UNIVERSITY OF TECHNOLOGY

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING

Year: second 2010-2011

ELECTRICAL MACHINES I

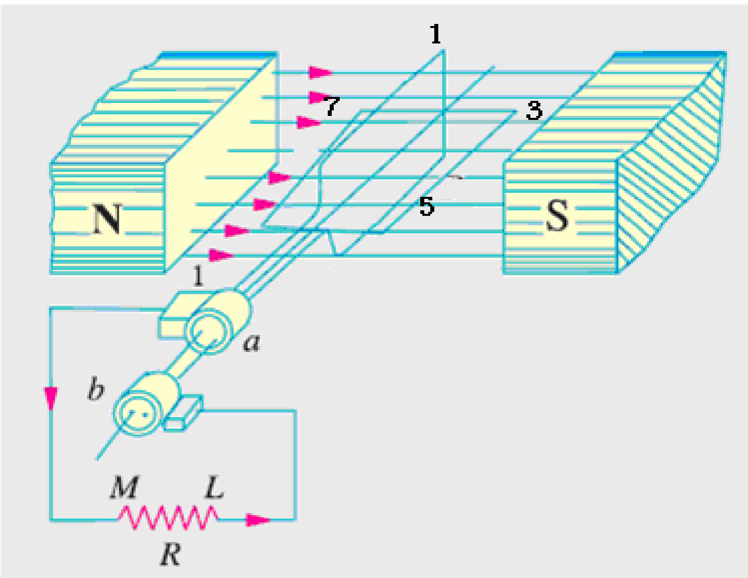
- *DC machines*
  - *General*
  - *Generators*
  - *Motors*

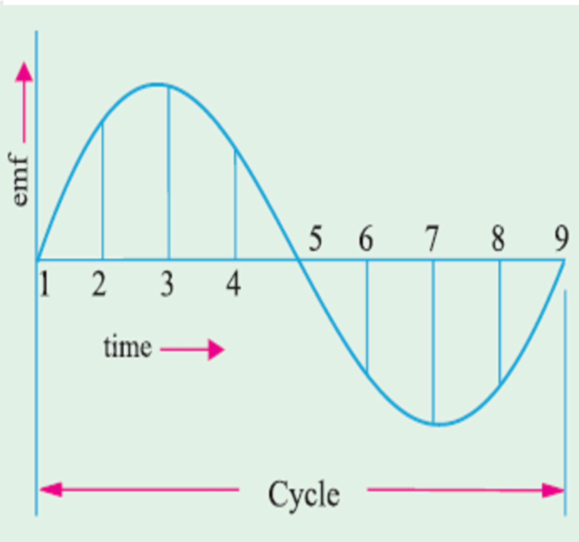
Recommended textbooks

- *M.G. Say & E.O. Taylor, "Direct Current Machines", Pitman Pub.*
- *Hughes," Electrical Technology", Prentice Hall*
- *B.L. Theraja, "A Textbook of Electrical Technology", Chand & Company LTD .*

DC GENERATORS

Generator Principle: An electrical generator is a machine which converts mechanical energy into electrical energy. The energy conversion is based on the principle of the production of dynamically induced emf, where a conductor cuts magnetic flux, dynamically induced emf is produced in it according to Faraday's Laws of electromagnetic Induction. This emf 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 and (*ii*) a conductor or conductors which can so move as to cut the flux. The following figure shows a single-turn rectangular copper coil rotating about its own axis in a magnetic field provided by either permanent magnets or electromagnets. The two ends of the coil are joined to two slip-rings '*a*' and '*b*' 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'.



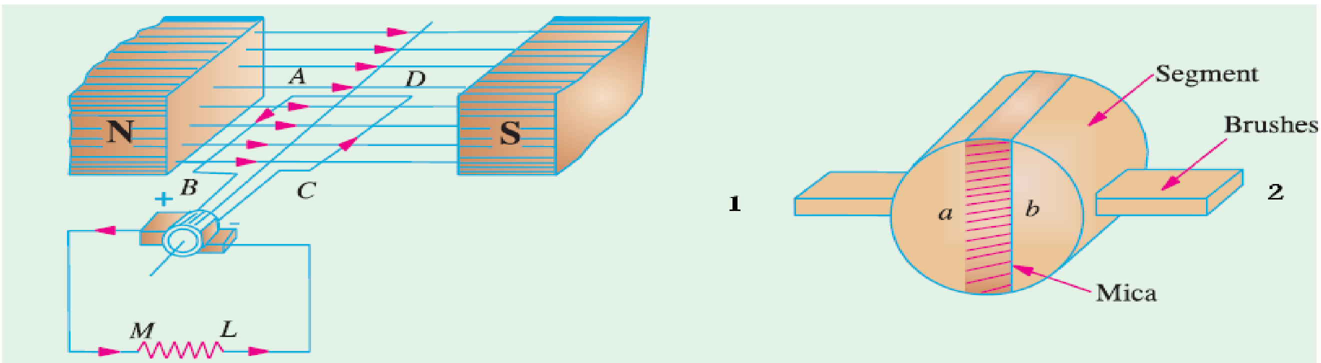


As the coil rotates in clock-wise direction and assumes successive positions in the field the, flux linked with it changes. Hence, an emf is induced in it which is proportional to the rate of change of flux linkages ($e = Nd\phi/dt$).

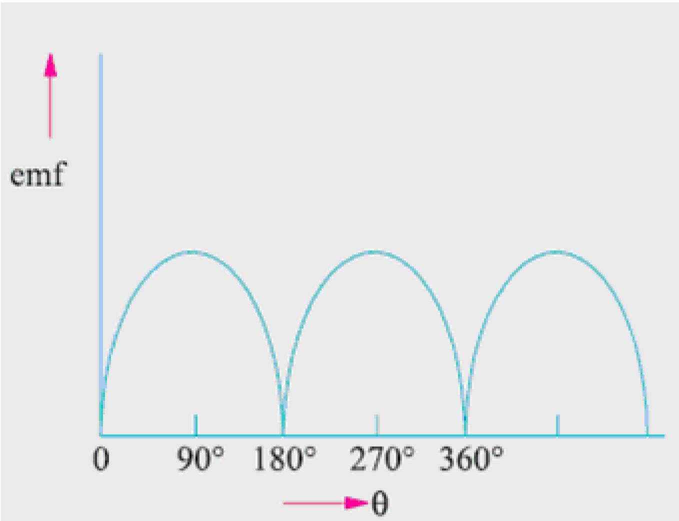
❖ When the plane of the coil is at right angles to lines of flux i.e. when it is in position 1, then flux linked with the coil is maximum, but rate of change of flux linkages is minimum. Hence, there is no induced emf in the coil.

- ❖ As the coil continues rotating further, the rate of change of flux linkages (and hence induced emf in it) increases, till position 3 is reached where θ = 90º, the coil plane is horizontal i.e. parallel to the lines of flux. The flux linked with the coil is minimum but rate of change of flux linkages is maximum. Hence, maximum emf is induced in the coil at this position.
- ❖ From 90º to 180º, the flux linked with the coil gradually increases but the rate of change of flux linkages decreases. Hence, the induced emf decreases gradually till in position 5 of the coil, it is reduced to zero value.
- ❖ From 180º to 360º, the variations in the magnitude of emf are similar to those in the first half revolution. Its value is maximum when coil is in position 7 and minimum when in position 1. But it will be found that the direction of the induced current is the reverse of the previous direction of flow.

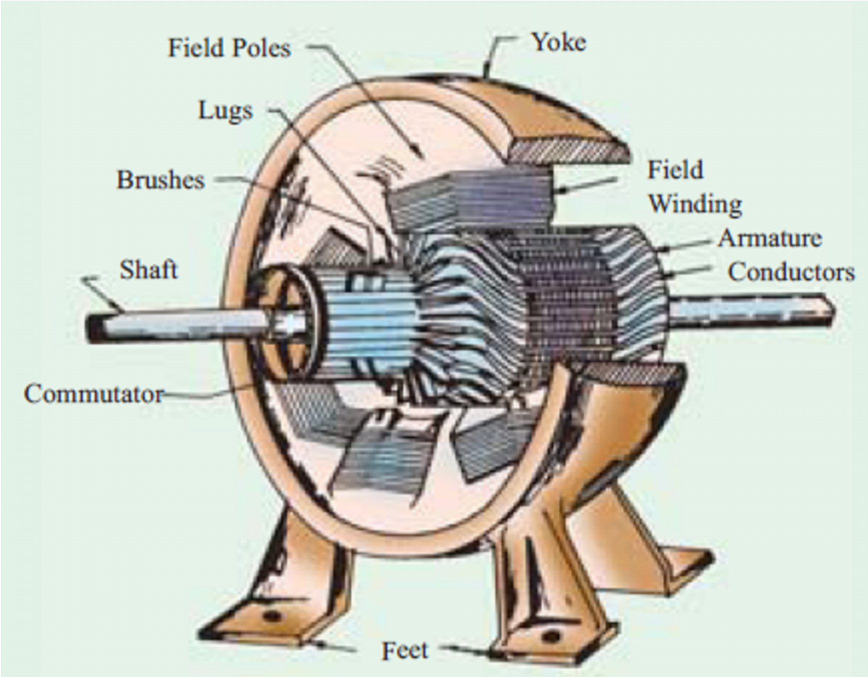
For making the flow of current unidirectional in the external circuit, the slip-rings are replaced by split-rings. The split-rings are made out of a conducting cylinder which is cut into two halves or segments insulated from each other by a thin sheet of mica or some other insulating material. As before, the coil ends are joined to these segments on which rest the carbon or copper brushes. It is seen that in the first half revolution current flows along (ABMLCD) i.e. the brush No.1 in contact with segment 'a' acts as the positive end of the supply and 'b' as the negative end. In the next half revolution, the direction of the induced current in the coil has reversed. But at the same time, the positions of segments 'a' and 'b' have also reversed with the result that brush No.1 comes in touch with the segment which is positive i.e. segment 'b' in this case. Hence, current in the load resistance again flows from M to L. The waveform of the current through the external circuit is as shown in below. This current is unidirectional but not continuous like pure direct current.



- The position of brushes is so arranged that the change over of segments ‘a’ and ‘b’ from one brush to the other takes place when the plane of the rotating coil is at right angles to the plane of the lines of flux. It is so because in that position, the induced emf in the coil is zero.
- The current induced in the coil sides is alternating as before. It is only due to the rectifying action of the split-rings (also called commutator) that it becomes unidirectional in the external circuit.

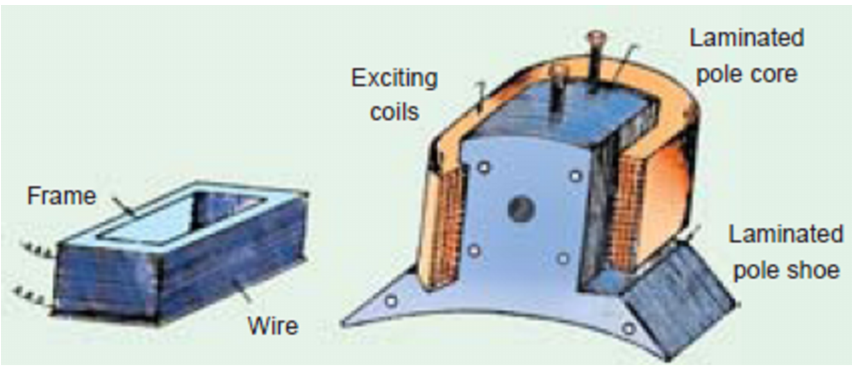


Practical Generator: The actual generator which consists of the following essential parts: 1.Magnetic Frame or Yoke 2.Pole-Cores and Pole-Shoes 3.Pole Coils or Field Coils 4.Armature Core 5.Armature Windings or Conductors 6.Commutator 7.Brushes 8.Bearings.



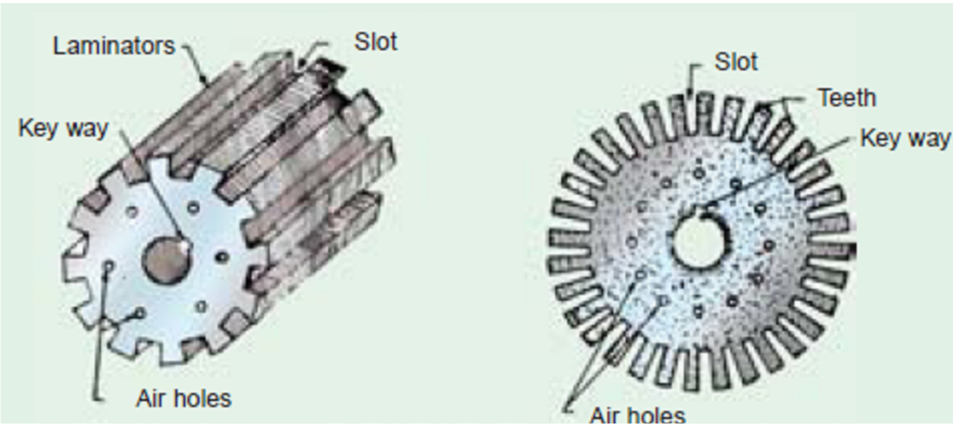
Yoke: The outer frame or yoke serves double purpose: (i) It provides mechanical support for the poles and acts as a protecting cover for the whole machine. (ii) It carries the magnetic flux produced by the poles. In small generators where cheapness rather than weight is the main consideration, yokes are made of cast iron. But for large machines usually cast steel or rolled steel is employed.

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) as shown below.



Pole Coils: The field coils or pole coils, which consist of copper wire or strip, are former-wound for the correct dimension. Then, the former is removed and wound coil is put into place over the core. When current is passed through these coils, they electromagnetise the poles which produce the necessary flux that is cut by revolving armature conductors.

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 slots are either die-cut or punched on the outer periphery of the disc and the keyway is located on the inner diameter as shown. In small machines, the armature stampings are keyed directly to the shaft. Usually, these laminations are perforated for air ducts which permit axial flow of air through the armature for cooling purposes.

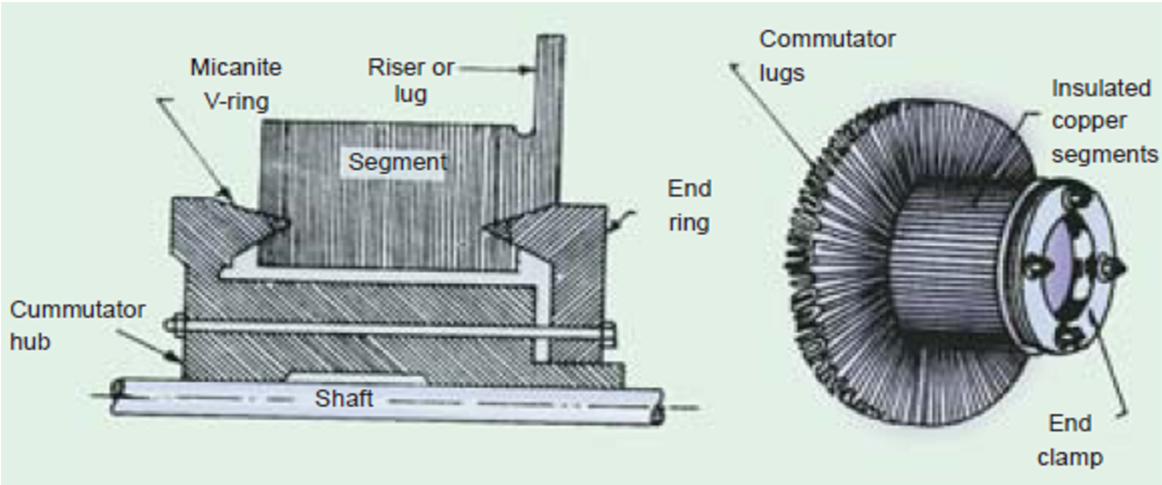


The purpose of using laminations is to reduce the loss due to eddy currents. Thinner the laminations, greater is the resistance offered to the induced emf, smaller the current and hence lesser the $I^2 R$ loss in the core.

Armature Windings: The armature windings are usually former-wound. These are first wound in the form of flat rectangular coils and are then pulled into their proper shape in a coil puller. Various conductors of the coils are insulated from each other. The conductors are placed in the armature slots which are lined with tough insulating material. This slot insulation is folded over above the armature conductors placed in the slot and is secured in place by special hard wooden or fiber wedges.

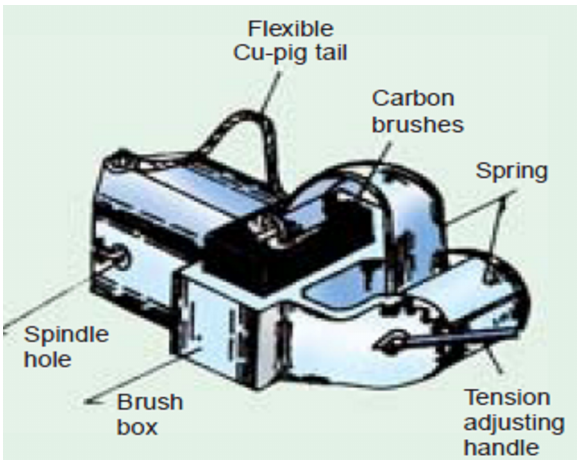
Commutator: The functions of the commutator are to facilitate collection of current from the armature conductors, and to convert the alternating current induced in the armature conductors into unidirectional current in the external load circuit. It is of cylindrical structure and is built up of wedge-shaped segments of high-conductivity hard-drawn or drop forged 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 riser. To prevent them from flying out under the action of centrifugal forces, the segments have V-grooves, these grooves being insulated by conical micanite rings.



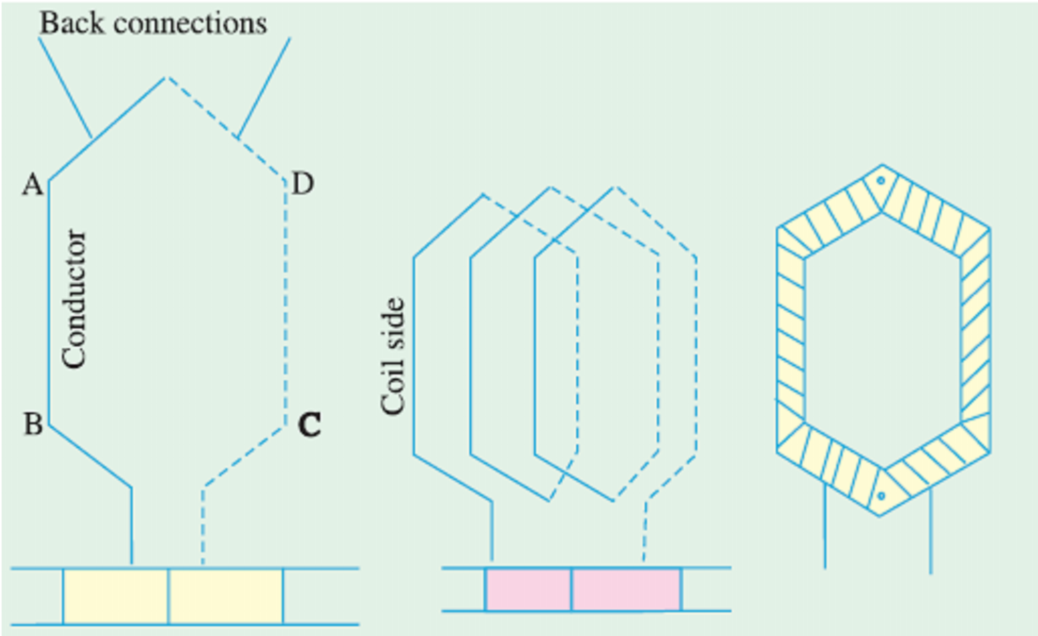
Brushes and Bearings: The brushes, whose function is to collect current from commutator, are usually made of carbon or graphite and are in the shape of a rectangular block. These brushes are housed in brush-holders, the brush-holder is mounted on a spindle and the brushes can slide in the rectangular box open at both ends. The brushes are made to bear down on the commutator by a spring. A flexible copper pigtail mounted at the top of the brush conveys current from the brushes to the holder. The number of brushes per spindle depends on the magnitude of the current to be collected from the commutator.

Because of their reliability, ball-bearings are frequently employed, though for heavy duties, roller bearings are preferable. The ball and rollers are generally packed in hard oil for quieter operation and for reduced bearing wear, sleeve bearings are used which are lubricated by ring oilers fed from oil reservoir in the bearing bracket.



***Armature Windings*:** the following terms is used in connection with armature winding:

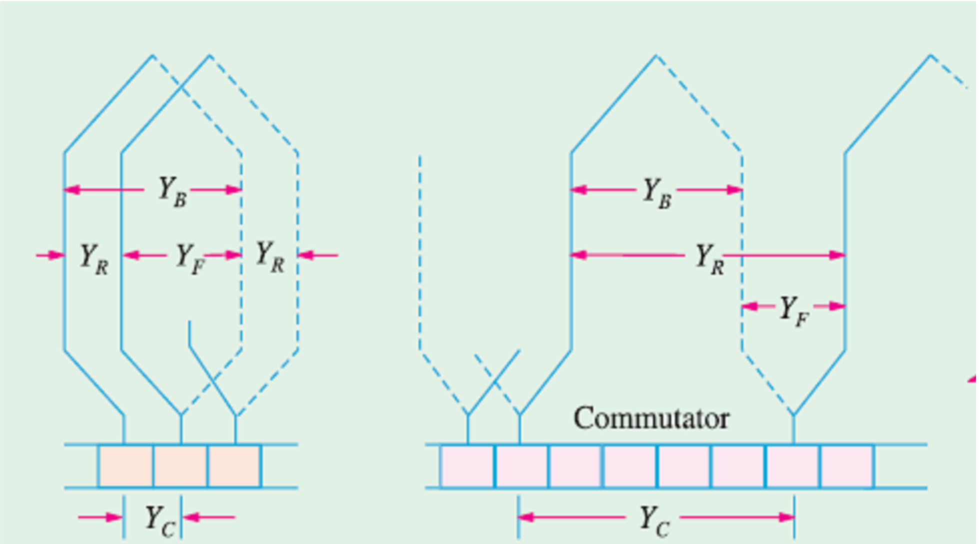
- Pole-pitch: the distance between two adjacent poles. It is equal to the number of armature conductors (or armature slots) per pole. If there are 48 conductors and 4 poles, the pole pitch is 48/4 = 12.
- Conductor: The length of a wire lying in the magnetic field and in which an emf is induced, is called a conductor (or inductor) as, for example, length AB or CD in the following figure.



- Coil and Winding Element: the two conductors AB and CD along with their end connections constitute one coil of the armature winding. The coil may be single turn coil or multi-turn coil. Multi-turn coil may have many conductors per coil side. The group of wires or conductors constituting a coil side of a multi-turn coil is wrapped with a tape as a unit and is placed in the armature slot. Since the beginning and the end of each coil must be connected to a commutator bar, there are as many commutator bars as coils for both the lap and wave windings. The side of a coil (1-turn or multi-turn) is called a winding element. The number of winding elements is twice the number of coils.
- Coil-span or Coil-pitch (YS): It is the distance, measured in terms of armature slots (or armature conductors) between two sides of a coil. If the pole span or coil pitch is equal to the pole pitch. Then winding is called full-pitched. It means that coil span is 180 electrical degrees. In this case, the coil sides lie under opposite poles, hence the induced emfs in them are additive. Therefore, maximum emf is

induced in the coil as a whole, it being the sum of the emfs induced in the two coil sides. If the coil span is less than the pole pitch, then the winding is fractional-pitched. In this case, there is a phase difference between the emfs. In the two sides of the coil. Hence, the total emf round the coil which is the vector sum of emfs in the two coil sides is less in this case as compared to that in the first case.

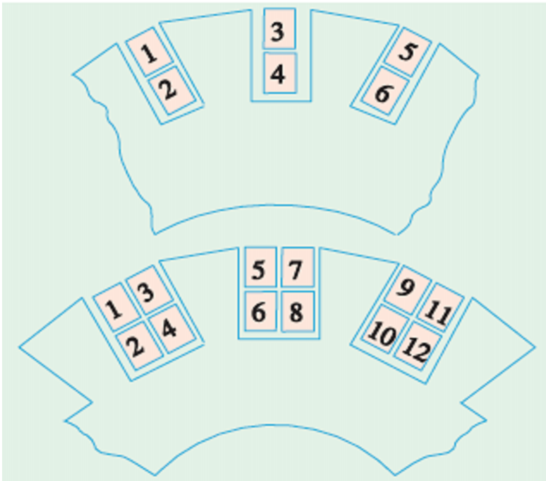
- Back Pitch (YB): The distance, measured in terms of the armature conductors, which a coil advances on the back of the armature is called back pitch.
- Front Pitch (YF): The number of armature conductors or elements spanned by a coil on the front (or commutator end of an armature) is called the front pitch.



- Resultant Pitch (YR): It is the distance between the beginning of one coil and the beginning of the next coil to which it is connected.
- Commutator Pitch (Yc): It is the distance (measured in commutator bars or segments) between the segments to which the two ends of a coil are connected.
- Single-layer Winding: It is that winding in which one conductor or one coil side is placed in each armature slot. Such a winding is not much used.
- Two-layer Winding: In this type of winding, there are two conductors or coil sides per slot arranged in two layers. Usually, one side of every coil lies in the upper half of one slot and other side lies in the lower half of some other slot. Such windings in which two coil sides occupy each slot are most commonly used

for all medium-sized machines. 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.

- Multiplex Winding: In such windings, there are several sets of completely closed and independent windings. If there is only one set of closed winding, it is called simplex wave winding. If there are two such windings on the same armature, it is called duplex winding and so on. The multiplicity affects a number of parallel paths in the armature. For a given number of armature slots and coils, as the multiplicity increases, the number of parallel paths in the armature increases thereby increasing the current rating but decreasing the voltage rating.



Lap and Wave Windings: Two types of windings mostly employed are known as Lap Winding and Wave Winding.

1. Simplex Lap-winding: In lap winding, the finishing end of one coil is connected to a commutator segment and to the starting end of the adjacent coil situated under the same pole and so on, till all the coils have been connected. This type of winding derives its name from the fact it doubles or laps back with its succeeding coils. Following points regarding simplex lap winding should be carefully noted :

   a) The back and front pitches are odd and of opposite sign. But they cannot be equal. They differ by 2 or.

   b) Resultant pitch YR is even, YR =YB – YF=2.

   c) The number of slots for a 2-layer winding is equal to the number of coils. The number of commutator segments is also the same.

   d) The number of parallel paths in the armature (A)=P where P the number of poles.

e) If YB > YF i.e. YB = YF + 2, then we get a progressive or right-handed winding i.e. a winding which progresses in the clockwise direction as seen from the commutator end. In this case, YC = + 1.

f) If YB < YF i.e. YB = YF -2, then we get a retrogressive or left-handed winding i.e. one which advances in the anti-clockwise direction when seen from the commutator side. In this case, YC = -1.

g) $\left.\begin{aligned} Y_f &= \frac{Z}{p} - 1 \\ Y_B &= \frac{Z}{P} + 1 \end{aligned}\right\}$ for progressive winding, $\left.\begin{aligned} Y_f &= \frac{Z}{p} + 1 \\ Y_B &= \frac{Z}{P} - 1 \end{aligned}\right\}$ for retrogressive winding

Z/P must be even to make the winding possible.

h) The total number of brushes is equal to the number of poles.

i) The number of armature conductors (connected in series) in any parallel path is Z/P.

j) Generated emf $E_g = e.m.f$ per one conductor$\times \frac{Z}{P} = e_{av} \times \frac{Z}{P}$

k) The equivalent armature resistance can be found as follows: Let l = length of each armature conductor; S = cross-section area of the conductor, A = no. of parallel paths in armature=P, R = resistance of one conductor then $R = \frac{\rho l}{S}$,

Resistance of each path (R_{path}) $= \frac{\rho l Z}{SA}$ There are *A* paths in parallel, hence the total resistance of the armature (R_a) $= \frac{1}{A} \times \frac{\rho l Z}{SA} = \frac{\rho l Z}{SA^2}$

l) If *Ia* is the total armature current, then current per parallel path (or carried by each conductor) is *Ia*/*P*.

Example: Draw a developed diagram of a simple 2-layer lap-winding for a 4-pole generator with 16 coils.

Solution: The number of commutator segments = 16

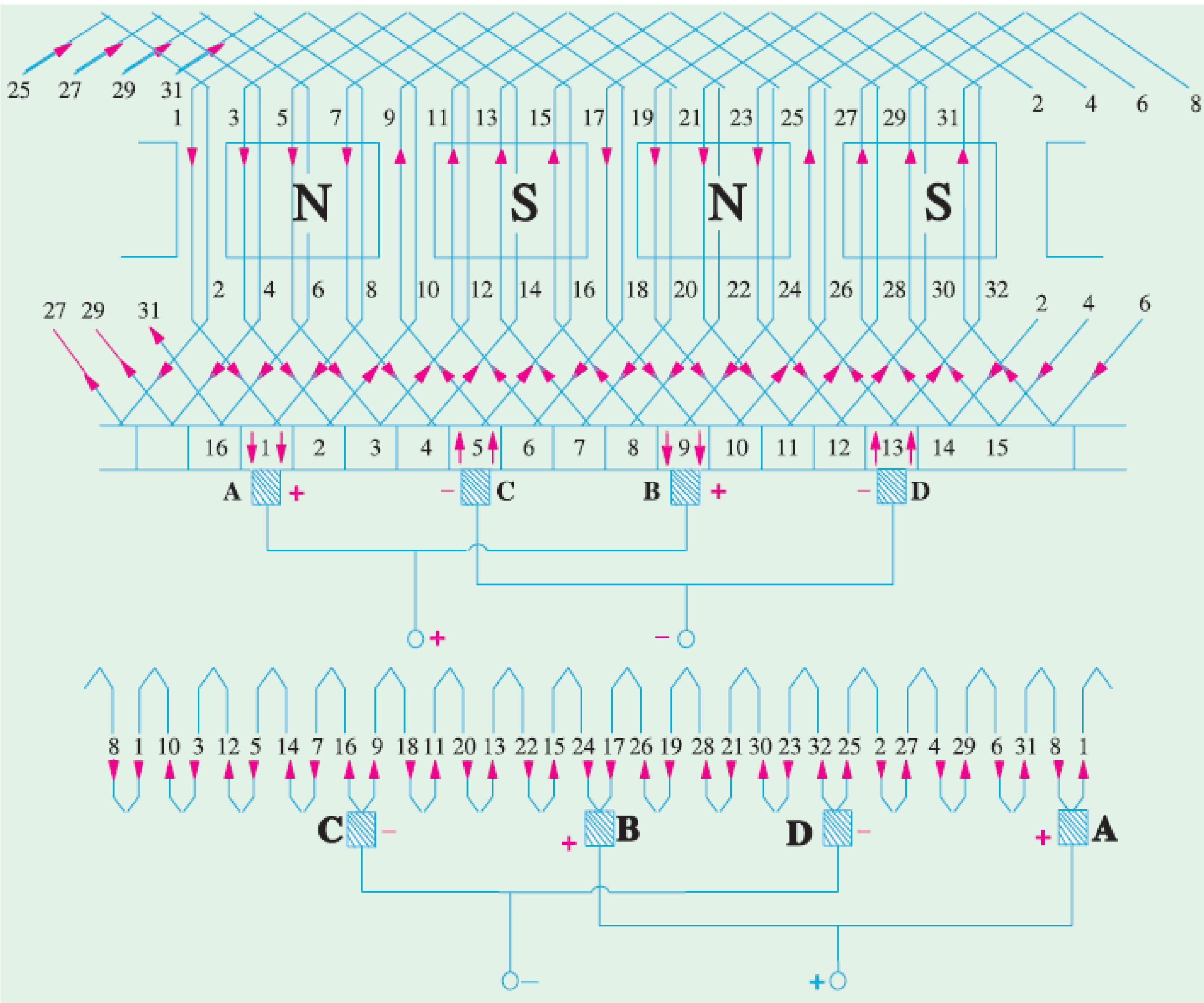
Number of conductors or coil sides 16 × 2 = 32

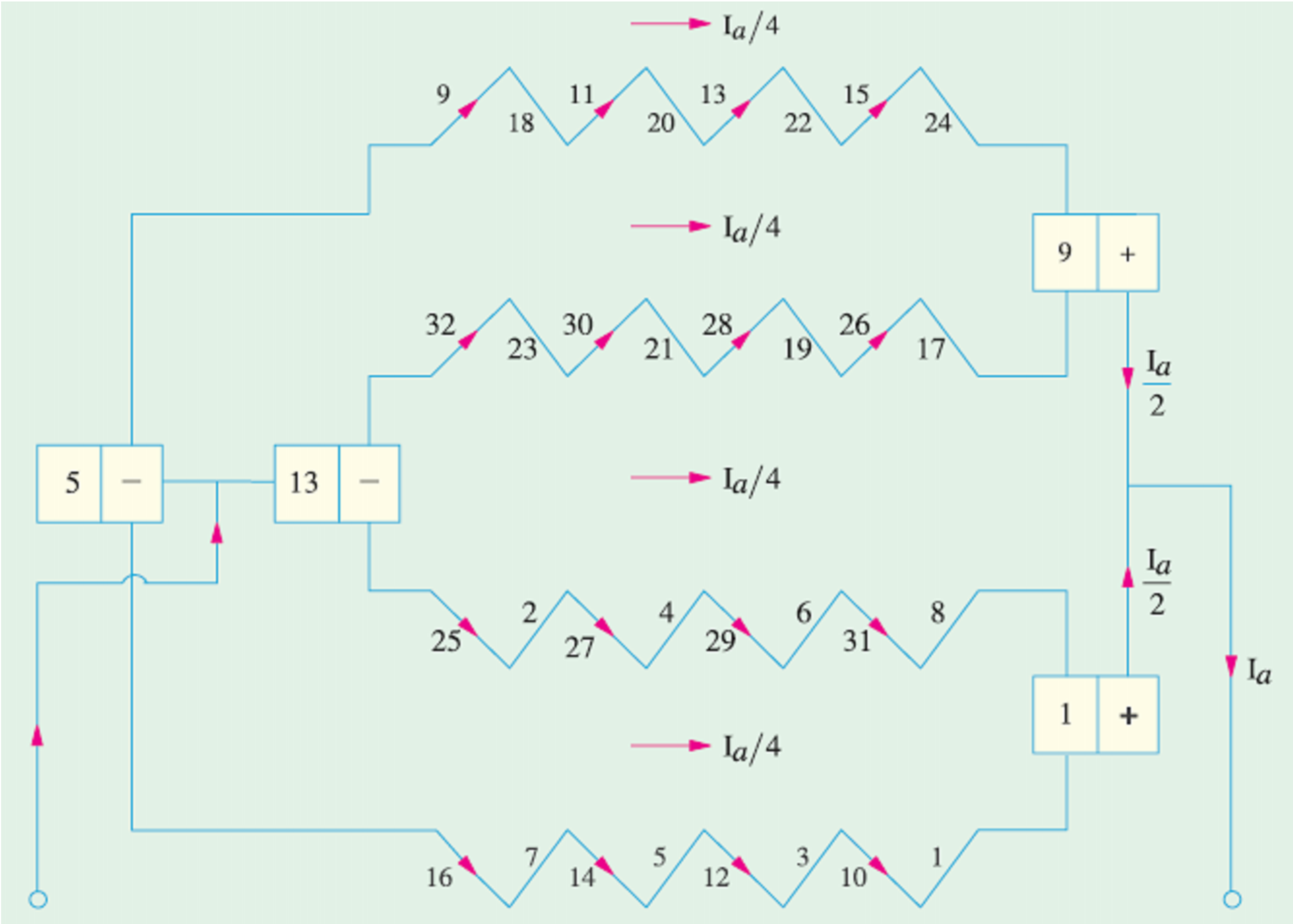
Pole pitch = 32/4 = 8

$Y_F = \frac{Z}{P} - 1 = \frac{32}{4} - 1 = 7$ and $Y_B = \frac{Z}{P} + 1 = \frac{32}{4} + 1 = 9$

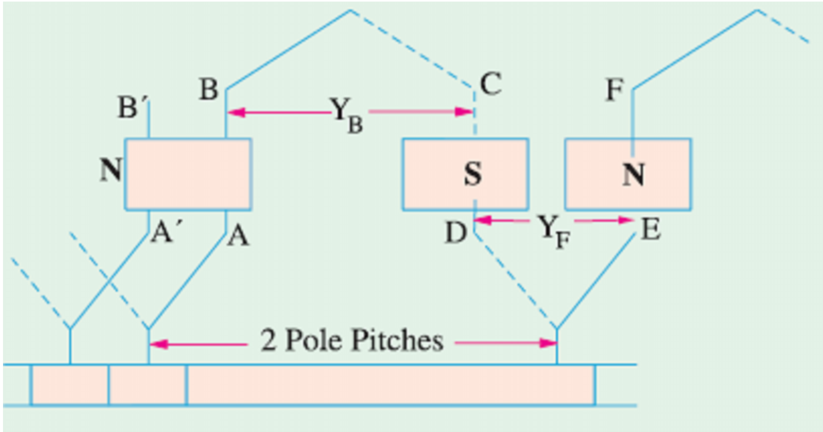
The simple winding table is given as under:

Back Connections	Front Connections
1 to (1 + 9) = 10 ----------------------------	10 to (10 - 7) = 3
3 to (3 + 9) = 12 ----------------------------	12 to (12 - 7) = 5
5 to (5 + 9) = 14 ----------------------------	14 to (14 - 7) = 7
7 to (7 + 9) = 16 ----------------------------	16 to (16 - 7) = 9
9 to (9 + 9) = 18 ----------------------------	18 to (18 - 7) = 11
11 to (11 + 9) = 20 -------------------------	20 to (20 - 7) = 13
13 to (13 + 9) = 22 -------------------------	22 to (22 - 7) = 15
15 to (15 + 9) = 24 -------------------------	24 to (24 - 7) = 17
17 to (17 + 9) = 26 -------------------------	26 to (26 - 7) = 19
19 to (19 + 9) = 28 -------------------------	28 to (28 - 7) = 21
21 to (21 + 9) = 30 -------------------------	30 to (20 - 7) = 23
23 to (23 + 9) = 32 -------------------------	32 to (32 - 7) = 25
25 to (25 + 9) = 34 = (34 - 32) = 2 -----	2 to (34 - 7) = 27
27 to (27 + 9) = 36 = (36 - 32) = 4 -----	4 to (36 - 7) = 29
29 to (29 + 9) = 38 = (38 - 32) = 6 -----	6 to (38 - 7) = 31
31 to (31 + 9) = 40 = (40 - 32) = 8 -----	8 to (40 - 7) = 33 = (33 - 32) = 1





Simplex Wave Winding: conductor AB is connected to CD lying under S-pole and then to EF under the next N-pole. In this way, the winding progresses, passing successively under every N-pole and S-pole till it returns to a conductor A′B′ lying under the original pole. Because the winding progresses in one direction round the armature in a series of 'waves', it is known as wave winding. If, after passing once round the armature, the winding falls in a slot to the left of its starting point then the winding is said to be retrogressive. If, however, it falls one slot to the right, then it is progressive. Assuming a 2-layer winding and supposing that conductor AB lies in the upper half of the slot, then going once round the armature, the winding ends at A′B′ which must be at the upper half of the slot at the left or right.



Following points regarding simplex wave winding should be carefully noted:

a) Average pitch $Y_A = \frac{Y_B + Y_F}{2}$ and $Y_A = \frac{Z \mp 2}{P}$

b) Both pitches YB and YF are odd and of the same sign.

c) Resultant pitch YR = YF + YB.

d) Commutator pitch, YC = YA (in lap winding YC = ±1).

Also, Y_C=No. of commutator bars±1/ No. of pair of poles.

e) The number of coils i.e. NC can be found from the relation $N_C = \frac{PY_A \pm 2}{2}$.

f) Only two brushes are necessary, though their number may be equal to the number of poles.

g) The number of parallel paths through the armature winding is two irrespective of the number of generator poles.

h) The generator emf is equal to the emf induced in any one of the two parallel paths. If e_{av} is the emf induced/conductor, then generator emf (Eg)= e_{av} . Z/2.

i) The equivalent armature resistance (R_a)=R_{path}/2.

j) If Ia is the total armature current, then current carried by each path or conductor is obviously Ia/2 whatever the number of poles.

Example: Draw a developed diagram of a simplex 2-layer wave-winding for a 4-pole dc generator with 30 armature conductors. Hence, point out the characteristics of a simple wave winding.

Solution: $Y_A = \frac{30 \pm 2}{4}$ = 8 or 7. Taking Y_A=7, we have Y_B=Y_F=7 .The simple winding table is as under:

Back Connections   Front Connections

1 to (1 + 7) = 8------------------------------8 to (8 + 7) = 15

15 to (15 + 7) = 22--------------------------22 to (22 + 7) = 29

29 to (29 + 7) = 36 = (36 - 30) = 6-------6 to (6 + 7) = 13

13 to (13 + 7) = 20--------------------------20 to (20 + 7) = 27

27 to (27 + 7) = 34 = (34 - 30) = 4-------4 to (4 + 7) = 11

11 to (11 + 7) = 18--------------------------18 to (18 + 7) = 25

25 to (25 + 7) = 32 = (32 - 30) = 2-------2 to (2 + 7) = 9

9 to (9 + 7) = 16----------------------------16 to (16 + 7) = 23

23 to (23 + 7) = 30--------------------------30 to (30 + 7) = 37 = (37 - 30) = 7

7 to (7 + 7) = 14----------------------------14 to (14 + 7) = 21

21 to (21 + 7) = 28--------------------------28 to (28 + 7) = 35 = (35 - 30) = 5

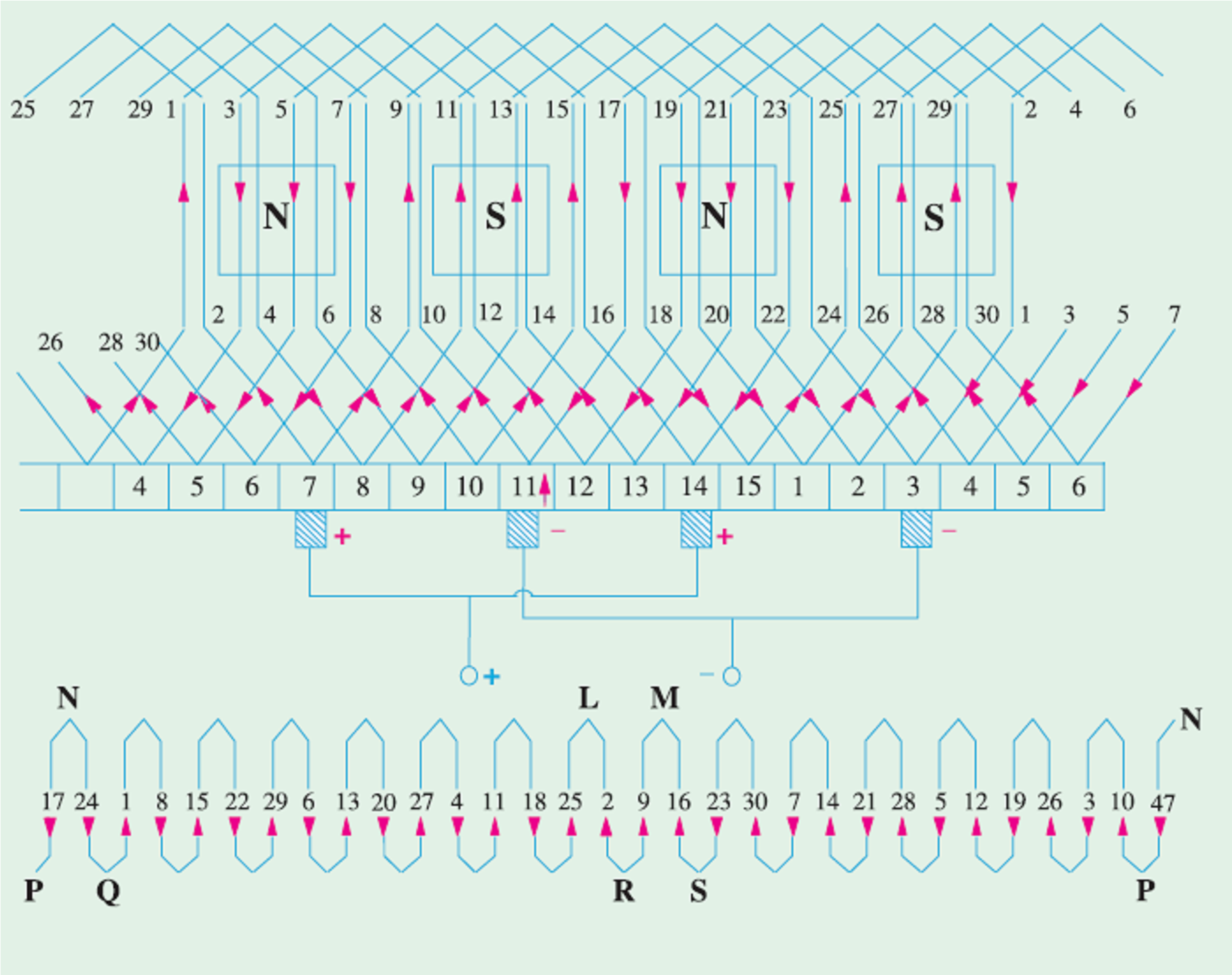
5 to (5 + 7) = 12----------------------------12 to (12 + 7) = 19

19 to (19 + 7) = 26--------------------------26 to (26 + 7) = 33 = (33 - 30) = 3

3 to (3 + 7) = 10----------------------------10 to (10 + 7) = 17

17 to (17 + 7) = 24--------------------------24 to (24 + 7) = 31 = (31 - 30) = 1

Since we come back to the conductor No. 1 from where we started, the winding gets closed at this stage.



Dummy or Idle Coils: These are used with wave-winding and are resorted to when the requirements of the winding are not met by the standard armature punchings available in armature-winding shops. These dummy coils do not influence the electrical characteristics of the winding because they are not connected to the commutator. They are exactly similar to the other coils except that their ends are cut short and taped. They provide mechanical balance for the armature because an armature having some slots without windings would be out of balance mechanically. For example, suppose number of armature slots is 15, each containing 4 sides and the number of poles is 4. For a simplex wave-windings, Dummy coils YA $=\frac{Z\pm2}{P}=\frac{60\pm2}{4}$, which does not come out to be an integer as required by this winding. However, if we make one coil dummy so that we have 58 active conductors, then $Y_A = \frac{58+2}{4}$ = 14 or 15. This makes the winding possible.

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 emf than the lap winding. Conversely, for the same emf, 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 emfs 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.

Types of Generators: Generators are usually classified according to the way in which their fields are excited. Generators may be divided into (a) separately-excited generators and (b) self-excited generators.

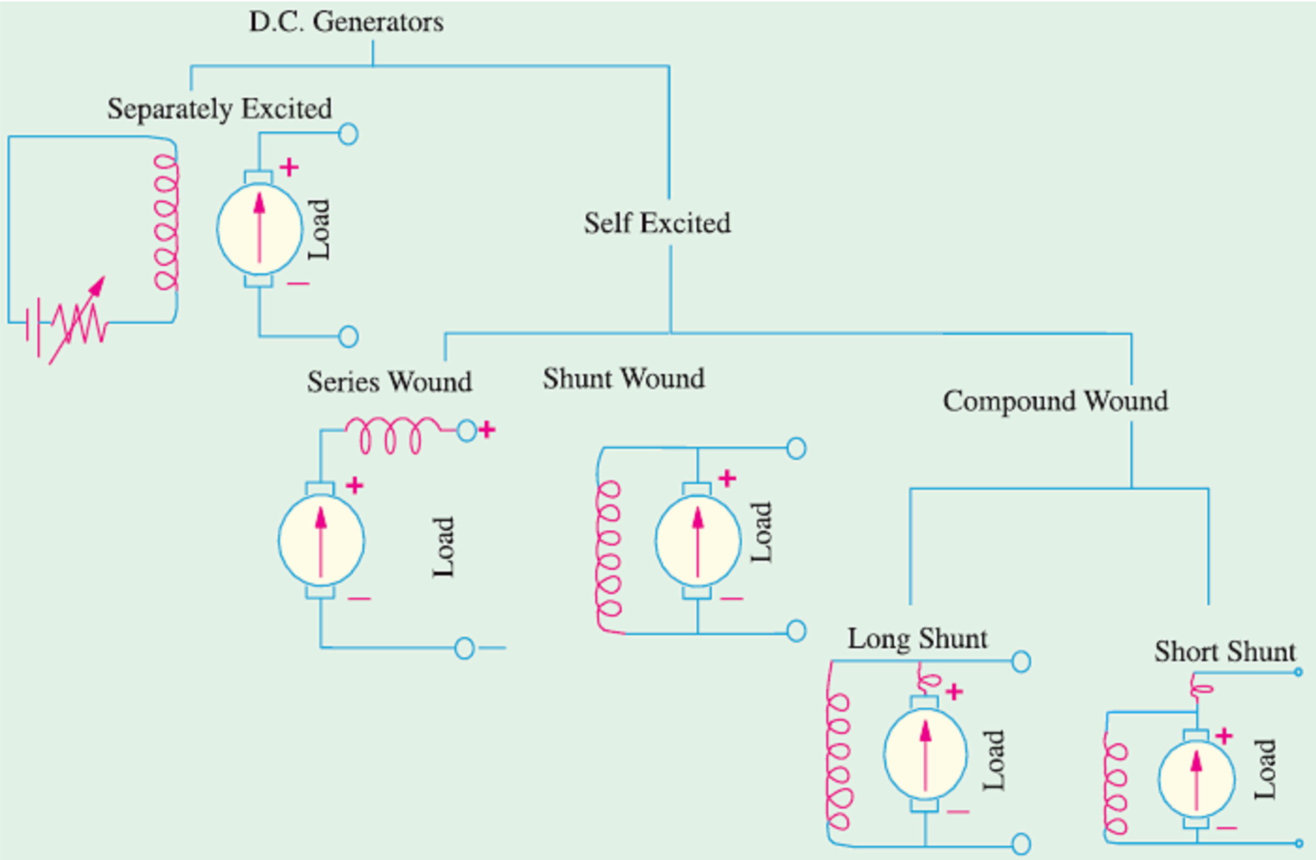
(a) Separately-excited generators are those whose field magnets are energized from an independent external source of dc current.

(b) Self-excited generators are those whose field magnets are energized by the current produced by the generators themselves. 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.

(ii) **Series Wound:** The field windings are joined in series with the armature conductors. 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.

(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. 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 commutatively-compounded. On the other hand if series field opposes the shunt field, the generator is said to be differentially compounded.



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 V for carbon brushes.

Generated EMF Equation of a Generator:

Let Φ = flux/pole in Weber

Z = total number of armature conductors= No. of slots x 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 = emf induced in any parallel path in armature

Generated emf (E_g) = emf generated in any one of the parallel paths (E).

Average emf generated/conductor $= \frac{d\phi}{dt}$ volt ($\because$ n = 1)

Now, flux cut/conductor in one revolution $d\Phi = \Phi P$ Wb

No. of revolutions/second = N/60 $\therefore$ Time for one revolution, dt = 60/N second

Hence, according to Faraday's Laws of Electromagnetic Induction,

EMF generated/conductor $= \frac{d\phi}{dt} = \frac{\phi PN}{60}$ volt

No. of conductors (in series) in one path = Z/A

For a simplex wave-wound generator: A=2

EMF generated/path $= \frac{\phi PN}{60} \times \frac{Z}{2} = \frac{\phi ZPN}{120}$ volt

For a simplex lap-wound generator: A=P, No. of conductors (in series) in one path=Z/P

EMF generated/path $= \frac{\phi PN}{60} \times \frac{Z}{P} = \frac{\phi NZ}{60}$ volt

Total Loss in a DC Generator: The various losses occurring in a generator can be divided as follows:

(a) Copper Losses

i) Armature copper loss = Ia^2Ra where Ra = resistance of armature and interpoles and series field winding etc. This loss is about 30 to 40% of full-load losses.

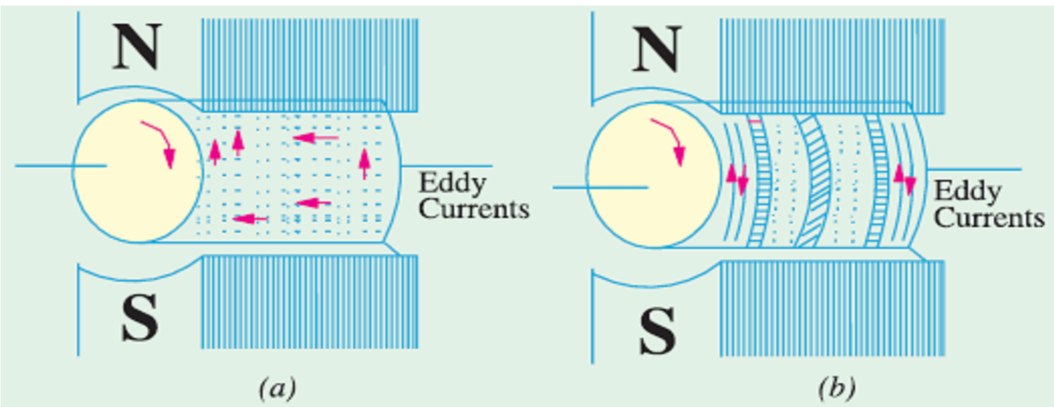
ii) Field copper loss: In the case of shunt generators, it is practically constant and $I_{sh}^2R_{sh}$ (or VI_{sh}). In the case of series generator, it is = $I_{se}^2 R_{se}$ where R_{se} is resistance of the series field winding. This loss is about 20 to 30% of F.L. losses.

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): 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. 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. up to 1.5 Wb/m^2), hysteresis loss is given by Steinmetz formula. According to this formula, $W_h = \eta B_{max}^{1.6} f V$ (watt), where B_{max} = maximum flux density, 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, Caststeel= 750−3000 J/m^3 and Cast iron =2700−4000 J/m^3. For reducing the hysteresis loss, those metals are chosen for the armature core which have 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.

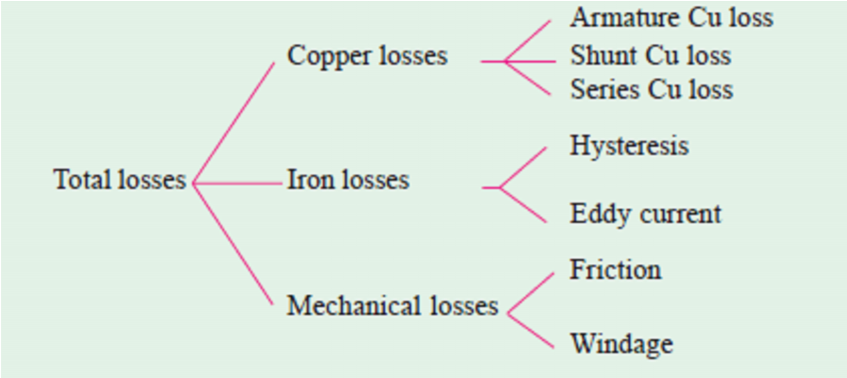
ii) Eddy Current Loss (W_e): When the armature core rotates, it also cuts the magnetic flux. Hence, an emf is induced in the body of the core according to the laws of electromagnetic induction. This emf though small, sets up large current in the body of the core due to its small resistance. This current 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. Eddy current loss (W_e) is given by the following relation: $W_e = KB_{max}^2 f^2 t^2 V^2$ (watt), where B_{max}=maximum flux density, f=frequency of magnetic reversals, t=thickness of each lamination and V = volume of armature core.



<u>(c) Mechanical Losses:</u> These consist of:

i) Friction loss at bearings and commutator.

(ii) air-friction or windage loss of rotating armature. Mechanical losses are about 10 to 20% of F.L. Losses. The total losses in a dc generator are summarized below:



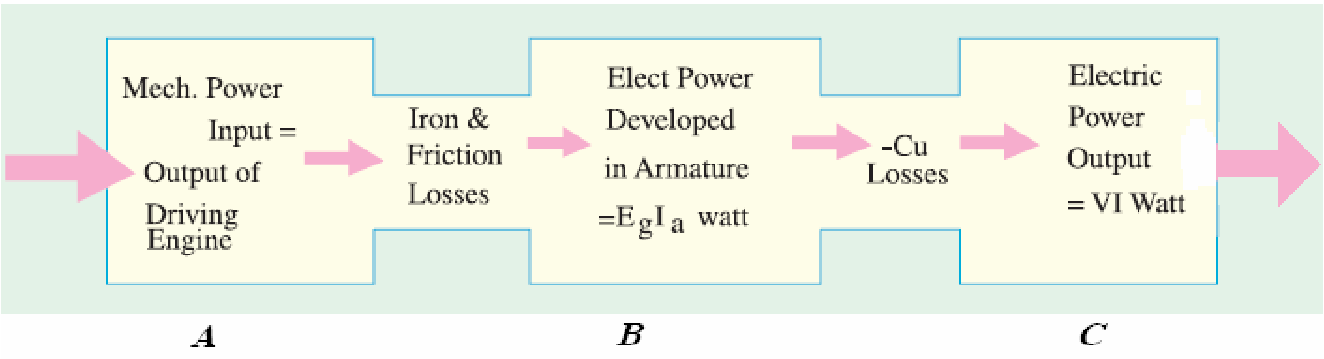
Magnetic and mechanical losses are collectively known as Stray Losses $W_{stray} = W_{Iron} + W_{mech.}$ field Cu loss is constant for shunt and compound generators. Hence, stray losses and shunt Cu loss are constant in their case. These losses are together known as standing or constant losses W_c. Hence, for shunt and compound generators:

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

Armature Cu loss $I_a^2R_a$ is known as variable loss because it varies with the load current.

Total loss = variable loss + constant losses (W_c)

Various power stages in the case of a dc generator are shown below :



Following are the three generator efficiencies:

1. Mechanical Efficiency:

η_m=total power generated in armature/mechanical input power

2. Electrical Efficiency:

η_e=output electrical power/ total power generated in armature

3. Overall or Commercial Efficiency

η_c = output electrical power / mechanical input power

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

Condition for Maximum Efficiency: Generator output = VI

Generator input=output +losses=VI + $I_a^2R_a + W_c = VI + (I + I_{sh})^2 R_a + W_c$ $(\because I_a = I + I_{sh})$

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

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

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

$$\frac{d}{dt}\left(\frac{IR_a}{V} + \frac{W_c}{VI}\right) = 0 \quad \text{or} \quad \frac{R_a}{V} - \frac{W_c}{VI^2} = 0 \quad \text{or} \quad I^2 R_a = W_c$$

Hence, generator efficiency is maximum when

Variable loss = constant loss

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

$$I^2 R_a = W_c \quad \text{or} \quad I = \sqrt{\frac{W_c}{R_a}}$$