DC Machines and Transformers (DCMT)

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UNIT–I:

Electromechanical Energy Conversion and introduction to DC machines

Principles of electromechanical energy conversion – singly excited and multi excited system– Calculation of force and torque using the concept of co-energy. Construction and principle of operation of DC machine – EMF equation for generator –Classification of DC machines based on excitation – OCC of DC shunt generator.

UNIT–II:

Performance of D.C. Machines

Torque and back-emf equations of dc motors– Armature reaction and commutation – characteristics of separately-excited, shunt, series and compound motors - losses and efficiency- applications of dc motors.

UNIT-III:

Starting, Speed Control and Testing of D.C. Machines

Necessity of starter – Starting by 3 point and 4 point starters – Speed control by armature voltage and field control – testing of DC machines - brake test, Swinburne's method –principle of regenerative or Hopkinson's method - retardation test -- separation of losses.

UNIT–IV:

Single-phase Transformers

Types and constructional details - principle of operation - emf equation - operation on no load and on load –

lagging, leading and unity power factors loads - phasor diagrams of transformers – equivalent circuit – regulation – losses and efficiency – effect of variation of frequency and supply voltage on losses – All day efficiency.

UNIT-V

Single-phase Transformers Testing

Tests on single phase transformers – open circuit and short circuit tests – Sumpner's test –separation of losses – parallel operation with equal voltage ratios – auto transformer -equivalent circuit – comparison with two winding transformers.

UNIT-VI

3-Phase Transformers

Polyphase connections - Y/Y, Y/Δ, Δ/Y, Δ/Δ and open Δ -- Third harmonics in phase voltages- three winding transformers: determination of Zp, Zs and Zt -- transients in switching – off load and on load tap changers -- Scott connection.

Pre-requisites

- Basic mathematical fundamentals
- Electrical circuits-II
- Engineering drawing

Learning objectives:

- Understand the unifying principles of electromagnetic energy conversion.
- Understand the construction, principle of operation and performance of DC machines.
- Learn the characteristics, performance, methods of speed control and testing methods of DC motors.
- To predetermine the performance of single phase transformers with equivalent circuit models.
- Understand the methods of testing of single-phase transformer.
- Analyze the three phase transformers and achieve three phase to two phase conversion.

UNIT I

Introduction D.C. Generator

Principles of Electromechanical Energy Conversion

Why do we study this?

— Electromechanical energy conversion theory is the cornerstone for the analysisof electromechanical motion devices.

— The theory allows us to express the electromagnetic force or torque in terms of the device variables such as the currents and the displacement of the mechanical system.

— Since numerous types of electromechanical devices are used in motion systems,it is desirable to establish methods of analysis which may be applied to a variety of Electromechanical devices rather than just electric machines.

Energy Balance Relationships

— Comprises

- Electric system
- Mechanical system
- Means whereby the electric and mechanical systems can interact

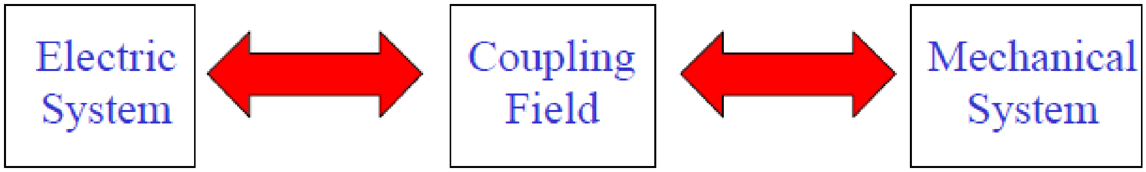
— Interactions can take place through any and all electromagnetic and electrostatic fields which are common to both systems, and energy is transferred as a result of this interaction.

— Both electrostatic and electromagnetic coupling fields may exist simultaneously and the system may have any number of electric and mechanical subsystems.

Electromechanical System in Simplified Form:

- Neglect electromagnetic radiation
- Assume that the electric system operates at a frequency efficiently low so thatthe electric system may be considered as a lumped-parameter system

- **Energy Distribution**
  - WE = total energy supplied *by* the electric source (+)
  - WM = total energy supplied *by* the mechanical source (+)



$$W_E = W_e + W_{eL} + W_{eS}$$
$$W_M = W_m + W_{mL} + W_{mS}$$

— WeS = energy stored in the electric or magnetic fields which are not coupled with the mechanical system

— WeL = heat loss associated with the electric system, excluding the couplingfield losses, which occurs due to:

- The resistance of the current-carrying conductors
- The energy dissipated in the form of heat owing to hysteresis, eddy currents, and dielectric losses external to the coupling field

— We = energy transferred to the coupling field by theelectric system

— WmS = energy stored in the moving member and the compliances of the mechanical system

— WmL = energy loss of the mechanical system in the form of heat due tofriction

— Wm = energy transferred to the coupling field by the mechanical system

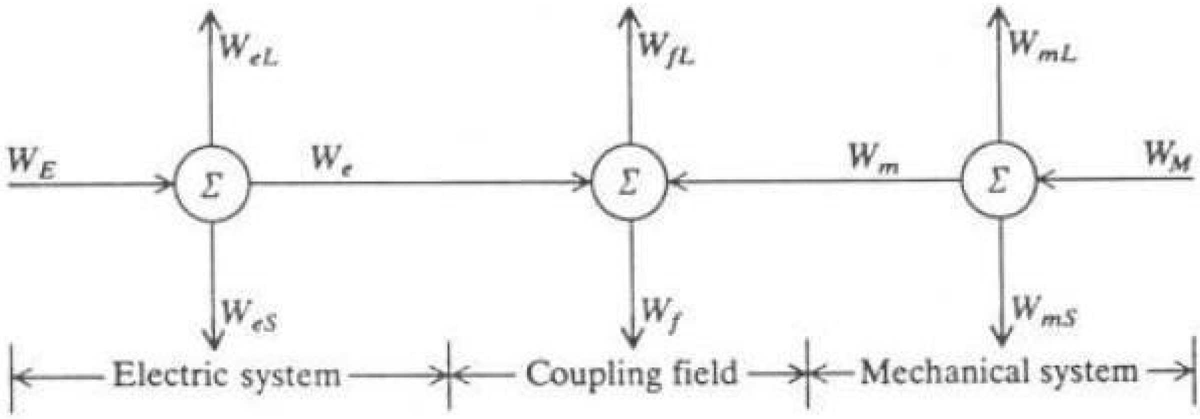
•WF = Wf + WfL = total energy transferred to the coupling field

— Wf = energy stored in the coupling field

— WfL = energy dissipated in the form of heat due to losses within thecoupling field (eddy current, hysteresis, ordi electric losses)

$$W_f + W_{fL} = \left(W_E - W_{eL} - W_{eS}\right) + \left(W_M - W_{mL} - W_{mS}\right)$$
$$W_f + W_{fL} = W_e + W_m$$

If the losses of the coupling field are neglected, then the field is conservative and Wf = We + Wm

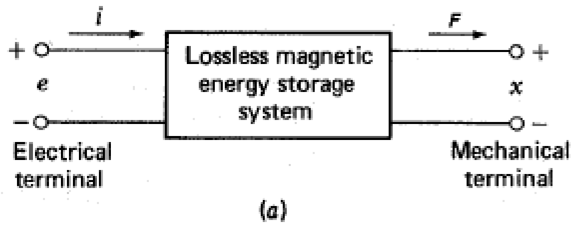


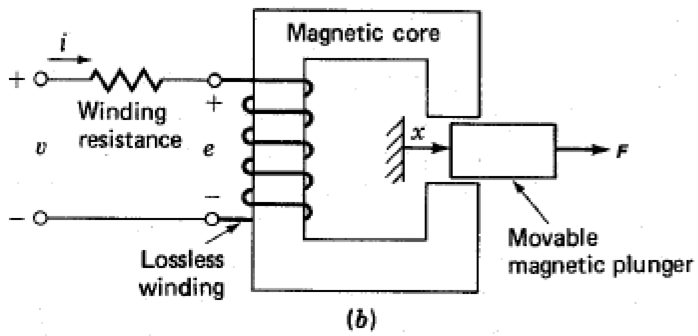
Force and Torque Calculation from Energy and Co-Energy:

A Singly Excited Linear Actuator

Consider a singly excited linear actuator as shown below. The winding resistance is R. At a certain time instant *t*, we record that the terminal voltage applied to the excitation winding is *v*, the excitation winding current *i*, the position of the movable plunger *x*, and the force acting on the plunger **F** with the reference direction chosen in the positive direction of the *x* axis, as shown in the diagram. After a time interval *dt*, we notice that the plunger has moved for a distance *dx* under the action of the force **F**. The mechanical done by the force acting on the plunger during this time interval is thus

$$dW_m = Fdx$$





A singly excited linear actuator

The amount of electrical energy that has been transferred into the magnetic field and converted into the mechanical work during this time interval can be calculated by subtracting the power loss dissipated in the winding resistance from the total power fed into the excitation winding as

$$dW_e = dW_f + dW_m = vidt - Ri^2dt$$

Because

$$e = \frac{d\lambda}{dt} = v - Ri$$

we can write

$$dW_f = dW_e - dW_m = eidt - Fdx$$
$$= id\lambda - Fdx$$

From the above equation, we know that the energy stored in the magnetic field is a function of the flux linkage of the excitation winding and the position of the plunger. Mathematically, we can also write

$$dW_f(\lambda, x) = \frac{\partial W_f(\lambda, x)}{\partial \lambda}d\lambda + \frac{\partial W_f(\lambda, x)}{\partial x}dx$$

Therefore, by comparing the above two equations, we conclude

$$i = \frac{\partial W_f(\lambda, x)}{\partial \lambda} \text{ and } \quad F = -\frac{\partial W_f(\lambda, x)}{\partial x}$$

From the knowledge of electromagnetics, the energy stored in a magnetic field can beexpressed as

$$W_f(\lambda, x) = \int_0^\lambda i(\lambda, x) d\lambda$$

For a magnetically linear (with a constant permeability or a straight line magnetization curve such that the inductance of the coil is independent of the excitation current) system, the above expression becomes

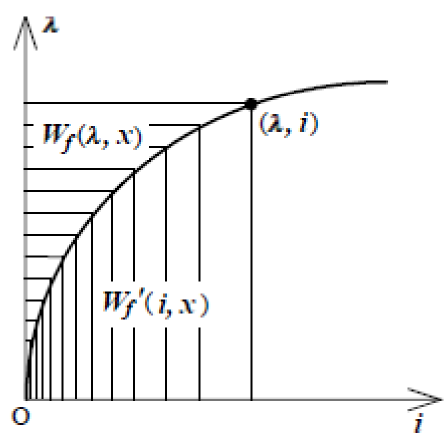
$$W_f(\lambda, x) = \frac{1}{2} \frac{\lambda^2}{L(x)}$$

and the force acting on the plunger is then

$$F = -\frac{\partial W_f(\lambda, x)}{\partial x} = \frac{1}{2}\left[\frac{\lambda}{L(x)}\right]^2 \frac{dL(x)}{dx} = \frac{1}{2} i^2 \frac{dL(x)}{dx}$$

In the diagram below, it is shown that the magnetic energy is equivalent to the area above the magnetization or *l-i* curve. Mathematically, if we define the area underneath the magnetization curve as the ***coenergy*** (which does not exist physically), i.e.

$$W_f'(i, x) = i\lambda - W_f(\lambda, x)$$



Energy and coenergy

we can obtain

$$\begin{aligned} dW_f'(i, x) &= \lambda di + i d\lambda - dW_f(\lambda, x) \\ &= \lambda di + F dx \\ &= \frac{\partial W_f'(i, x)}{\partial i} di + \frac{\partial W_f'(i, x)}{\partial x} dx \end{aligned}$$

Therefore,

$$\lambda = \frac{\partial W_f'(i,x)}{\partial i} \qquad \text{and} \qquad F = \frac{\partial W_f'(i,x)}{\partial x}$$

From the above diagram, the coenergy or the area underneath the magnetization curve can be calculated by

$$W_f'(i,x) = \int_0^i \lambda(i,x)di$$

For a magnetically linear system, the above expression becomes

$$W_f'(i,x) = \frac{1}{2}i^2 L(x)$$

And the force acting on the plunger is then

$$F = \frac{\partial W_f'(i,x)}{\partial x} = \frac{1}{2}i^2 \frac{dL(x)}{dx}$$

Doubly Excited Rotating Actuator

The general principle for force and torque calculation discussed above is equally applicable to multi-excited systems. Consider a doubly excited rotating actuator shown schematically in the diagram below as an example. The differential energy and coenergy functions can be derived as following:

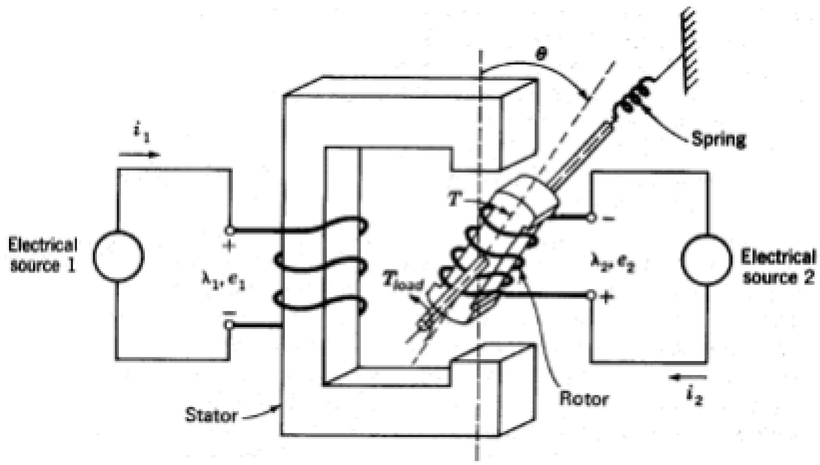
$$dW_f = dW_e - dW_m$$

Where

$$dW_e = e_1 i_1 dt + e_2 i_2 dt$$

$$e_1 = \frac{d\lambda_1}{dt}, \qquad e_2 = \frac{d\lambda_2}{dt}$$

And



A doubly excited actuator

Hence

$$\begin{aligned} dW_f(\lambda_1, \lambda_2, \theta) &= i_1 d\lambda_1 + i_2 d\lambda_2 - Td\theta \\ &= \frac{\partial W_f(\lambda_1, \lambda_2, \theta)}{\partial \lambda_1} d\lambda_1 + \frac{\partial W_f(\lambda_1, \lambda_2, \theta)}{\partial \lambda_2} d\lambda_2 \\ &+ \frac{\partial W_f(\lambda_1, \lambda_2, \theta)}{\partial \theta} d\theta \end{aligned}$$

and

$$\begin{aligned} dW_f'(i_1, i_2, \theta) &= d\left[i_1\lambda_1 + i_2\lambda_2 - W_f(\lambda_1, \lambda_2, \theta)\right] \\ &= \lambda_1 di_1 + \lambda_2 di_2 + Td\theta \end{aligned}$$

$$\begin{aligned} &= \frac{\partial W_f'(i_1, i_2, \theta)}{\partial i_1} di_1 + \frac{\partial W_f'(i_1, i_2, \theta)}{\partial i_2} di_2 \\ &+ \frac{\partial W_f'(i_1, i_2, \theta)}{\partial \theta} d\theta \end{aligned}$$

Therefore, comparing the corresponding differential terms, we obtain

$$T = -\frac{\partial W_f(\lambda_1, \lambda_2, \theta)}{\partial \theta}$$

or

$$T = \frac{\partial W_f'(i_1, i_2, \theta)}{\partial \theta}$$

For magnetically linear systems, currents and flux linkages can be related by constant inductances as following

$$\begin{bmatrix} \lambda_1 \\ \lambda_2 \end{bmatrix} = \begin{bmatrix} L_{11} & L_{12} \\ L_{21} & L_{22} \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix}$$

(or)

$$\begin{bmatrix} i_1 \\ i_2 \end{bmatrix} = \begin{bmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{21} & \Gamma_{22} \end{bmatrix} \begin{bmatrix} \lambda_1 \\ \lambda_2 \end{bmatrix}$$

where $L_{12}=L_{21}$, $\Gamma_{11}=L_{22}/\Delta$, $\Gamma_{12}=\Gamma_{21}=-L_{12}/\Delta$, $\Gamma_{22}=L_{11}/\Delta$, $\Delta=L_{11}L_{22}-L_{12}^2$.

The magnetic energy and coenergy can then be expressed as

$$W_f(\lambda_1, \lambda_2, \theta) = \frac{1}{2}\Gamma_{11}\lambda_1^2 + \frac{1}{2}\Gamma_{22}\lambda_2^2 + \Gamma_{12}\lambda_1\lambda_2$$

and

$$W_f'(i_1, i_2, \theta) = \frac{1}{2}L_{11}i_1^2 + \frac{1}{2}L_{22}i_2^2 + L_{12}i_1 i_2$$

Therefore, the torque acting on the rotor can be calculated as

$$T = -\frac{\partial W_f(\lambda_1, \lambda_2, \theta)}{\partial \theta} = \frac{\partial W_f'(i_1, i_2, \theta)}{\partial \theta}$$

$$= \frac{1}{2} i_1^2 \frac{dL_{11}(\theta)}{\partial \theta} + \frac{1}{2} i_2^2 \frac{dL_{22}(\theta)}{\partial \theta} + i_1 i_2 \frac{dL_{12}(\theta)}{\partial \theta}$$

Because of the salient (not round) structure of the rotor, the self-inductance of the stator is a function of the rotor position and the first term on the right hand side of the above torque expression is nonzero for that $dL11/dq^{1}0$. Similarly, the second term on the right hand side of the above torque express is nonzero because of the salient structure of the stator. Therefore, these two terms are known as the reluctance torque component. The last term in the torque expression, however, is only related to the relative position of the stator and rotor and is independent of the shape of the stator and rotor poles.

1. Introduction:

Although a far greater percentage of the electrical machines in service are a.c. machines, the

D.C machines are of considerable industrial importance. The principal advantage of the d.c. machine, particularly the d.c. motor, is that it provides a fine control of speed. Such an advantage is not claimed by any a.c. motor. However, d.c. generators are not as common as they used to be, because direct current, when required, is mainly obtained from an a.c. supply by the use of rectifiers. Nevertheless, an understanding of d.c. generator is important because it represents a logical introduction to the behaviour of d.c. motors. Indeed many d.c. motors in industry actually operate as d.c. generators for a brief period. In this chapter, we shall deal with various aspects of
d.c. generators.

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.

Simple Loop Generator

Consider a single turn loop ABCD rotating clockwise in a uniform magnetic field with a constant speed as shown in Fig.(1.1). 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 [See Fig. 1.1], the generated e.m.f. is zero because the coil sides (AB and CD) are cutting no flux but are moving parallel to it

(i) 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 in Fig. (1.2).

(i) 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 Fig. (1.2).

(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. (1.2).

(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, See Fig. 1.2) will be when the loop is at position 7 and zero when at position 1. This cycle repeats with each revolution of the coil.

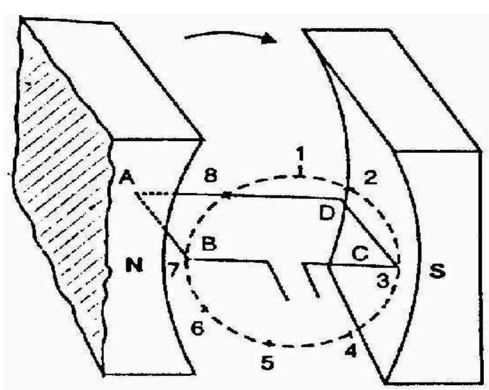


Fig. (1.1)

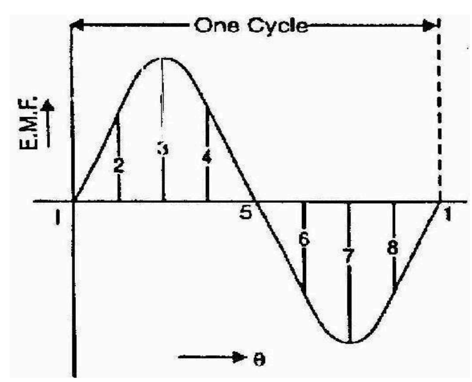


Fig. (1.2)

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. In fact,, a commutator is a mechanical Rectifier.

Action of Commutator

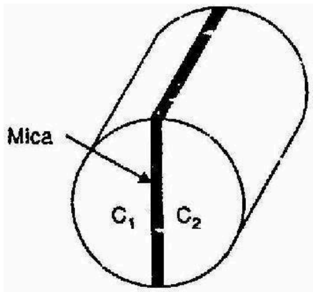
If, somehow, connection of the coil side to the external load is reversed at the same instant the current in the coil side reverses, the current through the load will be direct current. This is what a commutator does. Fig. (1.3) shows a commutator having two segments C_1 and C_2. It consists of a cylindrical 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

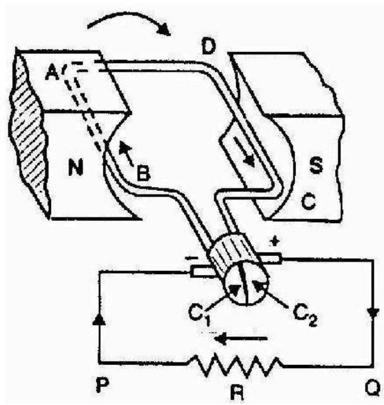
shown in Fig. (1.4). Two stationary carbon brushes rest on the commutator and lead current to the external load. With this arrangement, the commutator at all times connects the coil side under S-pole to the +ve brush and that under N-pole to the −ve brush.

(i) In Fig. (1.4), 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.

(i) 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.





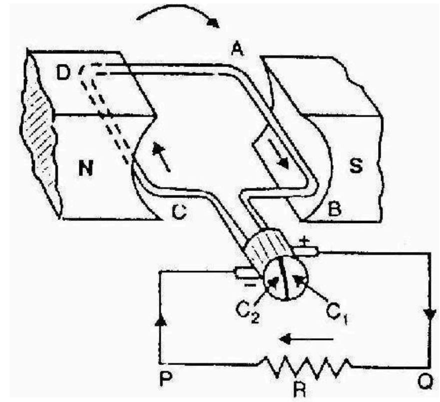


Fig.(1.3) **Fig.(1.4)Fig.(1.5)**

Thus the alternating voltage generated in the loop will appear as direct voltage across the brushes. The reader may note that e.m.f. generated in the armature winding of a d.c. generator is alternating one. It is by the use of commutator that we convert the generated alternating e.m.f. into direct voltage. The purpose of brushes is simply to lead (take) current from the rotating loop or winding to the external stationary load.

The variation of voltage across the brushes with the angular displacement of the loop will be as shown in Fig. (1.6). this is not a steady direct voltage but has a pulsating character. It is

because the voltage appearing across the brushes varies from zero to maximum value and back to zero twice for each revolution of the loop. A pulsating direct voltage such as is produced by a single loop is not suitable for many commercial uses. What we require is the steady direct voltage. This can be achieved by using a large number of coils connected in series. The resulting arrangement is known as armature winding.

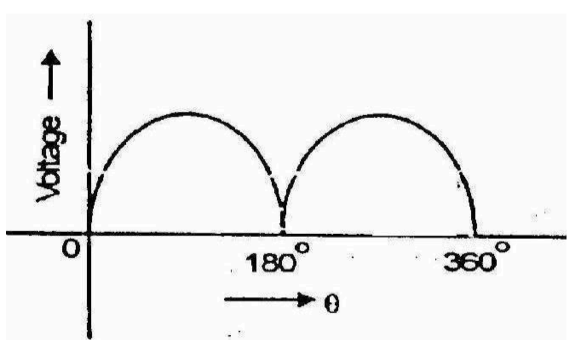


Fig. (1.6)

Construction ofd.c. Generator

The d.c. generators and d.c. motors have the same general construction. In fact, when the machine is being assembled, the workmen usually do not know whether it is a d.c. generator or motor.

Any d.c. generator can be run as a d.c. motor and vice-versa. All d.c. machines have five principal components viz., (i) field system (ii) armature core (iii) armature winding (iv) commutator (v) brushes [See Fig. 1.7].

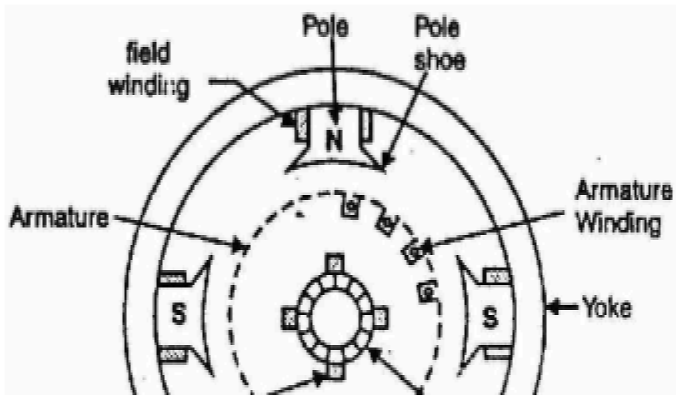


Fig. (1.7)

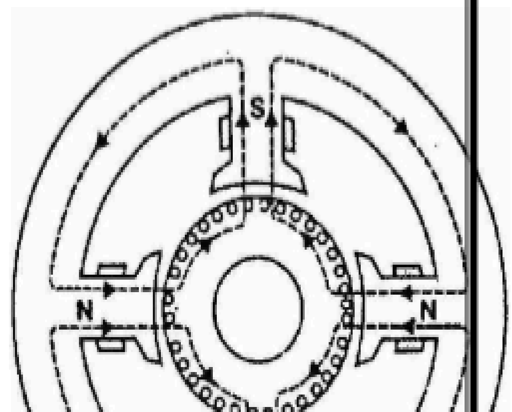


Fig. (1.8)

(i) Field system

The function of the field system is to produce uniform magnetic field within which the armature rotates. It consists of a number of salient poles (of course, even number) bolted to the inside of circular frame (generally called yoke). The yoke is usually made of solid cast steel whereas the pole pieces are composed of stacked laminations. Field coils are mounted on the poles and carry the d.c. 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 (See Fig. 1.8). Practical d.c. machines have air gaps ranging from 0.5 mm to 1.5 mm. Since armature and field systems are composed of materials that have high permeability, most of the m.m.f. of field coils is required to set up flux in the air gap. By reducing the length of air gap, we can reduce the size of field coils (i.e. number of turns).

(ii) Armature core

The armature core is keyed to the machine shaft and rotates between the field poles. It 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 Fig (1.9). The laminations (See Fig. 1.10) are individually coated with a thin insulating film so that they do not come in electrical contact with each other. The purpose of laminating the core is to reduce the eddy current loss. 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".

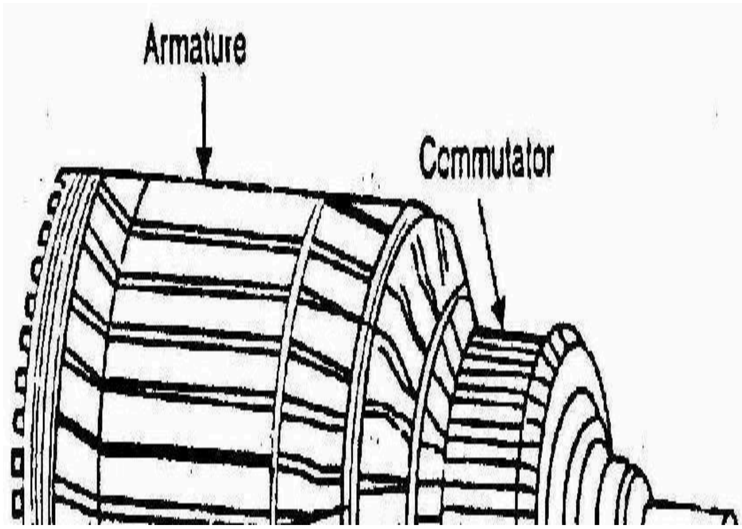


Fig. (1.9)

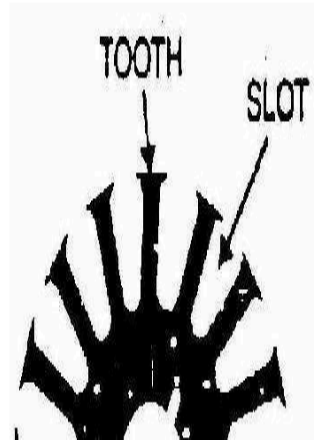


Fig. (1.10)

(iii) 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” e.m.f. 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.

(iv) 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 (See Fig 1.11). The armature conductors are soldered to the commutator segments in a suitable manner to give rise to the armature winding. Depending upon the manner in which the armature conductors are connected to the commutator segments, there are two types of armature winding in a d.c. machine viz., (a) lap winding (b) wave winding.Great care is taken in building the commutator because any eccentricity will cause the brushes to bounce, producing unacceptable sparking. The sparks may bum the brushes and overheat and carbonise the commutator.

(V) Brushes

The purpose of brushes is to ensure electrical connections between the rotating commutator and stationary external load circuit. The brushes are made of carbon and rest on the commutator. The brush pressure is adjusted by means of adjustable springs (See Fig. 1.12). If the brush pressure is very large, the friction produces heating of the commutator and the brushes. On the other hand, if it is too weak, the imperfect contact with the commutator may produce sparking.

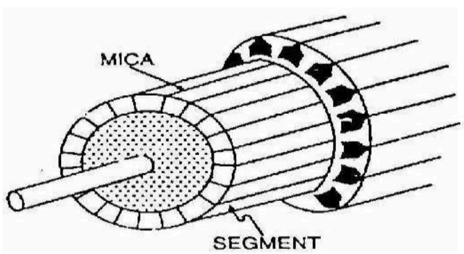


Fig. (1.11)

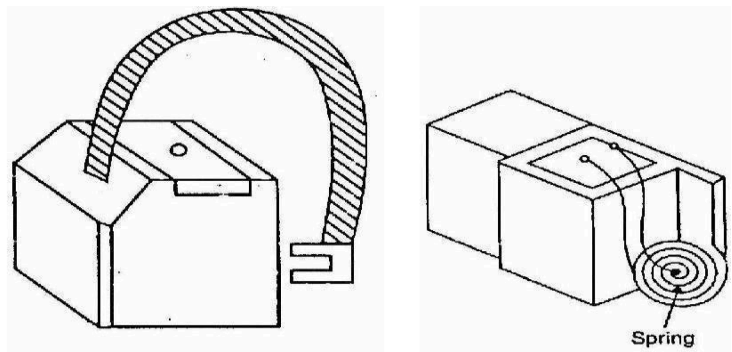


Fig. (1.12)

Multi pole machines have as many brushes as they have poles. For example, a 4-pole machine has 4 brushes. As we go round the commutator, the successive brushes have positive and negative polarities. Brushes having the same polarity are connected together so that we have two terminals viz., the +ve terminal and the - ve terminal.

General Features OF D.C. Armature Windings

(i) A d.c. machine (generator or motor) generally employs windings distributed in slots over the circumference of the armature core. Each conductor lies at right angles to the magnetic flux and to the direction of its movement Therefore, the induced e.m.f. in the conductor is given by;

$e = BlvVolts$

Where, B = magnetic flux density in Wb/m2 l=
length of the conductor in metres v =
velocity (in m/s) of the conductor

(i) The armature conductors are connected to form coils. The basic component of all types of armature windings is the armature coil. Fig. (1.13) (i) shows a single-turn coil. It has two conductors or coil sides connected at the back of the armature. Fig. 1.13 (ii) shows a 4-turn coil which has 8 conductors or coil sides.

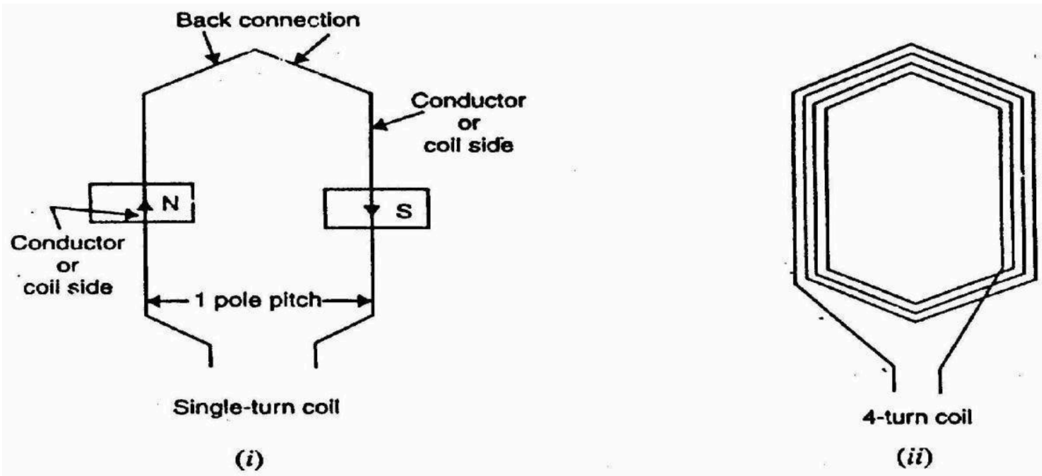
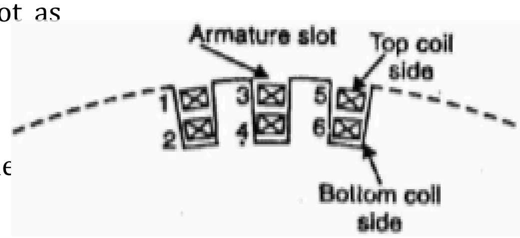


Fig. (1.13)

The coil sides of a coil are placed a pole span apart i.e., one coil side of the coil is under N-pole and the other coil side is under the next S-pole at the corresponding position as shown in Fig. 1.13 (i). Consequently the e.m.f.s of the coil sides add together. If the e.m.f. induced in one conductor is 2.5 volts, then the e.m.f. of a single-turn coil will be = 2 ⍰ 2.5 = 5 volts. For the same flux and speed, the e.m.f. of a 4-turn coil will be = 8 ⍰ 2.5 = 20 V.

(iii) Most of d.c. armature windings are double layer windings i.e., there are two coil sides per slot as shown in Fig. (1.14). One coil side of a coil.



lies at the top of a slot and the other coil side lies the bottom of some other slot. The coil ends then lie

side by side. In two-layer winding, it is desirable to number the coil sides rather than the slots. The coil sides are numbered as indicated in Fig. (1.14). The coil sides at the top of slots are given odd numbers and those at the bottom are given even numbers. The coil sides are numbered in order round the armature.

As discussed above, each coil has one side at the top of a slot and the other side at the bottom of another slot; the coil sides are nearly a pole pitch apart. In connecting the coils, it is ensured that top coil side is joined to the bottom coil side and vice-versa. This is illustrated in Fig. (1.15). The coil side 1 at the top of a slot is joined to coil side 10 at the bottom of another slot about a pole pitch apart. The coil side 12 at the bottom of a slot is joined to coil side 3 at the top of another slot. How coils are connected at the back of the armature and at the front (commutator end) will be discussed in later sections. It may be noted that as far as connecting the coils is concerned, the number of turns per coil is immaterial. For simplicity, then, the coils in winding diagrams will be represented as having only one turn (i.e., two conductors).

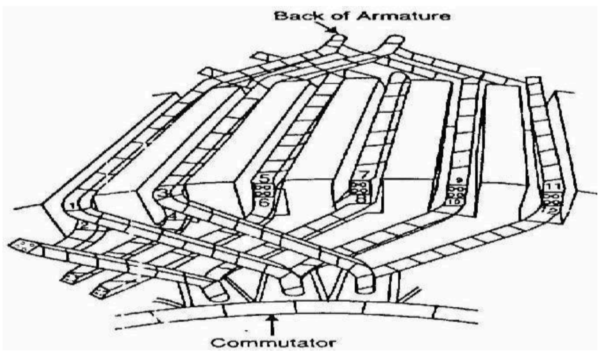


Fig. (1.15)

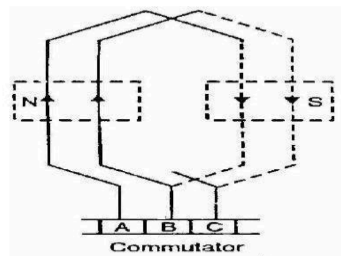


Fig. (1.16)

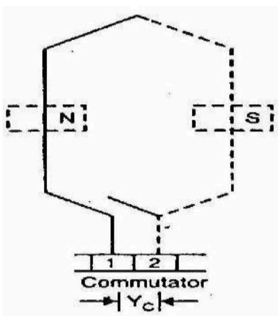
(iv) The coil sides are connected through commutator segments in such a manner as to form a series-parallel system; a number of conductors are connected in series so as to increase the voltage and two or more such series-connected paths in parallel to share the current. Fig(1.16) shows how the two coils connected through commutator segments (A, R, C etc) have their e.m.f.s added together. If voltage induced in each conductor is 2-5 V, then voltage between segments A and C = 4 2.5 = 10 V. It may be noted here that in the conventional way of representing a developed armature winding, full lines represent top coil sides (i.e., coil sides lying at the top of a slot) and dotted lines represent the bottom coil sides (i.e., coil sides lying at the bottom of a slot).

(v) The d.c. armature winding is a closed circuit winding. In such a winding, if one starts at some point in the winding and traces through the winding, one will come back to the starting point without passing through any external connection. D.C. armature windings must be of the closed type in order to provide for the commutation of the coils.

1.6 Commutator Pitch (Y_C)

The commutator pitch is the number of commutator segments spanned by each coil of the winding. It is denoted by Y_C.

In Fig. 1.17, one side of the coil is connected to commutator segment 1 and the other side connected to commutator segment 2. Therefore, the number of commutator segments spanned by the coil is 1 i.e., $Y_C = 1$. In Fig. 1.18, one side of the coil is connected to commutator segment 1 and the other side to commutator segment 8. Therefore, the number of commutator segments spanned by the coil = 8 − 1 = 7 segments i.e., $Y_C = 7$. The commutator pitch of a winding is always a whole number. Since each coil has two ends and as two coil connections are joined at each commutator segment,



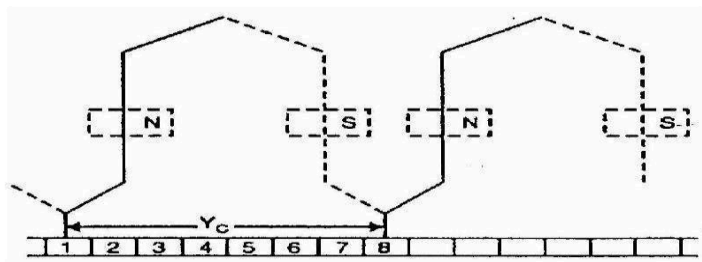


Fig. (1.17) **Fig. (1.18)**

Number of coils = Number of commutator segments

For example, if an armature has 30 conductors, the number of coils will be 30/2 = 15. Therefore, number of commutator segments is also 15. Note that commutator pitch is the most important factor in determining the type of d.c. armature winding.

Full-Pitched Coil

If the coil-span or coil pitch is equal to pole pitch, it is called full-pitched coil (See Fig. 1.19). In this case, the e.m.f.s in the coil sides are additive and have a phase difference of 0°. Therefore,
e.m.f. induced in the coil is maximum. If e.m.f. induced in one coil side is 2-5 V, then e.m.f. across the coil terminals = 2 × 2.5 = 5 V. Therefore, coil span should always be one pole pitch unless there is a good reason for making it shorter

Fractional pitched coil. If the coil span or coil pitch is less than the pole pitch,then it is called fractional pitched coil (See Fig. 1.20). In this case, the phase difference between the e.m.f.s in the two coil sides will not be zero so that the e.m.f. of the coil will be less compared to full-pitched coil. Fractional pitch winding requires less copper but if the pitch is too small, an appreciable reduction in the generated e.m.f. results

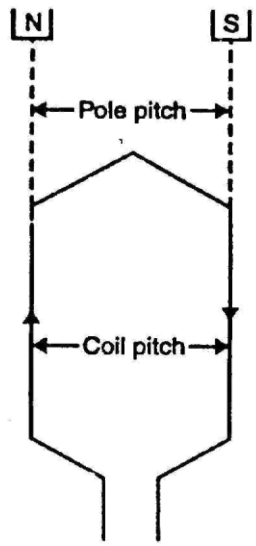


Fig. (1.19)

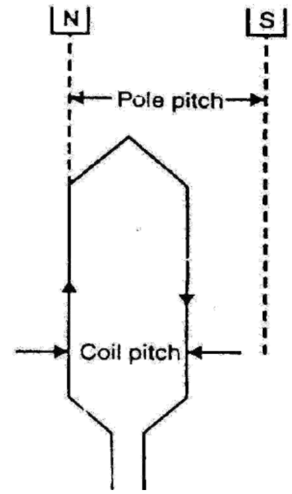


Fig.(1.2)

Types of D.C. Armature Windings

The different armature coils in a d.c. armature Winding must be connected in series with each other by means of end connections (back connection and front connection) in a manner so that the generated voltages of the respective coils will aid each other in the production of the terminal e.m.f. of the winding. Two basic methods of making these end connections are:

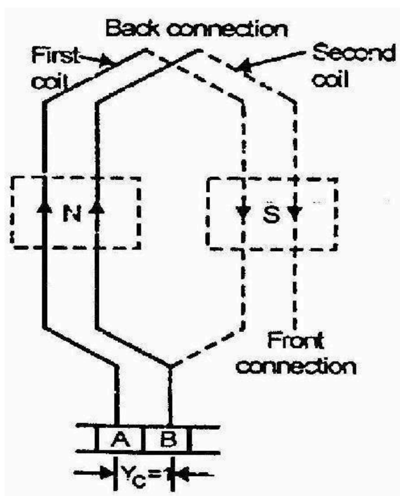
1. Simplex lap winding
2. Simplex wave winding

1. Simplex lap winding.

For a simplex lap winding, the commutator pitch Y_C = 1 and coil span $Y_S \cong$ 2 pole pitch. Thus the ends of any coil are brought out to adjacent commutator segments and the result of this method of connection is that all the coils of the armature .ire in sequence with the last coil connected to the first coil. Consequently, closed circuit winding results. This is illustrated in Fig. (1.21) where a part of the lap winding is shown. Only two coils are shown for simplicity. The name lap comes from the way in which successive coils overlap the preceding one.

2.Simplex wave winding

For a simplex wave winding, the commutator pitch $Y_C \cong$ 2 pole pitches and coil span = pole pitch. The result is that the coils under consecutive pole pairs will be joined together in series thereby adding together their e.m.f.s [See Fig. 1.22]. After passing once around the armature, the winding falls in a slot to the left or right of the starting point and thus connecting up another circuit. Continuing in this way, all the conductors will be connected in a single closed winding. This winding is called wave winding from the appearance (wavy) o fthe end connections.



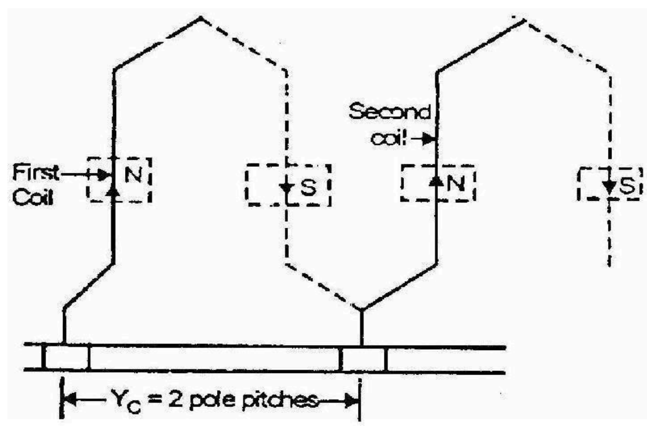


Fig. (1.21) **Fig. (1.22)**

Further Armature Winding Terminology

Apart from the terms discussed earlier, the following terminology requires discussion:

(i) Back Pitch (Y_B)

It is the distance measured in terms of armature conductors between the two sides of a coil at the back of the armature (See Fig. 1.23). It is denoted by Y_B For example, if a coil is formed by connecting conductor 1 (upper conductor in a slot) to conductor 12 (bottom conductor in another slot) at the back of the armature, then back pitch is Y_B = 12 - 1 = 11 conductors.

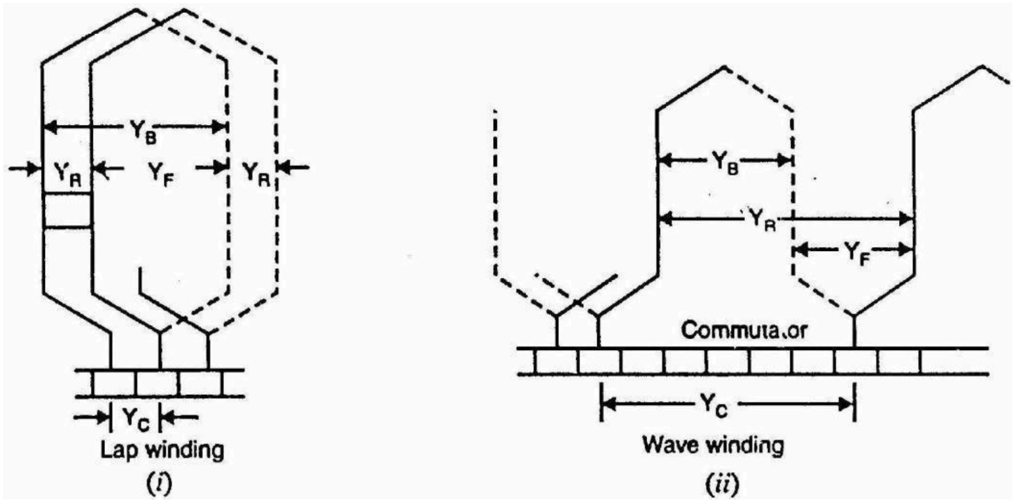


Fig. (1.23)

(ii) Front Pitch (Y_F)

It is the distance measured in terms of armature conductors between the coil sides attached to any one commutator segment [See Fig. 1.23]. It is denoted by Y_F For example, if coil side 12 and coil side 3 are connected to the same commutator segment, then front pitch is $Y_F = 12 - 3 = 9$ conductors.

(iii) Resultant Pitch (YR)

It is the distance (measured in terms of armature conductors) between the beginning of one coil and the beginning of the next coil to which it is connected (See Fig. 1.23). It is denoted by Y_R. Therefore, the resultant pitch is the algebraic sum of the back and front pitches.

(iv) Commutator Pitch (Y_C)

It is the number of commutator segments spanned by each coil of the armature winding.

For simplex lap winding, $Y_C = 1$

For simplex wave winding, Y_C – 2 pole pitches (segments)

(v) Progressive Winding

A progressive winding is one in which, as one traces through the winding, the connections to the commutator will progress around the machine in the same direction as is being traced along the path of each individual coil. Fig. (1.24) (i) shows progressive lap winding. Note that $Y_B > Y_F$ and $Y_C = +1$.

(vi) Retrogressive Winding

A retrogressive winding is one in which, as one traces through the winding, the connections to the commutator will progress around the machine in the opposite direction to that which is being traced along the path of each individual coil. Fig. (1.24) (ii) shows retrogressive lap winding. Note that $Y_F > Y_B$ and $Y_C = +1$. A retrogressive winding is seldom used because it requires more copper.

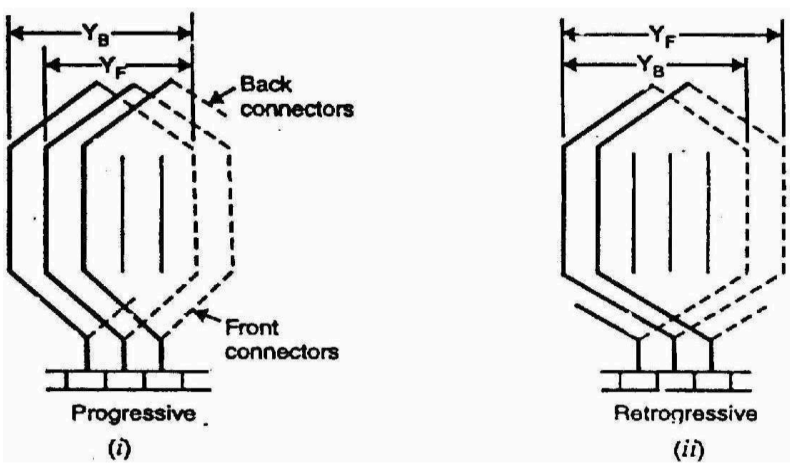


Fig. (1.24)

General Rules for D.C. Armature Windings

In the design of d.c. armature winding (lap or wave), the following rules may be followed:

(i) The back pitch (Y_B) as well as front pitch (Y_F) should be nearly equal to pole pitch. This will result in increased e.m.f. in the coils.

(i) Both pitches (Y_B and Y_F) should be odd. This will permit all end connections (back as well as front connection) between a conductor at the top of a slot and one at the bottom of a slot.

(**i**) The number of commutator segments is equal to the number of slots or coils (or half the number of conductors).

No. of commutator segments = No. of slots = No. of coils

It is because each coil has two ends and two coil connections are joined at each commutator segment

The winding must close upon itself i.e. it should be a closed circuit winding.

Relations between Pitches for Simplex Lap Winding

In a simplex lap winding, the various pitches should have the following relation:

(i) The back and front pitches are odd and are of opposite signs. They differ

 numerically by 2, $Y_B = Y_B = Y_F \pm 2$

$Y_B = Y_F + 2$ for progressive winding

$Y_B = Y_F$ 2 for retrogressive winding

(ii) Both Y_B and Y_F should be nearly equal to pole pitch.

(iii) Average pitch $=(Y_B + Y_F)/2$. It equals pole pitch (= Z/P).

(iv) Commutator pitch, $Y_C = \pm 1$

$Y_C = +1$ for progressive winding $Y_C =$

1 for retrogressive winding

(v) The resultant pitch (Y_B) is even, being the arithmetical difference of two odd numbers viz., Y_B and Y_F.

(vi) If Z = number of armature conductors and P = number of poles,

then, Polr - pitch Z/P

Since Y_B and Y_F both must be. about one pole pitch and differ numerically by 2,

It is clear that Z/P must be an even number to make the winding possible.

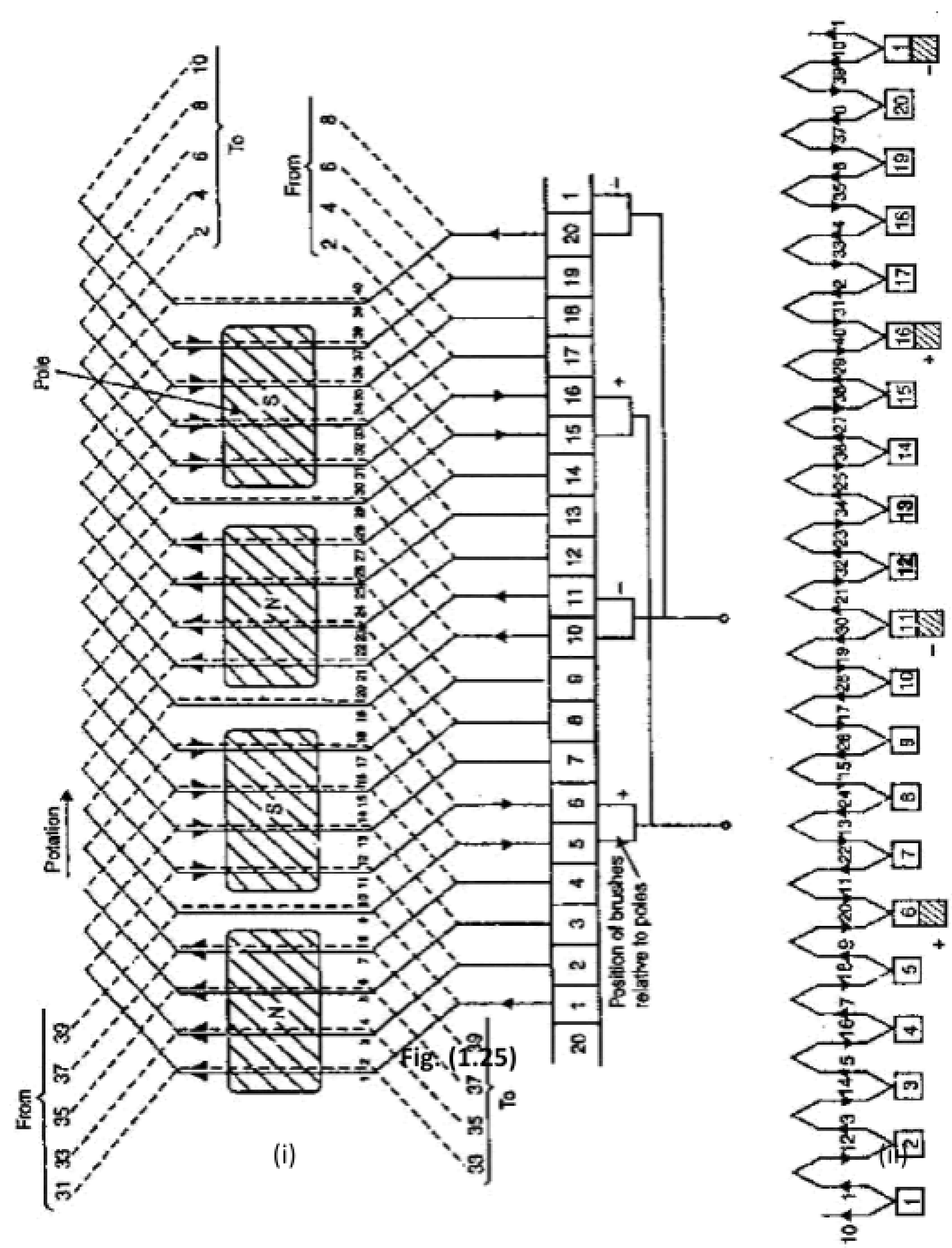
Developed diagram

Developed diagram is obtained by imagining the cylindrical surface of the armature to be cut by an axial plane and then flattened out. Fig. (1.25) (i) shows the developed diagram of the winding. Note that full lines represent the top coil sides (or conductors) and dotted lines represent the bottom coil sides (or conductors).

The winding goes from commutator segment 1 by conductor 1 across the back to conductor 12 and at the front to commutator segment 2, thus forming a coil. Then from commutator segment 2, through conductors 3 and 14 back to commutator segment 3 and so on till the winding returns to commutator segment 1 after using all the 40 conductors.

Position and number of brushes

We now turn to find the position and the number of brushes required. The brushes, like field poles, remain fixed in space as the commutator and winding revolve. It is very important that brushes are in correct position relative to the field poles. The arrowhead marked "rotation" in Fig. (1.25) (i) shows the direction of motion of the conductors. By right-hand rule, the direction of e.m.f. in each conductor will be as shown.In order to find the position of brushes, the ring diagram shown in Fig. (1.25)
(ii) is quite helpful. A positive brush will be placed on that commutator segment where the currents in the coils are meeting to flow out of the segment. A negative brush will be placed on that commutator segment where the currents in the coils are meeting to flow in. Referring to Fig. (1.25) (i), there are four brushes two positive and two negative. Therefore, we arrive at a very important conclusion that in a simplex lap winding, the number of brushes is equal to the number of poles. If the brushes of the same polarity are connected together, then all the armature conductors are connected in four parallel paths; each path containing an equal number of conductors in series. This is illustrated in Fig. (1.26). Since segments 6 and 16 are connected together through positive brushes and segments 11 and 1 are connected together through negative brushes, there are four parallel paths, each containing 10 conductors in series. Therefore, in a simplex lap winding, the number of parallel paths is equal to the number of pole



(i)
(ii)
Pole
Rotation
From
To
Position of brushes relative to poles

Fig. (1.25)

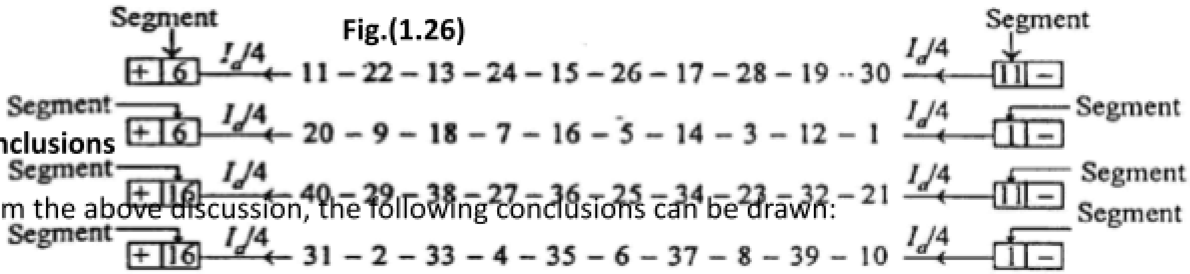


Fig.(1.26)

Conclusions

From the above discussion, the following conclusions can be drawn:

(ii) The armature winding is divided into as many parallel paths as the number of poles. If the total number of armature conductors is Z and P is the number of poles, then,

Number of conductors/path = Z/P

In the present case, there are 40 armature conductors and 4 poles. Therefore, the armature winding has 4 parallel paths, each consisting of 10 conductors in series.

(iii) E.M.F. generated = E.M.F. per parallel path

$$= \text{average e.m.f. per conductor} \times \frac{Z}{P}$$

(iv) Total armature current, $I_a = P \times$ current per parallel path

(v) The armature resistance can be found as under:

Let l = length of each conductor; a = cross-sectional area

A = number of parallel paths = P (for simplex lap winding)

$$\text{Resistance of whole winding, } R = \frac{\rho l Z}{a}$$

Since there are A (= P) parallel paths, armature resistance R_a is given by:

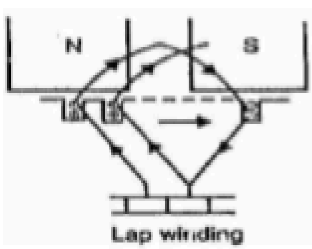
$$R_a = \frac{1}{A} \times \frac{\text{Resistance per parallel path}}{A} = \frac{\rho l Z}{aA} * \frac{1}{A}$$

$$R_a = \frac{\rho l Z}{aA^2}$$

Simplex Wave Winding

The essential difference between a lap winding and a wave winding is in the commutator connections. In a simplex lap winding, the coils approximately pole pitch apart are connected in series and the commutator pitch $Y_C = \pm 1$ segment. As a result, the coil voltages add. This is illustrated in Fig. (1.27). In a simplex wave winding, the coils approximately pole pitch apart are connected in series and the commutator pitch $Y_C \sim 2$ pole pitches (segments). Thus in a wave winding, successive coils "wave" forward under successive poles instead of "lapping" back on themselves as in the lap winding. This is illustrated in Fig. (1.28).

The simplex wave winding must not close after it passes once around the armature but it must connect to a commutator segment adjacent to the first and the next coil must be adjacent to the first as indicated in Fig. (1.28). This is repeated each time around until connections are made to all the commutator segments and all the slots are occupied after which the winding automatically returns to the starting point. If, after passing once around the armature, the winding connects to a segment to the left of the starting point, the winding is retrogressive [See Fig. 1.28 (i)]. If it connects to a segment to the right of the starting point, it is progressive [See Fig. 1.28 (ii)]. This type of winding is called wave winding because it passes around the armature in a wave-like form.



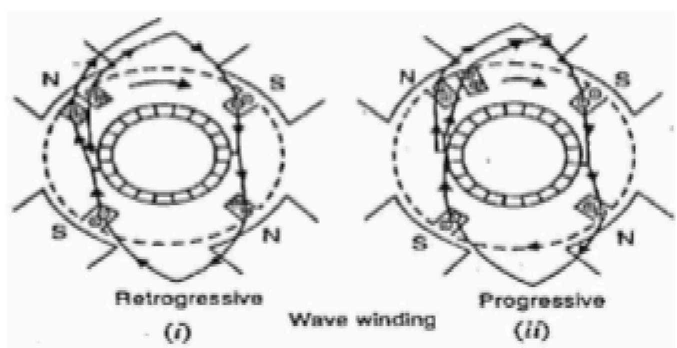


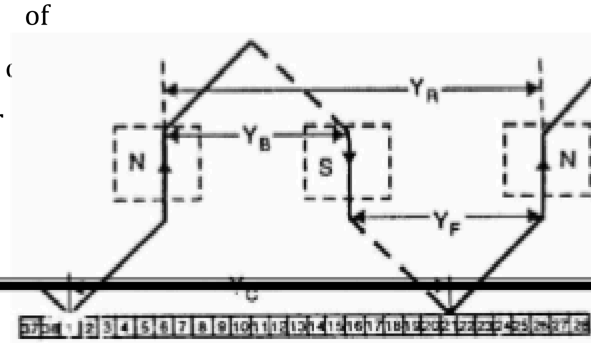
Fig. (1.27) **Fig. (1.28)**

Various pitches

The various pitches in a wave winding are defined in a manner similar to lap winding.

(i) The distance measured in terms of armature conductors between the two sides of a coil at the back of the armature is called back pitch Y_B (See Fig. 1.29). The Y_B must be an odd integer so that a top conductor and a bottom conductor will be joined.

(i) The distance measured in terms of armature conductors between the sides attached to any one commutator



segment is called front pitch Y_B (See Fig.

1.29). The Y_B must be

an odd integer so that a top conductor

and bottom conductor will be joined.**Fig. (1.29))**

(**i**) Resultant pitch, $Y_R = Y_B + Y_F$(See Fig. 1.29)The resultant pitch must be an even integer since Y_B and Y_F are odd. Further Y_R is approximately two pole pitches because Y_B as well as Y_F is approximately one pole pitch.

(iv)

$Y_B + Y_C$ 2

Average Pitch $Y_A =$

When one tour of armature has been completed, the winding should connect to the next top conductor (progressive) or to the preceding top conductor (retrogressive). In either case, the difference will be of 2 conductors or one slot. If P is the number of poles and Z is the total number of armature conductors, then,

P Y_A Z 2

$Y_A =$ Z + 2 P

Since P is always even and $Z = PY_A \pm 2$, Z must be even. It means that Z

$\pm 2/P$ must be an integer. In Eq.(i), plus sign will give progressive winding and the negative sign retrogressive winding.

(v) The number of commutator segments spanned by a coil is called commutator pitch (Y_C) (See Fig. 1.29). Suppose in a simplex wave winding,

P = Number of poles; N_C = Number of commutator segments; Y_C =Commutator pitch.

Number of pair of poles = P/2

If $Y_C P/2 = N_C$, then the winding will close on itself in passing once around the armature. In order to connect to the adjacent conductor and permit the winding to proceed,

P

$$Y_C * 2 = N_C \pm 1$$

$$Y_C = \frac{}{2N_C \pm 2} =$$

$$\frac{N_C \pm 1}{P/2} = \frac{\text{No. of commutator segments} \pm 1}{P}$$

of pair of poles

N

o

.

$(2N = Z)$

$Y = \frac{2NC \pm 2}{} = \frac{Z \pm 2}{} = Y$

$C \quad P \quad P \quad A \quad C$

$$Commutator pitch, Y_C = Y_A = \frac{YB + YF}{2}$$

In a simplex wave winding Y_B, Y_F and Y_C may be equal. Note that Y_B, Y_F and Y_B are in terms of armature conductors whereas Y_C is in terms of commutator segments.

Design of Simplex Wave Winding

In the design of simplex wave winding, the following points may be kept in mind:

(i) Both pitches Y_B and Y_F are odd and are of the same sign.

(ii) Average pitch, $Y_A = \frac{Z \pm 1}{P}$ (i)

(iii) Both Y_B and Y_F are nearly equal to pole pitch and may be equal or differ by 2. If they differ by 2, they are one more and one less than Y_A.

(iv) Commutator pitch is given by;

$$Y_C = Y_A = \frac{\text{Number of commutator segments} \pm 1}{\text{Number of pair of poles}}$$

The plus sign for progressive winding and negative for retrogressive winding. (v)

$\frac{Z \pm 2}{} = Y_A$

Since Y_A must be a whole number, there is a restriction on the value of Z. With Z = 180,

this winding is impossible for a 4-pole machine because Y_A is not a whole number.

(vi) Z P Y_A 2

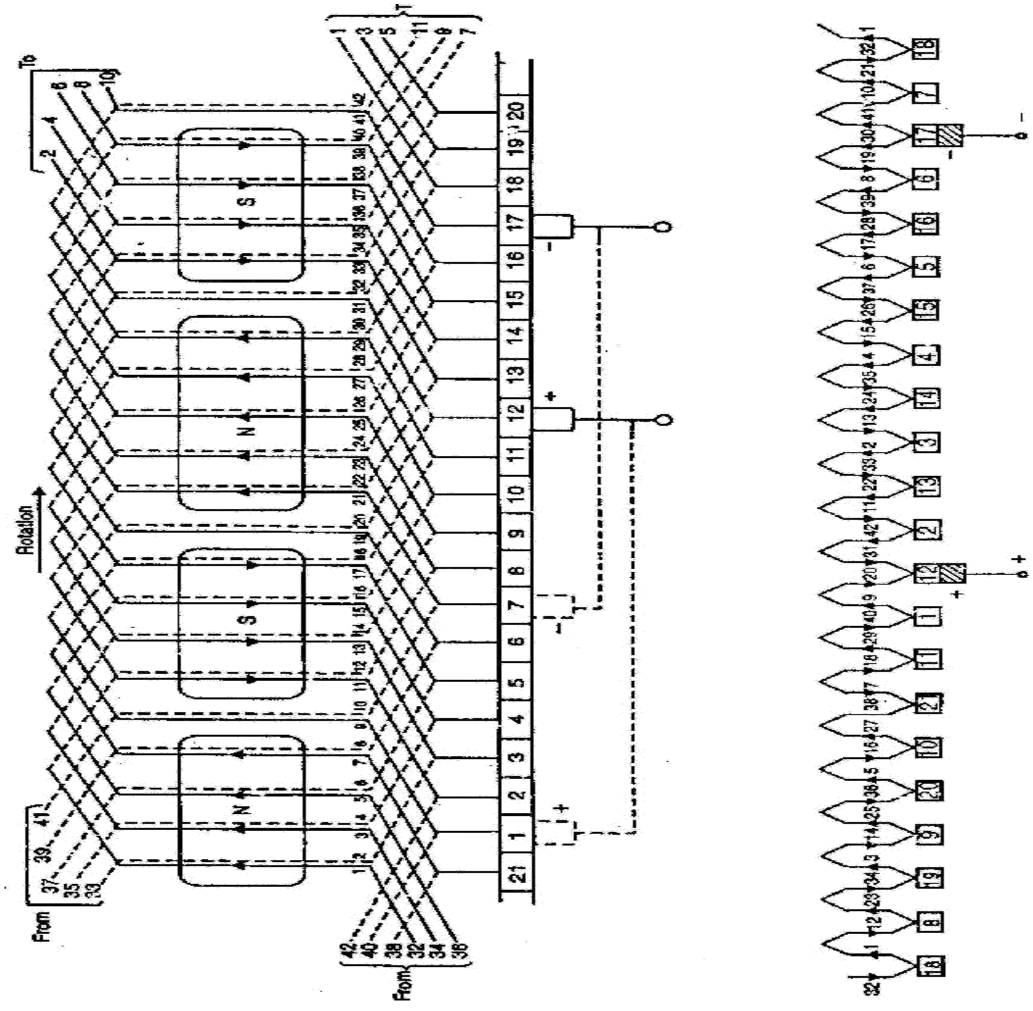
$Number of coils = \frac{}{2}$

Z

$$= \frac{PY_A + 2}{2}$$

Developed diagram

Fig. (1.30) (i) shows the developed diagram for the winding. Note that full lines represent the top coil sides (or conductors) and dotted lines represent the bottom coil sides (or conductors). The two conductors which lie in the same slot are drawn nearer to each other than to those in the other slot



i) ii)

Fig.1.30

Referring to Fig. (1.30) (i), conductor 1 connects at the back to conductor 12(1 + 11) which in turn connects at the front to conductor 23 (12 + 11) and so on round the armature until the winding is complete. Note that the commutator pitch Y_C = 11 segments. This means that the number of commutator segments spanned between the start end and finish end of any coil is 11 segments.

Position and number of brushes

We now turn to find the position and the number of brushes. The arrowhead marked rotation" in Fig. (1.30) (i) shows the direction of motion of the conductors. By right hand rule, the direction of e.m.f. in each conductor will be as shown.

In order to find the position of brushes, the ring diagram shown in Fig. (1.30) (ii) is quite helpful. It is clear that only two brushes one positive and one negative are required (though two positive and two negative brushes can also be used). We find that there are two parallel paths between the positive brush and the negative brush. Thus is illustrated in Fig. (1.31).

Therefore, we arrive at a very important conclusion that in a simplex wave winding, the number of parallel paths is two irrespective of the number of poles. Note that the first parallel path has 11 coils (or 22 conductors) while the second parallel path has 10 coils (or 20 conductors). This fact is not important as it may appear at first glance. The coils m the smaller group should supply less current to the external circuit. But the identity of the coils in either parallel path is rapidly changing from moment to moment. Therefore, the average value of current through any particular coil is the same.

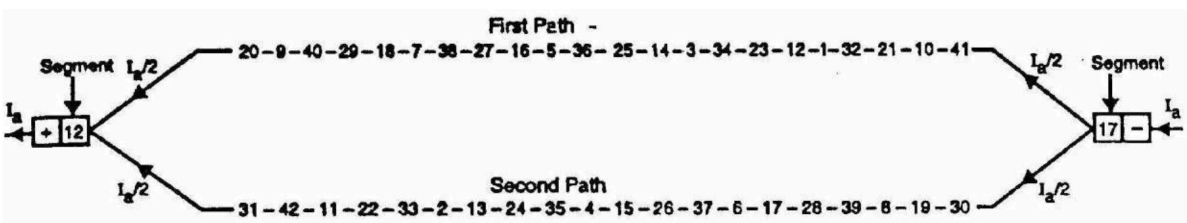


Fig. (1.31)

Conclusions

From the above discussion, the following conclusions can be drawn:

(i) Only two brushes are necessary but as many brushes as there are poles may be used.

(ii) The armature winding is divided into two parallel paths irrespective of the number of poles. If the total number of armature conductors is Z and P is the number of poles, then,

Number of conductors/path ▯ Z/2

(iii) E.M.F. generated = E.M.F. per parallel path

= Average e.m.f. per conductor x

(iv) Total armature current, I_a = 2 current per parallel path The armature can be wave-wound if Y_A or Y_C is a whole number

Dummy Coils

In a simplex wave winding, the average pitch Y_A (or commutator pitch Y_C) should be a whole number. Sometimes the standard armature punchings available in the market have slots that do not satisfy the above requirement so that more coils (usually only one more) are provided than can be utilized. These extra coils are called dummy or dead coils. The dummy coil is inserted into the slots in the same way as the others to make the armature dynamically balanced but it is not a part of the armature winding.

Let us illustrate the use of dummy coils with a numerical example. Suppose the number of slots is 22 and each slot contains 2 conductors. The number of poles is 4. For simplex wave wound armature,

$$Y_A = \frac{Z \pm 2}{P} = \frac{2 \times 22 \pm 2}{4} = \frac{44 \pm 2}{4} = 11\frac{1}{2} \text{ or } 10\frac{1}{2}$$

Since the results are not whole numbers, the number of coils (and hence segments) must be reduced. If we make one coil dummy, we have 42 conductors and

$$Y_A = \frac{42 \pm 2}{4} = 11 \text{ or } 10$$

This means that armature can be wound only if we use 21 coils and 21 segments. The extra coil or dummy coil is put in the slot. One end of this coil is taped and the other end connected to the unused commutator segment (segment 22) for the sake of appearance. Since only 21 segments are required, the two (21 and 22 segments) are connected together and considered as one.

Applications of Lap and Wave Windings

In multi polar machines, for a given number of poles (P) and armature conductors (Z), a wave winding has a higher terminal voltage than a lap winding because it has more conductors in series. On the other hand, the lap winding carries more current than a wave winding because it has more parallel paths.

In small machines, the current-carrying capacity of the armature conductors is not critical and in order to achieve suitable voltages, wave windings are used. On the other hand, in large machines suitable voltages are easily obtained because of the availability of large number of armature conductors and the current carrying capacity is more critical. Hence in large machines, lap windings are used.

Note: In general, a high-current armature is lap-wound to provide a largenumber of parallel paths and a low-current armature is wave-wound to provide a small number of parallel paths

Multiplex Windings

A simplex lap-wound armature has as many parallel paths as the number of poles. A simplex wave-wound armature has two parallel paths irrespective of the number of poles. In case of a 10-pole machine, using simplex windings, the designer is restricted to either two parallel circuits (wave) or ten parallel circuits (lap). Sometimes it is desirable to increase the number of parallel paths. For this purpose, multiplex windings are used. The sole purpose of multiplex windings is to increase the number of parallel paths enabling the armature to carry a large total current. The degree of multiplicity or plex determines the number of parallel paths in the following manner:

(i) A lap winding has pole times the degree of plex parallel paths.

Thus a duplex lap winding has 2P parallel paths, triplex lap winding has 3P parallel paths and so on. If an armature is changed from simplex lap to duplex lap without making any other change, the number of parallel paths is doubledand each path has half as many coils. The armature will then supply twice as much current at half the voltage

(ii) A wave winding has two times the degree of plex parallel paths.
Number of parallel p�ths, A = 2 plex

Note that the number of parallel paths in a multiplex wave winding depends upon the degree of plex and not on the number of poles. Thus a duplex wave winding has 4 parallel paths, triplex wave winding has 6 parallel paths and so on.

Function of Commutator and Brushes

The e.m.f. generated in the armature winding of a d.c. generator is alternating one. The commutator and brushes cause the alternating e.m.f. of the armature conductors to produce a p.d. always in the same direction between the terminals of the generator. In lap as well as wave winding, it will be observed that currents In the coils to a brush are either all directed towards the brush(positive brush) or all directed away from the brush (negative brush)

Further, the direction of current in coil reverses as it passes the brush. Thus when the coil approaches the contact with the brush, the current through the coil is in one direction; when the coil leaves the contact with the brush, the current has been reversed. This reversal of current in the coil as the coil passes a brush is called commutation and fakes place while the coil is short-

circuited by the brush. These changes occur in every coil in turn. If, at the instant when the brush breaks contact with the commutator segment connected to the coil undergoing commutation, the current in the coil has not been reversed, the result will be sparking between the commutator segments and the brush.

The criterion of good commutation is that it should be sparkless. In order to have sparkless commutation, the brushes on the commutator should be placed at points known as neutral point where no voltage exists between adjacent segments. The conductors connected to these segments lie between the poles in position of zero magnetic flux which is termed as magnetic neutral axis (M.N.A)

E.M.F. Equation of a D.C. Generator

We shall now derive an expression for the e.m.f. generated in a d.c. generator. Let ϕ = flux/pole in Wb

Z = total number of armature conductors P = number of poles

A = number of parallel paths = 2 ... for wave winding = P ... for lap winding

N = speed of armature in r.p.m.

E_g = e.m.f. of the generator = e.m.f./parallel path Flux cut by one conductor in one revolution of the armature,

$d\phi = P\phi$ webers Time taken to complete one revolution,

dt = 60/N second

e.m.f. of generator, e.m.f/conductor $= d\phi/dt = \frac{\phi PN}{60}$

E_g = e.m.f. per parallel path

= (e.m.f/conductor) × No. of conductors in series per parallel path

$$\frac{\phi PNZ}{60A}$$

$E_g =$ ________

Where, A=2 for wave winding

A=P For lap winding

Armature Resistance (R_a)

The resistance offered by the armature circuit is known as armature resistance (R_a) and includes:

(i) resistance of armature winding

(ii) resistance of brushes

The armature resistance depends upon the construction of machine. Except for small machines, its value is generally less than 1Ω.

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. (1.32) shows the connections of a separately excited generator. The voltage output depends upon the speed of rotation of armature and the field current ($E_g = P\Phi ZN/60A$). 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.

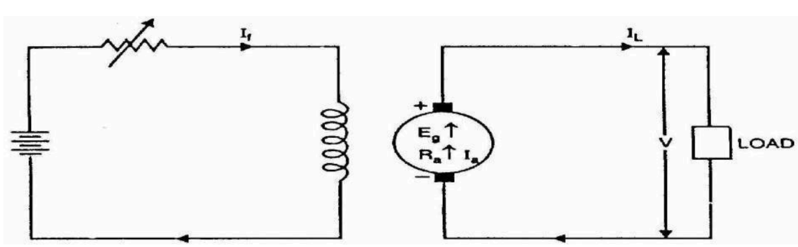


Fig. (1.32)

Armature current, $I_a = I_L$

Terminal voltage, $V = E_g - I_a R_a$ Electric power developed = $E_g I_a$

Power delivered to load = $E_g I_a - I_a^2 R_a = I_a [E_g - I_a R_a] = VI_a$

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. Fig. (1.33) 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, $I_a = I_{se} = I_L = I$(say) Terminal voltage, $V = E_g - I(R_a + R_{se})$ Power developed in armature = $E_g I_a$ Power delivered to load=

$$E_g I_a - I_a^2 (R_a + R_{se}) = I_a [E_g - I_a (R_a + R_{se})] = VI_a \text{ or } VI_L$$

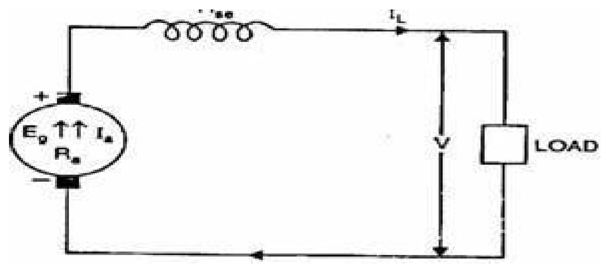


Fig. (1.33)

(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. Fig. (1.34) shows the connections of a shunt-wound generator.

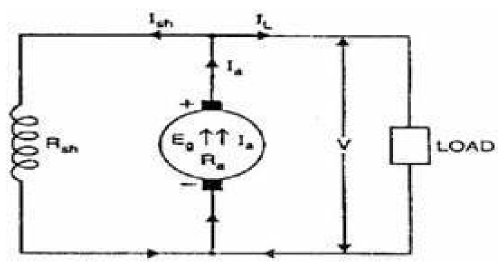


Fig. (1.34)

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

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

Terminal voltage, $V = E_g - I_a R_a$

Power developed in armature = $E_g I_a$Power delivered to load = VI

(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 [See Fig.

1.35 (i)].

(b) Long Shunt in which shunt field winding is in parallel with both series field and armature winding [See Fig. 1.35 (ii)].

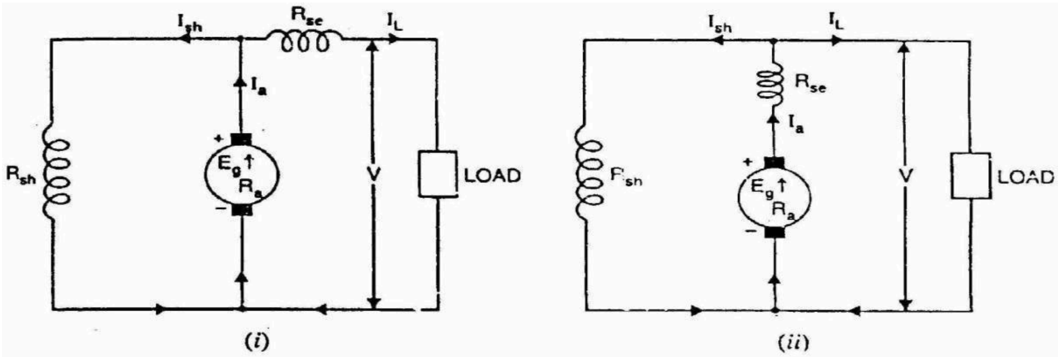


Fig. (1.35)

Short shunt

Series field current, $I_{se} = I_L$ Shunt field current, $I_{sh} = \frac{V - I_{se}R_{se}}{R_{sh}}$

Terminal voltage, $V = E_g - I_aR_a - I_{se}R_{se}$ Power developed in armature = E_gI_a Power delivered to load = VI_L

Long shunt

Series field current, $I_{se} = I_a = I_L + I_{sh}$ Shunt field current, $I_{sh} = V/R_{sh}$ Terminal voltage, $V = E_g - I_a(R_a + R_{se})$ Power developed in armature = E_gI_a

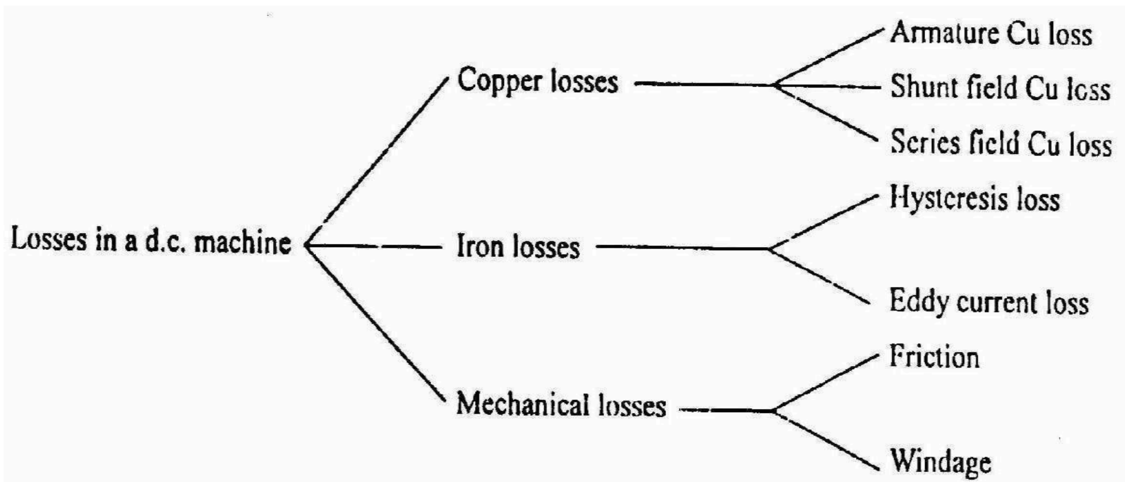
Power delivered to load = VI_L

<u>Brush Contact Drop</u>

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

Losses in a D.C. Machine

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



1. Copper losses

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

(i) Armature copper loss = $I^2_a R_a$

(ii) Shunt field copper loss = $I_{sh}^2 R_{sh}$

(iii) Series field copper loss = $I_{se}^2 R_{se}$

Note. There is also brush contact loss due to brush contact resistance (i.e.,resistance between the surface of brush and surface of commutator). This loss is generally included in armature copper loss.

2. Iron or Core losses

These losses occur in the armature of a d.c. machine and aredue 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

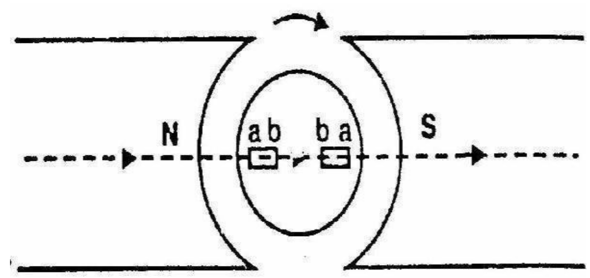


Fig. (1.36)

Hysteresis loss occurs in the armature of the d.c. machine since any given part of thearmature is subjected to magnetic field reversals as it passes under successive poles. Fig. (1.36) 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

Hysteresis loss, $P_h = \eta B^{16}_{max} f V$ 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 m^3

η = Steinmetz hysteresis co-efficient

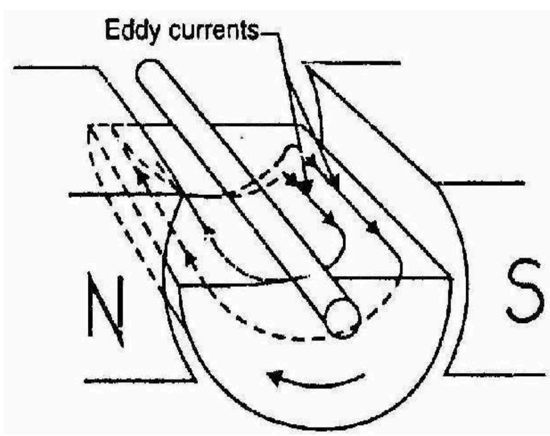
In order to reduce this loss in a d.c. machine, armature core is made of such materials which have a low value of Steinmetz hysteresis co-efficient e.g., silicon steel.

(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 Fig. (1.37). 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.

If a continuous solid iron core is used, the resistance to eddy current path will be small due to large cross-sectional area of the core. Consequently, the magnitude of eddy current and hence eddy current loss will be large. The magnitude of eddy current can be reduced by making core resistance as high as practical.

The core resistance can be greatly increased by constructing the core of thin, round iron sheets called laminations [See Fig. 1.38]. The laminations are insulated from each other with a coating of varnish. The insulating coating has a high resistance, so very little current flows from one lamination to the other. Also, because each lamination is very thin, the resistance to current flowing through the width of a lamination is also quite large. Thus laminating a core increases the core resistance which decreases the eddy current and hence the eddy current loss



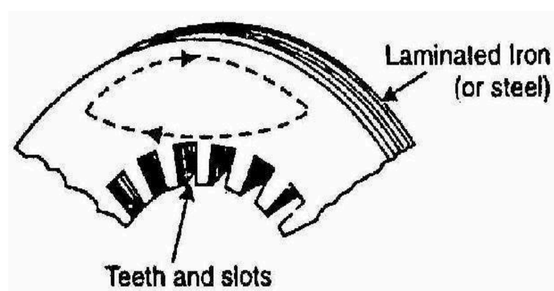


Fig. (1.37) **Fig. (1.38)**

$$Eg\ Ia - I^2a\ Ra + Rse = Ia\ [Eg - Ia\ Ra + Rse = VIa\ orVIL$$

$$Eddycurrentloss, P_e = K_e f^2 t^2 V Watts$$

K_e=Constant depending upon the electrical resistance of core and system of units used

B_{max} = Maximum flux density in Wb/m2 f =

Frequency of magnetic reversals in Hz

t = Thickness of lamination in m V =

Volume of core in m^3

It may be noted that eddy current loss depends upon the square of lamination thickness. For this reason, lamination thickness should be kept as small as possible.

3. Mechanical losses

These losses are due to friction and windage.

(i) Friction loss e.g., bearing friction, brushes 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.

Constant and Variable Losses

The losses in a d.c. generator (or d.c. motor) may be sub-divided into (i) constant losses (ii) variable 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 ($I^2_a R_a$)

(b) Copper loss in series field winding ($I^2_{se} R_{se}$)

Total losses = Constant losses + 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 Fig. (1.39).

A ⍰ B = Iron and friction losses B ⍰ C

= Copper losses

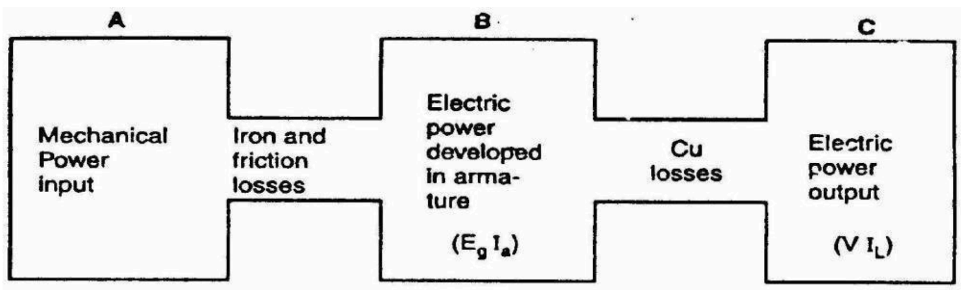


Fig. (1.39)

(i) Mechanical efficiency

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

(ii) Electrical efficiency

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

(ii) Commercial or overallefficiency

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

Clearly $\eta_c = \eta_m \times \eta_e$

Unless otherwise stated, commercial efficiency is always understood.

Now,

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

<u>**Condition for Maximum Efficiency**</u>

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.

Generator output = V I_L

Generator input = Output + Losses

= V I_L + Variable losses + Constant losses

$$= VI_L + I_a^2 R_a + W_C$$

$$= VI_L + (I_L + I_{sh})^2 R_a + W_c \qquad (since\ I_a = I_L + I_{sh})$$

The shunt field current I_{sh} is generally small as compared to I_L and therefore, it can be neglected.

$$\therefore \text{Generator input} = VI_L + I_L^2 R_a + W_C$$

$$\eta = \frac{output}{input} = \frac{VI_L}{VI_L + I_L^2 R_a + W_c}$$

$$= \frac{1}{1 + \frac{I_L R_a}{V} + \frac{W_c}{V I_L}}$$

The efficiency will be maximum when the denominator of above Equation is minimum i.e.,

$$\frac{d}{dI_L}\left(\frac{I_L R_a}{V} + \frac{W_c}{V I_L}\right) = 0$$

$$\frac{R_a}{V} - \frac{W_c}{V I_L^2} = 0$$

$$\text{or} \quad \frac{R_a}{V} = \frac{W_c}{V I_L^2}$$

$$\text{or } I_L^2 R_a = W_c$$

Hence Variable loss = Constant loss

$$(I_L \approx I_a)$$

The load current corresponding to maximum efficiency is given by;

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

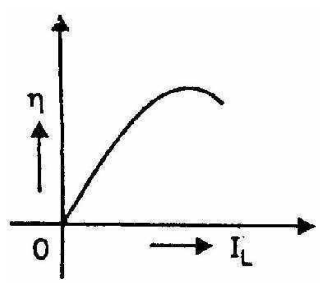


Fig. 1.40

Hence, the efficiency of a d.c. generator will be maximum when the load current is such that variable loss is equal to the constant loss. Fig (1.40) shows the variation of efficiency with load current.

UNIT II

PERFORMANCE OF DC MACHINES

Principle of Operation:

DC motor operates on the principle that when a current carrying is placed in a magnetic field, it experiences a mechanical force give n by F = BIL newton. Where „B" = flux density in wb/$m^{2'}$, „I" is the current and „L" is the length of the conductor. The direction of force can be found by Fleming"s left hand rule. Constructionally, there is no difference between a DC generator and DC motor.

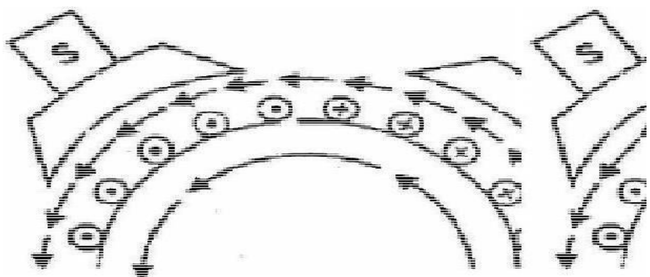


Figure 2.1

Figure 2.1 shows a multipolar DC motor. Armature conductors are carrying current downwards under North Pole and upwards under South Pole. When the field coils are excited, with current carrying armature conductors, a force is experienced by each armature conductor whose direction can be found by Fleming"s left hand rule. This is shown by arrows on top of the conductors. The collective force produces a driving torque which sets the armature into rotation. The function of a commutator in DC motor is to provide a continuous and unidirectional torque.

In DC generator the work done in overcoming the magnetic drag is converted into electrical energy. Conversion of energy from electrical form to mechanical form by a DC motor takes place by the work done in overcoming the opposition which is called the „back emf".

BACK EMF:

Back emf is the dynamically induced emf in the armature conductors of a dc motor when thearmature is rotated. The direction of the induced emf as found by Flemings right hand rule is in opposition to the applied voltage. Its value is same as that of the induced emf in a DCGenerator i.e. is

This emf is called as back emfE_b"The work done in overcoming this opposition is converted into mechanical

$$E_b = \left(\frac{\phi Z n}{60}\right) X \frac{P}{A} \text{volts.}$$

energy.

SIGNIFICANCE OF BACK EMF:

Figure 2.2 shows a DC shunt motor. The rotating armaturegenerating the back emfE_b"is like a battery of emfE_b"connected across a supply voltage of „V" volts.

$$\text{From Figure 2.2, } I_a = \frac{V - E_b}{r_a} \text{ where } r_a = armature\ resistance.$$

$$E_b = \frac{\phi Z N P}{60A} \text{Volts.} \quad E_b \propto N.$$

If E_b is large, armature current will be less and vice versa. Hence E_b acts like a governor i.e., it makes the motor self- regulating so that it draws as much current as required by the motor.

VOLTAGE EQUATION OF A MOTOR:

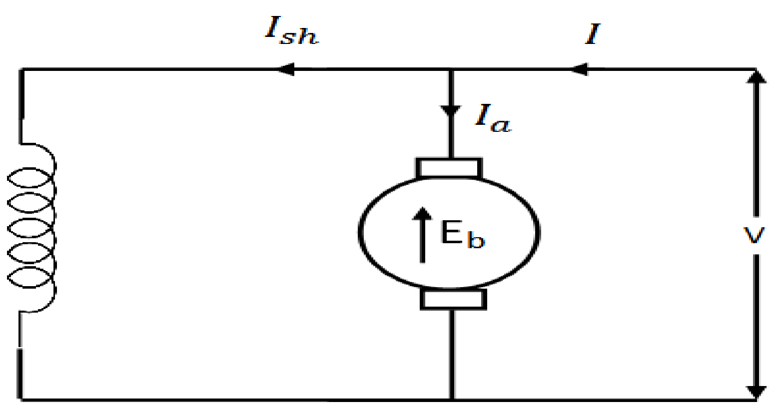


Figure 2.2

The voltage 'V' applied across the motor armature has to

i) Overcome the back emf E_b and

ii) Supply the armature ohmic drop $I_a r_a$

Hence $V = E_b + I_a r_a$.....1 This is known as voltage equation of DC motor.

Multiplying both sides of voltage equation by I_a

$VI_a = E_b I_a + I_a^2 r_a$.......2

$VI_a = electrical\ input\ to\ the\ armature.$

$E_b I_a = P_m = electrical\ equivalent\ of\ mechanical\ power\ developed\ in\ the\ armature.$

$I_a^2 r_a = armature\ copper\ loss$

CONDITION FOR MAXIMUM POWER:

Mechanical power developed by the motor is $P_m = VI_a - I_a^2 r_a$.......3

Condition for maximum power is $\frac{dP_m}{dI_a} = 0$

$$\frac{dP_m}{dI_a} = V - 2I_a r_a = 0$$

$$\frac{V}{2} = I_a r_a$$

$V = E_b + \frac{V}{2}$ $\quad\quad$ $E_b = \frac{V}{2}$ 4

Thus the mechanical power developed by the motor is maximum when the back emf is equal to half the applied voltage.

TORQUE:

Torque is the twisting moment about an axis. It is measured by the product of the force and the radius at which the force acts. Consider a pulley of radius „r‟ metre acted upon a circumferential force of „F‟ newton which causes it to rotate at „N‟ rotations per second (r.p.s) as show in Figure. 2.3

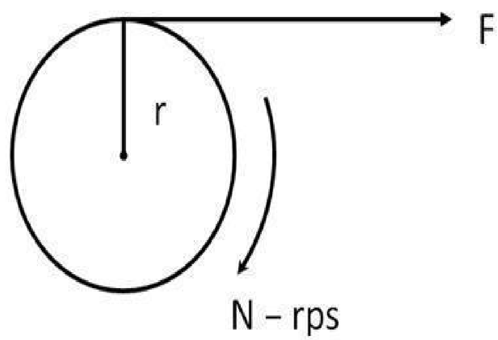


Figure 2.3

$T = F \times r$ N-metre

Work done by this force in one revolution = Force X Distance = $F \times 2\pi r$ joule.

Power Developed = $F \times 2\pi r \times N$ joule/sec.

$= (F \times r)\, 2\pi N$ joule/sec

$2\pi N$ = angular revolution ω in rad/sec. And $F \times r$ = Torque 'T'

Therefore Power Developed = $T \times \omega$ joule/sec or watts…….. 5

2.6 (i) ARMATURE TORQUE OF A MOTOR:

Let T_a = armature torque in N –m developed by the armature of a motor running at N.rps.

Therefore P = T_a X 2π N Watts …….. 6

Electrical equivalent of mechanical power developed $P_m = E_b I_a$

$E_b I_a = T_a X\ 2\pi N$

$T_a = \frac{1}{2\pi}\frac{E_b I_a}{N}$ N – m ……....7

= $0.0162\frac{E_b I_a}{N}$ kg-m ……..8

Also, on substituting for E_b i.e., $\Phi ZN\left(\frac{P}{A}\right) I_a$

$\Phi ZN\left(\frac{P}{A}\right) I_a = T_a X\ 2\pi N$

Therefore $T_a = \frac{1}{2\pi}\Phi z I_a\left(\frac{P}{A}\right)$ N-mtrs

$T_a = 0.159\ \Phi\ Z\ I_a\left(\frac{P}{A}\right)$ N-mtrs …..9

$= 0.162\ \Phi\ Z\ I_a\left(\frac{P}{A}\right)$ kg-mtrs ……..10

(1 Kg = 9.81 N)

From the above equation for torque, it is seen that

(i) $T \propto \Phi I_a$

(ii) $T \propto {I_a}^2$ - For series motor (because $\Phi \propto I_a$) before saturation. After saturation $T \propto I_a$.

(iii) $T \propto I_a$ - For shunt motor. (because Φ is constant in a shunt motor)

(ii) SHAFT TORQUE (TSH):

Some of the torque developed in the armature will be lost in supplying the iron and friction losses in the motor. The torque which is available for doing useful work is known as shaft torque „Tsh‟. The horse power obtained by using the shaft torque is called as Brake Horse Power (BHP).

$$BHP = \frac{T_{sh} X\ 2\pi N}{735.5} \text{..........}11$$

$$T_{sh} = \frac{BHP X\ 735.5}{2\pi N} = \frac{output\ in\ watts}{2\pi N} \text{N-m}$$

$$\text{Lost torque} = T_a - T_{sh}$$

$$= 0.159\ X\ \frac{Iron\ and\ Friction\ Losses\ in\ Watts}{N} \text{N-mtrs ....}12$$

$$= 0.162\ X \frac{Iron\ and\ Friction\ Losses\ in\ Watts}{N} \text{kg-mtrs ....}13$$

SPEED OF A DC MOTOR:

$$E_b = V - I_a r_a \quad \text{Or} \quad \Phi ZN\left(\frac{P}{A}\right) = V - I_a r_a$$

$$N = \frac{E_b}{\Phi Z}\left(\frac{A}{P}\right) \text{ r.p.s}$$

$$N = K\ \frac{E_b}{\Phi}$$

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

$$T_a \propto\ \emptyset\ I_a$$

$$\emptyset = Constant, \text{ if } \emptyset = \text{constant, then } T_a \propto\ I_a \text{ ....}14$$

(i) For series motor, $N_1 \propto \frac{E_{b1}}{\Phi_1}$

$N_2 \propto \frac{E_{b2}}{\Phi_2}$ where $E_{b1} = V - I_{a1} r_a$

$$E_{b2} = V - I_{a2} r_a$$

$$\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \frac{I_{a1}}{I_{a2}} \text{ Or } \frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \frac{\Phi_1}{\Phi_2} \ldots\ldots\ldots.15$$

(ii) For shunt motor.

$$\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \frac{\Phi_1}{\Phi_2}$$

Φ = constant for shunt motor

$\Phi_1 = \Phi_2$

$$\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \ldots\ldots\ldots\ldots.16$$

Speed regulation: is defined as the change in speed from No-load to full load when the rated load on the motor is reduced to zero, expressed as a percentage of rated speed.

$$\% \text{ speed regulation} = \frac{NoLoadspeed - Full\ loadspeed}{FullLoadspeed} = \frac{dN}{N} X\ 100$$

CHARACTERISTICS OF DC MOTORS:

There are three important characteristics.

1. Armature torque vs Armature current; T_a vs I_a (Electrical_characteristics)_

2. Speed vs armature current characteristic

3. Speed vs torque N vs T_a (Mechanical characteristics)

(i) CHARACTERISTICS OF SHUNT MOTORS

i) $\frac{T_a}{I_a}$ ii) $\frac{N}{I_a}$ iii) $\frac{N}{T_a}$

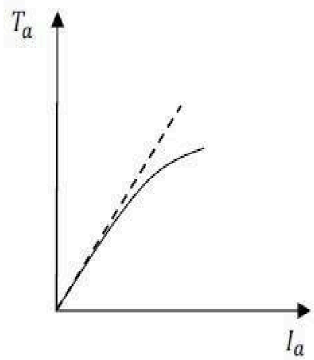


Figure 2.4

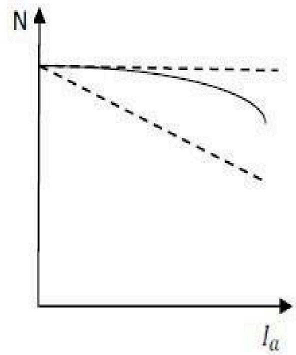


Figure 2.5

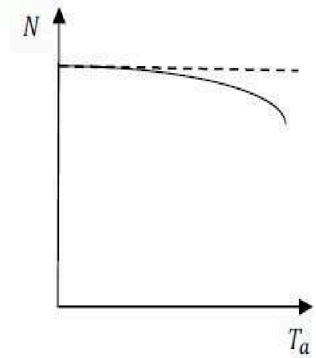


Figure 2.6

N α $\frac{E_b}{\emptyset}$ or N = $K_N(\frac{V - I_a R_a}{\emptyset})$; N = $\frac{K_N V}{\emptyset}$ - $\frac{K_N I_a r_a}{\emptyset}$ ------- (a)

$I_a = \frac{T}{K_T \emptyset}$ -------(b)

Substituting (b) in(a)

N = $\frac{K_N V}{\emptyset}$ - $\frac{K_N r_a}{K_T \emptyset^2}$ T --------- (17)

1. T_a vs I_a CHARACTERISTICS

For a shunt motor flux ∅ can be assumed practically constant (at heavy loads, ∅ decreases, due to increased armature reaction)

$T_a \propto \emptyset I_a$

$\emptyset = constant, T_a \propto I_a$

Therefore electrical characteristic of a shunt motor is a straight line through origin shown by dotted line in Figure 2.4. Armature reaction weakens the flux hence T_a vs I_a characteristic bends as shown

2. N vs I_a CHARACTERISTICS

$N \propto E_b$; E_b is practically almost constant.

Hence the speed is constant. However, E_b decreases slightly more than ∅ with increase in load and thus there is slight decrease in speed. This decrease in speed varies from 5 to 15% of full load speed and it depends on armature reaction and saturation. This characteristics is shown in Figure 2.5

3. N vs T_a CHARACTERISTICS

This characteristic can be deduced from 1 and 2, shown in figure 2.6

by dark line in figure 2.4, Shunt motors should never be started on heavy loads, since it draws heavy current under such condition.

Performance curves of DC shunt motor

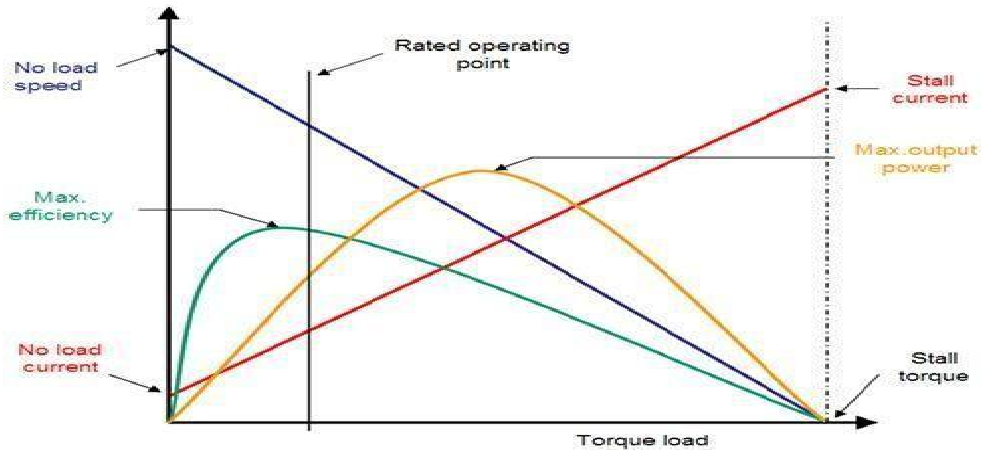


Figure 2.7

The four essential characteristics of shunt motor i.e., torque, speed, current and efficiency plotted as a function of horse power are known as performance curves of the motor, shown in figure 2.7 Shunt motor has a definite No-load speed hence can be used where a load is suddenly thrown off with field circuit remaining close. The drop in speed from No-load to full load is small and hence referred to as constant speed motor. The efficiency curve is usually of the same shape for all motors and generators. It is advantageous to have an efficiency curve which is fairly flat and the maximum efficiency near to full load. Certain value of minimum current is required

even when the output is zero as the input under No-load condition has to meet the losses within the machine.

The shunt motor is also capable of starting under heavy load condition but the current drawn by the motor will be very high compared to DC series motor.

$(T_a \propto I_a)$

As the series motor draws only one and half times the full load current

$$T_a \propto I_a^2, I_a \propto \sqrt{T_a}$$

CHARACTERISTICS OF SERIES MOTORS:

1. T_a **vs** I_a **CHARACTERISTICS**

$T_a \propto \emptyset I_a$

$\emptyset \propto I_a$

$T_a \propto I_a^2$ – upto saturation ………. 18

$T_a \propto I_a$ – after saturation ………. 19

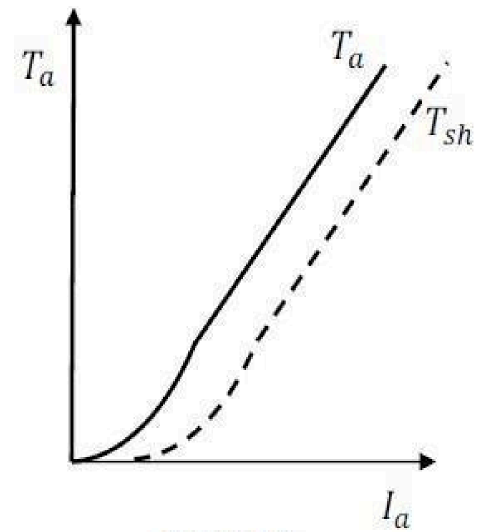


Figure 2.8

At light loads, I_a nd hence is $\emptyset$ small. But as I_a increases; T_a ncreases as the square of the current up to saturation. After saturation $\emptyset$ becomes constant, the characteristic becomes a straight line as shown in Figure 2.8. Therefore a series motor develops a torque proportional to the square of the armature current. This characteristic is suited where huge starting torque is required for accelerating heavy masses.

Ex. Hoists, electric trains, etc.

2. N vs I_a CHARACTERISTICS

$N \propto \frac{E_b}{\emptyset} E_b$ *is approximately constant*

$N \propto \frac{1}{\emptyset}$ …………20

If I_a increases, $\emptyset$ increases and hence speed decreases.

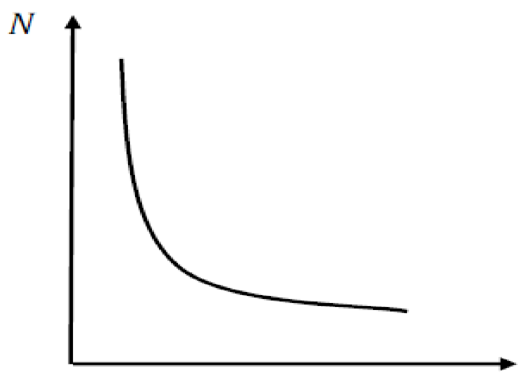


Figure 2.9 (a)

This characteristic is shown in figure 2.9(a). Change in E_b for various load currents is small. Hence may be neglected. Therefore the speed is inversely proportional to flux, because $N \propto \frac{E_b}{\emptyset}$

When the load is heavy, I_a is large and speed is low. When the load is low, current and hence flux will be small. Therefore speed becomes dangerously high. Hence a series motor should never be started without load on it.

3. $N\ vs\ T_a$ CHARACTERISTICS

$T_a \propto E_b I_a$

$E_b\ is\ constant$

Hence, $T_a \propto I_a$. Therefore, N vs T_a characteristic

can be deduced from 1 and 2 as shown in Figure 2.9 (b)

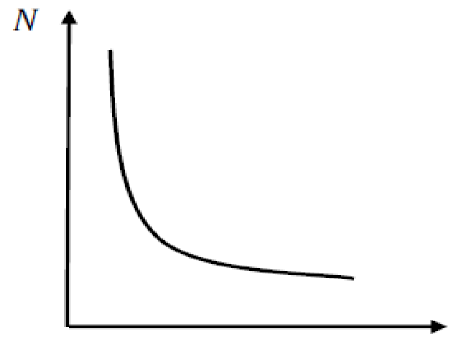


Figure 2.9 (b)

PERFORMANCE CURVES OF DC SERIES MOTOR

The performance curves of DC series motor are shown in Figure 2.10. The machine is so designed that it is having maximum efficiency near rated load.

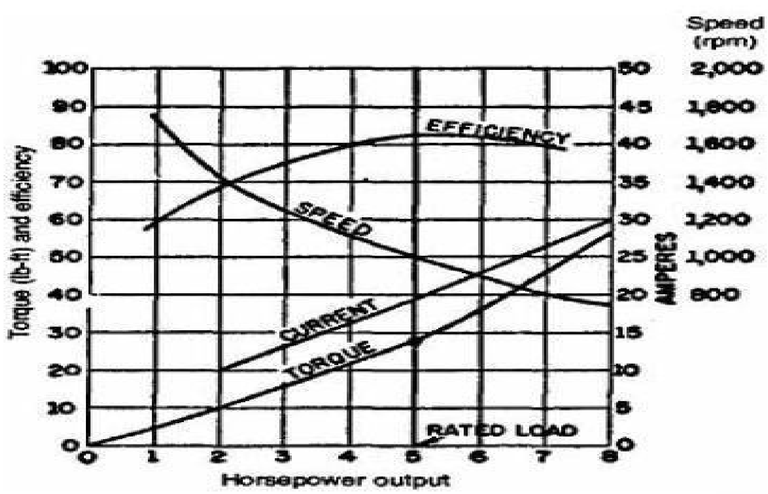


Figure 2.10

For a given input current, the starting torque developed by a DC series motor is greater than that developed by a shunt motor. Hence series motors are used where huge starting torques are necessary. Ex. Cranes, hoists, electric traction etc. The DC series motor responds by decreasing its speed for the increased in load. The current drawn by the DC series motor for the given increase in load is lesser than DC shunt motor. The drop in speed with increased load is much more prominent in series motor than that in a shunt motor. Hence series motor is not suitable for applications requiring a constant speed.

COMPOUND MOTOR CHARACTERISTICS:

Cumulative compound motors are used where series characteristics are required and in addition the load is likely to be removed totally such as in some types of coal cutting machines or for driving heavy machine tools which have to take sudden deep cuts quite often. Speed will not become excessively high due to shunt winding and the motor will be able to take heavy loads because of series winding. Differential compound motors: Series field opposes the shunt field; therefore the flux is decreased as the load is applied to the motor. This results in the motor speed remaining almost constant or even increasing with increase in load.

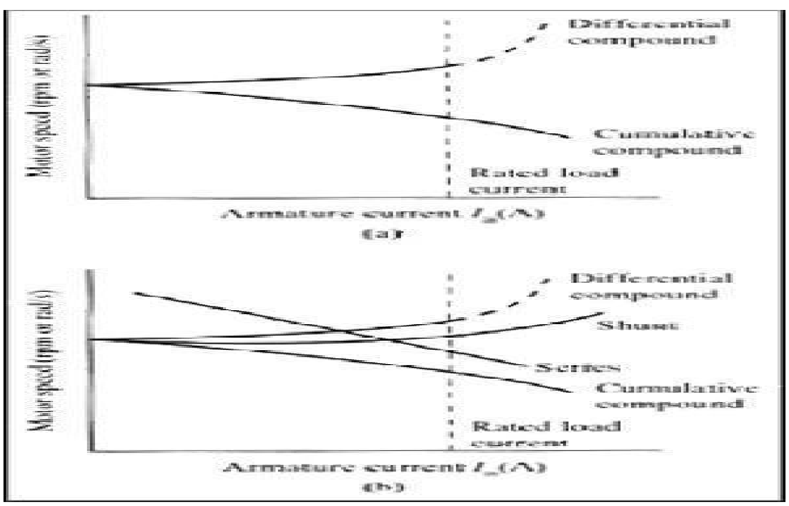


Figure 2.11

Summarizing,

1. $\frac{N}{I_a}$ Lies between shunt ($\emptyset$ = constant) and series ($\emptyset \propto I_a$]characteristics as shown in figure

2.11

Used in rolling mills where light and heavy loads are thrown on the motor

Armature Reaction and Commutation:

In a d.c. generator, the purpose of field winding is to produce magnetic field (called main flux) whereas the purpose of armature winding is to carry armature current. Although the armature winding is not provided for the purpose of producing a magnetic field, nevertheless the current in the armature winding will also produce magnetic flux (called armature flux). The armature flux distorts and weakens the main flux posing problems for the proper operation of the d.c. generator. The action of armature flux on the main flux is called armature reaction.

it was hinted that current in the coil is reversed as the coil passes a brush. This phenomenon is termed as commutation. The criterion for good commutation is that it should be sparkles. In order to have sparkless commutation, the brushes should lie along magnetic neutral axis. In this chapter, we shall discuss the various aspects of armature reaction and commutation in a d.c. generator.

Armature Reaction

So far we have assumed that the only flux acting in a d.c. machine is that due to the main poles called main flux. However, current flowing through armature conductors also creates a magnetic flux (called armature flux) that distorts and weakens the flux coming from the poles. This distortion and field weakening takes place in both generators and motors. The action of armature flux on the main flux is known as armature reaction.

The phenomenon of armature reaction in a d.c. generator is shown in Fig. (1.41). Only one pole is shown for clarity. When the generator is on no-load, a smal1 current flowing in the armature does not appreciably affect the main flux ϕcoming from the pole [See Fig 1.41 (i)]. When the generator is loaded, the current flowing through armature conductors sets up flux ϕ_1. Fig. (1.41) (ii) shows flux due to armature current alone. By superimposing ϕ_1 and ϕ_2, we obtain the resulting flux ϕ_3 as shown in Fig. (1.41) (iii). Referring to Fig (1.41) (iii), it is clear that flux density at; the trailing pole tip (point B) is increased while at theleading pole tip (point A) it is decreased. This unequal field distribution produces the following two effects:

(a) The main flux is distorted.

(b) Due to higher flux density at pole tip B, saturation sets in. Consequently, the increase in flux at pole tip B is less than the decrease in flux under pole tip A. Flux ϕ_3 at full load is, therefore, less than flux ϕ_1 at no load. As we shall see, the weakening of flux due to armature reaction depends upon the position of brushes

(c) The demagnetizing effect of armature mmf reduces the total flux per pole. The reduction in about 1 to 5% from no load to full load.

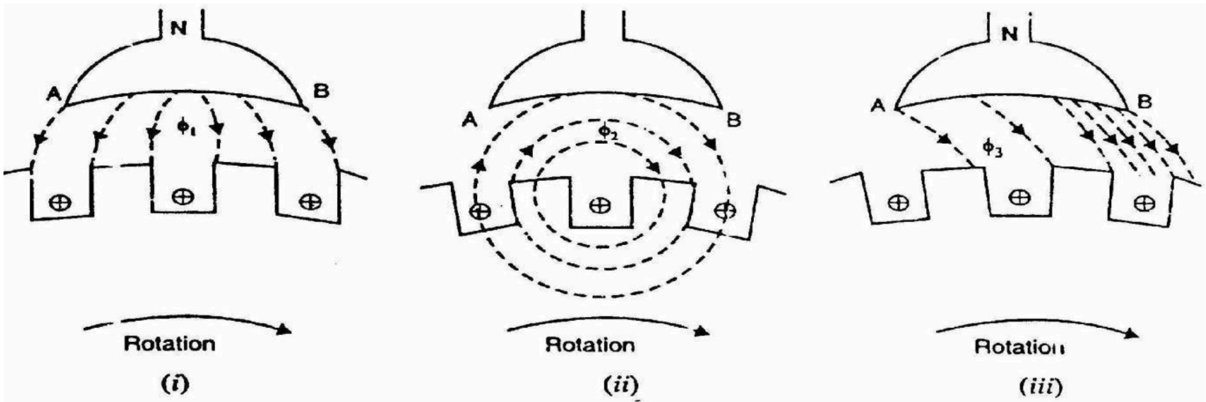


Fig. (1.41)

Geometrical and Magnetic Neutral Axes

The geometrical neutral axis (G.N.A.) is the axis that bisects the angle between the centre line of adjacent poles [See Fig. 1.42 (i)]. Clearly, it is the axis of symmetry between two adjacent poles.

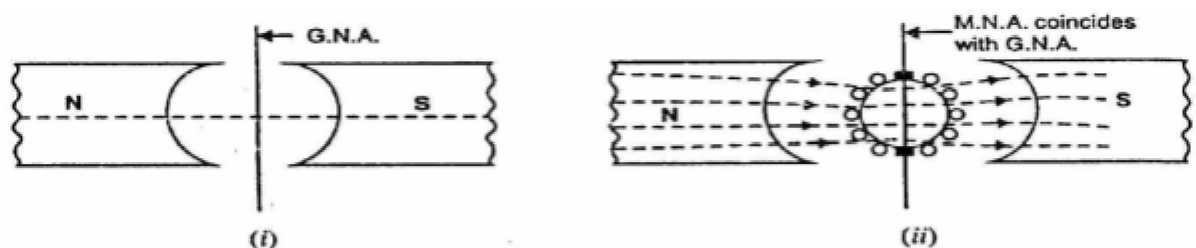


Fig. (1.42)

(i) The magnetic neutral axis (M. N. A.) is the axis drawn perpendicular to the mean direction of the flux passing through the centre of the armature. Clearly, no e.m.f. is produced in the armature conductors along this axis because then they cut no flux. With no current in the armature conductors, the M.N.A. coincides with G, N. A. as shown in Fig. (1.42).

(ii) In order to achieve sparkless commutation, the brushes must lie along M.N.A.

Explanation of Armature Reaction

With no current in armature conductors, the M.N.A. coincides with G.N.A. However, when current flows in armature conductors, the combined action of main flux and armature flux shifts the M.N.A. from G.N.A. In case of a generator, the M.N.A. is shifted in the direction of rotation of the machine. In order to achieve sparkless commutation, the brushes have to be moved along the new M.N.A. Under such a condition, the armature reaction produces the following two effects:

1. It demagnetizes or weakens the main flux.

2. It cross-magnetizes or distorts the main flux.

Let us discuss these effects of armature reaction by considering a 2-pole generator (though the following remarks also hold good for a multipolar generator).

(i) Fig. (1.43) (i) shows the flux due to main poles (main flux) when the armature conductors carry no current. The flux across the air gap is uniform. The m.m.f. producing the main flux is represented in magnitude and direction by the vector OF_m in Fig. (1.43) (i). Note that OF_m is perpendicular to G.N.A.

(i) Fig. (1.43) (ii) shows the flux due to current flowing in armature conductors alone (main poles unexcited). The armature conductors to the left of G.N.A. carry current "in" (?) and those to the right carry current "out" (•). The direction of magnetic lines of force can be found by cork screw rule. It is clear that armature flux is directed downward parallel to the brush axis. The m.m.f. producing the armature flux is represented in magnitude and direction by the vector OF_A in Fig. (1.43) (ii).

(i) Fig. (1.43) (iii) shows the flux due to the main poles and that due to current in armature conductors acting together. The resultant m.m.f. OF is the vector sum of OF_m and OF_A as shown in Fig. (1.43) (iii). Since M.N.A. is always perpendicular to the resultant m.m.f., the M.N.A. is shifted through an angle generator. Note that M.N.A. is shifted in the direction of rotation of the

In order to achieve sparkless commutation, the brushes must lie along the M.N.A. Consequently, the brushes are shifted through an angle so as to lie along the new M.N.A. as shown in Fig. (1.43) (iv). Due to brush shift, the m.m.f. F_A of the armature is also rotated through the same angle . It is because some of the conductors which were earlier under N-pole now come under S-pole and vice-versa. The result is that armature m.m.f. F_A will no longer be vertically downward but will be rotated in thedirection of rotation through an angle as shown in Fig. (1.43) (iv). Now F_A can be resolved into rectangular components F_c and F_d.

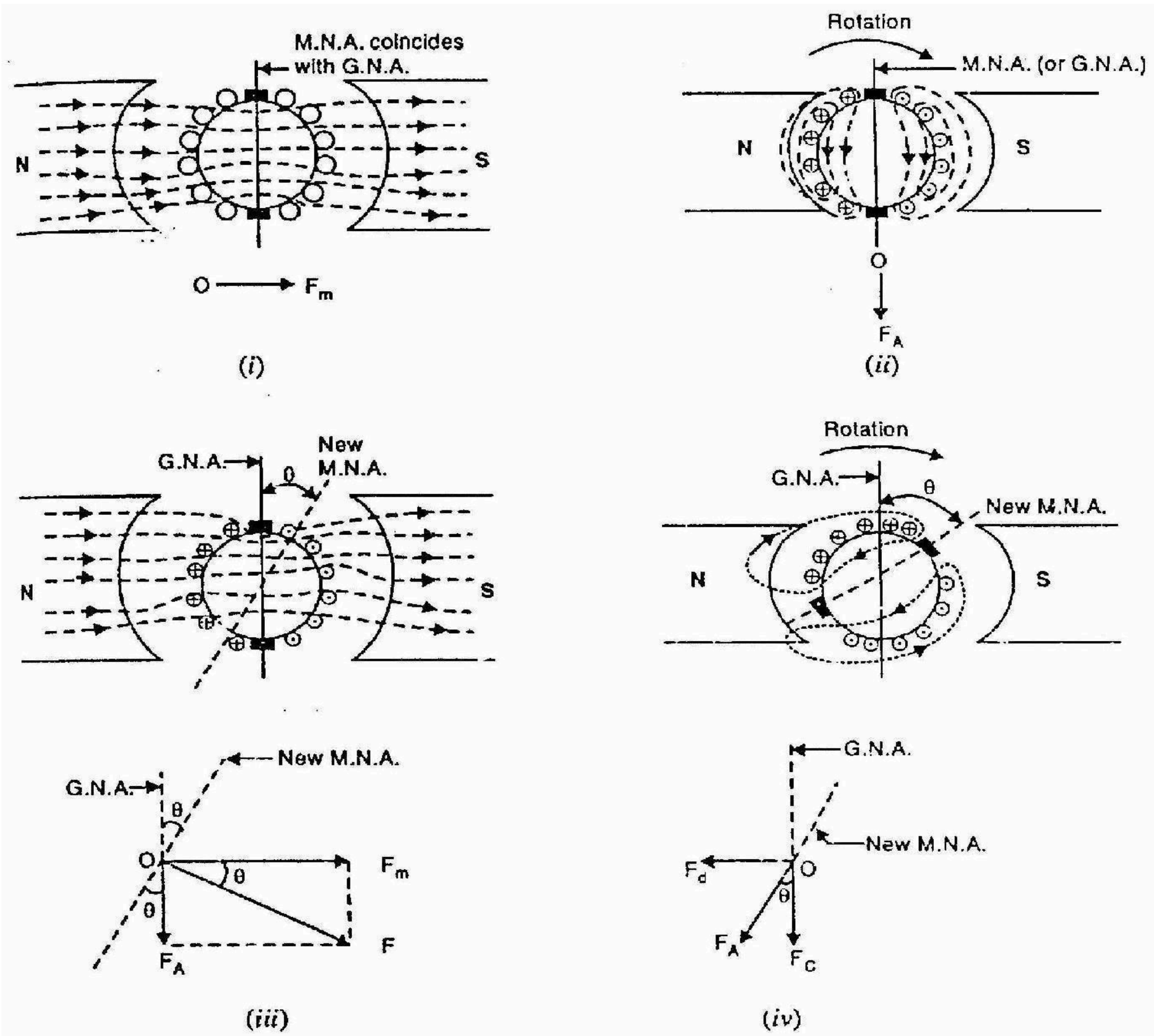


Fig. (1.43)

(a) The component F_d is in direct opposition to the m.m.f. OF_m due to main poles. It has a demagnetizing effect on the flux due to main poles. For this reason, it is called the demagnetizing or weakening component of armature reaction.

(b) The component F_c is at right angles to the m.m.f. OF_m due to main poles. It distorts the main field. For this reason, it is called the cross-magnetizing or distorting component of armature reaction.

It may be noted that with the increase of armature current, both demagnetizing and distorting effects will increase.

Conclusions

(i) With brushes located along G.N.A. (i.e., $\theta = 0°$), there is no demagnetizing component of armature reaction ($F_d = 0$). There is only distorting or cross-magnetizing effect of armature reaction.

(ii) With the brushes shifted from G.N.A., armature reaction will have both demagnetizing and distorting effects. Their relative magnitudes depend on the amount of shift. This shift is directly proportional to the armature current.

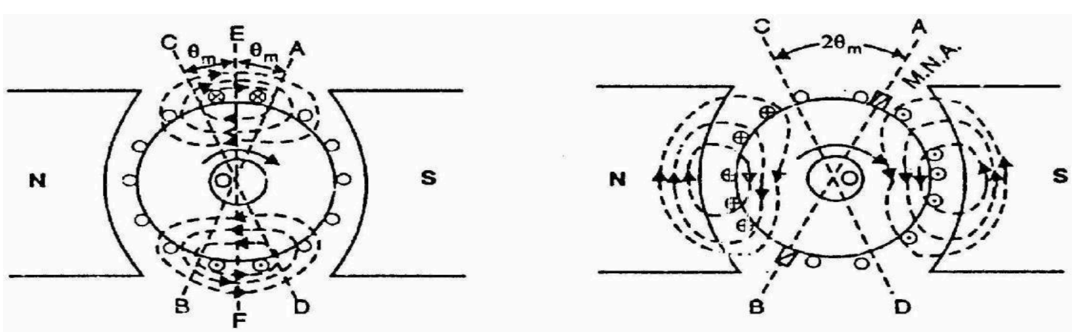
(iii) The demagnetizing component of armature reaction weakens the main flux. On the other hand, the distorting component of armature reaction distorts the main flux.

The demagnetizing effect leads to reduced generated voltage while cross-magnetizing effect leads to sparking at the brushes.

Demagnetizing and Cross-Magnetizing Conductors

With the brushes in the G.N.A. position, there is only cross-magnetizing effect of armature reaction. However, when the brushes are shifted from the G.N.A. position, the armature reaction will have both demagnetizing and cross-magnetizing effects. Consider a 2-pole generator with brushes shifted (lead) θ_m mechanical degrees from G.N.A. We shall identify the armature conductors that produce demagnetizing effect and those that produce cross-magnetizing effect.

The armature conductors $\theta°_m$ on either side of G.N.A. produce flux in direct opposition to main flux as shown in Fig. (1.44) (i). Thus the conductors lying within angles AOC = BOD = $2\theta_m$ at the top and bottom of the armature produce demagnetizing effect. These are called demagnetizing armature conductors and constitute the demagnetizing ampere-turns of armature reaction (Remember two conductors constitute a turn).



(i) (ii)

Fig.(1.44)

(ii) The axis of magnetization of the remaining armature conductors lying between angles AOD and COB is at right angles to the main flux as shown in Fig. (1.44) (ii). These conductors produce the cross-magnetizing (or distorting) effect i.e., they produce uneven flux distribution on each pole. Therefore, they are called cross- magnetizing conductors and constitute the cross-magnetizing ampere-turns of armature reaction.

Calculation of Demagnetizing Ampere-Turns Per Pole (AT_d/Pole)

It is sometimes desirable to neutralize the demagnetizing ampere-turns of armature reaction. This is achieved by adding extra ampere-turns to the main field winding. We shall now calculate the demagnetizing ampere-turns per pole (AT_d/pole).

Let Z= total number of armature conductors

I = current in each armature conductor

= $I_a/2$ ... for simplex wave winding

= I_a/P ... for simplex lap winding

θ_m = forward lead in mechanical degrees

Referring to Fig. (1.44) (i) above, we have, Total demagnetizing armature conductors

Total number of armature conductors in angles AOC and BOD = $\frac{4\theta_m}{360} \times Z$

Since two conductors constitute one turn,

Total number of turns in these angles = $\frac{2\theta_m}{360} \times ZI$

∴ demagnetizing amp-turns per pair of poles = $\frac{2\theta_m}{360} \times ZI$

∴ demagnetizing amp-turns/ poles = $\frac{\theta_m}{360} \times ZI$

i.e,

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

Cross-Magnetizing Ampere-Turns Per Pole ATc/Pole)

We now calculate the cross-magnetizing ampere-turns per pole (AT_c/pole). Total armature reaction ampere-turns per pole

$$= \frac{Z/2}{P} \times I = \frac{Z}{2P} \times I \text{ (Q two conductors make one turn)}$$

Demagnetizing ampere-turns per pole is given by;

$$\text{Demagnetizing amp-turns/ poles} = \frac{\theta_m}{360} \times ZI$$

(found above)

$$= Z\left(1 - \frac{2\theta_m}{360}\right)$$

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

$$P \quad 360 \quad P \quad 360$$

$$\therefore \text{Cross-magnetizing ampere-conductors/pole} = ZI\left(\frac{1}{P} - \frac{2\theta_m}{360}\right)$$

$$\therefore \text{Cross-magnetizing ampere-conductors/pole} = ZI\left(\frac{1}{2P} - \frac{\theta_m}{360}\right)$$

(remembering that two conductors make one turn)

$$AT_c \text{ per pole} = ZI\left(\frac{1}{2P} - \frac{\theta_m}{360}\right)$$

For neutralizing the demagnetizing effect of armature reaction, an extra number of turns may be put on each pole

No. of extra turns/pole = $\frac{AT_d}{I_{sh}}$ - for shunt generator

= $\frac{AT_d}{I_a}$ - for series generator

(a) Detrimental effects of armature reaction:

(1) Distortion of main field flux

It gives rise to 3 deterimental effects.

(i) Rise in iron losses

(ii) Poor commutation and

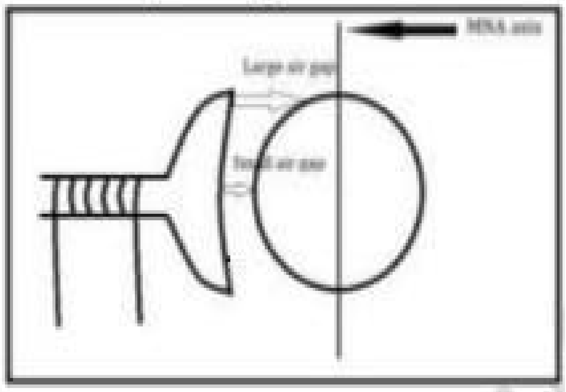
(iii) Sparking

(2) Net reduction of the main field flux influences the cost of the main field flux.

(i) iron losses: These losses depended on the maximum value of flux density in teeth and interpole shoes. Distorting main field flux, increases the flux density in teeth iron losses at full load is abiut 1.5 times no load value.

1.36(b) Methods of limiting the effects of Armature Reaction:

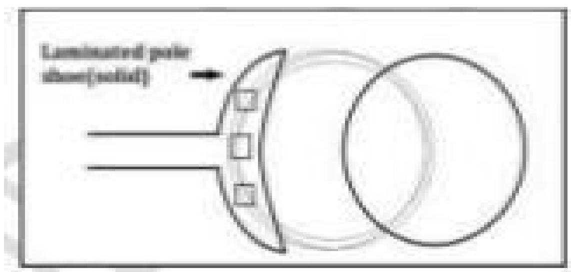
(i) High reluctance pole tips:



MNA axis
Large air gap
Small air gap

1. At the time of construction we use chamfered poles. These poles have larger air gap on the tips and smaller air gap at the center. These poles provide non uniform air gap. The effect of armature reaction is more near to edge of poles and negligible near the center of poles.
2. If air gap is kept non uniform i.e., larger air gap at the edge (pole tip) and smaller near the center of the pole and then armature flux near the pole tip decreases and armature reaction decreases.

(i) By laminated pole shoe:

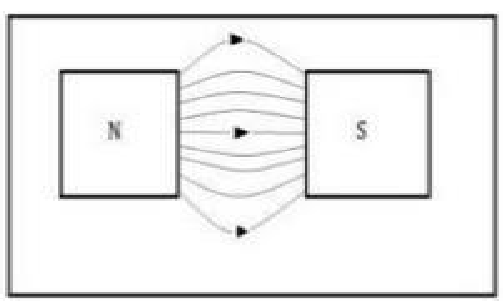


We insear laminated objects in the pole. By having laminated pole shoe the reluctance in the armature flux path increases. Hence the armature flux gap gets reduced.

(ii) By reduction in Armature flux:

The effect of armature reaction is reduced by creating more reluctance in the path of armature flux. This is achieved by using field pole laminations having several rectangular holes punched in them. It gives high reluctance in the path of armature flux. Due this armature cross flux reduces whereas main field remains almost unaffected.

(iii) By havig strong magnetic field:



During the design of dc machine it should be ensured that the main field m.m.f. if sufficiently in comparison with full load armature flux. Greater the main field, lesser will be the distortion.

(iv) Inter Poles

(v) Compensating winding

These two methods are explained in below in detail.

Compensating Windings

The cross-magnetizing effect of armature reaction may cause trouble in d.c. machines subjected to large fluctuations in load. In order to neutralize the cross magnetizing effect of armature reaction, a compensating winding is used A compensating winding is an auxiliary winding embedded in slots in the pole faces as shown in Fig. (1.45).

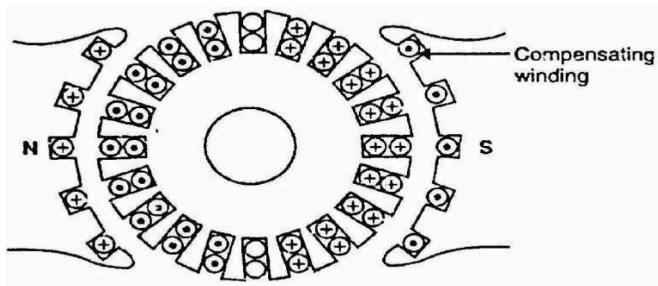


Fig. 1.45

The direction of current through the compensating conductors in any one pole face will be opposite to the direction of the current through the adjacent armature conductors [See Fig. 1.45]. Let us now calculate the number of compensating conductors/ pole face. In calculating the conductors per pole face required for the compensating winding, it should be remembered that the current in the compensating conductors is the armature current I_a whereas the current in armature conductors is I_a/A where A is the number of parallel paths.

Let Z_c = No. of compensating conductors/pole face Z_a = No. of active armature conductors

I_a = Total armature current

I_a/A = Current in each armature conductor

$$\therefore Z_c I_a = Z_a \times \frac{I_a}{A}$$

or $$Z_c = \frac{Z_a}{A}$$

The use of a compensating winding considerably increases the cost of a machine and is justified only for machines intended for severe service e.g., for high speed and high voltage machines.

AT/Pole for Compensating Winding

Only the cross-magnetizing ampere-turns produced by conductors under the pole face are effective in producing the distortion in the pole cores. If Z is the total number of armature conductors and P is the number of poles, then

$$\text{No. of armature conductors/pole} = \frac{Z}{p}$$

$$\text{No. of armature turns/pole} = \frac{Z}{2P}$$

$$\text{No. of armature turns under pole face} = \frac{Z}{2P} \times \frac{\text{Pole arc}}{\text{Pole pitch}}$$

If I is the current through each armature conductor, then,

$$\text{AT/pole required for compensating winding} = \frac{ZI}{2P} \times \frac{\text{Pole arc}}{\text{Pole pitch}}$$

$$= \text{Armature AT/pole} \times \frac{\text{Pole arc}}{\text{Pole pitch}}$$

Commutation

Fig. (1.46) shows the schematic diagram of 2-pole lap-wound generator. There are two parallel paths between the brushes. Therefore, each coil of the winding carries one half ($I_a/2$ in this case) of the total current (I_a) entering or leaving the armature.

Note that the currents in the coils connected to a brush are either all towards the brush (positive brush) or all directed away from the brush (negative brush). Therefore, current in a coil will reverse as the coil passes a brush. This reversal of current as the coil passes & brush is called commutation.

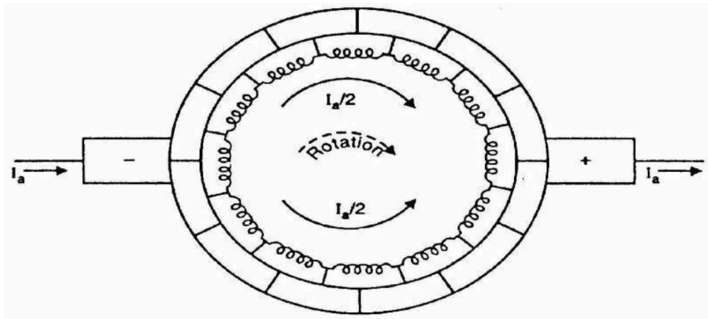


Fig. (1.46)

The reversal of current in a coil as the coil passes the brush axis is called commutation.

When commutation takes place, the coil undergoing commutation is short-circuited by the brush. The brief period during which the coil remains short-circuited is known as commutation period T_c. If the current reversal is completed by the end of commutation period, it is called ideal commutation. If the current reversal is not completed by that time, then sparking occurs between the brush and the commutator which results in progressive damage to both.

(i) Ideal commutation

Let us discuss the phenomenon of ideal commutation (i.e., coil has no inductance) in one coil in

the armature winding shown in Fig. (1.46) above. For this purpose, we consider the coil A. The brush width is equal to the width of one commutator segment and one mica insulation. Suppose the total armature current is 40 A. Since there are two parallel paths, each coil carries a current of 20 A

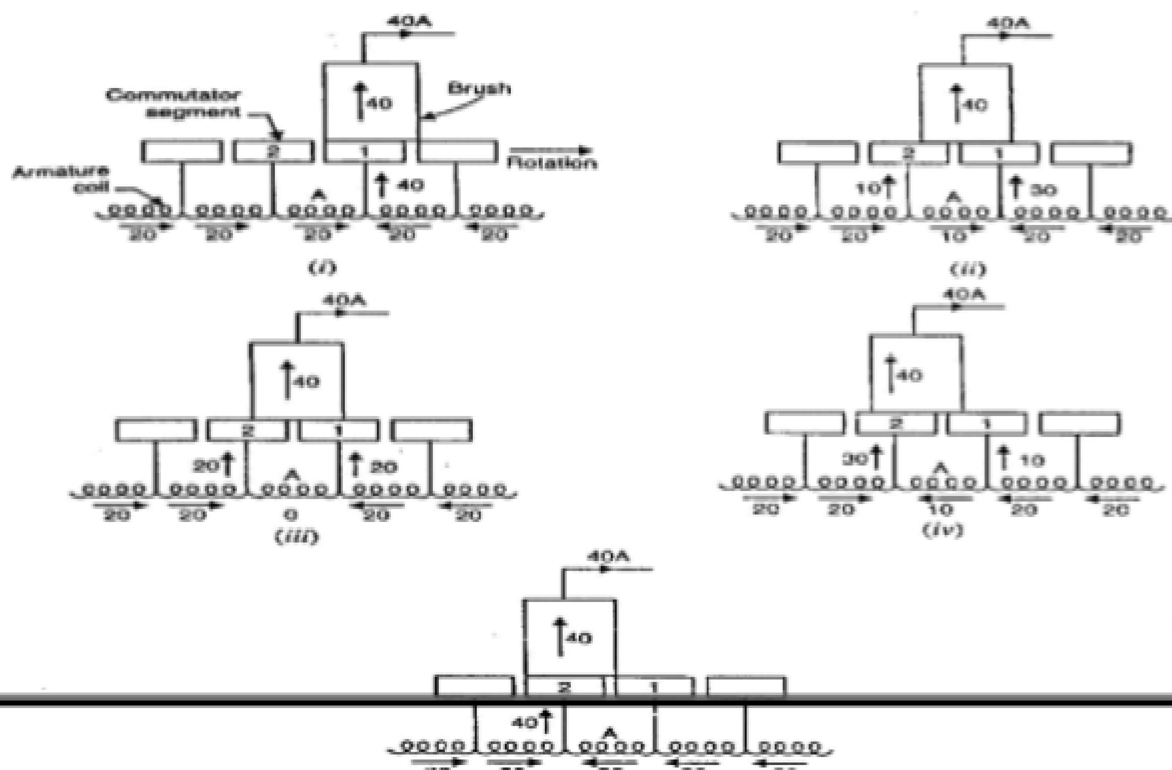


Fig. (1.47)

(i) In Fig. (1.47) (i), the brush is in contact with segment 1 of the commutator. The commutator segment 1 conducts a current of 40 A to the brush; 20 A from coil A and 20 A from the adjacent coil as shown. The coil A has yet to undergo commutation.

(ii) As the armature rotates, the brush will make contact with segment 2 and thus short-circuits the coil A as shown in Fig. (1.47) (ii). There are now two parallel paths into the brush as long as the short-circuit of coil A exists. Fig. (1.47) (ii) shows the instant when the brush is

one-fourth on segment 2 and three-fourth on segment 1. For this condition, the resistance of the path through segment 2 is three times the resistance of the path through segment 1 (Q contact resistance varies inversely as the area of contact of brush with the segment). The brush again conducts a current of 40 A; 30 A through segment 1 and 10 A through segment
2. Note that current in coil A (the coil undergoing commutation) is reduced from 20 A to 10 A.

(iii) Fig. (1.47) (iii) shows the instant when the brush is one-half on segment 2 and one-half on segment 1. The brush again conducts 40 A; 20 A through segment 1 and 20 A through segment 2 (Q now the resistances of the two parallel paths are equal). Note that now. Current in coil A is zero.

(iv) Fig. (1.47) (iv) shows the instant when the brush is three-fourth on segment 2 and one- fourth on segment 1. The brush conducts a current of 40 A; 30 A through segment 2 and 10 A through segment 1. Note that current in coil A is 10 A but in the reverse direction to that before the start of commutation. The reader may see the action of the commutator in reversing the current in a coil as the coil passes the brush axis.

(v) Fig. (1.47) (v) shows the instant when the brush is in contact only with segment 2. The brush again conducts 40 A; 20 A from coil A and 20 A from the adjacent coil to coil A. Note that now current in coil A is 20 A but in the reverse direction. Thus the coil A has undergone commutation. Each coil undergoes commutation in this way as it passes the brush axis. Note that during commutation, the coil under consideration remains short- circuited by the brush.

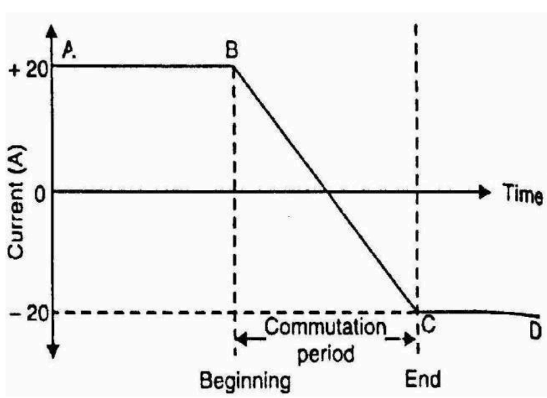


Fig. (1.48) shows the current-time graph for the coil A undergoing commutation. The horizontal line AB represents a constant current of 20 A upto the beginning of commutation. From the finish of commutation, it is represented by another horizontal line CD on the opposite side of the zero

(vi) line and the same distance from it as AB i.e., the current has exactly reversed. The way in which current changes from B to C depends upon the conditions under which the coil undergoes commutation. If the current changes at a uniform rate (i.e., BC is a straight line), then it is called ideal commutation as shown in Fig. (1.48). under such conditions, no sparking will take place between the brush and the commutator.

(vii) Practical difficulties

The ideal commutation (i.e., straight line change of current) cannot be attained in practice. This is mainly due to the fact that the armature coils have appreciable inductance. When the current in the coil undergoing commutation changes, self-induced e.m.f. is produced in the coil. This is generally called reactance voltage. This reactance voltage opposes the change of current in the coil undergoing commutation. The result is that the change of current in the coil undergoing commutation occurs more slowly than it would be under ideal commutation.

This is illustrated in Fig. (1.49). The straight line RC represents the ideal commutation whereas the curve BE represents the change in current when self-inductance of the coil is taken into account. Note that current CE (= 8A in Fig. 1.49) is flowing from the commutator segment 1 to the brush at the instant when they part company. This results in sparking just as when any other current-carrying circuit is broken. The sparking results in overheating of commutator-brush contact and causing damage to both. Fig. (1.50) illustrates how sparking takes place between the commutator segment and the brush. At the end of commutation or short-circuit period, the current in coil A is reversed to a value of 12 A (instead of 20 A) due to inductance of the coil. When the brush breaks contact with segment 1, the remaining 8 A current jumps from segment 1 to the brush through air causing sparking between segment 1 and the brush.

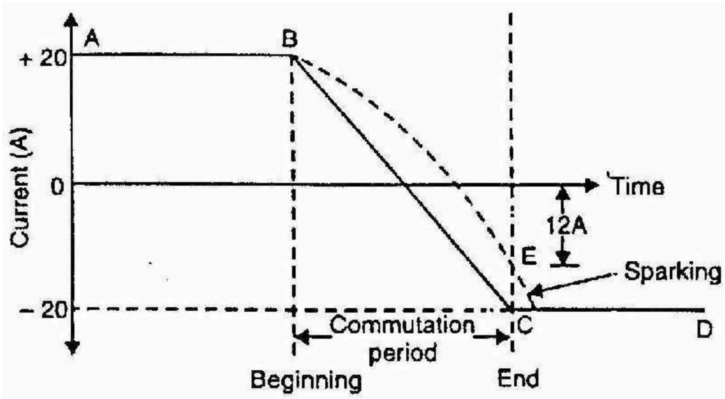


Fig. (1.49)

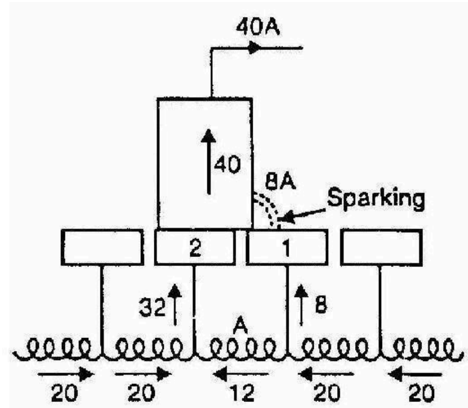


Fig. (1.50)

Calculation of Reactance Voltage

Reactance voltage = Coefficient of self-inductance x Rate of change of current

When a coil undergoes commutation, two commutator segments remain short-circuited by the brush. Therefore, the time of short circuit (or commutation period T_c) is equal to the time required by the commutator to move a distance equal to the circumferential thickness of the brush minus the thickness of one insulating strip of mica.

Commutation period(T_c) : It is defined as the time measuredfrom the instant the brush is fully on bar1, to the instant the brush is fully on bar2.

Let W_b = brush width in cm; W_m = mica thickness in cm v = peripheral speed of commutator in cm/s

$$\therefore \text{Commutation period, } T_c = \frac{W_b - W_m}{v} \text{ seconds}$$

The commutation period is very small, say of the order of 1/500 second.

Let the current in the coil undergoing commutation change from + I to I (amperes) during the commutation. If L is the inductance of the coil, then reactance voltage is given by;

∴ self induced or reactance voltage = $L \times \frac{2I}{T_C}$

$$=1.11 L \times \frac{2I}{TC}$$

(for linear commutation)

(for sinusoidal commutation)

The sum of the two emf‟s one due to self flux of the coil and the other due to the mutual flux of the neighboring coils is called reactance voltage.

The magnitude of reactance voltage is approximately proportional to the armature core length, coil pitch of the winding and square of the number of turns per coil. Reactance voltage can be minimized by using

(a) Small length of armature core by resorting to multipolar design

(b) Chorded – armature coils

(c) Smallest no of armature turns per coil.

Methods of Improving Commutation

Improving commutation means to make current reversal in the short-circuited coil as sparkles as possible. The following are the two principal methods of improving commutation:

(i) Resistance commutation

(ii) E.M.F. commutation

We shall discuss each method in turn.

Resistance Commutation

The reversal of current in a coil (i.e., commutation) takes place while the coil is short-circuited by the brush. Therefore, there are two parallel paths for the current as long as the short circuit exists. If the contact resistance between the brush and the commutator is made large, then current would divide in the inverse ratio of contact resistances (as for any two resistances in parallel). This is the key point in improving commutation.

This is achieved by using carbon brushes (instead of Cu brushes) which have high contact resistance. This method of improving commutation is called resistance commutation.

Figs. (1.51) and (1.52) illustrates how high contact resistance of carbon brush improves commutation (i.e., reversal of current) in coil A. In Fig. (1.51) (i), the brush is entirely on segment 1 and, therefore, the current in coil A is 20 A. The coil A is yet to undergo commutation. As the armature rotates, the brush short-circuits the coil A and there are two parallel paths for the current into the brush. Fig. (1.51) (ii) shows the instant when the brush is one-fourth on segment 2 and three-fourth on segment 1.

Figs. (1.51) and (1.52) illustrates how high contact resistance of carbon brush improves commutation (i.e., reversal of current) in coil A. In Fig. (1.51) (i), the brush is entirely on segment 1 and, therefore, the current in coil A is 20 A. The coil A is yet to undergo commutation. As the armature rotates, the brush short-circuits the coil A and there are two

parallel paths for the current into the brush. Fig. (1.51) (ii) shows the instant when the brush is one-fourth on segment 2 and three-fourth on segment 1.

The equivalent electric circuit is shown in Fig. (1.51) (iii) where R_1 and R_2 represent the brush contact resistances on segments 1 and 2. A resistor is not shown for coil A since it is assumed that the coil resistance is negligible as compared to the brush contact resistance. The values of current in the parallel paths of the equivalent circuit are determined by the respective resistances of the paths. For the condition shown in Fig. (1.51) (ii), resistor R_2 has three times the resistance of resistor R_1.

Therefore, the current distribution in the paths will be as shown. Note that current in coil A is reduced from 20 A to 10 A due to division of current in (he inverse ratio of contact resistances. If the Cu brush is used (which has low contact resistance), R_1 R_2 and the current in coil A would not have reduced to 10A.

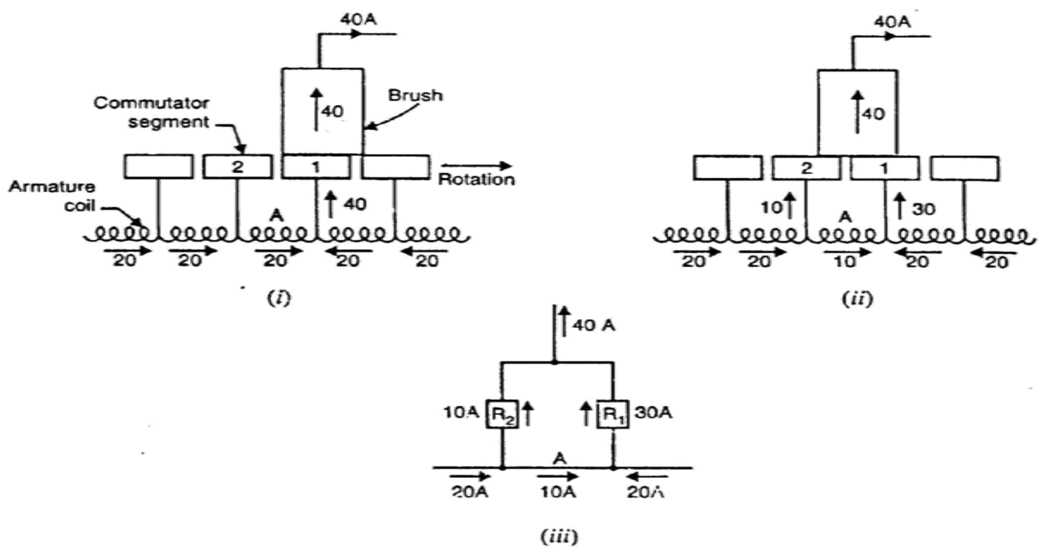


Fig. (1.51)

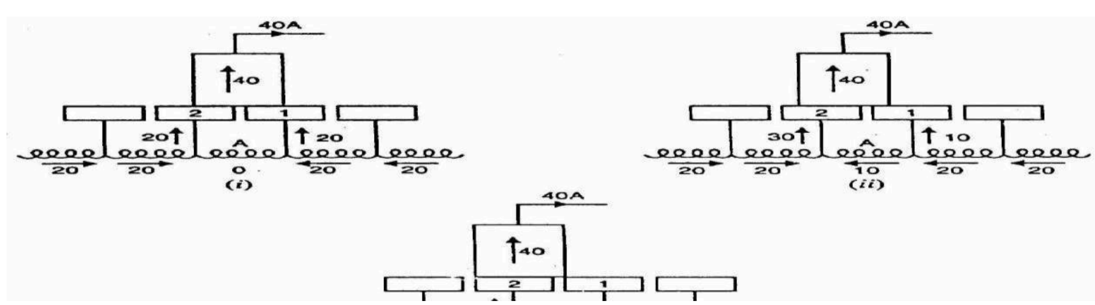


Fig. (1.52)

As the carbon brush passes over the commutator, the contact area with segment 2 increases and that with segment 1 decreases i.e., R_2 decreases and R_1 increases. Therefore, more and more current passes to the brush through segment 2. This is illustrated in Figs. (1.52) (i) and (1.52) (ii), When the break between the brush and the segment 1 finally occurs [See Fig. 1.52 (iii)], the current in the coil is reversed and commutation is achieved.

It may be noted that the main cause of sparking during commutation is the production of reactance voltage and carbon brushes cannot prevent it. Nevertheless, the carbon brushes do help in improving commutation. The other minor advantages of carbon brushes are:

(i) The carbon lubricates and polishes the commutator.

(i) If sparking occurs, it damages the commutator less than with copper brushes and the damage to the brush itself is of little importance.

In this resistance commutation carbon brushes are used for small d.c machines. And electrographite brushes wre used more frequently in all d.c machines. And copper brushes are used in low voltage (upto 30V) heavy current d.c machines. In this all three brushes are self lubricating.

E.M.F. Commutation

In this method, an arrangement is made to neutralize the reactance voltage by producing a reversing voltage in the coil undergoing commutation. The reversing voltage acts in opposition to the reactance voltage and neutralizes it to some extent. If the reversing voltage is equal to the reactance voltage, the effect of the latter is completely wiped out and we get sparkless commutation. The reversing voltage may be produced in the following two ways:

(i) By brush shifting

(ii) By using interpoles or compoles

(i) By brush shifting

In this method, the brushes are given sufficient forward lead (for a generator) to bring the short-circuited coil (i.e., coil undergoing commutation) under the influence of the next pole of opposite polarity. Since the short-circuited coil is now in the reversing field, the reversing voltage produced cancels the reactance voltage. This method suffers from the following drawbacks:

(i) The reactance voltage depends upon armature current. Therefore, the brush shift will depend on the magnitude of armature current which keeps on changing. This necessitates frequent shifting of brushes.

(ii) The greater the armature current, the greater must be the forward lead for a generator. This increases the demagnetizing effect of armature reaction and further weakens the main field.

(ii) By using interpoles or compotes

The best method of neutralizing reactance voltage is by, using interpoles or compoles.

Interpoles or Compoles

The best way to produce reversing voltage to neutralize the reactance voltage is by using interpoles or compoles. These are small poles fixed to the yoke and spaced mid-way between the main poles (See Fig. 1.53). They are wound with comparatively few turns and connected in series with the armature so that they carry armature current. Their polarity is the same as the next main pole ahead in the direction of rotation for a generator (See Fig. 1.53). Connections for a d.c. generator with interpoles is shown in Fig. (1.54).

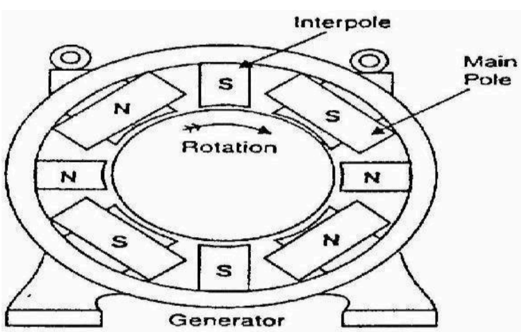


Fig. (1.53)

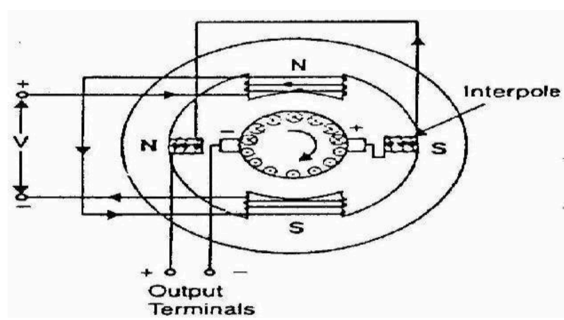


Fig. (1.54)

(i) Functions of Interpoles

The machines fitted with interpoles have their brushes set on geometrical neutral axis (no lead). The interpoles perform the following two functions:

(i) As their polarity is the same as the main pole ahead (for a generator), they induce an e.m.f. in the coil (undergoing commutation) which opposes reactance voltage. This leads to sparkless commutation. The e.m.f. induced by compoles is known as commutating or reversing e.m.f. Since the interpoles carry the armature current and the reactance voltage is also proportional to armature current, the neutralization of reactance voltage is automatic.

(i) The m.m.f. of the compoles neutralizes the cross-magnetizing effect of armature reaction in small region in the space between the main poles. It is because the two m.m.f.s oppose each other in this region.

Fig. (1.55) shows the circuit diagram of a shunt generator with commutating winding and compensating winding. Both these windings are connected in series with the armature and so they carry the armature current. However, the functions they perform must be understood clearly. The main function of commutating winding is to produce reversing (or commutating) e.m.f. in order to cancel the reactance voltage.

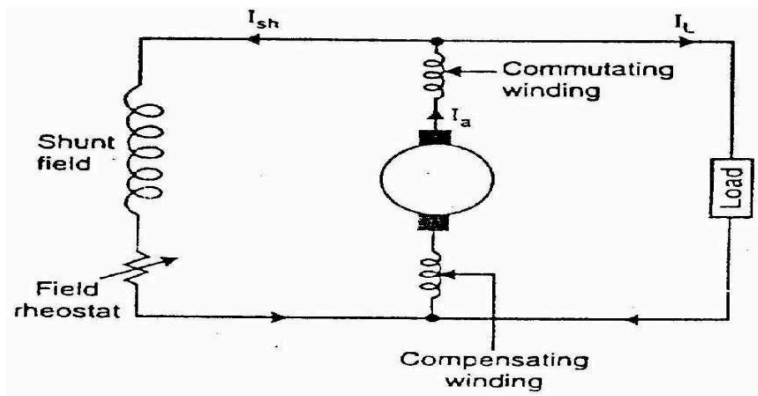


Fig. (1.55)

In addition to this, the m.m.f. of the commutating winding neutralizes the cross- magnetizing ampere-turns in the space between the main poles. The compensating winding neutralizes the cross-magnetizing effect of armature reaction under the pole faces.

Unit-III

Starting, Speed control and Testing of DC Machines

3.1 Speed control of shunt motor

We know that the speed of shunt motor is given by: *V-Irn=kφ* where, *Va* is the voltage applied across the armature and φ is the flux per pole and is proportional to the field current *If*. As explained earlier, armature current *Ia* is decided by the mechanical load present on the shaft. Therefore, by varying *Va* and *If* we can vary *n*. For fixed supply voltage and the motor connected as shunt we can vary *Va* by controlling an external resistance connected in series with the armature. *If* of course can be varied by controlling external field resistance *Rf* connected with the field circuit. Thus for .shunt motor we have essentially two methods for controlling speed, namely by:

1. varying armature resistance.
2. varying field resistance

i) Speed control by varying armature resistance

The inherent armature resistance *ra* being small, speed *n* versus armature current *Ia* characteristic will be a straight line with a small negative slope as shown in figure1. In the discussion to follow we shall not disturb the field current from its rated value. For shunt motor voltage applied to the field and armature circuit are same and equal to the supply voltage *V*. However, as the motor is loaded, *Iara* drop increases making speed a little less than the no load speed *n*0. For a well designed shunt motor this drop in speed is small and about 3 to 5% with

respect to no load speed. This drop in speed from no load to full load condition expressed as a percentage of no load speed is called the *inherent speed regulation* of the motor.

$$\text{Inherent \% speed regulation} = \frac{n - n_0}{n_0} \times 100$$

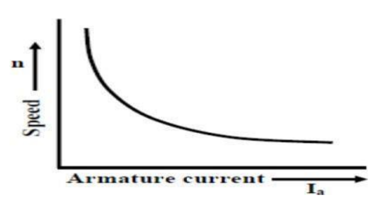


Fig.3.1: N v/s Ia Characteristics

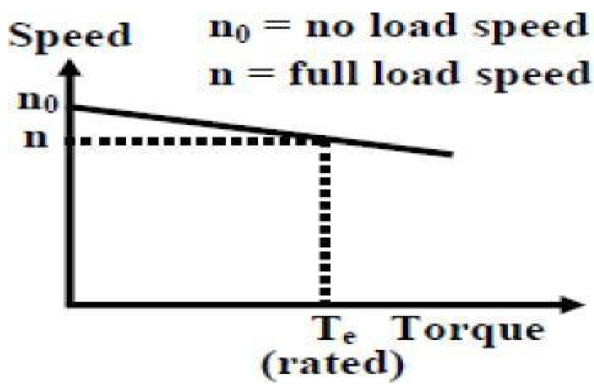


Fig 3.2 N v/s Te Characteristics

The slope of the *n* vs *Ia* or *n* vs *Te* characteristic can be modified by deliberately connecting external resistance *rext* in the armature circuit. One can get a family of speed vs. armature curves as shown in figures 3.1 and 3.2 for various values of *rext*. From these characteristic it can be explained how speed control is achieved. Let us assume that the load torque *TL* is constant and field current is also kept constant. Therefore, since steady state operation demands *Te* = *TL*, *Te* = *akI*φ too will remain constant; which means *Ia* will not change. Suppose *rext* = 0, then at rated load torque, operating point will be at C and motor speed will be

n. If additional resistance *rext*1 is introduced in the armature circuit, new steady state operating speed will be *n*1 corresponding to the operating point D. In this way one can get a speed of *n*2 corresponding to the operating point E, when *rext*2 is introduced in the armature circuit.

This same load torque is supplied at various speed. Variation of the speed is smooth and speed will decrease smoothly if *rext* is increased. Obviously, this method is suitable for controlling speed below the *base* speed and for supplying constant rated load torque which

ensures rated armature current always. Although, this method provides smooth wide range speed control (from base speed down to zero speed), has a serious draw back since energy loss takes place in the external resistance *rext* reducing the efficiency of the motor.

ii) Speed control by varying field current

In this method field circuit resistance is varied to control the speed of a d.c shunt motor. Let us rewrite .the basic equation to understand the method.

$$n = \frac{V - I_a r_a}{k\phi}$$

If we vary *If*, flux φ will change, hence speed will vary. To change *If* an external resistance is connected in series with the field windings. The field coil produces rated flux when no external resistance is connected and rated voltage is applied across field coil. It should be understood that we can only decrease flux from its rated value by adding external resistance. Thus the speed of the motor will rise as we decrease the field current and speed control above the *base* speed will be achieved. Speed versus armature current characteristic is shown in figure 3.3 for two flux values φ and 1φ. Since 1<φφ, the no load speed *'on* for flux value 1φ is more than the no load speed *no* corresponding to φ. However, this method will not be suitable for constant load torque. To make this point clear, let us assume that the load torque is constant at rated value. So from the initial steady condition, we have 1=*L ratedea ratedT=TkI*φ. If load torque remains constant and flux is reduced to 1φ, new armature current in the steady state is obtained from 11*aL ratekI=T* φ. Therefore new armature current is

$$I_{a1} = \frac{\phi}{\phi_1} I_{a\ rated}$$

But the fraction,1 1>φ; hence new armature current will be greater than the rated armature current and the motor will be overloaded. This method therefore, will be suitable for a load whose torque demand decreases with the rise in speed keeping the output power constant as shown in figure 3.3 Obviously this method is based on *flux weakening* of the main field. Therefore at higher speed main flux may become so weakened, that armature reaction effect will be more pronounced causing problem in commutation.

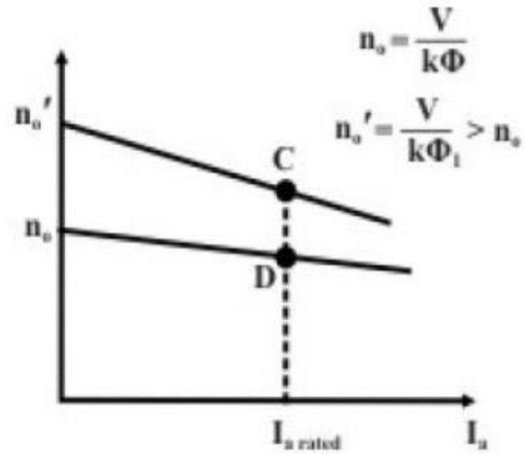


Fig. 3.3 :N v/s Ia Characteristics

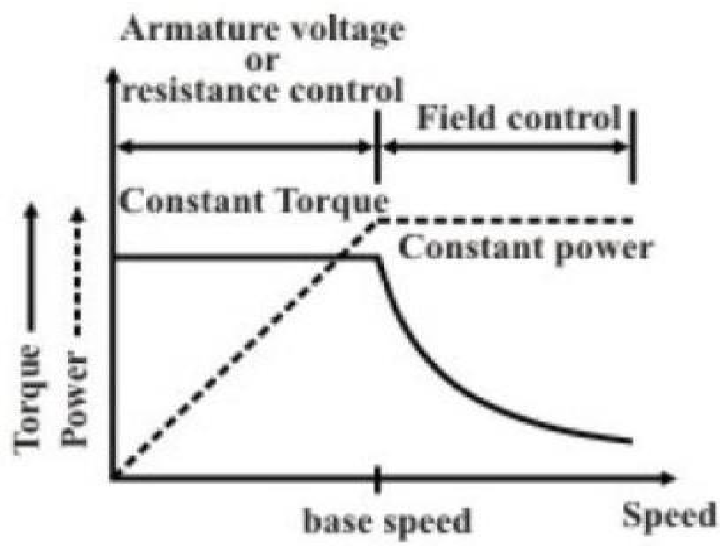
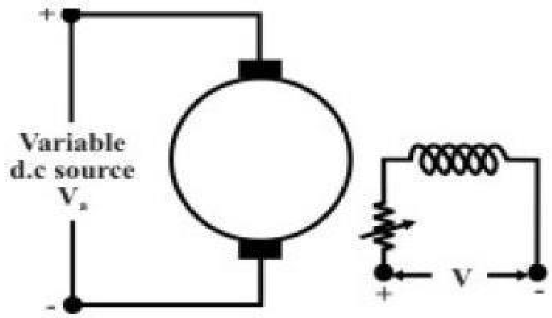
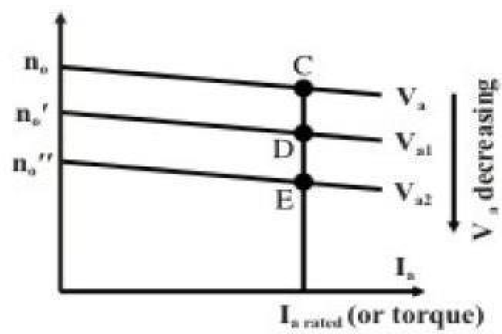


Fig.3. 4 : Constant Torque and Power Operation

iii) Speed control by armature voltage variation:

In this method of speed control, armature is supplied from a separate variable d.c voltage source, while the field is separately excited with fixed rated voltage as shown in figure 3.5. Here the armature resistance and field current are not varied. Since the no load speed 0=*aVkn*φ, the speed versus *Ia* characteristic will shift parallely as shown in figure for different values of *Va*.





As flux remains constant, this method is suitable for constant torque loads. In a way armature voltage control method is similar to that of armature resistance control method except that the former one is much superior as no extra power loss takes place in the armature circuit. Armature voltage control method is adopted for controlling speed from base speed down to very small speed as one should not apply across the armature a voltage which is higher than the ratedVoltage.

(a)Ward Leonard method: combination of *Va* and *If* control:

In this scheme, both field and armature control are integrated Arrangement for field control is rather simple. One has to simply connect an appropriate rheostat in the field circuit for this purpose. However, in the pre power electronic era, obtaining a *variable* d.c supply was not easy and a separately excited d.c generator was used to supply the motor armature. Obviously to run this generator, a *prime mover* is required. A 3-phase induction motor is used as the prime mover which is supplied from a 3-phase supply. By controlling the field current of the generator, the generated emf, hence *Va* can be varied. The potential divider connection uses two rheostats in parallel to facilitate reversal of generator field current.
First the induction motor is started with generator field current zero (by adjusting the jockey positions of the rheostats). Field supply of the motor is switched on with motor field rheostat set to zero. The applied voltage to the motor *Va*, can now be gradually increased to the rated value by slowly increasing the generator field current. In this scheme, no starter is required for the d.c motor as the applied voltage to the armature is gradually increased. To control the speed of the
d.c motor below base speed by armature voltage, excitation of the d.c generator is varied, while to control the speed above base speed field current of the d.c motor is varied maintaining constant *Va*.
Reversal of direction of rotation of the motor can be obtained by adjusting jockeys

of the generator field rheostats. Although, wide range smooth speed control is achieved, the cost involved is rather high as we require one additional d.c generator and a 3-phase induction motor of simialr rating as that of the d.c motor whose speed is intended to be controlled.

In present day, variable d.c supply can easily be obtained from a.c supply by using controlled rectifiers thus avoiding the use of additional induction motor and generator set to implement Ward leonard method.

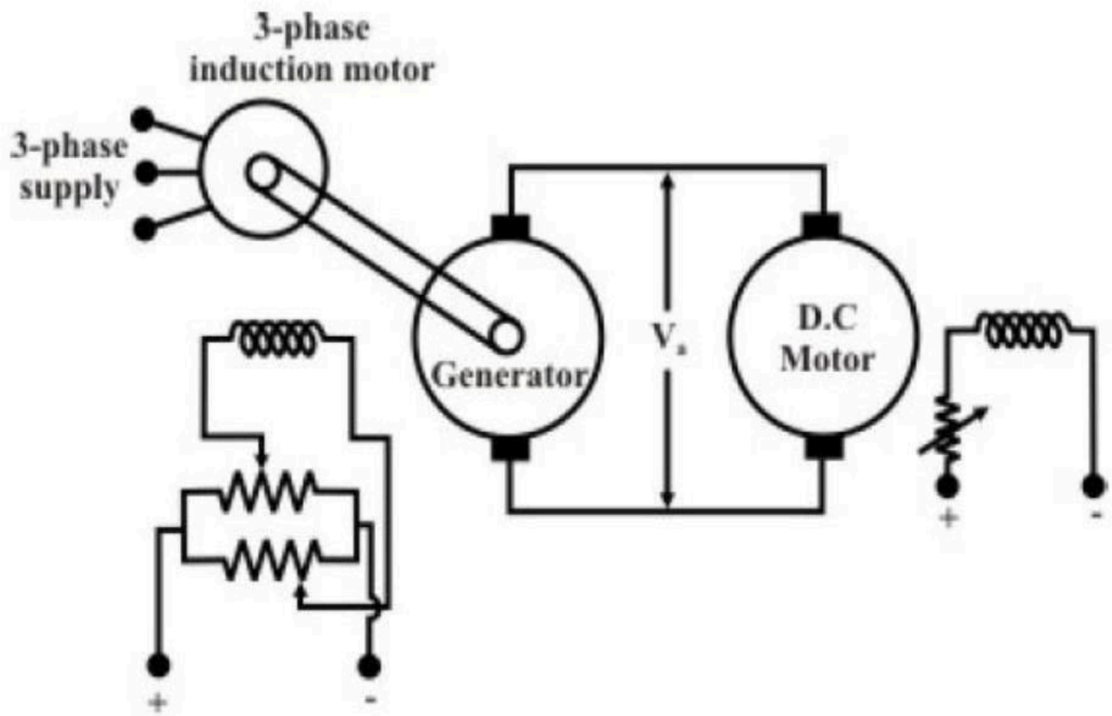


Fig 3.5: Scheme for Ward Leonard Method of Speed control

Some of the features of the Ward Leonard system are given below:

1. Absence of external resistance improves efficiency at all speeds and also when the generator emf becomes less than the back emf of the motor, the electrical power flows back from motor to generator, is converted to mechanical form and is returned to the mains via the driving AC motor.

2. Motor starts up smoothly therefore No starting device is required.

3. Speed reversal is smoothly carried out.

4. Fine speed control from zero to rated value in both the direct

This method of speed control is used in

a. High speed elevators

b. Colliery winders

Advantages

1. Absence of external resistance improves efficiency at all speeds

2. Motor starts up smoothly. No starting device is required

3. Speed reversal is smoothly carried out.

1.2 DC SERIES MOTOR:

Although a far greater percentage of electric motors in service are ac motors, the dc motor is of considerable industrial importance. The principal advantage of a dc motor is that its speed can be changed over a wide range by a variety of simple methods. Such a fine speed control is generally not possible with ac motors. In fact, fine speed control is one of the reasons for the strong competitive position of dc motors in the modem industrial applications.

The speed control of d.c. seriesmotors can be obtained by two methods (i) flux control method

(ii) armature-resistance control method. Armature-resistance control method method is mostly used.

I. Flux control method:

In this method, the flux produced by the series motor is varied. The variation of flux can be achieved in the following ways:

1. DIVERTER FIELD CONTROL:

In this method, a variable resistance (called field diverter) is connected in parallel with series field winding. A part of the line current passes through this diverter and thus weakens the field. Since $N \propto 1/\phi$, speed also varies with field flux. The lowest speed obtained by this method is the normal speed of motor when the current through diverter is zero, ie, diverter open circuited.

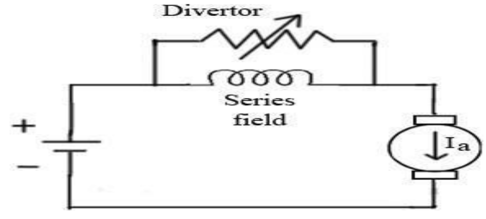


Fig.3.6 (a) Diverted field control

2. **Armature diverter :**

In order to obtain speeds below the normal speed, a variable resistance (called armature diverter) is connected in parallel with the armature. The diverter reduces the armature current. As a result flux get increased. So the speed decreases since N ∝ 1/ϕ.

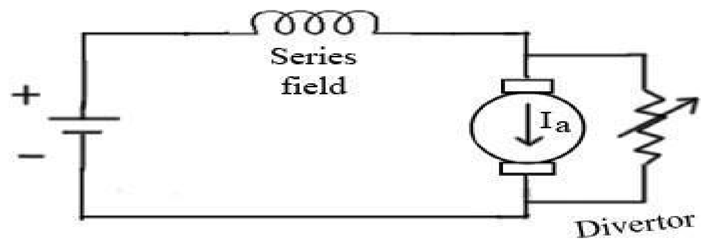
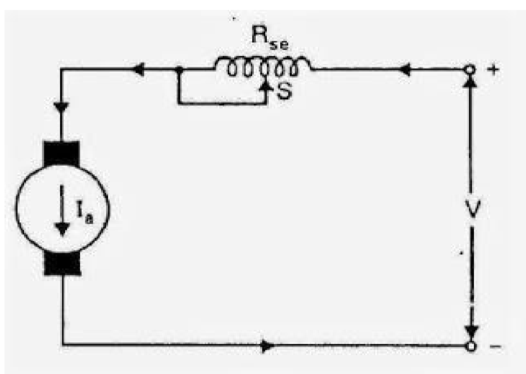


Fig 3.6(b) Armature diverter

3. **Tapped field control :**

In this method, the flux is reduced (and hence speed is increased) by decreasing the number of turns of the series field winding. The switch S can short circuit any part of the field winding, thus decreasing the flux and raising the speed. 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



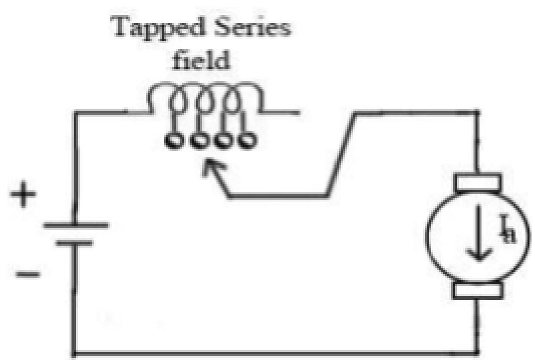


Fig 3.6 (c) Tapped field control

II. Armature-resistance Control:

In this method, a variable resistance is directly connected in series with the supply. This reduces the voltage available across the armature and hence the speed falls.

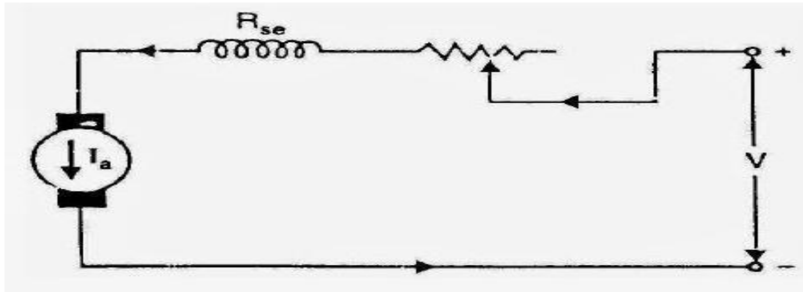


Fig.3.7 Armature-resistance Control

By changing the value of variable resistance, any speed below the normal speed can be obtained. This is the most common method employed to control the speed of d.c. series motors.

III. Series-Parallel Speed control of DC Series Motor

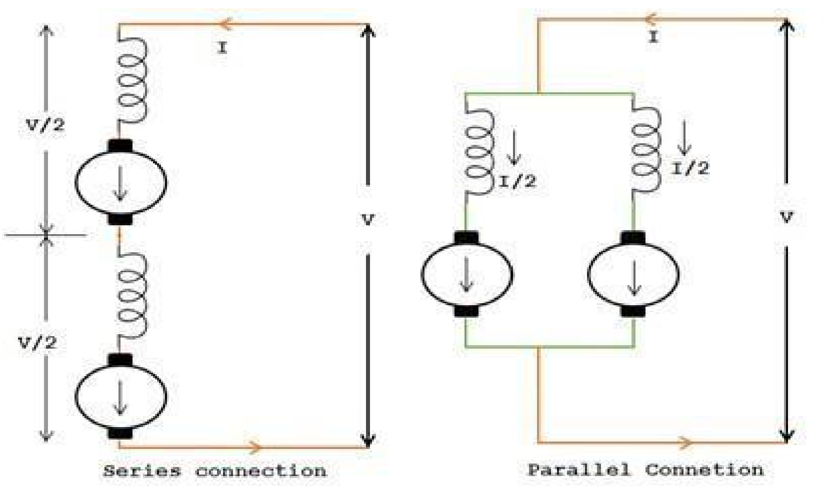


Fig.3. 8 Series-Parallel Speed control of DC Series Motor

To control the DC series motor this is another way called series parallel technique. This is the method normally used in traction by connecting two or more than that of the series motor are couple mechanically at the same load.

Whenever the series motors are connected in sequence (series) like shown in the figure, each and every armature of the motor receive the one-half of the rated voltage. Thus the speed will be less. If the series motors are connected in parallel, each and every armature of the motor receives the full normal voltage and hence the speed is also high. Thus we can achieve the two speeds (low or high) by connecting the motor either in series or parallel. Note for the same load on the pair of motors, the speed of the system would run nearly 4 times once motors are in parallel as while they are in series.

Starting of DC Motor:

The starting of DC motor is somewhat different from the starting of all other types ofelectrical motors. This difference is credited to the fact that a dc motorunlike other types of motor has a very high starting current that has the potential of damaging the internal circuit of the armature winding of dc motor if not restricted to some limited value. This limitation to the starting currentof dc motor is brought about by means of the starter. Thus the distinguishing fact about the starting methods of dc motor is that it is facilitated by means of a starter. Or rather a device containing a variableresistance connected in series to the armature winding so as to limit the starting current of dc motor to a desired optimum value taking into consideration the safety aspect of the motor.

why the DC motor has such high starting current ?

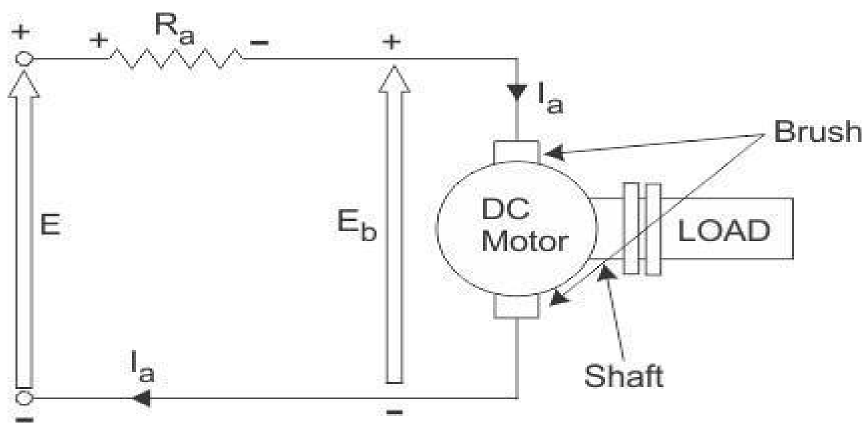
$$V = E_b + I_a R_a$$

Where V is the supply voltage, I_a is the armature current, R_a is the armature resistance. And the back emf is given by E_b. Now the back emf, in case of a dc motor, is very similar to the generated emf of a dc generator as it‟s produced by the rotational motion of the current carrying armature conductor in presence of the field. This back emf of dc motor is given by

$$E_b = \frac{\emptyset ZNP}{60A}$$

and has a major role to play in case of the starting of dc motor. From this equation we can see that E_b is directly proportional to the speed N of the motor. Now since at starting N = 0, E_b is also zero, and under this circumstance the voltageequation is modified to

$$V = 0 + I_a R_a$$



There fore $I_a = \frac{V}{Ra}$

For all practical practices to obtain optimum operation of the motor the armature resistance is kept very small usually of the order of 0.5 Ω and the bare minimum supply voltage being 220 volts. Even under these circumstance the starting current, I_a is as high as 220/0.5 amp = 440 amp. Such high starting current of dc motor creates two major problems.

1) Firstly, current of the order of 400 A has the potential of damaging the internal circuit of the armature winding of dc motor at the very onset.

2) Secondly, since thetorque equation of dc motor is given by

There fore $I_a = \frac{V}{Ra}$

Very high electromagnetic starting torque of DC motor is produced by virtue of the high starting current, which has the potential of producing huge centrifugal force capable of flying off the rotor winding from the slots.

Starting Methods of DC Motor:

As a direct consequence of the two above mentioned facts i.e. high starting current and high starting torque of DC motor, the entire motoring system can undergo total disarray and lead towards into an engineering massacre and non-functionality. To prevent such an incidence from occurring several starting methods of dc motor has been adopted. The main principal of this being the addition of external electrical resistance Rext to the armature winding, so as to increase the effective resistance to Ra + Rext, thus limiting the armature current to the rated value. The new value of starting armature current is desirably low and is given by.

$$\text{There fore } I_a = \frac{V}{Ra + Rext}$$

Now as the motor continues to run and gather speed, the back emf successively develops and increases, countering the supply voltage, resulting in the decrease of the net working voltage. Thus now,

$$\text{There fore } I_a = \frac{V - Eb}{Ra + Rext}$$

At this moment to maintain the armature current to its rated value, Rext is progressively decreased unless it‟s made zero, when the back emf produced is at its maximum. This regulation of the external electrical resistance in case of the starting of dc motor is facilitated by means of the starter.

Starters can be of several types and requires a great deal of explanation and some intricate level understanding. But on a brief over-view the main types of starters used in the industry today can be illustrated as:-

1) 3 point starter.

2) 4 point starter.

Used for the starting of shunt wound DC motor and compound wound DC motor.

STARTERS FOR DC MOTORS

(i) Three Point Starter:

It consists of resistances arranged in steps,R1 to R5 connected in series with the armature of the shunt motor. Field winding is connected across the supply through a protective devicecalled „NO – Volt Coil‟. Another protection given to the motor in this starter is „over load release coil‟. The arrangement is shown in Figure3.9

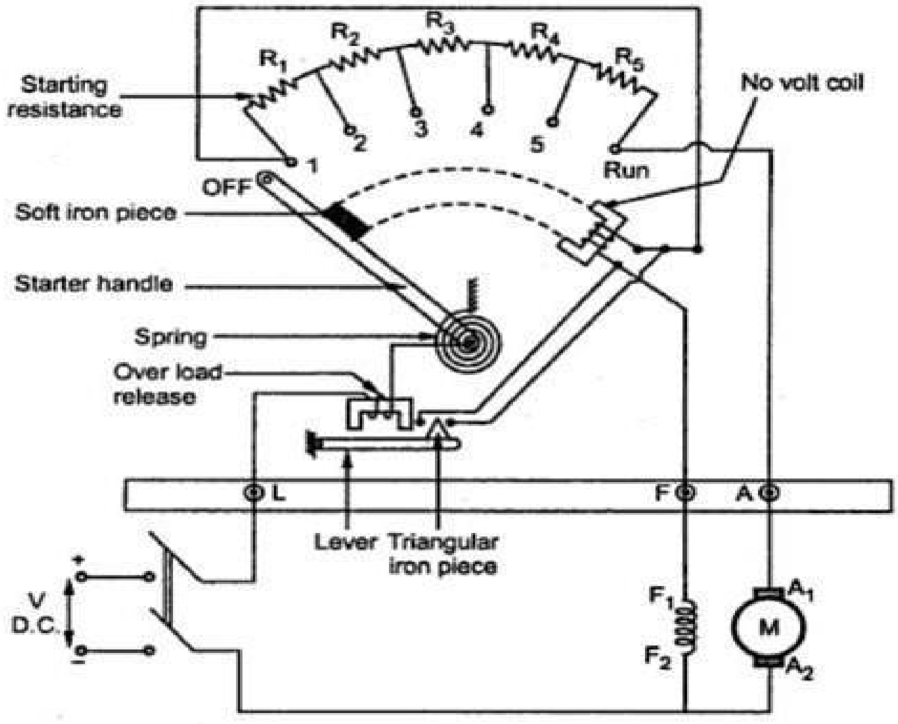


Figure 3.9 Three Point Starter

To start the motor the starter handle is moved from OFF position to run position gradually against the tension of a hinged spring. An iron piece is attached to the starter handle which is kept hold by the No-volt coil at Run position. The function of No volt coil is to get deenergised and release the handle when there is failure or disconnection or a break in the field circuit so that on restoration of supply, armature of the motor will not be connected across the lines without starter resistance. If the motor is over loaded beyond a certain predetermined value, then the electromagnet of overload release will exert a force enough to attract the lever which short circuits the electromagnet of No volt coil. Short circuiting of No volt coil results in deenergisation of it and hence the starter handle will be released and return to its off position due to the tension of the spring. In this type of starter, the shunt field current has to flow back through the starter resistance thus decreasing the shunt field current. This can be avoided by placing a brass arc on which the handle moves as shown in Figure 3.10.

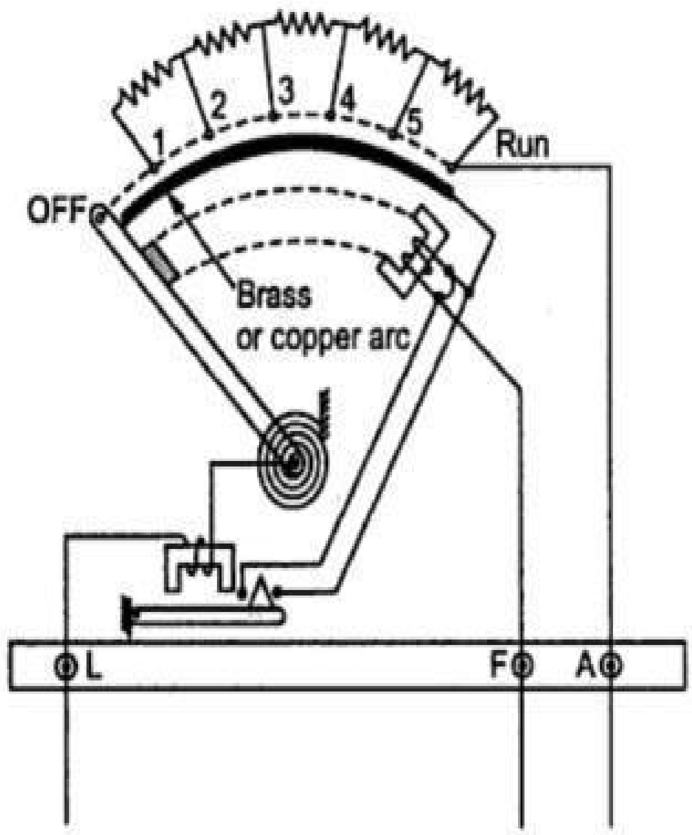


Figure 3.10

Construction of 3 Point Starter

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

1. 'L' Line terminal. (Connected to positive of supply.)

2. 'A' Armature terminal. (Connected to the armature winding.)

3. 'F' Field terminal. (Connected to the field winding.) And from there it gets the name 3 point starter.

Now studying the construction of 3 point starter in further details reveals that, the point 'L' is connected to an electromagnet called overload release (OLR) as shown in the figure. The other end of 'OLR' is connected to the lower end of conducting lever of starter handle where a spring is also attached with it and the starter handle contains also a soft iron piece housed on it. This handle is free to move to the other side RUN against the force of the spring. This spring brings back the handle to its original OFF position under the influence of its own force. Another parallel path is derived from the stud '1', given to the another electromagnet called No Volt Coil (NVC) which is further connected to terminal 'F'. The starting resistance at starting is entirely in series with the armature. The OLR and NVC acts as the two protecting devices of the starter.

Working of Three Point Starter

Having studied its construction, let us now go into the working of the 3 point starter. To start with the handle is in the OFF position when the supply to the DC motor is switched on. Then handle is slowly moved against the spring force to make a contact with stud No. 1. At this point, field winding of the shunt or the compound motor gets supply through the parallel path provided to starting resistance, through No Voltage Coil. While entire starting resistance comes in series with the armature. The high starting armature current thus gets limited as the current equation at this stage becomes $I_a = E/(R_a+R_{st})$. As the handle is moved further, it goes on making contact with studs 2, 3, 4 etc., thus gradually cutting off the series resistance from the armature circuit as the motor gathers speed. Finally when the starter handle is in 'RUN' position, the entire starting resistance is eliminated and the motor runs with normal speed.

This is because back emf is developed consequently with speed to counter the supply voltage and reduce the armature current. So the external electrical resistance is not required anymore, and is removed for optimum operation. The handle is moved manually from OFF to the RUN position with development of speed.

Working of No Voltage Coil of 3 Point Starter

The supply to the field winding is derived through no voltage coil. So when field current flows, the NVC is magnetized. Now when the handle is in the 'RUN' position, soft iron piece connected to the handle and gets attracted by the magnetic force produced by NVC, because of flow of current through it. The NVC is designed in such a way that it holds the handle in 'RUN' position against the force of the spring as long as supply is given to the motor. Thus NVC holds the handle in the 'RUN' position and hence also called hold on coil.

Now when there is any kind of supply failure, the current flow through NVC is affected and it immediately losses its magnetic property and is unable to keep the soft iron piece on the handle, attracted. At this point under the action of the spring force, the handle comes back to OFF position, opening the circuit and thus switching off the motor. So due to the combination of

NVC and the spring, the starter handle always comes back to OFF position whenever there is any supply problems. Thus it also acts as a protective device safeguarding the motor from any kind of abnormality.

Working of over load coil of 3 Point Starter

If any fault occurs on motor or overload, it will draw extreme current from the source. This current raise the ampere turns of OLR coil (over load relay) and pull the armature Coil, in consequence short circuiting the NVR coil (No volt relay coil). The NVR coil gets demagnetized and handle comes to the rest position under the influence of spring. Therefore the motor disconnected from the supply automatically.

Drawback of three point starter:

The use of a three point starter presents a problem. The speed of the motor is controlled by means of the field rheostat. To increase the speed of motor necessitates the setting of the field rheostat to higher resistance value. The current through the shunt field is reduced, and so is the current through the coil of the holding electromagnet. The reduced current through the coil weakens the strength of magnet and makes susceptible to line voltage variations. In the weakened condition a slight reduction in line voltage would further weaken the holding magnet, releasing the arm of the starter and thus disconnecting the motor from the line. Unscheduled stoppages of the motor make the three point starter quite unpopular.

FOUR POINT STARTER:

The 4 point starter like in the case of a 3 point starter also acts as a protective device that helps in safeguarding the armature of the shunt or compound excited dc motor against the high starting current produced in the absence of back emf at starting.

The 4 point starter has a lot of constructional and functional similarity to a three point starter, but this special device has an additional point and a coil in its construction, which naturally brings about some difference in its functionality, though the basic operational characteristic, remains the same.

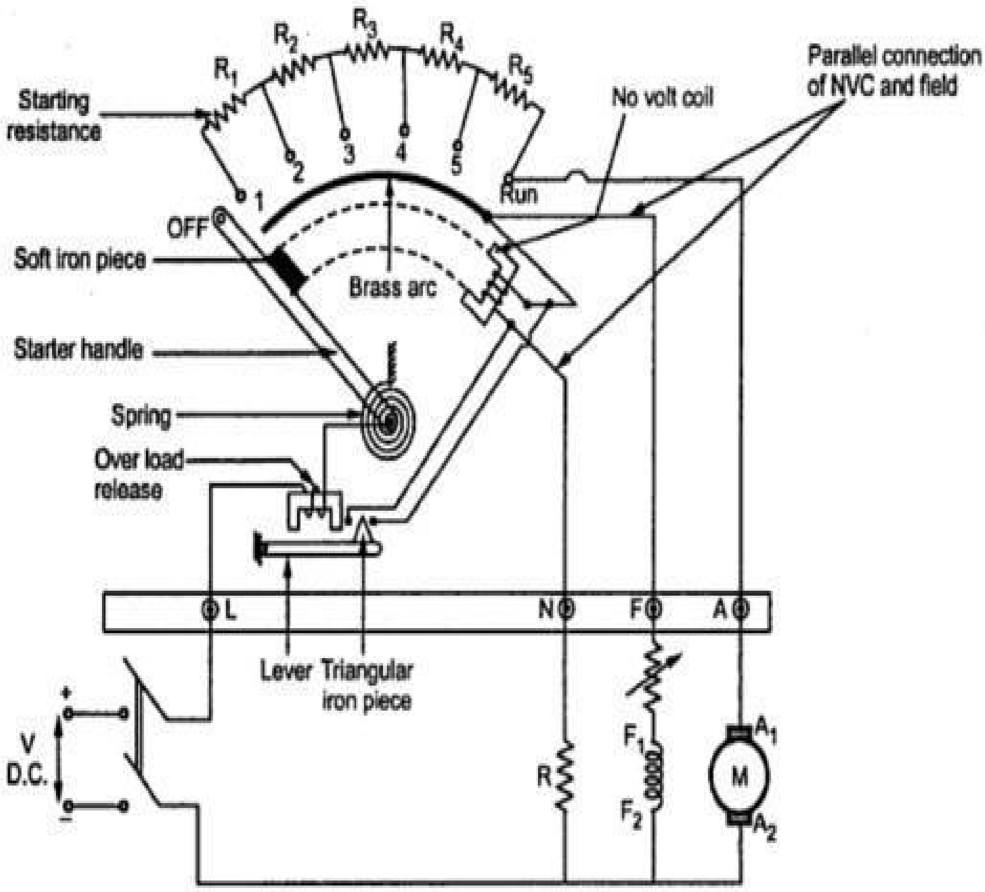


Figure 3.11 Four point starter

Figure 3.11 shows a four point starter. One important change is the No Volt Coil has been taken out of the shunt field and has been connected directly across the line through a Protecting resistance „R". When the arm touches stud one.

The current divides into three paths,

1. Through the starter resistance and the armature,
2. Through shunt field and the field rheostat and
3. Through No-volt Coil and the protecting resistance „R". With this arrangement, any change of current in shunt field circuit does not affect the current passing though the NO-volt coil because, the two circuits are independent of each other. Thus the starter handle will not be released to its off position due to changes in the field current which may happen when the field resistance is varied.

Construction and Operation of Four Point Starter

A 4 point starter as the name suggests has 4 main operational points, namely

1. 'L' Line terminal. (Connected to positive of supply.)

2. 'A' Armature terminal. (Connected to the armature winding.)

3. 'F' Field terminal. (Connected to the field winding.)

Like in the case of the 3 point starter, and in addition to it there is,

4. A 4th point N. (Connected to the No Voltage Coil)

The remarkable difference in case of a 4 point starter is that the No Voltage Coil is connected independently across the supply through the fourth terminal called 'N' in addition to the 'L', 'F' and 'A'. As a direct consequence of that, any change in the field supply current does not bring about any difference in the performance of the NVC. Thus it must be ensured that no voltage coil always produce a force which is strong enough to hold the handle in its 'RUN' position, against force of the spring, under all the operational conditions. Such a current is adjusted through No Voltage Coil with the help of fixed resistance R connected in series with the NVC using fourth point 'N' as shown in the figure above.

Apart from this above mentioned fact, the 4 point and 3 point starters are similar in all other ways like possessing is a variable resistance, integrated into number of sections as shown in the figure above. The contact points of these sections are called studs and are shown separately as OFF, 1, 2, 3, 4, 5, RUN, over which the handle is free to be manoeuvred manually to regulate the starting current with gathering speed.

Now to understand its way of operating let‟s have a closer look at the diagram given above. Considering that supply is given and the handle is taken stud No.1, then the circuit is complete and line current that starts flowing through the starter. In this situation we can see that the current will be divided into 3 parts, flowing through 3 different points.

i) 1 part flows through the starting resistance (R1+ R2+ R3…..) and then to the armature.

ii) A 2nd part flowing through the field winding F.

iii) And a 3rd part flowing through the no voltage coil in series with the protective resistance R.

So the point to be noted here is that with this particular arrangement any change in the shunt field circuit does not bring about any change in the no voltage coil as the two circuits are independent of each other. This essentially means that the electromagnet pull subjected upon the soft iron bar of the handle by the no voltage coil at all points of time should be high enough to keep the handle at its RUN position, or rather prevent the spring force from restoring the handle at its original OFF position, irrespective of how the field rheostat is adjusted.

This marks the operational difference between a 4 point starter and a 3 point starter. As otherwise both are almost similar and are used for limiting the starting current to a shunt wound DC motor or compound wound DC motor, and thus act as a protective device.

Losses and efficiency:

Motors convert *electrical* power (input power) into *mechanical* power (output power) while generators convert *mechanical* power (input power) into *electrical* power (output power). Whole of the input power cannot be converted into the output power in a practical machine due to various losses that take place within the machine. Efficiency η being the ratio of outputpower to input power is always less than 1 (or 100 %). Designer of course will try to make η as large as possible. Order of efficiency of rotating d.c machine is about 80 % to 85 %. It is therefore important to identify the losses which make efficiency poor.

(i) Major losses

Take the case of a loaded d.c motor. There will be copper losses in armature and field circuit. The armature copper loss is variable and depends upon degree of loading of the machine. For a shunt machine, the field copper loss will be constant if field resistance is not varied. Recall that rotor body is made of iron with slots in which armature conductors are placed. Therefore when armature rotates in presence of field produced by stator field coil, eddy current and hysteresis losses are bound to occur on the rotor body made of iron. The sum of eddy current and hysteresis losses is called the *core* loss or *iron* loss. To reduce *core* loss, circular varnished and slotted laminations or *stamping* are used to fabricate the armature. The value of the core loss will depend on the strength of the field and the armature speed. Apart from these there will be power loss due to *friction* occurring at the bearing & shaft and air friction (windage loss) due to rotation of the armature. To summarise following major losses occur in a d.c machine.

Field copper loss: It is power loss in the field circuit

1. During the course of loading if field circuit resistance is not varied, field copper loss remains constant.

2. Armature copper loss: It is power loss in the armature circuit since the value of armature current is decided by the load, armature copper loss becomes a function of time.

3. Core loss: It is the sum of eddy current and hysteresis loss and occurs mainly in the rotor iron parts of armature. With constant field current and if speed does not vary much with loading, core loss may be assumed to be constant.

4. Mechanical loss: It is the sum of bearing friction loss and the windage loss (friction loss due to armature rotation in air). For practically constant speed operation, this loss too, may be assumed to be constant.

Apart from the major losses as enumerated above there may be a small amount loss called *stray* loss occur in a machine. Stray losses are difficult to account. Power flow diagram of a d.c motor is shown in figure 4.1. A portion of the input power is consumed by the field circuit as field copper loss. The remaining power is the power which goes to the armature; a portion of which is lost as core loss in the armature core and armature copper loss. Remaining power is the grossMechanical power developed of which a portion will be lost as friction and remaining power will be the net mechanical power developed. Obviously efficiency of the motor will be given by:

$$\eta = \frac{P_{\text{net mech}}}{P_{\text{in}}}$$

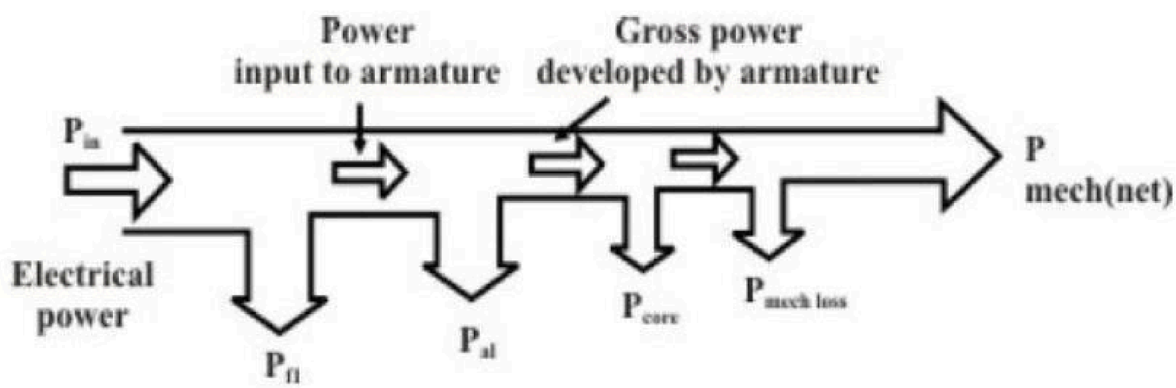


Fig 4.1 Power Flow Diagram of a DC motor

Similar power flow diagram of a d.c generator can be drawn to show various losses and input, output power

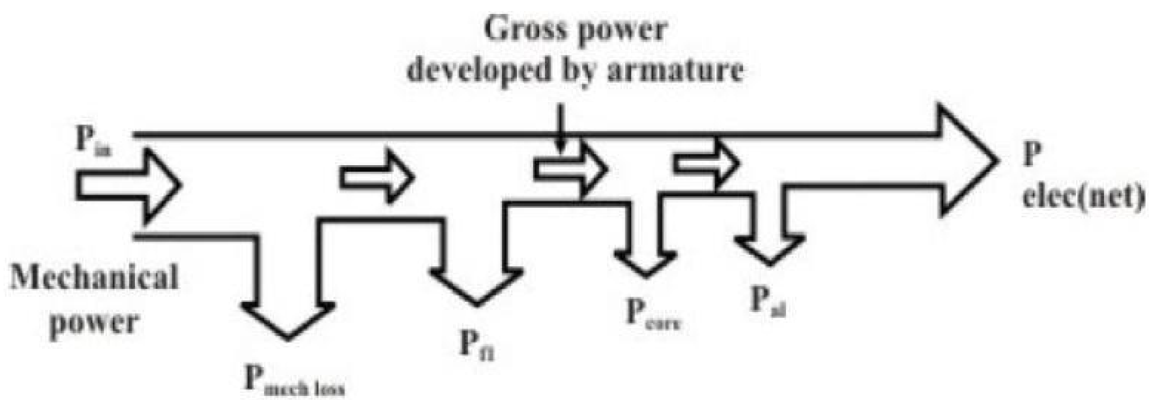


Fig 4.2 Power Flow Diagram of a DC Generator

Calculation of efficiency

Let field currents of the machines be are so adjusted that the second machine is acting as generator with armature current *Iag* and the first machine is acting as motor with armature current *Iam.* Also let us assume the current drawn from the supply be I_1. Total power drawn from supply is VI_1. which goes to supply all the losses (namely Cu losses in armature & field and rotational losses) of both the machines,

Now

$$
\begin{aligned}
\text{Power drawn from supply} &= VI_1 \\
\text{Field Cu loss for motor} &= VI_{fm} \\
\text{Field Cu loss for generator} &= VI_{fg} \\
\text{Armature Cu loss for motor} &= I_{am}^2 r_{am} \\
\text{Armature Cu loss for generator} &= I_{ag}^2 r_{ag} \\
\therefore \text{Rotational losses of both the machines} &= VI_1 - \left(VI_{fm} + VI_{fg} + I_{am}^2 r_{am} + I_{ag}^2 r_{ag}\right)
\end{aligned}
$$

Since speed of both the machines are same, it is reasonable to assume the rotational losses of both the machines are equal; which is strictly not correct as the field current of the generator will be a bit more than the field current of the motor, Thus, Rotational loss of each machine, $P_{rot} = \dfrac{VI_1 - \left(VI_{fm} + VI_{fg} + I_{am}^2 r_{am} + I_{ag}^2 r_{ag}\right)}{2}$

Once *Prot* is estimated for each machine we can proceed to calculate the efficiency of the machines as follows

(i) Efficiency of the motor

As pointed out earlier, for efficiency calculation of motor, first calculate the input power and then subtract the losses to get the output mechanical power as shown below,

$$\text{Total power input to the motor} = \text{power input to its field} + \text{power input to its armature}$$
$$P_{inm} = VI_{fm} + VI_{am}$$
$$\text{Losses of the motor} = VI_{fm} + I_{am}^2 r_{am} + P_{rot}$$
$$\text{Net mechanical output power } P_{outm} = P_{inm} - \left(VI_{fm} + I_{am}^2 r_{am} + P_{rot}\right)$$
$$\therefore \eta_m = \frac{P_{outm}}{P_{inm}}$$

(ii) Efficiency of the generator

For generator start with output power of the generator and then add the losses to get the input mechanical power and hence efficiency as shown below,

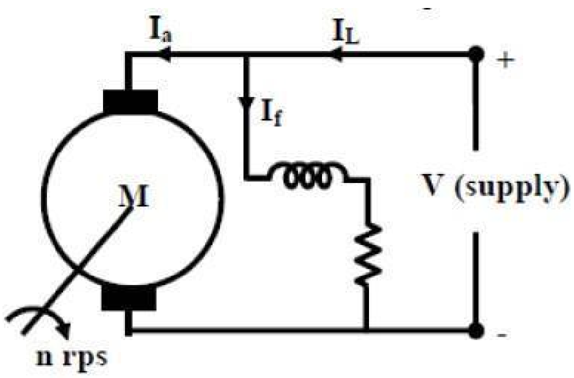
$$\text{Output power of the generator, } P_{outg} = VI_{ag}$$
$$\text{Losses of the generator} = VI_{fg} + I_{ag}^2 r_{ag} + P_{rot}$$
$$\text{Input power to the generator, } P_{ing} = P_{outg} + \left(VI_{fg} + I_{ag}^2 r_{ag} + P_{rot}\right)$$
$$\therefore \eta_g = \frac{P_{outg}}{P}$$

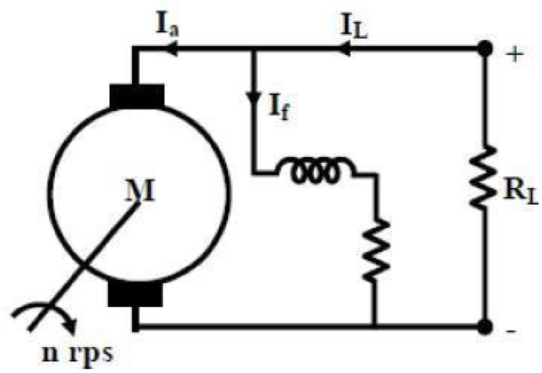
(iii) Condition for maximum efficiency

We have seen that in a transformer, maximum efficiency occurs when copper loss = core loss, where, copper loss is the variable loss and is a function of loading while the core loss is practically constant independent of degree of loading. This condition can be stated in a different way: maximum efficiency occurs when the variable loss is equal to the constant loss of the transformer.

Here we shall see that similar condition also exists for obtaining maximum efficiency in a d.c shunt machine as well.

Maximum efficiency for motor mode





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

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

Fig: Machine operates as Motor **Fig: Machine operates as generator**

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 *Ia* by *If* in the above expression for efficiency *m*η, 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 *m*η 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 $m\eta$ with respect to I_L and set it to zero as shown below

$$\frac{d\eta_m}{dI_L} = 0$$

$$\text{or, } \frac{d}{dI_L}\left(\frac{I_L r_a}{V} - \frac{P_{const}}{VI_L}\right) = 0$$

$$\text{or, } -\frac{r_a}{V} + \frac{P_{const}}{VI_L^2}$$

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

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

Testing of DC machines

Testing of DC machines can be broadly classified as

i) Direct method of Testing

ii) Indirect method of testing

(I) DIRECT METHOD OF TESTING:

In this method, the DC machine is loaded directly by means of a brake applied to a 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.

(II) 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 and Hopkinson‟s test are commonly used on shunt motors. But, as series motor cannot be started on No-load,these tests cannot be conducted on DC series motor.

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 figure4.3.

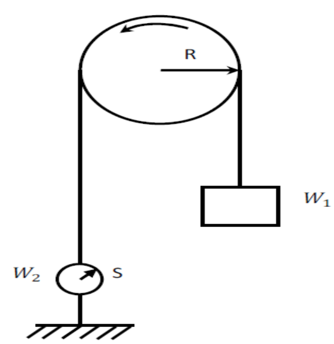


Figure 4.3

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

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

$= (W_1 - W_2) R\ X\ 2\ \pi\ N$ watts ………………. 3

Or 9.81 $(W_1 - W_2) R\ X\ 2\ \pi\ N$ watt.

$= 61.68$ N $(W_1 - W_2) R\ Watt$ ……….. 4

Input power = VI watts ………………. 5

Therefore efficiency $= \frac{output}{input} = \frac{61.68\ N\ (W_1 - W_2) R}{VI}$ ………… 6

W_1= suspended weight in kg

W_2 = Reading in spring balance in kg

R = radius of pulley

N = speed in rps

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

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.

Swinburne's Test:

For a d.c shunt motor change of speed from no load to full load is quite small. Therefore, mechanical loss can be assumed to remain same from no load to full load. Also if field current is held constant during loading, the core loss too can be assumed to remain same. In this test, the motor is run at rated speed under *no load* condition at rated voltage. The current drawn from the supply $I0$ and the field current $I\ sh$ are recorded.

This test is a no load test and hence cannot be performed on series motor. The circuit connection is shown in Figure 4.4. The machine is run on no load at rated speed which is adjusted by the shunt field resistance.

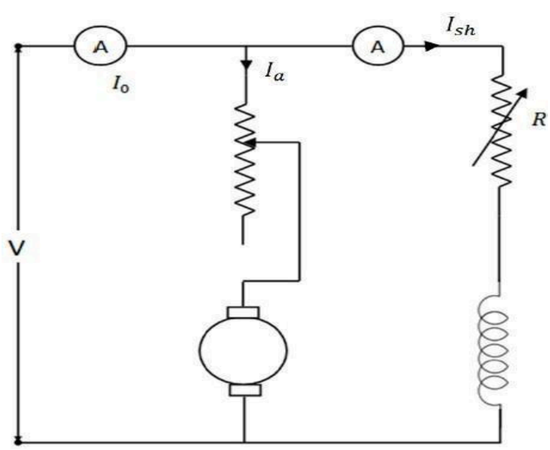


Figure 4.4

I_0 = No load current; Ish =
shunt field current
Iao = No load armature current = (Io - Ish) V=
Supply Voltage
No load input =VIo 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 Ia = I

– Ish if machine is motoring;

I + Ish if machine is generating

(a) 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

(b) 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

The biggest advantage of Swinburne's test is that the shunt machine is to be run as motor under *no load* condition requiring little power to be drawn from the supply; based on the no load reading, efficiency can be predicted for any load current. However, this test is not sufficient if we want to know more about its performance (effect of armature reaction, temperature rise, commutation etc.) when it is actually loaded. Obviously the solution is to load the machine by connecting mechanical load directly on the shaft for motor or by connecting loading rheostat across the terminals for generator operation. This although sounds simple but difficult to implement in the laboratory for high rating machines (say above 20 kW), Thus the laboratory must have proper supply to deliver such a large power corresponding to the rating of the machine. Secondly, one should have loads to absorb this power.

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.

Hopkinson's Or Regenerative Or Back To Back Test:

This is a regenerative test in which two identical DC shunt machines are coupled mechanically and tested simultaneously. One of the machines is run as a generator while the other as motor supplied by the generator. The set therefore draws only losses in the machines. The circuit connection is shown in Figure 4.5. The machine is started as motor and its shunt field resistance is varied to run the motor at its rated speed. The voltage of the generator is made equal to supply voltage by varying the shunt field resistance of the generator which is indicated by the zero reading of the voltmeter connected across the switch. By adjusting the field currents of the machines, the machines can be made to operate at any desired load within the rated capacity of the machines

CIRCUIT DIAGRAM

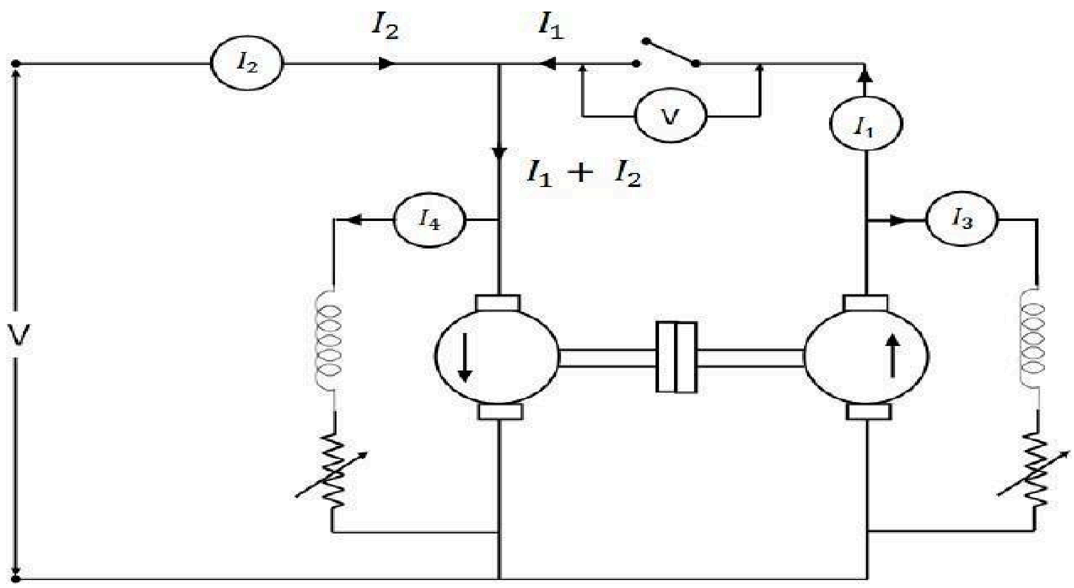


Figure 4.5

V= supply voltage

Motor input = V ($I_1 + I_2$)

Generator output = VI_1 (a)

If we assume both machines have the same efficiency „η", then,

Output of motor = η x input = η x V ($I_1 + I_2$) = input to generator

Output of generator = η x input = η x ηV ($I_1 + I_2$)) = η^2V ($I_1 + I_2$) (b)

Equating (a) and (b),

$VI_1 = \eta^2 V(I_1+I_2)$

Therefore, $\eta = \sqrt{\frac{I_1}{I_1+I_2}}$ ………………… 11

Armature copper loss in motor = $(I_1 + I_2 - I_4)^2 r_a$

Shunt field copper loss in motor = VI_4

Armature copper loss in generator = $(I_1 + I_3)^2 r_a$

Shunt field copper loss in generator = VI_3

Power drawn from supply = VI_2

Therefore stray losses = $VI_2 - [(I_1 + I_2 - I_4)^2 r_a + VI_4 + (I_1 + I_3)^2 r_a + VI_3]$ = W (say) …… 12

Stray losses/motor = $\frac{W}{2}$ ……………… 13

Therefore for generator

Total losses = $(I_1 + I_3)^2 r_a + VI_3 + \frac{W}{2} = W_g$ (say) ……………… 14

Output = VI_1, therefore $\eta_{generator} = \frac{VI_1}{VI_1+W_g} = \frac{output}{output+losses}$ ……….. 15

For motor,

Total losses $=(I_1 + I_2 - I_4)^2 r_a + VI_4 + \frac{W}{2} = W_m(say)$

Input to motor = $V(I_1 + I_2)$

Therefore $\eta_{motor} = \frac{V(I_1+I_2)-W_m}{V(I_1+I_2)}$ …………16

ALTERNATIVE CONNECTION:

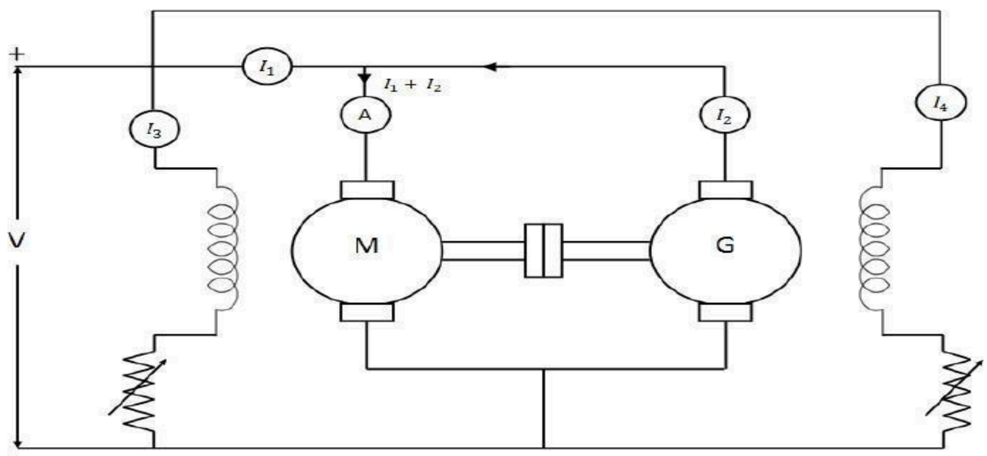


Figure 4.6

The Figure 4.6 shows an alternate circuit connection for this test. In this connection the shunt field windings are directly connected across the lines. Hence the input current is excluding the field currents. The efficiency is determined as follows:

Motor armature copper loss $=(I_1+I_2)^2 r_a$

Generator armature copper loss $= I_2{}^2 r_a$

Power drawn from supply = VI_1

Stray losses $= VI_1 - \left[(I_1+I_2)^2 r_a - I_2{}^2 r_a\right]$ = W(say) ………….. 17

Stray loss/motor $= \frac{W}{2}$ ……………. 18

(a) Motor efficiency:

motor input = armature input + shunt field input

$= V(I_1+I_2) + VI_3$

Motor loss = Armature copper loss + Shunt copper loss + stray losses = $(I_1 + I_2)^2 r_a + VI_3 + \frac{W}{2}$ .. 19

Therefore $\eta_{motor} = \frac{motor\ input - motor\ losses}{motor\ input}$ ………… 20

Generator efficiency 'η': Generator output = VI_2

Generator losses = $I_2^{\,2} r_a + VI_4 + \frac{W}{2}$ ……………… 21

ADVANTAGES:

i. The two machines are tested under loaded conditions so that stray load losses are accounted
ii. Power required for the test is small as compared to the full load powers of the two machines. Therefore economical for long duration tests like "Heat run tests".
iii. Temperature rise and commutation qualities can be observed.
iv. By merely adjusting the field currents of the two machines the two machines can beloaded easily and the load test can be conducted over the complete load range in a short time.

DISADVANTAGES:

i. Availability of two identical machines

ii. Both machines are not loaded equally and this is crucial in smaller machines.

iii. There is no way of separating iron losses of the two machines which are different because of different excitations.

iv. Since field currents are varied widely to get full load, the set speed will be greater than rated values.

The efficiency can be determined as follows:

Field test for series motor:

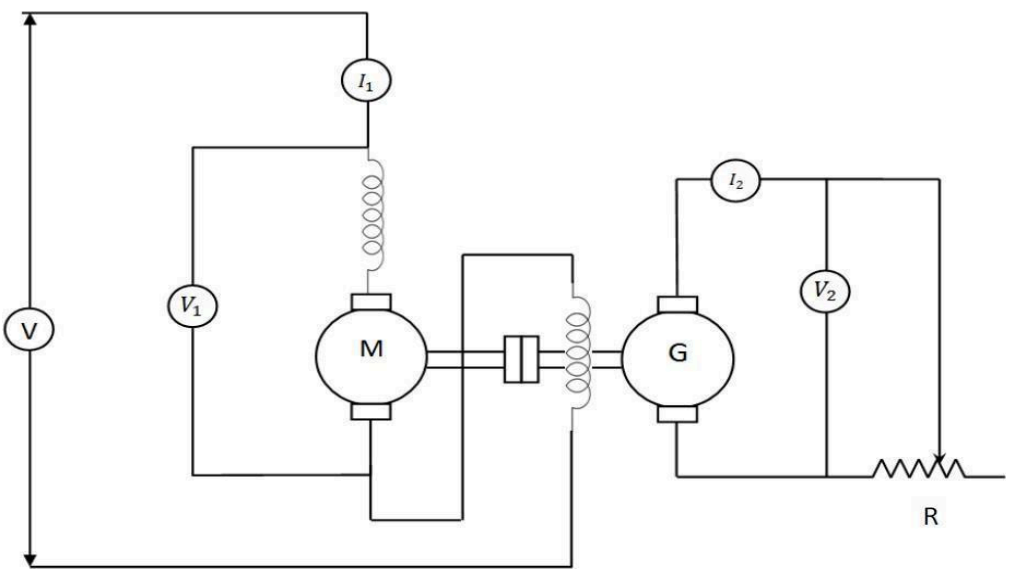


Figure 4.7

Figure 4.7 shows the circuit for fields test. This test is applicable to two similar series motor. One of the machine runs as a motor and drives a generator whose output is wasted in a variable load „R". Both machine field coils are in series and both run at same speed so that iron and friction losses are made equal. Load resistance „R" is varied till the motor current reaches its full load value.

V = Supply voltage

I_1 = Motor current

V_1 = Generator terminal voltage

$I2$ = Load current

Input = VI_1 and output =$V_2 I_2$ 22

Ra and Rse = hot resistances.

Total losses in the set $W_t = VI_1 - V_2I_2$ ……………………………..... 23

Armature and Field copper losses $W_c = (R_a + 2\, r_{se})\, I_1^2 + I_a^2 R_a$ ……… 24

Stray losses forthe set = $W_t - W_c$ ……………………………………...25

Stray losses per machine $W_s = \frac{W_t - W_c}{2}$ ………………………………… 26

Motor efficiency: input = $V_1 I_1$

Losses = $(R_a + R_{se})I_1^2 + W_s = W_m(say)$

$\eta_{motor} = \frac{VI_1 + W_m}{VI_1}$ ……….. 27

Generator efficiencyη of generator is of little use, because its field winding is separately excited

Generator output = VI_2

Field copper loss =$I_1^2 r_{se}$

Armature copper loss = $I_2^2 r_a$

Total losses = $I_1^2 r_{se} + I_2^2 r_a + W_s = W_g$ (say)……………………. 28

$\eta_{generator} = \frac{VI_2}{V_2 + W_g}$……………..29

Retardation or running down test:

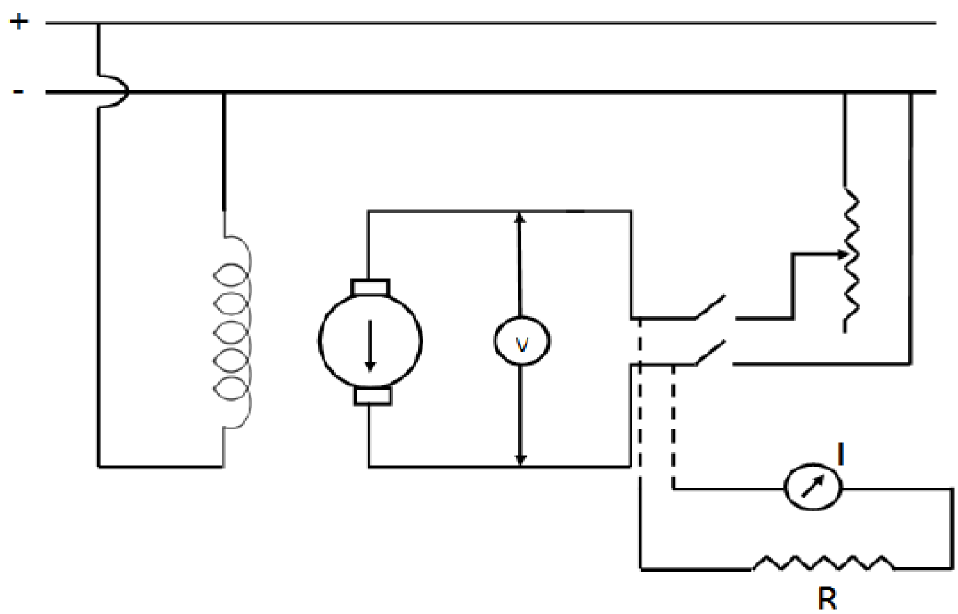


Figure 4.8

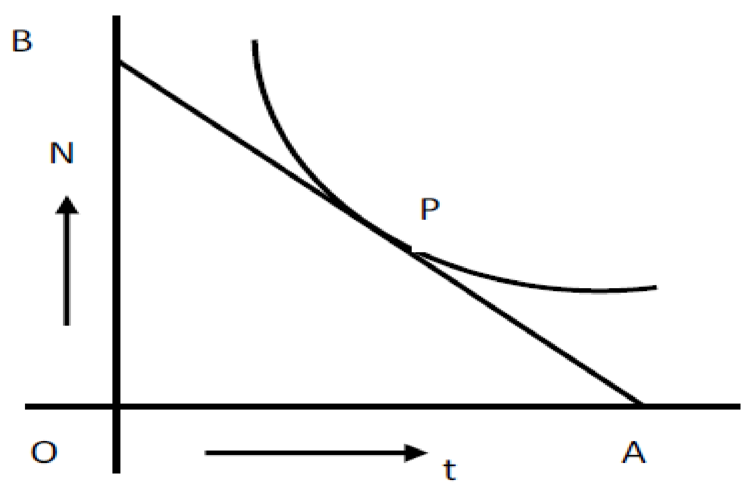


Figure 4.9

This method is applicable to shunt motors and generators and is used for finding the stray losses. If armature and shunt copper losses are known for a given load, efficiency can be calculated. The circuit is shown in figure 4.8.

Machine is speeded up slightly beyond its rated speed and then supply is cut off from thearmature while keeping the field excited. Armature will slow down and its kinetic energy isneeded to meet rotational losses. i.e., friction and windage losses.

Kinetic energy of the armature $= \frac{1}{2} I\omega^2$

I = Moment of inertia of the armature

ω = Angular velocity.

Rotational losses;

N = Rate of loss of K.E.

Rate of loss of Kinetic energy $W = \frac{d}{dt}\left[\frac{1}{2} I\omega^2\right]$

$I \text{ X } W \frac{d\omega}{dt}$.................. 30

Two quantities need to be known

(i) Moment of Inertia „I" (ii)

$\frac{d\omega}{dt}$ or $\frac{dN}{dt}$ (because $\omega \; \alpha \, N$)

(i) Finding $\frac{d\omega}{dt}$:

The voltmeter „V" in the circuit shown in Figure 4.8 is used as speed indicator by suitably graduating it because $E \propto N$. when the supply is cut off, the armature speed and hence voltmeter reading falls. Voltage and time at different intervals are noted and a curve is drawn between the time and speed as shown in Figure 4.9.In the Figure 4.9 AB - tangent drawn at P

There fore $\frac{dN}{dt} = \frac{OB\ (rpm)}{OA\ (sec)}$

$W = I\ X\ \omega\ X\ \frac{d\omega}{dt}$

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

$W = I \left(\frac{2\pi}{60}\right) \frac{d}{dt} \left(\frac{2\pi N}{60}\right)$

$W = \left(\frac{2\pi N}{60}\right)^2 I.N.\frac{dN}{dt} = 0.011\ X\ I\ X\ N\ X\frac{dN}{dt}$.............. 31

(ii) Finding Moment of Inertial 'I': There are two methods of finding the moment of inertia 'I'

(a) **I is calculated**:

(i) Slowing down curve with armature alone is calculated.

(ii) A fly wheel is keyed to the shaft and the curve is drawn again

(iii) For any given speed, $\frac{dN}{dt}$, and $\frac{dN}{dt_2}$ are determined as before.

Therefore $W = \left(\frac{2\pi}{60}\right)^2 I.N.\frac{dN}{dt_1}$ --- (32) 1st case

$W = \left(\frac{2\pi}{60}\right)^2 (I + I_1)N.\frac{dN}{dt_2}$ --- (33) 2nd case

Equation (32) = Equation (33), losses in both the cases will be almost same.

$I\frac{dN}{dt_1} = (I + I_1)\frac{dN}{dt_2}.\ \frac{I + I_1}{I}\left(\frac{dN}{dt_2}\right) = \frac{dN}{dt_1}$

$\frac{I+I_1}{I} = \frac{dN}{dt_2}$

$\Rightarrow I = I_1\ X\frac{t_2}{t_1 - t_2}$.............. 34

(b) **I is eliminated:** In this method, time taken to slow down is noted with armature alone and then a retarding torque is applied electrically i.e., a non inductive resistance is connected to the armature.

The additional loss is $I_a^2(R_a + R)$orVI_a

Let W¹ be the power then

$W=(\frac{2\pi}{60})^2 \text{IN}\frac{dN}{dt_1}$.................. 35

$W + W^1 = (\frac{2\pi}{60})^2\text{IN}\frac{dN}{dt_2}$........... 36; if dN is same.

$\frac{dN}{dt_1}$ =rate of change of speed without electrical load

$\frac{dN}{dt_2}$ =rate of change of speed with electrical load

$\frac{W + W1}{W} = \frac{\frac{dN}{dt_2}}{\frac{dN}{dt_1}}$...... 37 or $\frac{W + W1}{W} = \frac{dt_1}{dt_2}$ or $W = W^1 \times \frac{dt_2}{dt_1 - dt_2}$ or $W = W^1 \times \frac{t_2}{t_1 - t_2}$.......... 38

Problems:

1. The Hopkinson‟s test on two similar shunt machines gave the following Full load data. Line voltage = 110 V; Line current = 48 A; Motor armature current = 230 A; Field currents are 3 A and 3.5 A; Armature resistance of each machine is 0.035 W; brush drop of 1V/brush; Calculate the efficiency of each machine.

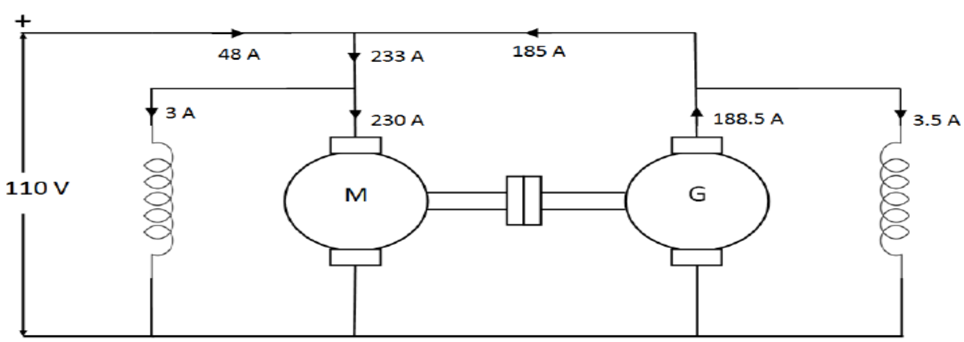


Figure 4.10

SOLUTION:

Motor: Armature copper loss $(230)^2 X\ 0.035 =$ 1851.5 W

Brush contact loss = 230 X 2 = 460 W

Total armature copper loss = 1851.5 + 460 = 2312 W Shunt

field copper loss = 110 X 3 = 330 W

Total copper loss = 2312 + 330 = 2642 W

Generator: Generator armature copper loss = $(188.5)^2 \times 0.035 = 1244$ W

Brush contact loss = 188.5 X 2 = 377 W

Total armature copper loss = 1244 + 377 = 1621 W.

Shunt field copper loss = 110 X 3.5 = 385 W

Therefore total copper loss = 1621 + 385 = 2006 W

Total copper loss for set = 2642 + 2006 = 4648 W

Total input = 110 X 48 = 5280 W

Therefore stray losses = 5280 – 4648 = 632 W

Stray losses/machine = $\frac{632}{2} = 316\ W$

Total losses = 2312 + 330 + 316 = 2958 W

Motor input = 110 X 233 = 25630 W. Motor output = 22672 W

$\eta_{motor} = \frac{22672}{25630} = 88.45\%$

$\eta_{generator}$: total losses = 1621 + 385 +316 = 2322

Output of generator = 110 X 185 = 20350 W.

Therefore $\eta = \frac{20350}{20350+2322} = 89.4\%$

2. In a Hopkinson‟s test on a pair of 500 V, 100 kW shunt generator. The following data was obtained:Auxiliary supply 30 A at 500 V; Generator output current 200 A; Field current 3.5 A and 1.8 A; ra = 0.075 W for each machine; voltage drop at brushes = 2 V/machine; calculate the efficiency of the machine as a generator.

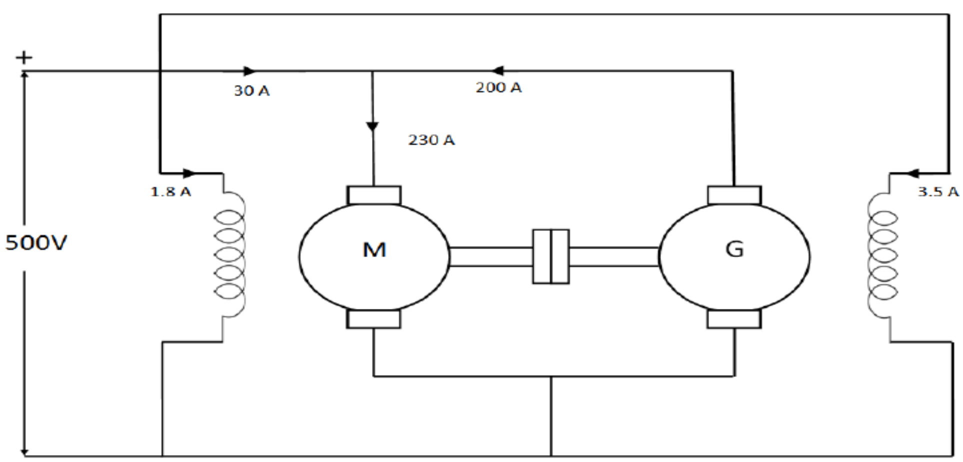


Figure 4.6

SOLUTION:

Motor armature copper loss = $(230)^2$ X 0.075 + 230 X 2 = 4428 W

Motor field copper loss = 500 X 1.8 = 900 W

Generator armature copper loss = $(200)^2$ X 0.075 + 200 X 2 = 3400 W

Generator field copper loss = 500 X 3.5 = 1750 W.

Total copper loss for 2 machines = 4428 + 900 + 3400 + 1750 = 10478 W

Power drawn = 500 X 30 = 15000 W

Therefore stray loss for the two machines = 15000 – 10478 = 4522 W.

Stray loss / machine = $\frac{4522}{2}$ = 2261 W

Therefore total losses in generator = 3400 + 1750 + 2261 = 7411 W

Generator output = 500 X 200 = 100000 W

$$\text{Therefore } \eta_{generator} = \frac{100000}{100000+7411} = 93.09\ \%$$

3. In a Hopkinson test on 250 V machine, the line current was 50 A and the motor current is 400 A not including the field currents of 6 and 5 A. the armature resistance of each machine was 0.015W. Calculate the efficiency of each machine.

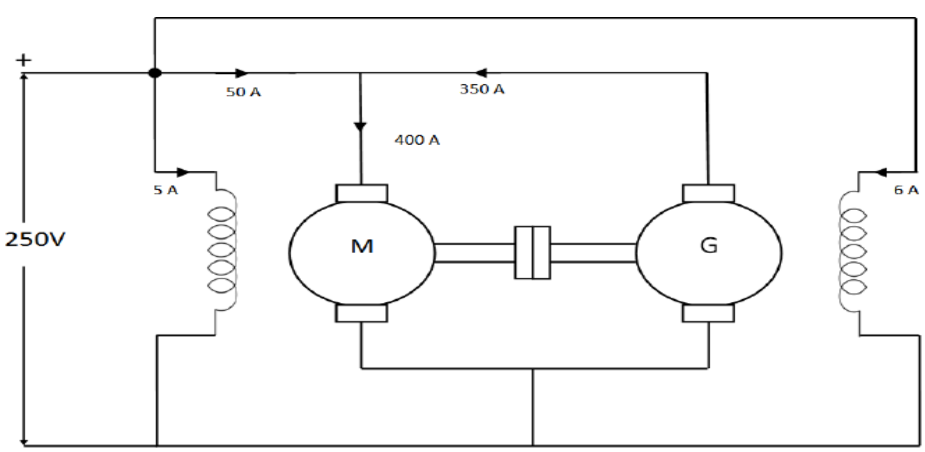


Figure 4.7

SOLUTION:

Motor armature copper loss = $(400)^2$ X 0.015 = 2400 W

Generator armature copper loss = $(350)^2$ X 0.015 = 1838 W

Input power = 250 X 50 = 12500 W

W_s = stray losses = 12500 – (2400 + 1838) = 8262 W; W_s per machine = $\frac{8262}{2} = 4130\ W$

Motor efficiency: armature copper loss of motor = 2400 W;

Motor field copper loss = 250 X 5 = 1250 W; Total motor losses = 2400 + 1250 + 4130 = 7780 W

Motor input = 250 X 400 + 250 X 5 = 101250 W.

Therefore $\eta = \frac{101250 - 7780}{101250} = 92.3\ \%$

Generator efficiency:

Generator armature copper loss = 1838 W;Generator field copper loss = 250 X 6 = 1500 W

Total losses of Generator = 1828 + 1500 + 4130 = 7468 W

Generator Output = 250 X 350 = 87500 W

Efficiency of Generator = $\frac{87500}{87500 + 7468} X\ 100 = 91.5\%$

UNIT–IV:

Single-phase Transformers

Introduction

The transformer is a device that transfers electrical energy from one electrical circuit to another electrical circuit. The two circuits may be operating at different voltage levels but always work at the same frequency. Basically transformer is an electro-magnetic energy conversion device. It is commonly used in electrical power system and distribution systems. It can change the magnitude of alternating voltage or current from one value to another. This useful property of transformer is mainly responsible for the widespread use of alternating currents rather than direct currents i.e., electric power is generated, transmitted and distributed in the form of alternating current. Transformers have no moving parts, rugged and durable in construction, thus requiring very little attention. They also have a very high efficiency as high as 99%.

Single Phase Transformer

A transformer is a static device of equipment used either for raising or lowering the voltage of an a.c. supply with a corresponding decrease or increase in current. It essentially consists of two windings, the primary and secondary, wound on a common laminated magnetic core as shown in Fig 1. The winding connected to the a.c. source is called primary winding (or primary) and the one connected to load is called secondary winding (or secondary). The alternating voltage V1 whose magnitude is to be changed is applied to the primary.

Depending upon the number of turns of the primary (N1) and secondary (N2), an alternating e.m.f. E2 is induced in the secondary. This induced e.m.f. E2 in the secondary causes a secondary current I2. Consequently, terminal voltage V2 will appear across the load.

If V2 > V1, it is called a step up-transformer.

If V2 < V1, it is called a step-down transformer.

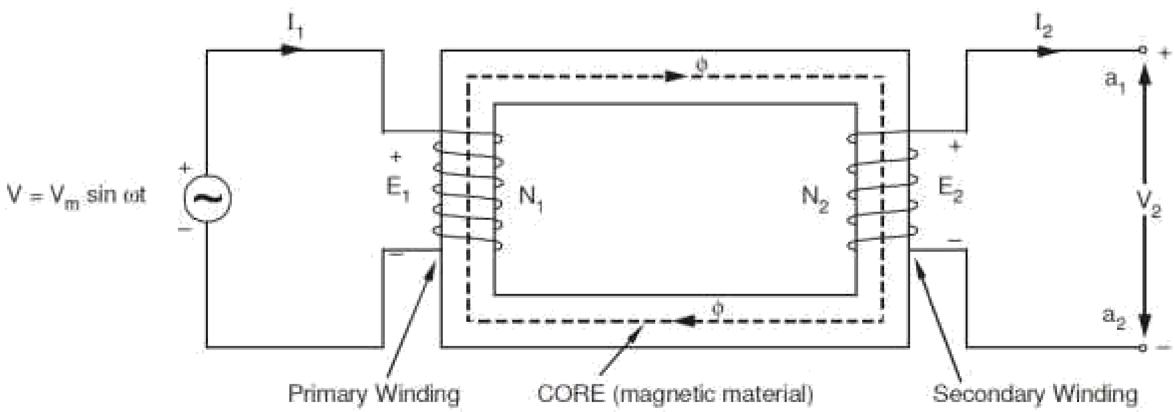


Fig. 2.1 Schematic diagram of single phase transformer

Constructional Details

Depending upon the manner in which the primary and secondary windings are placed on the core, and the shape of the core, there are two types of transformers, called (a) core type, and
(b) shell type.

Core-type and Shell-type Construction

In core type transformers, the windings are placed in the form of concentric cylindrical coils placed around the vertical limbs of the core. The low-voltage (LV) as well as the high- voltage (HV) winding are made in two halves, and placed on the two limbs of core. The LV winding is placed next to the core for economy in insulation cost. Figure 2.1(a) shows the cross- section of the arrangement. In the shell type transformer, the primary and secondary windings are wound over the central limb of a three-limb core as shown in Figure 2.1(b). The HV and LV windings are split into a number of sections, and the sections are interleaved or sandwiched i.e. the sections of the HV and LV windings are placed alternately.

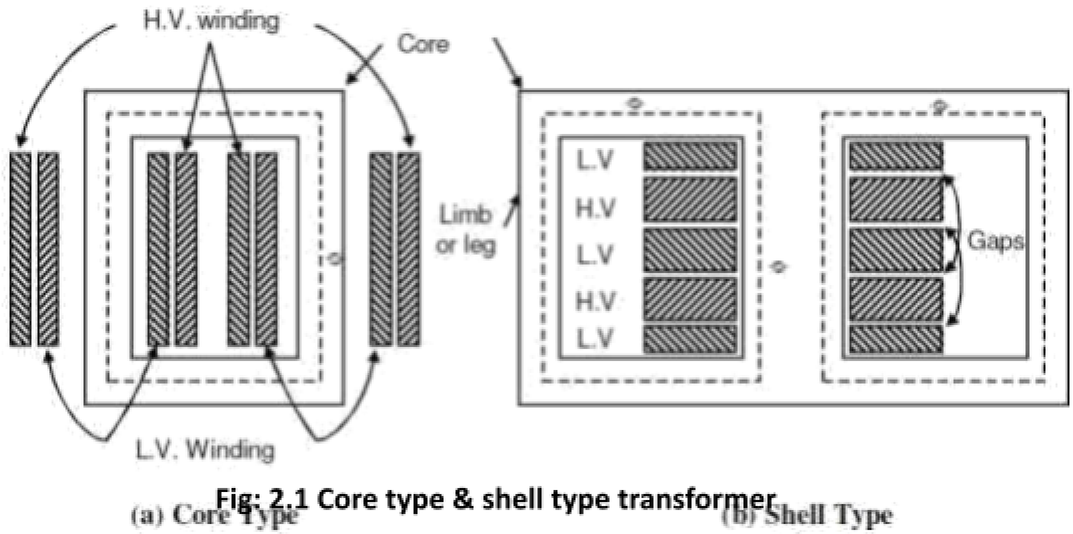


Fig: 2.1 Core type & shell type transformer

Core

The core is built-up of thin steel laminations insulated from each other. This helps in reducing the eddy current losses in the core, and also helps in construction of the transformer. The steel used for core is of high silicon content, sometimes heat treated to produce a high permeability and low hysteresis loss. The material commonly used for core is CRGO (Cold Rolled Grain Oriented) steel. Conductor material used for windings is mostly copper. However, for small distribution transformer aluminum is also sometimes used. The conductors, core and whole windings are insulated using various insulating materials depending upon the voltage.

Insulating Oil

In oil-immersed transformer, the iron core together with windings is immersed in insulating oil. The insulating oil provides better insulation, protects insulation from moisture and transfers the heat produced in core and windings to the atmosphere.

The transformer oil should possess the following qualities:

(a) High dielectric strength,

(b) Low viscosity and high purity,

(c) High flash point, and

(d) Free from sludge.

Transformer oil is generally a mineral oil obtained by fractional distillation of crude oil.

Tank and Conservator

The transformer tank contains core wound with windings and the insulating oil. In large transformers small expansion tank is also connected with main tank is known as conservator. Conservator provides space when insulating oil expands due to heating. The transformer tank is provided with tubes on the outside, to permits circulation of oil, which aides in cooling. Some additional devices like breather and Buchholz relay are connected with main tank. Buchholz relay is placed between main tank and conservator. It protect the transformer under extreme heating of transformer winding. Breather protects the insulating oil from moisture when the cool transformer sucks air inside. The silica gel filled breather absorbs moisture when air enters the tank. Some other necessary parts are connected with main tank like, Bushings, Cable Boxes, Temperature gauge, Oil gauge, Tapings, etc.

Principle of Operation

When an alternating voltage V1 is applied to the primary, an alternating flux ϕ is set up in the core. This alternating flux links both the windings and induces e.m.f.s E1 and E2 in them according to

Faraday's laws of electromagnetic induction. The e.m.f. E1 is termed as primary e.m.f. and

e.m.f. E2 is termed as secondary e.m.f.

Clearly, $$E_1 = -N_1 \frac{d\phi}{dt}$$

and $$E_2 = -N_2 \frac{d\phi}{dt}$$

$$\therefore \quad \frac{E_2}{E_1} = \frac{N_2}{N_1}$$

Note that magnitudes of E2 and E1 depend upon the number of turns on the secondary and primary respectively.

If N2 > N1, then E2 > E1 (or V2 > V1) and we get a step-up transformer. If N2 < N1, then E2 <

E1

(or V2< V1) and we get a step-down transformer.

If load is connected across the secondary winding, the secondary e.m.f. E2 will cause a current I2 to flow through the load. Thus, a transformer enables us to transfer a.c. power from one circuit to another with a change in voltage level.

<u>The following points may be noted carefully</u>

(a) The transformer action is based on the laws of electromagnetic induction.

(b) There is no electrical connection between the primary and secondary.

(c) The a.c. power is transferred from primary to secondary through magnetic flux.

(d) There is no change in frequency i.e., output power has the same frequency as the input power.

(e) The losses that occur in a transformer are:

(a) ***core losses***—eddy current and hysteresis losses

(b) ***copper losses***—in the resistance of the windings

In practice, these losses are very small so that output power is nearly equal to the input primary power. In other words, a transformer has very high efficiency.

E.M.F. Equation of a Transformer

Consider that an alternating voltage V1 of frequency f is applied to the primary as shown in Fig.2.3. The sinusoidal flux ϕ produced by the primary can be represented as:

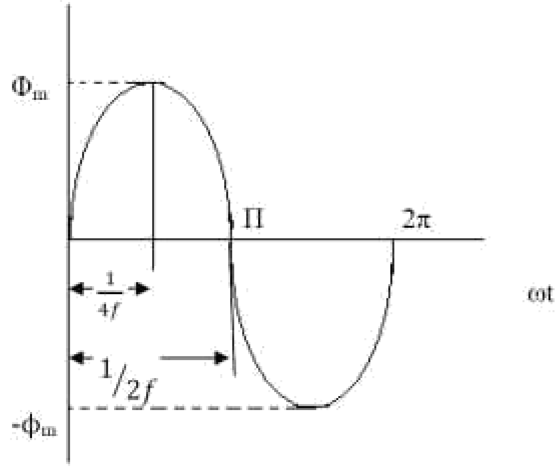
$\phi=\phi_m \sin\omega t$

When the primary winding is excited by an alternating voltage V1, it is circulating alternating current, producing an alternating flux ϕ.

ϕ - Flux

ϕ_m - maximum value of flux
N1 - Number of primary turns
N2 - Number of secondary turns
f - Frequency of the supply voltage

E1 - R.M.S. value of the primary induced e.m.f
E2 - R.M.S. value of the secondary induced e.m.f
The instantaneous e.m.f. e1 induced in the primary is -



Φm
Π
2π
ωt
1/4f
1/2f
-ϕm

From Faraday's law of electromagnetic induction -

$$\text{Average e.m.f per turns} = \frac{d\emptyset}{dt}$$

$d\phi$ = change in flux
dt = time required for change in flux

The flux increases from zero value to maximum value ϕm in 1/4f of the time period that is in 1/4f seconds.

The change of flux that takes place in 1/4f seconds = ϕm - 0 = ϕm webers

Voltage Ratio

Voltage transformation ratio is the ratio of e.m.f induced in the secondary winding to the e.m.f induced in the primary winding.

$$\frac{E2}{E1} = \frac{4.44\phi mf\ N2}{4.44\phi mf\ N1}$$

$$\boxed{\frac{E2}{E1} = \frac{N2}{N1} = K}$$

This ratio of secondary induced e.m.f to primary induced e.m.f is known as voltage transformation ratio

$$E_2 = KE_1 \qquad \text{where } K = \frac{N2}{N1}$$

1. If N2>N1 i.e. K>1 we get E2>E1 then the transformer is called step up transformer.

2. If N2< N1 i.e. K<1 we get E2< E2 then the transformer is called step down transformer.

3. If N2= N1 i.e. K=1 we get E2= E2 then the transformer is called isolation transformer or 1:1 Transformer

Current Ratio

Current ratio is the ratio of current flow through the primary winding (I1) to the current flowing through the secondary winding (I2). In an ideal transformer -

Apparent input power = Apparent output power.

V1I1 = V2I2

$$\frac{I1}{I2} = \frac{V2}{V1} = \frac{N2}{N1} = K$$

Volt-Ampere Rating

i) The transformer rating is specified as the products of voltage and current (VA rating).

ii) On both sides, primary and secondary VA rating remains same. This rating is generally expressed in KVA (Kilo Volts Amperes rating)

$$\frac{V1}{V2} = \frac{I2}{I1} = K$$

$$V_1I_1 = V_2I_2$$

$$\text{KVA Rating of a transformer} = \frac{V1I1}{1000} = \frac{V2I2}{1000} \quad \text{(1000 is to convert KVA to VA)}$$

V_1 and V_2 are the V_t of primary and secondary by using KVA rating we can calculate I_1 and I_2 Full load current and it is safe maximum current.

$$I_1 \text{ Full load current} = \frac{KVA\ Rating\ X\ 1000}{V1}$$

$$I_1 \text{ Full load current} = \frac{KVA\ Rating\ X\ 1000}{V2}$$

Transformer on No-load

a) Ideal transformer

b) Practical transformer

a) Ideal Transformer

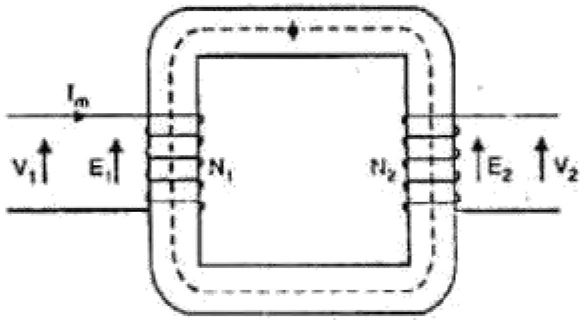
An ideal transformer is one that has

(i) No winding resistance

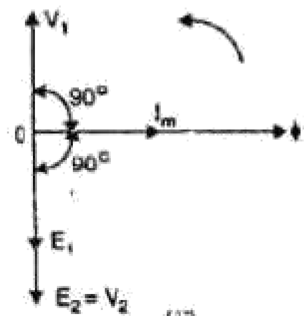
(ii) No leakage flux i.e., the same flux links both the windings

(iii) No iron losses (i.e., eddy current and hysteresis losses) in the core

Although ideal transformer cannot be physically realized, yet its study provides a very powerful tool in
the analysis of a practical transformer. In fact, practical transformers have properties that approach very close to an ideal transformer.



(i)



(ii)

Consider an ideal transformer on no load i.e., secondary is open-circuited as shown in *Fig.2.4 (i)*. under such conditions, the primary is simply a coil of pure inductance. When an alternating voltage V1 is applied to the primary, it draws a small magnetizing current Im which lags behind the applied voltage by 90°. This alternating current Im produces an alternating flux ϕ which is proportional to and in phase with it. The alternating flux ϕ links both the windings and induces
e.m.f. E1 in the primary and e.m.f. E2 in the secondary. The primary e.m.f. E1 is, at every instant, equal to and in opposition to V1 (Lenz's law). Both e.m.f.s E1 and E2 lag behind flux ϕ by 90°.However, their magnitudes depend upon the number of primary and secondary turns. *Fig. 2.4 (ii)* shows the phasor diagram of an ideal transformer on no load. Since flux ϕ is common to both the windings, it has been taken as the reference phasor. The primary
e.m.f. E1 and secondary e.m.f. E2 lag behind the flux ϕ by 90°. Note that E1 and E2 are in phase. But E1 is equal to V1 and 180° out of phase with it.

$$\frac{E2}{E1} = \frac{V2}{V1} = K$$

Phasor Diagram

i) Φ (flux) is reference

ii) Im produce ϕ and it is in phase with ϕ, V1 Leads Im by 90˚

E1 and E2 are in phase and both opposing supply voltage V1, winding is purely inductive
So current has to lag voltage by 90˚.

iii) The power input to the transformer

$P = V1.I1. \cos(90^\circ)$ $(\cos 90^\circ = 0)$

$P = 0$ (ideal transformer)

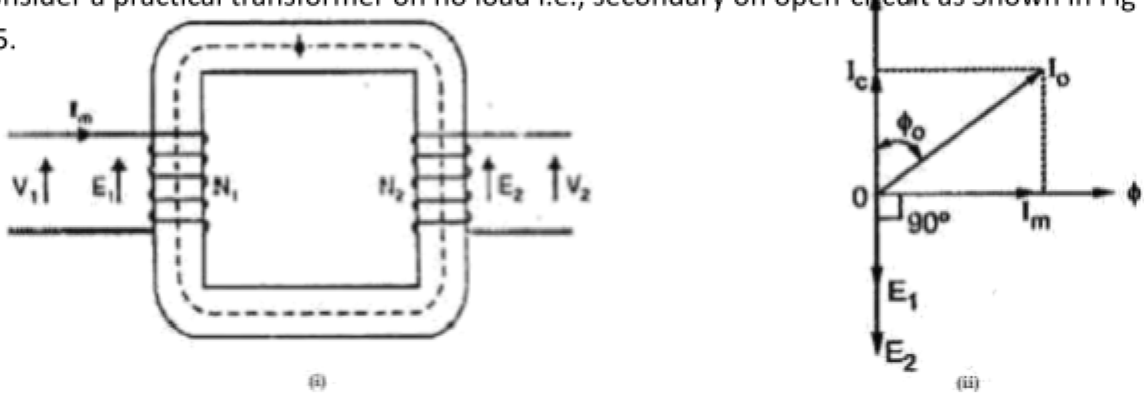
b) ***i) Practical Transformer* on no load**

A practical transformer differs from the ideal transformer in many respects. The practical transformer has (i) iron losses (ii) winding resistances and (iii) Magnetic leakage

(i) Iron losses. Since the iron core is subjected to alternating flux, there occurs eddy current and hysteresis loss in it. These two losses together are known as iron losses or core losses. The iron losses depend upon the supply frequency, maximum flux density in the core, volume of the core etc. It may be noted that magnitude of iron losses is quite small in a practical transformer.

(ii) Winding resistances. Since the windings consist of copper conductors, it immediately follows that both primary and secondary will have winding resistance. The primary resistance R1 and secondary resistance R2 act in series with the respective windings as shown in Fig. When current flows through the windings, there will be power loss as well as a loss in voltage due to IR drop. This will affect the power factor and E1 will be less than V1 while V2 will be less than E2.

Consider a practical transformer on no load i.e., secondary on open-circuit as Shown in Fig 2.5.



<u>Fig: 2.5 Phasor diagram of transformer at no load</u>

Here the primary will draw a small current I0 to supply -

(i) The iron losses and

(ii) A very small amount of copper loss in the primary.

Hence the primary no load current I0 is not 90° behind the applied voltage V1 but lags it by an angle ϕ0 < 90° as shown in the phasor diagram. No load input power, W0 = V1 I0 cos ϕ0

As seen from the phasor diagram in Fig.2.5 (ii), the no-load primary current I0

i) The component Ic in phase with the applied voltage V1. This is known as active or working or iron loss component and supplies the iron loss and a very small primary copper loss.

$Ic = I0 \cos \phi 0$

The component Im lagging behind V1 by 90° and is known as magnetizing component. It is this component which produces the mutual flux ϕ in the core.

$Im = I0 \sin \phi 0$

Clearly, Io is phasor sum of Im and Ic, $I_o = \sqrt{Im^2 + Ic^2}$

$$\text{No load P.F.,} \quad \cos\phi o = \frac{Ic}{Io}$$

The no load primary copper loss (i.e. Io^2R1) is very small and may be neglected.

Therefore, the no load primary input power is practically equal to the iron loss in the transformer i.e., No load input power, $W0 = V1Io\cos\phi o = Pi$ = Iron loss

b) ii)Practical Transformer on Load

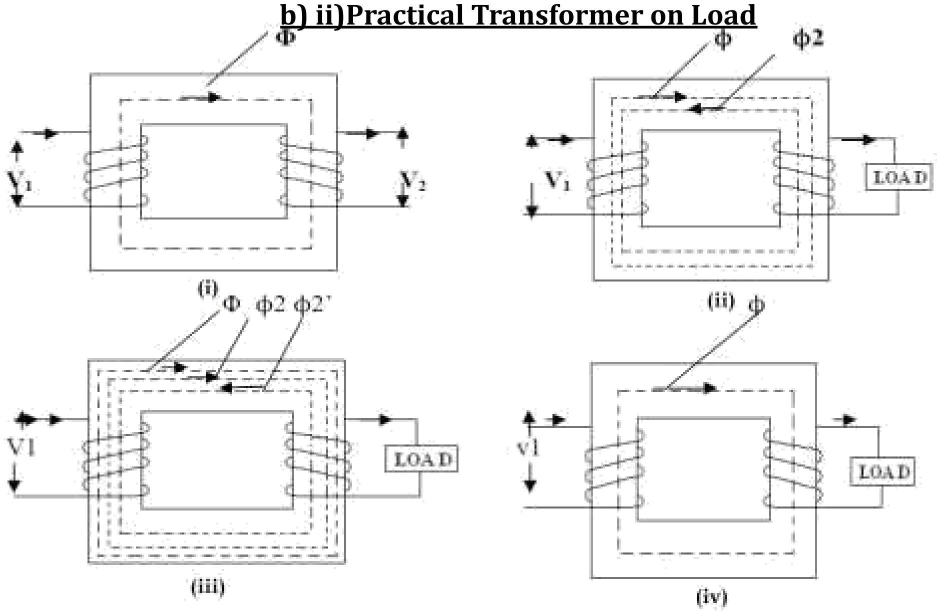


Fig: 2.6

At no load, there is no current in the secondary so that V2 = E2. On the primary side, the drops in R1 and X1, due to I0 are also very small because of the smallness of I0. Hence, we can say that at no load, V1 = E1.

i) When transformer is loaded, the secondary current I2 is flows through the secondary winding.

ii) Already Im magnetizing current flow in the primary winding fig. 2.6(i).

iii) The magnitude and phase of I2 with respect to V2 is determined by the characteristics of the load. a) I2 in phase with V2 (resistive load)

b) I2 lags with V2 (Inductive load)

c) I2 leads with V2 (capacitive load)

iv) Flow of secondary current I2 produce new Flux ϕ2 fig.2.6 (ii)

v) Φis main flux which is produced by the primary to maintain the transformer as constant magnetising component.

vi) Φ2 opposes the main flux ϕ, the total flux in the core reduced. It is called demagnetising Ampere- turns due to this E1 reduced.

vii) To maintain the ϕ constant primary winding draws more current (I2') from the supply (load component of primary) and produce ϕ2' flux which is oppose ϕ2 (but in same direction as ϕ), to maintain flux constant flux constant in the core fig.2.6 (iii).

viii) The load component current I2' always neutralizes the changes in the load.

ix) Whatever the load conditions, the net flux passing through the core is approximately the same as at no-load. An important deduction is that due to the constancy of core flux at all loads, the core loss is also practically the same under all load conditions fig.2.6 (iv).

$$\Phi_2 = \phi_2' \quad N_2 I_2 = N_1 I_2' \quad I_2' = \frac{N2}{N1} X I_2 = K I_2$$

Phasor Diagram

i) Take (ϕ) flux as reference for all load

ii) The no load I_o which lags by an angle ϕo. $Io = \sqrt{Ic^2 + Im^2}$.

ii) The load component I2', which is in anti-phase with I2 and phase of I2 is decided by the load.

iii) Primary current I1 is vector sum of Io and I2'

$$\vec{I_1} - \vec{I_o} + \vec{I_2'}$$

$$I_1 = \sqrt{Io^2 + I2'^2}$$

a) If load is Inductive, I2 lags E2 by ϕ2, shown in phasor diagram fig 2.7 (a).

b) If load is resistive, I2 in phase with E2 shown in phasor diagram fig. 2.7 (b).

c) If load is capacitive load, I2 leads E2 by ϕ2 shown in phasor diagram fig. 2.7 (c).

For easy understanding at this stage here we assumed E2 is equal to V2 neglecting various drops.

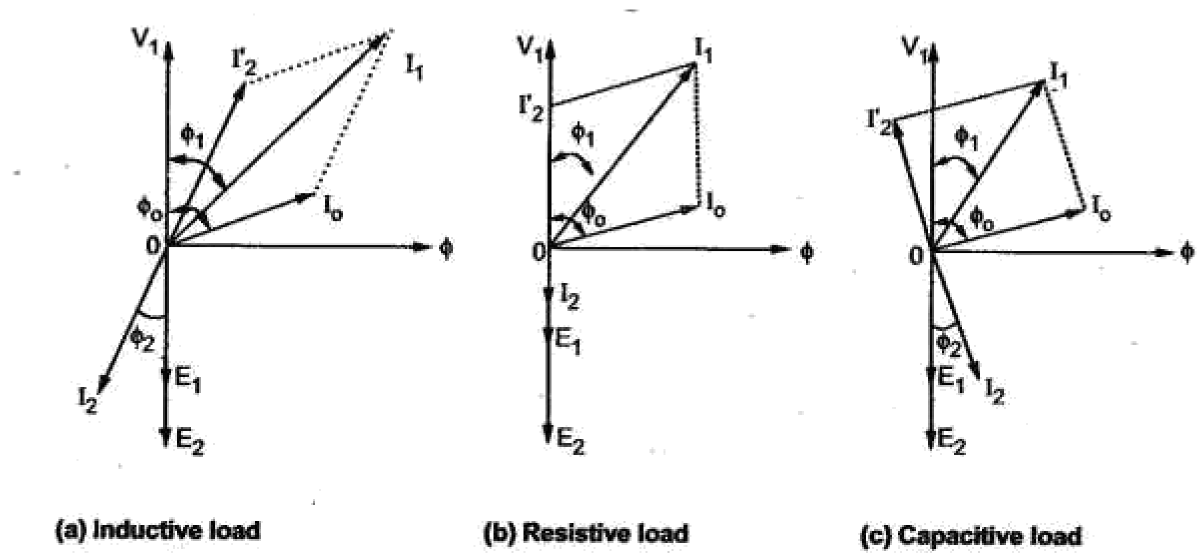


Fig: 2.7.a

$$\vec{I_1} - \vec{I_o} + \vec{I_2'}$$

$$I_1 \cong I_2' \qquad I_1 = \sqrt{Io^2 + I2'^2}$$

Balancing the ampere – turns

$$N_1 I_2' = N_1 I_1 + N_2 I_2$$

$$\frac{I1}{I2} = \frac{N2}{N1} = K$$

Now we going to construct complete phasor diagram of a transformer (shown in Fig: 2.7.b)

Effect of Winding Resistance

In practical transformer it process its own winding resistance causes power loss and also the voltage drop.

R1 – primary winding resistance in ohms. R2 – secondary winding resistance in ohms.

The current flow in primary winding make voltage drop across it is denoted as I1R1 here

$$\vec{E_1} = \vec{V_1} - \vec{I_1 R_1}$$

supply voltage V1 has to supply this drop primary induced e.m.f E1 is the vector difference between V1 and I1R1.

Similarly the induced e.m.f in secondary E2, The flow of current in secondary winding makes voltage drop across it and it is denoted as I2R2 here E2 has to supply this drop.
The vector difference between E2 and I2R2

$$\vec{V_2} = \vec{E_2} - \vec{I_2R_2}$$ (Assuming as purely resistive drop here)

Equivalent Resistance

1) It would now be shown that the resistances of the two windings can be transferred to any one of the two winding.

2) The advantage of concentrating both the resistances in one winding is that it makes calculations very simple and easy because one has then to work in one winding only.

3) Transfer to any one side either primary or secondary without affecting the performance of the transformer.

The total copper loss due to both the resistances

$$\text{Total copper loss} = I_1^2R_1 + I_2^2R_2$$
$$= I_1^2[R_1 + \frac{I2^2}{I1^2}]$$
$$= I_1^2[R_1 + \frac{1}{K} R_2]$$

$\frac{R2}{K^2}$ is the resistance value of R_2 shifted to primary side and denoted as R_2'.
R_2' is the equivalent resistance of secondary referred to primary

$$R_2' = \frac{R2}{K^2}$$

Equivalent resistance of transformer referred to primary fig (ii)

$$R_{1e} = R_1 + R_2' = R_1 + \frac{R2}{K^2}$$

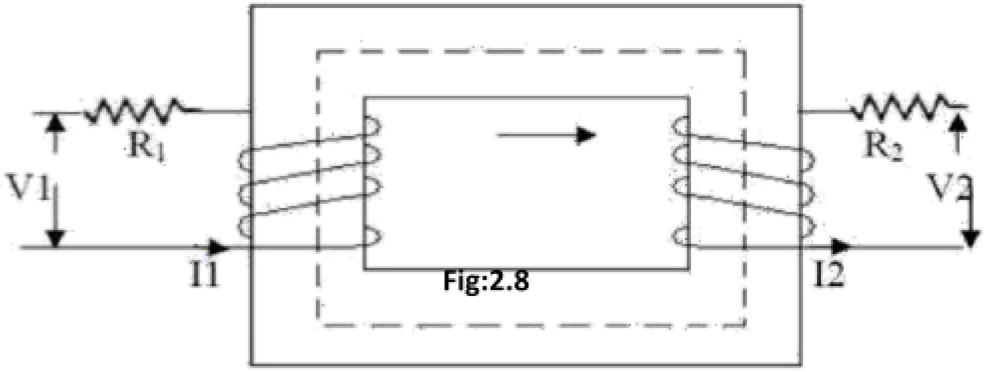
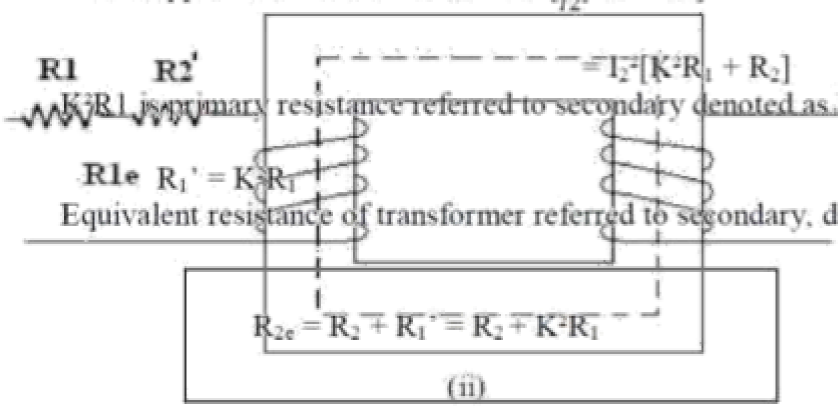


Fig:2.8

Similarly it is possible to refer the equivalent resistance to secondary



Total copper loss = $I_1^2R_1 + I_2^2R_2 = I_2^2\left[\frac{I_1^2}{I_2^2}R_1 + R_2\right]$

$= I_2^2[K^2R_1 + R_2]$

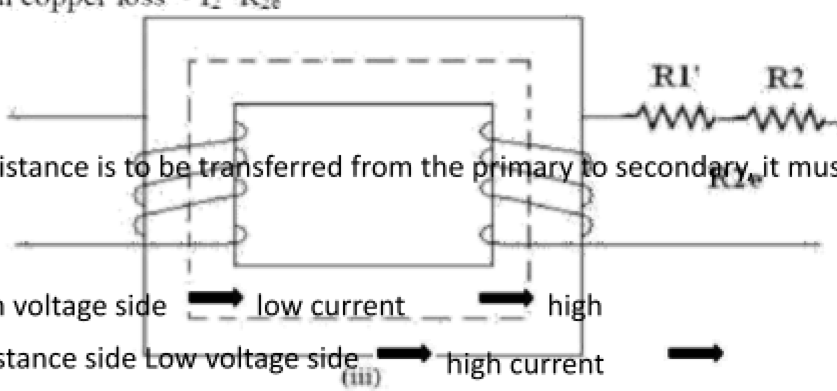
K^2R_1 is primary resistance referred to secondary denoted as R_1'.

$R_1' = K^2R_1$

Equivalent resistance of transformer referred to secondary, denoted as R2e

$R_{2e} = R_2 + R_1' = R_2 + K^2R_1$

Total copper loss = $I_2^2 R_{2e}$



Note:

i) When a resistance is to be transferred from the primary to secondary, it must be multiplied

High voltage side → low current → high resistance side Low voltage side → high current → side

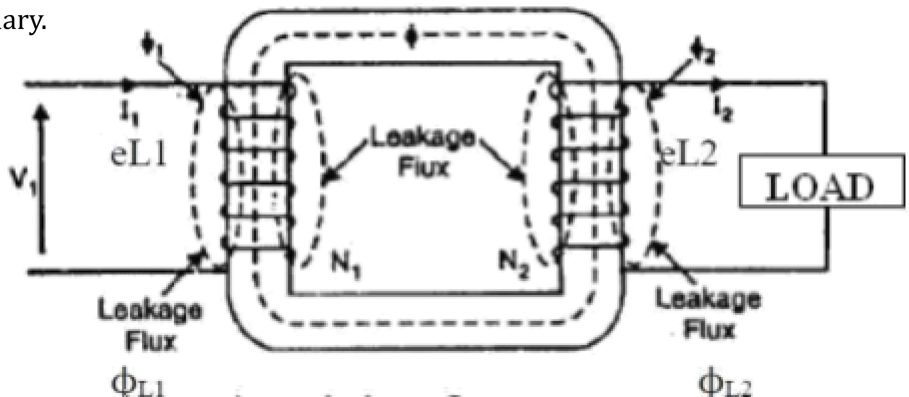
Effect of Leakage Reactance

i) It has been assumed that all the flux linked with primary winding also links the secondary winding. But, in practice, it is impossible to realize this condition.

ii) However, primary current would produce flux ϕ which would not link the secondary winding. Similarly, current would produce some flux ϕ that would not link the primary winding.

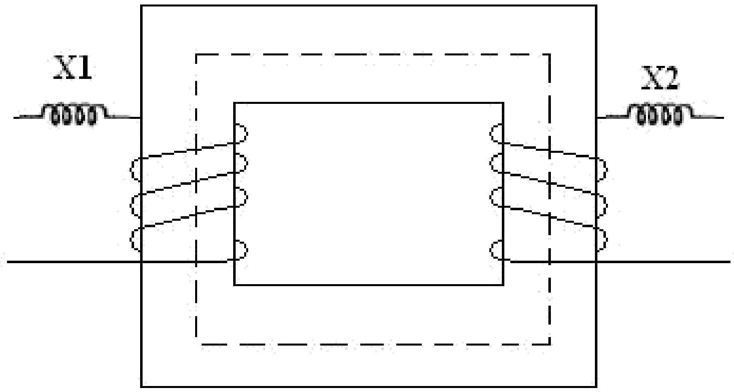
iii) The flux ϕL1 complete its magnetic circuit by passing through air rather than around the core, as shown in fig.2.9. This flux is known as primary leakage flux and is proportional to the primary ampere – turns alone because the secondary turns do not links the magnetic circuit of ϕL1. It induces an e.m.f eL1 in primary but not in secondary.

iv) The flux ϕL2 complete its magnetic circuit by passing through air rather than around the core, as shown in fig. This flux is known as secondary leakage flux and is proportional to the secondary ampere– turns alone because the primary turns do not links the magnetic circuit of ϕL2. It induces an e.m.f eL2 in secondary but not in primary.



ϕ_{L1} – primary leakage flux
ϕ_{L2} – secondary leakage flux
e_{L1} – self induced e.m.f (primary)
e_{L2} –self induced e.m.f (secondary)

Equivalent Leakage Reactance



Similarly to the resistance, the leakage reactance also can be transferred from primary to secondary. The relation through K^2 remains same for the transfer of reactance as it is studied earlier for the resistance

X1 – leakage reactance of primary. X2 - leakage reactance of secondary.

Then the total leakage reactance referred to primary is X1e given by

$$X_{1e} = X_1 + X_2'$$

$$X_2' = \frac{X2}{K^2}$$

The total leakage reactance referred to secondary is X_{2e} given by

$$X_{2e} = X_2 + X_1'$$
$$X_1' = K^2 X_1$$

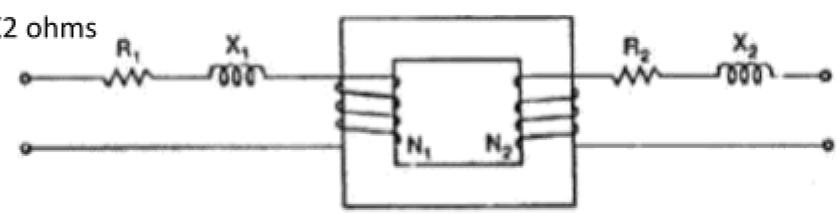
$$X_{1e} = X_1 + X_2'$$
$$X_{2e} = X_2 + X_1'$$

Equivalent Impedance

The transformer winding has both resistance and reactance (R1, R2, X1,X2).Thus we can say that the total impedance of primary winding isZ1 which is,

Z1 = R1 + jX1 ohms On secondary winding,

Z2 = R2 + jX2 ohms



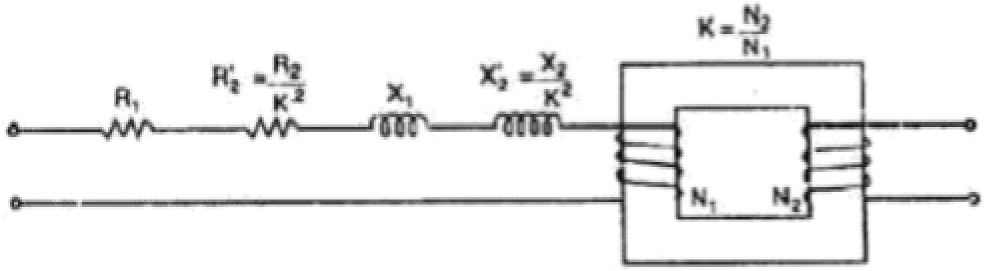
Individual magnitude of Z1 and Z2 are

$$Z_1 = \sqrt{R1^2 + X1^2}$$
$$Z_2 = \sqrt{R2^2 + X2^2}$$

Similar to resistance and reactance, the impedance also can be referred to any one side,

Z_{1e} = total equivalent impedance referred to primary

$$Z_{1e} = R_{1e} + jX_{1e} = Z_1 + Z_2' = Z_1 + \frac{Z2}{K^2}$$

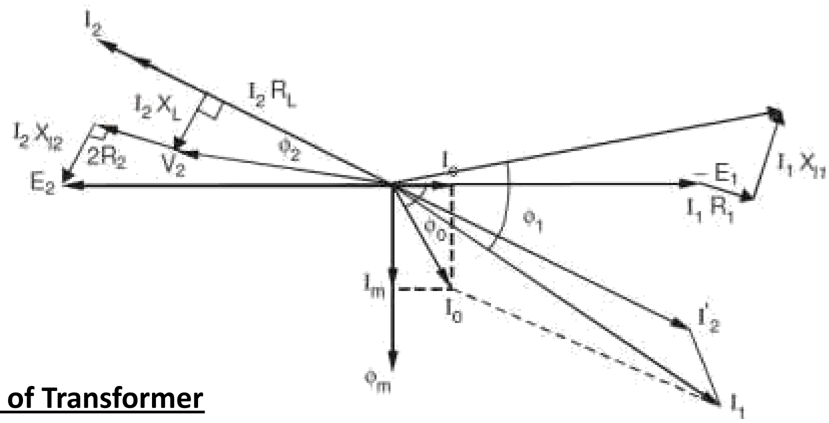


Complete Phasor Diagram of a Transformer *(for Inductive Load or Lagging pf)*

We now restrict ourselves to the more commonly occurring load i.e. inductive along with resistance,

$$\bar{V}_2 = \bar{E}_2 - \bar{I}_2\,(R_2 + j\,X_{l2})$$

and $$\bar{V}_1 = -\bar{E}_1 + \bar{I}_2\,(R_1 + j\,X_{l1})$$



Equivalent Circuit of Transformer

which has a lagging power factor. For drawing this diagram, we must remember that

No load equivalent circuit

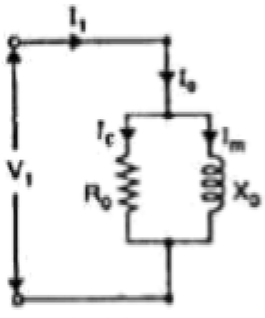


Fig:11

$I_m = I_o \sin \phi_o$ = magnetizing component
$I_c = Io \cos \phi_o$ = Active component

$$R_o = \frac{V1}{Ic}, \qquad X_o = \frac{V1}{Im}$$

i) Im produces the flux and is assumed to flow through reactance Xo called no load reactance while Ic is active component representing core losses hence is assumed to flow through the resistance R0

ii) Equivalent resistance is shown in fig.2.12.

iii) When the load is connected to the transformer then secondary current I2 flows causes voltage drop across R2 and X2. Due to I2, primary draws an additional current.

$$I_2' = \frac{I2}{K}$$

I1 is the phasor addition of Io and I2'. This I1 causes the voltage drop across primary resistance R1 and reactance X1.

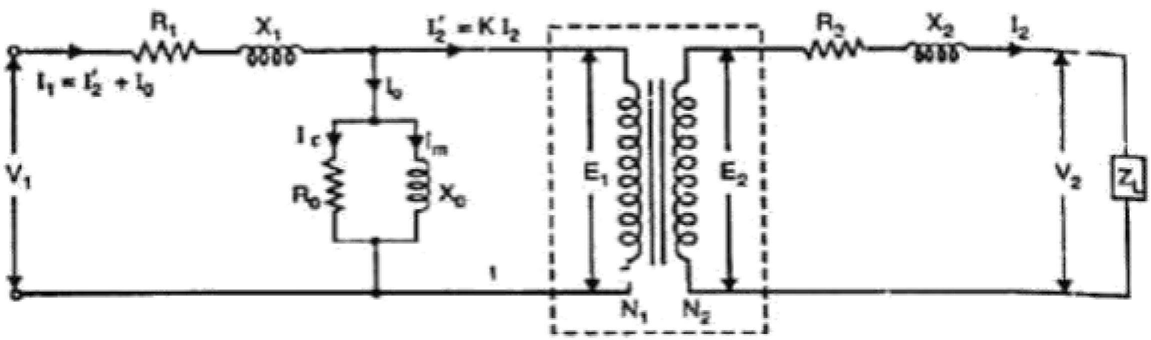


Fig: 2.12

To simplified the circuit the winding is not taken in equivalent circuit while transfer to one

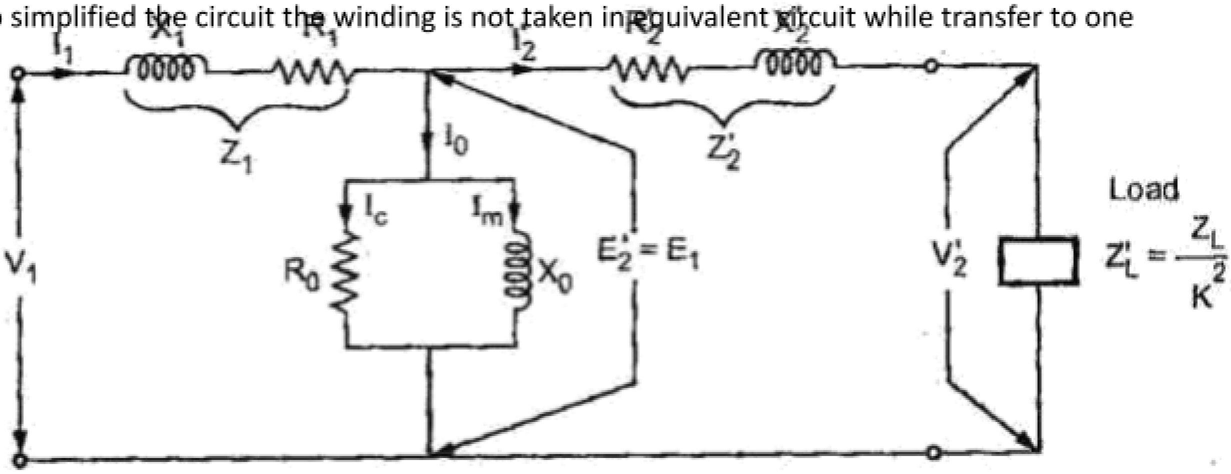


Fig: 2.13

Exact equivalent circuit referred to primary

Transferring secondary parameter to primary -

$$R_2' = \frac{R2}{K^2},\ X_2' = \frac{X2}{K^2},\ Z_2' = \frac{Z2}{K^2},\ E_2' = \frac{E2}{K'},\ I_2' = KI_2,\ K = \frac{N2}{N1}$$

High voltage winding	low current	high impedance
Low voltage winding	high current	low impedance

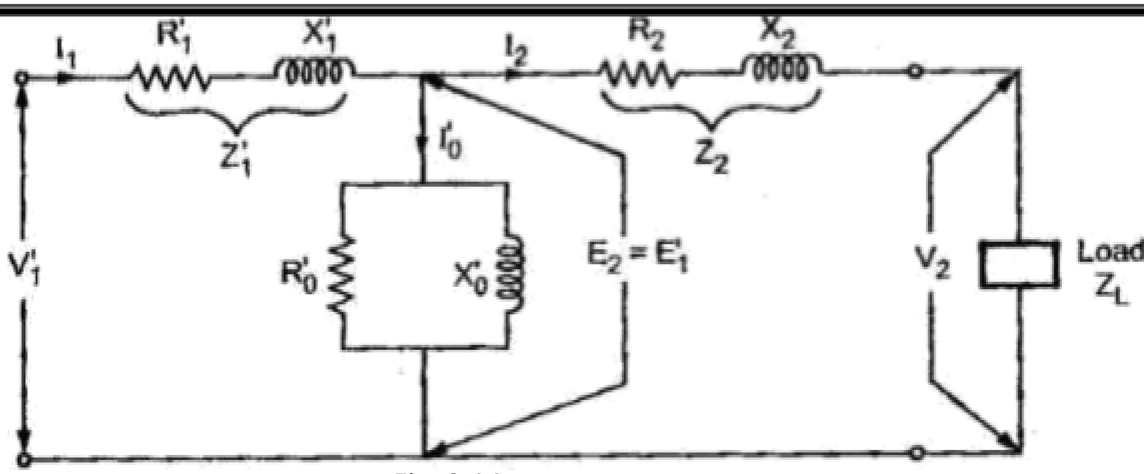


Fig: 2.14

Exact equivalent circuit referred to secondary

$R_1' = R_1K^2$, $X_1' = K^2X_1$, $E_1' = KE_1$

$Z_1' = K^2Z1$, $I_1' = \frac{I1}{K'}$, $I_o = \frac{Io}{K}$

Now as long as no load branch i.e. exciting branch is in between Z1 and Z2', the impedances cannot be combined. So further simplification of the circuit can be done. Such circuit is called approximate equivalent circuit.

Approximate Equivalent Circuit:

i) To get approximate equivalent circuit, shift the no load branch containing Ro and Xo to the left of R1 and X1.

ii) By doing this we are creating an error that the drop across R1 and X1 to Io is neglected due to this circuit because simpler.

iii) This equivalent circuit is called approximate equivalent circuit Fig: 2.15 & Fig: 2.16.

In this circuit new R1 and R2' can be combined to get equivalent circuit referred to primary R1e,similarly
X1 and X2' can be combined to get X1e.

$$R_{1e} = R_1 + R_2' = R_1 + \frac{R2}{K^2}$$

$$X_{1e} = X_1 + X_2' = X_1 + \frac{X2}{K^2}$$

$$Z_{1e} = R_{1e} + jX_1E, \qquad R_o = \frac{V1}{Ic}, \quad \text{and } X_o = \frac{V1}{Im}$$

$$I_c = I_o \cos\phi_o, \quad \text{and } I_m = I_o \sin\phi_o$$

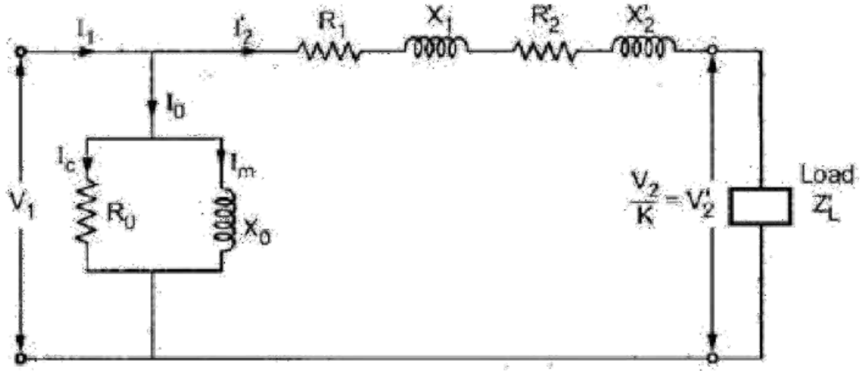
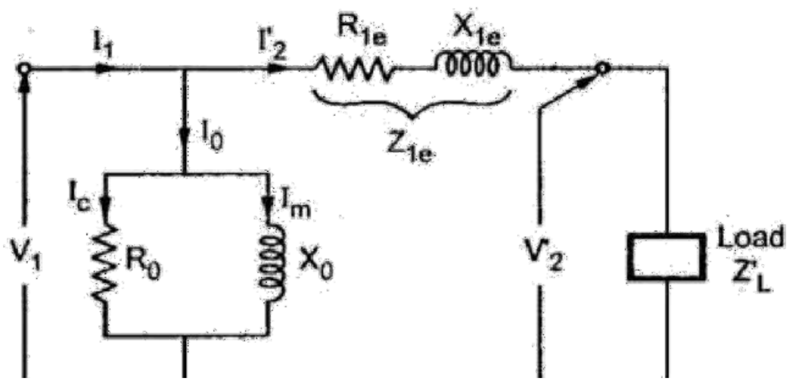
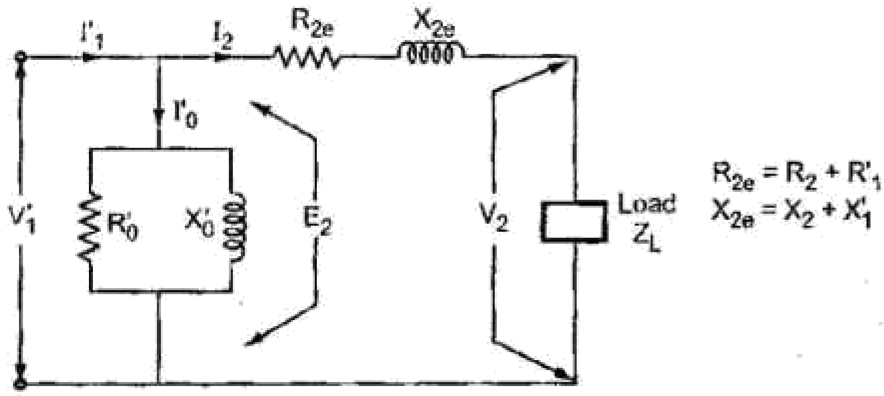


Fig.2.15Approximate equivalent circuit referred to primary



Approximate Voltage Drop in a Transformer



$$\vec{E_2} = \overrightarrow{I_2 R_{2e}} + \overrightarrow{I_2 X_{2e}} + \vec{V_2} = \vec{V_2} + \vec{I_2}(R_{2e} + jX_{2e}), \quad \vec{E_2} = \vec{V_2} + \overrightarrow{I_2 Z_{2e}}$$

Fig. 2.17

Primary parameter is referred to secondary there are no voltage drop in primary. When there is no load,

$I2 = 0$ and we get no load terminal voltage drop

in $V2o = E2$ = no load terminal voltage

$V2$ = terminal voltage on load

For Lagging P.F.

i) The current I2 lags V2 by angle $\phi 2$

ii) Take V2 as reference

iii) I2R2e is in phase with I2 while I2 X2e leads I2 by 90°

iv) Draw the circle with O as centre and OC as radius cutting extended OA at M. as OA = V2 and now OM = E2. The total voltage drop is AM = I2Z2e.

v) The angle α is practically very small and in practice M&N are very close to each other. Due to this the approximate voltage drop is equal to AN instead of AM

AN – approximate voltage

drop To find AN by

adding

AD& DN AD = AB cosϕ

= I2R2e cosϕ DN

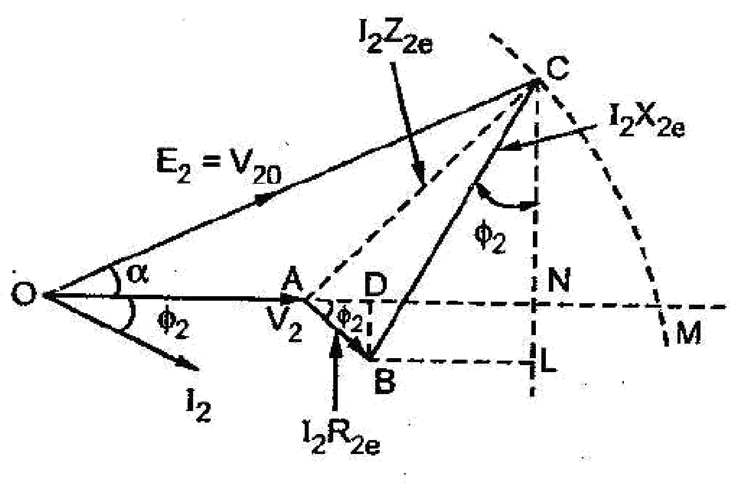
= BL sinϕ =

I2X2e sinϕ

AN = AD + DN = I2R2e cosϕ2 + I2X2e

sinϕ2 Assuming: ϕ2 = ϕ1 = ϕ

Approximate voltage drop = I2R2e cosϕ+I2X2e sinϕ (referred to secondary) Similarly: Approximate voltage drop = I1R1e cosϕ+I1X1e sinϕ (referred to primary)

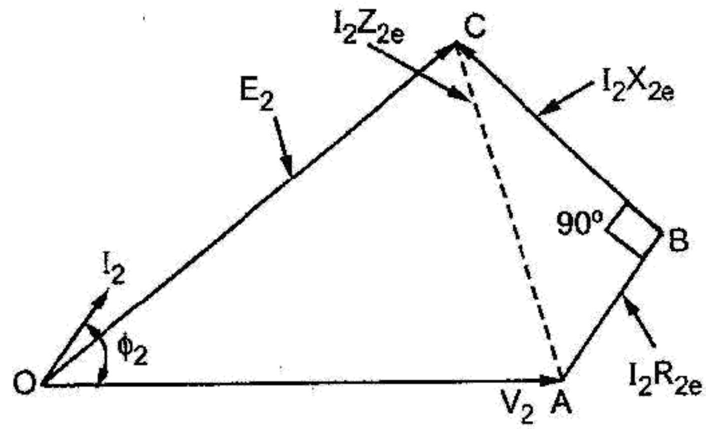


For Leading P.F Loading

I2 leads V2 by angle ϕ2

Approximate voltage drop = I2R2e cosϕ - I2X2e sinϕ (referred to secondary)

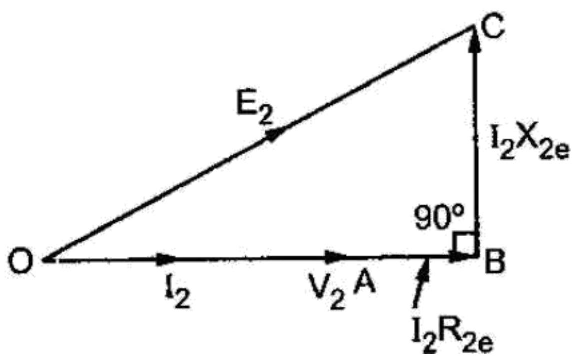
Similarly: Approximate voltage drop = I1R1e cosϕ - I1X1e sinϕ (referred to primary)



For Unity P.F. Loading

Approximate voltage drop = I2R2e (referred to secondary)

Similarly: Approximate voltage drop = I1R1e (referred to primary)



Cosϕ = 1

Sinϕ = 0

Fig: 2.20

Approximate voltage drop = E2 – V2

$= I_2R_{2e} \cos\phi \pm I_2X_{2e} \sin\phi$ (referred to secondary)

$= I_1R_{1e} \cos\phi \pm I_1X_{1e} \sin\phi$ (referred to primary)

Losses in a Transformer

The power losses in a transformer are of two types, namely;

1. Core or Iron losses
2. Copper losses

These losses appear in the form of heat and produce (i) an increase in Temperature and (ii) a drop in efficiency.

Core or Iron losses (Pi)

These consist of hysteresis and eddy current losses and occur in the transformer core due to the alternating flux. These can be determined by open-circuit test.

Hysteresis loss = $k_h f B_m^{1.6}$ watts /m^3

Kh – hysteresis constant depend on
material f - Frequency
Bm – maximum flux density

Eddy current loss = $K_e f^2 B_m^2 t^2$ watts /m^3

Ke – eddy current constant t - Thickness of the core
Both hysteresis and eddy current losses depend upon

(i) Maximum flux density Bm in the core

(ii) Supply frequency f. Since transformers are connected to constant-frequency, constant voltage supply, both f and Bm are constant. Hence, core or iron losses are practically the same at all lods.

Iron or Core losses, Pi = Hysteresis loss + Eddy current loss = Constant losses (Pi)

The hysteresis loss can be minimized by using steel of high silicon content .Whereas eddy current loss can be reduced by using core of thin laminations.

Copper losses (Pcu)

These losses occur in both the primary and secondary windings due to their ohmic resistance. These can be determined by short-circuit test. The copper loss depends on the magnitude of the current flowing

$$\text{Total copper loss} = I_1^2R_1 + I_2^2R_2 = I_1^2(R_1 + R_2') = I_2^2(R_2 + R_1')$$

$$\boxed{\text{Total loss} = \text{iron loss} + \text{copper loss} = Pi + Pcu}$$

through the windings.

Efficiency of a Transformer

Like any other electrical machine, the efficiency of a transformer is defined as the ratio of output power (in watts or kW) to input power (watts or kW) i.e.

Power output = power input – Total
losses Power input = power output +
Total losses

= power output + Pi + Pcu

$$\text{Efficiency} = \frac{power\ output}{power\ input}$$

$$\text{Efficiency} = \frac{power\ output}{power\ input + Pi + Pcu}$$

Power output = $V_2I_2\cos\phi$. Cos ϕ = load power factor

Transformer supplies full load of current I_2 and with terminal voltage V_2

Pcu = copper losses on full load = $I_2^2R_{2e}$

This is full load efficiency and I2 = full load current.

We can now find the full-load efficiency of the transformer at any p.f. without actually loading the transformer.

$$\text{Full load Efficiency} = \frac{\text{(Full load VA rating)X } \cos\phi}{\text{(Full load VA rating)X } \cos\phi + Pi + I2^2 R2e}$$

Also for any load equal to n x full-load,

Corresponding total losses = $P_i + n^2 P_{Cu}$

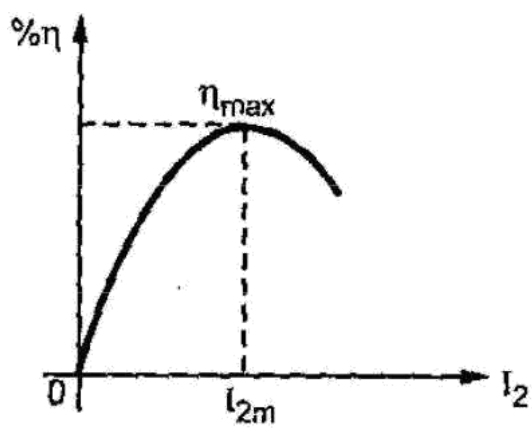
$$n = \text{fractional by which load is less than full load} = \frac{\text{actual load}}{\text{full load}}$$

$$n = \frac{\text{half load}}{\text{fullload}} = \frac{(\frac{1}{2})}{1} = 0.5$$

$$\text{Corresponding (n) \% Efficiency} = \frac{n\text{(VA rating)X } \cos\phi}{n\text{(VA rating)X } \cos\phi + Pi + n^2 Pcu} \text{ X } 100$$

Condition for Maximum Efficiency

Voltage and frequency supply to the transformer is constant the efficiency varies with the load. As load increases, the efficiency increases. At a certain load current, it loaded further the efficiency start decreases as shown in fig. 2.21.



The load current at which the efficiency attains maximum value is denoted as I_{2m} a n d maximum efficiency is denoted as ηmax, now we find -

(a) condition for maximum efficiency

(b) load current at which η_{max} occurs

(c) KVA supplied at maximum efficiency Considering primary side,

Load output = $V_1 I_1 \cos\phi_1$

Copper loss = $I_1^2 R_{1e}$ or $I_2^2 R_{2e}$

Iron loss = hysteresis + eddy current loss = Pi

$$\text{Efficiency} = \frac{V1I1\cos\phi1 - \text{losses}}{V1I1\cos\phi1} = \frac{V1I1\cos\phi1 - I1^2R1e + Pi}{V1I1\cos\phi1}$$

$$= 1 - \frac{I1R1e}{V1I21\cos\phi1} = \frac{Pi}{V1I1\cos\phi1}$$

Differentiating both sides with respect to I2, we get

$$\frac{d\eta}{dI2} = 0 - \frac{R1e}{V1\cos\phi1} = \frac{Pi}{V1I1^2\cos\phi1}$$

For η to be maximum, $\frac{d\eta}{dI2} = 0$. Hence, the above equation becomes

$$\frac{R1e}{V1\cos\phi1} = \frac{Pi}{V1I1^2\cos\phi1} \text{ or } Pi = I_1^2 R_{1e}$$

Pcu loss = Pi iron loss

The output current which will make Pcu loss equal to the iron loss. By proper design, it is possible to make the maximum efficiency occur at any desired load.

Load current I2m at maximum efficiency

KVA Supplied at Maximum Efficiency

For constant V2 the KVA supplied is the function of load current.

For η_{max} $I_2^2 R_{2e} = P_i$ but $I_2 = I_{2m}$

$$I^2_{2m} R_{2e} = Pi \qquad I_{2m} = \sqrt{\frac{Pi}{R2e}}$$

This is the load current at η_{max}

$(I_2)F.L$ = full load current

$$\frac{I2m}{(I2)F.L} = \frac{1}{(I2)F.L}\sqrt{\frac{Pi}{R2e}}$$

$$\frac{I2m}{(I2)F.L} = \sqrt{\frac{Pi}{[(I2)F.L]^2 R2e}} = \sqrt{\frac{Pi}{[Pcu]F.L}}$$

$$\boxed{I_{2m} = (I_2)\,F.L.\sqrt{\frac{Pi}{[Pcu]F.L}}}$$

This is the load current at η_{max} in terms of full load current

KVA Supplied at Maximum Efficiency

For constant V2 the KVA supplied is the function of load current.

$$\text{KVA at } \eta_{max} = I_{2m} V_2 = V_2(I_2)F.L. \times \sqrt{\frac{Pi}{[Pcu]F.L}}$$

$$\text{KVA at } \eta_{max} = (\text{KVA rating}) \times \sqrt{\frac{Pi}{[Pcu]F.L}}$$

Substituting condition for η_{max} in the expression of efficiency, we can write expression for η_{max} as ,

as Pcu = Pi

$$\% \, \eta_{max} = \frac{V2 \, I2m \cos\phi}{V2 \, I2m\cos\phi + 2Pi} \times 100$$

All Day Efficiency (Energy Efficiency)

In electrical power system, we are interested to find out the all-day efficiency of any transformer because the load at transformer is varying in the different time duration of the day. So all day efficiency is defined as the ratio of total energy output of transformer to the total energy input in 24 hours.

$$\text{All day efficiency} = \frac{\text{kWh output during a day}}{\text{kWh input during the day}}$$

UNIT-V

Single-phase Transformers Testing

Testing of Transformer

The testing of transformer means to determine efficiency and regulation of a transformer at any load and at any power factor condition.

There are two methods

i) Direct loading test

ii) Indirect loading test

a. **Open circuit test**

b. Short circuit test

Load test on transformer

This method is also called as direct loading test on transformer because the load is directly connected to the transformer. We required various meters to measure the input and output reading while change the load from zero to full load. Fig. 2.22 shows the connection of transformer for direct load test. The primary is connected through the variac to change the input voltage as we required. Connect the meters as shown in the figure below.

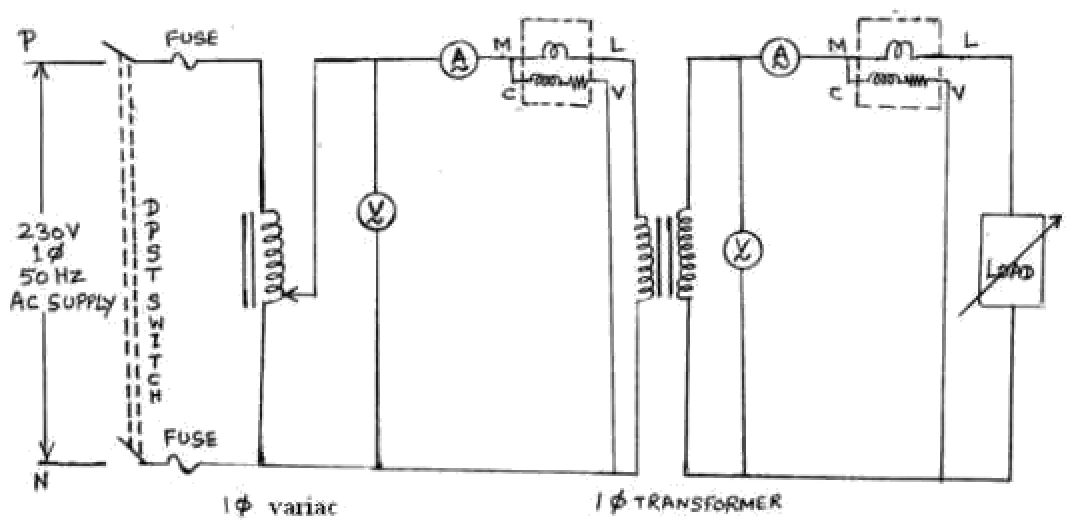


Fig: 2.22

The load is varied from no load to full load in desired steps. All the time, keep primary voltage V1 constant at its rated value with help of variac and tabulated the reading. The first reading is to be noted on no load for which I2 = 0 A and W2 = 0W.

Calculation

From the observed reading

W1 = input power to the
transformer W2 = output power
delivered to the load

$$\% \ \eta = \frac{W2}{W1} \text{ X } 100$$

The first reading is no load so $V2 = E_2$
The regulation can be obtained as

$$\% \ R = \frac{E2-V2}{} \text{ X } 100$$

The graph of % η and % R on each load against load current IL is plotted as shown in fig. 2.23.

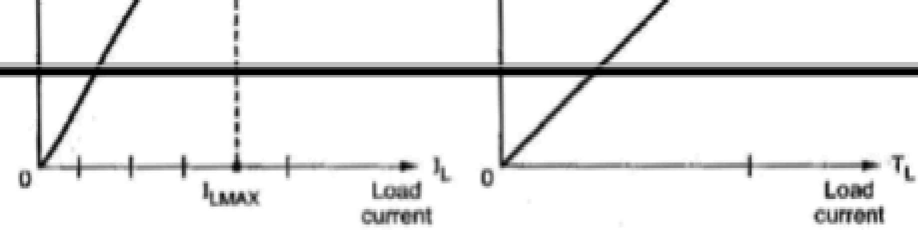


Fig: 2.23

Advantages:

1) This test enables us to determine the efficiency of the transformer accurately at any load.

2) The results are accurate as load is directly used.

Disadvantages:

1) There are large power losses during the test.

2) Load not avail in lab while test conduct for large transformer.

ii) a. Open-Circuit or No-Load Test

This test is conducted to determine the iron losses (or core losses) and parameters R0 and X0 of the transformer. In this test, the rated voltage is applied to the primary (usually low-voltage winding) while the secondary is left open circuited. The applied primary voltage V1 is measured by the voltmeter, the no load current I0 by ammeter and no-load input power W0 by wattmeter as shown in Fig.2.24.a. As the normal rated voltage is applied to the primary, therefore, normal iron losses will occur in the transformer core. Hence wattmeter will record the iron losses and small copper loss in the primary. Since no-load current I0 is very small (usually 2-10 % of rated current). Cu losses in the primary under no-load condition are negligible as compared with iron losses.

Hence, wattmeter reading practically gives the iron losses in the transformer. It is reminded that iron losses are the same at all loads.

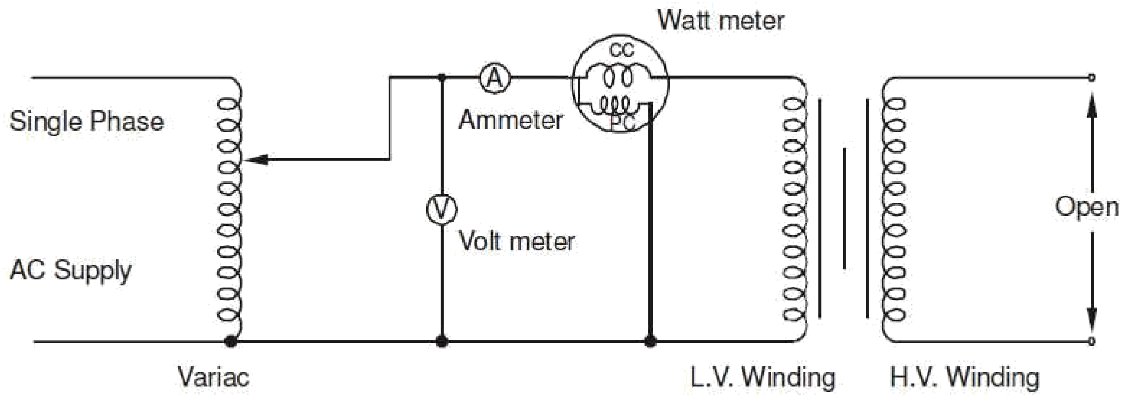


Fig: 2.24.a

Iron losses, P_i = Wattmeter reading = W_0
No load current = Ammeter reading = I_0
Applied voltage = Voltmeter reading = V_1

Input power, $W_0 = V_1 I_0 \cos \phi_0$

No - load p.f., $\cos\phi = \frac{Wo}{Vo\,Io}$ = no load power factor

$I_m = I_o \sin \phi_o$ = magnetizing component
$I_c = I_o \cos \phi_o$ = Active component

$R_o = \frac{Vo}{Ic}\ \Omega$, $X_o = \frac{Vo}{Im}\ \Omega$

Under no load conditions the PF is very low (near to 0) in lagging region. By using the above data we can draw the equivalent parameter shown in Figure 2.24.b.

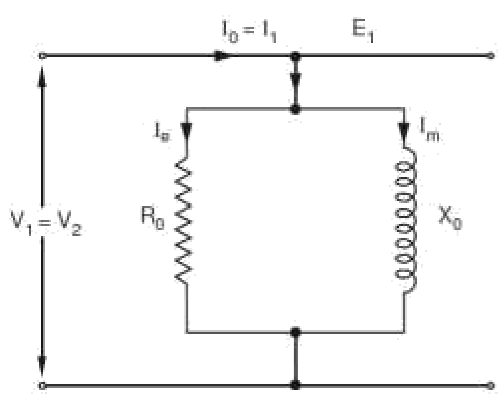


Fig: 2.24.b

Thus open-circuit test enables us to determine iron losses and parameters R0 and X0 of the transformer

ii) <u>b. Short-Circuit or Impedance Test</u>

This test is conducted to determine R1e (or R2e), X1e (or X2e) and full-load copper losses of the transformer. In this test, the secondary (usually low-voltage winding) is short-circuited by a thick conductor and variable low voltage is applied to the primary as shown in Fig.2.25. The low input voltage is gradually raised till at voltage VSC, full-load current I1 flows in the primary. Then I2 in the secondary also has full-load value since I1/I2 = N2/N1. Under such conditions, the copper loss in the windings is the same as that on full load. There is no output from the transformer under short-circuit conditions. Therefore, input power is all loss and this loss is almost entirely copper loss. It is because iron loss in the core is negligibly small since the voltage VSC is very small. Hence, the wattmeter will practically register the full load copper losses in the transformer windings.

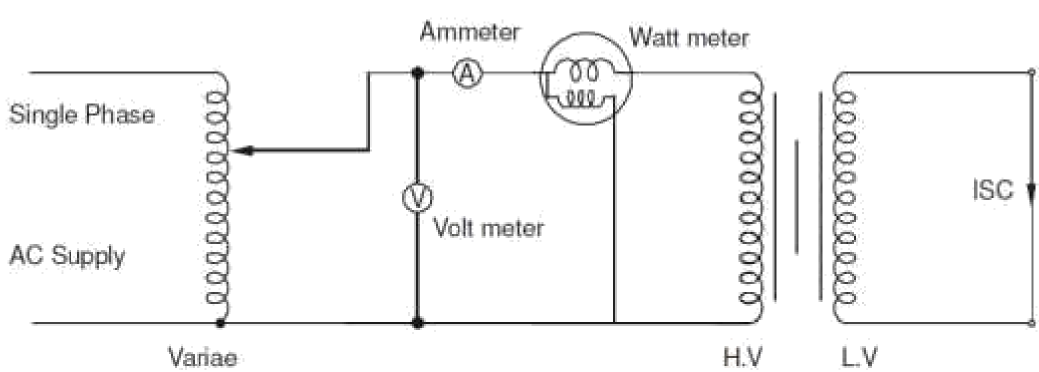


Fig: 2.25.a

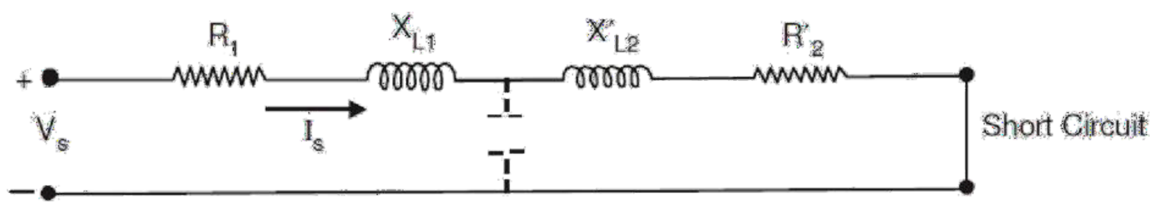
Full load Cu loss, PC = Wattmeter reading = W_{sc}
Applied voltage = Voltmeter reading = V_{SC}
F.L. primary current = Ammeter reading = I_1

$Pcu = I_1^2 R_1 + I_1^2 R_2' = I_1^2 R_{1e}$, $R_{1e} = \frac{Pcu}{I1^2}$

Where R_{1e} is the total resistance of transformer referred to primary.

Total impedance referred to primary, $Z1e = \sqrt{Z1e^2 - R1e^2}$,

short – circuit P.F, $\cos\Phi = \frac{Pcu}{Vsc\, I1}$ Thus short-circuit lest gives full-load Cu loss, R1e and X1e.



$$\text{equivalent resistance } R_{eq} = \frac{W_s}{I_s^2} = R_1 + R_2'$$

$$\text{and equivalent impedance } Z_{eq} = \frac{V_s}{I_s}$$

So we calculate equivalent reactance

$$X_{eq} = \sqrt{Z_{eq}^2 - R_{eq}^2} = X_{L1} + X_{L2}'$$

These R_{eq} and X_{eq} are equivalent resistance and reactance of both windings referred in HV side. These are know as equivalent circuit resistance and reactance.

Voltage Regulation of Transformer

Under no load conditions, the voltage at the secondary terminals is E2 and

$$E_2 \approx V_1 \cdot \frac{N_2}{N_1}$$

(This approximation neglects the drop *R*1 and *Xl*1 due to small no load current). As load is applied to the transformer, the load current or the secondary current increases. Correspondingly, the primary current *I*1 also increases. Due to these currents, there is a voltage drop in the primary and secondary leakage reactances, and as a consequence the voltage across the output terminals or the load terminals changes. In quantitative terms this change in terminal voltage is called Voltage Regulation.

Voltage regulation of a transformer is defined as the drop in the magnitude of load voltage (or secondary terminal voltage) when load current changes from zero to full load value. This is expressed as a fraction of secondary rated voltage.

$$\text{Regulation} = \frac{\text{Secondary terminal voltage at no load} - \text{Secondary terminal voltage at any load}}{\text{Secondary rated voltage}}$$

The secondary rated voltage of a transformer is equal to the secondary terminal voltage at no load (i.e. E2), this is as per IS.

Voltage regulation is generally expressed as a percentage.

$$\text{Percent voltage regulation (\% VR)} = \frac{E_2 - V_2}{E_2} \times 100.$$

So $$\frac{E_2 - V_2}{E_2} = \frac{I_2\ r_{eq}\ \cos\phi_2 \pm I_2\ x_{eq}\ \sin\phi_2}{E_2}$$

Note that E2, V2 are magnitudes, and not phasor or complex quantities. Also note that voltage regulation depends not only on load current, but also on its power factor. Using approximate equivalent circuit referred to primary or secondary, we can obtain the voltage regulation. From approximate equivalent circuit referred to the secondary side and phasor diagram for the circuit.

$$\frac{E_2 - V_2}{E_2} = \frac{I_2\ r_{eq}}{E_2}\cos\phi_2 \pm \frac{I_2\ x_{eq}}{E_2}\sin\phi_2$$

% Voltage regulation = (% resistive drop) $\cos\phi_2$ ± (% reactive drop) $\sin\phi_2$.

Ideally voltage regulation should be zero.

$$E_2 = V_2 + I_2\ r_{eq}\ \cos\phi_2 \pm I_2\ x_{eq}\ \sin\phi_2$$

where $r_{eq} = r_2 + r_1^1$ (referred to secondary) $x_e = x_2 + x_1^1$ (+ sign applies lagging power factor load and – sign applies to leading pf load).

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