DC machines

1. DC Generator

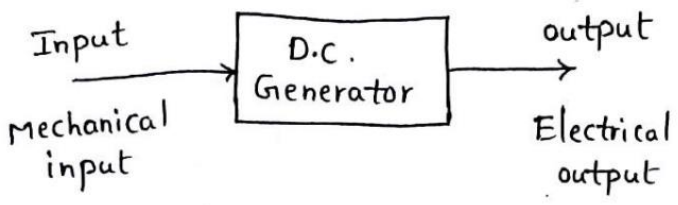


Fig. 4.1

2. DC Motor

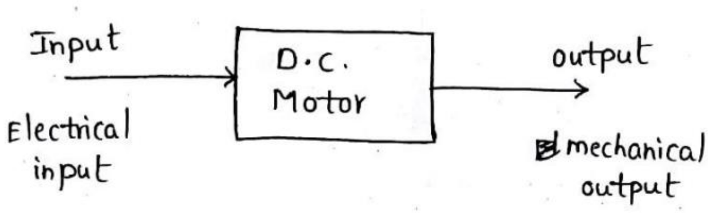


Fig. 4.2

DC Generator Converts Mechanical energy into Electrical Energy as shown in **Fig. 4.1**.

DC Motor Converts Electrical energy into Mechanical Energy as shown in **Fig. 4.2**.

CONSTRUCTIONAL DETAILS OF DC GENERATOR.

D.C. GENERATORS PRINCIPLE OF OPERATION

- **DC generator converts mechanical energy into electrical energy.**
- **When a conductor move in a magnetic field in such a way conductors cuts across a magnetic flux of lines and e.m.f. produces in a generator and it is defined by faradays law of electromagnetic induction**
- **e.m.f. causes current to flow if the conductor circuit is closed.**

The following are the basic requirements to be satisfied for generation of E.M.F

1. A uniform Magnetic field

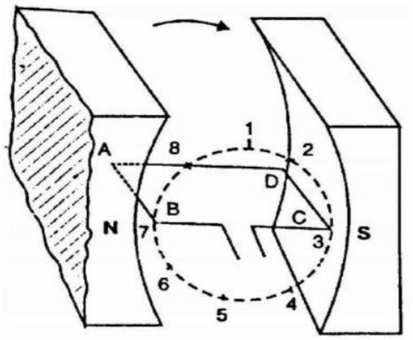
2. A System of conductors

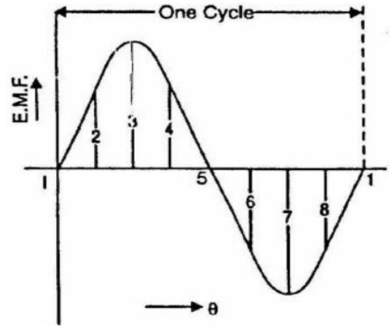
3. Relative motion between the magnetic field and conductors

- **Magnetic field :- Permanent Magnet (or) Electro Magnet (practical)**
- **Conductor :- Copper (or) Aluminum bars placed in slots cut around the periphery of cylindrical rotor**
- **Relative motion:- By Prime Mover or Turbine or I.C Engine (Internal combustion)**

Simple Loop D.C. Generator or Working of D.C Generator:

Consider a single turn loop ABCD rotating clockwise in a uniform magnetic field with a constant speed as shown in Fig.(4.3). As the loop rotates, the flux linking the coil sides AB and CD changes continuously. Hence the e.m.f. induced in these coil sides.





Explanation:

(i) When the loop is in position no. 1 [See Fig. 4.3], the generated e.m.f. is zero because the coil sides (AB and CD) are cutting no flux but are moving parallel to it.

(ii) When the loop is in position no. 2, the coil sides are moving at an angle to the flux and, therefore, a low e.m.f. is generated as indicated by point 2 in Fig. (4.4).

(iii) When the loop is in position no. 3, the coil sides (AB and CD) are at right angle to the flux and are, therefore, cutting the flux at a maximum rate, the generated e.m.f. is maximum as indicated by point 3 in Fig. (4.4).

(iv) When the loop is in position 4, the generated e.m.f. is less because the coil sides are cutting the flux at an angle and, therefore, a low e.m.f. is generated as indicated by

(v) When the loop is in position 5, the generated e.m.f. is zero because the coil sides (AB and CD) are cutting no flux but are moving parallel to it.

(vi) When the loop is in position 6, the coil sides move under a pole of opposite polarity and hence the direction of generated e.m.f. is reversed. The coil sides are moving at an angle to the flux and, therefore, a low e.m.f. is generated as indicated by point 6 in Fig. (4.4).

(vii) When the loop is in position no. 7, the coil sides (AB and CD) are at right angle to the flux and are, therefore, cutting the flux at a maximum rate, the generated e.m.f. is maximum as indicated by point 7 in Fig. (4.4).

(viii) When the loop is in position 8, the generated e.m.f. is less because the coil sides are cutting the flux at an angle and, therefore, a low e.m.f. is generated as indicated by point 8 in Fig. (4.4).

Construction of D.C Machine or D.C. Generator or D.C. Motor

A DC Machine is a Electro-Mechanical Energy Conversion Device, which can be operated as a DC generator or DC motor. The d.c. generators and d.c. motors have the same general construction. Any d.c. generator can be run as a d.c. motor and vice-versa

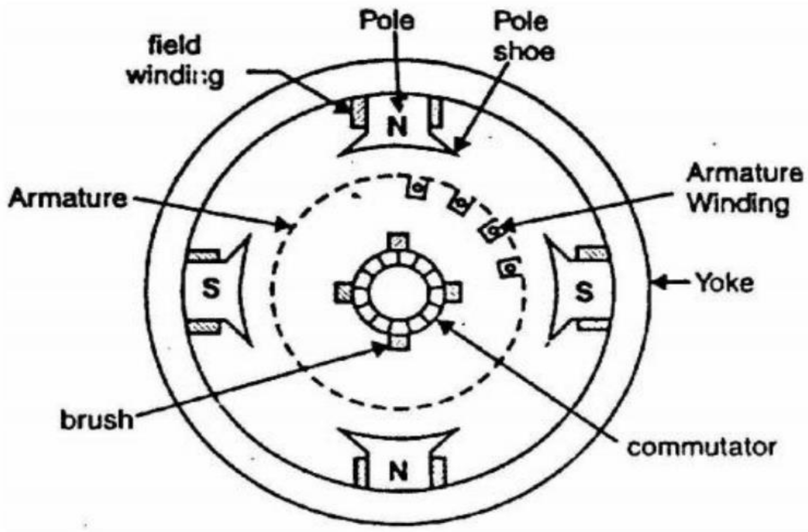


Fig 4.5

(i)Yoke

It is a stationary part.

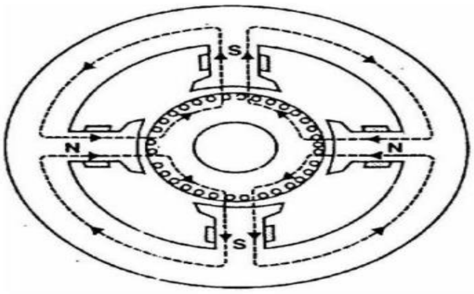
- The outer frame of a dc machine is called as yoke.
- It is made up of cast **iron** or steel. It not only provides mechanical strength to the whole assembly but also carries the magnetic flux produced by the field winding.
- Poles are joined to the yoke with the help of bolts or welding.

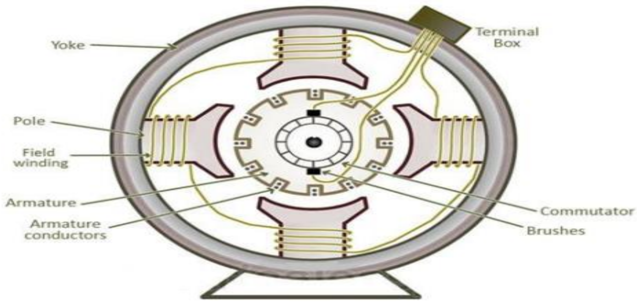
(ii) Field system

It is a stationary part.

a) Field Poles b) Field winding c) Pole shoe

- The function of the field system is to produce uniform magnetic field.
- It consists of a number of salient poles (of course, even number) bolted to the inside of circular frame (generally called yoke).
- Field coils are mounted on the poles and carry the d.c. exciting current. The field coils are connected in such a way that adjacent poles have opposite polarity. The m.m.f. developed by the field coils produces a magnetic flux that passes through the pole pieces, the air gap, the armature and the frame (See Fig. 4.6).
- Practical d.c. machines have air gaps ranging from 0.5 mm to 1.5 mm.





(iii) Armature core

It is a rotating part.

- The armature core is keyed to the machine shaft and rotates between the field poles.
- Conductors are placed on armature slots.
- It consists of slotted soft-iron laminations (about 0.4 to 0.6 mm thick) that are stacked to form a cylindrical core as shown in Fig (4.7).

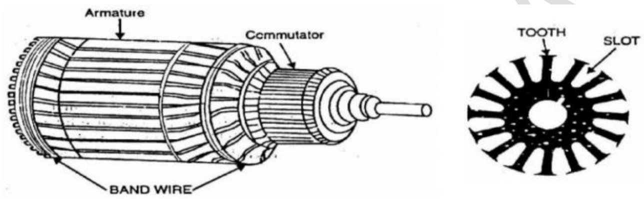


Fig 4.7

(iv) Armature winding

It is a rotating part.

- The slots of the armature core hold insulated conductors that are connected in a suitable manner. This is known as armature winding.
- This is the winding in which "working" e.m.f. is induced.
- The armature conductors are connected in series-parallel; the conductors being connected in series so as to increase the voltage and in parallel paths so as to increase the current.
- there are two types of armature winding in a d.c. machine viz.,
  (a) Lap winding
  (b) Wave winding.

(v) Commutator

It is a rotating part.

Which converts AC to DC and DC to AC

- A commutator is a mechanical rectifier which converts the alternating voltage generated in the armature winding into direct voltage across the brushes.
- The commutator is made of copper segments insulated from each other by mica sheets and mounted on the shaft of the machine (See Fig 4.8).
- The armature conductors are soldered to the commutator segments in a suitable manner to give rise to the armature winding.

(vi) Brushes

It is a stationary part.

- The purpose of brushes is to ensure electrical connections between the rotating commutator and stationary external load circuit.
- The brushes are made of carbon and rest on the commutator.
- The brush pressure is adjusted by means of adjustable springs (See Fig. 4.9).

E.M.F. Equation of a D.C. Generator

Derive an expression for the e.m.f. generated in a d.c. generator.

Let Φ = flux/pole in Wb
Z = total number of armature conductors
P = number of poles

N = speed of armature in r.p.m.
A = number of parallel paths A = 2 ... for wave winding
= P ... for lap winding

Eg = e.m.f. of the generator = e.m.f./parallel path

Flux cut by one conductor in one revolution of the armature,

$$d\,\Phi = P\,\Phi \text{ webers}$$

Time taken to complete one revolution,

$$dt = 60/N \text{ second}$$

$$\text{e.m.f generated/conductor} = \frac{d\Phi}{dt} = \frac{P\Phi}{60/N} = \frac{P\Phi N}{60} \text{ Volts}$$

e.m.f. of generator,
Eg = e.m.f. per parallel path
= (e.m.f generated/conductor) X No. of conductors in series per parallel path

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

$$\mathbf{Eg} = \frac{\Phi Z N}{60} X \frac{P}{A} \; Volts$$

where A = 2 for-wave winding

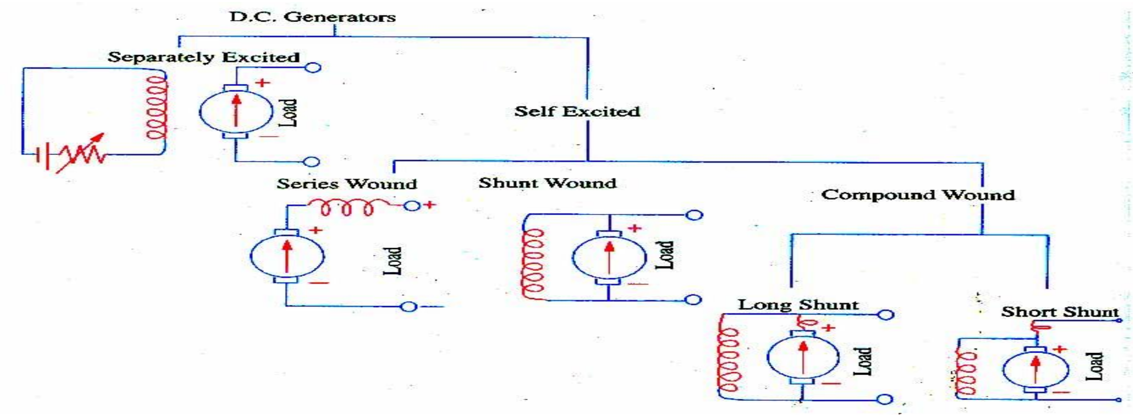
= P ... for lap winding

NOTE: Induced E.M.F $E_g \propto \Phi$ (Magnetic flux)

$E_g \propto N$ (Speed of the armature)

$E_g \propto Z$ (Number of conductors)

TYPES OF DC GENERATORS



Types of D.C. Generators

Generators are generally classified according to their methods of field excitation.

D.C. generators are divided into the following two classes:
(1) Separately excited d.c. generators
(2) Self-excited d.c. generators

(a) Series generator;
(b) Shunt generator;
(c) Compound generator

(i) Short shunt compound generator
(ii) Long shunt compound generator

(1) Separately Excited D.C. Generators

A d.c. generator whose field magnet winding is supplied from an independent external d.c. source (e.g., a battery etc.) is called a separately excited generator.

The voltage output depends upon the speed of rotation of armature and the field current. The greater the speed and field current, greater is the generated e.m.f.

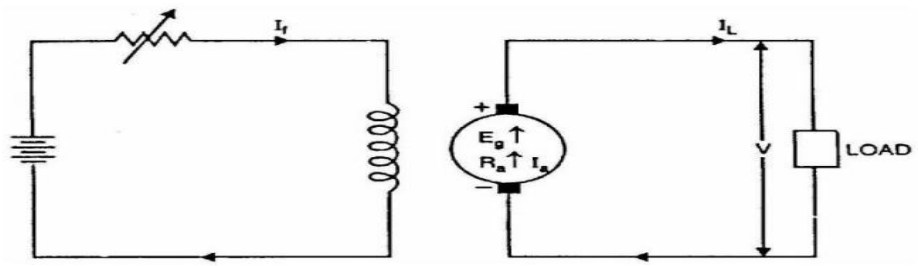


Fig 4.10

Apply KVL to right side circuit in fig 4.10

e.m.f. of the generator $E_g = V_L + I_aR_a$

Armature current, $I_a = I_L$

Electric power developed $P_d = E_gI_a$

Power delivered to load $P_L = V_LI_a$

(2)Self-Excited D.C. Generators

A D.C. generator whose field magnet winding is supplied current from the output of the generator itself is called a self-excited generator.

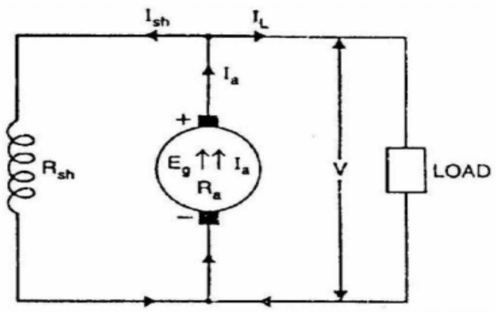
There are three types of self-excited generators depending upon the manner in which the field winding is connected to the armature, namely;
(a) Shunt generator
(b) Series generator
(c) Compound generator

i) Short shunt compound generator
(ii) Long shunt compound generator

(a) Shunt generator

In a shunt generator, the field winding is connected in parallel with the armature winding so that terminal voltage of the generator is applied across it.

The shunt field winding has many turns of fine wire having high resistance. Therefore, only a part of armature current flows through shunt field winding and the rest flows through the load.



Apply KVL to the circuit shown in fig 4.11

e.m.f. of the generator $E_g = V_L + I_a R_a$

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

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

Electric power developed $P_d = E_g I_a$

Power delivered to load $P_L = V_L I_L$

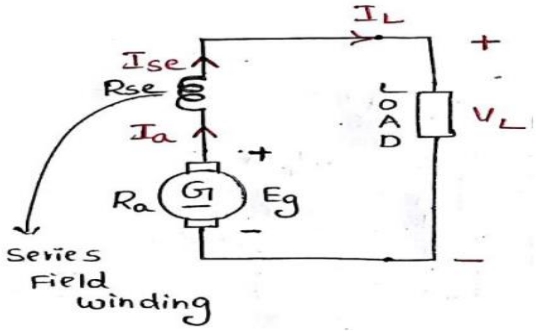
R_{sh}—Shunt field resistance

Shunt field winding have more number of turns and thin wire

(b) Series generator

In a series wound generator, the field winding is connected in series with armature winding so that whole armature current flows through the field winding as well as the load.

Since the field winding carries the whole of load current, it has a few turns of thick wire having low resistance.



e.m.f. of the generator $E_g = V_L + I_a(R_a+R_{se})$

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

Electric power developed $P_d = E_g I_a$

Power delivered to load $P_L = V_L I_L$

R_{se}—Series field resistance

Series field winding have more less of turns and thick wire

Applications: Boosters

(c) Compound generator

In a compound-wound generator, there are two sets of field windings on each pole—one is in series and the other in parallel with the armature.

(i) Short shunt compound generator

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

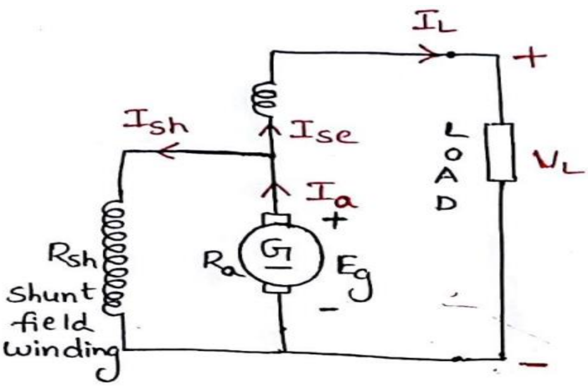


Fig 4.13

e.m.f. of the generator $E_g = V_L + I_a R_a + I_{se} R_{se}$

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

Apply KCL to the circuit

Armature Current $I_a = I_{se} + I_{sh}$

Apply KVL to the circuit

$$-V + I_{se}R_{se} + I_{sh}R_{sh} = 0$$

Shunt field current, Ish=$\dfrac{V_L + I_{se}R_{se}}{R_{sh}}$

Power developed in armature = $E_g I_a$
Power delivered to load = $V_L \, I_L$

(ii) Long shunt compound generator

In which shunt field winding is in parallel with both series field and armature Winding.

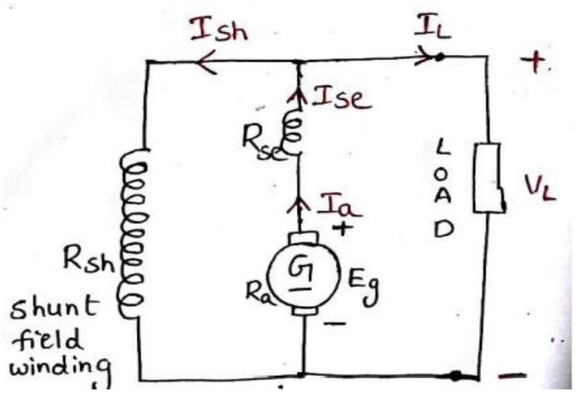


Fig 4.14

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

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

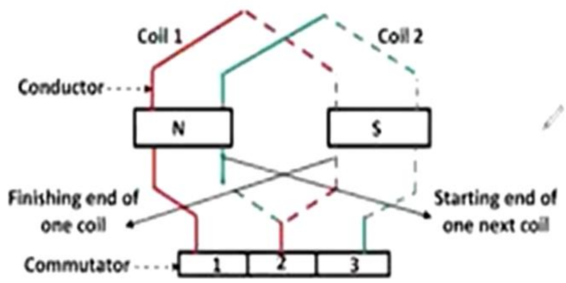
Apply KVL to the circuit in Fig 4.14

e.m.f. of the generator $E_g = V + I_a (R_a + R_{se})$

Power developed in armature = EgIa
Power delivered to load = $V_L \, I_L$

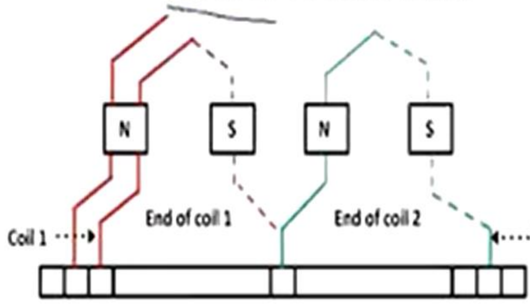
TYPES OF ARMATURE WINDINGS:

LAP WINDING



- The connection overlap each other as the winding proceeds.
- The numbers of the parallel path (A) are equal to the total of number poles (P). (A=P)
- The no. of brush set is equal to the no. of parallel paths.
- The e.m.f of lap winding is less.
- The lap winding used for high current, low voltage machines.

WAVE WINDING

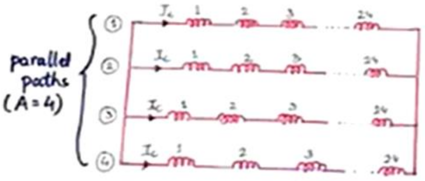


- The winding travels ahead without overlapping in a progressive manner.
- The number of parallel paths is equal to two. (A=2)
- The no. of brush set is equal to two.
- The e.m.f of wave winding is more.
- The applications of wave winding include low current and high voltage machines.

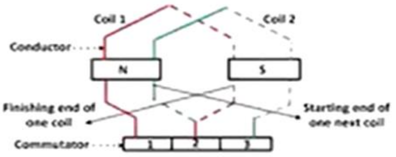
Concept of Parallel Path

Let, Z = No. of conductors.
P = No. of poles
A = No. of parallel paths

Example : For Lap Winding
$Z = 96$, $P = 4$
$\therefore \boxed{A = P = 4}$
So, total no. of conductors in single path $= \frac{Z}{A}$
$\Rightarrow 96/4 = 24$

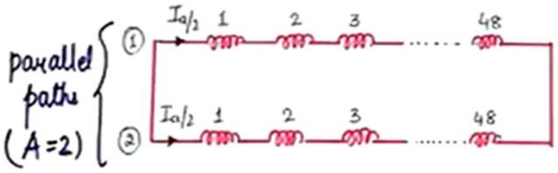


Total armature current, $\boxed{I_a = I_c \times A}$

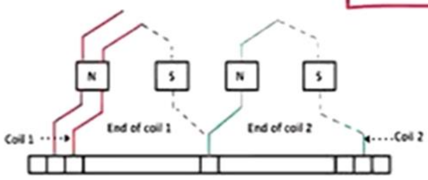


For Wave Winding :

$Z = 96$, $P = 4$
No. of parallel path, $\boxed{A = 2}$
So, total no. of conductors in single path $= \frac{Z}{A} = \frac{96}{2} = 48$



Total armature current, $\boxed{I_a = 2 \times \frac{I_a}{2}}$

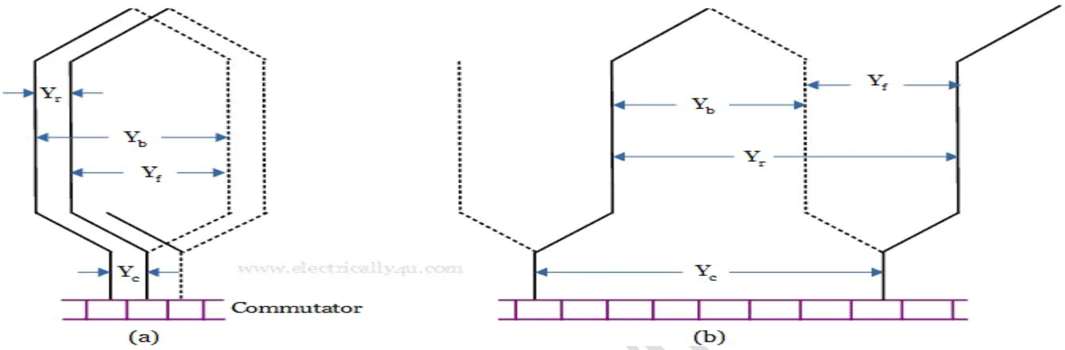


Back Pitch

The distance at which a coil advances on the back of the armature is called back pitch, denoted by Y_b. It can also be defined as the distance between the first and the last conductors of a coil. It is the same as coil span and is shown in the below figure(a) and (b).

Front Pitch

It is the distance between the second conductor of one coil and the first conductor of the next coil. Both the coils should be connected to the same commutator segments on the front, as shown in the figure (a) and (b) below. It is denoted by Y_f.



- **Resultant Pitch**

It is the distance between the beginning of one coil and the beginning of the next coil to which it is connected. It is illustrated in the above figure (a) and (b), denoted by Y_r.

- **Commutator Pitch**

It is the distance between the Commutator segments to which the two ends of a coil are connected. From the figure, you can observe, for lap winding, Commutator pitch (Y_c) is the difference of back pitch(Y_b) and front pitch(Y_f). For wave winding, it is the sum of the back pitch and front pitch.

<u>COMPARE SLIP RING AND SPLIT RING.</u>

Basis for Comparison	Slip Ring	Split Ring
Definition	The slip ring is used for transferring the power between the rotating and stationary structure of an AC machine	The split ring is used for reversing the direction of current.
Uses	It is used in AC machine.	It is used in DC machine.
Design	Continuous Ring	The ring is split into two or more parts.
Application	It supplies power from an AC generator to the AC motor.	For supplying pulsating voltage to the DC motor.

LOSSES

DC Generators convert Mechanical power into Electrical power and DC Motors convert Electric power to Mechanical power. In the process of conversion some power is lost.

The difference between the input power and the output power of a machine is the Power loss that occurs inside the machine.

Constant & Variable losses:

The losses are broadly classified as *constant losses* and *variable losses*. Constant losses are constant and are independent of the load where as the variable losses are dependent on the load. They are further classified in detail as below.

1. **Electrical or Copper Losses (I^2R Loss):** Current flow through the resistance of Armature and Field coils gives rise to I^2R losses and since the coils are normally made up of copper these losses are called Copper losses.

   Armature copper loss: $P_A = I_A^2 R_A$

   Field copper loss: $P_F = I_F^2 R_F$

2. **Brush losses**: The brush drop loss is the power lost across the contact potential at the brushes of the machine. It is given by the equation:

   $$P_{BD} = V_{BD} \times I_A$$

   where P_{BD} = brush drop loss

   V_{BD} = brush voltage drop

   I_A = armature current

   The brush losses are calculated in this manner because the voltage drops across a set of brushes are approximately constant over a large range of armature currents. Unless otherwise specified. The brush voltage drop is usually assumed to be about 2 V.

3. Iron or Core Losses

The *iron losses* occur in the armature core of the DC machine since the armature core is subjected to the magnetic field reversal i.e. changing magnetic field. The core losses are of two types viz.

- Hysteresis Loss
- Eddy Current Loss

Hysteresis Loss

The armature core of DC machine is subjected to magnetic field reversal when it passes under successive poles. An energy loss takes place due to molecular friction in the material of the armature core i.e. the domains of the core material resist being turned first in one direction and then in the other. Thus, some energy is expanded in the material of the armature core in overcoming this opposition and appears in the form of heat. This loss is known as hysteresis loss. The formula of hysteresis loss is,

$$\text{Hysteresis Loss, } P_h = \eta B_{max}^{1.6} f V \text{ Watts}$$

Where,

- η = Steinmetz hysteresis co-efficient,
- B_{max} = Maximum flux density in the core,
- f = frequency of magnetic reversal,
- V = volume of the core.

In order to reduce the hysteresis loss, the armature core is made of materials having narrower B-H curve such as silicon steel.

Eddy Current Loss

When the armature of DC machine rotates in the magnetic field produced by the poles, an emf is induced in the core and due to this induced emf, eddy currents are circulated in the armature core. The power loss due to these eddy currents is termed as *eddy current loss*. The eddy current loss is given by,

$$\text{Eddy current loss, } P_e = K_e B_{max}^2 f^2 t^2 V \text{ Watts}$$

4. **Mechanical Losses:** They are associated with the mechanical effects and they are mainly *Friction* and *windage* losses.
   - ***Friction losses*** are losses caused by the friction in the bearings of the machine and
   - ***Windage losses*** are due to the friction between the moving parts of the machine and the air flow in the machine housing.
5. **Stray Losses:** They are other miscellaneous losses that cannot be grouped into any of the above categories.

Stray Losses = Iron Losses + Mechanical Losses

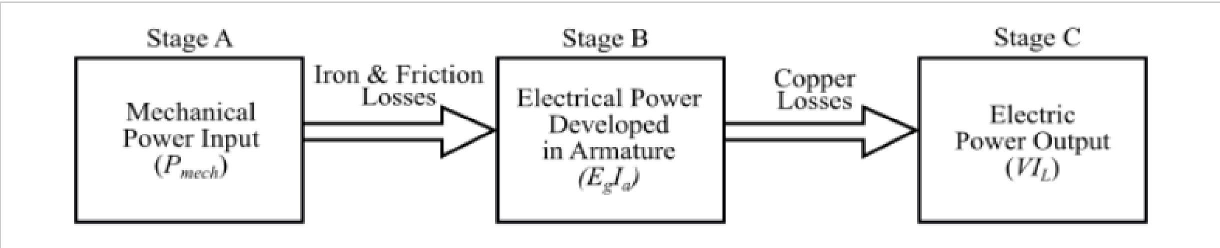
Efficiency of DC Generator

The *efficiency* of a *DC generator* is defined as the ratio of mechanical input power to the output electrical power.

$$\text{Efficiency, } \eta = \frac{\text{Electrical Power Output}(P_o)}{\text{Mechanical Power Input}(P_i)}$$

Explanation

Consider the power flow diagram of a DC generator (see the figure), here the power is represented in three stages as



By referring the power flow diagram,

$$\text{Iron and Friction Losses} = A - B$$

$$\text{Copper Losses} = B - C$$

Therefore, the efficiency of a DC generator can also be defined for the three stages as follows

- **Mechanical Efficiency** –

$$\eta_{mech} = \frac{B}{A} = \frac{\text{Power Developed in Armature } (E_g I_a)}{\text{Mechanical Power Input } (P_i)}$$

- **Electrical Efficiency** –

$$\eta_{elect} = \frac{C}{B} = \frac{\text{Electric Power Output } (VI_L)}{\text{Power Developed in Armature } (E_g I_a)}$$

- **Commercial Efficiency** – (always consider this unless stated otherwise)

$$\eta = \frac{C}{A} = \frac{\text{Power Output } (P_o)}{\text{Power input } (P_i)}$$

Condition for Maximum Efficiency

The efficiency of a DC generator is not constant but changes with the change in load.

Let, for a shunt generator,

$$\mathrm{I_L} \ = \text{load current}$$

$$\mathrm{V} \ = \text{terminal voltage}$$

Then, the output power of the DC generator is given by,

$$\text{Output Power}, = \mathrm{P_o} = \mathrm{VI_L}$$

$$\text{Total Input Power}, \ \mathrm{P_i} = \mathrm{P_o} + \text{Losses}$$

$$\Rightarrow \mathrm{P_i} = \mathrm{VI_L} + \mathrm{I_a^2R_a} + \mathrm{W_c}$$

$$\Rightarrow \mathrm{P_i} = \mathrm{VI_L} + (\mathrm{I_L} + \mathrm{I_{sh}})^2\mathrm{R_a} + \mathrm{W_c}$$

Where,

- $I_a^2R_a$=variable losses = Copper losses
- W_c= Constant losses = Iron losses + Mechanical losses

Practically, the shunt field current (I_{sh}) is very small as compared to load current (I_L), hence it can be neglected. Therefore,

$$\mathrm{P_i} = \mathrm{VI_L} + \mathrm{I_L^2R_a} + \mathrm{W_c}$$

Hence, the efficiency of DC generator will be,

$$\eta = \frac{\mathrm{P_o}}{\mathrm{P_i}} = \frac{\mathrm{VI_L}}{\mathrm{VI_L} + \mathrm{I_L^2R_a} + \mathrm{W_c}}$$

$$\eta = \frac{1}{1 + \left(\frac{\mathrm{I_LR_a}}{\mathrm{V}}\right) + \left(\frac{\mathrm{W_c}}{\mathrm{VI_L}}\right)}$$

The efficiency will be maximum when the denominator of the above expression is minimum. In order to determine minimum value of denominator, differential it with respect to variable (I_L in this case) and equate it to zero, i.e.

$$\frac{d}{dI_L}[1+(\frac{I_L R_a}{V})+(\frac{W_c}{VI_L})] = 0$$

$$\Rightarrow 0+\frac{R_a}{V}-\frac{W_c}{VI_L^2} = 0$$

$$\Rightarrow \frac{R_a}{V}=\frac{W_c}{VI_L^2}$$

$$\Rightarrow I_L^2 R_a = W_c$$

$$\Rightarrow \text{Variable Losses} = \text{Constant Losses}$$

Hence, the efficiency of a DC generator is maximum when the load current is such that the variable losses are equal to the constant losses.

The load current corresponding to maximum efficiency is given by,

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

Some of the General Differentiation Formulas are:

Power Rule:

$$\frac{d}{dx} x^n = n\, x^{n-1}$$

The derivative of a constant, a:

$$\frac{d}{dx} a = 0$$

Quotient rule

If the function f(x) is in the form of two functions [u(x)]/[v(x)], the derivative of the function is

If,

$$f(x) = \frac{u(x)}{v(x)}$$

then,

$$f'(x) = \frac{u'(x)\times v(x) - u(x)\times v'(x)}{(v(x))^2}$$

A shunt generator supplies 95 A at a terminal voltage of 240 V. The armature and shunt field resistances are 0.2 Ω and 60 Ω respectively. The iron and frictional losses are 2000 W. Find the efficiency of DC generator. Also determine the value of load current at which maximum efficiency occurs.

Solution –

Efficiency of DC Generator –

$$\text{Shunt field current, } I_{sh} = \frac{V}{R_{sh}} = \frac{240}{60} = 6A$$

$$\text{Armature current, } I_a = I_L + I_{sh} = 95 + 6 = 101A$$

$$\text{Armature cu losses} == I_a^2 R_a = (101)^2 \times 0.2 = 2040.2W$$

$$\text{Shunt field cu losses} = I_{sh}^2 R_{sh} = (6)^2 \times 60 = 2160W$$

$$\therefore \text{ Total cu losses} = 2040.2 + 2160 = 4200.2 \text{ W}$$

$$\Rightarrow \text{ Total Losses} = 2000 + 4200.2 = 6200.2 \text{ W}$$

$$\text{Output Power, } P_o = VI_L = 240 \times 95 = 22800W$$

Therefore, the input power will be

$$\text{Input Power, } P_i = P_o + \text{Losses} = 22800 + 6200.2 = 29000.2W$$

$$\therefore \text{ Efficiency, } \eta = \frac{P_o}{P_i} = \frac{22800}{29000.2} \times 100\% = 78.62\%$$

The Load Current Corresponding to Maximum Efficiency –

$$\text{Constant Losses, } W_c = \text{Shunt field cu loss} + \text{Stray losses}$$

$$\Rightarrow W_c = 2160 + 2000 = 4160W$$

$$I_L = \sqrt{\frac{W_c}{R_a}} = \sqrt{\frac{4160}{0.2}} = 144.22A$$