DC generator - principle - parts - types - function - e.m.f. equation

Objectives: At the end of this lesson you shall be able to
- **state the general concepts of rotating electrical machine**
- **state the principle of the DC generator**
- **explain the faraday's of laws of electro magnetic induction**
- **explain the production of dynamically induced e.m.f., its magnitude and direction**
- **describe the parts of a DC generator and their function**
- **classify and identify the different type of generators and their terminal markings**
- **derive the emf equation and calculation of a DC generator**
- **explain about separately excited DC generator with different types of windings.**

General concept of rotating electrical machine

In rotating machines, there are two parts, the stator and rotor. Rotating electrical machines are also of two types - DC and AC machines. Electrical machines are widely used. In DC machines the stator is used as a field and the rotor is used as an armature, while reverse is the case for AC machines. That is synchronous generators and synchronous motors. The induction motor is another kind of AC machine, which is singly excited; that is AC supply voltage is only given to the stator and no supply is given to the rotor. In DC machines and synchronous machines, the field is always excited.

Generator: An electrical generator is a machine which converts mechanical energy into electrical energy.

Principle of the generator: To facilitate this energy conversion, the generator works on the principle of Faraday's Laws of Electromagnetic Induction.

Faraday's Laws of Electromagnetic Induction: There are two laws.

The first law states

First law: Whenever the flux linking to a conductor an emf will be induced in the same conductor.

The second law states: The magnitude of such induced emf depends upon the rate of change of the flux linkage.

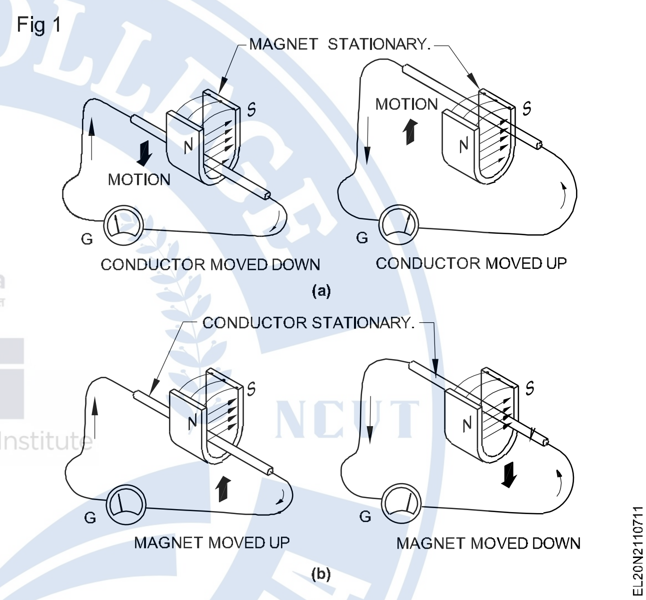
$$\text{emf} \propto \frac{\text{Change of flux}}{\text{Time taken for change}}.$$

Types of emf: According to Faraday's Laws, an emf can be induced, either by the relative movement of the conductor and the magnetic field or by the change of flux linking on a stationary conductor.

Dynamically induced emf: In case, the induced emf is due to the movement of the conductor in a stationary magnetic field as shown in Fig 1a or by the movement of the magnetic field on a stationary conductor as shown in Fig 1b, the induced emf is called dynamically induced emf.

As shown in Figs 1a & 1b, the conductor cuts the lines of force in both cases to induce an emf, and the presence of the emf could be found by the deflection of the needle of the galvanometer `G'. This principle is used in DC and AC generators to produce electricity.

Fig 1



Production of dynamically induced emf: Whenever a conductor cuts the magnetic flux, a dynamically induced emf is produced in it. This emf causes a current to flow if the circuit of the conductor is closed.

For producing dynamically induced emf, the requirements are:

- magnetic field
- conductor
- relative motion between the conductor and the magnetic field.

If the conductor moves with a relative velocity 'v' with respect to the field, then the induced emf `E' will be

$E = BLV \sin\theta$ Volts

where

B = magnetic flux density, measured in tesla

L = effective length of the conductor in the field in metres

V = relative velocity between field and conductor in metre/second

θ = the angle at which the conductor cuts the magnetic field.

Let us consider Fig 2a in which conductors A to I are placed on the periphery of the armature under magnetic poles. Assume for this particular generator shown in Fig 2a, the value of BLV = 100V.

Accordingly the conductor A induces an emf

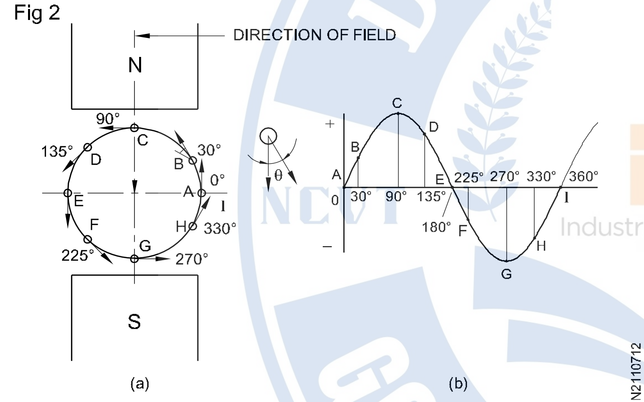
= BLV Sin θ where θ = zero and Sin zero is equal to zero

= 100 x 0 = zero.

Likewise for every position of the remaining conductors in the periphery, the emf induced could be calculated. If these values are plotted on a graph, it will represent the sine wave pattern of induced emf in a conductor when it rotates under N and S poles of uniform magnetic field.

As in Fig 2b the emf induced by this process is basically alternating in nature, and this alternating current is converted into direct current in a DC generator by the commutator.

Fig 2

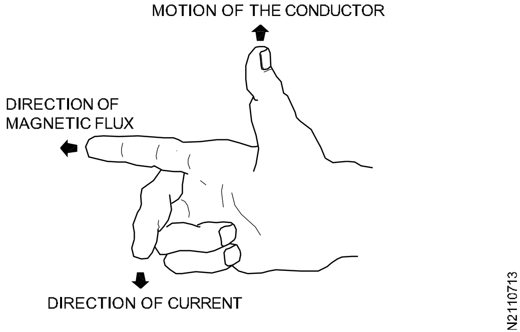


(a) (b)

PRODUCTION OF THE SINEWAVE

Fleming's right hand rule: The direction of dynamically induced emf can be identified by this rule. Hold the thumb, forefinger and middle finger of the right hand at right angles to each other as shown in Fig 3 such that the forefinger is in the direction of flux and the thumb is in the direction of the motion of the conductor, then the middle finger indicates the direction of emf induced, i.e. towards the observer or away from the observer.

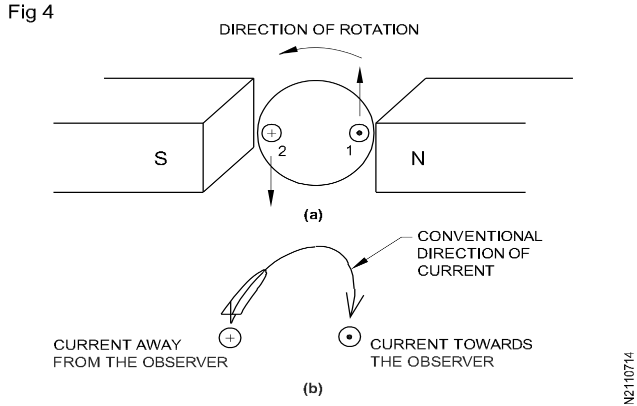
Fig 3



FLEMINGS RIGHT HAND RULE

Imagine a conductor moving in between north and south poles in an anticlockwise direction as shown in Fig 4a.

Fig 4



DIRECTION OF THE INDUCED CURRENT

Applying Fleming's right hand rule, we find that the conductor 1 which is moving upwards under the north pole will induce an emf in the direction towards the observer indicated by the dot sign and the conductor 2 which is moving down under the south pole will induce an emf in the direction away from the observer indicated by the plus sign.

Fig 4b indicates the current direction in the form of an arrow. The dot sign indicates the pointed head of the arrow showing the current direction towards the observer and the plus sign indicates the cross-feather of the arrow showing the current direction away from the observer.

Parts of DC generator

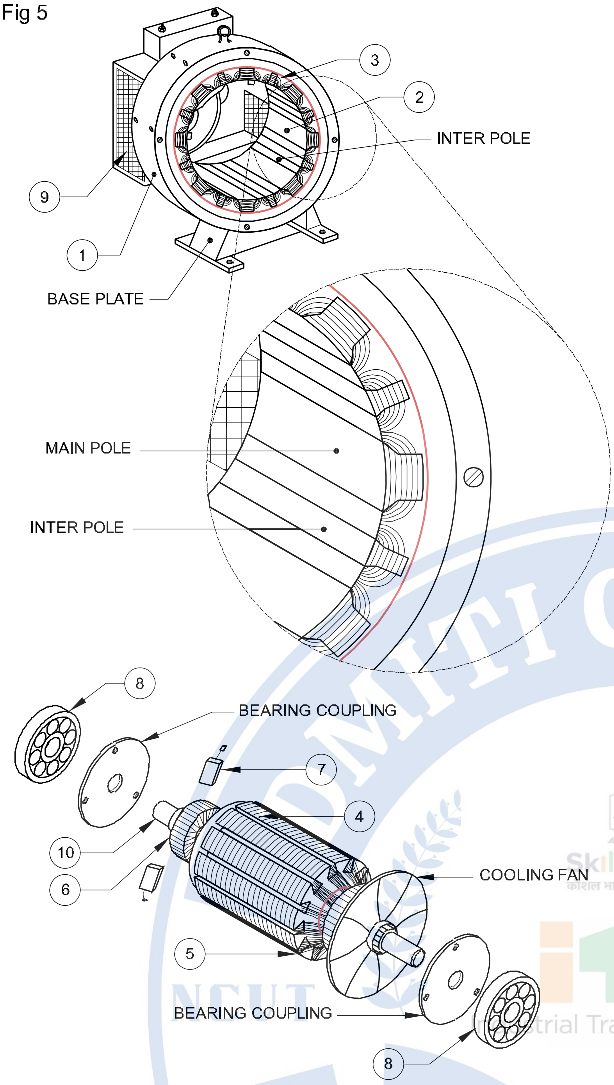
A DC generator consists of the following essential parts as shown in Fig 5.

1 Frame or yoke
2 Field poles and pole-shoes (Figs 6,7 & 8)
3 Field coils or field winding (Fig 8)
4 Armature core
5 Armature windings or armature conductors
6 Commutator
7 Brushes
8 Bearings and end plates
9 Air filter for fan
10 Shaft

Yoke: The outer frame or yoke serves a dual purpose. Firstly, it provides mechanical support for the poles and acts as a protecting cover for the whole machine. Secondly, it allows the magnetic circuit to complete through it. In small generators where cheapness rather than weight is the main consideration, yokes are made of cast iron. But for large machines usually cast steel or rolled steel is used.

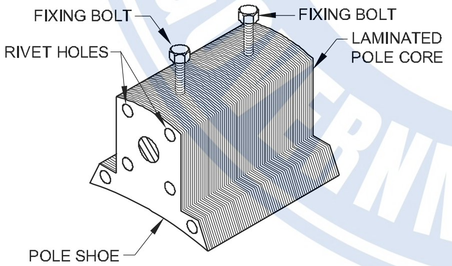
Pole cores and pole shoes (Fig 9): The field magnets consist of pole cores and pole shoes. The pole shoes serve two purposes; (i) they spread out the flux in the air gap uniformly and also, being of a larger cross-section, reduce the reluctance of the magnetic path, and (ii) they also support the field coils.

Fig 5



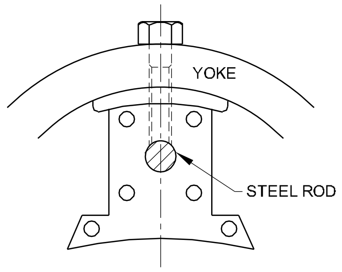
PARTS OF A DC MACHINE

Fig 6



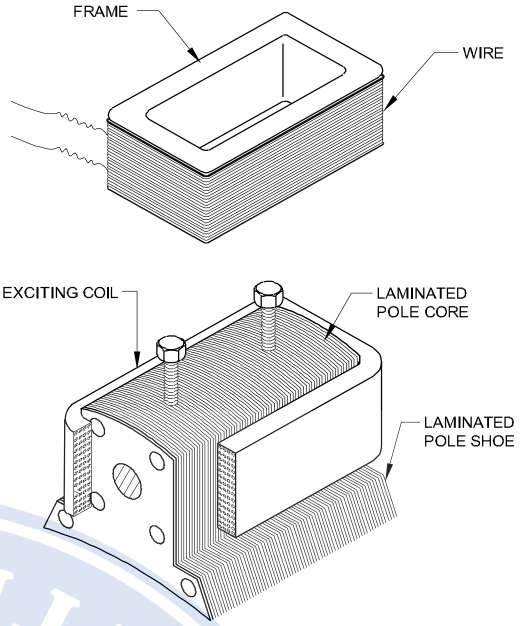
LAMINATED POLE CORE

Fig 7



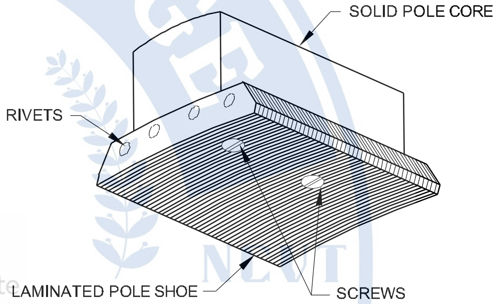
HOLDING SCREW BOLTED IN TO STEEL BAR POLE CORE ASSEMBLY

Fig 8



POLE ASSEMBLY

Fig 9



SEPERATE POLE SHOE BOLTED TO POLE CORE

Pole coils (Field coils): The field coils or pole coils, which consist of copper wire or strip are former-wound for the correct dimension. Then the former is removed and the wound coils are put into place over the core as shown in Fig 8.

When a current is passed through the coils, they magnetise the poles which produce the necessary flux that is cut by revolving armature conductors.

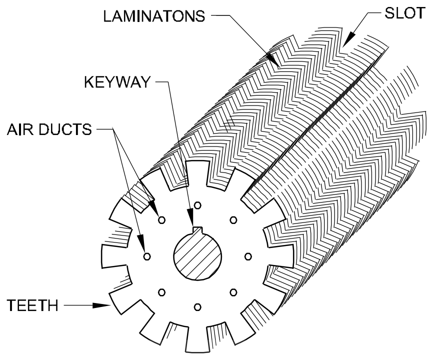
Both thick gauge wire winding (series) and thin gauge winding (shunt) are wound, one over the other with separate insulations, and the terminals are brought out separately.

Armature core: The armature core houses the armature conductors and rotate in the magnetic field so as to make the conductors to cut the magnetic flux. In addition to this, its most important function is to provide a path of very low reluctance to the field flux, thereby allowing the magnetic circuit to complete through the yoke and the poles.

The armature core is cylindrical or drum-shaped as shown in Fig 10, and build up of circular sheet steel discs or laminations approximately 0.5mm thick as shown in Fig 11.

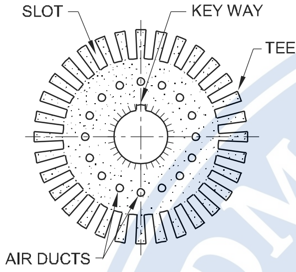
Armature windings: The armature windings are usually former-wound. These are first wound in the form of flat rectangular coils and are then pulled into their proper shape with a coil puller.

Fig 10



ARMATURE CORE MADE OF LAMINATION

Fig 11

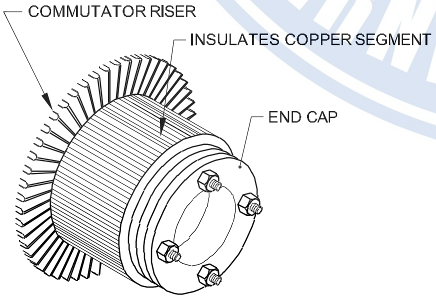


ARMATURE CORE LAMINATIONS

Commutator: The function of the commutator is to facilitate collection of current from the armature conductors. It rectifies i.e. converts the alternating current induced in the armature conductors into uni-directional current for the external load circuit. It is of cylindrical structure and is built up of wedge-shaped segments of high conductivity, hard-drawn or drop-forged copper. These segments are insulated from each other by thin layers of mica. The number of segments is equal to the number of armature coils.

Each commutator segment is connected to the armature conductor by means of a copper lug or riser, whose general appearance when assembled is shown in Fig 12.

Fig 12

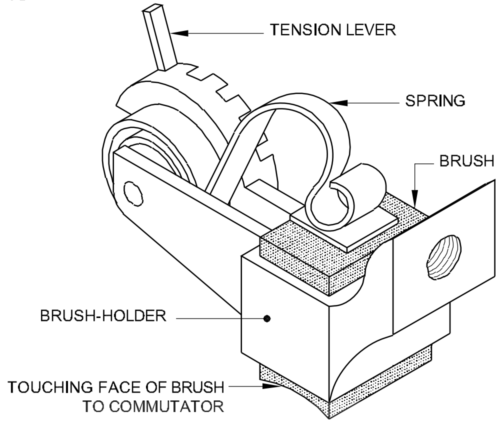


COMPLETE ASSEMBLY OF COMMUTATOR

Brushes: The brushes whose function is to collect current from the commutator are usually made of carbon and graphite and are in the shape of a rectangular block.

These brushes are housed in brush-holders, shown in Fig 13, which have a box-holder for the brush, a spring to maintain the brush tension and a hole to fix the holder to the rocker arm.

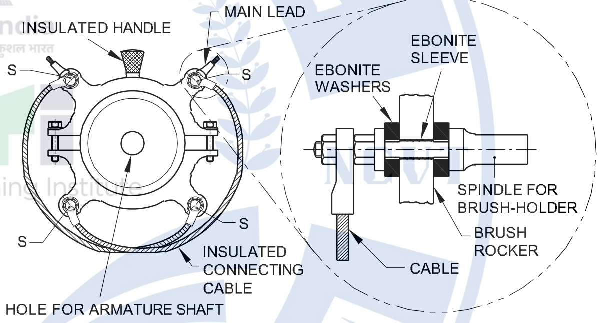
Fig 13



Brush-rocker: The spindle is used to have a number of brushes connected in a large machine. There may be only two brushes for a small machine. All the spindles are insulated and attached to the brush rocker.

The brush-rocker may either be supported by a bearing cover in a small machine or by brackets attached to the yoke as shown in Fig 14. The brush position to the neutral axis can be set by changing the position of the brush-rocker.

Fig 14

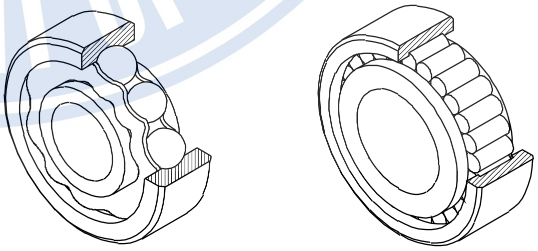


BRUSH-HOLDER

S-SPINDLE FOR BRUSH-HOLDER

Bearings (Fig 15): Because of their reliability ball bearings are frequently employed, though for heavy duties roller bearings are preferable.

Fig 15



BALL BEARING

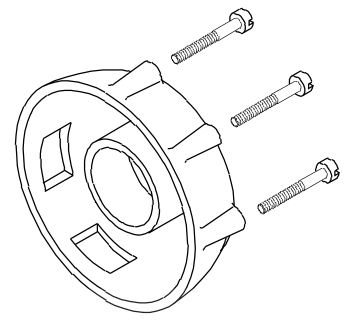
ROLLER BEARING

End plates (Fig 16): The bearings are housed in these end plates, and they are fixed to the yoke. They help the armature for frictionless rotation and to position the armature in the air gap of the field poles.

Cooling fan

DC Machines are often selected based upon a particular work or load requirement. In most cases, heat dissipation is achieved through a cooling fan fitted on the DC Machine shaft. Another method to remove heat from DC machine is by providing forced air cooling.

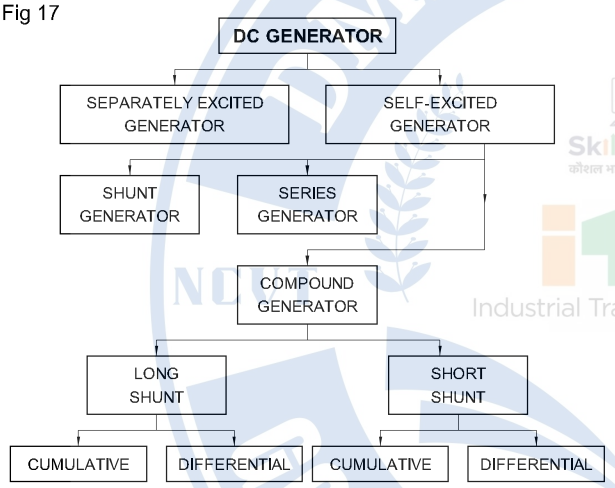
Fig 16



END PLATE 2-OFF

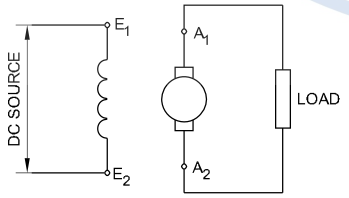
Types of DC generators: The type of a DC generator is determined by the manner in which the field excitation is provided. In general, the methods employed to connect the field and armature windings, fall into the following groups.(Fig 17)

Fig 17



Separately excited generator: The field excitation for a separately excited generator, shown in Fig 18, is supplied from an independent source, such as storage battery, separate DC generator or rectified DC supply from an AC source.

Fig 18



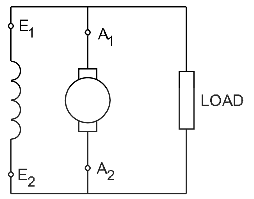
CONNECTION DIAGRAM OF SEPARATELY EXCITED DC GENERATOR

The field excitation voltage may be the same as that of generated (armature) voltage or may differ. Generally, the excitation voltage will be of low voltage, say 24, 36 or 48V DC.

Self-excited generator: The field excitation is provided by its own armature. In this type of generators, initially the voltage is built up by residual magnetism retained in the field poles. Self-excited generators may be further classified as shunt, series and compound generators.

Shunt generator: The field winding is connected to the armature terminals as shown in Fig 19. (i.e. shunt field winding is connected in parallel with armature winding). The shunt field contains many turns of relatively fine wire and carries a comparatively small current only which is a small percentage of the rated current of the generator.

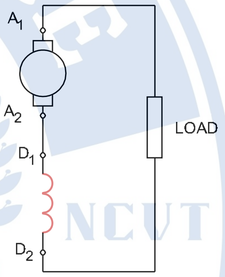
Fig 19



SHUNT GENERATOR

Series generator: The field winding is connected in series with the armature winding as shown in Fig 20. The series field winding has a few turns of heavy wire. Since it is in series with the armature it carries the load current.

Fig 20

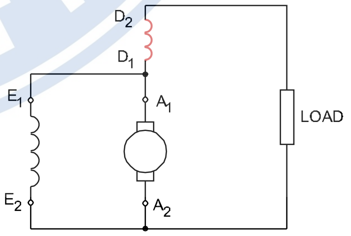


SERIES GENERATOR

Compound generator: The field excitation is provided by a combination of shunt and series field windings.

Short-shunt compound generator: This is a generator in which the shunt field is directly across the armature as shown in Fig 21.

Fig 21

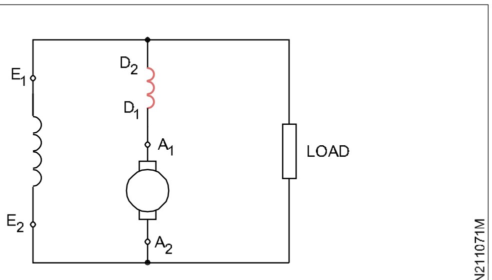


SHORT SHUNT COMPOUND GENERATOR

Long-shunt compound generator: This is a generator in which the shunt field is connected after the series field as shown in Fig 22.

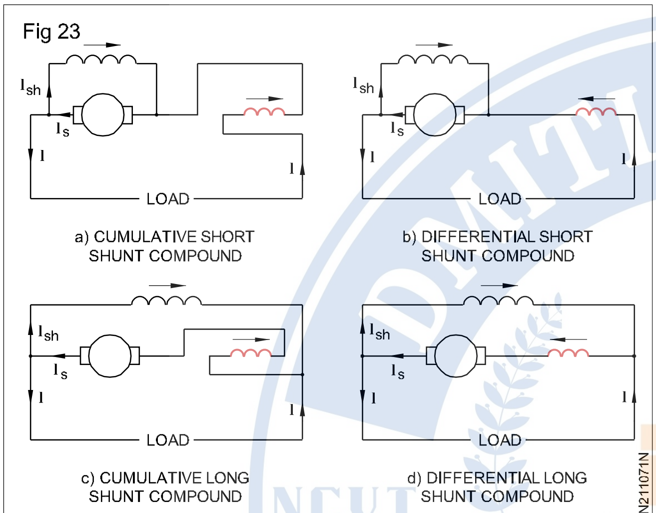
Differential and cumulative compound generator: The compound generators can also be further classified as cumulative and differential. In cumulative compound generators the magnetising forces of the shunt and the series field ampere-turns are cumulative, i.e. they both tend to set up flux in the air gap in the same direction. However, in case the ampere turns of the shunt winding oppose those of the series winding, the machine is said to be differentially compound wound generator. Both the types are shown in Fig 23.

Fig 22



LONG SHUNT COMPOUND GENERATOR

Fig 23



a) CUMULATIVE SHORT SHUNT COMPOUND

b) DIFFERENTIAL SHORT SHUNT COMPOUND

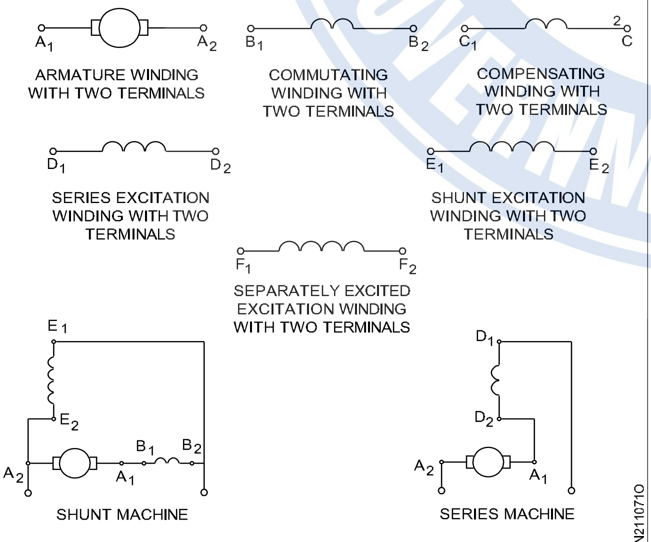
c) CUMULATIVE LONG SHUNT COMPOUND

d) DIFFERENTIAL LONG SHUNT COMPOUND

TYPES OF DC COMPOUND GENERATORS

Terminal markings : As per BIS 4718-1975 the terminal markings for DC commutator machines shall be according to the marking principles (Fig 24).

Fig 24



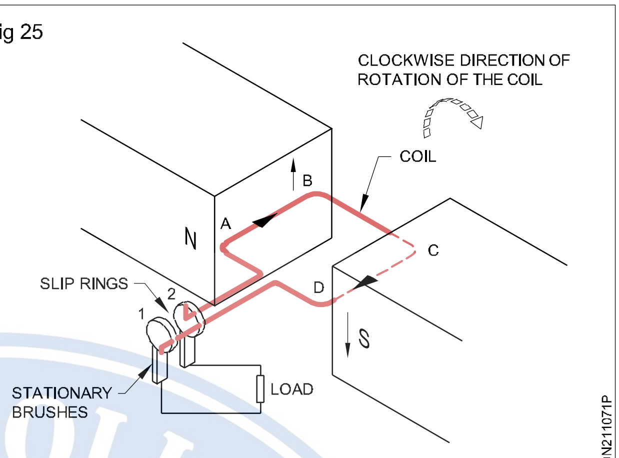
TERMINAL MARKING OF DC MACHINES AS PER BIS

Commutator (Split rings)

A generator produces electrical power with the help of the rotation of a group of conductors in a magnetic field. It uses the principle of electromagnetic induction to convert the input mechanical power into electrical power.

Slip rings: Let us consider a simple AC generator having a single loop of wire and rotated within a fixed magnetic field, as shown in Fig 25.

Fig 25



SIMPLE AC GENERATOR

Let each end of the single loop coil be connected to copper or brass rings called slip rings. These slip-rings are insulated from each other, insulated and mounted on the shaft. In a broader sense this rotating assembly (coil, shaft & slip-ring) is called armature. The wire loop (armature coil) is connected to an external circuit by means of two brushes which are positioned to rub against the slip-rings. As the armature is rotated at a uniform angular velocity, the generated voltage in the loop conductor will actually be of alternating voltage.

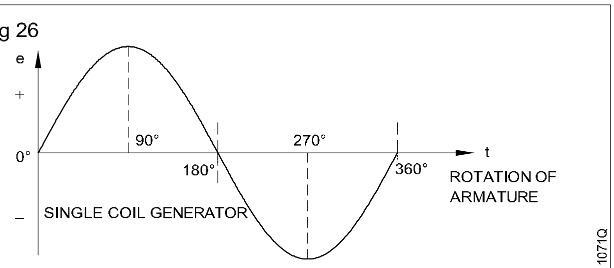
For the clockwise rotation indicated, the direction of generated voltage and the resulting current in the coil side under the north pole will be directed from A to B making the slip-ring 2 negative. This is readily confirmed by using Fleming's right hand rule. Similarly the direction of the induced voltage and the resulting current under the south pole is to be directed from C to D making the slip- ring 1 as positive. When the conductor AB moves from the north pole to the south pole, the direction of induced emf in it will reverse, so that the current will now flow from B to A making the slip-ring 2 positive. At the same time coil side CD has moved into the north pole region and its induced emf is reversed and current will flow from D to C making the slip-ring 1 negative.

Thus for one half of a revolution (for a two-pole generator) the emf is directed around the coils A to B & C to D. For the other half of the revolution the emf is directed around the coil D to C and B to A. The current in the externally connected load resistor via the stationary brushes in contact with the pair of slip rings `1'and `2' will be alternating (AC) in nature.

Wave-shape of the induced voltage: When the output voltage is plotted against Power degrees we get the output wave-form.

The output wave-form obtained across the load, shown in Fig 26, will not be of sinusoidal shape due to un-uniform magnetic field.

Fig 26



WAVE-FORM SHOWS COIL ROTATES UNDER UNIFORM MAGNETIC FIELD (SINE WAVE)

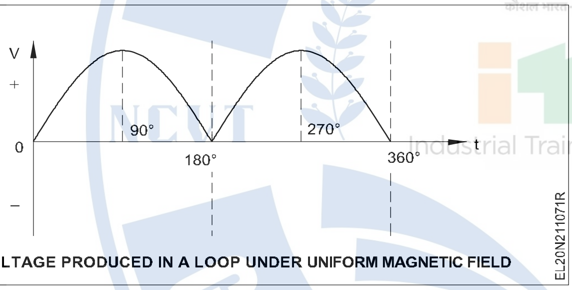
The output wave-form will be of sinusoidal shape as shown in Fig 26.

Simple generator with split-rings: A direct current generator is simply an AC generator provided with split rings instead of slip-rings.

The split ring is a ring made up of hard drawn copper cut into two segments, insulated from each other and the shaft in which it is mounted. A commercial generator uses a number of split rings called commutators. The split ring is a device for reversing the brush contact with the armature coil terminals, every time the induced current in the coil reverses, so that the output current taken by the brushes remains always in the same direction.

Fig 27 represents the generated voltage of a simple DC generator. The voltage is uni-directional due to the split ring action.

Fig 27



VOLTAGE PRODUCED IN A LOOP UNDER UNIFORM MAGNETIC FIELD

The induced emf by a single loop (one turn) coil is very small in magnitude and pulsating in nature as shown in Fig 27. Coils, having a number of turns in series, multiply the generated emf by the same number. However to get a steady (DC) current it is necessary to increase the pulses produced in the armature; thereby their average value is constant.

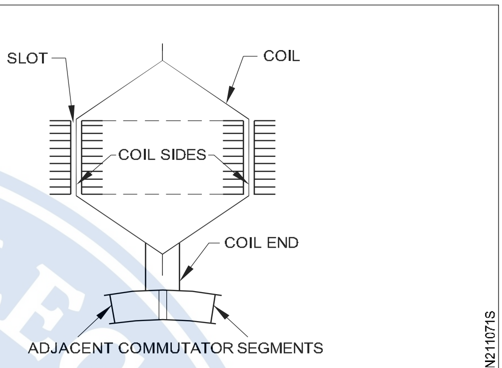
There are two ways to increase the number of pulses during each rotation of the armature.

- Increase the number of field poles.
- Increase the number of separate coils (multi-coil) in the armature.

The multi-coils necessitate a multiple segment split-rings which is called a commutator.

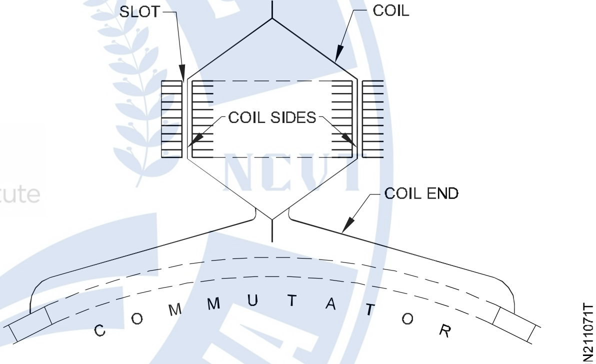
Armature windings (Fig 28 Lap winding, Fig 29 wave winding): We have seen earlier, when a single loop conductor is rotated through a magnetic field, an alternating voltage is induced in it. This alternating voltage can be changed into direct voltage (rectified) by the commutator. In practice, there are several coils in the armature, each with a large number of turns laid in the slots of the armature core. This arrangement of the coil is called armature winding. The ends of the coils are soldered to the commutator raisers, depending on the kind of winding i.e. lap or wave, which decides the number of parallel paths in the armature.

Fig 28



COIL END CONNECTION TO THE COMMUTATOR OF A SIMPLEX LAP WINDING

Fig 29



COIL END CONNECTION TO THE COMMUTATOR OF A SIMPLEX WAVE WINDING

i.e. lap or wave, which decides the numbers of parallel paths in the armature.

A preliminary knowledge about the different types of winding is essential to tackle problems related to the calculation of induced voltage in various types of generators.

Lap and wave windings could readily be identified by the manner in which the coil ends are connected to the commutator bars. As shown in Fig 28, in a simplex lap winding, the ends of a coil are connected to adjacent commutator segments. Fig 29 shows the simplex wave winding in which the coil ends are connected to the commutator segments almost equal to the distance between poles of the same polarity.

Table 1 shows the main differences between lap and wave winding.

Table 1

Lap winding	Wave winding
The two ends of each armature coil are connected to adjacent commutator segments in the case of simplex, two segments apart in duplex and three segments apart in triplex.	The two ends of each coil connect to the commutator segments placed between adjacent poles of the same polarity.
There are many parallel paths for current as there are field poles in the case of lap winding	There are two parallel paths regardless of the number of field poles in the case of simplex wave winding.
No. of parallel paths = Number of poles x plex of the winding	Number of parallel paths in wave windings = 2 x plex of the winding where plex for-simplex is 1, duplex is 2 and triplex is 3.
The number of brush positions is equal to the number of poles.	Only two brush positions are required regardless of the number of field poles.
Used for machines having low voltage and high current capacity.	Used in machines having low current and high voltage capacity.

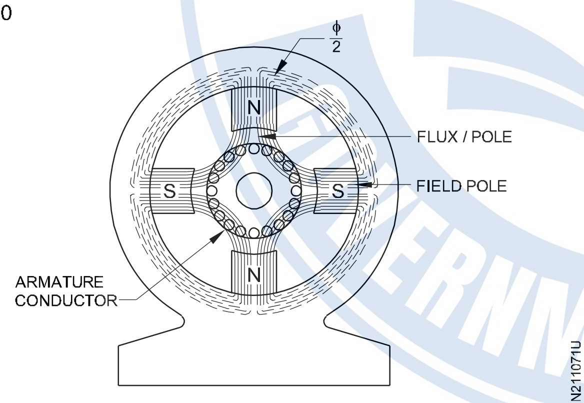
EMF equation of DC generator

When the armature of a DC generator, containing a number of conductors in the form of a winding, rotates at a specific speed in the magnetic field, emf is induced in the armature winding and is available across the brushes. The equation and the numerical problems given as examples will help an electrician to better his understanding about the construction of a DC machine.

Induced emf in a DC generator can be calculated as explained below.

Figure 30 is given for your reference.

Fig 30



4 - POLE DC GENERATOR

Let Ø = flux/pole in weber

Z = total number of armature conductors = No. of slots X No. of conductors/slot

P = No. of poles in the generator

A = No. of parallel paths in armature

N = armature revolution per minute (r.p.m.)

E = emf induced in the generator.

Average emf generated = Rate of change of flux per conductor in one revolution (Faraday's Laws of Electromagnetic induction)

$$\frac{d\varnothing}{dt} \text{ volt (since N = 1)}$$

Now, flux cut/conductor in one revolution, (dØ) = PØ Wb

No. of revolutions/second = N/60

Time for one revolution, (dt) = 60/N second

According to Faraday's Laws of Electromagnetic Induction, we have emf generated/conductor/second

$$= \frac{d\varnothing}{dt} = \frac{P\varnothing N}{60} \text{ volts}$$

emf generated in `Z' conductors in the armature assuming they are all in series $= \dfrac{P\varnothing ZN}{60}$ volts.

The emf generated in the armature of the DC generator when there are

`A' parallel paths in the armature

Could be written as $= \dfrac{\varnothing ZN}{60} \times \dfrac{P}{A}$ volts.

A = 2 - for simplex wave winding

= P - for simplex lap winding.

Example: A four-pole generator, having a simplex wave-wound armature has 51 slots, each slot containing 20 conductors. What will be the voltage generated in the machine, when driven at 1500 r.p.m assuming the flux per pole to be 7.0 mWb?

Solution: $E = \dfrac{\varnothing ZN}{60} \times \dfrac{P}{A}$ volts.

Here, Ø= 7x 10^{-3} Wb, Z = 51 x 20 = 1020, P=4, N = 1500 r.p.m.

A = 2 as the winding is simplex wave.

$$E = \frac{7 \times 10^{-3} \times 1020 \times 1500}{60} \times \frac{4}{2} = 357V.$$

An 8-pole DC generator has 960 armature conductors and a flux per pole of 20mWb running at 500 r.p.m. Calculate the emf generated when the armature is connected as (i) a simplex lap-winding, (ii) a simplex wave winding.

Solution

i Simplex lap winding

$$E = \frac{\varnothing ZN}{60} x \frac{P}{A}$$

$$E = \frac{20 \times 10^{-3} \times 960 \times 500}{60} \times \frac{8}{8} = 160V.$$

ii Simplex wave winding

$$E = \frac{20 \times 10^{-3} \times 960 \times 500}{60} \times \frac{8}{2} = 640V.$$

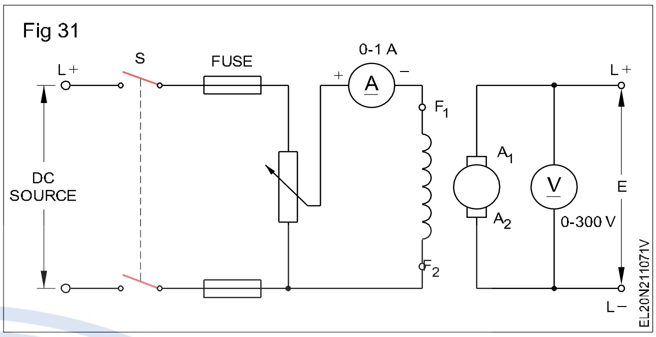
Separately excited DC generator

Introduction : A DC generator is the most commonly used separately excited generator, used for electroplating and battery charging. A separately excited generator is one in which the magnetic field is excited from an external DC source. The DC source may be a DC generator or a battery or a metal rectifier connected to an AC supply.

Generally a potential divider is connected across the DC source, and the required DC voltage is supplied to the field as shown in Fig 31.

An ammeter is connected in the field circuit to measure the field current. The shaft of the generator is coupled to a prime mover.

Fig 31



Advantages of a separately excited generator

The terminal voltage remains almost stable when compared to the self-excited generators because the field circuit is independent of the induced voltage.

As the field is independent, the $I_a R_a$ drop in the armature will not affect the field flux.

This generator can be used where a wide range of terminal voltage is required.

Disadvantage

1 The disadvantage of a separately excited generator is the inconvenience of providing a separate DC source for excitation.

2 Besides it is expensive.

Table 2

Reasons	Remedies
A break or opening in the armature or field circuit.	Test the field and armature circuits for open circuit. Locate the fault and rectify.
A short circuit in the armature or field.	Test the field and armature for short circuit. Locate the fault and rectify.
Loose brush connections or loose brush contact.	Tighten the brush connections. Check up the brush tension. Adjust, if necessary. If the brushes are worn out, replace them.
A dirty or severely pitted commutator.	Clean the commutator for dirt, dust and greasy material. Use trichloroethylene. If the segments are pitted, dress them up.
The speed is too low.	Increase the speed of the generator to its rated speed.
The DC supply for excitation is absent.	Check the DC supply across the field winding terminals. If the supply is not there, check the supply source and rectify the fault Where AC main supply is converted as DC supply through rectifiers, the fault may be located in the rectifier circuit.

Building up voltage of a DC shunt generator

Objectives: At the end of this lesson you shall be able to
- **explain the conditions and method of building up of voltage in a DC shunt generator**
- **explain the method of creating residual magnetism in the poles of a DC generator**
- **determine the magnetization characteristic of a DC shunt generator.**

Condition for a self-excited DC generator to build up voltage: For a self-excited DC generator to build up voltage, the following conditions should be fulfilled, assuming the generator is in sound condition.

- There must be residual magnetism in the field cores.
- The field resistance should be below the field critical resistance value.
- The generator should run at the rated speed.
- There must be a proper relation between the direction of rotation and the direction of field current. It could be explained as stated below.

The polarity of the induced voltage must be in such a direction as to produce the field current to assist the residual magnetism.

The polarity of the induced emf depends upon the direction of rotation and the polarity of the field poles depends upon the field current direction.

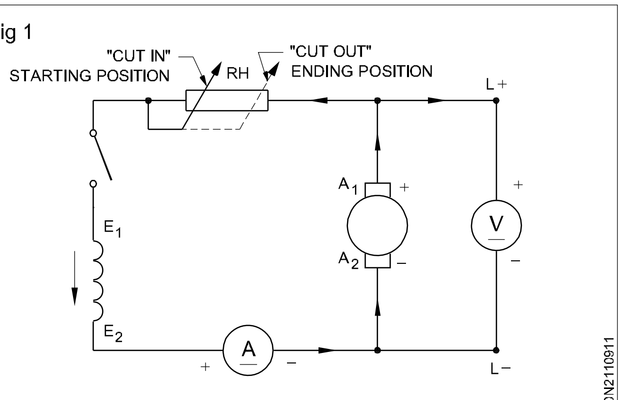
Even after fulfilling the above conditions, if the self-excited DC shunt generator fails to build up voltage, there may be other reasons as listed in Table 1.

Table 1

Sl.No.	Causes	Reasons	Remedies
1	A break or opening in the field or armature circuit.	Break or loose connection in the field or in the armature winding/circuit.	Locate the open circuit and rectify.
		High resistance in the field circuit beyond the field critical resistance value.	Reduce the resistance of the field regulator.
2	Loose brush connections or contacts.	Improper brush contact/loose brush connections.	Check the brushes for excessive wear, and replace them, if necessary. Check the commutator for pitting. If necessary, turn down the commutator. Always clean the commutator when poor brush contact is discovered. Check the brush tension and readjust it, if necessary Tighten any loose connections.
3	A dirty or severely pitted commutator.	Severe sparking due to overload.	In this case, follow the same procedure as outlined above.
4	A short circuit in the armature or field	Overload or excess heating.	Do a resistance check, ascertain, locate and remove the fault.

Method of building up voltage in a DC shunt generator: Fig 1 shows the circuit diagram for building up voltage in a DC shunt generator. When the generator is made to run at its rated speed initially, the voltmeter reads a small amount of voltage say, 4 to 10 volts. It is due to the residual magnetism. Since the field coils are connected across the armature terminals, this voltage causes a small amount of current to flow through the field coil. If the current flow in the field coils is in the correct direction, it will strengthen the residual magnetism and induce more voltage. As such, the generated voltage will rise marginally. This rise in voltage, in turn, will further strengthen the increasing field current and induce more voltage. This rise in voltage, in turn, will further strengthen the increasing field current. This cumulative action will build up voltage until saturation is reached. After saturation, any increase in the field current will not increase the induced voltage. However, the whole procedure of building up of voltage takes a few seconds only.

Fig 1



DC SHUNT GENERATOR

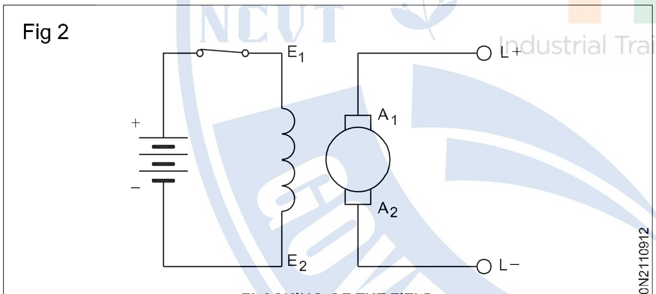
Method of creating residual magnetism: Without residual magnetism, a self-excited generator will not build up its voltage. A generator may lose its residual magnetism due to any one of the following reasons.

- The generator is kept idle for a long time.
- Heavy short circuit.
- Heavy overloading.
- The generator is subjected to too much heat.

When the generator loses its residual magnetism, it can be re-created as stated below.

Flashing of field: One of the methods to create residual magnetism is called the flashing of the `field'. This can be done by connecting the shunt field across a battery or any DC source for a few minutes as shown in Fig 2.

Fig 2

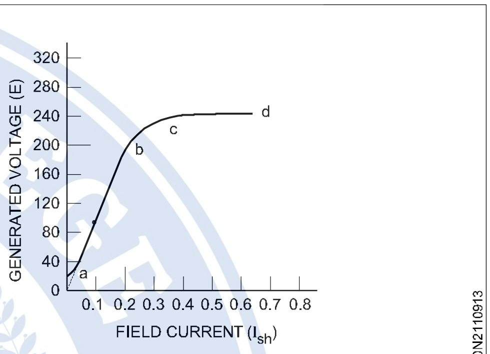


FLASHING OF THE FIELD

While flashing the field, the polarity of the magnetic field, now created, should be the same as that of the residual magnetic field it lost earlier.

Magnetisation characteristic of a DC shunt generator: The magnetisation characteristic curve shown in Fig 3 gives the relation between the field current and the induced voltage. Referring to the emf equation, the induced emf in a generator is proportional to the flux per pole and the revolutions per minute of the generator. At a constant speed, the generated emf becomes directly proportional to the field flux. In a given machine, the flux depends upon the field current. The graph (Fig 3) illustrates this feature. Because of the residual magnetism, the curved part below point `a' does not start at zero. Between the points `ab', the curve is in almost a straight line indicating that the voltage in the area is proportional to the field current.

Fig 3



MAGNETISATON CHARACTERISTIC OF A DC SHUNT GENERATOR

Power
Electrician - DC Generator

Related Theory for Exercise 2.1.110

Test a DC machine for continuity and insulation resistance

Objectives: At the end of this lesson you shall be able to
- **state the necessity of measuring the insulation resistance of an electrical machine**
- **state the required conditions for the tests**
- **state the reasons for the low value of insulation resistance in the machines**
- **state the method of improving the insulation resistance of DC machines.**

Necessity of measuring insulation resistance: The most important aspect in the maintenance of DC machines is taking care of the insulation. Power insulation of DC machine windings is designed for the satisfactory operation at the specified voltage, temperature and to retain the Power and mechanical strength and the dimensional stability over many years of operation. The insulation resistance of DC machines in service should be checked periodically,

A common device for measuring insulation resistance is a direct indicating insulation tester or Megger. The measurements are made at voltages 500/1000 volt DC depending upon the voltage rating of the machine.

Measurement of insulation resistance: Insulation resistance shall be measured between the winding and frame (earth), and between windings.

For low and medium voltage rated machines, the insulation resistance, when the high voltage test is applied, shall not be less than one megohm as per B.I.S. 9320 - 1979. The insulation resistance shall be measured with a DC voltage of about 500 V applied for a sufficient time for the reading of the indicator to become practically steady, such voltage being taken from an independent source or generated in the measuring instrument.

> **When it is required to dry out windings at site to obtain the minimum value of insulation resistance, it is recommended that the procedure for drying out as specified in IS:900-1965 may be followed.**

Reasons for low value insulation resistance: The low value of insulation resistance in DC machines is due to excess heat developed in the winding due to their routine working with full load condition or overloading at times or frequent starting with loads. In addition to this, high ambient temperatures are also the reason for low insulation resistance.

Method of improving insulation resistance: On identifying the weak insulation resistance, during the course of preventive maintenance observation in a DC machine, it is necessary to improve the insulation resistance to restore it to a safe value.

Improvement of insulation resistance could be done by any one of the following methods after cleaning the dust and dirt from the machinery.

- By blowing hot air through the machines.
- By heating the machine with carbon filament or incandescent lamps.
- By dismantling and varnishing the winding of the machine.

Table 1

Insulation resistance test

Date	Time	Weather condition	Duty cycle	Test between terminals	Insulation resistance	Remarks

Power
Electrician - DC Generator

Related Theory for Exercise 2.1.111

Start, run and reverse direction of DC motor

For this Exercise refer Ex.No. 2.2.116 - 119

Characteristics of DC generator

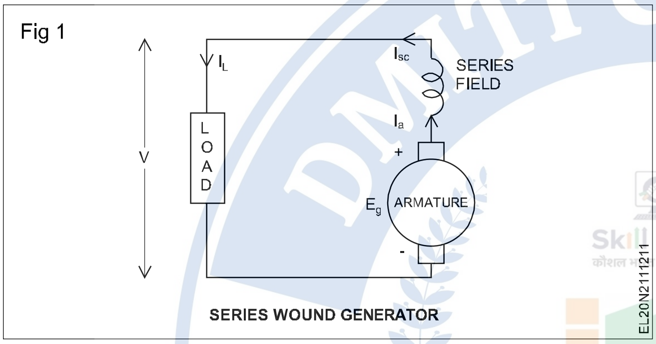
Objectives: At the end of this lesson you shall be able to

- **explain the characteristics of DC series generator**
- **explain the characteristics of DC shunt generator**
- **explain the characteristics of DC compound generator**
- **explain the operation of paralleling of DC shunt generators**
- **explain the effect of armature reaction and remedies**
- **explain losses and efficiency of DC generators**
- **explain the routine and maintenance of DC generator.**

Characteristics of series generator:

In these types of generators the field windings, armature windings and external load circuit all are connected in series as shown in Figure 1.

Fig 1



SERIES WOUND GENERATOR

Therefore, the same current flows through armature winding, field winding and the load. Let, $I = I_a = I_{sc} = I_L$. Here, I_a = armature current I_{sc} = series field current I_L = load current There are generally three most important characteristics of series wound DC generator which show the relation between various quantities such as series field current or excitation current, generated voltage, terminal voltage and load current.

Magnetic or open circuit characteristic of series wound DC generator

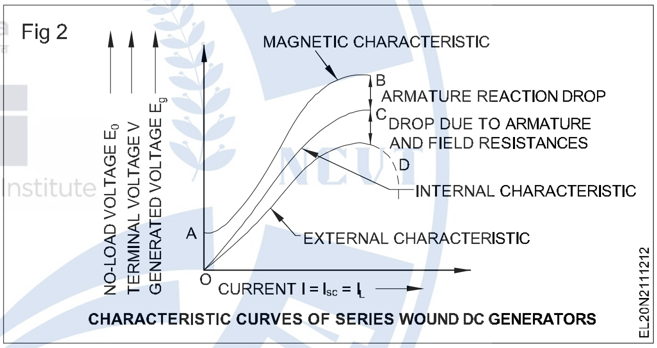
The curve which shows the relation between no load voltage and the field excitation current is called magnetic or open circuit characteristic curve. As during no load, the load terminals are open circuited, there will be no field current in the field since, the armature, field and load are series connected and these three make a closed loop of circuit. So, this curve can be obtained practically by separating the field winding and exciting the DC generator by an external source.

Here in the diagram below AB curve is showing the magnetic characteristic of series wound DC generator. The linearity of the curve will continue till the saturation of the poles. After that there will be no further significant change of terminal voltage of DC generator for increasing field current. Due to residual magnetism there will be a small initial voltage across the armature that is why the curve started from a point A which is a little above the origin O.

Internal characteristic of series wound DC generator

The internal characteristic curve gives the relation between voltage generated in the armature and the load current. This curve is obtained by subtracting the drop due to the demagnetizing effect of armature reaction from the no load voltage. So, the actual generated voltage (E_g) will be less than the no load voltage (E_0). That is why the curve is slightly dropping from the open circuit characteristic curve. Here in the diagram below OC curve is showing the internal characteristic or total characteristic of the series wound DC generator. (Fig 2)

Fig 2



CHARACTERISTIC CURVES OF SERIES WOUND DC GENERATORS

External characteristic of series wound DC generator

The external characteristic curve shows the variation of terminal voltage (V) with the load current (I_L). Terminal voltage of this type of generator is obtained by subtracting ohmic drop due to armature resistance (R_a) and series field resistance (R_{se}) from the actually generated voltage (E_g). Terminal voltage $V = E_g - I (R_a + R_{se})$ The external characteristic curve lies below the internal characteristic curve because the value of terminal voltage is less than the generated voltage. Here in the Figure 2 OD curve is showing the external characteristic of the series wound DC generator.

The external/load characteristic of a shunt generator: The external/load characteristic is important for judging the suitability of a generator for a particular purpose. When the DC shunt generator is loaded, it is found that the terminal voltage drops with increase in the load current. In a shunt generator, the field current appears to be constant, and, hence, `V' also should remain constant and be independent of the load. But, it is not so practically. There are two main reasons for the drop in terminal voltage. They are :

- armature resistance drop (directly)
- armature reaction drop (indirectly).

Because of the above two reasons, the terminal voltage is reduced. This in turn affects the field current also. The decreased field current reduces the field flux which further reduces the induced emf.

Armature resistance drop: According to formula

Terminal voltage = Induced emf – armature voltage drop

$V = E - I_aR_a$

where I_a is the armature current

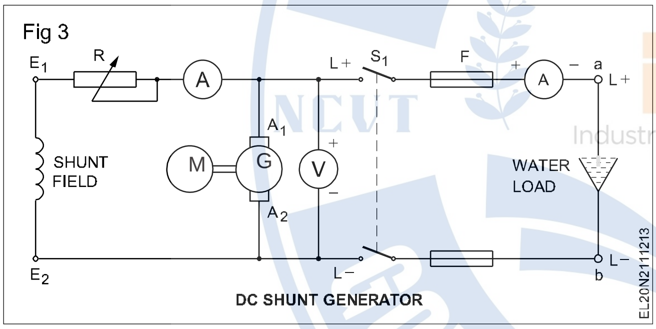
and R_a is the armature circuit resistance.

As such, when the load current is increased, more voltage is dropped in the armature circuit. Hence, the terminal voltage `V' decreases, under load condition.

Armature reaction drop: Due to the demagnetising effect of armature reaction, the main pole flux is weakened, and the induced emf (E) will be reduced in its magnitude.

The external characteristic gives the relation between terminal voltage and load current. Fig 3 gives the circuit diagram to determine this characteristic. The generator is first built up to its rated voltage. Then it is loaded in suitable steps up to full load. The terminal voltage and the corresponding load currents are noted for each step.

Fig 3

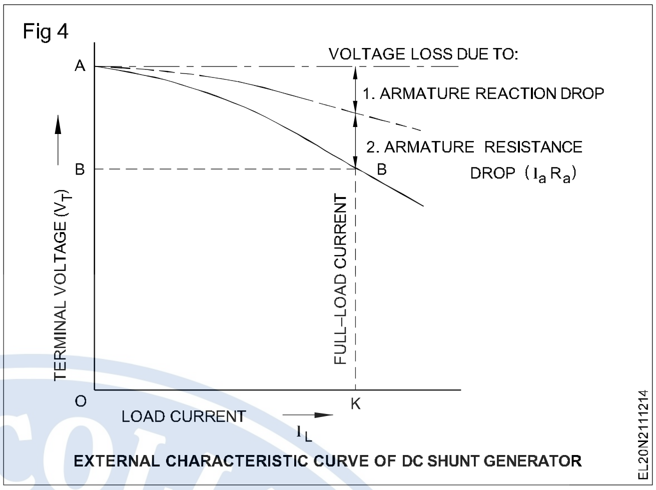


DC SHUNT GENERATOR

In this experiment, the field current has to be kept constant. This is due to the fact that when terminal potential decreases on load, the field which is connected across the armature will have a decreased current. This effect, if allowed, will reduce the field flux, thereby, decreasing the induced voltage. This effect cumulatively reduces the terminal voltage further. From the obtained values of the terminal voltage V_T and load current I_L, the external characteristic curve is plotted as shown in Fig 4, keeping in V_T on `Y' axis and I_L on X axis. From the curve it will be observed that the no-load voltage OA is maximum, and it falls to OB when loaded, to indicate that the full load current value is OK as noted in the name-plate of the generator.

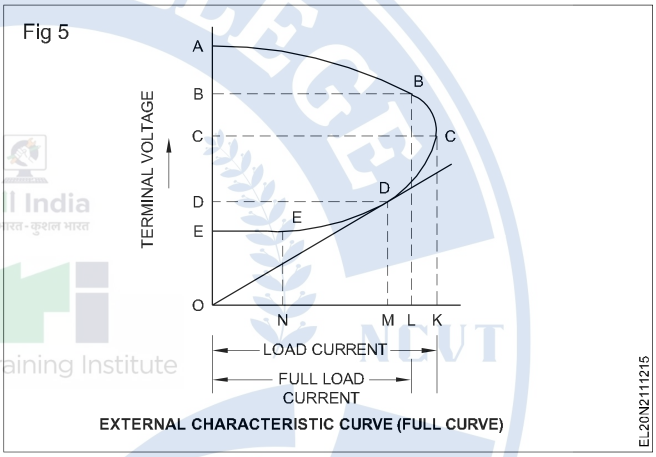
Fall of voltage from no load to full load, which is due to armature reaction, and the armature voltage drop are found to be not appreciable. Normally the generators are designed to deliver full load current I_L, and the fall of voltage will be about 5 to 8 percent of the no-load voltage which can be regarded as negligible. If the load current is further increased by decreasing the load resistance, the curve reaches a point `C' as shown in Fig 5. At this point, the terminal voltage falls to OC which will be an appreciable fall when compared to the no-load terminal voltage. At this point `C', though the load current is maximum (OK), the terminal voltage will be much less than the no-load voltage.

Fig 4



EXTERNAL CHARACTERISTIC CURVE OF DC SHUNT GENERATOR

Fig 5



EXTERNAL CHARACTERISTIC CURVE (FULL CURVE)

However, when the load resistance is further decreased the load current decreases to OM and V_T is reduced to `OD', that means the load current cannot be increased beyond OK and the point `C' is called the breakdown point. It is the maximum possible current that a generator can supply. Beyond this point `C', the curve drops rapidly with decrease in the load resistance, indicating that the load current is also decreasing, instead of increasing. At point `E' the generator is virtually short-circuited, and all the voltage induced is dropped to near zero due to IaRa drop and armature reaction. Rather, we can say OE is the residual voltage of the generator. Practically all the generators operate only on the portion `AB' of the curve where the efficiency of the generator is maximum.

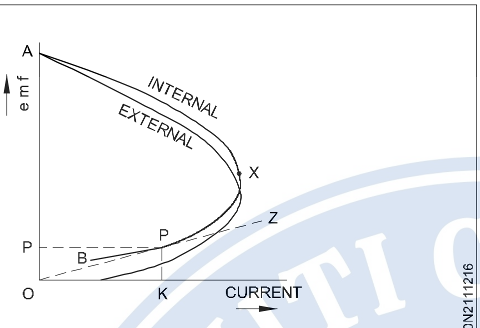
Internal characteristic: The internal characteristic gives the relation between induced voltage and the armature current. In a shunt generator,

$I_a = I_L + I_{sh} \qquad E = V_T + I_aR_a$

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

Load critical resistance: It is defined as the minimum value of load resistance with which the generator builds up voltage, and, just below this value of load resistance the DC shunt generator will fail to build up its voltage when started with the load. When the DC shunt generator is started with the load, the terminal voltage may not raise beyond about 10V, the reason is the load resistance is so low, as if the generator is short-circuited. In Fig 6 the tangent line `OZ' to the internal characteristic APB is drawn. Its slope will give the value of the load critical resistance. As the DC shunt generator will not build up emf when made to build up with load below this value of resistance, it is called the load critical resistance.

Fig 6



INTERNAL & EXTERNAL CHARACTERISTIC CURVE

Load critical resistance in ohms =

$$\frac{\text{Voltage at point 'P'}}{\text{Load current at point 'P' (amps)}} = \frac{OP}{OK}$$

There are thus two critical resistances for a shunt generator, one for the field circuit and the other for the load external circuit.

Applications of DC shunt generator: According to the load characteristic of the DC shunt generator, the drop in voltage from no load to full load is not appreciable, up to its rated value of load current. Hence, it can be called a constant voltage generator. Therefore, it can be used for constant loads like:

- centrifugal pump
- lighting load
- fans
- battery charging and electroplating.

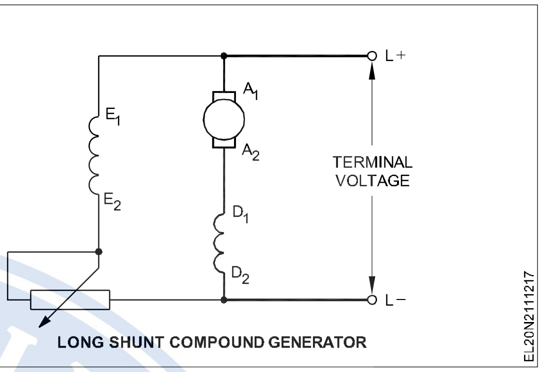
Compound generator: Combination of shunt field and series field within one generator provides two sources of excitation, and such a generator is called a compound generator.

Long shunt compound generator: When the shunt field is connected in parallel with the series combination of the armature and the series field, the generator is said to be connected as a long shunt compound generator which is shown in Fig 7.

Short shunt compound generator: When the shunt field is connected in parallel with only the armature, the generator is said to be connected as a short shunt compound generator which is shown in Fig 8.

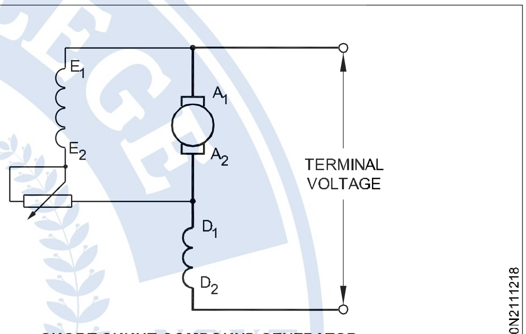
Cumulative compound generator: The shunt field excitation flux is usually more or less steady, and is affected only slightly as the terminal voltage fluctuates. The flux of the series field is quite variable because its ampere-turns depend upon the load current. When the load current is zero, it produces less flux (long shunt) or no flux (short shunt) and when the load current is high, it creates a good amount of flux. How much flux it must develop depends upon the extent to which it must compensate for the voltage drop. In a compound machine, the series field is wound directly over the shunt field with proper separation by insulations.

Fig 7



LONG SHUNT COMPOUND GENERATOR

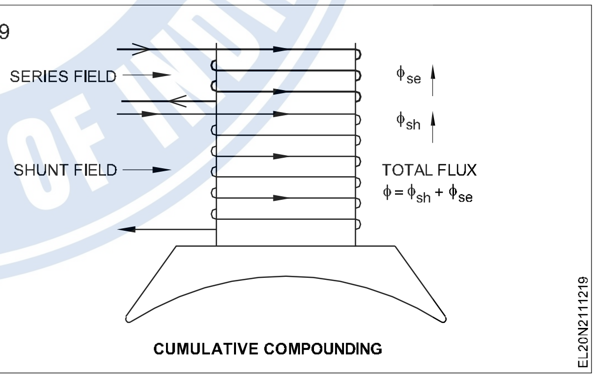
Fig 8



SHORT SHUNT COMPOUND GENERATOR

The series field coils may be connected to `assist' or `aid' the shunt field, as shown in Fig 9. Then this machine is said to be a cumulative (increasing by successive additions) compound generator. The ampere turns of the series field determines the amount of compounding.

Fig 9



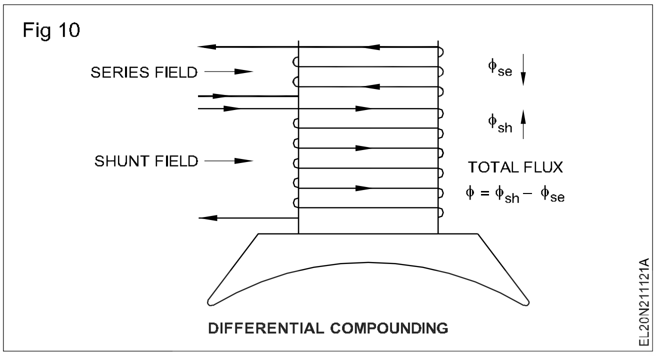
CUMULATIVE COMPOUNDING

Differentially compounded generator: If the flux produced by the series field opposes the shunt field flux as shown in Fig 10, then the action is called `bucking' and the machine is said to be a differential (decreasing by successive subtractions) compound generator.

External characteristics of DC compound generator

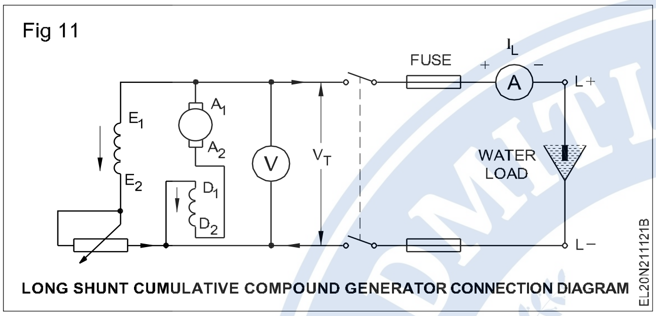
Cumulative compound generator: Fig 11 shows the connection diagram for a long shunt cumulative compound generator. In such a connection, the series field aids the shunt field and the total flux is equal to the sum of both the fluxes. By taking a set of readings for different load currents I_L and the corresponding terminal voltage V_T, we can draw a graph showing the relation between V_T and I_L. This curve is called the external characteristic curve. (Fig 12)

Fig 10



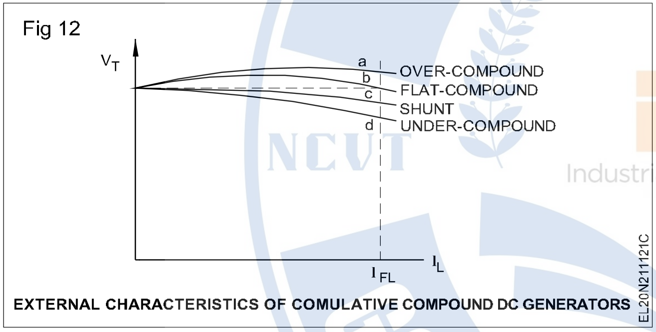
DIFFERENTIAL COMPOUNDING

Fig 11



LONG SHUNT CUMULATIVE COMPOUND GENERATOR CONNECTION DIAGRAM

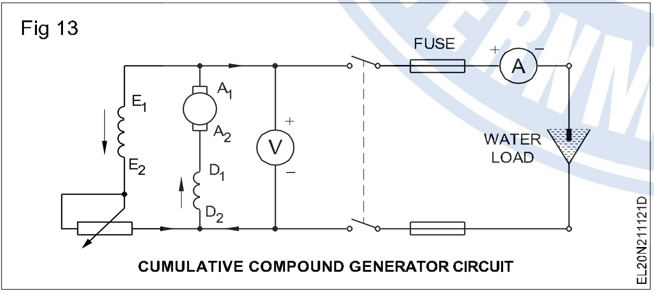
Fig 12



EXTERNAL CHARACTERISTICS OF COMULATIVE COMPOUND DC GENERATORS

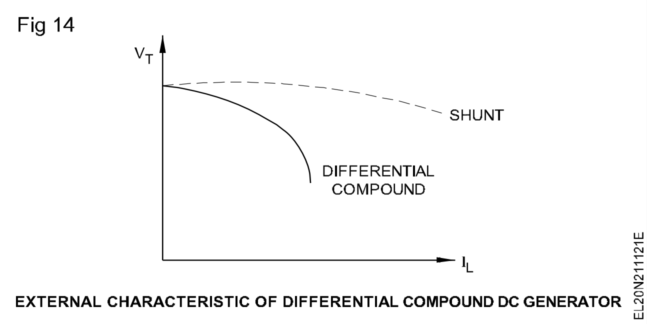
Differential compound generator: If the series field terminals are interchanged as shown in Fig 13, then the curve obtained may be as shown in Fig 14.

Fig 13



CUMULATIVE COMPOUND GENERATOR CIRCUIT

Fig 14



EXTERNAL CHARACTERISTIC OF DIFFERENTIAL COMPOUND DC GENERATOR

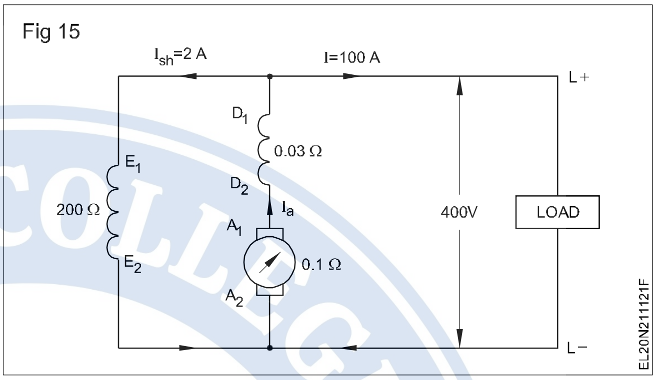
Application of a compound generator: Table 1 gives the different types of compound generators and their application in industry.

Example: A long-shunt compound generator delivers a load current of 100 A at 400 V, and has armature, series field and shunt field resistances of 0.1 ohm, 0.03 ohm and 200 ohm respectively. Calculate the generated voltage and the armature current. Allow 1 V per brush for contact drop.

Solution

Generator circuit is shown in Fig 15.

Fig 15



I_{sh} = 400/200 = 2 A

Current through armature and series winding is the same. Hence $I_a = I_{se}$ = 100 + 2 = 102 A.

Voltage drop in series field winding = $I_{se}R_{se}$ = 102 x 0.03 = 3.06 V

Armature voltage drop I_aR_a = 102 x 0.1 = 10.2 V.

Assuming 2 brushes,

drop at brushes = 2 x 1 = 2 V.

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

= 400 + 10.2 + 3.06 + 2 = 415.26 V

Parallel operation of DC generators

Parallel Operation of DC Generators: In a dc power plant, power is usually supplied from several generators of small ratings connected in parallel instead of from one large generator.

The necessity of parallel operation

1 **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.

The supply can be obtained 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.

2 **Efficiency:** Generators run most efficiently when load demand on power plant decreases, one or more generators can be shut down and the remaining units can be efficiently loaded.

3 **Maintenance and repair:** If generators are operated in parallel, the routine or emergency operations can be

performed by isolating the affected generator while load is being supplied by other units. This leads to both safety and economy.

4 **Increasing plant capacity:** When added capacity is required, the new unit can be simply paralleled with the old units to increase the plant capacity.

Table 1

Sl.No.	Type of compound generator	Uses
1	Cumulative compound generator	
	a. Over-compounded	Used where the load is at a considerable distance from the generator as in railways, street lights etc.
	b. Flat or level compound	Used where the load is nearby, such as lighting loads and power loads of small buildings or lathes which require constant voltage.
	c. Under-compounded	Used for electroplating, lighting, etc.
2	Differential compound generator	Used for arc welding generators.

Conditions for paralleling of DC Generators

1 Output voltage must be same

2 Polarities must be same

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. 22 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.

Operation of paralleling of DC Generator

1 The prime mover of generator 2 is brought up to the rated speed. Now switch S_4 in the field circuit of the generator 2 is closed.

2 Next circuit breaker CB_2 is closed and the excitation of generator 2 is adjusted till it generates voltage equal to the bus-bars voltage. This is indicated by voltmeter V_2.

3 Now the generator 2 is ready to be paralleled with generator 1. The main switch S_3 is closed, thus putting generator 2 in parallel with generator 1. Note the generator 2 is not supplying any load because its generated emf is equal to bus-bars voltage. The generator is said to be "floating" (i.e. not supplying any load) on the bus-bars (Fig 16).

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

5 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 generator 1 to zero (This will be indicated by ammeter A_1) open CB_1 and then open the main switch S_1.

Load Sharing: The load may be shifted from one generator to another merely by adjusting the field excitation. The load sharing of two generators which have unequal no-load voltages. Let E_1, E_2 = no-load voltages of the two generators R_1, R_2 = their armature resistances

Thus current output of the generators depends upon the values of E_1 and E_2. These values may be changed by field rheostats. The common terminal voltage (or bus-bars voltage) will depend upon (i) the emfs of individual generators and (ii) the total load current supplied. It is generally desired to keep the busbars voltage constant. This can be achieved by adjusting the field excitations of the generators operating in parallel.

Armature reaction

When armature conductors carry a lower load current, the mmf set up by the armature conductors interact with the main field flux in such a way that the field of the main field flux gets distorted and this is called cross-magnetizing effect.

However, the effect could be nullified by shifting the brush position of the generator by a small angle in the direction of rotation.

When the generator is loaded further, the pole tips get saturated which results in demagnetising the main field flux, thereby reducing the induced emf. This effect is called demagnetising effect, and can be explained further.

Fig 17 shows the flux distribution by the main field flux only. Since there is no current in the armature conductors, the flux is uniform. The GNA (Geometrical Neutral Axis) and MNA (Magnetic Neutral Axis) are coincident with each other.

Fig 18 shows the flux set up by the armature conductors alone. The current direction is marked as a plus sign(+), under the N.pole and dot (•) under the south pole as shown in the figure. The strength of this armature field (mmf) depends upon the armature current which, in turn, depends upon the load current.

Fig 16

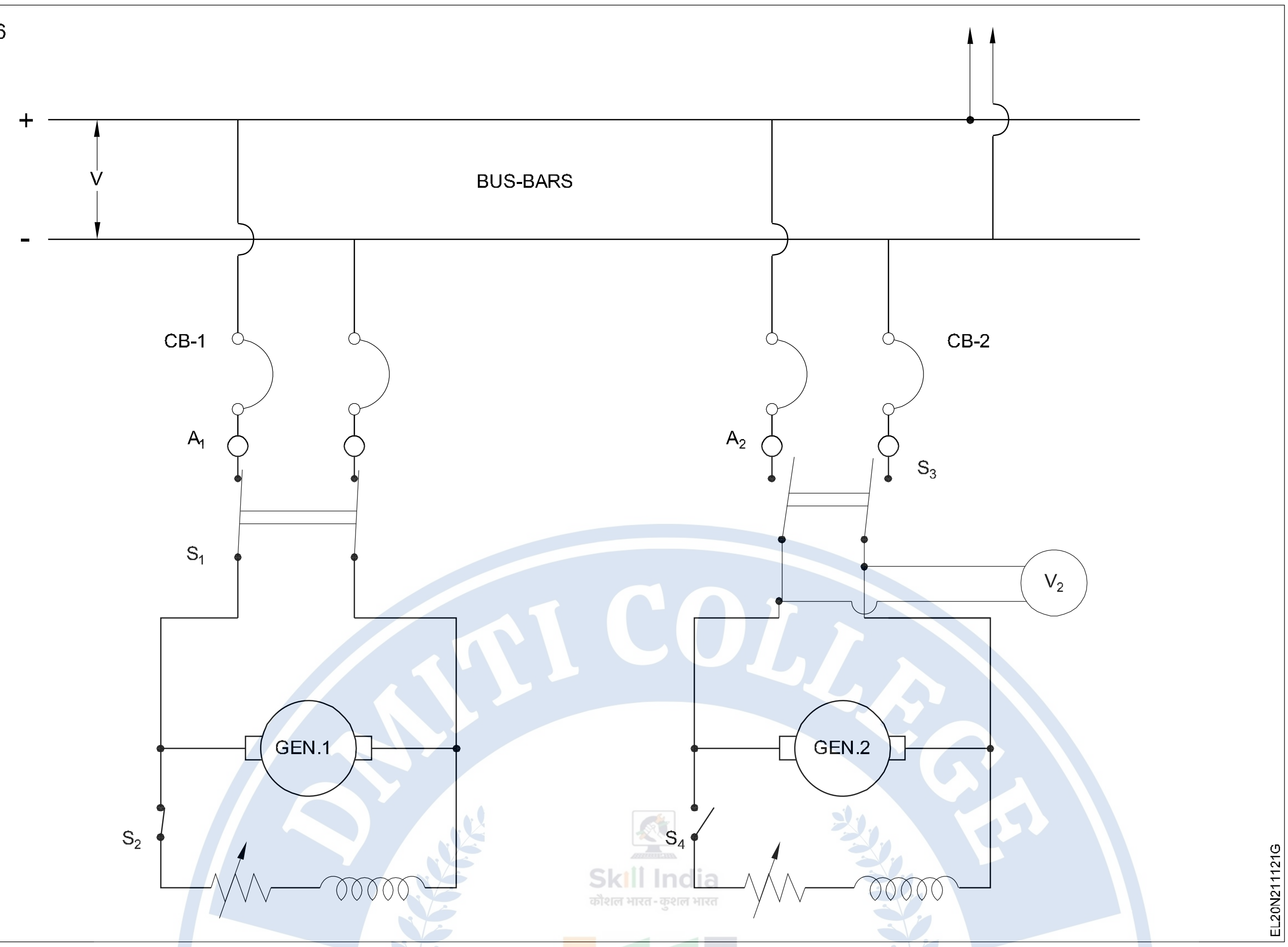
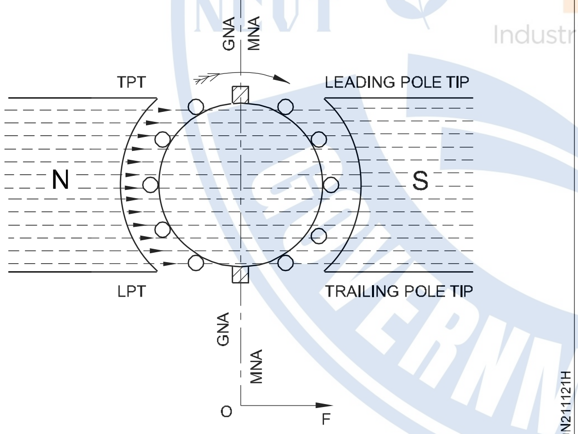
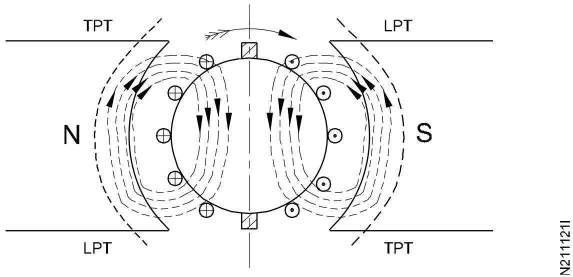


Fig 17



MAIN MAGNETIC FIELD OF A TWO - POLE DC MACHINE

Fig 18

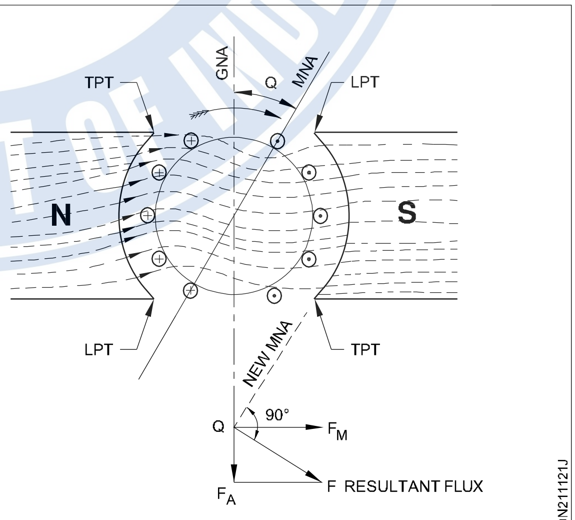


FLUX CREATED BY THE ARMATURE CURRENT

Cross-magnetising effect: Fig 19 shows the flux distribution by the combined effect of the main field and the armature mmf. The resulting field is found to have strengthened at the trailing pole tips and weakened at the leading pole tips. Due to this cross-magnetizing effect, the magnetic neutral axis (MNA) is shifted from the geometrical neutral axis (GNA) by an angle Q in the direction of rotation.

The effect of the main field flux (FF) and the armature flux (F_A) are shown by vectors in Fig 19. The magnetic neutral axis (MNA) should be at right angle to the resultant flux (F).

Fig 19



CROSS - MAGNETISING EFFECT

Remedy: The effect of the cross-magnetisation can be neutralized by shifting the brushes from GNA to MNA with the help of the rocker arm. Of course the amount of shifting depends upon the magnitude of the armature current. At the correct position of the brush, the induced emf will be maximum and the spark at the sides of brushes will be minimum.

Compensating winding: The demagnetizing effect due to armature reaction in large machines, which are subjected to fluctuation of load, can be neutralized by this winding.

This winding carries an equal current in the opposite direction to the current in armature conductors. So the flux set up by them is also in the opposite direction and of equal magnitude to that of the armature flux. Hence they neutralize each other, and thereby, the demagnetising effect is nullified at any load, even at fluctuating loads.

Commutation

When a DC generator is loaded, the current flows through the armature winding, commutator and brushes to the external circuit. During this process, whenever a brush spans the two commutator segments, the winding element connected to those commutator segments is short-circuited. The changes in current direction, which take place in the winding element, just before, during and after the short circuit is called commutation.

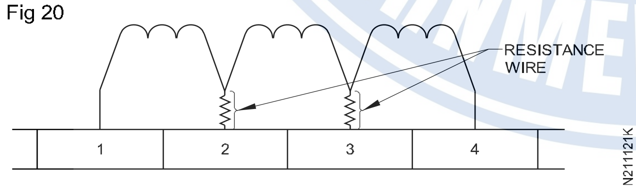
If the change in the current direction is gradual, then a smooth commutation takes place. On the other hand a sudden change in current in the winding element is called rough commutation which results in heavy sparking at the sides of brushes. If rough commutation is allowed to continue, the brushes and commutator get spoiled ultimately due to the excess heat produced by the sparks.

Remedies for rough commutation by providing interpoles

To avoid sparks in the brush position, the following methods are used which effectively change the rough commutation to smooth commutation.

- Resistance wires are introduced between the end connection of the coil to the commutator, as shown in Fig 20. This increased resistance helps the current to change its direction smoothly, increasing the timing and reducing the statically induced emf.

Fig 20

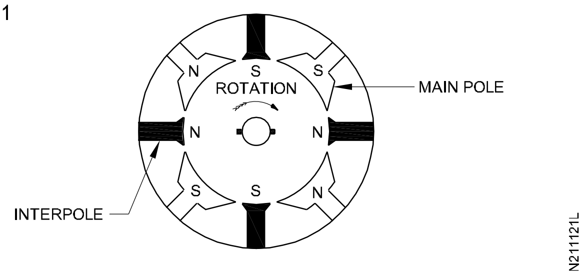


COMMUTATION WITH RESISTANCE WIRES

- High resistance brushes are used. Hence the contact resistance variation allows the current to change its direction smoothly, thereby reducing the statically induced emf.

- Small field poles called inter-poles are provided in between the main poles as shown in Fig 21. These inter-poles have their polarity the same as the next pole ahead in the direction of rotation of the, generators. Further, their winding is connected in series with the armature so that they carry the same current as that of the armature.

Fig 21

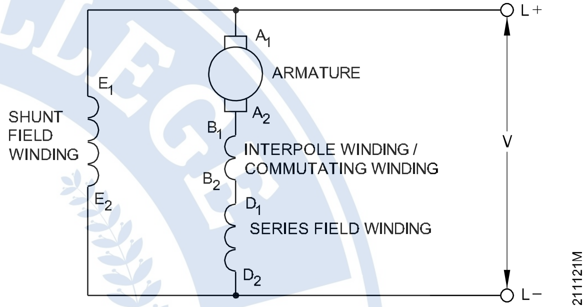


COMMUTATION WITH INTERPOLES

These inter-poles produce an emf opposite in direction to the statically induced emf, and have a magnitude depending upon the current. Thereby, the effect of statically induced emf is nullified.

These inter-poles are wound with less number of turns having thick gauge wire. Fig 22 shows the connection of inter-pole winding in a DC compound machine.

Fig 22



CONNECTION OF INTERPOLE WINDING IN A DC MACHINE

Losses and efficiency of DC machines

It is convenient to determine the efficiency of a rotating machine by determining the losses than by direct loading. Further it is not possible to arrange actual load for large and medium sized machines. By knowing the losses, the machine efficiency can be found by

$$\eta = \frac{\text{output}}{\text{output} + \text{losses}} \left(\text{For generators}\right)$$

$$\eta = \frac{\text{input - losses}}{\text{input}} \left(\text{For motors}\right)$$

In the process of energy conversion in rotating machines - current, flux and rotation are involved which cause losses in conductors, ferromagnetic materials and mechanical losses respectively. Various losses occurring in a DC machine are listed below (FIg 23 shows losses of DC machine.

Total losses can be broadly divided into two types

1 Constant losses

2 Variable losses

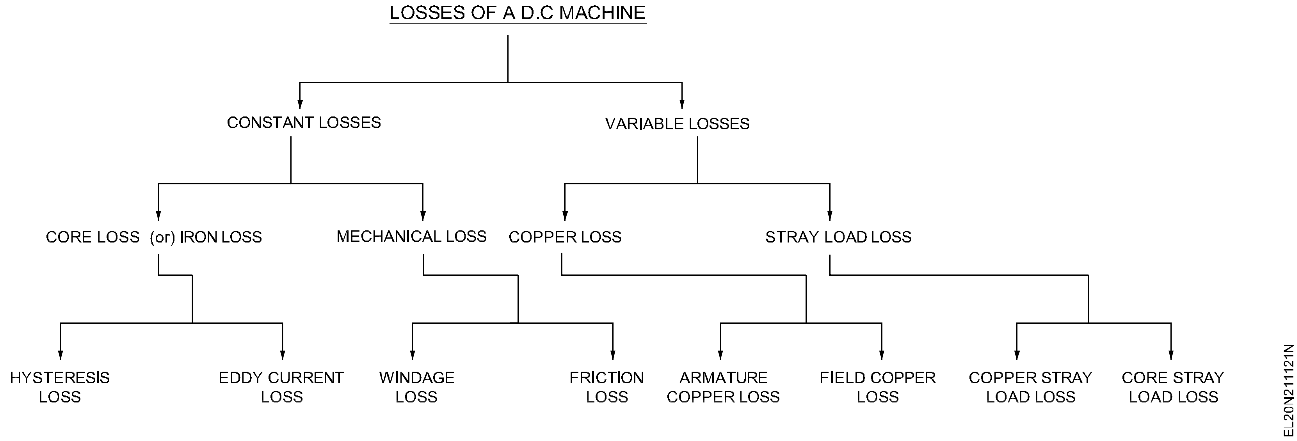
These losses can be further divided as

1 Constant losses - i) Core loss or iron loss

  a Hysteresis loss

  b Eddy current loss

Fig 23



ii Mechanical loss

a Windage loss

b Friction loss - brush friction loss and Bearing friction loss.

2 Variable losses - i) copper loss (I^2R)

a Armature copper loss

b Field copper loss

c Brush contact loss

ii Stray load loss

a Copper stray load loss

b Core stray load loss

Efficiency of a DC generator

Power flow in a DC generator

$$= \frac{\text{output}}{\text{output} + \text{losses}} = \frac{VI}{VI + I_a^2 r_a + W_e}$$

where w_e is constant loss

Condition for maximum efficiency

Generator output = VI

Generator input = output + losses

$= VI + I^2 a R_a + W_e$

$= VI + (I + I_{sh})^2 R_a + W_e \quad \therefore I_a = (I + I_{sh})$

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

$$\because \eta = \frac{\text{output}}{\text{input}} = \frac{VI}{VI + I^2 a R_a + W_e} = \frac{VI}{VI + I^2 R_a + W_e}$$

Efficiency is maximum when variable loss = constant loss.

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