Module 3

DC Machines

DC GENERATOR:

A machine which works on direct current is defined as a **D.C.Machine**. D.C.Machines are of two types.

(a) **D.C.Generator (b) D.C.Motor.**

<u>Constructional features: </u>Main parts consist of

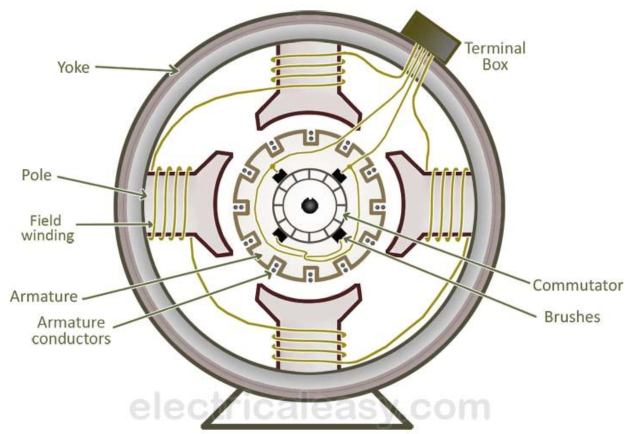
Yoke

Field system (poles)

Coil arrangement (armature)

Commutator

Brushes.



YOKE:

(i) It serves the purpose of outermost cover of the D.C. machine, so that the insulating materials get protected from harmful atmospheric elements like moisture, dust and various gases like SO_2, acidic fumes etc.

(ii) It provides mechanical support to the poles.

(iii) It forms a part of the magnetic circuit. It provides a path of low reluctance for magnetic flux. The low reluctance path is important to avoid wastage of power to provide same flux. Large current and hence the power is necessary if the path has high reluctance, to produce the same flux.

Choice of material: To provide low reluctance path, it must be made up of some magnetic material. It is prepared by using cast iron because it is cheapest. For large machines rolled steel, cast steel, silicon steel is used which provides high permeability i.e. low reluctance and gives good mechanical strength. As yoke does not need any machining or good finishing as it rough, casting is the best method of construction of yoke

POLES:

Each pole is divided into two parts Namely,

pole core and b) pole shoe This is shown in fig

Fig. 27 Pole structure

Function of pole core and pole shoe:

(i) pole core basically carries a field winding which is necessary to produce the flux.

(ii) It directs the flux produced through the air gap to armature core, to the next pole.

(iii) pole shoe enlarges the area of armature core to come across the flux, which

is necessary to produce larger induced e.m.f. .To achieve this, pole shoe has given a

particular shape.

Choice of material : It is made up of magnetic material like cast iron or cast steel.as it requires a definite shape and size, laminated construction is used. The laminations of required size and shape are stamped together to get a pole, which is then bolted to the yoke.

FIELD WINDING [F1-F2] :

The field winding is wound on the pole core with a definite direction.

Functions: i) To carry current due to which pole core on which the winding placed behaves as an electromagnet, producing necessary flux.

As it helps in producing the magnetic field i.e. exciting the pole as electromagnet, it is called

Field winding‟ or „Exciting winding‟.

Choice of material: As it has to carry current hence obviously made up of some conducting material. So Aluminum or Copper is the choice. But field coils are required to take any type of shape and bend about pole core and copper has good pliability i.e. it can bend easily. So copper is the proper choice. Filed winding is divided into various coils called bas field coils. These are connected in series with each other and wound in such a direction around pole cores, such that alternate „N‟ and „S‟ poles are formed.

ARMATURE:

It is further divided into two parts namely, (I) Armature core (II) Armature winding

Armature core is cylindrical in shape mounted on the shaft. It consists of slots on its periphery and the air ducts to permit the air flow through armature which serves cooling purpose.

(a) Functions:

(i) **Armature core** provides house for armature winding i.e. armature conductors.

(ii) To provide a path of low reluctance to the magnetic flux produced by the field winding.

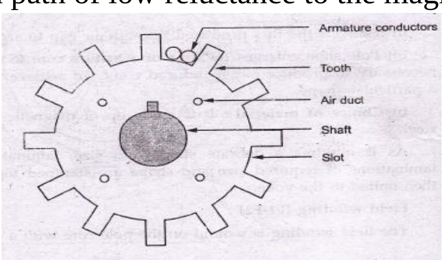


Fig. 28 Single circular lamination of armature core

(b) Choice of material : A it has to provide a low Reluctance path to the flux, it is made up of magnetic material

like cast iron or cast steel.

It is made up of laminated Construction to keep eddy current Loss as low as possible. A single circular Lamination used for the construction of the armature core is shown in Fig.

Armature winding is nothing but the interconnection of the armature conductors,

placed in the slots provided on the armature core periphery. When the armature

is rotated, in case of generator, magnetic flux gets cut by armature conductors

and e.m.f. gets induced in them.

Functions:

Generation of e.m.f. takes place in the armature winding in case of generators. To carry the current supplied in case of d.c. motors to do the useful work in the external circuit.

Choice of material: As armature windings carries entire current which depends on external load, it has to be made up of conducting material, which is copper.

Armature winding is generally former wound. The conductors are placed in the armature slots which are lined with tough insulating material.

COMMUTATOR:

We have seen earlier that the basic nature of e.m.f induced in the armature conductors is alternating. This needs rectifications in case of d.c. generator which is possible by device called commutator.

Functions:

(i) To facilitate the collection of current from the armature

conductors. (ii) To convert internally developed alternating e.m.f. to

unidirectional (d.c.) e.m.f. (iii) To produce unidirectional torque

in case of motors.

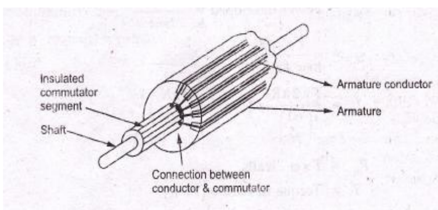


Fig. 29 Commutator

Choice of material: As it collects current from armature, it is also

made up of copper segments.

It is cylindrical in shape and is made up of wedge shaped segments of hard drawn, high conductivity copper. Those segments are insulated from each other by thin layer of mica. Each commutator segment is connected to the armature conductor by means of copper lug or strip. This connection is shown in the fig.

BRUSHES AND BRUSH GEAR:

Brushes and stationary and resting on the surface of the commutator.

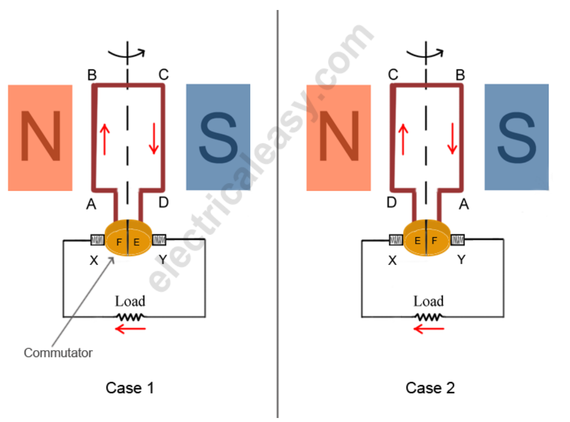
(a) Functions: i) To collect current from commutator and make it available to the stationary external circuit.

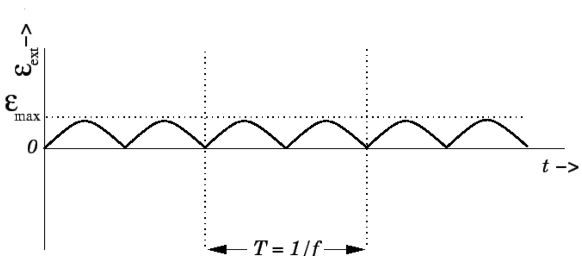
(b) Choice of material: Brushes are normally made up of soft material like carbon. Brushes are rectangular in shape. They are housed in brush holders, which are usually of box type. The brushers are made to press on the commutator surface by means of a spring, whose tension can be adjusted with the help of lever. A flexible copper conductor called pig tail is used to connect the brush to the external circuit.

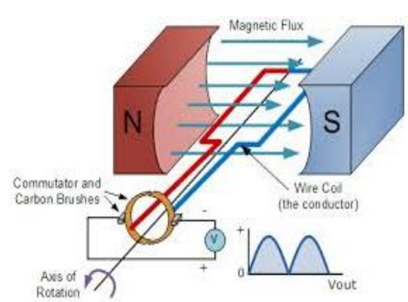
Bearings: Ball bearings are usually as they are more reliable. For heavy duty machines, roller bearings are preferred

WORKING OF DC GENERATOR:

According to Faraday's laws of electromagnetic induction, whenever a conductor is placed in a varying magnetic field (OR a conductor is moved in a magnetic field), an emf (electromotive force) gets induced in the conductor. The magnitude of induced emf can be calculated from the emf equation of dc generator. If the conductor is provided with a closed path, the induced current will circulate within the path. In a DC generator, field coils produce an electromagnetic field and the armature conductors are rotated into the field. Thus, an electromagnetically induced emf is generated in the armature conductors.







EMF EQUATION OF A DC GENERATOR

- Consider a DC Generator with the following parameters,
  P = number of field poles
  Ø = flux produced per pole in Wb (weber)
  Z = total no. of armature conductors
  A = no. of parallel paths in armature
  N = rotational speed of armature in revolutions per min. (rpm)

  Now,
  Average emf generated per conductor is given by **dΦ/dt**(Volts) ... eq. 1
- Flux cut by one conductor in one revolution =**dΦ = PΦ**….(Weber),
- Number of revolutions per second (speed in RPS) =**N/60**
- Therefore, time for one revolution =dt = **60/N** (seconds)
- From eq. 1, emf generated per conductor =**dΦ/dt = PΦN/60** (Volts) …..(eq. 2)
- Above equation-2 gives the emf generated in one conductor of the generator. The conductors are connected in series per parallel path, and the emf across the generator terminals is equal to the generated emf across any parallel path.
- Therefore, **Eg = PΦNZ / 60A**
  For simplex lap winding, number of parallel paths is equal to the number of poles (i.e. A=P),
  Therefore, for simplex lap wound dc generator, **Eg= PΦNZ / 60P**
  For simplex wave winding, number of parallel paths is equal to 2 (i.e P=2),
  Therefore, for simplex wave wound dc generator, **Eg = PΦNZ / 120**

TYPES OF DC GENERATORS: The DC generator converts the Mechanical power into electrical power. The magnetic flux in a DC machine is produced by the field coils carrying current. The circulating current in the field windings produces a magnetic flux, and the phenomenon is known as **Excitation**. DC Generator is classified according to the methods of their field excitation. **(i) Separately Excited (ii) Self Excited**

(i) **Separately Excited:**

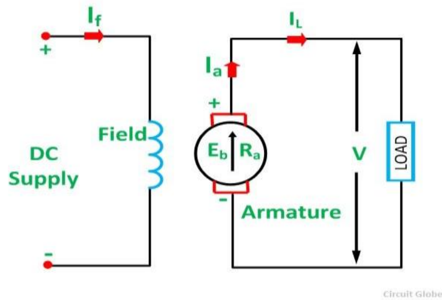
A DC generators whose field winding or coil is energized by a separate or external DC source is called a separately excited DC Generator. The flux produced by the poles depends upon the field current with the unsaturated region of magnetic material of the poles. i.e. flux is directly proportional to the field current. But in the saturated region, the flux remains constant.

$\mathbf{I_a = I_L}$ where $\mathbf{I_a}$ is the armature current and I_L is the line current.

Terminal voltage is given as $V = E_g - I_a R_a \quad \ldots\ldots(1)$

If the contact brush drop is known, then the equation (1) is written as

$$V = E_g - I_a R_a - 2v_b \quad .....(2)$$



The power developed and Power output is given by the equation shown below.

$$\text{Power developed} = E_g I_a \quad ....(3)$$

$$\text{Power output} = VI_L = VI_a \quad ....(4)$$

Self Excited DC Generator: Self-excited **DC Generator** is a device, in which the current to the field winding is supplied by the generator itself. In self-excited DC generator, the field coils mat be connected in parallel with the armature or in the series with the armature or it may be connected partly in series and partly in parallel with the armature windings. **The self-excited DC Generator is further classified as**

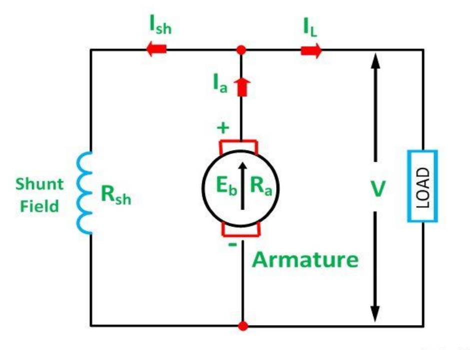
Shunt Wound Generator: In a **shunt wound generator,** the field winding is connected across the armature winding forming a parallel or shunt circuit. Therefore, full terminal voltage is applied across it. A very small field current I_{sh}, flows through it, because this winding has many turns of fine wire having very high resistance R_{sh} of the order of 100 ohms. The connection diagram of shunt wound generator is shown below

Shunt field current is given as $I_{sh} = \frac{V}{R_{sh}}$

Where R_{sh} is the shunt field winding resistance.

The current field I_{sh} is practically constant at all loads. Therefore, the DC shunt machine is considered to be a constant flux machine.

Armature current is given as $I_a = I_L + I_{sh}$



Terminal voltage is given by the equation shown below

$$V = E_g - I_a R_a$$

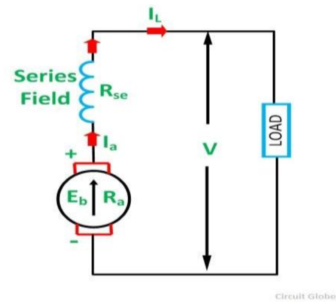
If the brush contact drop is included, the equation of the terminal voltage becomes

$$V = E_g - I_a R_a - 2v_b$$

$$\text{Power developed} = E_g I_a$$

$$\text{Power output} = VI_L$$

Series Wound Generator: A **series-wound generator** the field coils are connected in series with the armature winding The series field winding carries the armature current. The series field winding consists of a few turns of wire of thick wire of larger cross-sectional area and having low resistance usually of the order of less than 1 ohm because the armature current has a very large value Series field current is given as $I_{se} = I_L = I_a$



R_{se} is known as the series field winding resistance.

Terminal voltage is given as

$$V = E_g - I_aR_a - I_{se}R_{se}$$

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

If the brush contact drop is included, the terminal voltage equation is written as

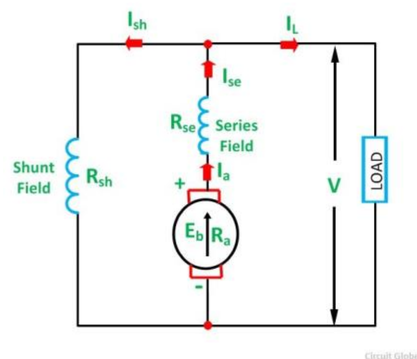
$$V = E_g - I_a(R_a + R_{se}) - 2V_b$$

$$\text{Power developed} = E_gI_a$$

$$\text{Power output} = VI_L = VI_a$$

COMPOUND WOUND GENERATOR: In a compound-wound generator, there are two field windings. One is connected in series, and another is connected in parallel with the armature windings. There are two types of compound-wound generator. **(i) Long shunt compound-wound (ii) Short shunt compound-wound**

(i) Long Shunt Compound Wound Generator :



In a long shunt wound generator**,** the shunt field winding is parallel with both armature and series field winding. The connection diagram of long shunt wound Generator is as shown here.

Shunt field current is given as $I_{sh} = \dfrac{V}{R_{sh}}$

Series field current is given as

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

Terminal voltage is given as $V = E_g - I_aR_a - I_{se}R_{se} = E_g - I_a(R_a + R_{se})$

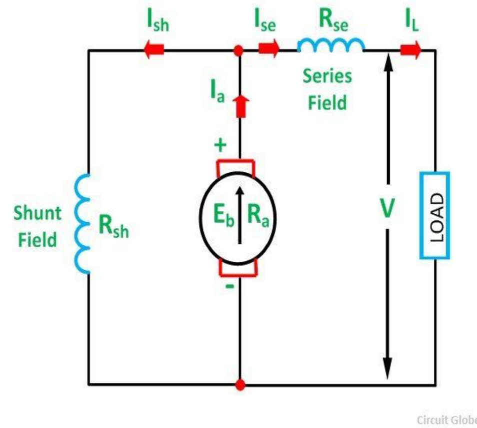
If the brush contact drop is included, the terminal voltage equation is

$$V = E_g - I_a(R_a + R_{se}) - 2V_b$$

$$\text{Power developed} = E_gI_a$$

$$\text{Power output} = VI_L$$

(ii) Short shunt compound-wound Generators: In **a** Short Shunt Compound Wound Generator, the shunt field winding is connected in parallel with the armature winding only. The connection diagram of short shunt wound generator is shown.



Series field current is given as $$I_{se} = I_L$$

Shunt field current is given as

$$I_{sh} = \frac{V + I_L R_{se}}{R_{sh}} = \frac{E_g - I_a R_a}{R_{sh}}$$

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

Terminal voltage is given as

$$V = E_g - I_a R_a - I_L R_{se}$$

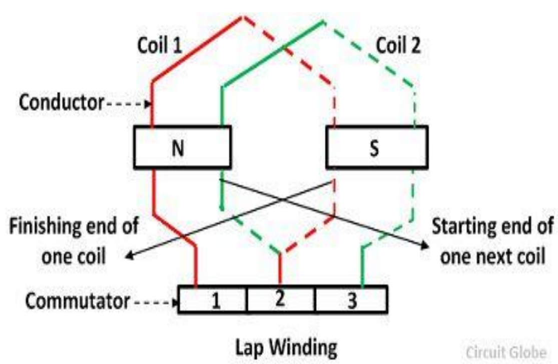
If the brush contact drop is included, the terminal voltage equation can be written as

$$V = E_g - I_a R_a - I_L R_{se} - 2V_b$$

$$\text{Power developed} = E_g I_a$$

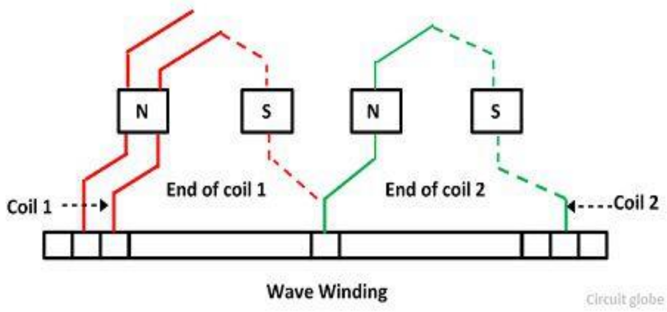
$$\text{Power output} = V I_L$$

LAP WINDING: In lap winding, the conductors are joined in such a way that their parallel paths and poles are equal in number. The end of each armature coil is connected to the adjacent segment on the commutator. The number of brushes in the lap winding is equal to the number of parallel paths, and these brushes are equally divided into negative and positive polarity.



The lap winding is mainly used in low voltage, high current machine applications. They are three types (i) Simplex Lap Winding (ii) Duplex Lap Winding (iii) Triplex Lap Winding.

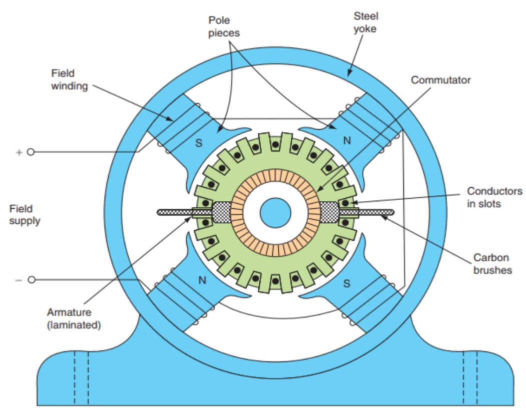
WAVE WINDING : In wave winding, only two parallel paths are provided between the positive and negative brushes. The finishing end of the one armature coil is connected to the starting end of the other armature coil commutator segment at some distance apart.



In this winding, the conductors are connected to two parallel paths irrespective of the number of poles of the machine. The number of brushes is equal to the number of parallel paths. The wave winding is mainly used in high voltage, low current machines.

DC MOTORS

CONSTRUCTION OF DC MOTOR: Its construction is same as that of DC Generator as shown below.



WORKING OF DC MOTOR: An electric motor is an electrical machine which converts electrical energy into mechanical energy. The basic working principle of a DC motor is: "whenever a current carrying conductor is placed in a magnetic field, it experiences a mechanical force". The direction of this force is given by Fleming's left-hand rule and its magnitude is given by F = BIL. Where, B = magnetic flux density, I = current and L = length of the conductor within the magnetic field.

Fleming's left hand rule: If we stretch the first finger, second finger and thumb of our left hand to be perpendicular to each other, and the direction of magnetic field is represented by the first finger, direction of the current is represented by the second finger, then the thumb represents direction of the force experienced by the current carrying conductor.

THE CONCEPT OF BACK EMF :

When the armature of a motor is rotating, the conductors are also cutting the magnetic flux lines and hence according to the Faraday's law of electromagnetic induction, an emf induces in the armature conductors. The direction of this induced emf is such that it opposes the armature current

(I_a). The circuit diagram below illustrates the direction of the back emf and armature current. Magnitude of the Back emf can be given by emf equation of a DC generator.

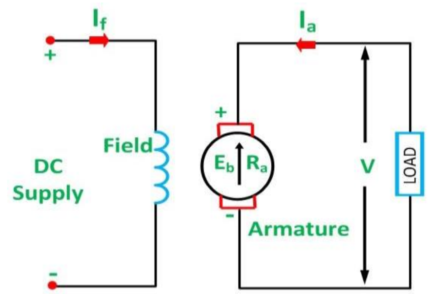
SEPARATELY EXCITED DC MOTORS:

As the name signifies, the field coils or field windings are energized by

a separate DC source as shown in the circuit diagram shown below

Here $I= I_a=I_L,$ Field winding I_f is nothing to do with I_a or I_L here

$\mathbf{V_t= E_b + I_a R_a}$



SELF EXCITED DC MOTOR:

(i) **Shunt Wound Motor:**

$$I = I_a + I_{sh} \dots \dots \dots .. (1) \qquad V = I_{sh}R_{sh} \dots \dots .. (2)$$

$$V = E + I_aR_a \dots \dots \dots (3)$$

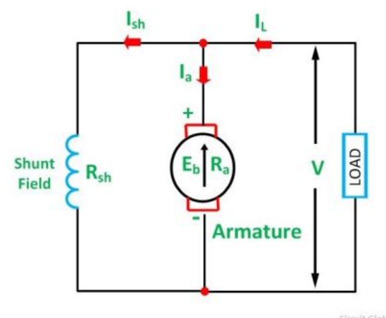
$$VI = P_m + I_a^2R_a + I_{sh}^2R_{sh} \dots\dots\dots\dots(4)$$

$$VI = P_m + I_a^2R_a + VI_{sh}$$

$$P_m = VI - VI_{sh} - I_a^2R_a = V(I - I_{sh}) - I_a^2R_a$$

$$P_m = VI_a - I_a^2R_a = (V - I_aR_a)I_a$$

$$P_m = EI_a \dots \dots \dots (5)$$

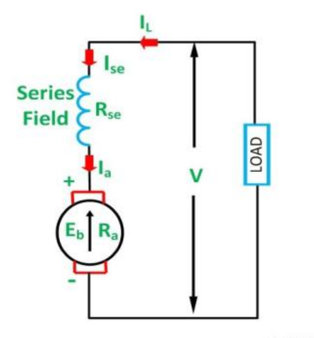


Series Wound Motor: In the series motor, the field winding is connected in series with the armature winding. The connection diagram is shown.

Here $I = I_{se} = I_a$

$$V = E + I(R_a + R_{se}) \dots \dots \dots (8)$$

$$VI = EI + I^2(R_a + R_{se}) \dots \dots \dots (9)$$



Power input = Mechanical power developed + losses in the armature +losses in the field

$$VI = P_m + I^2R_a + I^2R_a \dots \dots .. (10)$$

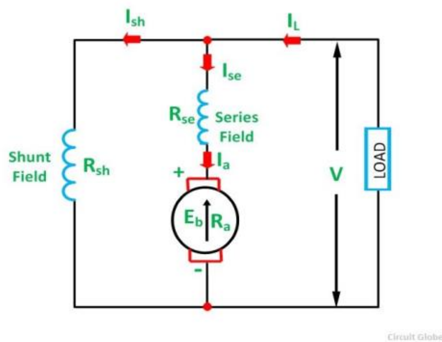
By comparing will get

$$P_m = EI \dots \dots \dots (11)$$

Compound Wound Motor:

The compound motor is further subdivided as **Cumulative Compound** Motor and **Differential Compound** Motor. In cumulative compound motor the flux produced by both the windings is in the same Direction. $\varphi_r = \varphi_{sh} + \varphi_{se}$

In differential compound motor, the flux produced by the series field windings is opposite to the flux produced by the shunt field winding, i.e $\varphi_r = \varphi_{sh} - \varphi_{se}$



TORQUE EQUATION OF DC MOTOR: When the current carrying current is placed in the magnetic field, a force is exerted or it which exerts turning moment or torque F x r. This torque is produced due to the electromagnetic effect, hence is called **Electromagnetic torque.**

We have $V = E_b + I_a R_a \quad \dots\dots (1)$

$$VI_a = E_b I_a + I_a^2 R_a \quad \dots\dots (2)$$

Where, VI_a is the electrical power input to the armature & $I^2{}_a R_a$ is the copper loss in the armature.

With equation no (2) we can say Total electrical power supplied to the armature = Mechanical power developed by the armature + losses due to armature resistance.

Now, the mechanical power developed by the armature is Pm. There fore $P_m = E_b\, I_a$

Also, the mechanical power developed in the rotating armature can be given with torque T and speed n.

$$P_m = \omega T = 2\pi\, nT \quad \dots\dots (4)$$

Where n is in revolution per seconds (rps) and T is in Newton-Meter.

Hence, $2\pi\, nT = E_b I_a$ or

$$T = \frac{E_b I_a}{2\pi n}$$

where $n = \frac{N}{60}$ n= in rps

But we haveWhere $E_b = \frac{\varphi ZNP}{60\ A}$ N is the speed in revolution per minute (rpm)

Therefore,

$$E_b = \frac{\varphi ZnP}{A}$$

So, the torque equation is given as $T = \frac{\varphi ZP}{2\pi A} . I_a$ $= 0.159\ ø\ Z\ P\ I_a/A$

For a particular DC Motor, the number of poles (P) and the number of conductors per parallel path (Z/A) are constant.

Where, $T = K\varphi I_a$

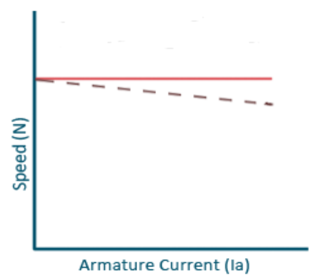
$$K = \frac{ZP}{2\pi A} \quad \text{or}$$

$$T \propto \varphi I_a \ldots \ldots (5)$$

Thus, from the above equation (5) it is clear that the torque produced in the armature is directly proportional to the flux per pole and the armature current. Moreover, the direction of electromagnetic torque developed in the armature depends upon the current in armature conductors. If either of the two is reversed the direction of torque produced is reversed and hence the direction of rotation. But when both are reversed, and direction of torque does not change.

CHARACTERISTICS OF DC SHUNT MOTORS:

Speed vs. Armature current (N-Ia):



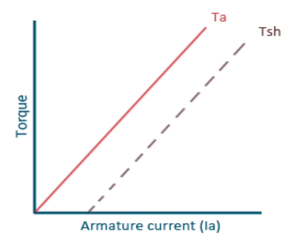
We have $E_b = \frac{\varphi ZNP}{60\ A}$

this $N \propto Eb/\phi$

Also we have $\mathbf{E_b = V - I_a R_a}$

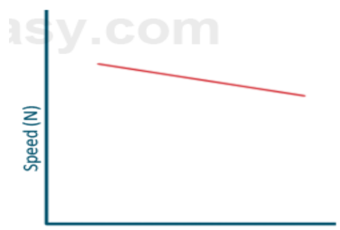
As flux ϕ is assumed to be constant, we can say $\mathbf{N \propto Eb}$.
But, as back emf is also almost constant, the speed should remain constant. But practically, ϕ as well as Eb decreases with increase in load. Back emf Eb decreases slightly more than ϕ, therefore, the speed decreases slightly. Generally, the speed decreases only by 5 to 15% of full load speed. Therefore, **a shunt motor can be assumed as a constant speed motor**. In speed vs. armature current characteristic in the following figure, the straight horizontal line represents the ideal characteristic and the actual characteristic is shown by the dotted line.

Torque vs. Armature current (Ta-Ia): We have $T \propto \phi\ I_a$



In case of DC shunt motors, we can assume the field flux ϕ to be constant.
Though at heavy loads, ϕ decreases in a small amount due to increased armature reaction. As we are neglecting the change in the flux ϕ, we can say that torque is proportional to armature current. Hence, the Ta-Ia characteristic for a dc shunt motor will be a straight line through the origin. Since heavy starting load needs heavy starting current, shunt motor should never be started on a heavy load.

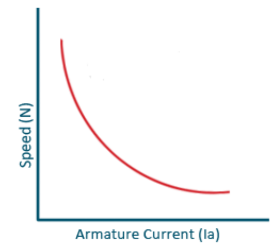
Torque vs Speed (Ta-N) :



The speed torque characteristics are almost similar to speed current characteristics. This characteristics can be obtained from Speed- Current and Torque-Current characteristics of Shunt Motor.

CHARACTERISTICS OF DC SERIES MOTORS:

Speed vs. Armature current (N-Ia):

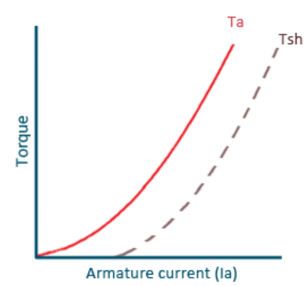


We have $N \propto V - I_a (R_a + R_{sc})/ \phi \propto E_b / \phi$

For small load current (and hence for small armature current) change in back emf

E_b **[**ie, $I_a (R_a + R_{sc})$] is small and it may be neglected. Hence, for small currents speed is inversely proportional to ϕ. As we know that in series motors flux is directly proportional to Ia, speed is inversely proportional to Ia. Therefore, when armature current is very small the speed becomes dangerously high. That is **why a series motor should never be started without some mechanical load**. But, at heavy loads, armature current Ia is large. And hence, speed is low which results in decreased back emf Eb. Due to decreased Eb, more armature current is allowed.

Torque vs Armature current (T_a-I_a): This characteristic is also known as **Electrical Characteristic.** We know that

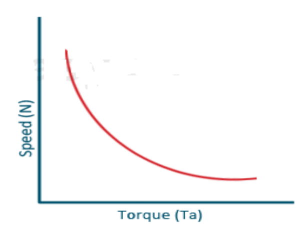


In DC series motors, field winding is connected in series with the armature, i.e. $I_a = I_f$. Therefore, before magnetic saturation of the field, flux ϕ is directly proportional to I_a Hence, before magnetic saturation Ta α $I_a{}^2$. Therefore, the Ta- I_a curve is parabola for smaller values of I_a. After magnetic saturation of the field poles, flux ϕ is independent of armature current Ia. Therefore, the torque varies proportionally to Ia only, $T \propto I_a$. Therefore, after magnetic saturation, Ta- I_a curve becomes a straight line.

The shaft torque (Tsh) is less than armature torque (Ta) due to stray losses. Hence, the curve Tsh vs Ia lies slightly lower.

In DC series motors, (prior to magnetic saturation) torque increases as the square of armature current, these motors are used where high starting torque is required.

Speed vs Torque (N-Ta):



This characteristic is also called as **mechanical characteristic**. From the above Two **characteristics (Speed Vs Armature current & Torque Vs Armature Current)of DC series motor**, it can be found that when speed is high, torque is low and vice versa. **The shape of the graph is called Rectangular Hyperbola.**

Applications of DC motors

elevators, steel mills, rolling mills, locomotives, and excavators etc.

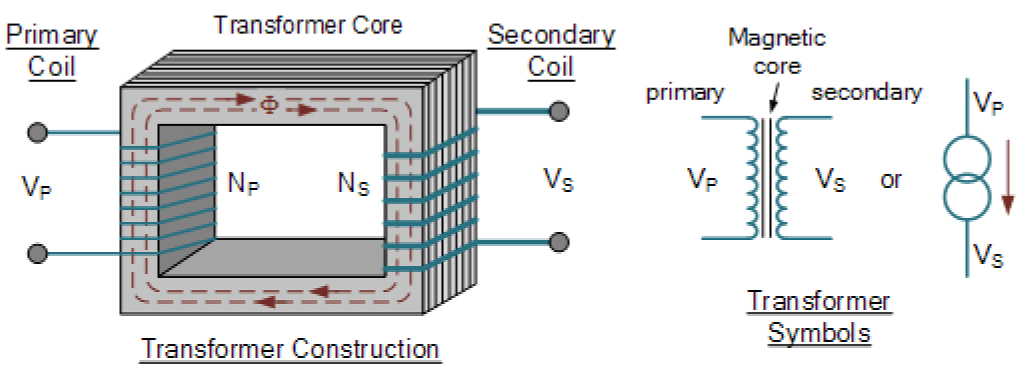
TRANSFORMERS

Necessity of transformer:

Transformers help improve power systems safety and efficiency by increasing and lowering voltage levels as and when needed. These are used in a wide range of residential and industrial applications, mainly and perhaps most significantly in long distance power distribution and regulation.

Electrical power is typically produced at 11Kv. AC power is distributed over long distances at very high voltages for economic reasons, say220 kV or 440 kV. In the generating stations, therefore, a step-up transformer is applied. Now, for safety reasons, the voltage at different substations is stepped down to different rates by step down transformer to feed the electricity to the different locations and thus the power is used at 400/230 V.

Working Principle of Transformers-



An electrical transformer uses the Faraday's electromagnetic induction law to work –"Change in the rate of flux connection is directly proportional to the induced EMF in a conductor or coil."
The physical basis of a transformer is the mutual induction between two circuits which are connected by a common magnetic flux. It typically has 2 windings: primary and secondary. Such windings share a laminated magnetic core, and the reciprocal induction between these circuits leads to the movement of electricity from one point to another.

Depending on the amount of connected flux between the primary and secondary windings, different flux contact rates can occur. A low reluctance path is common to both windings in order to ensure maximum flux relation, i.e. maximum flux passing through and linking from the primary to the secondary winding. This leads to increased work performance productivity and forms the transformer's cores.

Applying alternating voltage to the primary side windings produces an alternating flux in the core. It links all windings in the primary as well as the secondary side to induce EMF. When there is a load connected to the secondary section, EMF in the secondary winding causes a current, known as the load current.

This is how electrical transformers transmit AC power from one (primary) circuit to another (secondary) by converting electrical energy from one value to another, changing the rate of voltage but not the frequency.

Types and construction of single phase transformers:

A *single phase transformer* consists of two windings viz. *primary winding* and *secondary winding* put on a magnetic core. The magnetic core is made from thin sheets (called *laminations*) of *high graded silicon steel* and provides a definite path to the magnetic flux. These laminations reduce the *eddy-current losses* while the silicon steel reduces the *hysteresis losses*.

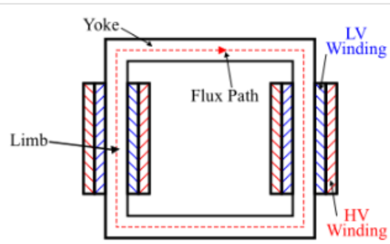
The laminations are insulated from each other by *enamel insulation coating*. The thin laminations are stacked together to form the core of the transformer. The air-gap between the laminations should be minimum so that the excitation current being minimum.

For a single phase transformer, there are two types of transformer constructions viz. the *core type* and the *shell type*.

Core Type Transformer Construction

In *core type construction* of the transformer, the magnetic circuit consists of two vertical lags (called *limbs*) and two horizontal sections called *yokes*. To minimise the effect of leakage flux, half of each winding is placed on each limb (see the figure).

The low-voltage winding is placed next to the core while the high-voltage winding over the low-voltage winding to reduce the insulation requirements. Therefore the two windings are arranged as *concentric coils* and known as *cylindrical winding*.



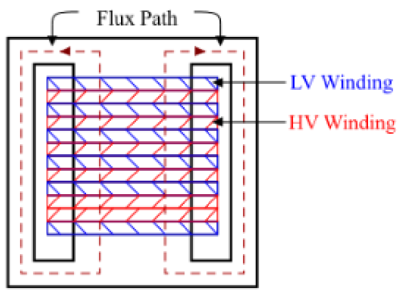
Core Type Construction

Features of core type transformer:

(i) Windings encircle the core
(ii) One magnetic circuit
(iii) Preferred in low power transformers where
(iv) Voltage ratings < 11KV
(v) Core is made from stacking silicon steel laminations-To reduce hysteresis and eddy current loss
(vi) Each lamination is coated with varnish to provide insulation
(vii) Windings are made of copper or aluminum

Shell Type Transformer Construction

In the *shell type construction* of transformer, the magnetic circuit consists of three limbs, both the primary and secondary windings are placed on the central limb and the two outer limbs complete the low reluctance flux path. The each winding is sub-divided into sections viz. the low voltage (LV) section and the high-voltage (HV) section, which are alternatively put one over the other in the form of sandwich (see the figure). Therefore, such windings are called *sandwich winding* or *disc winding*.



Shell Type Construction

Features of Shell Type Transformer

(i) Windings encircle the core
(ii) Two magnetic circuit
(iii) Preferred in high power transformers where voltage ratings > 11KV
(iv) Core is made from stacking silicon steel laminations- To reduce hysteresis and eddy current loss
Each lamination is coated with varnish to provide insulation
(vi) Windings are made of copper or aluminum

DIFFERENCES BETWEEN CORE TYPE AND SHELL TYPE TRANSFORMERS

SL. NO	CORE TYPE	SHELL TYPE
1.	The windings encircle the core	The core encircles most part of the windings.
2.	Single magnetic circuit	Double magnetic circuit.
3.	Core has 2 limbs	Core has 3 limbs.
4.	Cylindrical coils	Sandwiched coil are used.
5.	Natural cooling is effective	Natural cooling does not exist.
6.	Coils can be easily removed	Coils cannot be removed easily.
7.	Preferred for low voltage transformers.	Preferred for high voltage transformers.

EMF EQUATION OF A TRANSOFORMER

Due to the sinusoidally varying voltage V_1 applied to the primary voltage, the flux set up in the core, is given by

$$\Phi = \Phi_m \sin \omega t = \Phi_m \sin 2\pi ft$$

The resulting induced emf in a winding of N turns,

$$e = -N\frac{d\Phi}{dt} = -N\frac{d}{dt}(\Phi_m \sin \omega t)$$
$$= -N\omega\Phi_m \cos \omega t = \omega N\Phi_m \sin(\omega t - \pi/2)$$

Thus, the peak value of the induced emf, $E_m = \omega N\Phi m$

Therefore, the rms value of the induced emf E,

$$E = \frac{E_m}{\sqrt{2}} = \frac{\omega N\Phi_m}{\sqrt{2}} = \frac{2\pi fN\Phi_m}{\sqrt{2}} = 4.44 fN\Phi_m$$

or $\boxed{E = 4.44 fN\Phi_m}$

LOSSES IN TRANSFORMERS

There will be two main losses in transformers

1. Core loss (Constant Loss-Wi) (ii) Copper Loss (Variable Loss- Wcu)

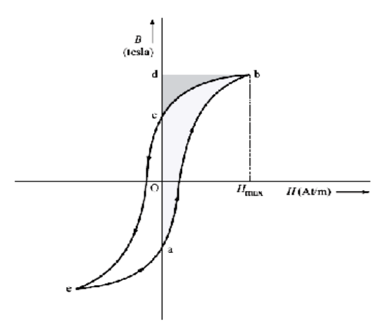
Iron Loss (core loss) : These are the Hysteresis Loss and Eddy current Loss.

Iron loss is a constant loss and does not vary with load.

Each time the magnetic field is reversed, a small amount of energy is lost due to hysteresis within the core.

Determined by conducting no load (open circuit) test.

HYSTERESIS LOSS:



When alternating current flows through the windings, the core material undergoes cyclic process of magnetization and demagnetization.

$$W_h = K_h B_m^{1.6} f V watt$$

K_h = hysteresis coefficient whose value depends upon the material
(K_h = 0.025 for cast steel, K_h = 0.001 for silicon steel)
Bm = Maximum Value of Flux Density in Tesla
f= Frequency in Hz
V= Volume of the core
High silicon content in the core minimizes the hysteresis loss

COPPER LOSS:

Current flowing through the windings causes resistive power loss

Heating of the conductors.

$$W_{cu} = I_1^2 R_1 + I_2^2 R_2 \ Watts$$

It varies as the square of the load currents

Loss can be determined by conducting short circuit test

EFFICIENCY OF A TRANSFORMER:

The **Efficiency** of the transformer is defined as the ratio of useful output power to the input power. The input and output power are measured in the same unit. Its unit is either in Watts (W) or KW. **Transformer efficiency** is denoted by **η**.

$$\eta = \frac{\text{output power}}{\text{input power}} = \frac{\text{output power}}{\text{output power + losses}}$$

$$\eta = \frac{\text{output power}}{\text{output power + iron losses + copper losses}}$$

$$\eta = \frac{V_2 I_2 \cos\varphi_2}{V_2 I_2 \cos\varphi_2 + P_i + P_c}$$

V_2 – Secondary terminal voltage

I_2 – Full load secondary current

$\cos\phi_2$ – power factor of the load

P_i – Iron losses = hysteresis losses + eddy current losses

P_c – Full load copper losses = $I_2^2 R_{es}$

Consider, if the x is the fraction of the full load, the efficiency of the transformer at any load x is expressed as

$$\eta_x = \frac{x \text{ X output}}{x \text{ X output} + P_i + x^2 P_c} = \frac{x V_2 I_2 \cos\varphi_2}{x V_2 I_2 \cos\varphi_2 + P_i + x^2 I_2^2 R_{es}}$$

The copper losses vary according to the fraction of the load.

CONDITION FOR MAXIMUM EFFICIENCY OF A TRANSFORMER:

The efficiency of the transformer along with the load and the power factor is expressed by the given relation:

$$\eta = \frac{V_2 I_2 \cos\varphi_2}{V_2 I_2 \cos\varphi_2 + P_i + I_2^2 R_{es}} = \frac{V_2 \cos\varphi_2}{V_2 \cos\varphi_2 + P_i / I_2 + I_2 R_{es}} \dots \dots \dots (1)$$

The value of the terminal voltage V_2 is approximately constant. Thus, for a given power factor the Transformer efficiency depends upon the load current I_2. In equation (1), the numerator is constant and the transformer efficiency will be maximum if the denominator with respect to the variable I_2 is equated to zero.

$$\frac{d}{dI_2} = \left(V_2 \, Cos\varphi_2 + \frac{P_i}{I_2} + I_2 R_{es} \right) = 0 \qquad \text{or} \qquad 0 - \frac{P_i}{I_2^2} + R_{es} = 0$$

Or

$$I_2^2 R_{es} = P_i \; \dots\dots\dots (2)$$

i.e COPPER LOSSES = IRON LOSSES

Thus, the transformer will give the maximum efficiency when their copper loss is equal to the iron loss.

$$\eta_{max} = \frac{V_2 I_2 Cos\varphi_2}{V_2 I_2 Cos\varphi_2 + 2P_i} \qquad as\ (P_c = P_i)$$

From the above equation, the value of output current I_2 at which the transformer efficiency will be maximum is given as

$$I_2 = \sqrt{\frac{P_i}{R_{es}}}$$

If x is the fraction of full load KVA at which the efficiency of the transformer is maximum then,

Copper losses = $x^2 P_c$ (where P_c is the full load copper losses)

Iron losses = P_i

For maximum efficiency

$\mathbf{x^2 P_c = P_i}$

Therefore $$x = \sqrt{\frac{P_i}{P_c}} \dots\dots\dots (3)$$

Thus, output KVA corresponding to maximum efficiency

$$\eta_{max} = x \text{ X full load KVA} \dots\dots\dots (4)$$

Putting the value of x from the above equation (3) in equation (4) we will get,

$$\eta_{max} = \sqrt{\frac{P_i}{P_c}} \text{ X full load KVA}$$

$$\eta_{max} = \text{Full load KVA X} \sqrt{\frac{\text{iron losses}}{\text{copper losses at full load}}} \dots\dots\dots (5)$$

The above equation (5) is the maximum efficiency condition of the transformer.