D.C. GENERATORS

Introduction

An electrical generator is a machine which converts mechanical energy (or power) into electrical energy (or power). The energy conversion is based on the principle of the production of dynamically (or motionally) induced e.m.f.

Whenever a conductor cuts magnetic flux, dynamically induced e.m.f. is produced in it according to *Faraday's Laws of Electromagnetic Induction*. This e.m.f. causes a current to flow if the conductor circuit is closed. Hence, two basic essential parts of an electrical generator are:

(*i*) A magnetic field
(*ii*) A conductor or conductors which can so move as to cut the flux.

1. Determination of Flux Direction

When a conductor carries a current, it creates a magnetic field around it. The direction of such magnetic field depends on the direction of the current passing through the conductor. So electric current and magnetism are very closely related to each other. This relationship plays an important role in the d.c. machines.

1.1 Determination of Flux Direction in a Current Carrying Conductor

It can be determined using *Right Hand Thumb Rule* which states that "Hold the current carrying conductor in the right hand such that the thumb is pointing in the direction of current and parallel to the conductor, then curled fingers point in the direction of the magnetic field or flux around it", Figure (1) explains the rule.

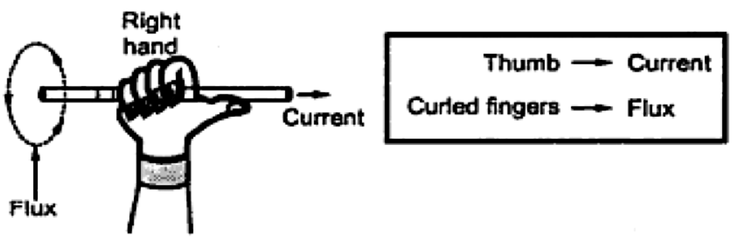
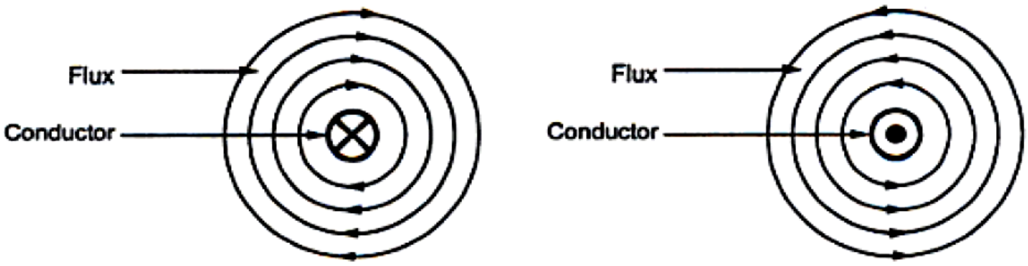


Figure (1)

Assume that the conductor to be placed perpendicular to the plane of the paper. So current moving away from the observer (inwards the paper) is denoted by a 'cross' while current coming towards the observer (outwards the paper) is denoted by a 'dot'.

Figure (2) shows the directions of flux for both cases when applying the *Right Hand Thumb Rule*.



(a) Current moving inwards the paper (b) Current moving outwards the paper

Figure (2)

1.2 Determination of Flux Direction in a Circular Conductor

It can be determined using *Right Hand Thumb Rule* which states that " hold the circular conductor in the right hand where the curled fingers point in the direction of the current through the circular conductor, then the thumb points to the north pole (N) (where the flux lines outs from the circular conductor core) & the second side of the circular conductor core represent the south pole(S) (where the flux lines enters the circular conductor core), this is shown in Figure (3).

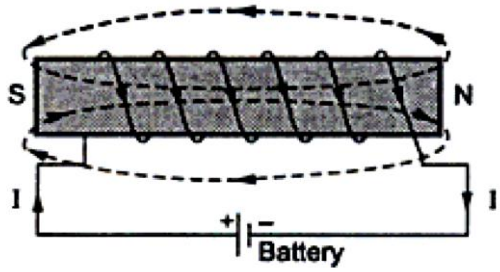


Figure (3): Directions of Flux around Circular Conductor

Notes:-

- The lines of flux always outs from the North-Pole (N).
- The lines of flux always enters the South-Pole (S).

Notes:- The direction of flux can be reversed either by changing direction of current through the conductor by reversing the polarities of the supply or by changing the direction of winding of the conductors around the core.

2. Simple Loop Generator

Construction

Figure (4) is shown a single-turn rectangular copper coil rotating about its own axis in a magnetic field provided by either permanent magnet or electromagnets. 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 (of carbon or copper) press against the slip-rings. Their function is to collect the current induced in the coil and to convey it to the external load resistance *R*. The rotating coil may be called 'armature' and the magnets as 'field magnets'.

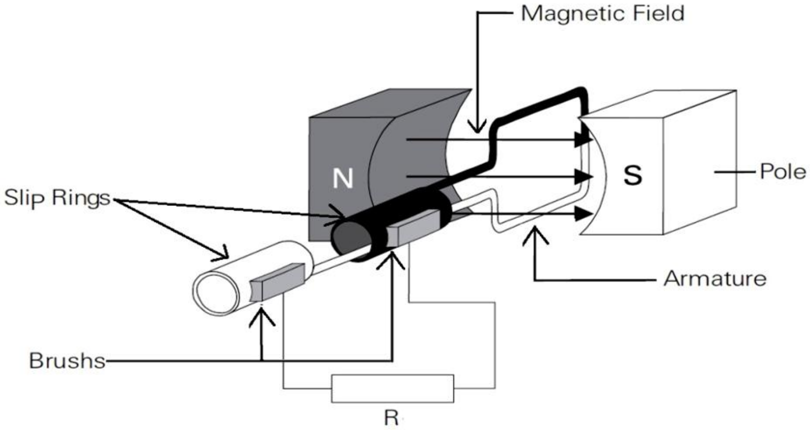


Figure (4): Simple Loop Generator

3. Basic Generator Operation

Generator at Initial Position

An armature rotates through the magnetic field. At an initial position of zero degrees (***the angle between the line perpendicular to the coil plane and the line of flux***), the armature conductors are moving parallel to the magnetic field and not cutting through any magnetic lines of flux. No voltage is induced.

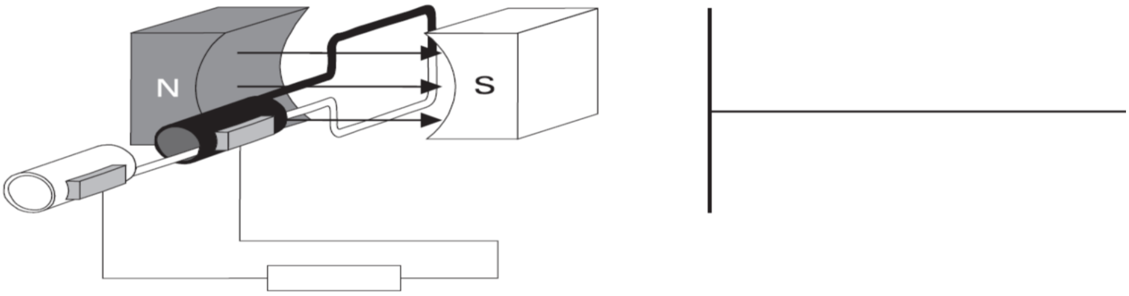


Figure (5): Generator at Initial Position (θ = 0)

Generator Operation from Zero to 90 Degrees

The armature rotates from zero to 90 degrees. The conductors cut through more and more lines of flux, building up to a maximum induced voltage in the positive direction.

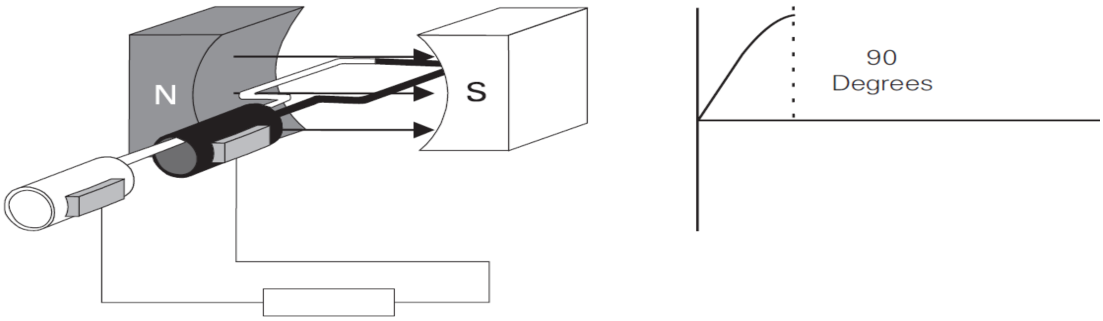


Figure (6): Generator at (θ = 90)

Generator Operation from 90 to 180 Degrees

The armature continues to rotate from 90 to 180 degrees, cutting less lines of flux. The induced voltage decreases from a maximum positive value to zero.

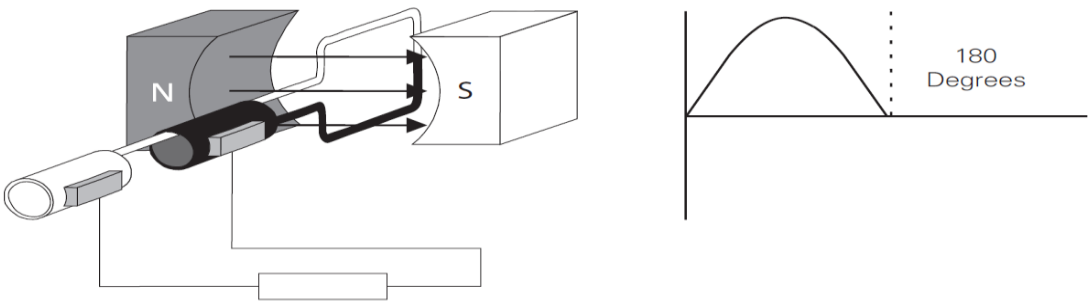


Figure (7): Generator at (θ = 180)

Generator Operation from 180 to 270 Degrees

The armature continues to rotate from 180 degrees to 270 degrees. The conductors cut more and more lines of flux, but in the opposite direction. voltage is induced in the negative direction building up to a maximum at 270 degrees.

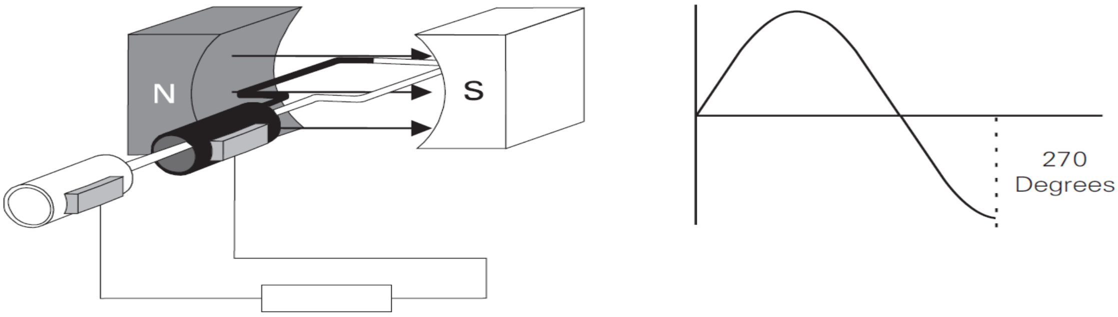


Figure (8): Generator at (θ = 270)

Generator Operation from 270 to 360 Degrees

The armature continues to rotate from 270 to 360 degrees. Induced voltage decreases from a maximum negative value to zero. This completes one cycle. The armature will continue to rotate at a constant speed. The cycle will continuously repeat as long as the armature rotates.

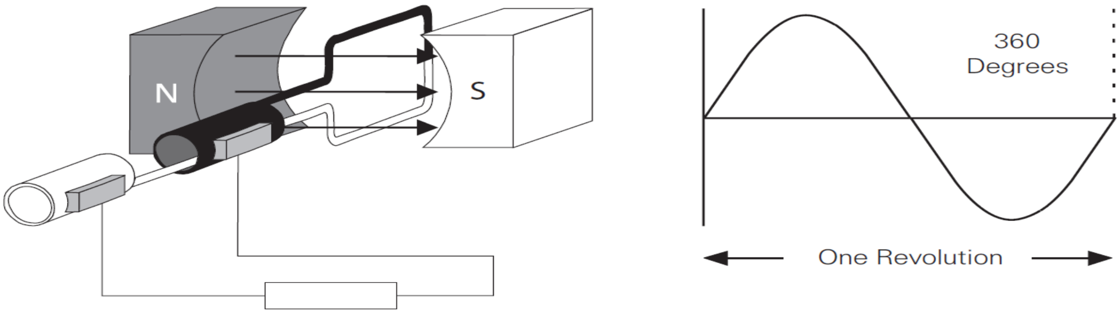


Figure (9): Generator at (θ = 360)

Therefore, we find that the current which we obtain from such a simple generator reverses its direction after every half revolution also changes its magnitude periodically. Such a current is known as alternating current (ac). The two half-cycles may be called positive and negative half-cycles respectively .

For making the flow of current unidirectional in the external circuit, the slip-rings are replaced by split-rings (commutator) (Figure (10)). The split-rings are made out of a conducting cylinder which is cut into two halves or segments insulated from each other by a thin sheet of mica or some other insulating material (Figure (11)).

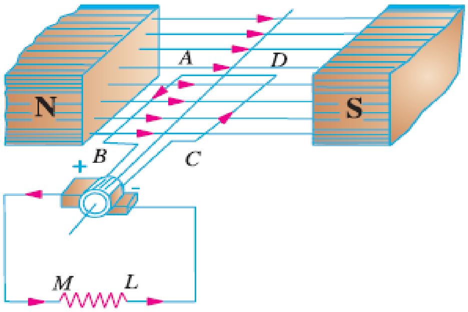


Figure (10)

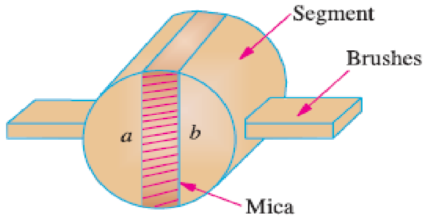
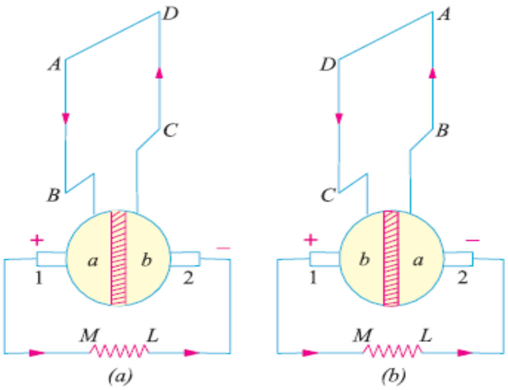


Figure (11)



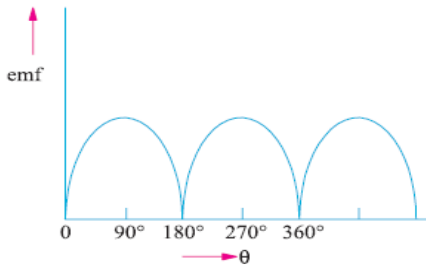
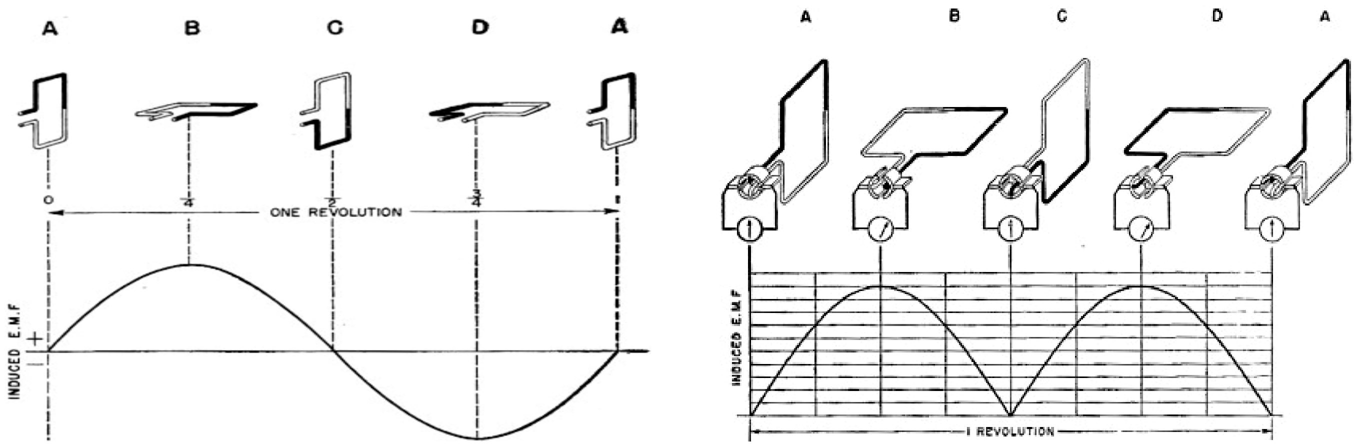


Figure (12)

Figure (13)

Due to the rectifying action of the split-rings (commutator), the alternating current induced in the coils becomes unidirectional in the external circuitonly. Hence, it should be clearly understood that the induced voltage in the armature of a d.c. generator, is alternating.



(a) A.C. generation

(b) D.C. generation

Figure (14)

Notes:- The number of voltage waves can be increased either by increasing the number of poles or by increasing the number of armature coils.

4. Determining the Direction of Induced Electromotive Force (e.m.f)

The direction of induced e.m.f. can be determined using *Fleming's Right Hand Rule* which states that ' outstretched the first three fingers so that every one of them is at right angles with the remaining two fingers. If the first finger (or thumb) refer to the direction of motion, second finger refer to the direction of flux so the third finger will refer to the direction of e.m.f. as shown in Figure (15).

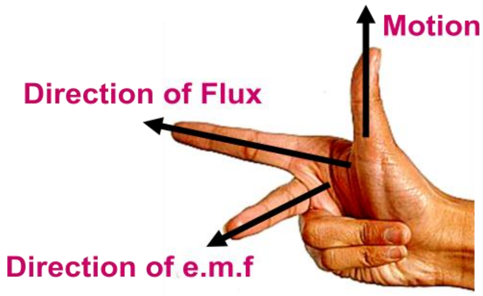


Figure (15): Fleming's Right Hand Rule

This rule mainly gives direction of current which induced e.m.f. in conductor will setup when closed path is provided to it.
Verify the direction of the current through the conductor in the four cases shown in the Figure (16) by using *Fleming's Right Hand Rule*.

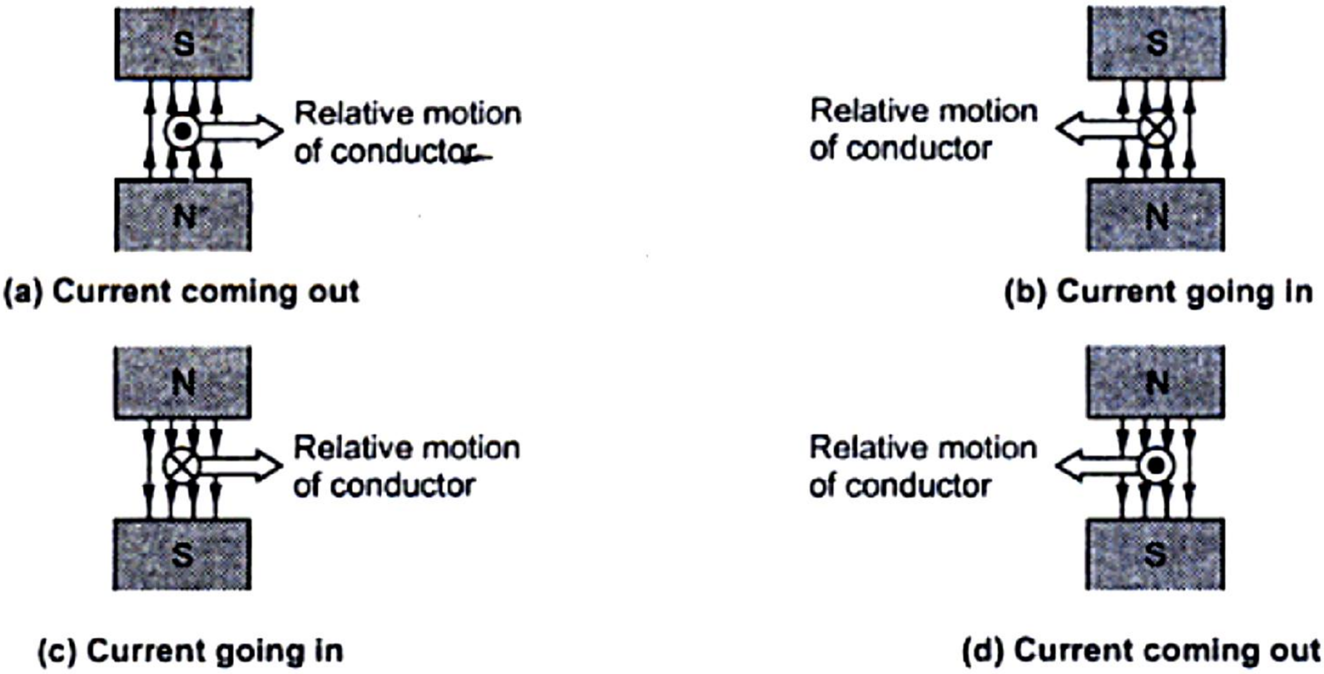


Figure (16): Fleming's Right Hand Rule

Notes:-

- If the direction of motion is reversed keeping flux direction same then the direction of induced e.m.f. and hence the direction of current is reversed.
- if flux direction is reversed keeping direction of motion same then the direction of induced e.m.f. and hence the direction of current is reversed.

5. Construction of Practical D.C. Machine

It consists of the following essential parts :
1) Magnetic Frame or Yoke
2) Pole-Cores and Pole-Shoes
3) Pole Coils or Field Coils
4) Armature Core
5) Armature Windings or Conductors
6) Commutator
7) Brushes and Bearings

1-Yoke

The outer frame or yoke serves double purpose:

(i) It provides mechanical support for the poles and acts as a protecting cover for the whole machine.

(ii) It carries the magnetic flux produced by the poles.

2-Pole Cores and Pole Shoes

The field magnets consist of pole cores and pole shoes. The pole shoes serve two purposes

(i) They spread out the flux in the air gap and also, being of larger cross-section, reduce the reluctance of the magnetic path

(ii) They support the exciting coils (or field coils).

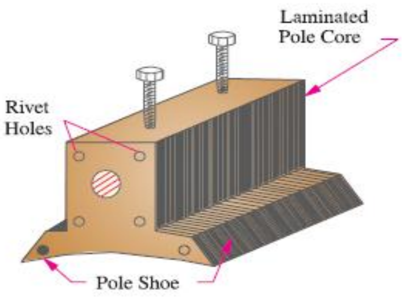


Figure (17): Pole Core

3-Pole Coils or Field Coils

The field coils or pole coils, which consist of copper wire or strip. When current is passed through these coils, they electromagnetise the poles which produce the necessary flux that is cut by revolving armature conductors.

Note:- Field winding is divided into various coils called field coils which connected in series with each other and wound in such a direction around pole cores, such that attains alternate (N) and (S) polarities of poles (Figure (18)). Poles polarities can be determined using *Right Hand Thumb Rule* as illustrated in section (1.2).

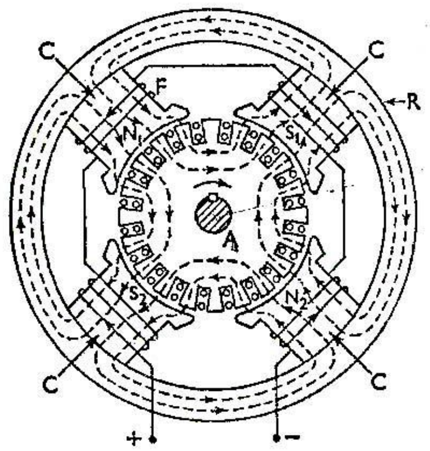


Figure (18): 4-pole d.c. machine

4-Armature Core

It houses the armature conductors or coils and causes them to rotate and hence cut the magnetic flux of the field magnets. In addition to this, its most important function is to provide a path of very low reluctance to the flux through the armature from a N-pole to a S-pole.

It is cylindrical or drum-shaped and is built up of usually circular sheet steel discs or laminations approximately 0.5 mm thick. The purpose of using laminations is to reduce the loss due to eddy currents. Thinner the laminations, greater is the resistance offered to the induced e.m.f., smaller the current and hence lesser the (I^2R) loss in the core.

5-Armature Windings

The conductors of armature windings are placed in the armature slots which are insulated.

6-Commutator

It rectified (converts) the alternating current induced in the armature conductors into unidirectional current in the external load circuit. It is of cylindrical shape consists of segments of high-conductivity material (usually copper). These segments are insulated from each other by thin layers of mica. The number of segments is equal to the number of armature coils. Each commutator segment is connected to the armature conductor by means of a copper lug or strip (or riser).

7-Brushes and Bearings

The brushes whose function is to collect current from commutator, are usually made of carbon or graphite and are in the shape of a rectangular block. These brushes are housed in brush-holders usually of the box-type variety.
The ball-bearings are generally packed in hard oil for quieter operation and for reduced friction.

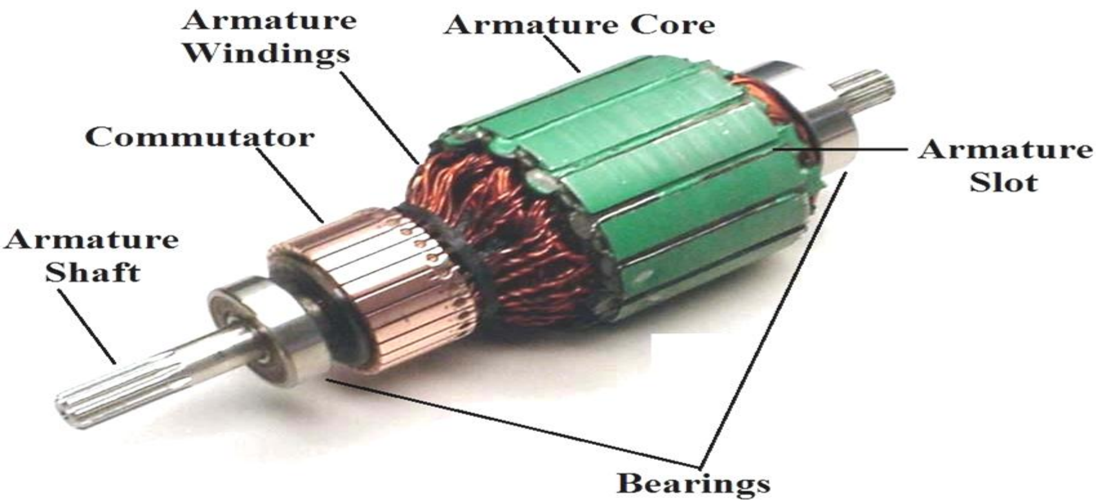


Figure (19): Armature of D.C. Machine

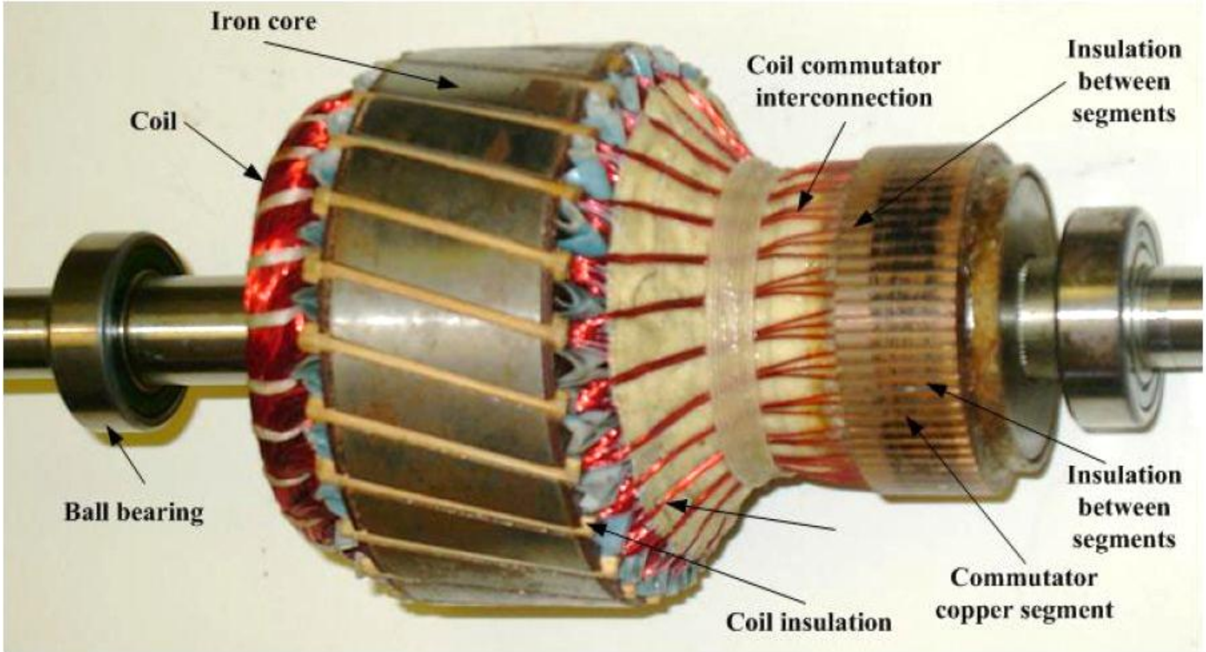


Figure (20): Armature of D.C. Machine

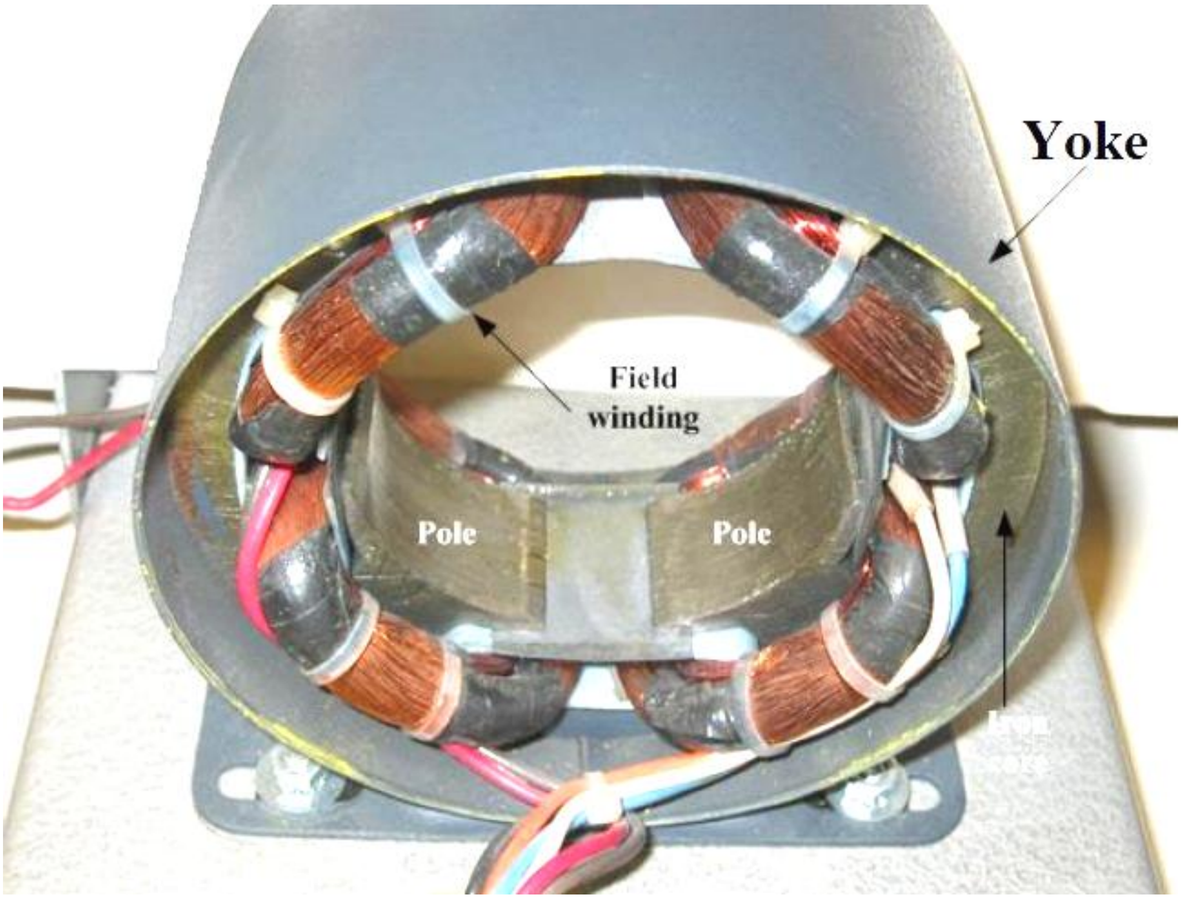


Figure (21): Yoke of D.C. Machine

6. Important Terms Related to Armature Winding ;-

1-Conductors(Z) :- it is the length of wire that lying in the magnetic field ,for example length AB or CD .

2-Coil :- the two conductors AB & CD along with their end connections constitute one coil of the armature winding . The coil may be single -turn (which have two conductors) or multi-turn (which have many conductors per coil sides) .

$$\boxed{Z = 2 \times \text{Number of turns}}$$

3-Winding element :- The group of wires or conductors constituting a coil side of a multi-turn coil is wrapped with a tape as a unit (Figure (22)) and is placed in the armature slot. The side of a coil (1-turn or multi turn) is called a winding element. Obviously, the number of winding elements is twice the number of coils.

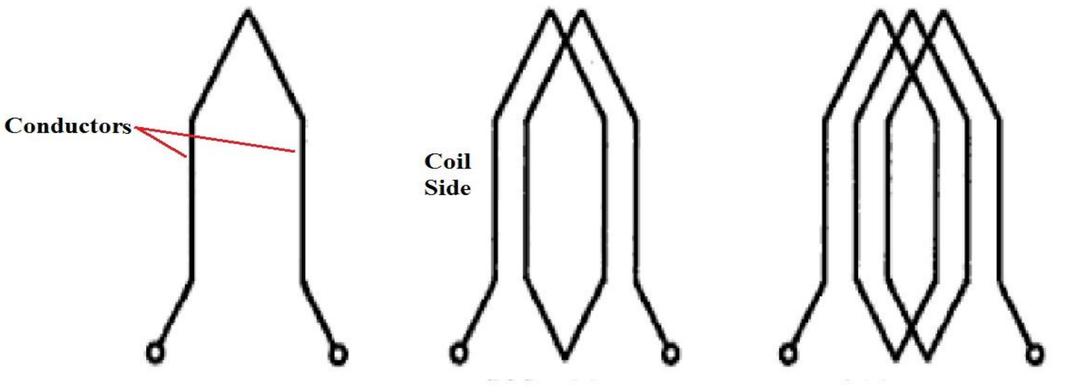


Figure (22)

4-Pole-pitch :- it is equal to the number of armature conductors (or armature slots) per pole ,or it is the distance between two adjacent poles .

5-Coil-span or Coil-pitch (Y_S):- it is the distance measured in terms of armature slots (or armature conductors) between two sides of a coil .

6- Full-pitch :- if the coil pitch is equal to the pole pitch ,then winding is called full-pitch .it means that coil span is 180 electrical degrees .in this case the coil sides lies under opposite poles , hence the induced e.m.fs in them are additive . Therefore maximum e.m.f is induced in the coil .

7-Fractional-pitch :- if the coil pitch is less than the pole-pitch then the winding is called fractional-pitch .In this case there is a phase difference between the e.m.fs in the two sides of the coil .Hence the total e.m.f around the coils less than fractional-pitch because it is the vector sum of e.m.fs in the two coil sides which is less than of arithmetic sum (full-pitch).

8-Back –pitch (Y_B):- it is the distance in terms of armature conductors between the beginning of a coil & the end of the same coil .

9-Front-pitch (Y_F) :- it is the distance in terms of armature conductors between the end of a coil & the beginning of the next coil to which it is connected .

10- Resultant-pitch (Y_R) :- it is the distance in terms of armature conductors between the beginning of one coil & the beginning of the next coil to which it is connected .

11-Commutator-pitch (Y_G):- it is the distance (measured in commutator bars or segments) between the segments to which the two ends of a coil are connected .

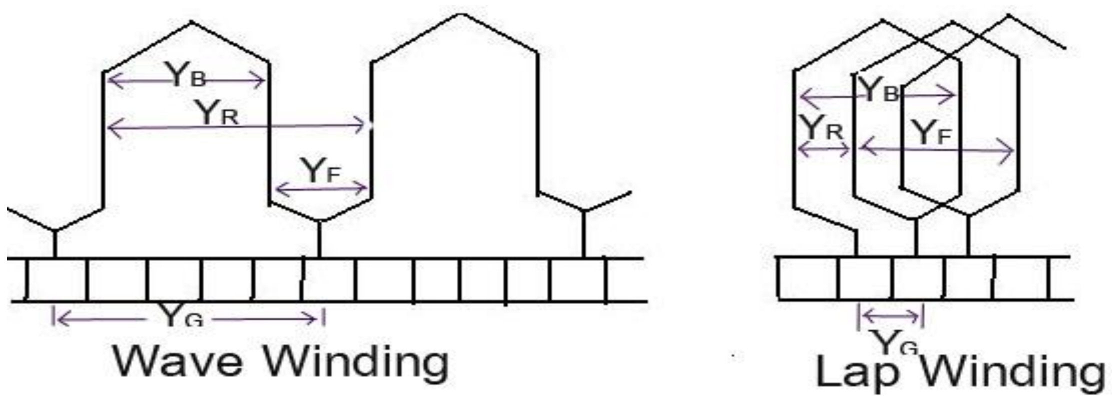


Figure (23)

12-Single-layer Winding (Simplex Winding) :- it is that winding in which one conductor or one coil side is placed in each armature slot , such winding is not mach used .

13-Two-layer Winding (Duplex Winding) :- In this type of winding, there are two conductors or coil sides per slot arranged in two layers. Sometimes 4 or 6 or 8 coil sides are used in each slot in several layers because it is not practicable to have too many slots (Figure (24)). The coil sides lying at the upper half of the slots are numbered odd i.e. 1, 3, 5, 7 etc. while those at the lower half are numbered even i.e. 2, 4, 6, 8 etc.If there is more than two layers are placed in each slot of armature conductors ,then it is called Multiplex Winding .

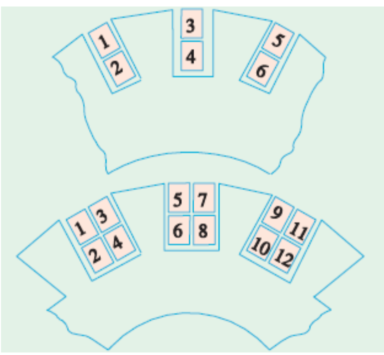
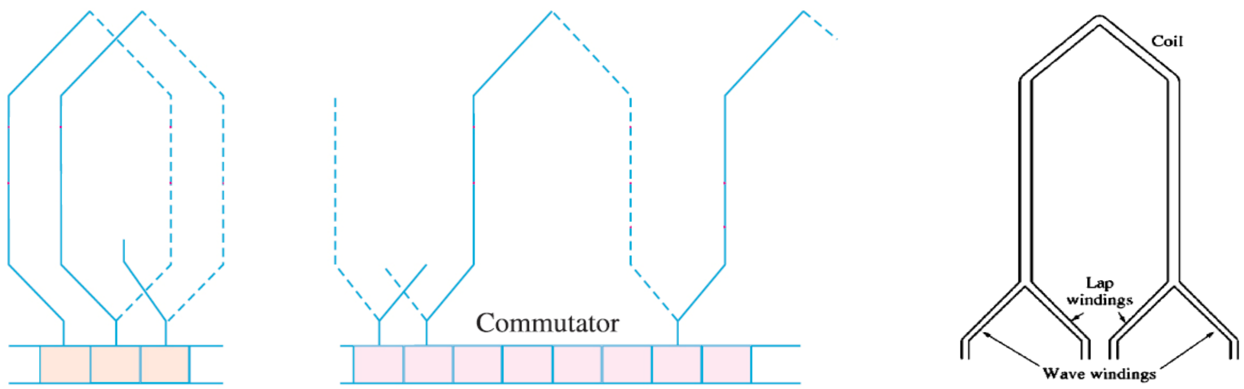


Figure (24)

14-Dummy or Idle Coils:- These are used with wave-winding when the armature having some slots without windings would be out of mechanical balance, so these coils provide mechanical balance for the armature. These dummy coils do not influence the electrical characteristics of the winding because they are not connected to the commutator.

7. Types of Armature Winding

There are two basic types of arrnature winding connections, *lap windings* and *wave windings*. In addition, there is a third type of winding, called a *frog-leg winding* (or self equalizing winding), which combines lap and wave windings on armature.



(a)lap-winding (b)wave winding (c) frog-leg winding

Figure (25)

Table (1)

NO.	Lap Winding	Wave Winding	Frog-Leg Winding
1	Number of parallel path, A=P (for simplex) Where, P:- number of poles	Number of parallel path, A=2 (for simplex)	Number of parallel path, A=2P (for simplex-lap)
2	Number of parallel path, A=mP (for multiplex) Where, P:- number of poles m:- number of multiplicity	Number of parallel path, A=2m (for multiplex) Where, m:- number of multiplicity	Number of parallel path, $A=2Pm_{lap}$ (for multiplex-lap) Where, m_{lap}:- number of multiplicity of lap winding
3	Number of brush sets required is equal to number of poles.	Number of brush sets required is always equal to two.	H.W
4	Preferable for high current, low voltage generator	Preferable for high voltage, low current generator	Preferable for medium voltage and current generator

Notes:-

If the end of a coil (or a set number of coils, for wave construction) is connected to a commutator segment ahead of the one its beginning is connected to, the winding is called a *progressive winding* (Figure (26-a)). If the end of a coil is connected to a commutator behind the one its beginning is connected to, the winding is called a *retrogressive winding*(Figure (26-b)). If everything else is identical, the direction of rotation of a progressive-wound rotor will be opposite to the direction of rotation of a retrogressive-wound rotor.

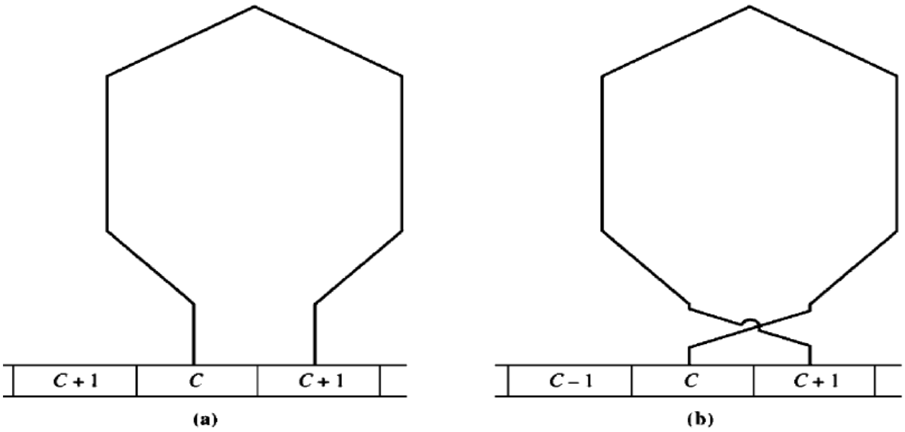


Figure (26): Progressive and retrogressive winding

8. Uses of Lap and Wave Windings:

The advantage of the wave winding is that, for a given number of poles and armature conductors, it gives more e.m.f. than the lap winding. Conversely, for the same e.m.f., lap winding would require large number of conductors which will result in higher winding cost and less efficient utilization of space in the armature slots. Hence, wave winding is suitable for small generators especially those meant for 500-600 V circuits.

Another advantage is that in wave winding, equalizing connections are not necessary whereas in a lap winding they definitely are. It is so because each of the two paths contains conductors lying under all the poles whereas in lap-wound armatures, each of the P parallel paths contains conductors which lie under one pair of poles. Any inequality of pole fluxes affects two paths equally, hence their induced e.m.fs. are equal. In lap-wound armatures, unequal voltages are produced which set up a circulating current that produces sparking at brushes. However, when large currents are required, it is necessary to use lap winding, because it gives more parallel paths. Hence, lap winding is suitable for comparatively low-voltage but high-current generators whereas wave-winding is used for high-voltage, low-current machines.

9. Types of Generators: - Generators are usually classified according to the way in which their fields are excited. Generators may be divided into

(a) Permanent magnet generators.
(b) Electromagnet generators
  (i) Separately-excited generators.
  (ii) Self-excited generators.

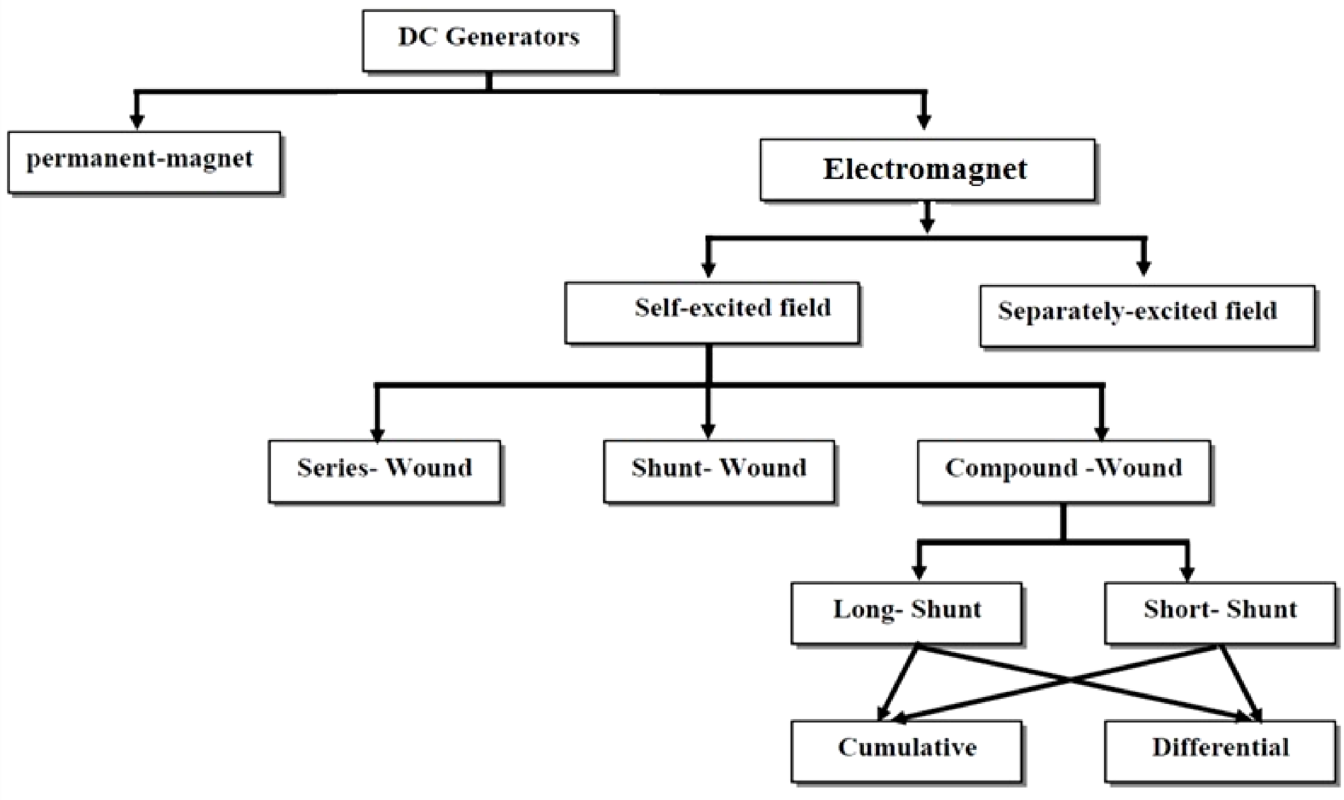


Figure (27): Types of d.c. Generators

(a) permanent-magnet field

permanent-magnet DC machines are widely found in a wide variety of **low-power** applications. The field winding is replaced by a permanent magnet, resulting in simpler construction. Chief among these is that they do not require external excitation and its associated power dissipation to create magnetic fields in the machine the space required for the permanent magnets may be less than that required for the field winding, and thus machine may be **smaller**, and in some cases **cheaper**, than their externally excited counter parts.

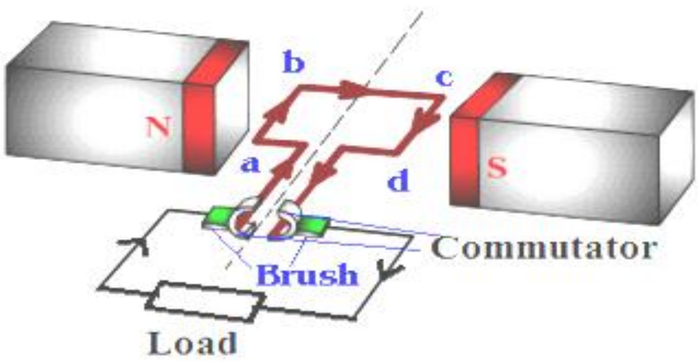


Figure (28): permanent magnet D.C. generator

(b) Separately-excited generators: are those whose field magnets are energised from an independent external source of d.c. current. It is shown in Figure (29).

$$\boxed{I_a = I_L}$$

$$\boxed{E_g = V + I_aR_a + V_{brushes}}$$

Where,
I_a : armature current.
I_L : load current.
E_g : generated voltage.
V : terminal voltage
R_a : armature winding resistance.
$V_{brushes}$: total brush contact drop

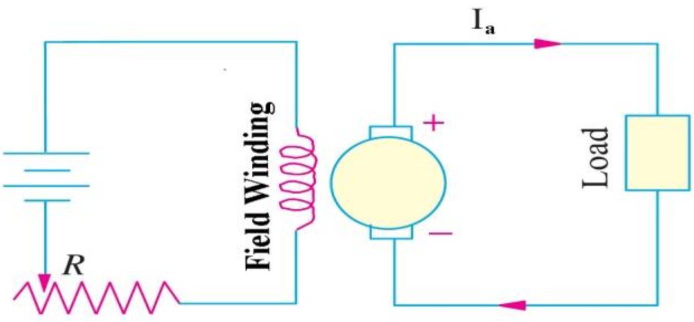


Figure (29): Schematic Diagram of Separately excited generators

(c) Self-excited generators: are those whose field magnets are energised by the current produced by the generators themselves. Due to residual magnetism, there is always present some flux in the poles. When the armature is rotated, some e.m.f. and hence some induced current is produced which is partly or fully passed through the field coils thereby strengthening the residual pole flux.
There are three types of self-excited generators named according to the manner in which their field coils (or windings) are connected to the armature.

(i) Shunt wound

The field windings are connected across or in parallel with the armature conductors and have the full voltage of the generator applied across them (Figure (30)).

$$\boxed{I_a = I_L + I_{sh}}$$

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

$$\boxed{E_g = V + I_aR_a + V_{brushes}}$$

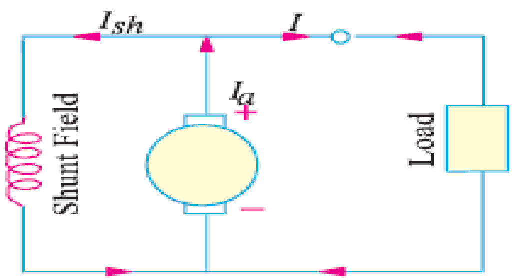


Figure (30): Schematic Diagram of Shunt Wound generators

Where :

I_{sh} : shunt field winding current.
R_{sh} : shunt field winding resistance.

(ii) Series Wound: In this case, the field windings are joined in series with the armature conductors (Figure (31)). As they carry full load current, they consist of relatively few turns of thick wire or strips. Such generators are rarely used except for special purposes i.e. as boosters etc.

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

$$E_g = V + I_aR_a + I_aR_{se} + V_{brushes}$$
$$= V + I_a(R_a + R_{se}) + V_{brushes}$$

Where :

I_{se} : series field winding current.
R_{se} : series field winding resistance.

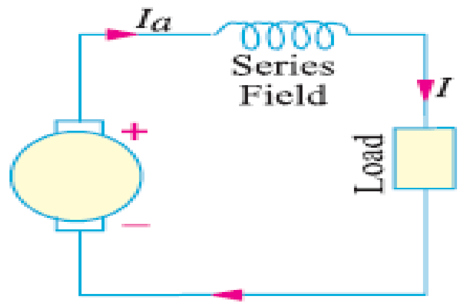


Figure (31): Schematic Diagram of Series Wound Generators

(iii) Compound Wound

It is a combination of a few series and a few shunt windings and can be either short-shunt or long-shunt as shown in Figure (32-a) & Figure (32-b) respectively. In a compound generator, the shunt field is stronger than the series field. When series field aids the shunt field, generator is said to be *cumulatively-compounded*. On the other hand if series field opposes the shunt field, the generator is said to be *differentially compounded*.

For short shunt:

$$I_L = I_{se}$$

$$I_a = I_L + I_{sh}$$

$$I_{sh} = \frac{V + I_L R_{se}}{R_{sh}}$$

$$E_g = V + I_aR_a + I_LR_{se} + V_{brushes}$$

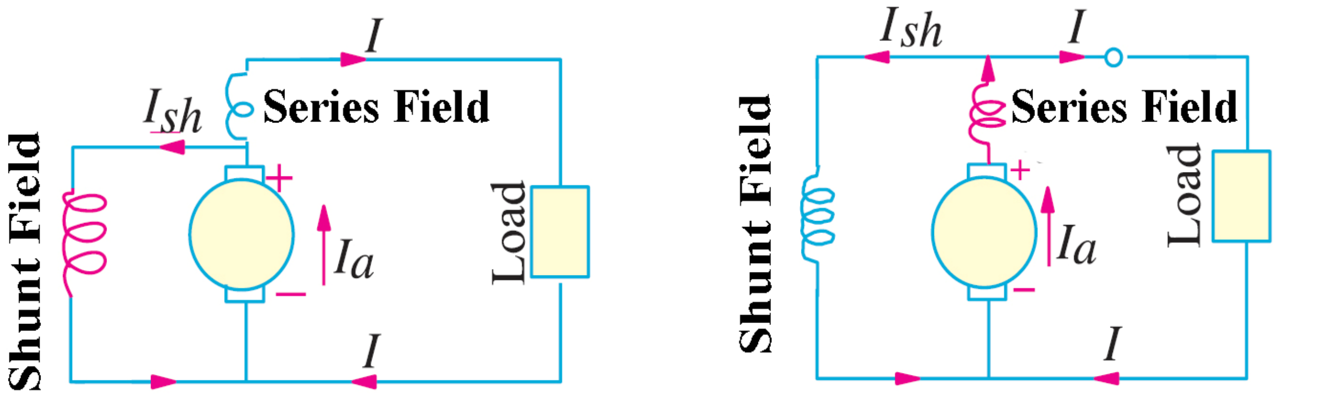
For long shunt:

$$I_a = I_{se}$$

$$I_a = I_L + I_{sh}$$

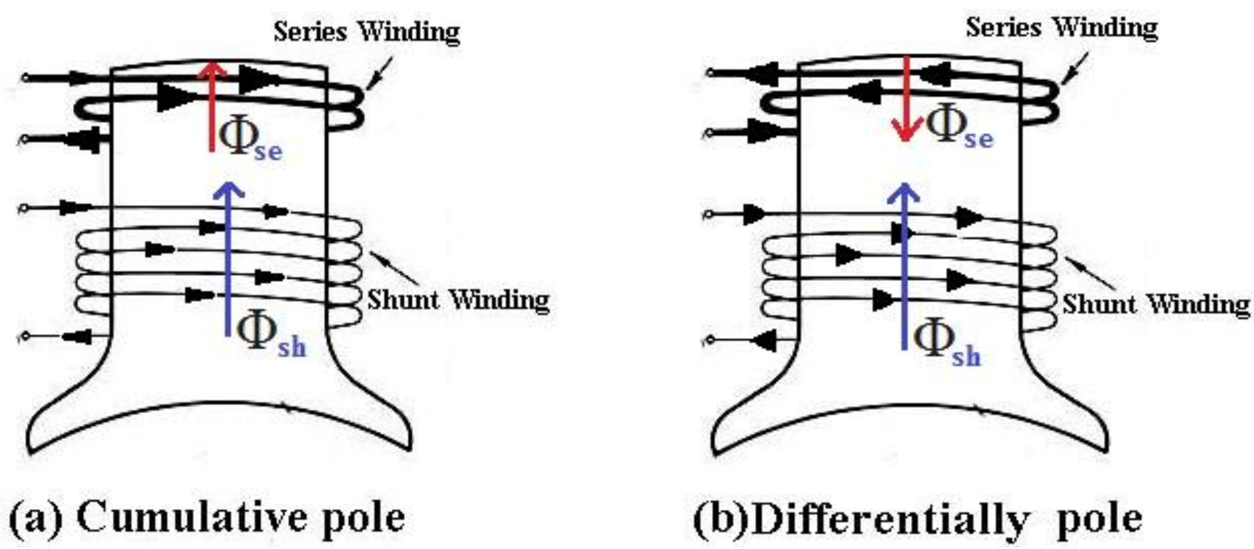
$$I_{sh} = \frac{V}{R_{sh}}$$

$$E_g = V + I_aR_a + I_aR_{se} + V_{brushes}$$
$$= V + I_a(R_a + R_{se}) + V_{brushes}$$



(a)Short-Shunt Compound Generator (b) Long-Shunt Compound Generator

Figure (32): Compound wound d.c. Generator



(a) Cumulative pole (b)Differentially pole

Figure (33): compound generator South poles

10. Brush Contact Drop

It is the voltage drop over the brush contact resistance when current passes from commutator segments to brushes and finally to the external load. Its value depends on the amount of current and the value of contact resistance. This drop is usually small and includes brushes of both polarities. However, in practice, the brush contact drop is assumed to have following constant values for all loads.

0.5 V for metal-graphite brushes.

2.0 V for carbon brushes.

Example1: A shunt generator delivers 450 A at 230 V and the resistance of the shunt field and armature are 50 Ω and 0.03 Ω respectively. Calculate the generated e.m.f.

Solution:

Current through shunt field winding is

$I_{sh} = 230/50 = 4.6$ A, Load current I = 450 A

∴ Armature current $I_a = I + I_{sh} = 450 + 4.6 = 454.6$ A

Armature voltage drop (I_aR_a)= 454.6 × 0.03 = **13.6 V**

E_g = terminal voltage + armature drop = $V + I_aR_a$

∴ e.m.f. generated in armature, $E_g = 230 + 13.6 =$ **243.6 V**

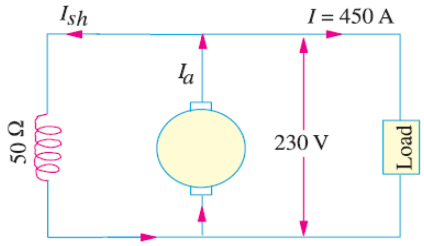


Figure (34)

Note: If there is no information about brush contact drop (V_{brush}), then we neglect it.

Example 2: A long-shunt compound generator delivers a load current of 50 A at 500 V and has armature, series field and shunt field resistances of 0.05 Ω, 0.03 Ω and 250 Ω respectively. Calculate the generated voltage and the armature current. Allow 1 V per brush for contact drop.

Solution:

$I_{sh} = 500/250 = 2$ A

Current through armature and series winding is

= 50 + 2 = 52 A

Voltage drop on series field winding

= 52×0.03 = 1.56 V

Armature voltage drop

$I_aR_a = 52 \times 0.05 = 2.6$ V

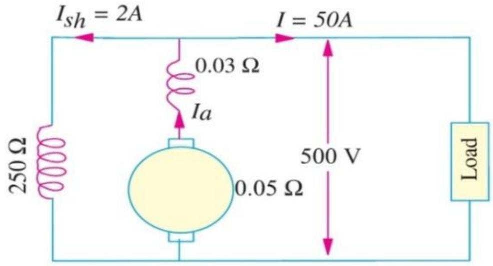


Figure (35)

Note: If there is no information about the number of brushes or the type of winding in the question, then we assume that the number of brushes are two (means wave winding).

Drop at brushes = 2×1 = 2 V

Now, $E_g = V + I_aR_a$ + series drop + brush drop = 500 + 2.6 + 1.56 + 2 = **506.16 V**

Example 3: A short-shunt compound generator delivers a load current of 30 A at 220 V, and has armature, series-field and shunt-field resistances of 0.05 Ω, 0.30 Ω and 200 Ω respectively. Calculate the induced e.m.f. and the armature current. Allow 1.0 V per brush for contact drop.

Solution:

Voltage drop in series winding = 30 × 0.3 = 9 V

Voltage across shunt winding = 220 + 9 = 229 V

$I_{sh} = 229/200 = 1.145$ A

$I_a = 30 + 1.145 = 31.145$ A

$I_aR_a = 31.145 \times 0.05 = 1.56$ V

Brush drop = 2× 1 = 2 V

$E_g = V$ + series drop + brush drop + I_aR_a

= 229 + 9 + 2 + 1.56 = 241.56 V

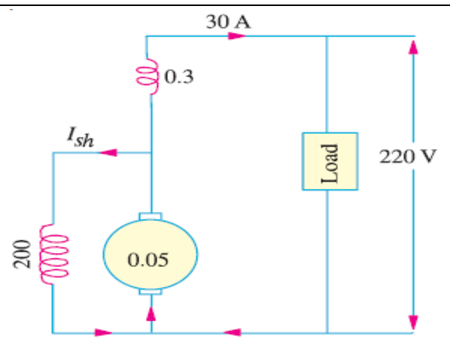


Figure (36)

Example 4: In a long-shunt compound generator, the terminal voltage is 230 V when generator delivers 150 A. Determine **(i)** induced e.m.f. **(ii)** total power generated and **(iii)** distribution of this power. Given that shunt field, series field, divertor and armature resistance are 92 Ω, 0.015 Ω, 0.03 Ω and 0.032 Ω respectively.

Solution:

$I_{sh} = 230/92 = 2.5$ A

$I_a = 150 + 2.5 = 152.5$ A

Note: Diverter is a resistance connected in parallel with series field winding.

Since series field resistance and diverter resistances are in parallel their combined resistance is

$$= \frac{0.03\times 0.015}{0.03+0.015} = 0.01\ \Omega$$

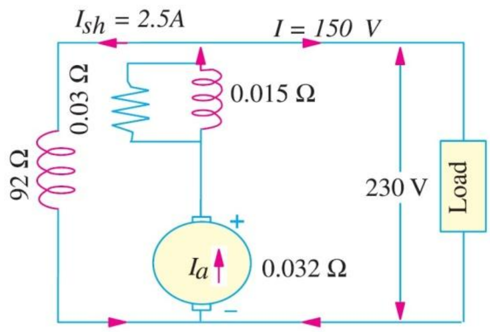


Figure (37)

Total armature circuit resistance is = 0.032 + 0.01 = 0.042 Ω

Voltage drop = 152.5× 0.042 = 6.4 V

(i) Voltage generated by armature, E_g = 230 + 6.4 = **236.4 V**

(ii) Total power generated in armature, $E_g I_a$ = 236.4×152.5 = **36,051 W**

(iii) Power lost in armature, $I_a R_a = (152.5)^2 \times 0.032 = 744$ W

Power lost in series field and divertor = $(152.5)^2 \times 0.01 = 232$ W

Power dissipated in shunt winding = VI_{sh} = 230×2.5 = 575 W

Power delivered to load = 230×150 = 34500 W

Total = 744+232+575+34500 = 36,051 W.

Example 5: The following information is given for a 300-kW, 600-V, long-shunt compound generator : Shunt field resistance = 75 Ω, armature resistance including brush resistance = 0.03 Ω, commutating field winding resistance = 0.011 Ω, series field resistance = 0.012 Ω, divertor resistance = 0.036 Ω. When the machine is delivering full load, calculate the voltage and power generated by the armature.

Solution:

Power output = 300,000 W

Output current = 300,000/600 = 500 A

I_{sh} = 600/75 = 8 A

I_a = 500 + 8 = 508 A

Since the series field resistance and divertor resistance are in parallel their combined resistance

is $= \frac{0.012\times 0.036}{0.012+0.036} = 0.009\ \Omega$

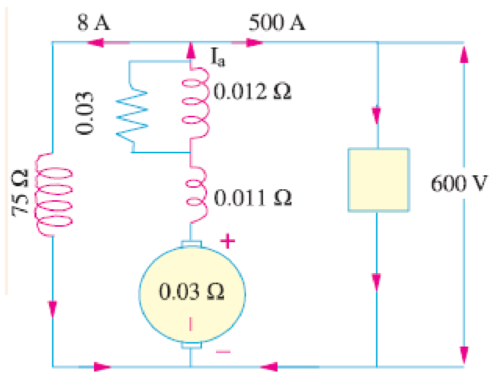


Figure (38)

Total armature circuit resistance

= 0.03 + 0.011 + 0.009 = 0.05 Ω

Voltage drop = 508×0.05 = 25.4 V

Voltage generated by armature = 600 + 25.4 = 625.4 V

Power generated = 625.4×508 = 317,700 = **317.7 kW**

11. Generated E.M.F. or E.M.F. Equation of a Generator

Let
Φ = flux/pole in weber
Z = total number of armature conductors = No. of slots × No. of conductors/slot
P = No. of generator poles
A = No. of parallel paths in armature
N = armature rotation in revolutions per minute (r.p.m.)
E_g = e.m.f. induced in any parallel path in armature

Average e.m.f. generated/conductor = $\frac{d\Phi}{dt}$ volt, (n=1) ...(1)
Where (n) is number of armature turns.

Now, flux cut/conductor in one revolution $d\Phi = \Phi P$ Wb ...(2)
No. of revolutions/second = N/60
∴ Time for one revolution, dt = 60/N second ...(3)
Hence, according to Faraday's Laws of Electromagnetic Induction (Equation (1)), so substitute Equations (2) and (3) in Equation (1), we get:

E.M.F. generated/conductor = $\frac{d\Phi}{dt} = \frac{\Phi PN}{60}$ volt ...(4)

For a simplex wave-wound generator

No. of parallel paths = 2
No. of conductors (in series) in one path = Z/2

E.M.F. generated/path = $\frac{\Phi PN}{60}\frac{Z}{2} = \frac{\Phi ZPN}{120}$ volt ...(5)

For a simplex lap-wound generator

No. of parallel paths = P
No. of conductors (in series) in one path = Z/P

E.M.F. generated/path = $\frac{\Phi PN}{60}\frac{Z}{P} = \frac{\Phi ZN}{60}$ volt ...(6)

In general generated e.m.f. $E_g = \frac{\Phi ZN}{60}\frac{P}{A}$ volt ...(7)

Where A = 2 (for simplex wave-winding)
= P (for simplex lap-winding)

Example 6: An 8-pole d.c. generator has 500 armature conductors, and a useful flux of 0.05 Wb per pole. What will be the e.m.f. generated if it is lap-connected and runs at 1200 rpm ? What must be the speed at which it is to be driven produce the same e.m.f. if it is wave-wound?

Solution.

With lap-winding, P = A = 8

$$E_g = \frac{\Phi Z N}{60}\frac{P}{A} = \frac{0.05 \times 500 \times 1200}{60}\ \frac{8}{8} = 500 \text{ volts}$$

If it is wave-wound, P = 8, A = 2, P/A = 4

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

$$500 = \frac{0.05 \times 500 \times N}{60}\ \frac{8}{2} \quad \Longrightarrow \quad \therefore N = 300 \text{ rpm}$$

Hence, with wave-winding, it must be driven at 300 rpm to generate 500 volts.

Additional Explanation: Assume 1 ampere as the current per conductor.

(*a*) Lap-wound, 1200 rpm : 500 V per coil-group, 8 groups in parallel

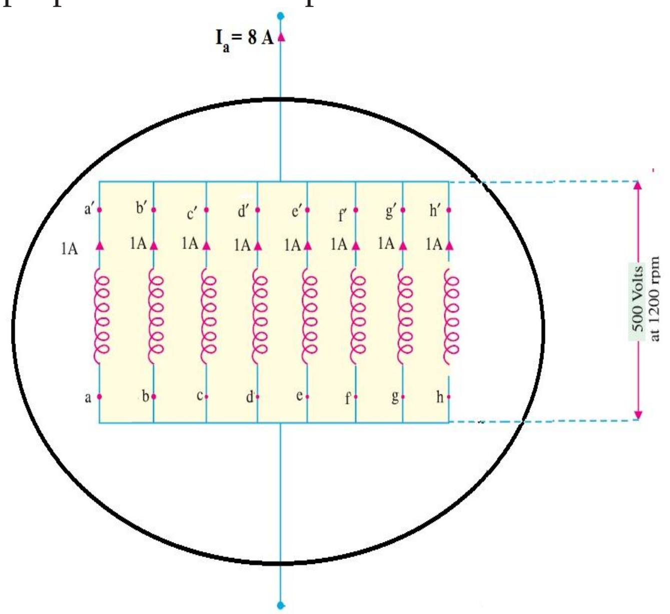
Net output current (I_a)= 8 amp as in Figure (39-a).

Power output (P_g)= $E_g I_a$=500 × 8 = 4 kW

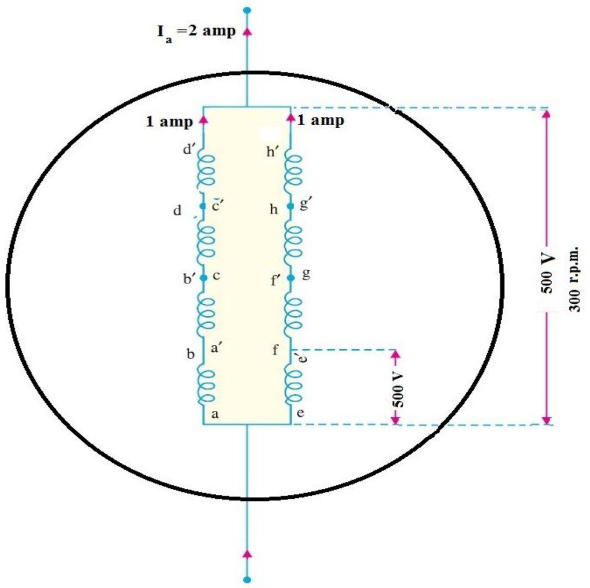
(*b*) Wave-wound, 300 rpm : 2 groups in parallel, one group has four coils in series, as shown in Fig Figure (39-b).

Total power-output (P_g)= $E_g I_a$ = 500 × 2 = 1000 W.

Note : power is reduced to one fourth that in case of lap wound, which is being proportional to the speed.



(a) Lap- wound Armature



(b) wave wound Armature

Figure (39)

Example 7: An 8-pole d.c. generator has 500 armature conductors, and a useful flux of 0.05 Wb per pole. What will be the e.m.f. generated if it is wave-connected and runs at 1200 rpm ? What must be the speed at which it is to be driven produce the same e.m.f. if it is lap-wound

Solution.

With wave-winding, A = 2

$$E_g = \frac{\Phi Z N}{60}\frac{P}{A} = \frac{0.05 \times 500 \times 1200}{60}\frac{8}{2} = 2000 \text{ volts}$$

Note : E_g in case of wave winding (2000v) which is greater than E_g in case of lap winding (500v), so wave wound generator give more voltage than lap wound generator for the same pole number, armature conductors and speed. hence wave wound generator use for high voltage applications (see section 8)

If it is lap-wound, A = P = 8,

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

$$2000 = \frac{0.05 \times 500 \times N}{60}\frac{8}{8} \Rightarrow \therefore N = 4800 \text{ rpm}$$

Hence, with lap-winding, it must be driven at 4800 rpm to generate 2000 volts.

Additional Explanation: Assume 1 ampere as the current per conductor.

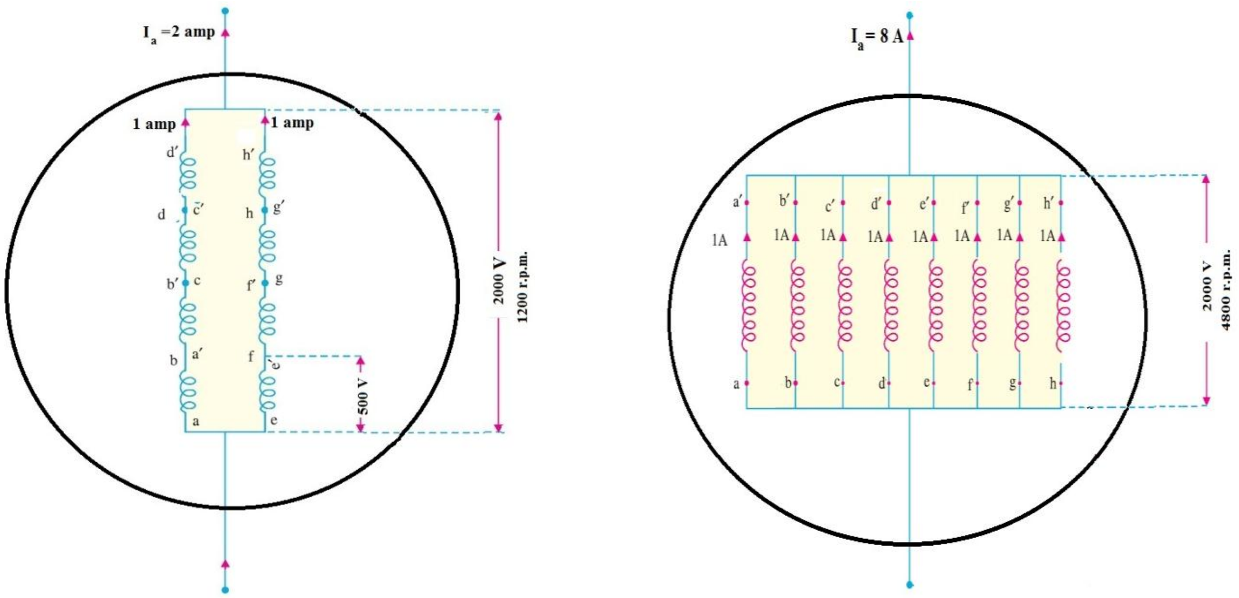
(*a*) Wave-wound, 1200 rpm : 2000 V per coil-group, 2 groups in parallel one group has four coils in series, Net output current (I_a)= 2 amp as in Figure (40-a).

Power output (P_g)= $E_g I_a$=2000 × 2 = 4 kW

(*b*) Lap-wound, 4800 rpm : 8 groups in parallel, as shown in Fig Figure (40-b).

Total power-output (P_g)= $E_g I_a$ = 2000 × 8 = 16 kW.

Note : power is increased to four times that in case of wave wound, which is being proportional to the speed.



(a) Wave-wound Armature (b) Lap-wound Armature

Figure (40)

Example 8: A 4-pole, Lap-connected d.c. machine has an armature resistance of 0.15 ohm. Find the armature resistance of the machine is rewound for wave-connection.

Solution.

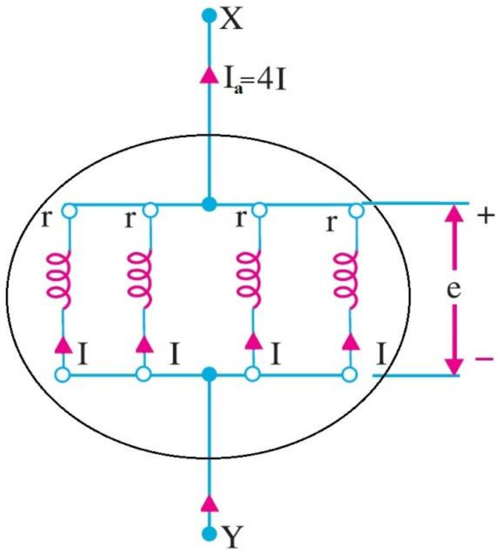
For lap-wound:

A 4-pole lap-winding has 4 parallel paths in armature,

$$\frac{1}{R_{a(lap)}} = \frac{1}{r} + \frac{1}{r} + \frac{1}{r} + \frac{1}{r}$$

$$\frac{1}{R_{a(lap)}} = \frac{4}{r}$$

$$\therefore r = 4R_{a(lap)} = 4 \times 0.15 = 0.6\ \Omega$$



(a) Lap-wound Armature

Note:

E_g = e (voltage in each parallel path), less than wave wound

I_a = 4I(sum of parallel paths current), more than wave wound

P= $E_g I_a$ = 4eI, equal to power in wave wound

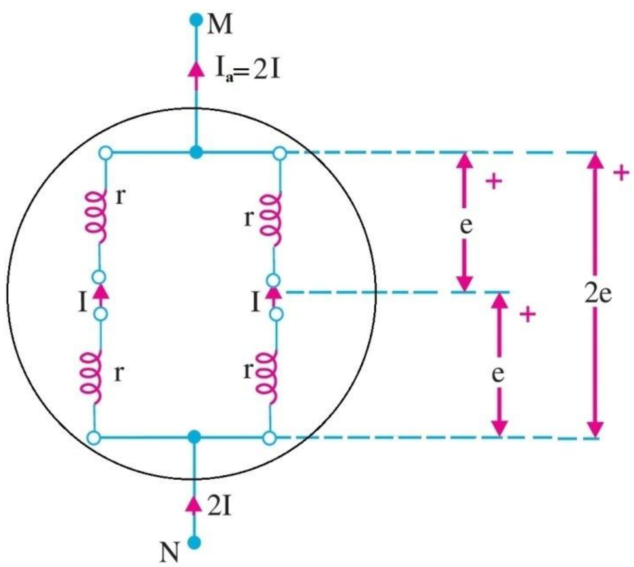
For wave-wound:

A 4-pole wave-winding has 2 parallel paths in armature,

$$\frac{1}{R_{a(wave)}} = \frac{1}{2r} + \frac{1}{2r}$$

$$\frac{1}{R_{a(wave)}} = \frac{1}{r}$$

$$R_{a(wave)} = r = 0.6\ \Omega$$



(b) Wave-wound Armature

Figure (41)

Note:

E_g = 2e (voltage in each parallel path), more than lap wound

I_a = 2I(sum of parallel paths current), less than lap wound

P= $E_g I_a$ = 4eI, equal to power in lap wound

Example 9: The armature of a four-pole d.c. shunt generator is lap-wound and generates 216 V when running at 600 r.p.m. Armature has 144 slots, with 6 conductors per slot. If this armature is rewound, wave-connected, find the e.m.f. generated with the same flux per pole but running at 500 r.p.m.
Also find power for both cases if each armature conductor carry 10A.

Solution:
Total number of armature conductors = $Z = 144 \times 6 = 864$ conductors

For a Lap winding,
A= P = 4,
generated e.m.f. $E_g = \frac{\Phi Z N}{60}\frac{P}{A} \Longrightarrow 216 = \frac{\Phi \times 864 \times 600}{60}\left(\frac{4}{4}\right)$
$\therefore \Phi = 25$ milli-weber

If the armature is rewound with wave-connection,
A = 2
Hence, at 500 r.p.m., with 25 mWb as the flux per pole.
generated e.m.f. $E_g = \frac{\Phi Z N}{60}\frac{P}{A} \Longrightarrow E_g = \frac{25\times10^{-3} \times 864 \times 500}{60}\left(\frac{4}{2}\right) = 360$ volts

Now to find output power for both cases,
Case (i): Lap-wound Machine at 600 r.p.m., Armature e.m.f.= 216 V
In simple lap-wound machines, since a four-pole machine has four parallel paths in armature, the total armature output-current is 40 amp.
Hence, armature-output power = $216 \times 40 \times 10^{-3} = 8.64$ Kw

Case (ii): Wave-wound machine, at 500 r.p.m., Armature e.m.f. = 360 V
Due to wave-winding, number of parallel paths in armature = 2, hence, the total armature output current = 20 amp
Thus, Armature - output-power = $360 \times 20 \times 10^{-3} = 7.2$ kw

Observation: With same flux per pole, the armature power outputs will be in the proportion of the speeds, as (7.2/8.64) = (5/6), $\Longrightarrow \left(\frac{P_{wave}}{P_{lap}} = \frac{N_{wave}}{N_{lap}}\right)$

Further Conclusion: In case of common speed for comparing Electrical Outputs with same machine once lap-wound and next wave-wound, there is no difference in the two cases. Lap-wound machine has lower voltage and higher current while the wave-wound machine has higher voltage and lower current.

Example 10: A long shunt d.c. compound generator delivers 110 kW at 220 V. If r_a = 0.01 ohm, r_{se} = 0.002 ohm, and shunt field has a resistance of 110 ohms, calculate the value of the induced e.m.f.

Solution:

Load current $(I_L) = \frac{P_{out}}{V_t} = \frac{110\times1000}{220} = 500$ A

Shunt field current $(I_{sh}) = \frac{220}{110} = 2$ A

Armature current $(I_a) = I_L + I_{sh} = 500 + 2 = 502$ A

$r_a + r_{se} = 0.012$ ohm

$E_g = V_t + I_a(r_a + r_{se}) = 220 + [502 \times (0.012)] = 226.024$ V

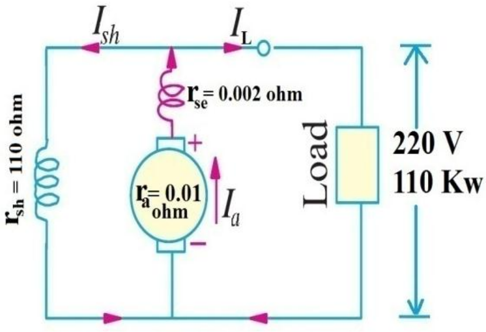


Figure (42)

Example 11: A d.c. shunt generator has an induced voltage on open-circuit of 127 volts. When the machine is on load, the terminal voltage is 120 volts. Find the load current if the field circuit resistance is 15 ohms and the armature-resistance is 0.02 ohm. Ignore armature reaction.

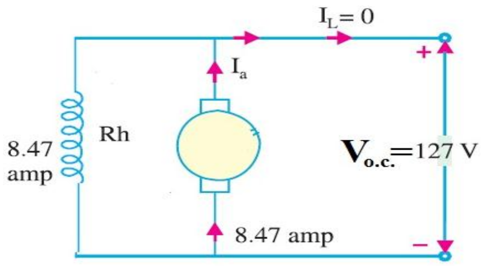
Solution:

Generator on no load: in this case we can find the generated e.m.f. directly because there is no voltage drop on load ($I_L = 0$, so $I_a = I_{sh}$), so the generated e.m.f. can be found by adding the O.C. voltage and voltage drop on armature resistance, as shown in Figure (43-a),

$V_{o.c.} = 127$ V

$I_a = I_{sh} = \frac{V}{R_{sh}} = \frac{V_{o.c.(or\ e.m.f)}}{R_{sh}} = \frac{127}{15} = 8.47$ A

$E_g = V_{o.c.} + I_a R_a = 127 + 8.47\times0.02 = 127.17$ volts



(a) Generator on no-load

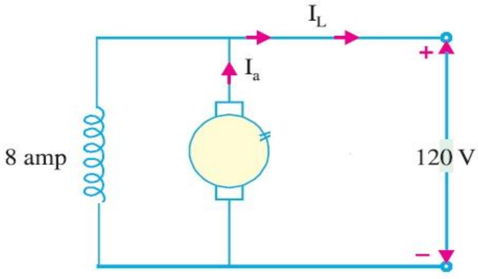
Figure (43-b), represent load cases,

$I_{sh} = \frac{V}{R_{sh}} = \frac{120}{15} = 8$ A

$E_g = V + I_a R_a \Longrightarrow 127.17 = 120 + I_a(0.02)$

$I_a = \frac{127.17-120}{0.02} = 358.5$ A

$\therefore I_L = I_a - I_{sh} = 358.5 - 8 = 350.5$ A



(b) Loaded Generator

Figure (43)

Example 12: An 8-pole d.c. shunt generator with 778 wave-connected armature conductors and running at 500 r.p.m. supplies a load of 12.5 Ω resistance at terminal voltage of 250 V. The armature resistance is 0.24 Ω and the field resistance is 250 Ω. Find the armature current, the induced e.m.f. and the flux per pole.

Solution:

Load current = V/R = 250/12.5 = 20 A

Shunt current = 250/250 = 1 A

Armature current = 20 + 1 = **21 A**

Induced e.m.f. = 250 + (21 × 0.24) = **255.04 V**

generated e.m.f. $E_g = \frac{\Phi Z N}{60}\left(\frac{P}{A}\right)$

$$\mathbf{255.04} = \frac{\Phi \times 778 \times 500}{60}\left(\frac{8}{2}\right)$$

∴ Φ = **9.83 mWb**

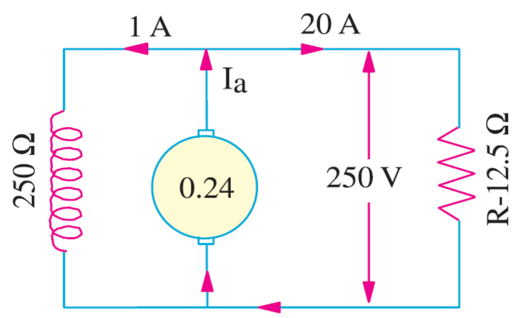


Figure (44)

Example 13: A 4-pole lap-connected armature of a d.c. shunt generator is required to supply the loads connected in parallel :

(1) 5 kW Geyser at 250 V, and

(2) 2.5 kW Lighting load also at 250 V.

The Generator has an armature resistance of 0.2 ohm and a field resistance of 250 ohms. The armature has 120 conductors in the slots and runs at 1000 rpm. Allowing 1 V per brush for contact drops and neglecting friction, find

(1) Flux per pole, **(2)** Armature-current per parallel path.

Solution:

Geyser current = 5000/250 = 20 A

Current for Lighting = 2500/250 = 10 A

Total current = 30 A

Field Current for Generator = $\frac{V}{R_{sh}} = \frac{250}{250} = 1$ A

Hence, Armature Current (I_a) = $I_L + I_{sh}$ = 31 A

Armature resistance drop = $I_a.R_a$ = 31 × 0.2 = 6.2 volts

Generated e.m.f. = V + $I_a.R_a$ + total brush contact drop = 250 + 6.2 + 2 = 258.2 V,

For a 4-pole lap-connected armature, Number of parallel paths = number of poles = 4

(1) The flux per pole is obtained from the emf equation,

$$E_g = \frac{\Phi Z N}{60}\frac{P}{A} \Longrightarrow 258.2 = \frac{\Phi \times 120 \times 1000}{60}\frac{4}{4}$$

Φ = 129.1 mWb

(2) Armature current per parallel path (I_a/path) = $\frac{I_a}{A}$ = 31/4 = 7.75 A.

Example 14: separately excited generator, when running at 1000 r.p.m. supplied 200 A at 125 V. What will be the load current when the speed drops to 800 r.p.m. if I_f is unchanged ? Given that the armature resistance = 0.04 ohm and brush drop = 2 V.

Solution:

Case1: speed is 1000 r.p.m.

N_1 = 1000 r.p.m.

The load resistance $R_L = \frac{V}{I_L} = \frac{125}{200} = 0.625\ \Omega$,

$E_{g1} = V + I_{L1}R_a$ + total brush contact drop

$= 125 + 200 \times 0.04 + 2 = 135$ V ;

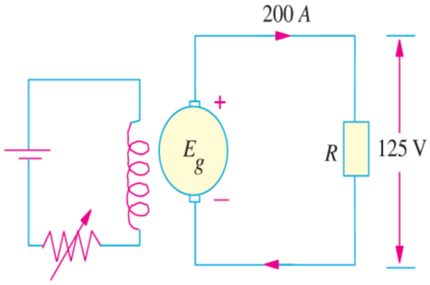


Figure (45)

Case2: speed is 800 r.p.m.

N_2 = 800 r.p.m.

E_{g2} =?

Note: as I_f unchanged, this means flux (Φ)is constant for both cases.

$E_g = \frac{\Phi Z N}{60}\frac{P}{A}$, As $(\frac{\Phi Z}{60}\frac{P}{A})$ is constant, $\Longrightarrow$ $\boxed{E_g \propto N}$

$\therefore \frac{E_{g2}}{E_{g1}} = \frac{N_2}{N_1}$ $\Longrightarrow$ $\boxed{E_{g2} = \frac{E_{g1} \times N_2}{N_1}}$

$\therefore E_{g2} = 135 \times (800/1000) = 108$ V

If I_{L2} is the new load current, then terminal voltage V is given by,

$E_{g2} = V + I_{L2}R_a$ + total brush contact drop

$\therefore V = E_{g2} - I_{L2}R_a$ – total brush contact drop

$V = 108 - 0.04 I_{L2} - 2$

$= 106 - 0.04\ I_{L2}$

& $I_{L2} = \frac{V}{R_L} = \frac{(106 - 0.04\ I_{L2})}{0.625}$ $\Longrightarrow$ $I_{L2} = 159.4$ A

Example 15: A 4-pole, 900 r.p.m. d.c. machine has a terminal voltage of 220 V and an induced voltage of 240 V at rated speed. The armature circuit resistance is 0.2 Ω. Is the machine operating as a generator or a motor ? Compute the armature current and the number of armature coils if the air-gap flux/pole is 10 mWb and the armature turns per coil are 8. The armature is wave wound.

Solution:

Since the induced voltage E is more than the terminal voltage v, the machine is working as a generator.

$E_g = V + I_a R_a$

$240 = 220 + I_a \times 0.2 \Longrightarrow I_a = 100\ A$

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

$$240 = \frac{10\times10^{-3}\times Z\times 900}{60}\frac{4}{2}$$

$\therefore Z = 800$

Since there are 8 turns in a coil, it means there are 16 active conductors/coil. Hence, the number of coils = 800/16 = 50.

Example 16: In a 120 V compound generator, the resistances of the armature, shunt and series windings are 0.06 Ω, 25 Ω and 0.04 Ω respectively. The load current is 100 A at 120 V. Find the induced e.m.f. and the armature current when the machine is connected as **(i)** long-shunt and as **(ii)** short-shunt.

Solution:

(i) Long Shunt [Figure (46-a)]

$I_{sh} = 120/125 = 4.8\ A$

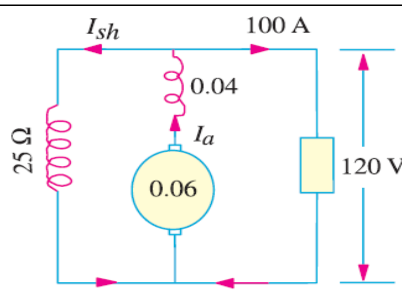
$I_L = 100\ A$

$I_a = 104.8\ A$

Voltage drop in series winding = 104.8 × 0.04 = 4.19 V

Armature voltage drop = 104.8 × 0.06 = 6.29 V

$\therefore\ E_g = 120 + 4.19 + 6.29 = 130.5\ V$



(a)

(ii) Short Shunt [Figure (46-b)]

Voltage drop in series winding = 100 × 0.04 = 4 V

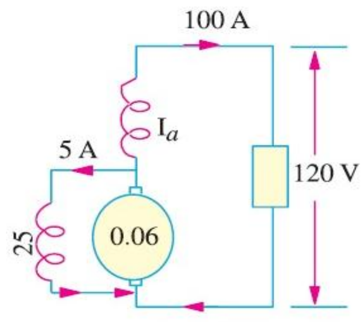
Voltage across shunt winding = 120 + 4 = 124 V

$\therefore\ I_{sh} = 124/25 = 5\ A$

$\therefore\ I_a = 100 + 5 = 105\ A$

Armature voltage drop = 105 × 0.06 = 6.3 V

$E_g = 120 + 6.3 + 4 = 130.3\ V$



(b)

Figure (46)

Example 17: A 4-pole, long-shunt lap-wound generator supplies 25 kW at a terminal voltage of 500 V. The armature resistance is 0.03 ohm, series field resistance is 0.04 ohm and shunt field resistance is 200 ohm. The brush drop may be taken as 1.0 V. Determine the e.m.f. generated.
Calculate also the No. of conductors if the speed is 1200 r.p.m. and flux per pole is 0.02 weber. Neglect armature reaction.

Solution:

$I = 25{,}000/500 = 50$ A, $I_{sh} = 500/200 = 2.5$ A

$I_a = I + I_{sh} = 50 + 2.5 = 52.5$ A

Series field drop = 52.5 × 0.04 = 2.1 V

Armature drop = 52.5 × 0.03 = 1.575 V

Brush drop = 2 × 1 = 2 V

Generated e.m.f., Eg = 500 + 2.1 + 1.575 + 2 = **505.67 V**

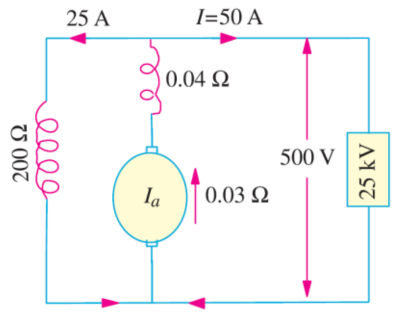


Figure (47)

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

$$505.67 = \frac{0.02 \times Z \times 1200}{60}\left(\frac{4}{4}\right)$$

∴ Z = **1264** conductors

Example 18: *A 4-pole, lap-wound, d.c. shunt generator has a useful flux per pole of 0.07 Wb. The armature winding consists of 220 turns each of 0.004 Ω resistance. Calculate the terminal voltage when running at 900 r.p.m. if the armature current is 50 A.*

Solution:

Since each turn has two sides,

$Z = 220 \times 2 = 440$; $N = 900$ r.p.m. ; $\Phi = 0.07$ Wb ; $P = A = 4$

$$\therefore E_g = \frac{\Phi Z N}{60}\frac{P}{A} = \frac{0.07 \times 440 \times 900}{60}\left(\frac{4}{4}\right) = 462 \text{ volt}$$

Total resistance of 220 turns (or 440 conductors) = 220×0.004 = 0.88 Ω

Since there are 4 parallel paths in armature,

∴ Resistance of each path (r) = 0.88/4 = 0.22 Ω

Now, there are four such resistances in parallel each of value 0.22 Ω

$$\frac{1}{R_{a(lap)}} = \frac{1}{r} + \frac{1}{r} + \frac{1}{r} + \frac{1}{r} \Longrightarrow \frac{1}{R_{a(lap)}} = \frac{4}{r}$$

$$\therefore R_{a(lap)} = \frac{r}{4} = \frac{0.22}{4} = 0.055\ \Omega$$

Armature drop = $I_a R_{a(lap)}$ = 50×0.055 = 2.75 Ω

Now, terminal voltage $V = E_g - I_a R_{a(lap)} = 462 - 2.75 =$ **459.25 volt.**

Example 19: A 4-pole, lap-wound, long-shunt, d.c. compound generator has useful flux per pole of 0.07 Wb. The armature winding consists of 220 turns and the resistance per turn is 0.004 ohms. Calculate the terminal voltage if the resistance of shunt and series field are 100 ohms and 0.02 ohms respectively ; when the generator is running at 900 r.p.m. with armature current of 50 A. Also calculate the power output in kW for the generator.

Solution:

Z=2× no. of turns = 2 × 220 = 440 conductors

$$E_g = \frac{\Phi Z N}{60}\frac{P}{A} = \frac{0.07\times440\times900}{60}\left(\frac{4}{4}\right) = 462 \text{ volt}$$

As found in (**Example 18**), $R_a = 0.055\ \Omega$

$R_a + R_{se} = 0.055 + 0.02 = 0.075\ \Omega$

Arm. circuit drop$[I_a(R_a+R_{se})] = 50 \times 0.075 = 3.75$ V

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

$V = 462 - 3.75 = 458.25$ V,

$I_{sh} = 458.25/100 = 4.58$ A

$I = 50 - 4.58 = 45.42$ A

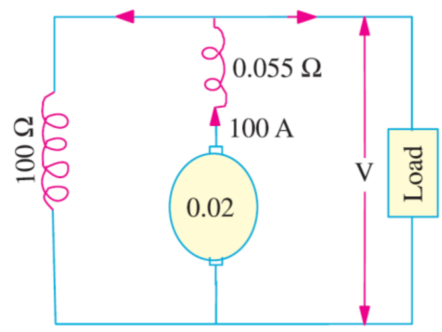


Figure (48)

Output Power = VI = 458.25 × 45.42 = 20,814 W = 20.814 kW

Example 20: A separately excited d.c. generator, when running at 1200 r.p.m. supplies 200 A at 125 V to a circuit of constant resistance.
What will be the current when the speed is dropped to 1000 r.p.m. and the field current is reduced to 80%?Armature resistance, 0.04 Ω and total drop at brushes, 2 V. Ignore saturation and armature reaction.

Solution:

We will find the generated e.m.f. when the load current is 200 A.

$$E_{g1} = V + V_b + I_aR_a = 125 + 2 + 200\times0.04 = 135 \text{ V},\ R_L = \frac{V}{I} = \frac{125}{200} = 0.625\ \Omega$$

Now, $E_{g1} \propto \Phi_1 N_1$ and $E_{g2} \propto \Phi_2 N_2$

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

or

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

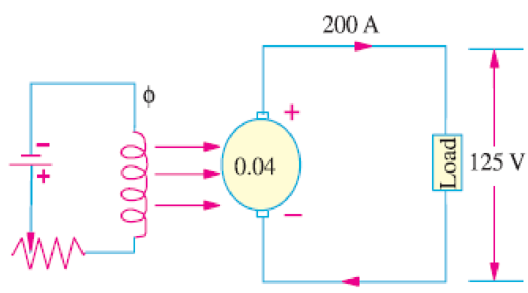


Figure (49)

$E_{g2} = V_2 + V_b + I_{L2}R_a$

$E_{g2} = I_{L2}R_L + V_b + I_{L2}R_a = I_{L2}(R_L + R_a) + V_b$

$90 = I_{L2}(0.625 + 0.04) + 2 \Longrightarrow I_{L2} = 132.33$ A

Example 21: A 4-pole, d.c. shunt generator with a shunt field resistance of 100 Ω and an armature resistance of 1 Ω has 378 wave-connected conductors in its armature. The flux per pole is 0.02 Wb. If a load resistance of 10 Ω is connected across the armature terminals and the generator is driven at 1000 r.p.m., calculate the power absorbed by the load.

Solution:

Induced e.m.f. in the generator is,

$$E_g = \frac{\Phi ZN}{60}\frac{P}{A} = \frac{0.02\times378\times1000}{60}\left(\frac{4}{2}\right) = 252 \text{ volt}$$

Now, let V be the terminal voltage *i.e.* the voltage available across the load as well as the shunt resistance (Figure (50)).

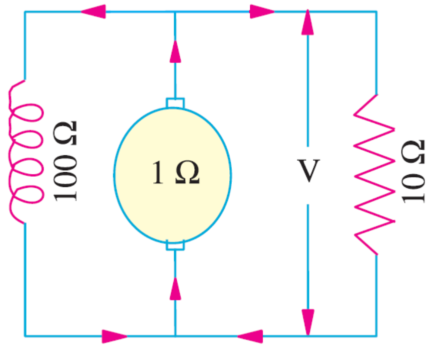


Figure (50)

Load current $(I_L) = \frac{V}{10}$ A

Shunt current $(I_{sh}) = \frac{V}{100}$ A

Armature current $(I_a) = \frac{V}{10} + \frac{V}{100} = \frac{11V}{100}$

Now, $V = E_g - I_aR_a$

$\therefore V = 252 - 1\times\frac{11V}{100}$

$\therefore V = 227$ volts

Load current $(I_L) = \frac{227}{10} = 22.7$ A,

Power absorbed by the load is = 227 × 22.7 = **5,153 W**

Example 22: A four-pole, lap-wound shunt generator has 300 armature-conductors and a flux/pole of 0.1 Wb. It runs at 1000 r.p.m. The armature and field-resistances are 0.2 ohm and 125 ohms respectively. Calculate the terminal voltage when it is loaded to take a load current of 90 A. Ignore armature reaction.

Solution:

First, the e.m.f .should be calculated,

$$E_g = \frac{\Phi ZN}{60}\frac{P}{A} = \frac{0.1\times300\times1000}{60}\left(\frac{4}{4}\right) = 500 \text{ volt}$$

$I_{sh} = \frac{500}{125} = 4$ A, $I_L = 90$ A, $I_a = I_L + I_{sh} = 90 + 4 = 94$ amp

$E_g = V_2 + I_aR_a$

$500 = V + 94 \times 0.20$

Terminal voltage, $V = 500 - 18.8 = 481.2$ volts

12. Total Loss in a D.C. Generator

The various losses occurring in a generator can be sub-divided as follows:

(a) Copper Losses:

(i) Armature copper loss = $I_a^2 R_a$ [**Note:** $E_g I_a$ is the power output from armature.]
where R_a = resistance of armature and interpoles and series field winding etc.
This loss is about 30 to 40% of full-load losses.

(ii) Field copper loss. In the case of shunt generators, it is practically constant and $I_{sh}^2 R_{sh}$ (or VI_{sh}). In the case of series generator, it is = $I_{se}^2 R_{se}$ where R_{se} is resistance of the series field winding.
This loss is about 20 to 30% of F.L. losses.

(iii) The loss due to brush contact resistance. It is usually included in the armature copper loss.

(b) Magnetic Losses: (also known as iron or core losses),

(i) hysteresis loss, $W_h \propto B_{max}^{1.6} f$

(ii) eddy current loss, $W_e \propto B_{max}^{2} f^2$

These losses are practically constant for shunt and compound-wound generators, because in their case, field current is approximately constant.
Both these losses total up to about 20 to 30% of F.L. losses.

(c) Mechanical Losses: These consist of :

(i) friction loss at bearings and commutator.

(ii) air-friction or windage loss of rotating armature.

These are about 10 to 20% of F.L. Losses.
The total losses in a d.c. generator are summarized below :

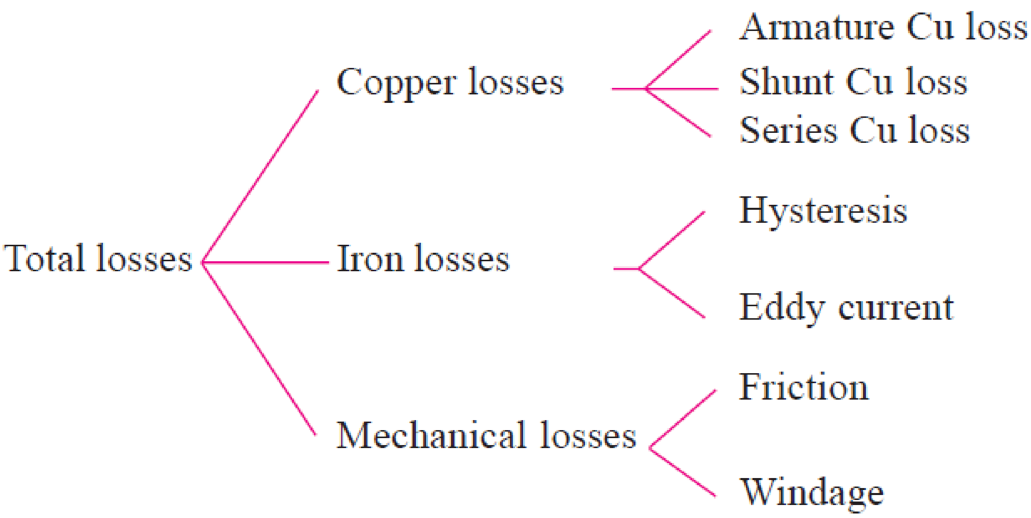


Figure (51)

13. Iron Loss in Armature

Due to the rotation of the iron core of the armature in the magnetic flux of the field poles, there are some losses taking place continuously in the core and are known as Iron Losses or Core Losses. Iron losses consist of **(i) Hysteresis** loss and **(ii) Eddy Current** loss.

(i) Hysteresis Loss (W_h): This loss is due to the reversal of magnetisation of the armature core. Every portion of the rotating core passes under N and S pole alternately, thereby attaining S and N polarity respectively. The core undergoes one complete cycle of magnetic reversal after passing under one pair of poles.

If P is the number of poles and N, the armature speed in r.p.m., then frequency of magnetic reversals is, $\boxed{f = PN/120}$

The loss depends upon the volume and grade of iron, maximum value of flux density B_{max} and frequency of magnetic reversals. For normal flux densities (i.e. upto 1.5 Wb/m^2), hysteresis loss is given by **Steinmetz** formula. According to this formula,

$$\boxed{W_h = \eta B_{max}^{1.6} f\, V \text{ watts}}$$

Where: V = volume of the core in m^3 & η = Steinmetz hysteresis coefficient.

Value of η for: Good dynamo sheet steel = 502 J/m^3, Silicon steel = 191 J/m^3, Hard Cast steel = 7040 J/m^3, Cast steel = 750 − 3000 J/m^3 and Cast iron = 2700 − 4000 J/m^3.

(ii) Eddy Current Loss (W_e): When the armature core rotates, it also cuts the magnetic flux. Hence, an e.m.f. is induced in the body of the core according to the laws of electromagnetic induction. This e.m.f. though small, sets up large current in the body of the core due to its small resistance. This current is known as eddy current.

The power loss due to the flow of this current is known as eddy current loss. This loss would be considerable if solid iron core were used.

In order to reduce this loss and the consequent heating of the core to a small value, the core is built up of thin laminations, which are stacked and then riveted at right angles to the path of the eddy currents. These core laminations are insulated from each other by a thin coating of varnish.

It is found that eddy current loss W_e is given by the following relation:

$$\boxed{W_e = K B_{max}^2 f^2 t^2 V^2 \text{ watt}}$$

Where: B_{max} = maximum flux density f = frequency of magnetic reversals, t = thickness of each lamination V = volume of armature core.

This loss varies directly as the square of the thickness of laminations, hence it should be kept as small as possible because it reduce the efficiency of the generator and raise the temperature of the core.

Eddy current loss is reduced by using laminated core but hysteresis loss cannot be reduced this way. For reducing the hysteresis loss, those metals are chosen for the armature core which has a low hysteresis coefficient. Generally, special silicon steels such as alloys are used which not only have a low hysteresis coefficient but which also possess high electrical resistivity.

14. Stray Losses

Usually, magnetic and mechanical losses are collectively known as ***Stray Losses***. These are also known as rotational losses for obvious reasons.

15. Constant or Standing Losses

Field Cu loss is constant for shunt and compound generators. Hence, stray losses and shunt Cu loss are constant in their case. These losses are together known as standing or constant losses W_c. Hence, for shunt and compound generators,

Total loss = armature copper loss + $W_c = I_a^2 R_a + W_c = (I + I_{sh})^2 R_a + W_c$.

Armature Cu loss $I_a^2 R_a$ is known as variable loss because it varies with the load current.
Total loss = variable loss + constant losses W_c

16. Power Stages

Various power stages in the case of a d.c. generator are shown below :

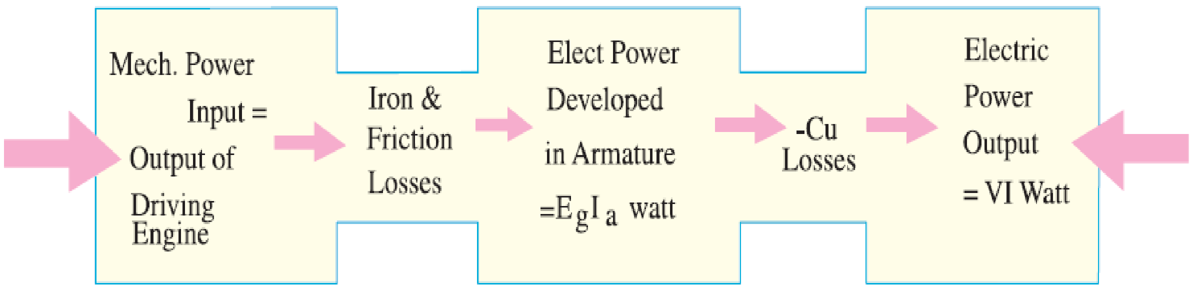


Figure (52)

Following are the three generator efficiencies:

1. Mechanical Efficiency

$$\eta_m = \frac{B}{A} = \frac{\text{total watts generated in armature}}{\text{mechanical power supplied}} = \frac{E_g I_a}{\text{output of driving engine}}$$

2. Electrical Efficiency

$$\eta_e = \frac{C}{B} = \frac{\text{watts available in load circuit}}{\text{total watts generated}} = \frac{VI}{E_g I_a}$$

3. Overall or Commercial Efficiency

$$\eta_c = \frac{C}{A} = \frac{\text{watts available in load circuit}}{\text{mechanical power supplied}}$$

It is obvious that overall efficiency ($\eta_c = \eta_m \cdot \eta_e$).For good generators, its value may be as high as 95%.

17. Condition for Maximum Efficiency

Generator output = VI

Generator input = output + losses

$= VI + I_a^2R_a + W_c$

$= VI + (I + I_{sh})^2R_a + W_c \qquad (\because I_a = I + I_{sh})$

However, if I_{sh} is negligible as compared to load current, then $I_a = I$ (approx.)

$$\therefore \eta = \frac{\text{output}}{\text{input}} = \frac{VI}{VI + I_a^2R_a + W_c}$$

$$= \frac{VI}{VI + I^2R_a + W_c} \qquad (\because I_a = I)$$

$$= \frac{1}{1 + \left(\frac{IR_a}{V} + \frac{W_C}{VI}\right)}$$

Now, efficiency is maximum when denominator is minimum i.e. when

$$\frac{d}{dI}\left(\frac{IR_a}{V} + \frac{W_C}{VI}\right) = 0$$

or

$$I^2R_a = W_C$$

Hence, generator efficiency is maximum when

Variable loss = constant loss.

The load current corresponding to maximum efficiency is given by the relation.

$I^2 R_a = W_c$

or

$$I = \sqrt{\frac{W_c}{R_a}}$$

Example 23: *A 10 kW, 250 V, d.c., 6-pole shunt generator runs at 1000 r.p.m. when delivering full-load. The armature has 534 lap-connected conductors. Full-load Cu loss is 0.64 kW. The total brush drop is 1 volt. Determine the flux per pole. Neglect shunt current.*

Solution:

Since shunt current is negligible ($I_{sh} = 0$), there is no shunt Cu loss. The copper loss occurs in armature only.

$I_L = I_a = 10000/250 = 40$ A

Armature Cu loss = $I_a^2R_a$ or $0.64\times10^3 = 40^2\times R_a$

$\therefore R_a = 0.4\ \Omega$

I_aR_a drop = $0.4\times40 = 16$ V ;

$\therefore$ Generated e.m.f. $E_g = V + I_aR_a$ + total brush drop $= 250 + 16 + 1 = 267$ V

Now, $E_g = \frac{\Phi ZN}{60}\frac{P}{A}$ volt

$$\therefore 267 = \frac{\Phi\times534\times1000}{60}\frac{6}{6}$$

$\therefore \Phi = 30\times10^{-3}$ Wb = **30 mWb**

Example 24: *A shunt generator delivers 195 A at terminal p.d.(potential difference) of 250 V. The armature resistance and shunt field resistance are 0.02 Ω and 50 Ω respectively. The iron and friction losses equal 950 W. Find*

(a) *E.M.F. generated*

(b) *Cu losses*

(c) *output of the prime motor*

(d) *Commercial, mechanical and electrical efficiencies.*

Solution:

(a) $I_{sh} = 250/50 = 5$ A

$I_a = 195 + 5 = 200$ A

Armature voltage drop = $I_aR_a = 200\times0.02 = 4$ V

∴ Generated e.m.f. = $V + I_aR_a = 250 + 4 =$ **254 V**

(b) Armature Cu loss = $I_a^2R_a$

$= 200^2\times0.02 = 800$ W

Shunt Cu loss = $V.I_{sh}$

$= 250\times5 = 1250$ W

∴ Total Cu loss = 1250 + 800 = **2050 W**

(c) Stray losses = 950 W

Total losses = Total Cu loss + Stray losses

= 2050 + 950 = 3000 W

Output power = 250×195 = 48,750 W

Input power = 48,750 + 3000 = 51750 W

∴ Output of prime mover = **51,750 W**

(d) Generator input power = 51,750 W

Stray losses = 950 W

Electrical power produced in armature = Generator input power − Stray losses

= 51,750 − 950 = 50,800 W

$\eta_m = (50{,}800/51{,}750)\times100 =$ **98.2%**

Electrical or Cu losses = 2050 W

$$\eta_e = \frac{48{,}750}{48{,}750 + 2{,}050}\times 100 = \mathbf{95.9\%}$$

$\eta_c = (48{,}750/51{,}750)\times100 =$ **94.2%**

Example 25: A long shunt dynamo running at 1000 r.p.m. supplies 20 kW at a terminal voltage of 220 V. The resistance of armature, shunt field, and series field are 0.04, 110 and 0.05 ohm respectively. Overall efficiency at the above load is 85%. Find :
(i) Copper loss,
(ii) Iron and friction loss.

Solution.

Load current (I_L) = $\frac{20,000}{220}$ = 90.91 amp, Shunt field current (I_f) = $\frac{220}{110}$ = 2 amp

Armature current, $I_a = I_L + I_f = 92.91$ amp

$$\eta_c = \frac{\text{generator output power}}{\text{generator input power}}$$

$$\therefore \text{generator input power} = \frac{\text{generator output power}}{\eta c} = \frac{20,000}{0.85} = 23529 \text{ watts}$$

Total losses in the machine = Input power − Output power = 23529 − 20,000 = 3529 watts

(i) ***Copper losses :***

Power loss in series field-winding + armature winding = $92.91^2 \times 0.09$ watts = 777 watts

Power-loss in shunt field circuit = $2^2 \times 110$ = 440 watts

Total copper losses = 777 + 400 = 1217 watts

(ii) Iron and friction losses = Total losses − Copper losses = 3529 − 1217 = 2312 watts

Example 26: A shunt generator has a F.L. current of 196 A at 220 V. The stray losses are 720 W and the shunt field coil resistance is 55 Ω. If it has a F.L. efficiency of 88%, find the armature resistance. Also, find the load current corresponding to maximum efficiency.

Solution:

Output power = $V \times I_L$ = 220 × 196 = 43,120 W ; η_c = 88% (overall efficiency)

$$\text{Input power} = \frac{\text{Output power}}{\eta c} = \frac{43,120}{0.88} = 49,000 \text{ W}$$

Total losses = Input power – Output power
= 49,000 − 43,120 = 5,880 W

$$\text{Shunt field current } (I_{sh}) = \frac{V}{R_{sh}} = \frac{220}{55} = 4 \text{ A}$$

$\therefore\ I_a = I_L + I_{sh} = 196 + 4 = 200$ A

$\therefore$ Shunt Cu loss = VI_{sh} = 220 × 4 = 880 W ; Stray losses = 720 W

Constant losses = Shunt Cu loss + Stray losses = 880 + 720 = 1,600

$\therefore$ Armature Cu loss = Total losses − Constant losses = 5,880 − 1,600 = 4,280 W

$$I_a^2 R_a = 4,280 \text{ W} \Longrightarrow 200^2 R_a = 4,280 \Longrightarrow \therefore R_a = \frac{4,280}{200^2} = \mathbf{0.107\ \Omega}$$

For maximum efficiency,

$$I^2 R_a = \text{constant losses} = 1,600 \text{ W} ;\ I = \sqrt{\frac{1,600}{0.107}} = \mathbf{122.34\ A}$$

Example 27: A long-shunt dynamo running at 1000 r.p.m. supplies 22 kW at a terminal voltage of 220 V. The resistances of armature, shunt field and the series field are 0.05, 110 and 0.06 Ω respectively. The overall efficiency at the above load is 88%. Find **(a)** Cu losses **(b)** iron and friction losses **(c)** the torque exerted by the prime mover.

Solution:

The generator is shown in Figure (53).

$I_{sh} = \frac{V}{R_{sh}} = \frac{220}{110} = 2$ A, $I_L = \frac{\text{Output power}}{V} = \frac{22{,}000}{220} = 100$ A,

$I_a = I_L + I_{sh} = 102$ A

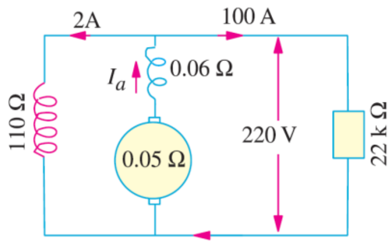


Figure (53)

(a) $I_a^2R_a = 102^2 \times 0.05 = 520.2$ W

Series field loss = $I_a^2R_{se} = 102^2 \times 0.06 = 624.3$ W

Shunt field loss = $I_{sh}^2R_{sh} = 2^2 \times 110 = 440$ W

Total Cu losses = 520.2 + 624.3 + 440 = **1584.5 W**

(b) Output power = 22,000 W ; Input power = $\frac{\text{Output power}}{\eta c} = \frac{22{,}000}{0.88} = 25{,}000$ W

∴ Total losses = Input power − Output power = 25,000 − 22,000 = 3,000 W

∴ Iron and friction losses = Total losses − Total Cu losses = 3,000 − 1,584.5 = **1,415.5 W**

Now, $P_{out} = \omega T = (\frac{2\pi N}{60})T$, where ω is angular speed = $\frac{2\pi N}{60}$, if N in .p.m.

$\therefore T = \frac{60\, Pout}{2\pi N} = \frac{25{,}000 \times 60}{1000 \times 6.284} =$ **238.74 N-m**

Example 28: A 4-pole d.c. shunt generator is delivering 20 A to a load of 10 Ω. If the armature resistance is 0.5 Ω and the shunt field resistance is 50 Ω, calculate the induced e.m.f. and the efficiency of the machine. Allow a drop of 1 V per brush.

Solution:

Terminal voltage = 20 × 10 = 200 V

I_{sh} = 200/50 = 4 A ; I_a = 20 + 4 = 24 A

I_aR_a = 24 × 0.5 = 12 V ; Brush drop = 2×1 = 2 V

∴ E_g = 200 + 12 + 2 = **214 V**, as in Figure (54).

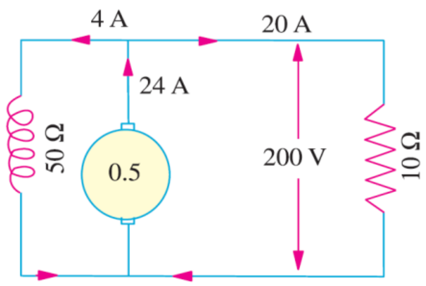


Figure (54)

Since iron and friction losses are not given, only electrical efficiency of the machine can be found out.

Total power generated in the armature = 214 × 24 = 5,136 W

Useful output = 200 × 20 = 4,000 W

∴ η_e = 4,000/5,136 = 0.779 or **77.9%**

Example 29: A long-shunt compound-wound generator gives 240 volts at F.L. output of 100A. The resistances of various windings of the machine are : armature (including brush contact) 0.1Ω, series field 0.02 Ω, interpole field 0.025 Ω, shunt field (including regulating resistance) 100 Ω. The iron loss at F.L. is 1000 W ; windage and friction losses total 500 W. Calculate F.L. efficiency of the machine.

Solution:

Output power = 240 × 100 = 24,000 W

Total armature circuit resistance = $(R_{brush\ contact} + R_{series\ field} + R_{interpole})$

$= 0.1 + 0.02 + 0.025 = 0.145\ \Omega$

$I_{sh} = 240/100 = 2.4\ A \therefore\ I_a = 100 + 2.4 = 102.4\ A$

$\therefore$ Armature circuit copper loss = $I_a^{\ 2}(R_{brush\ contact} + R_{series\ field} + R_{interpole})$

$= 102.4^2 \times 0.145 = 1{,}521\ W$

Shunt field copper loss = $I_{sh}\,V = 2.4 \times 240 = 576\ W$

Iron loss = 1000 W ; Friction loss = 500 W

Total loss = 1,521 + 1,500 + 576 = 3,597 W

$$\eta = \frac{\text{Output power}}{\text{Output power+Total loss}} = \frac{24{,}000}{24{,}000+3{,}597} = 0.87 = \mathbf{87\%}$$

Example 30: *In a d.c. machine the total iron loss is 8 kW at its rated speed and excitation. If excitation remains the same, but speed is reduced by 25%, the total iron loss is found to be 5 kW. Calculate the hysteresis and eddy current losses at*

(i) *full speed*

(ii) *half the rated speed.*

Solution:

$W_h = \eta B_{max}^{1.6}\ f\ V$ …(1)

$W_e = K B_{max}^{2}\ f^2\ t^2 V^2$ …(2)

$f = \frac{NP}{120}$ …(3)

Substitute equ.(3) in equ.(1), we get:

$$W_h = \eta B_{max}^{1.6}\left(\frac{NP}{120}\right) V = \left(\frac{\eta P V B_{max}^{1.6}}{120}\right) N$$

As $\left(\frac{\eta P V}{120}\right)$ is constant for the machine, and excitation is remain constant this means (B_{max}) is constant also. So we can represent these values by a constant (A)in the equation.

$\therefore\ W_h = AN$ …(4)

Substitute equ.(3) in equ.(2), we get:

$$W_e = KB_{max}^2 \left(\frac{NP}{120}\right)^2 t^2V^2 = \left(\frac{KP^2t^2V^2B_{max}^2}{120^2}\right) N^2$$

As $\left(\frac{KP^2t^2V^2}{120^2}\right)$ is constant for the machine, and excitation is remain constant this means (B_{max}) is constant also. So we can represent these values by a constant (D)in the equation.

$$W_e = DN^2 \qquad \ldots(5)$$

Total iron loss (W_i) = $W_h + W_e$

$$W_i = AN + DN^2 \qquad \ldots(6)$$

Case 1: [at rated speed (N_1) and rated excitation (B_1)]

$$W_i = AN + DN^2$$

$$\therefore 8 = AN_1 + DN_1^2 \qquad \ldots(7)$$

Case 2: [When speed is reduced by 25% and rated excitation remain constant]

$N_2 = 0.75N_1$ & $B_2 = B_1 =$constant

$$\therefore 5 = AN_2 + DN_2^2$$

$$5 = 0.75AN_1 + (0.75)^2DN_1^2 \qquad \ldots(8)$$

Divide equation (8) by (0.75), we get,

$$6.67 = AN_1 + 0.75\, DN_1^2 \qquad \ldots(9)$$

Subtract equation (7) from (9),

$$8 = AN_1 + DN_1^2$$

$$\underline{\mp 6.67 = \mp AN_1 \mp 0.75\, DN_1^2}$$

$$1.33 = 0.25\, DN_1^2 \Longrightarrow D = \frac{5.32}{N_1^2} \qquad \ldots(10)$$

Substitute equ.(10) in equ.(7), we get,

$$8 = AN_1 + \left(\frac{5.32}{N_1^2}\right)N_1^2 \Longrightarrow A = \frac{2.68}{N_1} \qquad \ldots(11)$$

(i) full speed,[full speed means rated speed(N_1)]

From equ.(4)& equ.(11),

$$W_h = AN_1 = \left(\frac{2.68}{N_1}\right) N_1 = 2.68 \text{ Kw}$$

From equ.(5)& equ.(10),

$$W_e = DN_1^2 = \left(\frac{5.32}{N_1^2}\right) N_1^2 = 5.32 \text{ Kw}$$

(ii) At half rated speed,[means (N_2= 0.5N_1)]

From equ.(4)& equ.(11),

$$W_h = AN_2 = \left(\frac{2.68}{N_1}\right) N_2 = \left(\frac{2.68}{N_1}\right) (0.5N_1) = 1.34 \text{ Kw}$$

From equ.(5)& equ.(10),

$$W_e = DN_2^2 = \left(\frac{5.32}{N_1^2}\right) N_2^2 = \left(\frac{5.32}{N_1^2}\right) (0.5N_1)^2 = 1.33 \text{ Kw}$$

Alternative Solution:

$W_h \propto f$ and $W_e \propto f^2$

Since f, the frequency of reversal of magnetization, is directly proportional to the armature speed,

$W_h \propto N$ and $W_e \propto N^2$

$\therefore$ $W_h = AN$ and $W_e = DN^2$, where A and D are constants.

Total loss $W = W_h + W_e = AN + DN^2$

Let the full rated speed be 1.

Then $8 = A\times1 + D\times1^2$

$8 = A + D$ ...(i)

Now, when speed is 75% of full rated speed, then

$5 = A\times(0.75) + D\times(0.75)^2$ ...(ii)

Multiplying (i) by 0.75 and subtracting (ii) from it, we get

$0.1875\,D = 1$

$\therefore$ $D = 1/0.1875 =$ **5.33 kW**

Substituting this value in (i) above

$8 = 5.33 + A$

$\therefore$ $A =$ **2.67 kW**

(i) W_h at rated speed = 2.67 kW,

W_e at rated speed = **5.33 kW**

(ii) W_h at half the rated speed = 2.67×0.5 = **1.335 kW**

We at half the rated speed= 5.33×0.5^2 = **1.3325 kW**

Example 31: The hysteresis and eddy current losses in a d.c. machine running at 1000 r.p.m. are 250 W and 100 W respectively. If the flux remains constant, at what speed will be total iron losses be halved ?

Solution:

Total loss $W = W_h + W_e = AN + DN^2$

Now,

$W_h = 250$ W $\quad \therefore A\times(1000/60) = 250$; $\quad A = 15$

$W_e = 100$ W $\quad \therefore D\times(1000/60)^2 = 100$; $\quad D = 9/25$

Let N be the new speed in r.p.s. at which total loss is one half of the loss at 1000 r.p.m.

New loss

$= (250 + 100)/2 = 175$ W

$\therefore$ $175 = 15\,N + (9/25)N^2$ or $9N^2 + 375\,N - 4{,}375 = 0$

$$\therefore N = \frac{-375 \pm \sqrt{375^2+36\times4{,}375}}{2\times9} = \frac{-375 \pm 546}{18} = 9.5 \text{ r.p.s} = \textbf{570 r.p.m.*}$$

* The negative value has been rejected–being mathematically absurd.

Note. It may be noted that at the new speed, $W_h = 250\times(570/1000) = 142.5$ W and $W_e = 100\times(570/1000)^2 = 32.5$ W. Total loss = 142.5 + 32.5 = 175 W.

Example 32: A d.c. shunt generator has a full load output of 10 kW at a terminal voltage of 240 V. The armature and the shunt field winding resistances are 0.6 and 160 ohms respectively. The sum of the mechanical and core-losses is 500 W. Calculate the power required, in kW, at the driving shaft at full load, and the corresponding efficiency.

Solution:

Field current =240/160

= 1.5 amp,

Load current = 10, 000/240

= 41.67 amp

Armature current = 41.67 + 1.5

= 43.17 amp

Field copper losses = 360 W,

Armature copper losses = $43.17^2 \times 0.6$

= 1118 W

Total losses in kW = 0.36 + 1,118 + 0.50

= 1,978 kW

Hence, Power input at the shaft = total losses + P_o = 1.978 + 10 = 11.978 kW

Efficiency = $\frac{10}{11.978} \times 100\%$

= 83.5%

Tutorial Problems (1)

[1] A 4-pole, d.c. generator has a wave-wound armature with 792 conductors. The flux per pole is 0.0121 Wb. Determine the speed at which it should be run to generate 240 V on no-load. **[751.3 r.p.m.]**

[2] A 20 kW compound generator works on full-load with a terminal voltage of 230 V. The armature, series and shunt field resistances are 0.1, 0.05 and 115 Ω respectively. Calculate the generated e.m.f. when the generator is connected short-shunt. **[243.25 V]**

[3] A d.c. generator generates an e.m.f. of 520 V. It has 2,000 armature conductors, flux per pole of 0.013 Wb, speed of 1200 r.p.m. and the armature winding has four parallel paths. Find the number of poles. **[4]**

[4] When driven at 1000 r.p.m. with a flux per pole of 0.02 Wb, a d.c. generator has an e.m.f. of 200 V. If the speed is increased to 1100 r.p.m. and at the same time the flux per pole is reduced to 0.019 Wb per pole, what is then the induced e.m.f. ? **[209 V]**

[5] Calculate the flux per pole required on full-load for a 50 kW, 400 V, 8-pole, 600 r.p.m. d.c. shunt generator with 256 conductors arranged in a lap-connected winding. The armature winding resistances is 0.1Ω, the shunt field resistance is 200 Ω and there is a brush contact voltage drop of 1 V at each brush on full load. **[0.162 Wb]**

[6] Calculate the flux in a 4-pole dynamo with 722 armature conductors generating 500 V when running at 1000 r.p.m. when the armature is (*a*) lap connected (*b*) wave connected. **[(*a*) 41.56 mWb (*b*) 20.78 mWb]**

[7] A 4-pole machine running at 1500 r.p.m. has an armature with 90 slots and 36 conductors per slot. The flux per pole is 10 mWb. Determine the terminal e.m.f. as d.c. Generator if the coils are lap-connected. If the current per conductor is 100 A, determine the electrical power. **[810 V, 324 kW]**

[8] An 8-pole lap-wound d.c. generator has 120 slots having 4 conductors per slot. If each conductor can carry 250 A and if flux/pole is 0.05 Wb, calculate the speed of the generator for giving 240 V on open circuit. If the voltage drops to 220 V on full load, find the rated output of the machine. **[600 r.p.m., 440 kW]**

[9] A 110-V shunt generator has a full-load current of 100 A, shunt field resistance of 55 Ω and stray losses of 500 W. If F.L. efficiency is 88%, find armature resistance. Assuming voltage to be constant at 110 V, calculate the efficiency at half F.L. And at 50% overload. Find the load current at max efficiency. **[0.078 Ω ; 85.8% ; 96.2 A]**

[10] A short-shunt compound d.c. Generator supplies a current of 100 A at a voltage of 220 V. If the resistance of the shunt field is 50 Ω, of the series field 0.025 Ω, of the armature 0.05 Ω, the total brush drop is 2 V and the iron and friction losses amount to 1 kW, find, ***(a)*** the generated e.m.f. ***(b)*** the copper losses ***(c)*** the output power of the prime-mover driving the generator and (*d*) the generator efficiency. **[(*a*) 229.7 V (*b*) 1.995 kW (*c*) 24.99 kW (*d*) 88%]**

[11] A 20 kW, 440-V, short-shunt, compound d.c. generator has a full-load efficiency of 87%. If the resistance of the armature and interpoles is 0.4 Ω and that of the series and shunt fields 0.25 Ω and 240 Ω respectively, calculate the combined bearing friction, windage and core-loss of the machine. **[725 W]**

[12] A long-shunt, compound generator delivers a load current of 50 A at 500 V and the resistances of armature, series field and shunt field are 0.05 ohm, 0.031 ohm and 250 ohm respectively. Calculate the generated electromotive force and the armature current. Allow 1.0 V per brush for contact drop. **[506.2 V ; 52 A]**

[13] In a 110-V compound generator, the resistances of the armature, shunt and the series windings are 0.06 Ω, 25 Ω and 0.04 Ω respectively. The load consists of 200 lamps each rated at 55 W, 110 V. Find the total electromotive force and armature current when the machine is connected ***(i)*** long shunt ***(ii)*** short shunt. Ignore armature reaction and brush drop. **[(*a*) 120.4, 104.4 A (*b*) 120.3 V, 104.6 A]**

[14] *Armature* of a 2-pole, 200-V generator has 400 conductors and runs at 300 r.p.m. Calculate the useful flux per pole. If the number of turns in each field coil is 1200, what is the average value of e.m.f induced in each coil on breaking the field if the flux dies away completely in 0.1 sec ?
Hint: Calculate the flux per pole generating 200 V at 300 rpm. Calculate the e.m.f. induced in 1200-turn field coil due to this flux reducing to zero in 0.1 sec, from the rate of change of flux-linkage. **[φ = 0.1 Wb, e = 1200 V]**

[15] A 1500 kW, 550-V, 16 pole generator runs at 150 rev. per min. What must be the useful flux if there are 2500 conductors lap-connected and the full-load copper losses are 25 kW? Calculate the no-load terminal voltage (generated e.m.f.). **[0.0895 Wb, 559.17 V]**

18. 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(reduce generated voltage)*..
(*ii*) *It cross-magnetises* or *distorts it (generate spark at brushes)*..

Figure (55) shows the flux distribution of a bipolar generator when there is no current in the armature conductors. It is seen that,

(a) the flux is distributed symmetrically with respect to the polar axis, which is the line joining the centers 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

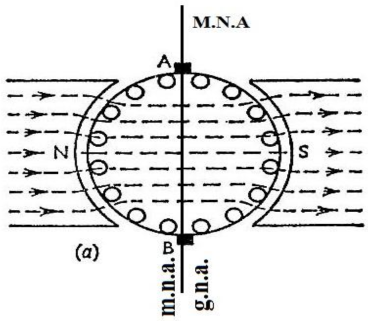


Figure (55)

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 (56) is shown the field (or flux) set up by the armature conductors *alone* when carrying current, the field coils being unexcited.
The direction of the armature current may be found by applying Fleming's Right-hand Rule. The current direction is downwards in conductors under *S*-pole and upwards in those under *N*-pole. The downward flow is represented by crosses and upward flow by dots.

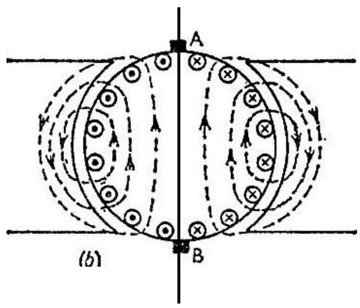


Figure (56)

Figure (57) 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.

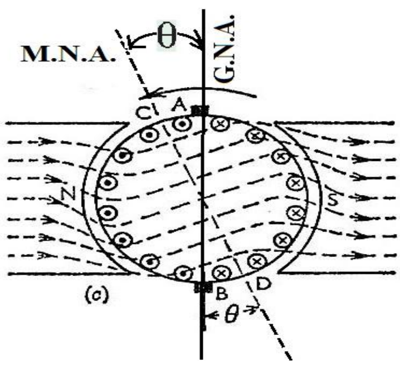
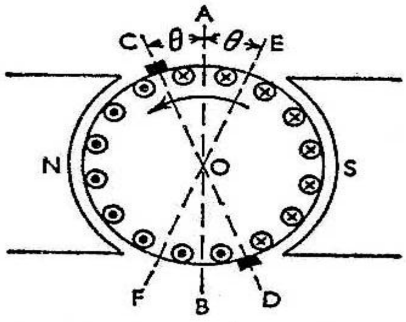


Figure (57)

19. Effect of forward brush shift (or lead)



Suppose the brushes to be shifted forward by an angle θ from axis AB to axis CD, as in Figure (58). Draw EF making the same angle θ on the other side of AB. Then with anticlockwise rotation of the armature, all the conductors on the left hand side of CD carry current outwards and all those on the other side carry current towards the paper.

Figure (58)

The armature ampere-turns can now be divided into two groups:

(a) Those due to conductors in angles COE and FOD, shown separately in Figure (59-a). These conductors are carrying current in such a direction as to try to set up a flux in opposition to that produced by the field winding, and their effect is to reduce the flux through the armature. Hence the ampere-turns due to these conductors are referred to as *demagnetizing* or *back ampere-turns.*

(b) Those due to conductors in angles COF and EOD and shown separately in Figure (59-b). The ampere-turns due to the current in these conductors are responsible for the distortion of the flux and are therefore termed the *distorting* or *cross ampere-turns.*

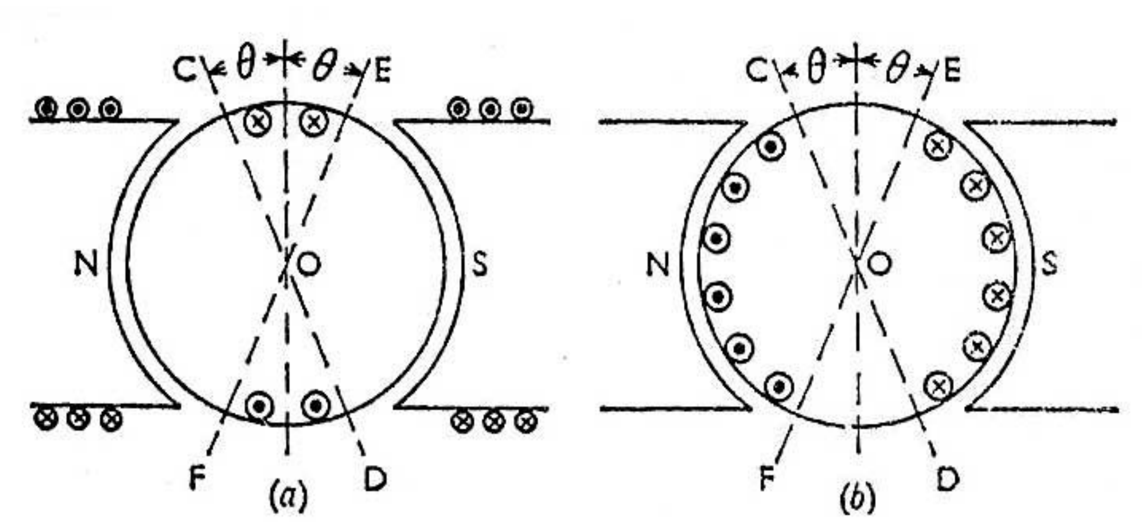


Figure (59):Demagnetizing and Cross-magnetizing Armature Ampere-Turns.

20. Demagnetising AT per Pole

Since armature demagnetizing ampere-turns are neutralized by adding extra ampere-turns to the main field winding, it is essential to calculate their number. But before proceeding further, it should be remembered that the number of turns is equal to half the number of conductors because two conductors-constitute one turn.

Let

Z = total number of armature conductors

I = current in each armature conductor

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

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

θ_m = forward lead in mechanical or geometrical or angular degrees.

Total number of armature conductors in angles *EOC* and *FOD/pair of poles* $= \frac{4\theta_m}{360} \times Z$

As two conductors constitute one turn,

$\therefore$ Total number of turns in these angles/*pair of poles* $= \frac{2\theta_m}{360} \times Z$

$\therefore$ Demagnetising amp-turns per pair of poles $= \frac{2\theta_m}{360} \times ZI$

$$\boxed{\therefore \text{ Demagnetising amp - turns/pole} = \frac{\theta_m}{360} \times ZI, \qquad \therefore AT_d \text{ per pole} = ZI \times \frac{\theta_m}{360}}$$

21. Cross-magnetising AT per pole

The conductors lying between angles *EOD* and *FOC* constitute what are known as distorting or cross-magnetizing conductors. Their number is found as under :

Total armature-*conductors*/pole both cross and demagnetizing = Z / P

Demagnetizing *conductors*/pole = $Z \times \frac{2\theta_m}{360}$ (found above)

$\therefore$ Cross-magnetizing *conductors*/pole $= \frac{Z}{P} - Z \times \frac{2\theta_m}{360} = Z\left(\frac{1}{P} - \frac{2\theta_m}{360}\right)$

$\therefore$ Cross-magnetizing *amp-conductors*/pole = $ZI\left(\frac{1}{P} - \frac{2\theta_m}{360}\right)$

Cross-magnetizing *amp-turns*/pole = $ZI\left(\frac{1}{2P} - \frac{\theta_m}{360}\right)$

(Remembering that two conductors make one turn)

$\therefore AT_c$/pole = $ZI\left(\frac{1}{2P} - \frac{\theta_m}{360}\right)$

Note. (*i*) For neutralizing the demagnetizing effect of armature-reaction, an extra number of turns may be put on each pole.

No. of extra turns/pole $= \dfrac{AT_d}{I_{sh}}$ –for shunt generator

$= \dfrac{AT_d}{I_a}$ –for series generator

If the leakage coefficient λ is given, then multiply each of the above expressions by it.

(*ii*) If lead angle is given in electrical degrees, it should be converted into mechanical degrees by the following relation.

$\theta_{(mechanical)} = \dfrac{\theta_{electrical}}{\text{Pair of Poles}}$ or $\theta_{(mechanical)} = \dfrac{\theta_{electrical}}{p/2} = \dfrac{2\theta_{electrical}}{p}$

22. 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 (60).

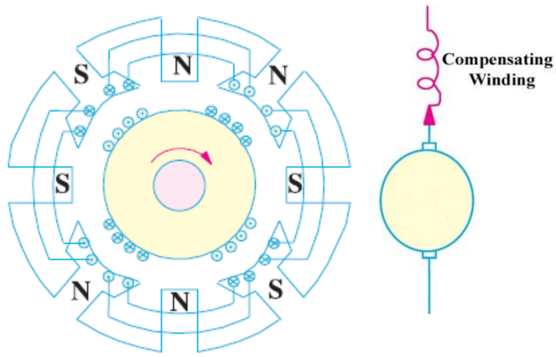


Figure (60)

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

Let

Z_c = No. of compensating conductors/pole face

Z_a = No. of active armature conductors/pole,

I_a = Total armature current

I_a/A = current/armature conductor

$\boxed{\therefore\ Z_cI_a = Z_a(I_a/A) \text{ or } Z_c = Z_a/A}$

Owing to their cost, 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.

23. No. of Compensating Windings

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

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

∴ No. of armature-turns immediately under one pole,

$$= \frac{Z}{2p} \times \frac{\text{pole arc}}{\text{pole pitch}} = 0.7 \times \frac{Z}{2p} \text{ (approx)}$$

∴ No. of armature amp-*turns/*pole for compensating winding,

$$= 0.7 \times \frac{Z}{2p} = 0.7 \times \text{armature amp-turns/pole}$$

Example 33: A 4-pole generator has a wave-wound armature with 722 conductors, and it delivers 100 A on full load. If the brush lead is 8°, calculate the armature demagnetizing and cross-magnetizing ampere turns per pole.

Solution:

$I = I_a/2 = 100/2 = 50\text{A};\ Z = 722;\ \theta_m = 8°$

$$AT_d/\text{pole} = ZI \times \frac{\theta_m}{360} = 722 \times 50 \times \frac{8}{360} = 802$$

$$AT_c/\text{pole} = ZI\left(\frac{1}{2P} - \frac{\theta_m}{360}\right) = 722 \times 50 \times \left(\frac{1}{2\times4} - \frac{8}{360}\right) = 37/8$$

Example 34: An 8-pole generator has an output of 200 A at 500 V, the lap-connected armature has 1280 conductors, 160 commutator segments. If the brushes are advanced 4-segments from the no-load neutral axis, estimate the armature demagnetizing and cross-magnetizing ampere-turns per pole.

Solution:

$I = 200/8 = 25\text{ A},\ Z = 1280,\ \theta_m = 4 \times 360/160 = 9°\ ;\ P = 8$

$$AT_d/\text{pole} = ZI \times \frac{\theta_m}{360} = 1280 \times 25 \times (9/360) = \mathbf{800}$$

$$AT_c/\text{pole} = ZI\left(\frac{1}{2P} - \frac{\theta_m}{360}\right) = 1280 \times 25 \times \left(\frac{1}{2\times8} - \frac{9}{360}\right) = \mathbf{1200}$$

Example 35: A 4-pole wave-wound motor armature has 880 conductors and delivers 120 A. The brushes have been displaced through 3 angular degrees from the geometrical axis. Calculate **(a)** demagnetizing amp-turns/pole **(b)** cross- magnetizing amp-turns/pole **(c)** the additional field current for neutralizing the demagnetization of the field winding has 1100 turns/pole.

Solution:

$Z = 880;\ I = 120/2 = 60\text{ A}\ ;\ \theta = 3°$ angular (*a*) $\therefore$ $AT_d = 880 \times 60 \times \frac{3}{360}$ = **440 AT**

(*b*) $\therefore$ $AT_c = 880 \times 60 \times \left(\frac{1}{8} - \frac{3}{360}\right)$ = **6,160**

or Total AT/pole = 440 × (60/4) = 6600

Hence,

AT_C/pole = Total AT/pole − AT_d / pole = 6600 − 440 = 6160

(*c*) Additional field current = 440/1100 = **0.4 A.**

Example 36: A 4-pole lap-wound Generator having 480 armature conductors supplies a current of 150 Amps. If the brushes are given an actual lead of 10°, calculate the demagnetizing and cross-magnetizing amp-turns per pole.

Solution:

10° mechanical (or actual) shift = 20° electrical shift for a 4-pole machine.

Armature current = 150 amp

For 4-pole lap-wound armature, number of parallel paths = 4.

Hence, conductor-current = 150/4 = 37.5 amps.

Total armature amp-turns/pole = $\frac{1}{2} \times \frac{(480 \times 37.5)}{4} = 2250$

Cross − magnetizing amp turns/pole = $2250 \times \left(1 - \frac{2 \times 20}{180}\right) = 1750$

Demagnetizing amp turns/pole = 2250 × (2 × 20°/180°) = 500

Example 37: A 4-pole generator supplies a current of 143 A. It has 492 armature conductors **(a)** wave-wound **(b)** lap-wound. When delivering full load, the brushes are given an actual lead of 10°. Calculate the demagnetizing amp-turns/pole. This field winding is shunt connected and takes 10 A. Find the number of extra shunt field turns necessary to neutralize this demagnetization.

Solution:

$Z = 492$; $\theta_m = 10°$; AT_d / pole = $ZI \times \frac{\theta_m}{360}$

$I_a = 143 + 10 = 153$ A ; I = 153/2 ... when wave-wound

= 153/4 ... when lap-wound

(*a*) $\therefore$ AT_d / pole = $492 \times \frac{153}{2} \times \frac{10}{360}$ = **1046 AT**

Extra shunt field turns = 1046/10 = **105 (approx.)**

(*b*) AT_d / pole = $492 \times \frac{153}{4} \times \frac{10}{360}$ = **523**

Extra shunt field turns = 523/10 = **52 (approx.)**

Example 38: A 4-pole, 50-kW, 250-V wave-wound shunt generator has 400 armature conductors. Brushes are given a lead of 4 commutator segments. Calculate the demagnetization amp-turns/pole if shunt field resistance is 50 Ω. Also, calculate extra shunt field turns/pole to neutralize the demagnetization.

Solution:

Load current supplied = 50,000/250 = 200 A

$I_{sh} = 250/50 = 5$ A ∴ $I_a = 200 + 5 = 205$ A

Current in each conductor I = 205/2 A

No. of commutator segments = Z/A   where A = 2 ... for wave-winding

∴ No. of segments = 400/2 = 200 ; θ = (4/200) × 360 = (36/5) degrees

∴ AT_d / pole $= 400 \times \frac{205}{2} \times \frac{36}{5 \times 360}$ = **820 AT**, Extra shunt turns/poles $= \frac{AT_d}{I_{sh}}$ = **164**

Example 39: Determine per pole the number **(i)** of cross-magnetizing ampere-turns **(ii)** of back ampere-turns and **(iii)** of series turns to balance the back ampere-turns in the case of a d.c. generator having the following data. 500 conductors, total current 200 A, 6 poles, 2-circuit wave winding, angle of lead = 10°, leakage coefficient = 1.3

Solution:

Current/path, I = 200/2 = 100 A, θ = 10° (mech), Z = 500

(a) AT_c / pole $= ZI\left(\frac{1}{2P} - \frac{\theta_m}{360}\right) = 500 \times 100\left(\frac{1}{2\times 6} - \frac{10}{360}\right)$ = **2,778**

(b) AT_d / pole = 500 × 100 × (10/360) = **1390**

(c) Series turns required to balance the AT_d are $= \lambda \times \frac{AT_d}{I_a}$ = 1.3 × (1390/200) = **9**

Example 40: A 22.38 kW, 440-V, 4-pole wave-wound d.c. shunt motor has 840 armature conductors and 140 commutator segments. Its full-load efficiency is 88% and the shunt field current is 1.8 A. If brushes are shifted backward through 1.5 segments from the geometrical neutral axis, find the demagnetizing and distorting amp-turns/pole.

Solution:

The shunt motor is shown diagrammatically in Figure (61).

Motor output = 22,380 W ; η = 0.88

∴ Motor input = 22,380/0.88 W

Motor input current (I) $= \frac{22,380}{0.88 \times 440}$ = 57.8 A

$I_{sh} = 1.8\ A$; $I_a = I - I_{sh}$ = 57.8 − 1.8 = 56 A

Current in each conductor = 56/2 = 28 A

θ = 1.5 × (360/140) = 27/7 degrees

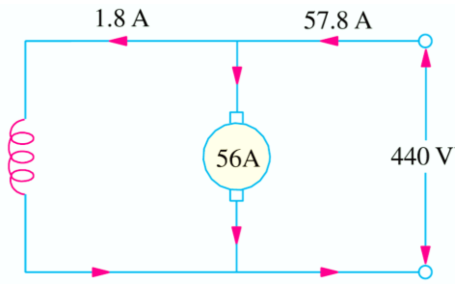


Figure (61)

∴ AT_d / pole $= 840 \times 28 \times \frac{27}{7 \times 360}$ = **252**

AT_c / pole $= ZI\left(\frac{1}{2P} - \frac{\theta_m}{360}\right) = 840 \times 28 \times \left(\frac{1}{8} - \frac{27}{7 \times 360}\right)$ = **2,688**

Example 41: A 400-V, 1000-A, lap-wound d.c. machine has 10 poles and 860 armature conductors. Calculate the number of conductors in the pole face to give full compensation if the pole face covers 70 % of pole span.

Solution:

$$\text{AT/pole for compensating winding} = \text{armature amp-turn/pole} \times \frac{\text{pole arc}}{\text{pole pitch}}$$

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

Here I = current in each armature conductor = 1,000/10 = 100 A

$Z = 860$; $P = 10$

∴ AT/pole for compensating winding = 0.7 × 860 × (100/(2 × 10)) = **3,010**

24. Commutation

The currents induced in armature conductors of a d.c. generator are alternating. To make their flow unidirectional in the external circuit, we need a commutator. Moreover, these currents flow in one direction when armature conductors are under *N*-pole and in the opposite direction when they are under *S*-pole. As conductors pass out of the influence of a *N*-pole and enter that of *S*-pole, the current in them is reversed. This reversal of current takes place along magnetic neutral axis or brush axis *i.e.* when the brush spans and hence short circuits that particular coil undergoing reversal of current through it. This process by which current in the short-circuited coil is reversed while it crosses the *M.N.A.* is called commutation. The brief period during which coil remains short-circuited is known as commutation period T_c.

If the current reversal i.e. the change from + I to zero and then to − I is completed by the end of short circuit or commutation period, then the commutation is ideal. If current reversal is not complete by that time, then sparking is produced between the brush and the commutator which results in progressive damage to both.

The main cause which retards or delays this quick reversal is the production of self-induced e.m.f. in the coil undergoing commutation. This self-induced e.m.f. is known as ***reactance voltage.*** This voltage, even though of a small magnitude, produces a large current through the coil whose resistance is very low due to short circuit which causes severe sparking at the brushes.

25. Methods of Improving Commutation

There are two practical ways of improving commutation *i.e.* of making current reversal in the short-circuited coil as sparkles as possible. These methods are known as,

(i) resistance commutation (consists of replacing low-resistance Cu brushes by comparatively high-resistance carbon brushes).

(ii) e.m.f. commutation (In this method, arrangement is made to neutralize the reactance voltage by producing a reversing e.m.f.(e.m.f. in opposition to the reactance voltage and if its value is made equal to the latter in the short-circuited coil under commutation, it will completely wipe it off), thereby producing quick reversal of current in the short-circuited coil which will result in sparkles commutation. The reversing e.m.f. may be produced in two ways which is done with the help of either brush lead or interpole, usually the later).

26. Interpoles or Commutating poles or Compoles

These are small poles fixed to the yoke and spaced in between the main poles. They are wound with comparatively few heavy gauge Cu wire turns and are connected in series with the armature so that they carry full armature current. Their polarity, in the case of a generator, is the same as that of the main pole ***ahead*** in the direction of rotation (Figure (62)).

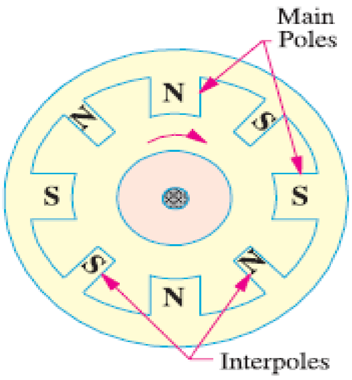


Figure (62)

The function of interpoles is:

(*i*) Improve the commutation. As their polarity is the same as that of the main pole ahead, they induce an e.m.f. in the coil (under commutation) which helps the reversal of current (neutralizes the reactance e.m.f. thereby making commutation sparkles).

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

Tutorial Problems (2)

[1] Calculate the demagnetizing amp-turns of a 4-pole, lap-wound generator with 720 conductors, giving 50 A, if the brush lead is 10º (mechanical). **[250 AT/pole]**

[2] A 250-V, 25-kW, 4-pole d.c. generator has 328 wave-connected armature conductors. When the machine is delivering full load, the brushes are given a lead of 7.2 electrical degrees. Calculate the cross-magnetizing amp-turns/pole & demagnetizing amp.turn/pole. **[1886, 164]**

[3] An 8-pole lap-connected d.c. shunt generator delivers an output of 240 A at 500 V. The armature has 1408 conductors and 160 commutator segments. If the brushes are given a lead of 4 segments from the no load neutral axis, estimate the demagnetizing and cross-magnetizing AT/pole. **[1056, 1584]**

[4] A 500-V, wave-wound, 750 r.p.m. shunt generator supplies a load of 195 A. The armature has 720 conductors and shunt field resistance is 100 Ω, P=4.
Find the demagnetizing amp-turns/pole & crossmagnetizing amp-turns/pole if brushes are advanced through 3 commutator segments at this load. Also, calculate the extra shunt field turns required to neutralize this demagnetization. **[600, 8400, 120]**

[5] A 4-pole, wave-wound generator has 320 armature conductors and carries an armature current of 400 A. If the pole arc/pole pitch ratio is 0.68, calculate the AT/pole for a compensating winding to give uniform flux density in the air gap. **[5440]**

[6] A 500-kW, 500-V, 10 pole d.c. generator has a lap-wound armature with 800 conductors. Calculate the number of pole-face conductors in each pole of a compensating winding if the pole face covers 75 percent of the pitch. **[60 conductors/pole]**