

GANDHI INSTITUTE OF ADVANCED COMPUTER AND RESEARCH
P.O: Rayagada-765002, Dist: Rayagada (ODISHA)

LECTURE NOTES ON
ENERGY CONVERSION – I
4TH semester,Diploma

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DEPARTMENT OF ELECTRICAL ENGINEERING

Detailed Contents:

UNIT	TOPIC TO BE COVERED
UNIT-1	D.C GENERATOR
	Operating principle of generator
	Constructional features of DC machine. Yoke, Pole & field winding, Armature, Commutator. Armature winding, back pitch, Front pitch, Resultant pitch and commutator- pitch. Simple Lap and wave winding, Dummy coils
	Different types of D.C. machines (Shunt, Series and Compound)
	Derivation of EMF equation of DC generators. (Solve problems)
	Losses and efficiency of DC generator. Condition for maximum efficiency and numerical problems
	Armature reaction in D.C. machine
	Commutation and methods of improving commutation. Role of inter poles and compensating winding in commutation
	Characteristics of D.C. Generators
	Application of different types of D.C. Generators
	Concept of critical resistance and critical speed of DC shunt generator
	Conditions of Build-up of emf of DC generator
	Parallel operation of D.C. Generators.
	Uses of D.C generators.

UNIT-2	D. C. MOTORS
	Basic working principle of DC motor
	Significance of back emf in D.C. Motor
	Voltage equation of D.C. Motor and condition for maximum power output(simple problems)
	Derive torque equation (solve problems)
	Characteristics of shunt, series and compound motors and their application.
	Starting method of shunt, series and compound motors
	Speed control of D.C shunt motors by Flux control method. Armature voltage Control method. Solve problems
	Speed control of D.C. series motors by Field Flux control method, Tapped field method and series-parallel method
	Determination of efficiency of D.C. Machine by Brake test method(solve numerical problems)
	Determination of efficiency of D.C. Machine by Swinburne's Test method(solve numerical problems)
	Determination of efficiency of D.C. Machine by Swinburne's Test method(solve numerical problems)
	Uses of D.C. motors
UNIT-3	SINGLE PHASE TRANSFORMER
	Working principle of transformer.
	Constructional feature of Transformer
	Arrangement of core & winding in different types of transformer. Brief ideas about transformer accessories such as conservator, tank, breather, and explosion vent etc.

	Explain types of cooling methods
	State the procedures for Care and maintenance
	EMF equation of transformer
	Ideal transformer voltage transformation ratio
	Operation of Transformer at no load, on load with phasor diagrams.
	Equivalent Resistance, Leakage Reactance and Impedance of transformer.
	To draw phasor diagram of transformer on load, with winding Resistance and Magnetic leakage with using upf, leading pf and lagging pf load.
	To explain Equivalent circuit and solve numerical problems.
	Approximate & exact voltage drop calculation of a Transformer.
	Regulation of transformer.
	Different types of losses in a Transformer. Explain Open circuit and Short Circuit test.(Solve numerical problems)
	Explain Efficiency, efficiency at different loads and power factors, condition for maximum efficiency (solve problems)
	Explain All Day Efficiency (solve problems)
	Determination of load corresponding to Maximum efficiency.
	Parallel operation of single phase transformer.
UNIT-4	AUTO TRANSFORMER
	Constructional features of Auto transformer.
	Working principle of single phase Auto Transformer.

	Comparison of Auto transformer with an two winding transformer (saving of Copper).
	Uses of Auto transformer.
	Explain Tap changer with transformer (on load and off load condition)
UNIT-5	INSTRUMENT TRANSFORMERS
	Explain Current Transformer and Potential Transformer
	Define Ratio error, Phase angle error, Burden.
	Uses of C.T. and P.T.

Books Recommended:

Electrical Technology – II By B. L. Thareja and A. K. Thareja
A Textbook of Electrical Machines By K R Siddhapura, D B Raval

COURSE OUTCOME:

After the completion of the course the students will be able to

CO1- Apply the knowledge of DC generator with construction and its EMF generated to solve various related numerical.

CO2- Apply the knowledge of D.C Motor with construction and its EMF generated to solve various related numerical.

CO3- Explain the principle and construction of Single-phase transformer and sketch the phase diagram.

CO4- Construction and working of auto transformers.

CO5- Explain current transformer and potential transformer with its uses.

DC GENERATOR

An electrical generator is a machine which converts mechanical energy (or power) into electrical energy (or power).

The energy conversion is based on the principle of the production of dynamically (or motionally) induced e.m.f. As seen from fig. 26.1, whenever a conductor cuts magnetic flux, dynamically induced em-f. is produced in it according to Faraday's Laws of Electromagnetic Induction. This em-f. causes a current to flow if the conductor circuit is closed.



Hence, two basic essential parts of an electrical generator are a magnetic field and (ii) a conductor or conductors which can so move as to cut the flux.

CONSTRUCTION:-

In fig. 26.1 is shown a single-turn rectangular coil ABCD rotating about its own axis in a magnetic field provided by either permanent magnet or electromagnets. The two ends of the coil

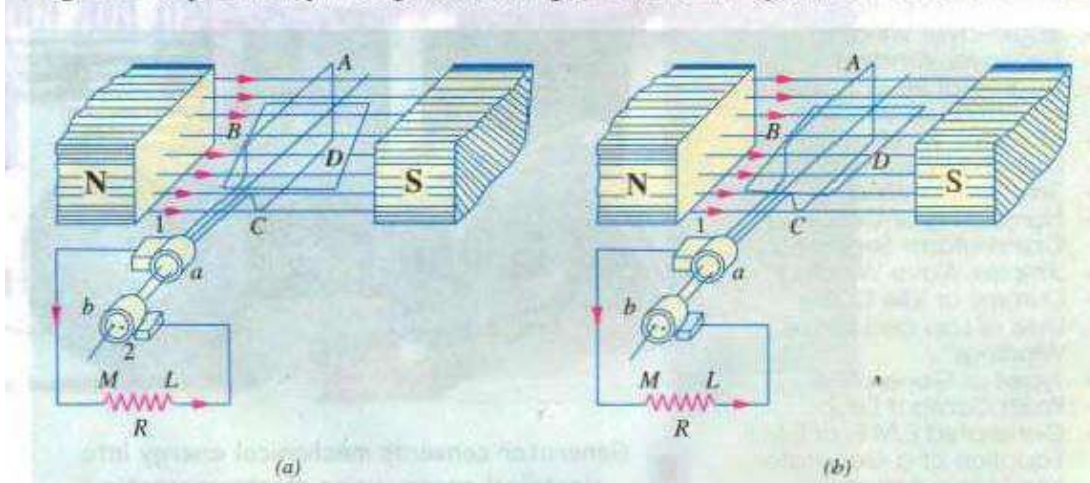


Fig. 26.1

magnetic field provided by either magnet or electromagnets. The two ends of the coil are joined to two slip-rings 'a' and 'b' which are insulated from each other and from the central shaft. Two collecting brushes (of carbon or copper) press against the slip-rings. Their function is to collect the current induced in the coil and to convey it to the external load resistance R.

The rotating coil may be called 'armature' and the magnets as 'field magnets'.

Working

Imagine the coil to be rotating in clock-wise direction (Fig. 26.2). As the coil assumes successive positions in the field, the flux linked with it changes. Hence, an e.m.f. is induced in it which is

proportional to the rate of change of flux linkages ($e = N \frac{d\phi}{dt}$). When the plane of the coil is at right angles to lines of flux i.e. when it is in position, 1, then flux linked with the coil is maximum but rate of change of flux linkages is minimum.

It is so because in this position, the coil sides AB and CD do not cut or shear the flux, rather they slide along them they move parallel to them. Hence, there is no induced e.m.f. in the coil. Let us take this no-e.m.f. or vertical position of the coil as the starting position. The angle of rotation or time will be measured from this position.

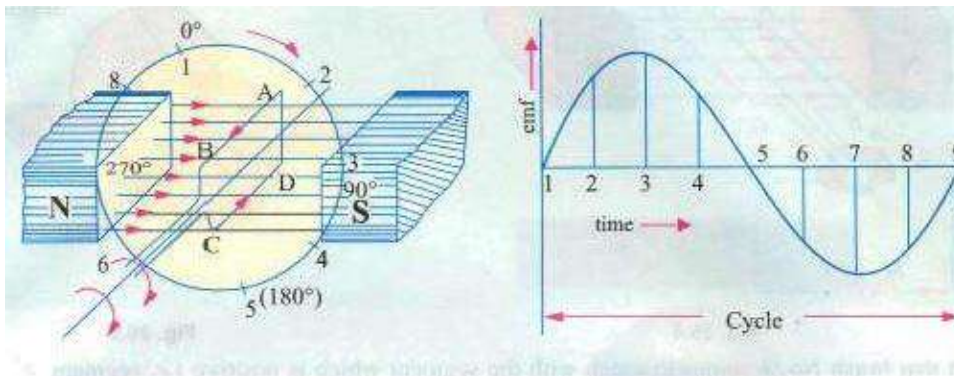


Fig. 26.2

Fig. 26.3

As the coil continues rotating further, the rate of change of flux linkages (and hence induced e.m.f. in it) increases. till position 3 is reached where $\theta = 90^\circ$. Here, the coil plane is horizontal i.e. parallel to the lines of flux. As seen, the flux linked with the coil is minimum but rate of change of flux linkages is maximum. Hence, maximum e.m.f. is induced in the coil when in this position (Fig. 26.3).

In the next quarter revolution i.e. from 90° to 180° , the flux linked with the coil gradually increases but the rate of change of flux linkages decreases. Hence, the induced e.m.f. decreases gradually till in position 5 of the coil, it is reduced to zero value.

So, we find that in the first half revolution of the coil, no (or minimum) e.m.f. is induced in it when in position 1, maximum when in position 3 and no e.m.f. when in position 5. The direction of this induced e.m.f. can be found by applying Fleming's Right-hand rule which gives its direction from A to B and C to D. Hence, the direction of current flow is ABCD (fig. 26.1). The current through the load resistance R flows from M to L during the first half revolution of the coil.

In the next half revolution i.e. from 180° to 360° , the variations in the magnitude of are similar to those in the first half revolution. Its value is maximum when coil is in position 7 and

minimum when in position I. But it will be found that the direction of the induced current is from D to C and B to A as shown in Fig. 26.1 Hence, the path Of current flow is along DUMBA which is just the reverse of the previous direction of now.

Therefore, we find that the current which we obtain from such a simple generator reverses its direction after every half revolution, Such a current undergoing periodic reversals is known as alternating current. It is, obviously, different from a direct current which continuously flows in one and the same direction. It should be noted that alternating current not only reverses its direction, it does not even keep its magnitude constant while flowing in any one direction. The two half-cycles may be called positive and negative half-cycles respectively (Fig. 26.3).

For making the now Of current unidirectional in the external circuit, the slip-rings are replaced by split-rings (Fig. 26.4). The split-rings are made out of a conducting cylinder which is cut into two halves or segments insulated from each other by a thin sheet of mica or some other insulating material (Fig. 26.5).

As before, the coil ends are joined to these segments on which rest the carbon or brushes. It is seen in Fig. 26.6 that in the first half revolution current flows along BMNC DJ i.e. the brush NO. 1 in contact with segment 'a' acts as the positive end of the supply and 'b' the negative end. In the next half revolution in Fig. 26.6 (b), the direction of the induced current in the coil has

reversed. But at the same time, the positions of segments 'a' and 'b' have also reversed with the

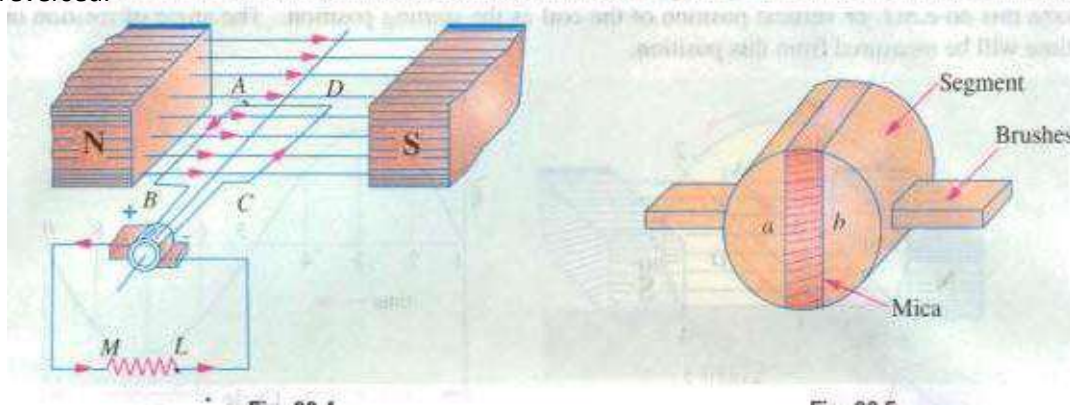
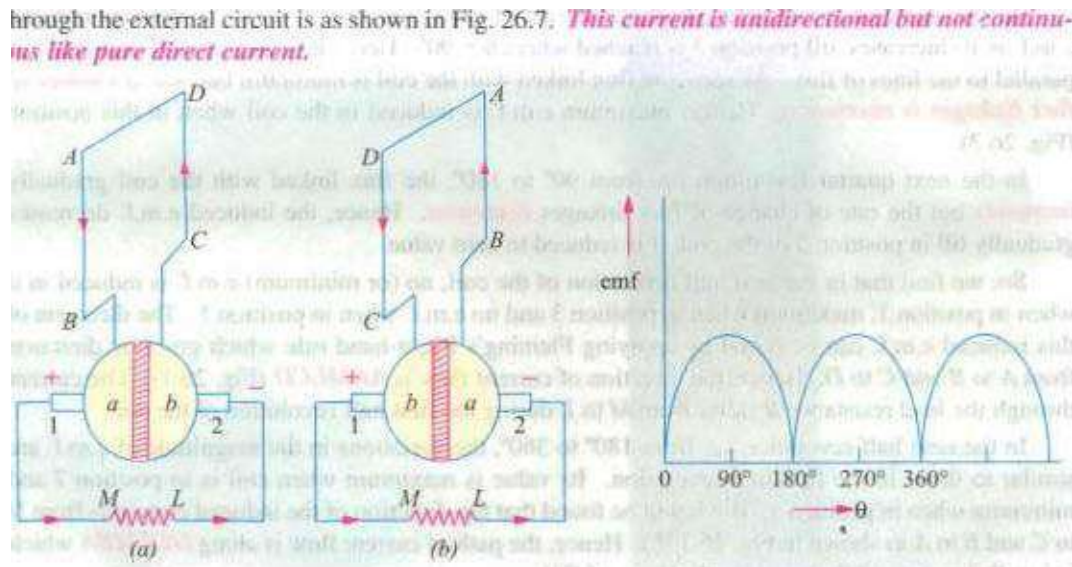


Fig. 26.4 Fig. 26.5 result that brush No. 1 comes in touch with the segment which is positive i.e. segment in this case. Hence, current in the load resistance again flows from M to



L. The Waveform of the current through the external circuit is as shown in Fig. 26.7. This current should be noted that the position of brushes is so arranged that the change over of segments 'a' and from one brush to the other takes place when the plane of the rotating coil is at right angles to the plane of the lines of It is so because in that position, the induced e.m.f. in the coil is zero.

Another important point worth remembering is that even now the current induced in the coil sides is alternating as before. It is only due to the rectifying action of the split-rings (also called commutator) that it becomes unidirectional in the external circuit. Hence, it should be clearly understood that in the armature of a generator, the induced voltage is alternating.

Generator-

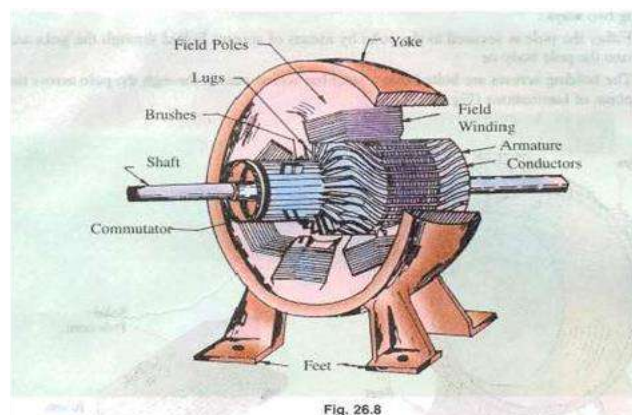


Fig. 26.8

26.5. Pole Cores and Pole Shoes

The field Consist or pole Cores and pole shoes. The pole shoes SCñre two purposes

- (i) they spread out the flux in the air gap and also, Of larger cross-section, reduce the reluctance Of the magnetic path • ii) they supiX3rt the exciting coils (or field coils) as shown in fig. 26.14.

There are two main types Of pole construction.

- (a) The pole core itself may a solid piece made out Of either cast iron Or cast steel but the pole shoe is laminated and is fastened to the pole face by means of counter sunk screws as shown in fig. 24.10.
- (b) In modern design. the complete Ne cores and pole shoes are built of thin laminations of annealed steel which æ rivetted together under hydraulic pressure (Fig. 26_11). The thickness Of laminations varies from 1 mm to 0.25 mm- The laminated poles may be secured to the yoke in any of the following two Ways:
 - (i) Either the pole is secured to the yoke by means of screws bolted through the yoke and into the pole body or
 - (ii) The holding screws are bolted into a bar which passes through the pole across the plane of laminations (Fig. 26.12).

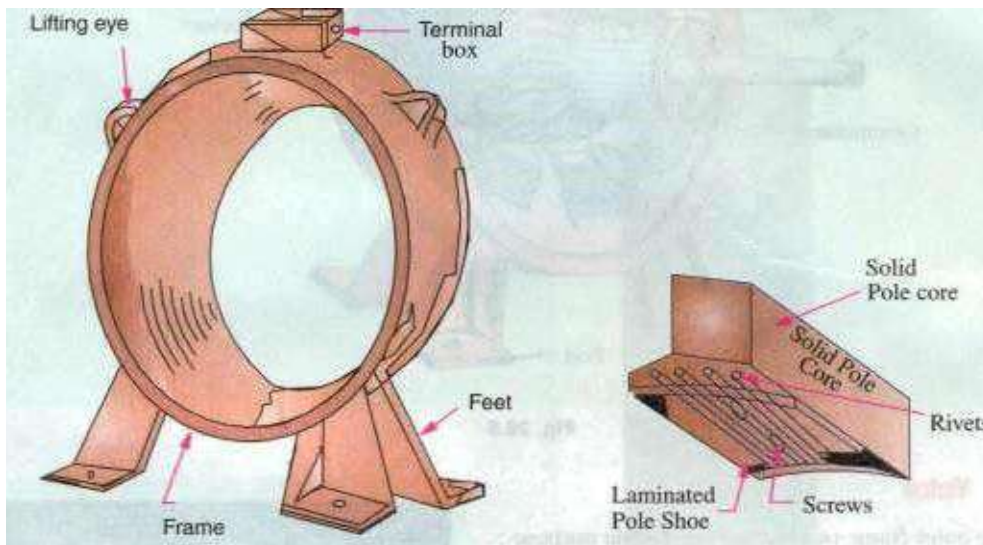
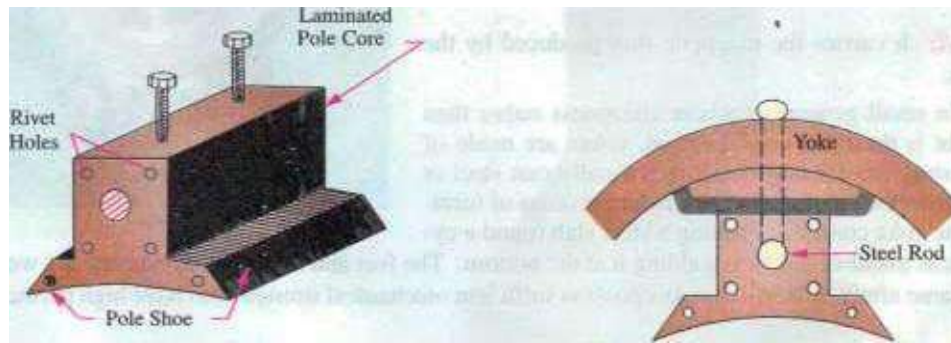


Fig. 26,9

Fig. 26.10



26.6. pole coas

The field coils or pole coils, which consist of copper wire or strip. are former-wound for the correct dimension (Fig. 26.13). Then. the former is removed and wound coil is put into place over the core as shown in Fig. 26.14.

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

26.7. Armature Core

It houses the armature conductors or coils and causes them to rotate and hence cut the magnetic flux Of the field magnets In addition to this, its most important function is to provide a path of very low reluctance to the flux through the armature from a tv-pole to a S-pole.

It is cylindrical or drum-shaped and is built up of usually circular sheet steel discs or laminations approximately 0.5 mm thick (Fig. 26.15). It is keyed to the shaft..

The slots are either die-cut or punched on the outer periphery Of the disc and the keyway is located on the inner diameter as shown. In small machines, the armature stampings are keyed directly to the shaft. Usually. these laminations are perforated for air ducts which permits axial now of air through the armature for cooling purposes. Such ventilating channels are clearly Visible in the laminations shown in Fig. 26.16 and Fig. 26.17.

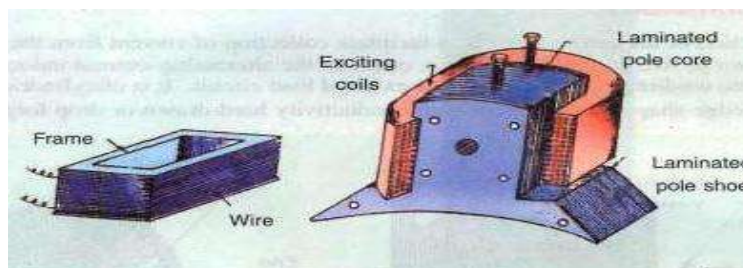
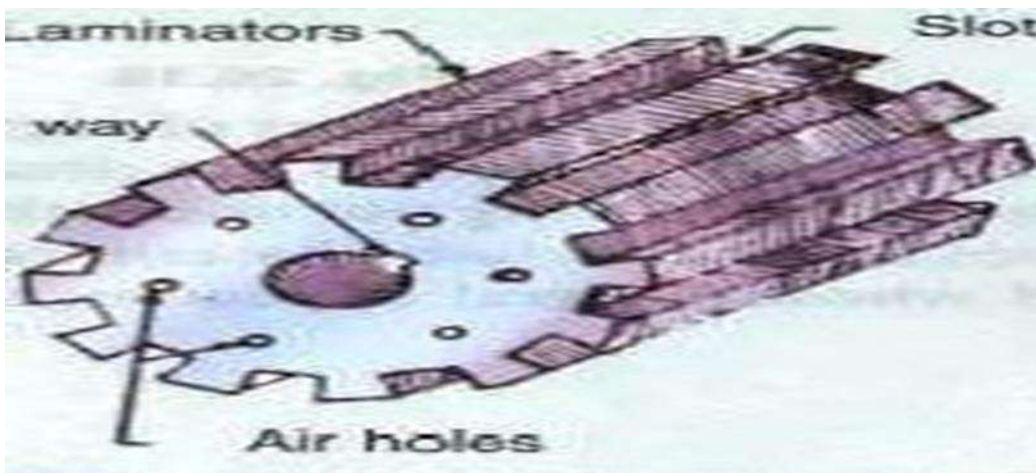
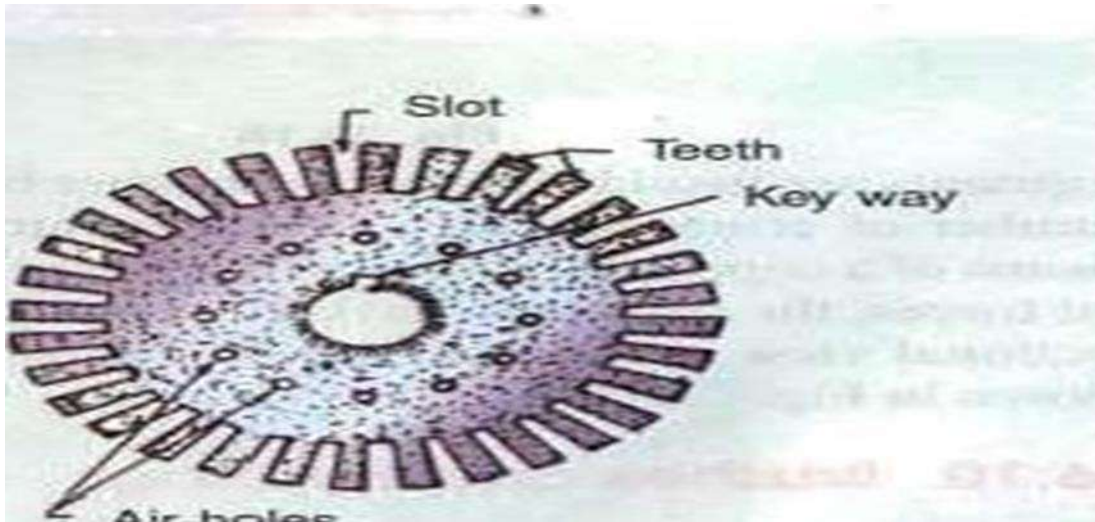


Fig. 26.13

Fig. 26.14

Up to armature diameters of about one metre, the circular stampings are cut out in one piece as shown in Fig. 26.16, But above this size, these circles, especially of such thin sections, are difficult to handle because they tend to distort and become wavy when assembled together. Hence, the circular laminations, instead of being cut out in one piece, are cut in number of suitable sections or segments which form part of a complete ring (Fig. 26.17).



A complete circular lamination is made up of four or six or even eight segmental laminations. Usually, two keyways are notched in each segment and are dove-tailed or wedge-shaped to make the laminations self-locking in position,

The purpose of using laminations is to reduce the loss due to eddy currents. Thinner the laminations, greater is the resistance offered to the induced $e_{rn.f.}$, smaller the current and hence lesser the R loss in the core.

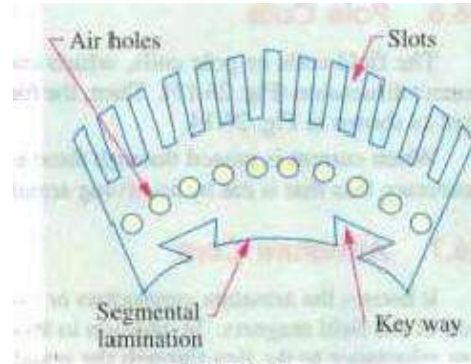


Fig. 26.17

s and are then pulled into their proper shape

26.8. Armature Windings

The armature windings are usually former-wound.

These are first wound in the form of flat rectangular coils and are then pulled into their proper shape in a coil puller. Various conductors of the coils are insulated from each other. The conductors are placed in the armature slots which are lined with tough insulating material. This slot insulation is folded over above the armature conductors placed in the slot and is secured in place by special hard wooden or fibre wedges,

26.9. Commutator

The function of the commutator is to facilitate collection of current from the armature conductors. As shown in Art. 26.2, rectifier converts the alternating current induced in the armature conductors into unidirectional current in the external load circuit. It is of cylindrical structure and is built up of wedge-shaped segments of high conductivity hard-drawn or drop forged copper. These

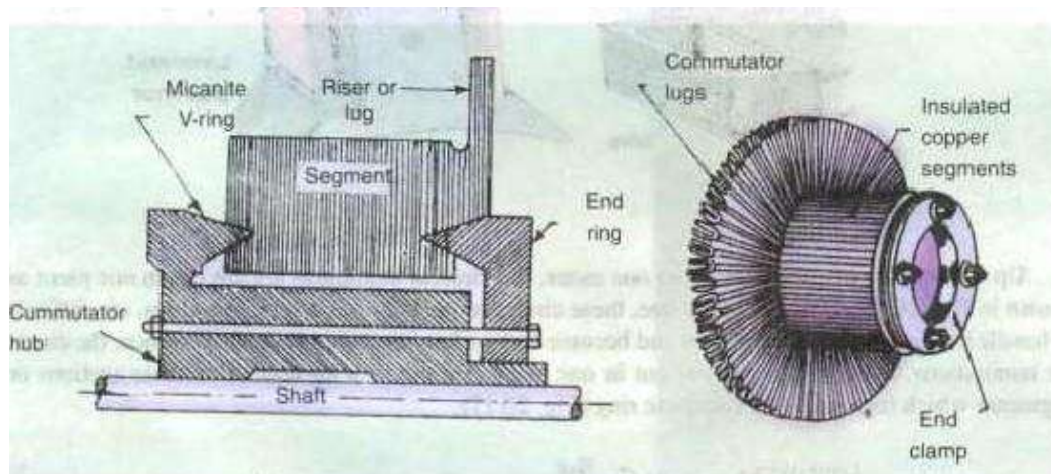


Fig. 26.18

Fig. 26.19

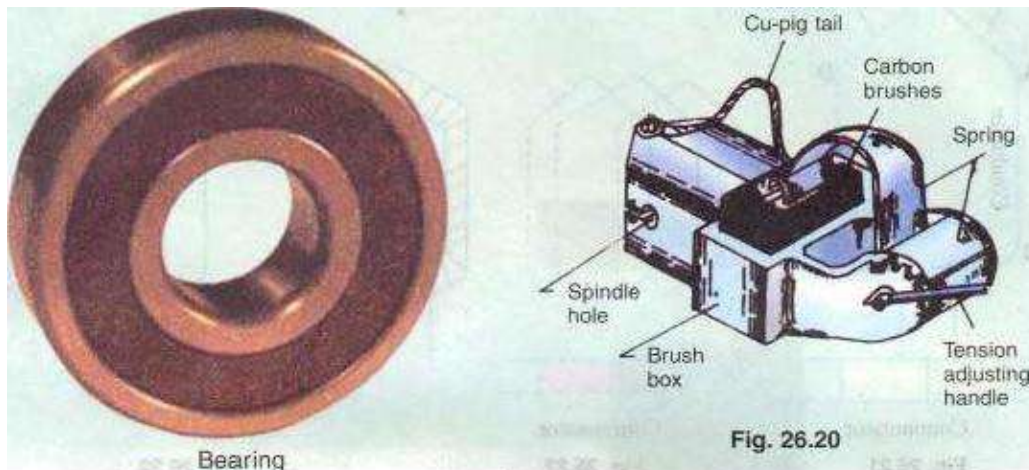
segments are insulated from each other by thin layers of mica. The number of segments is equal to the number of armature-coils. Each commutator segment is connected to the

armature conductor by means of a copper lug or strip (or riser). To prevent them from flying out under the action of centrifugal forces, the segments have V-grooves. These grooves being insulated by conical mica rings. A sectional view of commutator is in fig. 26.19. Its general shape when completed is shown in Fig. 26.19.

26.10. Brushes and Bearings

The function of brushes is to collect current from commutator. They are usually made of carbon or graphite and are in the shape of a rectangular block. These brushes are housed in brush-holders usually of the box-type variety. As shown in Fig. 26.20, the brush-holder is mounted on a spindle and the brushes can slide in the rectangular-box open at both ends. The brushes are made to bear down on the commutator by a spring whose tension can be adjusted by changing the position of lever in the notches. A flexible copper pigtail mounted at the top of the brush conveys current from the brushes to the holder. The number of brushes per spindle depends on the magnitude of the current to be collected from the commutator.

Flexible



Because of their reliability, ball-bearings are frequently employed. though for heavy duties, roller bearings are preferable. The ball and rollers are generally packed in hard oil for quieter operation and for reduced bearing wear, sleeve bearings are used which are lubricated by ring oilers fed from oil reservoir in the bearing bracket.

26.11. Armature Windings

NOW, We Will discuss the winding of an actual armature. But before doing this, the meaning of the following terms used in connection with armature winding should be clearly kept in mind,

26.12. Pole-pitch

It may be variously defined as :

(i) The periphery Of the armature divided by the number of poles or the generator i.e. the distance between two adjacent poles.

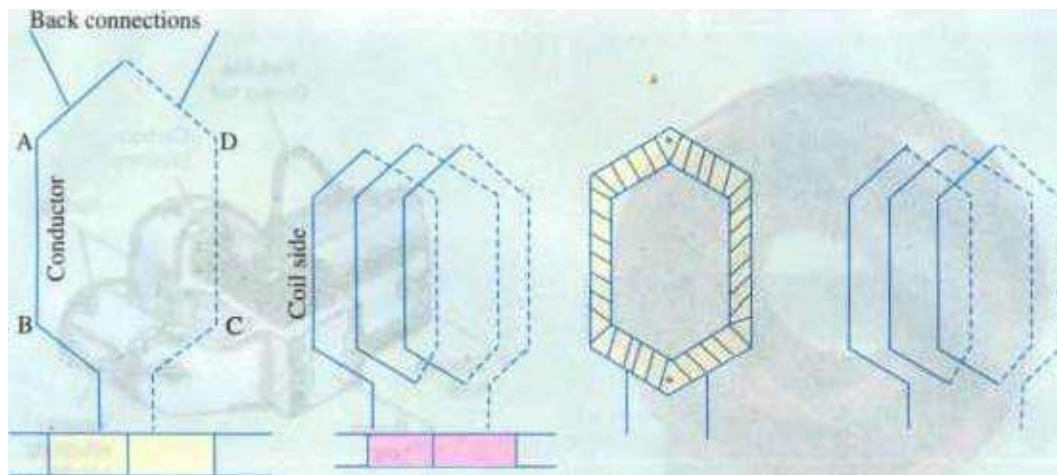
(ii) It is equal to the number Of armature

•conductors and 4 poles, the pole pitch is $48/4 = 12$.

26.13. Conductor

The length Of a Wire lying in the magnetic field and in which an e.m.f. is induced, is called a conductor (or inductor) for example, length AB or CD in Fig. 26.21.

With reference to Fig. 26.21 , the two conductors AB and CD along With their end connections constitute one coil Of the armature winding. The coil may be single-turn coil (Fig. 26.21) or multi-turn coil (Fig. 26.22). A single-turn coil will have two conductors. But a multi-turn coil may have many conductors per coil side, In Fig. 26.22, for example. each coil side has 3 conductors, The



Commutator

Commutator

Fig. 26.21

Fig. 26.22

Fig. 26.23

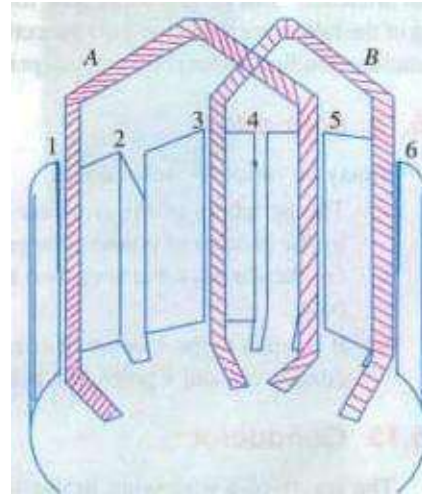
group of wires or conductors constituting a coil side of a multi-turn coil is wrapped with a tape as a unit (Fig. 26.23) and is placed in the armature slot. It may be noted that since the beginning and the end Of each coil must be connected to a commutator bar, there are as many commutator bars as coils for both the lap and wave windings (see Example 26.1).

The side of a coil (1-turn or multi-turn) is called a winding element. Obviously, the number of winding elements is twice the number of coils.

26.15. Coil-span or Coil-pitch CYs)

It is the distance, measured in terms of armature slots for armature conductors) between two sides of a coil. It is, in fact, the periphery of the armature spanned by the two sides of the coil.

If the pole span or coil pitch is equal to the pole pitch (as in the case of coil A in Fig. 26.24 where polepitch of 4 has been assumed). then winding is called full-pitched. It means that coil span is ISO electrical degrees. In this case. the coil sides lie under opposite poles, hence the induced e.m.fs. in them are additive. Therefore, maximum e.m.f. is induced in the coil as a Whole. it being the sum Of the e.m.f.s induced in the two coil sides. For example. if there are 36 slots and 4 poles. then coil span is $36/4 = 9$ slots. If number of slots is 35, then $Y_s = 35/4 = 8$ because it is customary to drop



If the coil span is less than the pitch (as in Coil Fig. 26.24

B where coil pitch is $\frac{1}{4}$ th of the pole pitch), then the

winding is fractional-pitched. In this case, there is a phase difference sides of the

Hence, the total e.m.f. round the coil Which is the vector sum of e.m.fs. in the two coil sides, is less in this case as compared to that in the first case.

26.16. Pitch of a Winding (Y)

In general, it may be defined as the distance round the armature between two successive conductors which directly connected together. Or, it is the distance between the beginnings Of two consecutive turns.

$-Y_F$ —for lap winding

$+Y_F$ —, for wave winding

In practice. coil-pitches as low as eight-tenths of a pole pitch are employed without much serious reduction in the e.m.f. Fractional-pitched windings are purposely used to effect substantial saving in the copper Of the end connections and for improving commutation.

26.17. Back Pitch

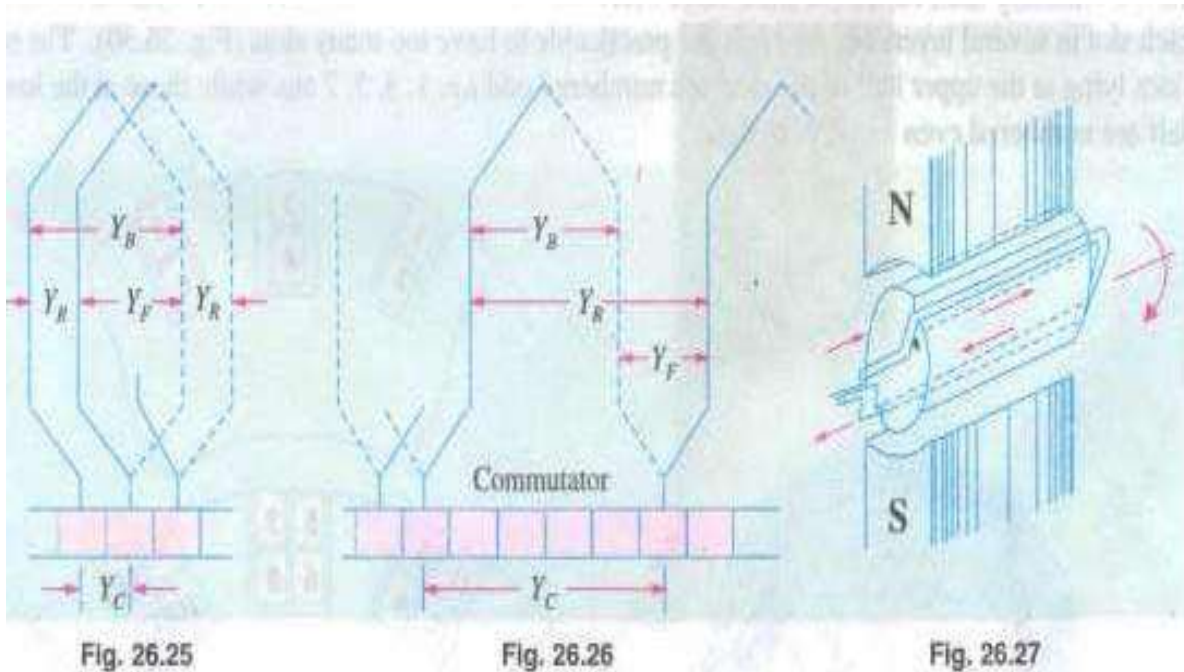
The distance, measured in terms of the armature conductors, which a coil advances on the back of the armature is called back pitch and is denoted by Y_R

As seen from fig_26_28, element 1 is connected on the back of the armature to element 8. Hence, $Y_B = (8 - 1) = 7$.

26.18. Front Pitch (Y_F)

The number of armature conductors or elements spanned by a coil on the front (or commutator end of an armature) is called the front pitch and is designated by Y_F . Again in Fig. 26.28, element 8 is connected to element 3 on the front of the armature, the connections made at the commutator segment. Hence, $Y_F = 8 - 3 = 5$.

Alternatively, the front pitch may be defined as the distance (in terms of armature conductors) between the second conductor of one coil and the first conductor of the next coil which are connected together at the front i.e. commutator end of the armature. Both front and back pitches for lap and wave-winding are shown in fig. 26.25 and 26_26.



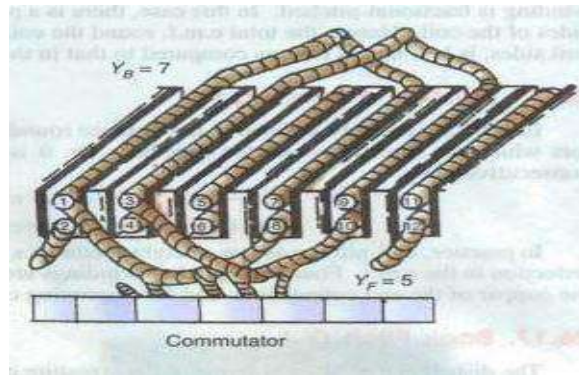
26.19. Resultant Pitch

It is the distance between the beginning of one coil and the beginning of the next coil to which it is connected (Fig. 26.25 and 26.26).

As a matter of precaution, it should be kept in mind that all these pitches, though normally stated in terms of armature conductors, are also sometimes given in terms of armature slots or commutator bars because commutator is, after all, an image of the winding.

26.20. Commutator Pitch

It is the distance (measured in commutator bars or segments) between the segments to which the two ends of a coil are connected. From Fig. 26.25 and 26.26 it is clear that for lap winding, Y_c is the difference of Y_B and Y_F whereas for wave winding it is the sum of Y_B and Y_F . Obviously, commutator pitch is equal to the



number of bars between coil leads. In general, equals the 'plex' of the lap-wound armature. Hence, it is equal 1, 2, 3, 4 etc. for simplex-, duplex, triplex—and quadruplex etc. lap-windings. Fig. 26.28

26-21. Single-layer Winding

It is that winding in which one conductor or one coil side is placed in each armature slot as shown in Fig. 26.27. Such a winding is not much used.

26.22. Two-layer Winding

In this of winding, there are two conductors or coil sides per slot arranged in two layers. Usually, one side of every coil lies in the upper half of one slot and other side lies in the lower half of some other slot at a distance of approximately one pitch away (Fig. 26.28). The transfer of the coil from one slot to another is usually made in a radial plane by means of a peculiar bend or twist at the back end as shown in Fig. 26.29. Such windings in which two coil sides occupy each slot are most commonly used for all medium-sized machines. Sometimes 4 Or 6 or 8 coil sides are used in each slot in several layers because it is not practicable to have too many slots (fig. 26.30). The coil sides lying at the upper half of the slots are numbered odd i.e. 1, 3, 5, 7 etc. while those at the lower

half are numbered even i.e. 2, 4, 6, 8 etc.

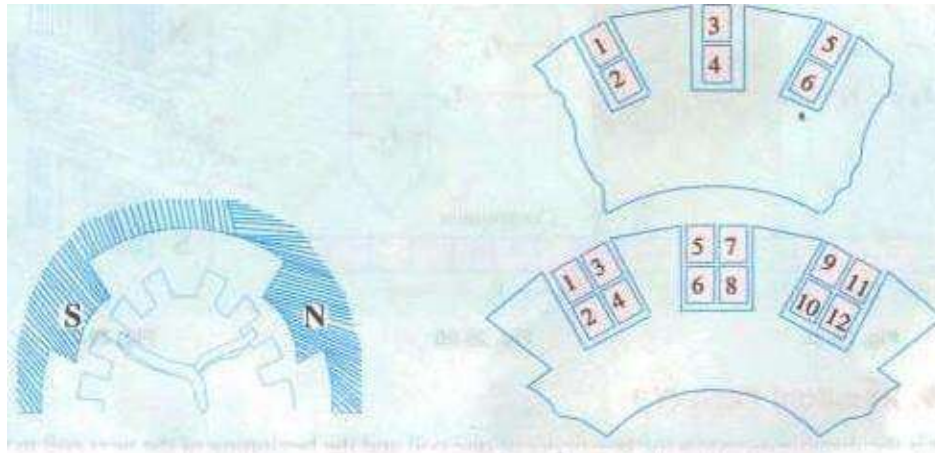


Fig. 26.29

Fig. 26.30

26.23. Degree of Re-entrant Of an Armature Winding

A winding is said to be Single re-entrant if on tracing through it once, all armature conductors are included on returning to the starting point. It is double re-entrant if only half the conductors are included in tracing through the winding once and so on,

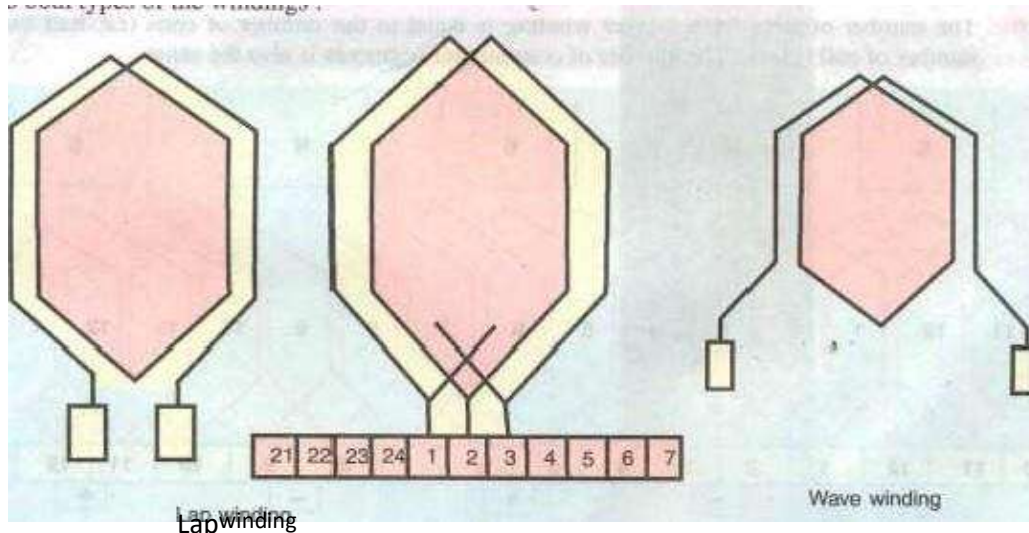
26.24. Multiplex Winding

In such windings, there are several sets of completely closed and independent windings. If there is only one set of closed winding, it is called simplex wave winding. If there are two such windings on the same armature, it is called duplex winding and so on. The multiplicity affects a number of parallel paths in the armature. For a given number of armature slots and coils, as the multiplicity increases, the number of parallel paths in the armature increases thereby increasing the current rating but decreasing the voltage rating.



26.25. Lap and Wave Windings

Two types of windings mostly employed for drum-type armatures are known as Lap Winding and Wave Winding. The difference between the two is merely due to the different arrangement of the end connections at the front or commutator end of armature.



Each winding can be arranged progressively or retrogressively and connected in simplex, duplex and triplex. The following rules, however, apply to both types of the windings :

(i) The front pitch and back pitch are each approximately equal to the pole-pitch i.e. windings should be full-pitched. This results in increased e.m.f, round the coils. For pur-

poses. fractional-pitched windings are deliberately used (Art_ 26.15).

(in Both pitches should be odd, otherwise it would be difficult to place the coils (which are former-wound) properly on the armature. Forexmaple, if YB and YF were both even, the all the coil Sides and conductors would lie either in the upper half Of the slots Or in the lower half. Hence. it would become impossiblefor one Aidèxsftthe coil in the upper half. Hence. it would become impossible One side of the coil to lie in the upper half of one slot and the other side of the same coil to lie in the lower half of other slot.

riii', The of commutator segmentsis equal to the number of slots or coils (or half the number Of conductors) because the front endsÃ'f conductors are joined to the segments in

The winding mustclose uponitselfi.e. if we start frotnû given point and move from onecoil] to•another, then all conductors should he traversed and we should reach the same poinragain Without a break or discontinuity io between.

26.26. Simplex Lap-winding*

It is shown in fig: 26-25 which employs single-turn coils. In lapwinding, the finishing end of one coil is connected to a commutator segment and to the starting end of the adjacent coil situated under the same pole and so on, till all the coils have been connected. This type of winding derives its name from the fact it doubles or laps back with its succeeding coils.

Following points regarding simplex lap winding should be

1. The back and front pitches are odd and of opposite sign. But they cannot differ by 2 or some multiple thereof.

2. Both should be nearly equal to a pole pitch.

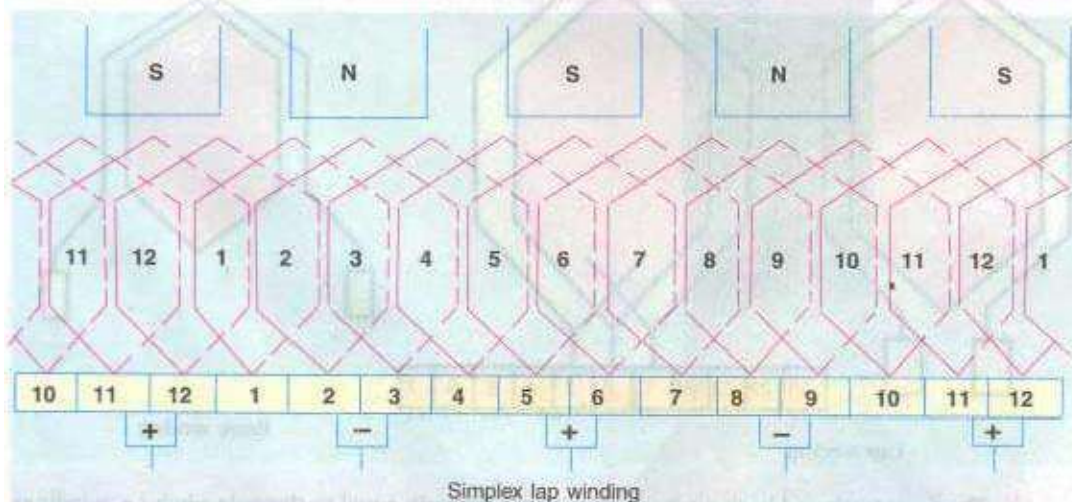
3. The average pitch $Y_A = \frac{Z}{2P}$. It equals pole pitch $= \frac{Z}{2P}$.

4. $\text{pitch} = \pm 1$ (In general, $= \pm m$)

5. Resultant pitch Y_R is even, being the arithmetical difference of two odd numbers, i.e.,

6. The number of slots for a 2-layer winding is equal to the number of coils (i.e. half the

number of coil sides). The number of commutator segments is also the same.



* However, where heavy currents are necessary, duplex or triplex lap windings are used. The duplex lap winding is obtained by placing two similar windings on the same armature and connecting the even-numbered commutator bars to one winding and the odd-numbered bars to the second winding. Similarly,

in triplex winding, there would be three windings, each connected to one-third of the commutator bars,

7. The number of parallel paths in the armature where m is the multiplicity of the winding and P the number of poles.

Taking the first condition, we have $Y_0 = Y_F \pm 2$.

(a) If $Y_B > Y_F$ i.e. $= Y_F + 2$, then we get a progressive or right-handed winding i.e. a winding which progresses in the clockwise direction as seen from the commutator end. In this case, obviously,

$$Y_C = +1$$

(b) If $Y_B < Y_F$ i.e. $= Y_F - 2$, then we get a left-handed winding i.e. one which advances in the anti-clockwise direction when seen from the commutator side. In this case, $Y_C = -1$.

(c) Hence, it is obvious that

$$\left. \begin{aligned} Y_F &= \frac{Z}{P} - 1 \\ Y_B &= \frac{Z}{P} + 1 \end{aligned} \right\} \text{for progressive winding} \quad \left. \begin{aligned} Y_F &= \frac{Z}{P} + 1 \\ Y_B &= \frac{Z}{P} - 1 \end{aligned} \right\} \text{for retrogressive winding}$$

Obviously, Y must be even to make the winding possible.

26.27. Numbering Of Coils and Commutator Segments

In the d.c. winding diagrams to follow, we will number the coils only (not individual turns). The upper side of the coil will be shown by a firm continuous line whereas the lower side will be shown by a broken line. The numbering of coil sides will be consecutive i.e. 1, 2, 3 etc. and such that odd numbers are assigned to the top conductors and even numbers to the lower sides for a two-layer winding. The commutator segments will also be numbered consecutively, the number of the segments will be the same as that of the upper side connected to it.

Example 26.1. Draw a developed diagram of a simple 2-layer lap-winding for 4-pole generator with 16 coils. Hence, point out the characteristics of a lap-winding.

(Elect. Engineering, Madras Univ. 1981)

Solution. The number of commutator segments = 16

Number of conductors or coil sides $16 \times 2 = 32$; pole pitch $32/4 = 8$

Now remembering that (i) Y_B and Y_F have to be odd and (ii) they have to differ by 2, we get for a progressive winding $Y_B = 9$; $Y_F = 7$ (retrogressive winding will result if $Y_B = 7$ and $Y_F = 9$). Obviously, commutator pitch $Y_C = +1$.

(Otherwise, as shown in An. 26.26, for progressive winding

$$Y_F = \frac{Z}{P} - 1 = \frac{32}{4} - 1 = 7 \text{ and } Y_B = \frac{Z}{P} - 1 = \frac{32}{4} + 1 = 9]$$

The Simple winding table is given as under:

Beck Connections	Front Connections
1 to (1 + 9) = 10	10 to (10 - 7) = 3
3 to (3 + 9) = 12	12 to (12 - 7) = 5
5 to (5 + 9) = 14	14 to (14 - 7) = 7
7 to (7 + 9) = 16	16 to (16 - 7) = 9
9 to (9 + 9) = 18	18 to (18 - 7) = 11
11 to (11 + 9) = 20	20 to (20 - 7) = 13
13 to (13 + 9) = 22	22 to (22 - 7) = 15
15 to (15 + 9) = 24	24 to (24 - 7) = 17
17 to (17 + 9) = 26	26 to (26 - 7) = 19
19 to (19 + 9) = 28	28 to (28 - 7) = 21

•• In general, $Y_B = Y_F \pm 2m$ where $m = 1$ for simplex lap winding and $m = 2$ for duplex lap winding etc.

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21 to (21 + 9) = 30	30 to (30 - 7) = 23
23 to (23 + 9) = 32	32 to (32 - 7) = 25
25 to (25 + 9) = 34 = (34 - 32) = 2	2 to (34 - 7) = 27
27 to (27 + 9) = 36 = (36 - 32) = 4	4 to (36 - 7) = 29
29 to (29 + 9) = 38 = (38 - 32) = 6	6 to (38 - 7) = 31
31 to (31 + 9) = 40 = (40 - 32) = 8	8 to (40 - 7) = 33 = (33 - 32) = 1

The winding ends here because we come back to the conductor from where we started.

We will now discuss the developed diagram which is one that is obtained by imagining the armature surface to be removed and then laid out flat so that the slots and conductors can be viewed without the necessity of turning round the armature in order to trace out the armature windings. Such a diagram is shown in Fig. 26.31.

Front end of the upper side of coil No. 1 is connected to a commutator segment (whose number is also 1). The backend is joined at the back to the 1 + 10th coil side in the lower half of 5th slot. The front end of coil side 10 is joined to commutator segment 2 to which is connected the front end of 10 - 7 = 3 i.e. 3rd coil side lying in the upper half of second armature slot. In this way, by travelling 9 coil sides to the right at the back and 7 to the left at the

front we complete the winding, thus including every coil side once till we reach the coil side 1 from where we started. Incidentally, it should be noted that all upper coil sides have been given odd numbers, whereas lower ones have been given even numbers as shown in the polar diagram (Fig. 26.32) Of the Winding of Fig. 26.31.

Brush positions can be located by finding the direction of currents flowing in the various conductors. If currents in the conductors under the influence of a N-pole are assumed to flow downwards (as shown), then these will now upwards in conductors under the influence of S-pole. By putting proper arrows on the conductors (shown separately in the equivalent ring diagram), it is found that commutator bars NO. 1 and 9 are the meeting points of c.m.fs. and hence currents are flowing out of these conductors. The positive brushes should, therefore, be placed at these commutator bars. Similarly, commutator bars No. 5 and 13 are the separating points of e.m.fs. hence negative brushes are placed there. In all, there are four brushes, two positive and two negative. If brushes of the same polarity are connected together, then all the armature conductors are divided into four parallel paths.

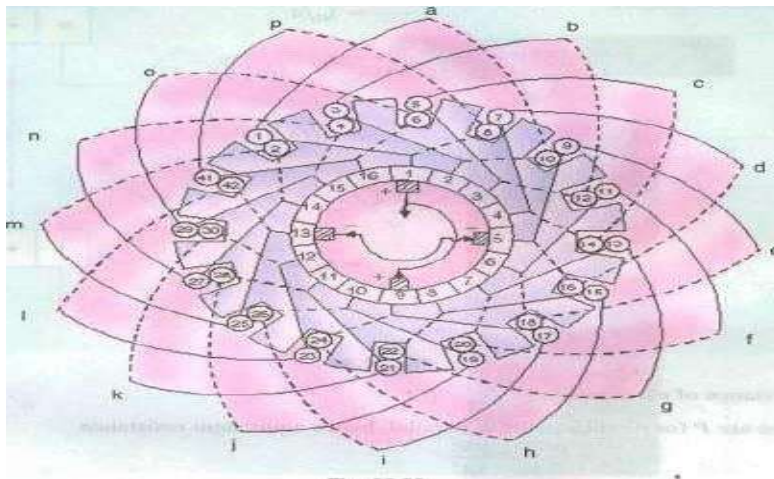


Fig. 26.33

Division of conductors into parallel paths is shown separately in the schematic diagram of Fig.

26.34. Obviously, if I is the total current supplied by the generator, then current carried by each parallel path is

Summarizing these conclusions, we have

1. The total number of brushes is equal to the number of poles.
2. There are as many parallel paths in the armature as the number of poles. That is why such a winding is sometimes called 'multiple circuit' or 'parallel' winding. In general, number of parallel paths in armature m_p where m is the multiplicity (plex) of the lap winding. For example, a duplex lap winding has $(6 \times 2) = 12$ parallel paths in its armature.
3. The e.m.f. between the +ve and -ve brushes is equal to the e.m.f. generated in any one of the parallel paths. If Z is the total number of armature conductors

and p the number of poles, then the number of armature conductors (connected in series) in any parallel path is Z/p

Resistance of each path— $\frac{R}{p}$

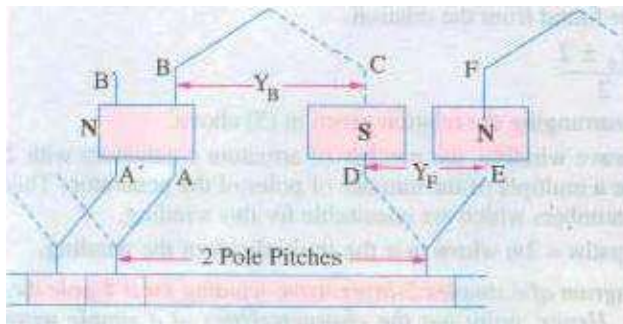
There are P (or A) such paths in parallel, hence equivalent resistance

If I_a is the total armature current, then current per parallel path (or carried by each conductor) is I_a/P .

26.28. Simplex Wave Winding•

From fig. 26.31, it is clear that in lap Winding, a Conductor (or coil side) under one pole is connected at the back to a conductor which occupies an almost corresponding position under the next pole of opposite polarity (as conductors 3 and 12). Conductor No. 12 is then connected to conductor No. 5 under the original pole but which is a little removed from the initial conductor No. 3. If, instead of returning to the same At-pole, the conductor No. 12 were taken forward to the next N-pole, it would make no difference so far as the direction and magnitude of the e.m.f. induced in the circuit are concerned

Like lap winding, a wave winding may be duplex, triplex or may have any degree of multiplicity. A simplex wave winding has two paths, a duplex wave winding four paths and a triplex paths etc.



As shown in Fig. 26.35, conductor AB is connected to CD lying under S-pole and then to EF under the next N-pole. In this way, the winding progresses, passing successively under every N-pole and S-pole till it returns to a conductor A'B' lying under the original pole. Because the winding progresses in one direction

round the armature in series of 'waves', it is known as wave Winding.

Fig. 26.35 If, after passing once round the armature, the winding falls in a slot to the left of its starting point A'B' in Fig. 26.35) then the winding is said to be retrogressive. If, however, it falls one slot to the right, then it is progressive.

Assuming a 2-layer winding and supposing that conductor AB lies in the upper half of the slot, then going once round the armature, the Winding ends at Which must be at The upper

half of the slot at the left or right. Counting in terms of conductors, it means that AB and A'B' differ by two conductors (although they differ by one slot).

From the above, following of poles, then or coil sides

$$\begin{aligned} Y_B &= \text{back pitch} \\ Y_F &= \text{front pitch} \end{aligned} \left. \vphantom{\begin{aligned} Y_B &= \text{back pitch} \\ Y_F &= \text{front pitch} \end{aligned}} \right\} \text{nearly equal to pole pitch}$$

$$Y_A = \frac{Y_B + Y_F}{2} = \text{average pitch}; Z =$$

$$Y_A \times P = Z \pm 2 \quad Y_A = \frac{Z \pm 2}{P}$$

is even and $Z = \frac{P}{2} \pm 2$, hence Z must always be even.

we can deduce the relations. If P — No. total No. Of conductors

Since p in another way.

is always even and always be even. Put it

means that must be an even integer.

The plus sign will give a progressive winding and the negative sign a retrogressive winding.

Points to Note :

1. Both pitches Y_B and Y_F are odd and of the same sign.

2. Back and front pitches are nearly equal to the pole pitch and may be equal or differ by 2, in which case, they are respectively one more or one less than the average pitch.

Resultant pitch Y_R

4. Commutator pitch,

Also.

5. The average pitch

It is clear that there is a restriction on

of Z . With $Z = 32$, this winding is impossible for a 4-pole machine (though lap winding is possible). Values of $Z = 30$ or 34 would be perfectly all right.

i.e. NC can be found from the relation, $P Y_A \pm 2$

This relation has been found by rearranging the relation given in (5) above.

7. It is obvious from (5) that for a wave winding, the number of armature conductors with 2 either added or subtracted must be a multiple of the number of poles of the generator. This restriction eliminates many even numbers which are unsuitable for this winding.

5. The number of armature parallel paths = $2m$ where m is the multiplicity of the winding.

Example 26.2. Draw a developed diagram of a simple 1-layer wave-winding for a 4-pole d.c. generator with 30 armature conductors. Hence, point out the characteristics of a simple wave

$$Y_C = Y_A \text{ (in lap winding } Y_C = \pm 1)$$

$$Y_C = \frac{\text{No. of Commutator bars} \pm 1}{\text{No. of pair of poles}}$$

which must be an integer is given by

$$Y_A = \frac{Z \pm 2}{P} = \frac{\frac{Z}{2} \pm 1}{P/2} = \frac{\text{No. of Commutator bars} \pm 1}{\text{No. of pair of poles}}$$

which integer. the value

winding.

(Elect. Engg-I, Nagpur Univ. 1991)

Solution. Here, $Y_A = \frac{30 \pm 2}{4} = 8^* \text{ or } 7$. Taking $Y_A = 7$, we have $Y_B = Y_F = 7$

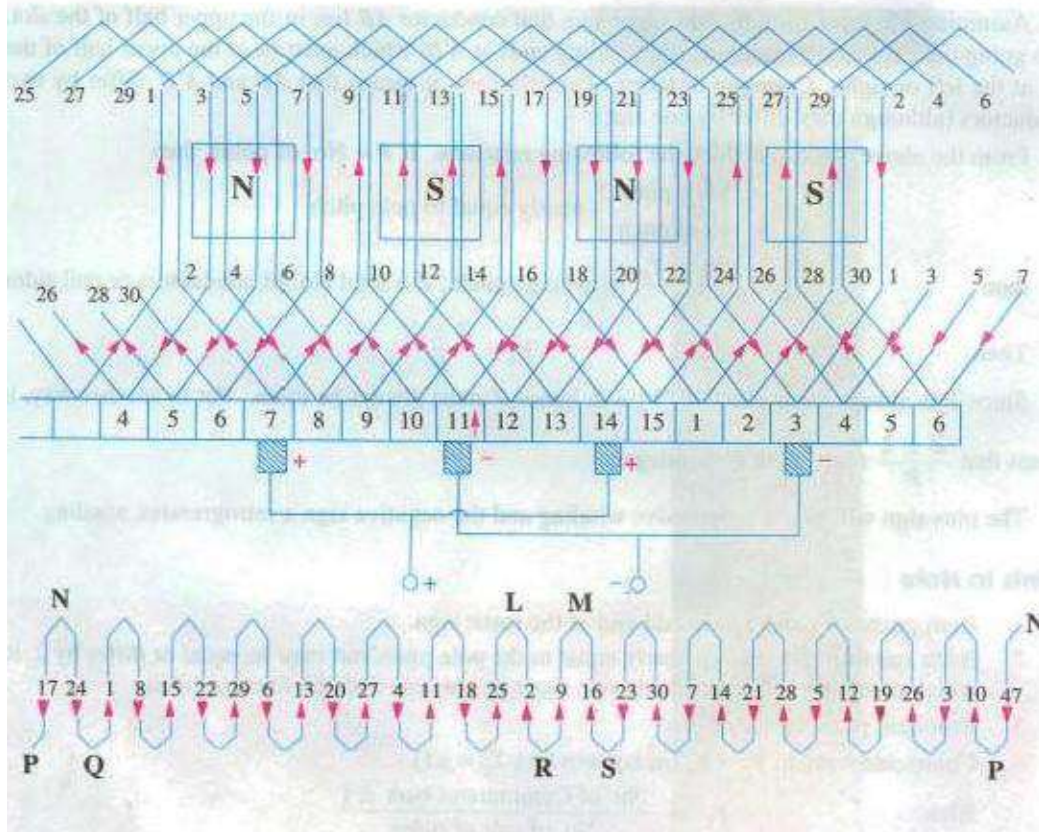


Fig. 26.36

As shown in fig. 26.36 and 26.37, conductor No. 5 is taken to conductor No. 5 4 7 12 at the back and is joined to commutator segment 5 at the front. Next, the conductor No. 12 is joined to commutator segment $5 + 7 = 12$ ($Y_c = 7$) to which is joined conductor No. $12 + 7 = 19$. Continuing this way, we come back NO. 5 from where we started. Hence, the winding closes itself.

If we take S, then the pitches would be : $Y_n 9$ and $Y_F 7$ or $Y_b = 7$ and $Y_F 9$. Incidentally, if $Y_A = Y_c$ is taken as 7, armature will rotate in one direction and if $Y_c = 8$, it will rotate in the opposite direction.

The simple winding table is as under ;

Back Connections	Front Connections
------------------	-------------------

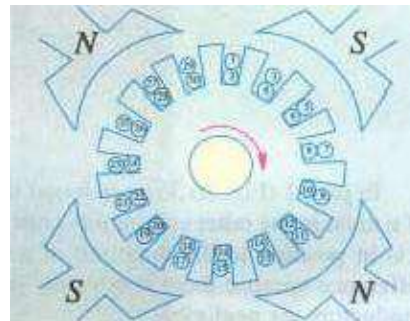
1 to $(1 + 7) = 8$	→	8 to $(8 + 7) = 15$
15 to $(15 + 7) = 22$	→	22 to $(22 + 7) = 29$
29 to $(29 + 7) = 36 = (36 - 30) = 6$	→	6 to $(6 + 7) = 13$
13 to $(13 + 7) = 20$	→	20 to $(20 + 7) = 27$
27 to $(27 + 7) = 34 = (34 - 30) = 4$	→	4 to $(4 + 7) = 11$
11 to $(11 + 7) = 18$	→	18 to $(18 + 7) = 25$
25 to $(25 + 7) = 32 = (32 - 30) = 2$	→	2 to $(2 + 7) = 9$
9 to $(9 + 7) = 16$	→	16 to $(16 + 7) = 23$
23 to $(23 + 7) = 30$	→	30 to $(30 + 7) = 37 = (37 - 30) = 7$
7 to $(7 + 7) = 14$	→	14 to $(14 + 7) = 21$
21 to $(21 + 7) = 28$	→	28 to $(28 + 7) = 35 = (35 - 30) = 5$
5 to $(5 + 7) = 12$	→	12 to $(12 + 7) = 19$
19 to $(19 + 7) = 26$	→	26 to $(26 + 7) = 33 = (33 - 30) = 3$
3 to $(3 + 7) = 10$	→	10 to $(10 + 7) = 17$
17 to $(17 + 7) = 24$	→	24 to $(24 + 7) = 31 = (31 - 30) = 1$

Since we come back to the conductor No. 1 from where we started, the winding gets closed at this

stage.

Brush Position

Location of brush position in wave-winding is slightly difficult. In Fig. 26.36 conductors are supposed to be moving from left to right over the poles. By applying Fleming's Right-hand rule, the directions of the induced e.m.fs in various armature conductors can be found. The directions shown in the figure have been found in this manner. In the lower part of Fig.



26.36 is shown the equivalent ring or spiral diagram which is very helpful in understanding the formation of various parallel paths in the armature. It is seen that the winding is electrically divided into two portions. One portion consists of conductors lying between points N and L and the other of conductors lying

between N and M. In the first portion, the general trend of Fig. 26.37 the induced e.m.fs, is from left to right whereas in the second

portion it is from right to left. Hence, in general, there are only two parallel paths through the winding, so that two brushes are required, one positive and one negative.

From the equivalent ring diagram, it is seen that point N is the separating point of the e.m.fs. induced in the two portions of the winding. Hence, this fixes the position of the negative brush. But as it is at the back and not at the commutator end of the armature, the

negative brush has two alternative positions i. e, either at point P or Q. These points on the equivalent diagram correspond to commutator segments NO. 3 and 11.

Now, we will find the position of the positive brush. It is found that there are two meeting points of the induced e.m.fs. i.e. points L and M but both these points are at the back or non-commutator end of the armature. These two points are separated by one loop only. namely. the loop composed of conductors 2 and 9, hence the middle point R of this loop fixes the position of the positive brush. which should be placed in touch with commutator segment No. 7. We find that for one position Of the brush, there are two alternative positions for the —ve brush.

Taking the -ve brush at point R and negative brush at point p, the winding is seen to be divided into the following two paths.

In path 1 (Fig. 26.36) it is found that e.m.f. in conductor 9 is in opposition to the general trend of e.m.fs. in the other conductors comprising this path. Similarly, in path 2. the e.m.f. in conductor 2 is in opposition to the direction of e.m.fs. in the path as a whole. However, this will make no difference because these conductors lie almost in the interpolar gap and, therefore e.m.fs. in these conductors are negligible.

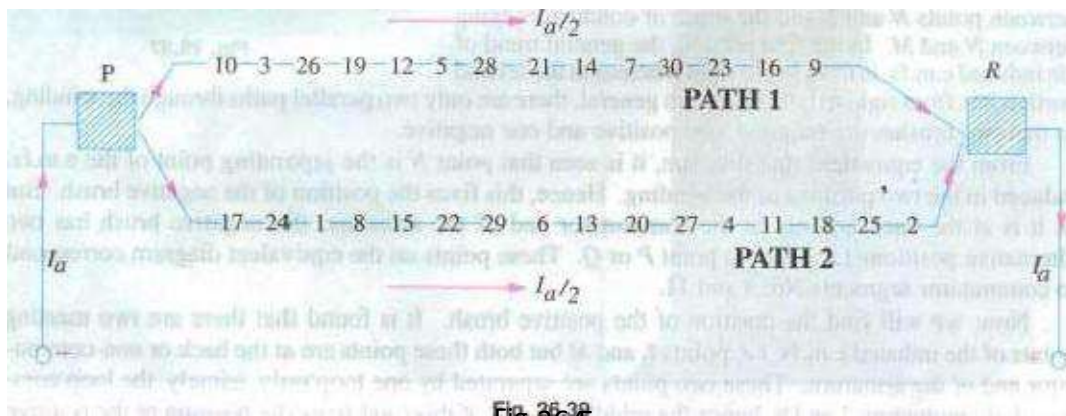


Fig. 26.36

Again, take the case of conductors 2 and 9 situated between points L and M. Since the armature conductors are in continuous motion over the pole faces, their positions as shown in the figure are only instantaneous. Keeping in this mind, it is obvious that conductor 2 is about to move from the influence of S-pole to that of the next N-pole. Hence, the e.m.f. in it is at the point of reversal. However, conductor 9 has already passed the position of reversal, hence its e.m.f. will not reverse. rather it will increase in magnitude gradually. It means that in a very short interval, point M will

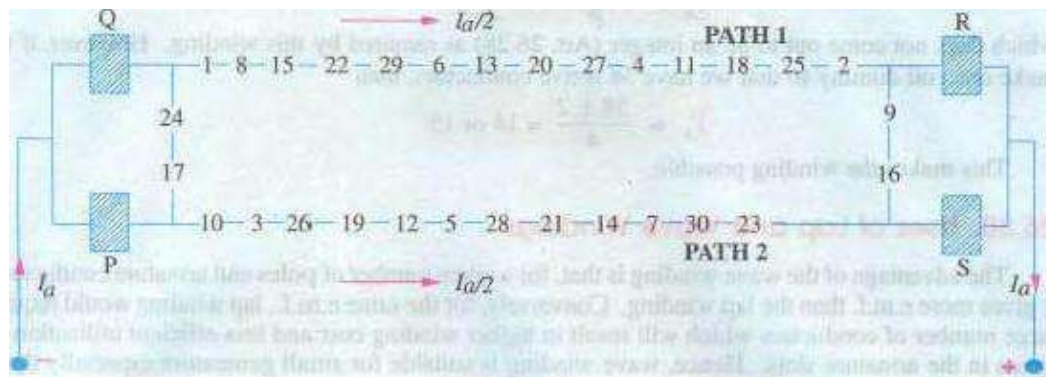


Fig. 26.40

become the meeting point of the c.m._fs. But as it lies at the back Of the armature, there are two alternative positions for the -Eve brush i.e. either point R which has already been considered or point Suhich corresponds to commutator segment 14. This is thesecond alternative position of the positive brush. Arguing in the same way. it can be shown that after another Short interval Of time. the alternative position Of the positive Will shift from segment 14 to segment 15. Therefore, if one positive brush is in the contact With segment 7, then the second positive bnIsh if used, should be in touch with both segments 14 and 15.

It may be noted that if brushes are placed in both alternative positions for both positive and negative (i.e. if in 4 brushes are used, two -eve and two —ve), then the effect is merely to shortcircuit the loop lying between brushes of the same polarity. This is shown in Fig. 26.40 it Will also be noted that irrespective of whether only two or four brushes are used, the number of parallel pallLS through the armature winding is still two.

Summarizing the above facts, we get

1. Only two brushes are necessary. though their number may be equal to the number of poles.
2. The number of paths through the armature winding is two irrespective Of the number of generator poles. That is why this winding is sometimes called 'two-circuit' or 'series'.
3. The generator e.m.f. is equal to the e.m.f. induced in any one of the two parallel paths. If e_{av} is the e.m.f. induced/conductor, then generator e.m.f. is $E \times 2$.
4. The equivalent armature resistance is nearly one-fourth Of the total resistance Of the armature winding,

5. If is the total armature current, then current carried by each path or conductor is obviously $1/2$ whatever the number of poles.



26.29. Dummy or Idle Coils

These are used with wave-winding and are resorted to when the requirements of the winding are not met by the standard armature punchings available in armature- winding shops. These dummy coils do not influence the electrical characteristics Of the winding because they are not connected to the commutator. They are exactly similar to the other coils except that their ends are cut short and taped. They are there simply to provide mechanical balance for the armature because an armature having some slots without windings would be out Of balance mechanically. For example. suppose number Of armature Slots is 15, each containing 4 sides and the number of poles is 4. For a simplex wave-windings, Dummy coils

$$60 \pm 2$$

4 which does not come out to be an integer (Art. 26.28) as required by this winding. However, if we make one coil dummy so that we have 58 active conductors. then

$$58 \pm 2$$

$$= 14 \text{ or } 15 \times 4$$

This makes the winding possible.

26.30. Uses Of Lap and Wave Windings

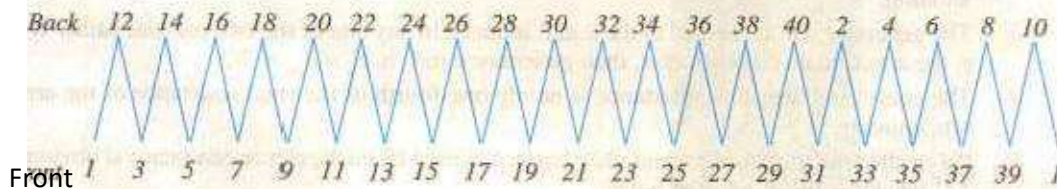
The advantage of the wave winding is that, for a given number of poles and armature conductors, it gives more e.m.f. than the lap winding. Conversely, for the same e.m.f., lap winding would require large number Of conductors which will result in higher winding cost and less efficient utilization of space in the armature slots. Hence, wave winding is suitable for small generators especially those meant for 500-600 V circuits.

Another advantage is that in Wave winding. equalizing connections are not necessary whereas in a lap winding they definitely are. It is so because each Of the two paths contains conductors lying under all the poles whereas in lap-wound armatures, each of the P parallel paths contains conductors which lie under one pair of poles. Any inequality of pole fluxes affects two paths equally, hence their induced e.m.fs. are equal. In lap-wound armatures, unequal voltages are produced which set up a circulating current that produces sparking at brushes.

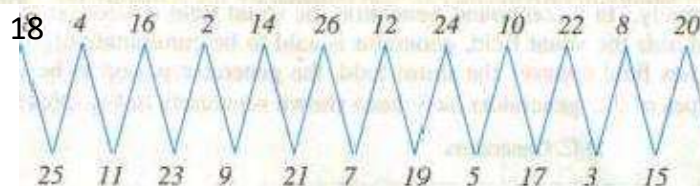
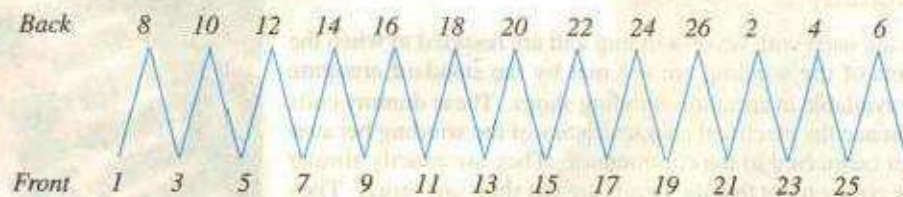
However, when large currents are required, it is necessary to use lap winding, because it gives more parallel paths.

Hence, lap winding is suitable for comparatively low-voltage but high-current generators whereas wave-winding is used for high-voltage, low-current machines.

1. Write down the winding table for a 2-layer simplex lap-winding for a 4-pole d.c. generator having 20 slots and 13 slots. What are the back and front pitches as measured in terms of armature conductors? [Hint : (a) No. of conductors = 40 ; $Y_B = 11$ and $Y_F = -9$] (Elect. Engineering, Madras Univ. 1978)



(b) No. of conductors = 26 ; $Y_B = 7$; $Y_F = -5$



Tutorial Problem No. 26.1 simplex wave winding for a 4-pole d.c. machine with 28 conductors? Explain

2. With a simplex 2-layer Wave winding having 26 conductors and 4-poles. write down the Winding table. What will be the front and back pitches of the winding? [Hint : $Y_F = 7$ and $Y_B = 5$]

(Electric Machinery-I, Madras Univ. Nov. 1979)

segments

26.31. Types of Generators

Generators are usually classified according to the way in which their fields are excited. Generators may be divided into separately-excited generators and self-excited generators.

(a) Separately-excited generators are those whose field magnets are energised from an independent external source Of d.c. current. It is shown diagrammatically in fig. 26.41.

- (b) Self-excited generators are those whose field magnets are energised by the current produced by the generators themselves. Due to residual magnetism, there is always present some flux in the. When the armature is rotated, some and hence some induced current is produced which is partly or fully passed through the field coils thereby strengthening the residual pole flux,

There are three types of self-excited generators named according to the manner in which their field coils (or windings) are connected to the armature. i) Shunt wound

The field windings are connected across or in parallel with the armature conductors

Example 26.9. An 8-pole dc. generator has 50 armature conductors, and a useful flux of 0.05 Wb per pole. What will be the e.m.f. generated if it is lap-connected and runs at 4200 rpm? What must be the speed at which it is to be driven to produce the same e.m.f. if it is Wave-wound?

[U.P. Technical Univ. 2001]

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Solution. With lap-winding, $P = a = 8$

$$\begin{aligned} E &= \phi (N/60) (P/a) \\ &= 0.05 \times 500 \times 20 \times 1/8 \\ &= 500 \text{ volts} \end{aligned}$$

for lap-winding

If it is wave-wound, $P = 8, a = 2, P/a = 4$

and $E = 0.05 \times 500 \times (N/60) \times 4$

For $E = 500$ volts, $N = 300$ rpm

Hence, with wave-winding, it must be driven at 300 rpm to generate 500 volts.

Additional Explanation. Assume 1 amp as the current per conductor.

(a) Lap-wound, 1200 rpm : 500 V per coil-group, 8 groups in parallel

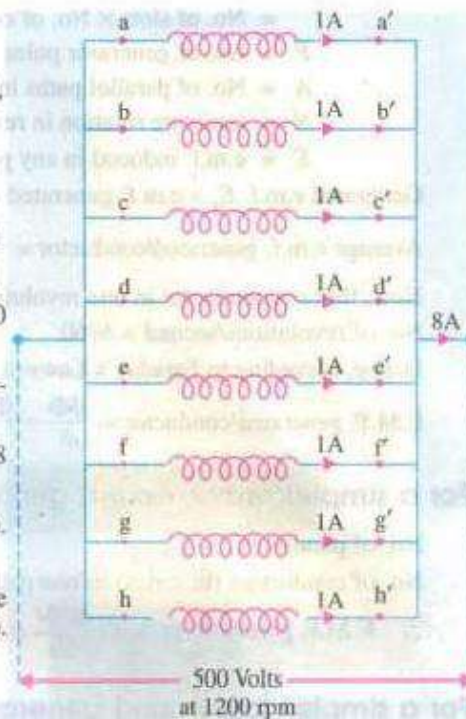
Net output current = 8 amp as in Fig. 26.51 (a).

Power output = 4 kW

(b) Wave-wound, 300 rpm : 2 groups in parallel, one group has four coils in series, as shown in Fig. 26.51 (b).

Total power-output is now

$$500 \times 2 = 1000 \text{ W.}$$



It is reduced to one fourth. being proportional to the

Example 26.26. A long-shunt dynamo, running at 1000 rpm, has a terminal voltage of 220 V. The resistances

of the armature, shunt field, and series field are 0.06 Ω respectively. The overall efficiency at the above load is (a) the friction losses (c) the torque exerted by the prime mover.

(Elect. Machinery-I. Bangalore Univ. 1987)

Solution. The generator is shown in Fig. 26.64.

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

$$1 - 100 \text{ A.}$$

$$= 102 \text{ A}$$

$$220 \text{ v}$$

$$\text{Drop in series field winding} = 102 \times 0.05 = 6.12 \text{ V}$$

$$- 1022 \times 0.05 = 520.2 \text{ W}$$

$$\text{Series field loss} = 0.06 \times 100^2 = 624.3 \text{ W} \quad \text{Shunt field loss} = 110 \times 2 = 220 \text{ W}$$

Example 26.28. A long-shunt compound-wound generator gives 240 volts at EL output of 100 A. The resistances of various windings of the machine are : armature (including brush contact) 0.1Ω series field 0.02Ω interpole field 0.025Ω shunt field (including regulating resistance) 100Ω . The iron loss EL is 1000 W ; windage and friction losses 500 W . Calculate EL efficiency of the machine. (Electrical Machinery-I, Indira Univ. 1989)

$$\text{Total armature circuit resistance} = 0.1 + 0.02 + 0.025 = 0.145 \Omega$$

$$240/100=2.4 \text{ A} \quad 2.4 \times 100 = 240 \text{ A}$$

$$\text{Armature circuit loss} = 240^2 \times 0.145 = 8280 \text{ W}$$

$$\text{Shunt field copper loss} = 2.4 \times 240 = 576 \text{ W}$$

$$\text{Iron loss} = 1000 \text{ W} ; \text{ Friction loss } 500 \text{ W}$$

$$24.000$$

$$\text{Total loss} = 1,521 + 8280 = 9801 \text{ W}$$

$$24.000 \text{ W}$$



DC MOTOR

Motor Principle

An Electric motor is a machine which converts electric energy into mechanical energy. Its action is based on the principle that when a current-carrying conductor is placed in a magnetic field, it experiences a mechanical force whose direction is given by Fleming's Left-hand Rule and whose magnitude is given by Constructionally, there is no basic difference between a d.c. generator and a d.c. motor. In fact, the same d.c. machine can be used interchangeably as a generator or as a motor. D.C. motors are also like generators, shunt-wound or series-wound or compound-wound.

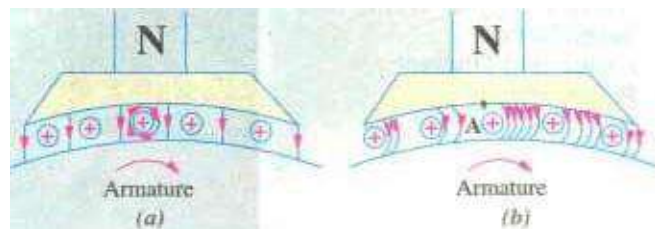
of Motor are supplied with current from the supply mains. they experience a force tending to rotate the armature. Armature conductors under N-pole are assumed carry current downwards (Crosses) and those under S-poles, to carry current upwards (dots). By applying Fleming's Left-hand Rule, the direction of the force on Fig.

each conductor can be found. It is shown by small arrows placed above each conductor. It will be seen that each conductor can be found. It will be seen that each conductor experiences a force F which tends to rotate the armature in anticlockwise direction. These forces collectively produce a driving torque which sets the armature rotating.

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

29.2. Comparison Of Generator and Motor Action

As said above, the same d.c. machine can be used, at least theoretically, interchangeably as a generator or as a motor. When operating as a generator, it is driven by a mechanical machine and it develops voltage which in turn produces a current flow in an electric circuit. When operating as a motor, it is supplied by electric Fig. 29.2 current and it develops torque which in turn produces mechanical rotation.



Let us first consider its operation as a generator and see how exactly and through which agency, mechanical power is converted into electric power.

In Fig. 29.2 part (a) of a generator whose armature is being driven clockwise by its prime mover is shown.

Fig. 29.2 (a) represents the fields set up independently by the main poles and the armature conductors like A in the figure. The resultant field or magnetic lines of flux are shown in Fig. 29.2 (b). It is seen that there is a crowding of lines of flux on the right-hand side of A. These magnetic lines of flux may be likened to the rubber bands under tension. Hence, the bent lines of flux exert a mechanical force on A much in the same way as the bent elastic rubber band of a catapult produces a mechanical force on the stone piece. It will be seen that this force is in a direction opposite to that of armature rotation. Hence, it is known as backward force or magnetic drag on the conductors. It is against this drag action on all armature conductors that the prime mover has to work. The work done in overcoming this opposition is converted into electric energy. Therefore, it should be clearly understood that it is only through the instrumentality of this magnetic drag that energy conversion is possible in a d.c. generator.

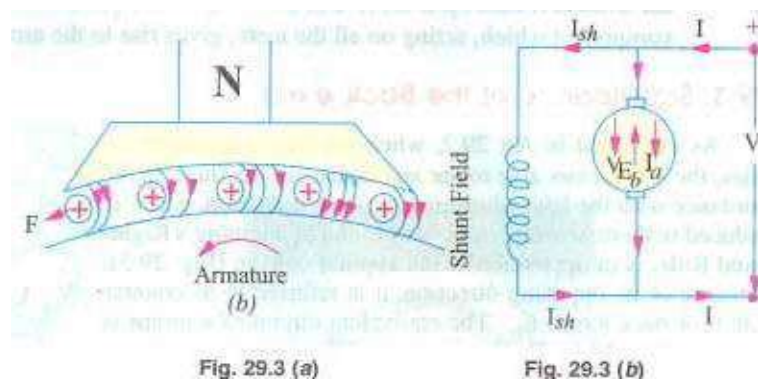
generator.

Next, suppose that the above d.c. machine is uncoupled from its prime mover and that current is sent through the armature conductors under a N.pole in the downward direction as shown in Fig. 29.3. The conductors will again experience a force in the anticlockwise direction ('Fleming's Left hand Rule').

Hence, the machine will

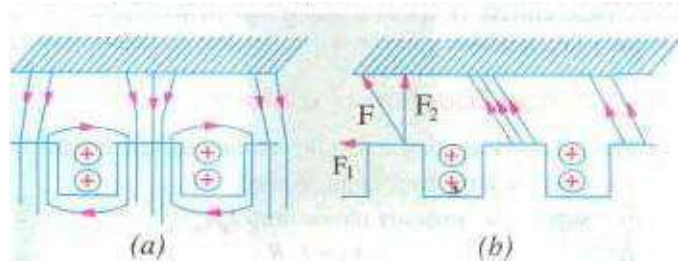
start rotating anticlockwise, thereby developing E_b torque which can produce mechanical rotation. The machine is then said to be motoring.

As said above, energy conversion is not possible unless there is some opposition whose overcoming provides the necessary means for such conversion. In the case of a generator, it was the magnetic drag which provided the necessary opposition. But what is the equivalent of that drag in the case of a motor? Well, it is the back e.m.f. It is explained in this manner:



As soon as the armature starts rotating, dynamically (or motionally) induced e.m.f. is produced in the armature conductors.

The direction of this induced e.m.f. as found by Fleming's Right-hand Rule, is outwards i.e. in direct opposition to the applied voltage (Fig. 29.3). This is why it is known as back e.m.f. or counter. Its value is the same as for the motionally induced e.m.f. in the



generator i.e. $\frac{P}{A}$ volts. The applied voltage V has to force current through the armature conductors against this back e.m.f. E_b . The electric work done in overcoming this opposition is converted into mechanical energy developed in the armature. Therefore, it is obvious that but for the production of this opposing e.m.f. energy conversion would not have been possible.

Now, before leaving this topic, let it be pointed out that in an actual motor with slotted armature, the torque is not due to mechanical force on the conductors themselves, but due to tangential pull on the armature teeth as shown in Fig. 29.4.

It is seen in Fig. 29.4 that the main flux is concentrated in the form of tufts at the armature teeth while the armature is shown by the dotted lines embracing the armature slots. The effect of

- fact, it seems to be one of the fundamental laws of energy conversion from one to another is that it is not possible until there is something to oppose the conversion. But for the presence of this opposition, there would simply be no energy conversion. In generators, opposition is provided by magnetic drag whereas in motors, back e.m.f. does this job. Moreover, it is only that part of the input energy which is used for overcoming this opposition that is converted into the other form.

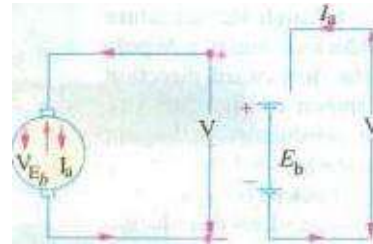
-armature flux on the main flux, as shown in Fig. 29.4 is two-fold,

(i) It increases the flux on the left-hand side of the teeth and decreases it on the right-hand side, thus making the distribution of flux density across the tooth section unequal.

(ii) it inclines the direction of lines of force in the air-gap so that they are not radial but are disposed in a manner shown in Fig. 29.4. The pull exerted by the poles on the teeth can now be resolved into two components. One is the tangential component F_t and the other vertical component F_v . The vertical component F_v , when considered for all the teeth round the armature, sums to zero. But the component F_t is not cancelled and it is this tangential component which, acting on all the teeth, gives rise to the armature torque.

29.3. Significance of the Back e.m.f.

As explained in Art 29.2, When the motor armature rotates, the conductors also rotate and hence cut the flux. In accordance with the laws of electromagnetic induction, e.m.f. is induced in them whose direction, as found by Fleming's Right hand Rule, is in opposition to the applied voltage (Fig. 29.5). Because of its opposing direction, it is referred to as counter e.m.f. or back



e.m.f. E_b . The equivalent circuit of a motor is shown in Fig. 29.6. The rotating armature generating the back e.m.f. E_b is like a battery of e.m.f. E_b put across a supply mains of V volts. Obviously, V has to drive I_a against the opposition of E_b . The power required to overcome this opposition is $E_b I_a$.

In the case of a cell, this power over an interval of time is converted into chemical energy, but in the present case, it is converted into mechanical energy.

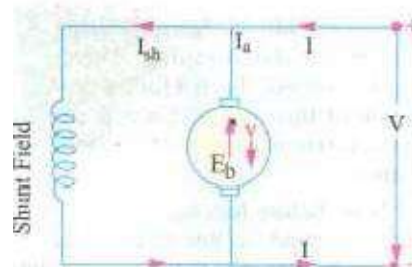
It will be seen that $I_a = \frac{V - E_b}{R_a}$

Resistance R_a

where R_a is the resistance of the armature circuit. As pointed out above, $E_b = \frac{P}{A} \frac{Z}{N}$ volt where N is in r.p.s.

Back e.m.f. E_b depends, among other factors, upon the armature speed. If speed is high, E_b is large, hence armature current seen from the above equation, is small. If the speed is less, then E_b is less, hence more current flows which develops motor (Art 29.7). so, we find that E_b acts like a governor i.e., it makes a motor self-regulating so that it draws as much as is just necessary.

draws as much current as is just necessary,



29.4. Voltage Equation Of a Motor

The voltage V applied across the motor armature has to overcome the back e.m.f. E_b and in supply the armature ohmic drop

This is known as voltage equation of a motor. Now, multiplying both sides by I_a , We get

As shown in Fig. 29.6, Fig.2g.6

$V I_a$ = Electrical input to the armature

$E_b I_a$ = Electrical equivalent Of mechanical power developed in the armature $I_a^2 R_a$ = Cu loss in the armature

Hence, out Of the arunature input, some is wasted in I^2R loss and the rest is converted into me— chanical power within the armature.

Itmay also be noted that motor efficiency is given by the ratio of power developed by the arma-

ture to its input i.e. $E_b I_a = E^*/V$. Obviously, higher the value of E_b compared to V , higher the motor efficiency.

29.5. Condition for Maximum Power

The gross mechanical power developed by a motor is $p_m = I_a (V - I_a R_a)$.

Differentiating both sides with to I_a and equating the result to zero, we get $V - 2I_a R_a = 0$ As

Thus gross mechanical power developed by a motor is maximum When back e.m.f. is equal to half the applied voltage, This condition is, however, not realized in practice, because in that ease current would be much beyond the normal current of the motor. Moreover, half the input would be wasted in the form of heat and taking other losses (mechanical and magnetic) into consideration, the motor efficiency will be well below 50 percent-

Example 29.1. A 220-V dc. machine has an armature resistance Of 0.5 the full-load

armature current is 20 A, find the induced e.m.f, when the machine acts as (i) generator (ii) motor
(Electrical Technology-I, Bombay Univ. 1987)

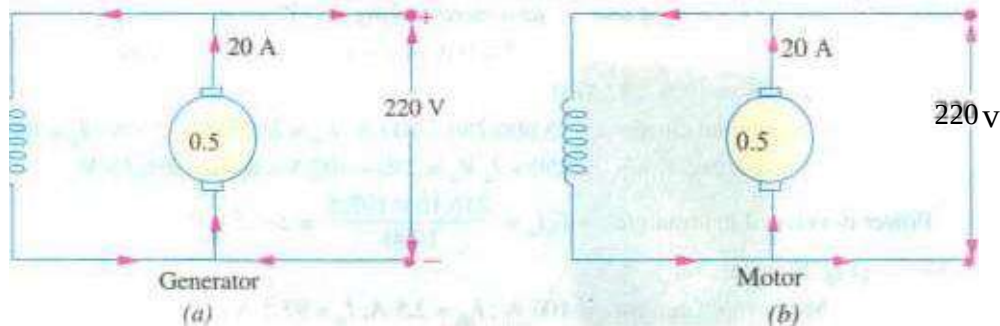


Fig.29.7

Solution. As shown in Fig. 29.7, the machine is assumed to be shunt-connected. In each ease, shunt current is considered negligible because its value is not given.

As Generator [Fig. (a)]

Example 29.2. A separately excited D, C. generaror has armature circuit resistance Of 0.1 Ohm and the brush-drop is 2 V. When running at 1000 r.p.m., it delivers a of 100 A at 250 V to a load of constant resistance If the generator speed drop to 700 cp. m., unaltered, find the current delivered load. AMIE, Electrical Machines, 2001) solution.

At $= 262 \times 700/1000 = 183.4 \text{ V}$ If is the new current. — 2 — $= 2.5$

•This gives 96.77 amp.

Extension to Question : With what loudresistance will the current be amp. at 700 r.p.m. ?

Solution.

Forlo- 100amp.and E 183.4 v, RL- 1.714 ohms.

Example 29.3. A shunt motor has armature resistance Of 0.8 n andfield resistance Of

200 Determine the back e.m.f. When giving an output of 7.46 kW at 85 pert-ent efficiency,

Solution. Motor input $7.46 \times 10^3/0.85 \text{ W}$

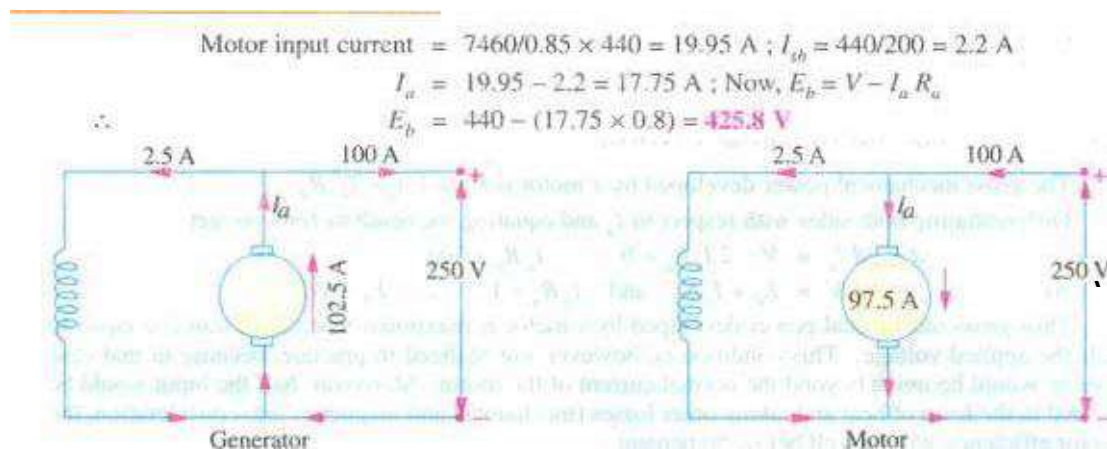


Fig.29.8 (a)

Fig.29.8(b)

Example 29.4. A 25-kW. dc. shunt generator has armature andfield resistances of 0.06 Q and 100 respectively Determine the total armature power dewloped when working (i) as a generator delivering 25 kW output and t ii) as a motor faking 25 kW input.

' Electrical •lèchnoloo, Punjab Univ,, June 1991

Solution. As Generator (Fig. 29.8 (a)/

output current $= 25,000/250 = 100 \text{ A}$ $I_{sh} = 250/100 = 2.5 \text{ A}$; $I_a = 102.5 \text{ A}$

Generated emm $= 250 + I_a R_a = 250 + 102.5 \times 0.06 = 256.15 \text{ V}$

256.15×102.5

Power developed in armature

As Motor (Fig

Motor input current

244.15 v

Power in armature = kW

Example shunt generator With terminal voltage of 200 volts delivering 12 amps the load 200 ohms. is driven at 1000 Calculate the flux per pole in the machine. If the machine has to be run as a motor With the same terminal voltage and drawing 5 amps from the mains, maintaining the same magnetic field, find the speed of the machine, [Sambalpur University. 19981

Soluti"n. Current distributions during two actions are indicated in Fig. 29.9 (a) and As a



generator, 13 amp

12 amp 5 amp

Supply

(a) Generator-action (b) Motor-action

Fig. 2"

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

$$\phi \frac{Z N}{60} \times \frac{P}{a} = 226 \text{ a}$$

For a Lap-wound

$$P = a$$

armature,

0.42375 wb

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

As a motor,

$$I_a = 4 \text{ amp}$$

Giving N

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

0.42375 32

$$N = \frac{60 \times 192}{0.42375 \times 32}$$

=850 r.p.m.

Tutorial Problems 29.1

1. What do you understand by the term 'back e.m.f.'? A d.c. supply has an armature resistance of 0.15Ω . Calculate

(a) The back e.m.f. when the armature current is 120 A.

The value of armature current when the back e.m.f. is 441.4 V.

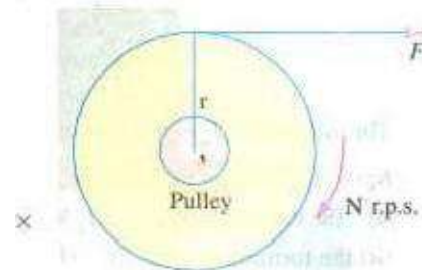
2. A d.c. motor connected to 460-V supply takes an armature current of 120 A on full load. If the circuit has a resistance of 0.25Ω , calculate the value of the back e.m.f. at this load.
3. A 4-pole d.c. motor takes an armature current of 150 A at 440 V. If its armature circuit has a resistance of 0.15Ω , what will the value of back e.m.f. at this load? 441.75 V

29.6. Torque

By the term torque is meant the turning or twisting moment of a force about an axis. It is measured by the product of the force and the radius at which this force acts.

Consider a pulley of radius r metre acted upon by a circumferential force of F Newton which causes it to rotate at N r.p.m. (Fig. 29.10).

Circumferential force of F Newton which



Then torque = $F \times r$ Newton-metre (N-m)

Work done by this force in one revolution

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

Now let ω be angular velocity in radian/second and F

—Torque

Power developed = $T \times \omega$ (Watt or P T Watt if N is in r.p.m.) then Fig. 29.10

Moreover, $\omega = \frac{2\pi N}{60}$ rad/s

Let T be

= $\frac{P}{\omega}$ or $P = T \times \omega$

29.7. Armature Torque Of a Motor

Let T_a be the torque developed by the armature of a motor running at N r.p.m. If T_a is in N-m, then power developed $T_a \times N$ watt

We also know that electrical power converted into mechanical power in the armature Alt 29.4) — $E_b I_a$ Watt

In the case of a series motor,

Windings carry full armature Current

(b) For shunt motors, Φ is practically constant, hence $T_a \propto I_a$
As seen from (iii) above

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

If N is in r.p.m., then

$$T_a = \frac{E_b I_a}{2\pi N/60} = 60 \frac{E_b I_a}{2\pi N} = \frac{60}{2\pi} \frac{E_b I_a}{N} = 9.55 \frac{E_b I_a}{N} \text{ N-m}$$

29.8. Shaft Torque

The whole of the armature torque, as calculated is not available for doing useful work. because a certain percentage of it is required for supplying iron and friction losses in the motor.

The torque Which is available for doing useful work is known as Shaft torque It is so called because it is available at the shaft_ The motor output is given by Output $\times 2\pi V$ Watt provided T_{sh} is in N-m and N in r.p.s.

Output in watts $T_{sh} = \frac{\text{Output in watts}}{2\pi N} \text{ N-m-N in r.p.s.}$

The difference and is due to motor. $= \frac{\text{Output in watts}}{2\pi N/60} \text{ N-m-N in r.p.m.}$ $(T_a - T_{sh})$ is known as lost torque iron and friction losses of the

$$= \frac{60}{2\pi} \frac{\text{output}}{N} = 9.55 \frac{\text{Output}}{N} \text{ N-m.}$$

Note. The value of back e.m.f. E_b can be found from the equation, $E_b = V - I_a R_a$

(iii the formula $E_b = Z \cdot V \times (P/A)$ volt

Example 29.6. A dc. motor takes an armature current I_a of 480 A! The armature circuit resistance is 0.2 Ω The machine has 6 poles and the armature is lap-connected with 864 conductors. The flu per pole is 0.05 Wb. Calculate the speed and the gross torque developed by the

armature. (Elect. Machines, A.M.I.E. Sec B. 1989)

Solution. $E_b = 480 - 480 \times 0.2 = 458V$,

$$0.05 \times 864 \times N/60$$

60

$$N = 636 \text{ r.p.m.}$$

$$T = 0.159 \times 0.05$$

Example 29.7. A 250 V, 4-pole, wave-wound Series motor has 782 conductors on its armature. It has armature and series field resistance of 0.75 Ohm. The motor takes a current of 15 A. Estimate its speed and gross torque developed if it has a flux per pole of 25 m Wb.

(Elect. Engg. II, Pune Univ. 1991)

Solution.

Example 29.8. A dc. Shunt motor. Find torque mechanical power developed for an armature current of 50 A. State the simplifying assumptions. (Basic Elect. Machine Nagpur Univ. 1993) Solution. A given d.c. machine develops the same e.m.f. in its armature conductors whether running as a generator or as a motor, Only difference is that this armature e.m.f. is known as back

e.m.f. When the machine is running as a motor.

$$\text{Mechanical power developed in the arm} \quad 50 \times 12.5 = 12.500 \text{ W}$$

$$T = 9.55 \quad 9.55 \times 250 \quad 79.0 \text{ N-m.}$$

Example 29.9. Determine speed and shaft torque of 220-V, 4-pole series motor with 800 conductors wave-connected supplying load of 82 kW by taking 45 A from the mains. The flux per pole is 25 m Wb and its armature circuit resistance is 0.6 Ohm.

(Elect. Machine AMIE sec. B Winter 1991)

$$I_a = 220/500 = 200/210$$

Example 29.11. 500-V, 37.3 kW, 1000 r.p.m. d.c. shunt motor has an efficiency of 90%. The armature circuit resistance 0.24 Ohm and there is a voltage drop of 2 V at the brushes. The field current is 1.8 A. Determine (i) full-load line current/ (in full load shaft torque in N-m and resistance in motor starter to limit the starting current to 1.5 times the full-load current. (Elect. Engg. I; M.S. Univ. Baroda 1987)

$$\begin{aligned} \text{Solution.} \quad \text{Motor input } W &= 37.300/0.9 = 41,444 \\ &= 41,444/500 = 82.9 \text{ A} \end{aligned}$$

$$F.L. \text{ line current} = 41.444/500 \text{ (W)}$$

$$= 356 \text{ N-m}$$

If R is the Starter resistance (which is in series with armature), then

Example 29.12. A 4-pole, 220-V shunt motor has 540 lap-wound conductors. It takes 32 A from the supply and develops output power of 5.595 kW. The field winding takes 1 A. The resistance is 0.09 Ohm and the flux per pole is 30 m Wb. Calculate the speed and the torque developed in newton-metre. (Electrical Nagpur Univ. 1992)

$$\text{Solution.} \quad I_a = 31 \text{ A} \quad V$$

,pZN P

Now. 217.2 =

60 A 60 N = 804.4 r.p.m.

T. $9.55 \times \text{output in watts} = 9.55 \times 595 = 66.5 \text{ N-m}$

804.4

Example 29.13 Find the lead and full-load speeds for a four-pole, 220-V. and 20-kW. shunt motor having the following data :

Field—current = 5 amp, armature resistance = Ohm.

Flux per pole 0.04 Wb. number of armature-conductors = 160, lap wave-connection, full load current = 95 amp. No load current 29 A. Neglect armature reaction.

(Bharathidasan Univ. April 1997)

Solution. The machine draws a supply current of 9 amp at no load. Out of this, 5 amps are required for the field hence the armature carries a no-load current of 4 amp.

At load, armature-current is 90 amp. The armature-resistance-drop increases and the back e.m.f. decreases. resulting into decrease in speed under load compared to that at No-Load. :
 $E_b = 220 - 90 \times 0.04 = 182.4 \text{ volts}$

Substituting this.

$182.4 \times 160 \times$

No-Load speed. No — 1030.5 r.p.m.

Armature current A, $E_a = 220 - 90 \times 0.04 = 182.4 \text{ V}$ $(182.4/219.84) \times 1030.5 = 864.4 \text{ rpm}$.

Example 29.13 A 6-pole. 6-circuit D.C. shunt motor takes 29 A at a speed of 350 r.p.m. The flux per pole is 80 milli-webers. the number of armature turns is 600. and of the torque is lost in windage. friction and iron-loss. Calculate the brake-horse-power.

(Manonmaniam Sundaranar Univ. NOV. 1998)

Solution. Number of armature turns = 600

Therefore, Z = Number of armature conductors = 1200 If electromagnetic torque developed is $T \text{ N-m}$.

Armature 'X'Watt T $T \times 2 \text{ 't}$

= T Watts

To calculate armature power in terms of Electrical parameters, E must be known.

$$- SOX \quad x$$

— 560 volts

With the armature current Of 400 Armature power = 560* 400 watts Equating the two,

$T = 560 \times \frac{100}{36.67} = 6108.5 \text{ Nw-m}$, Since 3 % of this torque is required for overcoming different loss-terms,

$$\text{Net torque} = 0.97 \times 6180.5 = 5925 \text{ Nw-m}$$

For Brake-Horse-power, net output in kW should be computed first. Then "kW" is to be converted to "BHP". with 1 HP = 0.746 kw,

$$\text{Net output in kW} = 5925 \times 36.67 \times 10^{-3} = 217.27 \text{ kW}$$

Converting this to BHP- the Output = 291.25 HP

Example 29.13 Determine the torque established by the armature Of a four-pole D.C motor having 774 conductors, two pa/hs in parallel, 24 milli-webers of pole-flux and the armature current is 50 Amps. (Bharathiar Univ. April 1998)

Solution. Expression for torque in terms Of the parameters concerned in this problem is as follows :

$T = 0.159 Z L_p / a \text{ Nw-m}$ Two paths in parallel for a 4-pole case means a wave winding.

$$T = 0.159 \times (24 \times 774 \times 50 \times 4 / 2)$$

$$= 29536 \text{ Nw-m}$$

Example 29.13 A 500-V D.C shunt motor draws a line-current of 5 A on tight-load. If armature resistance is 0.15 ohm and field resistance is 200 ohms, determine the efficiency of the machine running as a generator delivering load current Of 40 Amps.

(Bharathiar Univ. April 1998)

Solution. (i) No Load. running as a motor :

$$\text{Input Power} = 500 \times 5 = 2500 \text{ watts field copper-loss} = 500 \times 2.5 = 1250 \text{ watts}$$

Neglecting armature copper-loss at no load (since it comes out to be $2.5^2 \times 0.15 = 0.9375$ watt). the balance of 1250 watts of power goes towards no load losses of the machine running at rated speed, These losses are mainly the no load mechanical losses and the core-loss.

(ii) As a Generator, delivering 40 A 10 load :

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

Losses : Field copper-loss = 1250 watts

(b' Armature copper-loss = $42.5^2 \times 0.15 = 271$ watts

(c) NO load losses = 1250 watts

Total losses = 1521 watts

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

Extension to the Question : At Bihar speed should the Generator be run, if the shunt-field is not changed, in the above case ? Assume that the motor was running 600 r.p.m, Neglect armature'

Solution. As a motor on no-load.

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

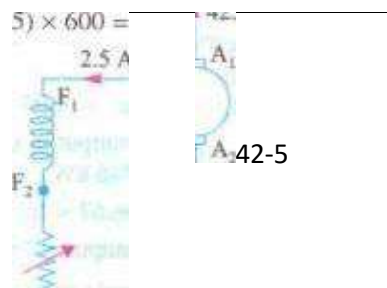
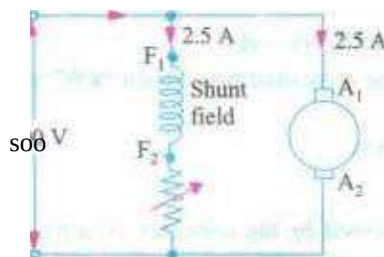
As a Generator With an armature current Of 42.5 A.

$$E_{b0} = 500 + 42.5 \times 0.15 = 506.375 \text{ V}$$

Since, the terminal voltage is same in both the cases. shunt field current remains as 2.5 amp. With armature reaction is ignored, the flux/pole remains same. The e.m.f. then becomes proportional to the speed. If the generator must driven at N r.p.m.

$$N = (506.375/499.625) \times 600 = 608.1 \text{ r.p.m.}$$

23 A 40 A



(a) Motor at no load (b) Generator loaded

Fig. 29.11

Note. Alternative to this slight increase in the speed is to increase field current with the help of decreasing the rheostatic resistance in the field-circuit.

Example 29.13 A dc. series motor takes 40 A at 220 V and runs at 800 r.p.m- If the armature and field resistance are 0.2 Ω and 0.1 Ω respectively and the iron and friction losses are 0.5 W find the torque developed in the armature. What will be the output of the motor ?

Solution. Armature torque is given by $T_a = 9.55 \frac{E_b I_a}{N}$ N-m is given by
 $T_a = 9.55$
 $E_b = V - I_a (R_a + R_{se}) = 220 - 40 (0.2 + 0.1) = 208 \text{ V}$
 $T_a = 9.55 \times 208 \times 40 / 800 = 99.3 \text{ N-m}$
 Cu loss in armature and field resistance = $40^2 \times 0.3 = 480 \text{ W}$ series-field

[Iron and friction losses = 500 W Total losses 480 + 500 = 980 W

Motor power input = $220 \times 40 = 8800 \text{ W}$

Motor output $8800 - 980 = 7820 \text{ W} = 7.82 \text{ kW}$

Example 29.14. A cutting tool exerts a tangential force of 400 N on a steel bar of diameter 10 cm which is being turned in a simple lathe. The lathe is driven by a chain at 840 rpm. from a 220 V dc. Motor which runs at 1800 r.p.m- Calculate the current taken by the motor if its efficiency is 80 % What size is the motor pulley if the lathe pulley has a diameter of 24 cm .

(Elect. Technology-II, Gujarat Univ. 1985)

Solution. Torque Tangential force x radius = $400 \times 0.05 = 20 \text{ N-m}$

Output power = $T \times 2\pi \times \text{rev/s}$ watt $20 \times (840/60) \text{ watt} = 2800 \text{ W}$

Motor input = $2800 / 0.8 = 3500 \text{ W}$

Current drawn by motor = $3500 / 220 = 15.9 \text{ A}$

Let N_1 and D_1 be the speed and diameter of the driver pulley respectively and N_2 and D_2 the respective speed and diameter of the lathe pulley.

10 cm

$N_1 \times D_1 = N_2 \times D_2$ or

Example 29.15. The armature winding of a 200-V.4-pole. series motor is lap-connected. There are 280 slots and each slot has 4 conductors. The current is 45 A and the torque per pole is 18 N-m.

The field resistance is 0.3 Ω; resistance and the iron and friction losses total 1000 W. The pulley diameter is 0.5 m. Find the pull in newton at the rim of the pulley.

(Elect. Engg. Sec. A. 1991)

800

Solution. Total input

Now Iron +

Friction losses

Output

= 9 x 55 x 6580 - 12SN-m

488

$$E_b = V - I_a R_a = 200 - 45(0.5 + 0.3) = 164 \text{ V}$$

$$E_b = \frac{\Phi ZN}{60} \cdot \left(\frac{P}{A}\right) \text{ volt}$$

$$164 = \frac{18 \times 10^{-3} \times 280 \times 4 \times N}{60} \times \frac{4}{4} \quad \therefore N = 488 \text{ r.p.m.}$$

$$\text{input} = 200 \times 45 = 9,000 \text{ W}; \text{ Cu loss} = I_a^2 R_a = 45^2 \times 0.8 = 1,620 \text{ W}$$

$$\text{losses} = 800 \text{ W}; \text{ Total losses} = 1,620 + 800 = 2,420 \text{ W}$$

$$\text{output} = 9,000 - 2,420 = 6,580 \text{ W}$$

Let F be the pull in newtons at the rim of the pulley.

$$F \times 0.205 = 128.8$$

$$F = 128.8 / 0.205 \text{ N} = 634 \text{ N}$$

Example 29.16. A 4-pole, 240 V. wave connected shunt motor gives 1119 kW when running at 1000 r.p.m. and drawing armature and field currents of 50 A and A respectively. has 540

conductors. Its resistance is 0.1Ω . Assuming a drop of 1 volt per brush, find (a) total torque (b) useful torque (c) useful flux / pole (d) rotational losses and (e) efficiency.

Solution.

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

Also

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

$$(a) \quad \text{Armature torque } T_a = 9.55 \frac{E_b I_a}{N} \text{ N-m} = 9.55 \times \frac{233 \times 50}{1000} = 111 \text{ N-m}$$

$$(b) \quad T_{sh} = 9.55 \frac{\text{output}}{N} = 9.55 \times \frac{11,190}{1000} = 106.9 \text{ N-m}$$

$$(c) \quad E_b = \frac{\Phi ZN}{60} \times \left(\frac{P}{A}\right) \text{ volt}$$

$$\therefore 233 = \frac{\Phi \times 540 \times 1000}{60} \times \left(\frac{4}{2}\right) \quad \therefore \Phi = 12.9 \text{ mWb}$$

$$(d) \quad \text{Armature input} = V I_a = 240 \times 50 = 12,000 \text{ W}$$

$$\text{Armature Cu loss} = I_a^2 R_a = 50^2 \times 0.1 = 250 \text{ W}; \text{ Brush contact loss} = 50 \times 2 = 100 \text{ W}$$

$$\therefore \text{Power developed} = 12,000 - 350 = 11,650 \text{ W}; \text{ Output} = 11.19 \text{ kW} = 11,190 \text{ W}$$

$$\therefore \text{Rotational losses} = 11,650 - 11,190 = 460 \text{ W}$$

$$(e) \quad \text{Total motor input} = VI = 240 \times 51 = 12,340 \text{ W}; \text{ Motor output} = 11,190 \text{ W}$$

$$\therefore \text{Efficiency} = \frac{11,190}{12,340} \times 100 = 91.4 \%$$

Example 29.17. A 460-V series motor runs at 500 rpm. taking a current of 40 A. Calculate the speed and percentage change in torque if load is reduced so that it is taking 30 A. Total resistance of the armature and field circuits is 0.8Ω . Assume, $\omega \propto I_a$ is proportional to the field current.

(Elect. Engg.-I, Kerala Univ. 1988)

Solution. Since $\Phi \propto I_a$, hence $T \propto I_a^2$

$$\therefore T_1 \propto 40^2 \text{ and } T_2 \propto 30^2 \quad \therefore \frac{T_2}{T_1} = \frac{9}{16}$$

Example 29.15. A 460-V, 55.95 kW, 750 r.p.m. shunt motor drives a load having a moment of inertia of

2

inertia of 252.8 kg-m. Find approximate time to attain full speed when starting from rest against full-load torque if starting current varies between 1.4 and 1.8 times full-load current.

Solution. Let us suppose that the starting current has a steady value of $(1.4 + 1.8)/2 = 1.6$ times full-load value.

Full-load output 55.95 kW = 55,950 W Speed 750 r.p.m. = 12.5 r.p.s.

Fl. shaft torque $T = \text{power} / \omega = \text{power} / (2\pi n/60) = 55,950 \times (60/2\pi) = 712.4 \text{ N-m}$

During starting period, average available torque

— 1.6

This torque acts on the moment of inertia $I = 252.8 \text{ kg-m}^2$.

12.5

(b)

$$427.4 = 252.8 \times \frac{1}{2} \times \frac{d\omega}{dt} \quad \text{or} \quad dt = \frac{427.4 \times 2}{252.8 \times d\omega}$$

Example 29.19. A 14.92 kW, 400 V, 400 r.p.m. d.c. shunt motor draws a current of 40 A when running at full-load. The moment of inertia of the rotating system is 7.5 kg-m². If the starting current is 1.2 times full-load current, calculate (a) full-load torque and (b) the time required for the motor to attain the rated speed against full-load.

(Gujarat Univ. 1988)

Solution. FL output 14.92 kW = 14,920 W ;

Now, $T_m = \text{output} / \omega = 14,920 / (2\pi \times 400/60) = 71.2 \text{ N-m}$

During the starting period, the torque available for accelerating the motor armature is

$T = 0.2 \times 71.2 = 14.24 \text{ N-m}$

NOW, torque $I \frac{d\omega}{dt} = 14.24$ second

29.9. Speed Of a D.C. Motor

From the voltage equation of a motor (An. 27.4), we get

$$E_b = V - I_a R_a \quad \text{or} \quad \frac{\Phi Z N}{60} \left(\frac{P}{A} \right) = V - I_a R_a$$

$$N = \frac{V - I_a R_a}{\Phi} \times \left(\frac{60A}{ZP} \right) \text{ r.p.m.}$$

$$V - I_a R_a = E_b \quad \therefore \quad N = \frac{E_b}{\Phi} \times \left(\frac{60A}{ZP} \right) \text{ r.p.m. or } N = K \frac{E_b}{\Phi}$$

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

on $N \propto E_b / \Phi$

For Series Motor

Let N_1 = Speed in the 1st case : I_{a1} , armature current in the 1st case =
flux/pole in the first Φ_1 case

N_2 = corresponding quantities in the 2nd case.

Then, using the above relation, we get

$$N_1 \propto \frac{E_{b1}}{\Phi_1} \quad \text{where } E_{b1} = V - I_{a1} R_a ; \quad N_2 \propto \frac{E_{b2}}{\Phi_2} \quad \text{where } E_{b2} = V - I_{a2} R_a$$

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

prior to saturation of magnetic poles ; $\Phi \propto I_a \quad \therefore \quad \frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{I_{a1}}{I_{a2}}$

For Shunt Motor

In this case the same equation applies.

$$\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{\Phi_1}{\Phi_2} \quad \text{If } \Phi_2 = \Phi_1, \text{ then } \frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}}$$

29.10. Speed Regulation

The term speed regulation refers to the change in speed Of a motor With change in applied load torque. other conditions remaining constant. By change in speed here is meant the change which occurs under these conditions due to inherent properties of the motor itself and not those changes which are affected through manipulation of rheostats or other speed-controlling devices.

The speed regulation is defined as the change in speed when the load is reduced from rated value to zero, expressed as percent Of the rated load speed.

$$\% \text{ speed regulation} = \frac{\text{NL speed} - \text{FL speed}}{\text{FL speed}} \times 100$$

F.L speed

29.11. Torque and Speed of a D.C. Motor

It will be proved that though torque of a motor is admittedly a function of flux and armature Current. yet it is independent speed. In fact. it speed Which on torque and not *vice-versa*. It has proved earlier that

...Art. 27.9

..Art 27.7

It is seen from above that increase in would decrease the speed but increase the armature torque. It cannot be so because torque always tends to produce rotation. If torque increases, motor speed must increase rather than decrease. The apparent inconsistency between the above two equations can be reconciled in the following Way :

Suppose that the flux of a motor is decreased by decreasing the field current, Then, following sequence of events take place

1. Back e.m.f. E_b ($V - I_a R_a$) drops instantly (the speed remains constant because of inertia of the heavy armature).

2. Due to decrease in E_b , I_a is increased because $I_a = (V - E_b) / R_a$. Moreover, a small reduction in flux produces a proportionately large increase in armature current.

3. Hence, the equation T_a a small decrease in I_a is more than counterbalanced by a large increase in I_a with the result that there is a net increase in T_a .

4. This increase in T_a produces an increase in motor speed.

It is seen from above that with the applied voltage V held constant, motor speed varies inversely as the flux. However, it is possible to increase and, at time, increase the speed provided I_a is held constant as is actually done in a d.c. servomotor.

Example 29.20. A 4-pole series motor has 944 wave-connected armature conductors. At a certain load, the per pole is 34.6 and the total mechanical torque developed is 209 N-m. Calculate the line current taken by the motor and the speed at which it will run with an applied voltage of 500 V. Total motor resistance is 3 Ohm

(Elect. Engg. See A Part 11 June 1991)

Solution. $0.1590 \text{ Z/a (P/A) N-m}$

$209 = 0.159 \times 34.6 \times 10^{-3} \times 944 \times 1, (4/2); I_a = 20.1 \text{ A}$

as given in Art.

$10^{-3} \times 944 \times N \times 2$

Example 29.21. A 25th V' shunt motor runs at 1000 r.p.m. at no-load and takes 84. The total armature and shunt field resistances are respectively 0.2 Ω and 250 Ω . Calculate the speed when loaded and taking 50 A. Assume the

—240.2 V

2402

1000 248.6

Example 29.22. A dc. series motor operates at 800 r.p.m. with a line current of 100 A from

Example 29.23. A 230-V d.c. shunt motor has an armature resistance of 0.5Ω and field resistance of 115Ω . At no load, the speed is 1200 r.p.m. and the armature current 2.5 A. On application of rated load, the speed drops to 1120 r.p.m. Determine the line current and power input when the motor delivers rated load. (Elect. Technology, Kerala Univ. 1988b)

Solution.

Line current drawn by motor Power input at rated load

Example 29.24. A belt-driven shunt generator running 300 r.p.m. on 220-V bus-bars continues to run as a motor when the belt breaks, then taking kW. What will be its speed? Given armature resistance = 0.025Ω and contact drop under each brush = 1 V. Ignore armature reaction. (Elect. Machines (E-3) AMIE sec-c Winter 1991)

Solution. As Generator [Fig. 29.12 Load current.

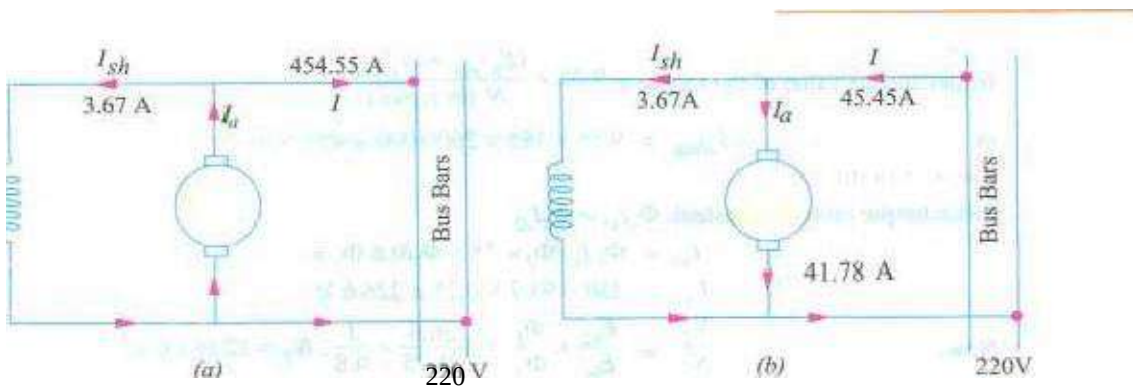


Fig. 29.12

As Motor [Fig. 29.12

Input line current

—45.45—3.67
1.04- 2X I —216.96 V

because

(b)

$$\begin{aligned} \text{current} &= 100,000/220 = 45.45 \text{ A}; I_{sh} = 3.67 \text{ A}; I_a = 41.78 \text{ A}; \\ I_a R_a &= 41.78 \times 0.025 = 1.04 \text{ V}; E_{b2} = 216.96 \text{ V} \\ \frac{N_2}{N_1} &= \frac{E_{b2}}{E_{b1}} \times \frac{\Phi_1}{\Phi_2}; \text{ since } \Phi_1 = \Phi_2 \\ \frac{N_2}{1200} &= \frac{216.96}{233.45}; N_2 = 279 \text{ r.p.m.} \end{aligned}$$

current A: = 220/60 = 3.67

—41.78 A; —220—

is constant

300

Example 29.25. A dc. shunt machine generates 250, Von open circuit al 1000 r.p.m. Effective armature resistance is 0.5 Q. field resistance is 250 n, input to machine running as n motor on noload is 4 A at 250 V. Calculate speedofmachine as a motor taking 40 A at 250 V.

Armaturun• maction weakens field by (Electrical Machines-I, Univ.1987

Solution. Consider the case when the machine runs as motor on no-load.

$$\text{Now, } = 250/250 - A: \text{ Hence, } G = -4 — \quad E_m 250 - 0.5 \times 3 \quad 248.5 \text{ V}$$

It is given that When armatureruns at 1000 it generates 250 V. When it generates V, it must be running at a speed = $1000 \times 248.5/250 = 994 \text{ rpm}$.

$$\begin{aligned} \text{When } I_a &= 40 - 1 = 39 \text{ A}; E_b = 250 - 39 \times 0.5 = 230.5 \text{ V} \quad \text{Also, } \Phi_0/\Phi = 1/0.96 \\ \frac{N}{E} &= \frac{E_b}{E_{b0}} \quad \therefore \quad \frac{N}{994} = \frac{230.5}{248.5} \times \frac{1}{0.96} \end{aligned}$$

Hence, 994
N = 960 r.p.m.

Example 29.26.

A 250-V shunt motor giving /'1-92 kW al 1000 r.p.m. rakes an armature current of 75 A, The armature resistance is 0.25 ohm and the load torque remains constant. *If the flux* is reduced by 20 percent Of its normal value before the speed changes, find rhe instantaneous value Of the armature current and the ,orque. Determine the final Of the armature cur.'ent and speed.

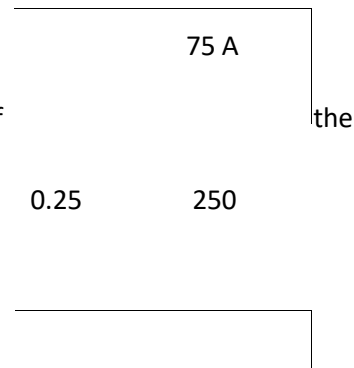
œleet. Engg. AMIETE 'New Scheme) 1990) solution. Eh, - $250 - 75 \times 0.25 = 231.25 \text{ V}$, as inFig.29.13.

When flux is reduced by 20%, the back e.m.f. is also reduced instantly by because speed remains constant due to inertia of heavy armature (Arl_ 29. II).v

Instantaneous value ofback e.m.f. — $231.25 \times 0.8 = 185 \text{ v}$

= 260 A

Fig. 29.13



Instantaneous value of the torque =

$$\text{The torque} = 9.55 \times \frac{(E_b)_{\text{inst}} \times (I_a)_{\text{inst}}}{N \text{ (in r.p.m.)}}$$

$$(T)_{\text{inst}} = 9.55 \times 185 \times 260/1000 = 459 \text{ N-m}$$

Steady Conditions

Since torque remains constant,

$$\text{Instant, } \Phi_1 I_{a1} = \Phi_2 I_{a2}$$

$$I_{a2} = \Phi_1 I_{a1} / \Phi_2 = 75 \times \Phi_1 / 0.8 \Phi_1 = 93.7 \text{ A}$$

$$E_{b2} = 250 - 93.7 \times 0.25 = 226.6 \text{ V}$$

$$\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{\Phi_1}{\Phi_2} = \frac{226.6}{231.25} \times \frac{1}{0.8}; N_2 =$$

Now. 1225 r.p.m.

Example 29.27. A 220-V, dc. shunt field resistance is 100

V, d.c. shunt motor takes 4 A at no-load when running at 700 r.p.m. The resistance of armature at standstill gives a drop of 6 volts across 1 A were passed through it. Calculate (a) speed on load

armature terminals when 10 A were passed through torque in At-m and (c) efficiency. The normal input of the motor is 8 kW.

(Electrotechnics-n; MS. Univ. Baroda 1988 j

Solution. 200/100=2 A

EL. Power input

- 40-2-38 A; $R_a = 6/10 = 0.6 \Omega$

— 198.8 V; 1772 V

; N — 623.9 r.p.m.

700 198.8

T. 9.55 $9.55 \times 1772 \times 38/623.9 = 103 \text{ N-m}$

(c) N. L. power input = $200 \times 4 = 800 \text{ W}$; $0.6 \times 10 = 2.4 \text{ W}$

Constant losses - $800 - 2.4 = 797.6 \text{ W}$; FL. loss = 866.4 W

Total EL. losses $797.6 + 866.4 = 1664 \text{ W}$; output = $83 \text{ M} - 1664 = 6336 \text{ W}$ EL Motor efficiency = 0.792 or 79.2 %

Example 29.28. The input 230 V, dc. shunt motor is 11 kW. Calculate (a) the torque developed (h) the efficiency (e) the speed at this load. The particulars of the motor are as follows :

No-load current = 5 A; No-load speed = 1200 r.p.m.

Arm. resistance = 0.2Ω ; shunt field resistance = 110Ω .

Solution. No-load No-load armature Cu loss

input

Constant losses When input is 11 kW.

Input current Arm. Cu loss

Total loss

Output

Efficiency

(c) Back e.m.f. at no-load

Back e.m.f. at given load

Speed N

Elect. Technology ;

Bombay University 1988' -

220x5= 1,100W:

$$I_{sh} = 220/110 = 2A; I_{ao} = 5 -$$

$$= 3^2 \times 0.5 \quad W$$

$$= 1.100 - 4.5 = 1,095W$$

$$= 11,0/220 = 50A ;$$

Armature current = 2 =
A

$$= 482 \times 0.5 = 1,152 w;$$

$$= \text{Arm. Cu loss} + \text{Constant losses} = 1\,152 + 1095.5 = 2248 W$$

$$= 11.000 - 2,248 = 8,752 w$$

$$8,752 w$$

$$220 - 13 \times 0.5 = 218.5 V$$

$$= 196 v$$

$$196/218.5 =$$

r.p.m.

196 x 48

-87.1 N.m

Example 29.29. The armature circuit resistance a 18.65 kW 250- V series motor is 0.1 / the brush voltage drop is 3V, and the seriesfield resistance is 0.05. When the motor takes 80 A, speed is

600 r.p.m. Calculate the speed when the current is 100 A.

(Elect. Machines, A.M.I.E. sec. B, 1993b)

Solution.

Since 80/100

474 r.p.m.

$$E_{b1} = 250 - 80(0.1 + 0.05) - 3 = 235 \text{ V.}$$

$$E_{b2} = 250 - 100(0.1 + 0.05) - 3 = 232 \text{ V}$$

$$\Phi \propto I_a, \text{ hence, } \Phi_1 \propto 80, \Phi_2 \propto 100, \Phi_1/\Phi_2 = 8/10$$

$$\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{\Phi_1}{\Phi_2} \text{ or } \frac{N_2}{600} = \frac{232}{235} \times \frac{80}{100}; N_2 =$$

Example A 220-volt d. c. series motor is running at a speed of 800 p.p.m. and draws 100 A. Calculate at what speed the motor will run when developing half the torque. Total resistance

(Elect. Machines ; A.M.I.E. Sec. B, 1991)

Of the armature and field is 0.1 Ohm.

Assume that the magnetic circuit is unsaturated.

Solution.

Since field is unsaturated,

$$\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{\Phi_1}{\Phi_2} = \frac{E_{b2}}{E_{b1}} \times \frac{I_{a1}}{I_{a2}} \quad (\because \Phi \propto I_a)$$

$$T \propto \Phi I_a \propto I_a^2, \quad (\because T_1 \propto I_{a1}^2 \text{ and } T_2 \propto I_{a2}^2)$$

$$T_2/T_1 = (I_{a2}/I_{a1})^2 \text{ or } 1/2 = (I_{a2}/I_{a1})^2; I_{a1} = I_{a2}/\sqrt{2} = 70.7 \text{ A}$$

$$E_{b1} = 220 - 100 \times 0.1 = 210 \text{ V}; E_{b2} = 220 - 70.7 \times 0.1 = 212.9 \text{ V}$$

$$\frac{N_2}{800} = \frac{212.9}{210} \times \frac{100}{70.7}; N_2 = 1147 \text{ r.p.m.}$$

29.12. Motor Characteristics

The characteristic Curves Of a motor are those curves which show relationships between the following quantities.

1. Torque and armature Current characteristic. It is known as **electrical** Characteristic
2. Speed and armature current i.e. M/a characteristic.
3. Speed and torque i.e. ω characteristic. It is also known as mechanical characteristic. It can be found from (1) and (2) above.

While discussing motor characteristics, the following two relations should always be kept in mind :

$$T_a \propto \Phi I_a \text{ and } N \propto \frac{1}{\Phi}$$

29.13. Characteristics of Series Motors

We have seen that $T \propto I_a^2$ In this case, as field windings also carry the armature current, ϕ increases up to the point of magnetic saturation, Hence. before saturation,

$T \propto I_a^3$ and

At light loads, ϕ is small. But as I_a increases, ϕ increases as the square of the current. Hence, $T \propto I_a^3$ curve is a parabola as shown in Fig. 29.14. After saturation, ϕ is almost independent of I_a hence $T \propto I_a$ only. So the characteristic becomes a straight line. The shaft torque T is less than torque due to Stray losses. It is shown dotted in the figure. so we conclude that (prior to magnetic saturation) on heavy loads, a series motor exerts a torque proportional to the square of armature current. Hence, in cases where huge starting torque is required for accelerating heavy masses quickly as in hoists and electric trains etc.. series motors are used.

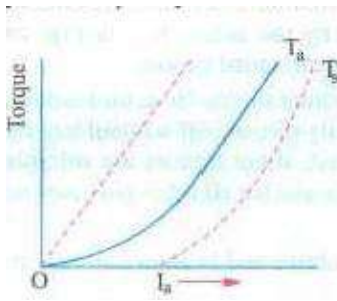


Fig. 29.14

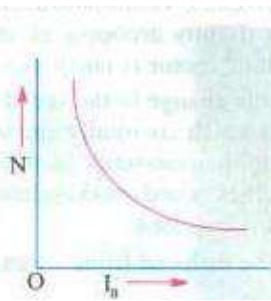


Fig. 29.15

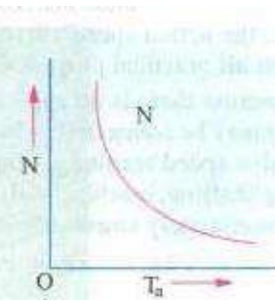


fig. 29.16

2. MI. Characteristics. Variations of N can be deduced from the formula :

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

Change in E_b for various load currents is small and hence may be neglected for the time being. With increased I_a , Φ also increases. Hence, speed varies inversely as armature current as shown in Fig. 29.15.

When load is heavy, I_a is large. Hence, N is low (this decreases E_b and allows more armature current to flow). But when load current and hence I_a falls to a small value, speed becomes dangerously high. Hence, a series motor should never be started without some mechanical (not belt-driven) load on it otherwise it may develop excessive speed and get damaged due to heavy centrifugal forces so produced. It should be noted that series motor is a variable speed motor.

3. Or mechanical characteristic. It is found from above that when speed is high, torque is low and vice-verso. The relation between the two is as shown in Fig. 29.16.

29.14. Characteristics of Shunt Motors

1. Characteristic

Assuming C_P to be practically constant (though at heavy loads, decreases somewhat due to increased armature reaction) we find that T_a .

Hence, the electrical characteristic as shown in Fig. 29.17, is practically a straight line through the origin. Shaft torque is shown dotted. Since a heavy starting load will need a heavy starting current, shunt motor should never be started on (heavy) load.

2. Characteristic

If E_b is constant, then N is also practically constant. speed is, for most purposes, constant (Fig. 29.18).

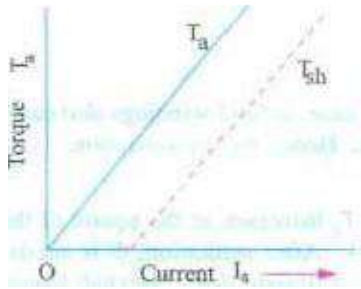


Fig. 29.17

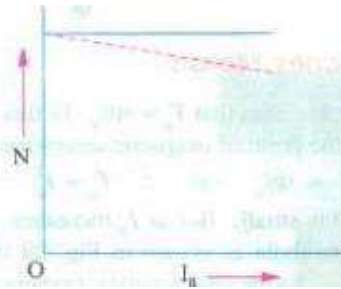


Fig. 29.18

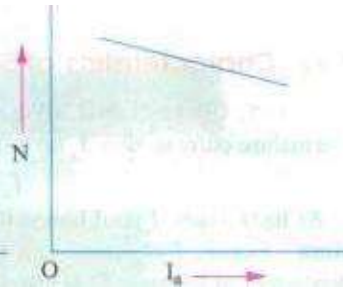


Fig. 29.19

But strictly speaking, both E_b and P_d decrease with increasing load. However, E_b decreases slightly more than so that on the whole, there is some decrease in speed. The drop varies from 5 to 10% of full-load speed, being dependent on saturation, armature reaction and brush position. Hence, the actual speed curve is slightly drooping as shown by the dotted line in Fig. 29.18. But, for all practical purposes, shunt motor is taken as a constant-speed motor.

Because there is no appreciable change in the speed of a shunt motor from no-load to fullload, it may be connected to loads which are totally and suddenly thrown off without any fear of excessive speed resulting. Due to the constancy of their speed, shunt motors are suitable for driving shafting, machine tools, lathes, wood-working machines and for all other purposes where an approximately constant speed is required.

3. N/T_a Characteristic Can be deduced from (1) and (2) above and is shown in Fig. 29.19.

29.15. Compound Motors

These motors have both series and shunt windings. If series excitation helps the shunt excitation i.e. series flux is in the same direction (Fig. 29.20): then the motor is said to be cumulatively compounded. If on the other hand, series field opposes the shunt field, then the motor is said to be differentially compounded.



The characteristics of such motors lie in between those of shunt and series motors as shown in Fig. 29.21, Compound Motors

(a) Cumulative-compound Motors

Such machines are used where series characteristics are required and where, 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 cuts quite often. Due to shunt windings, speed will not become excessively high but due to series windings, it will be able to take heavy In conjunction with fly-wheel functioning as load equalizer), it is employed where there Fig. 29.20 are sudden temporary loads as in rolling mills. The fly-wheel supplies its stored kinetic energy when motor slows down due to sudden heavy load. And when due to the removal Of load motor speeds up, it gathers up its kinetic energy.

Compound-wound motors have greatest application With loads that require high starting torques or pulsating loads (because such motors smooth out the energy demand required of a pulsating load). They are used to drive electric shovels, metal-stamping machines, reciprocating pumps, hoists and compressors etc.

'b) Differential—compound Motors

Since series field opposes the shunt field; the flux is decreased as load is applied to the motor. This results in the motor speed remaining almost constant Or even increasing With increase in load (because, $N \propto \frac{E_b}{\phi}$). Due to this reason, there is a decrease in the rate at which the motor torque increases With load. Such motors are not in common use. But because they can be designed to give an accurately constant Speed under all conditions, they find limited application for experimental and research work.

One Of the biggest drawback Of such a motor is that due to weakening Of flux With increases in load, there is a tendency towards speed instability and motor running away unless designed properly.

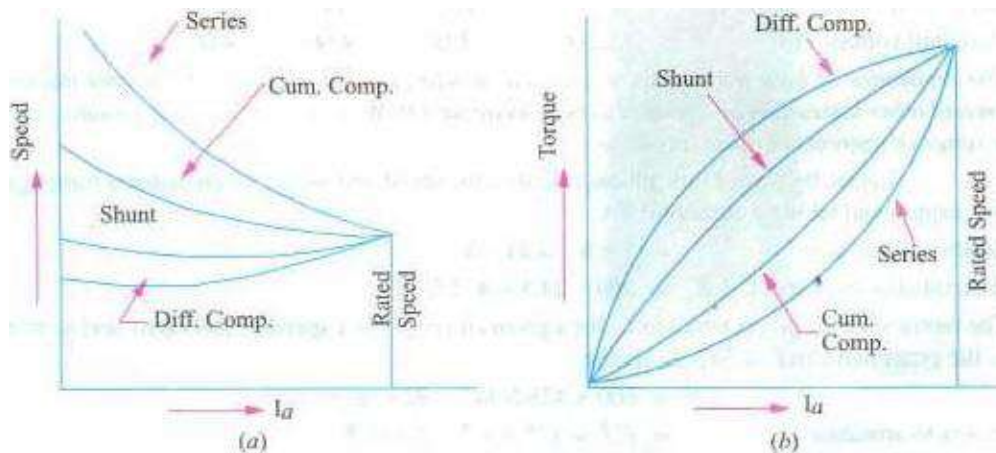


Fig. 29.21

Example 29—32. The following results were obtained from a static torque motor:

Current (A)	20	30	40	50
Torque (N • m)	128.8	230.5	349.8	462

Deduce the speed/torque curve for the machine when supplied at a constant voltage of 460 V. Resistance and field winding is 0.5 Ω. Ignore iron and friction losses.

Solution. Taking the case when input current is

20 A, we have

Motor input = $460 \times 20 = 9,200 \text{ W}$

Field and armature Cu loss

= $20^2 \times 0.5 = 200 \text{ W}$

Ignoring iron and friction losses.

output = $9,200 - 200 = 9,000 \text{ W}$

Now, $T \times 2\pi N = \text{Output in watts.}$

$128.8 \times 2\pi \times N = 9,000$ so $N = 9,000 / 2\pi \times 128.8$ Torque (N.m)

= 11.12 r.p.s. = 667 r.p.m.

Similar calculations for other values of current are Fig. 29.22 tabulated below :

Current (A)	20	30	40	50
-------------	----	----	----	----



Input (W) loss (W)	9.200	13,800	18.400	23.000	1,250
Output (W)	9.200	13,350	11.600	21.850	
Speed (r.p.m.)	667	551	480	445	
Torque (N-tm)	128.8	2305	349.8	4692	

From these values, the speed/torque curve can be drawn as shown in Fig. 29.22.

Example 29.22. A fan which requires 8 (5.968 kW) at 700 r.p.m. is coupled directly to a d.c. series motor. Calculate the input to the motor when the supply voltage is 500 V, assuming that power required for fan varies as the cube of the speed. For the purpose of obtaining the magnetisation characteristics, the motor was running as a self-excited generator at 600 r.p.m. and the relationship between the terminal voltage and the load current was found to be as follows :

load current (A) 7 10.5 14 27.5 terminal voltage (V) 347 393 434 458

The resistance of both the armature and field windings of the motor is 3.5 Ω and the core friction and other losses may be assumed to be constant at 450 W for the speeds corresponding to the above range of currents at normal voltage. (London)

Solution. Let us, by way of illustration, calculate the speed and output when motor is running off a supply and taking a current of 14 A.

Series Voltage drop $14 \times 3.5 = 49.5 \text{ V}$

Generated or back e.m.f. $E_b = 458 - 49.5 = 408.5 \text{ V}$

The motor speed is proportional to E_b for a given current. For a speed of 600 r.p.m. and a current

of 14 A, the generated e.m.f. is 347 V. Hence,

$N \propto 408.5/347 = 823 \text{ r.p.m.}$

Power to armature $= 14^2 \times 3.5 = 686 \text{ W}$ Output Armature $= 408.5 \times 14 = 5719 \text{ W}$
 $W = 5719 - 686 = 5033 \text{ W}$ power required by the fan at 823 r.p.m. is $= 5.968 \times 823^2/700^2 = 9.498 \text{ kW}$

These calculations are repeated for the other values of Current in the following table.

Input current (A)			14	27.5
Series drop (V)	24.5	36.7	49	96.4
Back e.m.f. (V)	475	463.3	451	403.6

E_b at 600 r.p.m. (V)	347	393	434	458
Speed N (r.p.m.)	823	707	623	528
Armature power (W)	3329	4870	6310	11100
Motor output (W)	2879	4420	5860	10650
Power required by fan (kW)	9.698	6.146	4.222	2.566

In Fig. 29.23 (i) the motor output in kW and (ii) power required by fan in kW against input current is plotted. Since motor output equals the input to fan, hence the intersection point of these curves gives the value of motor input current under the given conditions.

(a)

Input current corresponding to intersection point = 12 A

∴ Motor input = $500 \times 12 = 6,000 \text{ W}$

29.16. Performance Curves

(a) Shunt Motor

In Fig. 29.24 the four essential characteristics of a shunt motor are shown *i.e.* torque, current speed and efficiency, each plotted as a function of motor output power. These are known as the **performance curves** of a motor.

It is seen that shunt motor has a definite no-load speed. Hence, it does not 'run away' when load is suddenly thrown off provided the field circuit remains closed. The drop in speed from no-load to full-load is small, hence this motor is usually referred to as **constant speed** motor. The speed for any load within the operating range of the motor can be readily obtained by varying the field current by means of a field rheostat.

The efficiency curve is usually of the same shape for all electric motors and generators. The shape of efficiency curve and the point of maximum efficiency can be varied considerably by the designer, though it is advantageous to have an efficiency curve which is fairly flat, so that there is little change in efficiency between load and 25% overload and to have the maximum efficiency as near to the full load as possible.

It will be seen from the curves, that a certain value of current is required even when output is zero. The motor input under no-load conditions goes to

4.5

meet the various losses occurring

within the machine.

kW output

Fig. 29.24

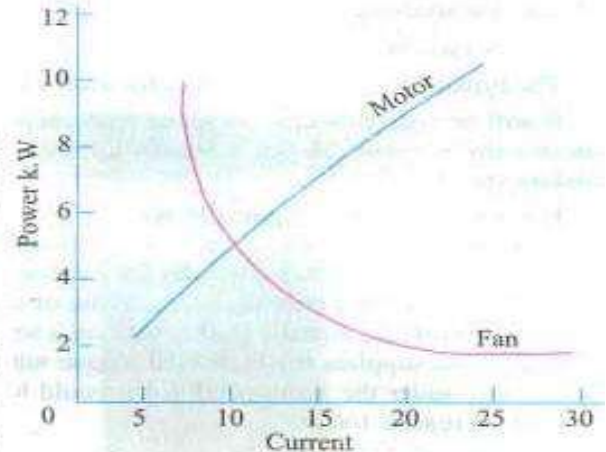
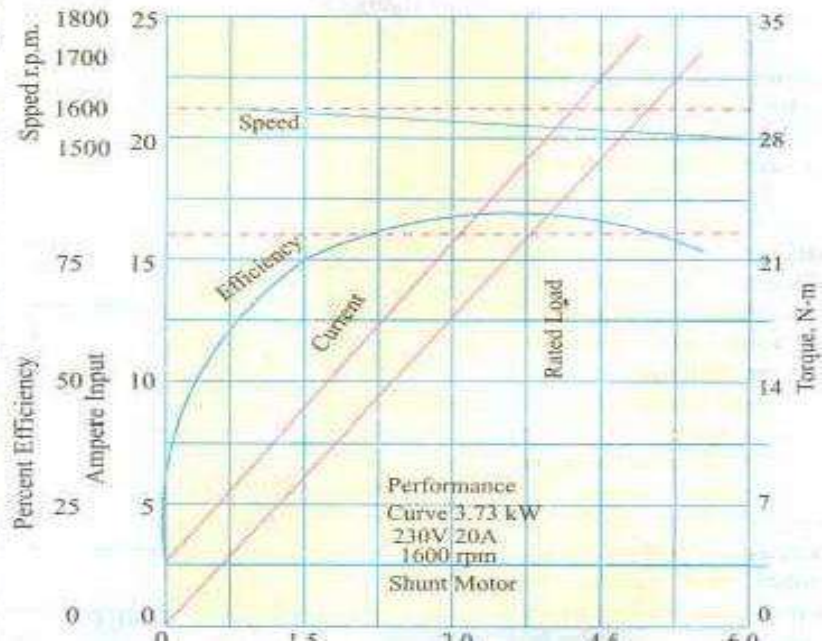


Fig. 29.23



As compared to other motors, a shunt motor is said to have a lower starting torque. this should not be taken to mean that shunt motor is incapable of starting a heavy load. Actually, it means that series and compound motors are capable of starting heavy loads with less excess of current inputs over normal values than the shunt motors and that consequently the depreciation on the motor

Will be relatively less. For example, if twice full load torque is required at start, then shunt motor draws $I_a \propto \sqrt{T_a}$ where twice the full-load current I_{a0} whereas series motor draws only $T_a \propto I_a^2$ or $I_a \propto \sqrt{T_a}$ approximately one and a half times the full/ load current

The shunt motor is widely used with loads that require essentially constant speed but where high starting torques are not needed- Such loads include centrifugal pumps, fans, winding reels conveyors and machine tools etc.

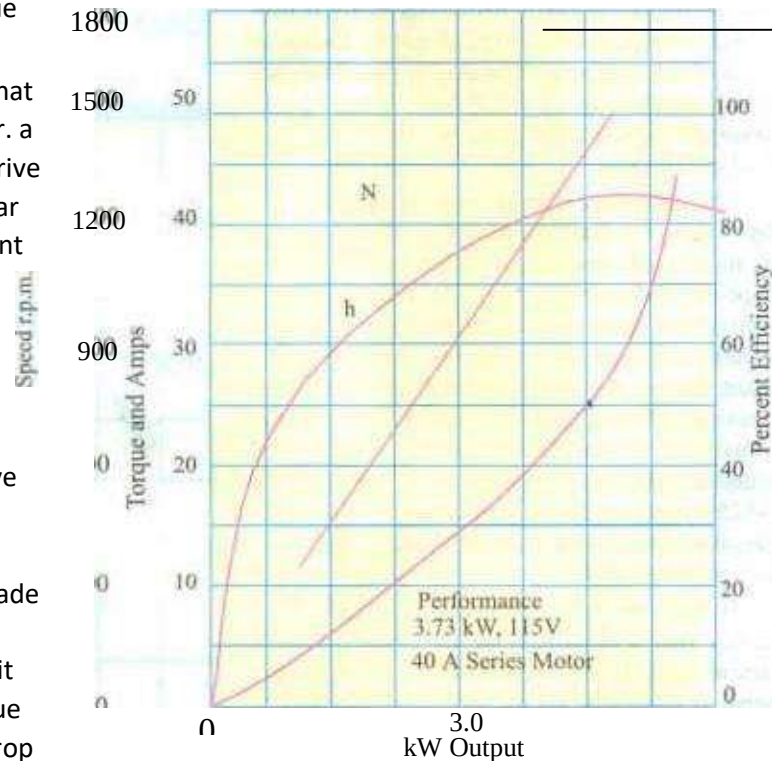
(b' Series Motor

The typical performance curves a series motor are shown in Fig. 29.25.

It will be seen that drop in speed with increased load is much more prominent in series motor than in a shunt motor. Hence, a series motor is not suitable for applications requiring a Substantially constant speed.

For a given current input, the starting torque developed by a series motor is greater than that developed by a shunt motor. Hence, series motors are used where huge starting torques are necessary i.e. for street cars, cranes, hoists and for electric-railway operation. In addition to the huge starting torque, there is another unique characteristic of series motors which makes them especially desirable for traction work i.e. When a load comes on a series motor, it responds by decreasing its speed (and hence, E_b) and supplies the increased torque with a small increase in current. On the other hand a shunt motor under the same conditions would hold its speed nearly constant and would supply the

required increased torque
 With a large increase Of
 input current. Suppose that
 instead Of a series motor. a
 shunt motor is used to drive
 a Street car. When the ear
 ascends a grade, the shunt
 motor maintains the
 speed for car at
 approximately the Same
 value it had on the level
 ground. but the motor
 tends to take an excessive
 current. A series motor.
 however. automatically
 slows down on such a grade
 because Of increased
 current demand, and so it
 600 develops more torque
 at reduced speed. The drop
 in speed permits the motor



to develop a large torque 300 With hut a moderate increase of power Hence. under the
 same load conditions. rating of the series motor would bc less than for a shunt motor,

Fig. 2925

29.17. Comparison Of Shunt and Series Motors

(a) Shunt Motors

The different characteristics have been discussed in Art.

29.14. It is clear that i") speed of a shunt motor is
 sufficiently constant.

(b) for the Same Current input, its starting torque is not a
 high as that of series motor. Hence. it is used.

(c) When the speed to be maintained approximately
 constant from NL to F.L i.e. for driving a line of shafting
 etc. (d) When it is required to drive the load at various speeds. any onc speed being kept
 constant for relatively long period i.e. for individual driving of such machines as lathes. The
 shunt regulator enables the required speed to be obtained easily and economically.

Shunt Motors

Summary or Applications



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

(b) Series Motors

The operating characteristics have been discussed in Art 29.13. These motors have a relatively high starting torque.

2. have good accelerating torque
3. have low speed high loads and dangerously high speed at low loads. Hence, such motors used

1. when a large starting torque required i.e. for driving hoists, cranes, trams etc.

2. when the motor can be directly coupled to a load such as a fan whose torque increases with

3. if constancy of speed is not essential, then, in fact, the decrease of speed with increase of load has the advantage that the power absorbed by the motor does not increase as rapidly as the torque. For instance, when torque is doubled, the power approximately increases by about 50 to only



4. a series motor should not be used where there is a possibility of the load decreasing to a very small. Thus, it should not be used for driving centrifugal pumps or for a belt-drive of any kind.

Series Motors

29.18. Losses and Efficiency

The losses taking place in the motor are the same as in generators. These are (i) Copper losses, (ii) Magnetic losses and (iii) Mechanical losses,

The condition for maximum power developed by the motor is

$$I_a R_a = V/2 = E_b$$

The condition for maximum efficiency is that armature Cu losses are equal to constant losses. (Art. 26.39).

29.19. Power Stages

The various stages of energy transformation in a motor and also the various losses occurring in it are shown in the power diagram of Fig. 29.26.

Overall or commercial efficiency — A' Electrical efficiency = $\frac{P_{mech}}{P_{in}}$, Mechanical efficiency

c

$$11m = -h$$

The efficiency curve for a motor is similar in shape to that for a generator (Art. 24.85).

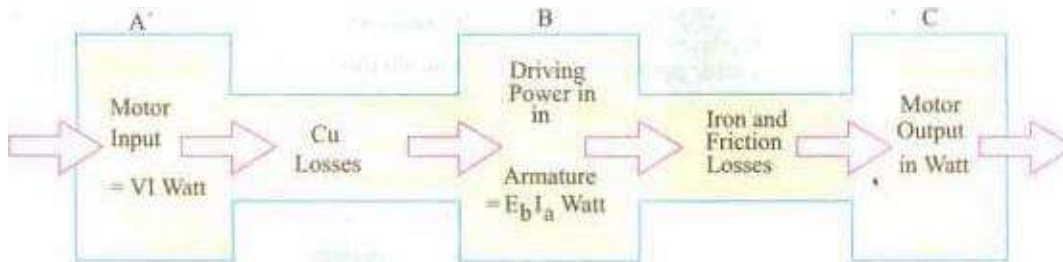


Fig 2926

It is seen that A — H = copper losses and B — C = iron and friction losses.

Example 29.34, One of the two similar 500 V shunt machines A and B running light takes 3 A. When A is mechanically coupled to B, the input to A is 33 A with B unexcited and 4.5 A when B is separately-excited to generate 500 V. Calculate the friction and windage loss and core loss of each machine. Machinery-I, Madras Univ. (1985)

Solution. When running light, machine input is used to meet the following losses (i) armature Cu loss (ii) shunt Cu loss (iii) iron loss and mechanical losses i.e. friction and windage losses. Obviously, these no-load losses of each machine equal 500×3 W.

(a) With B unexcited

In this case, only mechanical losses take place in B, there being neither Cu loss nor iron-loss because B is unexcited. Since machine A draws 0.5 A more current, Friction and windage loss of B $500 \times 0.5 = 250$ W.

(b) With B excited

In this case, both iron losses as well as mechanical losses take place in machine B. Now, machine

A draws, $4.5 - 3 = 1.5$ A more current.

Iron and mechanical losses of B = $1.5 \times 500 = 750$ W

Iron loss of B = $750 - 250 = 500$ W

Example A 220 V shunt motor has an armature resistance of 0.2 ohm and field resistance of 100 ohm. The motor draws 5 A at 220 V 500 r.p.m. at no load. Calculate the speed and shaft torque if the motor draws 52 A at rated voltage. (Elect. Machines Nagpur Univ. 1993)

Solution.

210

1500 219.4

For finding the shaft torque, we will find the motor output when it draws a current of 52 A. First we will use the no-load data for finding the constant losses of the motor.

No load motor input $220 \times 5 = 1100$ W; Arm. Cu loss = $3^2 \times 0.2 = 1.8$ W

∴ Constant or standing losses of the motor = $1100 + 1.8 = 1098$ W

When loaded, arm. cu loss = $50^2 \times 0.2 = 500$ W

Hence, total motor losses = $1098 + 500 = 1598$ W

Motor input on load = $220 \times 52 = 11,440$ W; output = $11,440 - 1598 = 9842$ W

$= 955 \times \text{output} / V = 9.55 \times 9842 / 1436 = 64.8$ N-m

Example 29—V'. 250 V shunt motor on no load runs at 1000 rpm and takes 5 amperes. Armature and shunt field resistances are 0.2 and 250 ohms respectively. Calculate the speed when loaded taking current of 50 A. The armature reaction weakens the field by 3%.

(Elect. Engg.-I Nagpur Univ. 1993)

Sol

2402

1000 rpm 2492 0.97 pf

Example 29.37. A 500 V d.c. shunt motor takes a current of 5 A on no-load. The resistances of the armature and field circuit are 0.22 ohm and 250 Ohm respectively. Find the efficiency when loaded and taking a current of 100 A (b) the percentage change of speed. State precisely the assumptions made. (Elect. Engg.-I. MS. Univ. Baroda 1987)

Solution. No-load condition

$$I_{sh} = 500/250 = 2 \text{ A}; I_{a0} = 5 - 2 = 3 \text{ A}; E_{b0} = 500 - (3 \times 0.22) = 499.34 \text{ V}$$

$$I_a \text{ loss} = 3^2 \times 0.22 = 1.98 \text{ W}; \text{ Motor input} = 500 \times 5 = 2500 \text{ W}$$

$$\text{Losses} = 2500 - 2498 = 2 \text{ W}$$

Arm. Cu

Constant

It is assumed that these losses remain constant under all load conditions.

Loaded condition

$$(a) \text{ Motor current } 100 \text{ A}; I_a = 100 - 2 = 98 \text{ A}; E_b = 500 - (98 \times 0.22) = 478.44 \text{ V}$$

Example 29—39. A d.c. shunt machine while running as generator develops a voltage of 250 V at 1000 rpm on no-load. Armature resistance of 0.5 Ω and field resistance of 250 Ω. When the machine runs as motor: input to it at no-load is 4.4 250 V. Calculate the speed and efficiency of the machine if it runs as a motor taking 40 A at 250 V. Armature reaction weakens by 3% (Electrical Technology, Aligarh Muslim Univ. '989')

Solution.

NOW. When running as a generator, the machine gives 250 V at 1000 r.p.m. If this machine was running as motor at 1000 r.p.m., it will obviously have a back e.m.f. of 250 V produced in its armature. Hence $N_1 = 1000$ r.p.m. and $E_{b1} = 250$ V.

When it runs as a motor, drawing 40 A, the back e.m.f. induced in its armature is $E_{b2} = 250 - (40 \times 1) \times 0.5 = 230.5$ V; Also $\Phi_2 = 0.96 \Phi_1$, $N_2 = ?$

Using the above equation We have

$$\frac{230.5}{250} \times \frac{\Phi_1}{0.96 \Phi_1}; N_2 = 960 \text{ r.p.m.}$$

1000

Efficiency

No-load input represents motor losses which consists of (i) armature Cu loss $I_a^2 R_a$ Which is variable.

(ii) constant losses W , which consists of (i) shunt Cu loss (ii) magnetic losses and (iii) mechanical losses.

No-load input or total losses $250 \times 4 = 1000$ W

Arm. Cu loss = $I_a^2 R_a = 40^2 \times 0.5 = 800$ W

When motor draws a line current of 40 A, its armature current is $(40 - 1) = 39$ A Cu loss = $39^2 \times 0.5 = 760.5$ W; Total losses = $800 + 760.5 = 1560.5$ W

Input $250 \times 40 = 10000$ W; output = $10000 - 1560.5 = 8439.5$ W

$\therefore$ Efficiency = $\frac{8439.5}{10000} \times 100 = 84.395\%$

Example 29.40. The armature Winding Of a 4-pole, 250 V dc. shunt motor is lap connected. There are 120 slots, each slot containing 8 conductors. The flux is 20 mWb and current taken by motor is 25 A. The resistance of armature and field circuit are 0.1 Ω and 125 Ω respectively. If the rotational losses amount to 100 W, find,

(i) gross torque (ii) useful torque and efficiency. (Elect. Machines Nagpur Univ. 1993)

Field Cu loss = $I_f^2 R_f = (25 \times 0.1) = 247.7$ W

20X 10-3 X 960X, V 4

NOW, $E_{b1} = 250 - (25 \times 0.1) = 247.7$ V; $N_1 = 1000$ r.p.m.

247.7X23

Gross torque or armature torque $T_g = 9.55 \times \frac{247.7 \times 25}{1000} = 70.4$ N-m

773

Rotational losses = 100 W; Total motor losses = $100 + 500 + 53 = 1053$ W

Motor input = $250 \times 25 = 6250$ W; Motor output = $6250 - 1053 = 5197$ W

$$T_{sh} = 9.55 \times \text{output in N} = 9.55 \times 4887 / 773 = 60.4 \text{ N-m}$$

$$\text{Efficiency} = 4887 / 6250 = 0.782 = 78.2\%$$

Example 29.11. A 20-hp (14.92 kW) 230-V, 1150-r.p.m. 4-pole, shunt motor has a total of 620 conductors arranged in two parallel paths and yielding an armature circuit resistance of 0.2 Ω.

When it delivers rated power at rated speed, it draws a line current of 74.8 A and a field current of 3 A. Calculate (i) the flux per pole the torque developed (iii) the rotational losses expressed as a percentage of power.

Solution.

Now.

of Armature Torque,

$$\text{Driving power in armature} = E_b I_a = 215.64 \times 71.8 = 15.483 \text{ kW}$$

$$14.920 = \text{W} \quad \text{Output } 14.920 \text{ W; Rotational losses} = 15.483 - 14.920 = 0.563 \text{ kW}$$

$$\text{Motor input} = 17.204 \text{ W; Total } 17.204 - 14.920 = 2.284 \text{ kW}$$

Losses expressed as percentage of power input = $2.284 / 17.204 = 0.133$ or 13.3%

Example 29.42. A 7.46 kW; 250 V shunt motor takes a line current of 30 A when running light. Calculate the efficiency as a motor when delivering full load output, if the armature and field resistances are 0.5 Ω and 250 Ω respectively. Also, what output power will the efficiency be maximum? Is it possible to obtain this output from the machine? (MS. Univ. Baroda 1985)

Solution. When loaded lightly

$$\text{Total motor input (Or total no-load losses)} = 250 \times 30 = 7.5 \text{ kW}$$

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

∴ Iron losses and friction losses = $7.5 - 250 - 0.8 = 6.25 \text{ kW}$ These losses would be assumed constant.

Let I_a be the full-load armature current, then armature input is = $(250 \times I_a)$ W. EL output = $7.46 \times 1000 = 7460 \text{ W}$ The losses in the armature :

(i) Iron and friction losses = 6250 W

$$\text{Armature } Cu \text{ loss} = I_a^2 \times 0.5 = 250 I_a - 7460 - 6250 - I_a^2 \times 0.5$$

$$I_a = 365 \text{ A}$$

$$\text{EL input current} = 36.5 + I = 37.5 \text{ A ; Motor input} = 250 \times 37.5 \text{ W}$$

$$\text{EL output} = 7,460 \text{ W}$$

FL efficiency $100/250 \times 37.5 = 79.6\%$ NOW. efficiency is maximum When armature Cu loss equals Constant loss.

$$\text{i.e. } 1.242 \text{ W} = I_a^2 R_a = 49.84 \text{ A}$$

$$\text{Armature input} = 250 \times 49.84 = 12,460 \text{ W}$$

$$\text{Armature Cu loss} = 49.84^2 \times 0.5 = 1,242 \text{ W; Iron and friction losses} = 992 \text{ W}$$

$$\text{Armature output} = 10,226 \text{ W}$$

$$\text{Output power} = 10,226 \text{ W} = 10.226 \text{ kW}$$

As the input current for maximum efficiency is beyond the full-load motor current, it is never realised in practice.

Input

Example 29.45. A 50-h.p. (373 kW), 460-V d.c. shunt motor running light takes a current of 4 A and runs at a speed of 660 r.p.m. The resistance of the armature circuit (including brushes) is 0.3Ω and that of the shunt field circuit 270Ω .

Determine when the motor is running at full load

(i) the current input (ii) the speed Determine the armature current at which efficiency is greatest. Ignore the effect of armature reaction. (1991)

$$\text{Solution. } 460/270 = 1.7$$

When running light

$$I_a = 4 - 1.7 = 2.3 \text{ A; Armature Cu loss} = 2.3^2 \times 0.3 = 1.5 \text{ W (negligible)}$$

$$\text{No-load armature input} = 460 \times 2.3 = 1,058 \text{ W}$$

As armature Cu loss is negligible, hence 1,058 W represents iron, friction and windage losses which will be assumed to be constant.

Let full-load armature input current be I_a / Then

$$\text{Armature input} = I_a \text{ W; Armature Cu loss} = I_a^2 \times 0.3 \text{ W}$$

$$= 38.358 = I_a \Rightarrow I_a = 88.5 \text{ A}$$

$$\text{Full Current input} = 88.5 + 1.7 = 90.2 \text{ A}$$

$$= 660 \times 433.5 / 459 = 624 \text{ r.p.m.}$$

For maximum efficiency, $10^2 R_a$ constant losses (Art. 24.37) exo.3 = 1,841

Tutorial Problems 29.3

A 4-POle 250—V. motor a armature With

(a) the torque (b) the speed

(b) the output torque and (d) the efficiency. if the motor current is 50 A The value Of flux per pole under these conditions is 22 mWb and the corresponding iron. friction and windage losses total 810 W. Armature resistance 0.19 field resistance 0.14 Ω .

Ha) 173.5 N-m (b) r.p.m. (c) N.m (d) 86.9%

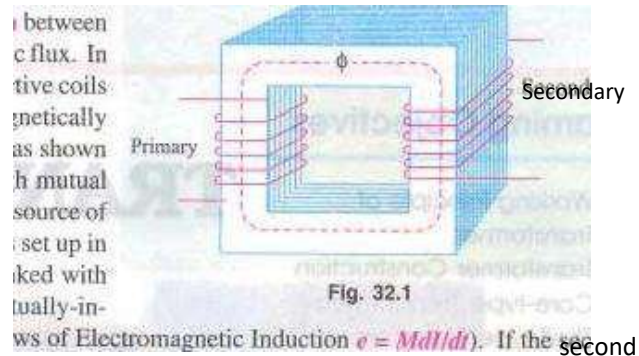
2. no-load, a shunt motor takes 5 A at 250 V. resistances of the field and armature circuits are 250 Ω and 0.1 respectively. Calculate the output power and efficiency of motor when the total supply current is 81 A at the same supply voltage. State any assumptions made.

91 % . It is that windage. friction and eddy current losses are independent of the current and speed

SINGLE PHASE TRANSFORMER

. Working Principle Of a Transformer

A transformer is a static (or stationary) piece of apparatus by means of which electric power in one circuit is transformed into electric power of the same frequency in another circuit. It can raise or lower the voltage in a circuit but with a corresponding decrease or increase in current. The physical basis of a transformer is mutual



induction between two circuits linked by a common magnetic flux. In its simplest form, it consists of two inductive coils which are electrically separated but magnetically linked through a path of low reluctance as in Fig. 32.1. The two coils possess high mutual inductance. If one coil is connected to an alternating voltage, an alternating flux is set up in the laminated core, most of which is linked to the other coil in which it produces mutually-induced e.m.f. According to Faraday's Laws of Electromagnetic Induction, if a coil circuit is closed, a current flows in it and so electric energy is transferred (entirely magnetically) from the first to the second coil. The first coil, in which electric energy is fed from the a.c. supply mains, is called primary winding and the other from which energy is drawn out, is called secondary winding. In brief, a transformer is a device that

1. transfers electric power from one circuit to another
2. it does so without a change of frequency
3. it accomplishes this by electromagnetic induction and
4. where the two electric circuits are in mutual inductive influence of each other.

32.2. Transformer Construction Ironcore

The simple elements of a transformer consist of two coils having mutual inductance and a laminated steel core. The primary and secondary two coils are insulated from each other and the steel core. Other necessary parts are :

some suitable container for assembled core 110/120 220/240; and windings ; suitable medium for Volts insulating the core and its windings from its container suitable bushings (either of porcelain, oil-filled or capacitor-type) for primary insulating and bringing out the terminals of windings

from "0/120

types of Principle of transformer

the core is constructed of transformer sheet steel laminations assembled to provide continuous magnetic path With a minimum of air-gap included. The steel used is of high silicon content, sometimes heat treated

Fig. 32.2 to produce a high permeability and a low hysteresis loss at the

usual operating flux densities. The eddy current loss is minimised by laminating the core, the laminations being insulated from each other by a light coat of cote-plate varnish or by an oxide layer on the surface. The thickness of laminations varies from 0.35 mm for a frequency of 50 Hz to 0.5 mm for a frequency of 25 Hz. The core laminations (in the strips) are joined as shown in

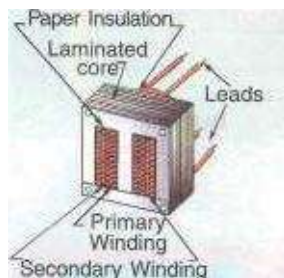
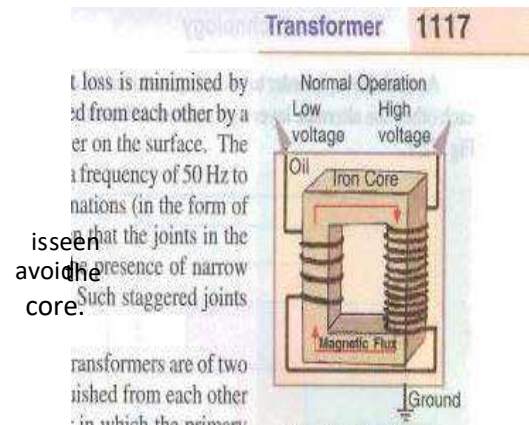


Fig. 32.2. It alternate layers are staggered in order to avoid the presence of narrow gaps right through the cross-section of the core. Such staggered joints are said to be 'imbricated'.

Constructionally, the general types, distinguished from each other merely by the manner in which the primary

Core-type transformer and secondary coils are placed around the laminated core. The two types are known as (i) core-type and (ii) shell-type. Another recent development is spiral-core or wound-core type, the trade name being spirakore transformer,

In the so-called core type transformers, the windings surround a large winding considerable part of the core whereas in shell-type transformers. the core



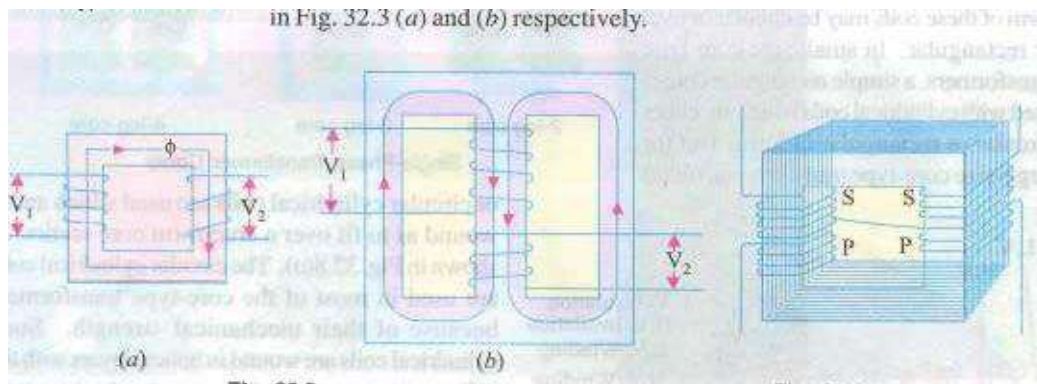


Fig. 32.3

Shell-Type transformer surrounds a considerable portion of the windings as shown schematically in Fig. 32.3 (a) and (b) respectively

In this simplified diagram for the core type transformers [Fig. 32.3] the primary and secondary winding are shown located on the opposite legs (or limbs) of the core. but in actual construction, these are always interleaved to reduce leakage flux. As shown in Fig. 32.4, half the primary and half the secondary winding have been placed side by side or concentrically on each limb, not primary on one limb (or leg) and the secondary on the other,,

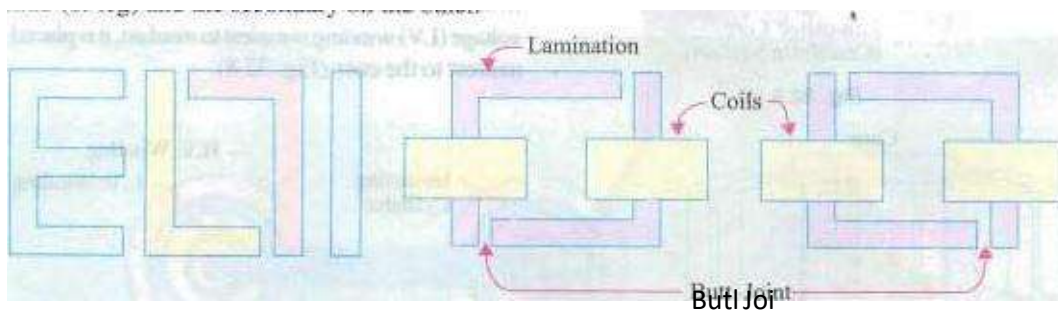


Fig. 32.5

Fig. 32.6

In both core and shell-type transformers, the individual laminations are cut in the form of long strips of Vs, Es and rs as shown in Fig. 32.5. The assembly of the complete core for the two types of transformers is shown in Fig. 32.6 and Fig. 32.7.

As said above, in order to avoid high reluctance at the joints where the laminations are butted against each other, the alternate layers are stacked differently to eliminate these joints as shown in Fig. 32.6 and

Fig. 32.7.

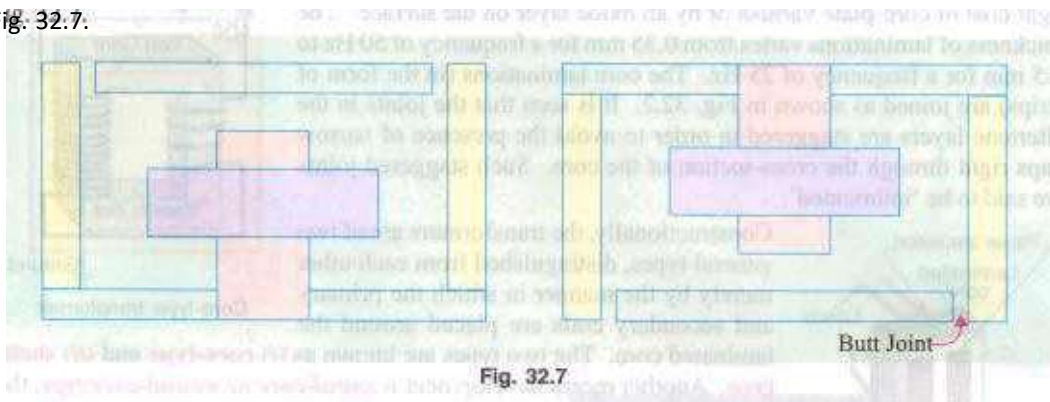


Fig. 32.7

Because of laminations and insulation, the net or effective area is reduced. due allowance for which has to be made (Ex. 32.6). 'tis found that. in general, the reduction in core sectional area due to the presence of paper, surface oxide etc. is of the order of 10% approximately.

As pointed out above. rectangular cores With ~~rectangular~~ cylindrical coils can be used for small-size ~~cott-ty~~ pc transformers as shown in fig. 32.9 (a) but for large ~~•si7Æd~~ transformers, it becomes wasteful to use rectangular cylindrical coils and so circular Cylindrical coils are preferred. For such purposes. square cores may be used as shown in Fig. 32.9 (b) where circles represent the tubular former carrying the coils. Obviously. a considerable amount of useful space is still wasted. A common improvement on square core is to employ cruciform Core as in Fig. 32.9 (c) which demands, at least, two sizes of core strips. For very large transformers. further core-stepping is done as in fig. 32.9 (d) where at least three sizes of core plates are necessary. not only gives high space factor but also results in reduced length of the mean turn and the consequent R loss. Three stepped core is the one most commonly used although more Steps may be for very large transformers as in fig. 32.9 From the geometry of Fig. 32.9, it can be shown that maximum gross core section for Fig. 32.9 (b) is $0.5d^2$ and for Fig. 32.9 (c) it is $0.616d^2$ where d is the diameter of the cylindrical coil.

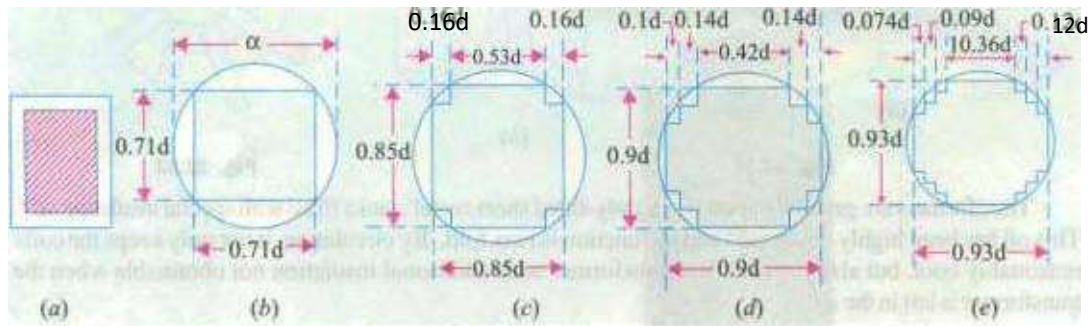
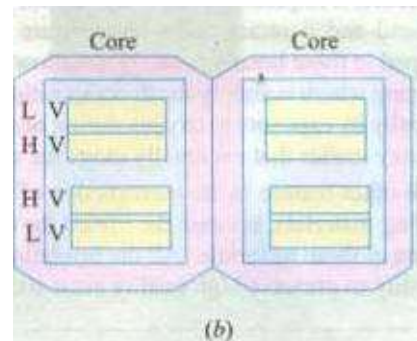
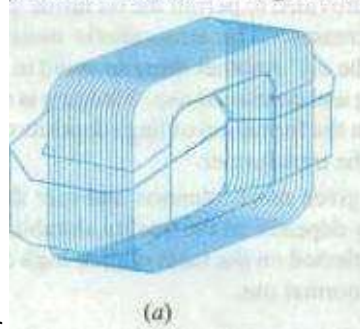


Fig. 32.9

32.4. Shell-type Transformers

In these case also, the coils are form-wound but are multi-layer disc type usually wound in the In these case also, the coils are form-wound but are multi-layer disc form of pancakes. The different layers of such multi-layer discs are insulated from each other by paper. The complete winding consists of stacked discs with insulation space between the coils—the spaces forming horizontal cooling and insulating ducts. A shell-type transformer may have a simple rectangular form as shown in Fig. 32.10



rectangular form as shown in Fig. 32. or it may have distributed form as shown in Fig. 32. 11.

Fig. 32.10

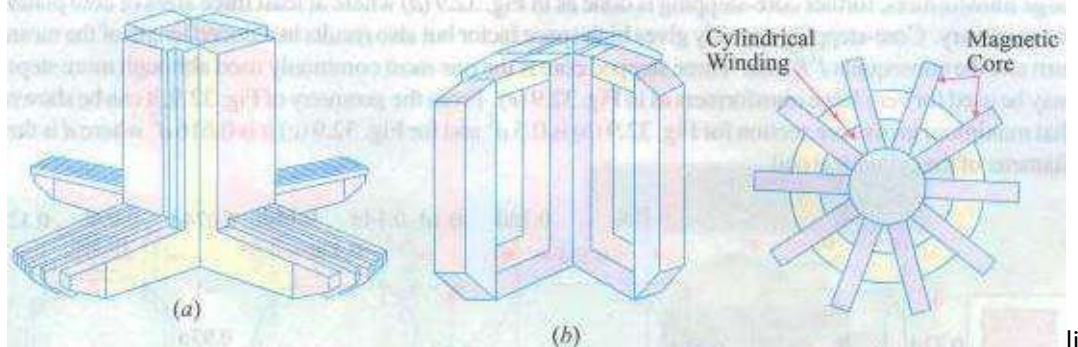
A very commonly-used shell-type transformer is the one known as Berry Transformer—so called after the name of its designer and is cylindrical in form. The transformer core consists of laminations arranged in groups which radiate out from the centre as shown in section in Fig. 32.12.

It may be pointed out that cores and coils of transformers must be provided with rigid mechanical bracing in order to prevent movement and possible insulation damage.

bracing reduces vibration and the objectionable noise—a humming sound—during operation.

The spiral-core transformer employs the newest development in construction. The core is assembled of a continuous strip or ribbon of transformer steel wound in the form of a circular or elliptical cylinder. Such construction allows the core flux to follow the grain of

the iron. Cold-rolled steel Of high silicon content enables the designer to use considerably higher operating flux densities With lower loss per kg. The use of higher flux density reduces the weight per VA. Hence, the advantages of such construction are (i) a relatively more rigid core (ii) lesser weight and size per kVA rating (iii) lower iron losses at higher operating flux densities and (iv) lower cost of manufacture.



a relatively more rigid (ii) lesser weight and size per kVA rating (iii) lower iron losses at higher

Fig. 32.11

Fig. 32.12

Transformers are generally housed in tightly-fitted sheet-metal tanks filled with special insulating oil. This oil has been highly developed and its function is two-fold. By circulation, it not only keeps the coils reasonably cool, but also provides the transformer with additional insulation not obtainable when the transformer is left in the air.

In cases where a smooth tank surface does not provide sufficient cooling area, the sides of the tank are corrugated or provided with radiators mounted on the sides. Good transformer oil should be absolutely free from alkalis, sulphur and particularly from moisture. The presence of even an extremely small percentage of moisture in the oil is highly detrimental from the insulation viewpoint because it lowers the dielectric strength of the oil considerably. The importance of avoiding moisture in the transformer oil is clear from the fact that an addition of 8 parts of water in 1 reduces the insulating quality of the oil to a value generally recognized as below standard. Hence, the tanks are sealed air-tight in smaller units. In the case of large-sized transformers where complete air-tight construction is impossible, chambers known as breathers are provided to permit the oil inside the tank to expand and contract as its temperature increases or decreases. The atmospheric moisture is entrapped in these breathers and is not allowed to pass on to the oil. Another thing to avoid in the oil is sludging which is simply the decomposition of oil with long and continued use. Sludging is caused principally by exposure to oxygen during heating and results in the formation of large deposits of dark and heavy matter that eventually clog the cooling ducts of the transformer.

No other feature in the construction of a transformer is given more attention and care than the insulating materials, because the life of the unit almost solely depends on the quality, durability and handling of these materials. All the insulating materials are selected

on the basis of their high quality and ability to preserve high quality even after many years of normal use.

Instead of natural mineral oil, now-a-days synthetic insulating fluids known as ARKAREL (trade name) are used. They are non-inflammable and, in the presence of an electric arc, do not decompose to produce inflammable gases. One such fluid commercially known as PYROCLOR is being extensively used because it possesses remarkable stability as a dielectric and even after long shows no deterioration through slogging, oxidation, acid or moisture formation. Unlike mineral oil, it shows no rapid burning.

All the transformer leads are brought out of their cases through suitable bushings. There are many designs of the SC, their size and construction depending on the voltage of the leads. For moderate voltages, porcelain bushings are used to insulate the leads as they come out through the tank. In general, they look almost like the insulators used on the transmission lines. In high voltage installations, oil-filled or capacitor—type bushings are employed.

The choice of core or shell-type construction is usually determined by cost, because similar characteristics can be obtained with both types. For very high-voltage transformers or for multiwinding design, shell type construction is preferred by many manufacturers. In this type, usually the mean length of coil turn is longer than in a comparable core-type design. Both core and shell forms are used and the selection is decided by many such as voltage rating, kVA rating, weight, insulation stress, heat distribution etc.

Another means of classifying the transformers is according to the type of cooling employed. The following types are in common use :

(a) oil-filled self-cooled (b) oil-filled water-cooled (c) air-blast type

Small and medium size distribution transformers—so called because of their use on distribution systems as distinguished from line transmission—are of type The assembled windings and cores of such transformers are mounted in a welded, oil-tight steel tank provided with steel cover. After putting the core at its proper place, the tank is filled with purified, high quality insulating oil. The oil serves to convey the heat from the core and the windings to the case from where it is radiated to the surroundings. For small size, the tanks are usually smooth-surfaced, but for larger sizes, the cases are frequently corrugated or fluted to get greater heat radiation area without increasing the cubical capacity of the tank. Still larger sizes are provided with radiators or pipes.

Construction of very large self-cooled transformers is expensive, a more economical form of construction for such large transformers is provided in the oil-immersed, water-cooled type. As before, the windings and the core are immersed in the oil, but there is mounted near the surface of oil, a cooling coil through which cold water is kept circulating. The heat

is carried away by this water. The largest transformers such as those used with high-voltage transmission lines; are constructed in this

Oil-filled transformers are built for outdoor duty and as these require no housing other than their own, a great saving is thereby effected. These transformers require only periodic inspection.

For voltages below 25,000 V, transformers can be built for cooling by means of an air-blast. The transformer is not immersed in oil, but is housed in a thin sheet-metal box open at both ends through which air is blown from the bottom to the top by means of a fan or blower.

32.5. Elementary Theory of an Ideal Transformer

An ideal transformer is one which has no losses i.e. its windings have no ohmic resistance, there is no magnetic leakage and hence which has no I^2R and core losses. In other words, an ideal transformer consists of two purely inductive windings on a loss-free core. It may, however, be noted that it is impossible

to realize such a transformer in practice, yet for convenience, we will start with such a transformer and step by step approach an actual transformer

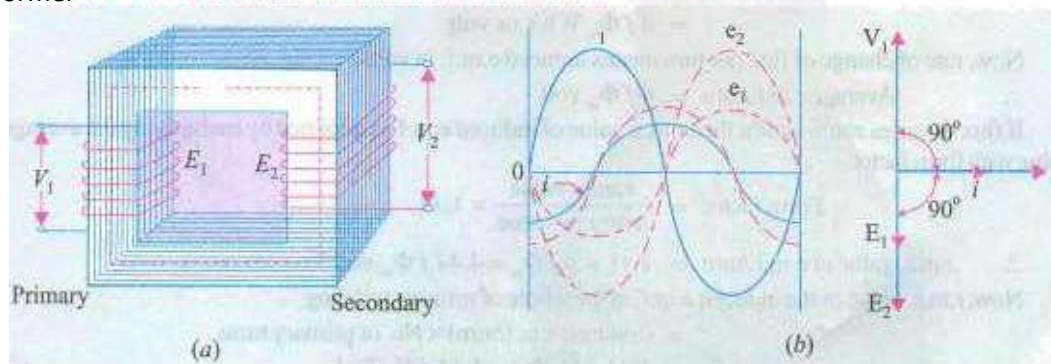


Fig. 32.13

Consider an ideal transformer [Fig. 32.13 whose secondary is open and whose primary is connected to sinusoidal alternating voltage V_1 . This potential difference causes an alternating current to flow in the primary. Since the primary coil is purely inductive and there is no output

(secondary being open) the primary draws the magnetising current only.

The function of this current is merely to magnetise the core. It is small in magnitude and lags V_1 by 90° . It produces an alternating flux ϕ which is, at all times, proportional to the current.

Assuming permeability of the magnetic circuit to be constant) hence, ϕ is in phase with i_1 . This changing flux is linked both with the primary and the secondary windings. Therefore, it produces self-induced e.m.f. in the primary. This self-induced e.m.f. E_1 is, at every instant, equal to and in opposite to V_1 . It is also known as Counter e.m.f. or back e.m.f. of the primary.

Similarly, there is induced in the secondary an induced e.m.f. E_2 which is known as mutually induced e.m.f. This e.m.f. is antiphase with V_1 , and its magnitude is proportional to the rate of change of flux and the number of secondary turns

The instantaneous values of applied voltage, induced e.m.f.s, flux and magnetising current are shown by sinusoidal waves in Fig. 32.13.

(c) shows the Vectorial representation of the effective values of the above quantities.

(c) shows the Vectorial representation of the effective values of the above quantities.

32.6. E.M.F. Equation Of a Transformer

Let N_1 = No. of turns in primary

N_2 = No. of turns in secondary

ϕ_m = Maximum flux in core in Wb

f = Frequency of a.c, input in Hz

As shown in fig. 32.14, flux increases from its zero value to its maximum value ϕ_m in one quarter of the cycle i.e. in $1/4$ of the cycle.

Average rate of change of flux =

$$\frac{\phi_m}{1/4f} = \frac{4\phi_m}{f} \text{ Wb/s}$$

increases from its zero value to its maximum value ϕ_m in one quarter of the cycle i.e. in $1/4$ of the cycle.

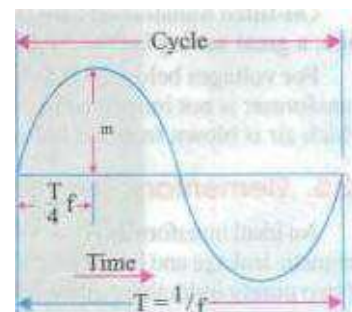
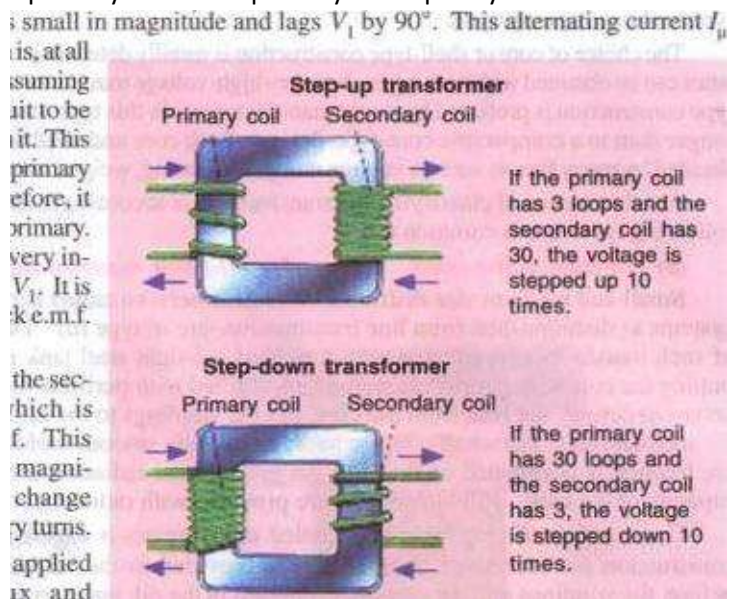


Fig. 3214

= or volt

Now, rate of change of flux per turn means induced e.m.f. in volts

Average e.m.f./turn = 4 f ϕ_m volt

If flux varies sinusoidally then r.m.s. value of induced e.m.f. is obtained by multiplying the average value with form factor. r.m.s. value

Form factor = 1.11

average value

r.m.s. value of e.m.f./turn = 1.11 $\times$ 4 = 4.44 volt

Now, r.m.s. value of the induced e.m.f. in the whole of primary winding

= (induced e.m.f./turn) $\times$ No. of primary turns

Hence, currents are in the inverse ratio of the (voltage) transformation ratio.

Example 32.1. The maximum flux density in the core of a 250/3000-V, 50-Hz single-phase transformer is 1.2 Wb/m². If the e.m.f. per turn is 8 volt, determine (i) primary and secondary turns are core.

(Electrical Engg.-I, Nagpur Univ. 1991)

Solution. (i) $E = \text{e.m.f. induced/turn}$

(ii) We may use $\phi_m = 4.44 f N B_m A$

3000 = 4.44 $\times$ 50 $\times$ 375 $\times$ L $\times$ A; A = 0.03 m².

Example 32.2. The rating of a 100-kVA, 11000/550 V, 50-Hz, 1-ph, Core type transformer has a cross-section of 20 cm $\times$ 20 cm. Find the number of H, V, and L turns per phase and the e.m.f. per turn if the core density is not to exceed Tesla. Assume a stacking factor of 0.9. What will happen if its primary voltage increased by 10% on no-load?

(Elect. Machines, AMIE, Sec. B 1991)

Solution. $\phi_m = 1.3$ T

11,000 = $\phi_m \times 1060$

550 = $\phi_m \times 0.036$; N₂ = 53

= 1060 = 53

$$\text{e.m.f./turn} = 10.4 \text{ V or } 550/53 = 10.4 \text{ V}$$

Keeping supply frequency constant, if primary voltage is increased by 10%, magnetising current will increase by much more than 10%. However, due to saturation, flux density will increase only and so will the eddy current and hysteresis losses.

Example 32.3. A single-phase transformer has 400 primary and 1000 secondary turns. The net cross-sectional area of the core is 60 cm^2 . If the primary winding be connected to a 50-Hz supply at 520 V, calculate (i) the peak value density in the core (ii) the voltage induced in

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Solution.

$$K = N_2/N_1 = 1000/400 = 2.5$$

$$(i) \quad E_2/E_1 = K \therefore E_2 = KE_1 = 2.5 \times 520 = 1300 \text{ V}$$

$$(ii) \quad E_1 = 4.44 f N_1 B_m A$$

$$\text{or} \quad 520 = 4.44 \times 50 \times 400 \times B_m \times (60 \times 10^{-4}) \therefore B_m = 0.976 \text{ Wb/m}^2$$

the secondary winding. (Elect. Engg-E. rune Unh'. 1989) Example 32.4, 'A 25-kVA transformer has 500 turns on the primary and 50 turns on the secondary winding. The primary is connected to 3000-V 50-Hz supply. Find the full-load primary and secondary currents, the secondary e.m.f. and the maximum flux in the core. Neglect leakage drops and no-load primary current (Elect. & Elect. Engg., Madras Univ. 1985)

$$\text{Solution.} \quad K = N_2/N_1 = 50/500 = 1/10$$

Now, full-load

$$\text{e.m.f. per turn on primary side} = 3000/500 = 6 \text{ Secondary e.m.f.}$$

operates with a number of H.V. and L.V.

(iii) full load H. V. and L phase-currents,

Solution Maximum value of flux has been given as 0.05 Wb.

$$(ii) \text{ e.m.f. per turn} = 4.44 f$$

$$= 4.44 \times 50 \times 0.05 = 11.1 \text{ volts}$$

(i) Calculations for number of turns on two sides:

Voltage per phase on delta-connected primary winding 11000 volts

Voltage per phase on star-connected secondary winding $550/1.732 = 317.5 \text{ volts}$ T1 = number of turns on primary, per phase voltage per phase/e.m.f. turn

T. number of turns on secondary. per phase voltage per phase/e.m.f. per turn $317.5/11.1 = 28.6$

Note : Generally, Low-voltage-turns calculated first. the figure is rounded off to next higher even integer. In this case, it be 30. The number of turns on primary side is calculated by turns-ratio.

In this case,

This, however, reduces the flux and results into less saturation. This, in fact, is an elementary aspect in Design-calculations for transformers. (Explanation is added here only to overcome a doubt whether a fraction is acceptable as a number of L.V. turns).

(ii) Full load and L.V. phase currents :

Output per phase =

H.V. phase-current

L.V. phase-current =

Example 32.6. A single-phase transformer has 500 turns in the primary and turns in the secondary. The cross-sectional area of the core is 80 sq. cm. (the primary winding is connected to a 50 Hz supply at 500 V. calculate (i) Peak flux-density, and (ii) Voltage induced in the secondary.

(Bharathiar University November 1997)

, Solution. From the

(i) Peak flux density, B_m

(ii) Voltage induced in secondary is from transformation ratio or turns ratio $V_2 = 500 \times \frac{1200}{500} = 1200$ volts

e.m.f. equation for transformer, obtained

$$500 = 4.44 \times 50 \times \phi_m \times 500$$

$$\phi_m = 1/222 \text{ Wb}$$

$$B_m = \phi_m / (80 \times 10^{-4}) = 0.563 \text{ wb/m}$$

$$\frac{V_2}{V_1} = \frac{N_2}{N_1}$$

$$V_2 = 500 \times \frac{1200}{500}$$

Example 32.7. A 25 kVA. single-phase transformer has 250 turns on primary and 400 turns on secondary winding. The primary is connected to 50 Hz mains. Calculate (i) primary and Secondary currents on full-load, (ii) Secondary e.m.f.. (iii) maximum flux in the core.

(Bharathiar Univ. April 1998)

Solution. = Secondary voltage rating, = secondary e.m.f.

1500 — 250, giving $V_2 = 240$ volts

(in Primary current $25000/1500 = 16.67$ amp Secondary current $25000/240 = 104.2$ amp

(iii) If ϕ_m is the maximum core-flux in Wb;

$$1500 = 4.44 \times \text{giving } \phi_m = 0.027 \text{ Wb or } 27 \text{ mWb}$$

Example 32.8. A single-phase, 50 Hz, core-type transformer has square cores of 20 cm side. Permissible maximum flux-density is 1.5 Wb/m^2 . Calculate number of turns per Limb on the High and low voltage sides for a 3000/220 V ratio. (Manonmuni Sundaranan, April 1998)

Solution. E-MF. equation gives the number of turns required on the two sides. We shall first calculate the L.V.-turns, round the figure off to the next higher even number, so that given maximum

flux density is not exceeded. With the corrected number of L.V. turns, calculate H.V.-turns by transformation ratio. Further, there are two Limbs. Each Limb accommodates half-L.V. and half-H.V.]

Winding from the view-point of reducing leakage reactance.

Starting with calculation for LV. turns, T_L

$$4.44 \times 50 \times (20 \times 20 \times 10^{-4}) \times T_L = 220$$

$$= 220 / 8.0 = 24.77$$

Select

$$= 26 \times 3000 / 220 = 354, \text{ selecting the nearest even integer.}$$

$$\text{of H.V. turns on each Limb} = /$$

$$\text{Number Of LV. turns on each Limb} = 13$$

32.8. Transformer with Losses but no Magnetic Leakage

We will consider two cases (i) when such a transformer is On no load and (ii) when it is loaded.

32.9. Transformer on No-load

In the above discussion. we assumed ideal transformer i.e. One in which there Were no losses and copper losses. But practical conditions require that certain modifications be made in the foregoing theory. When an actual transformer is put on load. there is iron loss in the core and copper loss in the Windings (both primary and secondary) and these losses are not entirely negligible.

Even when the transformer is on no-load, the primary input current is not wholly reactive. The primary input current under no-load conditions has to supply (i) iron losses in the core

i.e. hysteresis loss and eddy current loss and (ri) a very small copper loss in primary (there being no Cu loss in secondary as it is open). Hence, the no-load primary input current at 90° behind V_1 but lags it by an angle $\phi_0 < 90^\circ$. No-load input power

$$W_0 = V_1 I_0 \cos \phi_0$$

Where $\cos \phi_0$ is primary power factor under no-load conditions. No-load condition pf of an actual transformer is shown vectorially in Fig. 32.16.

As seen from Fig. 32.16, primary current I_0 has two components :

(i) One in phase with V_1 . This is known as active or working or iron loss component I_w because it mainly supplies the iron loss plus small quantity of primary Cu loss,

$$I_w = I_0 \cos \phi_0$$

(ii) The other component is in quadrature with V_1 and is known as magnetising component I because its function is to sustain the alternating flux in the core. It is wattless.

$$I = I_0 \sin \phi_0$$

Obviously, I_0 is the vector sum of I_w and I . Hence the following should be noted carefully :

1. The no-load primary current I_0 is small as compared to the full-load primary current. It is about 1 per cent of the full-load current.
2. Owing to the fact that the permeability of the core varies with the instantaneous value of the exciting current, the wave of the exciting or magnetising current is not truly sinusoidal. As such it should not be represented by a vector because only sinusoidally varying quantities are represented by rotating vectors. But, in practice, it makes no appreciable difference.
3. As I_0 is very small, the no-load primary Cu loss is negligibly small which means that no-load primary input is practically equal to the iron loss in the transformer.
4. As it is principally the core-loss which is responsible for shifting the known as hysteresis' angle advance.

Example 32.9. (a) A 2, 200/200-1" transformer draws a no-load primary current of 0.6 A and absorbs 400 watts. Find the magnetising and iron loss currents.

(b) A 2200/250-1" transformer takes A at a p.f. of 0.3 on open circuit. Find magnetising and working components of no-load primary current.

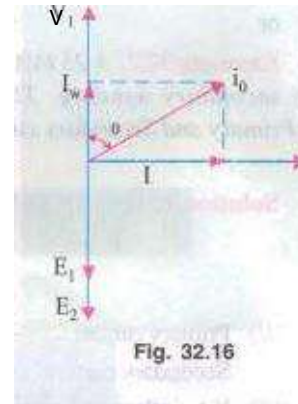


Fig. 32.16

Solution. Iron-loss current

no-load input in watts $\frac{400}{200} = 0.182$ A primary voltage 200

Magnetising component 0.182×0.672 A

The two components are shown in fig. 29 5.

Example 32.10. A Single-phase transformer has 500 turns on the primary and 40 turns on the secondary winding. The mean length of the magnetic path in the iron core is 150 cm and the joints are equivalent to an air-gap of 0.5 cm. When a p.d. of 200 V is applied to the primary maximum flux density is 1.2 Wb/m^2 . Calculate (a) the cross-sectional area of the core (b) no-load secondary voltage (c) the no-load current drawn by the primary (d) power factor no-load. Given that AT/cm for density of 1.2 Wb/m^2 in iron to be 5, the corresponding iron loss is 2 W/kg at 50 Hz, and the density of iron as 7.8 g/cm^3 .

Solution. $\frac{40}{500} = 0.08$

This is the net cross-sectional area. However, the gross area would be about 10% more for the insulation between laminations.

$K = \frac{N}{A}, \frac{40}{500} = 0.08$

$\therefore$ NL, secondary voltage = $K E$

750

$\frac{80.0001}{100} = 0.8$

Total iron loss = $950 + 965 = 1915$ W

Max. value of magnetising current drawn by primary = $\frac{1915}{500} = 3.83$ A

Assuming this current to be sinusoidal, its r.m.s. value is $\frac{3.83}{\sqrt{2}} = 2.71$ A

Volume of iron = length $\times$ area =

Density 7.8 g/cm^3 Mass of iron = $7.8 \times 1000 \times 2.35 = 18.33 \text{ kg}$

Total iron loss

Iron loss component of no-load primary current is $I_w = \frac{18.33}{3000} = 0.0061$ A

$2.71^2 + 0.0061^2 = 7.35$ A

(d) power factor $\cos \phi_0 = \frac{0.0061}{7.35} = 0.0008$

32.10. Transformer on Load 10

magnitude and phase of I_2 with respect to V_1 is determined by the characteristics of the transformer. Current I_2 is in phase with V_1 if load is non-inductive, it lags if load is inductive and it leads if load is capacitive.

The secondary current sets up its own flux which is in opposition to the main primary flux which is due to the primary ampere-turns $N_1 I_1$. These are known as demagnetising ampere-turns. The opposing secondary flux weakens the primary flux momentarily, hence primary back e.m.f. E_1 tends to be reduced. For a moment V_1 gains the upper hand over E_1 , and hence causes more current to flow in primary.

Let the additional primary current be I_1' . It is known as load component of primary current. Current I_1' is in phase with V_1 . The additional primary m.f. $N_1 I_1'$ sets up its own flux which is in opposition to Φ_1 (but is in the same direction as Φ_2) and is equal to it in magnitude. Hence, the two cancel each other out. So, we find that the magnetic effects of secondary current I_2 are immediately neutralized by the additional primary current I_1' which is brought into existence exactly at the same instant as I_2 . The whole process is illustrated in Fig. 32.17.

Fig. 32.17

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.

As $\Phi_2 = \Phi_1' \therefore N_2 I_2 = N_1 I_1' \therefore I_1' = \frac{N_2}{N_1} \times I_2 = K I_2$

Hence, when transformer is on load, the primary winding has two currents in it; one is I_0 and the other is I_1' which is anti-phase with I_2 and K times in magnitude. *The total primary current is the vector sum of I_0 and I_1' .*

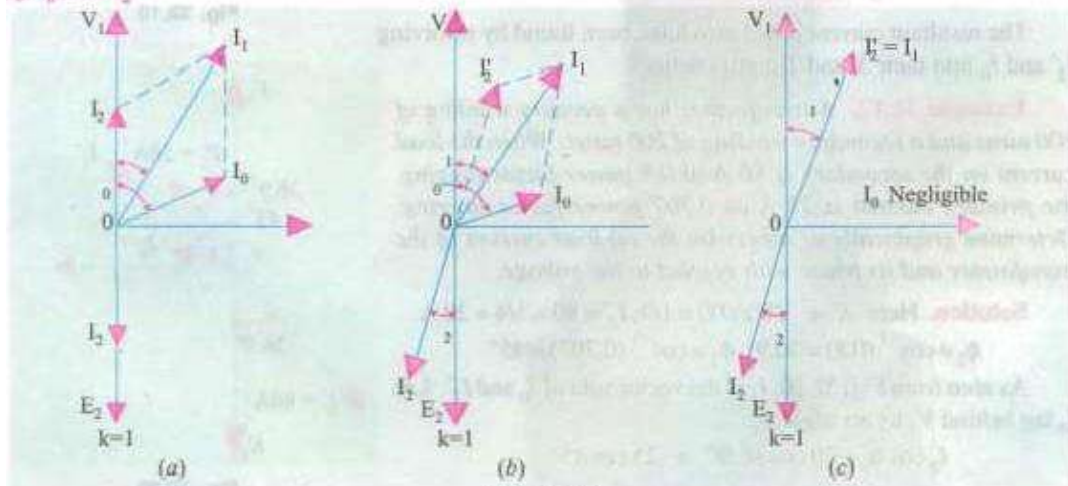


Fig. 32.18

Hence, whatever the load conditions, the net flux passing through is approximately of core flux at all loads, the core loss

In Fig. 32.18 are shown the vector diagrams for a transformer when load is non-inductive and when it is inductive (a similar diagram could be drawn for capacitive load). Voltage transformation ratio of unity is assumed so that primary vectors are equal to the

secondary vectors. With reference to fig. 32.18 12 is secondary current in phase with E_2 (strictly speaking it should be $1/2$). It causes primary current which is anti-phase with it and equal to it in magnitude ($R = 1$). Total primary current I_1 is the vector sum of I_0 and I_2' and lags behind V_1 by an angle ϕ_1 .

In Fig. 32.18 (b) vectors are drawn for an inductive load. Here I_2 lags E_2 (actually by ϕ_2). Current I_2' is again antiphase with E_2 and equal to it in magnitude. As before, the vector sum of I_2' and I_0 and lags behind V_1 by

It will be observed that neglect I_0 as in Fig. 32.18 then

is slightly greater than ϕ_2 . But if we neglect I_0 and under this assumption

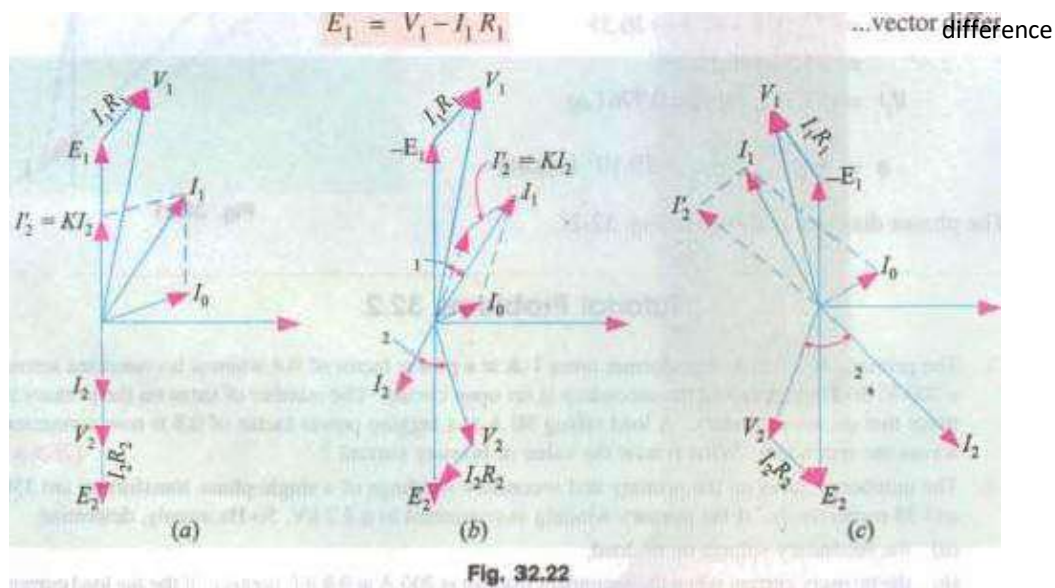
$$N_2 I_1 = N_1 I_2 \quad \therefore \quad \frac{I_2'}{I_2} = \frac{I_1}{I_2} = \frac{N_2}{N_1} = K$$

that But if we as compared to

NIG =

It shows that under full-load conditions, the ratio of primary and secondary currents is constant. This important relationship is made the basis of current transformer—a transformer which is used with a low-range ammeter for measuring currents in circuits where the direct connection of the ammeter is impracticable.

Fig. 32.20



The vector diagrams for non-inductive, inductive and capacitive loads are shown in Fig. 32.22 (a), (b) and (c) respectively.

32.12. Equivalent Resistance

In Fig. 32.23 a transformer is shown whose primary and secondary windings have resistances of R_1 and R_2 respectively. The resistances have been shown external to the windings.

It would now be shown that the resistances of the two windings can be transferred to any one of the two windings. 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. It will be proved that a resistance of R_2 in secondary is equivalent to R_2/K^2 in primary. The value will be denoted by the equivalent Fig. 32.23 secondary resistance as referred to primary

The copper loss in secondary is $I_2^2 R_2$. This loss is supplied by primary which takes a current of I_1 . Hence if R_2' is the equivalent resistance in primary which would have caused the same loss as in secondary, then

Now, if we neglect R_1 , then $I_2/I_1 = N_1/N_2$, Hence, $R_2' = R_2/K^2$

Similarly, equivalent primary resistance as referred to secondary is $R_1' = K^2 R_1$

In Fig. 32.24, secondary resistance has been transferred to primary side leaving secondary circuit resistanceless. The resistance $R_{01} = R_1 + R_2' = R_1 + R_2/K^2$ is known as the equivalent or effective resistance of

of the transformer as referred to primary and may be designated as R_{01} .

$$\therefore R_{01} = R_1 + R_2' = R_1 + R_2/K^2$$

Similarly, the equivalent resistance of the transformer as referred to secondary is

$$R_{02} = R_2 + R_1' = R_2 + K^2 R_1$$

This fact is shown in Fig. 32.25 where all the resistances of the transformer have been concentrated in the secondary winding.

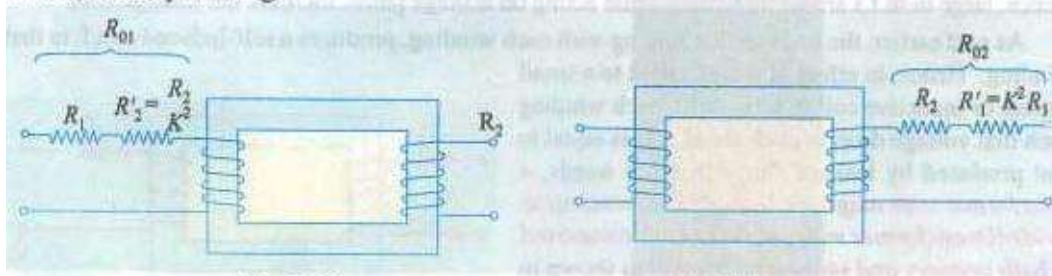


Fig. 32.24

Fig. 32.25

the referred to primary and may be designated as

It is to be noted that

1. A resistance of R_1 in primary is equivalent to R_1 in secondary. Hence, it is called equivalent resistance as referred to secondary i. e. R_1 .

2. A resistance of R_2 in secondary is equivalent to R_2/K^2 in primary. Hence, it is called the equivalent secondary resistance as referred to primary i. e. R_2/K^2 .

J. Total or effective resistance of the transformer as referred to primary is

$R_{01} = \text{primary resistance} + \text{equivalent secondary resistance as referred to primary}$

$$= R_1 + R_2' = R_1 + R_2/K^2$$

4. Similarly, total transformer resistance as referred to secondary is,

$$R_{02} = \text{secondary resistance} + \text{equivalent primary resistance as referred to secondary}$$

$$= R_2 + R_1' = R_2 + K^2 R_1$$

Actually $I_2 \neq 2/I_2' = I/K$ and not $I_2 \neq 2/I_1$. However, if I_0 is neglected, then $I_2' = I_1$.

Note : (tis important to remember that

(a) When shifting any primary resistance to the secondary, *nut/ply it by (b When shifting secondary resistance to the primary, divide it hy R.

(CJ however. when shifting any voltage from one.inding toanother

32.13. Magnetic Leakage

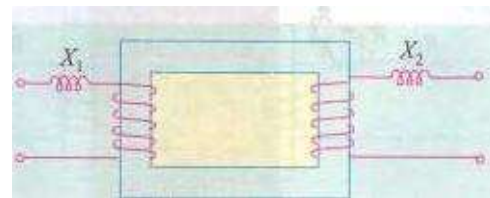
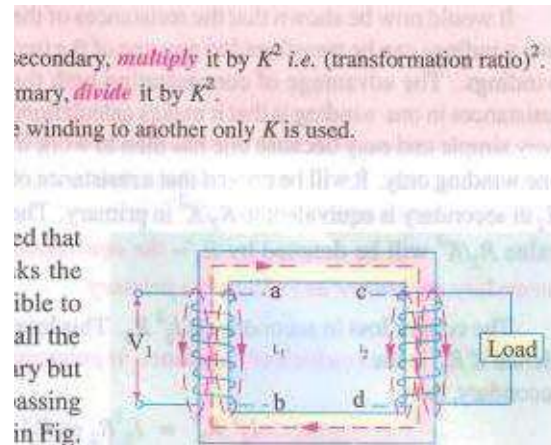
In the preceding discussion. it has been assumed that all the flux linked with

primary winding also links the secondary winding. But, in practice, it is impossible to realize this condition. It is found, however, that all the flux linked with primary does not linkthe secondary but partofiti.e_OL completes itsmagnetic circuit bypassing through air than around the core, as shown in Fig. 32.26. This leakage flux is produced when the m.m.f. due to primary ampere-turns existing between points,a and Fig. 32.26 b, acts along the leakage paths. Hence, this flux is known asprimary leakagejh'.r and is proportional to the primary ampere-turns alone because the secondary turns do not link the magnetic circuit Of .The flux is in time phase with I_1 . It induces an e.m.f. in primary but notin secondary.

Similarly. secondary ampere-turns (or m.m.f.) acting acrosspoints c and d set up leakage flux Φ_L which is linked with secondary winding alone (and not With primary turns). This flux in time phase with I_2 and produces a self-induced e.m.f. in secondary (but not in primary).

At no load and light loads. theprimary and secondary ampere-turns are small, hence leakage fluxes arenegligible. But When load is increased. both primary and secondary windings carry huge currents. Hence. large m.m.f.s are Set up which, while acting on leakage paths, increase the leakageflux.

As said earlier, the leakage flux linking with each winding, produces a self-induced e,m.f. in that winding. Hence, in effect, it is equivalent to a small choker or inductive coil in series with each winding such that voltage drop in each series coil is equal to that produced by leakage flux. In other words, a transformer With



magnetic leakage is equivalent to an ideal transformer With inductive coils connected in both primary and secondary circuits as shown in

Fig. 32.27 such that the internal e.m.f. in each inductive Fig. 32.27 coil is equal to that due to the corresponding leakage flux in the actual transformer.

$$X_1 = e_{L1}/I_1 \text{ and } X_2 = e_{L2}/I_2$$

The terms X_1 and X_2 are known as primary and secondary leakage reactance-s respectively.

Following few points should be kept in mind :

1. The leakage flux links one or the other winding but not both. hence it does not contribute to the transfer of energy from the primary to the secondary winding.
2. The primary voltage V_1 will have to supply reactive drop $I_1 X_1$, in addition to $I_1 R_1$. Similarly E_2 will have to supply $I_2 R_2$ and $I_2 X_2$.
3. In an actual transformer, the primary and secondary windings are not placed on separate legs or limbs as shown in Fig. 32.27 because due to their being widely separated, large primary and secondary leakage fluxes would result. These leakage fluxes are minimised by sectionalizing and interleaving the primary and secondary windings as in Fig. 32.6 or Fig. 32.8.

32.14. Transformer with Resistance and Leakage Reactance

In Fig. 32.28 the primary and secondary windings of a transformer with reactances taken out of the windings are shown. The primary impedance is given by $Z_1 = \sqrt{R_1^2 + X_1^2}$

Z_1 , Z_2 :

Similarly, secondary impedance is given by

The resistance $Z_2 = \sqrt{R_2^2 + X_2^2}$ and

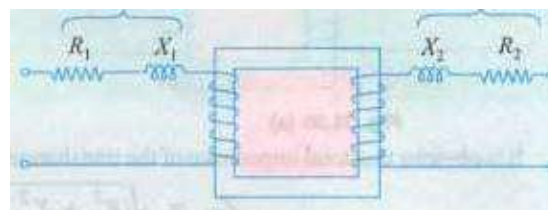
leakage reactance of each winding is responsible for some voltage drop in each winding.

In primary, the leakage reactance drop is $I_1 X_1$ (usually 1 or 2% of V_1). Fig. 32.28

Hence

Similarly, there are $I_2 R_2$ and $I_2 X_2$ drops in secondary which combine with V_2 to give E_1 .

The vector diagram for such a transformer for different kinds of loads is shown in fig. 32.29. In these diagrams, vectors for resistive drops are drawn parallel to current vectors whereas reactive drops are perpendicular to the current vectors. The angle ϕ gives the power factor angle of the transformer.



It may be noted that leakage reactances can also be transferred from one winding to the other in the same way as resistance.

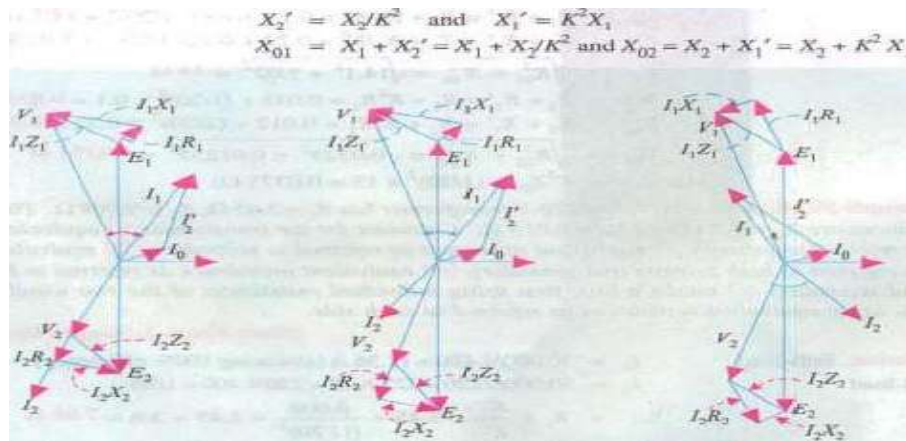


Fig. 32.29

It is obvious that the total impedance of the transformer as referred to the primary is given by

32.30 (a)

$$Z_{01} = \sqrt{R_{01}^2 + X_{01}^2} \quad \text{...Fig.}$$

Fig. 32.30 (b)

$$Z_{02} = \sqrt{R_{02}^2 + X_{02}^2} \quad \text{...Fig.}$$

Example 32.15. A

30 kVA, 2400/120-V, 50-Hz transformer has a high-voltage winding

resistance of 0.1 and a leakage reactance of 0.22 Ω. The low-voltage winding resistance is 0.035 Ω and the leakage reactance is 0.009 Ω. Find the equivalent winding resistance, reactance and impedance referred to the (i) high-voltage side and (ii) the low-voltage side.

(Electrical Machines-I, Bangalore Univ. 1987)

Solution.

$$K = 120/2400 = 1/20; R_1 = 0.1 \Omega, X_1 = 0.22 \Omega$$

$$R_2 = 0.035 \Omega \text{ and } X_2 = 0.012 \Omega$$

(i) Here, high-voltage side is, obviously, the primary side. Hence, values as referred to primary side are

$$R_{01} = R_1 + R_2' = R_1 + R_2/K^2 = 0.1 + 0.035/(1/20)^2 = 14.1 \Omega$$

$$X_{01} = X_1 + X_2' = X_1 + X_2/K^2 = 0.22 + 0.12/(1/20)^2 = 5.02 \Omega$$

$$Z_{01} = \sqrt{R_{01}^2 + X_{01}^2} = \sqrt{14.1^2 + 5.02^2} = 15 \Omega$$

(ii)

$$R_{02} = R_2 + R_1' = R_2 + K^2 R_1 = 0.035 + (1/20)^2 \times 0.1 = 0.03525 \Omega$$

$$X_{02} = X_2 + X_1' = X_2 + K^2 X_1 = 0.012 + (1/20)^2 \times 0.22 = 0.01255 \Omega$$

$$Z_{02} = \sqrt{R_{02}^2 + X_{02}^2} = \sqrt{0.03525^2 + 0.01255^2} = 0.0374 \Omega$$

$$(\text{or } Z_{02} = K^2 Z_{01} = (1/20)^2 \times 15 = 0.0375 \Omega)$$

Example 32.16. A 50-kVA, 4,400/220-V transformer has $R_1 = 3.45 \Omega$, $R_2 = 0.009 \Omega$. The values of reactances are $X_1 = 5.2 \Omega$ and $X_2 = 0.015 \Omega$. Calculate for the transformer (i) equivalent resistance as referred to primary (ii) equivalent resistance as referred to secondary (iii) equivalent reactance as referred to primary (iv) equivalent reactance as referred to secondary (v) equivalent impedance as referred to both primary and secondary

Example 32.16. A Of reactances are X, = 5.2 lance as referred to primary tance as referred ta both primary and secondary

'nary and secondary total Cu loss, first using individual tvsistances Of the two windings and secondly, using equivalent resistances as referred to each side.

Solution. Full-load

(Elect. Engg.-I, Nagpur Univ. 1993)

Full-load

$$I_1 = 50,000/4,400 = 11.36 \text{ A (assuming 100\% efficiency)}$$

$$I_2 = 50,000/220 = 227 \text{ A; } K = 220/4,400 = 1/20$$

(i)

$$R_{01} = R_1 + \frac{R_2}{K^2} = 3.45 + \frac{0.009}{(1/20)^2} = 3.45 + 3.6 = 7.05 \Omega$$

(ii)

Also,

$$R_{02} = R_2 + K^2 R_1 = 0.009 + (1/20)^2 \times 3.45 = 0.009 + 0.0086 = 0.0176 \Omega$$

$$R_{02} = K^2 R_{01} = (1/20)^2 \times 7.05 = 0.0176 \Omega \text{ (check)}$$

AlsoCu 10»

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32.16. Total Approximate Voltage Drop in a Transformer

When the transformer is On no-toad then VI is approximately equal to EI. Hence E2 = KEI = WI. Also. E2 = 0 V: where 0V2 is secondary terminal voltage on noload, hence no-load secondary terminal voltage is WI. The secondary voltage on load is V2.

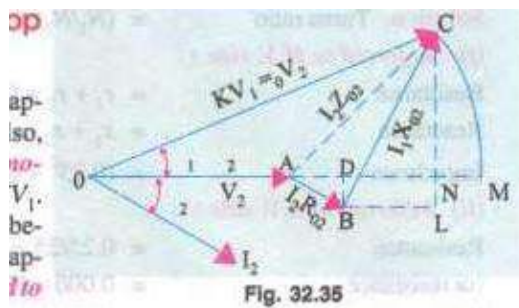


Fig. 32.35

utting OA produced at M. The total voltage drop $I_1 R_1 + I_2 R_2$

The difference between the two is 12 as shown in Fig. 32.35. The approximate voltage drop of the transformer as referred to secondary is found thus :

With O as the centre and radius OC draw an arc cutting OA produced at M. The total voltage drop $7-02 = AC = AM$ which is approximately equal to AN. From B draw BD perpendicular on OA produced.

Draw CN to OM and draw BL parallel to OM.

Approximate voltage drop

$$= AN = AD + DN$$

$$+ 12 X_{02} \sin \phi = I_2 R_{02} \cos \phi \quad \text{where}$$

$$\phi_1 = \phi_2 = \phi \text{ (approx).}$$

This is the value of approximate voltage drop for a lagging power factor,

The different figures for unity and leading power factors are shown in Fig. 32.36 (a) and (b) respectively.

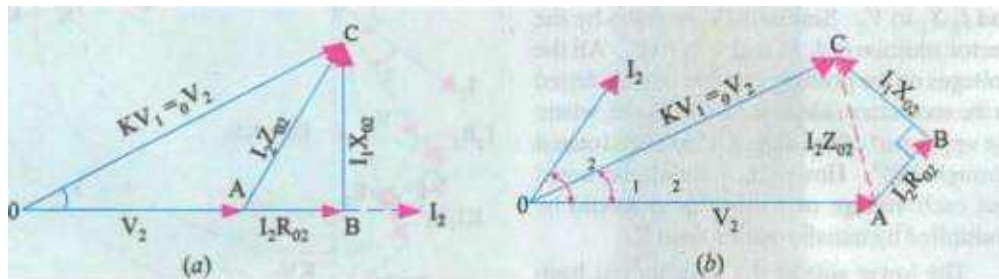


Fig. 32.36

The approximate voltage drop for a leading power factor

In general, approximate voltage drop is

It may be noted that voltage drop as referred to

% voltage drop in secondary

$$\begin{aligned} & (I_2 R_{02} \cos \phi \pm I_2 X_{02} \sin \phi) \\ & \text{Voltage drop as referred to primary is} \\ & (I_1 R_{01} \cos \phi \pm I_1 X_{01} \sin \phi) \\ & \text{is} = \frac{I_2 R_{02} \cos \phi \pm I_2 X_{02} \sin \phi}{V_2} \times 100 \\ & = \frac{100 \times I_2 R_{02}}{V_2} \cos \phi \pm \frac{100 I_2 X_{02}}{V_2} \sin \phi \end{aligned}$$

$$= v_r \cos \phi \pm v_x \sin \phi$$

$$v_r = \frac{100 I_2 R_{02}}{V_2} = \text{percentage resistive drop} = \frac{100 I_1 R_{01}}{V_1}$$

$$v_x = \frac{100 I_2 X_{02}}{V_2} = \text{percentage reactive drop} = \frac{100 I_1 X_{01}}{V_1}$$

drop for becomes

voltage drop

approximate primary is

32.17. Exact Voltage Drop

With reference to Fig. 3235, it is to be noted that exact voltage drop is AM and not $A\tilde{N}$. If we add the quantity NM to $'W$, we will get the exact value of the voltage drop.

Considering

Considering the right-angled triangle OCN , we get

$$NC^2 = OC^2 - ON^2 = (OC + ON)(OC - ON) = (OC + ON)(OM - ON) = 2 OC \times NM$$

$$\therefore NM = NC^2 / 2 OC \quad \text{Now, } NC = LC - LN = LC - BD$$

$$\therefore NC = I_2 X_{02} \cos \phi - I_2 R_{02} \sin \phi \quad \therefore NM = \frac{(I_2 X_{02} \cos \phi - I_2 R_{02} \sin \phi)^2}{2_0 V_2}$$

$\therefore$ For a **lagging** power factor, exact voltage drop is

$$= AN + NM = (I_2 R_{02} \cos \phi + I_2 X_{02} \sin \phi) + \frac{(I_2 X_{02} \cos \phi - I_2 R_{02} \sin \phi)^2}{2_0 V_2}$$

For a **leading** power factor, the expression becomes

$$= (I_2 R_{02} \cos \phi - I_2 X_{02} \sin \phi) + \frac{(I_2 X_{02} \cos \phi + I_2 R_{02} \sin \phi)^2}{2_0 V_2}$$

In general, the voltage drop is

$$= (I_2 R_{02} \cos \phi \pm I_2 R_{02} \sin \phi) + \frac{(I_2 X_{02} \cos \phi \pm I_2 R_{02} \sin \phi)^2}{2_0 V_2}$$

Percentage drop is

the

right-angled triangle OCN , we get

$$20v/ \quad \begin{array}{|c|c|c|} \hline (12Ro, co. \pm & \sin & \\ \hline \end{array} \quad \begin{array}{|c|c|c|} \hline \cos & \sin & \\ \hline \end{array}$$

$$= (V_2 \cos \phi \pm V_2 \sin \phi) + (1/200) (V_2 \cos \phi \pm V_2 \sin \phi)^2$$

The upper signs are to be used for a lagging power factor and the lower ones for a leading power

Example 32.21. A 230/460-8/ transformer has a primary resistance of 0.2 and reactance Of 0.5 Ω and the corresponding values for the secondary are 0.75 Ω and 1.8 Ω respectively. Find the

secondary terminal voltage when supplying 10 A at 0.8 p.f. lagging.

(Electric Machines-II, Bangalore Univ. 1991)

$$K = 460/230 = 2; R_{02} = R_2 + K^2 R_1 = 0.75 + 2^2 \times 0.2 = 1.55 \Omega$$

$$X_{02} = X_2 + K^2 X_1 = 1.8 + 2^2 \times 0.5 = 3.8 \Omega$$

$$\text{drop} = I_2 (R_{02} \cos \phi + X_{02} \sin \phi) = 10 (1.55 \times 0.8 + 3.8 \times 0.6) = 35.2 \text{ V}$$

$$\text{age} = 460 - 35.2 = 424.8 \text{ V}$$

Solution.

Voltage drop

$\therefore$ Secondary terminal voltage =

Example 32.22. Calculate the regulation of a transformer in which the percentage resistance drop is 1.0% and percentage reactance drop is 5.0% when the power factor is (a) 0.8 lagging (b) unity and (c) 0.8 leading. (Electrical Engineering, Bannras Hindu Univ. 1988)

Solution. We will use the approximate expression of Art 30.16.

(a) p.f. = $\cos \phi = 0.8$ lag $\mu = v_r \cos \phi + v_x \sin \phi = 1 \times 0.8 + 5 \times 0.6 = 3.8\%$

(b) p.f. = $\cos \phi = 1$ $\mu = 1 \times 1 + 5 \times 0 = 1\%$

(c) p.f. = $\cos \phi = 0.8$ lead $\mu = 1 \times 0.8 - 5 \times 0.6 = -2.2\%$

Example 32.23. A transformer has a reactance drop of 5% and a resistance drop of Find the

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$\mu = v_r \cos \phi + v_x \sin \phi$
 where v_r is the percentage resistive drop and v_x is the percentage reactive drop.
 Differentiating the above equation, we get $\frac{d\mu}{d\phi} = -v_r$
 For regulation to be maximum, $d\mu/d\phi = 0 \therefore -v_r = 0$
 or $\tan \phi = v_x/v_r = 5/2.5 = 2 \therefore \phi = \tan^{-1}(2) = 63.5^\circ$

lagging power factor at which the voltage regulation is maximum and the value of 'hi' regulation,
 (Elect. FAEgg. Punjab Univ. 1991)

Solution. The percentage voltage regulation (p) is given by

$\mu = v_r \cos \phi + v_x \sin \phi$

$$-v_r \sin \phi + v_x \cos \phi = 0$$

Now, $\cos \phi = 0.45$ and $\sin \phi = 0.892$

Maximum percentage regulation = $(2.5 \times 0.45) + (5 \times 0.892) = 5.585\%$

Maximum percentage regulation is 5.585 and occurs at a power factor of 0.45 (lag).

Example 32.24. Calculate the percentage voltage drop for a transformer with a percentage resistance of 2.5% and a reactance of 5% of rating 500 kVA when it is delivering 400 kVA at lagging, 'Elect. Machinery-I,

(%R) $I \cos \phi$ • **Solution.** % drop

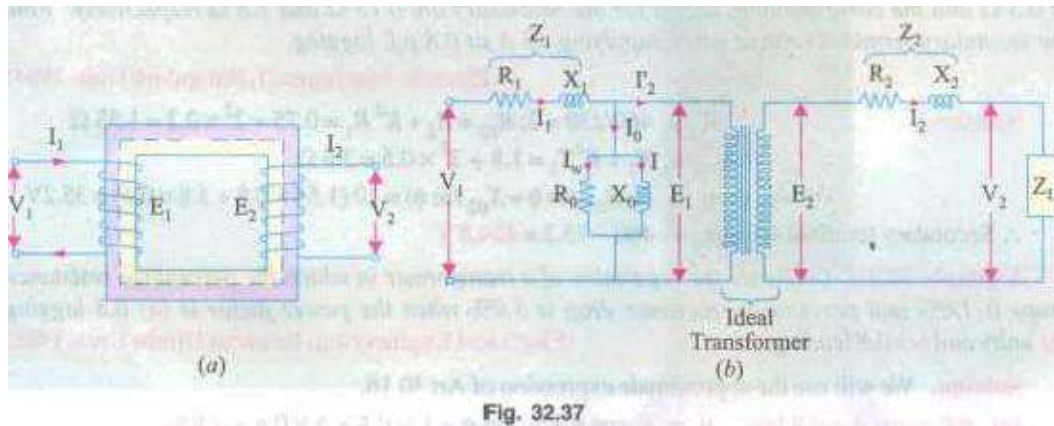
Where I_f is the full-load current and I the actual current.

In the present case,

32.18. Equivalent Circuit

The transformer shown diagrammatically in Fig. 32.37 (a) can be resolved into an equivalent circuit in which the resistance and leakage reactance of the transformer are

imagined to be external to the winding whose only function then is to transform the voltage (Fig. 32.37 (b)). The no-load



current I_0 is simulated by pure inductance X_0 taking the magnetising component I_g and a non-inductive resistance R_0 taking the working component I_s , connected in parallel across the primary circuit. The value of E_1 is obtained by subtracting vectorially V_1 from V_2 . The value of $X_0 = E_1/I_0$ and of $R_0 = I_0$ is clear that E_1 and E_2 are related to each other by expression

To make transformer calculations simpler, it is preferable to transfer voltage, current and impedance

Transformer 1143

either to the primary or to the secondary. In that case, we would have to work in one winding only which is more convenient.

The primary equivalent of the secondary induced voltage is $E_2' = E_2/K = E_1$.

Similarly, primary equivalent of secondary terminal or Output voltage is $V_2' = V_2/K$ Primary equivalent of the secondary current is $I_2' = K I_2$.

impedance to primary K^2 is used.

For transferring secondary $R_2' = R_2/K^2, X_2' = X_2/K^2, Z_2' = Z_2/K^2$

This same relationship is used for shifting an external load impedance to the primary).

The secondary circuit is shown in Fig. 32.38(O) and its equivalent primary values are shown in fig.

32.38 (b).

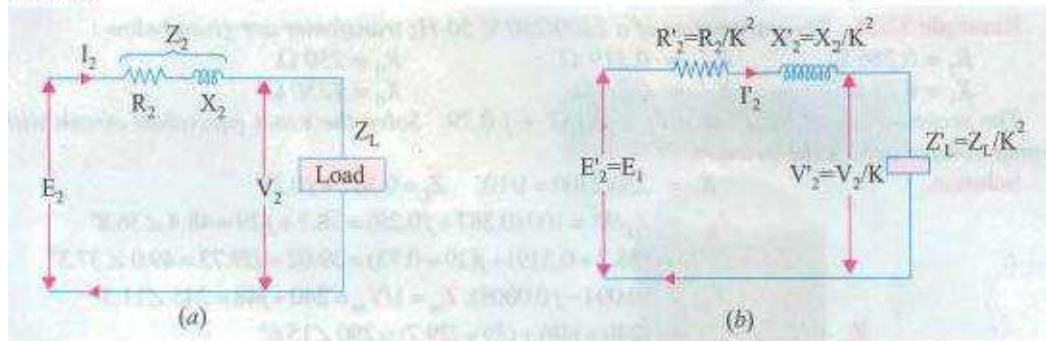


Fig. 32.38

The total equivalent circuit of the transformer is obtained by adding in the primary impedance as shown in Fig. 32.39. This is known as the exact equivalent circuit but it presents a somewhat harder circuit problem to solve. A simplification can be made by transferring the exciting circuit across the terminals as in Fig. 32.40 or in Fig. 32.41 (a). It should be noted that in this case $X_0 = V_1/I_0$.

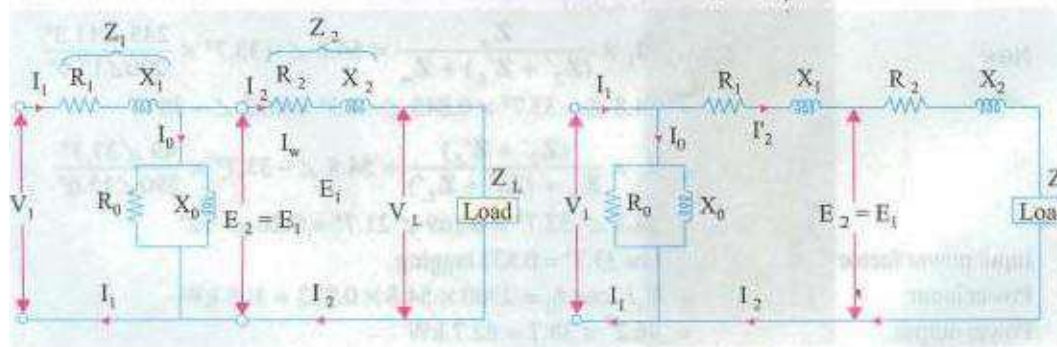


Fig. 32.39

Fig. 32.40

Further simplification may be achieved by omitting I_0 altogether as shown in Fig. 32.41 (b).

From Fig. 32.39 it is found that total impedance between the input terminal is

$$Z = Z_1 + Z_m \parallel (Z_2' + Z_L') = \left(Z_1 + \frac{Z_m (Z_2' + Z_L')}{Z_m + (Z_2' + Z_L')} \right)$$

where $Z_2' = R_2' + jX_2'$ and Z_m = impedance of the exciting circuit.

can be made by transferring the exciting circuit across the terminals as in

This is so because there are two parallel circuits, one having an impedance of Z_1 and the other having Z_2' and Z_L' in series with each other.

$$V_1 = I_1 \left[Z_1 + \frac{Z_m (Z_2' + Z_L')}{Z_m + (Z_2' + Z_L')} \right]$$

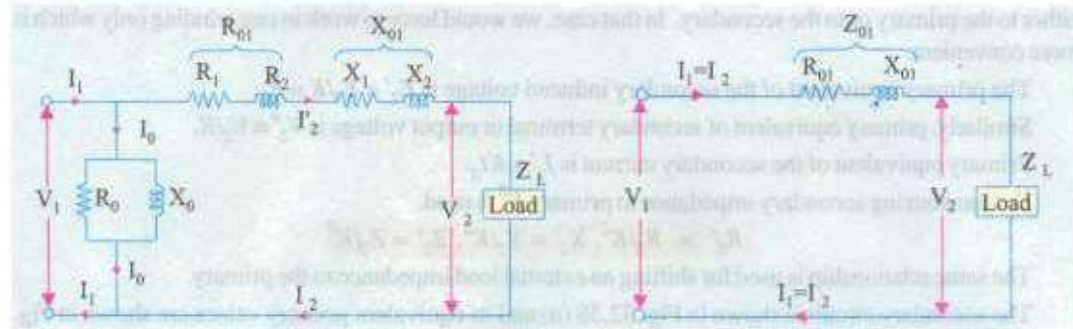


Fig. 32.41 (a)

Fig. 32.41 (b)

Example 32.25. The parameters of a 2300/230 V, 50-Hz transformer are given below :

$$R_1 = 0.286 \, \Omega \quad R_2' = 0.319 \, \Omega \quad R_0 = 250 \, \Omega$$

$$X_1 = 0.73 \, \Omega \quad X_2' = 0.73 \, \Omega \quad X_0 = 1250 \, \Omega$$

The secondary load impedance $Z_L = 0.387 + j0.29$. Solve the exact equivalent circuit with normal voltage across the primary.

Solution.

$$K = 230/2300 = 1/10; \quad Z_L = 0.387 + j0.29$$

$$Z_L' = Z_L/K^2 = 100(0.387 + j0.29) = 38.7 + j29 = 48.4 \angle 36.8^\circ$$

$$\therefore Z_2' + Z_L' = (38.7 + 0.319) + j(29 + 0.73) = 39.02 + j29.73 = 49.0 \angle 37.3^\circ$$

$$Y_m = (0.004 - j0.0008); \quad Z_m = 1/Y_m = 240 + j48 = 245 \angle 11.3^\circ$$

$$Z_m + (Z_2' + Z_L') = (240 + j48) + (39 + j29.7) = 279 \angle 15.6^\circ$$

$$\therefore I_1 = \frac{V_1}{Z_1 + \frac{Z_m(Z_2' + Z_L')}{Z_m + (Z_2' + Z_L')}} = \left[\frac{2300 \angle 0^\circ}{0.286 + j0.73 + 41.4 \angle 33^\circ} \right]$$

$$= \frac{2300 \angle 0^\circ}{42 \angle 33.7^\circ} = 54.8 \angle -33.7^\circ$$

Now

$$I_2' = I_1 \times \frac{Z_m}{(Z_2' + Z_L') + Z_m} = 54.8 \angle -33.7^\circ \times \frac{245 \angle 11.3^\circ}{290 \angle 15.6^\circ}$$

$$= 54.8 \angle -33.7^\circ \times 0.845 \angle -4.3^\circ = 46.2 \angle -38^\circ$$

$$I_0 = I_1 \times \frac{(Z_2' + Z_L')}{Z_m + (Z_2' + Z_L')} = 54.8 \angle -33.7^\circ \times \frac{49 \angle 37.3^\circ}{290 \angle 15.6^\circ}$$

$$= 54.8 \angle -33.7^\circ \times 0.169 \angle 21.7^\circ = 9.26 \angle -12^\circ$$

Input power factor

$$= \cos 33.7^\circ = 0.832 \text{ lagging}$$

Power input

$$= V_1 I_1 \cos \phi_1 = 2300 \times 54.8 \times 0.832 = 105 \text{ kW}$$

Power output

$$= 46.2^2 \times 38.7 = 82.7 \text{ kW}$$

Primary Cu loss

$$= 54.8^2 \times 0.286 = 860 \text{ W}$$

Secondary Cu loss

$$= 46.2^2 \times 0.319 = 680 \text{ W}; \text{ Core loss} = 9.26^2 \times 240 = 20.6 \text{ kW}$$

$$\eta = (82.7/105) \times 100 = 78.8\%; \quad V_2' = I_2' Z_L' = 46.2 \times 48.4 = 2,240 \text{ V}$$

$$\therefore \text{Regulation} = \frac{2300 - 2240}{2240} \times 100 = 2.7\%$$

Example 32.26. A transformer has a primary winding with a voltage-rating of 600 V. Its

transformer has a primary winding With a voltage-ratingOf 600 V. secondary-voltage rating is 1080 V With an additional tap a! 720 V. An 8 kW resistive load is connected across IOSO-V output terminals. A purely inductive load of 10k VA is connected across the

tapping point and common second00' terminal so as get 720 V. Calculate the primary current and its power-factor Correlate if with the existing secondary loads. Neglect losses and magnetizing current. (Nagpur University, Winter 1999)

Solution. Loads are onnectedas shown in Fig. 32142.



8000

=7.41 at unity p,f.

1080

= 10000/720=13.89atzerolaggingp.f.

These arereflected on to the primary sides with appropriate raùos ofturns, with corresponding powerfactors. If the conesponding transformed currents are represented by theabovesymbols modified by

dashed superscripts,

$$I'_{r2} = 7.41 \times 1080/600 = 13.34 \text{ A at unity p.f.}$$

$$I'_{L2} = 13.89 \times 720/600 = 16.67 \text{ A at zero lag. p.f.}$$

Hence,

$$I'_{r2} = [I'^2_{r2} + I'^2_{L2}]^{0.5} = 21.35 \text{ A, at 0.625 lag p.f.}$$

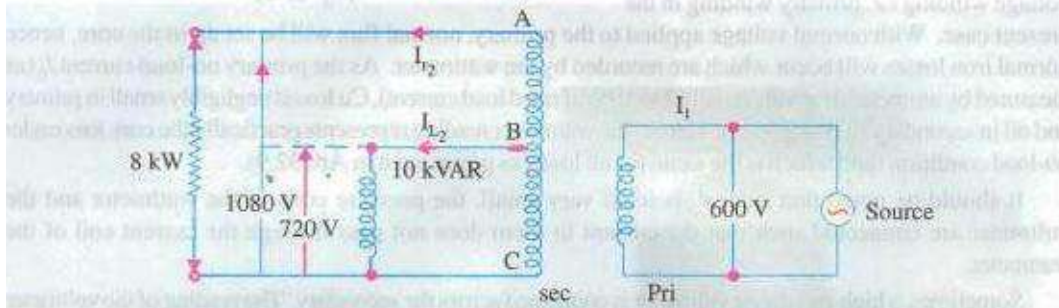


Fig. 32.42

Correlation : Since losses and magnetizing current are ignored, the calculations for primary current and its power-factor can also be made with data pertaining to the two Loads (in kW/kVAR), as supplied by

the 600 V Source.

S = Load to be supplied : 8 kW at unity p.f, and 10 kVAR lagging $s = P + jQ = 8 + j10 \text{ kVA}$

Power—factor =

$$(8^2 + 10^2)^{0.5} = 12.8 \text{ kVA}$$

Primary current = 12.8 x

$$\cos \phi = 8/12.8 = 0.625 \text{ lag} \quad 1000/600 = 21.33 \text{ A}$$

32.19. Transformer Tests

As shown in Ex 32.25, the performance of a transformer can

be calculated on the basis of its equivalent

circuit which contains (Fig. 32.41) four main parameters, the equivalent resistance as referred to primary (or secondary R_{02}), the equivalent leakage reactance as referred to primary (or secondary X_{02}), the core-loss conductance G_0 (or resistance R_{0j}) and the magnetizing susceptance B_0 (or reactance X_{0j}). These constants or parameters



can be easily determined by two tests (i) open-circuit test and (ii) short-circuit test. These tests are very economical and convenient, because they furnish the required information without actually loading the transformer. In fact, the testing of very large machinery consists of running two tests similar to the open

and short-circuit tests of a transformer.

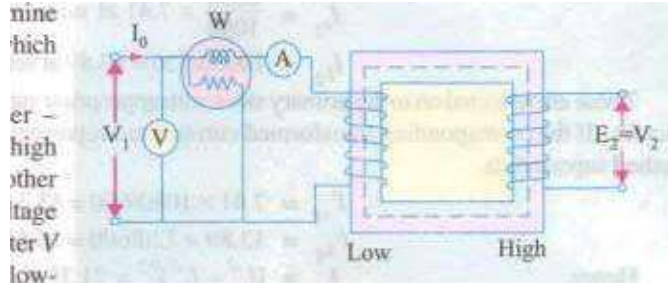
Small transformer

32.20. Open-circuit or No-load Test

The purpose Of this test is to determine no-load loss or core loss and no-load I_0 which is helpful in finding x_0 and R_0 ,

One winding of the transformer — whichever is convenient but usually high voltage Winding —

is left open and the Other is connected to its supply of normal voltage and frequency. A wattmeter W, voltmeter V and an ammeter A are connected in the voltage winding i.e. primary winding in the Fig. 32.43 present case. With normal voltage applied to the primary, normal flux will be set up in the core, hence normal iron losses will which are recorded by the wattmeter. As the primary no-load current I_0 (as measured by ammeter) is small (usually 2 to 5% of rated load current), Cu loss is negligibly small in primary and nil in secondary (it being open). Hence, the wattmeter reading represents [Actually the core loss under no-load condition and which is same for all loads as pointed out in Art_ 32.9



It should be noted that since I_0 is itself very small, the pressure coils of the wattmeter and the voltmeter are connected such that the I_0 does not pass through the current coil of the

Sometimes, connected across the secondary. The reading of the voltmeter gives the induced e.m.f. in the secondary winding. This helps to find transformation ratio K.

The no-load vector diagram is shown in Fig. 32.16. If W is the wattmeter reading (in fig. 32.43).

$$W = V I_0 \cos \phi_0 \therefore \cos \phi_0 = \frac{W}{V I_0}$$

$$= I_0 \sin \phi_0 \quad \text{and}$$

Or since the current is practically all exciting current when a is on no-load (i.e. I_0 and as the voltage drop in primary leakage impedance is hence the exciting admittance Y_0 of the transformer is given by $I_0 V$, Y_0 or $Y_0 = \frac{W}{V^2}$,

$$\text{The exciting conductance } G_0 \text{ is given by } \quad V I_0^2 G_0 \text{ or } G_0 =$$

$$\text{The exciting susceptance} = (Y_0^2 - G_0)$$

Example. 32.27. In no-load test of single-phase transformer, the following test data were obtained :

Primary voltage : 220 V : Secondary voltage : ~~110 V~~ primary current : 0.5 A ; Power input : 30 W.

Find the following:

(i) The turns ratio (in the magnetising component of no-load current) (iii) its working (or loss) component (ii) the iron loss.

Resistance of the primary winding = 0.6 ohm.

Draw the no-load phasor diagram to scale. (Elect. Machine A.M.1-F, A99t)

Solution.

$$\text{--- (iii) } I_0 \cos \phi_0 = 0.5 \times 0.273 = 0.1365 \text{ A}$$

$$\text{Primary Cu loss} = 0.5^2 \times 0.6 = 0.15 \text{ W} \quad \text{Iron loss} = 30 - 0.15 = 29.85 \text{ W}$$

Example 32.28. A 200/1000 V 50 single-phase transformer gave results.

SC.

(i) Calculate the parameters of the equivalent circuit referred to the L side.

(ii) Calculate the output secondary voltage delivering 3 kW primary being 200 V, Find the percentage regulation also.

(Nagpur University, November 19%)

Solution. (i) Shunt branch parameters from O.C. test (L.V. side) :

$$I_0 = 200/90 = 2.22 \text{ A}, \quad 200/444 = 0.45 \text{ amp} = 1.11 \text{ amp}, \quad \phi_0 = 200/1.11$$

All these are referred to LV. side.

(ii) Series branch parameters from S.C test (H.V side):

Since the S.C. test has been conducted from H.V. side, the parameters will refer to H.V. side. They should be converted to the parameters referred to L.V. side by transforming them suitably.

From S.C. Test readings,

These are referred to H.V. side.

Equivalent circuit can be drawn with R_{eq} calculated above and r , and X_{eq} as above.

$$\text{L.V. Current at rated load} = 5000/200 = 25 \text{ A}$$

$$I_{L.V.} \cos \phi = 18.75 \text{ A}$$

3222 Short-Circuit or Impedance Test

This is an economical method for determining the following : iii EAuivalent innrrrdance or G), leakage reactance (X_o , or $X_o:$) and total resistance (or R_z) of the transformer as referred to the winding in which the meaSuring irwtruments are placed.

(iii Cu loss at full load (and at any desired load). 'This loss is used in calculating the efficiency of the transformer liii'

Knowing Z_o , or $Z_o:$, the total voltage drop in the transformer as referred Fig. 32.45 to primary or secondary can be calculated and hence regulation Of the transformer determin

In this test. one winding, usually the low-voltage winding, is solidly short-circuited by a thick conductor (or through an ammeter Which may serve the additional Of indicating rated load curtrnt) as shown in FIE, 32.45.

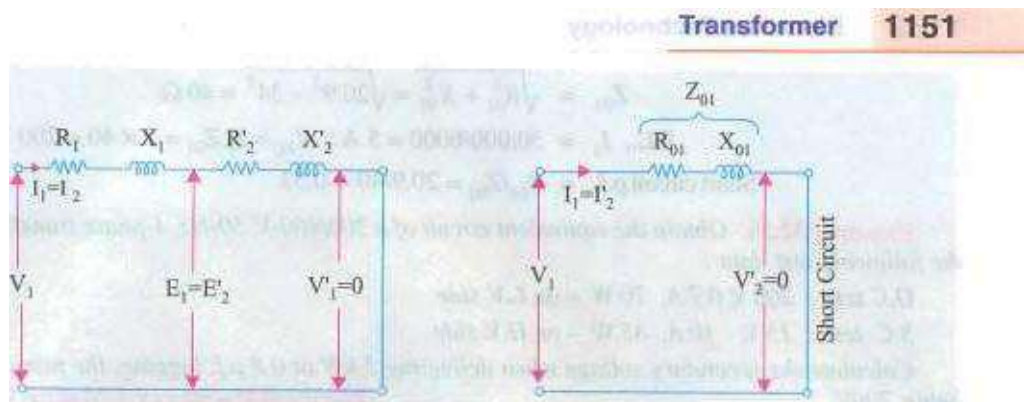
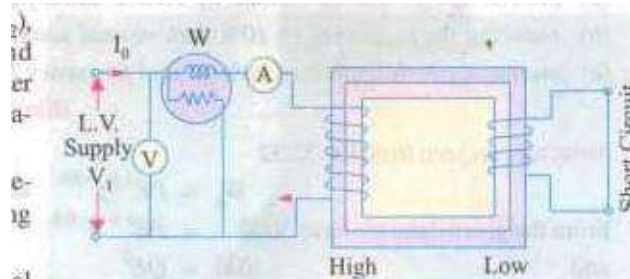


Fig. 32.46

A low voltage (usually 5 to a normal primary voltage) at correct frequency (though for Cu losses it is not essential) is applied to the primary and is cautiously increased till full-load currents are flowing both in primary and secondary indicated by the respective ammeters).

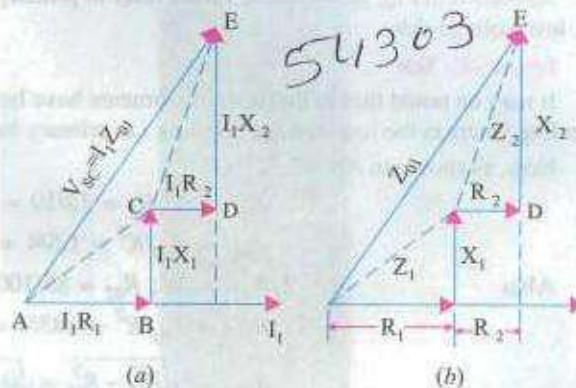
Since, in this test, the applied voltage is a small percentage of the normal voltage, the mutual flux Φ produced is also a small percentage of its normal value (Art. 32.6). Hence, core losses are very small. With the result that the wattmeter reading represents the full-load Cu loss or condition is shown in Fig. 32.46. If V_{sc} is the voltage required to circulate rated load currents, then $Z_{01} = V_{sc}/I_1$.

$$\text{Also } W = I_1^2 R_{01}$$

$$\therefore R_{01} = W/I_1^2$$

$$\therefore X_{01} = \sqrt{(Z_{01}^2 - R_{01}^2)}$$

In Fig. 32.47 (a) the equivalent circuit vector diagram for the short-circuit test is shown. This diagram is the same as shown in Fig. 32.34 except that all the quantities are referred to the primary side. It is obvious that the entire voltage V_{sc} is consumed in the impedance drop of the two windings.



If R_1 can be measured, then knowing R_{01} , we can find $R_2' = R_{01} - R_1$. The

I^2R loss for the whole transformer i.e. both primary Cu loss and secondary Cu loss, The equivalent circuit of the transformer under short-circuit condition is shown in Fig. 32.46, If is the voltage required to =

Fig. 32.47 impedance triangle can then be divided into the appropriate equivalent triangles for primary and secondary as shown in Fig. 32.47(b).

32.23. Why Transformer Rating in kVA ?

As seen, Cu loss of a transformer depends on current and iron loss on voltage. Hence, total transformer loss depends on volt-ampere (VA) and not on phase angle between voltage and current i.e. it is independent of load power factor. That is why rating of transformers is in kVA and not in kW, Example 32—35. The primary and secondary Windings of a 30 kVA 76000/230, V, 1-phase transformer have resistance of 0.016 ohm respectively. The reactance of the transformer referred to the primary is 34 Ohm.



Fig. 32.53 (a)

Fig. 32.53 (b)

$$\therefore R_{02} = \frac{\text{short-circuit power}}{\text{F.L. secondary current}} = \frac{100}{12^2} = 0.694 \Omega$$

$$Z_{02} = 20/12 = 1.667 \Omega; X_{02} = \sqrt{(1.667^2 - 0.694^2)} = 1.518 \Omega$$

As R_0 and X_0 refer to primary, hence we will transfer these values to primary with the help of transformation ratio.

$$K = 500/250 = 2 \quad \therefore R_{01} = R_{02}/K^2 = 0.694/4 = 0.174 \Omega$$

$$X_{01} = X_{02}/K^2 = 1.518/4 = 0.38 \Omega; Z_{01} = Z_{02}/K^2 = 1.667/4 = 0.417 \Omega$$

The equivalent circuit is shown in Fig. 32.53 (a).

Efficiency

Total Cu loss = $I_2^2 R_{02} = 100 \times 0.694 = 69.4 \text{ W}$; Iron loss = 80 W

$$\text{Total loss} = 69.4 + 80 = 149.4 \text{ W} \quad \therefore \eta = \frac{5000 \times 0.8 \times 100}{4000 + 149.4} = 96.42\%$$

The applied voltage V_1' is the vector sum of V_1 and $I_1 Z_{01}$ as shown in Fig. 32.53 (b).

$$I_1 = 20 \text{ A}; I_1 R_{01} = 20 \times 0.174 = 3.84 \text{ V}; I_1 X_{01} = 20 \times 0.38 = 7.6 \text{ V}$$

Neglecting the angle between V_1 and V_1' , we have

$$V_1'^2 = OC^2 = ON^2 + NC^2 = (OM + MN)^2 + (NB + BC)^2$$

$$= (250 \times 0.8 + 3.84)^2 + (250 \times 0.6 + 7.6)^2$$

$$V_1'^2 = 203.5^2 + 157.6^2 \quad \therefore V_1' = 257.4 \text{ V}$$

Example 32.48. A 230/230 V, 3 kVA transformer gave the following results :

O.C. Test : 230 V, 2 amp, 100 W

S.C. Test : 15 V, 13 amp, 120 W

Determine the regulation and efficiency at full load 0.80 p.f. lagging.

(Sambalpur

1998)

Solution. This is the case of a transformer with turns ratio as 1 : 1. Such a transformer is mainly required for isolation.

Transformer 1161

Rated Current = 13 amp

230

Co-losses at rated load 120 watts from S.C. test

Core losses = 100 Watts, from O.C. test

At full load. VA output = 3000

At 0.8 lag p.f. Power output

Required efficiency =

From S.C. test.

Approximate voltage regulation

13.51

In terms of the voltage regulation = $230 \times 100\% - 5.874\%$

Example 32.49. A 10 kVA, 500/250 V. single-phase transformer has its maximum efficiency of 94% When delivering Estimate its efficiency when delivering its full-load output p.f. of 0.8 lagging. (Nagpur University, November 1998)

Solution. Rated output at unity p.f. = 10000 W. Hence, % of rated Output = 9,000 W

Input with efficiency =

Losses =

At maximum efficiency, variable copper-loss = constant = Core

$$574/2 = 287 \text{ W} \quad \text{loss} = 574/2$$

At rated current, Let the copper-loss be P_c

At 90% load with unity p.f.. the copper-loss is expressed as $0.9^2 \times P_c$.

Hence, $P_c = 287/0.81 = 354 \text{ W}$

(b) Output at full-load, 0.8 lag p.f. = $10,000 \times 0.80 = 8000 \text{ W}$

At the corresponding load, Full Load copper-loss = 354 W

Hence, efficiency = $8000 / (8000 + 354 + 287) = 0.926$ or 92.6%

For calculation of voltage-magnitudes, approximate formula for voltage regulation can be used.
For the present case of 0.8 lagging p.f.

$$V_1 = V_2 + [r \cos \phi + x \sin \phi] I$$

$$= \frac{230 + 43.5}{0.316} \times$$

$$= 230 + 43.5 (0.0634 + 0.1896) = 230 + 11 \text{ V, } 241 \text{ volts.}$$

It means that H.V. side terminal voltage must be 241 V for keeping 230 V at the specified load.

(b) Approximate for voltage regulation is : $V_r' =$

With Lagging p.f., sign is retained. With leading power-factor, the —ve sign is applicable.
For the voltage-regulation to be zero, only leading Bf. condition can prevail. $\sin \phi = 0$

$$= \frac{-0.0792}{0.316} = -0.25$$

$$= 140. \cos \phi = 0.97 \text{ leading}$$

$$\text{Corresponding } \sin \phi = \sin 0.243$$

H.V. terminal voltage required is 230 V to maintain 230 V at since regulation condition is under discussion.

Example 32.51. A 5 kVA, 2200/220 single-phase transformer has the following parameters.

H. V. side $r_1 = 3.4 \text{ Ohms}$, $x_1 = 7.2 \text{ ohms}$

L V: side : $r_2 = 0.028 \text{ ohms}$, $x_2 = 0.060 \text{ Ohms}$

Transformer is made to deliver rated current at 0.8 lagging p.f. to a load connected on the L V. side. If the load voltage is 220 V calculate the terminal voltage on H. V side

(Neglect the exciting current). (Rajiv Gandhi Technicl University, Bhopal. Summer 2001)

Solution. Calculations may be done referring all the parameters the LV. side first. Finally, the voltage required on H.V. side can be obtained after transformation.

ref. to L.V. side = $5000/220 = 22.73 \text{ A}$

Total winding resistance ref. to L.V. side = $r_1' + r_2 = (220/2200)^2 \times 3.4 + 0.028$

Total winding-leakage-reactance ref. to L.V. side = $x_1' + x_2$
 $= (220/2200)^2 \times 7.2 + 0.060 = 0.132 \text{ ohm}$

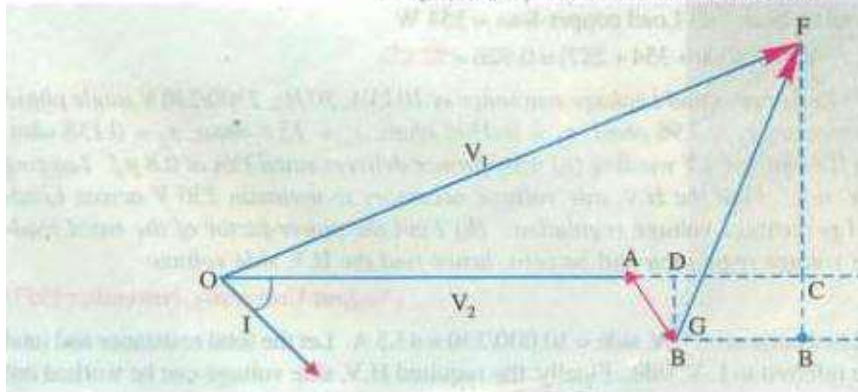


Fig. 32.53(c)

In the phasor diagram of Fig. 32.53 (c),

$OA = V_2 = 220 \text{ volts}, I = 22.73 \text{ A}$ at lagging phase angle of 36.87°

$AB = Ir, AD = Ir \cos \phi = 22.73 \times 0.062 \times 0.80 = 1.127 \text{ V}$

$DC = Ix \sin \phi = 22.73 \times 0.132 \times 0.60 = 1.80 \text{ V}$

Rated

$OC = 220 + 1.127 + 1.80 = 222.93 \text{ volts}$

$BD = Ix \sin \phi = 0.85 \text{ V}$

$VF = xco. = 2.40 \text{ V}$

$CF = 240 - 0.85 = 155 \text{ v}$

$V_1' = OF = \sqrt{(222.93^2 + 1.55^2)^{0.50}} = 222.935 \text{ volts}$

Required terminal voltage of H.V. side - $V_1 = 222935 (2200/220) = 222935 \text{ volts}$

[Note. In approximate and fast calculations. CF is Often for calculation of magnitude or The Concerned expression is: $V_1 \sin \phi$, for lagging P.f.]

Example 32.52. A VA, 200/400 V. single-phase transformer takes 0.7 amp and 65 W on Open circuit. When the low-voltage Winding is short-circuited and 5 V is applied to the high-voltage terminals. the current and power are 10 A and 75 W respectively. Calculate the full-load efficiency at unity factor and full-load regulation at 0.80 power-factor lagging.

(Nagpur University April 1999)

Solution. At a load of 4 kVA. the rated currents are : **L.V**side $4000/200 = 20\text{amp}$

And H.V. side : $4000/400 = 10\text{amp}$

From the test data. full-load copper-loss 75 AV

And Constant core-loss = 65 W

From S.C. test, $Z = 15/10 = 1.5\text{ohms}$

$$R = 75/100 = 0.75\text{ ohm}$$

$$X = \sqrt{1.5^2 - 0.75^2} = 1.30$$

1.52	—	ohms
0.752		

All these series-parameters are referred to the H.V. side, since the S.C. test has been conducted from H.V. side.

Full-load efficiency at unity p.f. = $40 / (40 + 65 + 75)$
 = 0.966-966%

Full load voltage regulation at 0.80 lagging p.f.

Thus, due to loading, H.M side voltage will drop by 16.14 volts (i.e. terminal voltage for the load will be 383.86 volts), when EV. side is energized by 200-V source.

32.25. Percentage Resistance, Reactance and Impedance

These quantities are usually measured by the voltage drop at full-load current expressed as a percentage Of the normal voltage Of the winding on Which calculations are made.

'i' percentage resistance at full-load

x 100

% Cu loss at full-load

...Art-3216

(ii) Percentage reactance at full-load

(iii) Percentage impedance at full-load

It may be noted that percentage resistance, reactance and impedance have the same value whether referred to primary or secondary.

$$= 1.648 + 5.87 = 7.52\%$$

Example 32.57. A transformer has copper loss of 3.5% when tested at full-load. Calculate its full-load regulation at (i) (ii) 0.8 p.f. lagging and (iii) 0.8 p.f. Leading. (Bharathidasan Univ. April 1997)

Solution. The test-data at full-load gives following parameters :

p.a. resistance = 0.015, p.o. reactance = 0.035

(t) Approximate Voltage — Regulation at unity p.f. full load

$$= 0.015 \cos 0 + 0.035 \sin 0$$

$$= 0.015 \text{ per unit} = 1.5\%$$

(ii) Approximate Voltage — Regulation at 0.80 Lagging p.f.

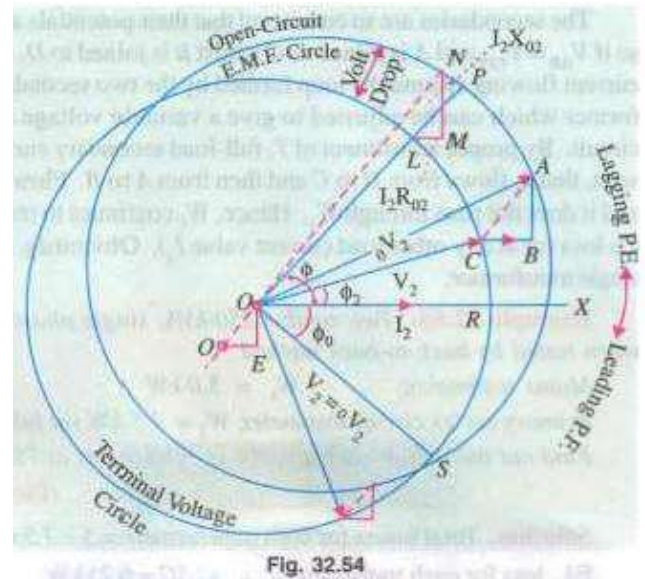
(iii) Approximate Voltage Regulation

$$= (0.015 \times 0.8) + (0.035 \times 0.6) = 0.033 \text{ per unit} = 3.3\%$$

at 0.8 leading p.f.

$$= I_r \cos \phi - I_x \sin \phi$$

$$= (0.015 \times 0.8) - (0.035 \times 0.6) = -0.009 \text{ per unit} = -0.9\% \text{ at 0.8}$$



32.26. Kapp Regulation Diagram

It has been shown that secondary terminal voltage falls as the load on the transformer is increased when p.f. is lagging and it increases when the power factor is leading. In other words, secondary terminal voltage not only depends on the load but on power factor also (Art. 32.16). For finding the voltage drop (Or rise) which is further used in determining the regulation of the transformer, a graphical construction is employed which was proposed by late Dr. Kapp.

For drawing Kapp regulation diagram, it is necessary to know the equivalent resistance and reactance as referred to secondary i.e. R_{02} and X_{02} . If I_2 is the secondary load current, then

secondary terminal voltage On load V_2 . is obtained by subtracting I_2 and $I_2 \times X_2$ voltage drops vectorially from secondary no-load voltage $O V_2$.

NOW, ϕ is constant, hence it is represented by a circle of constant radius OA as in Fig. 32.54. This circle is known as no-load or open-circuit e.m.f. circle. For a given load, $O I_2$ represents the load current and is taken as the reference vector, CB represents $I_2 R_m$ and is parallel to $O I_2$, AB represents $I_2 \times X_2$ and is drawn at right angles to CB . Vector OC obviously represents V_2 and is drawn at right angles to CB . Vector OC obviously represents secondary terminal voltage. Since I_2 is constant, the drop triangle ABC remains constant in size. It is seen that end point C of V_2 lies on another circle whose centre is O' . This point C lies at a distance of $I_2 R_m$ vertically below the point O and a distance of $I_2 X_2$ to its left as shown in Fig. 32.54.

Suppose it is required to find the voltage drop on full-load at a lagging power factor of $\cos \phi$. Then a radius OLP is drawn inclined at an angle of ϕ with OX . $LM = I_2 R_m$ and is drawn horizontal. $MN = I_2 \times X_2$ and is drawn perpendicular to LM . Obviously, ON is no-load voltage V_2 . Now, ON is V_2 . Similarly, OL is V_2 . The voltage drop $OP - OL = LP$.

Hence, percentage regulation • down is — $\frac{OP - OL}{OP} \times 100 = \frac{LP}{OP} \times 100$

It is seen that for finding voltage drop, triangle LMN need not be drawn, but simply the radius OL .

The diagram shows clearly how the secondary terminal voltage falls as the angle of lag increases. Conversely, for a leading factor, the fall in terminal voltage decreases till for an angle of 0° leading, the fall becomes zero; hence $V_2 = V_2$. For angles greater than secondary terminal voltage V_2 greater than V_2 .

The Kapp diagram is very helpful in determining the variation of regulation with

the radii of the circles. diagram has to be drawn on a very large scale, if sufficiently accurate results are

32.27. Sumpner Or Back-to-Back Test

This test provides data for finding the regulation, efficiency and heating under load conditions and is employed only when two similar transformers are available. One transformer is loaded on the other and both are connected to supply. The power taken from the supply is that necessary for supplying the losses of both transformers and the negligibly small in the control circuit.

As shown in Fig. 32.55, primaries of the two transformers are connected in parallel across the same a.c. supply. With switch S open, the wattmeter W_1 reads the core loss for the two transformers.

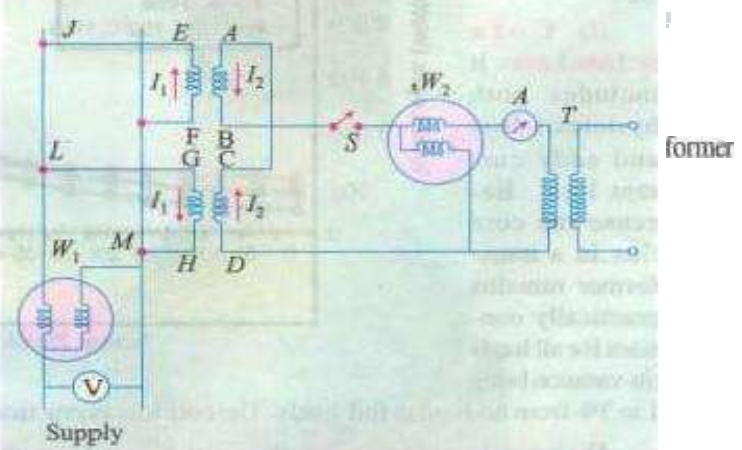


Fig. 32.55

power factor but it has the disadvantage that since the lengths of the sides of the impedance triangle are small as compared to the secondaries are so connected that their potentials are in opposition to each other. This would so if $V_{AB} = V_{CD}$ and A is joined to C whilst B is joined to D. In that case, there would be no secondary current flowing around the loop formed by the two secondaries. This is an auxiliary low-voltage transformer which can be adjusted to give variable voltage and hence current in the secondary loop circuit. By proper adjustment of T, full-load secondary current can be made to flow as shown. It is seen, that I_2 flows from D to C and then from A to B. Flow of I_2 is confined to the loop FEJLGHMF and it does not pass through W_1 . Hence, W_1 continues to read the core loss and W_2 measures full-load Cu loss (or at any other load current value I_2). Obviously, the power taken in is twice the losses of a single transformer.

Example 32.58. Two similar 250-kVA, single-phase transformers when tested by back-to-back method.

Mains $W_1 = 5.0$ kW

Primary series circuit Wattmeter, $W_2 = 7.5$ kW at full-load current, Find the individual transformer efficiencies at

Solution. Total losses for both transformers $= 5 + 7.5 = 12.5$ kW EL. loss for each transformer $= 12.5/2 = 6.25$ kW

$$\text{Copper-loss at 75\% load} = \left(\frac{3}{4}\right)^2 \times \frac{7.5}{2} \text{ kW} = 2.11 \text{ kW}$$

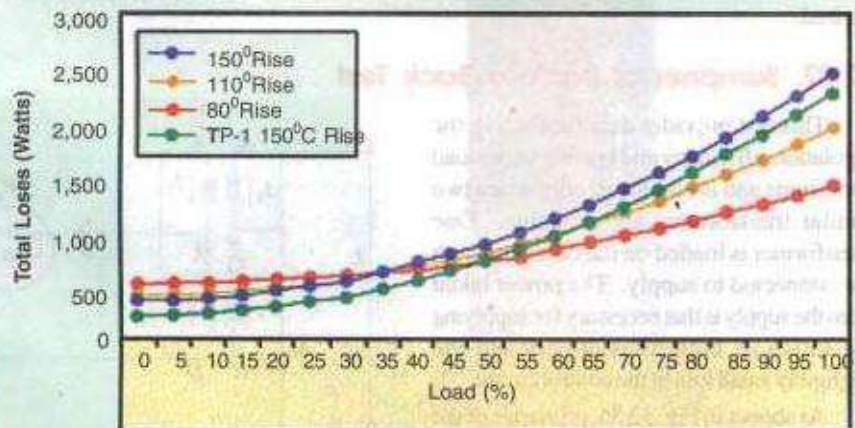
Output of each transformer at 75% F.L. and 0.8 p.f. = $(250 \times 0.75) \times 0.8 = 150 \text{ kW}$

$$\eta = \frac{150}{150 + 2.5 + 2.11} = 97\%$$

32.28. Losses in a Transformer

In a static transformer, there are no friction or windage losses. Hence, the only losses occurring

(i) **Core Iron Loss:** It includes both hysteresis loss and eddy current loss. Because the core flux in a transformer remains practically constant.



0

Stant for all loads Typical 75kVA Transformer LossesNS, Load

(its tx•ing

I to 3% from no-load to full-load). The core loss is practically the same at all loads.

$$W_h = \eta B_{\max}^{1.6} f$$

These losses are minimized by using steel of high silicon content for the core and by using very thin laminations. Iron or core loss is found to be O.C. (esc, The load measures core loss

(ii) **Copper loss.** This loss is resistance

= $11^2 R_1 + R_{ot} + I$ is clear that Cu loss is proportional to (current/ or kVA. In other words, Cu loss at half the full-load is one-fourth of that at full-load.

The value of Cu loss is found from the short-circuit test (Art. 32.22).

32.29. Efficiency Of a Transformer

As in the case with other types of electrical machines, the efficiency of a transformer at a particular load and power factor is defined as the output divided by the input—the two being measured in the same units (either watts or kilowatts)

$$\text{Efficiency} = \frac{\text{Output}}{\text{Input}}$$



But a transformer being a highly efficient piece of equipment, has very small loss, hence it is impractical to measure transformer efficiency by measuring input and output. These quantities are nearly of the same size. A better method is to determine the losses and then to calculate the efficiency from

$$\text{Efficiency} = \frac{\text{Output}}{\text{Output} + \text{losses}} = \frac{\text{Output}}{\text{Output} + \text{Cu loss} + \text{iron loss}}$$

$$\eta = \frac{\text{Input} - \text{Losses}}{\text{Input}} = 1 - \frac{\text{losses}}{\text{Input}}$$

Output

It may be noted here that efficiency is based on power output in watts and not in volt-amperes, although losses are proportional to VA. Hence, at any volt-ampere load, the efficiency depends on power factor, being maximum at a power factor of unity.



Efficiency can be computed by determining core loss from the no-load or open-circuit test and Cu loss from the short-circuit test.

32.30. Condition for Maximum Efficiency

cu loss

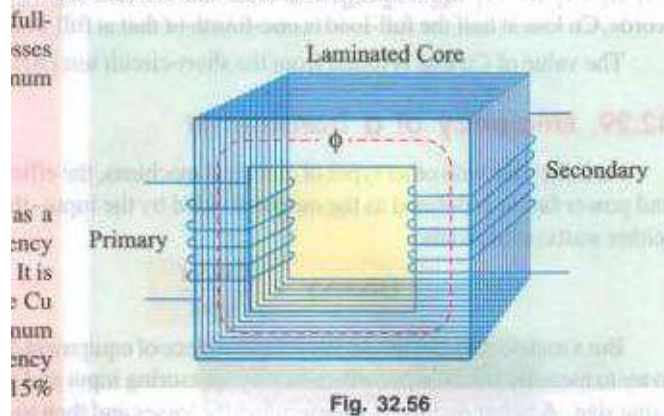
For η to be maximum.

The output current corresponding to maximum efficiency is $I_2 = \sqrt{W_i/R_{02}}$.

It is this value of the output current which will make the Cu loss equal to the iron loss. By design, it is possible to make the maximum efficiency occur at any desired load.

Note. If we are given iron loss and full-load Cu loss, then the load at which two losses would equal (i.e. to maximum efficiency) is given by

which will make the Cu loss equal to the iron loss. By proper design, maximum efficiency occurs at any desired load.



In Fig. 32.56, Cu losses are plotted against power input and the efficiency curve as deduced from these is also shown. It is obvious that the point of intersection of the Cu and iron loss curves gives the point of maximum efficiency. It is seen that the efficiency is high and is practically constant from full-load to overload. (ii) The efficiency at any load is given by

where x

Example 323. In a 25-kVA, 2000/200 V. single-phase transformer, the iron and full-load copper losses are 350 and 400 W respectively. Calculate the efficiency at unity power factor on

(i) full load (ii) half full-load.

(Elect. Engg. & Electronic. Bangalore Univ. 1990 and

Solution. (i) Full-load Unity p.f.

Similar example in U.P. Technical University 2001)

Total loss =

FL output at u.p.f. = 25 x 1 = 25 kW

Cu loss = 400 W Iron loss remains constant at 350 W. Total loss = 350 + 400 = 750 W.

Half-load output at u.p.f. = 12.5 kW

Example 320. W_i and p_c be the iron and copper losses of a transformer on full-load. Find the ratio of P_1 and P_2 such that maximum efficiency occurs at half-load.

Sec. B, Summer 1992)

Solution. If P_i is the Cu loss at full-load, its value at 75% of full-load is $\frac{1}{4}P_i$. At maximum efficiency, it equals the iron loss P_w which remains constant throughout. Hence, at maximum efficiency,

$$P_w = \frac{1}{4}P_i \text{ or } P_i = 4P_w$$

Example 32.61. A 11000/230 V, 150-kVA, 1-phase, transformer has core loss of 1.4 kW and EL Cu loss of 160 kW. Determine

- the load for max efficiency and value of efficiency at unity p.f.
- the efficiency at half load 0.8 p.f. leading (Basic Elect-Machine, Nagpur Univ. 1993)

Solution. (i) Load for corresponding to maximum efficiency is

Since Cu loss equals iron loss at maximum efficiency, total loss output
 $= 160 \times 1 = 160 \text{ kW}$

$$= 160 / 162.8 = 0.982 \text{ or } 98.2\%$$

- Cu loss at half full-load $= 160 (1/2)^2 = 40 \text{ kW}$ Total loss $= 1.4 + 40 = 41.4 \text{ kW}$

Half EL output at 0.8 p.f. $= (150/2) \times 0.8 = 60 \text{ kW}$
 $\text{Efficiency} = \frac{60}{60 + 41.4} = 0.97 \text{ or } 97\%$

Example 32.62. A 5-kVA, 230/300-V 50-Hz transformer was tested for the iron losses 'With normal excitation and Cu losses at full-load and these were found to be 40 W and 112 W respectively.

Calculate the efficiencies of the transformer at 0.8 power factor for the following VA outputs :

1.25 2.5 3.75 so 6.25 7.5

Plot efficiency vs kVA output curve.

(Elect. Engg. -I, Bombay Univ. 1987)

Solution. F.L. Cu loss = 112 W ; Iron loss = 40 W

(i) Cu loss at 1.25 kVA = $112 \times (1.25/5)^2 = 7 \text{ W}$

Total loss = $40 + 7 = 47 \text{ W}$ Output = $1.25 \times 0.8 = 1 \text{ kW} = 1,000 \text{ W}$

$\eta = 100 \times 1,000 / 1,047 = 95.51 \%$

(ii) Cu loss at 2.5 kVA = $112 \times (2.5/5)^2 = 28 \text{ W}$

Total loss = $40 + 28 = 68 \text{ W}$

Output = $2.5 \times 0.8 = 2 \text{ kW}$

$\eta = 2,000 \times 100 / 2,068 = 96.71 \%$

(iii) Cu loss at 3.75 kVA

= $112 \times (3.75/5)^2 = 63 \text{ W}$

Total loss = $40 + 63 = 103 \text{ W}$

$\eta = 3,000 \times 100 / 3,103 = 96.68 \%$

(iv) Cu loss at 5 kVA

= 112 W

Total loss = 152 W = 0.152 kW

Output = $5 \times 0.8 = 4 \text{ kW}$

$\eta = 4 \times 100 / 4.142 = 96.34 \%$

(v) Cu loss at 6.25 kVA

= $112 \times (6.25/5)^2 = 175 \text{ W}$

Total loss = 125 W = 0.125 kW ; Output = $6.25 \times 0.8 = 5 \text{ kW}$

$\eta = 5 \times 100 / 5.215 = 95.88 \%$

(vi) Cu loss at 7.5 kVA = $112 \times (7.5/5)^2 = 252 \text{ W}$

Total loss = 292 W = 0.292 kW ; Output = $7.5 \times 0.8 = 6 \text{ kW}$

$\eta = 6 \times 100 / 6.292 = 95.36 \%$

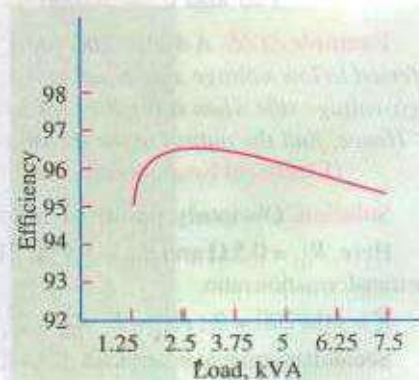


Fig. 32.57

The curve is shown in Fig. 32.57.

Example 32.63. 200-kVA transformer has an efficiency of 98% at full load. The max. efficiency occurs at three quarters of full-load. Calculate the efficiency at half load. Assume negligible magnetizing current and p.f. 0.8 at all loads. (Elect. Punjab Univ. Jan. 1991)

Solution. As given, the transformer has a max. efficiency of 98% at 0.75 full load.

EL. output = $200 \times 0.8 = 160 \text{ kW}$; EL. input = $160 / 0.98 = 163.265 \text{ kW}$

F.L. losses = $163.265 - 160 = 3.265 \text{ kW}$ EL output = $25 \times 0.8 = 20 \text{ kW} = 20,000 \text{ W}$

Full-load = $20,000 \times 100 / (20,000 + 3,265) = 86.4\%$

Example 32.6*. A 4-kVA, 230/115-V, 1-phase transformer has equivalent resistance and reactance referred to low-voltage side equal to 0.512 Ω and 1.5 Ω respectively. Find the terminal voltage on

the high-voltage side When supplies 3/4 full-load at power factor 0.8, the supply voltage being 220 V. Hence, find the output transformer and its efficiency if the core losses are 100 W.

(Electrical Engineering : Bombay Univ. 1985)

Solution. Obviously, primary is the low-voltage side and the secondary is the high-voltage side.

Here, I_1 and I_2 can be transferred to the secondary side with the help of the transformation ratio.

Secondary current when load is 3/4 the full-load is $(\frac{3}{4} \times 400) / 75 = 160$ A

Total drop as referred to transformer secondary is

Terminal voltage on high-voltage side under given load condition is $= 400 - 39 = 361$ V
 Iron loss 100 W

$= 212.5$ W output $= (\frac{3}{4} \times 400) \times 0.8 = 2.4$ kW

Input $= 212.5 + 2.4 \times 1000 = 2612.5$ W $\eta = \frac{2400}{2612.5} = 91.87\%$

Example 32.66. A 20-kVA, 440/220 V, 50 Hz transformer has iron loss 100 W. The Cu loss is found to be 200 W when delivering half full-load current. Determine efficiency when

delivering full-load current at 0.8 lagging power factor

When the efficiency will be maximum. (Electrical Engineering, MS. Univ., Baroda 1987)

Hence, efficiency would be maximum at 90% of EL

Example 32.67. Consider a 4-kVA, 200/400 V single-phase transformer supplying full-load current at 0.8 lagging power factor. The open-circuit and short-circuit test results are as follows :

O.C. test : 200 V, 0.5 A, 70 W (H.V. side)

S.C. test : 200 V, 10 A, 60 W (L.V. side)

Calculate efficiency, secondary voltage and current into primary at the above load.

Calculate the load at unity power factor corresponding to maximum efficiency. (Electrical Machines Nagpur Univ. 1993)

Solution. Full-load current $= \frac{4000}{400} = 10$ A

It means that S.C. test has been carried out with full secondary flowing, Hence, 60 W represents full-load Cu loss of the transformer.

EL losses $= 60 +$

$$\text{EL. n} = 3.2/3.33 = 0.96 \text{ or } 96\%$$

Example 32.68. A 600 kVA, 1-phase transformer has an efficiency of 92 % both at full-load and half-load at unity power factor. Determine its efficiency at 60 % of full-load at 0.8 power factor lag.

Sol. B,

x kVA

2

$(x \times W_A) \times \cos \phi + W_i + \frac{1}{4} W_{cu}$ where x represents percentage of full-load, W_i is iron loss and W_{cu} is full-load Cu loss,

At full load, Here x =

$$\frac{W_i}{W_{cu}} = \frac{52.174 \text{ kW}}{360 \text{ kW}}$$

At half load, efficiency =

*100;

$$= 85.9\%$$

has an efficiency of 92 % at full-load and also at half-load. Determine its efficiency when it operates at 0.8 p.f. and 60 % of load. (Electric Machines, Kerala Univ. 1987)

Solution. The fact that efficiency is the same (92 %) at both full-load and half-load will help us to find the iron and copper losses.

At full-load

Output - 600 kW ;

Since Cu loss becomes one-fourth of its full-load value, hence $\frac{x}{4} = 26$. Solving for x and y, we get 17.4 kW ; y =

$$\text{At 60 full-load Cu loss} = 0.62 \times 34.5 = 21.29 \text{ kW ; Total loss} = 17.4 + 21.29 = 38.69 \text{ kW}$$

$$\frac{360 \text{ kW}}{388.69} = 0.925 \text{ or } 92.5\%$$

Example 32.70. The maximum efficiency of a 100-kVA, single phase transformer is 98 % and occurs at full load at 0.8 p.f. If the leakage impedance of transformer is 0.02 pu, find the voltage regulation at rated load of 0.8 power factor lagging.

(Elect. Machines-I, Nagpur Univ. 1993)

Solution. Since maximum efficiency occurs at 80 percent of full-load at 0.8 p.f.,

$$64/0.98=65.3 \text{ kW}$$

$$\text{Cu loss at full-load} = 0.65/0.8^2 = 1 \text{ kW}$$

$$\text{Cu loss} \frac{100}{100}$$

$$\times 100 - 1 \times$$

$$100$$

$$\% \text{ age regn,} = + 5 \text{ (0.6)}$$

Example 32.71. A 10kVA, 500V/230V single phase transformer has eddy current and hysteresis losses of 1.0 and 0.6 per cent of output on full load. What will be the percentage losses if the transformer is used on 500V-110V system keeping the full-load current constant?

Assume unity power factor operation. Compare the full load efficiencies for the two cases.

(Elect. Machines, B, 1991)

Solution. We know that $E \propto \phi f$. When both excitation voltage and frequency are doubled, flux remains unchanged.

FL. output at upf 10kVA $\times$ 1.0 = 10kW

$$\text{FL Cu loss} = 1.5 \times 10/100 = 0.15 \text{ kW} : \text{Eddy current loss}$$

$$= 0.5 \times 10 = 0.05 \text{ kW} : \text{Hysteresis loss} = 0.6 \times 10$$

Now, full-load current is kept constant but voltage is increased from 500V to 1000V. Hence, output will be doubled to 20 kW. Due to constant current, Cu loss would also remain constant.

$$\text{New Cu loss} = 0.15 \text{ kW, \% cu loss}$$

Now, eddy current loss

$$\text{New eddy current loss} = 0.05 \times 100 = 5 \%$$

$$\text{Now, } = 0.06 \times (50/25) = 0.12 \text{ kW, \%}$$

$$\text{at } 0.8 \text{ p.f.} \quad \text{a/ normal voltage}$$

Solution.

Example 32.73. A single phase transformer is rated at 100kVA, 2300/230V, 50 Hz. The maximum flux density in the core is 1.2 Wb/m² and the net cross-sectional area of the core is 0.04m².

Determine

- (a) The number of primary and Secondary turns needed.
- (b) If the mean length of the magnetic circuit is 2.5 m and the relative permeability is 1200, determine the magnetising current. Neglect the current drawn for the core loss.
- (c) On short-circuit with full-load current flowing, the power input is 1200 W and an open circuit with rated voltage, the power input was 400 W. Determine the efficiency of the transformer at 75 % of full-load with 0.8 p.f lag.
- (d) If the same transformer is connected to a supply frequency
- (i.e., 100 What is effect on its efficiency ? (Elect. Engg., Bombay U. is. 19tB)

—9.21 A

Output— $100 \times (3/4)$

(d) When frequency is doubled, iron loss is increased because

(i) hysteresis loss is doubled—

(ii) eddy current loss is quadrupled — We Hence, efficiency will decrease

what is the power-factor at which the regulation will be zero; (ii) positive-maximum ? (b) If its maximum efficiency occurs at full-load (at unity p.f, what will be efficiency under these conditions ?

Solution : Approximate percentage regulation is given, in this case, by the relationship

$$I \quad 5.4 \sin \theta.$$

(a) Regulation :

(i) If regulation is zero, negative sign must be applicable. This happens at leading p.f.

$$\text{Corresponding pf.} = \text{leading}$$

$$= 18.44^\circ \text{ leading}$$

(ii) For maximum positive regulation, lagging p.f. is a must. From phasor diagram, the can be obtained.

$$\text{Corresponding } \tan \quad 5.4/1.8$$

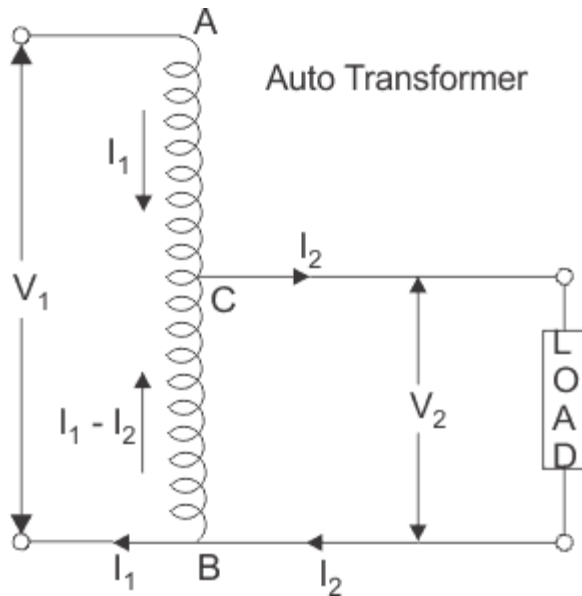
% Voltage regulation = $1.8 \cos \theta + 5.4 \sin \theta = 5.7\%$ (b) Efficiency : Maximum efficiency occurs at such a iron losses =

AUTO TRANSFORMER

An **autotransformer** is a kind of [electrical transformer](#) where primary and secondary shares same common single winding. So basically it's a one winding transformer.

Autotransformer Theory

In an auto transformer, one single winding is used as primary winding as well as secondary winding. But in two windings transformer two different windings are used for primary and secondary purpose. A circuit diagram of auto transformer is shown below.



The winding AB of total turns N_1 is considered as primary winding. This winding is tapped from point 'C' and the portion BC is considered as secondary. Let's assume the number of turns in between points 'B' and 'C' is N_2 .

If V_1 [voltage](#) is applied across the winding i.e. in between 'A' and 'C'.

So voltage per turn in this winding is $\frac{V_1}{N_1}$

Hence, the voltage across the portion BC of the winding, will be,

$\frac{V_1}{N_1} \times N_2$ and from the figure above, this voltage is V_2

$$\text{Hence, } \frac{V_1}{N_1} \times N_2 = V_2$$

$$\Rightarrow \frac{V_2}{V_1} = \frac{N_2}{N_1} = \text{Constant} = K$$

As BC portion of the winding is considered as secondary, it can easily be understood that value of constant 'k' is nothing but [turns ratio](#) or voltage ratio of that **auto transformer**. When load is connected between secondary terminals i.e. between 'B' and 'C', load current I_2 starts flowing. The [current](#) in the secondary winding or common winding is the difference of I_2 and I_1 .

Copper Savings in Auto Transformer

Now we will discuss the savings of copper in auto transformer compared to conventional two winding transformer.

We know that weight of copper of any winding depends upon its length and cross-sectional area. Again length of conductor in winding is proportional to its number of turns and cross-sectional area varies with rated current.

So weight of copper in winding is directly proportional to product of number of turns and rated current of the winding.

Therefore, weight of copper in the section AC proportional to,

$$(N_1 - N_2)I_1$$

and similarly, weight of copper in the section BC proportional to,

$$N_2(I_2 - I_1)$$

Hence, total weight of copper in the winding of auto transformer proportional to,

$$(N_1 - N_2)I_1 + N_2(I_2 - I_1)$$

$$\Rightarrow N_1I_1 - N_2I_1 + N_2I_2 - N_2I_1$$

$$\Rightarrow N_1I_1 + N_2I_2 - 2N_2I_1$$

$$\Rightarrow 2N_1I_1 - 2N_2I_1 \text{ (Since, } N_1I_1 = N_2I_2 \text{)}$$

$$\Rightarrow 2(N_1I_1 - N_2I_1)$$

In similar way it can be proved, the weight of copper in two winding transformer is proportional to,

$$N_1I_1 - N_2I_2$$

$$\Rightarrow 2N_1I_1 \quad (\text{Since, in a transformer } N_1I_1 = N_2I_2)$$

$$N_1I_1 + N_2I_2$$

$$\Rightarrow 2N_1I_1 \text{ (Since, in a transformer } N_1I_1 = N_2I_2 \text{)}$$

Let's assume, W_a and W_{tw} are weight of copper in auto transformer and two winding transformer respectively,

$$\text{Hence, } \frac{W_a}{W_{tw}} = \frac{2(N_1 I_1 - N_2 I_1)}{2(N_1 I_1)}$$

$$= \frac{N_1 I_1 - N_2 I_1}{N_1 I_1} = 1 - \frac{N_2 I_1}{N_1 I_1}$$

$$= 1 - \frac{N_2}{N_1} = 1 - k$$

$$\therefore W_a = W_{tw}(1 - k)$$

$$\Rightarrow W_a = W_{tw} - kW_{tw}$$

$\therefore$ Saving of copper in auto transformer compared to two winding transformer,

$$\Rightarrow W_{tw} - W_a = kW_{tw}$$



Auto transformer employs only single winding per phase as against two distinctly separate windings in a conventional transformer.

Advantages of using Auto Transformers

1. For transformation ratio = 2, the size of the **auto transformer** would be approximately 50% of the corresponding size of two winding transformer. For transformation ratio say 20 however the size would be 95 %. The saving in cost of the material is of course not in the same proportion. The saving of cost is appreciable when the ratio of transformer is low, that is lower than 2. Thus auto transformer is smaller in size and cheaper.

2. An auto transformer has higher efficiency than two winding transformer. This is because of less ohmic loss and core loss due to reduction of transformer material.
3. Auto transformer has better [voltage regulation](#) as [voltage drop](#) in [resistance](#) and reactance of the single winding is less.

Disadvantages of Using Auto Transformer

1. Because of [electrical conductivity](#) of the primary and secondary windings the lower voltage circuit is liable to be impressed upon by higher voltage. To avoid breakdown in the lower voltage circuit, it becomes necessary to design the low voltage circuit to withstand higher voltage.
2. The [leakage flux](#) between the primary and secondary windings is small and hence the impedance is low. This results into severer short circuit currents under fault conditions.
3. The connections on primary and secondary sides have necessarily needs to be same, except when using interconnected starring connections. This introduces complications due to changing primary and secondary phase angle particularly in the case of delta/delta connection.
4. Because of common neutral in a star/star connected auto transformer it is not possible to earth neutral of one side only. Both their sides should have their neutrality either earth or isolated.
5. It is more difficult to maintain the electromagnetic balance of the winding when voltage adjustment tappings are provided. It should be known that the provision of tapping on an auto transformer increases considerably the frame size of the [transformer](#). If the range of tapping is very large, the advantages gained in initial cost is lost to a great extent.

Applications of Auto Transformers

1. Compensating [voltage drops](#) by boosting supply voltage in distribution systems.
2. Auto transformers with a number of tapping are used for starting induction and synchronous motors.
3. **Auto transformer** is used as variac in laboratory or where continuous variable over broad ranges are required.

INSTRUMENT TRANSFORMER

Instrument Transformers are used in AC system for [measurement of electrical quantities](#) i.e. [voltage](#), [current](#), power, energy, [power factor](#), frequency. **Instrument transformers** are also used with [protective relays](#) for [protection of power system](#).

Basic function of **Instrument transformers** is to step down the AC System voltage and current. The voltage and current level of power system is very high. It is very difficult and costly to design the measuring instruments for measurement of such high level voltage and current. Generally [measuring instruments](#) are designed for 5 A and 110 V.

The measurement of such very large electrical quantities, can be made possible by using the Instrument transformers with these small rating measuring instruments. Therefore these instrument [transformers](#) are very popular in modern power system.



Advantages of Instrument Transformers

1. The large voltage and current of AC Power system can be measured by using small rating measuring instrument i.e. 5 A, 110 – 120 V.
2. By using the instrument transformers, measuring instruments can be standardized. Which results in reduction of cost of measuring instruments. More ever the damaged measuring instruments can be replaced easy with healthy standardized measuring instruments.

3. Instrument transformers provide electrical isolation between high voltage power circuit and measuring instruments. Which reduces the [electrical insulation](#) requirement for measuring instruments and protective circuits and also assures the safety of operators.
4. Several measuring instruments can be connected through a single [transformer to power system](#).
5. Due to low voltage and current level in measuring and protective circuit, there is low power consumption in measuring and protective circuits.

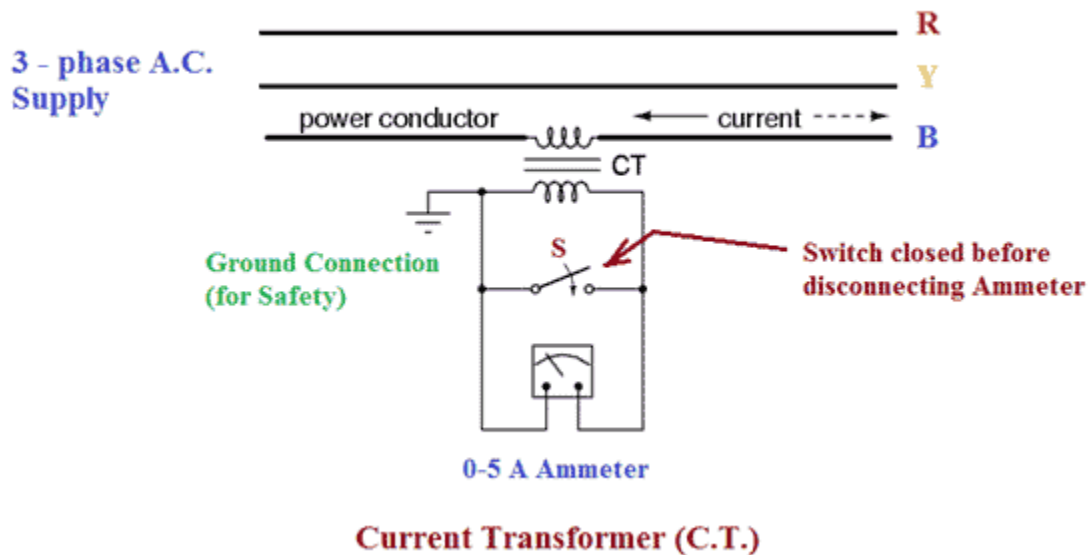
Types of Instrument Transformers

Instrument transformers are of two types –

1. Current Transformer (C.T.)
2. Potential Transformer (P.T.)

Current Transformer (C.T.)

[Current transformer](#) is used to step down the current of power system to a lower level to make it feasible to be measured by small rating Ammeter (i.e. 5A ammeter). A typical connection diagram of a current transformer is shown in figure below.

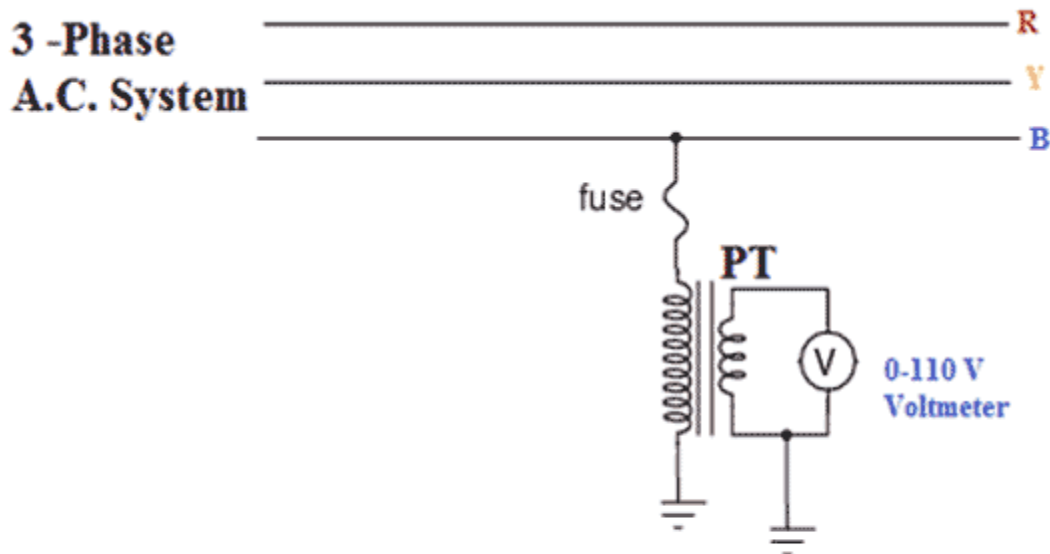


Primary of C.T. is having very few turns. Sometimes bar primary is also used. Primary is connected in series with the power circuit. Therefore, sometimes it also called **series transformer**. The secondary is having large no. of turns. Secondary is connected directly to an ammeter. As the ammeter is having very small resistance.

Hence, the secondary of current transformer operates almost in short circuited condition. One terminal of secondary is earthed to avoid the large voltage on secondary with respect to earth. Which in turns reduce the chances of insulation breakdown and also protect the operator against high voltage. More ever before disconnecting the ammeter, secondary is short circuited through a switch 'S' as shown in figure above to avoid the high voltage build up across the secondary.

Potential Transformer (P.T.)

[Potential transformer](#) is used to step down the voltage of power system to a lower level to make is feasible to be measured by small rating [voltmeter](#) i.e. 110 – 120 V voltmeter. A typical connection diagram of a [potential transformer](#) is showing figure below.



Potential Transformer (P.T.)

Primary of P.T. is having large no. of turns. Primary is connected across the line (generally between on line and earth). Hence, sometimes it is also called the **parallel transformer**. Secondary of P.T. is having few turns and connected directly to a voltmeter. As the voltmeter is having large resistance. Hence the secondary of a P.T. operates almost in open circuited condition. One terminal of secondary of P.T. is earthed to maintain the secondary voltage with respect to earth. Which assures the safety of operators.

Difference between C.T. and P.T.

Few differences between C.T. and P.T. are listed below –

Sl. No.	Current Transformer (C.T.)	Potential Transformer (P.T.)
1	Connected in series with power circuit.	Connected in Parallel with Power circuit.
2	Secondary is connected to Ammeter.	Secondary is connected to Voltmeter.
3	Secondary works almost in short circuited condition.	Secondary works almost in open circuited condition.
4	Primary current depends on power circuit current.	Primary current depends on secondary burden.
5	Primary current and excitation vary over wide range with change of power circuit current	Primary current and excitation variation are restricted to a small range.
6	One terminal of secondary is earthed to avoid the insulation break down.	One terminal of secondary can be earthed for Safety.
7	Secondary is never be open circuited.	Secondary can be used in open circuit condition.