LECTURE NOTES

ON

ELECTRICAL MACHINES - I

2025 - 2026

B. Tech III Semester

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Energy Balance

According to the principle of conservation of energy, the energy can not be created or destroyed but it can be transformed from one form to another. The process of energy transformation is reversible but there are certain losses due to practical devices. Hence in energy conversion process the entire energy can not be transformed from one form to another. The loss in the process is called **energy loss.** In addition to the loss, some part of energy gets stored in the medium like magnetic field. This is called **energy stored.** There exists a perfect energy balance in the process of electromechanical energy conversion. Thus the input energy has three parts, transformed energy, energy loss and stored energy. The energy loss gets converted to heat energy in the electromechanical devices. Thus the **energy balance equation** for generating and motoring actions can be written as,

$$\begin{bmatrix}\text{Electrical energy}\\ \text{input from}\\ \text{electrical system}\end{bmatrix} = \begin{bmatrix}\text{Mechanical}\\ \text{transformed}\\ \text{output energy}\end{bmatrix} + \begin{bmatrix}\text{Change}\\ \text{energy}\\ \text{stored}\end{bmatrix} + \begin{bmatrix}\text{Total energy loss}\\ \text{i.e. energy dissipated}\\ \text{in the form of heat}\end{bmatrix}$$

... For motor (1)

$$\begin{bmatrix}\text{Mechanical energy}\\ \text{input from}\\ \text{mechanical system}\end{bmatrix} = \begin{bmatrix}\text{Electrical}\\ \text{transformed}\\ \text{energy output}\end{bmatrix} + \begin{bmatrix}\text{Change in}\\ \text{energy}\\ \text{stored}\end{bmatrix} + \begin{bmatrix}\text{Total energy loss}\\ \text{i.e. energy}\\ \text{dissipated}\end{bmatrix}$$

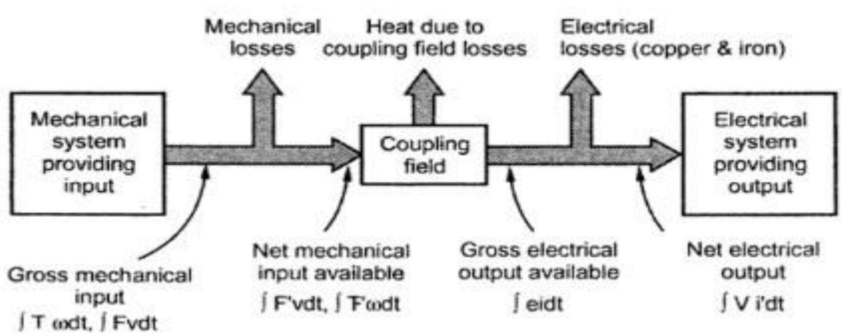
... For generator (2)

In these energy balance equations, the transformed energy terms are always positive but change in energy stored may be positive or negative. If energy stored increases, it is positive while if it decreases it is negative. The energy dissipated in the form of heat can

Energy Flow in Electromechanical Energy Conversion Device

For any electromechanical energy conversion, there are two systems, electrical system and mechanical system. These systems are coupled through a coupling field which is mostly a magnetic one.

Now for a generator, input is mechanical energy but entire input can not reach to the coupling field for the conversion. Part of it gets lost in the form of friction and windage losses. The available mechanical input is converted to electrical by the device via coupling field. But net output can not be equal to converted electrical energy as some part of it gets lost in the form of electrical losses such as copper (I^2R) losses and core or iron losses. The Fig. 2.2 shows the **energy flow diagram** of electromechanical energy conversion device working as a generator.



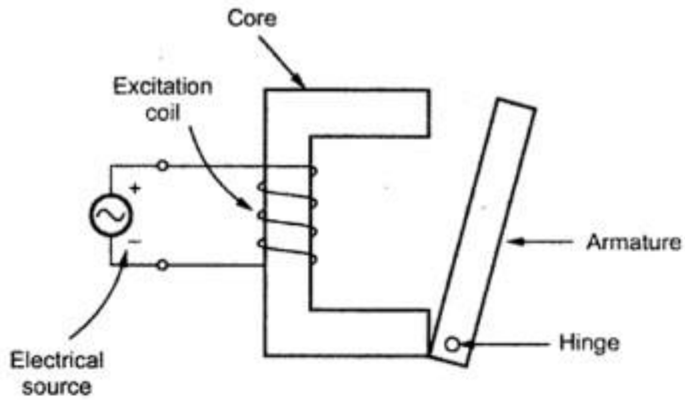


Fig. 2.4 Singly excited system

In special devices more than one excitation coils are necessary. Such systems are called multiple excited systems. Very commonly used multiple excited systems use two excitation coils and are called **doubly excited systems**. The examples are synchronous motors, alternators, d.c. shunt machines, loudspeakers etc. in which separate excitation coils are provided on stator and rotor. The Fig. 2.5 shows one such type of doubly excited magnetic system. Let us study the details of these two types of magnetic systems.

Electromechanical-Energy-Conversion Principles

The electromechanical-energy-conversion process takes place through the medium of the electric or magnetic field of the conversion device of which the structures depend on their respective functions.

- Transducers: microphone, pickup, sensor, loudspeaker
- Force producing devices: solenoid, relay, and electromagnet
- Continuous energy conversion equipment: motor, generator

Forces and Torques in Magnetic Field Systems

The Lorentz Force Law gives the force *F* on a particle of charge *q* in the presence of electric and magnetic fields.

$$F = q\left(E + v \times B\right)$$

Where, *F* : newtons, *q*: coulombs, *E*: volts/meter, *B* : telsas, *v*: meters/second

- In a pure electric-field system,

$$F = qE$$

- In pure magnetic-field systems,

$$F = q\left(v \times B\right)$$

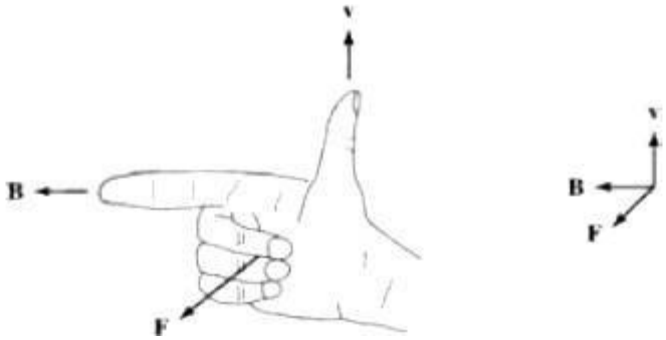


Figure : Right hand rule

- For situations where large numbers of charged particles are in motion,

$$F_v = \rho\left(E+v\times B\right)$$

$$J = \rho v$$

$$F_v = J\times B$$

ρ (charge density): coulombs/m^3, F_v (force density): newtons/m^3, $J = \rho v$ (current density): amperes/m^2.

Most electromechanical-energy-conversion devices contain magnetic material.

- Forces act directly on the magnetic material of these devices which are constructed of rigid, non-deforming structures.
- The performance of these devices is typically determined by the net force, or torque, acting on the moving component. It is rarely necessary to calculate the details of the internal force distribution.
- Just as a compass needle tries to align with the earth's magnetic field, the two sets of fields associated with the rotor and the stator of rotating machinery attempt to align, and torque is associated with their displacement from alignment.
    - In a motor, the stator magnetic field rotates ahead of that of the rotor, pulling on it and performing work.
    - For a generator, the rotor does the work on the stator.

The Energy Method

> Based on the principle of conservation of energy: energy is neither created nor destroyed; it is merely changed in form.

> Fig. 1.2 shows a magnetic-field-based electromechanical-energy-conversion device.

- A lossless magnetic-energy-storage system with two terminals
- The electric terminal has two terminal variables: e (voltage), i (current).
- The mechanical terminal has two terminal variables: f_{fld} (force), x (position)
- The loss mechanism is separated from the energy-storage mechanism.

– Electrical losses: ohmic losses...
– Mechanical losses: friction, windage...

> Fig. 1.3: a simple force-producing device with a single coil forming the electric terminal, anda

movable plunger serving as the mechanical terminal.
- The interaction between the electric and mechanical terminals, i.e. the electromechanical energy conversion, occurs through the medium of the magnetic stored energy.

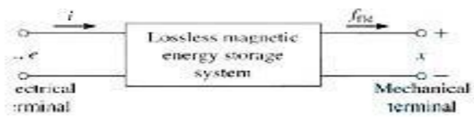


Fig 1.2 Schematic diagram of magnetic-electromechanical-energy-conversion

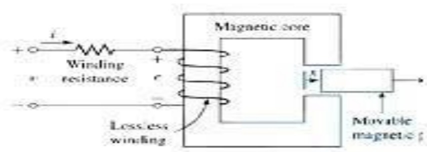


Fig. 1.3 Schematic diagram of simple force-producing device

- W_{fld} : the stored energy in the magnetic field

$$\frac{dW_{fld}}{dt} = ei - f_{fld}\frac{dx}{dt}$$

$$e = \frac{d\lambda}{dt}$$

$$dW_{fld} = i\,d\lambda - f_{fld}\,dx$$

- From the above equation force can be solved as a function of the flux λ and the mechanicalterminal position *x*.
- The above equations form the basis for the energy method

Energy Balance

Consider the electromechanical systems whose predominant energy-storage mechanism is in magnetic fields. For motor action, the energy transfer can be accounted as

$$\begin{pmatrix}\text{Energy input}\\ \text{form electric}\\ \text{sources}\end{pmatrix} = \begin{pmatrix}\text{Mechanical}\\ \text{energy}\\ \text{output}\end{pmatrix} + \begin{pmatrix}\text{Increase in energy}\\ \text{stored in magnetic}\\ \text{field}\end{pmatrix} + \begin{pmatrix}\text{Energy}\\ \text{converted}\\ \text{into heat}\end{pmatrix}$$

The ability to identify a lossless-energy-storage system is the essence of the energy method.

- This is done mathematically as part of the modeling process.
- For the lossless magnetic-energy-storage system of Fig. 1.2 can be rearranged and gives

$$dW_{elec} = dW_{mech} + dW_{fld}$$

where

$dW_{elec} = id\lambda$ = differential electric energy input

$dW_{mech} = f_{fld}dx$ = differential mechanical energy output

dW_{fld} = differential change in magnetic stored energy

- Here *e* is the voltage induced in the electric terminals by the changing magnetic stored energy. It is through this reaction voltage that the external electric circuit supplies powerto the coupling magnetic field and hence to the mechanical output terminals.

$$dW_{elec} = ei\ dt$$

- The basic energy-conversion process is one involving the coupling field and its actionand reaction on the electric and mechanical systems.
- Combining above two equation –

$$dW_{elec} = ei\ dt = dW_{mech} + dW_{fld}$$

Energy in Singly-Excited Magnetic Field Systems

In energy-conversion systems the magnetic circuits have air gaps between the stationary and moving members in which considerable energy is stored in the magnetic field.

> This field acts as the energy-conversion medium, and its energy is the reservoir between the electric and mechanical system.

Fig. 1.4 shows an electromagnetic relay schematically. The predominant energy storage occurs in the air gap, and the properties of the magnetic circuit are determined by the dimensions of the air gap.

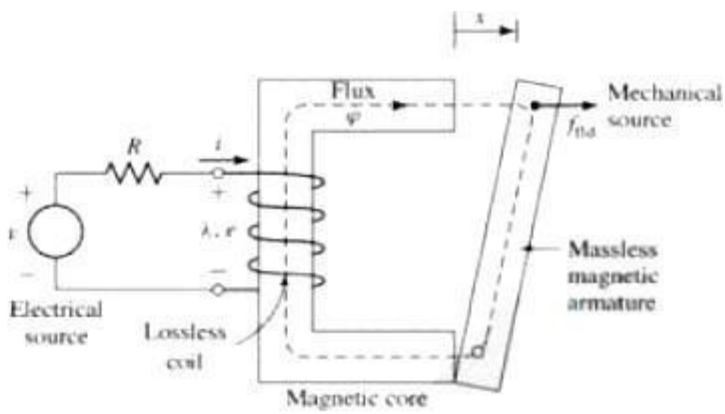


Fig.1.4 Schematic of an electromagnetic relay

W_{fld} is uniquely specified by the values of λ and x. Therefore, λ and x are referred to as state variables.

Since the magnetic energy storage is lossless, it is conservative system. W_{fld} is the same regardless of how λ and x are brought to their final values. Fig 1.5 shows where tow separate the paths.

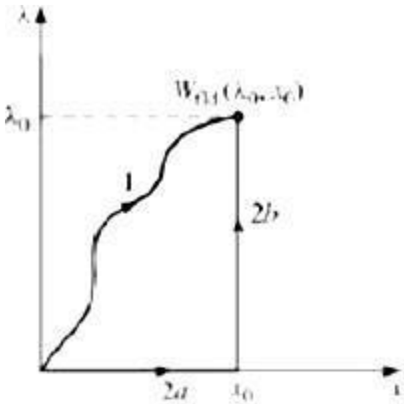


Fig. 1.5 Integration paths for W_{fld}

On path 2a, $d\lambda=0$ and $f_{fld}=0$. Thus $df_{fld}=0$ on path 2a.

On path 2b, $dx=0$. Therefore the following equation will result

$$W'_{fld} = \int_V \left(\int_{H_c}^{H_0} B \cdot dH \right) dV$$

For magnetically linear systems the energy and co-energy are numerically equal

$$\frac{1}{2}\lambda^2 / L = \frac{1}{2}Li^2, \ \frac{1}{2}B^2/\mu = \frac{1}{2}\mu H^2$$

Graphical representation of energy and co-energy in singly excited magnetic field system is shown below.

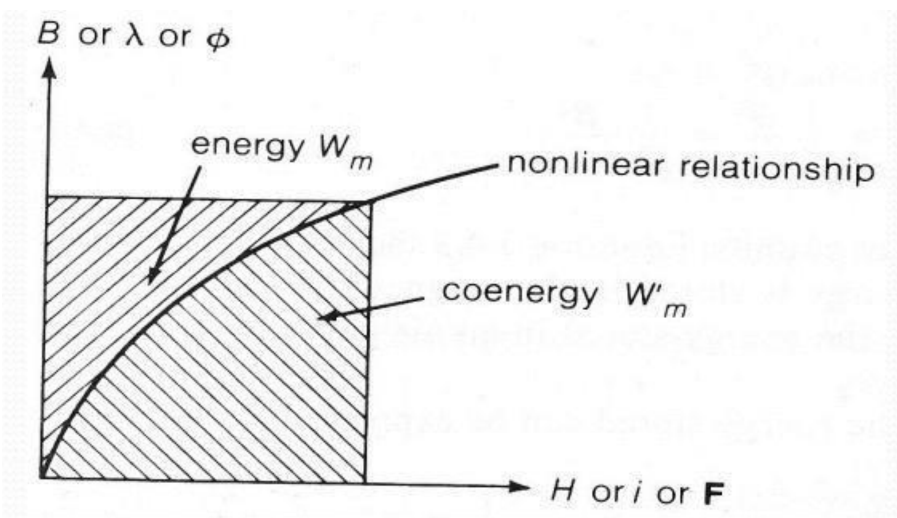


Figure: Graphical representation of energy and co-energy

Multiply Excited Magnetic Field Systems:

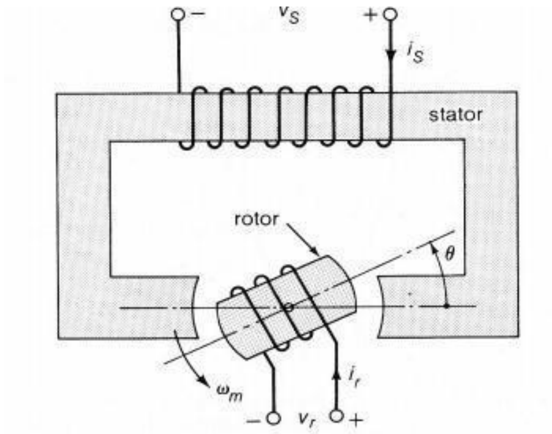


Figure: Doubly excited magnetic field system

The flux linkages of the stator and rotor windings can be expressed as functions of the coil currents:

$$\lambda_s = L_{ss}\, i_s + L_{sr}\, i_r$$

$$\lambda_r = L_{sr}\, i_s + L_{rr}\, i_r$$

where L_{ss} and L_{rr} are the self-inductances of the stator and rotor coils respectively, and L_{sr} is the stator-rotor mutual inductance. All these inductances are generally functions of the angle θ between the magnetic axes of the stator and rotor windings.

$$\begin{aligned} v_s &= R_s\, i_s + p\,\lambda_s \\ &= R_s\, i_s + L_{ss}(p\, i_s) + i_s(p\, L_{ss}) + L_{sr}(p\, i_r) + i_r(p\, L_{sr}) \end{aligned}$$

$$\begin{aligned} v_r &= R_r\, i_r + p\,\lambda_r \\ &= R_r\, i_r + L_{sr}(p\, i_s) + i_s(p\, L_{sr}) + L_{rr}(p\, i_r) + i_r(p\, L_{rr}) \end{aligned}$$

Neglecting the reluctances of the stator- and rotor-iron circuits, the electromagnetic torque can be found either from the energy or coenergy stored in the magnetic field of the air-gap region:

$$T_e = -\frac{\partial W_m(\lambda_s, \lambda_r, \theta)}{\partial \theta} = +\frac{\partial W_m'(i_s, i_r, \theta)}{\partial \theta}$$

For a linear system, the energy or coenergy stored in a pair of mutually coupled inductors is given by

$$W_m'(i_1, i_2, \theta) = \frac{1}{2} L_{ss}\, i_s^2 + L_{sr}\, i_s\, i_r + \frac{1}{2} L_{rr}\, i_r^2$$

DC GENERATORS

Principle of Operation of a D.C. Generator

All the generators work on a principle of dynamically induced e.m.f. This principle nothing but the Faraday's law of electromagnetism induction. It states that, 'whenever the number of magnetic lines of force i.e. flux linking with a conductor or a coil changes, an electromotive force is set up in that conductor or coil.' The change in flux associated with the conductor can exist only when there exists a relative motion between a conductor and the flux. The relative motion can be achieved by rotating conductor with respect to flux or by rotating flux with respect to a conductor. So a voltage gets generated in a conductor, as long as there exists a relative motion between conductor and the flux.

Such an induced e.m.f. which is due to the physical movement of coil or conductor with respect to flux or movement of flux with respect to coil or conductor is called dynamically induced e.m.f.

Key Point:

So a generating action requires following basic components to exist,

i) The conductor or a coil

ii) The relative motion between conductor and flux.

In a particular generator, the conductors are rotated to cut the magnetic flux, keeping flux stationary. To have a large voltage as the output, the number of conductors are connected together in a specific manner, to form a winding. This winding is called armature winding of a d.c. machine. The part on which this winding is kept is called armature of a d.c. machine. To have the rotation of conductors, the conductors placed on the armature are rotated with the help of some external device. Such an external device is called a prim mover. The commonly used prim movers are diesel engines, steam engines, steam turbines, water turbines etc. The necessary magnetic flux is produced by current carrying winding which is called field winding. The direction of the induced e.m.f. can be obtained by using Fleming's right hand role.

Single Loop DC Generator

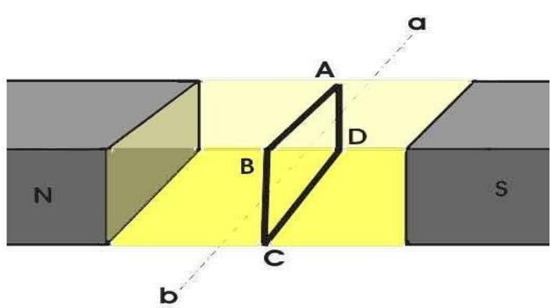


Figure: Single Loop Generator

In the figure above, a single loop of conductor of rectangular shape is placed between two opposite poles of magnet.

Let's us consider, the rectangular loop of conductor is ABCD which rotates inside the magnetic field about its own axis ab. When the loop rotates from its vertical position to its horizontal position, it cuts the flux lines of the field. As during this movement two sides, i.e. AB and CD of the loop cut the flux lines there will be an emf induced in these both of the sides (AB and BC) of the loop.

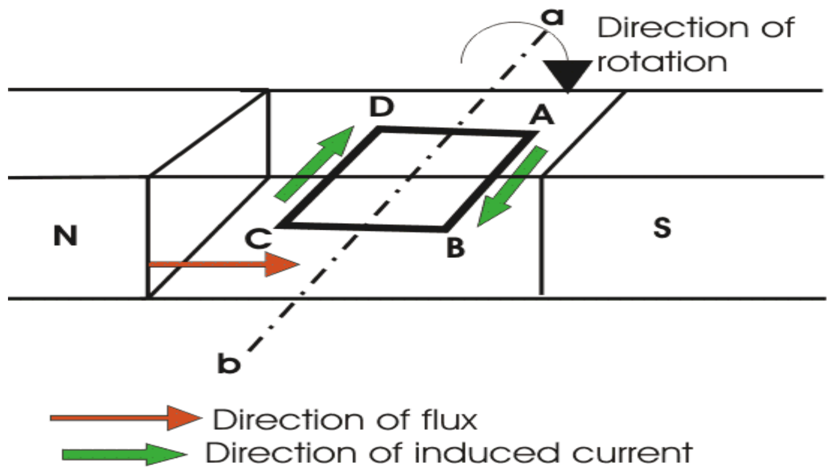


Figure: Single Loop Generator

As the loop is closed there will be a current circulating through the loop. The direction of the current can be determined by Flemming's right hand Rule. This rule says that if you stretch thumb, index finger and middle finger of your right hand perpendicular to each other, then thumbs indicates the direction of motion of the conductor, index finger indicates the direction of magnetic field i.e. N - pole to S - pole, and middle finger indicates the direction of flow of current through the conductor.
Now if we apply this right hand rule, we will see at this horizontal position of the loop, current will flow from point A to B and on the other side of the loop current will flow from point C to D.

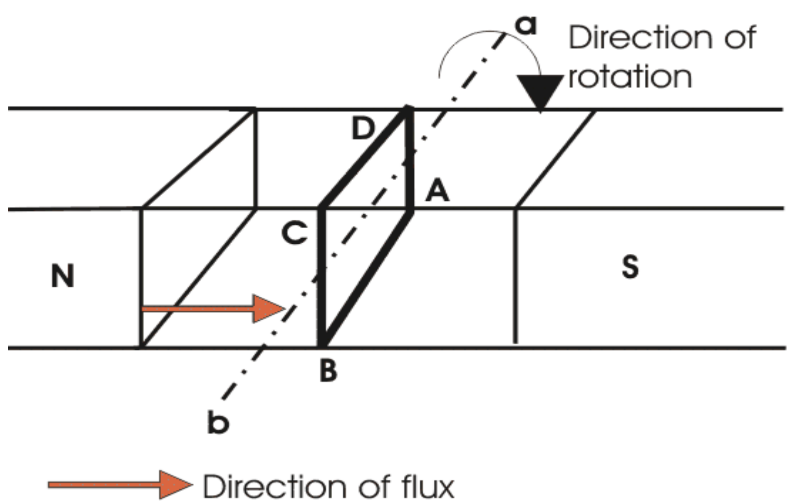


Figure: Single Loop Generator

Now if we allow the loop to move further, it will come again to its vertical position, but now upper side of the loop will be CD and lower side will be AB (just opposite of the previous vertical position). At this position the tangential motion of the sides of the loop is parallel to the flux lines of the field. Hence there will be no question of flux cutting and consequently there will be no current in the loop. If the loop rotates further, it comes to again in horizontal position. But now, said AB side of the loop comes in front of N pole and CD comes in front of S pole, i.e. just opposite to the previous horizontal position as shown in the figure beside.

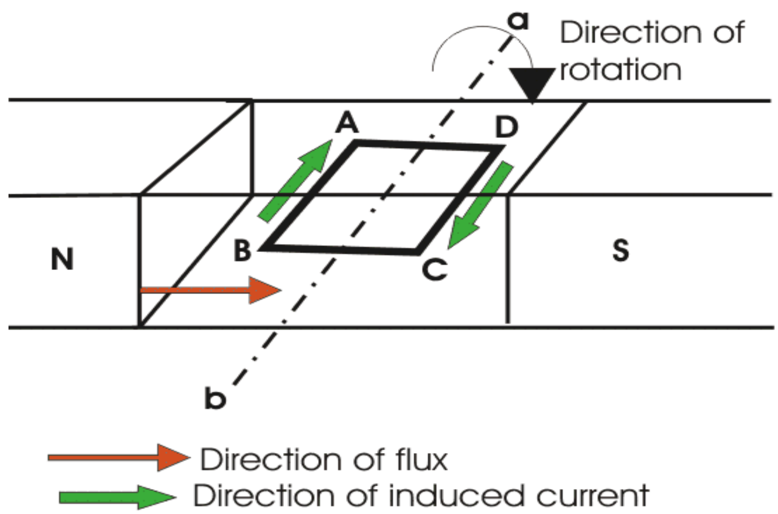


Figure: Single Loop Generator

Here the tangential motion of the side of the loop is perpendicular to the flux lines, hence rate of flux cutting is maximum here and according to Flemming's right hand Rule, at this position current flows from B to A and on other side from D to C. Now if the loop is continued to rotate about its axis, every time the side AB comes in front of S pole, the current flows from A to B and when it comes in front of N pole, the current flows from B to A. Similarly, every time the side CD comes in front of S pole the current flows from C to D and when it comes in front of N pole the current flows from D to C.

If we observe this phenomena in different way, it can be concluded, that each side of the loop comes in front of N pole, the current will flow through that side in same direction i.e. downward to the reference plane and similarly each side of the loop comes in front of S pole, current through it flows in same direction i.e. upwards from reference plane. From this, we will come to the topic of principle of DC generator. Now the loop is opened and connected it with a split ring as shown in the figure below. Split ring are made out of a conducting cylinder which cuts into two halves or segments insulated from each other. The external load terminals are connected with two carbon brushes which are rest on these split slip ring segments.

Working Principle of DC Generator

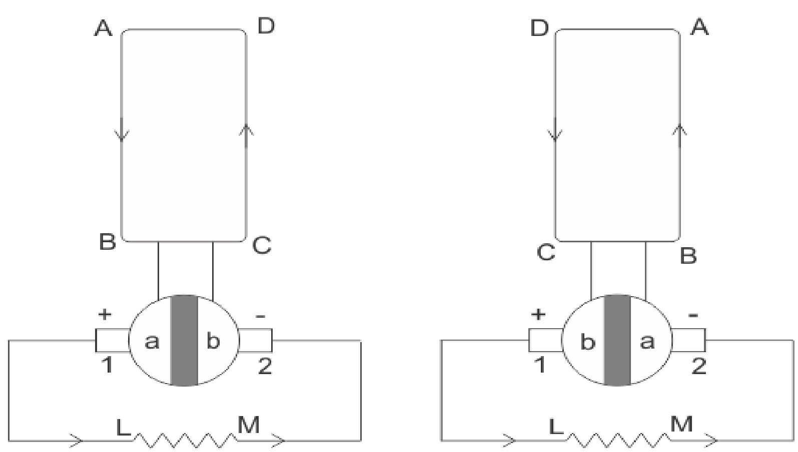


Fig: Commutation action

It is seen that in the first half of the revolution current flows always along ABLMCD i.e. brush no 1 in contact with segment a. In the next half revolution, in the figure the direction of the induced current in the coil is reversed. But at the same time the position of the segments a and b are also reversed which results that brush no 1 comes in touch with the segment b. Hence, the current in the load resistance again flows from L to M. The wave from of the current through the load circuit is as shown in the figure. This current is unidirectional.

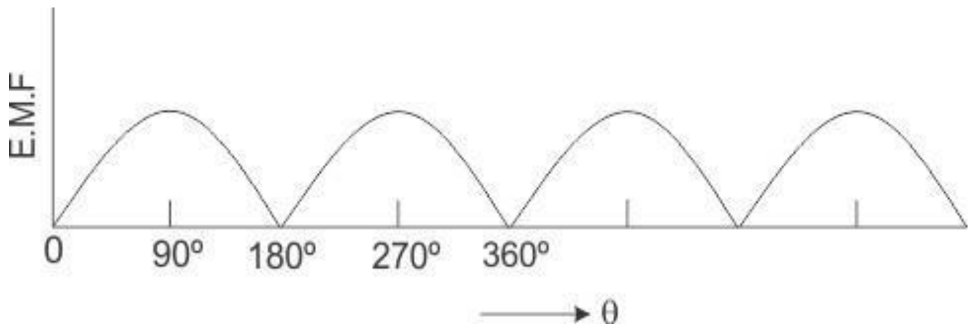


Fig: Output waveform of generator

This is basic working principle of DC generator, explained by single loop generator model. The position of the brushes of DC generator is so arranged that the change over of the segments a and b from one brush to other takes place when the plane of rotating coil is at right angle to the plane of the lines of force. It is so become in that position, the induced emf in the coil is zero.

Construction of a DC Machine:

A DC generator can be used as a DC motor without any constructional changes and vice versa is also possible. Thus, a DC generator or a DC motor can be broadly termed as a DC machine. These basic constructional details are also valid for the construction of a DC motor. Hence, let's call this point as construction of a DC machine instead of just 'construction of a DC generator.

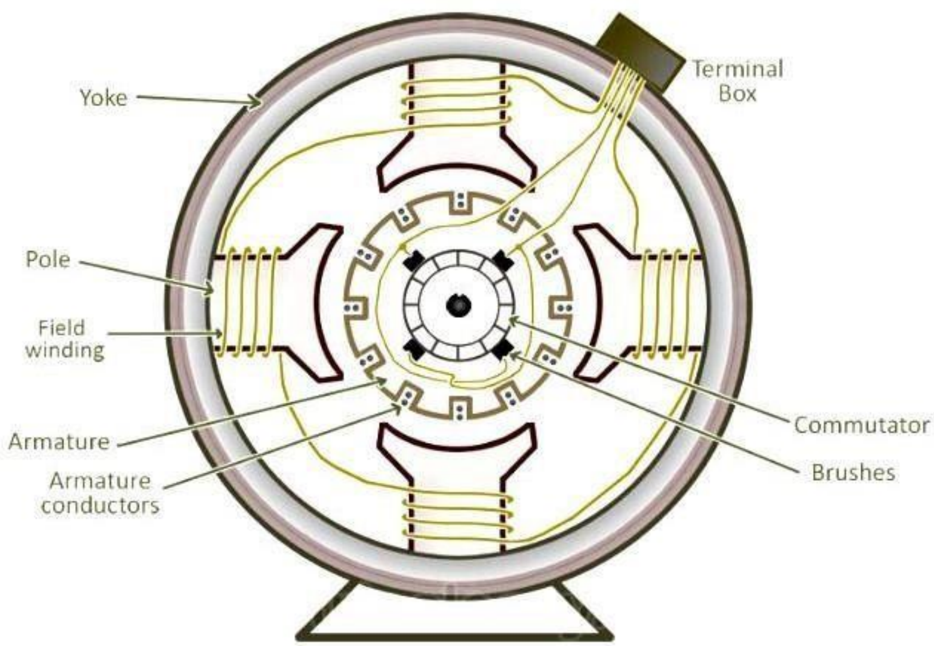


Figure 1: constructional details of a simple 4-pole DC machine

The above figure shows constructional details of a simple 4-pole DC machine. A DC machine consists of two basic parts; stator and rotor. Basic constructional parts of a DC machine are described below.

1. **Yoke:** 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.

2. **Poles and pole shoes:** Poles are joined to the yoke with the help of bolts or welding. They carry field winding and pole shoes are fastened to them. Pole shoes serve two purposes; (i) they support field coils and (ii) spread out the flux in air gap uniformly.

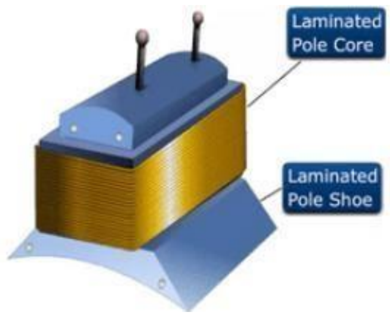


Figure 2: Pole Core and Poles Shoes representation

3. **Field winding:** They are usually made of copper. Field coils are former wound and placed on each pole and are connected in series. They are wound in such a way that, when energized, they form alternate North and South poles.

4. **Armature core:** Armature core is the rotor of a dc machine. It is cylindrical in shape with slots to carry armature winding. The armature is built up of thin laminated circular steel disks for reducing eddy current losses. It may be provided with air ducts for the axial air flow for cooling purposes. Armature is keyed to the shaft.

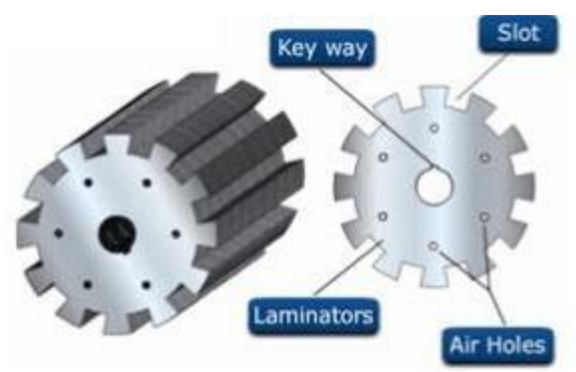


Figure 3: Armature of DC machine

5. **Armature winding:** It is usually a former wound copper coil which rests in armature slots. The armature conductors are insulated from each other and also from the armature core. Armature winding can be wound by one of the two methods; lap winding or wave winding. Double layer lap or wave windings are generally used. A double layer winding means that each armature slot will carry two different coils.

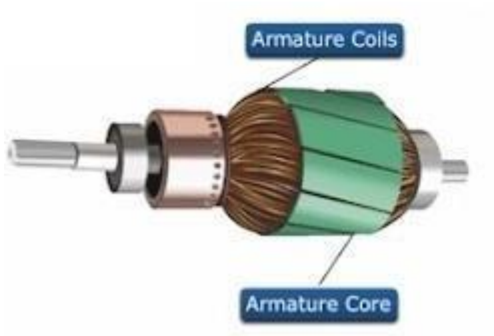


Figure 4: Armature Winding/coil of DC machine

6. **Commutator and brushes:** Physical connection to the armature winding is made through a commutator-brush arrangement. The function of a commutator, in a dc generator, is to collect the current generated in armature conductors. Whereas, in case of a dc motor, commutator helps in providing current to the armature conductors. A commutator consists of a set of copper segments which are insulated from each other. The number of segments is equal to the number of armature coils. Each segment is connected to an armature coil and the commutator is keyed to the shaft. Brushes are usually made from carbon or graphite. They rest on commutator segments and slide on the segments when the commutator rotates keeping the physical contact to collect or supply the current.

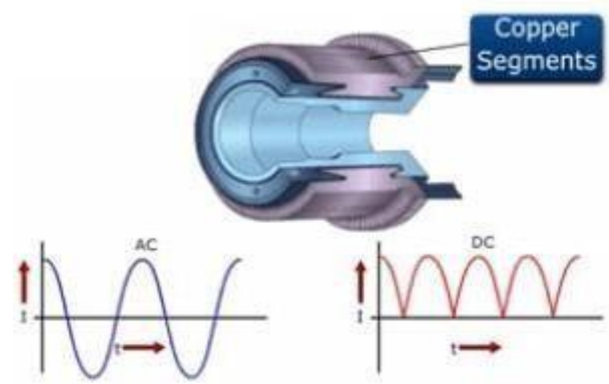


Figure 5: Commutator of DC machine

Armature Winding Terminology:

Now we are going to discuss about armature winding in details. Before going through this section, we should understand some basic terms related to armature winding of DC generator.

Pole Pitch:

The pole pitch is defined as peripheral distance between centers of two adjacent poles in DC machine. This distance is measured in term of armature slots or armature conductor come between two adjacent pole centers. Pole Pitch is naturally equal to the total number of armature slots divided by the number of poles in the machine.

If there are 96 slots on the armature periphery and 4 numbers of poles in the machine, the numbers of armature slots come between two adjacent poles centres would be 96/4 = 24. Hence, the pole pitch of that DC machine would be 24.

As we have seen that, pole pitch is equal to total numbers of armature slots divided by total numbers of poles, we alternatively refer it as armature slots per pole.

Coil side:

Coil of dc machine is made up of one turn or multi turns of the conductor. If the coil is made up of single turn or a single loop of conductor, it is called single turn coil. If the coil is made up of more than one turn of a conductor, we refer it as a multi-turn coil. A single turn coil will have one conductor per side of the coil whereas, in multi turns coil, there will be multiple conductors per side of the coil. Whatever may be the number of conductors per side of the coil, each coil side is placed inside one armature slot only. That means all conductors of one side of a particular coil must be placed in one single slot only. Similarly, we place all conductors of opposite side of the coil in another single armature slot.

Coil Span

Coil span is defined as the peripheral distance between two sides of a coil, measured in term of the number of armature slots between them. That means, after placing one side of the coil in a particular slot, after how many conjugative slots, the other side of the same coil is placed on the armature. This number is known as coil span.

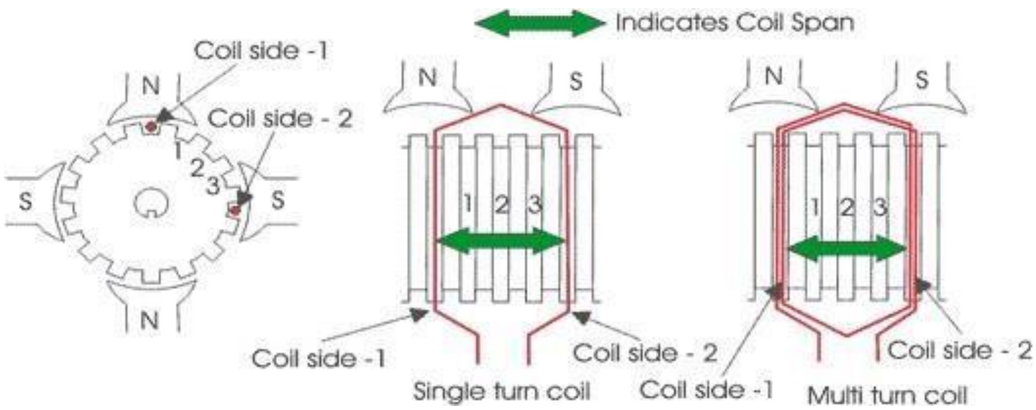


Figure: Armature windings

If the coil span is equal to the pole pitch, then the armature winding is said to be full - pitched. In this situation, two opposite sides of the coil lie under two opposite poles. Hence emf induced in one side of the coil will be in 180^{o} phase shift with emf induced in the other side of the coil. Thus, the total terminal voltage of the coil will be nothing but the direct arithmetic sum of these two emfs. If the coil span is less than the pole pitch, then the winding is referred as fractional pitched. In this coil, there will be a phase difference between induced emf in two sides, less than 180o. Hence resultant terminal voltage of the coil is vector sum of these two emf's and it is less than that of full-pitched coil.

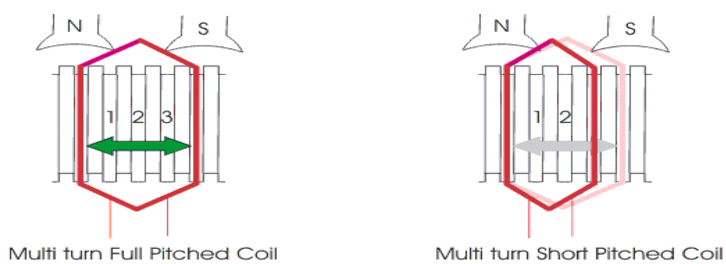
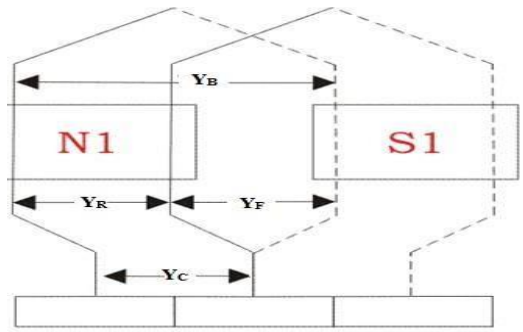


Figure: full pitched and half pitched coils

In practice, coil pitch (or Span) as low as eight tenth of a Pole Pitch, is employed without much serious reduction in emf. Fractional pitched windings are purposely used to effect substantial saving in copper of the end connection and for improving commutation.

Pitch of Armature Winding



Back Pitch (Y_B)

A coil advances on the back of the armature. This advancement is measured in terms of armature conductors and is called back pitch. It is equal to the number difference of the conductor connected to a given segment of the commutator.

Front Pitch (Y_F)

The number of armature conductors or elements spanned by a coil on the front is called front pitch. Alternatively, we define the front-pitch as the distance between the second conductor of the next coil which connects the front, i.e., commutator end of the armature. In other words, it is the number difference of the conductors connected together at the back end of the armature. We are showing both front and back pitches for a lap, and a wave windings in the figure below.

Resultant Pitch (Y_R)

It is the distance between the beginning of one coil and the beginning of the next coil to which it is connected. As a matter of precautions, we should keep in mind that all these pitches, though normally stated concerning armature conductors, are also times of armature slots or commutator bars.

Commutator Pitch (Y_C)

Commutator pitch is defined as the distance between two commutator segments which two ends of same armature coil are connected. We measure commutator pitch in term of commutator bars or segment.

Single Layer Armature Winding

We place armature coil sides in the armature slots differently. In some arrangement, each one side of an armature coil occupies a single slot. In other words, we place one coil side in each armature slot. We refer this arrangement as single layer winding.

Two Layer Armature Winding

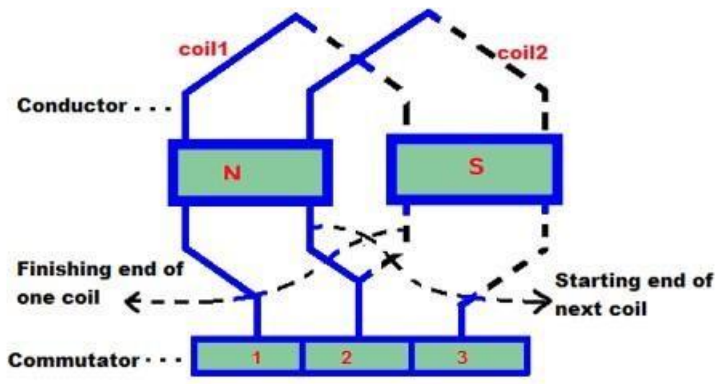
In other types of armature winding, arrangement two coil sides occupy every armature slot; one occupies upper half, and another one occupies the lower half of the slot. We so place the coils in two layers winding that if one side occupies upper half, then another side occupies the lower half of some other slot at a distance of one coil pitch away.

Armature Winding of A DC Machine

Based on type of winding connections we classified armature winding of a dc machine into two types. These winding connections are same for DC generator & DC motor.
Types of Windings in DC Machine,
1. Lap winding.
2. Wave winding.

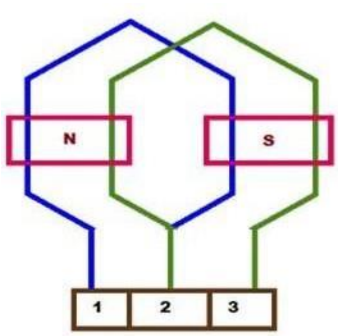
Lap winding of a DC Machine

In this type of winding the completing end of one coil is connected to a commutator segment and to the start end of adjacent coil located under the same pole and similarly all coils are connected. This type of winding is known as lap because the sides of successive coils overlap each other.

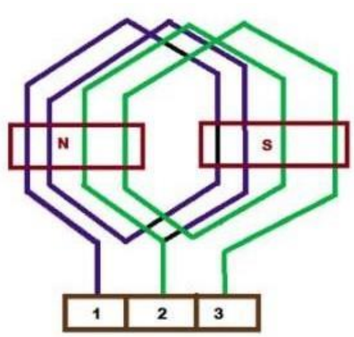


LAP winding

Lap winding may be simplex (single) or multiplex (duplex or triplex) winding. In simplex lap winding the connection of the winding is that there are as many parallel paths as there are number of poles.
Whereas for duplex, the number of parallel paths are equal to twice that of the number of poles and for triplex it is thrice. For this reason, the lap winding is called multiple or parallel winding. The sole purposes of such type of windings are,
(a) To increase the number of parallel paths enabling the armature current to increase i.e., for high current output.
(b) To improve commutation as the current per conductor decreases.



Simplex lap winding



Duplex lap winding

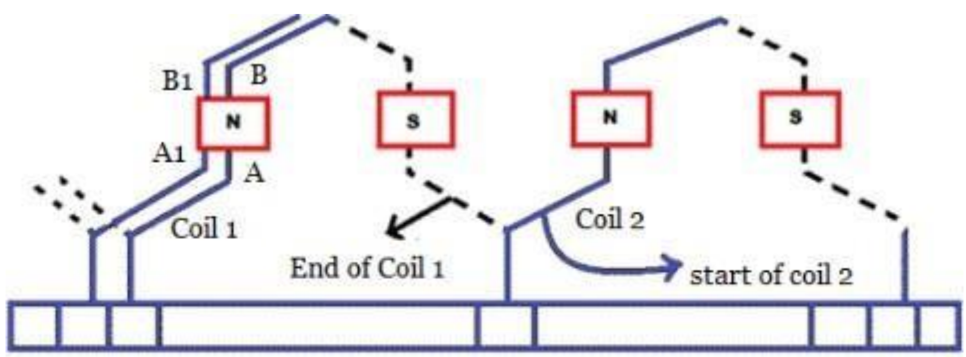
Notes on Lap winding

1. The coil or back pitch Y_B must be approximately equal to pole pitch i.e., $Y_B = Z/P$.

2. The back pitch and front pitch are odd and are of opposite sign. They differ from each other by 2m, where m = 1,2,3 for simplex, duplex, and triplex respectively.
   i.e., $Y_B = Y_F \pm 2m$
   When $Y_B > Y_F$ i.e., $Y_F + 2m$ then the winding progresses from left to right and such a winding is known as progressive winding. If $Y_B < Y_F$ i.e., $Y_B = Y_F - 2m$ then the winding progresses from right to left and such a winding is known as retrogressive winding.
3. The average pitch, $Y_{AVE} = (Y_B + Y_F)/2$.
4. Resultant pitch, Y_R is always even as difference between two odd numbers is even and is equal to 2m.
5. Commutator pitch, Y_C = m i.e., , 2, 3, 4 etc. for simplex, duplex, triplex, quadruplex etc.
6. Number of parallel paths = mP. Where, m = multiplicity.
   Example: For instance, the number of parallel paths for a 6-pole duplex lap winding is given by 6 x 2 = 12 paths.
7. The total number of poles are equal to the total number of brushes.
8. If Ia is the total armature current, then current per parallel path is Ia /P.
9. Lap winding is used for low voltage and high current machines.

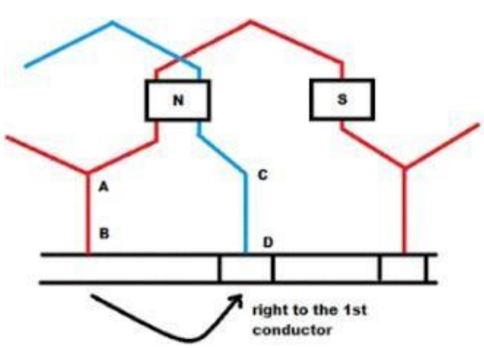
Wave winding of a DC Machine

In wave winding the coils which are carrying current in one direction are connected in series circuit and the carrying current in opposite direction are connected in another series circuit. A wave winding is shown in figure.

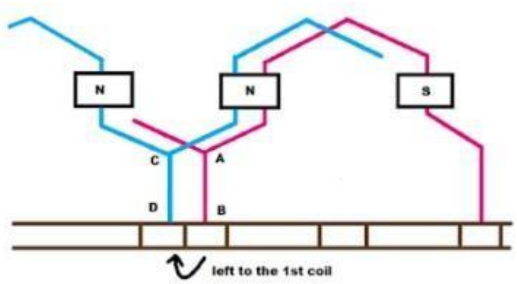


Wave Winding

If after passing once around the armature the winding falls in a slot to the left of its starting point then winding is said to be retrogressive. If it fails one slot to the right it is progressive.



Progressive Wave winding



Retrogressive wave winding

Notes on Wave winding

The following are the important points to be remembered pertaining to wave winding,

1. Both pitches Y_B and Y_F are odd and of same sign.
2. Back and front pitches may be equal or differ by 2 and are merely equal to pole pitch.
3. Resultant pitch, $Y_R = Y_F + Y_B = (Z \pm 2)/2$

P = Number of poles

Z = Total number of conductors.

4. Commutator pitch, $Y_C = Y_A$ (Average pitch)

Y_C =(Number of commutator bars ± 1)/(Number of pair of poles).

5. Number of parallel paths are equal to 2m,where m is the multiplicity.
6. The number of brushes required are two irrespective of the number of poles.
7. If Ia is the total armature current then current carried by each path or conductor is Ia/2.
8. Since a wave winding is a series winding, it is used for high voltage and low current machine.

Emf Equation of a DC Generator

As the armature rotates, a voltage is generated in its coils. In the case of a generator, the emf of rotation is called the Generated emf or Armature emf and is denoted as Er = Eg. In the case of a motor, the emf of rotation is known as Back emf or Counter emf and represented as Er = Eb. The expression for emf is same for both the operations. I.e., for Generator as well as for Motor

Derivation of EMF Equation of a DC Machine – Generator and Motor

Let,

- **P** – Number of poles of the machine
- **ϕ** – Flux per pole in Weber.
- **Z** – Total number of armature conductors.
- **N** – Speed of armature in revolution per minute (r.p.m).
- **A** – Number of parallel paths in the armature winding.

In one revolution of the armature, the flux cut by one conductor is given as

$$\text{Flux cut by one conductor} = P\varphi \quad \text{wb} \ldots\ldots (1)$$

Time taken to complete one revolution is given as

$$t = \frac{60}{N} \quad \text{seconds} \quad \ldots\ldots (2)$$

Therefore, the average induced e.m.f in one conductor will be

$$e = \frac{P\varphi}{t} \quad \ldots\ldots (3)$$

Putting the value of (t) from Equation (2) in the equation (3) we will get

$$e = \frac{P\varphi}{60/N} = \frac{P\varphi N}{60} \quad \text{volts} \quad \ldots\ldots (4)$$

The number of conductors connected in series in each parallel path = Z/A.

Therefore, the average induced e.m.f across each parallel path or the armature terminals is given by the equation shown below.

$$E = \frac{P\varphi N}{60} \times \frac{Z}{A} = \frac{PZ\varphi N}{60\,A} \text{ volts or}$$

$$E = \frac{PZ\varphi n}{A} \quad \ldots\ldots(5)$$

Where n is the speed in revolution per second (r.p.s) and given as

$$n = \frac{N}{60}$$

For a given machine, the number of poles and the number of conductors per parallel path (Z/A) are constant. Hence, the equation (5) can be written as

$$E = K\varphi n$$

Where, K is a constant and given as

$$K = \frac{PZ}{A}$$

Therefore, the average induced emf equation can also be written as

$$E \propto \varphi n \quad \text{or}$$

$$E = K_1 \varphi N$$

Where K_1 is another constant and hence induced emf equation can be written as

$$E \propto \varphi N \quad \text{or}$$

$$E \propto \varphi \omega$$

Where ω is the angular velocity in radians/second is represented as

$$\omega = \frac{2\pi N}{60}$$

Thus, it is clear that the induced emf is directly proportional to the speed and flux per pole. The polarity of induced emf depends upon the direction of the magnetic field and the direction of rotation. If either of the two is reverse the polarity changes, but if two are reversed the polarity remains unchanged.

This induced emf is a fundamental phenomenon for all the DC Machines whether they are working as a generator or motor.

If the machine DC Machine is working as a Generator, the induced emf is given by the equation shown below.

$$E_g = \frac{PZ\varphi N}{60\ A} \quad \text{volts}$$

Where $\mathbf{E_g}$ is the **Generated Emf**

If the machine DC Machine is working as a Motor, the induced emf is given by the equation shown below.

$$E_b = \frac{PZ\varphi N}{60\ A} \quad \text{volts}$$

In a motor, the induced emf is called **Back Emf ($\mathbf{E_b}$)** because it acts opposite to the supply voltage.

Types of DC Generators – Separately Excited and Self Excited

The DC generator converts the electrical 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.

By excitation, the DC Generators are classified as Separately excited DC Generators and Self-excited DC Generators. There is also Permanent magnet type DC generators. The self-excited DC Generators are further classified as Shunt wound DC generators; Series wound DC generators and Compound wound DC generators. The Compound Wound DC generators are further divided as long shunt wound DC generators, and short shunt wound DC generators.

The field pole of the DC generator is stationary, and the armature conductor rotates. The voltage generated in the armature conductor is of alternating nature, and this voltage is converted into the direct voltage at the brushes with the help of the commutator.

The detailed description of the various types of generators is explained below.

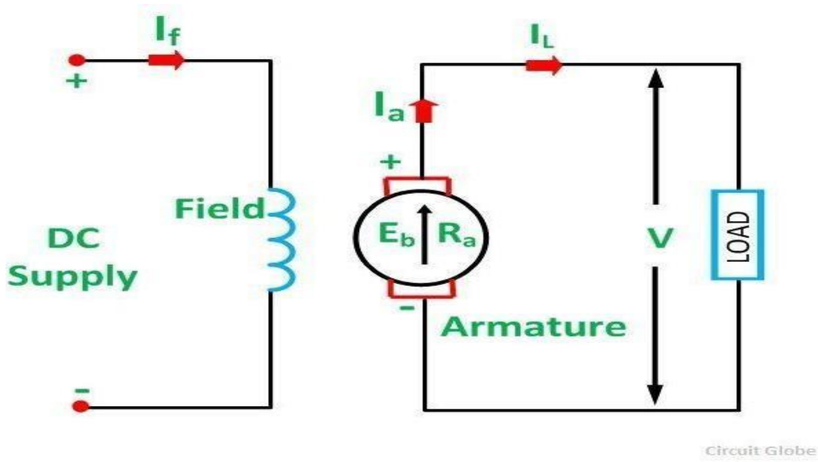
Permanent Magnet type DC Generator

In this type of DC generator, there is no field winding is placed around the poles. The field produced by the poles of these machines remains constant. Although these machines are very compact but are used only in small sizes like dynamos in motorcycles, etc. The main disadvantage of these machines is that the flux produced by the magnets deteriorates with the passage of time which changes the characteristics of the machine.

Separately Excited DC Generator

A DC generator 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.

The figure of self-excited DC Generator is shown below.



Separately Excited DC Generator

Here,

$I_a = I_L$ where I_a is the armature current and I_L is the line current.

Terminal voltage is given as

$$V = E_g - I_a R_a \quad \ldots..(1)$$

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

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

The power developed is given by the equation shown below.

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

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

Power output is given by the equation (4) shown above.

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 in the series, or it may be connected partly in series and partly in parallel with the armature windings.

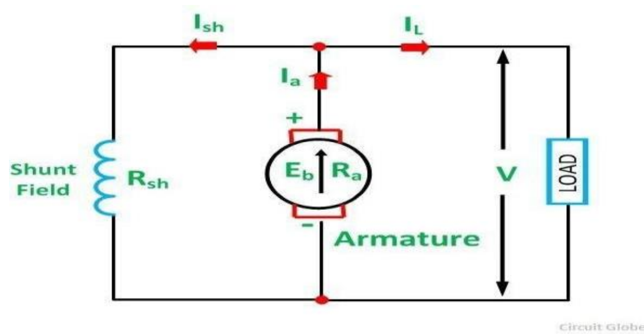
The self-excited DC Generator is further classified as

1. Shunt Wound Generator
2. Series Wound Generator
3. Compound Wound Generator

1. 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 Wound DC Generator

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

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

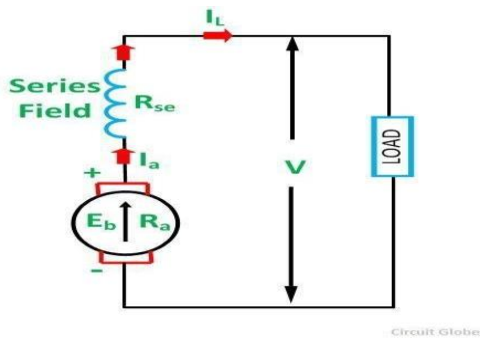
$$\text{Power developed} = E_g I_a$$

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

2. 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.

Its convectional diagram is shown below.



Series Wound DC Generator

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

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

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

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

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

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

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

The flux developed by the series field winding is directly proportional to the current flowing through it. But it is only true before magnetic saturation after the saturation flux becomes constant even if the current flowing through it is increased.

3. Compound Wound Generator

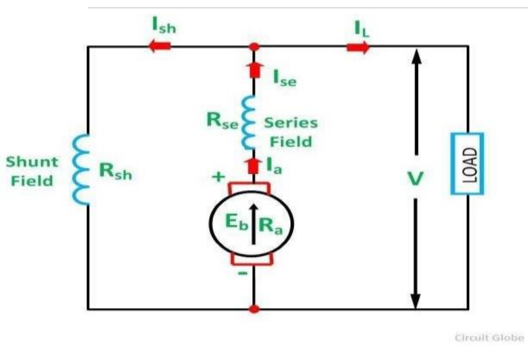
In a Compound Wound Generator, there are two sets of the field winding on each pole. One of them is connected in series having few turns of thick wire, and the other is connected in parallel having many turns of fine wire with the armature windings. In other words, the generator which has both shunt and series fields is called the compound wound generators.

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

It is connected in two ways. One is a long shunt compound generator, and another is a short shunt compound generator. If the shunt field is connected in parallel with the armature alone then the machine is called the short compound generator. In long shunt compound generator, the shunt field is connected in series with the armature. The two types of generators are discussed below in details.

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 shown below.



Long Shunt Compound Wound Generator

Shunt field current is given as

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

Series field current is given as

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

Terminal voltage is given as

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

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

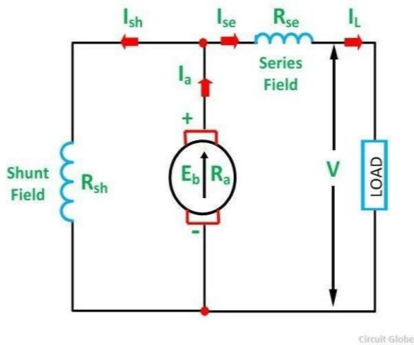
$$V = E_g - I_a (R_a + R_{se}) - 2V_b$$

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

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

Short Shunt Compound Wound Generator

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 below.



Short Shunt Compound Wound Generator

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 is written as

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

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

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

In this type of DC generator, the field is produced by the shunt as well as series winding. The shunt field is stronger than the series field. If the magnetic flux produced by the series winding assists the flux produced by the shunt field winding, the generator is said to be Cumulatively Compound Wound generator.

If the series field flux opposes the shunt field flux, the generator is said to be Differentially Compounded.

Voltage buildup in self excited Generator or Dc Shunt Generato

A self excited DC generator supplies its own field excitation . A self excited generator shown in figure is known as a shunt generator because its field winding is connected in parallel with the armature. Thus the armature voltage supplies the field current.

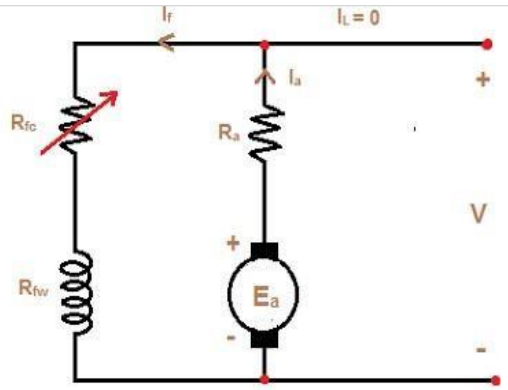


Figure - Equivalent circuit of a shunt dc generator

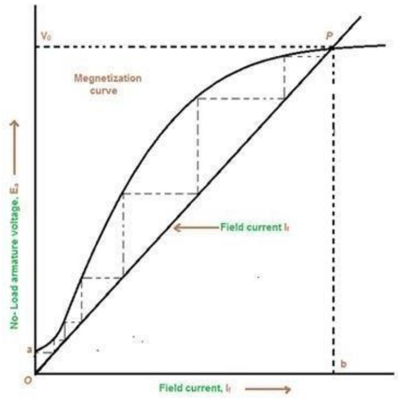
This generator will build up a desired terminal voltage. Assume that the generator in figure has no load connected to it and armature is driven at a certain speed by a prime mover. we shall study the condition under which the voltage buildup takes place. Due to this residual flux, a small voltage Ear will be generated. It is given by

$$E_{ar} = K \phi_{res} \omega$$

This voltage is of the order of 1V or 2V . It causes a current If to flow in the field winding in the generator. The field current is given by

$$I_f = \frac{V}{R_f}$$

This field current produces a magneto motive force in the field winding, which increases the flux. This increase in flux increases the generated voltage Ea. The increased armature voltage Ea increases the terminal voltage V. with the increase in V, the field current **If** increases further. This in turn increases Φ and consequently Ea increases further. The process of the voltage buildup continues. Figure shows the voltage buildup of a dc shunt generator.



OCC Characteristics of DC generator

The effect of magnetic saturation in the pole faces limits the terminal voltage of the generator to a steady state value.
We have assumed that the generator is no load during the buildup process. The following equations describe the steady state operation.

$$I_a = I_f$$

$$V = E_a - I_a R_a = E_a - I_f R_a$$

Since the field current If in a shunt generator is very small, the voltage drop If Ra can be neglected, and V= Ea
The Ea versus If curve is the magnetization curve shown in figure

For the field circuit V = If Rf

The straight line given by V = If Rf is called the **field-resistance line**.

The field resistance line is a plot of the voltage If Rf across the field circuit versus the field If. The slop this line is equal to the resistance of the field circuit.

The no-load terminal voltage V0 of thr generator. thus, the intersection point *P* of the magnetization curve and the field resistance line gives the no-load terminal voltage V0(*bP*) and the corresponding field current (*Ob*). Normally , in the shunt generator the voltage buildup to the value given by the point *P*. at this point Ea = If Rf = V0.

If the field current corresponding to point P is increase further , there is no further increase in the terminal voltage.

The no-load voltage is adjusted by adding resistance in series with shunt field. This increase slope of this line causing the operating point to shift at lower voltage

The operating point are graphical solution of two simultaneous equation namely , the magnetization curve and field resistance line . A graphical solution is preferred due to non-linear nature of magnetization curve.
Self excited generator are designed to obtain no-load voltage from 50% to 125% of the rated value while varying the added resistance in field circuit from maximum to zero value.

Critical Field Resistance:

Figure below shows the voltage buildup in the dc shunt generator for various resistances of the field circuit.

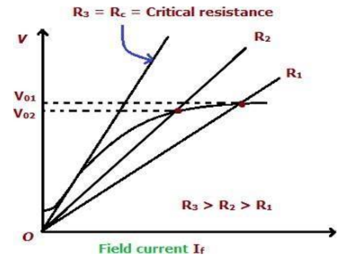


Fig: Determination of critical resistance

A decrease in the resistance of the field circuit reduces the slope of the field resistance line result in higher voltage. If the speed remains constant, an increase in the resistance of field circuit increases the slop of field resistance line, resulting in a lower voltage. If the field circuit resistance is increased to Rc which is terminal as the critical resistance of the field, the field resistance line becomes a tangent to the initial part of the magnetization curve. When the field resistance is higher than this value, the generator fails to excite.

Critical Speed:

Figure shows the variation of no-load voltage with fixed Rf and variable speed of the armature.

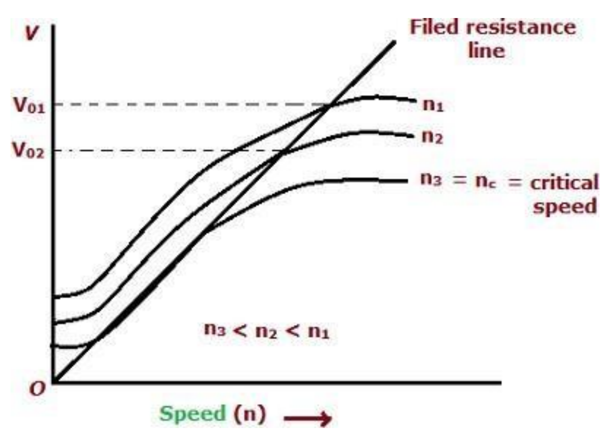


Fig: Determination of critical speed

The magnetization curve varies with the speed and its ordinate for any field current is proportional to the speed of the generator. all the points on the magnetization curve are lowered, and the point of intersection of the magnetization curve and the field resistance line moves downwards. at a particular speed, called the critical speed, the field resistance line becomes tangential to the magnetization curve. below the critical speed the voltage will not build up.

In Brief, the following condition must be satisfied for voltage buildup in a self-excited generator. There must be sufficient residual flux in the field poles.

1. the field terminal should be connected such a way that the field current increases flux in the direction of residual flux.
2. The field circuit resistance should be less than the critical field circuit resistance.

If there is a no residual flux in the field poles, Disconnected the field from the armature circuit and apply a dc voltage to the field winding. this process is called Flashing the field. It will induce some residual flux in the field poles.

Causes for Failure to Self Excite and Remedial Measures

There may be one or more of the following reasons due which a self excited generator may fail to build up voltage.

1. No residual magnetism

The start of the buildup process needs some residual magnetism in the magnetic circuit of the generator. If there is little or no residual magnetism. because of inactivity or jarring in shipment, no voltage will be induced that can produce field current.

2. Reversal of Field Connections

The voltage induced owing to residual magnetism acts across the field and results in flow or current in the field coils in such a direction as to produce magnetic flux in the same direction as the residual flux.

Reversal of connections of the field winding destroys the residual magnetism which causes the generator failure to build up voltage.

3. In case of dc series wound generators

The resistance in the load circuit may be more than its critical resistance, which may be due to

(i) open-circuit
(ii) high resistance of load circuit
(iii) faulty contact between brushes and commutator and
(iv) commutator surface dirty or greasy.

4. In case of shunt wound generator

(a) the resistance of the shunt field circuit may be greater than the critical resistance;
(b) the resistance in the load circuit may be lower than the critical resistance;
(c) the speed of rotation may not be equal to rated one.

Remedy

In case the generator is started up for the first time, it may be that no voltage will be built up either because the poles have no residual magnetism or the poles have retained some residual magnetism but the field winding connections are reversed so that the magnetism developed by the field winding on start has destroyed the residual magnetism and the machine can not "build up". In both the cases, the field coils must be connected to a dc source (a storage battery) for a short while to magnetise the poles. The application of external source of direct current to the field is called flashing of the field.

Armature Reaction in DC Machines

In a DC machine, two kinds of magnetic fluxes are present; 'armature flux' and 'main field flux'. The effect of armature flux on the main field flux is called as armature reaction.

MNA And GNA

EMF is induced in the armature conductors when they cut the magnetic field lines. There is an axis (or, you may say, a plane) along which armature conductors move parallel to the flux lines and, hence, they do not cut the flux lines while on that plane. MNA (Magnetic Neutral Axis) may be defined as the axis along which no emf is generated in the armature conductors as they move parallel to the flux lines. Brushes are always placed along the MNA because reversal of current in the armature conductors takes place along this axis.

GNA (Geometrical Neutral Axis) may be defined as the axis which is perpendicular to the stator field axis.

Armature Reaction

The effect of armature reaction is well illustrated in the figure below.

Consider, no current is flowing in the armature conductors and only the field winding is energized (as shown in the first figure of the above image). In this case, magnetic flux lines of the field poles are uniform and symmetrical to the polar axis. The 'Magnetic Neutral Axis' (M.N.A.) coincides with the 'Geometric Neutral Axis' (G.N.A.).

The second figure in the above image shows armature flux lines due to the armature current. Field poles are de-energised

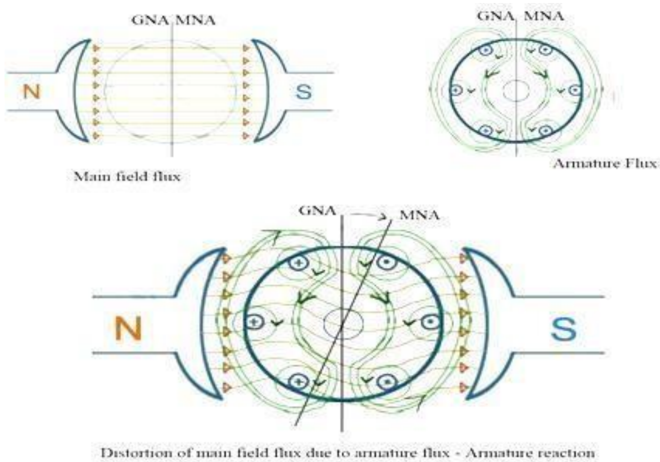


Fig: Armature reaction

Now, when a DC machine is running, both the fluxes (flux due to the armature conductors and flux due to the field winding) will be present at a time. The armature flux superimposes with the main field flux and, hence, disturbs the main field flux (as shown in third figure the of above image). This effect is called as armature reaction in DC machines.

The Adverse Effects Of Armature Reaction:

1. Armature reaction weakens the main flux. In case of a dc generator, weakening of the main flux reduces the generated voltage.
2. Armature reaction distorts the main flux, hence the position of M.N.A. gets shifted (M.N.A. is perpendicular to the flux lines of main field flux). Brushes should be placed on the M.N.A., otherwise, it will lead to sparking at the surface of brushes. So, due to armature reaction, it is hard to determine the exact position of the MNA

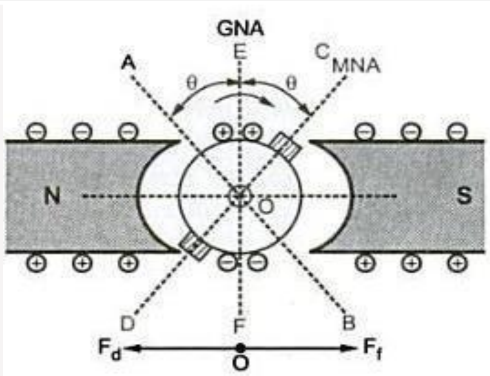
For a loaded dc generator, MNA will be shifted in the direction of the rotation. On the other hand, for a loaded dc motor, MNA will be shifted in the direction opposite to that of the rotation.

How To Reduce Armature Reaction?
Usually, no special efforts are taken for small machines (up to few kilowatts) to reduce the armature reaction. But for large DC machines, compensating winding and interpoles are used to get rid of the ill effects of armature reaction.

Compensating winding: Now we know that the armature reaction is due to the presence of armature flux. Armature flux is produced due to the current flowing in armature conductors. Now, if we place another winding in close proximity of the armature winding and if it carries the same current but in the opposite direction as that of the armature current, then this will nullify the armature field. Such an additional winding is called as compensating winding and it is placed on the pole faces. Compensating winding is connected in series with the armature winding in such a way that it carries the current in opposite direction.

Interpoles: Interpoles are the small auxiliary poles placed between the main field poles. Winding on the interpoles is connected in series with the armature. Each interpole is wound in such a way that its magnetic polarity is same as that of the main pole ahead of it. Interpoles nullify the quadrature axis armature flux.

Demagnetizing and Cross Magnetizing Conductors



The conductors which are responsible for producing demagnetizing and distortion effects are shown in the Fig.1.

The brushes are lying along the new position of MNA which is at angle θ from GNA. The conductors in the region AOC = BOD = 2θ at the top and bottom of the armature are carrying current in such a direction as to send the flux in armature from right to left. Thus these conductors are in direct opposition to main field and called demagnetizing armature conductors.

The remaining armature conductors which are lying in the region AOD and BOC carry current in such a direction as to send the flux pointing vertically downwards i.e. at right angles to the main field flux. Hence these conductors are called cross magnetizing armature conductors which will cause distortion in main field flux.

These conductors are shown in the Fig. 2

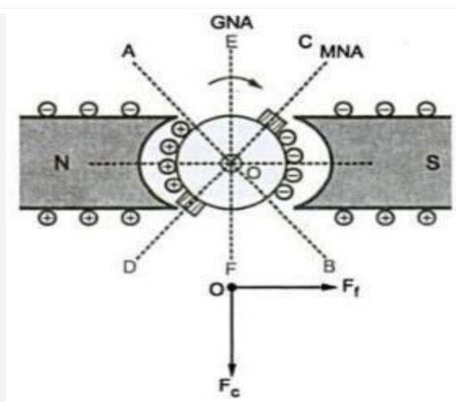


Fig. 2 Conductors which are responsible for producing Cross magnetization ffects

Calculation of Demagnetizing and Cross Magnetizing Amp-Turns

Let us the number of demagnetizing and cross magnetizing amp-turns

Let Z = Total number of armature conductors

P = Number of poles

I = Armature conductor current in Amperes

= $I_a/2$ for simplex wave winding

= I_a/P for simplex lap winding

θ_m = Forward lead of brush in mechanical degrees.

The conductors which are responsible for demagnetizing ampere-turns are lying in the region spanning 4 θ_m degrees. The region is between angles AOC and BOD, as shown in the Fig. 2.

∴ Total number of armature conductors lying in angles AOC and BOD.

$$= \frac{4\theta_m}{360} \times Z$$

Since two conductors from one turn,

$$\text{Total number of turns in these angles} = \frac{1}{2} \cdot \frac{4\theta_m}{360} \times Z$$

$$= \frac{2\theta_m}{360} \times Z$$

$$\therefore \text{Demagnetising amp-turns} = \frac{2\theta_m}{360} \times IZ$$

$$\therefore \text{Demagnetising amp-turns / pole} = \frac{\theta_m}{360} \times IZ$$

$$\therefore \quad \boxed{AT_d \text{ per pole } = ZI \times \frac{\theta_m}{360}}$$

The conductor which are responsible fro cross magnetizing ampere turns are lying between the angles AOD and BOC, as shown in the Fig.2.

Total armature-conductors / pole = Z/P

From above we have found an expression for demagnetizing conductors per pole.

$$\text{Demagnetising conductors / pole} = Z = \frac{2\theta_m}{360}$$

$$\therefore \text{Cross magnetising conductors/pole} = \frac{Z}{P} - Z\frac{2\theta_m}{360}$$

$$= Z\left[\frac{1}{P} - \frac{2\theta_m}{360}\right]$$

$$\therefore \text{Cross magnetising amp-conductors / pole} = ZI\left[\frac{1}{P} - \frac{2\theta_m}{360}\right]$$

Since two conductors from one turn,

$$\text{Cross magnetising amp-turns / pole} = \frac{1}{2} \cdot ZI\left[\frac{1}{P} - \frac{2\theta_m}{360}\right]$$

$$= ZI\left[\frac{1}{2P} - \frac{\theta_m}{360}\right]$$

$$\therefore \quad \boxed{AT_c \text{ per pole} = ZI\left[\frac{1}{2P} - \frac{\theta_m}{360}\right]}$$

If the brush shift angle is given in electrical degrees then it should be converted into mechanical degrees by using the relation,

$$\boxed{\theta_{mechanical} = \frac{\theta_{electrical}}{\text{Pair of poles}} = \frac{\theta_{electrical}}{P/2} = \frac{2\theta_{electrical}}{P}}$$

Example :

A wave wound 4 pole d.c. generator with 480 armature conductors supplies a current of 144 A. The brushes are given an actual lead of 10^o. Calculate the demagnetizing and cross magnetizing amp turns per pole.

Solution :

$P = 4$, $Z = 480$, $I_a = 144$ A

For wave wound,

$I = I_a/2 = 144/2 = 72$ A

$\theta_m = 10^o$

$$AT_d/\text{pole} = ZI\frac{\theta_m}{360}$$

$$= \frac{480 \times 72 \times 10}{360}$$

$$= \mathbf{960}$$

$$AT_c/\text{pole} = ZI\left[\frac{1}{2P} - \frac{\theta_m}{360}\right] = 480 \times 72\left[\frac{1}{2 \times 4} - \frac{10}{360}\right]$$

$$= \mathbf{3360}$$

Compensating Winding and Interpoles in DC Generator

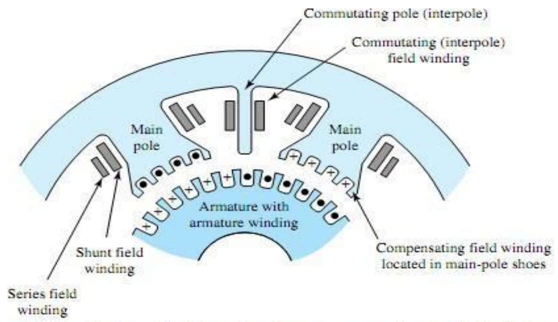
In DC compound machine setup by armature current opposes magnetic field flux, this is known as armature reaction. The armature reaction has two effects (i) Demagnetizing effect and (ii) Cross magnetizing effect. Demagnetizing effect weakens the main field flux which in turn decreases the induced e.m.f (as $E \propto Ø$)). To overcome this effect a few extra turns/poles are added in series to main field winding. This creates a series field which serves two purposes,

(i) It helps to neutralize the demagnetizing effect of armature reaction.

(ii) If wound for cumulative compounded machine the electrical performance will be improved.

Compensating winding:

All armature conductors placed under the main poles region produces e.m.f which is at right angle (90°) to the main field e.m.f. This e.m.f causes distortion in main field flux. This is known as cross magnetizing effect. To minimize the cross magnetizing effect compensating winding is used. This compensating winding produces an m.m.f which opposes the m.m.f produced by armature conductors.



Section of a dc machine illustrating the arrangement of various field windings.

This objective is achieved by connecting compensating winding in series with armature winding. In absence of compensating winding, cross magnetizing effect causes sparking at the commutators and short circuiting the whole armature winding.

Let, Zc = Number of compensating conductors/pole

Za = Number of active armature conductors/pole

Ia = Armature current.

ZcIa= Za (Ia/A)

Where,

Ia/A=Armature current/conductor

Zc= Za/A

Compensating Winding Disadvantages

This winding neutralizes the cross magnetizing effect due to armature conductors only but not due to interpolar region. This winding is used in large machine in which load is fluctuating.

Interpoles

Cross magnetizing effect in interpolar region is by interpoles (also known as compoles (or) commutating poles). These interpoles are small in size and placed in between the main poles of yoke. Like compensating winding, interpoles are also connected in series with armature winding such that the m.m.f produced by them opposes the m.m.f produced by armature conductor in interpolar region. In generators, the interpole polarity is same as that of main pole ahead such that they induce an e.m.f which is known as commutating or reversing e.m.f. This commutating e.m.f minimizes the reactance e.m.f and hence sparks or arcs are eliminated.

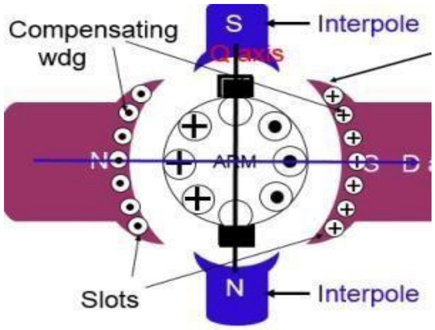


Fig: Intepoles

Compensating winding and Interpoles are used for same purpose but the difference between them is, interpoles produce e.m.f for neutralizing reactance e.m.f whereas compensating winding produces an m.m.f which opposes the m.m.f produced by conductors.

COMMUTATION:

The process of reversal of current in the short circuited armature coil is called 'Commutation'. This process of reversal takes place when coil is passing through the interpolar axis (q-axis), the coil is short circuited through commutator segments. Commutation takes place simultaneously for 'P' coils in a lap-wound machine and two coil sets of P/2 coils each in a wave-wound machine.

The process of commutation of coil 'B' is shown below. In figure '1.29' coil 'B' carries current from left to right and is about to be short circuited in figure '1.30' brush has moved by 1/3 rd of its width and the brush current supplied by the coil are as shown. In figure '1.31' coil 'B' carries no current as the brush is at the middle of the short circuit period and the brush current in supplied by coil C and coil A. In figure '1.32' the coil B which was carrying current from left to right carries current from right to left. In fig '1.33' spark is shown which is due to the reactance voltage. As the coil is embedded in the armature slots, which has high permeability, the coil posses appreciable amount of self inductance. The current is changed from +I to –I. So due to self inductance and variation in the current from +I to –I, a voltage is induced in the coil which is given by L dI/dt. Fig '1.34' shows the variation of current plotted on the time axis. Sparking can be avoided by the use of interpoles or commutating-poles.

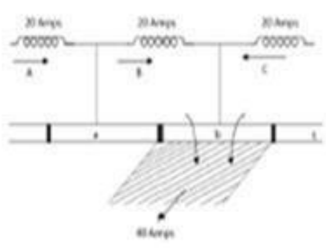


Figure '1.29'

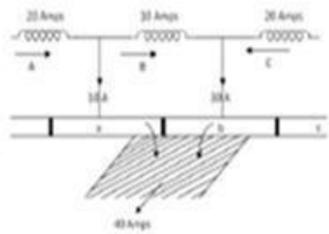


Figure '1.30'

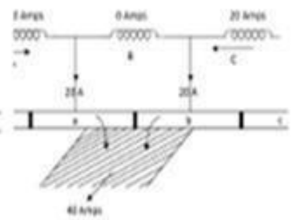


Fig '1.31'

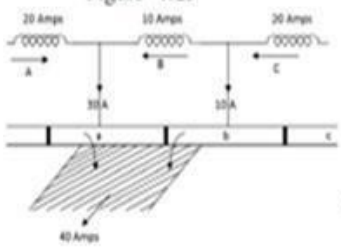


Figure '1.32'

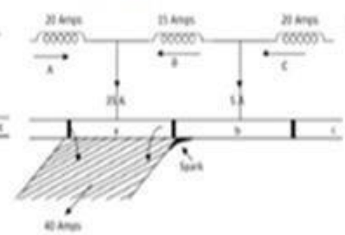


Figure '1.33'

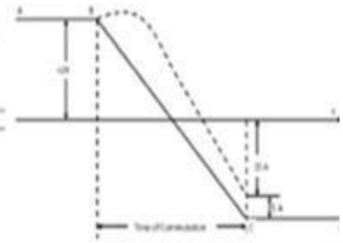


Figure '1.34'

Fig: Commutation process

METHODS OF IMPROVING COMMUTATION:

Methods of Improving Commutation: There are two practical ways of improving commutation i.e. of making current reversal in the short-circuited coil as sparkless as possible. These methods are known as (i) resistance commutation and (ii) emf. commutation (which is done with the help of either brush lead or interpoles, usually the later).

Resistance Commutation: This method of improving commutation consists of replacing low-resistance Cu brushes by comparatively high-resistance carbon brushes. When current I from coil C reach the commutator segment b, it has two parallel paths open to it. The first part is straight from bar 'b' to the brush and the other parallel path is via the short-circuited coil B to bar 'a' and then to the brush. If the Cu brushes are used, then there is no inducement for the current to follow the second longer path, it would preferably follow the first path. But when carbon brushes having high resistance are used, then current I coming from C will prefer to pass through the second path. The additional advantages of carbon brushes are that (i) they are to some degree self lubricating and polish the commutator and (ii) should sparking occur, they would damage the commutator less than when Cu brushes are used. But some of their minor disadvantages are: (i) Due to their high contact resistance (which is beneficial to sparkless commutation) a loss of approximately 2 volt is caused. Hence, they are not much suitable for small machines where this voltage forms an appreciable percentage loss. (ii) Owing to this large loss, the commutator has to be made somewhat larger than with Cu brushes in order to dissipate heat efficiently without greater rise of temperature. (iii) because of their lower current density (about 7-8 A/cm2 as compared to 25-30 A/cm2 for Cu brushes) they need larger brush holders.

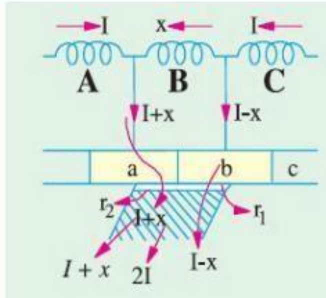


Fig: Resistance Commutation

EMF Commutation: In this method, arrangement is made to neutralize the reactance voltage by producing a reversing emf in the short-circuited coil under commutation. This reversing emf, as the name shows, is an emf in opposition to the reactance voltage and if its value is made equal to the latter, it will completely wipe it off, thereby producing quick reversal of current in the short-circuited coil which will result in sparkless commutation. The reversing emf may be produced in two ways: (i) either by giving the brushes a forward lead sufficient enough to bring the short-circuited coil under the influence of next pole of opposite polarity or (ii) by using Interpoles. The first method was used in the early machines but has now been abandoned due to many other difficulties it brings along with.

Interpoles of Compoles: These are small poles fixed to the yoke and spaced in between the main poles. They are wound with comparatively few heavy gauge Cu wire turns and are connected in series with the armature so that they carry full armature current. Their polarity, in the case of a generator, is the same as that of the main pole ahead in the direction of rotation. The function of interpoles is two-fold: (i) As their polarity is the same as that of the main pole ahead, they induce an emf in the coil (under commutation) which helps the reversal of current. The emf induced by the compoles is known as commutating or reversing emf. The commutating emf neutralizes the reactance emf thereby making commutation sparkless. With interpoles, sparkless commutation can be obtained up to 20 to 30% overload with fixed brush position. In fact, interpoles raise sparking limit of a machine to almost the same value as heating limit. Hence, for a given output, an interpole machine can be made smaller and, therefore, cheaper than a non-interpolar machine. As interpoles carry armature current, their commutating emf is proportional to the armature current. This ensures automatic neutralization of reactance voltage which is also due to armature current. (ii) Another function of the interpoles is to neutralize the cross-magnetising effect of armature reaction. Hence, brushes are not to be shifted from the original position.

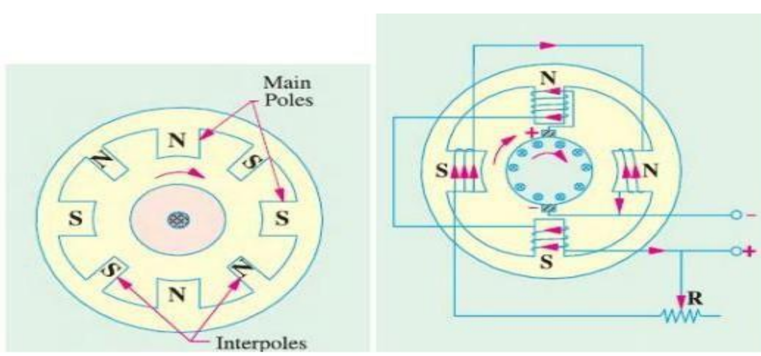


Fig: Interpoles of Compoles

OF as before, represents the mmf due to main poles. OA represents the crossmagnetising mmf due to armature. BC which represents mmf due to interpoles, is obviously in opposition to OA, hence they cancel each other out. This cancellation of crossmagnetisation is automatic and for all loads because both are produced by the same armature current. The distinction between the interpoles and compensating windings should be clearly understood. Both are connected in series and thier m.m.fs. are such as to neutralize armature reaction. But compoles additionally supply mmf for counteracting the reactance voltage induced in the coil undergoing commutation. Moreover, the action of the compoles is localized; they have negligible effect on the armature reaction occurring on the remainder of the armature periphery.

Characteristics of DC Generators

Generally, following three characteristics of DC generators are taken into considerations: (i) Open Circuit Characteristic (O.C.C.), (ii) Internal or Total Characteristic and (iii) External Characteristic. These characteristics of DC generators are explained below.

1. Open Circuit Characteristic (O.C.C.) (E_0/I_f)

Open circuit characteristic is also known as magnetic characteristic or no-load saturation characteristic. This characteristic shows the relation between generated emf at no load (E_0) and the field current (I_f) at a given fixed speed. The O.C.C. curve is just the magnetization curve and it is practically similar for all type of generators. The data for O.C.C. curve is obtained by operating the generator at no load and keeping a constant speed. Field current is gradually increased and the corresponding terminal voltage is recorded. The connection arrangement to obtain O.C.C. curve is as shown in the figure below. For shunt or series excited generators, the field winding is disconnected from the machine and connected across an external supply.

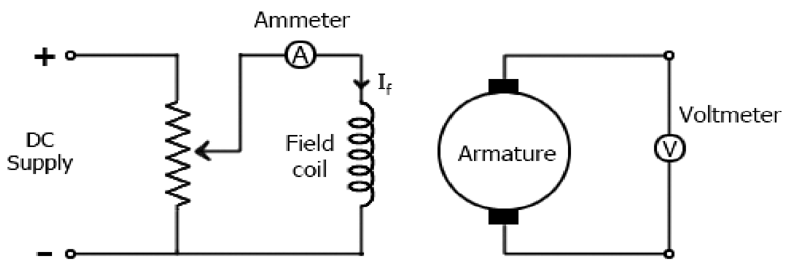
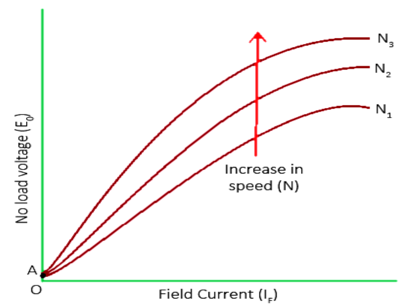


Fig: Circuit for OCC

Now, from the emf equation of dc generator, we know that Eg = kϕ. Hence, the generated emf should be directly proportional to field flux (and hence, also directly proportional to the field current). However, even when the field current is zero, some amount of emf is generated (represented by OA in the figure below). This initially induced emf is due to the fact that there exists some residual magnetism in the field poles. Due to the residual magnetism, a small initial emf is induced in the armature. This initially induced emf aids the existing residual flux, and hence, increasing the overall field flux. This consequently increases the induced emf. Thus, O.C.C. follows a straight line. However, as the flux density increases, the poles get saturated and the ϕ becomes practically constant. Thus, even we increase the If further, ϕ remains constant and hence, Eg also remains constant. Hence, the O.C.C. curve looks like the B-H characteristic.



Open Circuit Characteristic (O.C.C.)

The above figure shows a typical no-load saturation curve or open circuit characteristics for all types of DC generators.

2. Internal or Total Characteristic (E/I_a)

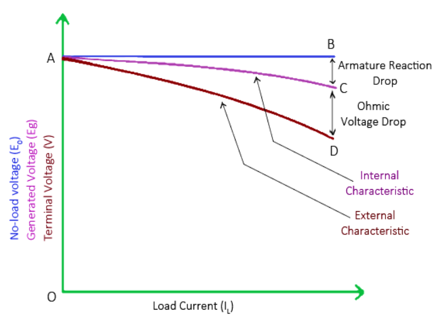
An internal characteristic curve shows the relation between the on-load generated emf (Eg) and the armature current (Ia). The on-load generated emf Eg is always less than E0 due to the armature reaction. Eg can be determined by subtracting the drop due to demagnetizing effect of armature reaction from no-load voltage E0. Therefore, internal characteristic curve lies below the O.C.C. curve.

3. External Characteristic (V/I_L)

An external characteristic curve shows the relation between terminal voltage (V) and the load current (IL). Terminal voltage V is less than the generated emf Eg due to voltage drop in the armature circuit. Therefore, external characteristic curve lies below the internal characteristic curve. External characteristics are very important to determine the suitability of a generator for a given purpose. Therefore, this type of characteristic is sometimes also called as performance characteristic or load characteristic.

Internal and external characteristic curves are shown below for each type of generator.

Characteristics of Separately Excited DC Generator:



Characteristics of separately excited DC generator

If there is no armature reaction and armature voltage drop, the voltage will remain constant for any load current. Thus, the straight line AB in above figure represents the no-load voltage vs. load current IL. Due to the demagnetizing effect of armature reaction, the on-load generated emf is less than the no-load voltage. The curve AC represents the on-load generated emf Eg vs. load current ILi.e. Internal characteristic (as Ia = IL for a separately excited dc generator). Also, the terminal voltage is lesser due to ohmic drop occurring in the armature and brushes. The curve AD represents the terminal voltage vs. load current i.e. external characteristic.

Characteristics of DC Shunt Generator

To determine the internal and external load characteristics of a DC shunt generator the machine is allowed to build up its voltage before applying any external load. To build up voltage of a shunt generator, the generator is driven at the rated speed by a prime mover. Initial voltage is induced due to residual magnetism in the field poles. The generator builds up its voltage as explained by the O.C.C. curve. When the generator has built up the voltage, it is gradually loaded with resistive load and readings are taken at suitable intervals. Connection arrangement is as shown in the figure below.

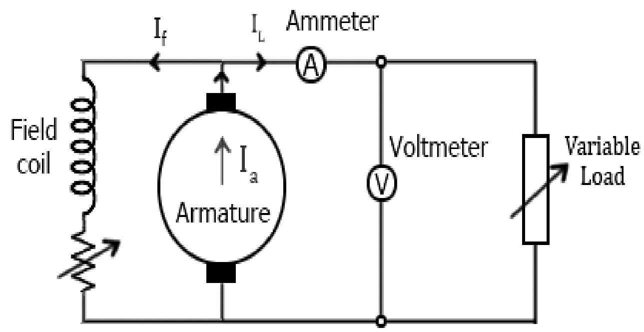
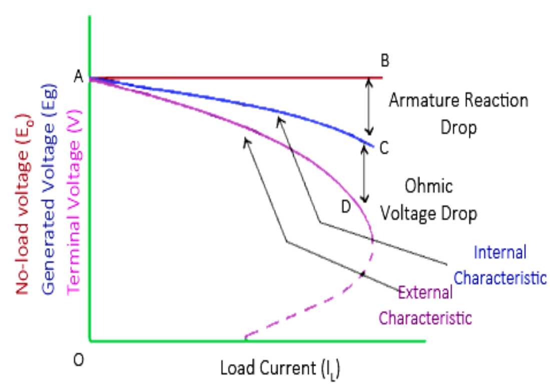


Fig: Circuit for External characteristics of shunt generator

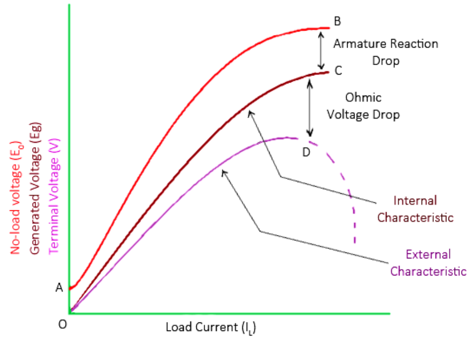
Unlike, separately excited DC generator, here, IL≠Ia. For a shunt generator, Ia=IL+If. Hence, the internal characteristic can be easily transmitted to Eg vs. IL by subtracting the correct value of Iffrom Ia.



Characteristics of DC shunt generator

During a normal running condition, when load resistance is decreased, the load current increases. But, as we go on decreasing the load resistance, terminal voltage also falls. So, load resistance can be decreased up to a certain limit, after which the terminal voltage drastically decreases due to excessive armature reaction at very high armature current and increased I2R losses. Hence, beyond this limit any further decrease in load resistance results in decreasing load current. Consequently, the external characteristic curve turns back as shown by dotted line in the above figure.

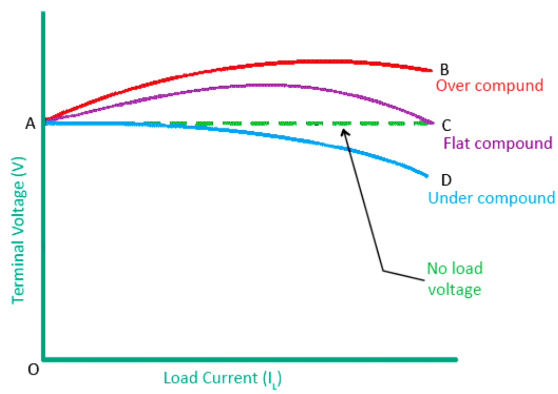
Characteristics of DC Series Generator



Characteristics of DC series generator

The curve AB in above figure identical to open circuit characteristic (O.C.C.) curve. This is because in DC series generators field winding is connected in series with armature and load. Hence, here load current is similar to field current (i.e. IL=If). The curve OC and OD represent internal and external characteristic respectively. In a DC series generator, terminal voltage increases with the load current. This is because, as the load current increases, field current also increases. However, beyond a certain limit, terminal voltage starts decreasing with increase in load. This is due to excessive demagnetizing effects of the armature reaction.

Characteristics Of DC Compound Generator



External characteristic of DC compound generator

The above figure shows the external characteristics of DC compound generators. If series winding amp-turns are adjusted so that, increase in load current causes increase in terminal voltage then the generator is called to be over compounded. The external characteristic for over compounded generator is shown by the curve AB in above figure.

If series winding amp-turns are adjusted so that, the terminal voltage remains constant even the load current is increased, then the generator is called to be flat compounded. The external characteristic for a flat compounded generator is shown by the curve AC.

If the series winding has lesser number of turns than that would be required to be flat compounded, then the generator is called to be under compounded. The external characteristics for an under compounded generator are shown by the curve AD.

Parallel Operation of D.C. Generators:

Here this explains you the parallel operation of dc generators and load sharing among them for the continuous power supply. In a DC power plant, power is usually supplied from several generators of small ratings connected in parallel instead of from one large generator. This is due to the following reasons:

(i) Continuity of service:

If a single large generator is used in the power plant, then in case of its breakdown, the whole plant will be shut down. However, if power is supplied from a number of small units operating in parallel, then in case of failure of one unit, the continuity of supply can be maintained by other healthy units.

(ii) Efficiency:

Generators run most efficiently when loaded to their rated capacity. Electric power costs less per kWh when the generator producing it is efficiently loaded. Therefore, when load demand on power plant decreases, one or more generators can be shut down and the remaining units can be efficiently loaded.

(iii) Maintenance and repair:

Generators generally require routine-maintenance and repair. Therefore, if generators are operated in parallel, the routine or emergency operations can be performed by isolating the affected generator while the load is being supplied by other units. This leads to both safety and economy.

(iv) Increasing plant capacity:

In the modern world of increasing population, the use of electricity is continuously increasing. When added capacity is required, the new unit can be simply paralleled with the old units. In many situations, a single unit of desired large capacity may not be available. In that case, a number of smaller units can be operated in parallel to meet the load requirement. Generally, a single large unit is more expensive.

(v) Non-availability of single large unit:

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

Connecting Shunt Generators in Parallel:

The generators in a power plant are connected in parallel through bus-bars. The bus-bars are heavy thick copper bars and they act as +ve and -ve terminals. The positive terminals of the generators are connected to the +ve side of bus-bars and negative terminals to the negative side of bus-bars.

Fig. (3.15) shows shunt generator 1 connected to the bus-bars and supplying load. When the load on the power plant increases beyond the capacity of this generator, the second shunt generator 2 is connected in parallel with the first to meet the increased load demand. The procedure for paralleling generator 2 with generator 1 is as under:

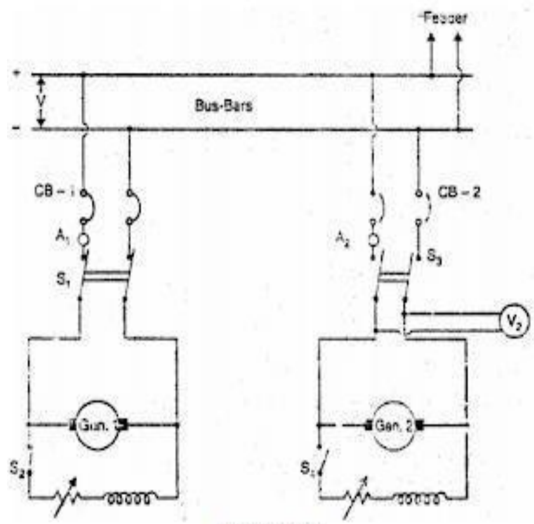


Fig. (3.15)

Parallel operation of shunt generators

(i) The prime mover of generator 2 is brought up to the rated speed. Now switch S4 in the field circuit of the generator 2 is closed.

(ii) Next circuit breaker CB-2 is closed and the excitation of generator 2 is adjusted till it generates a voltage equal to the bus-bars voltage.This is indicated by voltmeter V2.

(iii) Now the generator 2 is ready to be paralleled with generator 1. The main switch S3 is closed, thus putting generator 2 in parallel with generator 1. Note that generator 2 is not supplying any load because it's generated e.m.f. is equal to bus-bars voltage.The generator is said to be “floating” (i.e., not supplying any load) on the bus-bars.

(iv) If generator 2 is to deliver any current, then it's generated voltage E should be greater than the bus-bars voltage V. In that case, the current supplied by it is I = (E - V)/Ra where Ra is the resistance of the armature circuit. By increasing the field current (and hence induced e.m.f. E), the generator 2 can be made to supply the proper amount of load.

(v) The load may be shifted from one shunt generator to another merely by adjusting the field excitation. Thus if generator 1 is to be shut down, the whole load can be shifted onto generator 2 provided it has the capacity to supply that load. In that case, reduce the current supplied by generator 1 to zero (This will be indicated by ammeter A1) open C.B.-1 and then open the main switch S1.

Load Sharing of two generators:

The load sharing between shunt generators in parallel can be easily regulated because of their drooping characteristics.The load may be shifted from one generator to another merely by adjusting the field excitation.Let us discuss the load sharing of two generators which have unequal no-load voltages.

Let E1, E2 = no-load voltages of the two generators

R1, R2 = their armature resistances

V = common terminal voltage (Bus-bars voltage)

then I1 = (E1 - V)/R1 and I2= (E2-V)/R2

Thus the current output of the generators depends upon the values of E1 and E3.These values may be changed by field rheostats.The common terminal voltage (or bus-bars voltage) will depend upon

(i) the e.m.f.s of individual generators and

(ii) the total load current supplied.

It is generally desired to keep the bus bars voltage constant. This can be achieved by adjusting the field excitations of the generators operating in parallel.

Compound Generators in Parallel:

Under-compounded generators also operate satisfactorily in parallel but over compounded generators will not operate satisfactorily unless their series fields are paralleled. This is achieved by connecting two negative brushes together as shown in Fig. (3.16) (i). The conductor used to connect these brushes is generally called equaliser bar. Suppose that an attempt is made to operate the two generators in Fig. (3.16) (ii) in parallel without an equalizer bar. If, for any reason, the current supplied by generator 1 increases slightly, the current in its series field will increase and raise the generated voltage.

This will cause generator 1 to take more load. Since total load supplied to the system is constant, the current in generator 2 must decrease and as a result, its series field is weakened. Since this effect is cumulative, the generator 1 will take the entire load and drive generator 2 as a motor. Under such conditions, the current in the two machines will be in the direction shown in Fig. (3.16) (ii). After machine 2 changes from a generator to a motor, the current in the shunt field will remain in the same direction, but the current in the armature and series field will reverse.

Thus the magnetising action, of the series field opposes that of the shunt field. As the current taken by the machine 2 increases, the demagnetizing action of series field becomes greater and the resultant field becomes weaker. The resultant field will finally become zero and at that time machine 2 will short circuit machine 1, opening the breaker of either or both machines.

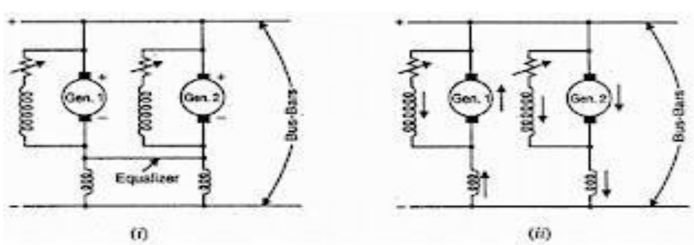


Fig. (3.16)

Fig: Parallel operation of compound generators

When the equalizer bar is used, a stabilizing action exists? And neither machine tends to take the entire load. To consider this, suppose that current delivered by generator 1 increase. The increased current will not only pass through the series field of generator 1 but also through the equalizer bar and series field of generator 2.Therefore, the voltage of both the machines increases and the generator 2 will take a part of the load.

PARALLEL OPERATION OF DC SERIES GENERATOR

The interesting thing about the parallel operation of DC series generator is that DC series generators are not usually employed for supply of power. Instead DC series motors are arranged in parallel to operate as DC series generators during Electric Braking.

- Series generators are rarely used in industry for supplying loads. Some applications like electric braking may employ them and operate two or more series generates in parallel.
- The excitation of the machine I increase, increasing the load current delivered. As the total current is I the current supplied by machine II reduces, so also its excitation and induced emf.

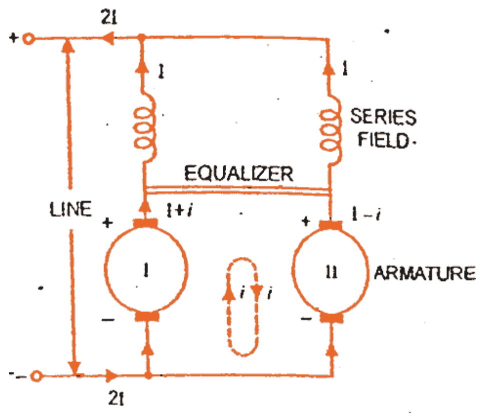


Fig: Parallel operation of Series generators

- Thus machine I takes greater and greater fraction of the load current with machine II shedding its load. Ultimately the current of machine II becomes negative and it also loads the first machine.
- Virtually there is a short circuit of the two sources, the whole process is thus highly unstable. One remedy is for a problem as this is to make the two fields immune to the circulating current between the machines.
- With the equalizer present, a momentary disturbance does not put the two machines out of action.
- A tendency to supply a larger current by a machine strengthens the field of the next machine and increases its induced emf . This brings in stable conditions for operation rapidly.

Use of Equalizer Bars:

Here comes the use of equalizer bars in the parallel operation of DC series generators. The possibility of reversal of either machine can be prevented by preventing the flow of circulating current produced due to inequalities of induced emfs of the machines through the series field winding.

- This Aim can be achieved by connecting a heavy copper bar of negligible resistance across the two machines as shown in the figure.
- Now the circulating current does not affect the field winding, but it get confined to the armature and the equalizing bars.
- Now if the armature current increases, the terminal voltage drop occurs and the original condition is restored.

Cross connection of Field windings:

If the field coils are cross-connected when the series motors are connected in parallel, then any increase in the current of the armature of generator 1, the increased current flows occurs through the field coil of generator 2. This increases the electromotive force of generator, which opposes the change in load sharing trying to stabilize the operation of the two generators at the original operating condition itself. Thus it will give more positive and better operation than equalizer connection.

1)

Comparison of Lap and Wave Type Winding

Sr. No.	Lap winding	Wave winding
1.	Number of parallel paths (A) = Poles (P)	Number of parallel paths (A) = 2 (always)
2.	Number of brush sets required is equal to number of poles.	Number of brush sets required is always equal to two.
3.	Preferable for high current, low voltage capacity generators.	Preferable for high voltage, low current capacity generators.
4.	Normally used for generators of capacity more than 500 A.	Preferred for generators of capacity less than 500 A.

2)

Example *A d.c. shunt generator has shunt field winding resistance of 100 Ω. It i supplying a load of 5 kW at a voltage of 250 V. If its armature resistance is 0.22 Ω calculate the induced e.m.f. of generator.*

Solution : Consider shunt generator as shown in the Fig. 3.9.

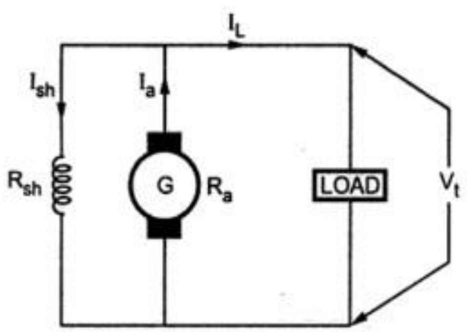


Fig. 3.9

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

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

Now $V_t = 250$ V

and $R_{sh} = 100\ \Omega$

$$\therefore \quad I_{sh} = \frac{250}{100} = 2.5 \text{ A}$$

Load power = 5 kW.

$$\therefore \quad P = V_t \times I_L$$

$$\therefore \quad I_L = \frac{P}{V_t} = \frac{5\times10^3}{250} = 20 \text{ A}$$

$$\therefore \quad I_a = I_L + I_{sh} = 20 + 2.5 = 22.5 \text{ A}$$

Now $E = V_t + I_a R_a$ (neglect V_{brush})

3)

Causes of Failure to Excite Self Excited Generator

The causes of failure, the method of detection and the corresponding remedy are given in the Table 3.1.

Sr. No.	Cause	Method of detection	Remedy
1.	Absence of residual magnetism due to ageing.	Zero reading on voltmeter after rotating armature.	Operate the generator as separately excited first and then as a self excited.
2.	Wrong field winding connections. Due to this, flux gets produced in opposite direction to residual flux. So residual flux cancels the main flux.	Voltmeter reading decreases rather than increasing as generator is started.	Interchange the field connections.
3.	Field resistance is more than the critical resistance.	Voltmeter shows zero reading.	Reduce the resistance of field circuit using proper field divertor.
4.	Generator is driven in opposite direction.	This wipes out the residual flux and fails to excite.	Drive the generator in proper direction.

4)

Critical Field Resistance in D.C. Shunt Generator

Consider the magnetisation characteristics of a d.c. shunt generator shown in the Fig. 3.14.

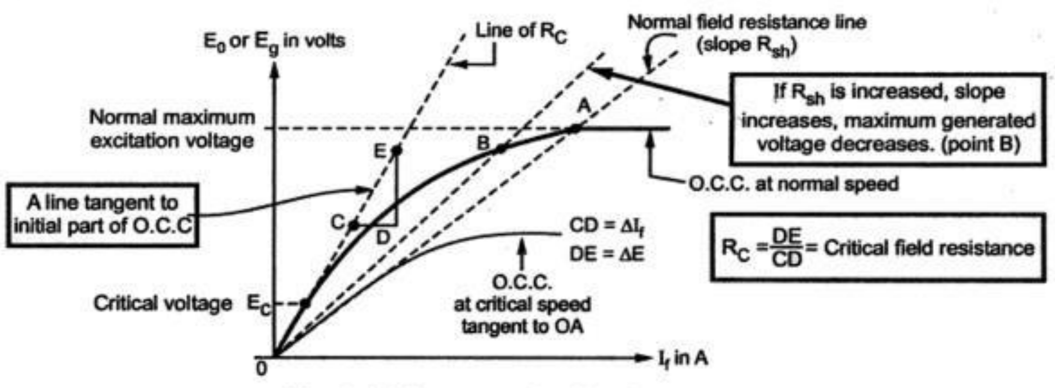


Fig. 3.14 Concept of critical resistance

The Fig. 3.14 shows that generator voltage builds in step till point A. This point is intersection of field resistance line with the open circuit characteristics (O.C.C.). The voltage corresponding to point A is the maximum voltage it can generate. If the slope of field resistance line is reduced by decreasing the field resistance, the maximum voltage generator can build will be higher than that corresponding to point A. Similarly if the slope of field resistance line is increased by increasing the field resistance, the maximum

5)

Example *A separately excited generator when running at 1200 r.p.m. supplies a current of 200 A at 125 V to a circuit of constant resistance. What will be the current when the speed drops to 1000 r.p.m. if the field current is unaltered ? Armature resistance is 0.04 Ω and the total voltage drop at the brushes is 2 V. Ignore the change in armature reaction.* [JNTU, May-2004 (Set-1, 4), Nov.-2008 (Set-1)]

Solution : $N_1 = 1200$ r.p.m., $I_{a1} = 200$ A, $V_{t1} = 125$ V, $N_2 = 1000$ r.p.m., $R_a = 0.04\ \Omega$

For separately excited generator with constant field current,

$$E_g \propto N$$

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

Now $$E_{g1} = V_{t1} + I_{a1} R_a + \text{Brushdrop} = 125 + 200 \times 0.04 + 2$$

$$= 135 \text{ V}$$

$$\therefore \quad \frac{135}{E_{g2}} = \frac{1200}{1000}$$

$$\therefore \quad E_{g2} = 112.5 \text{ V}$$

But $$E_{g2} = V_{t2} + I_{a2} R_a + \text{Brush drop} \quad \text{...(1)}$$

For the load of constant resistance,

$$R_L = \frac{V_{t1}}{I_{a1}} = \frac{V_{t2}}{I_{a2}} \quad \text{... } I_L = I_a \text{ due to separately excited}$$

$$\therefore \quad R_L = \frac{125}{200} = \frac{V_{t2}}{I_{a2}}$$

$$\therefore \quad V_{t2} = 0.625\ I_{a2} \quad \text{...(2)}$$

Using in (1), $$112.5 = 0.625\ I_{a2} + I_{a2} \times 0.04 + 2$$

$$\therefore \quad 0.665\ I_{a2} = 110.5$$

$$\therefore \quad I_{a2} = 166.165 \text{ A} \quad \text{...New current}$$

Example : *In a 110 V, d.c. compound generator, the resistance of the armature, shunt field and series field are 0.06 Ω, 25 Ω and 0.04 Ω respectively. The load consists of 200 lamps each rated at 55 W, 110 V. Find the total e.m.f. generated and the armature current when the machine is connected in (a) long shunt and (b) short shunt.*

[JNTU, May-2004 (Set-2), Nov.-2008 (Set-1)]

Solution : a) Long shunt compound

$$V_t = 110 \text{ V}$$

Each lamp $P = 55 \text{ W} = V_t I$

$$\therefore \quad I / \text{lamp} = \frac{55}{110} = 0.5 \text{ A}$$

$$\therefore \quad \text{Total } I_L = 200 \text{ lamps} \times 0.5 = 100 \text{ A}$$

$$I_{sh} = \frac{V_t}{R_{sh}} = \frac{110}{25} = 4.4 \text{ A}$$

$$\therefore \quad I_a = I_L + I_{sh} = \mathbf{104.4\ A}$$

$$E_g = V_t + I_a R_a + I_a R_{se} = 110 + 104.4\,[0.06 + 0.04]$$

$$= \mathbf{120.44\ V}$$ ...Generated e.m.f.

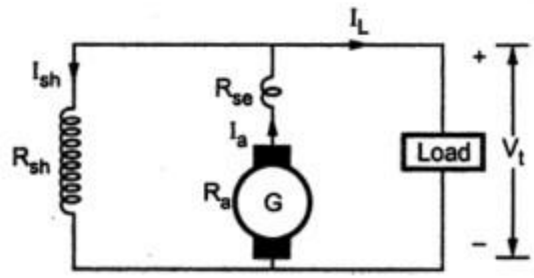


Fig. 3.29

b) Short shunt compound

The load current remains same

$$I_{sh} = \frac{V_t + I_L R_{se}}{R_{sh}} = \frac{110 + 100 \times 0.04}{25} = 4.56 \text{ A}$$

$$\therefore \quad I_a = I_L + I_{sh} = \mathbf{104.56\ A}$$

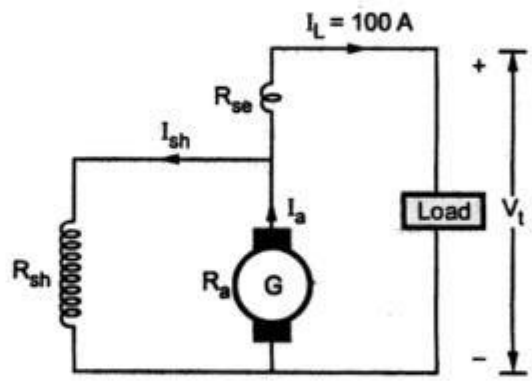


Fig. 3.30

$$\therefore \quad E_g = V_t + I_a R_a + I_L R_{se} = 110 + 104.56 \times 0.06 + 100 \times 0.04$$

$$= \mathbf{120.2736\ V}$$ ...Generated e.m.f.