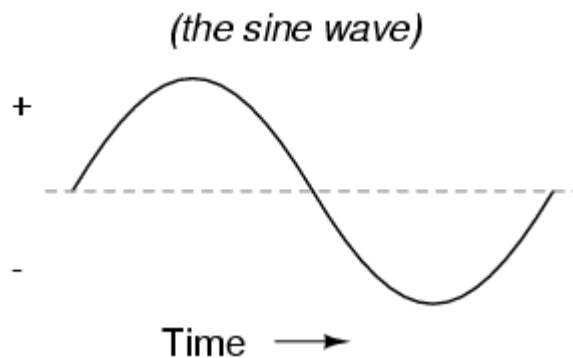


Chapter One

D.C. Generators

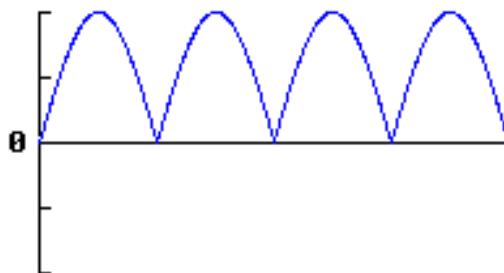
Alternating Current (AC)

In alternating current the electric charges flow changes its direction periodically. AC is the most commonly used and most preferred electric power for household equipment office and buildings Alternating current can be identified in wave form called as sine wave



Direct Current (DC)

Unlike alternating current, the flow of current in direct current do not changes periodically. The current flows in a single direction in a steady voltage. The major uses of DC is to supply power for electrical devices and also to charge batteries. For example, mobile phone batteries, flashlights, flat-screen television, hybrid and electric vehicles.



Difference Between Alternating Current and Direct Current

Alternating Current	Direct Current
AC can carry and safe to transfer longer distance even between two cities, and maintain the electric power.	DC cannot travel for very longer distance. If does, it loses electric power.
The rotating magnets cause the change in direction of electric flow.	The steady magnetism makes the DC to flow in a single direction.
The frequency of AC is depended upon the country. But, generally the frequency is 50Hz or 60Hz.	DC has no frequency of zero frequency.
In AC the flow of current changes its direction backwards periodically.	It flows in single direction steadily.
Electrons in AC keep changing its directions – backward and forward	Electrons only move in one direction – that is forward.

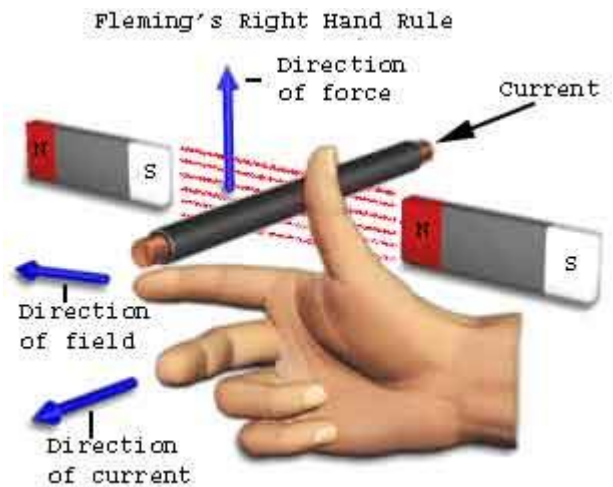
Generator Principle

An electric generator is a machine that converts mechanical energy into electrical energy. An electric generator is based on the principle that whenever flux is cut by a conductor, an e.m.f. is induced which will cause a current to flow if the conductor circuit is closed. The direction of induced e.m.f. (and hence current) is given by **Fleming's right hand rule**. Therefore, the essential components of a generator are:

- (a) A magnetic field
- (b) Conductor or a group of conductors
- (c) Motion of conductor w.r.t. magnetic field.

Fleming Right Hand Rule

As per Faraday's law of electromagnetic induction, whenever a conductor moves inside a magnetic field, there will be an induced current in it. If this conductor gets forcefully moved inside the magnetic field, there will be a relation between the direction of applied force, magnetic field and the current. This relation among these three directions is determined by **Fleming's Right Hand Rule**.



This rule states "Hold out the right hand with the first finger, second finger and thumb at right angle to each other. If forefinger represents the direction of the line of force, the thumb points in the direction of motion or applied force, then second finger points in the direction of the induced current.

Simple Loop Generator

Consider a single turn loop ABCD rotating clockwise in a uniform magnetic field with a constant speed as shown below. As the loop rotates, the flux linking the coil sides AB and CD changes continuously. Hence the e.m.f. induced in these coil sides also changes but the e.m.f. induced in one coil side adds to that induced in the other.

- (i) When the loop is in position no. 1 the generated e.m.f. is zero because the coil sides (AB and CD) are cutting no flux but are moving parallel to it.
- (ii) When the loop is in position no. 2, the coil sides are moving at an angle

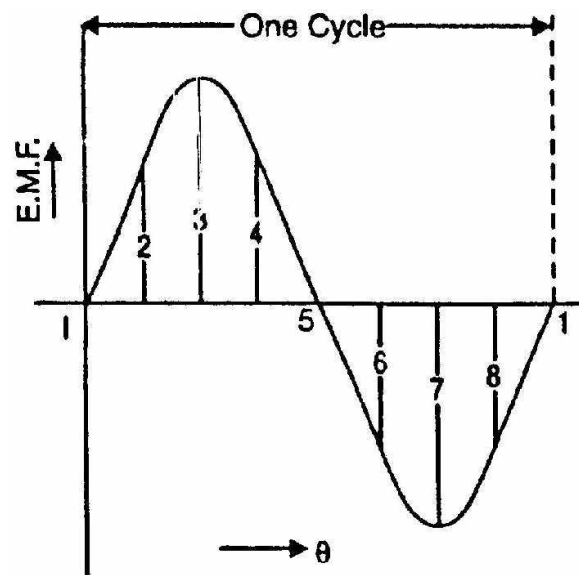
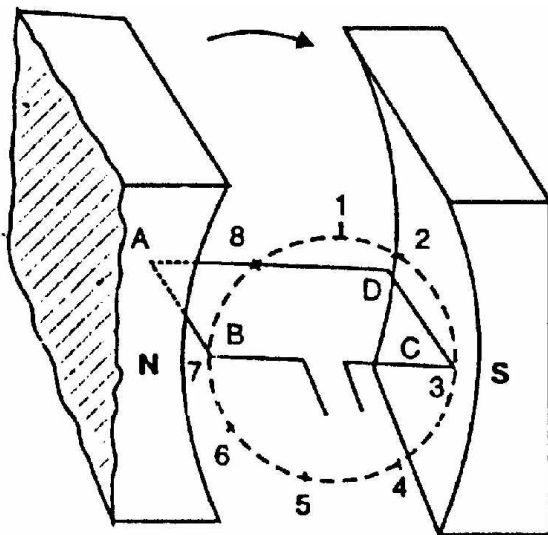
to the flux and, therefore, a low e.m.f. is generated as indicated by point 2.

(iii) When the loop is in position no. 3, the coil sides (AB and CD) are at right angle to the flux and are, therefore, cutting the flux at a maximum rate. Hence at this instant, the generated e.m.f. is maximum as indicated by point 3 in Figure

(iv) At position 4, the generated e.m.f. is less because the coil sides are cutting the flux at an angle.

(v) At position 5, no magnetic lines are cut and hence induced e.m.f. is zero as indicated by point 5 in Fig.

(vi) At position 6, the coil sides move under a pole of opposite polarity and hence the direction of generated e.m.f. is reversed. The maximum e.m.f. in this direction (i.e., reverse direction) will be when the loop is at position 7 and zero when at position 1. This cycle repeats with each revolution of the coil.



Note that e.m.f. generated in the loop is alternating one. It is because any coil side, say AB has e.m.f. in one direction when under the influence of N-pole and in the other direction when under the influence of S-pole. If a load is connected across the ends of the loop, then alternating current will flow through the load. The alternating voltage generated in the loop can be converted into direct voltage by a device called commutator. We then have the d.c. generator. In fact, a commutator is a mechanical rectifier.

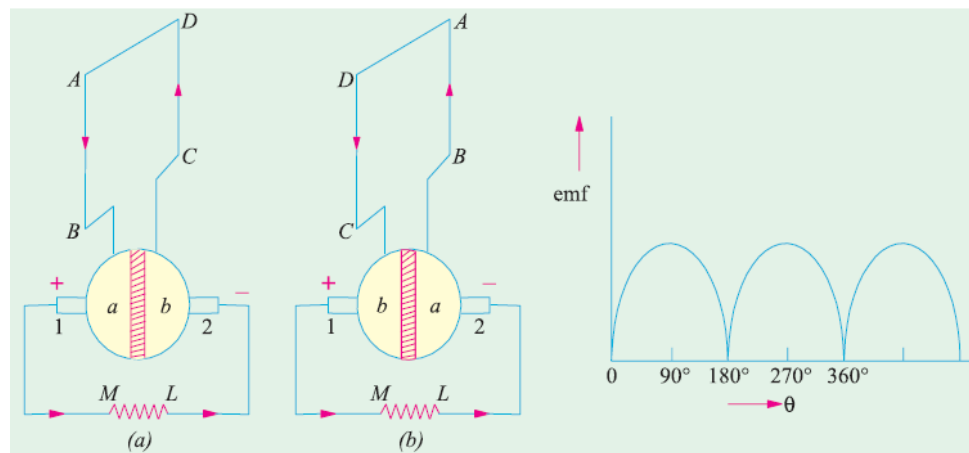
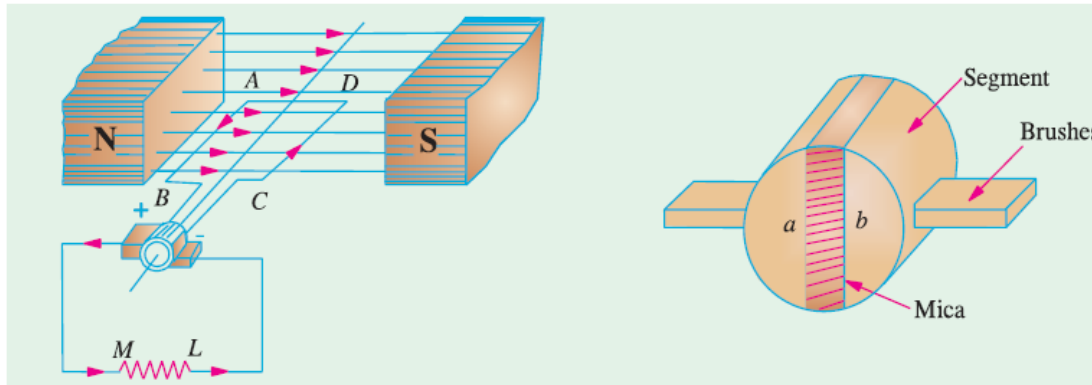
Commutator

If, somehow, connection of the coil side to the external load is reversed at the same instant the current in the coil side reverses, the current through the load will be direct current. This is what a commutator does. The figure shows a commutator having two segments C_1 and C_2 . It consists of a cylindrical metal ring cut into two halves or segments C_1 and C_2 respectively separated by a thin sheet of mica.

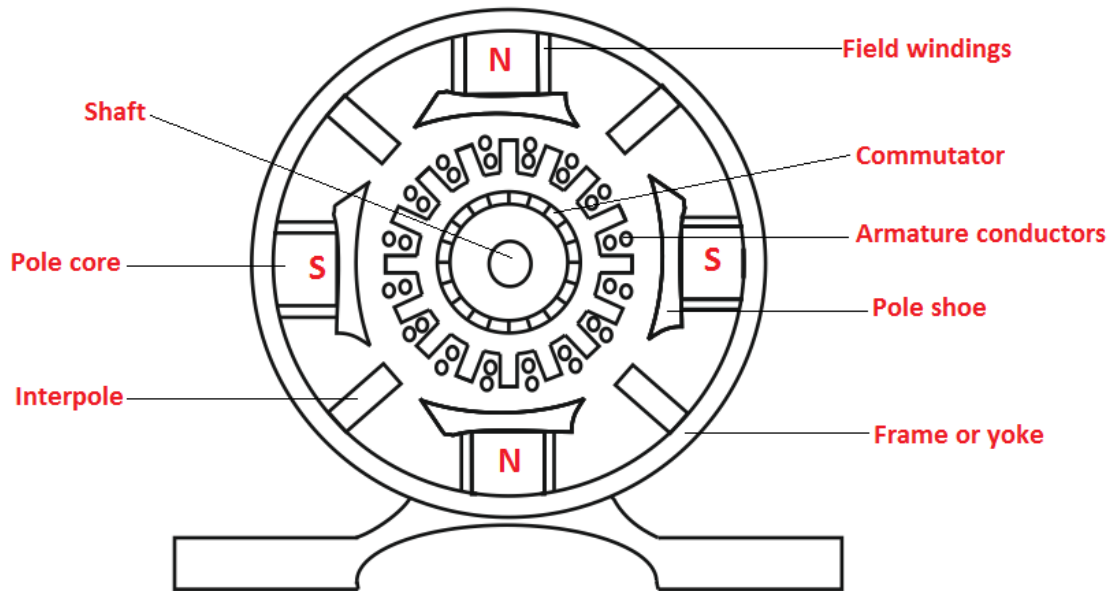
The commutator is mounted on but insulated from the rotor shaft. The ends of coil sides AB and CD are connected to the segments C_1 and C_2 respectively as shown. Two stationary carbon brushes rest on the commutator and lead current to the external load. With this arrangement, the commutator at all times connects the coil side under S-pole to the +ve brush and that under N-pole to the -ve brush.

- (i) In Fig below, the coil sides AB and CD are under N-pole and S-pole respectively. Note that segment C_1 connects the coil side AB to point P of the load resistance R and the segment C_2 connects the coil side CD to point Q of the load. Also note the direction of current through load. It is from Q to P.

- (ii) After half a revolution of the loop (i.e., 180° rotation), the coil side AB is under S-pole and the coil side CD under N-pole as shown in Fig. (1.5). The currents in the coil sides now flow in the reverse direction but the segments C_1 and C_2 have also moved through 180° i.e., segment C_1 is now in contact with +ve brush and segment C_2 in contact with -ve brush. Note that commutator has reversed the coil connections to the load i.e., coil side AB is now connected to point Q of the load and coil side CD to the point P of the load. Also note the direction of current through the load. It is again from Q to P.

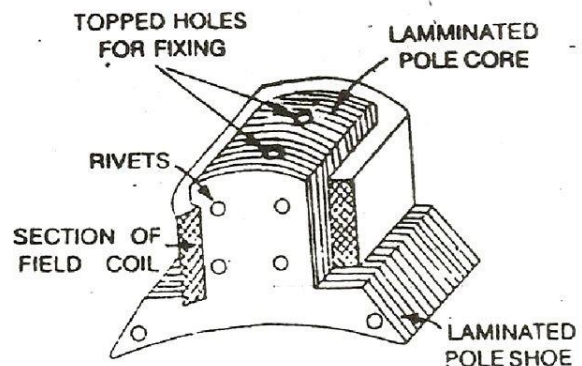


Construction of a DC Generator



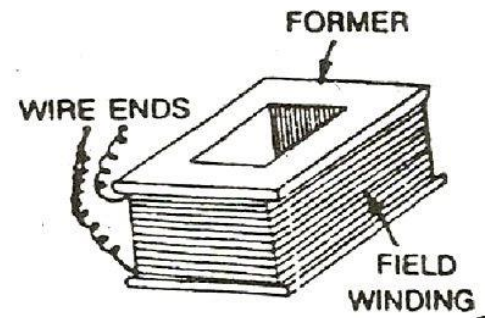
1. **Yoke:** The outer frame of a dc machine is called as yoke. It is made up of cast iron or steel. It not only provides mechanical strength to the whole assembly but also carries the magnetic flux produced by the field winding.

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:** Each pole core has one or more field coils (windings) placed over it to produce a magnetic field. The copper wire is used for the construction of field or exciting coils. The coils are wound on the former and then placed around the pole core

When direct current passes through the field winding, it magnetizes the poles, which in turns produces the flux. The field coils of all the poles are connected in series in such a way that when current flows through them, the adjacent poles attain opposite polarity.



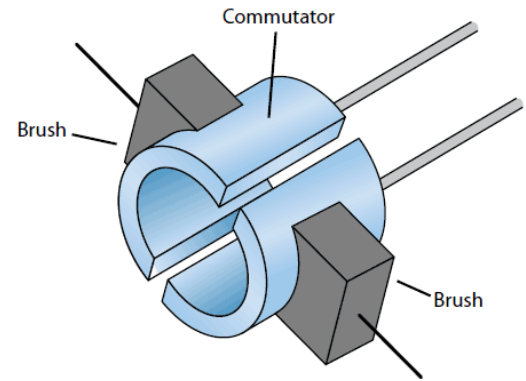
4. **Armature core:** Armature core is the rotor of the machine. It is cylindrical in shape with slots to carry armature winding. The armature is built up of thin laminated circular steel disks for reducing eddy current losses.

The armature core of a DC generator or machine serves the following purposes.

- It houses the conductors in the slots.
- It provides an easy path for the magnetic flux



5. **Commutator and brushes:** The function of a commutator, in a dc generator, is to collect the current generated in 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.



6. Shaft

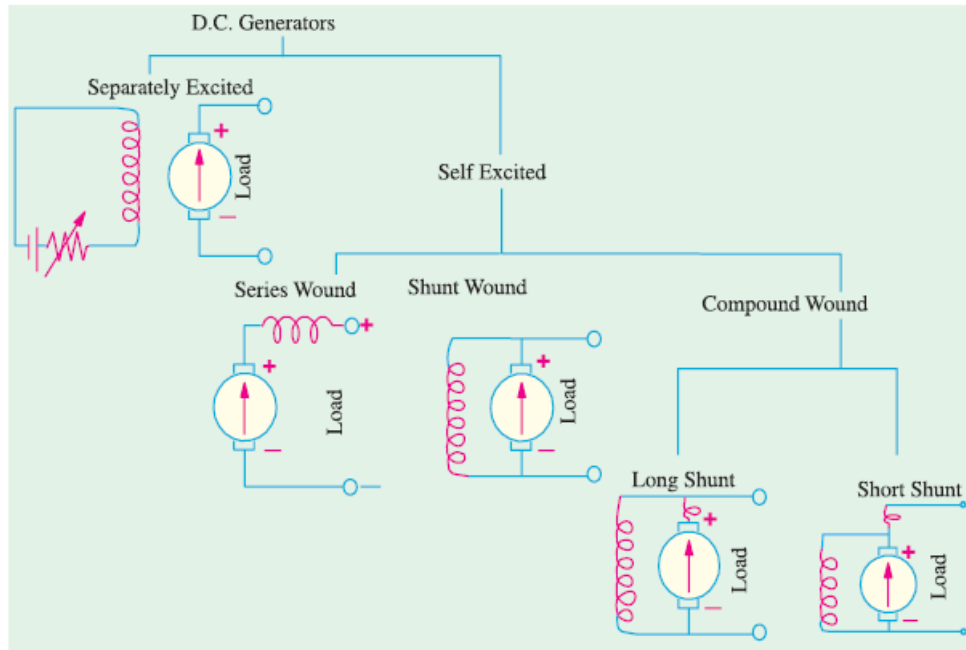
The shaft is made of mild steel with a maximum breaking strength. The shaft is used to transfer mechanical power from or to the machine. The rotating parts like armature core, commutator, cooling fans, etc. are keyed to the shaft.

Types of D.C. Generators

The magnetic field in a d.c. generator is normally produced by electromagnets rather than permanent magnets. Generators are generally classified according to their methods of field excitation. On this basis, d.c. generators are divided into the following two classes:

- (i) Separately excited d.c. generators
- (ii) Self-excited d.c. generators

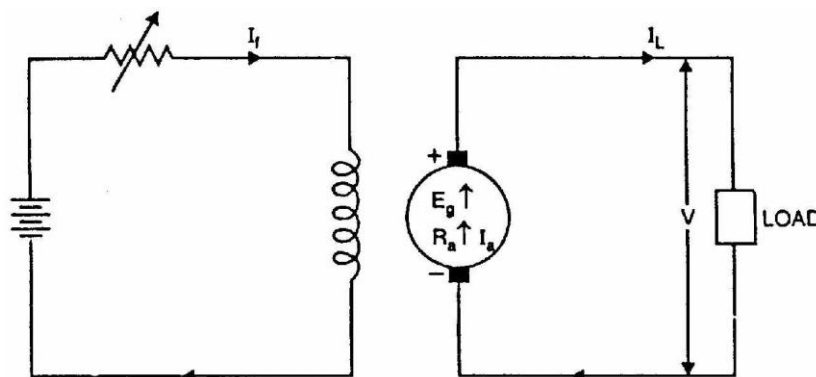
The behaviour of a d.c. generator on load depends upon the method of field excitation adopted



Separately Excited D.C. Generators

A d.c. generator whose field magnet winding is supplied from an independent external d.c. source (e.g., a battery etc.) is called a separately excited generator. Fig. below shows the connections of a separately excited generator.

The voltage output depends upon the speed of rotation of armature and the field current. The greater the speed and field current, greater is the generated e.m.f. It may be noted that separately excited d.c. generators are rarely used in practice. The d.c. generators are normally of self-excited type.



Armature current, $I_a = I_L$

e.m.f generated, $E_g = V + I_a R_a$

Electric power developed = $E_g I_a$

Power delivered to load = $V I_a$

Self-Excited D.C. Generators

A d.c. generator whose field magnet winding is supplied current from the output of the generator itself is called a self-excited generator. There are three types of self-excited generators depending upon the manner in which the field winding is connected to the armature, namely;

- (i) Series generator;
- (ii) Shunt generator;
- (iii) Compound generator

(i) Series generator

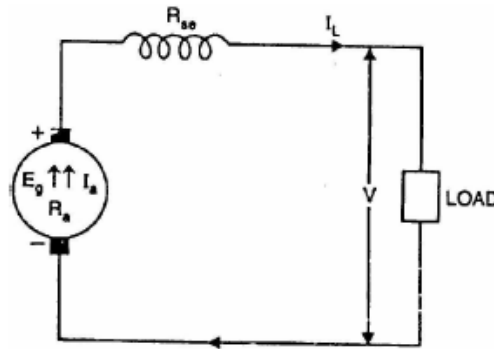
In a series wound generator, the field winding is connected in series with armature winding so that whole armature current flows through the field winding as well as the load. Figure below shows the connections of a series wound generator. Since the field winding carries the whole of load current, it has a few turns of thick wire having low resistance. Series generators are rarely used except for special purposes e.g., as boosters.

Armature current, $I_a = I_{se} = I_L = I$

e.m.f generated, $E_g = V + I(R_a + R_{se})$

Power developed in armature = $E_g I_a$

Power delivered to load = $V I$ or $V I_L$



(ii) Shunt generator

In a shunt generator, the field winding is connected in parallel with the armature winding so that terminal voltage of the generator is applied across it. The shunt field winding has many turns of fine wire having high resistance. Therefore, only a part of armature current flows through shunt field winding and the rest flows through the load.

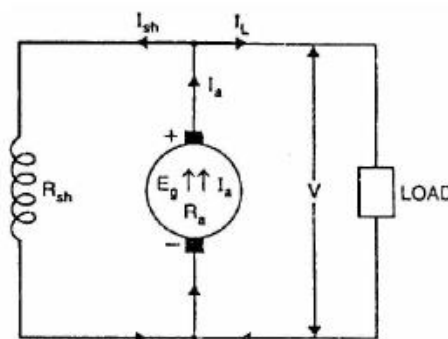
Shunt field current, $I_{sh} = V/R_{sh}$

Armature current, $I_a = I_L + I_{sh}$

e.m.f generated, $E_g = V + I_a R_a$

Power developed in armature = $E_g I_a$

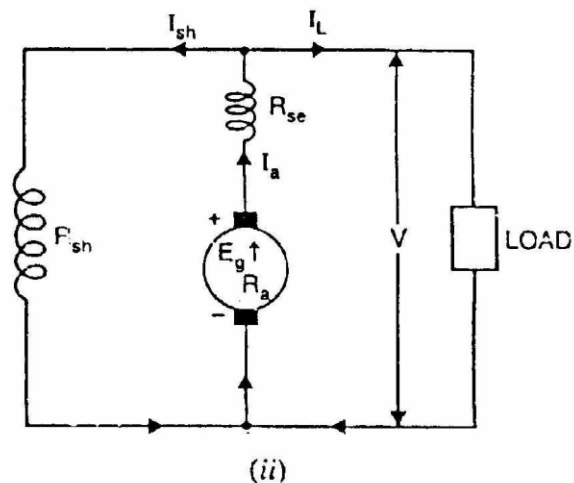
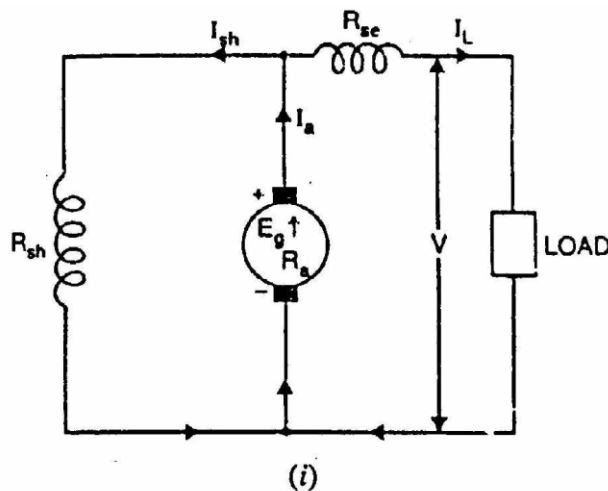
Power delivered to load = $V I_L$



(iii) Compound generator

In a compound-wound generator, there are two sets of field windings on each pole—one is in series and the other in parallel with the armature. A compound wound generator may be:

- (a) Short Shunt in which only shunt field winding is in parallel with the armature winding
- (b) Long Shunt in which shunt field winding is in parallel with both series field and armature winding



Short shunt

Series field current, $I_{se} = I_L$

$$\text{Shunt field current} = I_{sh} = \frac{V + I_{se}R_{se}}{R_{sh}}$$

e.m.f generated, $E_g = V + I_a R_a + I_{se} R_{se}$

Power developed in armature = $E_g I_a$

Power delivered to load = $V I_L$

Long shunt

Series field current, $I_{se} = I_a = I_L + I_{sh}$

Shunt field current, $I_{sh} = V/R_{sh}$

e.m.f generated, $E_g = V + I_a(R_a + R_{se})$

Power developed in armature = $E_g I_a$

Power delivered to load = $V I_L$

Brush Contact Drop

It is the voltage drop over the brush contact resistance when current flows.

Obviously, its value will depend upon the amount of current flowing and the value of contact resistance. This drop is generally small.

Ex1: A shunt generator delivers 450 A at 230 V and the resistance of the shunt field and armature are 50Ω and 0.03Ω respectively. Calculate the generated e.m.f.

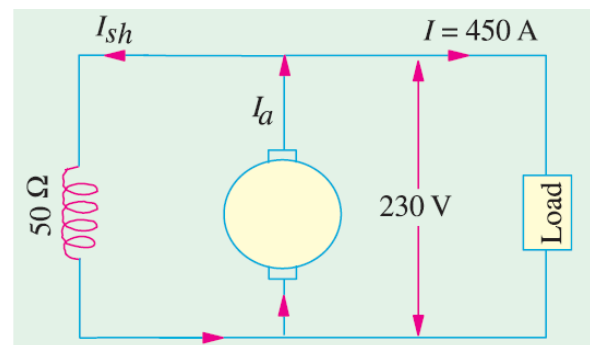
Solution:

$$\text{Shunt current } I_{sh} = \frac{230}{50} = 4.6 \text{ A}$$

$$\begin{aligned} \text{Armature current } I_a &= I + I_{sh} \\ &= 450 + 4.6 = 454.6 \text{ A} \end{aligned}$$

$$\begin{aligned} \text{Armature voltage drop } I_a R_a &= 454.6 \cdot 0.03 \\ &= 13.6 \text{ V} \end{aligned}$$

$$\begin{aligned} E_g &= \text{terminal voltage} + \text{armature drop} \\ &= V + I_a R_a = 230 + 13.6 = 243.6 \text{ V} \end{aligned}$$



Ex2/long-shunt compound generator delivers a load current of 50 A at 500 V and has armature, series field and shunt field resistances of 0.05 Ω, 0.03 Ω and 250 Ω respectively. Calculate the generated voltage and the armature current. Allow 1 V per brush for contact drop.

Solution:

$$I_{sh} = \frac{500}{250} = 2 \text{ A}$$

Current through armature and series winding is

$$= 50 + 2 = 52 \text{ A}$$

Voltage drop on series field winding

$$= 52 \times 0.03 = 1.56 \text{ V}$$

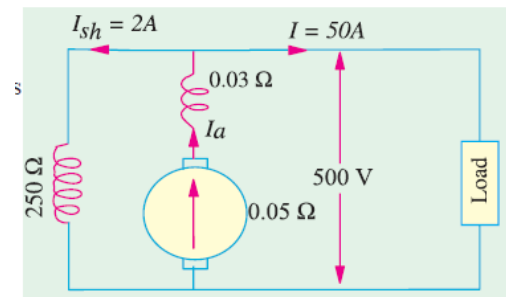
Armature voltage drop

$$I_a R_a = 52 \times 0.05 = 2.6 \text{ V}$$

Drop at brushes = 2 × 1 = 2 V

Now, $E_g = V + I_a R_a + \text{series drop} + \text{brush drop}$

$$= 500 + 2.6 + 1.56 + 2 = 506.16 \text{ V}$$



Ex3: A short-shunt compound generator delivers a load current of 30 A at 220 V, and has armature, series-field and shunt-field resistances of 0.05 Ω, 0.30 Ω and 200 Ω respectively. Calculate the induced e.m.f. and the armature current. Allow 1.0 V per brush for contact drop.

Solution:

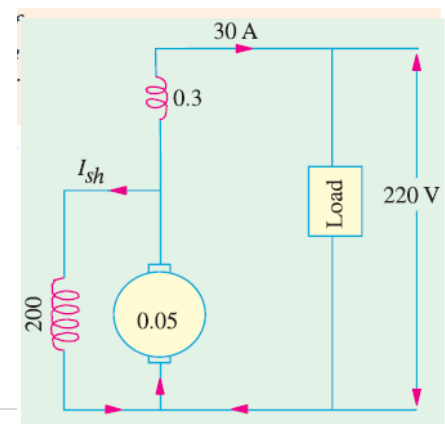
$$\text{drop in series winding} = 30 \times 0.3 = 9 \text{ V}$$

$$\text{Voltage across shunt winding} = 220 + 9 = 229 \text{ V}$$

$$I_{sh} = 229/200 = 1.145 \text{ A}$$

$$I_a = 30 + 1.145 = 31.145 \text{ A}$$

$$I_a R_a = 31.145 \cdot 0.05 = 1.56 \text{ V}$$



$$\text{Brush drop} = 2 \cdot 1 = 2 \text{ V}$$

$$E_g = V + \text{series drop} + \text{brush drop} + I_a R_a$$

$$= 220 + 9 + 2 + 1.56 = 232.56 \text{ V}$$

Ex4: In a long-shunt compound generator, the terminal voltage is 230 V when generator delivers 150 A. Determine (i) induced e.m.f. (ii) total power generated and . Given that shunt field, series field, divertor and armature resistance are 92 Ω, 0.015 Ω, 0.03 Ω and 0.032 Ω respectively.

Solution:

$$I_{sh} = 230/92 = 2.5 \text{ A}$$

$$I_a = 150 + 2.5 = 152.5 \text{ A}$$

Since series field resistance and divertor resistances are in parallel (their combined resistance is

$$= 0.03 \times 0.015/0.045 = 0.01 \Omega$$

Total armature circuit resistance is

$$= 0.032 + 0.01 = 0.042 \Omega$$

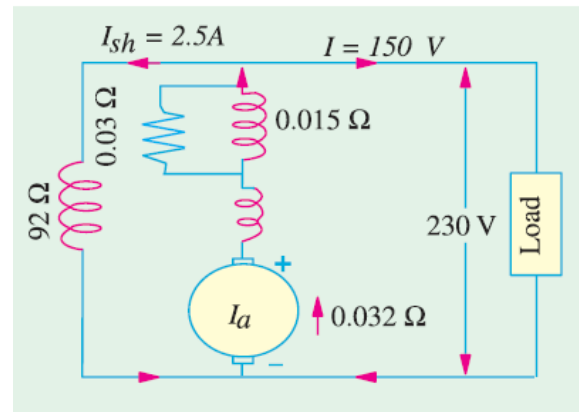
$$\text{Voltage drop} = 152.5 \times 0.042 = 6.4 \text{ V}$$

(i) Voltage generated by armature

$$E_g = 230 + 6.4 = 236.4 \text{ V}$$

(ii) Total power generated in armature

$$E_g I_a = 236.4 \times 152.5 = 36,051 \text{ W}$$



Generated E.M.F. or E.M.F. Equation of a Generator

Let Φ = flux/pole in weber

Z = total number of armature conductors

= No. of slots . No. of conductors/slot

P = No. of generator poles

A = No. of parallel paths in armature

N = armature rotation in revolutions per minute (r.p.m.)

E = e.m.f. induced in any parallel path in armature

Generated e.m.f. E_g = e.m.f. generated in any one of the parallel paths *i.e.* E .

Average e.m.f. generated/conductor = $d\Phi/dt$ v ($\because n = 1$)

Now, flux cut/conductor in one revolution $d\Phi = \Phi P$ Wb

No. of revolutions/second = $N/60$ \therefore Time for one revolution, $dt = 60/N$ second

Hence, according to Faraday's Laws of Electromagnetic Induction,

E.M.F. generated/conductor = $\frac{d\Phi}{dt} = \frac{\Phi P N}{60}$ volt

$$E_g = \frac{\Phi P N Z}{60} \cdot \frac{A}{Z}$$

Where, $A=2$ for a simplex wave-wound generator

$A=P$ for a simplex lap-wound generator

Ex5: An 8-pole d.c. generator has 500 armature conductors, and a useful flux of 0.05 Wb per pole. What will be the e.m.f. generated if it is lap-connected and runs at 1200 rpm ? What must be the speed at which it is to be driven produce the same e.m.f. if it is wave-wound?

Solution:

$$E_g = \frac{\Phi P N Z}{60} \cdot \frac{1}{A}$$

$$\Phi = 0.05 \text{ Wb}, Z = 500, A = p, N = 1200 \text{ rpm}$$

Thus, $E_g = 500 \text{ V}$

$$\Phi = 0.05 \text{ Wb}, Z = 500, A = 2, p = 8, N = 1200 \text{ rpm}$$

Thus, $N = 300 \text{ rpm}$

Ex6: An 8-pole d.c. shunt generator with 778 wave-connected armature conductors and running at 500 r.p.m. supplies a load of 12.5Ω resistance at terminal voltage of 250 V. The armature resistance is 0.24Ω and the field resistance is 250Ω . Find the armature current, the induced e.m.f. and the flux per pole.

Solution:

$$\text{Load current} = V/R = 250/12.5 = 20 \text{ A}$$

$$\text{Shunt current} = 250/250 = 1 \text{ A}$$

$$\text{Armature current} = 20 + 1 = 21 \text{ A}$$

$$\text{Induced e.m.f.} = 250 + (21 \times 0.24) = 255.04 \text{ V}$$

$$E_g = \frac{\Phi P N Z}{60} \cdot \frac{1}{A}$$

$$255.04 = \frac{\Phi \times 8 \times 500}{60} \cdot \frac{778}{2}$$

$$\Phi = 9.83 \text{ mWb}$$

Ex7: A 4-pole lap-connected armature of a d.c. shunt generator is required to supply the loads connected in parallel:

- (1) 5 kW Geyser at 250 V, and
- (2) 2.5 kW Lighting load also at 250 V.

The Generator has an armature resistance of 0.2 ohm and a field resistance of 250 ohms. The armature has 120 conductors in the slots and runs at 1000 rpm. Allowing 1 V per brush for contact drops and neglecting friction, find Flux per pole.

Solution:

$$\text{Geyser current} = 5000/250 = 20 \text{ A}$$

$$\text{Current for Lighting} = 2500/250 = 10 \text{ A}$$

$$\text{Total current} = 30 \text{ A}$$

$$\text{Field Current for Generator} = 1 \text{ A (250v}\backslash\text{250ohm)}$$

$$\text{Hence, Armature Current} = 31 \text{ A}$$

$$\text{Armature resistance drop} = 31 \times 0.2 = 6.2 \text{ volts}$$

$$\text{Generated e. m. f.} = 250 + 6.2 + 2(2 \text{ brushes}) = 258.2 \text{ V,}$$

$$E_g = \frac{\Phi P N Z}{60} \cdot \frac{1}{A}$$
$$258.2 = \frac{\Phi \times 1000 \times 120}{60}$$

$$\Phi = 129.1 \text{ mWb}$$

Ex8: A 4-pole, d.c. shunt generator with a shunt field resistance of 100Ω and an armature resistance of 1Ω has 378 wave-connected conductors in its armature. The flux per pole is 0.02 Wb. If a load resistance of 10Ω is connected across the armature terminals and the generator is driven at 1000 r.p.m., calculate the power absorbed by the load.

Solution:

Induced e.m.f. in the generator is

$$E_g = \frac{\Phi P N Z}{60} \cdot \frac{1}{A}$$

$$E_g = \frac{0.02 \times 4 \times 1000}{60} \cdot \frac{378}{2} = 252 \text{ V}$$

$$\text{Load current} = V/10$$

$$\text{Shunt current} = V/100$$

$$\text{Armature current} = \frac{V}{10} + \frac{V}{100} = \frac{11V}{100}$$

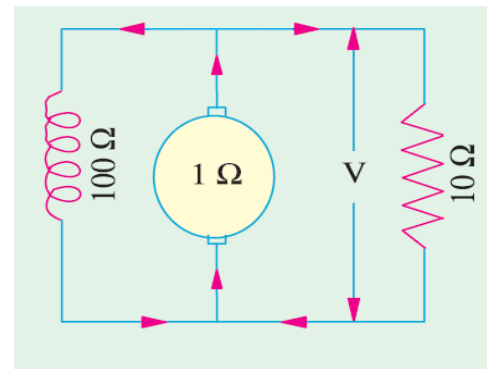
$$V = E_g - \text{armature drop}$$

$$V = 252 - 1 \times \frac{11V}{100}$$

$$V = 227 \text{ V}$$

$$\text{Load current} = 227/10 = 22.7 \text{ A}$$

$$\text{Power absorbed} = 227 \times 22.7 = 5135 \text{ W}$$



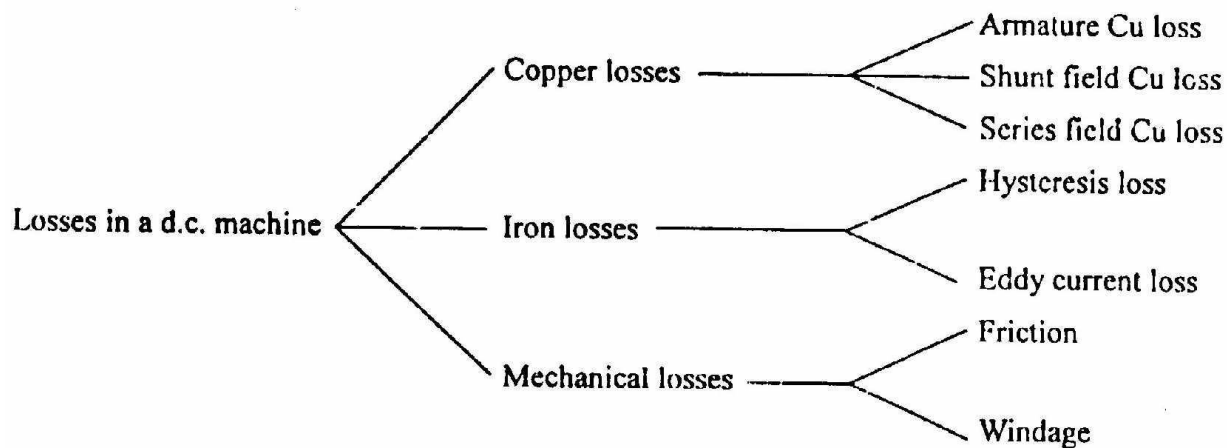
Losses in a D.C. Machine

The losses in a d.c. machine (generator or motor) may be divided into three classes

- (i) copper losses
- (ii) iron or core losses and
- (iii) mechanical losses.

All these losses appear as heat and thus raise the temperature of the machine.

They also lower the efficiency of the machine.



Copper losses

These losses occur due to currents in the various windings of the machine.

- (i) Armature copper loss $= I_a^2 R_a$
- (ii) Shunt field copper loss $= I_{sh}^2 R_{sh}$
- (iii) Series field copper loss $= I_{se}^2 R_{se}$

Iron or Core losses

These losses occur in the armature of a d.c. machine and are due to the rotation of armature in the magnetic field of the poles. They are of two types viz., (i) hysteresis loss (ii) eddy current loss.

(i) Hysteresis loss

Hysteresis loss occurs in the armature of the d.c. machine since any given part of the armature is subjected to magnetic field reversals as it passes under successive poles. Fig. below shows an armature rotating in two-pole machine.

Consider a small piece ab of the armature. When the piece ab is under N-pole, the magnetic lines pass from a to b. Half a revolution later, the same piece of iron is under S-pole and magnetic lines pass from b to a so that magnetism in the iron is reversed. In order to reverse continuously the molecular magnets in the armature core, some amount of power has to be spent which is called hysteresis loss. It is given by Steinmetz formula. This formula is:

$$\text{Hysteresis loss, } P_h = \eta B_{max}^{1.6} f V \quad \text{watts}$$

Where

B_{max} = Maximum flux density in armature

f = Frequency of magnetic reversals

= NP/120 where N is in r.p.m.

V = Volume of armature in m³

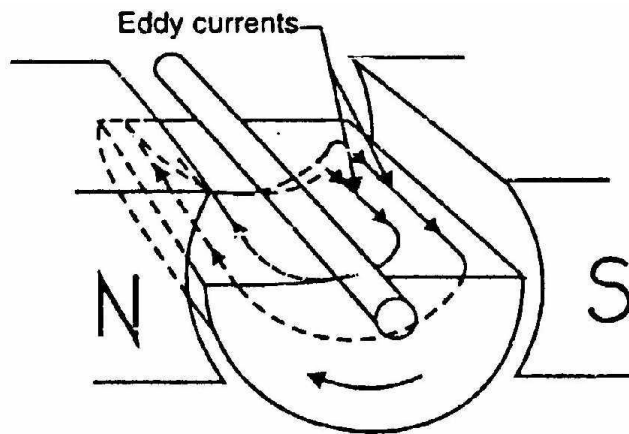
η = Steinmetz hysteresis co-efficient

In order to reduce this loss in a d.c. machine, armature core is made of such materials which have a low value of Steinmetz hysteresis co-efficient e.g., silicon steel.

(ii) Eddy current loss

In addition to the voltages induced in the armature conductors, there are also voltages induced in the armature core. These voltages produce circulating currents in the armature core as shown in Figure below These are called eddy currents and power loss due to their flow is

called eddy current loss. The eddy current loss appears as heat which raises the temperature of the machine and lowers its efficiency



Mechanical losses

These losses are due to friction and windage.

- (i) friction loss e.g., bearing friction, brush friction etc.
- (ii) windage loss i.e., air friction of rotating armature.

These losses depend upon the speed of the machine. But for a given speed, they are practically constant.

Note. Iron losses and mechanical losses together are called stray losses.

(i) Constant losses

Those losses in a d.c. generator which remain constant at all loads are known as constant losses. The constant losses in a d.c. generator are:

- (a) iron losses
- (b) mechanical losses
- (c) shunt field losses

(ii) Variable losses

Those losses in a d.c. generator which vary with load are called variable losses.

The variable losses in a d.c. generator are

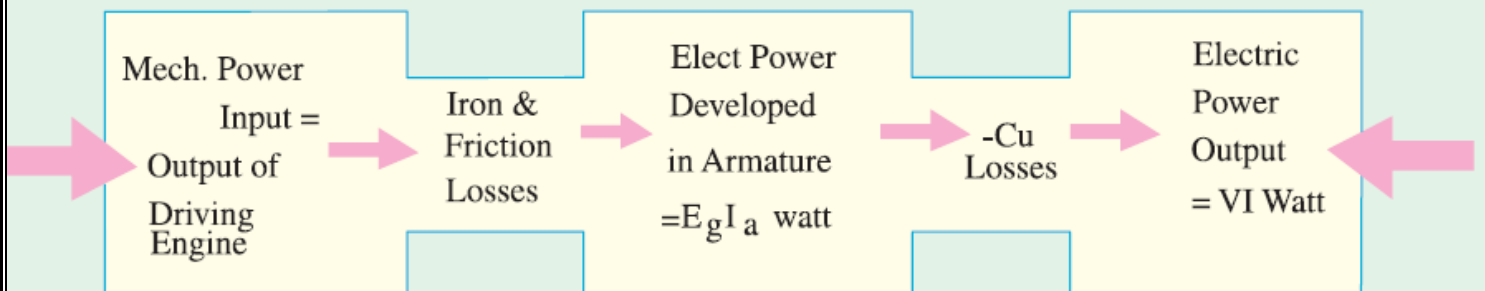
- (a) Copper loss in armature winding, $I_a^2 R_a$
- (b) Copper loss in series field winding, $I_{se}^2 R_{se}$

$$\text{Total losses} = \text{Constant losses} + \text{Variable losses}$$

Note. Field Cu loss is constant for shunt and compound generators

Power Stages

The various power stages in a d.c. generator are represented diagrammatically in the following figure.



Mechanical efficiency

$$\eta_m = \frac{B}{A} = \frac{E_g I_a}{\text{Mechanical power input}}$$

Electrical efficiency

$$\eta_e = \frac{C}{B} = \frac{V I_L}{E_g I_a}$$

Commercial or overall efficiency

$$\eta_c = \frac{C}{A} = \frac{V I_L}{\text{Mechanical power input}}$$

$$\eta_c = \eta_e \cdot \eta_m$$

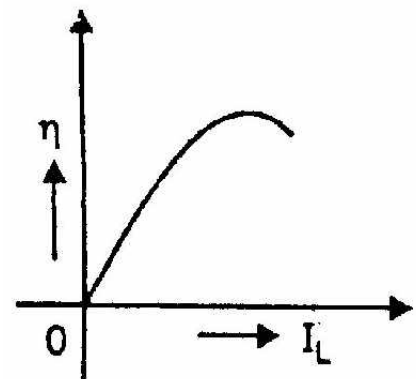
Condition for Maximum Efficiency

The efficiency of a d.c. generator is not constant but varies with load. Consider a shunt generator delivering a load current I_L at a terminal voltage V .

Variable loss = Constant loss

The load current corresponding to maximum efficiency is given by;

$$I_L = \sqrt{\frac{W_C}{R_a}}$$



Ex9: A 10 kW, 250 V, d.c., 6-pole shunt generator runs at 1000 r.p.m. when delivering full-load. The armature has 534 lap-connected conductors. Full-load Cu loss is 0.64 kW. The total brush drop is 1 volt. Determine the flux per pole. Neglect shunt current.

Solution:

Since shunt current is negligible, there is no shunt Cu loss. The copper loss occurs in armature only.

$$I = I_a = 10,000/250 = 40 \text{ A}$$

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

$$640 = 40^2 \cdot R_a \quad R_a = 0.4 \Omega$$

$$I_a R_a \text{ drop} = 0.4 \times 40 = 16 \text{ V}$$

$$\text{Generated e.m.f} = 250 + 16 + 1 = 267 \text{ V}$$

$$E_g = \frac{\Phi P N Z}{60} \cdot \frac{1}{A}$$

$$267 = \frac{\Phi \times 6 \times 1000}{60} \cdot \frac{534}{6}, \quad \Phi = 30 \text{ mWb}$$

Ex10: A shunt generator delivers 195 A at terminal p.d. of 250 V. The armature resistance and shunt field resistance are 0.02 Ω and 50 Ω respectively. The iron and friction losses equal 950 W. Find (a) E.M.F. generated (b) Cu losses (c) output of the prime motor (d) Commercial, mechanical and electrical efficiencies.

Solution:

$$I_{sh} = \frac{250}{50} = 5 \text{ A}; \quad I_a = 195 + 5 = 200 \text{ A}$$

$$\text{Armature voltage drop} = I_a R_a = 200 \times 0.02 = 4 \text{ V}$$

$$\therefore \text{Generated e.m.f} = 250 + 4 = 254 \text{ V}$$

$$\text{Armature Cu loss} = I_a^2 R_a = 2002 \times 0.02 = 800 \text{ W}$$

$$\text{Shunt Cu loss} = V \cdot I_{sh} = 250 \times 5 = 1250 \text{ W}$$

$$\text{Total Cu loss} = 1250 + 800 = 2050 \text{ W}$$

$$\text{Total losses} = 2050 + 950 = 3000 \text{ W}$$

$$\text{Output} = 250 \times 195 = 48,750 \text{ W}$$

$$\text{Input} = 48,750 + 3000 = 51,750 \text{ W} \quad \text{Output of prime motor}$$

$$\text{Electrical power produced in armature} = 51,750 - 950 = 50,800 \text{ W}$$

$$\eta_m = \left(\frac{50,800}{51,750} \right) \times 100 = 98.2\%$$

$$\eta_e = \left(\frac{48750}{48750 + 2050} \right) \times 100 = 95.9\%$$

$$\eta_c = \left(\frac{48750}{51750} \right) \times 100 = 94.2\%$$

Find the load current corresponding to maximum efficiency?

Ex11: long-shunt dynamo running at 1000 r.p.m. supplies 22 kW at a terminal voltage of 220 V. The resistances of armature, shunt field, and the series field are 0.05, 110 and 0.06 Ω respectively. The overall efficiency at the above load is 88%. Find (a) Cu losses (b) iron and friction losses (c) the torque exerted by the prime mover

Solution:

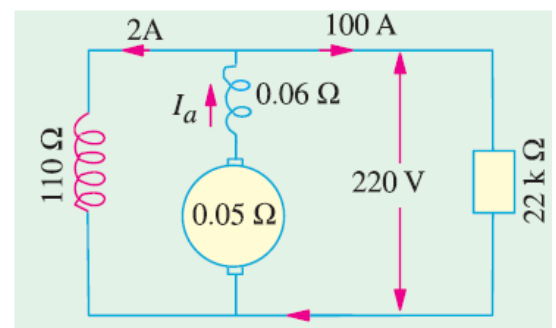
$$I_{sh} = 220/110 = 2 \text{ A}$$

$$I = 22,000/220 = 100 \text{ A,}$$

$$I_a = 102 \text{ A}$$

$$\text{Drop in series field winding} = 102 \times 0.06 = 6.12 \text{ V}$$

$$I_a^2 R_a = 1022 \times 0.05 = 520.2 \text{ W}$$



$$\text{Series field loss} = 102^2 \times 0.06 = 624.3 \text{ W}$$

$$\text{Shunt field loss} = 4 \times 110 = 440 \text{ W}$$

$$\text{Total Cu losses} = 520.2 + 624.3 + 440 = 1584.5 \text{ W}$$

$$\text{Input} = \frac{22,000}{0.88} = 25,000 \text{ W}$$

$$\therefore \text{Total losses} = 25,000 - 22,000 = 3,000 \text{ W}$$

$$\therefore \text{Iron and friction losses} = 3,000 - 1,584.5 = 1,415.5 \text{ W}$$

$$\text{Power} = T \frac{2\pi N}{60} \quad T = 238.74 \text{ N.m}$$

Parallel Operation of Shunt Generators

Power plants, whether in d.c. or a.c. stations, will be generally found to have several smaller generators running in parallel rather than large single units capable of supplying the maximum peak load. These smaller units can be run single or in various parallel combinations to suit the actual load demand. Such practice is considered extremely desirable for the following reasons

(i) Continuity of Service

Continuity of service is one of the most important requirements of any electrical apparatus. This would be impossible if the power plant consisted only of a single unit, because in the event of breakdown of the prime mover or the generator itself, the entire station will be shut down.

(ii) Efficiency

Usually, the load on the electrical power plant fluctuates between its peak value sometimes during the day and its minimum value during the late night hours. Since generators operate most efficiently when delivering full load, it is economical to use a single small unit when the load is light. Then, as the load demand increases, a larger generator can be substituted for the

smaller one or another smaller unit can be connected to run in parallel with the one already in operation.

(iii) Maintenance and Repair

It is considered a good practice to inspect generators carefully and periodically to forestall any possibility of failure or breakdown. This is possible only when the generator is at rest which means that there must be other generators to take care of the load

(iv) Increasing plant capacity

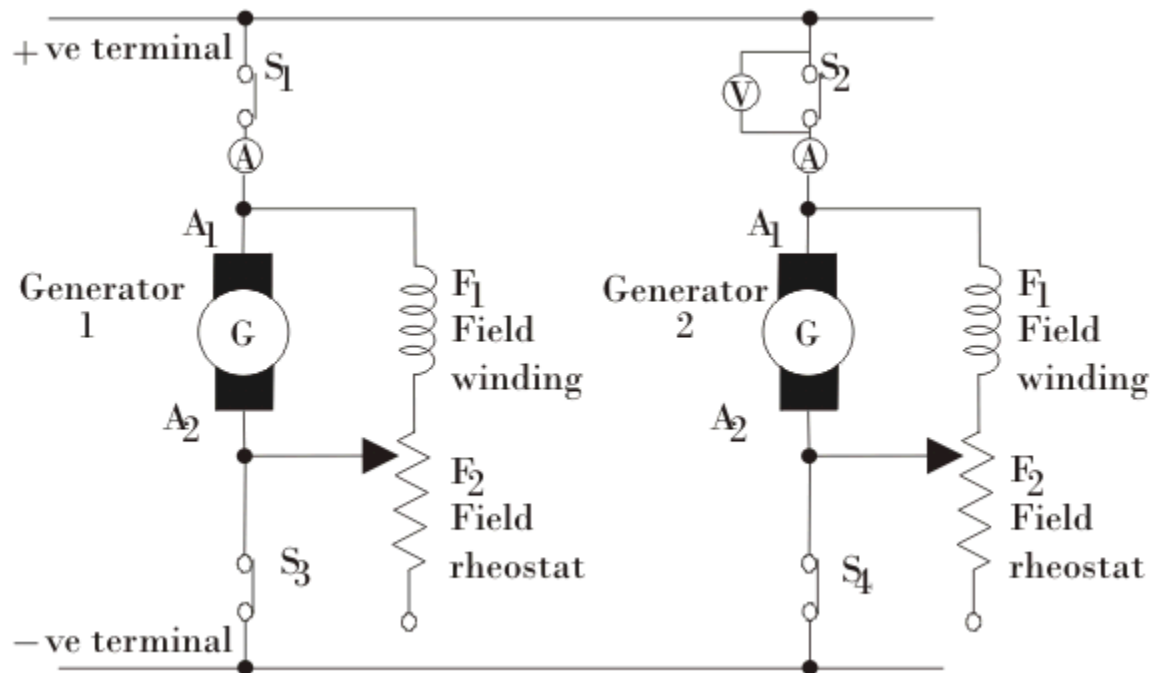
In the modern world of increasing population, the use of electricity is continuously increasing. When added capacity is required, the new unit can be simply paralleled with the old units.

Connecting Shunt Generators in Parallel

the generators in a power plant, connected by heavy thick copper bars, called bus-bars which act as positive and negative terminals. To connect the generators in parallel, Positive terminal of the generators are connected to the positive terminal of the bus-bars and negative terminals of generators are connected to negative terminal of the bus-bars, as shown in the figure.

1. To connect the 2 generators with the 1 existing working generators, first we have to bring the speed of the prime mover of the 2nd generator to the rated speed. At this point switch S_4 is closed.
2. The circuit breaker V_2 (voltmeter) connected across the open switch S_2 is closed to complete the circuit. The excitation of the generator 2 is increased with the help of field rheostat till it generates voltage equal to the voltage of bus-bars.

3. The main switch S_2 is then closed and the generator 2 is ready to be paralleled with existing generator. But at this point of time generator 2 is not taking any load as its induced e.m.f. is equal to bus-bar voltage. The present condition is called floating, that means ready for supply but not supplying current to the load.
4. The main switch S_2 is then closed and the generator 2 is ready to be paralleled with existing generator. But at this point of time generator 2 is not taking any load as its induced e.m.f. is equal to bus-bar voltage. The present condition is called floating, that means ready for supply but not supplying current to the load.



$$I_1 = \frac{E_1 - V}{R_1}$$

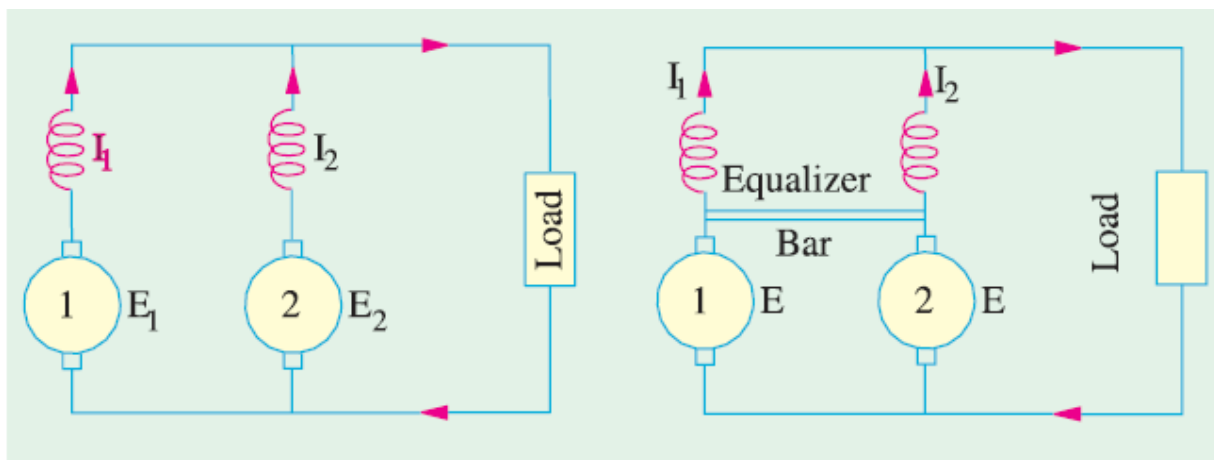
$$I_2 = \frac{E_2 - V}{R_2}$$

Series Generators in Parallel

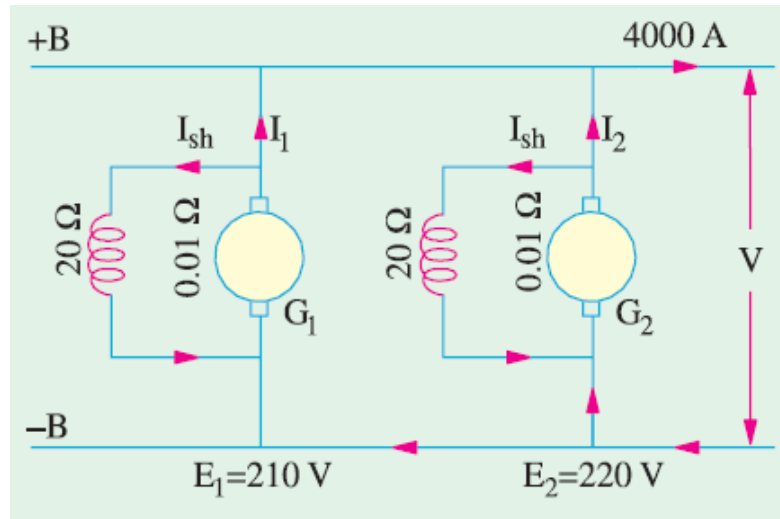
Suppose E_1 and E_2 are initially equal, generators supply equal currents and have equal shunt resistances. Suppose E_1 increases slightly so that $E_1 > E_2$. In that case, I_1 becomes greater than I_2 . Consequently, field of machine 1 is strengthened thus increasing E_1 further whilst the field of machine 2 is weakened thus decreasing E_2 further.

A final stage is reached when machine 1 supplies not only the whole load but also supplies power to machine 2 which starts running as a motor.

This condition can be prevented by using equalizing bar because of which two similar machines pass approximately equal currents to the load, the slight difference between the two currents being confined to the loop made by the armatures and the equalizer bar.



Ex12/ Two shunt generators each with an armature resistance of 0.01 ohm and field resistance of 20 ohm run in parallel and supply a total load of 4000 A. The e.m.f.s are respectively 210 V and 220 V. Calculate the bus-bar voltage and output of each machine.



V = bus-bar voltage

I_1 = output current of G1

I_2 = output current of G2

$$I_1 + I_2 = 4000 \text{ A}, \quad I_{sh} = V/20.$$

$$I_{a1} = \left(I_1 + \frac{V}{20} \right); \quad I_{a2} = \left(I_2 + \frac{V}{20} \right)$$

In each machine,

V + armature drop = induced e.m.f.

$$V + I_{a1} R_a = E_1$$

$$\text{or } V + \left(I_1 + \frac{V}{20} \right) \times 0.01$$

= 210 ...1st machine

$$\text{Also } V + I_{a2} R_a = E_2$$

$$\text{or } V + \left(I_2 + \frac{V}{20} \right) \times 0.01 = 220 \dots \text{2nd machine}$$

$$\text{Subtracting, we have } 0.01 (I_1 - I_2) = 10 \text{ or } I_1 - I_2 = 1000$$

$$\text{Also, } I_1 + I_2 = 4000 \text{ A} \therefore I_1 = 2500 \text{ A}; I_2 = 1500 \text{ A}$$

Substituting the value of I_1 above, we get

$$V + (2500 + V/20) \times 0.01 = 210 \therefore V = 184.9 \text{ V}$$

$$\text{Output of 1st generator} = 184.9 \times 2500/1000 = 462.25 \text{ kW}$$

$$\text{Output of 2nd generator} = 184.49 \times 1500/1000 = 277.35 \text{ kW}$$

Ex13/ Two d.c. generators A and B are connected to a common load. A had a constant e.m.f. of 400 V and internal resistance of 0.25 Ω while B has a constant e.m.f. of 410 V and an internal resistance of 0.4 Ω . Calculate the current and power output from each generator if the load voltage is 390 V. What would be the current and power from each and the terminal voltage if the load was open-circuited.

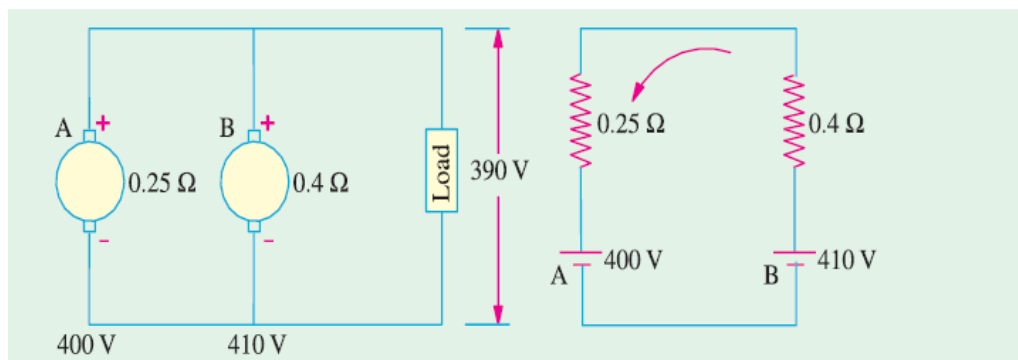


Fig. 27.20

Solution:

Since the terminal or output voltage is 390 V, hence

$$\text{Load supplied by A} = (400 - 390)/0.25 = 40 \text{ A}$$

$$\text{Load supplied by B} = (410 - 390)/0.4 = 50 \text{ A}$$

$$\therefore \text{Power output from A} = 40 \times 390 = 15.6 \text{ kW}$$

$$\text{Power output from B} = 50 \times 390 = 19.5 \text{ kW}$$

If the load is open-circuited as shown in figure above, then the two generators are put in series with each other and a circulatory current is set up between them.

$$\text{Net voltage in the circuit} = 410 - 400 = 10 \text{ V}$$

$$\text{Total resistance} = 0.4 + 0.25 = 0.65 \Omega$$

$$\therefore \text{circulatory current} = 10/0.65 = 15.4 \text{ A}$$

$$\text{The terminal voltage} = 400 + (15.4 \times 0.25) = 403.8 \text{ V}$$

Obviously, machine B with a higher e.m.f. acts as a generator and drives machine A as a motor.

$$\text{Power taken by A from B} = 403.8 \times 15.4 = 6,219 \text{ W}$$

Part of this appears as mechanical output and the rest is dissipated as armature Cu loss.

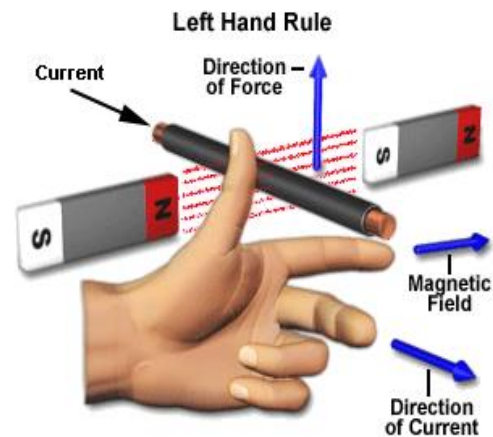
Chapter Two

D.C. Motors

A machine that converts d.c. power into mechanical power is known as a d.c. motor. 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 whose direction is given by Fleming's Left-hand Rule

Fleming's Left Hand Rule

Whenever a current carrying conductor is placed in a magnetic field, the conductor experiences a force which is perpendicular to both the magnetic field and the direction of current. According to **Fleming's left hand rule**, if the thumb, fore-finger and middle finger of the left hand are stretched to be perpendicular to each other as shown in the illustration at left, and if the fore finger represents the direction of magnetic field, the middle finger represents the direction of current, then the thumb represents the direction of force.



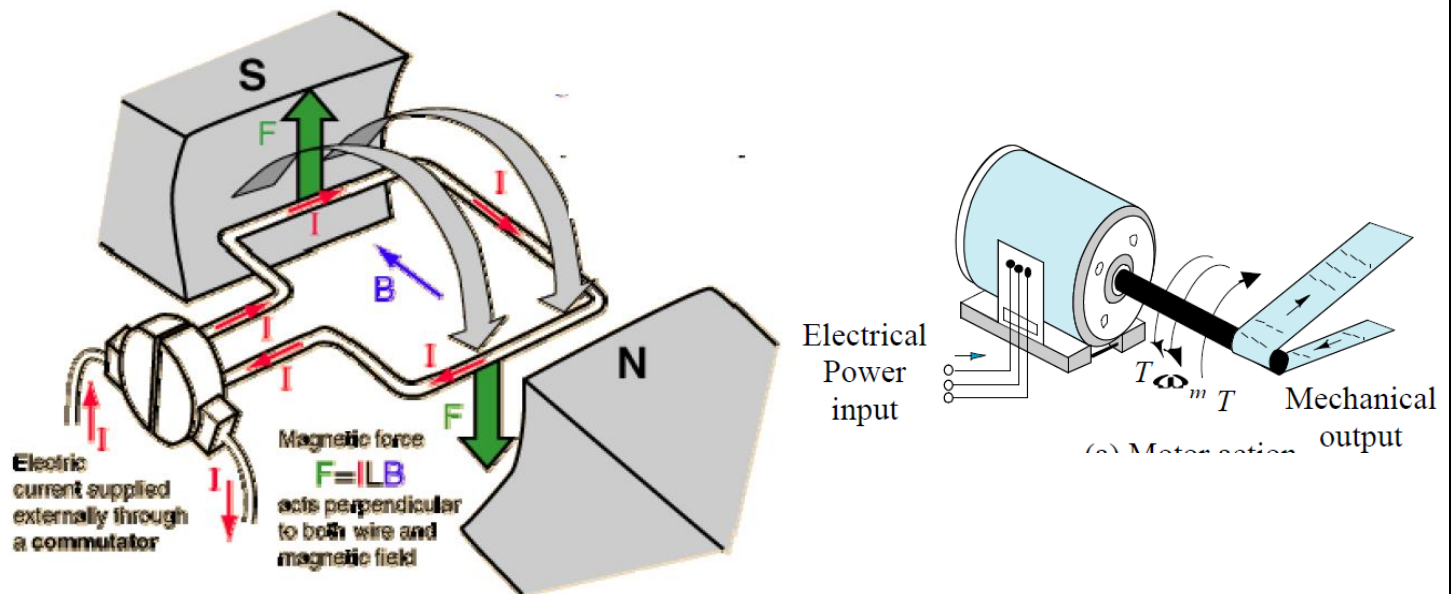
Constructionally, there is no basic difference between a d.c. generator and a d.c. motor. In fact, the same d.c. machine can be used interchangeably as a generator or as a motor. D.C. motors are also like generators, shunt-wound or series-wound or compound-wound.

It should be noted that the function of a commutator in the motor is the same as in a generator. By reversing current in each conductor as it passes from one pole to another, it helps to develop a continuous and unidirectional torque.

When operating as a generator, it is driven by a mechanical machine and it develops voltage which in turn produces a current flow in an electric circuit. When operating as a motor, it is supplied by electric current and it develops torque which in turn produces mechanical rotation.

Principle of operation

Consider a coil in a magnetic field of flux density B . When the two ends of the coil are connected across a DC voltage source, current I flows through it. A force is exerted on the coil as a result of the interaction of magnetic field and electric current passing through the conductor. The force on the two sides of the coil is such that the coil starts to move in the direction of force.



Voltage Equation of a Motor

The voltage V applied across the motor armature has to

- (i) Overcome the back e.m.f. E_b and
- (ii) Supply the armature ohmic drop $I_a R_a$.

$$V = E_b + I_a R_a$$

This is known as voltage equation of a motor.

Now, multiplying both sides by I_a , we get

$$V I_a = E_b I_a + I_a^2 R_a$$

$V I_a$ = Electrical input power to the armature

$E_b I_a$ = Electrical equivalent of mechanical power developed in the armature

$I_a^2 R_a$ = Cu loss in the armature

Hence, out of the armature input, some is wasted in $I^2 R$ loss and the rest is converted into mechanical power within the armature.

Condition for Maximum Power

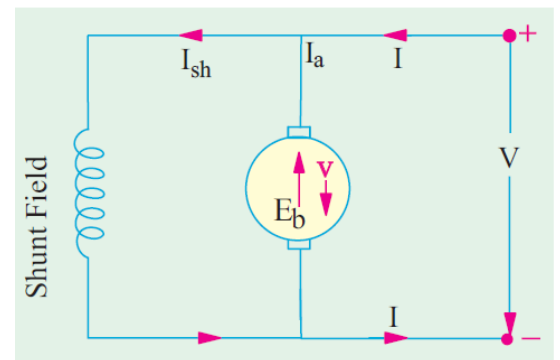
The gross mechanical power developed by a motor is

$$P_m = V I_a - I_a^2 R_a$$

Differentiating both sides with respect to I_a and equating the result to zero, we get

$$V - 2 I_a R_a = 0$$

$$I_a R_a = V/2$$



$$A_s V = E_b + I_a R_a$$

$$E_b = V/2$$

Thus gross mechanical power developed by a motor is maximum when back e.m.f. is equal to half the applied voltage.

Limitations

In practice, we never aim at achieving maximum power due to the following reasons:

- (i) The armature current under this condition is very large too much beyond the normal current of the motor
- (ii) Half of the input power is wasted in the armature circuit in the form of heat. In fact, if we take into account other losses (iron and mechanical), the efficiency will be well below 50%.

Ex1: A 4 pole, 32 conductors, lap-wound d.c. shunt generator with terminal voltage of 200 volts delivering 12 amps to the load has $R_a = 2$ ohm and field circuit resistance of 200 ohms. It is driven at 1000 r.p.m. Calculate the flux per pole in the machine. If the machine has to be run as a motor with the same terminal voltage and drawing 5 amps from the mains, maintaining the same magnetic field, find the speed of the machine.

Solution:

$$I_a = 13 \text{ amp. (12 A (I load) + 1A (Ish))}$$

$$E_g = 200 + 13 \times 2 = 226 \text{ V}$$

$$\frac{\phi P N Z}{60 A} = 226$$

For a Lap-wound armature,

$$P = A$$

$$\phi = \frac{226 \times 60}{1000 \times 32} = 0.423 \text{ wb}$$

As a motor,

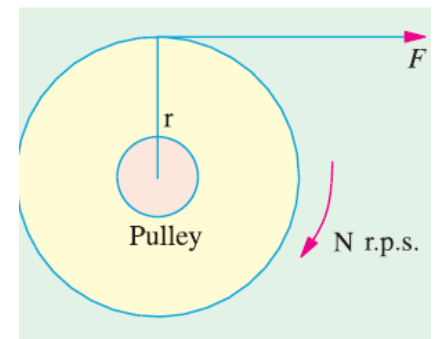
$$I_a = 4 \text{ A } (5\text{A} (1) - 1\text{A Ish})$$

$$E_b = 200 - 4 \times 2 = 192 \text{ V}$$

$$\text{Giving } N = \frac{60 \times 192}{0.423 \times 32} = 850 \text{ r. p. m}$$

Torque

By the term torque is meant the turning or twisting moment of a force about an axis. It is measured by the product of the force and the radius at which this force acts. Consider a pulley of radius r meter acted upon by a circumferential force of F Newton which causes it to rotate at N r.p.m.



Then torque $T = F \times r$ (N. m)

Work done by this force in one revolution = Force \times distance = $F \times 2\pi r$ Joule

Power developed = $F \times 2\pi r \times N$ Joule/second or Watt = $(F \times r) \times 2\pi N$ Watt

Now $2\pi N$ = Angular velocity ω in radian/second and $F \times r$ = Torque T

\therefore Power developed = $T \times \omega$ watt or $P = T \omega$ Watt

Moreover, if N is in r.p.m., then

$$\omega = 2\pi N/60 \text{ rad/s}$$

$$P = \frac{2\pi N}{60} \times T$$

Armature Torque of a Motor

Let T_a be the torque developed by the armature of a motor running at N r.p.s. If T_a is in N/M, then power developed

$$= T_a \times 2\pi N \text{ watt}$$

We also know that electrical power converted into mechanical power in the armature

$$= E_b I_a \quad \text{watt}$$

$$T_a = \frac{E_b I_a}{2\pi N} \quad \text{N.m , N in r.p.s}$$

$$T_a = 9.55 \frac{E_b I_a}{N} \quad \text{N.m , N in r.p.m}$$

And

$$E_b = \frac{\phi ZNP}{A} \quad , \text{N in r.p.s}$$

By substituting the three equations above we get,

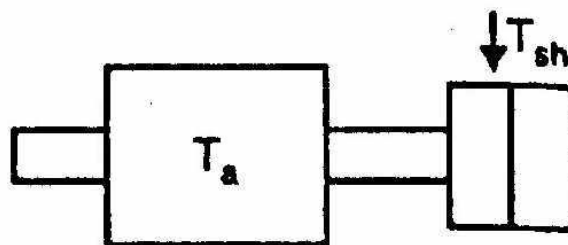
$$T_a \times 2\pi N = \frac{\phi ZNP}{A} \cdot I_a$$

$$T_a = 0.159 \frac{\phi ZP}{A} \cdot I_a \quad \text{N.m}$$

Shaft Torque (T_{sh})

The torque which is available at the motor shaft for doing useful work is known as shaft torque. It is represented by T_{sh}. Figure below illustrates the concept of shaft torque. The total or gross torque T_a developed in the armature of a motor is not available at the shaft because a part of it is lost in overcoming the **iron** and **frictional** losses in the motor. Therefore, shaft torque T_{sh} is somewhat less than the armature torque T_a. The difference T_a – T_{sh} is called lost torque

$$T_{sh} = 9.55 \frac{\text{output}}{N} \quad \text{N.m , N in r.p.m}$$



Ex2: Determine developed torque and shaft torque of 220-V, 4-pole series motor with 800 conductors wave-connected supplying a load of 8.2 kW by taking 45 A from the mains. The flux per pole is 25 mWb and its armature circuit resistance is 0.6 Ω.

Solution

Developed torque or gross torque is the same thing as armature torque.

$$T_a = 0.159 \frac{\phi Z P}{A} \cdot I_a$$

$$T_a = 0.159 \frac{0.025 \times 800 \times 4}{2} \times 45 = 286.2 \text{ N.m}$$

$$E_b = V - I_a R_a = 220 - 45 \times 0.6 = 193 \text{ V}$$

$$E_b = \frac{\phi P N Z}{60 A}$$

$$193 = \frac{0.025 \times 4 \times N \cdot 800}{60 \cdot 2} \rightarrow N = 289.5 \text{ r. p. m}$$

$$\text{Output} = 2\pi N T_{sh}$$

$$8200 = 2\pi \times \frac{289.5}{60} T_{sh} \rightarrow T_{sh} = 270.5 \text{ N.m}$$

Speed of a DC motor

$$N = \frac{E_b A \times 60}{\phi Z P} \rightarrow \rightarrow \rightarrow N = K \frac{E_b}{\phi}$$

It shows that speed is directly proportional to back e.m.f. E_b and inversely to the flux ϕ

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

For series and shunt motor,

Let N_1 = Speed in the 1st case ; I_{a1} = armature current in the 1st case

ϕ_1 = flux/pole in the first case

N_2, I_{a2}, ϕ_2 = corresponding quantities in the 2nd case.

Then, using the above relation, we get

$$N_1 \propto \frac{E_{b1}}{\phi_1} \text{ where } E_{b1} = V - I_{a1}R_a$$

$$N_2 \propto \frac{E_{b2}}{\phi_2} \text{ where } E_{b2} = V - I_{a2}R_a$$

$$\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{\phi_1}{\phi_2}$$

Also,

$$T_a = 0.159 \frac{\phi Z P}{A} \cdot I_a$$

$$T_a = K \phi I_a$$

$$T_a \propto \phi I_a$$

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

Speed Regulation

The speed regulation of a motor is the change in speed from full-load to no-load and is expressed as a percentage of the speed at full-load

$$\% \text{ speed regulation} = \frac{\text{N. L speed} - \text{F. L speed}}{\text{F. L speed}} \cdot 100$$

Ex3: A 250-V shunt motor runs at 1000 r.p.m. at no-load and takes 8A. The total armature and shunt field resistances are respectively 0.2 Ω and 250 Ω . Calculate the speed when loaded and taking 50 A. Assume the flux to be constant.

Solution:

$$\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{\phi_1}{\phi_2}$$

$$I_{sh} = \frac{250}{250} = 1A$$

$$E_{b1} = 250 - (7 \times 0.2) = 248.6 \text{ V}$$

$$E_{b2} = 250 - (49 \times 0.2) = 240.2 \text{ V}$$

$$\frac{N_2}{1000} = \frac{240.2}{248.6} \times 1 \rightarrow N_2 = 966.6 \text{ r. p. m}$$

Ex4: A 220V d.c. shunt motor runs at 500 r.p.m. when the armature current is 50 A. Calculate the speed if the torque is doubled. Given that $R_a = 0.2 \Omega$ (neglect armature reaction).

Solution:

$$T_a \propto \phi I_a$$

since ϕ is constant, $T_a \propto I_a$

$$T_{a1} \propto I_{a1}, T_{a2} \propto I_{a2}$$

$$\frac{T_{a2}}{T_{a1}} = \frac{I_{a2}}{I_{a1}}$$

$$2 = \frac{I_{a2}}{50} \rightarrow I_{a2} = 100A$$

Now,

$$\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \quad \text{since } \phi \text{ is constant}$$

$$E_{b1} = 220 - 50 \times 0.2 = 210V$$

$$E_{b2} = 220 - 100 \times 0.2 = 200V$$

$$\frac{N_2}{500} = \frac{200}{210} \rightarrow N_2 = 476 \text{ r.p.m.}$$

Ex5: A 230-V d.c. shunt motor has an armature resistance of 0.5Ω and field resistance of 115Ω . At no load, the speed is 1,200 r.p.m. and the armature current 2.5 A. On application of rated load, the speed drops to 1,120 r.p.m. Determine the line current and power input when the motor delivers rated load.

Solution:

$$E_{b1} = 230 - (0.5 \times 2.5) = 228.75 V$$

$$E_{b2} = 230 - 0.5 I_{a2}$$

$$\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}}$$

$$\frac{1120}{1200} = \frac{230 - 0.5I_{a2}}{228.75}$$

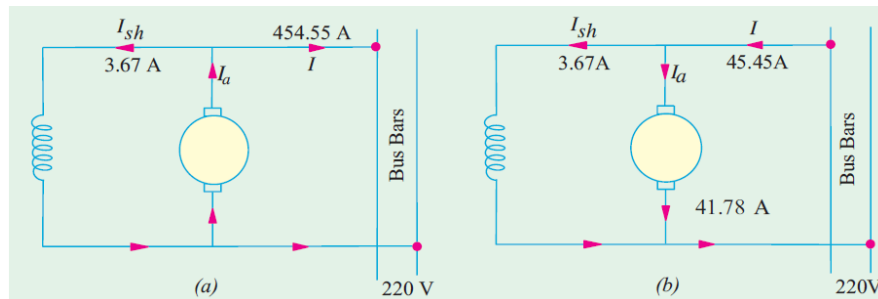
$$I_{a2} = 33 \text{ A}$$

Line current drawn by motor = $I_{a2} + I_{sh} = 33 + (230/115) = 35 \text{ A}$

Power input at rated load = $230 \times 35 = 8,050 \text{ W}$

Ex5: belt-driven 100-kW, shunt generator running at 300 r.p.m. on 220-V busbars continues to run as a motor when the belt breaks, then taking 10 kW. What will be its speed ? Given armature resistance = 0.025Ω , field resistance = 60Ω and contact drop under each brush = 1 V , Ignore armature reaction.

Solution:



As a generator,

$$I = 100,000/220 = 454.55 \text{ A}$$

$$I_{sh} = 220/60 = 3.67 \text{ A}$$

$$I_a = I + I_{sh} = 458.2 \text{ A}$$

$$I_a R_a = 458.2 \times 0.025 = 11.45$$

$$E_g = 220 + 11.45 + 2 \times 1 = 233.45 \text{ V}$$

As a motor,

$$\text{Input line current} = 10,000/220 = 45.45 \text{ A}$$

$$I_{sh} = 220/60 = 3.67 \text{ A}$$

$$I_a = 45.45 - 3.67 = 41.78 \text{ A}$$

$$I_a R_a = 41.78 \times 0.025 = 1.04 \text{ V}$$

$$E_b = 220 - 1.04 - 2 = 216.96 \text{ V}$$

$$\frac{N_b}{N_g} = \frac{E_b}{E_g} \times \frac{\phi_g}{\phi_b}, \phi_g = \phi_b$$

$$\frac{N_2}{300} = \frac{216.9}{233.4} \rightarrow \rightarrow \rightarrow N_2 = 279 \text{ r.p.m}$$

Repeat the above example considering the armature reaction (weakens the field by 3%).

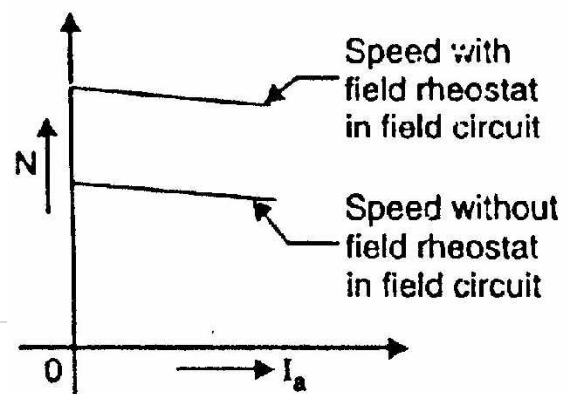
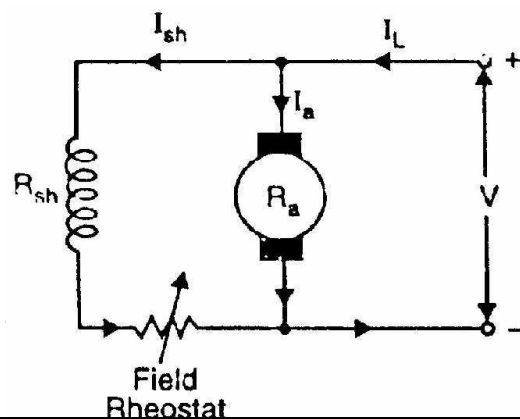
Speed Control of D.C. Shunt Motors

1. Flux control method

It is based on the fact that by varying the flux, the motor speed can be changed and hence the name flux control method. In this method, a variable resistance (known as shunt field rheostat) is placed in series with shunt field winding.

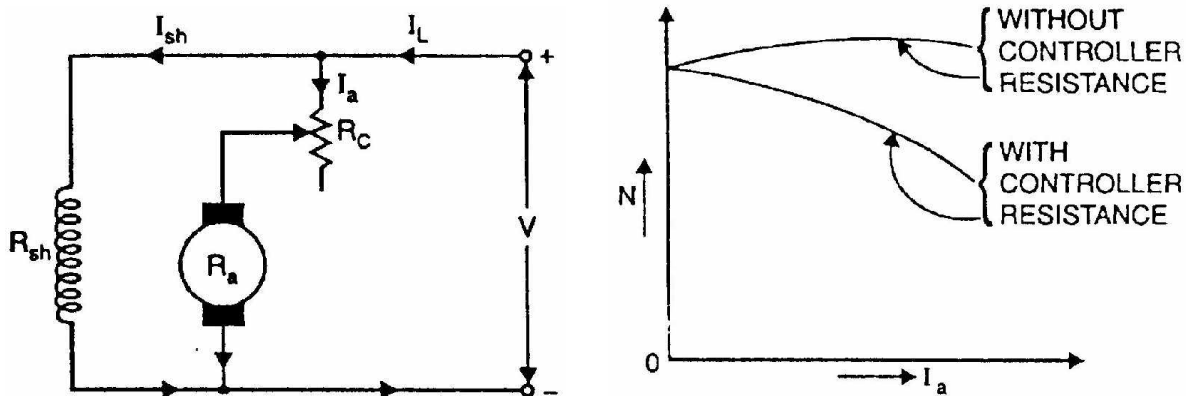
The shunt field rheostat reduces the shunt field current I_{sh} and hence the flux ϕ .

Therefore, we can only raise the speed of the motor above the normal speed. Generally, this method permits to increase the speed in the ratio 3:1.



2. Armature control method

This method is based on the fact that by varying the voltage available across the armature, the back e.m.f and hence the speed of the motor can be changed. This is done by inserting a variable resistance R_c (known as controller resistance) in series with the armature.



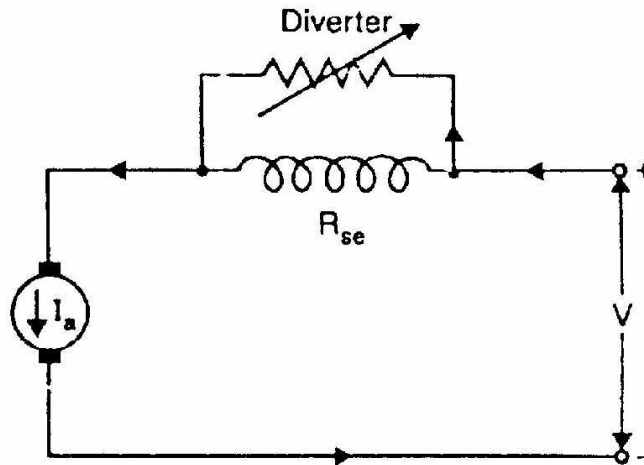
$$N \propto V - I_a(R_a + R_c)$$

Due to voltage drop in the controller resistance, the back e.m.f. (E_b) is decreased. The highest speed obtainable is that corresponding to $R_c = 0$ i.e., normal speed. Hence, this method can only provide speeds below the normal speed.

Speed Control of D.C. Series Motors

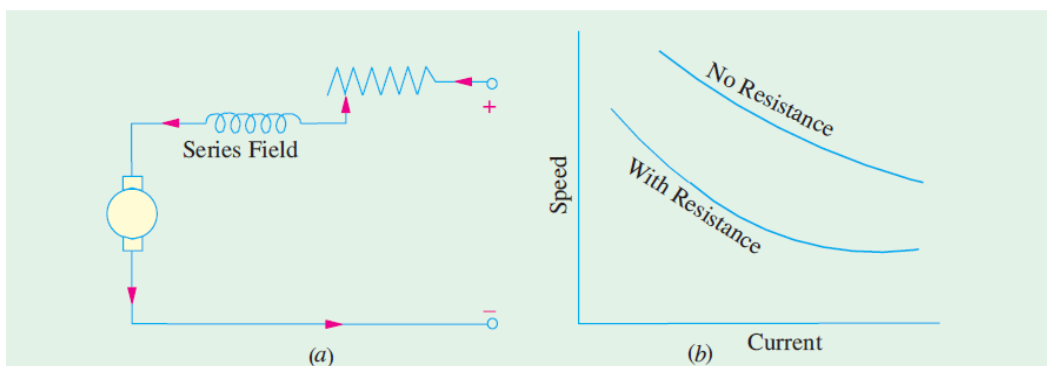
1. Flux control method (Field diverters)

The series winding are shunted by a variable resistance known as field diverter. Any desired amount of current can be passed through the diverter by adjusting its resistance. Hence the flux can be decreased and consequently, the speed of the motor increased.



2. Variable Resistance in Series with Motor

By increasing the resistance in series with the armature (Fig. 30.14) the voltage applied across the armature terminals can be decreased. With reduced voltage across the armature, the speed is reduced. However, it will be noted that since full motor current passes through this resistance, there is a considerable loss of power in it.

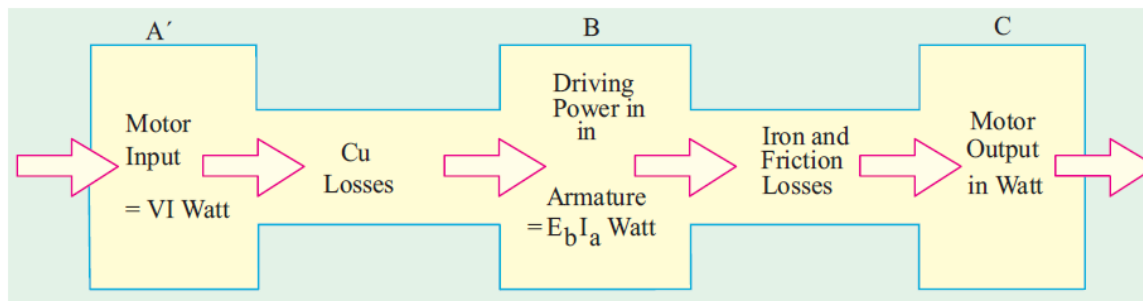


Applications of D.C. Motors

Type of motor	Characteristics	Applications
Shunt	<p>Approximately constant speed</p> <p>Medium starting torque (Up to 1.5 F.L. torque)</p>	<p>For driving constant speed line shafting</p> <p>Lathes</p> <p>Centrifugal pumps</p> <p>Machine tools</p> <p>Blowers and fans</p> <p>Reciprocating pumps</p>
Series	<p>Variable speed</p> <p>Adjustable varying speed</p> <p>High Starting torque</p>	<p>For traction work i.e. Electric locomotives</p> <p>Rapid transit systems</p> <p>Trolley, cars etc.</p> <p>Cranes and hoists</p> <p>Conveyors</p>
Compound	<p>Variable speed</p> <p>Adjustable varying speed</p> <p>High starting torque</p>	<p>For intermittent high torque loads</p> <p>For shears and punches</p> <p>Elevators</p> <p>Conveyors</p> <p>Heavy planers</p> <p>Heavy planers</p> <p>Rolling mills; Ice machines;</p> <p>Printing presses; Air compressors</p>

Power stages

The various stages of energy transformation in a motor and also the various losses occurring in it are shown in the following figure.



Overall or commercial efficiency $\eta_c = C/A$

Electrical efficiency $\eta_e = B/A$

Mechanical efficiency $\eta_m = C/B$

The condition for maximum efficiency is that armature Cu losses are equal to constant losses.

$$I_a^2 R_a = \text{constant losses}$$

Ex6: A 4-pole, 240 V, wave connected shunt motor gives 11.19 kW when running at 1000 r.p.m. and drawing armature and field currents of 50 A and 1.0 A respectively. It has 540 conductors. Its resistance is 0.1 Ω . Assuming a drop of 1 volt per brush, find (a) total torque (b) useful torque (c) useful flux / pole and (d) efficiency.

Solution:

$$E_b = V - I_a R_a - \text{brush drop} = 240 - (50 \times 0.1) - 2 = 233 \text{ V}$$

Also, $I_a = 50 \text{ A}$

$$T_a = 9.55 \frac{E_b I_a}{N}$$

$$= 9.55 \frac{233 \times 50}{1000} = 111 \text{ N.m}$$

$$T_{sh} = 9.55 \frac{\text{output}}{N} = 9.55 \times \frac{11190}{1000} = 106.7 \text{ N.m}$$

$$E_b = \frac{\phi P N Z}{60 A}$$

$$233 = \frac{\phi \times 4 \times 1000}{60} \frac{540}{2} \rightarrow \phi = 12.9 \text{ Wb}$$

Total motor input = $VI = 240 \times 51 = 12,340 \text{ W}$

Efficiency = $11190/12340 = 90.6\%$.

Ex7: A 200-V, d.c. shunt motor takes 4 A at no-load when running at 700 r.p.m. The field resistance is 100Ω and the resistance of armature is 0.6 ohms. Calculate (a) speed on load (b) torque in N-m and (c) efficiency (d) armature current when efficiency is maximum. The normal input of the motor is 8 kW. Neglect armature reaction.

Solution:

(a) $I_{sh} = 200/100 = 2 \text{ A}$

F.L. Power input = 8,000 W

F.L. line current = $8,000/200 = 40 \text{ A}$

$I_a = 40 - 2 = 38 \text{ A}$

$E_{bo} = 200 - 2 \times 0.6 = 198.8 \text{ V}$

$$E_b = 200 - 38 \times 0.6 = 177.2 \text{ V}$$

$$\frac{N}{N_0} = \frac{E_b}{E_{b0}}$$

$$\frac{N}{700} = \frac{177.2}{198.8} \rightarrow N = 924 \text{ r. p. m}$$

$$(b) T_a = 9.55 E_b I_a / N = 9.55 \times 177.2 \times 38 / 623.9 = 103 \text{ N-m}$$

$$(c) \text{N.L. power input} = 200 \times 4 = 800 \text{ W}$$

$$\text{N.L Arm. Cu loss} = I_a^2 R_a = 2^2 \times 0.6 = 2.4 \text{ W}$$

$$\begin{aligned} \text{Constant losses} &= \text{N.L. power input} - \text{N.L Arm. Cu loss} \\ &= 800 - 2.4 = 797.6 \text{ W} \end{aligned}$$

$$\text{F.L. arm. Cu loss} = 38 \times 38 \times 0.6 = 866.4 \text{ W}$$

$$\begin{aligned} \text{Total F.L. losses} &= \text{Constant losses} + \text{F.L. arm. Cu loss} \\ &= 797.6 + 866.4 = 1664 \text{ W} \end{aligned}$$

$$\begin{aligned} \text{F.L. output} &= \text{F.L. Power input} - \text{Total F.L. losses} \\ &= 8000 - 1664 = 6336 \text{ W} \end{aligned}$$

$$\text{F.L. Motor efficiency} = 6336 / 8,000 = 79.2\%$$

(d) When efficiency is maximum,

$$I_a^2 R_a = \text{constant losses}$$

$$I_a^2 \times 0.6 = 797.6 \rightarrow I_a = 36.5 \text{ A}$$

Ex8: A 500-V D.C. shunt motor draws a line-current of 5 A on light-load. If armature resistance is 0.15 ohm and field resistance is 200 ohms determine the efficiency of the machine running as a generator delivering a load current of 40 A. At what speed should the generator be run if the shunt-field is not changed in the above case? Assume that the motor was running at 600 r.p.m.

Solution:

(i) No Load, running as a motor :

$$\text{Input Power} = 500 \times 5 = 2500 \text{ watts}$$

Neglecting armature copper-loss at no load (since it comes out to be $2.5^2 \times 0.15 = 1$ watt)

(ii) As a Generator, delivering 40 A to load :

$$\text{Output delivered} = 500 \times 40 \times 10^3 = 20 \text{ kW}$$

Losses :

(a) Armature copper-loss = $42.5^2 \times 0.15 = 271$ watts

(b) No load losses = 2500 watts

$$\text{Total losses} = 2.771 \text{ kW}$$

$$\text{Generator Efficiency} = (20/22.771) \times 100 \% = 87.83 \%$$

As a motor on no-load,

$$E_{b0} = 500 - I_a \times R_a = 500 - 0.15 \times 2.5 = 499.625 \text{ V}$$

As a Generator with an armature current of 42.5 A,

$$E_{g0} = 500 + 42.5 \cdot 0.15 = 506.375 \text{ V}$$

Since, the terminal voltage is same in both the cases, shunt field current remains as 2.5 amp.

With armature reaction is ignored, the flux/pole remains same. The e.m.f. then becomes proportional to the speed. If the generator must be driven at N r.p.m.

$$N = (506.375/449.625) \times 600 = 608.1 \text{ r.p.m.}$$

Ex9: A 7.46 kW, 250-V shunt motor takes a line current of 5 A when running light.

Calculate the efficiency as a motor when delivering full load output, if the armature and field resistance are 0.5 Ω and 250 Ω respectively. At what output power will the efficiency be maximum? Is it possible to obtain this output from the machine?

Solution:

Total motor input (or total no – load losses) = $250 \times 5 = 1,250 \text{ W}$

$I_{sh} = 250/250 = 1 \text{ A} \therefore I_a = 5 - 1 = 4 \text{ A}$

Field Cu loss = $250 \times 1 = 250 \text{ W};$

Armature Cu loss = $4^2 \times 0.5 = 8 \text{ W}$

Iron losses and friction losses = $1250 - 250 - 8 = 992 \text{ W}$

These losses would be assumed constant.

Let I_a be the full-load armature current, then armature input is = $(250 \times I_a) \text{ W}$

F.L. output = $7.46 \times 1000 = 7,460 \text{ W}$

Armature Cu loss = $I_a^2 \times 0.5 \text{ W}$

$250 I_a = 7,460 + 992 + I_a^2 \times 0.5$

$I_a = 36.5 \text{ A}$

F.L. input current = $36.5 + 1 = 37.5 \text{ A}$

Motor input = $250 \times 37.5 \text{ W}$

F.L. efficiency = $(7460 / 250 \times 37.5) * 100\% = 79.6\%$

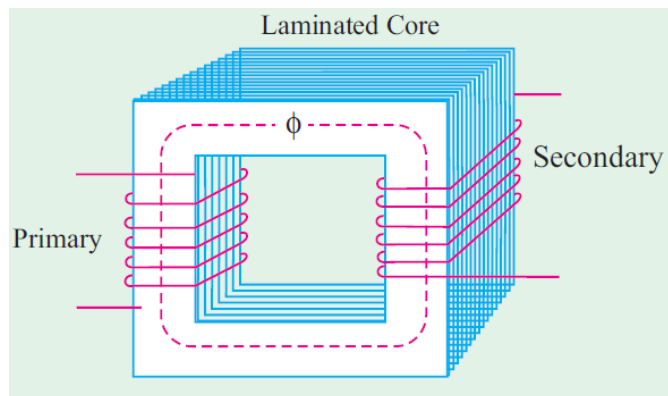
Rest of the solution is H.W.

Chapter Three

Transformers

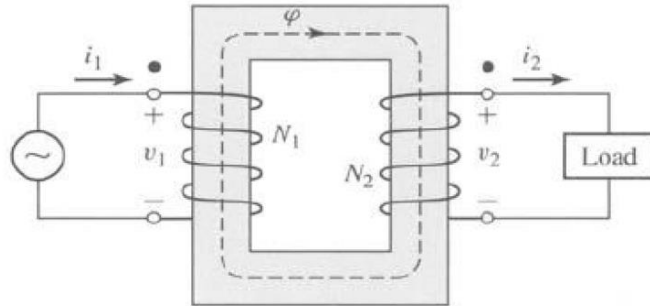
Transformer is a device which transfers electrical energy (power) from one voltage level to another voltage level with a corresponding decrease or increase in current. Unlike in rotating machines (generators and motors), there is no energy conversion. Being a static machine the efficiency of a transformer could be as high as 99%.

Transformer consists of two inductive coils which are electrically separated but magnetically linked through a path of low reluctance. The two coils possess high mutual inductance.



Transformer consists of;

- Primary windings, connected to the alternating voltage source
- Secondary windings, connected to the load;
- Iron core, which link the flux in both windings;



The primary and secondary voltages are denoted by V_1 and V_2 respectively. The current entering the primary terminals is I_1 .

Step-up transformer

If the primary coil has 3 loops and the secondary coil has 30, the voltage is stepped up 10 times.

Step-down transformer

If the primary coil has 30 loops and the secondary coil has 3, the voltage is stepped down 10 times.

E.M.F. Equation of a Transformer

Let N_1 = No. of turns in primary

N_2 = No. of turns in secondary

Φ_m = Maximum flux in the core in webers

f = Frequency of a.c. input in Hz

$$E_1 = 4.44 f N_1 \Phi_m = 4.44 f N_1 B_m A$$

Similarly, value of the e.m.f. induced in secondary is,

$$E_2 = 4.44 f N_2 \Phi_m = 4.44 f N_2 B_m A$$

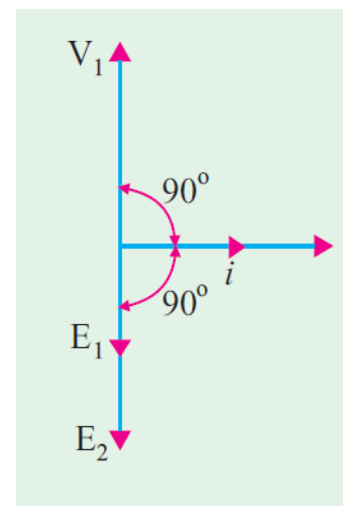
B_m = maximum flux density in core in wb/m^2

A = area of the core

$$\frac{E_1}{N_1} = \frac{E_2}{N_2} = 4.44 f \Phi_m$$

Ideal Transformer

An ideal transformer is one which has no losses i.e. its windings have no ohmic resistance, there is no magnetic leakage and hence which has no I^2R and core losses. In other words, an ideal transformer



consists of two purely inductive coils wound on a loss-free core.

Consider an ideal transformer whose secondary is open and whose primary is connected to sinusoidal alternating voltage V_1 . The primary draws the magnetising current I_μ which produces an alternating flux ϕ . self-induced e.m.f. E_1 is equal to and in opposition to V_1 . It is also known as counter e.m.f. or back e.m.f. of the primary

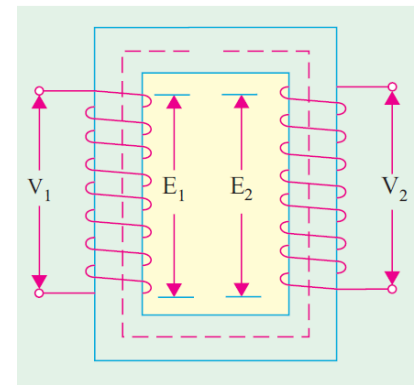
$$E_1 = V_1 \quad , \quad E_2 = V_2$$

Voltage transformation ratio

$$\frac{E_2}{E_1} = \frac{N_2}{N_1} = K$$

This constant K is known as voltage transformation ratio.

- If $K > 1$, then transformer is called step-up transformer.
- If $K < 1$, then transformer is known as step-down transformer.



for an ideal transformer, input VA = output VA

$$V_1 I_1 = V_2 I_2$$

$$\frac{I_2}{I_1} = \frac{V_1}{V_2} = 1/K$$

Example 1 : The maximum flux density in the core of a 250/3000-volts, 50-Hz single-phase transformer is 1.2 Wb/m². If the e.m.f. per turn is 8 volt, determine

(i) primary and secondary turns (ii) area of the core. Assume an ideal transformer.

Solution:

(i) $E_1 = N_1 \times \text{e.m.f. induced/turn}$

$$N_1 = 250/8 = 32$$

$$N_2 = 3000/8 = 375$$

(ii) $E_2 = 4.44 f N_2 B_m A$

$$3000 = 4.44 \times 50 \times 375 \times 1.2 \times A$$

$$A = 0.03\text{m}^2$$

Example 2: A single-phase transformer has 400 primary and 1000 secondary turns. The net cross-sectional area of the core is 60 cm². If the primary winding be connected to a 50-Hz supply at 520 V, calculate (i) the voltage induced in the secondary winding. (ii) the peak value of flux density in the core

Solution:

(i) $K = N_2/N_1$

$$= 1000/400 = 2.5$$

$$E_2/E_1 = K$$

$$E_2 = KE_1$$

$$= 2.5 \times 520 = 1300 \text{ V}$$

(ii)

$$E_1 = 4.44 f N_1 B_m A$$

$$520 = 4.44 \times 50 \times 400 \times B_m \times (60 \times 10^{-4})$$

$$B_m = 0.976 \text{ Wb/m}^2$$

Example 3 : A 25-kVA ideal transformer has 500 turns on the primary and 50 turns on the secondary winding. The primary is connected to 3000-V, 50-Hz supply. Find the full-load primary and secondary currents, the secondary e.m.f. and the maximum flux in the core.

Solutions:

$$K = N_2/N_1 = 50/500 = 1/10$$

$$\text{Now, full-load } I_1 = 25,000/3000 = 8.33 \text{ A}$$

$$V_1 I_1 = V_2 I_2$$

$$\text{F.L. } I_2 = I_1/K = 10 \times 8.33 = 83.3 \text{ A}$$

$$E_2 = K E_1 = 3000 \times 1/10 = 300 \text{ V}$$

$$\text{Also, } E_1 = 4.44 f N_1 \Phi_m$$

$$3000 = 4.44 \times 50 \times 500 \times \Phi_m$$

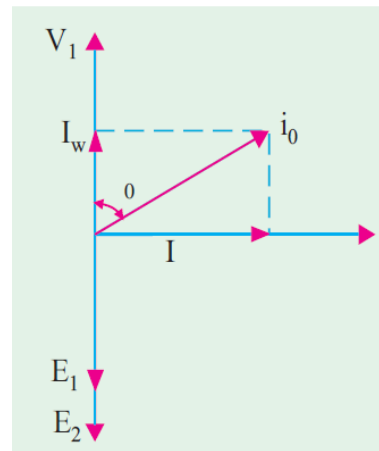
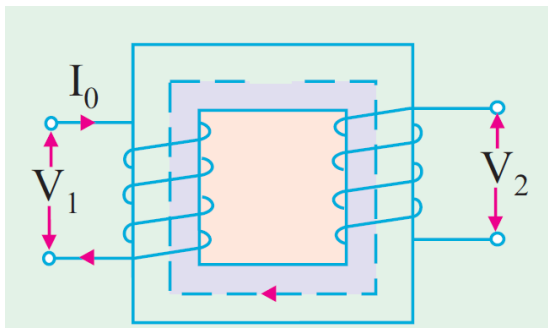
$$\therefore \Phi_m = 27 \text{ mWb}$$

Transformer on no-load

In the above discussion, we assumed an ideal transformer i.e. one in which there were no core losses and copper losses. But practical conditions require that certain modifications be made in the foregoing theory.

When an actual transformer is put on load, there is **iron loss** in the **core** and **copper loss in the windings (both primary and secondary)** and these losses are not entirely negligible.

Hence, the no-load primary input current I_0 is not at 90° behind V_1 but lags it by an angle $\phi_0 < 90^\circ$.



I_0 has two components:

- (i) One in phase with V_1 . This is known as active or working or iron loss component

I_w

$$I_w = I_0 \cos \phi_0$$

(ii) The other component is known as magnetising component I_{μ}

$$I_{\mu} = I_o \sin \phi_o$$

where $\cos \phi_o$ is primary power factor under no-load conditions.

Hence,

$$I_o^2 = (I_{\mu}^2 + I_w^2)$$

As I_o is very small, the no-load primary Cu loss is negligibly small which means that no-load primary input is practically **equal to the iron loss in the transformer.**

No-load input power;

$$w_o = V_1 I_w = V_1 I_o \cos \phi_o \text{ (w)}$$

Example 4: (a) A 2,200/200-V transformer draws a no-load primary current of 0.6 A and absorbs 400 watts. Find the magnetizing and iron loss currents. (b) A 2,200/250-V transformer takes 0.5 A at a p.f. of 0.3 on open circuit. Find magnetizing and working components of no-load primary current.

Solution:

(a) Iron –loss current

$$= \frac{\text{no load input}}{\text{primary voltage}} = \frac{400}{2200} = 0.182 \text{ A}$$

Now,

$$I_o^2 = (I_\mu^2 + I_w^2)$$

Magnetizing component

$$I_\mu = \sqrt{(0.6^2 - 0.182^2)} = 0.572 \text{ A}$$

(b)

$$I_o = 0.5 \text{ A}$$

$$\cos \phi_o = 0.3$$

$$I_w = I_o \cos \phi_o = 0.5 \times 0.3 = 0.15 \text{ A}$$

$$I_\mu = \sqrt{(0.5^2 - 0.15^2)} = 0.476 \text{ A}$$

Example 5: A 2400 V/400V single-phase transformer takes a no-load current of 0.5A and the core loss is 400 W. Determine the values of the angle ϕ_o and the magnetising and core loss components of the no-load current.

Solution:

Iron losses = 400 w

Iron losses = No-load input power =

$$w_o = V_1 I_o \cos \phi_o$$

$$400 = 2400 \times 0.5 \times \cos \phi_o$$

$$\cos \phi_o = 0.3333$$

$$\phi_o = \cos^{-1} 0.3333 = 70.53^\circ$$

$$I\mu = I_o \sin \phi_o = 0.471 \text{ A}$$

$$I_w = I_o \cos \phi_o = 0.167 \text{ A}$$

Transformer on-load

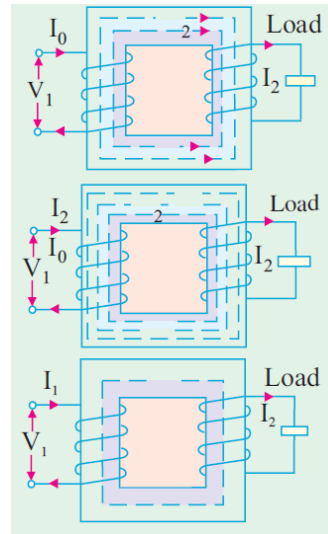
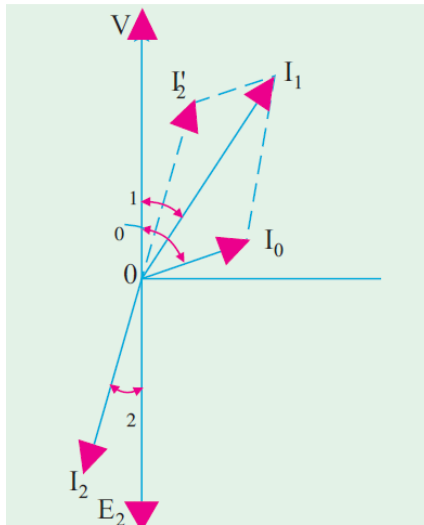
When the secondary is loaded, the secondary current I_2 is set up. The magnitude and phase of I_2 with respect to V_2 is determined by the characteristics of the load. The secondary current sets up its own m.m.f. ($=N_2I_2$) and hence its own flux Φ_2 which is in opposition to the main primary flux Φ which is due to I_o . The opposing secondary flux Φ_2 weakens the primary flux Φ momentarily, hence primary back e.m.f. E_1 tends to be reduced. For a moment V_1 gains the upper hand over E_1 and hence causes more current to flow in primary.

Let the additional primary current be I_2' . This current sets up its own flux Φ_2' which is in opposition to Φ_2 (but is in the same direction as Φ) and is equal to it in magnitude. Hence, the two cancel each other out. So,

$$\Phi_2 = \Phi_2'$$

$$N_2I_2 = N_1I_2'$$

$$I_2' = \frac{N_2}{N_1} \times I_2 = KI_2$$



$$I_0 \cos \phi_0 + I_2' \cos \phi_2 = I_1 \cos \phi_1$$

$$I_0 \sin \phi_0 + I_2' \sin \phi_2 = I_1 \sin \phi_1$$

Example 6: A single-phase transformer with a ratio of 440/110-V takes a no-load current of 5A at 0.2 power factor lagging. If the secondary supplies a current of 120 A at a p.f. of 0.8 lagging, estimate the current taken by the primary.

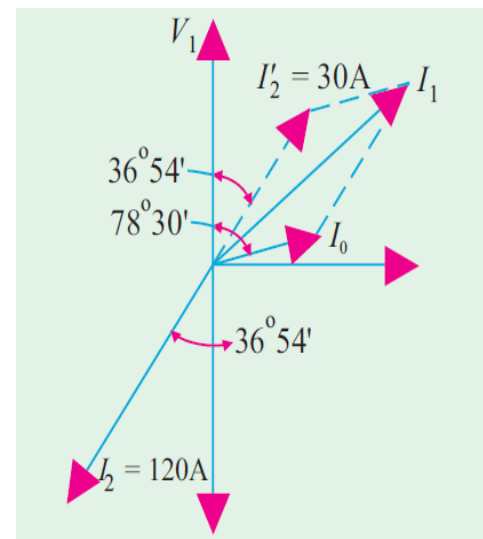
Solution:

$$\cos \phi_0 = 0.2$$

$$\phi_0 = \cos^{-1} 0.2 = 78.46^\circ$$

$$\cos \phi_2 = 0.8$$

$$\phi_2 = \cos^{-1} 0.8 = 36.86^\circ$$



$$K = V_2/V_1 \\ = 110/440 = 1/4$$

$$I_2' = KI_2 = 30 \times 0.25 = 30 \text{ A}$$

$$I_0 = 5 \text{ A}$$

Angle between I_0 and I_2'

$$\phi_z = 78.46^\circ - 36.86^\circ = 41.6^\circ$$

$$I_1 = \sqrt{I_2'^2 + I_0^2 + 2I_2'I_0 \cos(\phi_z)}$$

$$I_1 = 33.9 \text{ A}$$

Example 7: A transformer has a primary winding of 800 turns and a secondary winding of 200 turns. When the load current on the secondary is 80 A at 0.8 power factor lagging, the primary current is 25 A at 0.707 power factor lagging. Determine graphically and the no-load current of the transformer and its phase with respect to the voltage.

Solution:

$$K = 200/800 = 1/4$$

$$I_2' = (80)(1/4) = 20 \text{ A}$$

$$\phi_2 = \cos^{-1} 0.8 = 36.9^\circ$$

$$\phi_1 = \cos^{-1} 0.707 = 45^\circ$$

$$I_0 \cos \phi_0 + I_2' \cos \phi_2 = I_1 \cos \phi_1$$

$$I_0 \cos \phi_0 + 20 \cos 36.9 = 25 \cos 45$$

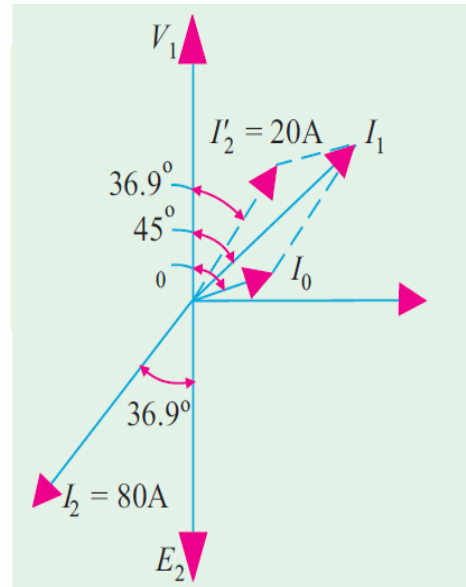
$$I_0 \cos \phi_0 = 1.675 \text{ A}$$

$$I_0 \sin \phi_0 + I_2' \sin \phi_2 = I_1 \sin \phi_1$$

$$I_0 \sin \phi_0 = 5.675 \text{ A}$$

$$\tan \phi_0 = \frac{5.675}{1.675} = 3.388$$

$$\phi_0 = 73.3^\circ$$



Now,

$$I_0 = \frac{5.675}{\sin 73.3} = 5.93 \text{ A}$$

Transformer losses and efficiency

There are broadly two sources of losses in transformers **on load**, these being copper losses and iron losses.

- **Copper losses** are **variable** and result in a heating of the conductors, due to the fact that they possess resistance. If R_1 and R_2 are the primary and secondary winding resistances then the total copper loss

$$I_1^2 R_1 + I_2^2 R_2$$

- **Iron losses** are constant for a given value of **frequency** and **flux density** and are of two types – hysteresis loss and eddy current loss.

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

$$\eta = 1 - \frac{\text{losses}}{\text{input power}}$$

$$\text{Output power} = V_2 I_2 \cos \phi_2$$

Total losses = copper loss + iron losses

input power = output power + losses

For maximum efficiency

Cu loss = Iron loss

$$w_i = I_1^2 R_1 \text{ or } I_2^2 R_2$$

The output current corresponding to maximum efficiency is;

$$I_2 = \sqrt{\frac{W_i}{R_2}}$$

Load KVA corresponding to maximum efficiency is given by;

$$= \text{Full load (KVA)} \times \sqrt{\frac{\text{iron loss}}{\text{F.L cu loss}}}$$

Example 8: A 200 kVA rated transformer has a full-load copper loss of 1.5 kW and an iron loss of 1 kW. Determine the transformer efficiency at (a) full load and 0.85 power factor. (b) a half full load and 0.85 power factor.

Solution:

$$\begin{aligned} \text{(a) Full-load output power} &= V_2 I_2 \cos \phi_2 \\ &= 200 \times 0.85 = 170 \text{ KW} \end{aligned}$$

$$\begin{aligned} \text{Total losses} &= \text{copper loss} + \text{iron loss} \\ &= 1 + 1.5 = 2.5 \text{ KW} \end{aligned}$$

$$\begin{aligned} \text{Input power} &= \text{output power} + \text{total losses} \\ &= 170 + 2.5 = 172.5 \text{ KW} \end{aligned}$$

$$\begin{aligned} \eta &= 1 - \frac{\text{losses}}{\text{input power}} \\ \eta &= 1 - \frac{2.5}{172.5} = 98.55\% \end{aligned}$$

$$\begin{aligned} \text{(b) Half full load output power} &= 0.5 \times 200 \times 0.85 \\ &= 85 \text{ KW} \end{aligned}$$

Copper loss (or I^2R loss) is proportional to current squared. Hence the copper loss at half full-load is;

$$(0.5)^2 (1500) = 375 \text{ W}$$

$$\text{Iron loss} = 1000 \text{ W (constant)}$$

$$\text{Total loss} = 1000 + 375 = 1375 \text{ W}$$

$$\text{Input power} = 85000 + 1375 = 86375 \text{ W}$$

$$\eta = 1 - \frac{1375}{86375} = 98.41\%$$

Example 9: A 11000/230 V, 150-kVA, 1-phase, 50-Hz transformer has core loss of 1.4 kW and F.L. Cu loss of 1.6 kW. Determine

- (i) the kVA load for max. efficiency and value of max. efficiency at unity p.f.
- (ii) the efficiency at half F.L. 0.8 p.f. leading

Solution:

Load corresponding to max. efficiency is

$$\begin{aligned} &= \text{F. L (KVA)} \times \sqrt{\frac{\text{iron loss}}{\text{F. L cu loss}}} \\ &= 150 \times \sqrt{\frac{1.4}{1.6}} = 140 \text{ KVA} \end{aligned}$$

Since Cu loss equals iron loss at maximum efficiency,

$$\text{Total loss} = 1.4 + 1.4 = 2.8 \text{ KW}$$

$$\text{Output} = 140 \times 1 = 140 \text{ KVA}$$

$$\eta_{\max} = \frac{140}{142.8} = 98\%$$

$$\text{Cu at half full load} = 1.6 \times (1/2)^2 = 0.4 \text{ KW}$$

$$\text{Total loss} = 0.4 + 1.4 = 1.8 \text{ KW}$$

$$\text{Half F.L. output at 0.8 p.f.} = (150/2) \times 0.8 = 60 \text{ KW}$$

$$\eta = \frac{60}{60 + 1.8} = 97\%$$

Example 10: A 200-kVA transformer has an efficiency of 98% at full load. If the max. efficiency occurs at three quarters of full-load, calculate the efficiency at half load. Assume negligible magnetizing current and p.f. 0.8 at all loads.

Solution:

As given, the transformer has a F.L. efficiency of 98 % at 0.8 p.f.

$$\text{F.L. output} = 200 \times 0.8 = 160 \text{ kW}$$

$$\text{F.L. input} = 160/0.98 = 163.265 \text{ kW}$$

$$\text{F.L. losses} = 163.265 - 160 = 3.265 \text{ kW}$$

This loss consists of F.L. Cu loss x and iron loss y .

$$x + y = 3.265 \text{ kW}$$

It is also given that η_{max} occurs at three quarters of full-load when Cu loss becomes equal to iron loss.

$$\text{Cu loss at 75 \% of F.L.} = x (3/4)^2 = 9x/16$$

Since y remains constant, hence

$$9x/16 = y$$

By substituting the two equations, we get;

$$x + 9x/16 = 3265$$

$$x = 2090 \text{ W}; y = 1175 \text{ W}$$

Half-load Unity p.f

$$\text{Cu loss} = 2090 \times (1/2)^2 = 522 \text{ W}$$

$$\text{total loss} = 522 + 1175 = 1697 \text{ W}$$

$$\text{Output} = 100 \times 0.8 = 80 \text{ kW}$$

$$\eta = \frac{80}{80 + 1.697} = 97.9\%$$

Cooling of Transformers

In all electrical machines, the losses produce heat and means must be provided to keep the temperature low. In generators and motors, the rotating unit serves as a fan causing air to circulate and carry away the heat. However, a transformer has no rotating parts. Therefore, some other methods of cooling must be used.

Heat is produced in a transformer by the iron losses in the core and I^2R loss in the windings. To prevent undue temperature rise, this heat is removed by cooling.

1. In small transformers (below 50 kVA), natural air cooling is employed i.e., the heat produced is carried away by the surrounding air
2. Medium size power or distribution transformers are generally cooled by housing them in tanks filled with oil. The oil serves a double purpose, carrying the heat from the windings to the surface of the tank and insulating the primary from the secondary.
3. For large transformers, external radiators are added to increase the cooling surface of the oil filled tank. The oil circulates around the transformer and moves through the radiators where the heat is released to surrounding air. Sometimes cooling fan for large transformers, external radiators are added to increase the cooling surface of the oil filled tank. The oil circulates around the transformer and moves through the radiators where the heat is released to surrounding air. Sometimes cooling fans blow air over the radiators to accelerate the cooling processes blow air over the radiators to accelerate the cooling process.

All-day transformer

The ordinary or commercial efficiency of a transformer is defined as the ratio of output power to the input power i.e.,

$$\text{Commercial efficiency} = \text{Output power} / \text{Input power}$$

There are certain types of transformers whose performance cannot be judged by this efficiency. For instance, distribution transformers used for supplying lighting loads have their primaries energized all the 24 hours in a day but the secondary supply little or no load during the major portion of the day. It means that a constant loss (i.e., iron loss) occurs during the whole day but copper loss occurs only when the transformer is loaded and would depend upon the magnitude of load.

Consequently, the copper loss varies considerably during the day and the commercial efficiency of such transformers will vary from a low value (or even zero) to a high value when the load is high. The performance of such transformers is judged on the basis of energy consumption during the whole day (i.e., 24 hours). This is known as all-day or energy efficiency.

The ratio of output in kWh to the input in kWh of a transformer over a 24-hour period is known as all-day efficiency i.e.,

$$\eta_{all-day} = \frac{\text{kWh output in 24 hours}}{\text{kWh input in 24 hours}}$$

Example 11. A 100-kVA lighting transformer has a full-load loss of 3 kW, the losses being equally divided between iron and copper. During a day, the transformer operates on full-load for 3 hours, one half-load for 4 hours, the output being negligible for the remainder of the day. Calculate the all-day efficiency.

Solution:

It should be noted that lighting transformers are taken to have a load p.f. of unity.

$$\text{Iron loss for 24 hour} = 1.5 \times 24 = 36 \text{ kWh}$$

$$\text{F.L. Cu loss} = 1.5 \text{ kW}$$

$$\text{Cu loss for 3 hours on F.L.} = 1.5 \times 3 = 4.5 \text{ kWh}$$

$$\text{Cu loss at half full-load} = 1.5/4 \text{ kW}$$

$$\text{Cu loss for 4 hours at half the load} = (1.5/4) \times 4 = 1.5 \text{ kWh}$$

$$\text{Total losses} = 36 + 4.5 + 1.5 = 42 \text{ kWh}$$

$$\text{Total output} = (100 \times 3) + (50 \times 4) = 500 \text{ kWh}$$

$$\eta_{\text{all-day}} = 500 \times 100/542 = 92.26 \%$$

Incidentally, ordinary or commercial efficiency of the transformer is

$$= 100/(100 + 3) = 0.971 \text{ or } 97.1 \%$$

Example 12: A 5-kVA distribution transformer has a full-load efficiency at unity p.f. of 95 %, the copper and iron losses then being equal. Calculate its all-day efficiency if it is loaded throughout the 24 hours as follows :

No load for 10 hours Quarter load for 7 hours

Half load for 5 hours Full load for 2 hours

Assume load p.f. of unity.

Solution:

$$\text{Output} = 5 \times 1 = 5 \text{ kW} ; \text{Input} = 5/0.95 = 5.264 \text{ kW}$$

$$\text{Losses} = (5.264 - 5.000) = 0.264 \text{ kW} = 264 \text{ W}$$

Since efficiency is maximum, the losses are divided equally between Cu and iron.

$$\text{Cu loss at F.L. of 5 kVA} = 264/2 = 132 \text{ W} ; \text{Iron loss} = 132 \text{ W}$$

$$\text{Cu loss at one-fourth F.L.} = (1/4)^2 \times 132 = 8.2 \text{ W}$$

$$\text{Cu loss at one-half F.L.} = (1/2)^2 \times 132 = 33 \text{ W}$$

$$\text{Quarter load Cu loss for 7 hours} = 7 \times 8.2 = 57.4 \text{ Wh}$$

$$\text{Half-load Cu loss for 5 hours} = 5 \times 33 = 165 \text{ Wh}$$

$$\text{F.L. Cu loss for 2 hours} = 2 \times 132 = 264 \text{ Wh}$$

$$\text{Total Cu loss during one day} = 57.4 + 165 + 264 = 486.4 \text{ Wh} = 0.486 \text{ kWh}$$

$$\text{Iron loss in 24 hours} = 24 \times 132 = 3168 \text{ Wh} = 3.168 \text{ kWh}$$

$$\text{Total losses in 24 hours} = 3.168 + 0.486 = 3.654 \text{ kWh}$$

Since load p.f. is to be assumed as unity.

$$\text{F.L. output} = 5 \times 1 = 5 \text{ kW} ; \text{Half F.L. output} = (5/2) \times 1 = 2.5 \text{ kW}$$

$$\text{Quarter load output} = (5/4) \times 1 = 1.25 \text{ kW}$$

$$\text{Transformer output in a day of 24 hours} = (7 \times 1.25) + (5 \times 2.5) + (2 \times 5) = 31.25 \text{ kWh}$$

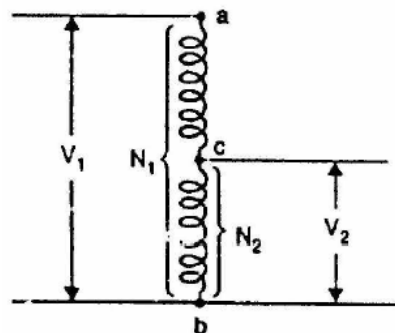
$$\text{Efficiency all day} = 89.53 \%$$

Auto Transformers

An autotransformer has a single winding on an iron core and a part of winding is common to both the primary and secondary circuits. Fig (i) below shows the connections of a step-down autotransformer whereas Fig. (ii) Shows the connections of a step-up autotransformer. In either case, the winding ab having

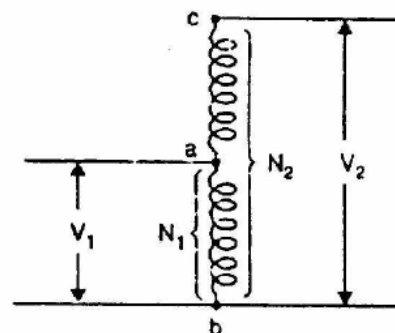
N_1 turns is the primary winding and winding be having N_2 turns is the secondary winding. Note that the primary and secondary windings are connected electrically as well as magnetically. Therefore, power from the primary is transferred to the secondary conductively as well as inductively ((transformer action). The voltage transformation ratio K of an ideal autotransformer is

$$K = \frac{V_2}{V_1} = \frac{N_2}{N_1} = \frac{I_1}{I_2}$$



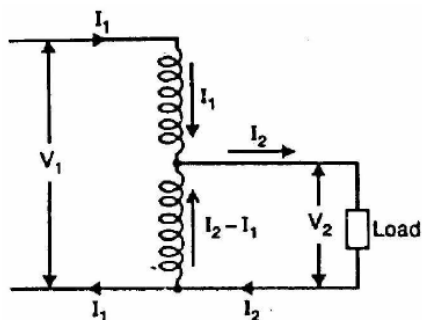
Step-down autotransformer

(i)

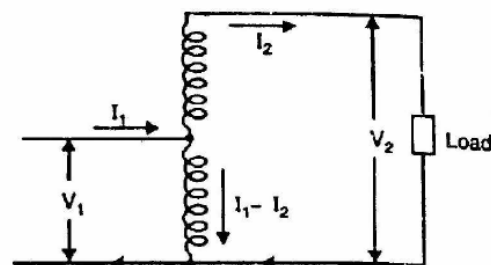


Step-up autotransformer

(ii)



Step-down autotransformer



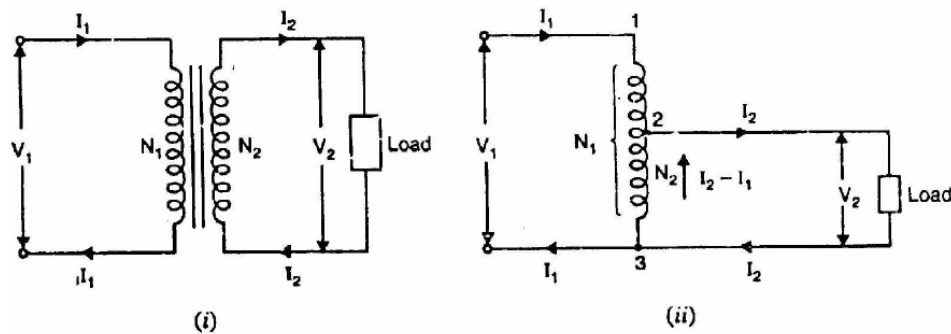
Step-up autotransformer

Saving of Copper in Autotransformer

For the same output and voltage transformation ratio $K(N_2/N_1)$, an autotransformer requires less copper than an ordinary 2-winding transformer.

The length of copper required in a winding is proportional to the number of turns and the area of cross-section of the winding wire is proportional to the current rating. Therefore, the volume and hence weight of copper required in a winding is proportional to current \times turns i.e.,

Weight of Cu required in a winding \propto current \times turns



Winding transformer

Weight of Cu required $\propto (I_1 N_1 + I_2 N_2)$

Autotransformer

Weight of Cu required in section 1-2 $\propto I_1(N_1 - N_2)$

Weight of Cu required in section 2-3 $\propto (I_2 - I_1)N_2$

\therefore Total weight of Cu required $\propto I_1(N_1 - N_2) + (I_2 - I_1)N_2$

$$\begin{aligned}
 \frac{\text{Weight of Cu in autotransformer}}{\text{Weight of Cu in ordinary transformer}} &= \frac{I_1(N_1 - N_2) + (I_2 - I_1)N_2}{I_1N_1 + I_2N_2} \\
 &= \frac{N_1I_1 - N_2I_1 + N_2I_2 - N_2I_1}{N_1I_1 + N_2I_2} \\
 &= \frac{N_1I_1 + N_2I_2 - 2N_2I_1}{N_1I_1 + N_2I_2} \\
 &= 1 - \frac{2N_2I_1}{N_1I_1 + N_2I_2} \\
 &= 1 - \frac{2N_2I_1}{2N_1I_1} \quad (\because N_2I_2 = N_1I_1) \\
 &= 1 - \frac{N_2}{N_1} = 1 - K
 \end{aligned}$$

$$\begin{aligned}
 \therefore \text{Wt. of Cu in autotransformer (} W_a \text{)} \\
 &= (1 - K) \times \text{Wt. in ordinary transformer (} W_o \text{)}
 \end{aligned}$$

or $W_a = (1 - K) \times W_o$

\therefore Saving in Cu = $W_o - W_a = W_o - (1 - K)W_o = K W_o$

or Saving in Cu = $K \times$ Wt. of Cu in ordinary transformer

Thus if $K = 0.1$, the saving of Cu is only 10% but if $K = 0.9$, saving of Cu is 90%. Therefore, the nearer the value of K of autotransformer is to 1, the greater is the saving of Cu.

Advantages of autotransformers

- (i) An autotransformer requires less Cu than a two-winding transformer of similar rating.
- (ii) An autotransformer operates at a higher efficiency than a two-winding transformer of similar rating.

-
- (iii) An autotransformer has better voltage regulation than a two-winding transformer of the same rating.
 - (iv) An autotransformer has smaller size than a two-winding transformer of the same rating.
 - (v) An autotransformer requires smaller exciting current than a two-winding transformer of the same rating.