Unit – 1 (BEE) R19& R20 Regulations – I ECE II Semester

DC Machines: Principle of operation of DC generator – emf equation – types of DC machines – torque equation of DC motor – applications – three point starter - losses and efficiency - Swinburne's test - speed control methods – OCC of DC generator- Brake test on DC Shunt motor-numerical problems

PRINCIPLE OF OPERATION OF DC GENERATOR

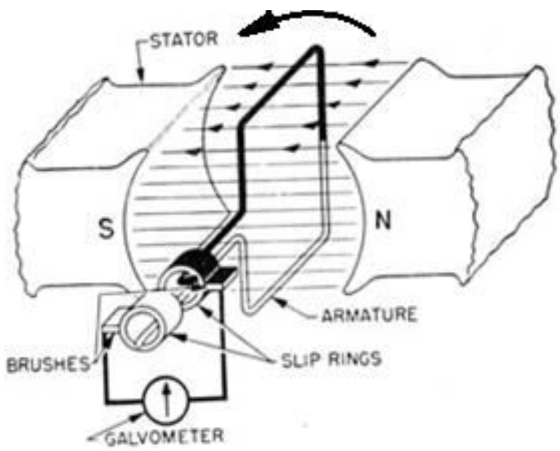
1. DC Generator is an electro mechanical energy conversion device used to ***convert mechanical energy to electrical energy.***
2. It works as per ***Faradays laws of electromagnetic induction*** which states that

> I Law: *"Whenever the conductor cuts the magnetic flux a dynamical emf is induced in the conductor"*
> II Law: *"The magnitude of the emf induced is directly proportional to the rate of change of flux linkages"*

3. ***Fleming's right hand rule*** is used to obtain the direction of the current in the coil of the DC Generator.

Simple loop dc generator:

The simple loop dc generator is assumed to have the following parts as shown in Fig (a)

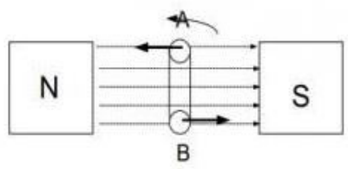


- Two permanent magnets (North pole and South pole) as stator
- A single turn rectangular coil named as Armature (placed on the shaft) as rotor
- Two Slip rings rotating along with the armature coil
- Two static carbon brushes mounted on the slip rings
- External load or galvanometer

The rectangular shaped armature coil is assumed to be rotated in anticlockwise with an angular velocity of ω rad/sec.

The working operation of the simple loop generator is explained over one complete rotation of the coil for 360^0 and is shown in the below figure at different positions of the coil.

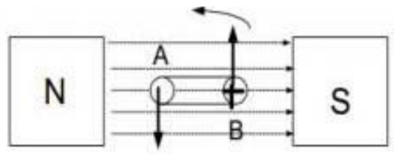
At 0 degrees Position (1):



Position 1: (θ =0°)minimum $\frac{d\phi}{dt}$

1. This position is also known as the "Neutral Plane";
2. In this position the loop is parallel to the magnetic lines of flux
3. In this position there is maximum flux passing through the coil.
4. No EMF is induced in the coil because of no "Change in flux through the loop".

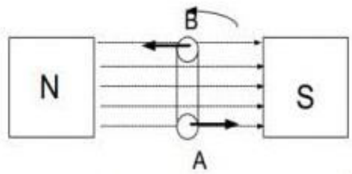
At 90 degrees Position (2):



Position 2: (θ =90°) maximum$\frac{d\phi}{dt}$

1. After the loop has been rotated 90 degrees clockwise through the magnetic field the flux linkage through it now becomes zero.
2. But the rate of change of flux through it was maximum,
3. This results in an induced EMF which climbs from zero to its peak value.

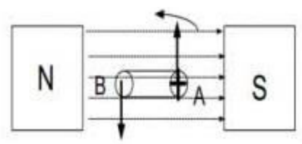
At 180 degrees Position (3):



Position 3: (θ =180°)minimum $\frac{d\phi}{dt}$

1. Once again the coil is rotated 90 degrees clockwise resulting in the completion of a 180 degrees cycle.
2. Here the loop is perpendicular to the magnetic lines of force
3. This means that there is maximum flux density through it resulting the EMF to falls back to zero.

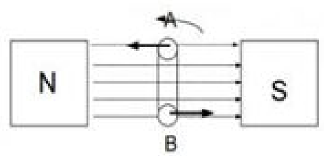
At 270 degrees Position (4):



Position 4: (θ =270°) maximum$\frac{d\phi}{dt}$

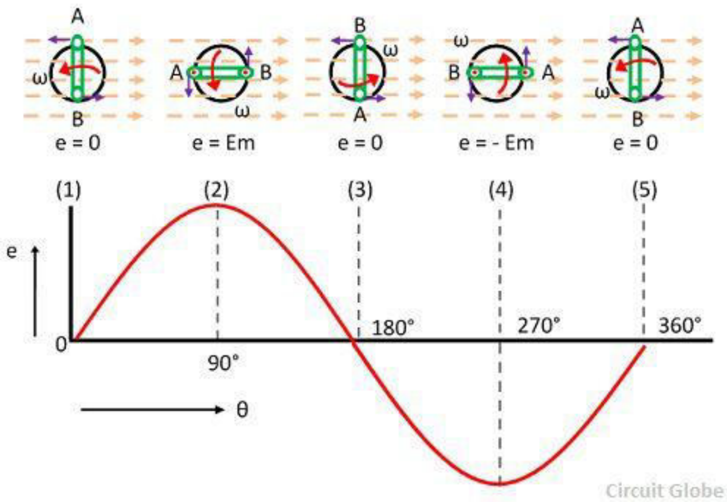
1. At 270 degrees the flux linkage through the loop is once again zero,
2. but the rate of change of flux is maximum.
3. In this position, the EMF induced goes up to its peak value, but this time it's in the reverse direction.

At 360 degrees Position(5):



Position 5 : (θ =0°)minimum $\frac{d\phi}{dt}$

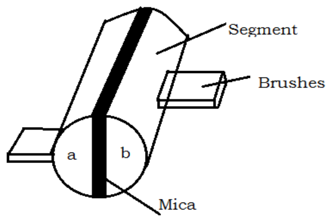
1. The loop is rotated through another 90 degrees such that it has completed a rotation of 360 degrees.
2. The flux linkage through it is maximum and the voltage decreases back to zero.



- Hence, it is observed that the nature of the emf induced in the armature coil is alternating quantity (i.e, positive voltage during first half cycle and negative voltage during second half cycle)
- Thus, to convert the induced alternating ac to dc nature the Commutator (or) split rings are used in the place of the slip rings of a simple loop generator.

ACTION OF COMMUTATOR:

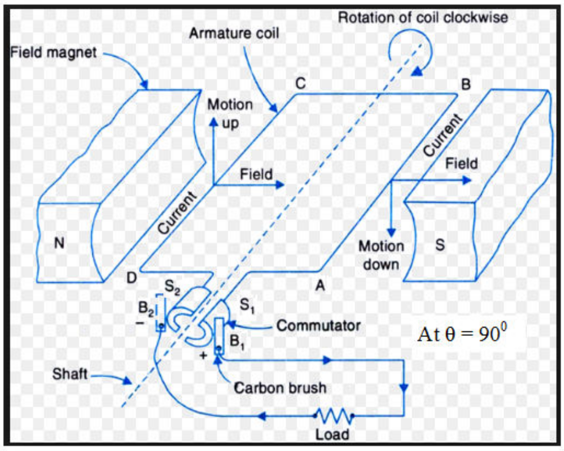
- The Commutator is a mechanical rectifier used to convert AC to DC

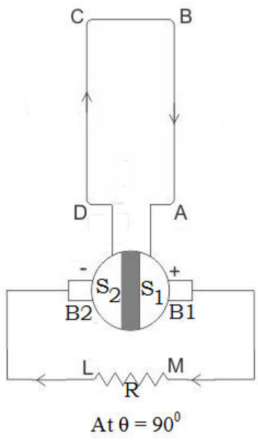


- Here, the split rings or Commutator segments (s_1 and s_2) are placed instead of slip rings
- The split rings or commutator are made out of conducting cylinder, which is cut into two halves or segments insulated from each other by a thin sheet of mica.
- Brushes B_1 and B_2 are mounted on two Commutator segments having + and - polarities

At θ = 90^{0}position :

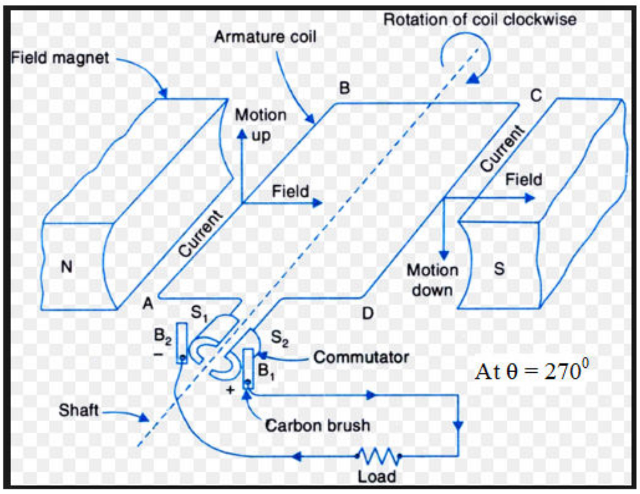
- Conductor AB is under South Pole and Conductor CD are under North Pole, with coil rotating in clock wise direction.
- Using Flemings right hand rule, the current in the conductor AB is from B-A and in conductor CD is from D-C
- Therefore the current flow is in the path of A – S_1 - B_1 – **M – L** - B_2 - S_2 – D – C – B - A

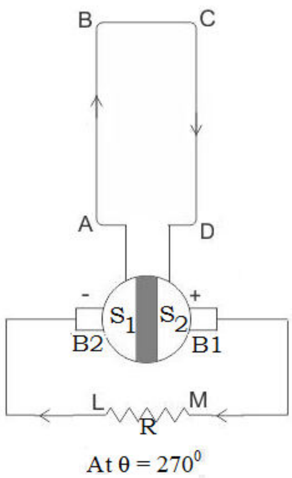


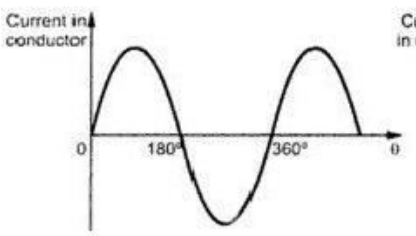


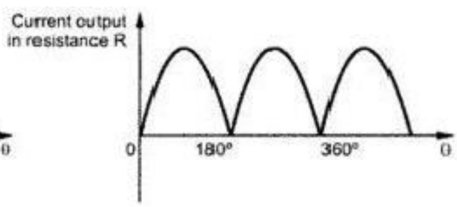
At θ = 270° position :

- Conductor AB is under North Pole and Conductor CD are under South Pole, with coil rotating in clock wise direction.
- Using Flemings right hand rule, the current in the conductor AB is from A-B and in conductor CD is from C-D
- Therefore the current flow is in the path of A – B – C - D- S_2- B_1 – **<u>M – L</u>** - B_2 – S_1- A







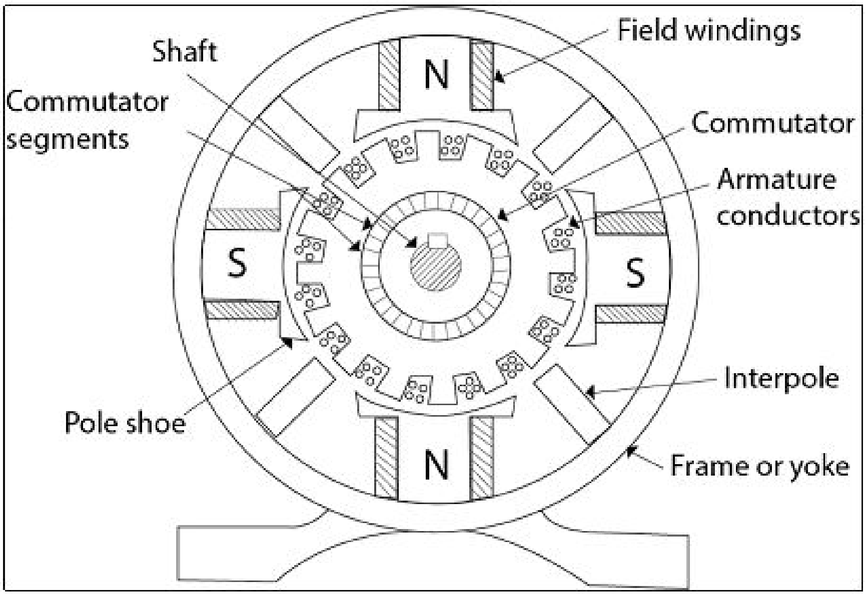


- Thus using the Commutator, the current in the load is unidirectional from M to L at all positions i.e current in coil is alternating and current in Resistance R is unidirectional (pulsating DC)

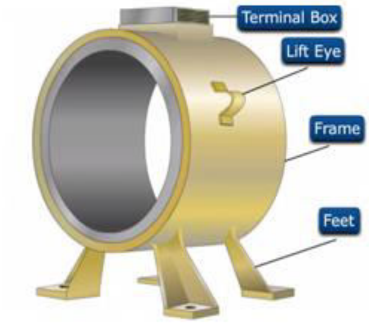
CONSTRUCTION OF DC GENERATOR

A DC generator has the following parts

1. Yoke (or) Magnetic frame
2. Pole core and pole shoe
3. Field winding (or) Pole coils
4. Armature Core
5. Armature winding
6. Commutator
7. Brushes
8. Bearing

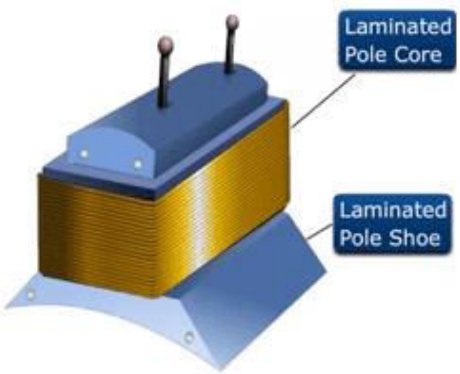


Yoke:



- Yoke or the outer frame of DC generator serves two purposes,
  1. It holds the magnetic pole cores of the generator and acts as cover of the generator.
  2. It carries the magnetic field flux.
- Yoke is made of cast iron for small rating generators, due to the cheaper in cost but heavier than steel.
- Yoke is made of lighter cast steel or rolled steel for larger rating generators , where weight of the machine is concerned.

Pole core and pole shoe



- The field magnets consist of pole cores and pole shoes.
- The pole core is fixed to the inner periphery of the yoke by means of bolts through the yoke and into the pole body.
- The pole core carries the field winding and there are two types of construction

  One: Solid pole core, where it is made of a single piece of cast iron or cast steel.

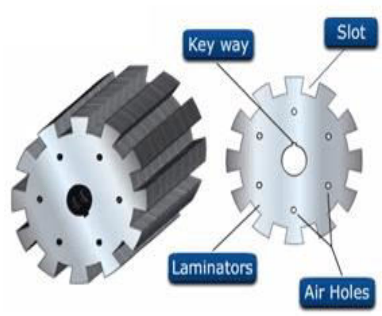
  Two: Laminated pole core, where it made of numbers of thin, limitations of annealed steel which are riveted together.
- The thickness of the lamination is in the range of 0.04" to 0.01".
- The ***pole shoes*** serve two purposes:

1. They spread out the flux in the air gap and also, being of larger cross-section, reduce the reluctance of the magnetic path
2. They support the exciting coils (or field coils)

Field winding (or) Pole coils

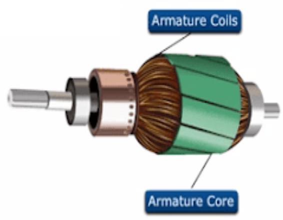
- The function of the field system is to produce uniform magnetic field within which the armature rotates.
- Field coils are mounted on the poles and carry the dc exciting current.
- The field coils are connected in such a way that adjacent poles have opposite polarity.
- The m.m.f. developed by the field coils produces a magnetic flux that passes through the pole pieces, the air gap, the armature and the frame.
- Practical d.c. machines have air gaps ranging from 0.5 mm to 1.5 mm.
- By reducing the length of air gap, we can reduce the size of field coils

Armature Core



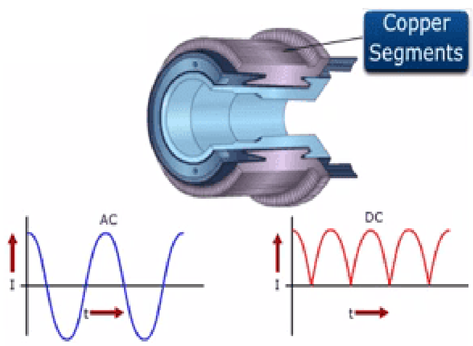
- The armature core consists of slotted soft-iron laminations (about 0.4 to 0.6 mm thick) that are stacked to form a cylindrical core as shown in adjacent figure.
- The purpose of laminating the core is to reduce the eddy current loss.
- Thinner the lamination, greater is the resistance offered to the induced e.m.f., smaller the current and hence lesser the I^2R loss in the core.
- The laminations are slotted to accommodate and provide mechanical security to the armature winding and to give shorter air gap for the flux to cross between the pole face and the armature "teeth".

Armature winding



- The slots of the armature core hold insulated conductors that are connected in a suitable manner. This is known as armature winding.
- This is the winding in which "working" emf is induced. The armature conductors are connected in series-parallel; the conductors being connected in series so as to increase the voltage and in parallel paths so as to increase the current.
- The armature winding of a D.C. machine is a closed-circuit winding; the conductors being connected in a symmetrical manner forming a closed loop or series of closed loops.
- There are two types of armature winding based on the connection to the Commutator they are (a) Lap winding and (b) Wave winding

Commutator

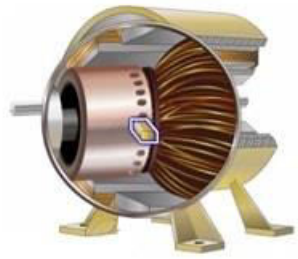


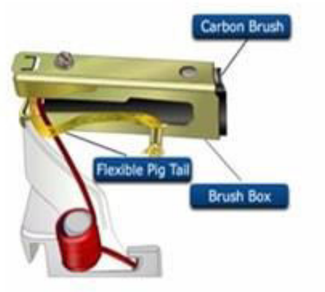
- A Commutator is a mechanical rectifier which converts the alternating voltage generated in the armature winding into direct voltage across the brushes
- The Commutator is made of copper segments insulated from each other by mica sheets and mounted on the shaft of the machine
- The armature conductors are soldered to the

Commutator segments in a suitable manner to give rise to the armature winding

Brushes

- The function of the brushes in DC generator is to collect current from Commutator segments.
- The brushes are made of carbon and rest on the Commutator.
- The brush pressure is adjusted by means of adjustable springs.





Bearing of DC Generator

- For small machine, ball bearing is used and for heavy duty DC generator, roller bearing is used.

The bearing must always be lubricated properly for smooth operation and long life of generator.

EMF EQUATION

Let,

E = Average emf induced in volts
Z = No. of armature conductors
N = Speed of the rotor in RPM
P = No. of the poles
A = No. of parallel paths
Φ = Flux per pole in Weber's

As per Faradays second Law,

- The magnitude of the induced emf (e) is directly proportional to the rate of change of flux linkages (ψ)

$$e\alpha\frac{d\Psi}{dt} = e\alpha\, N\frac{d\Phi}{dt} = e = k\, N\frac{d\Phi}{dt},\ \text{In SI unit system } k=1, \qquad \therefore e = N\frac{d\Phi}{dt}$$

- Emf per conductor is $e = \frac{d\Phi}{dt}$

Where,

- $d\Phi$ = total flux in the airgap that cuts the conductor for one revolution.

  As (P) No. of poles and each pole produces the Φ flux, then $d\Phi = P\Phi$

- dt = time taken by the conductor to cut the flux of $d\Phi$

  i.e The time taken for the armature coil to complete one rotation $dt = \frac{60}{N}$ sec

Thus,

$$e = \frac{P\phi}{\left(\frac{60}{N}\right)} = \frac{P\phi N}{60}$$

As there are (A) No. of parallel paths with 'Z' No. of conductors, then the emf per parallel path is given by

$$e = \frac{P\phi N}{60} * \left(\frac{Z}{A}\right) = \frac{\phi ZN}{60} * \frac{P}{A}$$

Therefore, average value of the emf induced is $E = \frac{\phi ZN}{60} * \frac{P}{A}$

The No. of parallel paths in the armature winding depends on the type of the armature windings

For Wave connected Armature (A=2)

$$E = \frac{\phi ZN}{60} * \frac{P}{2}$$

For Lap connected Armature (A=P)

$$E = \frac{\phi ZN}{60} * \frac{P}{P}$$

Differences between LAP and WAVE windings

Lap Winding	Wave Winding
The lap winding can be defined as a coil which can be lap back toward the succeeding coil.	The wave winding can be defined as the loop of the winding can form the signal shape.
The connection of the lap winding is, the armature coil end is connected to the nearby section on the commutators.	The connection of the wave winding is, the armature coil end is connected to commutator sections at some distance apart.
The numbers of the parallel paths are equal to the total of number poles.	The number of parallel paths is equal to two.
Another name of lap winding is **multiple winding** otherwise **Parallel Winding**	Another name of wave winding is **Series Winding** otherwise Two-circuit
The e.m.f of lap winding is Less	The e.m.f of wave winding is More
The no. of brushes in lap winding is Equivalent to the no. of parallel paths.	The no. of brushes in wave winding is Equivalent toTwo
The types of lap winding are **Simplex lap winding** & Duplex lap winding.	The types of wave winding are **Progressive & Retrogressive**
The efficiency of the lap winding is Less	The efficiency of the wave winding is High
The additional coil used in the lap winding is Equalizer Ring	The additional coil used in the wave winding is Dummy coil
The winding cost of the lap winding is High	The winding cost of the wave winding is Low
The **lap winding used for** high current, low voltage machines.	The **applications of wave winding** include low current and high voltage machines.

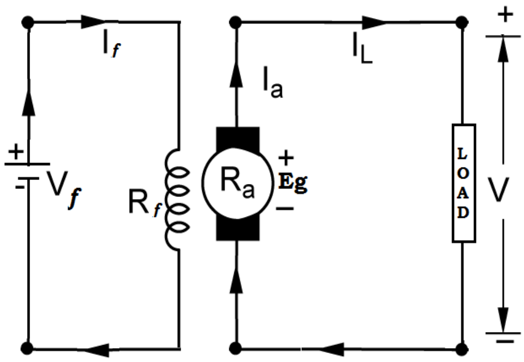
TYPES OF DC GENERATORS

Based on the excitation given to the field winding, the dc generators are classified in to two types

a. Separately excited dc generator
b. Self excited dc generator

SEPARATELY EXCITED DC GENERATOR:

1. In a separately excited generator field winding is energized from a separate voltage source in order to produce flux in the machine and is shown in the below figure.



2. The flux produced will be proportional to the field current in unsaturated condition of the poles.
3. The armature conductors when rotated in this field will cuts the magnetic flux and generates the emf (Eg).
4. The emf will circulate the current against the armature resistance (Ra), brushes and to the load.
5. Applying KVL to the armature loop the Eg is

$$E_g = V + I_a R_a + V_{brush}$$

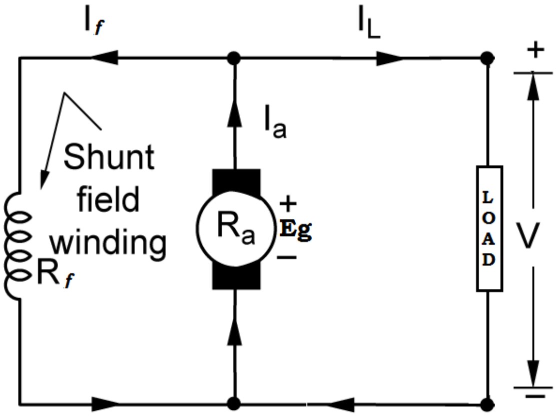
$I_a = I_L$ and $I_L = \frac{P_L}{V}$ and

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

SELF EXCITED DC GENERATOR:

1. In self excited generator field winding is energized from the armature induced emf and there is an electrical connection in between this armature and field winding.
2. There are three possibilities of connecting the field winding to the armature they are
   a. Shunt generator
   b. Series generator
   c. Compound generator
      i. Long shunt compound generator
      ii. Short shunt compound generator

DC SHUNT GENERATOR

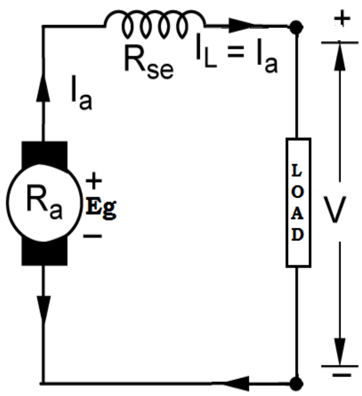


1. In the dc shunt generator the field winding circuit is connected in parallel to the armature circuit and as well as to the load.
2. The armature current is divided in to the field and the load as I_f and I_L.
3. The shunt field winding has ***more number of turns with thin wire***, so that resistance of the field will be in the range of hundreds and was designed to withstand for the rated voltage.
4. Applying KVL to the armature loop the E_g is

$$E_g = V + I_a R_a + V_{brush}$$

$I_a = I_L + I_f$ and $I_L = \frac{P_L}{V}$ and $I_f = \frac{V}{R_f}$

DC SERIES GENERATOR



1. In the dc series generator the field winding circuit is connected in series to the armature circuit and as well as to the load.
2. Here the armature current is equal to the series field current and also equal to the load.

5. The series field winding has ***less number of turns with thick wire***, so that resistance of the field will be in the smaller values and was designed to carry the rated current.
6. Applying KVL to the armature loop the E_g is

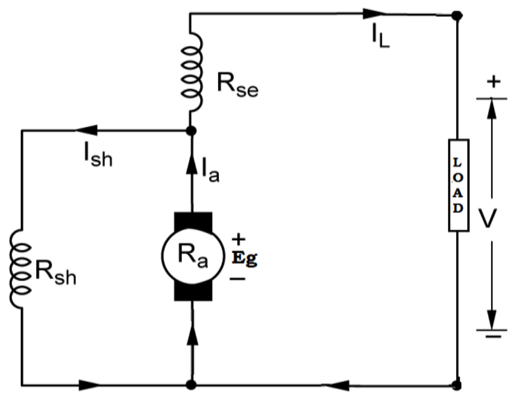
$$E_g = V + I_a(R_a + R_{se}) + V_{brush}$$

$$I_a = I_L = I_{se} \quad \text{and} \quad I_L = \frac{P_L}{V}$$

<u>DC COMPOUND GENERATORS</u>

1. A compound generator has two field coils wound over the field poles.
2. The coil having large number of turns and thinner cross sectional area is called the shunt field coil and the other coil having few numbers of turns and large cross sectional area is called the series field coil.
3. Based on the series field winding connected to the armature the compound generators are classified as long shunt generator and short shunt generator

<u>Short Shunt DC Compound Generator</u>

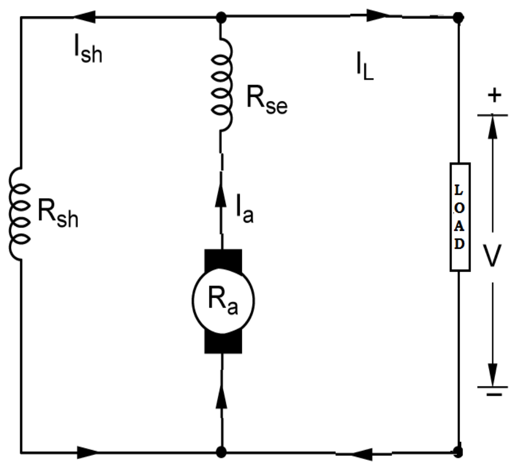


1. In a short shunt dc compound generator, the series field is connected in series to the load and shunt field winding is connected in parallel to the armature and the series combination of the load and series winding.
2. Thus, the series field current will depend on the load variations which will effect in further the shunt field current.
3. Applying KVL to the armature loop the E_g is

$$E_g = V + I_a R_a + I_L R_{se} + V_{brush}$$

$$I_a = I_L + I_{se} \quad \text{and} \quad I_L = \frac{P_L}{V} \quad \text{and} \quad I_f = \frac{V + I_L R_{se}}{R_f}$$

<u>Long Shunt DC Compound Generator</u>



1. In a long shunt dc compound generator, the series field is connected in series to the armature and shunt field winding is connected in parallel to the armature and to the load.
2. Applying KVL to the armature loop the E_g is

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

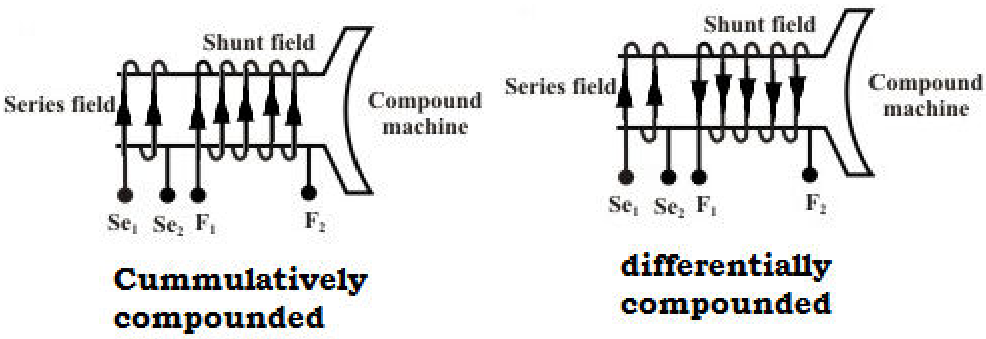
$$I_a = I_L + I_{se} \quad \text{and} \quad I_L = \frac{P_L}{V} \quad \text{and}$$

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

- Also, the dc compound generators are further classified into two types based on the compounding of the series flux to the shunt flux. They are cumulatively compounded and differentially compounded generators
- In the cumulatively compound generator, the series flux aids to the shunt field flux and the

net flux increases, whereas in the differentially compounded generators the series flux opposes the shunt field flux and the net resultant flux decreases.

- The below figure shows the arrangement of the series and shunt field coils iin the pole core in both cumulative and differentially compounded generators.

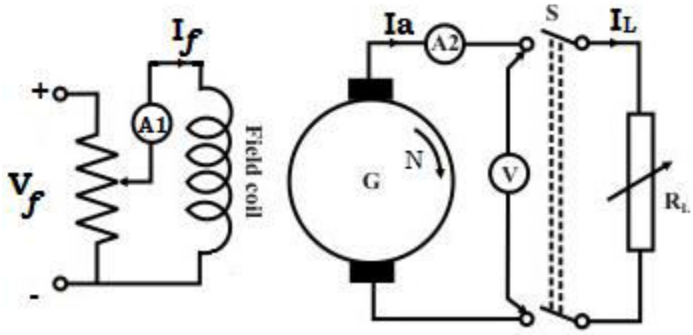


<u>CHARACTERISTICS OF DC GENERATOR</u>

There are three characteristics to be analyzed for any type of the dc generator, they are

1. Open circuit characteristics (or) No-Load characteristics (or) Magnetization characteristics (E_0 *Vs* I_f)
2. Internal characteristics (E_g *Vs* I_a)
3. External or Load characteristics (V *Vs* I_L)

<u>OCC or No-Load Characteristics of Separately excited DC Generator :</u>

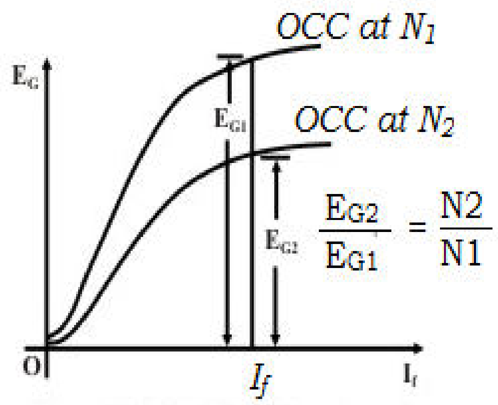


1. OCC is the characteristics drawn between open circuit voltage (E_0) for various field currents (I_f) at constant speed.
2. In this generator field winding is excited from a separate source V_f as shown in above circuit, hence field current is independent of armature terminal voltage
3. The generator is driven by a prime mover at rated speed, say constant speed *N* rpm.
4. With switch *S* in opened condition, field coil is excited via a *potential divider* connection from a separate d.c source and field current is gradually increased by moving the wiper from minimum position gradually.
5. The field current will establish the flux per pole Φ.
6. The voltmeter V connected across the armature terminals of the machine will record the generated emf $\left(E = \frac{PZ}{60A} * \phi N = k * \phi N\right)$. Where *k* is a constant of the machine.

7. As field current is increased, E_0 will increase.
8. E_0 versus I_f plot at constant speed N *rpm* is shown in below figure.
9. It may be noted that even when there is no field current, a small voltage (OD) is generated due to *residual flux* and the small voltage is called *residual voltage.*
10. If field current is increased, φ increases linearly initially and O.C.C follows a straight line.
11. However, when saturation sets in, φ practically becomes constant and hence E_g too becomes constant.
12. In other words, O.C.C follows the B-H characteristic, hence this characteristic is sometimes also called the magnetization characteristic of the machine.

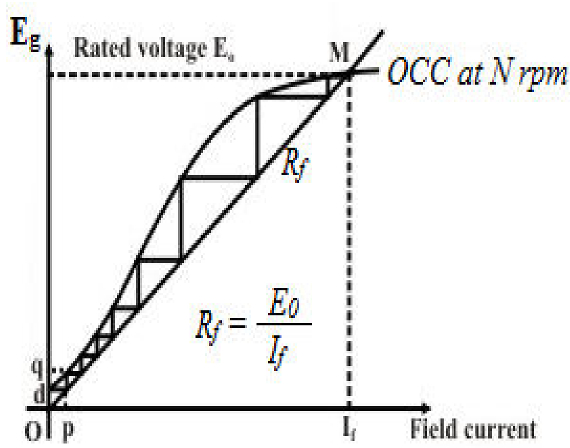
Procedure to draw OCC at different speeds

1. It is important to note that if O.C.C is known at a certain speed N_1, O.C.C at another speed N_2 can easily be predicted from the emf equation $E = k * \phi N$
2. Emf at speed N_1 rpm for a field current of I_f, producing the flux Φ is E_1 and is given by $E_1 = k * \phi N_1$
3. Emf at speed N_2 rpm for the same field current of I_f, producing the flux Φ is E_2 and is given by $E_2 = k * \phi N_2$
4. Therefore, the emf E_2 at speed N_2 is
$$\frac{E_2}{E_1} = \frac{k * \phi N_2}{k * \phi N_1} \Rightarrow \frac{E_2}{E_1} = \frac{N_2}{N_1} \Rightarrow E_2 = E_1 \times \frac{N_2}{N_1}$$



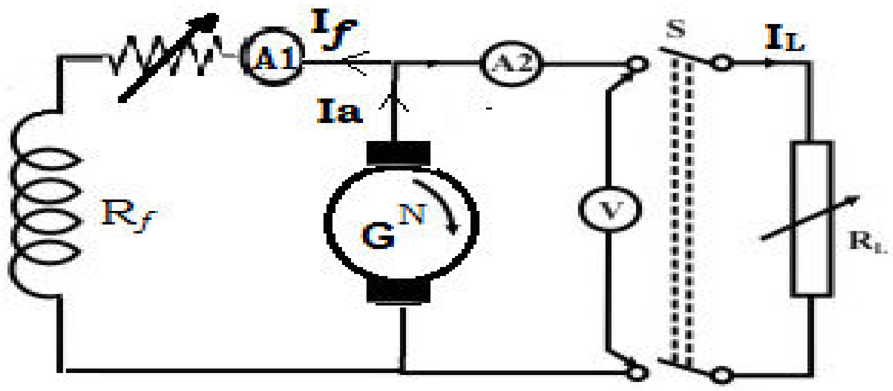
EMF BULID P PROCESS IN A SELF EXCITED DC GENERATOR

1. For the buildup of emf in the self excited dc generator, the poles or magnets ***must have residual flux*** in them.
2. Therefore, if the generator is driven at rated speed of N rpm, then a small voltage ($k\varphi_{res}N$) will be induced across the armature.
3. This small voltage will be directly applied across the field circuit since it is connected in parallel with the armature.
4. Hence a small field current flows producing additional flux.

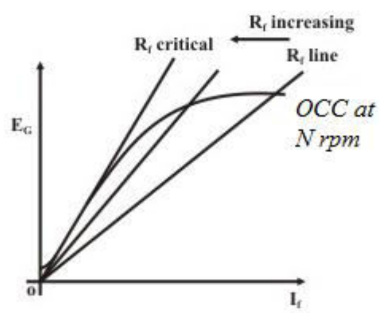


5. If it so happens that this additional flux aids the already existing residual flux, total flux now becomes more and generating more voltage.
6. This more voltage will drive more field current generating more voltage.
7. Both field current and armature generated voltage grow *cumulatively*.
8. This process will be explained clearly from the plot shown above
9. Initially voltage induced due to residual flux is observed from O.C.C as Od.
10. The field current thus produced can be obtained from field circuit resistance line and given by Op. With this Op filed current the flux is increased and correspondingly the induced voltage also increases from Od to Oq and so on. In this way voltage build up process continues along the stair case.

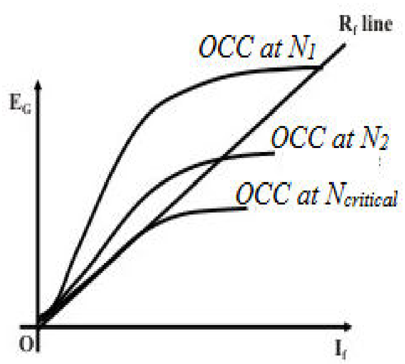
<u>OCC or No-Load Characteristics of self excited DC shunt Generator</u>



1. The OCC of the shunt generator is obtained in a similar way to the dc separately excited generator by disconnecting its field winding from the armature and connecting it to a separate dc source



2. Therefore, the OCC curve at rated speed N rpm is shown in the above figure, with Od as residual voltage and increases gradually.
3. Later, the R_f line is drawn which is a straight line passing through the origin having a slope of its value R_f
4. This R_f line intersects the OCC at point M and gives the rated voltage of the generator.
5. If the R_f value is increased then its slope increases and the voltage generated by the generator reduces and if the value of the R_f is such that it becomes the tangential to the given OCC, then the field resistance is called critical field resistance($R_{f\,critical}$).



6. At this critical field resistance, the emf or voltage of the generator will be very small and it doesn't generates any voltage if the R_f selected is greater than the R_{fc}
7. Thus, ***R_f must be always less than the R_{fc}***
8. Similarly, for the $R_f < R_{fc}$, if the speed decreases then also the voltage generated by the generator reduces.
9. Thus the generator doesn't generates any voltage at a speed called critical speed for which the given R_f line will become the tangent for the OCC drawn at N_c and is shown in the fig.
10. If the speed of the generator is made to run less than its critical speed then no emf will be induced, so the ***speed must be always greater than the critical speed.***

Conditions to build up the emf in the generator:

1. The magnets in the machine must have the ***residual flux.***
2. Field winding connection should be such that the residual flux is strengthened by the field current in the coil. If due to this, no voltage is being built up, reverse the field terminal connection.
3. Total field circuit resistance ***must be less than the critical field resistance.***
4. Speed of the generator ***must be greater than the critical speed.***

APPLICATIONS OF D.C.GENERATORS

Separately Excited DC Generators

1. Because of their ability of giving wide range of voltage output, they are generally used for testing purpose in the laboratories.
2. Separately excited generators operate in a stable condition with any variation in field excitation. Because of this property they are used as supply source of DC motors, whose speeds are to be controlled for various applications. Example- Ward Leonard Systems of speed control.

Applications of Shunt Wound DC Generators

- The application of shunt generators is very much restricted for its dropping voltage characteristic.
- They are used to supply power to the apparatus situated very close to its position.
- These types of DC generators generally give constant terminal voltage for small distance operation with the help of field regulators from no load to full load.

1. They are used for general lighting.
2. They are used to charge battery because they can be made to give constant output voltage.

3. They are used for giving the excitation to the alternators.
4. They are also used for small power supply (such as a portable generator).

Applications of Series Wound DC Generators

- These types of generators are restricted for the use of power supply because of their increasing terminal voltage characteristic with the increase in load current from no load to full load.
- They give constant current in the dropping portion of the characteristic curve. Because of this property they can be used as constant current source and employed for various applications.

1. They are used for supplying field excitation current in DC locomotives for regenerative breaking.
2. These are used as boosters to compensate the voltage drop in the feeder in various types of distribution systems such as railway service.
3. In series arc lightening this type of generators are mainly used.

Applications of Compound Wound DC Generators

- Among various types of DC generators, the compound wound DC generators are most widely used because of its compensating property.
- Depending upon number of series field turns, the cumulatively compounded generators may be over compounded, flat compounded and under compounded.
- Thus the desired terminal voltage can be obtained by compensating the voltage drop due to armature reaction and ohmic drop in the in the line.

  Such generators have various applications.

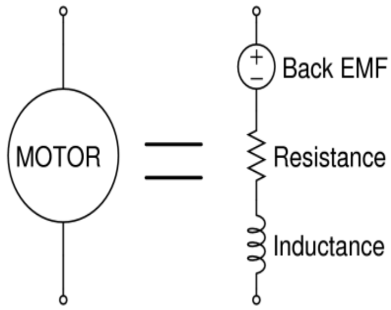
  1. Cumulative compound wound generators are generally used for lighting, power supply purpose and for heavy power services because of their constant voltage property. They are mainly made over compounded.
  2. Cumulative compound wound generators are also used for driving a motor.
  3. For small distance operation, such as power supply for hotels, offices, homes and lodges, the flat compounded generators are generally used.
  4. The differential compound wound generators, because of their large demagnetization armature reaction, are used for arc welding where huge voltage drop and constant current is required.

WORKING PRINCIPLE OF DC MOTOR

- A dc motor is a electro mechanical energy conversion device that converts *electrical energy into mechanical energy.*
- Its operation is based on the principle that ***"when a current carrying conductor is placed in a magnetic field, the conductor experiences a mechanical force"***.
- The direction of the force is given by Fleming's left hand rule which states that " Stretch the first three fingers of left hand mutually perpendicular to each other in such a way that central finger indicates the direction of the current in the conductor, fore finger in the direction of the magnetic field, then the thumb indicates the direction of the force developed on the conductor The magnitude of the force developed on the conductor is F = BIL Sinθ

BACK EMF

When the armature of a d.c. motor rotates under the influence of the driving torque, the armature conductors move through the magnetic field and hence an e.m.f. is induced in them as per Faradays laws of electromagnetic induction.



This induced e.m.f. acts in opposite direction to the applied voltage V (Lenz's law) and is known as back or counter e.m.f. E_b .

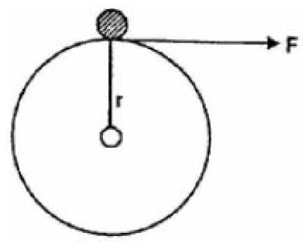
Significance of Back E.M.F

The presence of back e.m.f. makes the d.c. motor a self-regulating machine i.e., it makes the motor to draw as much armature current as is just sufficient to develop the torque required by the load. Back e.m.f. in a d.c. motor regulates the flow of armature current i.e., it automatically changes the armature current to meet the load requirement.

ARMATURE TORQUE OF A DC MOTOR

Torque is the turning and twisting moment of a force about an axis and is measured by the product of force (F) and radius (r) at right angle to which the force acts i.e T = F*r

Let



T = Torque developed on the rotor of the motor in Nm

Φ = Flux per pole in weber

Z = No. of the armature conductors

I_a= Armature current in A

P = No. of poles

A = No. of Parallel paths

r = radius of the pulley in mts

Work done by the pulley, W= Force * distance = F * 2πr

Power = $\frac{\text{work done}}{\text{time}}$ $\quad$ $P = \frac{F \times 2\pi r}{60/N} = \frac{F \times 2\pi r \times N}{60} = \frac{2\pi N}{60} \times (F * r) = \frac{2\pi NT}{60} = \omega T \Rightarrow P = \omega T$

As, power developed in the armature is the gross mechanical power and is given by

$P = E_g I_a$, therefore $E_g I_a = \omega T$

$$\frac{\phi ZN}{60}\left(\frac{P}{A}\right) I_a = \frac{2\pi NT}{60} \quad \because E_g = \frac{\phi ZN}{60}\left(\frac{P}{A}\right)$$

$$\frac{\phi Z}{2\pi}\left(\frac{P}{A}\right) I_a = T$$

$$\therefore T = \frac{\phi Z}{2\pi}\left(\frac{P}{A}\right) I_a$$

$$T = \frac{1}{2\pi} \phi Z I_a \frac{P}{A}$$

Also, from the fundamentals, the gross torque or armature torque is

$$P = \omega T \Rightarrow E_b I_a = \omega T$$

$$T = \frac{E_b I_a}{\omega} = \frac{E_b I_a * 60}{2\pi N} = \left(\frac{60}{2\pi}\right) * \frac{E_b I_a}{N} = 9.55 \frac{E_b I_a}{N} = 9.55 \frac{P_m}{N}$$

Also, the shaft torque or useful torque is

$$P_{sh} = \omega T_{sh}$$

$$T_{sh} = \frac{P_{sh}}{\omega} = \frac{P_m - Mechloss}{\omega} = \left(\frac{60}{2\pi}\right) * \frac{P_{sh}}{N} = 9.55 \frac{P_{sh}}{N}$$

Therefore,

$$T \propto \phi I_a$$

Torque relations in a dc motor

$$\frac{T_2}{T_2} = \frac{\phi_2 I_{a2}}{\phi_1 I_{a1}}$$

Speed of a DC Motor

$$E_b = V - I_a R_a$$

But $\quad E_b = \frac{P\phi ZN}{60\,A}$

$$\therefore \quad \frac{P\phi ZN}{60\,A} = V - I_a R_a$$

or $\quad N = \frac{(V - I_a R_a)}{\phi} \frac{60\,A}{PZ}$

or $\quad N = K \frac{(V - I_a R_a)}{\phi} \quad$ where $\quad K = \frac{60\,A}{PZ}$

But $V - I_a R_a = E_a$

$$\therefore \quad N = K\frac{E_b}{\phi}$$

or $$N \propto \frac{E_b}{\phi}$$

Therefore,

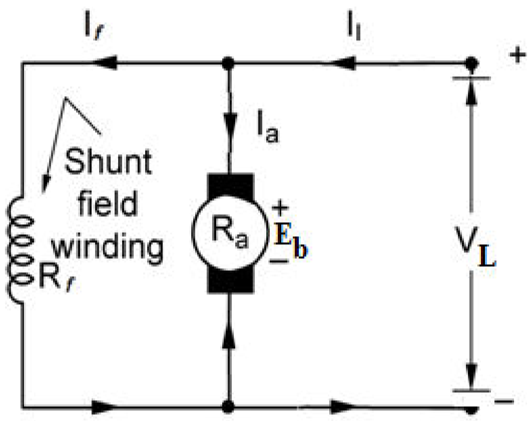
In a dc motor speed is directly proportional to back emf, E_b and inversely proportional to flux, φ.

TYPES OF D.C. MOTORS

Based on the field winding excited from the armature the dc motors are of three types

1. DC Shunt motor
2. DC Series motor
3. DC compound motor
   a. Long Shunt Compound motor
   b. Short Shunt Compound motor

DC SHUNT MOTOR



1. In the dc shunt motor the field winding circuit is connected in parallel to the armature circuit and as well as to the line.
2. The line current I_L is divided in to the field and the armature as I_f and I_a.
3. The shunt field winding has ***more number of turns with thin wire***, so that resistance of the field will be in the range of hundreds and was designed to withstand for the rated voltage.
4. Applying KVL to the armature loop the E_g is

$$E_b = V_L - I_a R_a - V_{brush}$$

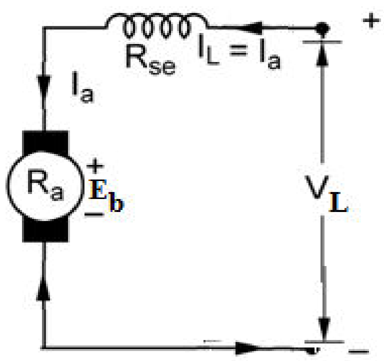
$$I_a = I_L - I_f \quad \text{and} \quad I_L = \frac{P_L}{V} \quad \text{and} \quad I_f = \frac{V}{R_f}$$

DC SERIES MOTOR

3. In the dc series motor the field winding circuit is connected in series to the armature circuit and as well as to the line.
4. Here the armature current is equal to the series field current and also equal to the line.
7. The series field winding has ***less number of turns with thick wire***, so that resistance of the field will be in the smaller values and was designed to carry the rated current.
8. Applying KVL to the armature loop the E_g is

$$E_b = V_L - I_a(R_a + R_{se}) - V_{brush}$$

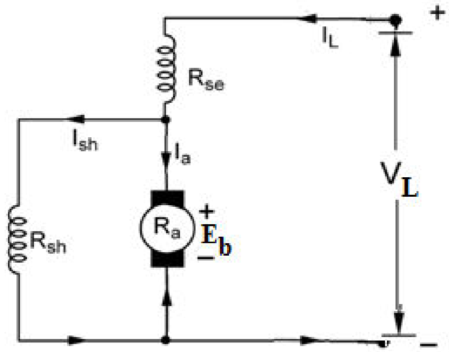
$$I_a = I_L = I_{se} \quad \text{and} \quad I_L = \frac{P_L}{V}$$



DC COMPOUND MOTORS

4. A compound motor has two field coils wound over the field poles.
5. The coil having large number of turns and thinner cross sectional area is called the shunt field coil and the other coil having few numbers of turns and large cross sectional area is called the series field coil.
6. Based on the series field winding connected to the armature the compound motors are classified as long shunt motor and short shunt motor

- ***SHORT SHUNT MOTOR***



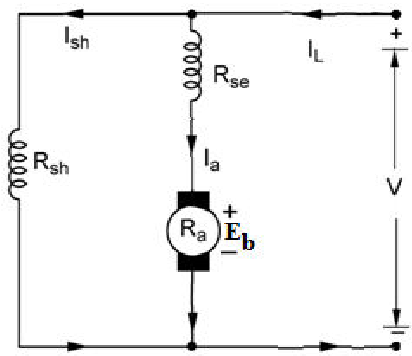
4. In a short shunt dc compound motor, the series field is connected in series to the line and shunt field winding is connected in parallel to the armature and the series combination of the line and series winding.
5. Thus, the series field current will depend on the line variations which will effect in further the shunt field current.
6. Applying KVL to the armature loop the E_g is

$$E_b = V_L - I_a R_a - I_L R_{se} - V_{brush}$$

$$I_a = I_L - I_f \quad \text{and} \quad I_L = \frac{P_L}{V} \quad \text{and}$$

$$I_f = \frac{V_L - I_L R_{se}}{R_f}$$

- ***LONG SHUNT MOTOR***

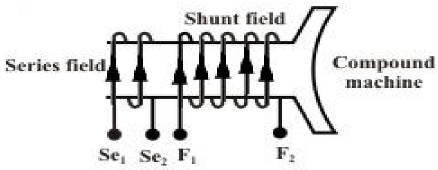


3. In a long shunt dc compound motor, the series field is connected in series to the armature and shunt field winding is connected in parallel to the armature and to the line.
4. Applying KVL to the armature loop the E_g is

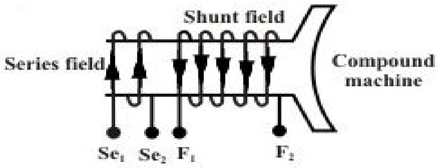
$$E_b = V_L - I_a(R_a + R_{se}) - V_{brush}$$

$$I_a = I_L - I_f \quad \text{and} \quad I_L = \frac{P_L}{V} \quad \text{and} \quad I_f = \frac{V}{R_f}$$

- Also, the dc compound motors are further classified into two types based on the compounding of the series flux to the shunt flux. They are cumulatively compounded and differentially compounded motors
- In the cumulatively compound motor, the series flux aids to the shunt field flux and the net flux increases, whereas in the differentially compounded motors the series flux opposes the shunt field flux and the net resultant flux decreases.
- The below figure shows the arrangement of the series and shunt field coils in the pole core in both cumulative and differentially compounded motors.



Cummulatively compounded



differentially compounded

APPLICATIONS OF D.C. MOTORS

1. Shunt motors

The characteristic of a shunt motor is an approximately constant speed motor. So, it is used where the speed is required to remain almost constant from no-load to full-load

***Industrial applications of shunt motor*:**

1. Lathes
2. Drills
3. Boring mills
4. Shapers
5. Spinning and weaving machines etc.

2. Series motors

It is a variable speed motor i.e., speed is low at high torque and vice-versa. It is used

(i) Where large starting torque is required e.g., in elevators and electric Traction

(ii) Where the load is subjected to heavy fluctuations and the speed is automatically required to reduce at high torques and vice-versa

***Industrial applications of series motor*:**

1. Electric traction
2. Cranes
3. Elevators,
4. Air compressors,
5. Vacuum cleaners
6. Hair drier
7. Sewing machines etc.

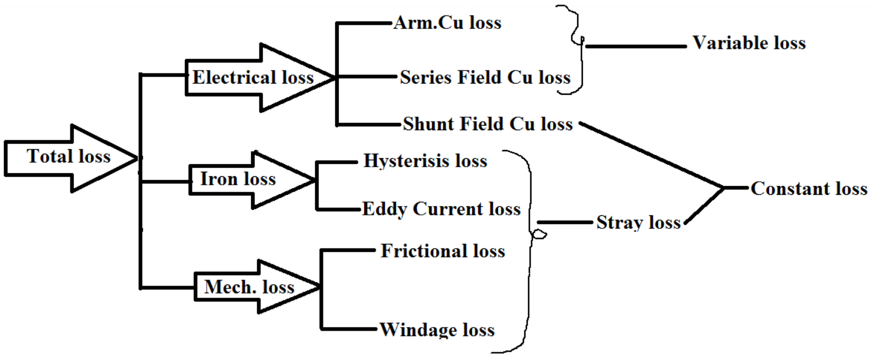
3. Compound motors

Differential-compound motors are rarely used because of their poor torque characteristics. However, cumulative-compound motors are used where a fairly constant speed is required with irregular loads or suddenly applied heavy loads.

***Industrial applications of Compound motor*:**

1. Presses,
2. Shears,
3. Reciprocating machines etc.

LOSSES IN DC MACHINE



Power Stages in DC Generator:

The power stages in a d.c. generator are represented diagrammatically in below Fig.

Mechanical Input - Electrical Power generated = A - B = Iron and friction losses

Electrical Power generated - Electrical Power output = B - C = Copper losses

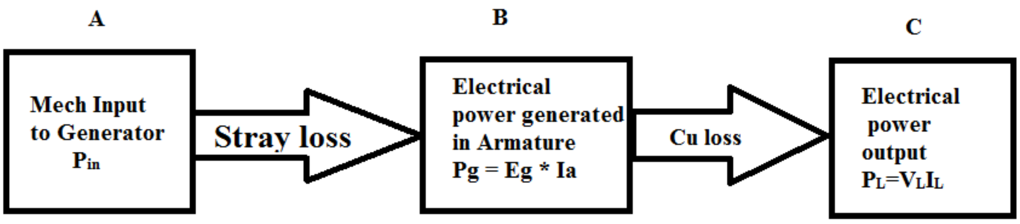
Efficiency is defined as the ratio of output power to the input power

Electrical efficiency, η_e = C/B

Mechanical efficiency, η_m = B/A

Overall efficiency, η_c = C/A

Therefore, Overall efficiency = Electrical efficiency * Mechanical efficiency

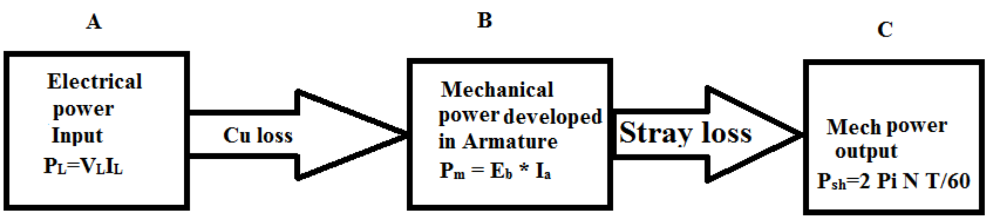


Power Stages in DC Motor:

The power stages in a d.c. motor are represented diagrammatically in below Fig.

Electrical Power input – Mechanical power developed = A - B = Copper losses

Mechanical power developed - Mechanical power output = B - C = Iron and friction losses



Electrical efficiency η_e = B/A

Mechanical efficiency η_m = C/B

Overall efficiency η_c = C/A

Condition for maximum efficiency for dc motor:

We assume that field current I_f remains constant during change of loading. Let,

$$
\begin{aligned}
P_{rot} &= \text{constant rotational loss} \\
V\,I_f &= \text{constant field copper loss} \\
\text{Constant loss } P_{const} &= P_{rot} + V\,I_f \\
\text{Now, input power drawn from supply} &= V\,I_L \\
\text{Power loss in the armature,} &= I_a^2 r_a \\
\text{Net mechanical output power} &= VI_L - I_a^2 r_a - (VI_f + P_{rot}) \\
&= VI_L - I_a^2 r_a - P_{const} \\
\text{so, efficiency at this load current } \eta_m &= \frac{VI_L - I_a^2 r_a - P_{const}}{VI_L}
\end{aligned}
$$

Now the armature copper loss $I_a^2 r_a$ can be approximated to $I_L^2 r_a$ as $I_a \approx I_L$. This is because the order of field current may be 3 to 5% of the rated current. Except for very lightly loaded motor, this assumption is reasonably fair. Therefore replacing I_a by I_f in the above expression for efficiency η_m, we get,

$$
\begin{aligned}
\eta_m &= \frac{VI_L - I_L^2 r_a - P_{const}}{VI_L} \\
&= 1 - \frac{I_L r_a}{V} - \frac{P_{const}}{VI_L}
\end{aligned}
$$

Thus, we get a simplified expression for motor efficiency η_m in terms of the variable current (which depends on degree of loading) I_L, current drawn from the supply. So to find out the condition for maximum efficiency, we have to differentiate η_m with respect to I_L and set it to zero as shown below.

$$
\begin{aligned}
\frac{d\eta_m}{dI_L} &= 0 \\
\text{or, } \frac{d}{dI_L}\left(\frac{I_L r_a}{V} - \frac{P_{const}}{VI_L}\right) &= 0 \\
\text{or, } -\frac{r_a}{V} + \frac{P_{const}}{VI_L^2} &
\end{aligned}
$$

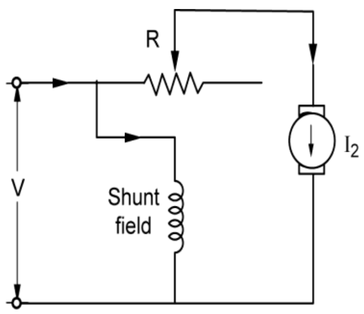
$$\therefore \text{Condition for maximum efficiency is } I_L^2 r_a \approx I_a^2 r_a = P_{const}$$

$$\text{So, the armature current at which efficiency becomes maximum is } I_a = \sqrt{P_{const}/r_a}$$

Necessity of starter:

- The function of the starter is ***to limit the starting current*** in the motor.

The current drawn by the motor armature is given by $I_a = \dfrac{V - E_b}{R_a}$



where V is the supply voltage,

E_b is the back emf and

R_a is the armature resistance of the motor.

- At starting, when motor is at rest there is no back emf in the armature (since $E_b \alpha N$)
  Now the total supply voltage is applied across the stationary armature and it will draw a very large current because of small armature resistance.
  Consider the case of 440 V, 5 HP (3.73 KW) motor having a cold armature resistance of 0.25 Ω and full load current of 50A.
  If this motor is started from the line directly, it will draw a starting current of **Fehler!** = 1760 A which is **Fehler!** = 35.2 times its full-load current.
  This excessive current will blow out the fuses and damages the commutator and brushes. To avoid this, a resistance is placed in series to the armature for the time duration until the motor pickups the speed.
  Once the motor pickups the speed, the back emf is developed and the current was limited by the small voltage (V_L-E_b) applied to the armature against the small resistance.
  Thus, the starter is used to limit this starting current by inserting the resistance only at the starting time.
  There are three types of starters used namely
  3 point starter b) Four point starter c) Two point starter

  <u>THREE POINT STARTER</u>

  The 3 terminals of the three point starter are marked A, B and C.
  First terminal A is connected to the handle arm (L) through the overload release (OLR) from the supply terminals
  Second terminal B is connected to the field winding of the motor through the Hold ON coil from the stud 1 of the external resistance placed in series to the armature.
  Third terminal C is connected to the armature by inserting the external resistance.
  The handle initially is at OFF position and when the supply is given, to start the motor the handle is dragged towards the stud 1.
  This position of the handle divides the line current into two paths one path to the armature through the current limiting resistance and second path to the field winding.
  Thus the current is limited by this resistance placed in series with the armature. Also as the speed picks up, the handle was dragged over the studs from off position to ON position.
  At this ON position all the external resistance is removed from the armature and the spring on the other side of the handle develops the restraining torque with the spring placed.
  The soft iron piece (S) on the handle is attracted by the hold on coil in normal running conditions

The resistance that was removed from the armature circuit will be added to the field circuit. Thus the field current is reduced, to overcome the drawback of weakening of the flux the field winding terminal is connected from the brass arc placed below the studs and is shown in the figure

Hold ON coil (or) No Volt Release (NVR)

The Normal function of the HOLD-ON coil is to hold on the arm in then full running position when the motor is in normal operation.

When the supply failure (or) disconnection, it is de-energised, so that handle is released from the hold on coil and pulled back by the spring to the OFF position.

The Hold ON coil protects the motor from dangerous speed when field circuit opens.

Over Load Release (OLR)

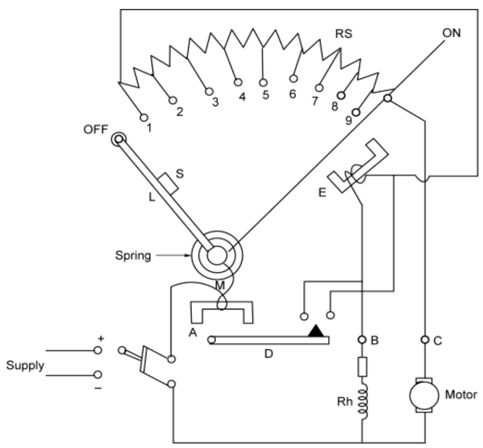
It consists of an electro-magnet connected in the supply line.

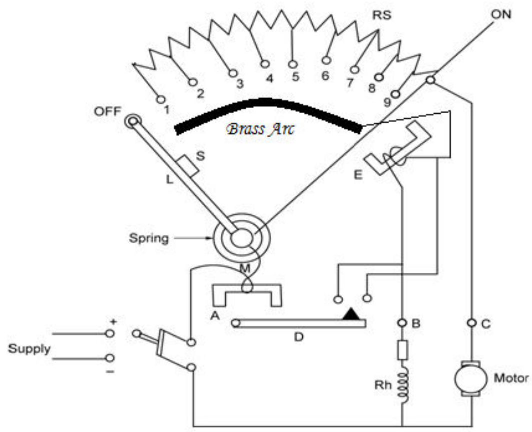
If motor becomes over loaded, then D is lifted and short circuits the electro-magnet. Hence arm is released and returns to OFF position.

Disadvantage of three point starter:

To control the speed of motor, a field rheostat is connected in the field circuit.The motor speed is increased by decreasing the flux ($N \propto I/\phi$). There is a difficulty that if too much resistance is added by the field rheostat, then field current is reduced very much so that the current in the hold on coil is unable to create enough Electromagnetic pull to overcome the spring tension. Hence arm is pulled back to OFF position.

Therefore the shunt motor with this three point starter is not suitable for adjustable speed drive applications.





Speed control of DC motors:

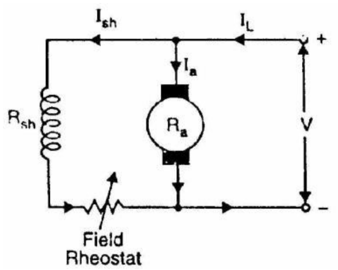
The speed of a d.c. motor is given by:

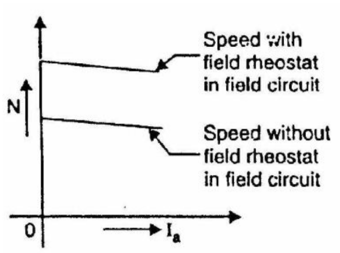
$N\alpha \frac{Eb}{\Phi}$ or $N\alpha \frac{V_L - I_a R}{\Phi}$ where R is Ra for shunt motor and (Ra + Rse). for series motor

From the above expression,
The speed of a d.c. motor is controlled
(i) By varying the flux per pole (f) known as flux control method.
(ii) By varying the R_a and is known as armature control method.
(iii) By varying the applied voltage V and is known as voltage control method.

Speed Control of D.C. Shunt Motor

a) Field control method:





1. In this field control method the variable is flux (f)
2. The rheostat is placed in series to the field winding, as the field resistance increases the field current decreases and this weakens the flux
3. The weakening of the flux increases the speed since speed is inversely proportional to the flux.
4. Thus using the field control, above base speeds can be controlled.
5. This method is also known as constant power method or variable torque method.

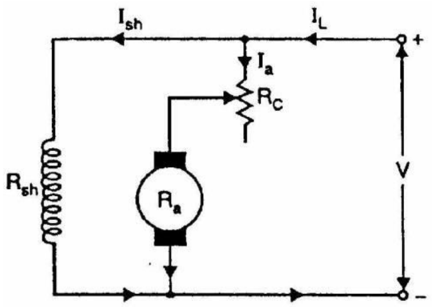
Advantages

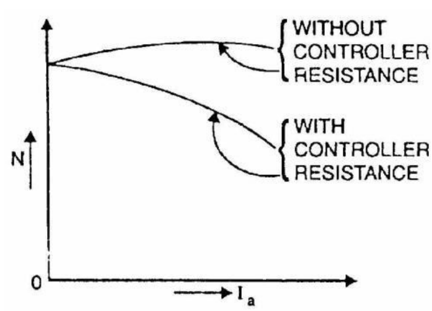
1. This is an easy and convenient method.
2. It is an inexpensive method since very little power is wasted in the shunt field rheostat due to relatively small value of I_f
3. The speed control exercised by this method is independent of load on the machine.

Disadvantages

1. Only speeds higher than the normal speed can be obtained.
2. There is a limit to the maximum speed obtainable by this method. It is because if the flux is too much weakened, commutation becomes poorer.

b) Armature control method





1. In this armature resistance control method the variable is R_a
2. The rheostat is placed in series to the armature winding, as the R_a increases the I_aR_a drop increases and this decreases the speed.
3. The decreasing of the back emf decreases the speed since speed is directly proportional to E_b.

4. Thus using the R_a control method, below base speeds can be controlled.
5. This method is also known as constant torque method or variable power method.

Disadvantages

1. A large amount of power is wasted in the controller resistance since it carries full armature current Ia.
2. The speed varies widely with load since the speed depends upon the voltage drop in the controller resistance and hence on the armature current demanded by the load.
3. The output and efficiency of the motor are reduced.
4. This method results in poor speed regulation.

c) Voltage control method by Ward-Leonard system

1. This method is used to get the wide range of speed control 10:1.
2. As the speed of the motor is directly proportional to the applied voltage to the armature, thus by applying the variable voltage the speed is controlled.
3. The armature of the shunt motor M (whose speed is to be controlled) is connected directly to a d.c. generator G driven by a constant-speed a.c. motor A.
4. The field of the shunt motor is supplied from a constant-voltage exciter E.
5. The field of the generator G is also supplied from the exciter E.
6. The voltage of the generator G can be varied by means of its field regulator.
7. By reversing the field current of generator G by controller FC, the voltage applied to the motor may be reversed.

Advantages

1. The speed of the motor can be adjusted through a wide range without resistance losses which results in high efficiency.
2. The motor can be brought to a standstill quickly, simply by rapidly reducing the voltage of generator G.
3. The disadvantage of the method is that a special motor-generator set is required for each motor and the losses in this set are high if the motor is operating under light loads for long periods.

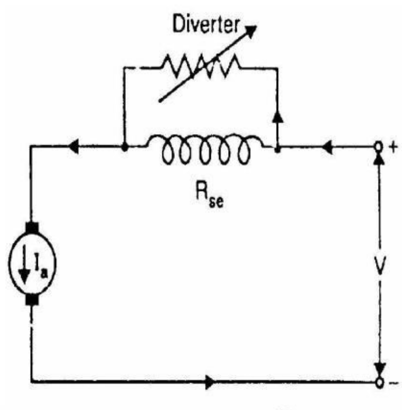
Speed Control of D.C. Series Motor

a) ***Flux control method***

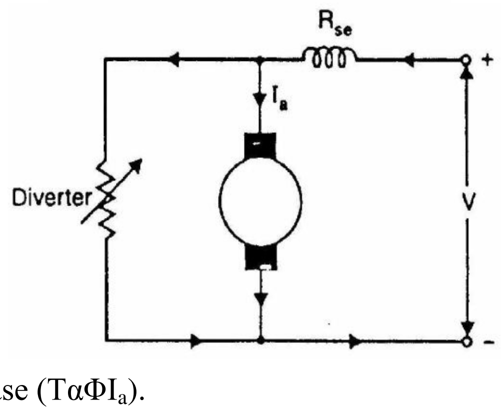
In this method, the flux produced by the series motor is varied and hence the speed.

The variation of flux can be achieved in the following ways:

(i) Field diverters.



1. In this method, a variable resistance (called field diverter) is connected in parallel with series field winding as shown in Fig.
2. Its effect is to shunt some portion of the line current from the series field winding, thus weakening the field and increasing the speed (Nα1/Φ).
3. This method can only provide speeds above the normal speed. The series field diverter method is often employed in traction work.

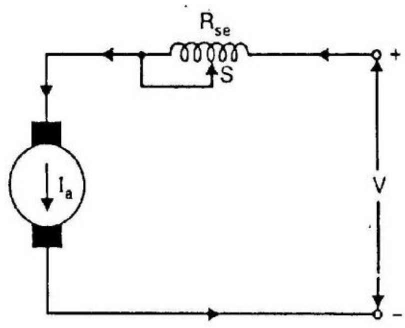


ii) Armature diverter.

1. In order to obtain speeds below the normal speed, a variable resistance (called armature diverter) is connected in parallel with the armature as shown in Fig.
2. The diverter shunts some of the line current, thus reducing the armature current.
3. Now for a given load, if Ia is decreased, the flux Φ must increase ($T \alpha \Phi I_a$).

4. Since (Nα1/Φ). The motor speed is decreased.
5. By adjusting the armature diverter, any speed lower than the normal speed can be obtained.

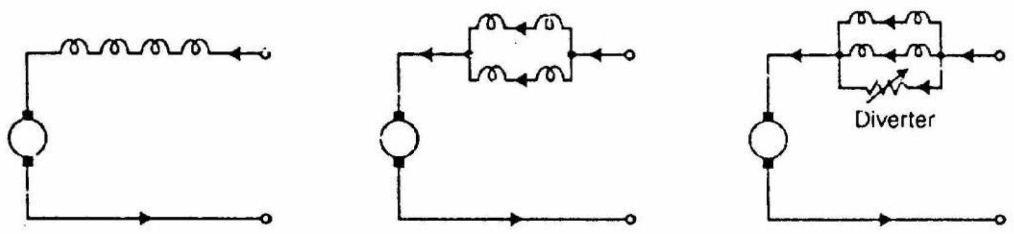
iii) Tapped field control.



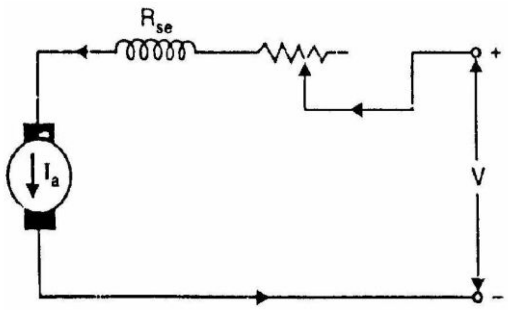
1. In this method, the flux is reduced by decreasing the number of turns of the series field winding as shown in Fig, and hence speed is increased
2. The switch S can short circuit any part of the field winding, thus decreasing the flux and raising the speed.
3. With full turns of the field winding, the motor runs at normal speed and as the field turns are cut out; speeds higher than normal speed are achieved.

iv) Paralleling field coils.

This method is usually employed in the case of fan motors. By regrouping the field coils as shown in Fig below, several fixed speeds can be obtained.



b) Armature-resistance control:



1. In this method, a variable resistance is directly connected in series with the supply to the complete motor as shown in Fig.
2. This reduces the voltage available across the armature and hence the speed falls.
3. By changing the value of variable resistance, any speed below the normal speed can be obtained.
4. This is the most common method employed to control the speed of d.c. series motors.
5. Although this method has poor speed regulation, this has no significance for series motors because they are used in varying speed applications.
6. The loss of power in the series resistance for many applications of series motors is not too serious since in these applications.

TESTING OF DC MACHINES:

Testing of DC machines can be broadly classified as

i) Direct method of Testing

ii) Indirect method of testing

Direct method of testing:

In this method, the DC machine is loaded directly by means of a brake applied to water cooled pulley coupled to the shaft of the machine. The input and output are measured and efficiency is determined by $\eta = \frac{output}{input}$

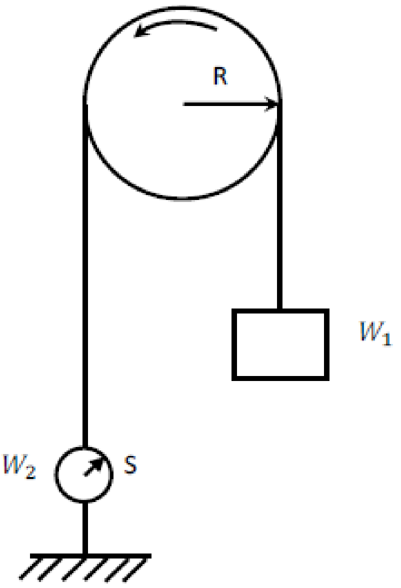
It is not practically possible to arrange loads for machines of large capacity.

Indirect method of testing:

In this method, the losses are determined without actual loading the machine. If the losses are known, then efficiency can be determined. Swinburne's test, Hopkinson's test and retardation tests are commonly used on shunt motors.

(i) BRAKE TEST: is a direct method of testing.

In this method of testing motor shaft is coupled to a Water cooled pulley which is loaded by means of weight as shown in figure



W_1= suspended weight in kg

W_2 = Reading in spring balance in kg

R = radius of pulley

N = speed in rpm

V = Supply voltage

I = Full Load Current

Net pull due to friction $= (W_1 - W_2)$ kg

$= 9.81\ (W_1 - W_2)$ Newton 1

Shaft torque $T_{sh} = (W_1 - W_2)R\ kg - mt.$

$= 9.81\ (W_1 - W_2)\ R\ N - mt$ 2

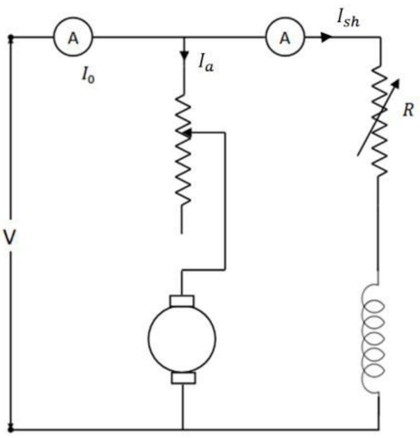
Motor output power $= T_{sh}\ X\ \frac{2\ \pi\ N}{60}$ Watt

Input power = VI watts 3

Therefore efficiency $= \frac{output}{input}$

This method of testing can be used for small motors only because for a large motor it is difficult to arrange for dissipation of heat generated at the brake.

(ii)Swinburne's Test:



This test is a no load test and hence cannot be performed on series motor.
The circuit connection is shown in Figure
The machine is run on no load at rated speed which is adjusted by the shunt field resistance.

Advantages

1. Economical, because no load input power is sufficient to perform the test
2. Efficiency can be pre-determined
3. As it is a no load test, it cannot be done on a dc series motor

Disadvantages

1. Change in iron loss from no load to full load is not taken into account. (Because of armature
reaction, flux is distorted which increases iron losses).
2. Stray load loss cannot be determined by this test and hence efficiency is over estimated.
3. Temperature rise of the machine cannot be determined.
4. The test does not indicate whether commutation would be satisfactory when the machine is loaded.

I_O = No load current; I_{sh} = shunt field current
I_{ao} = No load armature current = $(I_o - I_{sh})$
V= Supply Voltage

No load input $= VI_o$ watts.
No load power input supplies
(i) Iron losses in the core
(ii) Friction and windings loss and
(iii) Armature copper loss.

Let I = load current at which efficiency is required
$I_a = I - I_{sh}$ if machine is motoring; $I + I_{sh}$ if machine is generating

Efficiency as a motor:

Input = VI; $I_a^2 r_a = (I - I_{sh})^2 r_a$

Constant losses $W_c = VI_o - (I_o - I_{sh})^2 r_a$ …………… 7

Total losses $= (I - I_{sh})^2 r_a + W_c$

Therefore efficiency of motor $= \frac{input - losses}{input}$; $= \frac{VI - ((I - Ish)2ra + Wc)}{VI}$ ……. 8

EFFICIENCY OF A GENERATOR:

Output = VI

$I_a^2 r_a = (I + I_{sh})^2 r_a$

Total losses $= W_c + (I + I_{sh})^2 r_a$ …………………………………….. 9

Efficiency of generator $= \frac{output}{output + losses} = \frac{VI}{VI + (I + I_{sh})^2 r_a + W_c}$ ……… 10