*

Solution: Given that



Load current, $I_L = 50A$

Terminal voltage, V = 500V

Armature resistance, $R_a = 0.05\Omega$

Series field resistance, $R_{se} = 0.03\Omega$

Shunt field resistance, $R_{sh} = 250\,\Omega$

Brush contact drop, BCD $= 2\times1 = 2V$

Long shunt compound generator.

Shunt field current, $I_{sh} = \dfrac{V}{R_{sh}} = \dfrac{500}{250} = 2A$

Armature current, $I_a = I_L + I_{sh}$ = 50+2=52A

Generated Voltage, E_g =V+I_a R_a + $I_{se}R_{se}$ +BCD

$$=500+52\times 0.05+52\times 0.03+2\times 1= 57.16V$$

Solved Problem-7: *A short shunt compound generator supplies a current of 100A at a voltage of 250V. If the shunt, series and armature resistance are 50Ω, 0.025Ω and 0.05Ω respectively. Calculate the (a) Generated voltage, and (b) Power delivered to load. Allow a brush drop of 1V per brush.*

Solution: Given that

Load current, I_L =100A

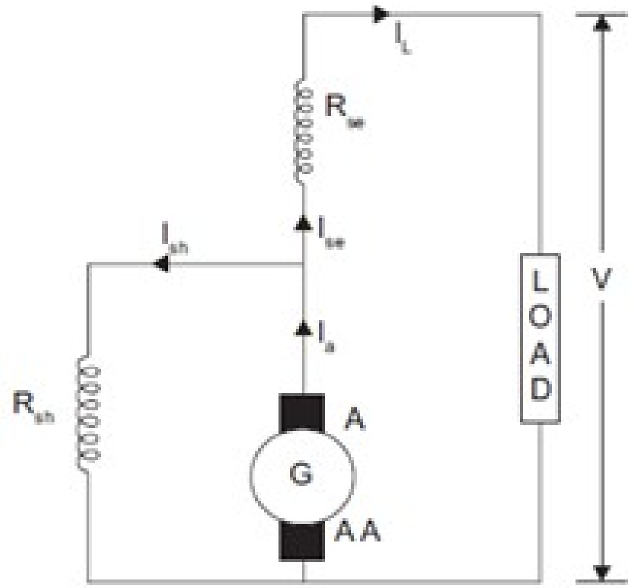
Terminal voltage, V=250V

Shunt field resistance, R_{sh} =50 Ω

Series field resistance, R_{se} = 0.025Ω

Armature resistance, R_a = 0.05Ω

Brush contact drop, BCD =2V



From the circuit diagram

$I_{sh} R_{sh} = V + I_{se} R_{se}$

$$\Rightarrow I_{sh} = \frac{V + I_{se} R_{se}}{R_{sh}} = \frac{250 + 100 \times 0.025}{50} = 5.05\ A\,[\because I_{se} = I_L = 100A]$$

Armature current, $I_a = I_{sh} + I_L = 5{\cdot}05 + 100 = 105{\cdot}05V$

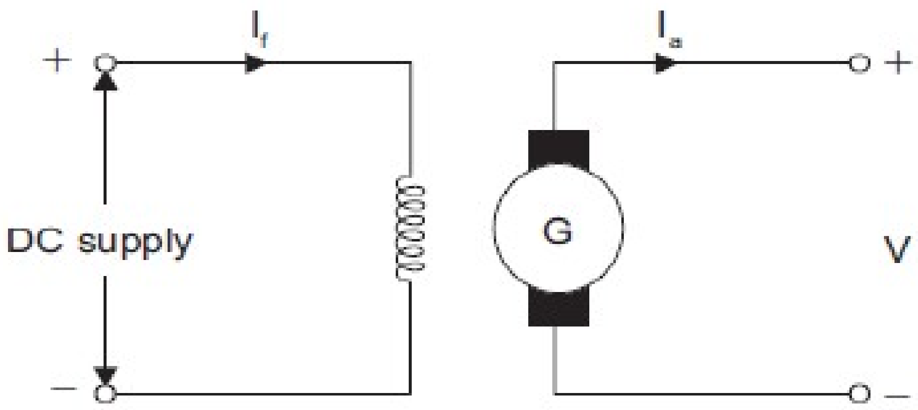
(a) Generated voltage

$$E_g = V + I_a R_a + I_{se} R_{se} + BCD = 250 + 105{\cdot}05 \times 0{\cdot}05\ 100 \times 0{\cdot}025 + 2 = 259{\cdot}75V$$

(b) Power delivered to load, $P_L = V I_L = 250 \times 100 = 25kW$

Solved Problem-8: *A separately excited DC generator when running at 1200 rpm supplies 200A at 125V to a circuit of constant resistance. What will be the current when the speed is dropped to 1000 rpm and the field current is reduced to 80%? Armature resistance = 0.04Ω and total drop at brushes = 2V. Ignore saturation and armature reaction.*

Solution: Given that



Speed, $N_1 = 1200$rpm

Armature current $I_{a1} = 200$A

Supply voltage $V_1 = 125$V

Field current, $I_{f1} = I_f$

speed $N_2 = 1000$rpm

Field current, $I_{f2} = 0.8\ I_f$

Armature resistance, $R_a = 0.04\ \Omega$

Brush contact drop, BCD = 2V

$E_{g1} = V_1 + I_{a1} R_a + BCD = 125 + 200 \times 0.04 + 2 = 135V$

Load resistance (constant), $R = \frac{125}{200} = 0.625\ \Omega$

$V_2 = I_{a2}R = 0.625\ I_{a2}$

$E_{g2} = V_2 + I_{a2}R_a + BCD = 0.625\ I_{a2} + 0.04\ I_{a2} + 2 = 0.665\ I_{a2} + 2$

For dc generator $N \propto \frac{E_g}{\Phi} \propto \frac{E_g}{I_f}$

$$\frac{N_2}{N_1} = \frac{E_{g2}}{E_{g1}} \times \frac{I_{f1}}{I_{f2}}$$

$$\Rightarrow \frac{1000}{1200} = \frac{E_{g2}}{135} \times \frac{I_f}{0.8 I_f}$$

$$\Rightarrow E_{g2} = \frac{1000 \times 135 \times 0.8}{1200} = 90\text{V}$$

$$\therefore E_{g2} = 90 = 0.665\ I_{a2} + 2 \Rightarrow I_{a2} = \frac{90 - 2}{0.665} = 132.3\ \text{A}$$

DC Machines

Armature Reaction

Prof. Sidhartha Panda
Department of Electrical Engineering
VSSUT, Burla

Armature Reaction

- In a DC generator, the armature current induces the armature flux and the main poles induce the field flux. The effect of armature flux on the main field flux is known as **armature reaction.**
- The armature reaction has two effects on the main field flux

  (i) Demagnetizing effect (or) weakens the main flux

  (ii) Cross magnetizing effect (or) distorts the main flux
- Cross **magnetizing effect causes** the **reduction in generated voltage** and the **demagnetizing effect causes sparking at the brushes.**
- **Magnetic Neutral Axis (MNA)** is defined as the axis along which no e.m.f. is produced in the armature conductors; because at that time they move parallel to the lines of flux.

- The MNA is always perpendicular to the resultant flux.
- The brushes and commutator are always placed along the MNA and hence this axis ix called axis of commutation.
- In armature conductors, reversal of current can takes place across this axis.
- **Geometric Neutral Axis (GNA)** is defined as the axis perpendicular to the stator field axis or polar axis.

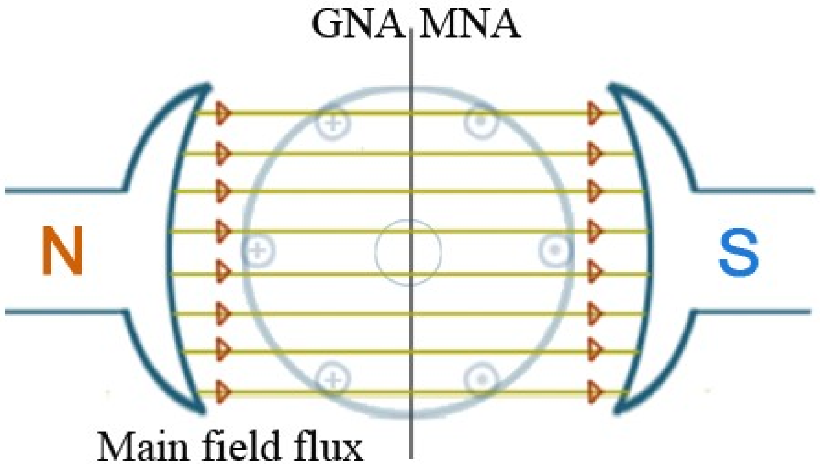


Figure (1.23): *Schematic diagram showing GNA and MNA*

Explanation of Armature Reaction

Case-(i): When no load is connected to the machine

- When there is no load on the generator, the current in the armature conductors is zero and hence the flux produced is zero. So there is no armature reaction in the generator

- Under this condition, there exists only the m.m.f of main poles, which produces the main flux, Φ_M.

- This flux is distributed symmetrically with respect to the polar axis, i.e. the central line of the north and south poles.

- In this case the MNA and GNA are coinciding as shown in the figure (1.24).

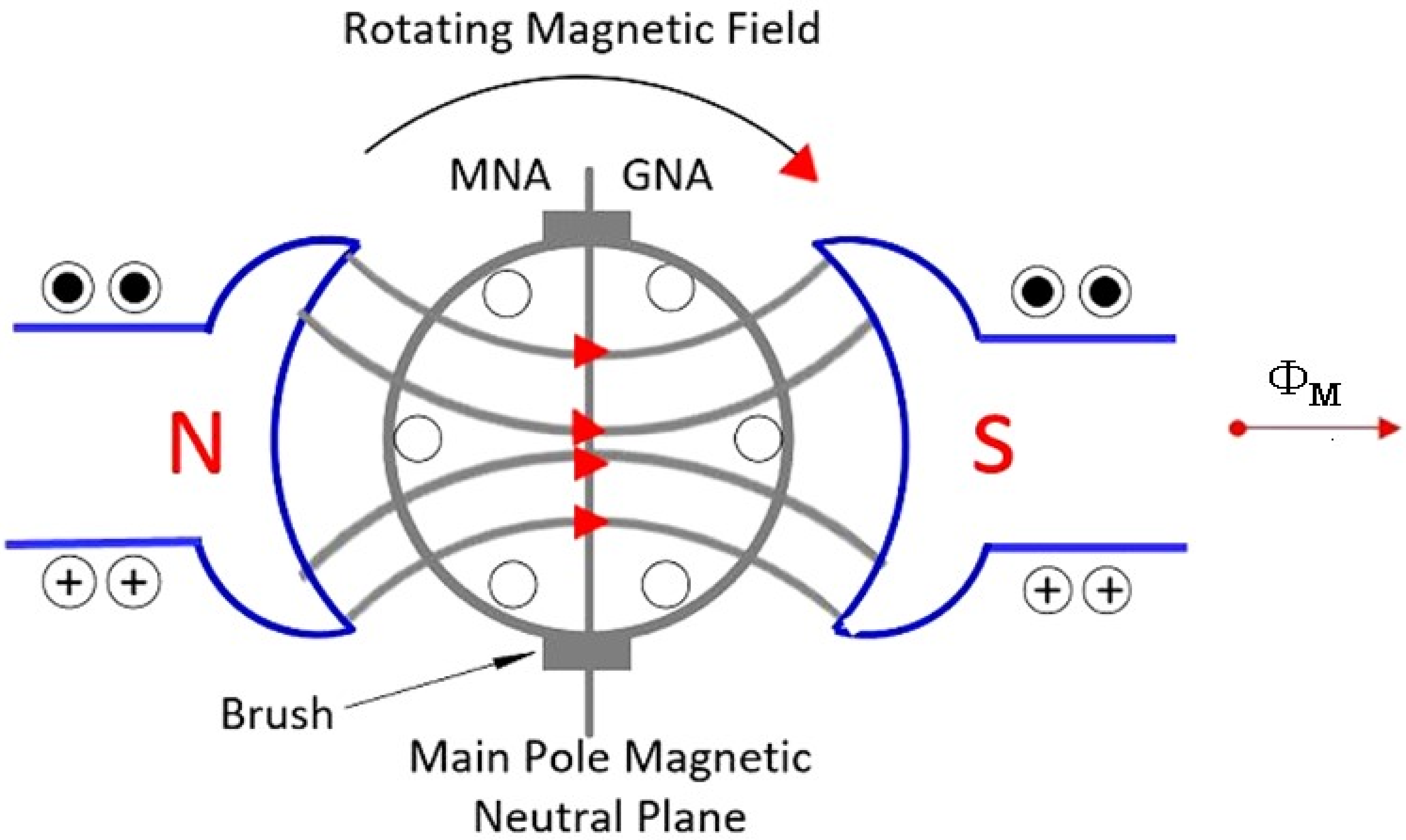


Figure (1.24): *Flux set-up by 2-pole DC generator*

Case-(ii): The armature conductors carrying current and no current flows in the field coils

- Figure (1.25) shows the flux set up by the armature conductors carrying current and the field coils are unexcited i.e. no current in the field coils.
- The direction of current in armature conductors may be determined by Fleming's Right Hand Rule and flux direction may be determined by Cork Screw Rule.
- The current direction is downwards in conductors under N-poles (represented by cross marks) and upwards in conductors under S–pole (represented by dots). These two current produces m.m.f and hence fluxes (Φ_A) through the armature in the downward direction.

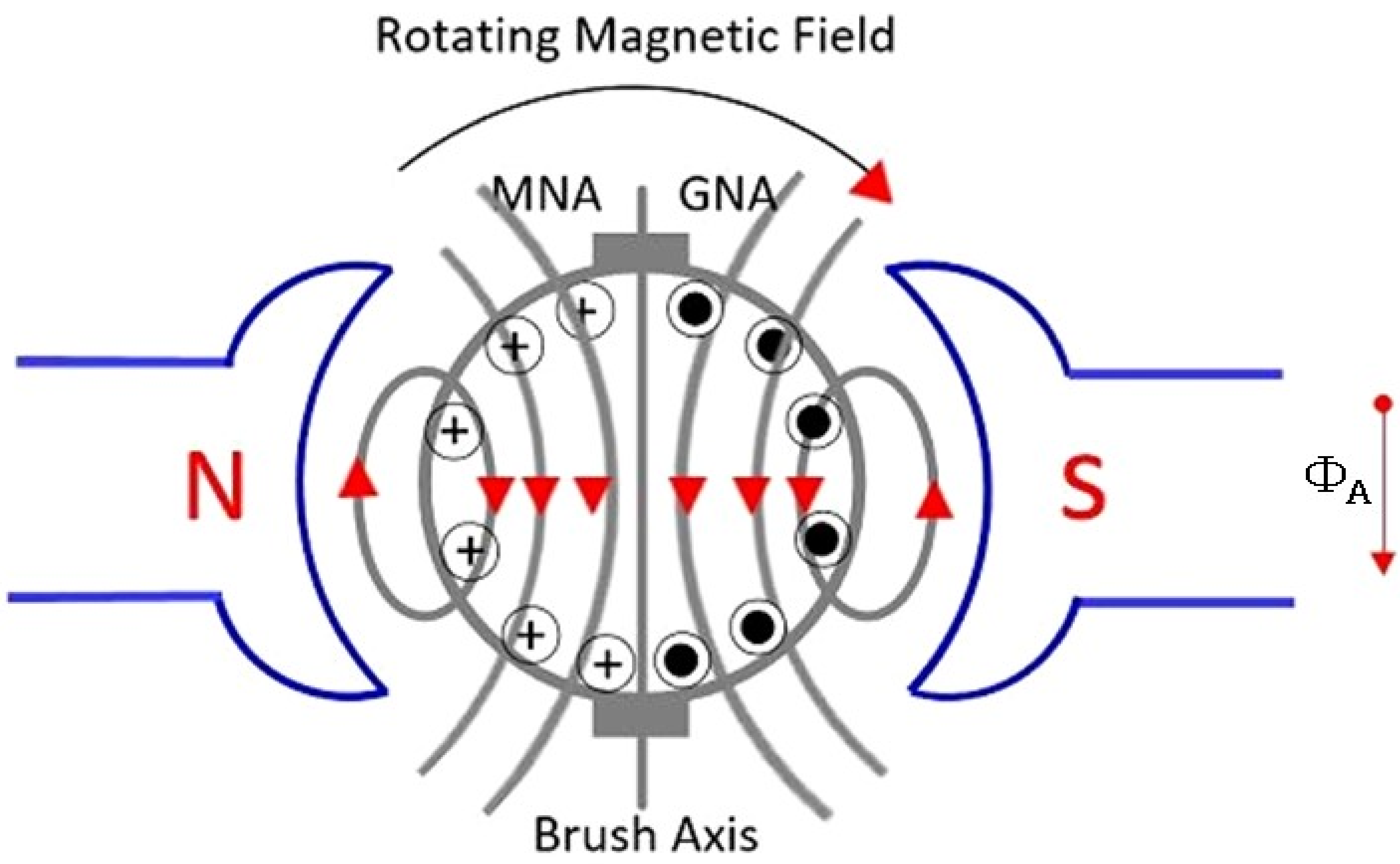


Figure (1.25): *The armature flux set-up by armature conductors*

Case-(iii): Field current and armature current acting simultaneously

- Under actual load conditions, the armature flux and main field flux exist simultaneously in the generator as shown in figure (1.26).
- The armature flux is produced by the current induces in the armature conductors while the field pole flux is induced because of the main field poles. These two flux combines and gives the resultant flux Φ_R
- When the field flux enters into the armature, they may get distorted. The distortion increases the density of the flux in the upper pole tip of north-pole and the lower pole tip of the south-pole. Similarly, the density of flux decreases in the lower pole tip of the north-pole and the upper pole tip of the south-pole.
- The resultant flux induces in the generator is shifted towards the direction of the rotation of generator.
- The magnetic neutral axis of poles is always perpendicular to the axis of the resultant flux. So the MNA is continuously shifted with the resultant flux

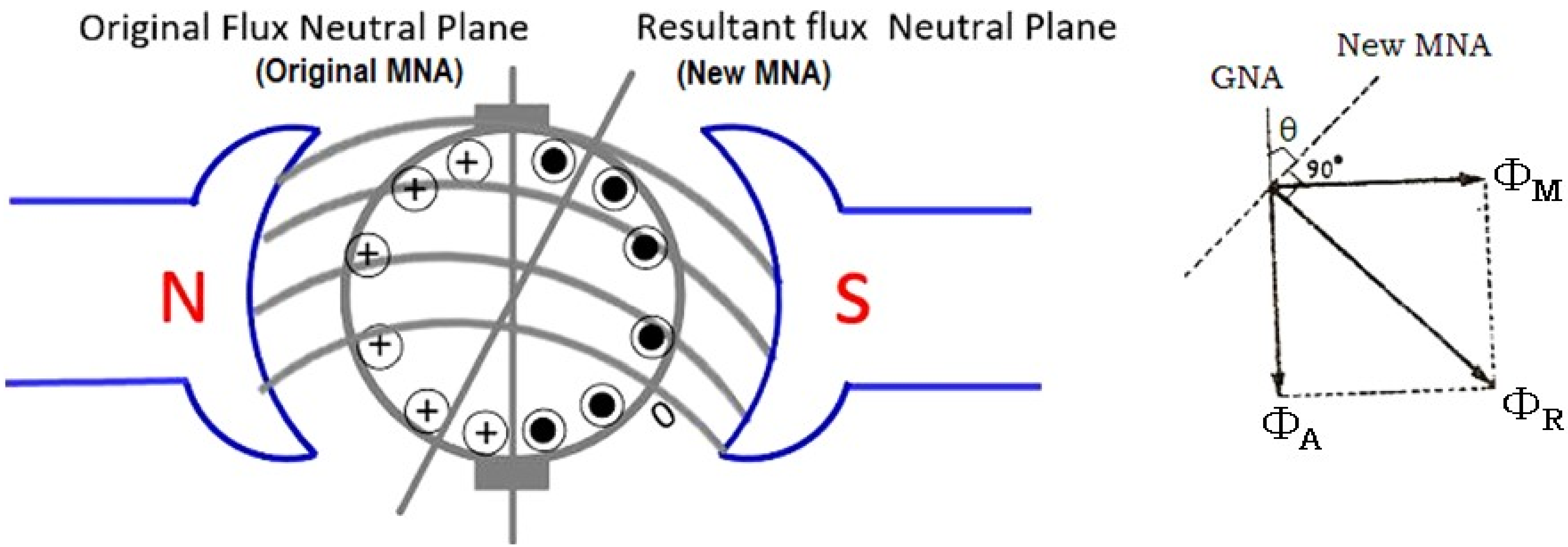


Figure (1.26): *Resultant flux distortion*

Effects of Armature Reaction:

- The effect of total flux reduction in the armature reaction is known as the demagnetizing effect.
- The resultant flux lines are distorted and there is a shift in the position of magnetic neutral axis. In case of generator, the MNA moves in the direction of rotation of the generator and opposite direction of rotation in the case of motor.
- If brushes are not shifted to MNA, sparking at brush contacts occur.
- It reduces the e.m.f induced in the armature.
- The efficiency of the generator decreases.

Demagnetizing ampere turns per pole (AT_d):

- It is sometimes desirable to neutralize the demagnetizing ampere turns of armature reaction. This is achieved by adding extra ampere turns to the main field winding. We shall now calculate the demagnetizing ampere turns per pole.

Let, Z = Total no of armature conductors, and

I_C = Current in each armature conductor

$= \frac{I_a}{2}$ ...... for simplex wave winding

$= \frac{I_a}{P}$ ...... for simplex lap winding

θ_m = forward or backward lead in mechanical degree

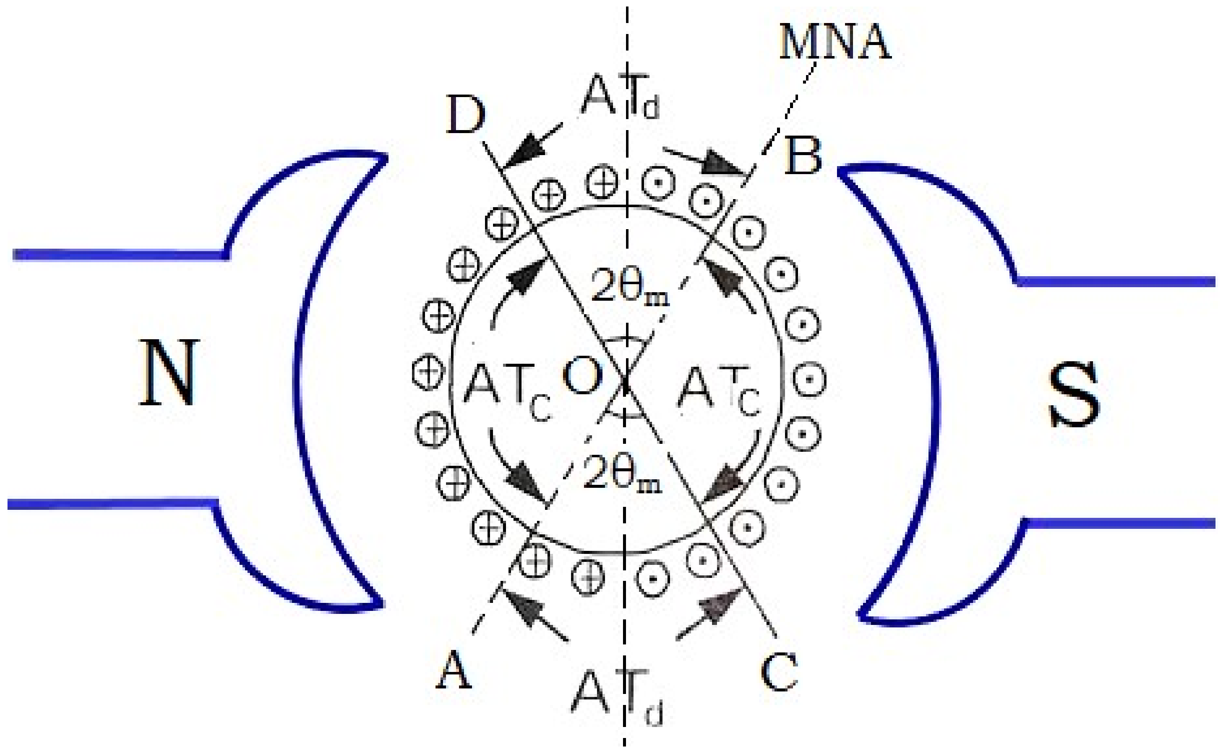


Figure (1.27): *Demagnetization and cross magnetization ampere turns*

Total number of armature conductors lying at top and bottom of the armature, i.e., in angles AOC and BOD $= \frac{4\theta_m}{360} \times Z$, causes demagnetization or weakens the main flux.

As one turn consists of two conductors, so total number of turns between these angles $= \frac{4\theta_m}{360} \times \frac{Z}{2}$, which lies under one pole pair

$$\therefore \text{Demagnetizing ampere turn per one pole pair} = \frac{2\theta_m}{360} \times Z \times I_C$$

$$\therefore \text{Demagnetizing ampere turn per pole} = \frac{2\theta_m}{360} \times \frac{ZI_C}{2} = \frac{\theta_m}{360} \times ZI_C$$

$$\text{i.e. } AT_d / pole = \frac{\theta_m}{360} \times ZI_C$$

Cross magnetizing ampere turns per pole (AT_c):

- Consider the conductors on both sides of the MNA and falls within the influence of the main pole flux. The conductors which lie between angles AOD and BOC constitute distorting field and called cross conductors. Their number is found as follows:

$$\text{Total number of armature conductors/pole} = \frac{Z}{P}$$

$$\text{Total number of turns/pole} = \frac{Z}{2P}$$

Total number of ampere turns/pole $AT/pole = \frac{Z}{2P} \times I_C$

Cross magnetizing ampere-turns/pole= AT/pole-AT_d/pole

$\therefore$ Cross magnetizing ampere-turns/pole$= \frac{ZI_C}{2P} - \frac{\theta_m}{360} \times ZI_C = ZI_C\left(\frac{1}{2P} - \frac{\theta_m}{360}\right)$

i.e. $AT_c / pole = ZI_C \times \left(\frac{1}{2P} - \frac{\theta_m}{360}\right)$

***Point to remember*:** For neutralizing the demagnetizing of armature reaction, an extra number of turns may be kept on each pole are determined from the following expressions:

Number of extra turns/pole $= \frac{AT_d}{I_{sh}}$ ..... for shunt wound generator

$= \frac{AT_d}{I_a}$ ...... for series wound generator

In case the leakage coefficient 'λ' is given, multiply each of the above expression by it.

***Point to remember*:** If θ_e is forward lead in electrical degrees, then forward lead in mechanical degrees θ_m for P number of poles is given as, $\theta_m = \frac{2\theta_e}{P}$

Compensating Winding:

- The function of compensating winding is to neutralize the cross magnetizing m.m.f of the armature reaction.
- A compensating winding is embedded in the pole faces parallel to the armature and is arranged such that its ampere-turns are equal in magnitude and opposite in direction to those of the armature conductors which lie opposite to the pole faces as shown in figure (1.28).

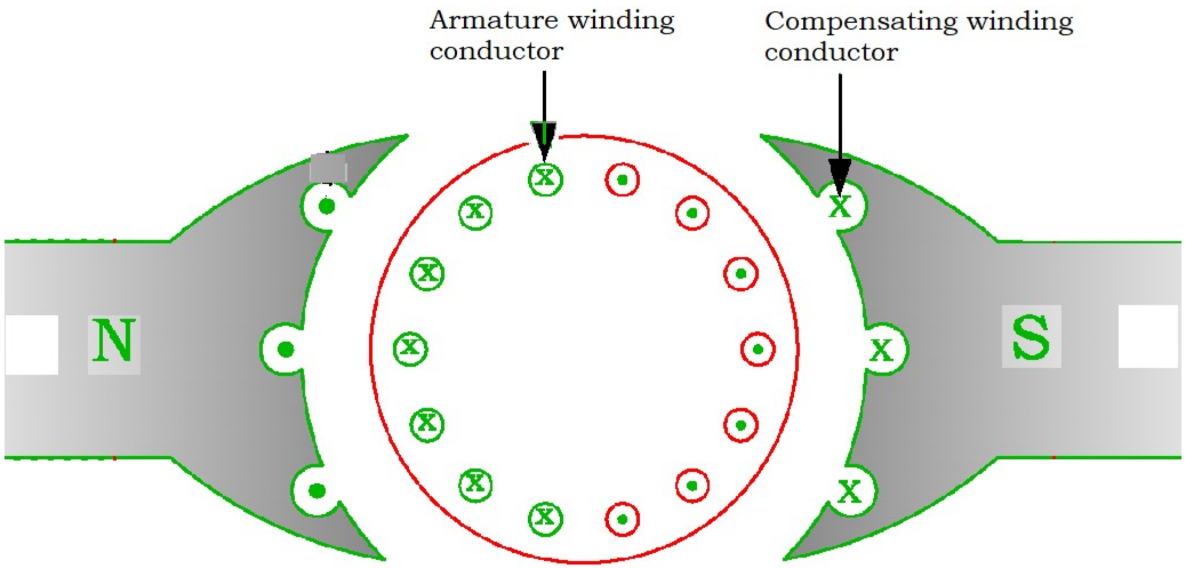


Figure (1.28): *Compensating winding*

- ❖ Compensating winding must neutralize the cross magnetizing ampere turns of the armature at all loads when it is connected in series with the armature.
- ❖ The no. of compensating windings to be used for a large machine under one pole can be derived as follows:

Number of armature conductors / pole = $\frac{Z}{P}$

Number of armature turns/pole = $\frac{Z}{2P}$

$\therefore$ Number of armature turns under one pole = $\frac{Z}{2P} \times \frac{pole\ arc}{pole\ pitch}$

In general, the value of ratio of $\frac{pole\ arc}{pole\ pitch}$ is considered as 0.7.

$\therefore$ Number of armature turns under one pole for compensating winding

$$= 0.7 \times \frac{Z}{2P}$$

$\therefore$ Number of armature ampere turns under one pole = $\frac{ZI_c}{2P} \times \frac{pole\ arc}{pole\ pitch}$

Solved Problem-10: A 200 kW, 400 V, 4-pole DC generator has 640 lap wound conductors. It is given a brush lead of 2.5 angular mechanical degrees from the geometric neutral. Calculate cross magnetizing turns per pole and demagnetizing turns per pole. (Neglect shunt field current)

Solution: Given that

Output power, $P_0 = 200\ kW$

Terminal voltage, V = 400 V

Number of poles, P = 4

Number of parallel paths, A = 4 ($\because$ for lap wound generator A = P)

Number of conductors, Z = 640

Lead of brushes $\theta_m = 2.5$

Armature current, $I_a = \dfrac{P_0}{V} = \dfrac{200 \times 10^3}{400} = 500\,\text{A}$

Current in each armature conductor, $I_C = \frac{I_a}{P} = \frac{500}{4} = 125\,\text{A}$

Cross magnetizing ampere-turns/pole,

$$AT_c = Z\left(\frac{1}{2P} - \frac{\theta_m}{360}\right) \times I_c = 640\left(\frac{1}{2\times 4} - \frac{2.5}{360}\right) \times 125 = 9440\,AT$$

Demagnetizing ampere turn per pole,

$$AT_d = \frac{\theta_m}{360} \times Z \times I_c = \frac{2.5}{360} \times 640 \times 125 = 555.55\,AT$$

Solved Problem-11: A 400 V, 800 A, lap wound DC generator has 8 poles, 720 armature conductors. Calculate the number of ampere turns in the pole face to give full compensation if the pole face covers 70% of pole spam.

Solution: Given that,

Terminal voltage, V = 400 V

Armature current, I_a = 800 A

Number of poles, P = 8

Number of parallel paths, A = 8 $(\because$ for lap wound generator A =P)
Number of conductors, Z = 720

$$\frac{pole\ arc}{pole\ pitch} = 70\% = 0.7$$

Current in each armature conductor $I_c = \frac{I_a}{P} = \frac{800}{8} = 100\,\text{A}$

$\therefore$ The number of armature ampere turns under one pole

$$= \frac{ZI_c}{2P} \times \frac{pole\ arc}{pole\ pitch} = \frac{720 \times 100}{2 \times 8} \times 0.7 = 3150 \text{ AT}$$

Solved Problem-12: A 6-pole, 120kW, 500V, wave wound DC shunt generator has 756 armature conductors. The shunt filed resistance 50 Ω when delivering full load the brushes are displaced from the geometrical neutral axis by 24 electrical degrees. Find the demagnetizing ampere turns/pole and cross magnetizing ampere turns/pole. Also determine the number of additional shunt field turns required to neutralize the demagnetizing effect.

Solution: Given that,

Output power, P_0 = 120 kW

Terminal voltage, V = 500 V

Number of poles, P = 6

Number of parallel paths, A = 2 ($\because$ for wave wound generator A =2)

Number of conductors, Z =756

Lead of brushes $\theta_e = 24$ electrical degrees

Shunt field resistance $R_{sh} = 50\Omega$

Load current, $I_L = \frac{P_0}{V} = \frac{120 \times 10^3}{500} = 240A$

Shunt field current, $I_{sh} = \frac{V}{R_{sh}} = \frac{500}{50} = 10A$

We know for a DC shunt generator,

Armature current, $I_a = I_L + I_{sh}$ = 240 + 10 = 250 A

Current in each armature conductor, $I_C = \frac{I_a}{2} = \frac{250}{2} = 125A$

Lead of brushes in mechanical degrees, $\theta_m = \frac{2\theta_e}{P}$

$$\Rightarrow \theta_m = \frac{2\times 24}{6} = 8^\circ$$

Cross magnetizing ampere-turns/pole,

$$AT_c = Z\left(\frac{1}{2P} - \frac{\theta_m}{360}\right)\times I_C = 756\left(\frac{1}{2\times 6} - \frac{8}{360}\right)\times 125 = 5775\,AT$$

Demagnetizing ampere turn per pole,

$$AT_d = \frac{\theta_m}{360}\times Z\times I_C \;= \frac{8}{360}\times 756\times 125 = 2100\,AT$$

Additional shunt turns/pole required to neutralize the demagnetization,

$$= \frac{AT_d}{I_{sh}} \;= \frac{2100}{10} = 210$$

Solved Problem-13: A 4-pole, 100 kW, 500 V, lap wound DC series generator has 756 armature conductors. The brushes are given an actual lead of 6 mechanical degrees at full load. Calculate demagnetizing ampere turns/pole and cross magnetizing ampere turns/pole. Also determine the number of additional series turns required to neutralize the demagnetizing effect. (Assume leakage coefficient = 0.9).

Solution: Given that,

Output power, P_0 = 100 kW

Terminal voltage, V = 500 V

Number of poles, P = 4

Number of parallel paths, A = 4 ($\because$ for lap wound generator A=P)

Number of conductors, Z = 756

Lead of brushes $\theta_m = 6°$

Armature current, $I_a = \frac{P_0}{V}$

Load current, $I_L = \frac{P_0}{V} = \frac{100 \times 10^3}{500} = 200A$

We know that for a DC series generator,

Armature current, $I_a = I_L$ = 200 A

Current in each armature conductor, $I_c = \frac{I_a}{P} = \frac{200}{4} = 50A$

Cross magnetizing ampere-turns/pole,

$$AT_c = Z\left(\frac{1}{2P} - \frac{\theta_m}{360}\right) \times I_C = 756\left(\frac{1}{2\times4} - \frac{6}{360}\right) \times 50 = 4095\,AT$$

Demagnetizing ampere turn per pole,

$$AT_d = \frac{\theta_m}{360} \times Z \times I_C \quad = \frac{6}{360} \times 756 \times 50 = 630\,AT$$

Additional series turns/pole required to neutralize the demagnetization

$$= \frac{AT_d}{I_a} \times \text{ Leakage coefficient } = \frac{630}{200} \times 0.9 = 3$$

DC Machines

Characteristics of a DC Generator

Prof. Sidhartha Panda
Department of Electrical Engineering
VSSUT, Burla

Characteristics of a DC generator

- The graphs or curves which show the performance of the generator under different operating conditions are known as characteristics.

- The operating characteristics of DC generators present graphically, the relationship between the basic quantities (terminal voltage V, armature current I_a, excitation current I_f and speed N) relevant to generator operation.
- Following are the three important characteristics of a DC generator.
  (i) Open Circuit or magnetization characteristic
  (ii) Internal or Total Characteristic and
  (iii) External Characteristic

- **Open Circuit Characteristic (OCC)**: Drawn b/n the generated e.m.f. at no-load (E_0) and the field current (I_f) at constant speed

- **Internal or Total Characteristic:** Drawn b/n the generated e.m.f. on load (E) and the armature current (I_a)

- **External Characteristics:** Drawn b/n the terminal voltage (V) and load current (I_L)

Characteristics of a Separately Excited DC Generator

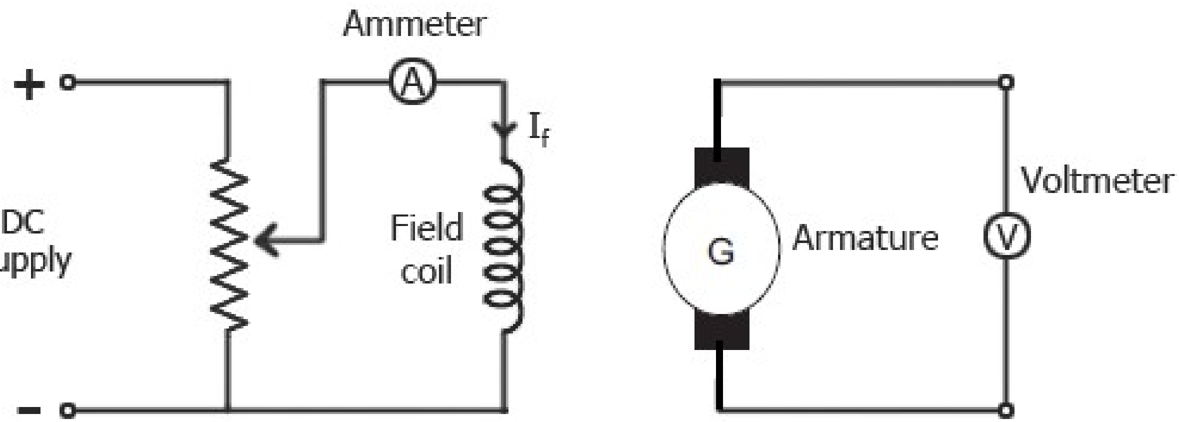


Figure (1.23): *Separately excited DC generator*

(i) Open Circuit Characteristics (OCC)

- The data for OCC curve is obtained by operating the generator at no load and keeping a constant speed.

- The plot of this curve is practically same for all types of generators, whether they are separately excited or self-excited.

- The field current (I_f) is increased from zero in steps and the corresponding values of generated e.m.f.(E_0) is recorded across the armature terminals.

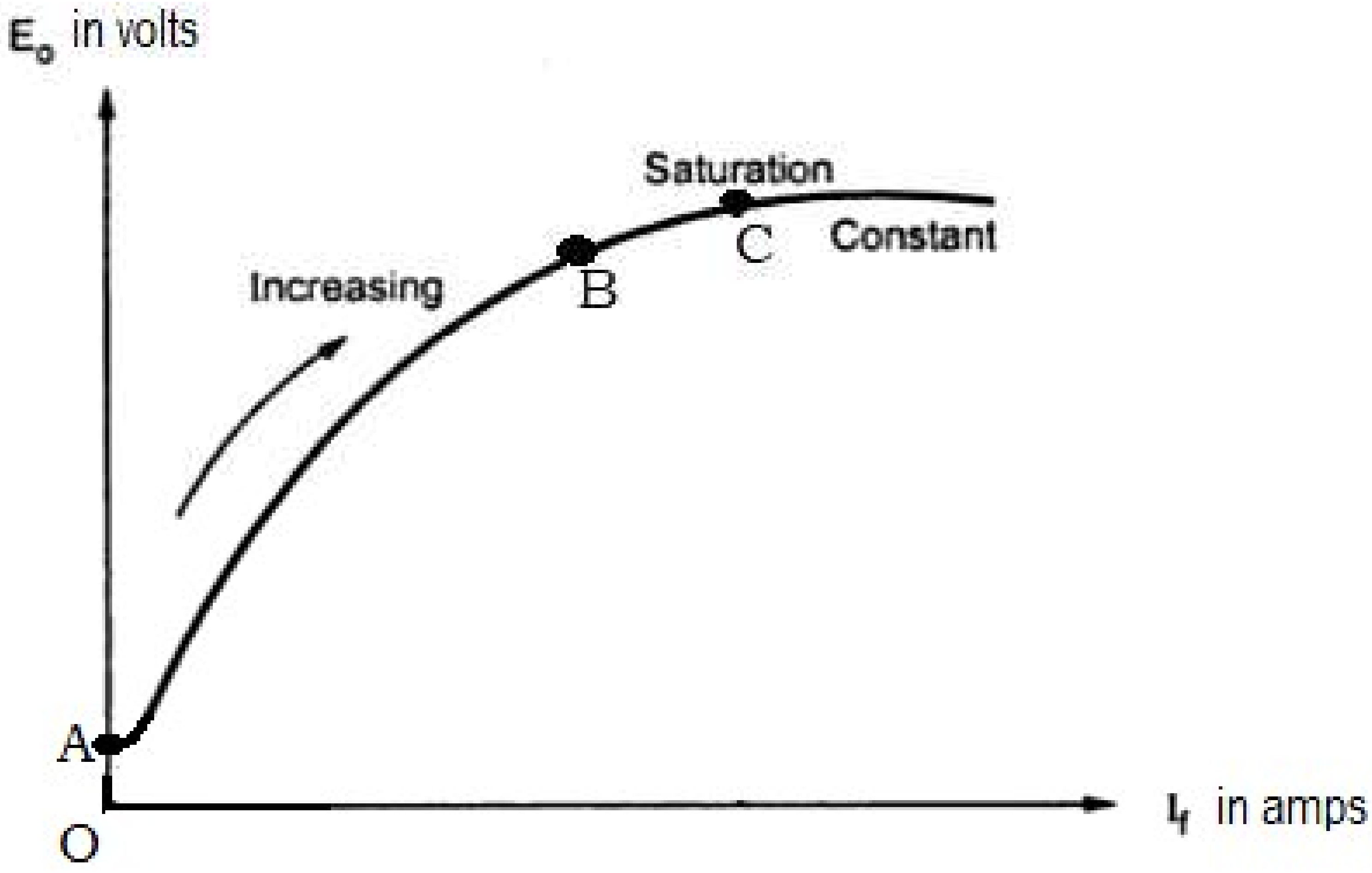


Figure (1.24): *OCC of a Separately excited DC generator*

- On plotting the relation between E_0 and I_f, we get the OCC as shown in figure (1.24).

- From the e.m.f. equation of a DC generator, $E_g = k\Phi$. Hence, the generated e.m.f. should be directly proportional to field flux i.e. field current. So AB is a straight line

- In the fig., even when the I_f is zero, some amount of e.m.f. (OA) is generated. This e.m.f is induced due to residual magnetism presented in the field poles.

- However, at some value of field current, the magnetic circuit (i.e. poles)gets saturated. So any further increase in I_f (beyond point C in figure 1.24) will not increase the flux. So, the generated voltage will remain almost constant with the increase in field current. That is why the upper portion of the curve is almost flat.

(ii) Internal and external or Load characteristics

- Let us consider the generator giving its no load voltage, E_0 for a constant field current, I_f.

- If there is no armature reaction and armature voltage drop in the machine then the voltage will remain constant. So, the plot b/n rated voltage and I_L is a straight line (AB) parallel to x-axis as shown in figure (1.25). Here, line AB indicating the no load voltage (E_0).

- When the generator is loaded, the voltage falls due to armature reaction and armature voltage drop, thereby giving slightly dropping characteristics.

- If we subtract voltage drops due to armature reaction for different loads from 'E_0', then we get the value of 'E'. So the curve AC is plotted in this way is known as **internal characteristic**.

❖ **External characteristic** (AD) lies below the internal characteristic because it takes into account the voltage drop due to armature circuit resistance (I_aR_a), i.e. $V=E-I_aR_a$

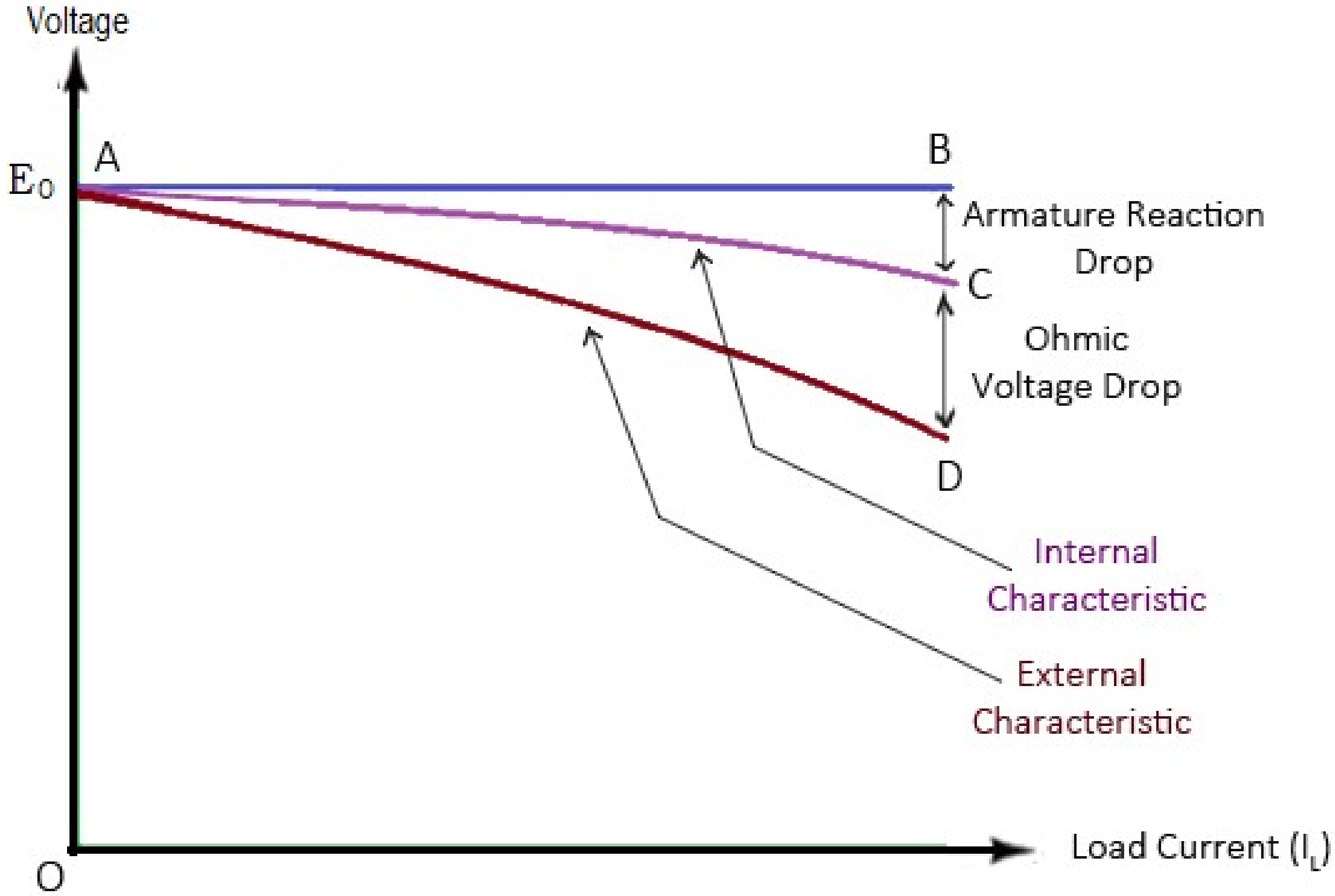


Figure (1.25): *Load characteristics of separately-excited DC Generator*

Voltage Build-up in a Self-excited Shunt Generator

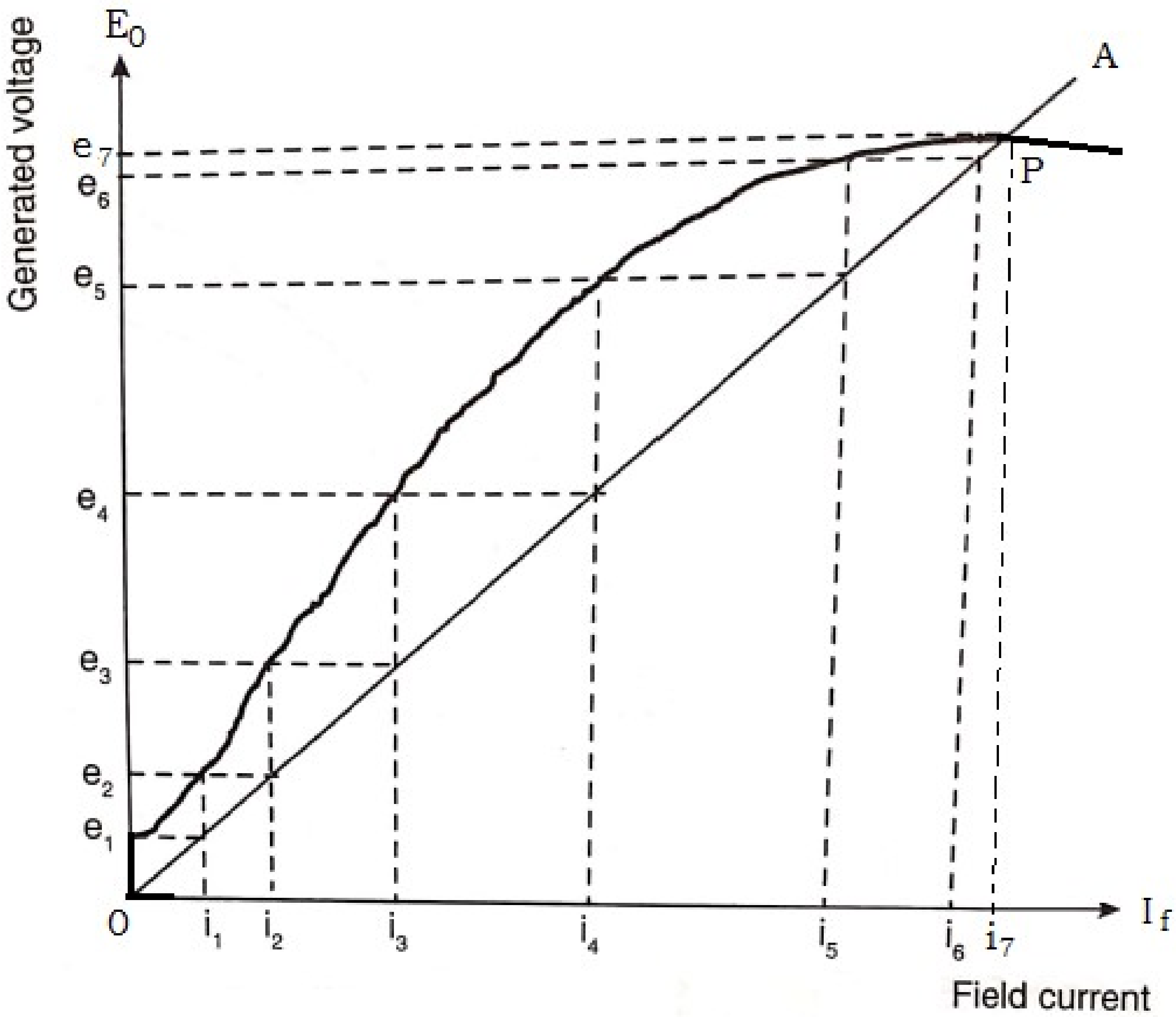


Figure (1.26): *Voltage build-up of in DC shunt generator*

- If the shunt generator is runs at a constant speed, some e.m.f. will be generated due to residual magnetism in the main poles.

- This small e.m.f. circulates a field current, which in turn produces additional flux to reinforce the original residual flux.

- When flux is increased, generated e.m.f. is increased (E_g=kΦ) which further increases the flux and so on.

- The plot between the generated e.m.f. and the shunt field current is as shown in figure (1.26). In the plot, the line OA represents the shunt field resistance line.

- As shown in figure (1.26), e_1 is the induced e.m.f. due to residual magnetism which appears across the field circuit and causes a field current i_1 to flow. The flux due to this current aids residual flux and hence generates, a larger induced e.m.f. e_2.

- In turn, this increased e.m.f. e_2 causes an even larger current i_2 which creates more flux for a still larger e.m.f. e_3 and so on.

- This process of voltage build-up will continue until that point where the field resistance line crosses the magnetization curve, that is, point P in the figure (1.26). Here the process stops.

(i) Conditions for voltage build-up in a DC shunt generator

- There should be some residual magnetism in the poles.

- For the given direction of rotation, the shunt field coils should be properly connected. That is, the coils should be connected such that the flux generated by the field current aids the residual flux.

- When excited at no load, the shunt field resistance should be less than the critical resistance.

- When excited on load, the shunt field resistance should be more than a certain minimum value of resistance

(ii) Critical Field Resistance

- ❖ The voltage build-up in a generator depends upon field circuit resistance. If the field circuit resistance is R_1 (line OA), then generator will build-up a voltage E_{01} as shown in figure (1.27).

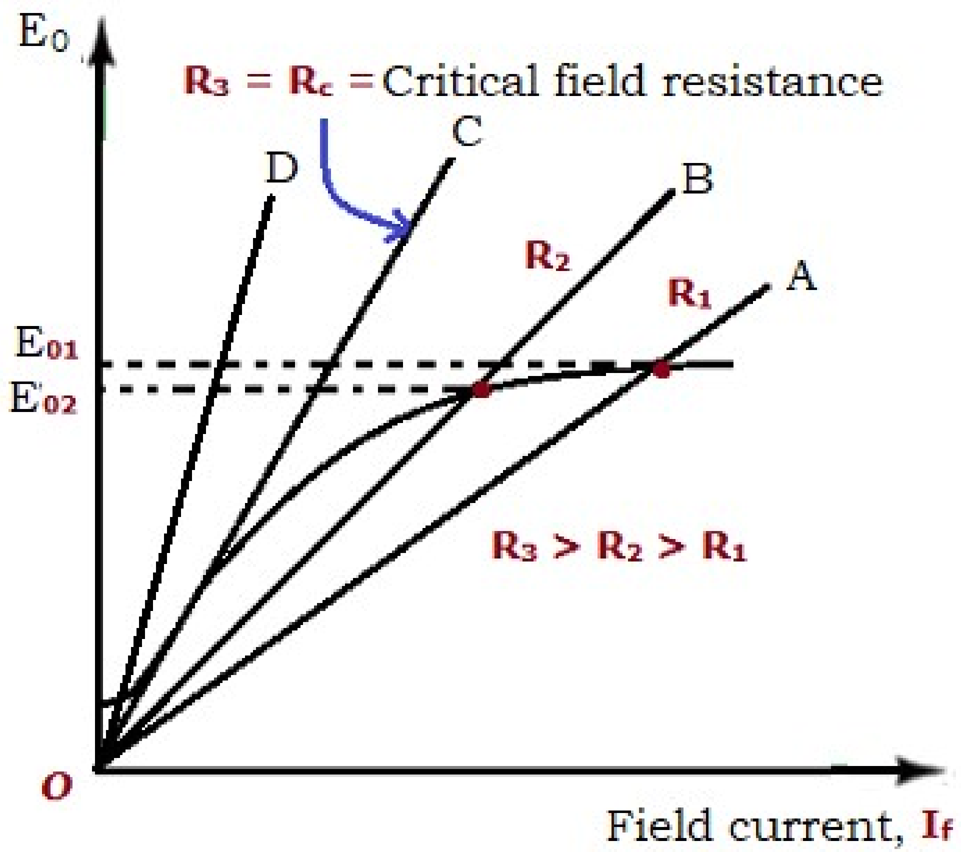


Figure (1.27): Determination of critical field resistance

- If the field circuit resistance is increased to R_2 (line OB), the generator will build up a voltage E_{02}, slightly less than E_{01}

- When the field resistance line becomes tangent (line OC) to OCC, the generator would just excite.

- If the field circuit resistance is increased beyond this point (say line OD), the generator will fail to excite.

- The field circuit resistance represented by line OC (tangent to OCC) is called critical field resistance, R_C for the generator. So the critical field resistance is defined as the maximum field circuit resistance for a given speed at which the shunt generator would excite.

- It should be noted that generator will build up voltage only if field circuit resistance is less than critical field resistance.

(iii) Critical Speed

- The critical speed is defined as the minimum speed of the armature which is required to build-up e.m.f. by the generator.

- In other words, the speed at which the machine just excites for the given field circuit resistance is called the critical speed of a shunt generator

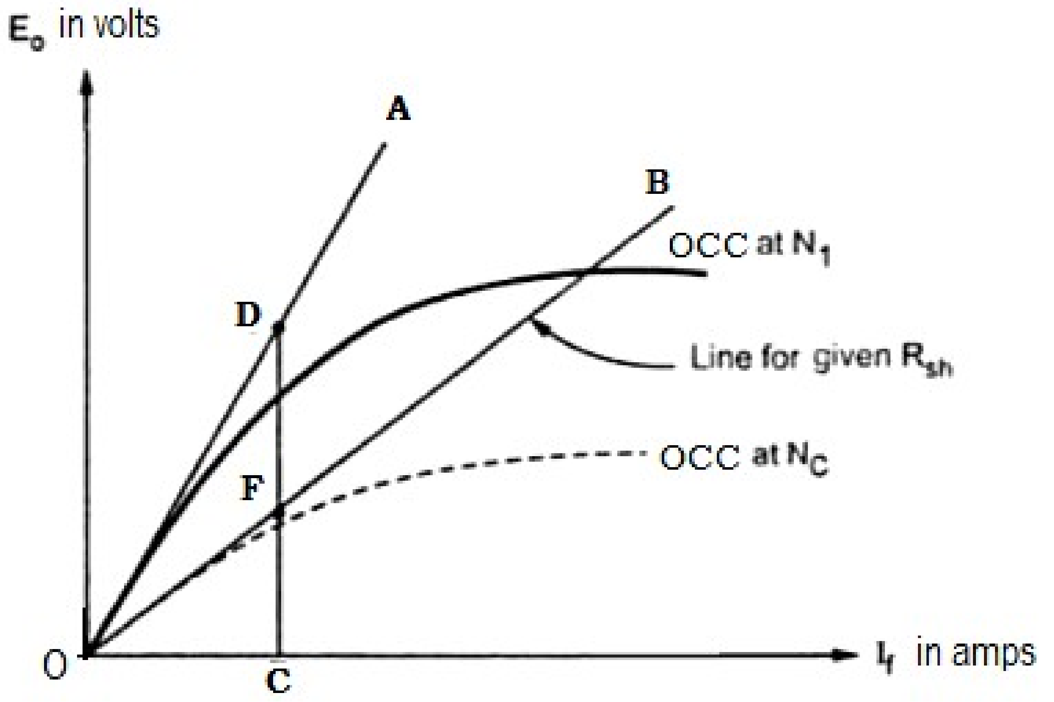


Figure (1.28): *Determination of critical speed*

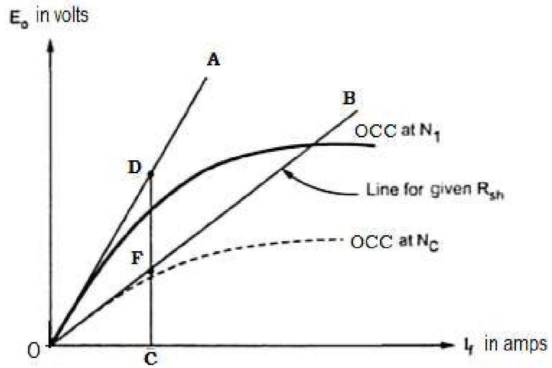
❖ The speed for which the given field resistance acts as critical resistance is called the critical speed, denoted as N_C. Thus if the line is drawn representing given R_{sh} then OCC drawn for such a speed to which this line is tangential to the initial portion, is nothing but the critical speed N_C.

❖ Graphically critical speed can be obtained for given R_{sh} as follows:

- Drawn OCC for given speed N_1.
- Draw a line tangential to this OCC say OA.
- Draw a line representing the given R_{sh} say OB.
- Select any field current say point C.
- Draw vertical line from C to intersect OA at D and OB at F.
- Then the critical speed N_C can be obtained as

$$\frac{N_C}{N_1} = \frac{CF}{CD}$$

$$\Rightarrow N_C = N_1 \times \frac{CF}{CD}$$



Characteristics of DC Shunt Generator

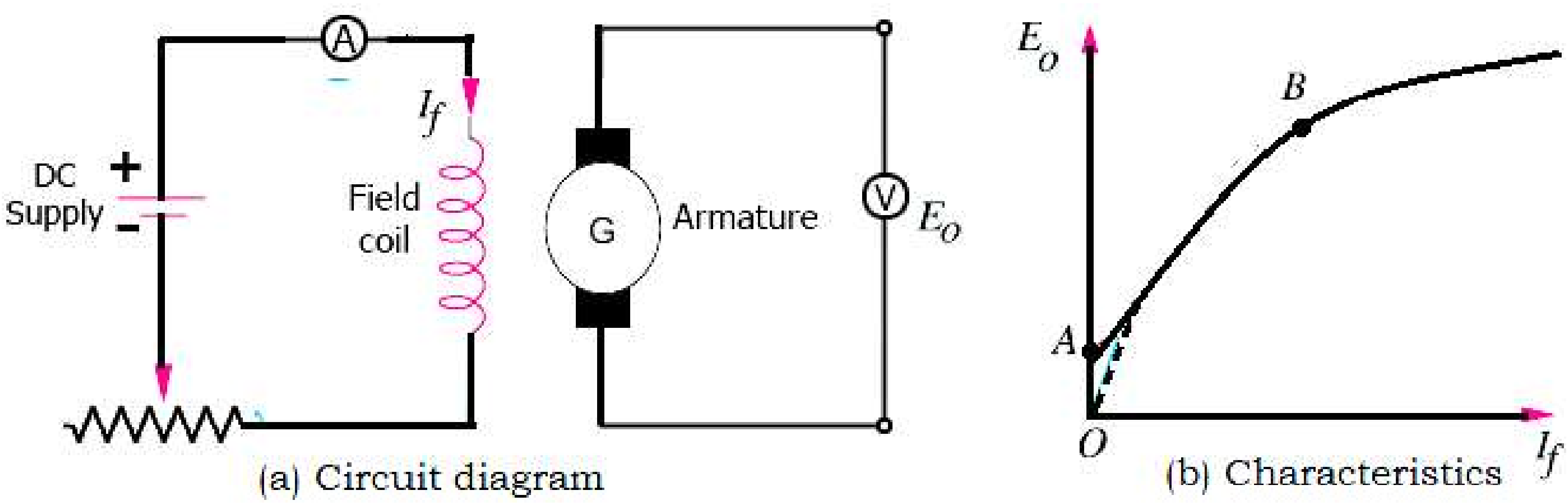


Figure (1.29): *OCC of a DC shunt generator*

(i) Open Circuit Characteristics (OCC)

- The OCC for self-excited generators whether shunt or series connected, are obtained in a similar way.
- The field current (I_f) is varied rheostatically and the corresponding generator e.m.f on no-load, E_0 is measured at constant speed.
- On plotting the relation between I_f and E_0 a curve of the form shown in figure 1.29(b) is obtained.

(ii) Internal and external characteristics or Load characteristics

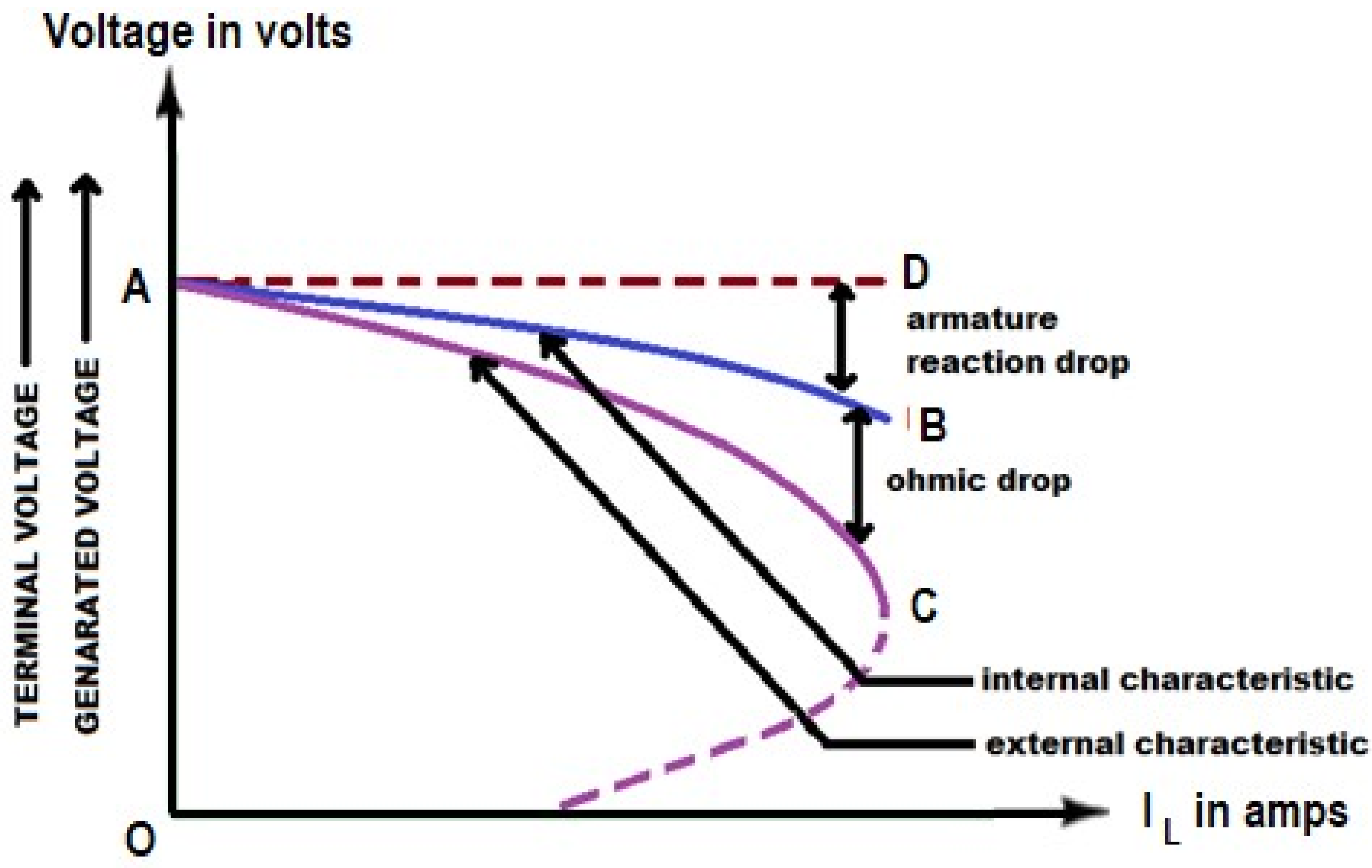


Figure (1.30): *Load characteristics of DC shunt generator*

- If there were no armature reaction and armature voltage drop, then the voltage would have remained constant as shown in the figure (1.30) by the horizontal line AD.

- But the main filed flux pattern gets distorted due to the armature reaction and hence, lesser flux gets linked with the armature conductors. This reduces the induced e.m.f, so curve AB shows internal characteristic of a DC generator.

- External characteristic lies below the internal characteristic (i.e. curve AC) because it takes into account the armature resistance drop i.e. I_aR_a drop. The values of V are obtained by subtracting I_aR_a from corresponding values of E i.e. $V=E-I_aR_a$.

Characteristics of a DC Series Generator

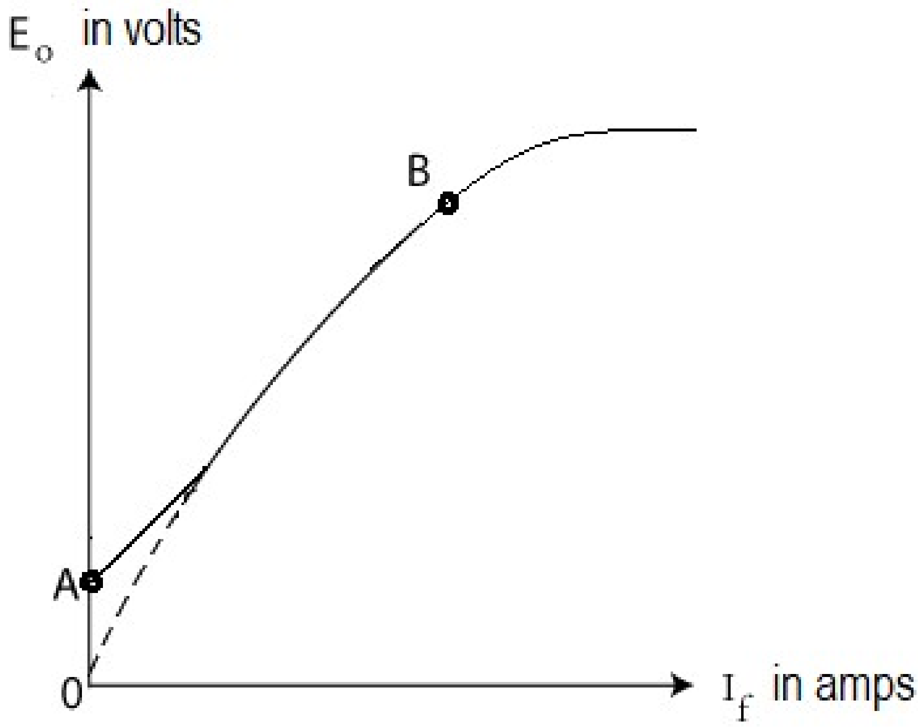


Figure (1.31): *OCC of a DC series generator*

(i) Open Circuit Characteristics (OCC)

- The OCC curve for a self-excited generators whether shunt or series wound is shown in above figure (1.31).
- Due to the 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.

(ii) Internal and external characteristics or Load characteristics

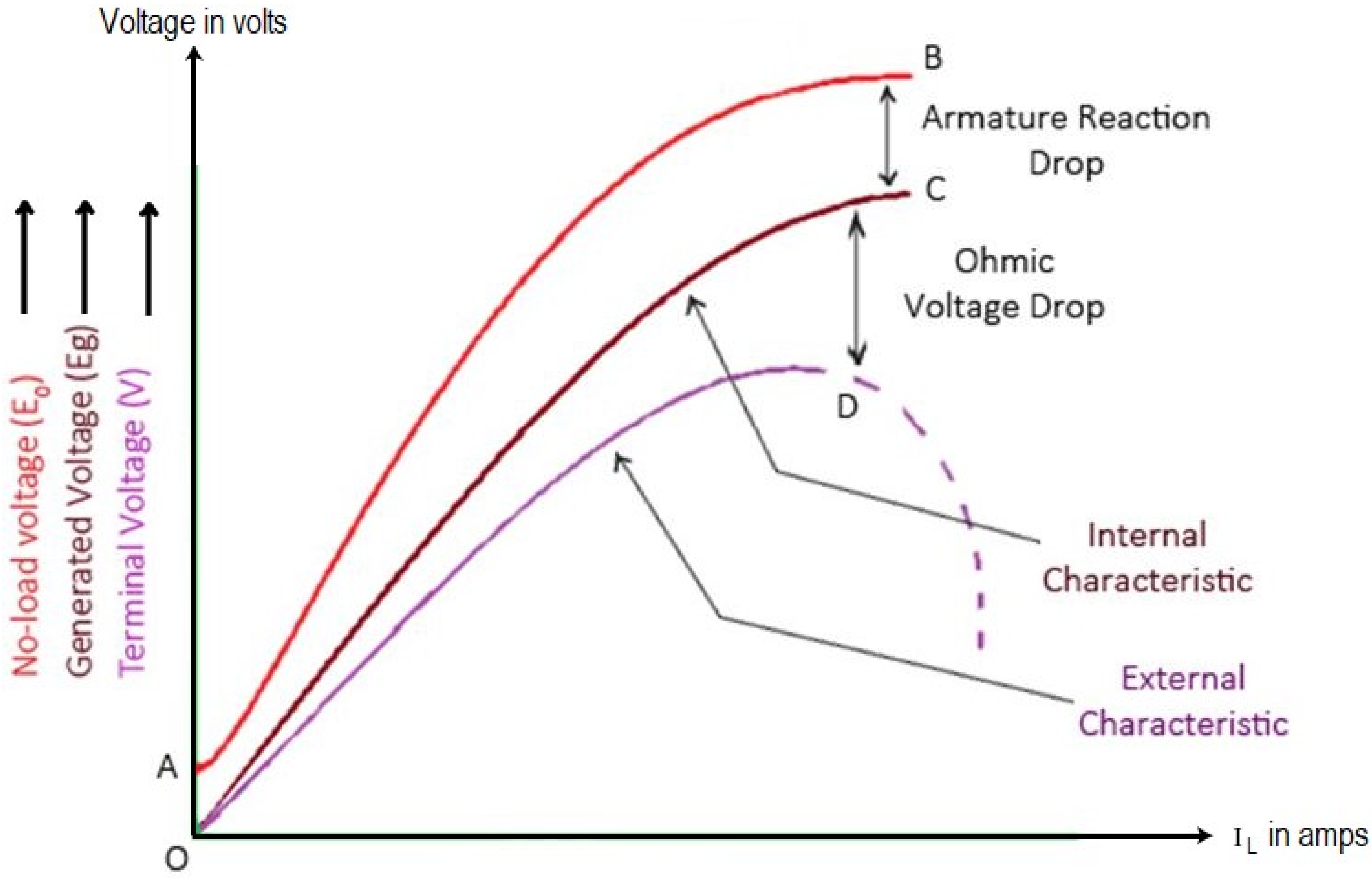


Figure (1.32): Characteristics of a DC series generator

- In the series generator, load connected across the armature terminals. As load current increase, series field current increases and hence flux is also increase. Therefore, induced e.m.f. E also increases.

- The **internal characteristics (i.e. OC)** is obtained by subtracting the drop due to the demagnetizing effect of armature reaction from the no load voltage. So, the induced e.m.f. (E) will be less than the no load voltage (E_0). Hence, the curve OC is slightly dropping from the open circuit characteristic curve AB as shown in figure (1.32).

- For series generator $V=E-I_a(R_a+R_{se})$by neglecting other drops. As load current I_L increases, armature current I_a increases. Thus the $I_a(R_a+R_{se})$drop increases and terminal voltage decreases. So the curve OD drawn b/n V and I_L is called **external characteristics.**

Characteristics of a DC Compound Generator

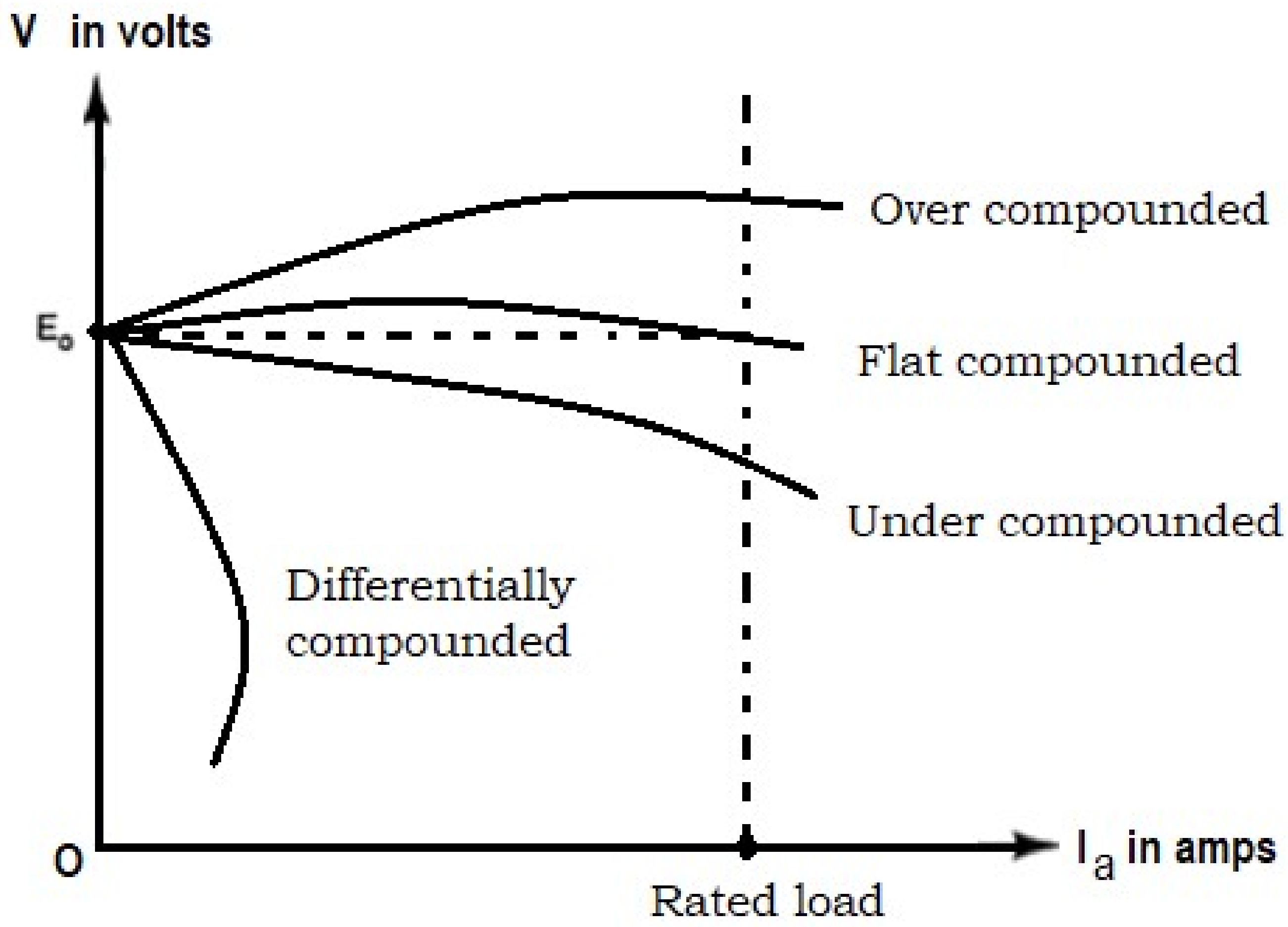


Figure (1.33): Characteristics of DC compound generator

- The compound wound generator has both shunt and series field windings.

- If the magnetic flux produced by the series winding assists the flux produced by the shunt winding, then the machine is said to be cumulative compounded. If the series field flux opposes the shunt field flux, then the machine is called the differentially compounded.

- In **differential compound generator** the net flux, $\Phi=\Phi_{sh}-\Phi_{se}$ decreases as the load increases. Therefore the terminal voltage is decreases very quickly as the load current increases.

- The cumulatively compound generator depending on the number of series field turns may be classified into (i) Over compound, (ii)flat or level compound, and (iii) under compound. The characteristic of DC compound wound generator are as shown in figure (1.33).

- **(i)Over compound generator:** In this case the number of series field turns are greater than the number of shunt field turns, so the net flux and hence the terminal voltage increases as the load current increases.

- **(ii)Level or flat compound generator:** In this case the number of series field turns are equal to the number of shunt field turns. So, the terminal voltage remains constant for any value of load current; which is within the limits.

- **(iii) Under compound generator:** In this case the number of series field turns are less than the number of shunt field turns. So, the net flux decreases as the load current increases and hence the terminal voltage decreases.

Solved Problem-13: The magnetization curve of a DC generator has the following data at a speed of 1000 rpm.

Field current, A	0.5	1	1.25	1.5
E.M.F, V	100	200	230	250

Determine the following: (a) If the field current is adjusted at 1.25 A, what must be speed to generate 250 V? (b) What is the field current to generate 200 V at speed 1000 rpm on no-load?

Solution: From the given table

For I_f=1.25 A, E_0=230V at 1000rpm

(i) If N_2 is the speed for generating E_0=250 V, then $E_g \propto N$

$$\frac{E_2}{E_1} = \frac{N_2}{N_1}$$

$$N_2 = N_1 \times \frac{E_2}{E_1} = 1000 \times \frac{250}{230} = 1087 rpm$$

(ii) From the given table, value of I_f for E_0=200 V is 1 A.

Solved Problem-14: The following is the magnetization characteristics of a DC shunt generator driven at 1000 rpm.

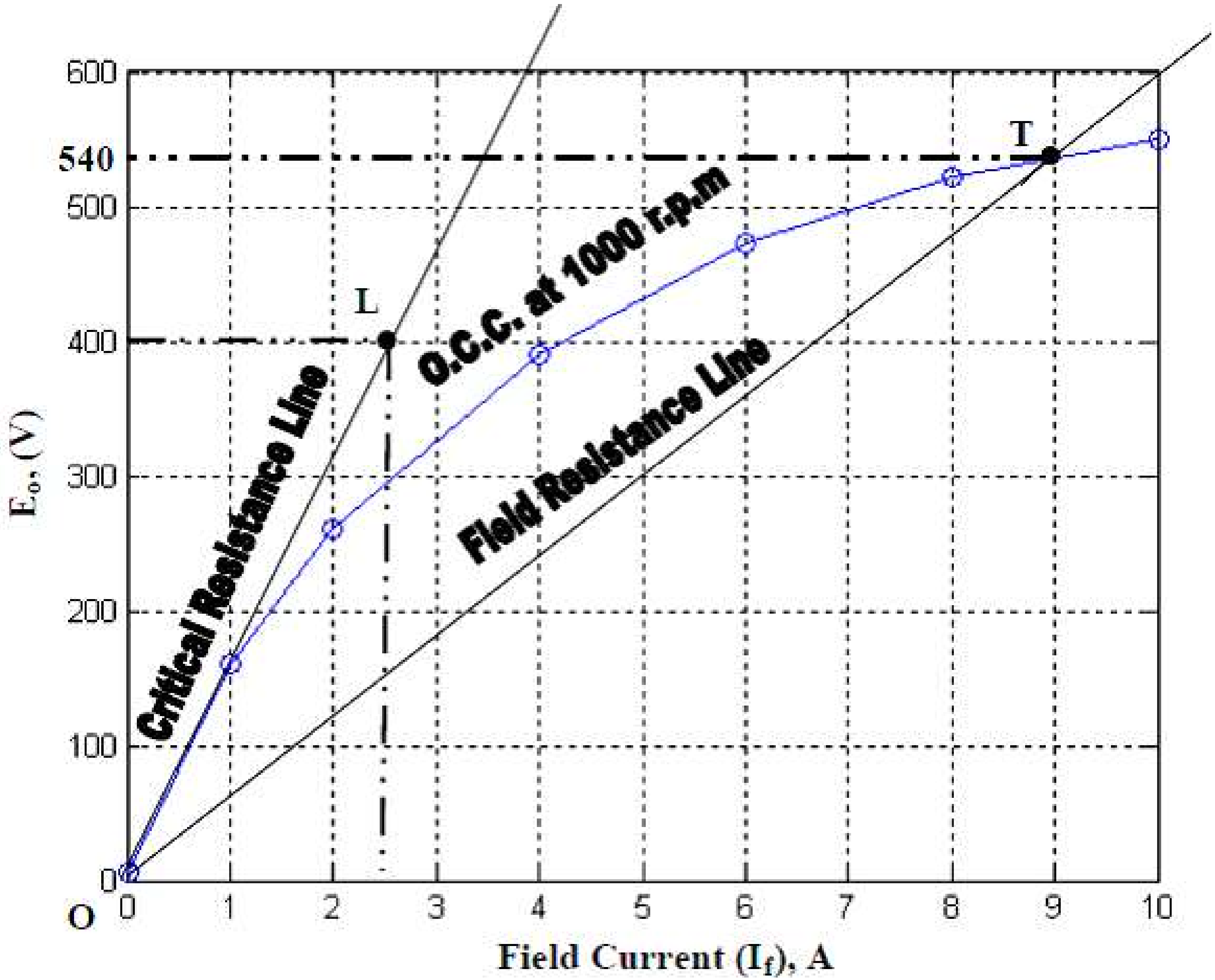
I_f in A	1	2	4	6	8	10
E_0 in V	160	260	390	472	522	550

Determine: (i) The voltage to which it will excite on open circuit.
(ii) The approximate value of the critical resistance of the shunt circuit. Take the armature and field resistance are 0.4 Ω and 60 Ω respectively

Solution: From the given table we can draw OCC

(i) Draw the OCC as shown in figure, draw the shunt resistance line (60 Ω) as usual. The intersection of shunt resistance line and OCC. gives the open circuit voltage of 540 V.

(ii) To find the critical resistance, draw the line (OL) which tangential to the initial straight part of the OCC The slope of (OL) gives the critical resistance. Take any point on line (OL), it is seen, Critical resistance =400/2.5 = 160Ω


600
540
500
400
300
200
100
0
O
0
1
2
3
4
5
6
7
8
9
10
L
T
E_o, (V)
Field Current (I_f), A
Critical Resistance Line
O.C.C. at 1000 r.p.m
Field Resistance Line

Solved Problem-15: The following table gives the OCC data of a DC shunt generator at 300 rpm.

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

(i) Plot the OCC for 375 rpm and determine the voltage to which the machine will excite if field circuit resistance is 40 Ω.

(ii) Determine the load current supplied by the generator, when its terminal voltage is 200 V. Take armature resistance 0.3 Ω. Assume speed to constant and armature reaction may be ignored.

(iii) What additional resistance would have to be inserted in the field circuit to reduce the voltage to 200 V at 375 rpm (no-load).

Solution: Speed of the armature, N = 300 rpm

While, E_0 is required for $N_2 = 375 rpm$ it is necessary to find new table for OCC by using the relation $E \propto N$

$$\Rightarrow \frac{E_1}{E_2} = \frac{N_1}{N_2}$$

$$\Rightarrow E_2 = E_1 \times \frac{375}{300} = 1.25E_1$$

So, the e.m.f. induced at 375 rpm would be increased $1.25E_0$ corresponding to different shunt field current values. A new table is given with the voltages multiplied by the above ratio.

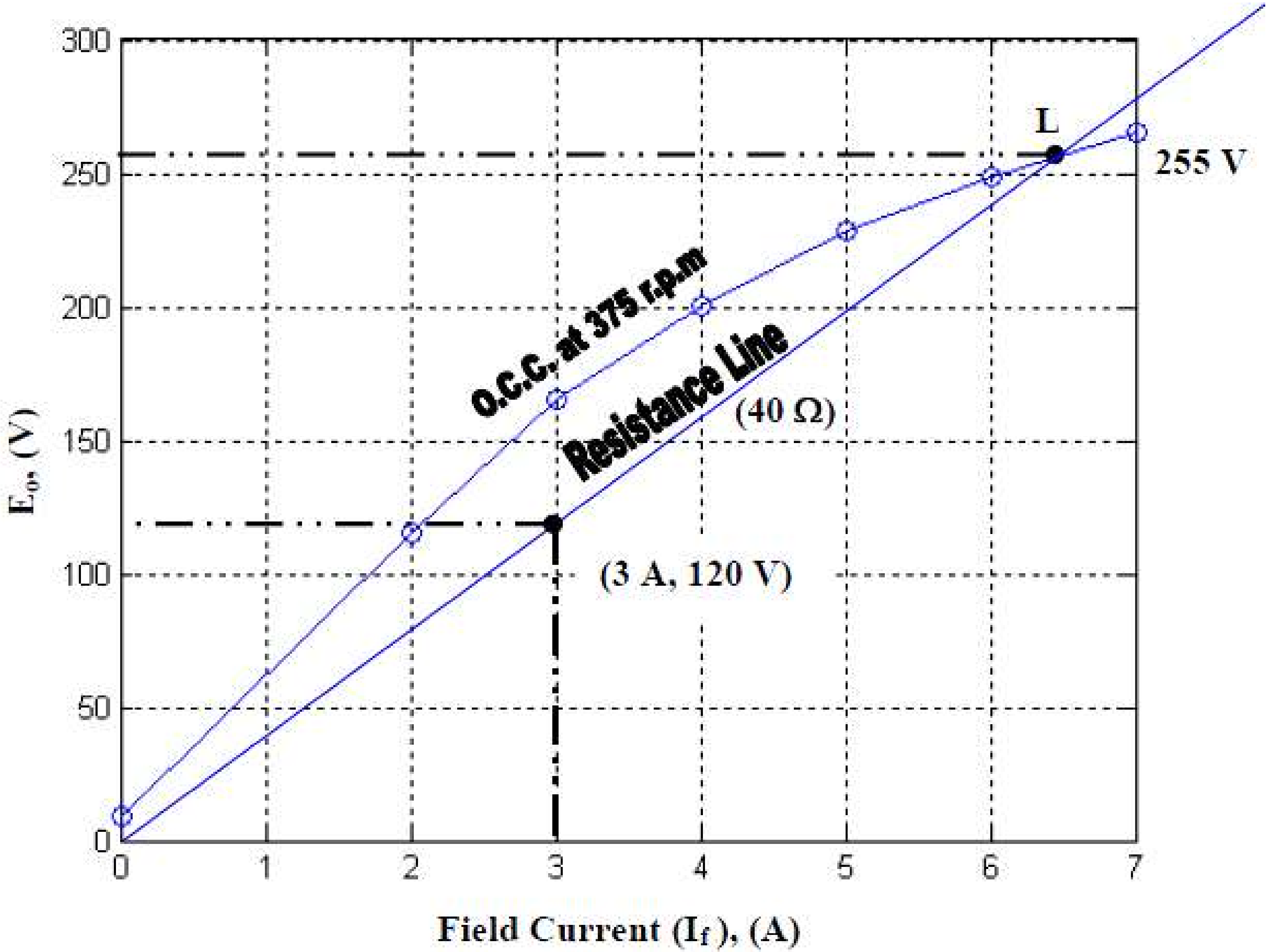
Field amperes	0	2	3	4	5	6	7
Armature volt	9.4	115	165	202.5	228.8	248.4	265

(i) The new OCC at 375 rpm is shown in the following figure. Line OL represent 40 Ω line. The voltage corresponding to point L to which the machine will excite if the field circuit resistance is 40 Ω =255 V.

(ii) In this case, shunt field resistance = 40 Ω

Terminal voltage = 200 V

∴ Field current = 200/40 = 5 A



300
250
200
150
100
50
0
0
1
2
3
4
5
6
7
L
255 V
O.C.C. at 375 r.p.m
Resistance Line
(40 Ω)
(3 A, 120 V)
E₀, (V)
Field Current (If), (A)

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

For generator, $E_g = V + I_a R_a$

$$I_a = \frac{E_g - V}{R_a} = \frac{228.8 - 200}{0.3} = 96A$$

∴ Load current, $I_L = I_a - I_f = 96 - 5 = 91A$

(iii) From the figure, it is clear that for exciting the generator to 200 V, field current should be 4 A.

Field circuit resistance = 200/4 = 50 Ω

∴ Additional resistance required =50-40=10 Ω

Solved Problem-16: A separately excited generator the magnetization characteristics at 1500 rpm is as follows:

I_f (Amp)	1	2	3	4	5	6	7	8
E_0 (Volt)	72.5	117.5	165	206.5	241	266	285	297.5

Determine the no-load terminal voltage of the machine when runs at 1000 rpm with 30 Ω field circuit resistance.

Solution: Given that,

Speed of the armature, N = 1500 rpm

While, E_0 is required for $N_2 = 1000 rpm$ it is necessary to find new table for OCC by using the relation $E \propto N$

$$\Rightarrow \frac{E_1}{E_2} = \frac{N_1}{N_2}$$

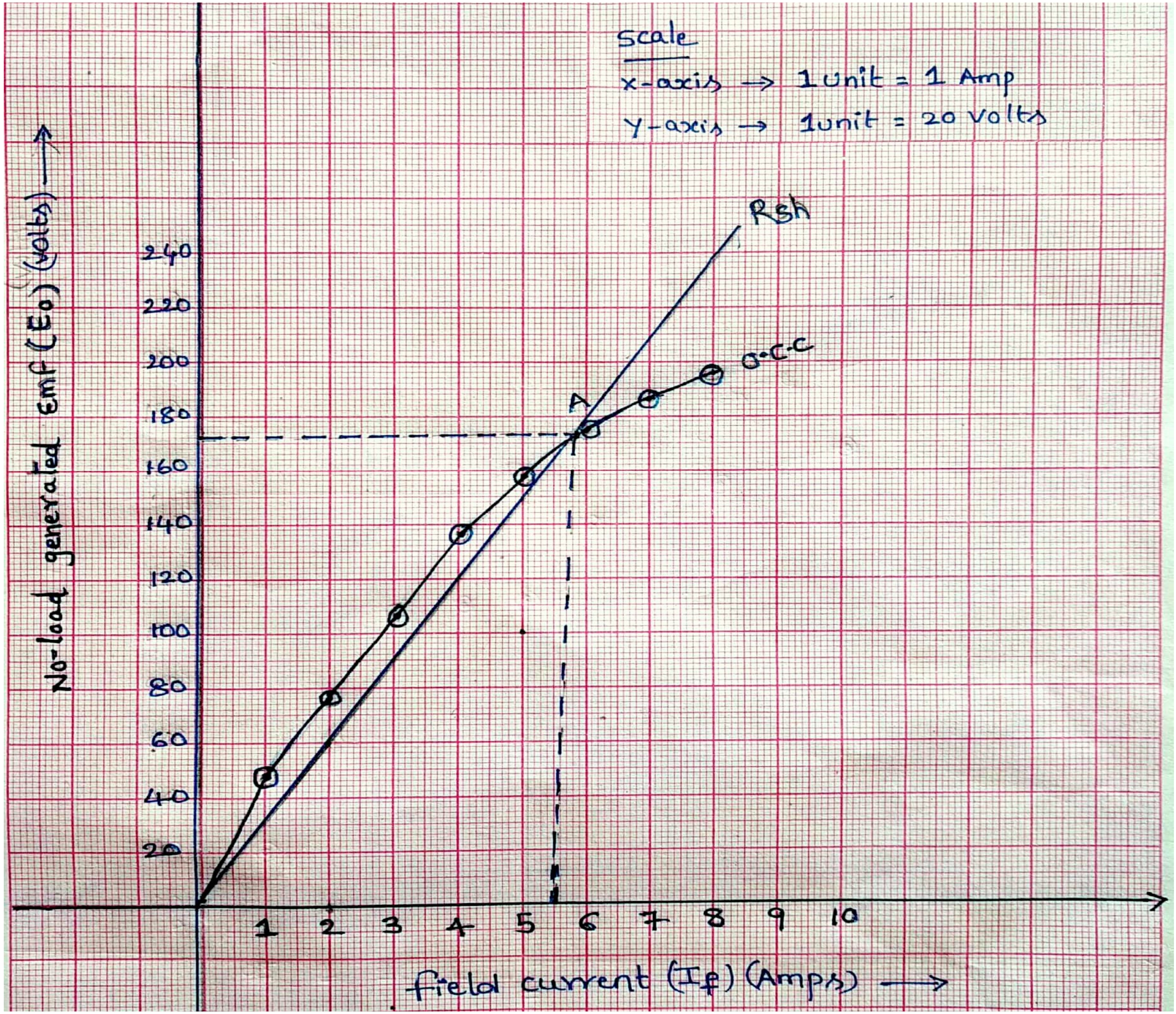
$$\Rightarrow E_2 = E_1 \times \frac{1000}{1500} = 0.66 E_1$$

I_f (Amp)	1	2	3	4	5	6	7	8
E_0 (Volt)	47.85	77.55	108.9	136.29	159.06	175.56	188.1	196.35

The OCC curve is drawn by using new table data as shown in the figure

Now, draw field resistance line $R_{sh} = 30\Omega$. From the graph $R_{sh} = 30\Omega$ line touches OCC curve at point 'A'.

Therefore, the corresponding no-load generated voltage form the graph E_0 =172 V



Scale
x-axis → 1 unit = 1 Amp
y-axis → 1 unit = 20 volts
No-load generated emf (E0) (volts)
240
220
200
180
160
140
120
100
80
60
40
20
Rsh
O.C.C
A
1
2
3
4
5
6
7
8
9
10
field current (If) (Amps)

Solved Problem-17: The OCC data of a 6 pole, 200 V shunt generator having 720 lap connected armature conductors running at 1000 rpm is as follows:

I_f (Amp)	0	0.5	1	2	3	4	5
E_0 (Volt)	20	60	120	195	240	260	285

Calculate (i) Critical filed resistance, (ii) Critical speed for field circuit resistance 80Ω, and (iii) Residual flux/pole.

Solution: Given that,

Number of Poles, P =6

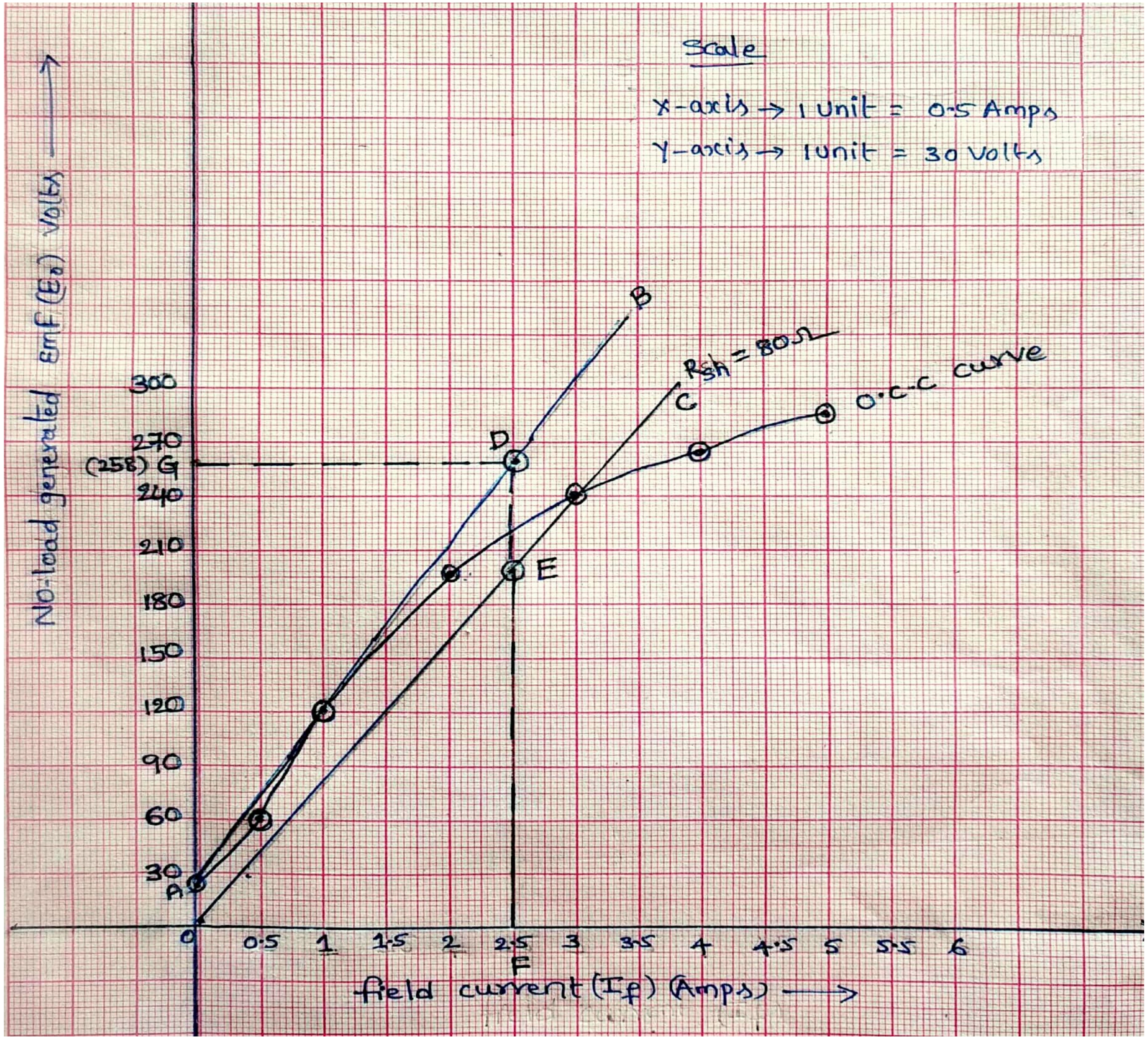
Terminal voltage, V = 200 V

Number of conductors, Z= 720

Number of parallel paths, A = 6 (for lap winding A= P)

Speed of armature N = 1000 rpm

OCC curve for the given data is shown in above Figure.


Scale
X-axis → 1 Unit = 0·5 Amps
Y-axis → 1 Unit = 30 Volts
No-load generated emf (E_0) Volts
field current (I_f) (Amps)
B
R_{sh} = 80Ω
C
O·C·C curve
D
E
F
A
(258) G
300
270
240
210
180
150
120
90
60
30
0
0·5
1
1·5
2
2·5
3
3·5
4
4·5
5
5·5
6

(i) Critical resistance = Slope of the line AB $= \frac{GD}{DF} = \frac{258}{2.5} = 103.2\Omega$

(ii)Draw a field resistance line $R_{sh} = 80\Omega$. So, slope of the line is 80Ω and equation is $E_0 = R_{sh} I_f$ = (80) (2.5) = 200V

Therefore, Critical speed can be obtained as from the curve as $\frac{EF}{DF} = \frac{N_C}{N}$

$$\Rightarrow \frac{200}{258} = \frac{N_C}{1000}$$

$$\Rightarrow N_C = 775 rpm$$

(iii) We have, e.m.f. equation for DC generator as

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

$$\Rightarrow 200 = \frac{\Phi(7250)(1000)}{60} \times \frac{6}{6}$$

$$\Rightarrow \Phi = 0.0016 Wb$$

Hence, residual flux /pole = 1.6 mWb

Applications of DC Generators

S.No	Type of generator	Applications	Examples
1.	Separately excited generator	Used for speed control of DC motors over a wide range. Widely used where wide range of terminal voltage is required.	Ward-Lenord system of speed control, electro plating
2.	Shunt generators	Used as exciters for supplying the current required to excite the field of AC generators.	Battery charging, excitation of alternators, in the process of electro-plating etc.
3.	Series generator	Used as boosters to compensate drop in the DC distribution systems.	Series arc lighting, series incandescent lighting, DC locomotives etc.
4.	Compound generator	Flat compound generators are used where constant voltage is required for different loading conditions. Over compound generators are used to compensate drop in feeders.	Railway circuits, arc welding sets, elevator motors, incandescent lamps etc.

DC Machines

Parallel Operation of DC Generators

Prof. Sidhartha Panda
Department of Electrical Engineering
VSSUT, Burla

Reasons for parallel operation of DC generators

- **Continuity of power supply:** In case of breakdown of generator, the supply of power will not get disturbed. If something goes wrong in one generator, the continuity of power can maintained by other healthy units.

- **Higher efficiency:** The performance and efficiency of a DC generator is high at rated load conditions. The load on the system is non-uniform, i.e., sometimes maximum and sometimes minimum. During period of light load, one or more units may be shut down, and those remaining operate at their rated capacity; there by efficiency increases.

- **Easy repair and maintenance:** For routine maintenance and inspection at the power stations, a unit must be shut down for a certain period. So repairing and overhauling (maintenance) is convenient. Consequently the cost of standby unit is much less when several units are installed.

- **Easy to increase plant capacity:** The growing need of electricity for increasing population shows the future need of excess generation. The plant capacity can be increased by connecting more generators in parallel.

- **Non-availability of single large unit:** In many situations, a single unit of desired large capacity may not be available. In that case a number of smaller units can be operated in parallel to meet the load requirement. Generally a single large unit is more expensive.

- **Economy of power generation:** The operating cost and cost of energy generated are reduced when several generators operate in parallel.

Requirements for parallel operation of DC generators

- **Voltages of both the machines should be same:** The no load voltages of both generators should be adjusted to the same value; otherwise, current will circulate through the two machines that will cause additional losses.

- **Polarities of both the generators must be identical:** The polarity of the voltages of two generators must be same; otherwise, large current will circulate in the armature windings of the generators which will damage the windings.

- **Generators should have identical external characteristics:** The external characteristic curve of the two generators should be identical; otherwise, the generator will not share the load properly.

- **Generators should have an equalizer connection:** For the case of compound generators in parallel there must be an "equalizer" connection to make the operation stable, otherwise, there will be motorization, i.e. one of the generator will act as a motor.

Parallel operation of DC shunt generators

❖ Consider a bus-bar and two generators are to be connected in parallel as shown in figure (1.40). The generator, G_1 is already connected to bus-bar and generator G_2 has to be connected in parallel with G_1 for increase in load demand. The procedure is as follows:

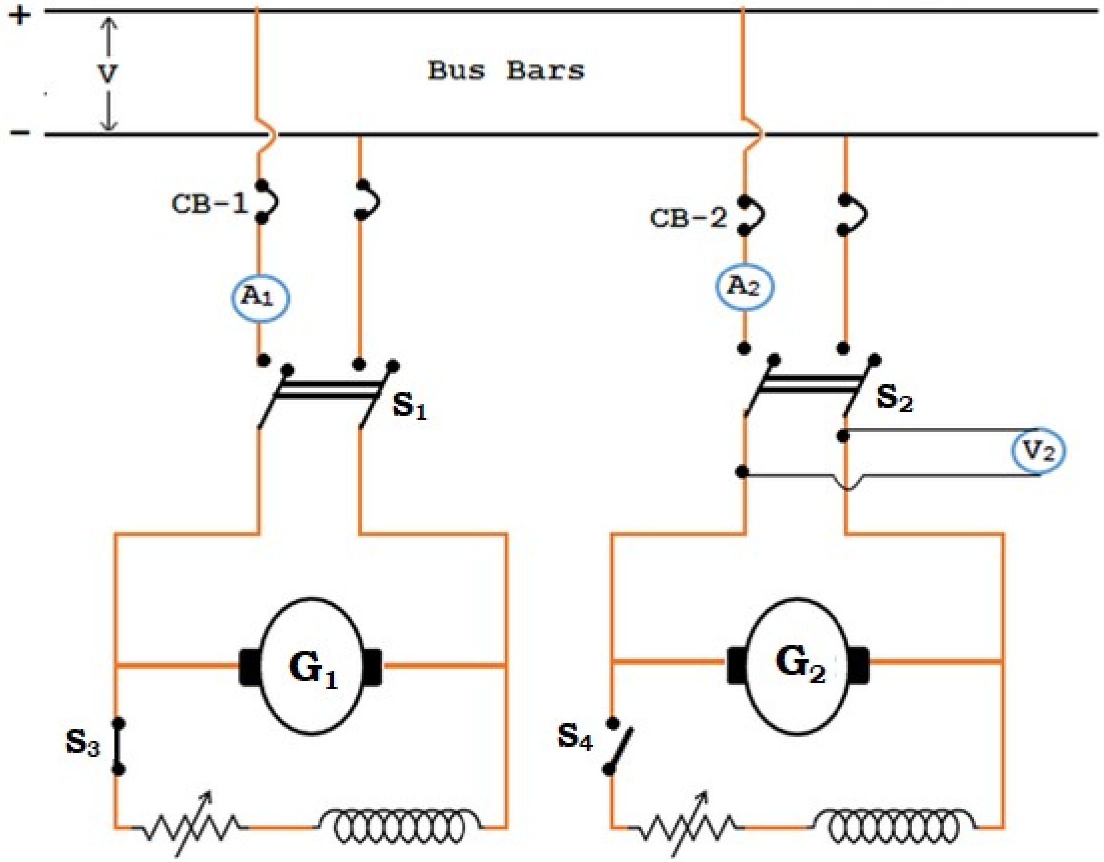


Figure (1.40): *Two shunt generators connected in parallel*

- Generator G_1 is connected to bus bars i.e., S_1 is closed, S_3 is closed, CB-1 is closed. Generator G2 is initially not connected to the bus bars i.e., S_2 is open, S_4 is open and CB-2 is open.

- Generator G_2 is brought to rated speed by prime mover and now the switch S_4 and circuit breaker CB-2 are closed. The excitation generator G_2 is adjusted such that the voltage in voltmeter V_2 is equal to the bus bar voltage.

- Generator G_2 can now be connected in parallel with generator G_1 by closing the switch S_2. However, this generator G_2 is said to be floating generator, since the generated e.m.f. in this generator is equal to bus bar voltage, hence cannot supply any load.

- To supply load from generator G_2, the induced e.m.f. is increased by giving the additional amount of excitation from the field. So that, the field current increases and it can deliver some current.

- The load can be shifted from one generator to other generator by adjusting the field excitation. The total load can be shifted on to one generator by shutting down the other generator.

- To shut-down a generator, the load current is made zero which is indicated in the corresponding ammeter, then the related switches S and CB are made open.

Load Sharing between two generators

❖ The load sharing between shunt generators connected in parallel can be easily regulated because of their drooping characteristics. Let us discuss the load sharing of two generators which have unequal no-load voltages as shown in the figure (1.41).

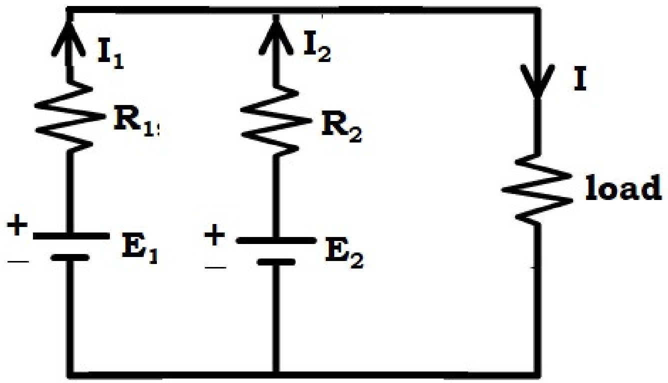


Figure (1.41): *Load sharing between two generators*

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

R_1, R_2 = armature resistances of the two generators

I_1, I_2 = currents supplied to the load by two generators

I =total load current shared by two generators

V = common terminal voltage (bus-bar voltage)

The external characteristic of the two generators can now be expressed as:

$$V = E_1 - I_1 R_1 \qquad \text{---} \quad (1)$$

$$V = E_2 - I_2 R_2 \qquad \text{---} \quad (2)$$

Total load current, $I = I_1 + I_2$ --- (3)

Solving above equations for I_1 and I_2, will get the load shared by two generators as

$$I_1 = \frac{E_1 - E_2}{R_1 + R_2} + \frac{IR_2}{R_1 + R_2} \qquad \text{---} \quad (4)$$

$$I_1 = \frac{E_1 - E_2}{R_1 + R_2} + \frac{IR_1}{R_1 + R_2} \qquad \text{---} \quad (5)$$

If the load on the generators is a fixed resistance R, eqns. (1) & (.2) can be rewritten as

$$E_1 = V + I_1 R_1 = IR + I_1 R_1 = (I_1 + I_2)R + I_1 R_1$$

$$\Rightarrow E_1 = (I_1 + I_2)R + I_1 R_1 \qquad \text{---} \quad (6)$$

$$E_2 = V + I_2 R_2 = IR + I_2 R_2 = (I_1 + I_2)R + I_2 R_2$$

$$\Rightarrow E_2 = (I_1 + I_2)R + I_2 R_2 \qquad \text{---} \quad (7)$$

Solving equations (6) & (7) , we get

$$I_1 = \frac{(E_1 - E_2)R + E_1 R_2}{R(R_1 + R_2) + R_1 R_2} \quad \text{--- (8)}$$

$$I_2 = \frac{(E_2 - E_1)R + E_2 R_1}{R(R_1 + R_2) + R_1 R_2} \quad \text{--- (9)}$$

Load current is given by

$$I = I_1 + I_2 = \frac{(E_1 - E_2)R + E_1 R_2}{R(R_1 + R_2) + R_1 R_2} + \frac{(E_2 - E_1)R + E_2 R_1}{R(R_1 + R_2) + R_1 R_2} = \frac{E_1 R_2 + E_2 R_1}{R(R_1 + R_2) + R_1 R_2} \quad \text{--- (10)}$$

Terminal voltage is given by

$$V = IR = \left(\frac{E_1 R_2 + E_2 R_1}{R(R_1 + R_2) + R_1 R_2} \right) R = \frac{E_1 R_2 + E_2 R_1}{R_1 + R_2 + (R_1 R_2 / R)} \quad \text{--- (11)}$$

❖ Using the eqns. (8) & (9), the load shared by each generator operating in parallel can be determined.

Solved Problem-16: Two shunt generators operating in parallel deliver a total current of 250 A. One of the generators is rated 50 kW and the other 100 kW. The voltage rating of both machine is 500 V and have regulations of 6% (smaller one) and 4%. Assuming linear characteristics, determine the (i) current delivered by each machine, and (b) terminal voltage.

Solution: Given that

Total load current supplied by the generators, I =250A

For generator 1:

Full load voltage drop = 500 × 0.06 = 30 V

Full load current = $\frac{50000}{500} = 100A$

Voltage drop/Amperes, R_1 = $\frac{30}{100} = 0.3\,V/A$

For generator 2:

Full load voltage drop = 500 × 0.04 = 20 V

Full load current = $\frac{100000}{500} = 200A$

Voltage drop/Amperes, R_2 = $\frac{20}{200} = 0.1V/A$

Let I_1 = Current output of generator 1

I_2 = Current output of generator 2

$\therefore I_1 + I_2 = 250A$ --- (1)

For DC generators, e.m.f. equation is given by $E = V + I_a R_a$

For generator 1, $V = 500 - 0.3I_1$ --- (2)

For generator 2, $V = 500 - 0.1I_2$ --- (3)

From eqns. (2) & (3), we get

$0.1I_2 = 0.3I_1$

$\Rightarrow I_2 = 3I_1$ --- (4)

From eqns. (1) & (4, we have

$4I_1 = 250 \Rightarrow I_1 = 62.5A$

$I_2 = 250 - I_1 = 250 - 62.5 = 187.5A$

(i) Load shared by generators: I_1=62.5A, I_2=187.5A

(ii) Terminal voltage or bus–bar voltage

$$V = 500 - 0.3I_1 = 500 - 0.3 \times 62.5 = 481.25\,V$$

Solved Problem-17: Three DC generators are connected to the common load. Generator 'A' has a constant e.m.f. of 400V and internal resistance of 0.2 Ω. Generator 'B' has a constant e.m.f. of 420V and internal resistance of 0.4 Ω. Generator 'C' has a constant e.m.f. of 440V and internal resistance of 0.6 Ω. Determine current and power output from each generator when the load voltage is 380 V.

Solution: Given that,

Terminal or load voltage, V = 380V

The e.m.f. and internal resistances of the three generators are given as

$E_A = 400V$ & $R_A = 0.2\Omega$

$E_B = 420V$ & $R_B = 0.4\Omega$

$E_C = 440V$ & $R_A = 0.6\Omega$

For generator A:

From e.m.f. equation of a DC generator is

$$I_A = \frac{E_A - V}{R_A} = \frac{400 - 380}{0.2} = 100A$$

$\therefore$ Output power of generator A, $P_A = VI_A$ = 380×100= 38 kW

For generator B:

From e.m.f. equation of a DC generator is

$$I_B = \frac{E_B - V}{R_B} = \frac{420 - 380}{0.4} = 100A$$

$\therefore$ Output power of generator B, $P_B = VI_B$ = 380×100 = 38 kW

For generator C:

From e.m.f. equation of a DC generator is

$$I_C = \frac{E_C - V}{R_C} = \frac{440 - 380}{0.6} = 100\,A$$

$\therefore$ Output power of generator C, $P_C = VI_C$ = 380×100= 38 kW

Solved Problem-18: Two DC generators each having linear external characteristics operate in parallel and supply a total load current of 180 A. The terminal potential difference of one machine falls from 240 V on no-load to 210 V when its current output is 120 A. The terminal potential difference of other machine falls from 240 V to 206 V when its armature current is 90 A. Determine current supplied by each machine and terminal voltage.

Solution: Given that

The total load current supplied by the generators, I = 180 A

For generator 1:

Voltage drop for 120 A = 240 - 210 = 30 V

Voltage drop/Amperes, $R_1 = \frac{30}{120} = 0.25V/A$

For generator 2:

Voltage drop for 90 A = 240 - 206 = 36 V

Voltage drop/Amperes, $R_2 = \frac{36}{90} = 0.4V/A$

Let I_1 = Current output of generator 1

I_2 = Current output of generator 2

$\therefore I_1 + I_2 = 180A$ --- (1)

For DC generators, e.m.f. equation is given by $E = V + I_a R_a$

For Generator 1, $V = 240 - I_1 \times 0.25$ --- (2)

For Generator 2, $V = 240 - I_2 \times 0.4$ --- (3)

From eqns. (2) & (3), we have

$$0.25I_1 = 0.4I_2$$

$$\Rightarrow I_1 = 1.6I_2 \qquad \text{--- (4)}$$

From eqn.(1), we have

$$I_1 + I_2 = 180\,A$$

$$\Rightarrow 1.6I_2 + I_2 = 180$$

$$\Rightarrow I_2 = 69.23\,A$$

$$I_1 = 1.6I_2 = 1.6 \times 69.23 = 110.77\,A$$

Output voltage of each generator,

$$V = 240 - 110.77 \times 0.25 = 212.3V \qquad (\because \text{from eqn.2})$$