

## UNIT-1

### DC MACHINES

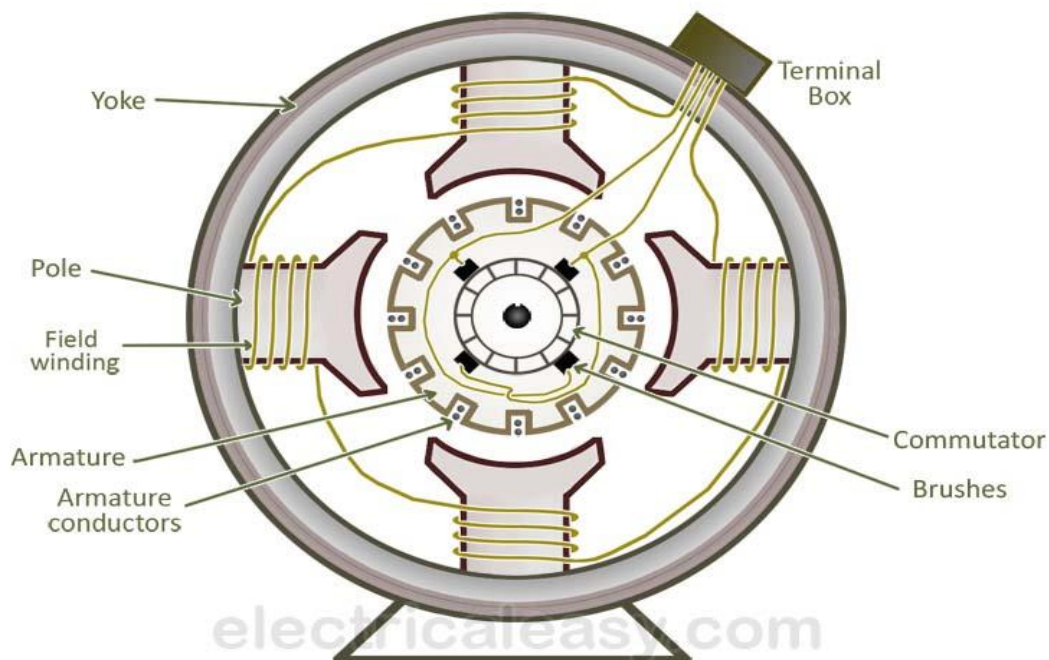
## Basic construction and working of a DC Generator.

### DC Generator

A dc generator is an [electrical machine](#) which converts mechanical energy into **direct current electricity**. This energy conversion is based on the principle of production of dynamically induced emf. This article outlines **basic construction and working of a DC generator**.

### Construction of a DC machine:

Note : 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'.



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.

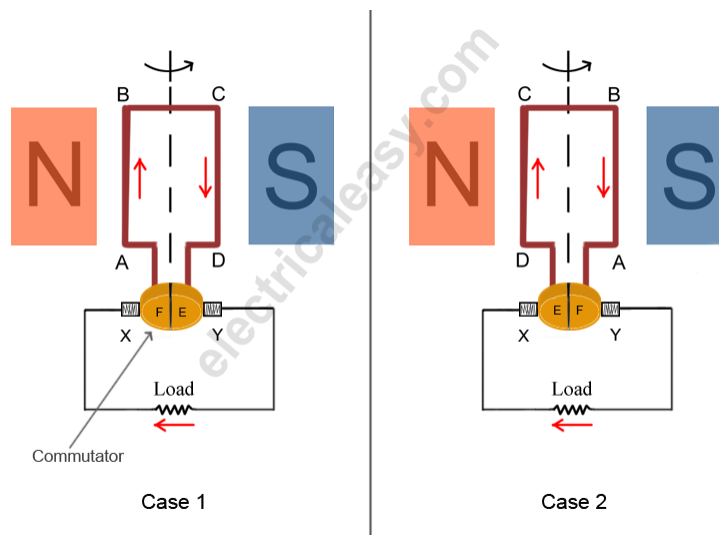
1. **Yoke:** The outer frame of a dc machine is called as yoke. It is made up of cast iron or steel. It not only provides mechanical strength to the whole assembly but also carries the magnetic flux produced by the field winding.
2. **Poles and pole shoes:** Poles are joined to the yoke with the help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

## Working principle of a DC generator:

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

### Need of a Split ring commutator:



According to Fleming's right hand rule, the direction of induced current changes whenever the direction of motion of the conductor changes. Let's consider an armature rotating clockwise and a conductor at the left is moving upward. When the armature completes a half rotation, the direction of motion of that particular conductor will be reversed to downward. Hence, the direction of current in every armature conductor will be alternating. If you look at the above figure, you will

know how the direction of the induced current is alternating in an armature conductor. But with a split ring commutator, connections of the armature conductors also gets reversed when the current reversal occurs. And therefore, we get unidirectional current at the terminals.

Types of a DC generator:

**DC generators can be classified in two main categories, viz; (i) Separately excited and (ii) Self-excited.**

**(i) Separately excited: In this type, field coils are energized from an independent external DC source.**

**(ii) Self-excited: In this type, field coils are energized from the current produced by the generator itself. Initial emf generation is due to residual magnetism in field poles. The generated emf causes a part of current to flow in the field coils, thus strengthening the field flux and thereby increasing emf generation. Self excited dc generators can further be divided into three types -**

- (a) Series wound - field winding in series with armature winding**
- (b) Shunt wound - field winding in parallel with armature winding**
- (c) Compound wound - combination of series and shunt winding**

### **Types of DC Generators**

**DC generators** are classified based on how their fields are excited (i.e. produced).

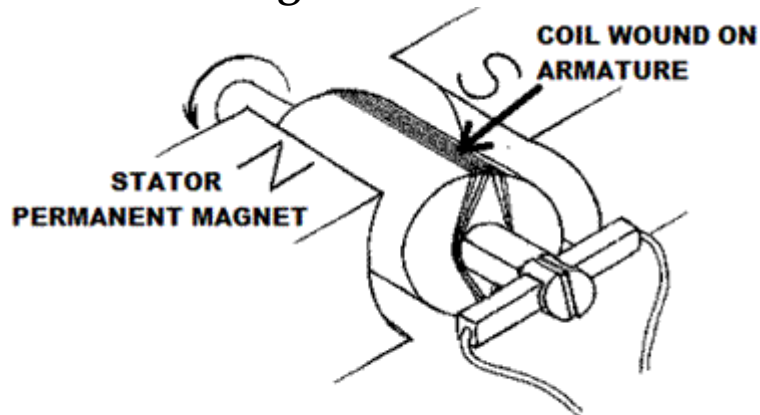
There are three methods of excitation, and thus three main **types of DC generators**:

1. **Permanent Magnet DC Generators** – Field coils excited by permanent magnets
2. **Separately Excited DC Generators** – Field coils excited by some external source
3. **Self Excited DC Generators** – Field coils excited by the generator itself

Self-excited DC generators can further be classified depending on the position of their field coils. The three types of self-excited DC generators are:

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

#### 4. Permanent Magnet DC Generator



#### PERMANENT MAGNET DC GENERATOR

- 5.
6. When the flux in the magnetic circuit is created through the use of permanent magnets, then it is known as a Permanent magnet DC generator.
7. It consists of an armature and one or several permanent magnets situated around the armature. This type of DC generator generates does not generate much power.
8. As such they are rarely found in industrial applications. They are normally used in small applications – like dynamos in motorcycles.

#### 9. Separately Excited DC Generator

10. These are the generators whose field magnets are energized by some external DC source, such as a battery.

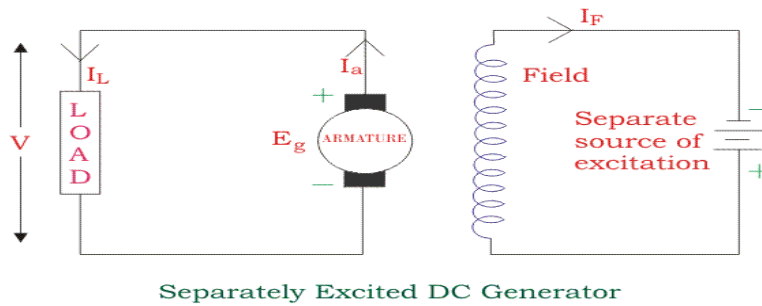
A circuit diagram of separately excited DC generator is shown in the figure below.

$I_a$  = Armature current

$I_L$  = Load current

$V$  = Terminal voltage

$E_g$  = Generated EMF (Electromagnetic Force)



Voltage drop in the armature =  $I_a \times R_a$  ( $R_a$  is the armature resistance)

Let,

$$I_a = I_L = I \text{ (say)}$$

Then,

$$\text{voltage across the load, } V = IR_a$$

Power generated is equal to

$$P_g = E_g \times I \text{ And power delivered to the external load is equal to}$$

$$P_L = V \times I$$

Self-excited DC generators are generators whose field magnets are energized by the current supplied by themselves. In these type of machines, field coils are internally connected with the armature.

Due to residual magnetism, some flux is always present in the poles. When the armature is rotated, some EMF is induced. Hence some induced current is produced. This small current flows through the field coil as well as the load and thereby strengthening the pole flux.

As the pole flux strengthened, it will produce more armature EMF, which cause the further increase of current through the field. This increased field current further raises armature EMF, and this cumulative phenomenon continues until the excitation reaches the rated value.

According to the position of the field coils, self-excited DC generators may be classified as:

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

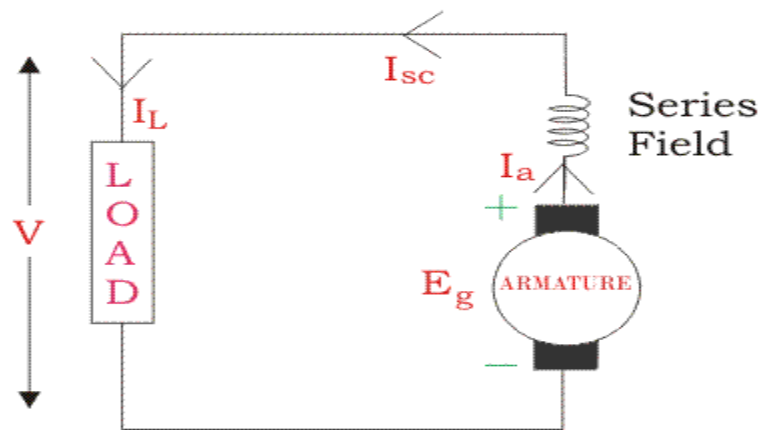
## Series Wound Generator

In these type of generators, the field windings are connected in series with armature conductors, as shown in the figure below.

Whole current flows through the field coils as well as the load. As series field winding carries full load current it is designed with relatively few turns of thick wire. The electrical resistance of series field winding is therefore very low (nearly  $0.5\Omega$ ).

Here:

- $R_{sc}$  = Series winding resistance
- $I_{sc}$  = Current flowing through the series field
- $R_a$  = Armature resistance
- $I_a$  = Armature current
- $I_L$  = Load current
- $V$  = Terminal voltage
- $E_g$  = Generated EMF



Series Wound Generator

Then,

$$I_a = I_{sc} = I_L = I \text{ (say)}$$

Voltage across the load is equal to,

$$V = E_g - I(I_a \times R_a)$$

Power generated is equal to,

$$P_g = E_g \times I$$

Power delivered to the load is equal to,

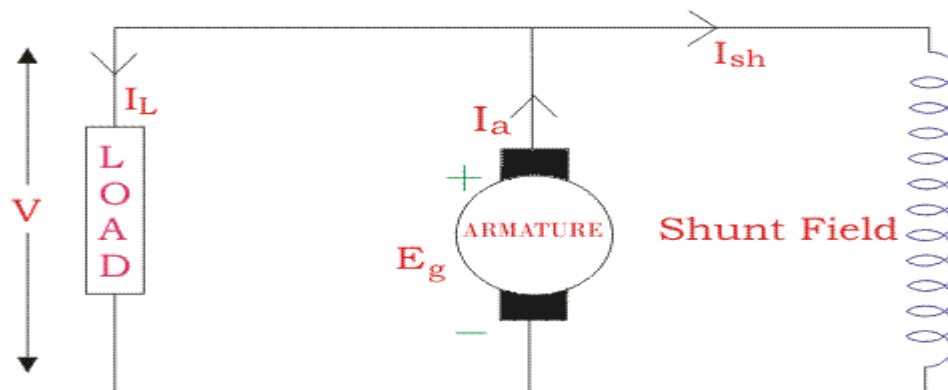
$$P_L = V \times I$$

## Shunt Wound DC Generators

In these type of DC generators, the field windings are connected in parallel with armature conductors, as shown in the figure below. In shunt wound generators the voltage in the field winding is same as the voltage across the terminal.

Here:

- $R_{sh}$  = Shunt winding resistance
- $I_{sh}$  = Current flowing through the shunt field
- $R_a$  = Armature resistance
- $I_a$  = Armature current
- $I_L$  = Load current
- $V$  = Terminal voltage
- $E_g$  = Generated EMF



Shunt Wound Generator



Here armature current  $I_a$  is dividing in two parts – one is shunt field current  $I_{sh}$ , and another is load current  $I_L$ .

So,

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

The effective power across the load will be maximum when  $I_L$  will be maximum. So, it is required to keep shunt field current as small as possible. For this purpose the resistance of the shunt field winding generally kept high ( $100 \Omega$ ) and large no of turns are used for the desired EMF.

Shunt field current is equal to,

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

Voltage across the load is equal to,

$$V = E_g - I_a R_a$$

Power generated is equal to,

$$P_g = E_g \times I_a$$

Power delivered to the load is equal to,

$$P_L = V \times I_L$$

## Compound Wound DC Generator

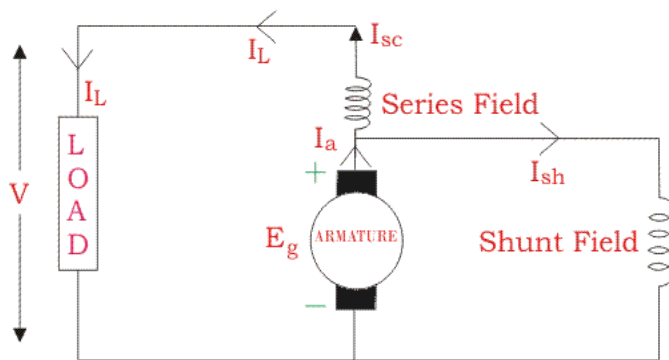
In series wound generators, the output voltage is directly proportional with load current. In shunt wound generators, the output voltage is inversely proportional with load current.

A combination of these two types of generators can overcome the disadvantages of both. This combination of windings is called compound wound DC generator.

Compound wound generators have both series field winding and shunt field winding. One winding is placed in series with the armature, and the other is placed in parallel with the armature. This type of DC generators may be of two types- short shunt compound-wound generator and long shunt compound-wound generator.

## Short Shunt Compound Wound DC Generator

Short Shunt Compound Wound DC Generators are generators where only the shunt field winding is in parallel with the armature winding, as shown in the figure below.



Short Shunt Compound Wound Generator

Series field current is equal to,

$$I_{sc} = I_L$$

Shunt field current is equal to,

$$I_{sh} = \frac{(V + I_{sc}R_{sc})}{R_{sh}}$$

Armature current is equal to,

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

Voltage across the load is equal to,

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

Power generated is equal to,

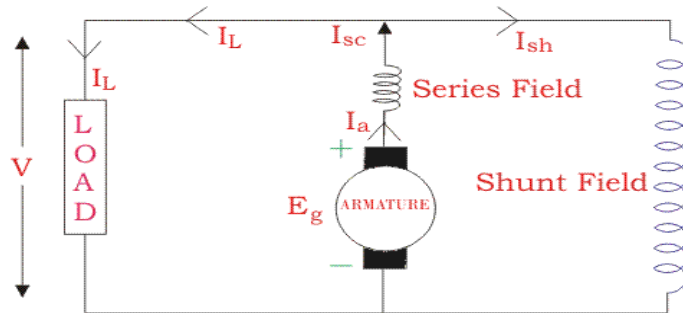
$$P_g = E_g \times I_a$$

Power delivered to the load is equal to,

$$P_L = V \times I_L$$

### Long Shunt Compound Wound DC Generator

Long Shunt Compound Wound DC Generator are generators where the shunt field winding is in parallel with both series field and armature winding, as shown in the figure below.



Long Shunt Compound Wound Generator

Shunt field current is equal to,

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

Armature current,  $I_a$  = series field current,

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

Voltage across the load is equal to,

$$V = E_g - I_a R_a - I_{sc} R_{sc} = E_g - I_a (R_a + R_{sc}) \quad [\because I_a = I_{sc}]$$

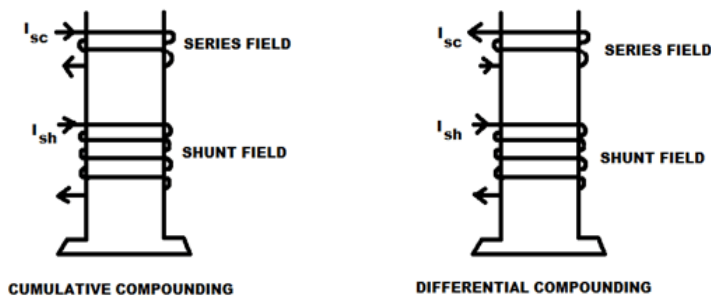
Power generated is equal to,

$$P_g = E_g \times I_a$$

Power delivered to the load is equal to,

$$P_L = V \times I_L$$

In a compound wound generator, the shunt field is stronger than the series field. When the series field assists the shunt field, generator is said to be **commutatively compound wound**.



On the other hand, if the series field opposes the shunt field, the generator is said to be **differentially compound wound**.

### Types of DC Motor

A **Direct Current Motor**, DC is named according to the connection of the field winding with the armature. Mainly there are two types of DC Motors. First, one is **Separately Excited** DC Motor and **Self-excited** DC Motor. The self-excited motors are further classified as **Shunt wound** or shunt motor, **Series wound** or series motor and **Compound wound** or compound motor.

The dc motor converts the electrical power into mechanical power is known as dc motor. The construction of the dc motor and generator are same. But the dc motor has the wide range of speed and good speed regulation which in electric traction. The working principle of the dc motor is based on the principle that the current carrying conductor is placed in the magnetic field and a mechanical force experience by it.

The DC motor is generally used in the location where require protective enclosure, for example, drip-proof, the fireproof, etc. according to the requirements. The detailed description of the various types of the motor is given below.

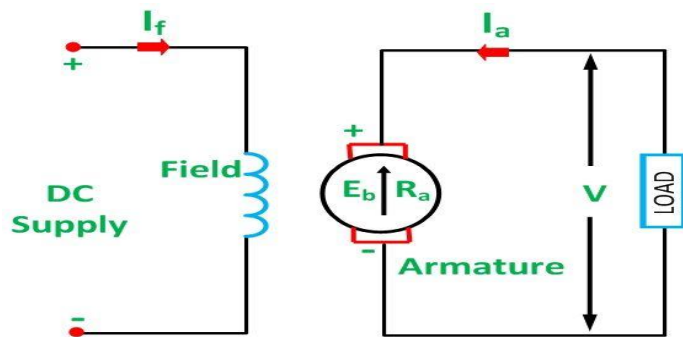
Contents:

- [Separately Excited DC Motor](#)
- [Self Excited DC Motor](#)
- [Shunt Wound Motor](#)

- [Series Wound Motor](#)
- [Compound Wound Motor](#)

### Separately Excited DC Motor

As the name signifies, the field coils or field windings are energised by a separate DC source as shown in the circuit diagram shown below.



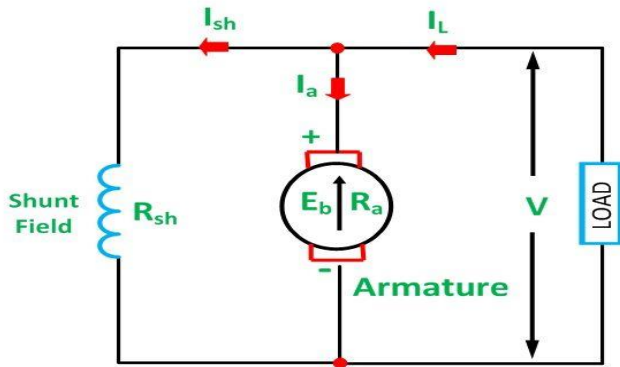
*Separately Excited DC Motor*

### Self Excited DC Motor

As the name implies self-excited, hence, in this type of motor, the current in the windings is supplied by the machine or motor itself. Self-excited DC Motor is further divided into shunt wound, and series wound motor. They are explained below in detail.

### Shunt Wound Motor

This is the most common types of DC Motor. Here the field winding is connected in parallel with the armature as shown in the figure below.



Circuit Globe

Shunt Wound DC Motor

The current, voltage and power equations for a shunt motor are written as follows.

By applying KCL at the junction A in the above figure.

The sum of the incoming currents at A = Sum of the outgoing currents at A.

$$I = I_a + I_{sh} \dots \dots \dots (1)$$

Where,

- I is the input line current
- I<sub>a</sub> is the armature current
- I<sub>sh</sub> is the shunt field current

Equation (1) is the current equation.

The voltage equations are written by using Kirchhoff's voltage law (KVL) for the field winding circuit.

$$V = I_{sh}R_{sh} \dots \dots \dots (2)$$

For armature winding circuit the equation will be given as

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

The power equation is given as

**Power input = mechanical power developed + losses in the armature + loss in the field.**

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

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

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

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

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

Multiplying equation (3) by  $I_a$  we get the following equations.

$$VI_a = EI_a + I_a^2 R_a \dots \dots \dots (6)$$

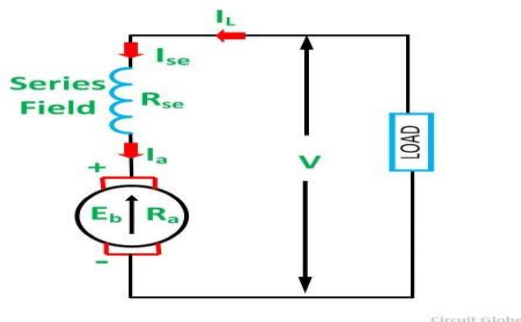
$$VI_a = P_m + I_a^2 R_a \dots \dots \dots (7)$$

Where,

$VI_a$  is the electrical power supplied to the armature of the motor.

### Series Wound Motor

In the series motor, the field winding is connected in series with the armature winding. The connection diagram is shown below.



Series Wound Motor

By applying the KCL in the above figure

$$I = I_{se} = I_a$$

Where,

$I_{se}$  is the series field current

The voltage equation can be obtained by applying KVL in the above figure

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

The power equation is obtained by multiplying equation (8) by  $I$  we get

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

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

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

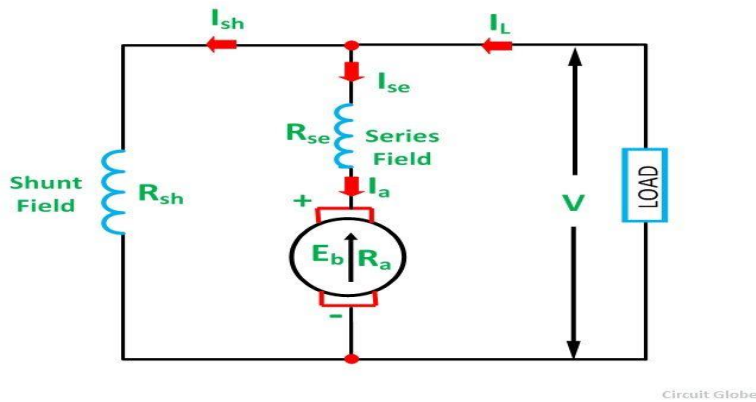
Comparing the equation (9) and (10), we will get the equation shown below.

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

Compound Wound Motor

A DC Motor having both shunt and series field windings is called a **Compound Motor**. The connection diagram of the compound motor is shown below.





*Compound Motor*

The compound motor is further subdivided as **Cumulative Compound Motor** and **Differential Compound Motor**. In cumulative compound motor the flux produced by both the windings is in the same direction, i.e.

$$\varphi_r = \varphi_{sh} + \varphi_{se}$$

In differential compound motor, the flux produced by the series field windings is opposite to the flux produced by the shunt field winding, i.e.

$$\varphi_r = \varphi_{sh} - \varphi_{se}$$

The positive and negative sign indicates that direction of the flux produced in the field windings.

### **Speed Control of DC Motor (Shunt, Series, and Compound)**

Often we want to control the speed of a **DC motor** on demand. This intentional change of drive speed is known as **speed control of a DC motor**.

Speed control of a DC motor is either done manually by the operator or by means of an automatic control device. This is different to **speed regulation** – where the speed is trying to be maintained (or ‘regulated’) against the natural change in speed due to a change in the load on the shaft.

The **speed of a DC motor** (N) is equal to:

$$N = \frac{V - I_a R_a}{k\phi}$$

Therefore speed of the 3 types of DC motors – shunt, series and compound – can be controlled by changing the quantities on the right-hand side of the equation above.

Hence the speed can be varied by changing:

1. The terminal **voltage** of the armature, V.
2. The external **resistance** in armature circuit,  $R_a$ .
3. The **flux** per pole,  $\phi$ .

Terminal voltage and external resistance involve a change that affects the armature circuit, while flux involves a change in the **magnetic field**. Therefore **speed control of DC motor** can be classified into:

1. Armature Control Methods
2. Field Control Methods

We will discuss how both of these methods control the speed of **DC series motors** and **DC shunt motors**.

### **Speed Control of DC Series Motor**

**Speed control methods for a DC series motor** can be classified as:

1. Armature Control Methods
2. Field Control Methods

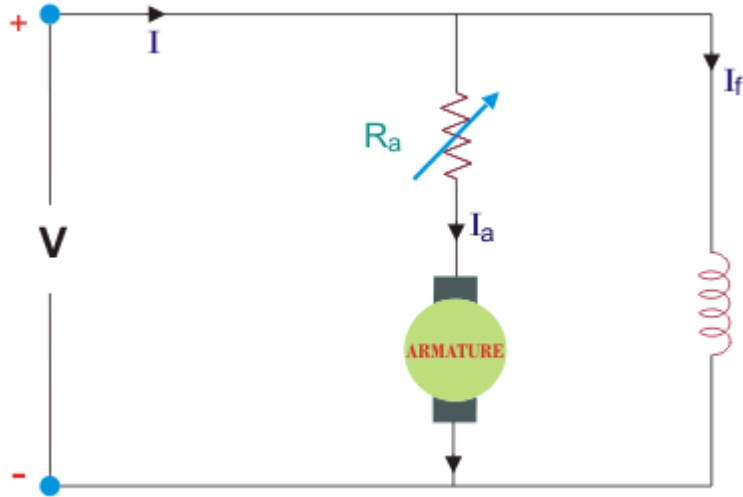
### **Armature Controlled DC Series Motor**

Speed adjustment of a DC series motor by **armature control** may be done by:

1. Armature Resistance Control Method
2. Shunted Armature Control Method
3. Armature Terminal Voltage Control

### **Armature Resistance Control Method**

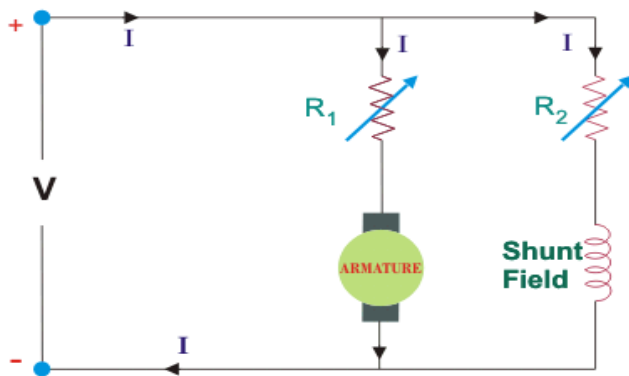
This is the most common method employed. Here the controlling resistance is connected directly in series with the supply of the motor as shown in the fig.



The power loss in the control resistance of DC series motor can be neglected because this control method is utilized for a large portion of time for reducing the speed under light load condition. This method of speed control is most economical for constant torque. This method of speed control is employed for [DC series motor](#) driving cranes, hoists, trains etc.

### Shunted Armature Control

The combination of a rheostat shunting the armature and a rheostat in series with the armature is involved in this method of speed control. The voltage applied to the armature is varied by varying series rheostat  $R_1$ . The exciting current can be varied by varying the armature shunting resistance  $R_2$ . This method of speed control is not economical due to considerable power losses in speed controlling resistances. Here speed control is obtained over wide range but below normal speed.



### Armature Terminal Voltage Control

The speed control of DC series motor can be accomplished by supplying the power to the motor from a separate variable voltage supply. This method involves high cost so it rarely used.

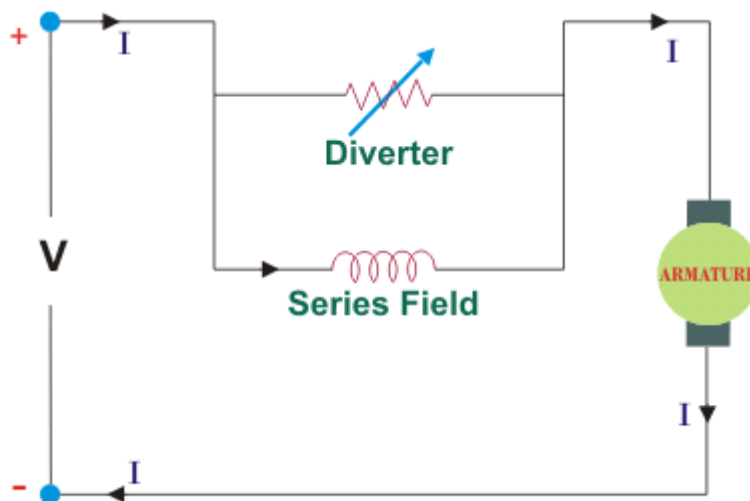
### Field Controlled DC Series Motor

Speed adjustment of a DC series motor by **field control** may be done by:

1. Field Diverter Method
2. Tapped Field Control

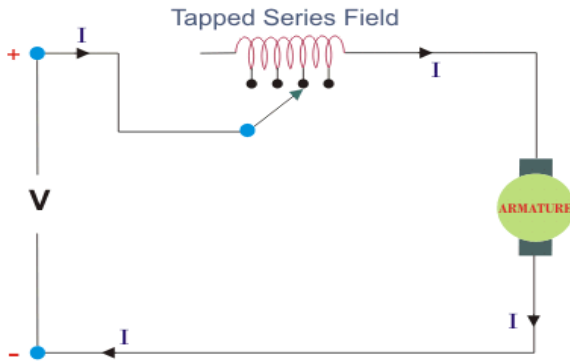
### Field Diverter Method

This method uses a diverter. Here the field flux can be reduced by shunting a portion of motor current around the series field. Lesser the diverter resistance less is the field current, less flux therefore more speed. This method gives speed above normal and the method is used in electric drives in which speed should rise sharply as soon as load is decreased.



### Tapped Field Control

This is another method of increasing the speed by reducing the flux and it is done by lowering number of turns of field winding through which current flows. In this method a number of tapping from field winding are brought outside. This method is employed in electric traction.



## Speed Control of DC Shunt Motor

The classification of **speed control methods** for a **DC shunt motor** are similar to those of a DC series motor. These two methods are:

1. Armature Control Methods
2. Field Control Methods

### Armature Controlled DC Shunt Motor

Armature controlled DC shunt motor can be performed in two ways:

1. Armature Resistance Control
2. Armature Voltage Control

#### *Armature Resistance Control*

In armature resistance control a variable resistance is added to the armature circuit. Field is directly connected across the supply so **flux** is not changed due to variation of series resistance. This is applied for DC shunt motor. This method is used in printing press, cranes, hoists where speeds lower than rated is used for a short period only.

#### *Armature Voltage Control*

This method of speed control needs a variable source of voltage separated from the source supplying the field current. This method avoids disadvantages of poor speed regulation and low efficiency of armature-resistance control methods.

The basic adjustable armature voltage control method of speed control is accomplished by means of an adjustable voltage generator is called **Ward Leonard System**. This method involves using a [motor-generator](#) (M-G) set. This method is best suited for steel rolling mills, paper machines, elevators, mine hoists, etc. This method is known as Ward Leonard System.

### *Advantages of Armature Controlled DC Shunt Motor*

1. Very fine speed control over whole range in both directions
2. Uniform acceleration is obtained
3. Good speed regulation
4. It has regenerative braking capacity

### *Disadvantages of Armature Controlled DC Shunt Motor*

1. Costly arrangement is needed, floor space required is more
2. Low efficiency at light loads
3. Drive produced more noise.

## **Field Controlled DC Shunt Motor**

By this method a DC Shunt motor's speed is controlled through a field rheostat.

## **Field Rheostat Controlled DC Shunt Motor**

In this method, speed variation is accomplished by means of a variable resistance inserted in series with the shunt field. An increase in controlling resistances reduces the field current with a reduction in flux and an increase in speed. This method of speed control is independent of load on the motor. Power wasted in controlling resistance is very less as field current is a small value. This method of speed control is also used in [DC compound motor](#).

### *Disadvantages of Field Rheostat Controlled DC Shunt Motor*

- Creeping speeds cannot be obtained.
- Top speeds only obtained at reduced torque.
- The speed is maximum at minimum value of flux, which is governed by the demagnetizing effect of armature reaction on the field.

## **Solid State Speed Control**

Static Ward Leonard drives are being used these days because of the drawbacks of the classical method. Rotating [M-G sets](#) are replaced by solid state converters to control DC motor speed. The converters used are [choppers](#) (in case of DC

supply) or controlled rectifiers (in case of AC supply). This method is not suitable for intermittent loads.

### DC Motor Speed Control Theory

To derive the speed of a DC motor, we start with the equation for the DC motor's EMF (Electromagnetic Force). We know that the EMF equation of DC motor is equal to:

$$E = \frac{NP\phi Z}{60A}$$

Hence rearranging the equation:

- $N = 60A E / PZ\phi$

With  $k = PZ/60A$ , then:

- $N = E / k\phi$

Hence with  $E = V - I_a R_a$ , we derive the speed of the DC motor (N):

$$N = \frac{V - I_a R_a}{k\phi}$$

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## **Three Point Starter: Diagram and Working Principle**

A **3 point starter** is a device that helps in the starting and running of a [DC shunt motor](#) or [compound wound DC motor](#) (similar to a [4 point starter](#)).



Now the question is why these [types of DC motors](#) require the assistance of the starter in the first place? Well, it's due to the presence of back emf ( $E_b$ ), which plays a critical role in governing the operation of the motor. The back emf develops as the motor armature starts to rotate in presence of the [magnetic field](#), by generating action and counters the supply [voltage](#). Hence the back emf at the starting of the motor is zero, but it develops gradually as the motor gathers speed.

The general motor emf equation is:

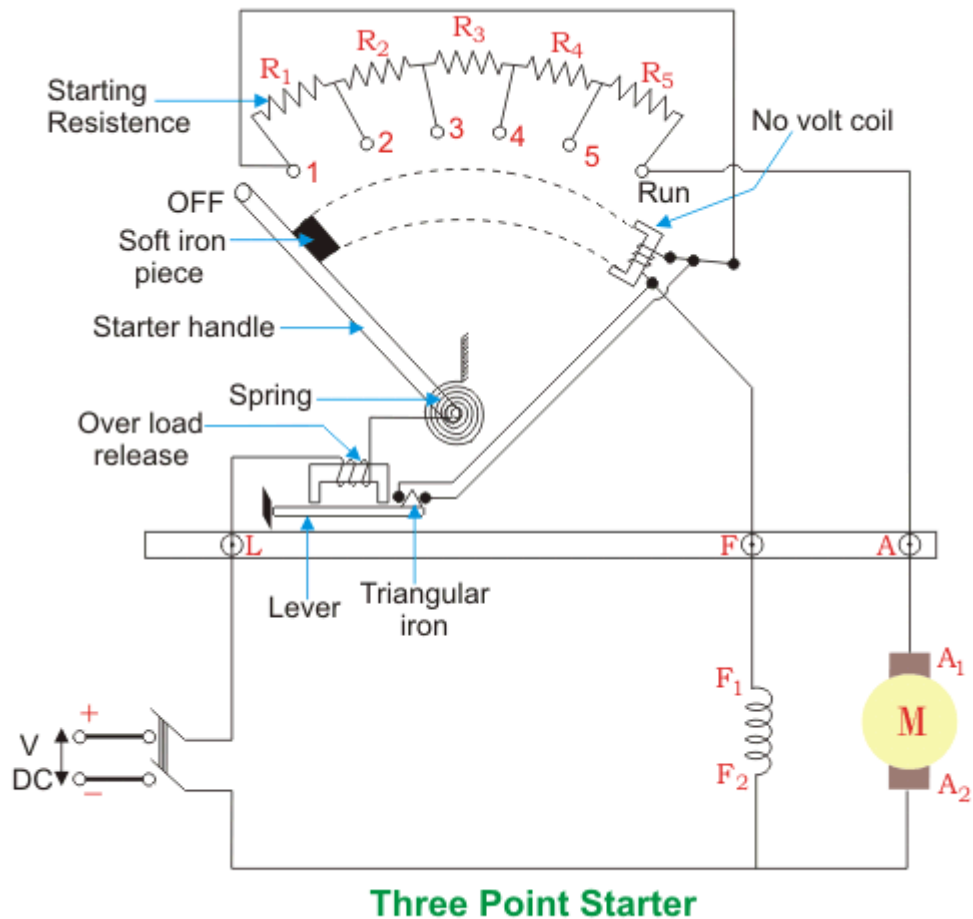
$$E = E_b + I_a \cdot R_a$$

Where  $E$ =Supply Voltage;  $E_b$ =Back EMF;  $I_a$ =Armature Current; and  $R_a$ =Armature Resistance. Since at starting  $E_b = 0$ , then  $E = I_a \cdot R_a$ . Hence we can rearrange for the armature current  $I_a$ :

$$\therefore I_a = \frac{E}{R_a}$$

We can see from the above equation that the [current](#) will be dangerously high at starting (as the armature resistance  $R_a$  is small). This is why it's important that we make use of a device like the **3 point starter** to limit the starting current to acceptably low value.

To understand how the starting current is restricted to the desired value, we need to look at the construction and **working of three-point starter**. The [electrical symbols](#) in the diagram below show all the essential parts of a three-point starter.



3 Point Starter

Diagram

## Construction of 3 Point Starter

Construction wise a starter is a variable resistance, integrated into the number of sections as shown in the figure beside. The contact points of these sections are called studs and are shown separately as **OFF, 1, 2, 3, 4, 5, RUN**. Other than that there are three main points, referred to as

1. 'L' Line terminal (Connected to positive of supply)
2. 'A' Armature terminal (Connected to the armature winding)
3. 'F' Field terminal (Connected to the field winding)

And from there it gets the name 3 point starter. Now studying the **construction of 3 point starter** in further details reveals that the point 'L' is connected to an electromagnet called overload release (OLR) as shown in the figure. The other end of OLR is connected to the lower end of conducting lever of starter handle where spring is also attached with it, and the starter handle also contains a soft iron piece

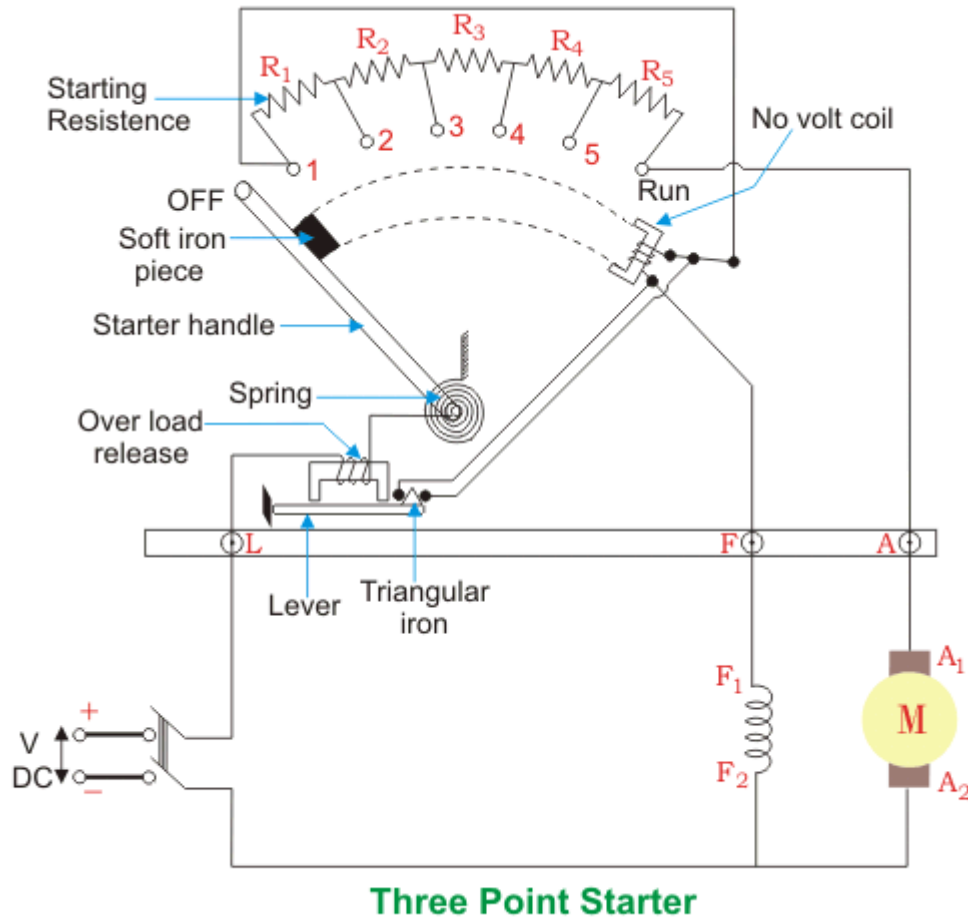
housed on it. This handle is free to move to the other side RUN against the force of the spring. This spring brings back the handle to its original OFF position under the influence of its own force. Another parallel path is derived from the stud '1', given to another electromagnet called No Volt Coil (NVC) which is further connected to terminal 'F.' The starting resistance at starting is entirely in series with the armature. The OLR and NVC act as the two protecting devices of the starter.

## Working of Three Point Starter

Having studied its construction, let us now go into the **working of the 3 point starter**. To start with the handle is in the OFF position when the supply to the DC motor is switched on. Then handle is slowly moved against the spring force to make contact with stud No. 1. At this point, field winding of the shunt or the compound motor gets supply through the parallel path provided to starting the resistance, through No Voltage Coil. While entire starting resistance comes in series with the armature. The high starting armature current thus gets limited as the current equation at this stage becomes:

$$I_a = \frac{E}{(R_a + R_{st})}$$

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As the handle is moved further, it goes on making contact with studs 2, 3, 4, etc., thus gradually cutting off the series resistance from the armature circuit as the motor gathers speed. Finally, when the starter handle is in 'RUN' position, the entire starting resistance is eliminated, and the motor runs with normal speed.

This is because back emf is developed consequently with speed to counter the supply voltage and reduce the armature current.

So the external electrical resistance is not required anymore and is removed for optimum operation. The handle is moved manually from OFF to the RUN position with the development of speed. Now the obvious question is once the handle is taken to the RUN position how it is supposed to stay there, as long as the motor is running.

To find the answer to this question let us look into the working of No Voltage Coil.

## Losses in DC Machine

As we know "Energy neither can be created nor it can be destroyed, it can only be transferred from one form to another". In DC machine, mechanical energy is

converted into the electrical energy. During this process, the total input power is not transformed into output power. Some part of input power gets wasted in various forms. The form of this loss may vary from one machine to another. These losses give in the rise in temperature of the machine and reduce the efficiency of the machine. In **DC Machine**, there are broadly four main categories of energy loss.

### **Copper Losses or Electrical Losses in DC Machine or Winding Loss**

The copper losses are the winding losses taking place during the current flowing through the winding. These losses occur due to the resistance in the winding. In a DC machine, there are only two windings, armature and field winding.

Thus copper losses categories in three parts; armature loss, the field winding loss, and brush contact resistance loss. The copper losses are proportional to the square of the current flowing through the winding.

#### **Armature Copper Loss in DC Machine**

$$\text{Armature copper loss} = I_a^2 R_a$$

Where,  $I_a$  is armature current and  $R_a$  is armature resistance.

These losses are about 30% of the total full load losses.

#### **Field Winding Copper Loss in DC Machine**

$$\text{Field winding copper loss} = I_f^2 R_f$$

Where,  $I_f$  is field current and  $R_f$  is field resistance.

These losses are about 25% theoretically, but practically it is constant.

#### **Brush Contact Resistance Loss in DC Machine**

Brush contact loss attributes to resistance between the surface of brush and commutator. It is not a loss which could be calculated separately as it is a part of variable losses. Generally, it contributes to both the types of copper losses. So, they are factors in the calculation of the above losses.

### **Core Losses or Iron Losses in DC Machine or Magnetic Losses**

As iron core of the armature is rotating in magnetic field, some losses occurs in the core which is called core losses. Normally, machines are operated with constant speed, so these losses are almost constant. These losses are categorized in two form; Hysteresis loss and Eddy current loss.

#### **Hysteresis Loss in DC Machine**

Hysteresis losses occur in the [armature winding](#) due to reversal of magnetization of the core. When the core of the armature exposed to the magnetic field, it undergoes one complete rotation of magnetic reversal. The portion of the armature which is under S-pole, after completing half electrical revolution, the same piece will be under the N-pole, and the magnetic lines are reversed in order to overturn the magnetism within the core. The constant process of magnetic reversal in the armature, consume some amount of energy which is called hysteresis loss. The percentage of loss depends upon the quality and volume of the iron.

### *The Frequency of Magnetic Reversal*

$$f = \frac{PN}{120}$$

Where,

P = Number of poles

N = Speed in rpm

### *Steinmetz Formula*

The Steinmetz formula is for the calculation of hysteresis loss.

$$\text{Hysteresis loss } P_h = \eta B_{max}^{1.6} fV \text{ watts}$$

Where,

$\eta$  = Steinmetz hysteresis co-efficient

$B_{max}$  = Maximum flux Density in armature winding

F = Frequency of magnetic reversals

V = Volume of armature in m<sup>3</sup>.

### **Eddy Current Loss in DC Machine**

According to [Faraday's law of electromagnetic induction](#), when an iron core rotates in the [magnetic field](#), an emf is also induced in the core. Similarly, when armature rotates in the magnetic field, the small amount of emf induced in the core which allows the flow of charge in the body due to the conductivity of the core. This current is useless for the machine. This loss of current is called eddy current. This loss is almost constant for the DC machines. It could be minimized by selecting the laminated core.

### **Mechanical Losses in DC Machine**

The losses associated with mechanical friction of the machine are called mechanical losses. These losses occur due to friction in the moving parts of the

machine like bearing, brushes etc, and windage losses occur due to the air inside the rotating coil of the machine. These losses are usually very small about 15% of full load loss.

### Stray Load Losses in DC Machine

There are some more losses other than the losses which have been discussed above. These losses are called stray-load losses. These miscellaneous losses are due to the short-circuit current in the coil undergoing commutation, distortion of flux due to the armature and many more losses which are difficult to find. These losses are difficult to determine. However, they are taken as 1% of the whole load power output.

### EFFICIENCY OF A DC GENERATOR:

Power flow in a DC generator is shown in Figure 3.1.

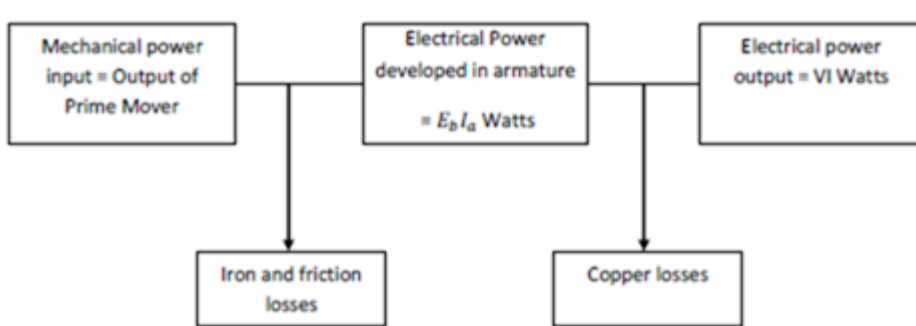


Figure 3.1

$$\text{Efficiency of a DC generator} = \frac{\text{output}}{\text{output} + \text{losses}} = \frac{VI}{VI + I_a^2 r_a + w_c} \dots\dots\dots 3$$

Where  $w_c$  is constant loss.

### CONDITION FOR MAXIMUM EFFICIENCY

Generator output = VI;

Generator input = VI + losses.

$$\text{Input} = VI + I_a^2 r_a + w_c$$

If the shunt field current is negligible, then  $I_a = I$  (approximately)

$$\text{Then, } \eta = \frac{VI}{VI + I_a^2 r_a + w_c} = \frac{1}{1 + \left(\frac{I_a^2 r_a + w_c}{VI}\right)} \dots\dots\dots 4$$

$$\text{For maximum efficiency } \frac{d}{dt} \left( \frac{I_a^2 r_a + w_c}{VI} \right) = 0 \text{ or } I^2 r_a = w_c \dots\dots\dots 5$$

Hence efficiency is maximum when variable loss = constant loss.

$$\text{The load current corresponding to maximum efficiency is } I^2 r_a = w_c \text{ or } I = \sqrt{\frac{w_c}{r_a}} \dots\dots\dots 6$$



## EFFICIENCY OF DC MOTOR:

The power flow in a DC motor is shown in Figure 3.2.

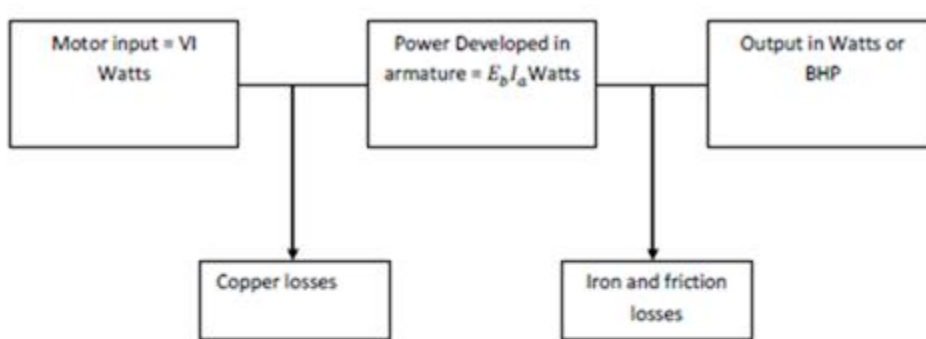


Figure 3.2

$$\text{Efficiency of a DC motor} = \frac{\text{input} - \text{losses}}{\text{input}}$$

$$= \frac{VI - I_a^2 r_a - w_c}{VI} \dots\dots\dots 7$$

The condition for maximum power developed is  $E_b = \frac{V}{2} = I_a r_a$ .

This is shown in equation.

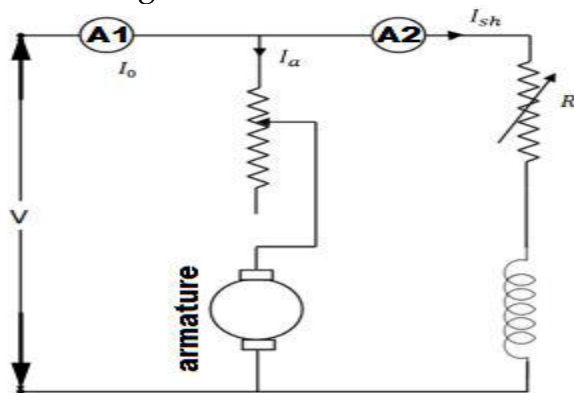
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$$I_a^2 r_a = w_c \dots\dots\dots 8$$

### Swinburne Test of DC Machine

This method is an indirect method of testing a DC machine. It is named after Sir James Swinburne. **Swinburne's test** is the most commonly used and simplest method of testing of shunt and compound wound DC machines which have constant flux. In this test the efficiency of the machine at any load is pre-determined. We can run the machine as a motor or as a generator. In this method of testing no load losses are measured separately and eventually we can determine the efficiency. The circuit connection for **Swinburne's test** is shown in figure below. The speed of the machine is adjusted to the rated speed with the help of the shunt regulator R as

shown in figure.



## Calculation of Efficiency

Let,  $I_0$  is the no load current (it can be measured by ammeter  $A_1$ )

$I_{sh}$  is the shunt field current (it can be measured by ammeter  $A_2$ )

Then, no load armature current =  $(I_0 - I_{sh})$

Also let,  $V$  is the supply voltage. Therefore, No load power input =  $VI_0$  watts.

In **Swinburne's test** no load power input is only required to supply the losses. The losses occur in the machine mainly are:

- Iron losses in the core
- Friction and windings losses
- Armature copper loss.

Since the no load mechanical output of the machine is zero in Swinburne's test, the no load input power is only used to supply the losses.

The value of armature copper loss =  $(I_0 - I_{sh})^2 R_a$

Here,  $R_a$  is the armature resistance.

Now, to get the constant losses we have to subtract the armature copper loss from the no load power input.

Then, **Constant losses**  $W_C = VI_0 - (I_0 - I_{sh})^2 R_a$

After calculating the no load constant losses now we can determine the efficiency at any load.

Let,  $I$  is the load current at which we have to calculate the efficiency of the machine.

Then, armature current ( $I_a$ ) will be  $(I - I_{sh})$ , when the machine is motoring.

And  $I_a = (I + I_{sh})$ , when the machine is generating.

Power input =  $VI$

Armature copper loss,  $P_{CU} = I^2 R_a = (I - I_{sh})^2 R_a$

Constant losses,  $W_C = VI_0 - (I_0 - I_{sh})^2 R_a$

$$\text{Total losses} = P_{CU} + W_C$$

∴ Efficiency of the motor:

$$\eta_m = \frac{\text{output}}{\text{input}} = \frac{\text{input} - \text{losses}}{\text{input}} = \frac{VI - (P_{CU} + W_C)}{VI}$$

### Calculation of Efficiency When the Machine is Generating on Load

Power input = VI

Armature copper loss,  $P_{CU} = I_2 R_a = (I + I_{sh})^2 R_a$

Constant losses,  $W_C = VI_0 - (I_0 - I_{sh})^2 R_a$

$$\text{Total losses} = P_{CU} + W_C$$

∴ Efficiency of the generator:

$$\eta_g = \frac{\text{output}}{\text{input}} = \frac{\text{input} - \text{losses}}{\text{input}} = \frac{VI - (P_{CU} + W_C)}{VI}$$

### Advantages of Swinburne's Test

The main advantages of this test are:

1.
  1. This test is very convenient and economical as it is required very less power from supply to perform the test.
  2. Since constant losses are known, efficiency of **Swinburne's test** can be pre-determined at any load.

### Disadvantages of Swinburne's Test

The main disadvantages of this test are :

1.
  1. Iron loss is neglected though there is change in iron loss from no load to full load due to armature reaction.
  2. We cannot be sure about the satisfactory commutation on loaded condition because the test is done on no-load.
  3. We can't measure the temperature rise when the machine is loaded. Power losses can vary with the temperature.
  4. In DC series motors, the Swinburne's test cannot be done to find its efficiency as it is a no load test.

