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. I , 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 now 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. I is shown a single-turn rectangular coil ABCD rotating about its own axis in a

magnetic field provided by either permanent magnet is or electromagnets. The two ends of the coil

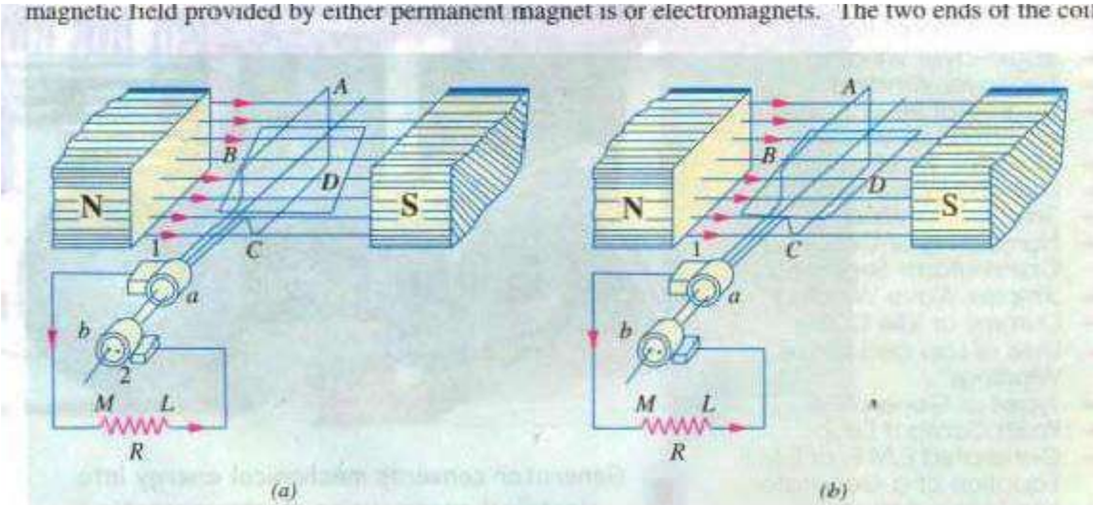


Fig. 26.1

magnetic field provided by either magnet is 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 il to the external load resistance R.

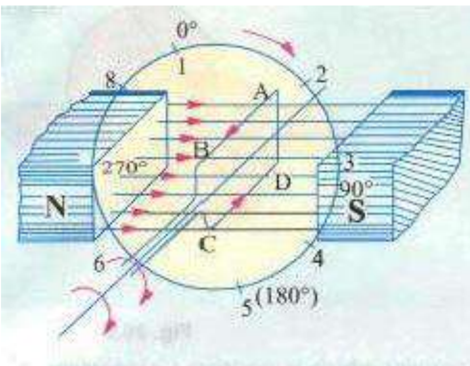
The rotating coil may bc called •armature' and the magnets as 'field magnets .

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 Ehanges. Hence. an e.m.f. is induced in it which is

proportional to the rate Of change Of flux linkages (e = NdcÞdt). When the plane Of the coil is at right angles to lines of flux i.e. when it is in position, I, then flux linked with the coil is maximum butrate Ofchange Offlux linkages is minimum.

It is so because in this position, the coil sidesAB and CD do not cutor 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.



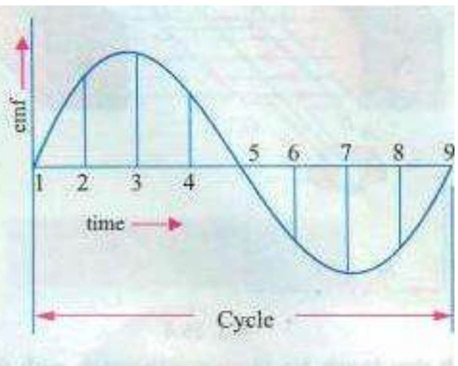


Fig. 26.2 Fig, 26.3

As the coil continues rotating further, the rate Of change Of flux linkages (and hence induced e_mf. in it) increases. till position 3 is reached where $6 = 90^0$. Here, the coil plane is horizontal i.e. parallel to the lines Of flux. As seen. the flux linked with the coil is minimum butrate ofchange Of 'lax 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 900 to 1800, the flux linked With the coil gradually incrënses but the rate Of change Of flux linkages decreases. Hence, the induced c.m.f. decreases gradually till in position 5 ofthe 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 l, maximum when in position 3 and noe.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 ABMLCD (fig. 26. l). The current through the load resistance R flows from M to L during the first half revolution of the coil.

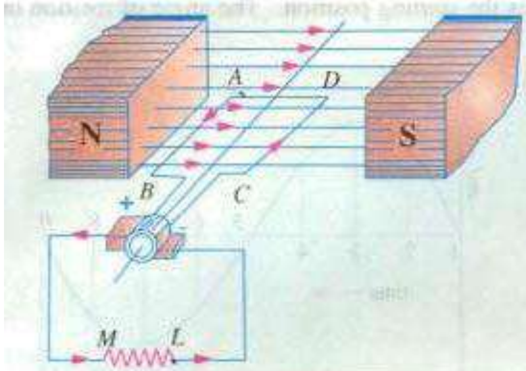
In the next half revolution i.e. from ISV to 360. the variations in the magnitude of are similar to those in the first half revolution. Its value is maximum when coil is in position 7 and minimum when in position I. But it will be found that the direction of the induced current is from D to C and B to 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 sueh a simple generator reverses its direction after every half revolution, Such a current undergoing periodic reversals is known as alternatingcurrent. 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 doesnoteven 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 endsare joined to these segments on Which rest thecarbon or brushes. It is seen IFig. 26,6 that in the first half revolution current flows along BMNI_CDJ i:e. the brush NO. I in contact with segment 'a' acts as the positive end of the supply and •b' the negative end. In the next half revolution IFig. 26.6 (b)l. 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



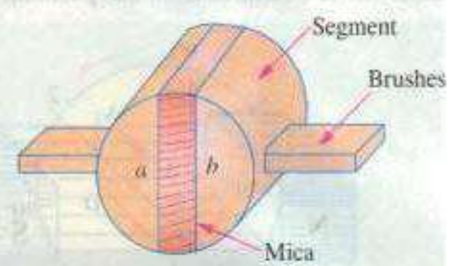
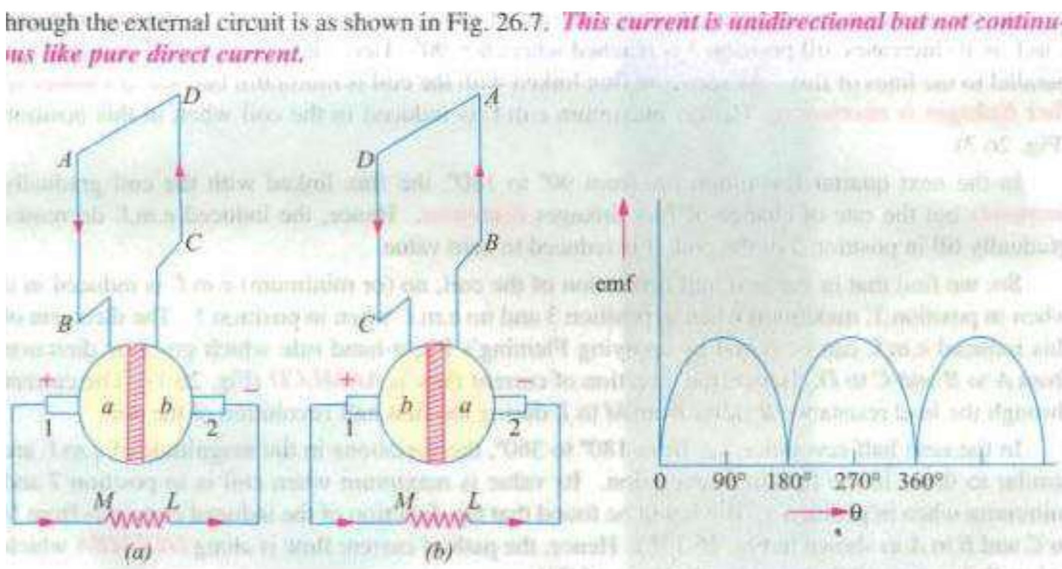


Fig. 26.4 Fig. 26.5 result that brush No. I comes in touch with the segment which is positive i.e. segment in this case. Hence. current in the load resistance again flows from M to



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 ofbrushes 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 clue to the rectifying action of the split-rings (also called commutator) that it becomes unidirectional in the external Circuit. Hence. it should be clearly undEr• stood that in the armature Of a generator. the induced voltage is alternating.

Generator-

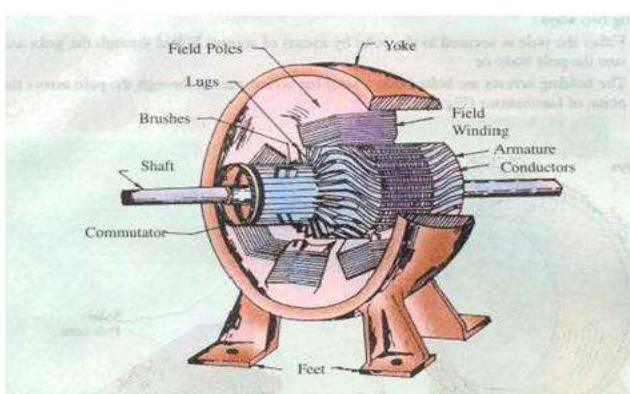


Fig. 26.8

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 eithercast 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 aœ rivetted together under hydraulic pressure (Fig. 26_11). The thickness Of laminations varies from I 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).

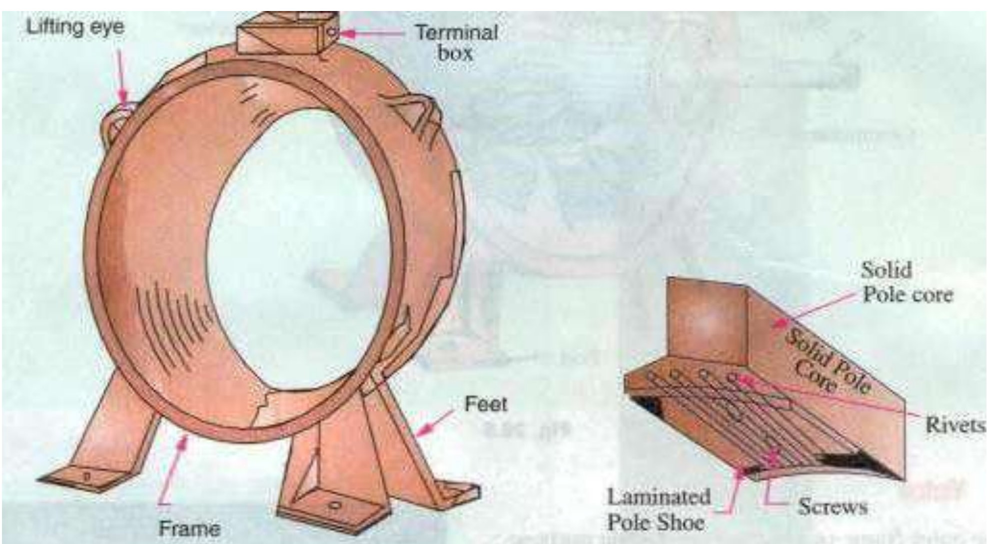
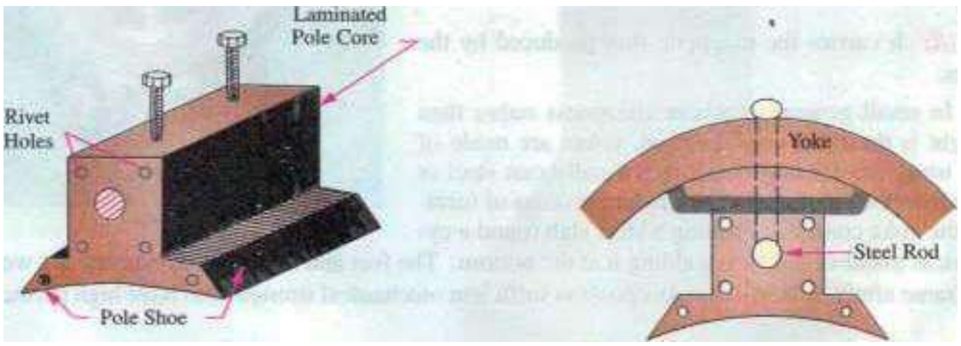


Fig. 26,9 Fig. 26.10



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-shiped and is built up of usually circular sheet steel discsorlaminations 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 lameter 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.

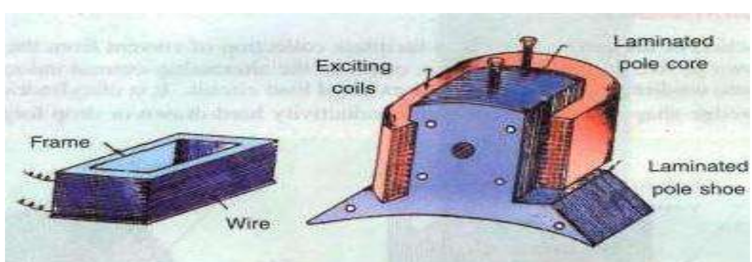
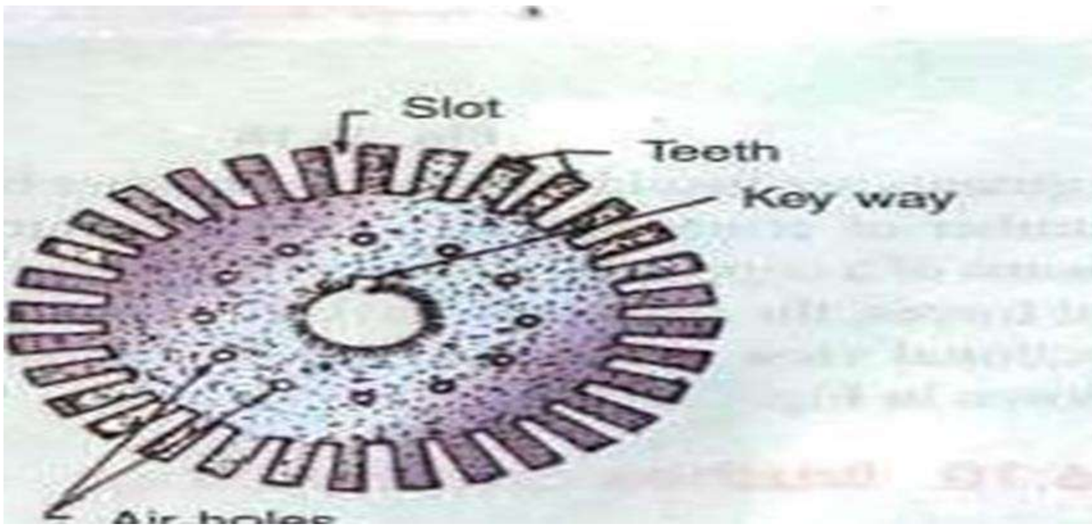
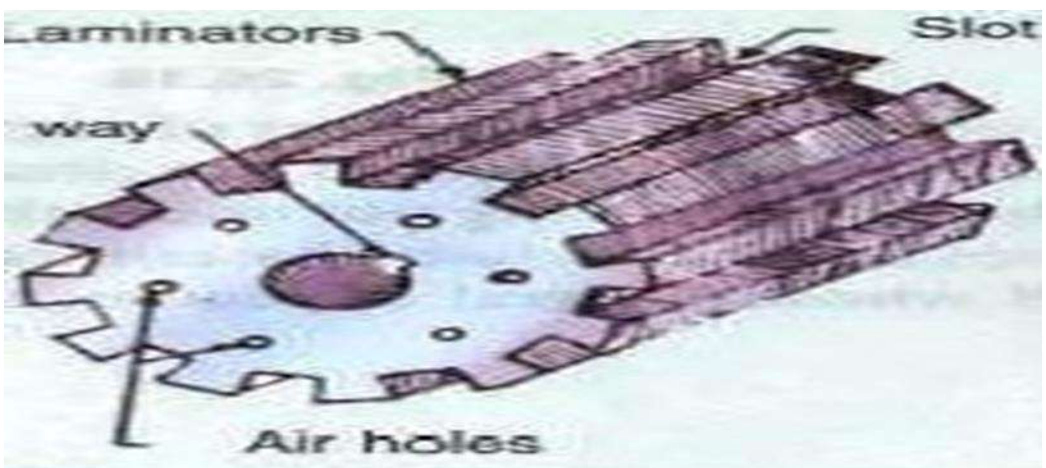


Fig. 26.13 Fig. 26.14

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 ofa 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 ana 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 10 the induced e_rn.f., smaller the current and hence lesser the R loss in the core.

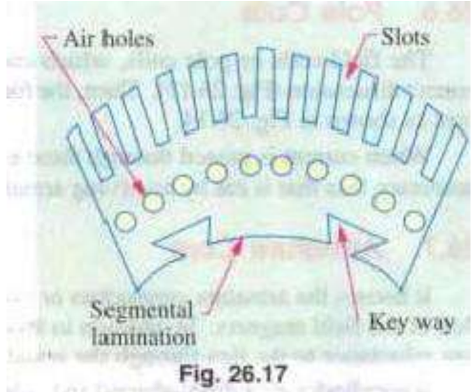


Fig. 26.17

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 nat rectangular coils and are then pulled into their 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 ofthe is to facilitate collection of current from the armature conduc• torS. As shown in Art. 26.2, rectifiedie•. 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 segrtients of high•conductivity hard-drawn or drop forged copper. These

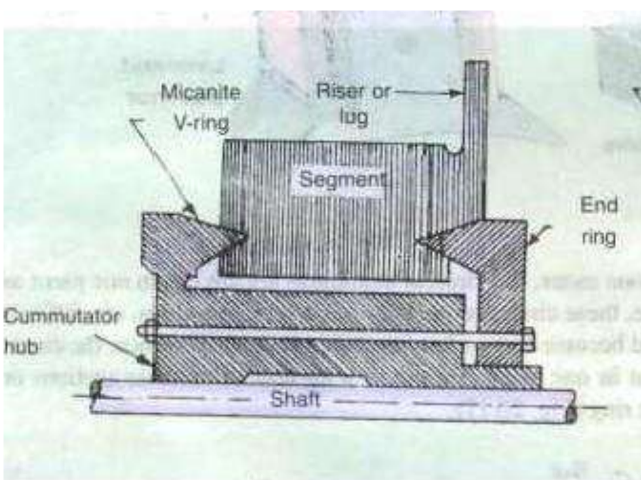


Fig. 26.18

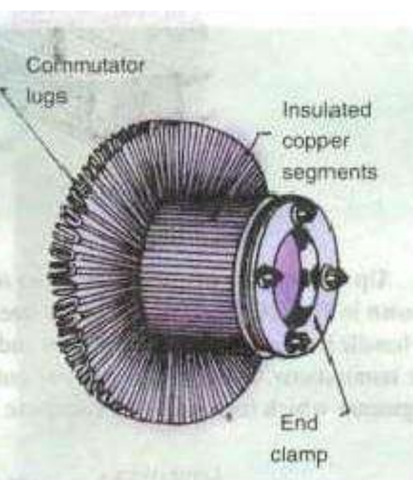


Fig. 26.19

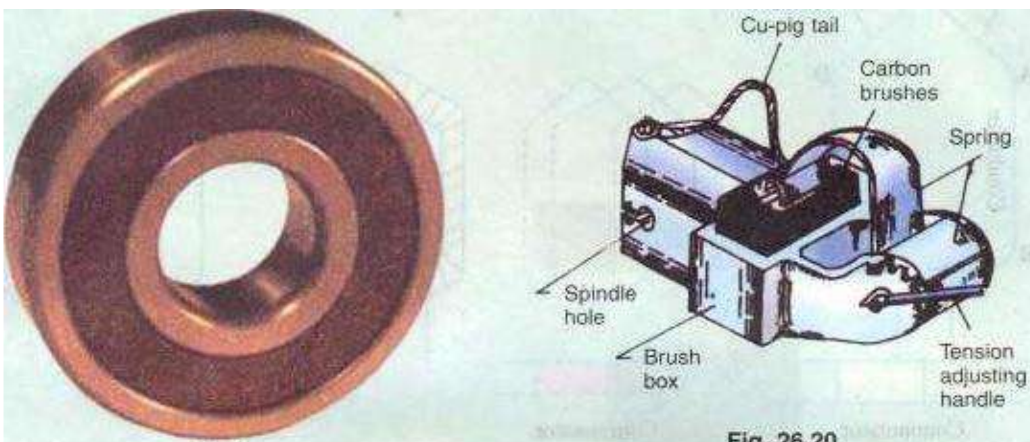
segments areinsulated from each Other by thin layers Oftliiea. L The number Of segments is equal to the number of armature-coils. F.qch commutator segment is connecled to the armature conductor by means of a copperÌugoi strip (or riseth To prevent them from flying out under the action of centrifugal forces, the Segments have V-grooves. these grooves being insulated by conical micanite rings. A sectional view Of commutator is in fig. 26. IS Whose general When completed is shown in Fig. 26.19.

Armature winding

26.10. Brushes and •Bearings

The brushes function is to collect current from commutator.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 a spindle and the brushesean slide in the rectangular-box Open at both ends. The bruéhes madeto bear down On the Commutator by a spring whose tension Cán be adjusted by Changing the 1Sositioñ 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 corrcnt to be collected from the commutator_

Flexible



Bearing

Fig. 26.20

Because Oftheirreliahility, hall-bearings are frequently eniployed. though for heavýdutieS, roller bearingsare preferable. The ball and rollers are generally packed in hard oil for quieter operation and for reduced bearing wear, sleeve bearingé 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 orthe generator i.e. the distance between two adjacent poles.

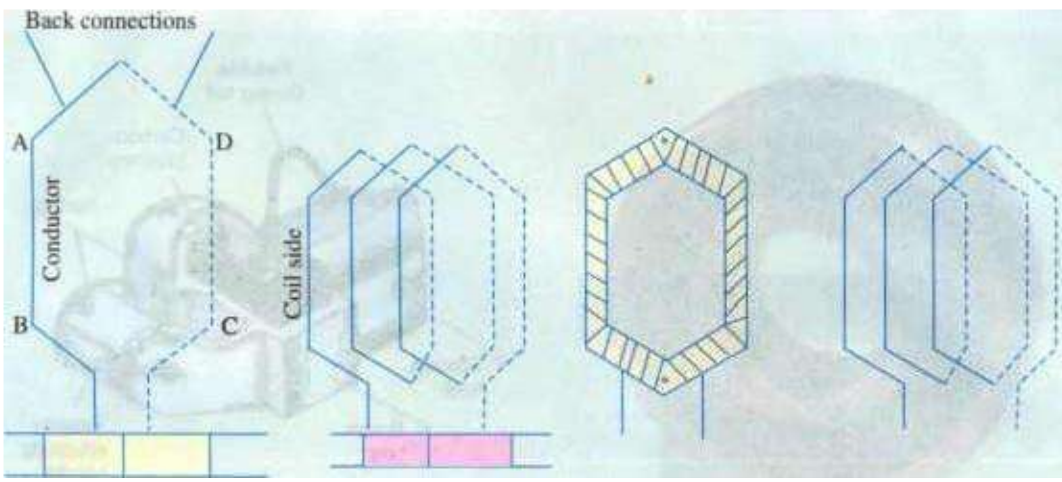
(ii) It is equal to the number Of armature

•conductors and 4 poles, the pole pitehis 48/4 12.

26.13. Conductor

The length Of a Wire lying in the magnetic field and in which an e.mf. is induced, is calleda conductor (or iyduçtot) for example, length AB orCD 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 multiturn 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, 2622, for example. each coil side has 3 conductors, The



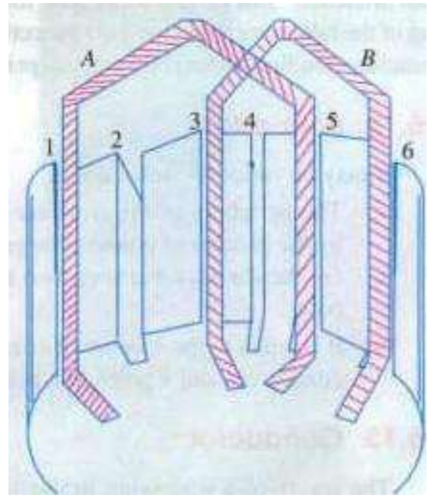
Cornmutator Commutator

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 noted that since the beginning and the end Of each coil must be connected to a commutator bar. there are as many commutaror bars as coils for both the lap and wave windings (see Example 26. I).

The side of a coil (I-turn or multiturn) is.illed a winding element. Obviously, the number of winding elements is twice the number of coils.

26.15. Col-spm 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 fall-pitched. It means that coil span is ISO electrical degrees. In this case. the coil sides lie under opposite poles, hence the induced e.rn.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 Ys = 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 314th of the pole pitch), then the

winding is fractional-pitchea_L 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. inAhe two coil sides, is less in this caseas 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 purposelyused to effect substantialsaving in the copper Of thecnd 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 YR

As scen from fig_ 26_28, element I is connected on the back Of the armature to element 8. Hence. $Y_B = (8 - 1) =$ 7.

26.18. Front Pitch (Yr)

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 Again in Fig. 26.28. element 8 is connected to elemcnt 3 on the front Of the armature, the connections made at the commutator segment. Hence, YF = 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 annature. Both front and back pitches for lap and wave-winding are shown in fig. 26.25 and 26_26.

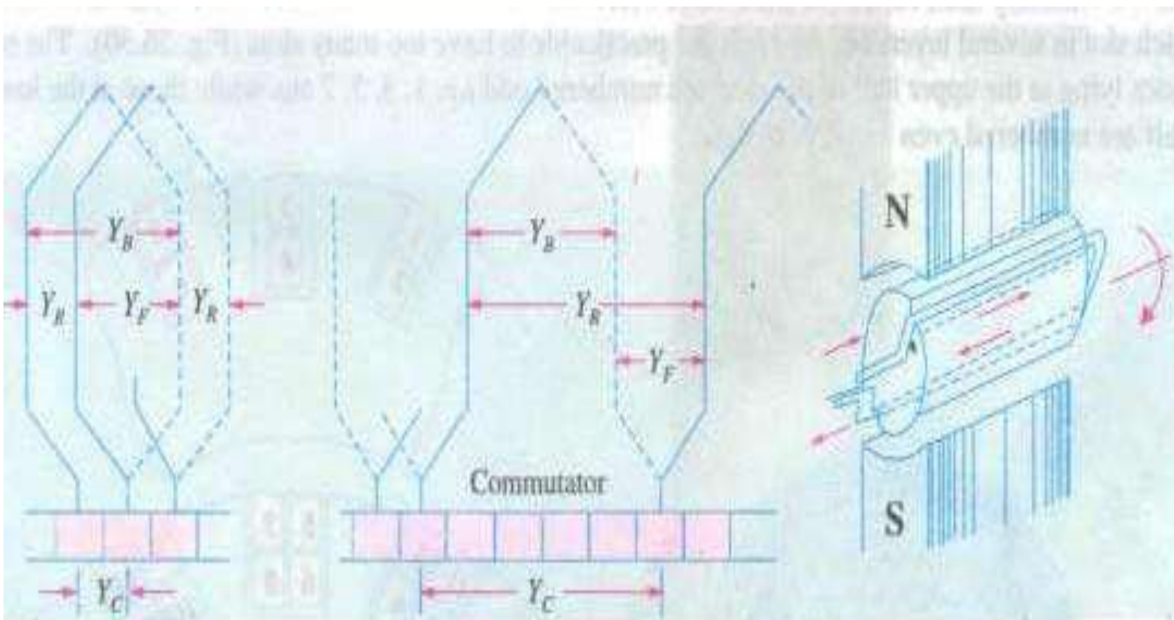


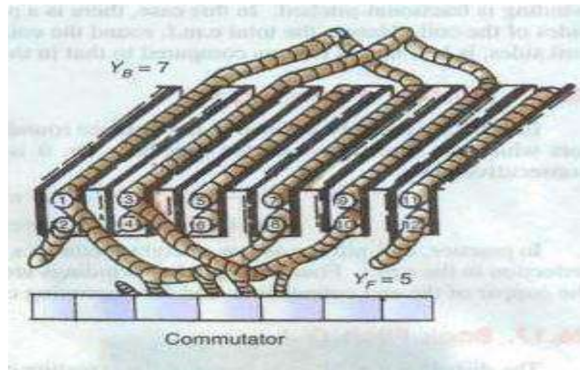
Fig. 26.25 Fig. 26.26 Fig. 26.27

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. 2625 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. Cornmutator Pitch (Y



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. Yc is the difference of YB and Y_F whereas for wavewinding it is the sum of Y_B and Yr 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 l, 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 conductoror 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 Ixr 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 al 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. I , 3.5, 7 etc. while those at the lower half are numbered even i.e. 2, 4. 6, 8 etc.

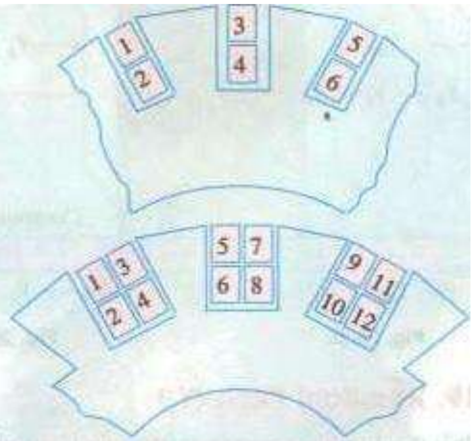


Fig. 26.29 Fig. 26.30

26.23. Degree of Re-entrant Of an Armature Winding

Multiplex Winding

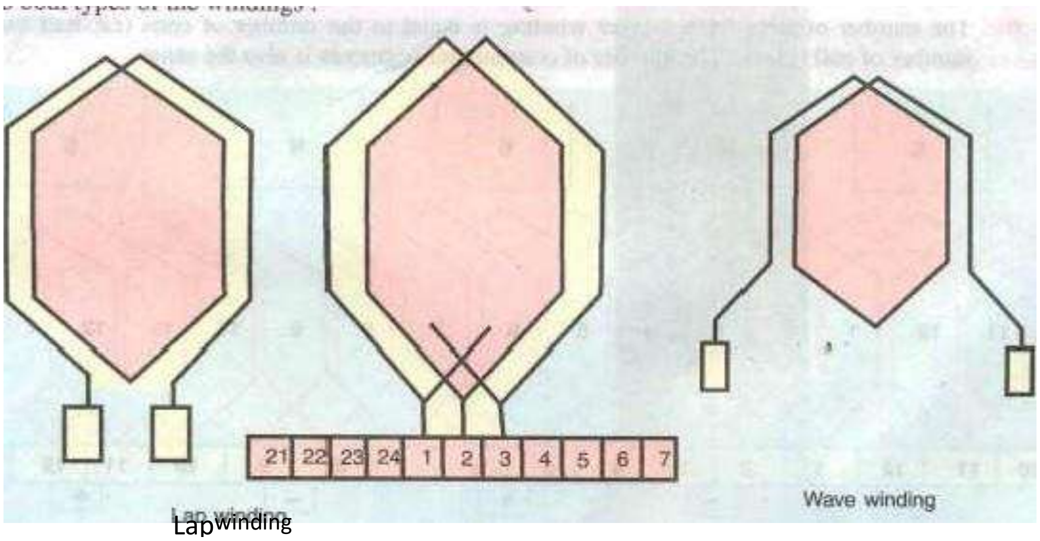
A winding is Saidto be Single re-entrant if on tracing through it once, all armature conductors are included on returning to the starting point. It is double re-entrant if only half the conductors are included in tracing through the winding once and so On,

26.24. Multiplex Winding

Insuch windings. there are several sets ofcompletely 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 ofwindings mostly employed for drum-type armatures are known as Lap Winding and Wave Winding. The difference between the two is merely due to the dtfferentarrangement of the end connections at the front or ommutatorend of armature.



Lapwinding

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, ifYB and YFwere 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 Aidèxsfthe 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 onecoi] 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 underthe same pole and so on, till and the coils have been connected. This type Of winding derives its name from the fact it doubles or laps hack With its succeeding cods.

Following points regarding simplex lap winding should be

1. The back and front pitches are •odd•and Of opposite Sign. But they Cannot They differ by 2 Or Some multiple thereof.

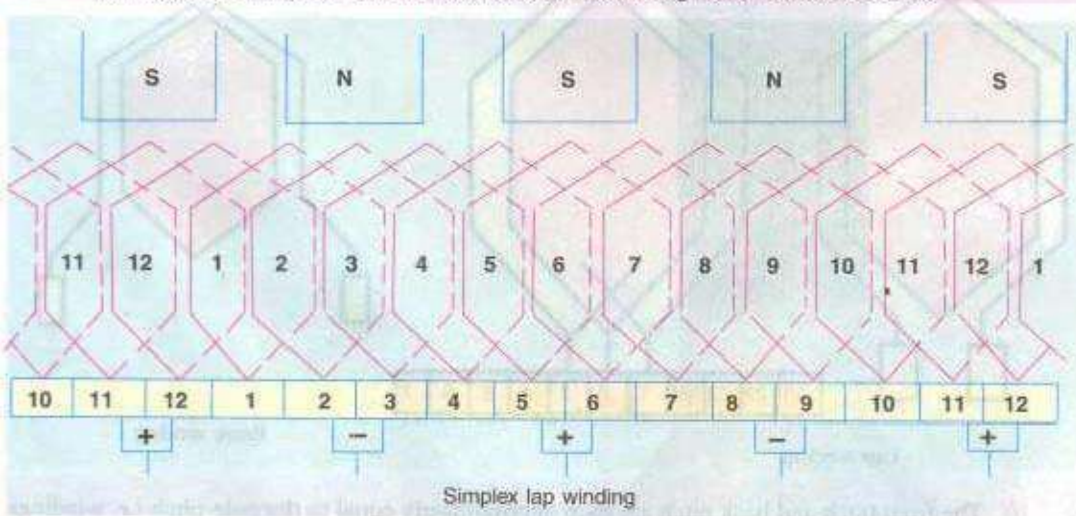
2. Both and should be nearly equal toa pole pitch.

3. The average pitch YA = . It equgls pole pitch = z

4. pitch = ± I (In keneral, = ± m)

S. Resultant pitch YR 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 bf coils (i.e. half the number of coil sides). The number of commutator segments is also the same.



Simplex lap winding

* 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 he odd-numbered ones to the second winding. Similarly.

in triples Winding. there would three Windings, cach connected to third of the commututor bars,

7. The numberofpárallel pathsin the armature where m is the multiplicityofthe winding and P the number of poles.

Taking the firstcondition. we have Yo = $Y_F \pm 2.$

(a) If YB > YF i.e. = YF • 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.o this case, obviously,

$Y_C = + 1.$
(b) 1If YB < YF i.e. YF —2, then we geta or left-handed winding i.e. one which advances in the anti-clockwise direction When seen from the commutator side. In this Case, Yc+$-1.$

(c) Hence, it is obvious that

$$\left.\begin{aligned} Y_F &= \frac{Z}{P} - 1 \\ Y_B &= \frac{Z}{P} + 1 \end{aligned}\right] \text{for progressive}$$ SQinding ûild $$\left.\begin{aligned} Y_F &= \frac{Z}{P} + 1 \\ Y_B &= \frac{Z}{P} - 1 \end{aligned}\right]$$ — + 1

forretrogfesgive winding

Obviously, up 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 I inc whereas the lower side Will be shown by a broken line. The numbering of coil sides will be consecutive i.e. l, 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 of the seg-ments will be the same as that of the upper side connected to it.

Example 26.1. Draw a developed diagram ofa simple 2-laýer lap-windingfor "-pole generator With 16 coilÅ. Hence, point out the chamcteristics Of a lap-winding.

(Elect. Engineering, Madras Univ. 1981)

Solution. The number of commutator segments = 16

Number Of conductors or coil sides 16 x 2 32 : pole pitch 32/4 = 8

Now remembering that (i) YB and YF have to be Odd and (ii) have to differ by 2, We get for a progressive winding YB = 9 ; YF — —7 (retrogressive winding Will result if YR 7 and YF = -9).Obviously, commutator pitch Yc —$-1.$

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

$Y_F = \frac{Z}{P} - 1 = \frac{32}{4} - 1 = 7$ 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	$\longrightarrow$	10 to (10 − 7) = 3
3 to (3 + 9) = 12	$\longrightarrow$	12 to (12 − 7) = 5
5 to (5 + 9) = 14	$\longrightarrow$	14 to (14 − 7) = 7
7 to (7 + 9) = 16	$\longrightarrow$	16 to (16 − 7) = 9
9 to (9 + 9) = 18	$\longrightarrow$	18 to (18 − 7) = 11
11 to (11 + 9) = 20	$\longrightarrow$	20 to (20 − 7) = 13
13 to (13 + 9) = 22	$\longrightarrow$	22 to (22 − 7) = 15
15 to (15 + 9) = 24	$\longrightarrow$	24 to (24 − 7) = 17
17 to (17 + 9) = 26	$\longrightarrow$	26 to (26 − 7) = 19
19 to (19 + 9) = 28	$\longrightarrow$	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	$\longrightarrow$	30 to (20 − 7) = 23
23 to (23 + 9) = 32	$\longrightarrow$	32 to (32 − 7) = 25
25 to (25 + 9) = 34 = (34 − 32) = 2	$\longrightarrow$	2 to (34 − 7) = 27
27 to (27 + 9) = 36 = (36 − 32) = 4	$\longrightarrow$	4 to (36 − 7) = 29
29 to (29 + 9) = 38 = (38 − 32) = 6	$\longrightarrow$	6 to (38 − 7) = 31
31 to (31 + 9) = 40 = (40 − 32) = 8	$\longrightarrow$	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 commutatorsegment (whose number is also I The backend is joined at the back to the I + 10th coil side in the lower half of5th 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 s N lying in the upper half of second armature slot. In this way. by 26.32 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 I 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 directionofcurrents flowing in the various conductors. Ifcurrents 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), il is found that commutator bars NO. I 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 iuto four parallel paths.

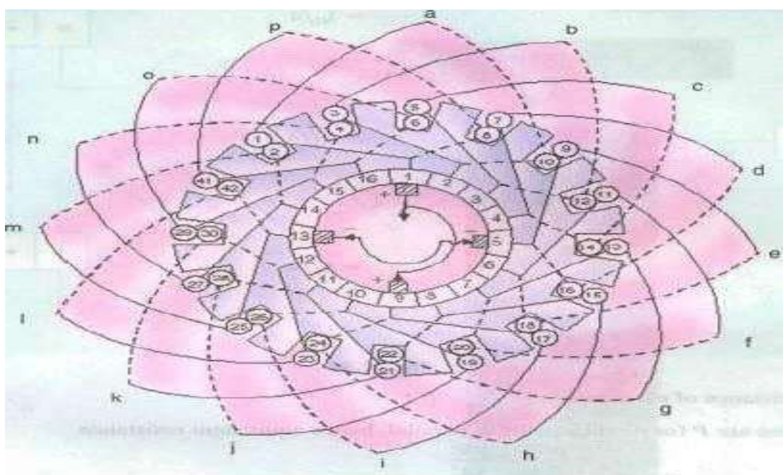


Fig. 26.33

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

26.34. Obvi0LLsIy, if is the total current supplied by the Eenerator, 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. Thereareas many parallel paths in the armature as the numberofpoles. That is why such a winding is sometimes as 'multiple circuit' or •parallel' winding. general, number Of parallel paths in armature mp where m is the multiplicity (plex) Of the lap winding. For example, a duplex lap winding has (6 x 2) = 12 parallel paths in its armature.

3. The e.m.f. between the +veand—ve brushesisequa/ 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"

Resistance of each path— PIZ

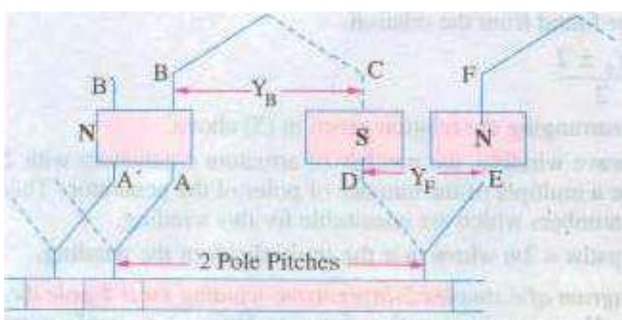
There are P (or A) such paths in parallel, hence equivalent resistance

5 If is the total armature current. then current per parallel path (or carried by each conductor) is 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 takenfonvard lothe next N.pnle, it would make no difference so fartLs the direction and magnitude of the e.m_f. induced in the circuit are concerned

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



As shown in Fig. 26.35. conductor AB Lis connected to CD lying under S-pole and then to EF under the next N•p01e, 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 bc 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 most be atThe upper half of the slot at the left orTight. Counting in terms of conductors, it means that AB and A'B' differ by two conductors (although they diner by one slot).

From the above, we can deduce the following relations. If P —No. Ofpoles, then total No. Of conductors orcoil Sides

$$Y_B = \text{back pitch}, \quad Y_F = \text{front pitch} \quad \Big\}\ \text{nearly equal to pole pitch}$$

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

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

Since p is always even and s even and $Z = PY_R \pm 2$, hence Z must always be even. Put it in another way.

means that must an even integer.

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

Points to Note :

1. Both pitches YB and YFare odd and of the same sign.

2. Back and front pitches are nearly equal to the pole pitch and unay be equal or differ by 2, in which case. they are respectively one more or one less than the average40itch. 3. Resultant pitch YR $= Y_F + Y_B$.

4. Commutator pitch, $Y_C = Y_A$ (in lap winding $Y_C = \pm 1$).

Also.

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

5. The average pitch which must be an integer is given by

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

It is clear that 10 he an integer. there is a restriction on the.alue of Z With Z = 32. this winding i'. impossible for 4-polc machine (though lap winding is possible). Valuesor Z = 30 or 34 would be perfectly ah-ight_

i.a NC can be found from the relation, PYA ±2

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

7. rt 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.

S. Thé number of armature parallel paths = 2m where m is the multiplicity of the winding.

Example 26.2. Draw a developeddiagram Ofa simplei *-layer wave-winding for* a 4-pole dc. generator With 30 armature conductors. Henée, point Out the characteristics Of a simple wave winding. **(Elect. Engg-I, Nagpur Univ. 1991)**

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

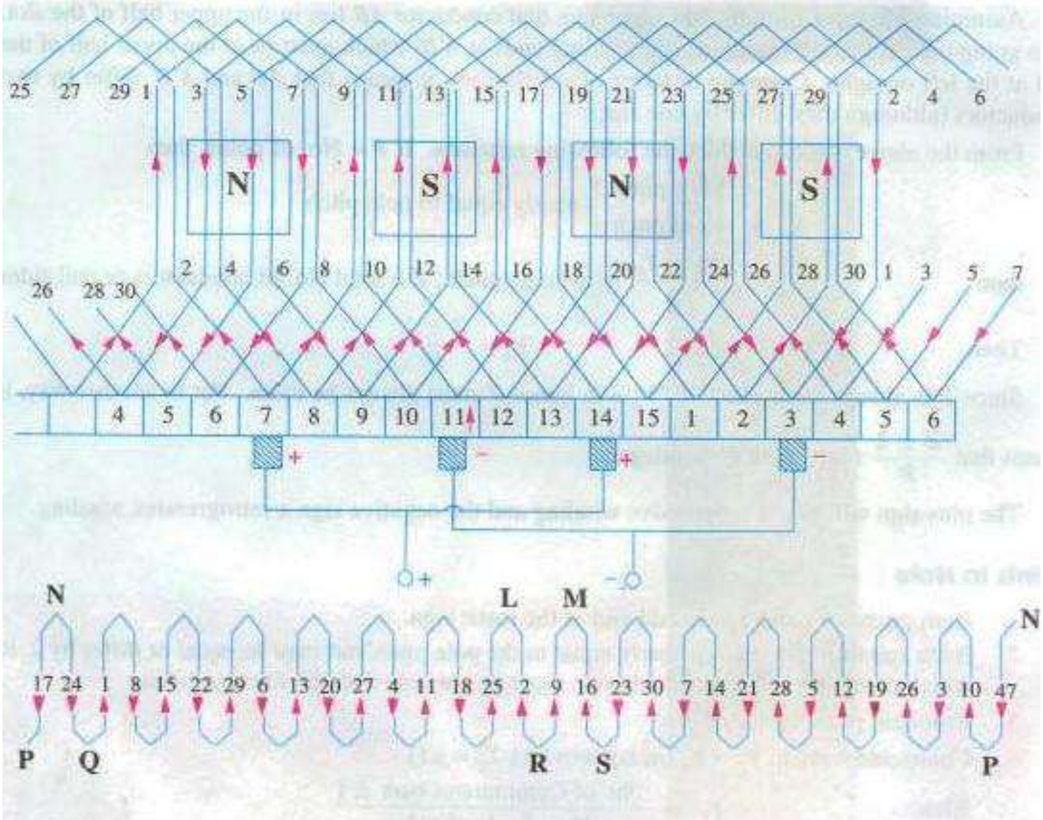


Fig. 26.36

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 commutatorSegment5 + 7 = 12 (Yc = 7) to which isjoined conductor No. 12+ 7 = 19. Continuing this Way, we come back NO. 5from where We started. Hence. the winding Closes itself.

If we take S, then the pitches would be : Yn 9 and YF 7 or Yb = 7 and YF 9. Incidentally, if YA = Yc is taken as 7, art-nature Vill rotate in one direction and if Yc = 8, it Will rotate in the Opposite direction.

The simple winding table is as under ;

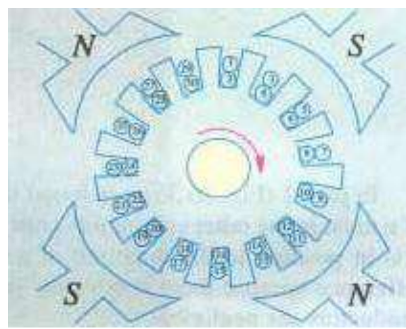
Back Connections Front Connections

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

Sincewe 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 polcs_ 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 ofconductors 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 separatiqg 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 thc 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 ll.

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 -eve 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.r. in conductor 9 is in opposition to the general trend ofe.m.fs. in the Other conductor"s comprising this path. Similarly, in path 2. the e.m.f. in conductor 2 is in position to the direction Of e.rn.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.

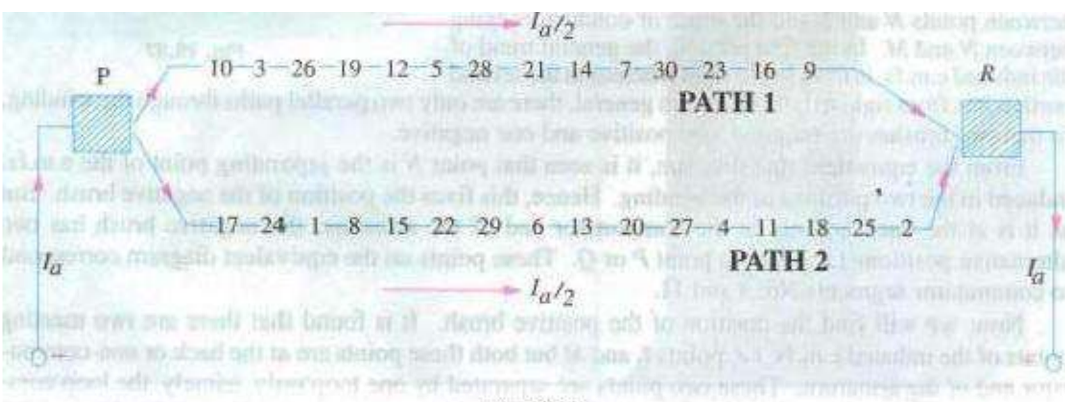


Fig. 26.39

Fig.26Æ

Again, take the case of conductors 2and 9situated 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.nind. itis 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 reversing. 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

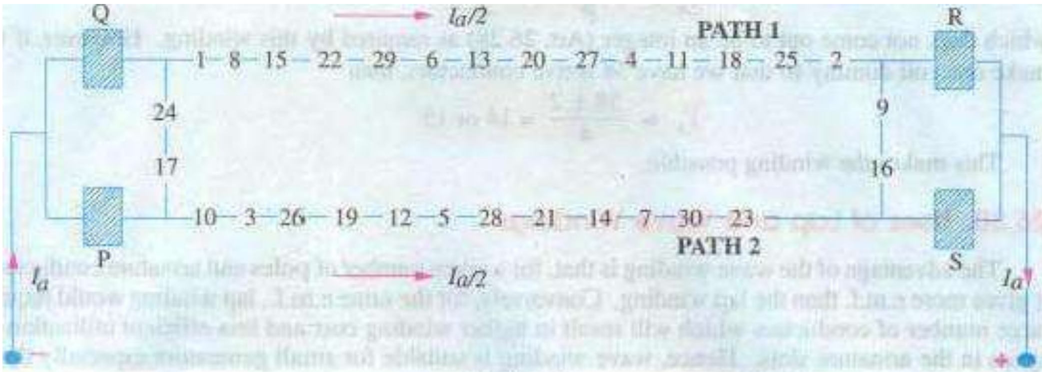


Fig. 26.40

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 bnlSh if used, should be in touch with both segments 14 and 15.

Il 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 beequal tothe number of poles. 2. The number of paths through the armature winding is two irrespective Ofthe number of generator poles. That ig 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 ofthe two parallel paths. •If eav is the e.m.f. induced/conductor, then generator e.nl.f. is E x "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 byeach path orconductor 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±2

4 which does not come out tobe 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 ± 2

— 14 or 15 4

This makesthe winding possible.

26.30. Uses Of Lap and Wave Windings

The advantage of the wave winding is that, for a given number ofpoles 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.

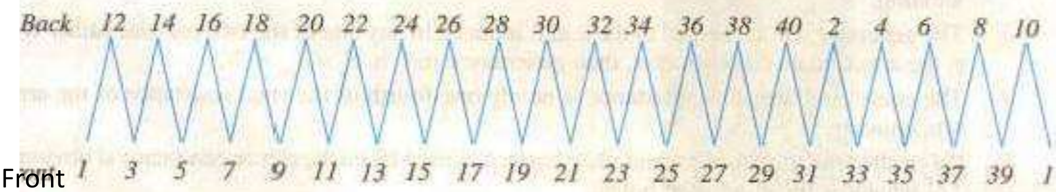
Another advantage is that in Wave winding. equalizing connections are not necessary whereas in a lap winding they definitely are. It is so because each Of the two paths contains conductors lying under all the poles whereas in lap-wound armatures, each of the P parallel paths contains conductors which 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 laœe currents are required, it is necessary to use lap winding, because it gives more parallel paths.

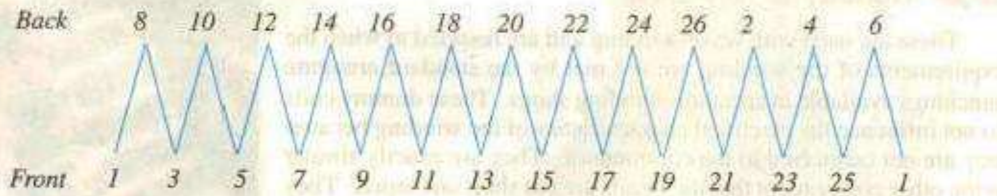
Hence, lap winding is suitable forcomparatively low-voltage but high-currentgenerators whereas wave-winding is used for high-voltage, low-current machines.

1. Write down the winding table for a 2-layer simplex lap-winding for a 4-pole d.c. generator having (a) 20 slots and (b) 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 2-1ayer 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 diagramatically in fig. 26.41.

(b) Self-excited generators are those whose field magnets are energised by the current
(produce.d 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. lib Shunt wound

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

Example 26.9. An 8•p01e dc. generator has 5(H) armature conductors, and a useful flux Of O. 05 Wb per pole. What Will be the e.m.f. generated ifit is lap-connected and runs at 4200 rpm ? What must be the speed at which is to be driven produce the same it is Wave-wound?

[U.P. Technical Univ. 2001)

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

$$E = \phi\ (N/60)\ (P/a)$$
$$= 0.05 \times 500 \times 20 \times 1,$$
$$= 500 \text{ volts}$$

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

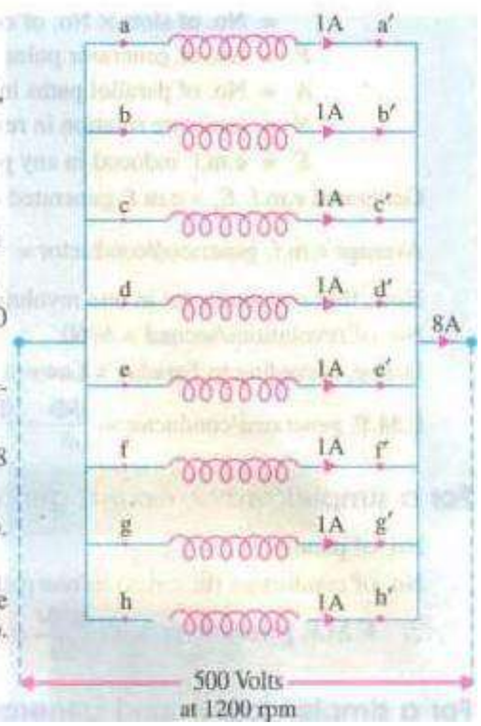
Net output current = 8 amp as in Fig. 26.51 (a).

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

$500 \times 2 = 1000$ W.



It is reduced to one fourth. being proportional to the

Example 26.26. A long-shunt dynamo, running ut 1000 voltage Of 220 V. The resistances

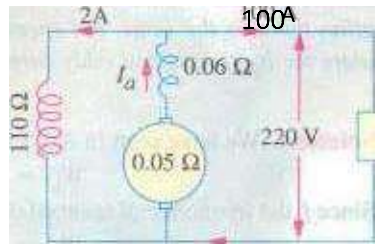
0.06 Q respectively. The overall efficiency at the above load is friction losses (c) the torque exerted by theprime,mover.

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

Solution. The generator is shown in Fig. 26.64.

220/110=2 A

1 - 100 A.



= 102 A

220 v

Drop in series field winding = 102 x = 6.12 V

- 1022 xo.05 =520.2 W

Series field loss — 0.06 = 624.3 W Shunt field loss = 4k 110=440 w

Example 26.28. A long-shunt compound-wound generator gives 240 volts at EL output of 100 A. The resislances of various windings ofthe machine are : armature (including brush contact) O. J Ω series field 0.02 Q interpole field 0.025 shunt field (including regulating resistance' 100 Q. The iron loss EL is 1000 W ; windage andfriction losses 10101 SOO W. Calculate EL efficiency of the machine. i Electrical Machinery-I, Indot•e Univ. 1989)

output 240x

Total armature circuit resistance = 0.1 + 0.02 + 0.025 0.145 n

240/100=2ÅA 2.4= 102.4 A

Armature circuit loss = 102.4^2 x O. 1,521 W

Shunt field copper loss = 2.4 x 240=576 W

Iron loss = W ; Friction loss 500 W

24.000

Total loss = 1,521 -087= 87%

24.000 1597

DC MOTOR

Motor Principle

An Electric motor is a machine which converts electric energy into mechanical energy. ILS action is based on the principle that when a current-carrying conductor is placed in a magnetic field. it experiences a mechanical forec 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 tact, the same d_c_ machine can bc used interchangeably as a generator or as a motor. D.C_ motors are also like generators. shunt-wound or series-wound or compound-wound.

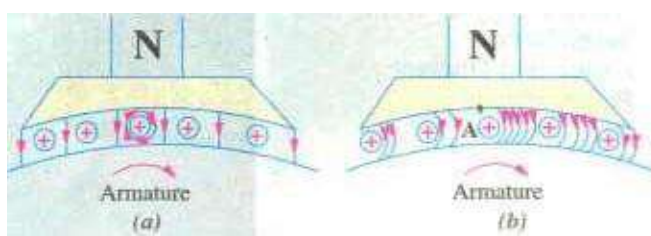
of Motor are supplied with current from the supply mains. they expenencc a force tending to rotate the armature. Armature conductors under At-pole arc assumed carry current downwards (Crosses) and those under S-poles, to carry current upwards (dots). By applying Fleming's Left•harud Rule, the direction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

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

It should be noted that the function of a commutatorin the motor is the same as in a generator. By revetsing current in each conductor as it passes from one pole toanother, ithelps to developa continuous and unidirectional torque.

29.2. Cornparison Of Generator and Motor Action

As said above, the same d-c. machine can be used. at least theoretical iy, 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.

Lel 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 pan of a generator whose armature is being driven clockwise by its prime nlover 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 on flux are shown in Fig. 29_2 (b) It is Seen that there is a crowding of'iries of flux on the right-hand side ofA. These magnetic lines of flux may be likened to the rubber bands under tension. Hence. the bent lines Of flux up 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 he 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 armat•uœconductor that the prime mover has to work. The WOEk done in overcoming this opposition is converted into electric energy. Therefore. it should be clearly understood thal it is only through the instrumentality of this magnetic drag that energy conversion is possible in a d.c.

generator.

Next, suppose thal the above d.c. machine is un• coupled from its prime mover and that current is sent through the armature conductols under a N.polc in the downward direction as shown in Fig. 29.3 The conduclors will again experience a forec in the anticlockwise direction ('Fleming's Left hand RAIle)_

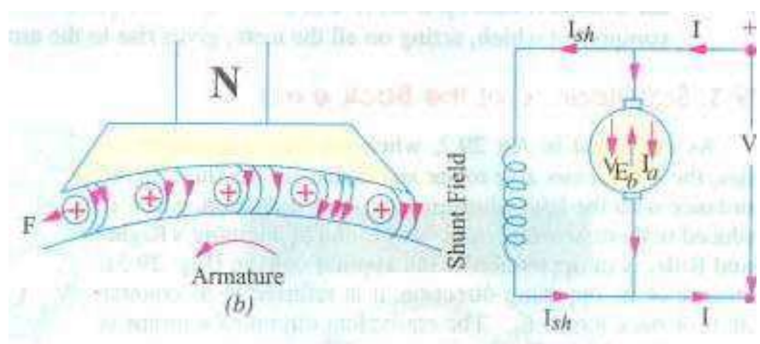


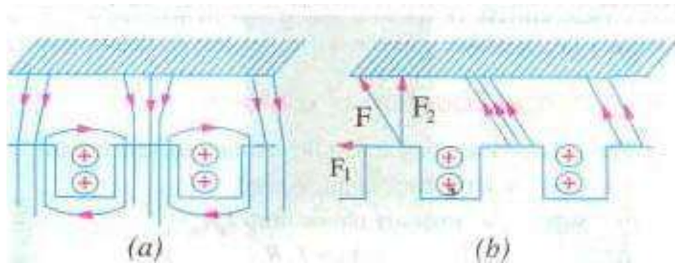
Fig. 29.3 (a) Fig. 29.3 (b)

Hence. the machine Will

Start rolating anticiockwise. thereby developingÆi torque which can produce mechanical rotation. The machine is then said to be motoring.

As said above, energy conversion is not possi'le unless there is some opposition whose over% coming 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, i' i' the hack e.rn,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_eu. in dilect 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.mf in the generator i.e. 14, ('ÞZ'V'x (P/A) volts. The applied voltage Vhas to be forcecurrent through the armature- conductors against this back e_m.f. Eh. The electric work done in overcoming this opposition is convened into mechanical energy developed in the armature. Therefore. it is obvious that bulfor the pro. auction of this opposing e.m.f. energy conversion Would not have been possible.



Now. before leaving this topic, 29,4 Fig. let it be pointed out thai 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 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 he one of the fundamental laws or no energy conve4Sion from one to another is ['ossible until there is some one to oppose the conversion. Hut forthe presence of this opposition, there would simply t-,c no energy conversion. Jn generators. opposition is provided by magnetic drag whereas in motors. back c.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.

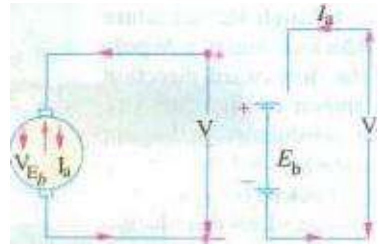
-armature flux on the main flux, as shown in Fig. 29.4 is two-fold ,

(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 he resolved into two components. One is the tangential component Fl and the other vertical component e. The vertical component Fl. when considered for all the teeth round the armature, up zero. But the comlN)nent FI 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 rotales, the conductors also rotate and hence cut the flux. In ac. cordanee with the laws of electromagnetic induction, emi,f. is induced in them whose direction, as found by Fleming's Righthand Rule. is in opposition to the applied voltage (Fig. 29.5). Becáusc Of its opposing direction. it is referred to as counter• e,rn.f. or back e.m.f. Eh. The equivalent circuit of a motor is shown in Fig. 29.6. The rotating armature generating the hack e. m.f. Eh is like battery Of e.m.f. Eh put across a supply mains of V volts. Obviously, V has to drive la against the opposition Fig, 29.5 of Eh. The power required to overcome thig opposition is Eh/n.



In the case of a cell. (his power over an inter,'al of time is converted into chemical energy, but in the present case, it is converted into mechanical energy.

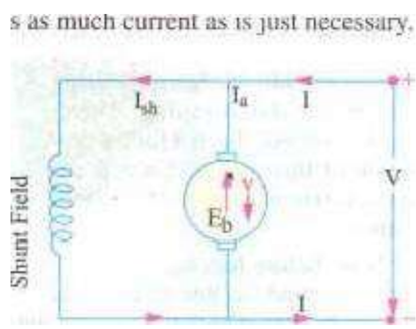
It will be seen that I Net volta½ _ $V - V_b$

a

Resistance Ra

where R is the resistance Of the armature circuit. As pointed out above, Eh = CÞZV (P/A) volt where N is in r.p.s.

Back e_m.f_ depends, among other faclors. upon the armatuœ speed. If speed is high. Eb is large, hence armature cunent seen from the above equation, is small. If the speed is less. then Eb is less, hence more current flows which develops motor (Art 29.7). so. we find that Eh acts like a governor i.e„ it makes a motor self-regulating so that it draws as much 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. Ebund in supply the armature ohmic drop

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

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

V = Eectrical input to the armature

Eh/o = Electrical equivalent Of mechanical power developed in the armature I: R , = Cu loss in the armature

Hence. out Of the arunature input, some is wasted in 1^2R loss and the rest is converted into me— chanical power within the armature.

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

ture to its input i.e. EBIJV la = E*/V. Obviously. higher the value of Eb compared to V. higher the motor efficiency.

29.5. Condition for Maximum Power

The gross mechanical power developed hy a motor is pm = la — I: Ra.

Differentiating both sides with to la and equating the result to zero. we get v—2/aRa-O As and

Thus gross mechanical power developed by a motor is maximum When back e.tn_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 OS the full-load

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

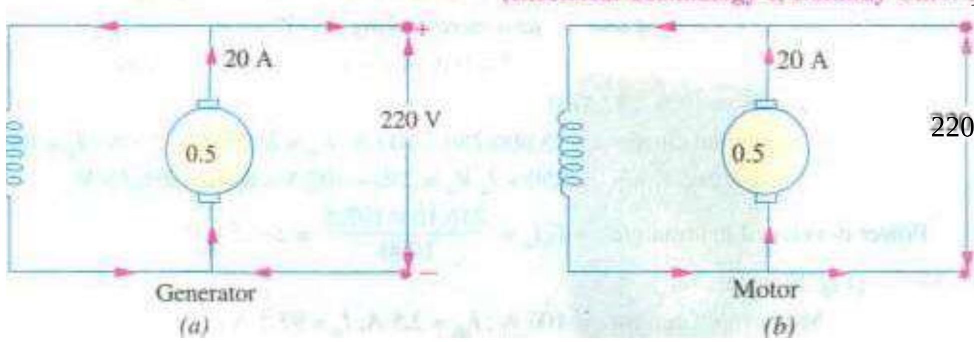


Fig.29.7

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. V

Example 29.2. A separately excited D, C. generaror has armature circuit resistance OfO. I 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 ofconstant resistance If the generator speed drop to 700 cp. m., unaltered, find the current delivered load. AMIE, Electrical Machines, 2001) solution.

At = 262 X 700/1000 = 183.4 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- IOOamp.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 of7.46 kW at 85 pert-ent efficiency,

Solution. Motor input 7.46 x 10^3/0.85 W

Motor input current $= 7460/0.85 \times 440 = 19.95$ A ; $I_{sh} = 440/200 = 2.2$ A

$I_a = 19.95 - 2.2 = 17.75$ A ; Now, $E_b = V - I_a R_a$

$\therefore \quad E_b = 440 - (17.75 \times 0.8) = \mathbf{425.8\ V}$

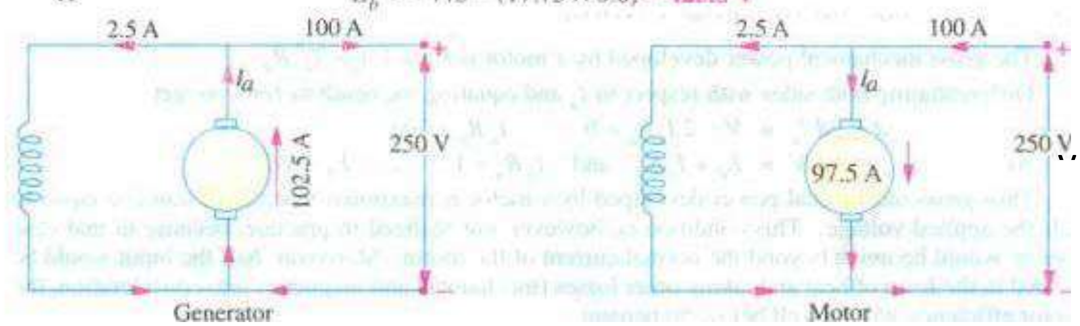


Fig. 29.8 (a) Fig. 29.8(b)

Example 29.4. A 25-kW. dc. shunt generator has *armature and*field 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 A $I_{sh} = 250/100 = 2.5$ A ; $I_a =$ 102.5 A

Generated emm = 250+1 R„-250+ 102.5 xo.06=256.15 V

256.15 x 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 magneticfield, 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

V

200

V

2m

generator, 1 3 amp

12 amp 5 amp

Supply

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

Fig. 2"

$E_g = 200 + 13 \times$ 2=226 V

$\phi \frac{ZN}{60} \times \frac{P}{a} = 226$ 60 a

For a Lap-wound $P = a$ armature,

0.42375 wb $\phi = \frac{226 \times 60}{1000 \times 32} =$

Asa motor, $I_a = 4$ amp

$E_b =$ 200-4x2—192V

Giving N $= \phi ZN/60$

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

=850 r.p,m.

Tutorial Problems 29.1

l. What do you nderstand by the term 'back c,rn.f.• Ad.e_ supply has an armature resistance of O. IS Q, Calculate

(a) The Of hack e,m.f. when the armature current is 120 A.

The value of armature current when the hack is 4414 V.

2. A d.c. motor connected to 460-V supply utkes an armaturc Current Of 120 A on full load. If the circuit has a of 0.25 Q, calculate the value of the back c.m.f. at this load. | •130 VI A 4•poIe d:c_ motor takes an armature current Of 150 A at

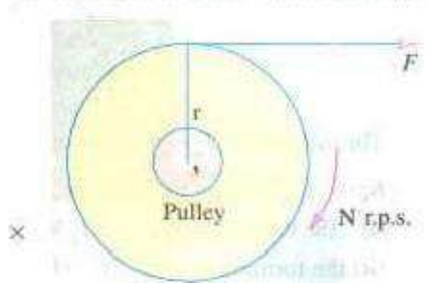
3. resislance 440 V. If its armature circuit has a of O. IS Q. what will the value Of back c.rn.f, at this load ? 1417.5 VI

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 acircumfcrential force of F Newton which Causes i' to rotate at N r.p.rn. (Fig. 29.10).

cumferential force of F Newton which



Then torque = Ex r Newton-metre(N - m)

Work done by this force in one revolution

= Force distance = F x 2rtr Joule Power developed = F x 2 rtrx N Joulusecond or Watt

Now 2 lt.'V Angular velocity in radian/second and F

—Torque r

∴Power developed = Tx (D watt or P T Watt if N isin then Fig. 29.10

Moreover, m = 2 wV/60 rad's

2 It,'V

= $\frac{2\pi N}{2\pi}$ × T or P— 60

29.7. Armature Torque Of a Motor

Let Ta bethe torque developed by the armature of a motor running at N r.p.s• If is in MM, then power developed Tu x N watt

We also know that electrical Ix»ver converted into mechanical Il'w•er in the armature Alt 29.4) — Eh/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 x2mV Watt provided Tsh is in N-m and N in r.p,s.

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

$= \frac{\text{Output in watts}}{2\pi N/60}$ N-m $-N$ in r.p.m.

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

The difference (Ta — T,h) is known as lost torque and is due to iron and friction tosses of the motor.

Note. The value of back e.m.f. Eh can be found from the equation, Eb = V — la Ra

(iii the formula Eb = Z.'V x (P/A) volt

Example 29.6. A dc. motor takes an armature current Of at 480 V! The armature circuit resistance is 0.2 Q The machine has 6•poies and the armature is lap-connected with 864 conductors. The flu per pole is 0.05 Wh. Calculate the speed and the gross torque developed by the

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

Solution. Eh 480—110 xo.2—458V,

0.05 x 864 x N 6

60

N 636 cp.m.

T. = 0.159 xo.05

Example 29.7. A 25CL •a-pole, wave-wound Series motor has 782 conductors on its armature. If has armature and seriesfield resisiance Of0.75 Ohm. The motor takes a currvnt A. Estimate its speed and gmss to rque developed if it has a per pole of 25 m Wb.

(Elect. Engg.•ll, pone Univ. 1991)

Solution.

Example 29.8. A dc. Shunt 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 us a motor, Only difference is that this armaturee.m.f. is known as back its

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

Mechanical power developed in the arm 50 = 12.500 W

T. —9.55 9.55 x 250 79.0 N-m.

Example 29.9. Determine developed and shaft torque of220-V,4-pole series motor with 800 conductors Wove-connected supplying load 0/82 kW by taking45 Afrom the mains. Theflltv per pole is 25 m Wh and its armature circuit resistance is 0.6 Q.

(Elect. Machine AMIE sec. B Winter 1991)

. N2/500=200/210

Example 29.11. -500-V.37.3 kW. 1000 r.p.m. d,c. shunt motor has on full-load an efficiency OJ 90 The annature circuit resistance 0.24 Q and there is Iola/ voltage drop Of 2 V al the brushes. The field curren' is 1.8 A. Determine (i) full-load line curren/ (in full load shaft torque in N-m and resistance in motor starter 'o limit the starting cumm to 1.5 rimes the full-load current. (Elect. Engg. l; M.S. Univ. Baroda 1987)

Solution. Motor input W = 37,300/0.9 = 41,444

= 41.444/500 = 82.9 A

F.l. line current = 41.444/S(.WJ

= 356N-m

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

Example 29.12. A "-pole. 220- V shunt motor has 540 lap-wound conductor. rakes 32 A from the supply nminsanddevelops output power of5.595 kW Thefield winding takes A. The resistance is 0.09 Q and the per pole is 30 mWb_ Calculate the speed and rhe torque developed in newton-metre. (Electrical Nagpur Univ. 1992'

Solution. = 31 A V

,ÞZN P

Now. 217.2 =

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

T. 9.55 x output in watts = 9.55 x 595 = 66.5 N-m

804.4

Example 29.13 Find the lead andfull-load speedsfor afour-pole, 220-V. and 20-kW. shunt motor having thefollowing data :

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

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

(Bharathitbasan 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 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., = — 4 x 0.04 = volts

Substituting this.

004 x 160 x

No-Load speed. No — 1030.5 r.p.m.

Armature current A, Ea — 90 x 0.04 216.4 V (216.4/219.84) x 1030.5 = 1014.4 rpm.

F•ample 29. i 3 Armature Ofa 6-pole. 6-circuit D.C. shunt motor takes A at a speed Of 350 r.p.m_ Theflux per pole is 80 milli-webers. the number Ofarmature rums is 600. and ofthe 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 TNw — m.

Armature 'X'Wer T T x 2 't

= Twatts

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

- SOX x

— 560 volts

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

T = 560 x 100/36.67—6108-5 Nw—m, Since 3 % of this torque is required for overcoming different loss-terms,

n-

Net torque = 0.97 x 6180.5 = 5925 Nw-m

For Brake-Horse-power, net output in kW should be computed first. Then ••kW" is to be co vetted to "BHV'. with 1 HP = 0.746 kw,

Net output in kW = 5925 36.67 10-3 —217.27 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 ofpole-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 = 0.1590ZL„p/aNw-m Two paths in parallel for a 4-pole case means a wave winding.

T 0.159 X (24 x 774x50x4/2

= 29536 Nvv-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 O. IS ohm and field resistance is 200 ohms, determine the efficiency of the machine running as a generator delivering load current Of40 Amps.

gBharathiar Univ. April 1998)

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

Input Power = x 5 = 2500 watts field copper-loss = 500 x 2.5= 1250 watts

Neglecting armature copper-loss at no load (since it comes out to be 2.5^2 x 0.15 I 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 :

Output delivered 500x40x10^{-3} = 20 kW

Losses : Field copper-loss = 1250 watts

(b' Armature copper-loss = 42.5' x = 271 watts

(c) NO load losses = 1250 watts

Total losses kW

Generator Efficiency (20/22.771) x 100 % = 87.83 %

Extension to the Question : At Bihar speed should the Generator bé run, ifthe 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.

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

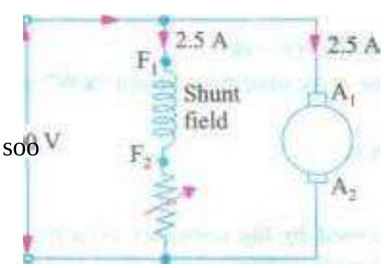
As a Generator With an armature culTent Of 42.5 A.

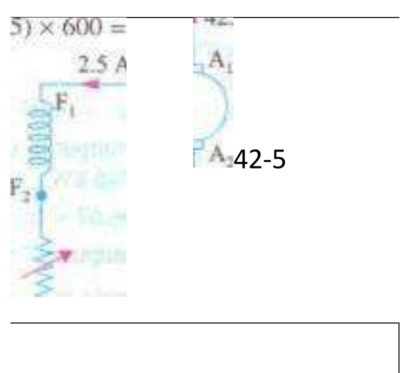
E_{b0} =— 500+42.5xo.15 -506.375V

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. lithe generator must driven at N rp.m.

N = (506-375/449.625) 608.1 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 andfield res/stancc are 0.2 Q and O. I Q respectively and the iron andfriction are O.S W find the torque developed in the armature. What Will be the output Ofthe motor ?

Solution. Armature torque is given by $T_a = 9.55 \dfrac{E_b\, I_a}{N}$ N-m is given by Ta = 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 toss in armature and series-field resistance = 40^2 0.3 ies-field resistance = $40^2 \times 0.3 = 480$ W

[Ton and friction losses = SOO W Total losses 480 + 500 = 980 W

Motor power input = 220 40 = 8.800 W

Motor output 8.800 - 7.820 W = 7.82kW

Example 29.14. A curring tool exerts a tangential force of 400 N on a steel bar of diameter Which is being t"rned 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- Culc•ulule the current taken by the motor ifits efficiency is 80 Whal size is the motor pulley ifthe lathe pulley has a diameter of24 cm .

(Elect. Technology-Il, G"aiior Univ. 1985)

Solution. Torque Tangential force x radius = 400 x 0.05 = 20•N-m

Output power = T. x 27th' watt 20 x x (840/60) watt = I W

Motor Motor input - 1,760/0.8 - 2,200 W

Current drawn by motor = 2200/220 10 A

Let N, and be the speed and diameter of the driver pulley respectively and N2 and t): the respective speed and diameter of the lathe pulley.

10 cm

N, x D, or

Example 29.1 S. The armature winding Ofa 200-V.4-pole. series motor is lap-connected. There Ire 280 slots and each slog has conductors. The current is 45 and thejit" per pole is 18 m W/O.

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

(Elect. Engg. Sec. A. 1991'

900

Solution. Total input $E_b = V - I_a R_a = 200 - 45(0.5 + 0.3) = 164$ V

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

Friction losses

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

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

= 9 x 55 x 6580 - 12SN-m

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

488

ut $= 9{,}000 - 2{,}420 = 6{,}580$ W

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

FxO.205 = 128.8 F = 128.8/0.205 N = 634 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 0.1 Ω. 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. $E_b = V - I_a R_a -$ brush drop $= 240 - (50 \times 0.1) - 2 = 233$ V

Also $I_a = 50$ A

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

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

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

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

(d) Armature input $= V I_a = 240 \times 50 =$ **12,000 W**

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

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

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

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

$\therefore$ Efficiency $= \frac{11{,}190}{12240} \times 100 =$ **91.4 %**

Example 29.17. A 460-Vseries motor runs at 500 rpm. taking a currergof40A. Calculate the speed and percentage change in torque if load is reduced so the is taking 30 A. Total resistance Ofthe armature andfield circuits is 0.8 Assume,i71Lx is pmportional to thefield current.

(Elect. Engg.-lt. Kerala Univ. 1988)

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

$\therefore$ $T_1 \propto 40^2$ and $T_2 \propto 30^2$ $\therefore$ $\frac{T_2}{T_1} = \frac{9}{16}$ T, Example 29. IS. A 460-1'.'55.95 750 r.p.m. shunt motor drives a load having a moment Of

2

inertia Of 252.8 kg-m. Find approximate time to attain full speed When starting from against full-load torque if starting current varies between 1.4 and /.8 timesfull-load current.

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

Full-load output 55.95 kW = 55,950 W Speed 750 = 12—5 r.p-S.

Fl.. shaft torque T = power/co = power/21tN = 55,950 x (750/60) 712.4 N-m

During starting period, average available torque

— 1.6

This torque acts on the moment of inertial I 252.8 km-rn:.

12.5

427,4 = 252.8 x 252.8 x dl 46.4 s

Example 29.19. A 14.92 kW 400 V. 400 -rpm. d.c. shunt motor draws a current of40A when running atfull-load. The moment ofinertia ofthe rotating system is 7.5 kg-m^2. Ifthe starring current is .2 rimesfull-load current. calculate (a) full•load torque fbj the time requiredfor the motor ro attain the rated speed against full-load.

Gujarat Univ. 1988)

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

Now. Tm-output 14.920/2-„x

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

T—O.2x356-71.2N.m

NOW, torque I dt 4.41 second

29.9. Speed Of a D.C. Motor

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

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

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

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

It shows that speed is directly proportional to back can-f. Eb and inversely 10 the flux Φ

Now

$N \propto E_b/\Phi$. on

For Series Motor

Let N_1 = Speedin the 1st case : la, armature current in the 1st case = Φ_1 tluxlpole in the first cwse

I_{a2}, Φ_2 = corresponding quantities in the 2nd case.

Then. using the above relation, we get

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

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

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.

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

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 thosc changes which are affected through manipulation of rheostats or other speed-controlling devices.

The speed regulation is defined ws the change in speed when the load is reduced from ruled value ro zero, expressed a.s percent Of the rated load speed.

% speed regulation = NL speed — FL speed x

F.L srwed

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 aluays tends to produce rotation. If torque increases, motor speed must increu•e 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:

l. Back e.m_f_ Eb ,VCÞ/K) drops instantly (the speed remains constant because of inertia of the heavy armature).

2. Due to decrease in Eh, is increased because l. = (V— Moreover. asmall reduction in flux produces a proportionately large increase in armature current.

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

4• This increase in ra 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, increxse 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 laken by the motor and the speed at which it Will run With an applied voltage Of500 V Total motor resistance is 3 Ohm

(Elect. Engg. See A Part 11 June 1991

Solution. 0.1590 Z/a (P/A) N-m

209 — 0.159 x 34.6* 10-3 *944 x 1, (4/2); la = 20.1 A

as given in Art.

10-3x944xNx2

Example 29.21. A 25th V' shunt motor runs at 1000 r.p.m. at no-load and takes 84. The total armature and shuntfield resistances are respectively 0.2£2 and 250 Q. Calculate the speed when loaded and raking 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- Vd.c. shunt motorhas an armature resistance OfO_5 Q andfield resistance Of 115 Q At no load. the speed is 1.200 r.p,m. and the armature current 2.5 A On application Of rated load. the speed drops to J, 120 r.p.m. Determine rhe line current and power input when rhe motor delivers rated load. (Elect. 'Iëchnoloxy, Kerala Univ. 1988b 1986)

Solulion.

Line current drawn by motor Power input at rated load

Esample 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 belf breaks, then taking k W. What Will be its speed ? Given armature resistance = 0.025 resistance = 60 and contact drop under each brush =

I V. Ignore armature reaction. (Elect. Machines (E-3) AMIE sec-c Winter 1991)

Solution. As Generator [Fig. 29.12 Load current.

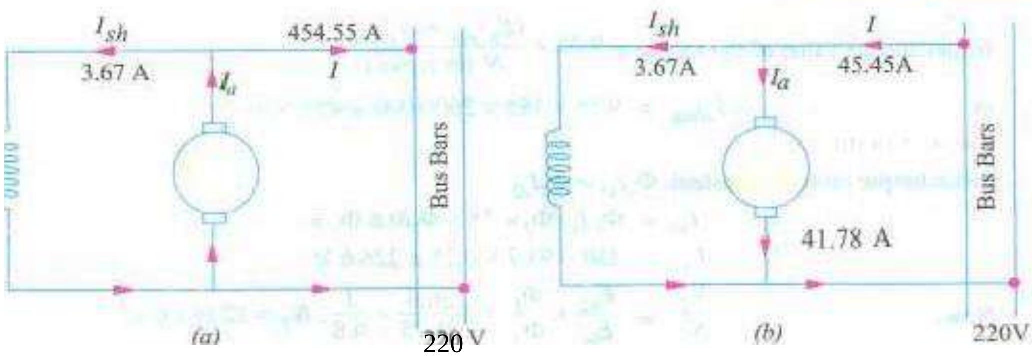


Fig. 29.12

As Motor [Fig. 29.12 (b)]

Input tine current = 100,000/220 = 45.45 A; I_{sh} current A: = 220/60 = 3.67 A

—45.45—3.67 '8 A; $I_a R_a = 41.78 \times 0.025 = 1.04$ V; E_{b2} —41.78 A; -220— 1.04- 2X I —216.96 V

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

$$\frac{N_2}{300} = \frac{216.96}{233.45}; N_2 = 279 \text{ r.p.m.}$$

233.45

because is constant

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

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

Now, = 250/250 - A: Hence, G =-4— Em 250-0.5 x 3 2485 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 x 248.5/250 = 994 rpm.

Hence, 994

ze, N_0 = 994 r.p.m.

When n Loaded

$I_a = 40 - 1 = 39$ A; $E_b = 250 - 39 \times 0.5 = 230.5\ V$ Also, $\Phi_0/\Phi = 1/0.96$

$$\frac{N}{E} = \frac{E_b}{E_{b0}} \quad \therefore \quad \frac{N}{994} = \frac{230.5}{248.5} \times \frac{1}{0.96}$$

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 resistauce 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 × 0.25 = 231.25 V, as inFig.29.13.

75 A

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

0.25 250

Instantaneous value ofback e.m.f. —231.25 0.8 = 185 v

= 260 A

Fig. 29.13

Instantaneous value of the torque = he torque = $9.55 \times \frac{(E_b)_{inst} \times (I_a)_{inst}}{N\ (in\ r.p.m.)}$

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

Steady Conditiorrs

Since torque remains constant, nstant, $\Phi_1 I_{a1} = \Phi_2 I_{a2}$

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

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

Now. $\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{\Phi_1}{\Phi_2} = \frac{226.6}{231.25} \times \frac{1}{0.8}$; $N_2 =$ 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 The resistance of armature at standstill gives a drop of 6 volts across armature terminals when 10 A were passed thmugh A were passed through it. Calculate (a) speed on load torque in At-m and (c) efficiency. The normal input Of the motor is 8 k W.

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

Solution. 200/100=2 A

EL. Power input

- 40-2-38 A; Ra=6/lO-O.6Ç2

— 198.8 V; 1772 V

; N —623.9 r.p.m.

700 198.8

T. 9.55 9.55 x 1772 x 38/623.9=103 N-m

(c) N. L. power input = 200 x 4-800 W; x 06—2.4 W

Constant losses - 800—2.4 = 797.6 W; FL. loss = 866.4 W

Total EL. losses 797.6 866.4 = 1664 W: output = 83M) - 1664 6336 W EL Motor efficiency = 0.792 or 79.2 %

Example 29.28. The input 23m V, dc. shunt motor is //kW. Calculate(a) the torque developed (h) the efficiency (e) the speed at this load. The particulars the molor areas follows :

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

A rm. resistance = £2; shuntfield resistance = 110£2.

Solution. No—load input No-load armature Cu loss

Constant losses When input is Il kW.

Input current Arm. Cu loss

Total loss

Output

Efficiency

(c) Back e.rn.f. at no-load
Back e.rn.f. at given load

Speed N

(Elect. Technology ;
Bombay University 1988' -
220x5= 1,100W:
$I_{sh} = 220/110 = 2A;\ I_{ao} = 5 -$

= 3^2 xo.5 W

- 1.100—4.5 =
1,095SW

- 11,0/220 = 50A ;
Armature current = 2 =
A

= 482 x 05 . - — 1,152 w;

= Arm. Cu loss + Constant
losses = 1 152 + 1095.5 =
2248 W

= 11.000- 2,248 — s, 752 w

8,752x

220-13 x 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 O. / 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 rhe current is 100 A.

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

Solution.

$$E_{b1} = 250 - 80\,(0.1 + 0.05) - 3 = 235 \text{ V}$$
$$E_{b2} = 250 - 100\,(0.1 + 0.05) - 3 = 232 \text{ V}$$

Since 80/100

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

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

474 r.p.m.

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 rhe motor "'ill run when developing half the torq"e. Total msistance

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

Of the armature andfield is 0.1 Ohm. Assume that the magnetic circuit is unsaturated.

Solution.

Since field is unsaturated,

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

$$T_a \propto \Phi I_a \propto I_a^2. \qquad (\therefore\ T_1 \propto I_{a1}^2 \text{ and } T_2 \propto I_{a2}^2)$$

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

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

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

29.12. Motor Characteristics

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

I. and armature Current characteristic. It is nown as *electrical* Characteristic

2. Speed and armature current i.e. M/a characteristic.

3. Speed and torque i.e. characteristic. It is also known as mechanical chargcteristic. It can be found from (I) and (2) above.

While discussing •notor characteristics, the tòllowing two relations should always be kept in mind :

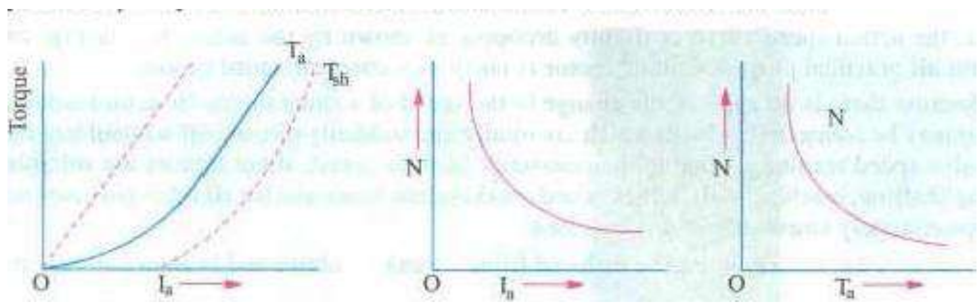
$T_a \propto \Phi I_a$ and N $\propto$ —

29.13. Characteristics of Series Motors

We have seen that T In this case, as field windings also earn' the armature current, rÞ up to the point of magnetic saturation, Hence. before saturation,

T and

At light loads. and hence is small. But as la increases, increases as the square of the current. Hence. Tall„ curve is a parabola as shown in Fig. 29.14. After saturation, is almost independent of hence To la 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 SIEed can be deduced from the fGrrnula :

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

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

When load is heavy, ia is large. Hence, is low (this decreases Eb and allows more armature current to now). But when load current and hence la falls io 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

Characteristic

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

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 is 'Issumcd constant, then N E,_ As Eh is also practically Constant. speed is, for most purposes. constant (Fig. 29.18).

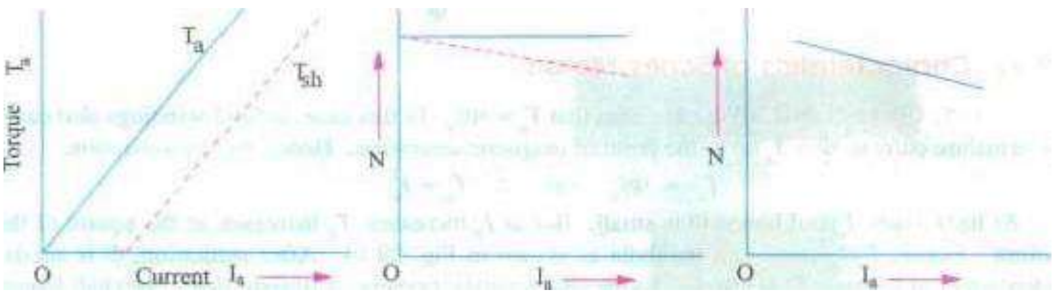


Fig. 29.17 Fig. 29.18 Fig. 29.19

But strictly speaking. both Eh and (Pde-crease with increasing load. However. Eb decreases slightly more than so that on the Whole, there is some decrease in speed. The drop varies from 5 to 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 practica] 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. Characteristic Can be deduced from and (2) above and is shown in Fig. 29.19_

29.15. Compound Motors

These motors have both series and shunt windings. If scries excitation helps the shunt excitation i.e. series flux is in the same direction (Fig. 29.20): then the tor is said to be cummulatively 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 conjunclion with fly-wheel ffunctioning 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 Eb/(tD). Due to this reason, there is a decrexse 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.

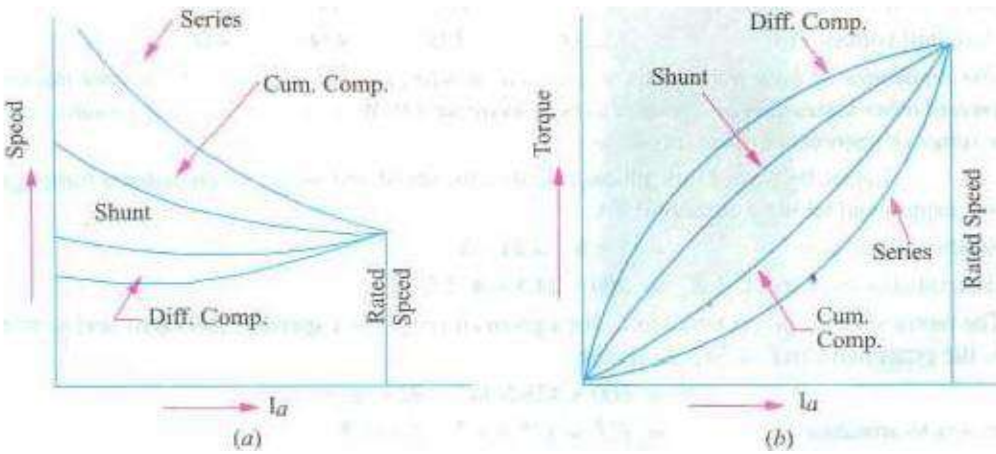


Fig.29Æi

Example 29—32. Thefollowing results were obtainedfmm a static torque a seriesmotor :

Current (A)	20	30	40	50
Torque (N • m)	128.8	230.5	349.8	46.2

Deduce the speed/tOrque curve for the machine When supplied at a constant voltage Of460 V. Resistance andfield winding is 0.5 Q. Ignore imn andfriction losses.

Solution. Taking the case When input current is

20 A, we have

Motor input = 460 x 20 = 9.200 W

Field and armature Cu loss

= 202 xos=200w

Ignoring iron and friction losses.

output = 9,200 – 200 = 9,000w

Now. Tah x 21t,V = Output in watts.

128.8 × 2π × N= 9,000 0 100 200 300 400 soo N - 9,000/21tx 128.8 Torque (NW.m)

= 11.12 r.p.s. = 667r.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-tn)	128.8	2305	349.8	4692

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

Example Aýàn Which requires 8 (5.968 k W) at 700 r.p.m. is coupled directly to a d.c. series motor. Calculate the inpui tv the motor when the supply volraýe is5m 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 al 600 r.p.m. and the relationship between the tenninal voltage and the load current was found ro be asfollows :

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

The resistance Of both the armature and field windings Of the motor is 3.5 Q and the core. friction and other losses may be assumed to be constant at 450 Wfor the speeds corresponding 10 the above range Ofcurrents at normal voltage. (London)

Solution. Let us. by way of illustration. calculate the speedand output when motor is running off a supply and taking a current of IA.

Series Voltage drop 7x3.5-24SV

Generated or back e.tn.f. Eh = —24.5 = 475—5 V

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

Of 7A. the generated e_m.f is 347 V. Hence,

N Ox475.5/347 -823 r.p.m.

Power to armature - -3.329W Output Armature —450 = 3,329 — 450 = 2.879 W = 2.879 kW power required by the fan at 823 r.p.m. is = 5.968 x $823^2/700^2$ = 9.498 kW

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

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

.F. 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	1 1.100
Motor output W)	2.879	4.420	5.860	10.65
Power required by fan (kW)	9.698	6.146	4.222	2566

In Fig. 29.23 (i' the motor outputin kW and (ii' power required by fan in kW against input currentis plotted. Since motor output equals the inpul 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 × 12 = **6,000 W**

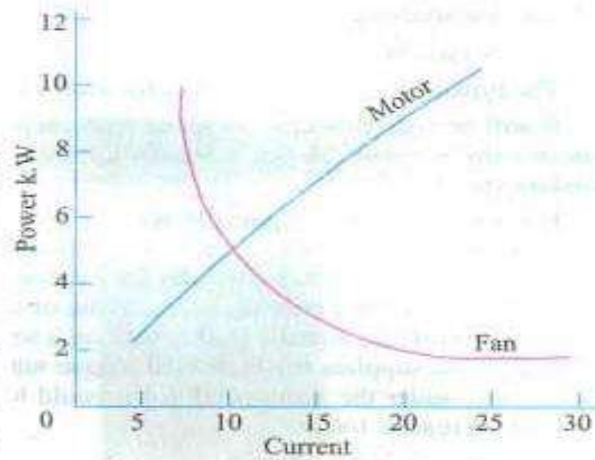


Fig. 29.23

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 farily 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 meet the various losses occuring within the machine.

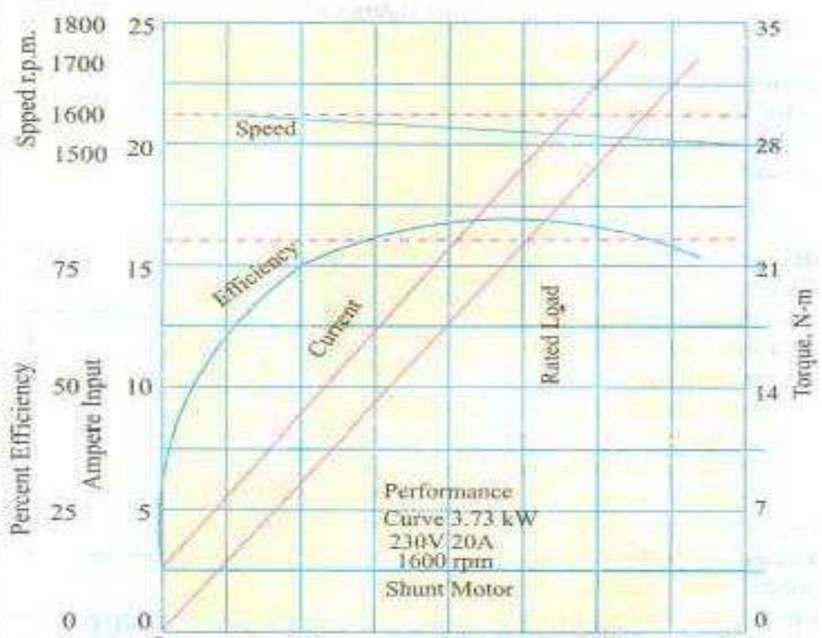


Fig. 29.24

As compared to other motors. a shunt motor is said to have a lower starting torque. this should not bc taken of 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 fuli load torque is required at Start, then shunt motor draws $I_a \propto \sqrt{T_a}$) whe twice the full-load current Iaor whereas series motor draws only $T_a \propto I_a^2$ or $I_a \propto$ approximately

one and a half times the fill/ 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 ptominent in series motor than in a shunt motor. Hence, a series motor is not suitable for applications requiring a Substantially constant svxed.

For a given curreng input, the siarting torque developed by a series motor is greater than that developed by a shunt motor. Hence. series motors are used where huge starting torques ure necessary i.e. for street cars, cranes, hoists and for electric-railway operation. In addition to the huge starling 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,) and supplies the increased torque with a small increase in 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,

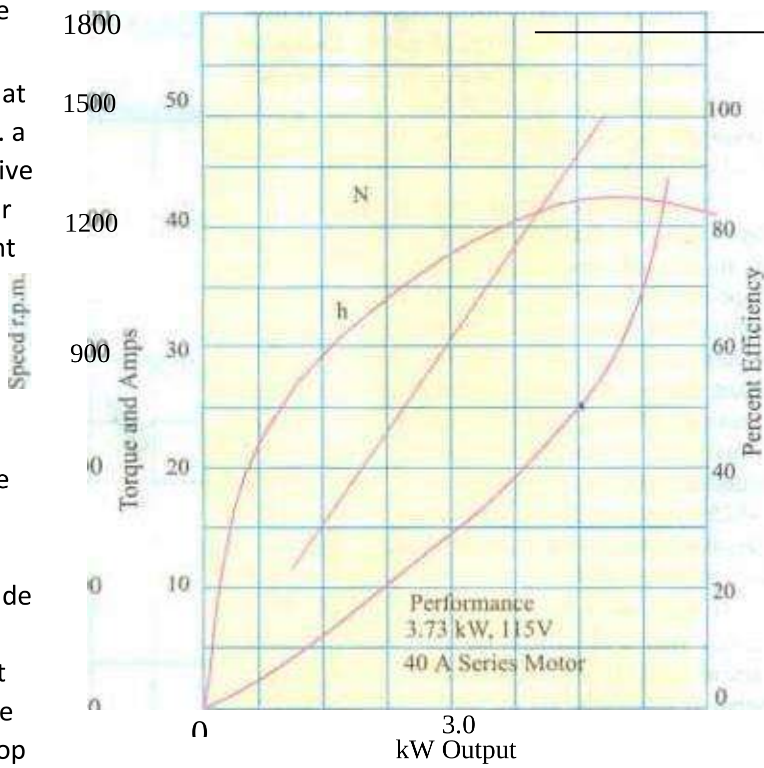


Fig. 2925

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.

(i) When the speed to be maintained approximately constant from NL to F.L i.e. for driving a line of shafting etc. ij 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	Characterivtic•	Applicatio
Shunt	Approximately constant speed Adjustable speed Medium starting torque (Up to IS EL. torque)	For driving constant speed linc shafting Lathes Centrifugal pumps Machine tools Blowers and fans Reciprocating pumps
Series	Variable speed Adjustable variying Slxed High Starting torque	For traction work [e. Electric locomotives Rapid transit systems Trolley. ears etc. Cranes and hoists Conveyors
Comulalive 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 1. have a relatively huge starting torques.

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

I. 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 ofspeed 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 sh0uld not 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) Coplrr losses (ii) Magnetic lcvsse_s and iiii• 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 now diagram of Fig. 29.26.

Overall or commercial efficiency —A' Electrical efficiency = —Ã , Mechanical efficiency

c

11m = -h

The efficiency curve for a motor is similar in shape to that for a generator (Art. 24ß5).

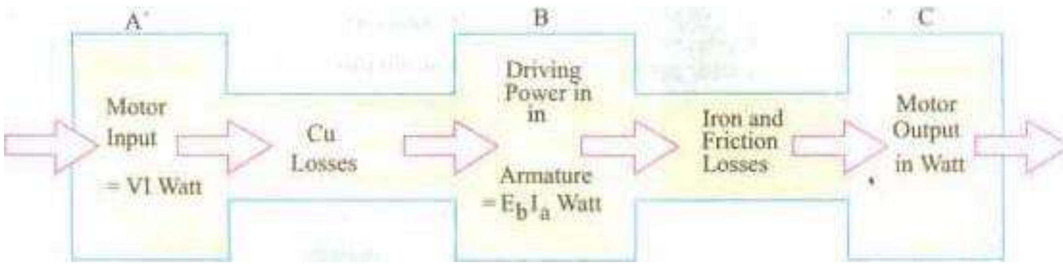


Fig.2926

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

Example 29.34, One' ofthe r,vo similar 50th V' *hunt machines* A and B running lighl 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 ro generate 500 V Calculate thefriction and windage loss and core loss ofeach machine. Machinery-I, Madras Univ. 1985)

Solution. When running light. machine input is used to meet the following losses (i' armature Cu loss shunt Cu loss ' iii' iron loss and mechanical tosses i.e. friction and windagc losses. Obviously, these no-load losses fcu• each machine equal 500 X 3 W.

(a) With B unexcited

In this case. only mechanical losses take place in B. there being neither Cu loss nor iron-loss tecause B is unexcitcd_ Since machine A draws 05 A more currentFriction and windage loss of B 500 x 0.5 250 W

(b) With B excited

Inthis case, both iron losses as well as mechanical losses take place in machine B. NOW, machine

A draws, 4.5 — 3 = I .5 A more current.

Iron and mechanical losse• of B = IS X 500 750 W

Iron of B = 750 - 250 W

Example A 220 Shunt motor has an am-alary resistance Of0.2 ohm andfield resistance of The motor draws 5 A al 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 x 5 = W; Arm. Cu loss = 3^2 k W

∴ Constant or standing losses of the motor = 1100 1098

When oaded, arm. cu loss - 50^2 x 0.2 500 W

Hence. total motor losses = 1098 + 500 = 1598 W

Motor inputonload - 220 x 52 = 11,440 W; output — 11,440- 1598 = 9842 W

= 955 x outputhV = 9.55 x 9842/1436 N-m

Example 29—V'. 250 Vshunt motor on no runs 1000 and takes 5 amperes. Armature and shunt field resistances are 0.2 and 250 ohms respectively Calculate 'he speed when loaded taking current Of50 A. The armature r•ection weakens thefield by 3%.

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

Sol

2402

1000 2492 0.97 q

Example 29.37. A 500 Vt}.c. shunt motor takes a current Of5 A On no-load The resislanees Of the armature andfield circuit are 0.22 ohm and 250 Ohm respectively. Find 'he efficiency when loaded and taking a current of 100 A (b) the pem.•enrage change of speed. State precisely the assumptions made. (Elect. Engg-l. MS. Univ. Baroda 1987)

Solution. No-Lond condition

I_{sh} = 500/250 = 2 A; I_{a0} = 5 − 2 = 3 A; E_{b0} = 500 − (3 × 0.22) = 499.34 V

Arm. Cu loss = 3^2 × 0.22 = 2 W; Motor input = 500 × 5 = 2500 W

Constant losses = 2500-2=2498 W

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

I .o:ad condition

(a) Motor current 100 A; Ia = 100 − 2 = 98 A; E_b = 500 − (98 × 0.22) = 478.44 V

Example 29—39. A dc. shunt machine While running as generator develops a voltage Of 250 V at J000 on no-load. armature resistance Of 0.5£2 andfield resistance Of 250 When the machine runs us motor: inpul to it at no-load is 4.4 250 V. Calculate the speed and efficiency Ofthe machine it runs a motor taking 40 A at 250 Armature reaction weakens by (Electrical Technoloky. Aligarh Muslim Unis. '989'

Solution.

NOW. When running as a generator, the machine gives 250 V al 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, = r.p.m. and Eh, 250 V.

When it runs as a motor. drawing 40 A. the back e.m.f. induced in its armature is Eb2 =

$250 - (40 - 1) \times 0.5 = 230.5$ 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 r.p.m.**

1000

Emciencv

No-load input represents motor losses which consists of (a) armature Cu Ra Which is variable.

(b) constant losses W, which consists of jii shunt Cu loss (iib magnetic losses and 'iii' mechanical losses.

No-load input or total losses 250 x 4 W

Arm. cu loss = W, W, = = 995.5 W

When motor draws a line current of 40 A, its armature current is (40 — I = 39 A cu loss = 760.5 W: Total losses- 760.54 1756 W

Input 250x40= 10.000 W: output = 10.0 - 1756=8.244 W

- 8.244x IOW10.ooo=82..wrt

Example 29.40. The armature Winding Of a 4-poie•, 250 V dc. shunt motor is lap connected. There are 120 slots, each slot containing 8 conductors. The is 20 mWb and current taken by motor is 25 A. The resistance of armature andfield circuit are O. I and 125 respeclively. If the rotational losses amount 10 be 810 Wfind,

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

Soil"ion. - (23 x 0.1) -247.7 V

<u>20X IO-3 X960X,V</u> 4

NOW, A 247.7 = 60 (4)— : N —773 r.p.nL

<u>247.7X23</u>

Gross torque or armature torque T. 9.55 9.55 x = 70.4 N - m

773

Rotational losses = 810 W: Total motor losses = 810 + 500 +53 = 1363 W

Motor input = 250 x 25 = 6250 W; Motor output - 6250 - 1363-4887 W

T_{sh} = 9.55 x outputiN = 9.55 x 4887/773 - 60-4 N-m

(iii) Efficiency = 4887/6250 = 0.782 = 782%

Example 29.11. A 20-hp (14.92 kWh 230-V, 1150-r.p.m. 4-pole, shun' motor has a total of 620 conductors arranged in two parallel paths and yielding an armature circuit resistance OfO. 2 Q

When it delivers rared power a' rated speed. it draws a line current Of 74.8 A and a field current Of 3 A. Calculate (i' theflu.x per pole the torque developed (iii)lhe rotational losses expressed as a percentage ofpower.

Solution.

(i) Now.

f Armature Torque,

(iii) Driving powerinarmature= Ei,la = 215.64* 71.8= 15.483 W

= VI = 230 x 74.8 Outpul14,920 W; Rotational losses = 15.483— 14.920= W

(iv) Motor input- - 17.204 W: Total 17204- 14.920 W

Losses expressed as pcteentage Of power input = 2284/ 17,204 = O. 1 33 or 13.3%

Example 29.42. A 7.46 kW: 250• V shunt motor rakes a line current A When running light. Calculate the efficiency as a motor when deliveringfull load output, if the armature andjie/d resistame are 0.5 Q and 250£2 respectively. A,' output power will rhe efficiency be maximum ? Is it possible obtain this output from the machine ? MS. Univ. Baroda 1985)

Solution. When loaded lightly

Total motor input (Or total no-load losses) = 250 x 5 = 1.250 W

fieldCu10ss = 250* 1 =250 W;

∴ Iron losses and friction losses = 1250 — 250 — 8 = 992 W These losses would be assumed constant.

Let bc the full-load armature current, then armature input is = (250 x W EL output = 7.46 x 1000=7.460W The losses in the armature :

(i) Iron and friction losses = 992 W

(ii) Armature Cu loss = la: *0.05 w 2501. —_ 7,460 + 992 + I_a^2 × 0.5

O = 365 A

EL input curTent = 36.5+ I = 37.5 A ; Motor input = 250 x 37S W

EL output = 7,460 W

FL efficiency 100/250 x 375-79.6% NOW. efficiency is maximum When armature Cu loss equals Constant loss.

i.e. 1.242 Worla=49.84A

Armature input 250 x 49.84 12.460 W

Armature Cu loss 49.84^2 x 0.5 1242 W; Iron and friction losses = 992 W

Armatureoutput 10.226 w

Output power = 10,226 W = 10.226 kW

As the input current for maximum efficiency is beyond the full-load motor current, it is never realiscd 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 ar a speed of 660 r.p.rn. The resistance of the armature circuit (including brushes) is 0.3 n and that ofthe shuntfield circuit 270 Q.

Determine when the motor is running atfull load

(ij rhe current input (ii the speed Determine the armature current at which efficiency is gnat-imam. Ignore the effect ofarmature reaction.1991)

Solution. 460/270= 1.7

When running light

I_a= 4— 1.7 = 2.3 A; Armature Cu loss —2.3^2 *0.3 1.5 W (negligible)

No-load armature input = 460 x 2.3 = 1 ,058 W

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

Let full-load armature input current be / Then

Armature input = I W; Armature Cu loss x 0.3 W

= 38.358=0 la = 88.5 A

fij Current input= 88.5+ 1.7=90.2A

= 660 x 433.5/459a=624r.p.m.

For maximum efficiency, 10^2 Ra 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 sreed

(b) the outpat torque and (d) the efficiency. if the motor current is 50 A The value Of flux per pole under these conditions is 22 mWh and the corresponding iron. friction and wirxtagc losses total 810 W. Armature resistancc O. 19 field resistance 0.14 Q.

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

2. no-load, a shunt tyotor takes 5 A at 250 V. resistances of the field and armature circuits are 250 Q and O. I respectively. Calculate the output power andefficiency 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 Josses are independent of the current and speedl

SINGLE PHASE TRANSFORMER

. Working Principle Of a Transformer

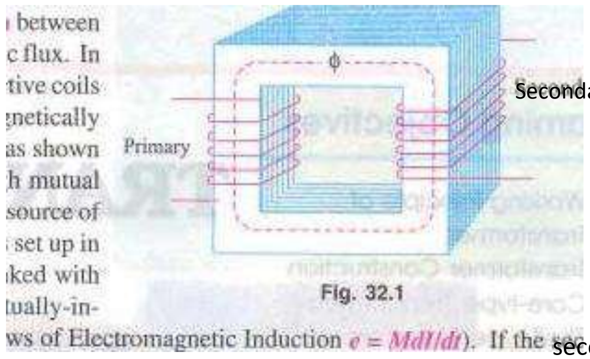


Fig. 32.1

A transformer is a static (or stationary) piece ofapparatus by means of which electric power in onecircuit is transformed into electric power of the same frequency in another circuit. It can raise or lower the voltage in a circuit hut With a corresponding decrease or increase in curmt. The physiCal Laminated Core basisofa transformeris mutual induction between two cimuits linked by a common magnetic flux. In its simplest form, it consists Of two inductive which are electrically separated bat 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 a alternating voltage, an altemating flux is set up in the laminated core. most of which is linked the other coil in which it produces mutually-induced e.m,f.facCording to Faraday's Laws Of Electromagnetic coil circuit is closed, a current flows in it and so electric energy is transrewed (entirely magnetically) from the first to the second coil. The first coil, in which electric energy is fed from thea.c. supply mains, is calledprimary winding and the other from which energy is drawnout, is called secondary winding. In brief. a tKånsformer is a device that

1. transfers electric power from one circuit to another

2: it does so without a change of frequency

3. itaccomplishes this by electromagnetic induction and

4. where the two electric circuits arein mutual inductive influence of eachother.

32.2. Transformer Construction Ironcore

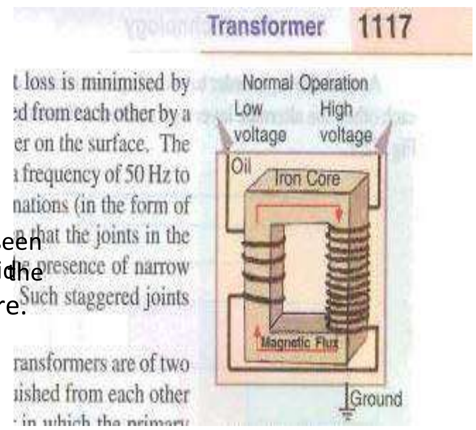
The simple elements of a transformer consist of two coils having mutual inductance and a laminated steel core. The primary secondary two coils arc insulated from each other and the steel core. Other necessary parts are :

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 ondary insulating and bringing out the terminals of windings from "0/120

types ofPrinciple ot 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 ahigh permeability and a low hysteresis loss at the



usual operating flux densities. The eddy current loss laminating the core, the laminationsbeing insulated from each other by a light coat of cote-plate vanlish or by an oxide layer on the surface. The thickness of laminations valieS from 0.35 mm for a frequency of 0.5 mm for a frequency Of 25 Hr.. The core laminations (in the strips) are joined as shown in Fig. 32.2. It alternate layers are staggered in order to gaps right through the cross-section of the are said to be 'imbricated'.

isseen avoid the core.

Constructional/y, 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 ale known as (i) core-type and (ii) shentype. Another recent development is spiral-core-or wo«nd-coretype, lhc trade name beingspirakore transformer,

In the so-called core type transformers, the windings surround a ary Winding considerable par/ ofthe core whereas in shell-type transformers. the core

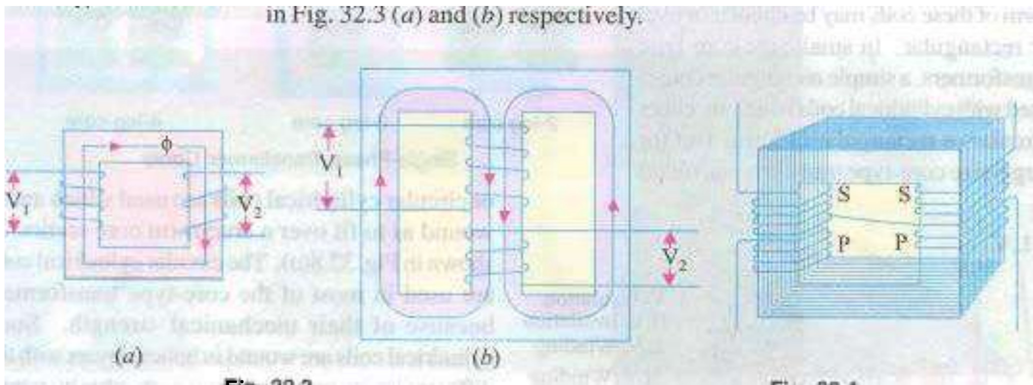
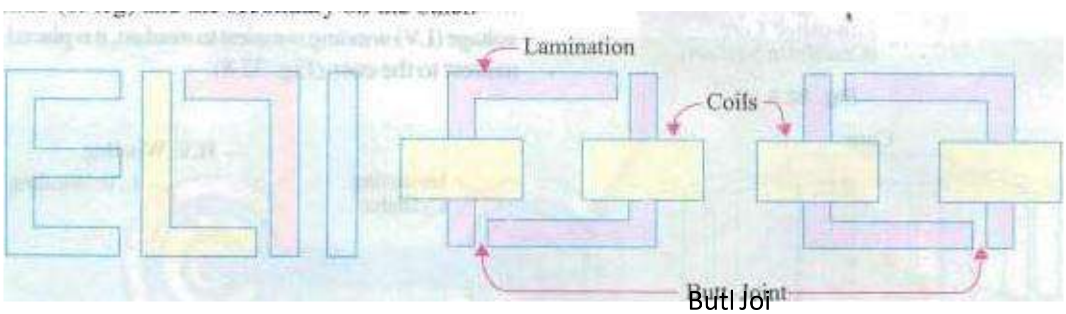


Fig.32'3

Shell-Type transformer surrounds a considerableportion ofrhe windings asshownschematically in Fig. 32.3 (a) and (b) respectively

In thesimplified 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 llux_ As shown in Fig. 32.4, halfthe primary and halfthe secondary winding have been placed side byside or concentrically on each limb, not primary on one limb (or leg) and the secondary On the other„



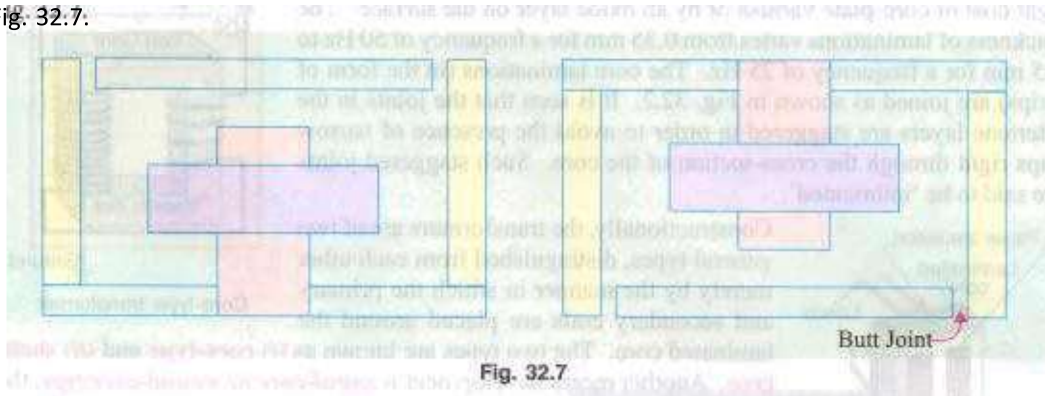
Butl Joi

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 saidabove, in order to avoid high reluctance at thejoints where the laminationsare buttedagainst each other, the alternate layersare stackeddifferently to eliminatethesejointsas shown in Fig. 32.6and

Fig. 32.7.



Because oflaminations and insulation, the net oreffective area is reduced. due allowance for which has to be made (Ex. 32.6). 'tis found that. in general, the reduction in coresectional areadueto the presence ofpaper, surface oxide etc. is of the order of 10% approximately.

As pointed out above. rectangularcores With ectangularcylindrical coils can be used forsmall-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. 329 (b) where circles represent the tubular former carry ing 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 ofthe mean turn and the consequent R loss. Three stepped core is the one most commonly used although more Steps may be forveo' large transformers as in fig. 32.9 From the geometry Offig. 329, it can shown that maximum gross core section for Fig. 32.9 (b) is 0.5 and for Fig. 32.9 (c) it is 0.616 where d is the diameterofttE cylindrical coil.

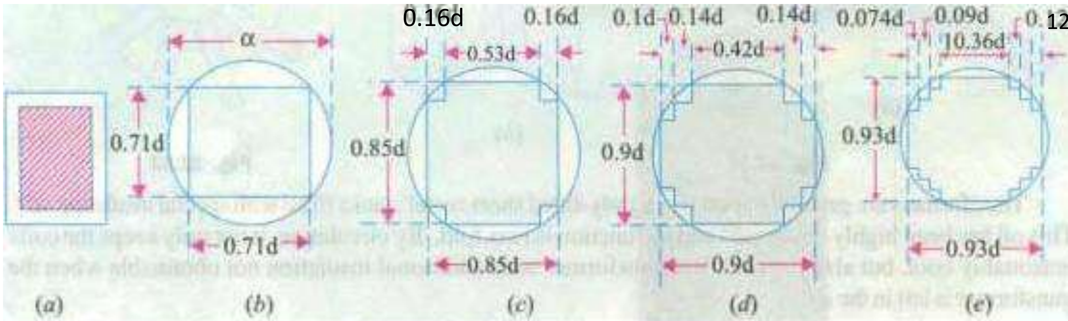


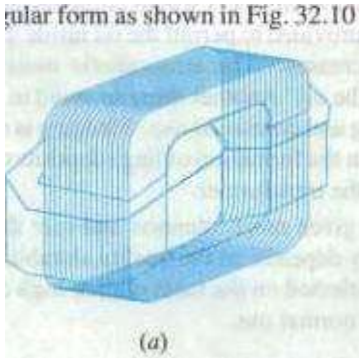
Fig. 32.9

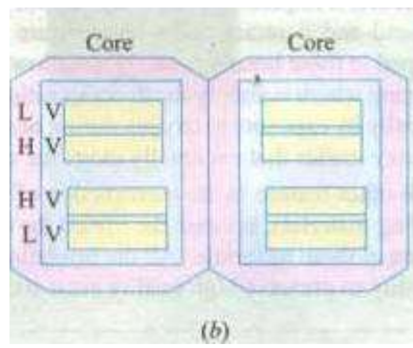
32.4. Shell-type Transformers

In these case also, the coils are form-would but are multi-layer disc type usually wound in the

In these case also, the coils are form-would but are multi-layer disc form of pancakes. The different layers of such multi-layer discs are insulated from each other by pavrr. 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

gular 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. I I.

Fig. 32.10

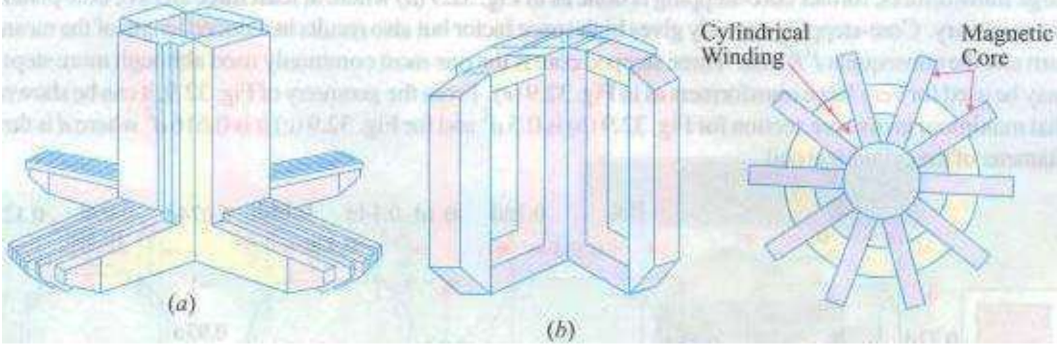
A very commonly-used shell-type transformer is the one known as Berry Transformer—so called after the name of its designer and is cylindrical in form. The transformer core consists Of laminations arranged in groups which radiate out from the centre as shown in section in Fig. 32.12.

It may be poi ated out that cores and coils Oftransformers must be provided With rigidmechanical bracing in Olderto prevent movement and possible insulation damage.

bracing reduces vibrationand the objectionable noise—a hummingsound-duringoperation.

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 œduees the weight per WA. Hence, the advantages ofsuch construction are

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.



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a relatively more rigid (ii) lesser weight and size per kVA rating (iiö lower iron losses athigher

Fig. 32.11 Fig. 32.12

Transformers ale generally housed in tightly-fitted sheet-metal ; tanks filled with special insulating 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 proyide sufficient cooling area, the sides Ofthe tank are corrugated or provided with radiators mountedon the sides. Good transformer oil should he absolutely free from alkalies, sulphur and particularly from moisture. The presence of even an extremely small percentage ofmoisture in the oil is highly detrimental from the insulation viewpoint because it lowers the dielectric strength Of the Oil considerably. The importanceofavoiding moisture in the transformer Oil is clear from the fact an addition Of 8 parts of Water in I reduces the insulating quality Of the Oil to a value generally recogniud 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 10 avoid in the oil is sledging which is simply the decomposition of oil with long and continued use. Sledging is caused principally by exposure to oxygen•during heating and results in the formation Of large deposits ofdark and heavy matter that eventually clogs the cooling ducts the transformer.

NO Other feature in the construction Of a transformer is given more attention and care than the insulating materials. because the life on 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 qualityeven after many years of normal use.

Insteadofnatural mineral oil. now-a-days synthetic ilLsulating fluids known as ASKAREIAS (trade name) are used. They arc non-inflammable and, ihe influence of an electric arc, do not decompose to produce inflammableeases. One such fluid commercially known as PYROCLOR is being eOensively used because it possesses remarkablestability as adielectric and even after long shows no deterioration through sledging. oxidation,acidormoisture formation. Unlike mineral Oil, iUshowsmo rapid burning.

All the transformer leadsarebroughtoutoftheircases through suitable bushingS. There are many designs Of the-SC, their-size and constnlction depending on the voltage Of the leads. For moderate voltages, porcelain bushings are Lsed to insulate the leadsas they come out through the tank. In general, they look almost like the insulators used on the transmission lines. Inhigh voltage installations, Oil-filled orcapacitor— type bushings areemployed.

The choice ofcore or shell-type construction is usually determined by cost, because similar characteristics can be obtained withboth types. For very high-voltage transformers or formultiwinding design, shelltype constmction is preferred by many manufacturers. In this type. usually the mean length ofcoil turn is longer than in a comparable core-type design. Both core and shell forms areused and the selection is decided by many such as voltage rafing, kVA rating, weight. insulation stress, heat distributionetc.

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

(a) oil-Aled self-cooled (b) oil-filled Wafer-cooled (c' áir-biast 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 senes to convey the heat from the core and the windings to the case from where it is radiated the surroundings. For small size, the tanks are usually smooth-surfaced, but for largersizes. 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 cote are immersed in the Oil, but there is mounted near the Surface of oil, a coolingcoil thmughâh'hichcold Water is kept circulating. The heat is carried awayby this water. The largest transformers such as those used With high-voltage transmission lines; are constructed in this

Oil-filled transformers are bail t for outdoor duty and as these require no housing Other than their own. a great saving is thereby eflCcted. These transformers require only periodic inspection.

For voltages below 25.000 V. transformers can bc built for cooling by means of an air-blast. The transformer is not immersed in oil. bat is housed in a thin sheet-metal box open at both ends through which air is blown from the bottom to the top hy 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 windingshave noohmic resistance. there is no magnetic leakage and hence which has no 1^2R and core losses. In other words. an ideal transformerconsists oftwo purely inductive wound on a loss-free core. It may, however, be notedthai iv is impoçsible

10 realize such a transformerin practice, yet ror cani•enience, will start with such a former

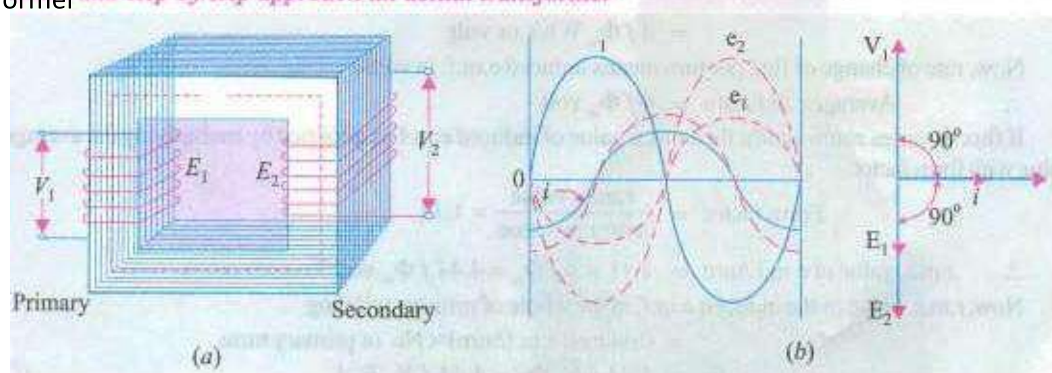
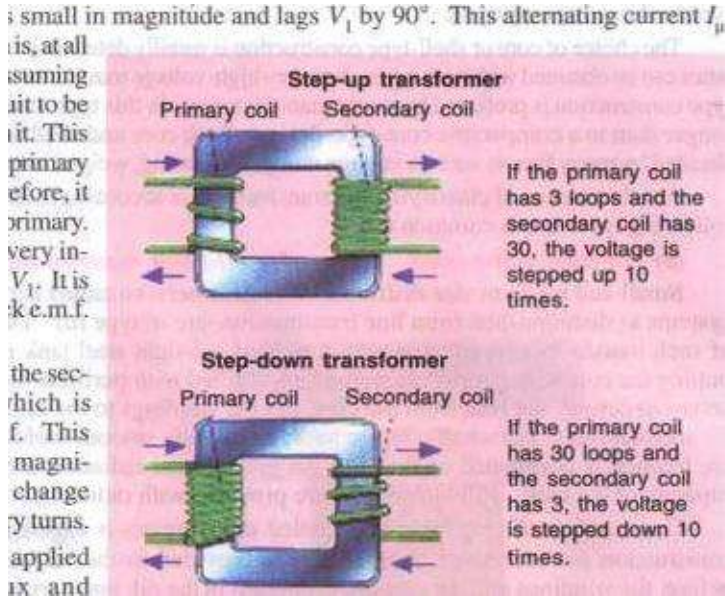


Fig. 32.13

Consider an ideal transformer [Fig. 32.13 whose secondary is open and whose primaryis connected to sinusoidal alternating voltage VI. This potential difference causes an alternating curtent to flow in theprimary. Since the primary coil is purely inductive and there is no output (seconda/y being open) the primary draws the magnetising current only. The function Of this current is merely to magnetise the core. it is small in magnitåde and lags VI by 90•. produces an alternating flux Owhich is. at all times, pmportional to the cun-ent OLssuming permeability of the magnetic circuit to be constant) hence. is in phase with it. This changing flux islinked bothwith the and the secondary windings. Therefore, it produces self-induced e.m.f, in the primary This self-induced e.m.f. Et is. at every inStant, equal to and in to VI. It is also known as Counter e.m.f. or back e. ofthe primary.

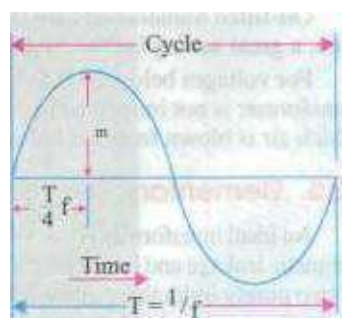


Similarly, there is pnxiuced in the secondary an induced e.tn.f. E2 which is known as mutually induced c-m.f. This e.m.f. is antiphase with V, and its magnitude is proportional to the rate of change Of flux and the numberof secondary turns

The instantaneous values Of applied voltage. induced e.m.fs. flux and magnetising current are shown by sinu- Step-up transformer soidal wavesinFig. 32.13 fig. 32.13

(c) shows the Vectorial repœsentation Ofthe effective values Of the above quantities.

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



Let NI = No. Of turns in primary

Nk = No. ofturns in secondary

= Maximum flux in core in w&rs

f =Frequency of a.c, input in Hz

As shown in fig. 32.14, flux increases fromits zero value to maximum value 4'nin one quarter of the cycle i.e. in 1/4/second.

$$= \frac{\Phi_m}{1/4f}$$

$$4 f \Phi_m \text{ Wb/s}$$

∴Average rate of change of flux =

Fig. 3214

= or volt

Now. rate ofchangeofflux perturn means induced e_m-f_ involts_

Avetagee.rn.f./turn = 4fcbm volt

If flux varies sinusoidally then r.m.s. value ofinduced e.m.f. isobtained by multiplying theaverage valuewith formfactor. rm. S. value

Formfactor =-1.11

average value

∴rms. valueofe.m.f]turn = 1.11 x 4 4.44 volt

Now. r.ms. valueofthe induced e.m.f. in the whole ofprimary winding

= (inducede.tn.fjturn)xNo. ofprimarytums

Hence. currents aræin the inverse ratioof the (voltage) transformation ratio.

Example 32.1. The 2maximumflux density:tn die core ofa 250/3000-Võlts,SO-Hzsingle-Þhase transformer is 1.2 Wb,4n. Ifthe e.m.j: per furn is 8 volt, determine (i) primary and secondary turns areg core.

(ElectricalEngg.-l, Nagpnr Univ. 1991)

Solution. (i} E = xe.m.f.induced/turn

(ii) We may use = — 4.44 Bm A

3000 4.44x 50 x 375 xL2xA; A = 0.03m2.

Example 32.2. The of a IOO-kVA. 11000/550 V: _50-HZ„ I -ph, Copé type transformer has a cross-section of20cmX 20em. Find the numberofH. V,and L turns perphase and the e,m.f: per turn if rhe coredensiry is nor 'o exceed Tesla. Assume a stacking factor Of0.9' What will happen if its primary voltage increased bv on no-load ?

(Elect. Machines, AM.LE, Sec. By 1991)

Solution. 1.3

11,000 = x 1060

550 = xL3 X 0.036: N2=53

= 1060=53

e.m.f.}tum = 10.4 V or 550/53= 104 v

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

Example 323. A single-phase transformer has 400 primary and 1000 secondary turns. The net cross-sectional area ofthe core is 60 cm^2 . Iftheprimary winding be connected a 50-Hz supply ar 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) $E_2/E_1 = K \quad \therefore \quad E_2 = KE_1 = 2.5 \times 520 =$ **1300 V**

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

or $520 = 4.44 \times 50 \times 400 \times B_m \times (60 \times 10^{-4}) \quad \therefore B_m =$ **0.976 Wb/m²**

the secondary Winding. (Elect. Engg-E. rune Unh'. 1989) Example 32.4, '4 25-kVA transformer has 500 turns on the primary and 50 turns on the second. ary winding. The primary is connected to 3000-1' SO-Hz supply. Find the full-load primary and secondary currenfs, the secondary e.nt.f: and the maximum flux in the core. Neglect leakage drops and no-load primary cgrrenÇ (Elect. & Elect.mnic Engg„ Madras Univ. 1985)

Solution. K = N2/Nt-50/500-1/10

Now, full-load

e.m.f.per turn on primary side = 30/500—6 Secondary e.m.f.

r operates With a number ofH.V. and L V.

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

SolutionMaximumvalue offlux has twen given as 0.05 Wb.

(ii) e.m.f. per turn 4.44 f

= 4.44 x 50 x 0.05 = 11.1 volts

(i) Calculations fornumtvofturns on two sides:

Voltage phase on delta-connected primary winding 11000 volts

Voltage per phase on star-connected secondary winding 550/1.732 = 317.5 volts T1 = numberofturnson primary, per phase voltage perphase}e.m.f. turn

T. numberof 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 higlEr even integer. _In this case. it be 30. Theo. 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 ofL.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 tranžformer has 500 turns in the primary and turns in the secondary. The cross-sectional area Ofthe core is 80 sq. cm. (fthe primary windingì.ç connected to a 50 H: supply at500 V. calculate (i) Peakflux-density, and lii) Voltage induced in the secondary.

(Bharathinr University November 199T

, Solution. From the

(i) Peakfluxdensity, 20

.m.f. equation for transformer,

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

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

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

(ii) Wtageinducedin secondary is obtained from tmnsformationratioorturnsratio

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

V2 — 500k12CW500= 1200volts

Example 32.7. A 25 kVA. single•phase trttnSfOñ7ier41ås 250 rurnS on primàrÿ *and 40* thè secondary winding. The primary is connected to 50 H: mains. Calculate (i) primary and Secondary currents on"'Il-load, (ii)$ecendary e.m.f.. (iìi) maximumflux in the core.

(Bharathiar Univ. April 1998)

If V_2

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

V_2

1500 — 250 , giving V2 = 240 volts

(in Primary current 25000/1500-16.67amp Secondary curent 25000/240—104.2amp

(iiib If0mis the maximum core-flux in Wb;

1500 = 4.44 x givingÇ=O.027Wbor27mWb

Example 32.8. A asingle-phase, 50 "z, core-type transformer has Square cores of20 cm side. Permissible maximumflux-density is" Wb/m^2. Calculate number of 'urns per Limb on•he High and larw•volroge sides for u 3000/220 V ratio. Manonmnnium Sundaranar cniv. 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 halfH.V]

Winding from the view-point of reducing leakage reactance.

Starting with calculation for LV. tums, Ty

4.44x50xt(20x20x Tz=220

= 220/8.0=24.77

Select

= 26 x 3000/220 = 354, selecting the nearest even integer.

of H.V turns on each Limb = /

Number OfLV. 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 (i" 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 copperlosses. But practical conditions require that certain modifications be made in the foregoing theory. When an actual transformer is put on load. there iviroiilošsin the core andcopperlossin the Windings (both primary and secondary) and these losses arenot entirely negligible.

Even when the transformer is on no-load, the primary input current is not wholly reactive. Theprimary input current under nozload conditions hastosupply (i) iron losses in the core i.e. hysteresis lossand eddy current loss and (ri) a very small copper le8s in primary (there being no Cu loss in seconda/y as it is open). Hence, the ncAoad primary input Current at 90^0 behind VI but lags it by an angle $\phi_0 < 90^0$. No-load input power

Wo = Vilo cos ϕ_0

Where cos is primary power factor underm-load Conditions. No-load Condition pf an actual transformer is shown vectorially in Fig. 32.16.

As seen from Fig. 32.16, primary current 10 has two components :

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

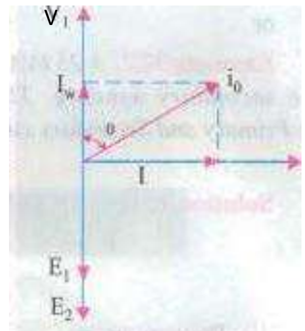


Fig. 32.16

I_w =10 COSϕ_0

(ii) The Other component is in quadrature With VI and is known as magnerising Component I because its function is to sustain the alternating flux in the core. It is wattless.

losin4)o

Obviously, 10 the vector sum of [wand I . hence The following should noted carefully :

l. The no-load primary current Ibis small as compared to the full-load primary current. It is about 1 per cent of the full-load current.

2. Owing to the fáét that the permeabilityofthe cofe 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 10 is very small, the no-load primalY Cu loss is negligibly small which means that no-load primary input is practically equal t" the iron loss in the transformer.

4. As it is principally the core-loss Whichis responsible for shiftin the known as hysteresis' angle advance.

Example 32.9. (a) A 2, 200/200-1' transformer draws a no- load primary èurrent Of0.6 A and absorbs 400 watts. Find the magnetising and iron loss currents.

(h) 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.

Solution. Iron-loss current

no-load input in watts 400 -- = 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 transfoñnèr/tas 500 turns on the primary andJ4tJturns on the secondary winding. The•neon length Of rhe magnetic path in rhe iron core is 150 cm and the joints are quivalent'o an air-gap ofO. When a p.d. V is applied to the primary maximum flux density is 1.2 Wb/m^2. Calculate (a/ the cross-sectional areaof the core (b) no-load secondary voltage (c) rhe 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 10 be 2 ivátt/kg 50 Hz, and the density of iron as 7.8 kram/cm^3.

Solution. = 4.44x50x500*12xA

This is thenetcross-sectional area. However, the grossarea would be about for the insulation between laminations.

K = N/A', -40/500=4/50

NL, secondary voltage - KEI

750

80.0001=955

Total forgiven = 950+965=945.5

Max. value ofmagnetising current drawn by primary =845.5/500 = 1.691 A

Assuming this culTent to be sinusoidal, its is = I -691/ 1.196 A

Volumeofiron = length xarea=

Density 7.8 gram/em^3 Mass ofiron = 7.8/1(m-263.25kg

Total iron loss

Iron loss component Of no-load primary current is Iw =526.5/3000— O. 176 A

1.196^2 +0.1762 —0.208 A

(d) powerfactor.cos,bo - 174=0.176/1208-0.1457

32.10. Transformer on Load 10

magnitude and phase of 12 with respect 'o V: is determined by the teristics ofthe Current', is in With V, ifload is non-inductive,it lags if load is inductive and it ieads ifload is cal•live.

The secondary current sets up its own and hence its own flux which is in opposition to the main primary flux which is due to The secondary ampere-turns N, 12 are known as demagnerising amp-turns. The opposing secondãry flux weakens the primary momentarily, hence primary back e.m_f- E, tendsto reduced. For a moment V, gains the uprrr hand over E, and hence causes more current to now in primary.

Let the additional primary current be V. It is known as load Ofprimary current. current is antiphase With V, The additional primary man-f. NI 12 sets up its own flux which is in opposition to CÞ, (but is in the same direction 4') and is equal to it in magnitude. Hence. the two cancel each other out. So. we find that the magnetic effects of secondary current 12 are immediately neutralized by the additional primary current l:' which is brought into existence exactly at the same instant as 12. The wholeprœess 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 $\Phi_2 = \Phi_2'$ $\therefore$ $N_2I_2 = N_1I_2'$ $\therefore$ $I_2' = \frac{N_2}{N_1} \times I_2 = KI_2$

Hence, when transformer is on load, the primary winding has two currents in it; one is I_0 and the other is I_2' 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_2'*

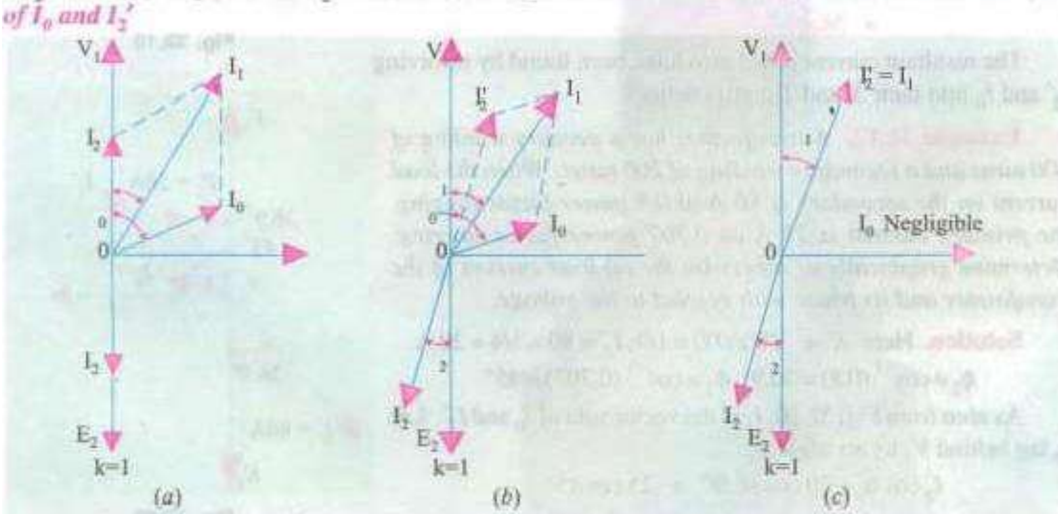


Fig. 32.18
Fig.

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

In Fig. 32.18 are shown the vector diagrams fora loaJtransformer when load is non-inductive and When it is.inductive(a similar diagram could be drawn for capacitive load). Voltage transformation ratio ofunity is assumed so that primary vectorsare equal to the secondary vectors. With reference to fig. 32.18 12 is secondary current in phase with E2 (strictly speaking it shouldbe 1/2). It causes primary current which is anti-phase With it and equal to it in magnitude (R = l). Total primary current I is the vector sum Of and 12' and lags behind VI by an angle ϕ_1.

In Fig. 32.18 (b) vectors are drawn for an inductive load. Here 12 lags Ea (actually by ϕ_2. Current 12' is again antiphase with Gand equal to itin magnitude. As before, IOS the vectorsgmof/2' and 10 and lags behind V, by

It will be observed isslightly greater than ϕ_2. But if we neglect I_0 a that But if we neglect 10 Moreover. under this assumption ascomparedt042' as in Fig. 32.18 then

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

NIG =

It shows that under full-load conditions, the ratio of primary and secondary currents is constanL This important relationship is made the basis of current transformer—a transformer which is used with alow-range ammeter for measuring currents incircuits Where the direct connection Of the ammeter is impracticable.

Fig. 3220

$E_1 = V_1 - I_1 R_1$ ...vector difference

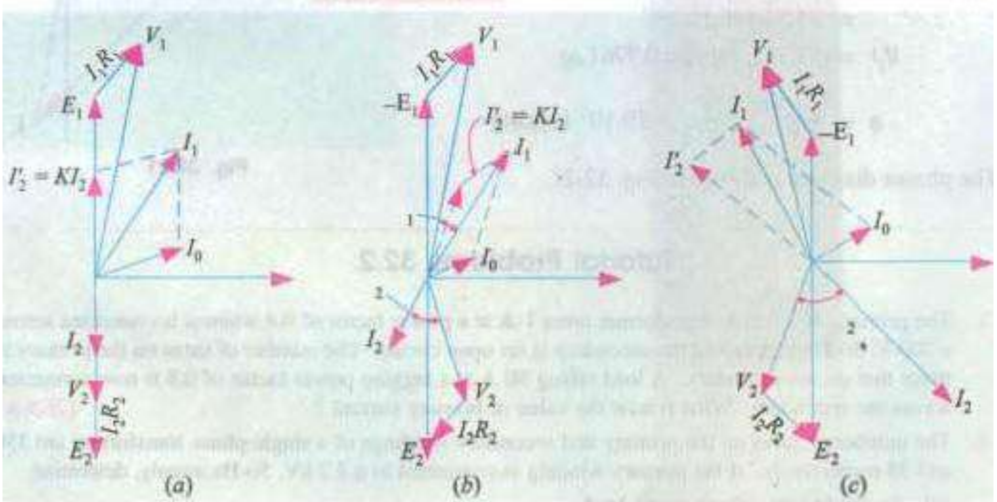


Fig. 32.22

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 RI and R: respectively. The resistances have been shown external to the windings.

It would now be shown that the resistances ofthe two windings can be transferredto any one ofthe 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: in secondary is equivalent to R2iK^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 12^2 Ra, This loss is supplied by primary which takes a current ofll. Hence if R:' is the equivalent resistance in primary which would have caused the same loss as in secondary, then

Now. if we neglect 10, then 12/11 I/N , Hence, R/ R2/F

Similarly, equivalent primary resistance as refetïcd to secondary is R = I

In Fig. 32.24, secondary resistance has been transferred to primary side leaving secondary Circuit resistanceless. The resistance RI 4 R:' = RI + RI/K^2 is known as the equivalent or effective resistnnez Of

of the transformer as referred to primary and may be designated as R_{01}.

$$\therefore \quad R_{01} = R_1 + R_2' = R_1 + R_2 / K^2$$

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 has been concentrated in the secondary winding.

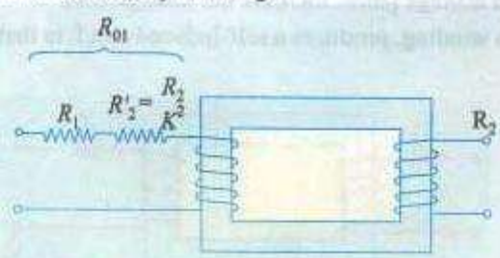


Fig. 32.24

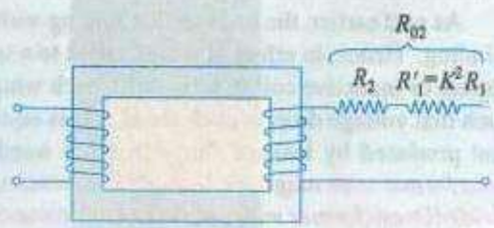


Fig. 32.25

the referred to primary and may be designated as

It is to be noted that

L a resistance of RI in primary is equivalent to FRI in secondary. Hence, it is called equivalent resistance as referred to secondary i. e. R I .

2. a resistance of R2 in secondary is equivalent to R2./K^2 in primary. Hence. it is called the equivalent secondary resistance as referred to primary e.

J. Total or effective resistance of the transformer as referred to primary is

Rot = primary resistance + 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,

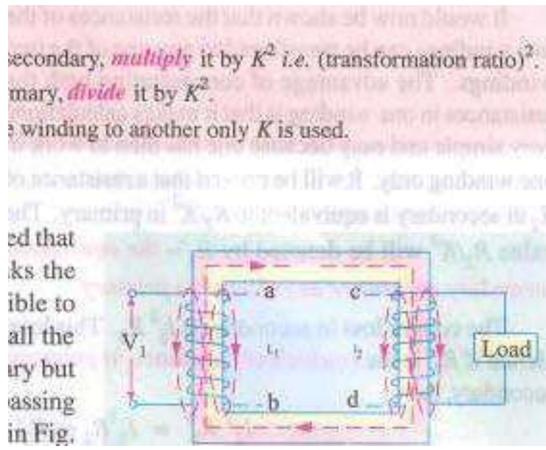
$$R_{02} = \text{secondary resistance + equivalent primary resistance as referred to secondary}$$
$$= R_2 + R_1' = R_2 + K^2R_1$$

* Actually $I_2 \# 2/I_2' = I/K$ and not $I_2 \# 2/I_1$. 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/iply it by (b When shifting secondary resistance to the primary, divide it hy R.

(CJ however. when shifting any voltage from one.inding toanother



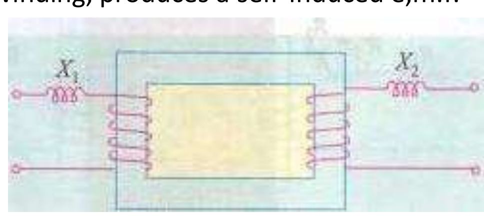
32.13. Magnetic Leakage

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 betueen points,a and Fig. 32.26 b, acts along the leakage paths. Hençe, 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 ll . 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 12 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 connecred in both primary and secondary circuils as shown in

Fig. 32.27 such that the internale.rn.f. in each inductive Fig. 32.27 coil is equal to that due to the corresponding leakage flux in the actual transformer.

$X_1 = e_{L1}/I_1$ and $X_2 = e_{L2}/I_2$

The terms X, and Xïare known as primary andsecondary leakage reactance-s respectively.

Following few points should be kept in mind :

1.The leakage flux links one or the other winding but no' both. hence it in nosvåy contributes to the transfer ofenergy from the primary to the secondary winding.

2. The primaryvoltage VI will havetosupply reactive drop/1X, in addition to Similarly E2 will have to supply 12 R2 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, z:

Similarly, secondary impedance is given by

$Z_2 = \sqrt{(R_2^2 + X_2^2)}$

The resistance and leakage reactance Of each winding is responsible for some voltage drop in each winding. In primary, the leakage reactance drop is llXi (usually I or 2% of VI). Fig. 32.28

Hence

Similarly, there are 12R2 and '2X2 drops in secondary which combine with V: to give El.

The vector diagram for such a transformer for different kinds ofloads 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 Vi and gives the power factor angle of the transformer.

It may be noted that leakage reactances can also transferred from one winding to the other in the same way as resistance.

$$X_2' = X_2/K^2 \quad \text{and} \quad X_1' = K^2 X_1$$
$$X_{01} = X_1 + X_2' = X_1 + X_2/K^2 \text{ and } X_{02} = X_2 + X_1' = X_2 + K^2 X_1$$

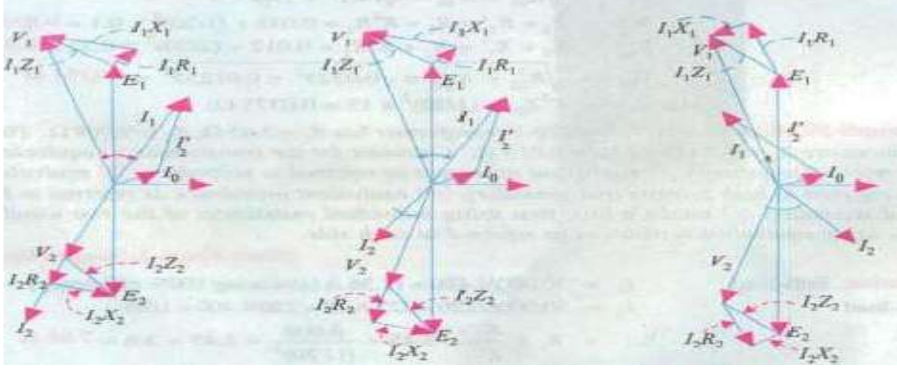


Fig. 32.29

Itis obvious that total impedanceofthe transformer as referred to primary is givenby

$$Z_{01} = \sqrt{(R_{01}^2 + X_{01}^2)} \quad \text{...Fig.}$$

32.30 (a)

$$Z_{02} = \sqrt{(R_{02}^2 + X_{02}^2)} \quad \text{...Fig.}$$

Fig. 32.30 (b)

Example 32.15. A 30 kVA, 2400/120-V, 50-Hz transformer has a high voltage winding

transformer has a high voltagewinding resistance Of0.1 and a leakage reactance of 0.22Q. The IOW voltage winding resistance is 0.035 Q and the leakage reac'ance is Q Find the equivalent winding resistance, reacrance and Impedance referred to the O) high voltage side and (it) the low-voltage side.

(Electrical Machines-I, Bangalore Univ. 1987)

Solution. $K = 120/2400 = 1/20;\ R_1 = 0.1\ \Omega,\ X_1 = 0.22\ \Omega$

$R_2 = 0.035\ \Omega$ 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*)

$$R_{02} = R_2 + R_1' = R_2 + K^2R_1 = 0.035 + (1/20)^2 \times 0.1 = 0.03525\ \Omega$$

$$X_{02} = X_2 + X_1' = X_2 + K^2X_1 = 0.012 + (1/20)^2 \times 0.22 = 0.01255\ \Omega$$

$$Z_{02} = \sqrt{R_{02}^2 + X_{02}^2} = \sqrt{0.0325^2 + 0.01255^2} = 0.0374\ \Omega$$

$$(\text{or } Z_{02} = K^2Z_{01} = (1/20)^2 \times 15 = 0.0375\ \Omega)$$

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 seóndary (Y) equivalent reac-

equivalent impedance as referred to both pri-

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 $I_1 = 50{,}000/4{,}400 = 11.36$ A (assuming 100% efficiency)

$I_2 = 50{,}000/2220 = 227$ 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*)

$$R_{02} = R_2 + K^2R_1 = 0.009 + (1/20)^2 \times 3.45 = 0.009 + 0.0086 = 0.0176\ \Omega$$

Also,

$$R_{02} = K^2R_{01} = (1/20)^2 \times 7.05 = 0.0176\ \Omega \text{ (check)}$$

AlsoCu 10»

32.16. Total Approximate Voltage Drop in a Transformer

When the transformer is On no-toad then VI is approximately equal to El. 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.

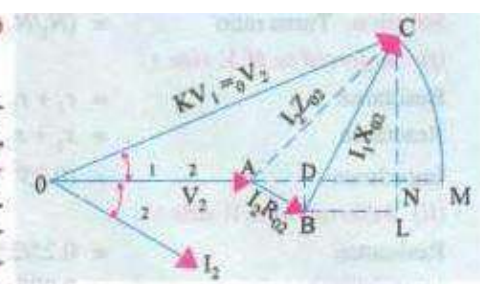


Fig. 32.35

utting *OA* produced at *M*. The total voltage drop I_2

The difference tween the two is 12 as shown in Fig. 32.35. The approximate voltage drop of the transformeras referredto secondary is found thus :

W'th O as the centre and radius OCdraw an arc cutting OAproduced 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 0M and draw BL parallel to 0M.

Approximate voltage drop

= AN=AD+DN

+ 12Xcnsin $= I_2R_{02}\cos\phi$ $\phi$where $\phi_1 = \phi_2 = \phi$ (approx).

This is the value of approximate voltage drop for a laeging power factor,

The different figures for unity and leading power factors are shown in Fig. 32.36 (a) and (b) reqxctively.

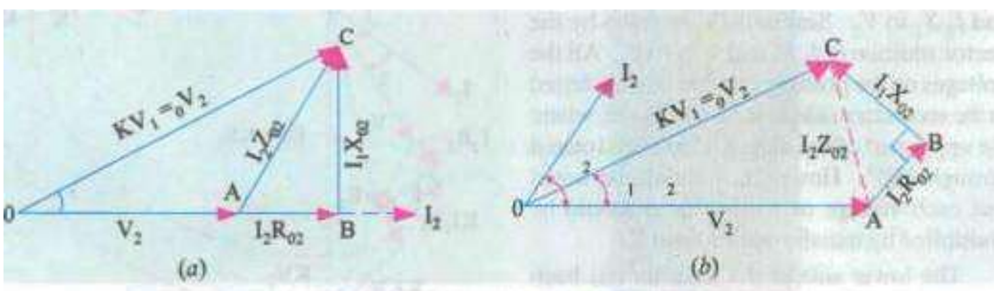


Fig. 32.36

The approximate voltage drop for leading rx»wer factor becomes

$(I_2R_{02}\cos\phi \pm I_2X_{02}\sin\phi)$

In general, approximate voltage drop is

ge drop is $(I_2R_{02}\cos\phi \pm I_2X_{02}\sin\phi)$

It may be noted that approximate voltage drop as referred to primary is

iate voltage drop as referred to primary is

$(I_1R_{01}\cos\phi \pm I_1X_{01}\sin\phi)$

% voltage drop in secondary

$$\text{is} = \frac{I_2R_{02}\cos\phi \pm I_2X_{02}\sin\phi}{{}_0V_2}\times 100$$

$$= \frac{100\times I_2R_{02}}{{}_0V_2}\cos\phi \pm \frac{100\,I_2X_{02}}{{}_0V_2}\sin\phi$$

= vrcos$*v.sino

$$v_r = \frac{100\,I_2R_{02}}{{}_0V_2} = \text{percentage resistive drop} = \frac{100\,I_1R_{01}}{V_1}$$

$$v_x = \frac{100\,I_2X_{02}}{{}_0V_2} = \text{percentage reactive drop} = \frac{100\,I_1X_{01}}{V_1}$$

32.17. Exact Voltage Drop

With reference to Fig. 3235, it is to be noted that exact voltage drop isAM and notAÑ, If we add the quantity NM to 'W, we will get theexact valueof the voltage drop.

Considering

Considering the right-angled triangle OCN, we get

$$NC^2 = OC^2 - ON^2 = (OC + ON)(OC - ON) = (OC + ON)(OM - ON) = 2\,OC \times NM$$

$$\therefore \quad NM = NC^2/2.OC \quad \text{Now, } NC = LC - LN = LC - BD$$

$$\therefore \quad NC = I_2 X_{02} \cos\phi - I_2 R_{02} \sin\phi \quad \therefore NM = \frac{(I_2 X_{02} \cos\phi - I_2 R_{02} \sin\phi)^2}{2_0 V_2}$$

∴ 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

$$= (I_2 R_{02} \cos\phi \pm I_2 R_{02} \sin\phi) + \frac{(I_2 X_{02} \cos\phi \pm I_2 R_{02} \sin\phi)^2}{2_0 V_2}$$

Percentagedropis the

right-angled triangle OCN, we get

_ 00

20v/ (12Ro, co. ± sin cos sin

2

= (v, COS ± v, sin O) + (1/200) (vx V, sinO)

The upper signs are to be used for a logging 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 Q and rhe corresponding values for the secondary are 075 Q and 1.8£2 respectively. Find the secondary terminal voltage when supplying 10 A at 0.8 p.f. lagging.

(Electric. Machines-II, Bangalore Univ. 1991)

Solution.

$$K = 460/230 = 2; \; R_{02} = R_2 + K^2 R_1 = 0.75 + 2^2 \times 0.2 = 1.55\,\Omega$$

$$X_{02} = X_2 + K^2 X_1 = 1.8 + 2^2 \times 0.5 = 3.8\,\Omega$$

Voltagedrop

$$= I_2 (R_{02} \cos\phi + X_{02} \sin\phi) = 10\,(1.55 \times 0.8 + 3.8 \times 0.6) = 35.2\text{V}$$

∴Secondary terminal voltage = $460 - 35.2 = 424.8$ V

Example 32.22. Calculate the regulation ofa transformer in which the percentage resistance drops 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)

Soluion. We will use the approximate expression of Art 30.16.

(*a*) p.f. = cos ϕ = 0.8 lag $\quad \mu = v_r \cos\phi + v_x \sin\phi = 1 \times 0.8 + 5 \times 0.6 = 3.8\%$

(*b*) p.f. = cos ϕ = 1 $\quad \mu = 1 \times 1 + 5 \times 0 = 1\%$

(*c*) p.f. = cos ϕ = 0.8 lead $\quad \mu = 1 \times 0.8 - 5 \times 0.6 = -2.2\%$

Example 32.23. A transformer has a reaciance drop of5% and a resistancedmp of Find the lagging power factor at which the voltage regulation is maximum and the value of 'hi' regulation, (Elect. FAEgg. Punjab Univ. 1991)

$$\mu = v_r \cos\phi + v_x \sin\phi$$

where v_r is the percentage resistive drop and v_x is the percentagereactivedrop.

Differentiating the above equation, we get $\frac{d\mu}{d\phi} = -v_r$

For regulation to be maximum, $d\mu/d\phi = 0 \quad \therefore \quad -v$

or $\tan\phi = v_x/v_r = 5/2.5 = 2 \therefore \phi = \tan^{-1}(2) = 63.5°$ N

Solution. The percentage voltage regulation (p) is given by

sine. v coso

— vrsin vs cos = O

635[0] Now, cos = 0.45 and sin = 0.892

Maximum percentage regulation = (2.5 x 0.45) + (5 x 0.892) 5 $85

Maximum percentageregulation is 5.585 and occurs ata power factor of0Æ5 (lag).

Example 32.24. Calculate the percentage voltage drop for a transformer with a percentage resistance of 2.5% and.' reactance of 5% of rating 500 kVA when ir is delivering 400 kVA at lagging, 'Elect. Machinery-I,

(%R) I cosO• Solution. % drop

Where If is the full-load cutTCnt and / 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

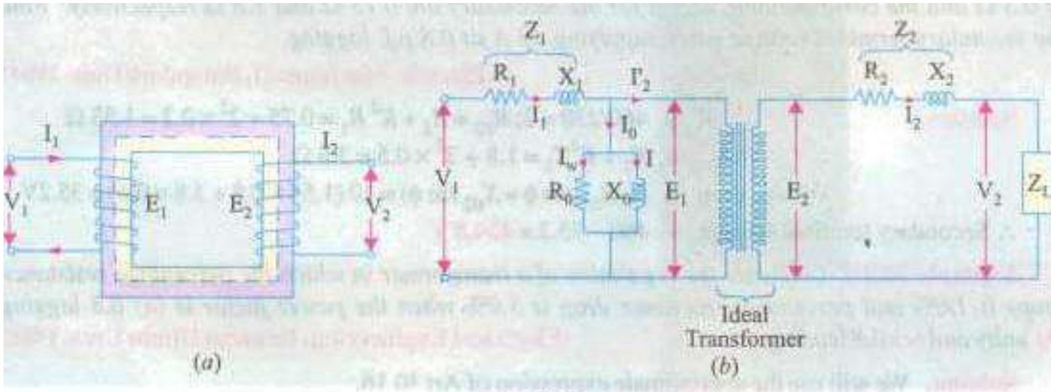


Fig. 32.37

current 10 is simulated by pure inductance Xo taking the magnetising component lg and a non-inductive resistance Ro taking the working component Is, connected in parallel across the primary circuit. The value of El is obtained by subtracting vector-idly 7-1 from VI. The value of Xo = El/loandof Ro = It is clear that El and E, are related to each other by expression

To maketransformer calculations simpler, it is preferable to transfer voltage, current and impedance

Transformer 1143

citherto the primary Or to the secondary. In thatcase. we would have to work in onewinding only which is more convenient.

The primary equi ofthe secondary induced voltageis E2' E2jK= El.

Similarly. primary equivalent Ofsecondary terminal or Output voltage is V,' V2/K Primary equivalentofthe secondary current is 12' = K12.

For transferring secondary mpedance to primary K^2 is used.

$$R_2' = R_2/K^2, X_2' = X_2/K^2, Z_2' = Z_2/K^2$$

Thesamerelationship is Lised for shifting an external load impedance to the primal)'.

The secondary circuitis shown in Fig. 32.38(O) and its equivalent primary values areshown infig.

32.38 (*b*).

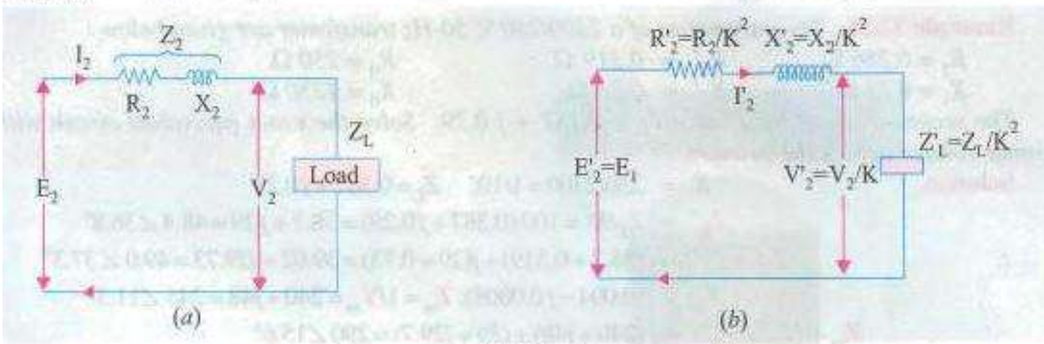


Fig. 32.38

The total equivalent circuit of the transformer is obtained by adding in the primar, impedance as shown

The total equivalent circuit ofthetransformeris obtainedby adding in the in Fig. 32.39. This is kncrwn 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 $X_0 = V_1/I_\mu$.

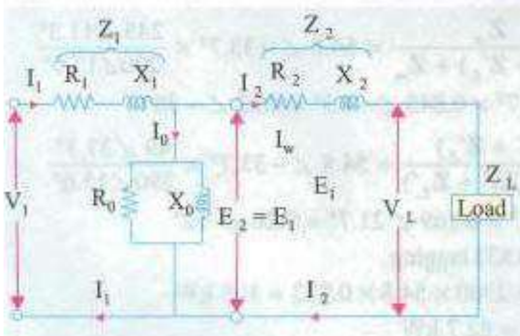


Fig. 32.39

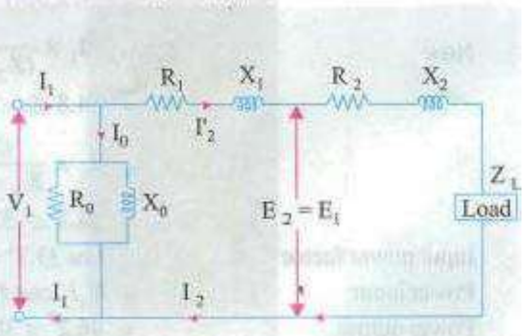


Fig. 32.40

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

$$\mathbf{Z} = \mathbf{Z}_1 + \mathbf{Z}_m \,||\, (\mathbf{Z}_2' + \mathbf{Z}_L') = \left(\mathbf{Z}_1 + \frac{\mathbf{Z}_m (\mathbf{Z}_2' + \mathbf{Z}_L')}{\mathbf{Z}_m + (\mathbf{Z}_2' + \mathbf{Z}_L')} \right)$$

where $\mathbf{Z}_2' = R_2' + jX_2'$ and $\mathbf{Z}_m$ = impedance of the exciting circuit.

can bemade by transferring the exciting circuit aero:'S the tenninalsasin

This is so because there are two parallel circuits, one having an impedance ofZin andthe other having Z' and ZL' in series with each other.

$$\mathbf{V}_1 = \mathbf{I}_1 \left[\mathbf{Z}_1 + \frac{\mathbf{Z}_m (\mathbf{Z}_2' + \mathbf{Z}_L')}{\mathbf{Z}_m + (\mathbf{Z}_2' + \mathbf{Z}_L')} \right]$$

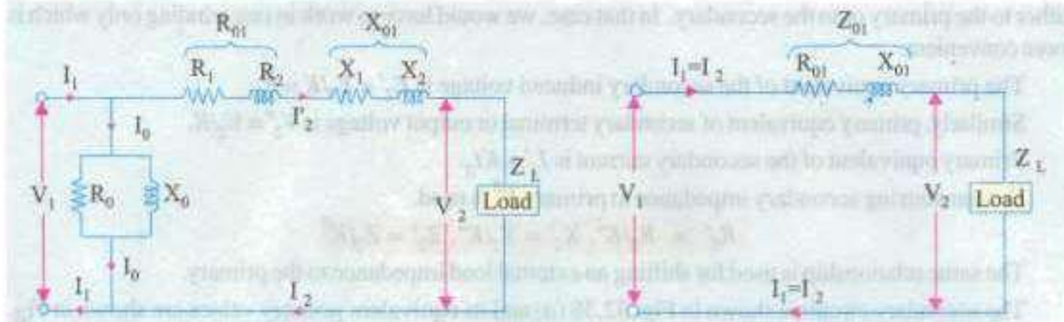


Fig. 32.41 (a) Fig. 32.41 (b)

Example 32.25. *The parametres of a 2300/230 V, 50-Hz transfomer 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 $Z_L = 0.387 + j\,0.29$. *Solve the exact equivalent circuit with normal voltage across the primary.*

Solution.

$$K = 230/2300 = 1/10; \quad Z_L = 0.387 + j0.29$$

$$\mathbf{Z}_L' = \mathbf{Z}_L/K^2 = 100\,(0.387 + j0.29) = 38.7 + j29 = 48.4\angle 36.8°$$

$$\therefore \quad \mathbf{Z}_2' + \mathbf{Z}_L' = (38.7 + 0.319) + j(29 + 0.73) = 39.02 + j29.73 = 49.0\angle 37.3°$$

$$Y_m = (0.004 - j\,0.0008);\ \mathbf{Z}_m = 1/\mathbf{Y}_m = 240 + j48 = 245\angle 11.3°$$

$$\mathbf{Z}_m + (\mathbf{Z}_2' + \mathbf{Z}_L') = (240 + j48) + (39 + j29.7) = 290\angle 15.6°$$

$$\therefore \quad \mathbf{I}_1 = \frac{\mathbf{V}_1}{\mathbf{Z}_1 + \dfrac{\mathbf{Z}_m(\mathbf{Z}_2' + \mathbf{Z}_L')}{\mathbf{Z}_m(\mathbf{Z}_2' + \mathbf{Z}_L')}} = \left[\frac{2300\angle 0°}{0.286 + j0.73 + 41.4\angle 33°}\right]$$

$$= \frac{2300\angle 0°}{42\angle 33.7°} = 54.8\angle -33.7°$$

Now

$$\mathbf{I}_2' = \mathbf{I}_1 \times \frac{\mathbf{Z}_m}{(\mathbf{Z}_2' + \mathbf{Z}'_L) + \mathbf{Z}_m} = 54.8\angle -33.7° \times \frac{245\angle 11.3°}{290\angle 15.6°}$$

$$= 54.8\angle -33.7° \times 0.845\angle -4.3° = 46.2\angle -38°$$

$$\mathbf{I}_0 = \mathbf{I}_1 \times \frac{(\mathbf{Z}_2' + \mathbf{Z}'_L)}{\mathbf{Z}_m + (\mathbf{Z}_2' + \mathbf{Z}_L')} = 54.8\angle -33.7° \times \frac{49\angle 37.3°}{290\angle 15.6°}$$

$$= 54.8\angle -33.7° \times 0.169\angle 21.7° = 9.26\angle -12°$$

Input power factor $= \cos 33.7° = 0.832$ lagging

Power input $= V_1 I_1 \cos\phi_1 = 2300 \times 54.8 \times 0.832 = 105$ kW

Power output $= 46.2^2 \times 38.7 = 82.7$ kW

Primary Cu loss $= 54.8^2 \times 0.286 = 860$ W

Secondary Cu loss $= 46.2^2 \times 0.319 = 680$ W; Core loss $= 9.26^2 \times 240 = 20.6$ kW

$$\eta = (82.7/105) \times 100 = 78.8\%;\ V_2' = I_2' Z_L' = 46.2 \times 48.4 = 2{,}240\text{V}$$

$$\therefore \quad \text{Regulation} = \frac{2300 - 2240}{2240} \times 100 = \mathbf{2.7\%}$$

Example 32.26. *A transformer has a primary winding with a voltage-rating of 600 V. Its*

32.26.

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 onnected as shown in Fig. 32142.

Transformer 1145

32.30. Open-circuit or No-load

8000

=7.41 at unity p,f.

1080

= 10000/720=13.89atzerolaggingp.f.

These arereflected on to the primary sides with appropriate raùos ofturms, with corresponding powerfactors. If the conesponding transformed currents are represented by theabovesymbols modified by dashed superscripts,

$$I'_{r_2} = 7.41 \times 1080/600 = 13.34 \text{ A at unity p.f.}$$

$$I'_{L_2} = 13.89 \times 720/600 = 16.67 \text{ A at zero lag. p.f.}$$

Hence, $$I_{r_2} = [I'^2_{r_2} + I'^2_{L_2}]^{0.5} = 21.35 \text{ A, at 0.625 lag p.f.}$$

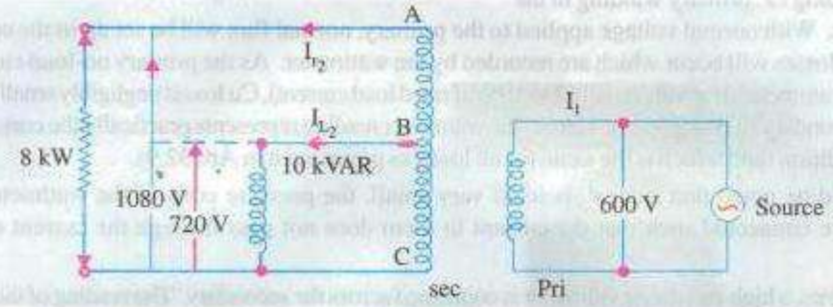


Fig. 32.42

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 unityp.f, and I O kVAR lagging s = P+iQ=g-j 10kVA S =

Power—factor = $(8^2 + 10^2)^{0.5} = 12.8$ kVA

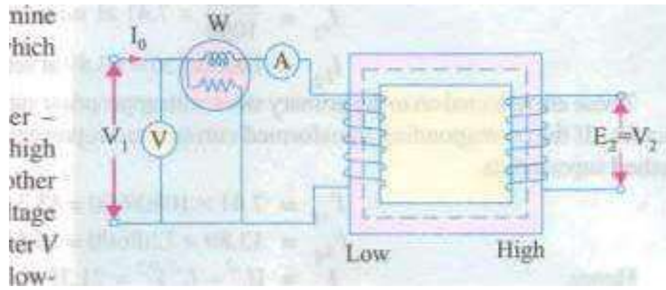
Primarycurrent = 12.8 x $\cos\phi = 8/12.8 = 0.625$ lag 1000/600=21.33 A

32.19. Transformer Tests

As shown in Ex 32.25. the periòrmanee ofa transfonnerean calculate on thebasisofitsequivalent circuit which contains (Fig. 32.41) four main parameters, the equivalent resistanceRot as referred to primary (or secondary R02), the equivalent leakage reactance as referred to primary (or secondary x02), the core-lossconductance Go (or resistance Roj und the magnetiSing susceptance BO (or reactance Xoj. These constants or parameters can beeasily determined by two tests (i) open-circuit test and iil short. circuit test. These tests are very economical and convenient. because they furnish the required information without actually loading the transformer. fact, the testing of very large machinery consists of running two tests similar to the open and short-circuittests of atransformer.

Small transformer

32.20. Open-circuit or No-load Test



The purpose Of this test is to determine no-load loss orcore loss and no-load 10 which is helpful in finding xo and Ro,

One winding of the transformer — whichever is convenient but usually high vollage Winding — is left open and the Other is connected to its supply ofnormal voltage and frequency. A wattmeter W. voltmeter V and an ammeter A are connectedin the voltage winding i.e. primary winding in the Fig. 3243 present case. With normal voltage applied to the primary. normal fluxwill be set up in the core. hence normal iron losses Will which arc recorded by the wattmeter. As the primary no-load current 10 (as measured byammeter) is small (usually 2 to ofrated load cunænl), Cu loss is negligibly small in primary and nil in secondary fit being open). Hence. the wattmeter reading represents [Tactically thecole 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 is itself very small. the pressure coils Of the wattmeter and the voltmeter are connected such that the in them does not pass through the culTent coil Of the

Sometimes, connected acrossthe secondary. Thereading Ofthe voltmeter gives the induced e-m.f. in thesecondary winding._ Thishelps to find transformation ratio K.

The no-load vector diagramis shown in Fig. 32.16. If W is the wattmeter reading (in fig. 32,435.

W = VI locos $0 :. cosOo= VWVl /o

= losin$o. and

Or since the current is practically all-exciting current when a is on no-load (i.e. 10 and as the voltage drop in primary leakage impedance is hence the exciting admittance YO of the transformer is given by 10 V, Yo or Yo = WV,.

The exciting conductance Go is given by VI^2 Go or GO =

The exciting susceptance = (Y0^2 — G)

Example. 3227. In no-load rest of single-phase transformer, the following tesr data were obtained :

Primary voltage : 220 V : Secondary volt"ge : 110 V : primary current : 0.5 A ; Power input : 30 W.

Find thefollowing:

(i' The turns ratio (in the magtierisingcomponouofno-loadeurrent(iii' its working (orloss) component ii the iron loss.

Resistance ofthe primary winding = 0.6ohm.

Draw the no-load phasor diagram to scale. (Elect. Machine A.M.1-F„A99t))

Solution.

(iiij Gcos.-O.5x0.273—O.1365A

PrimaryCuloss = 0:52 x 0.6£0.15 w Iron loss = 30-0.15=29.85 w

Example 32.28.' 5 WA 200/1000 V50 single-phasefransfOrmeÈ gave results .

SC.

O) Calculate the parametersof the equivalent circuit rcferred 10 the L side.

(ii) Calculafe 'he output secondary voltage delivering 3 kW primary being 200 V, Find (he percènrakg regulation also.

(Nagpur University, November 19%)

Solution. (i) Shunt branch parameters from O.C. test (L.V. side) :

- 200/90 =4440hms, 200/444 = 0.45 amp = 1.1 1 amp, & = 200/1.11

All these are referred to LV. side.

(ii) Series.hranch 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 referredto H,V' side.

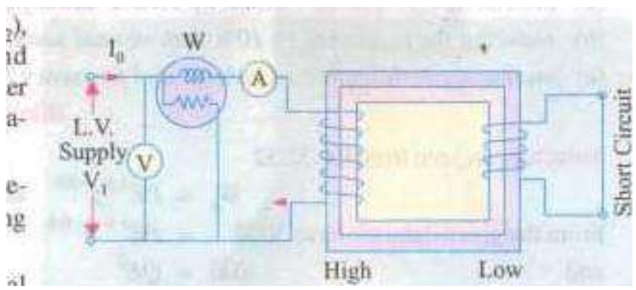
Equivalent circuit can be drawn with Round Xm calculated.tbove and r, and Xl.s above.

L V. Current at rated load= 5000/200 = 25 A

LN. lagging = 18.75 A

3222 Short-Circuit or Impedance Test

This is an economical method for determining the following : iii EAuivalent irnrrdance or G), leakage reactance (Xo, or Xo:) and total resistance (orR,z) ofthe transformer as referred to the winding in which the meaSuring irwtruments are placed.



(iii Cu loss at full load (andatanydesired load). 'This loss is used in calculating the efficiency ofthe transformer liii' Knowing Zo, or Zo:, the total voltage drop in the transformer as referred Fig. 32.45 to primary or secondary can be calculated and hence regulation Ofthe transformerdetermin

In this test. one winding, usually the low-voltage winding, issolidly short-circuited by a thickconductor (or through an ammeter Which may serve the additional Of indicating rated load curtrnt) as shown in FIE, 32.45.

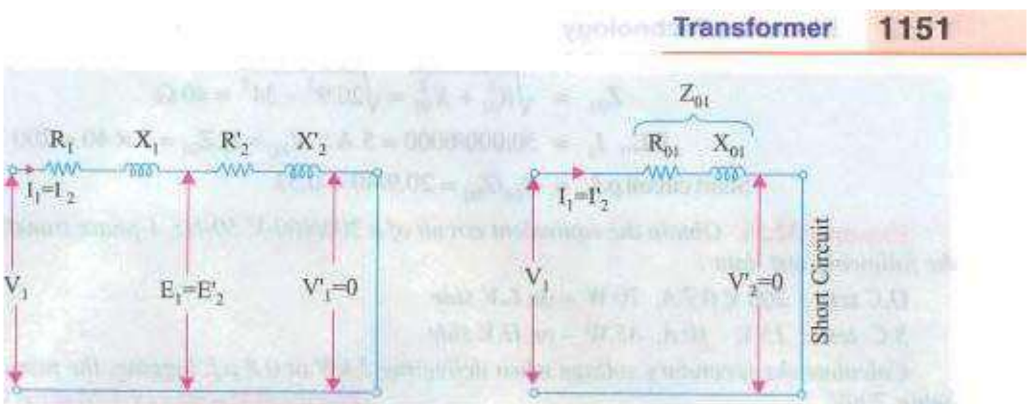


Fig. 32.46

A low voltage (usually 5 to arnormal primary voltage) at correcl frequency (though forCu losses it is not essential) is applied to the primary and is cautiously increased till full-loadcurrents are flowing both in primary and secondary indicated by the respecti ve ammeters).

Since, in this test. the applied voltage is a small percentage of the normal voltage, the mutual flux tÞ produced is also asmall percentage of its normal value (Art. 32.6), Hence. core losses are very small With the result that the wattmeter reading represent the full-load Cu loss or

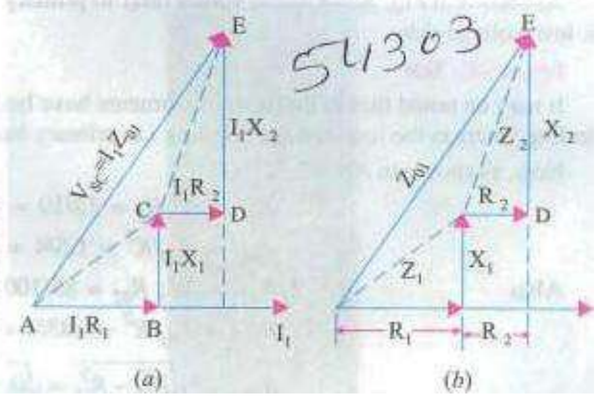
condition is shown in Fig. 32.46. If V_{sc} is the voltage required to circulate rated load currents, then $Z_{01} = V_{sc}/I_1$

Also $W = I_1^2 R_{01}$

$\therefore \quad R_{01} = W/I_1^2$

$\therefore \quad X_{01} = \sqrt{(Z_{01}^2 - R_{01}^2)}$

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, can be measured, then knowing ROI, wc can find R2' Ro — RI. The

1^2R loss forthe whole transformer i.e. both primary Cu loss and secondary Cu loss, The equivalent circuitof the tramsformer under shon-cicœuit 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 cunent 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 kVÄ 76000/230, V, I-phase transformer have resistance Of 0.016 ohm respectivelv. The mactance ofthe transformer referred to the primary is 34 Ohm.

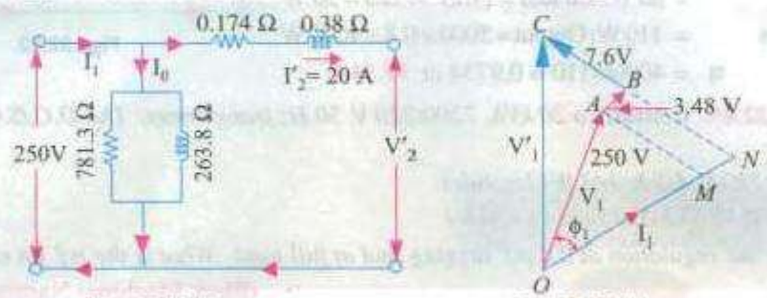


Fig. 32.53 (a) Fig. 32.53 (b)

$$\therefore \quad R_{02} = \frac{\text{short-circuit power}}{\text{F.L. secondary current}} = \frac{100}{12^2} = 0.694\ \Omega$$

$$Z_{02} = 20/12 = 1.667\ \Omega\ ;\ X_{02} = \sqrt{(1.667^2 - 0.694^2)} = 1.518\ \Omega$$

As R_0 and X_0 refer to primary, hence we will transfer these values to primary with the help Of transformation ratio.

$$K = 500/250 = 2 \quad \therefore \quad R_{01} = R_{02}/K^2 = 0.694/4 = 0.174\ \Omega$$

$$X_{01} = X_{02}/K^2 = 1.518/4 = 0.38\ \Omega\ ;\ Z_{01} = Z_{02}/K^2 = 1.667/4 = 0.417\ \Omega$$

The equivalent circuit is shown in Fig. 32.53 (*a*).

Efficiency

Total Cu loss $= I_2^2 R_{02} = 100 \times 0.694 = 69.4$ W ; Iron loss = 80 W

Total loss = 69.4 + 80 = 149.4 W $\quad \therefore \quad \eta = \dfrac{5000 \times 0.8 \times 100}{4000 + 149.4} = \mathbf{96.42\%}$

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

$$V_1'^2 = OC^2 = ON^2 + NC^2 = (OM + MN)^2 + (NB + BC)^2$$

$$= (250 \times 0.8 + 3.48)^2 + (250 \times 0.6 + 7.6)^2$$

$$V_1'^2 = 203.5^2 + 157.6^2 \quad \therefore \quad V_1' = \mathbf{257.4\ V}$$

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 I : 1. Suchá transformer is mainly œquired 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

Atfull load. VAoutput - — 3000

At 0.8 lag p. Poweroutput

Required efficiency =

From S.C. test.

Approximate v01tage regulation

<u>13.51</u>

In terms of the voltage regulation = 230 x 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 ifs full-load output p.f. of 0.8 lagging. (Nagpur UniveÑty, November 1998'

Solution. Rated output ag unity p.f. = 10000 W. Hence, of rated Output = 9,000 W

Input with efficiency =

Losses =

At maximum efficiency, variablecopper-loss = constant =Core 574/2 = 287 W loss = 574/2

At rated current, Let the copper-loss pc walls

At 90% load with unity p.f.. the copper-loss is expressed as 0.90^2 x Pi.

Hence, P, = 287/0.81=354W

(b) Output at full-load, 0.8 lag p.f. = 10,000 × 0.80 = 8000 W

At the corresponding load, Full Load copper-loss = 354 W

Hence. efficiency -8000/(8000 + 354 + 287) = 0.926-92.6<0

ofcalculation of voltage-magnitudes, approximav fOrrnuJa for voltage regulation can be used. For the present case of 0.8 lagging p.f.

VI' = V2+/[rcosQ+xsint$l

<u>230+43.5 (0.316 x</u>

= 230*43.5 (0.0634 + O. 18961—230+ 11 V, 241 volts.

It means that H.V. side terminal voltage must 2410 for keeping 230 V at the specified load.

(b) Approximate for voltage regulation is : V,' — =

With Laggingp.f., sign is retained. With leadingpoWer-factor. the—ve sign is applicable. For the voltage-regulation to be zero. only leading Bf. condition can prevail. sin O

= nix-0.0792/0316=0.25

= 140. cos 4=0.97 leading

Corresponding sino = Sin 0.243

H.V. terminal voltage required is23m V to maintain 230 V at since regulation condition is under discussion.

Example 32.51. A 5 kVA. 2200Q20 single-phase transformer has thefollowing parameters.

H. V. side r, = 3.4 Ohms. x, = 7.2 ohms

L V: side : r: = 0.028 ohms, 0.060 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 Vt calculate the terminal voltage on H. V side

(Neglect the exciting current). (Rajiv Gandhi Tichnicnl University, Bhopal.Summer 2001)

Solution. Calculations may be done referring all the parameters the LV. side first. Finally, the voltage required onH.V. side can be obtained after transformation.

ref. to L V. side = 5000/220-22.73A

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 = $x_1' + x_2$

$$= (220/2200)^2 \times 7.2 + 0.060 = 0.132 \text{ ohm}$$

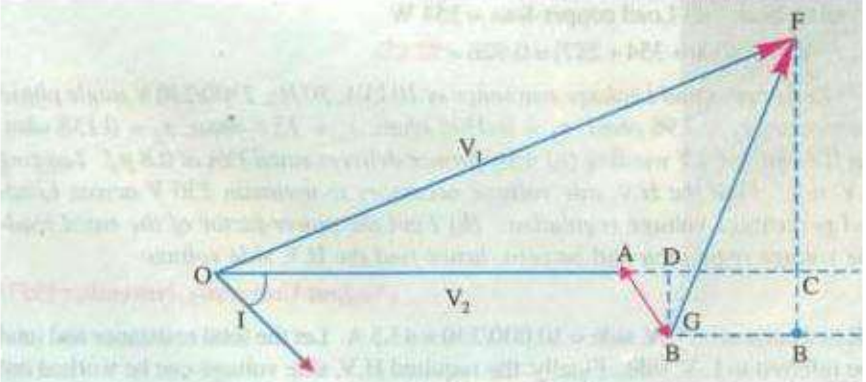


Fig. 32.53(c)

In the phasor diagram of Fig. 32.53 (c).

$$QA = V_2 = 220 \text{ volts}, I = 22.73 \text{ A at lagging phase angle of } 36.87^\circ$$

$$AB = Ir, \; AD = Ir\cos\phi = 22.73 \times 0.062 \times 0.80 = 1.127 \text{ V}$$

$$DC = Ix\sin\phi = 22.73 \times 0.132 \times 0.60 = 1.80 \text{ V}$$

Rated

OC =220+ 1.127 + 1.80=222.93 volts

BD = 'r sin 4' = O. 85N

VF = xco.=2.40V

CF =240-0.85= 155 v

V,' = OF = $(222.93^2 + 1.55^2)^{0.50}$ = 222.935 volts

Required terminal voltage of H.V. side - VI - 222935 (2200/220) = 2229g5 volts

[Note. In approximate and fast calculations. CF is Often forcalculationof magnitude or The Concerned expression is: V, sin O, for lagging P.f.l

Example 32.52. A VA, 200/400 V. single-phase transformer takes O. 7amp and 65 W on Opencircuit. When the low-voltage Winding is short-circuited and / 5 V is applied '0 the high-voltage terminals. the current and power are TO A and 75 W respectively. Calculate thefun-load efficiency at unity factor and full•load regulation al 0.80 power-factor lagging.

(Nagpur UniversityApril 1999)

Solution. At a load of 4 kVA. the rated currents are : L.V side 4000/200 = 20amp

And H.V. side : 4000/400 = 10amp

From the test data. full-load copper-loss 75 AV

And Constant core-loss = 65 W

From S.C. test, Z = 15/10-1.Sohms

$$R = 75/100 = 0.75 \text{ ohm}$$

$$x = \sqrt{1.5^2 - 0.75^2} =$$ = 130 1.52 — 0.752 ohms

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 / 65 75)

= 0.966-966%

Full load voltageregulation 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 Impedadce

These quantities are usually measured by the voltage drop át 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 impedanceat full-load

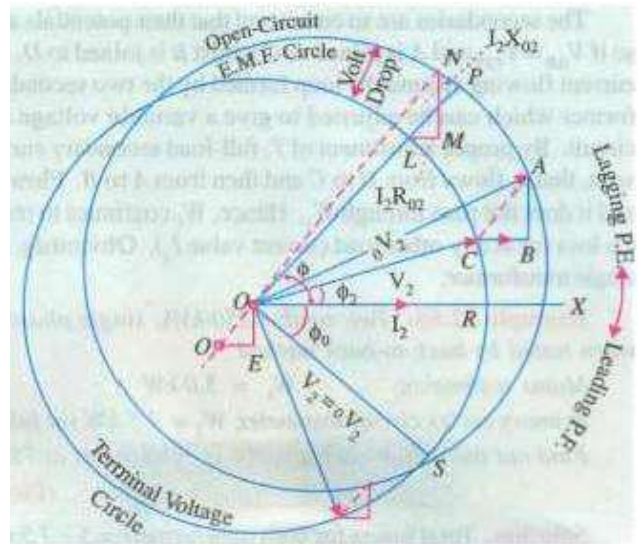


Fig. 32.54

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 iràhsformer has coppeNossof and reactance-drop of3.5% when tested at full-load. Calculate its full-load regulation at (i) (ii) 0.8 pl. Lagging and (iii) 0.8 p'. Leading. (Bharathithasan 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

= 0.015cos040.035sin4'

=0.015 perunit=1.5%

(ii) Approximate Voltage — Regulationat 0.80 Lagging p.r.

(iii) Approximate Voltage Regulation

$= (0.015 \times 0.8) + (0.035 \times 0.6) = 0.033$ per unit $= 3.3\%$

lation at 0.8 leading p.f.

$= I_r \cos\phi - I_x \sin\phi$

$= (0.015 \times 0.8) - (0.035 \times 0.6) = -0.009$ per unit $= -0.9\%$ 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 whenp_f_ is lagging and it increases when the powerfactoris leading. In other words, secondary terminal voltage not only depends on the load but on power factoralso (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. R02 and x02_ If is the secondary load current, then secondary terminal voltage On load V2. is obtained by subtracting 12 and 12 x02 voltage drops vectorially from secondary no-load voltage 0V2.

NOW, o VI is constant, hence it represented by a circle Ofconstant radius OA as in 32.54. This circle is known as no-load or open-circuit e.m.f. circle. Fora given load. 012 represents the load current and is taken as the reference vector, CB represents 12 Rm and is parallel to 012,AB represents I_2 x02 and is drawn at right angles to CB. Vector OC obviously represents and is drawn at right anglestoCB. Vector OCobviously represents secondary terminal voltage Since 12 isconstant, the drop triangle ABC remains constant in sizz It is seen that end point C of V: lies on another circle whose centre is O'. This point (Y lies ata distance of 12 venically low the v»int O and a distance of l, Rm to its left as shown in Fig. 32.54.

Suppose it is required to find the voltage drop On full-load at a lagging cower factor ofcos then aradius OLP is drawn inclined at an angle of with OX. LM = 12 and is drawn horizontal MN = 12 x02 and is drawn perpendicular to 1M. Obviously, ON is noload voltage ov:. Now, ON OP ov2. Similarly. OLis V2. 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 I-MN need not be drawn. but simply the radius OLD.

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 foran angle of 00 leading, the fall becomes zero; hence V, = ov2. For angles greater than secondary terminal voltage V: greater than oV_2

The Kapp diagram is very helpful in determining the variation ofregulation with

the radii of thecircles. diagram has to be drawn on a very large scale, if sufficiently accurate results are

32.27. Sumpner Of Back-to-Back Test

This test provides data for finding the regulation. efficie1EY and heating under load conditions and is employed only when two similar transformers are available. One 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 rEgligibly small in the control circuit.

As shown in Fig. 3255. primaries of the two transformers are connected in parallel across the same a.c. supply. With switch S open, the wattmeter WI reads the core loss for the two t.ra1VSfornErs.

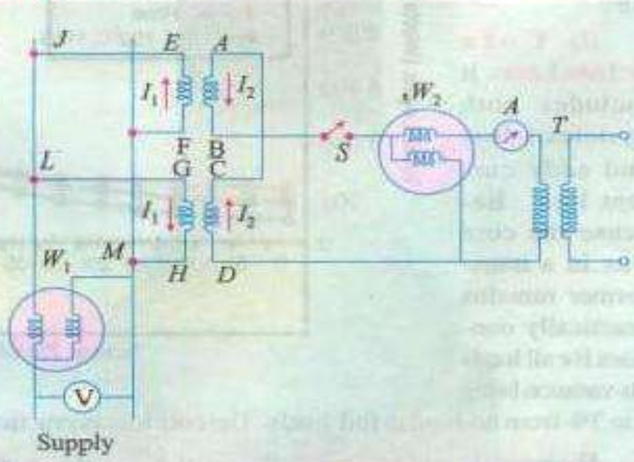


Fig. 32.55

powerfactorbutithas the disadvantage that since the lengths ofthe 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 VAB = vCD 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 bythe two secondaries. Tis anauxiliary low-voltage transformer which can be adjusted to given variable voltage and hence current in thesecondary loop circuit. By proper adjustment of T, full-load secondary current can be made to flow as shown. It is seen, that 12 flows from D to C and then fromA to B. Flow of is confined to the loopFEJLGHMF and it does not pass through WI. Hence, W, continues toread the core loss and W2measures full-load Cu loss (or at any other load current value 12). Obviously, the power takenin is twice the lossesofa single transformer.

Example 32.58. Two similar 250-kVA, single-phase transformers when tested by back-to-back method:

MainsWI = 5.0 kW

Primary series circuit Wattmeter, W2 Z-5 kW fat full-load cu"rent), Find Old the individual transformer efficiencies at

Solution. Total losses for both transformers —5 + 7.5 = 12.5 kW EL. loss for each transformef = 12.5/2= 6.25 kW

Copper-loss at 75% load $= \left(\frac{3}{4}\right)^2 \times \frac{7.5}{2}$ kW = 2.11 kW

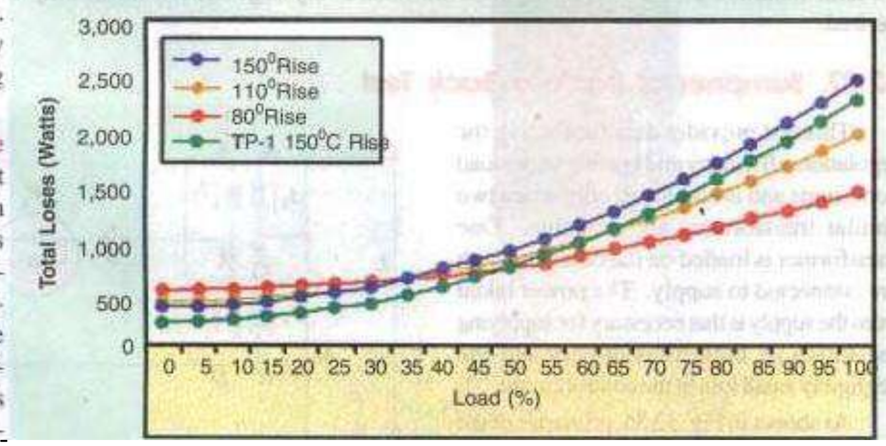
Output of each transformer at 75% F.L. and 0.8 p.f. = $(250 \times 0.75) \times 0.8 = 150$ kW

$$\eta = \frac{150}{150 + 2.5 + 2.11} = 97\%$$

32.28. Losses in a Transformer

In a static transformer, there are no friction or windage losses. Hence, the only losses occuring are :

(i) Core or Iron Loss : It includes both hysteresis loss and eddy current loss. Because the core flux in a transformer remains practically constant for all loads



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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 practicallýthe sam at all loads.

Wh = $\eta B^{1.6}_{max} f$

These losses are minimized by using steelofhigh silicon content for the core and by using very thin laminations. Iron or core loss is found tbeO,Ç. (esc, The load measures core loss

(ii) Copper loss. This loss is resistance

= 11^2R1 + Rot + Itis clear that Culossikproportionalto (current/ or kVA. In other words, Cu loss at half thelull-load is one-fourth ofthat at full-toad.

The value OfCUIOSS is found from the shon-circuit test (Art. 32.22).

32.29. Efficiency Of a Transformer

Asisthe case with other types ofelectrical machines, the efficiency of atransformer at a particular load and power factor isdefined as the outputdivided 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 ahighly efficient piece ofequipment, has very small loss, hence it is impracticål to to measure transformer, efficiency by measuring input and output. These quantities are nearlyofthe same sire, A better method is to determine the losses and then to calculate theefficiency from

$$\text{Efficiency} = \frac{\text{Output}}{\text{Output} + \text{losses}} = \frac{\text{Output}}{\text{Output} + \text{Cu loss} + \text{iron loss}}$$

$$\eta = \frac{\text{Input} - \text{Losses}}{\text{Input}} = 1 - \frac{\text{losses}}{\text{Input}}$$

Ou!pyt

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 anyvolt-ampere load. theefficiency depends on power o-load or open-circuit factor, beingmaximum at a power factorofunity.

Efficiency can be computed by determiningcore from testand Cu lossfrom the short-circuittest,

32.30. Condition for Maximum Efficiency

culoss

For nto be maximum.

The output current cormsrxmdingto maximum efficiency is 12$= \sqrt{(W_i/R_{02})}$.

It is this value of theoutput current which will make the Cu loss equal to theironlosg. By design. it is possible to make the maximum efficiency occur at any desired load.

Iron loss	
cu loss	

Note. If we arc given iron loss and fullload Cu loss. then the load at Which two losses would equal (i.e. to maximum efficiency) is given by

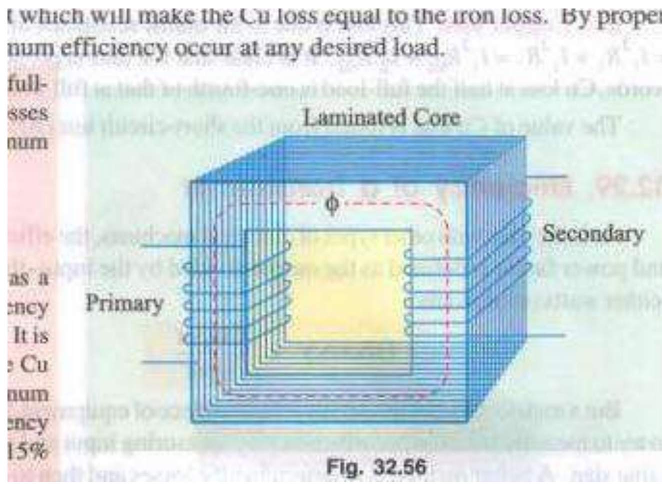


Fig. 32.56

-In Fig, 3256, Cu lóses are plotted tkm:ntagc Of power input and the cfficicngy 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 seen that the efficiencý is high and is practically constant from full-load to overload. (íi) The efficiency atany load is given by

where x

Example 323. In a 25-kVA, 2000/200 V. single-phase transformer. the iron andfull-load copper losses are 350 and 400 W respectively. Calculate the efficiency at unity power factor on

(i) full load (ii) halffull-load. (Elect. Engg. & Electronic. Bangalore Univ. 1990 and Similarexample in U.P. Technical University 2001)

Soluti'm. (i) Full-load Unity pl.

Total loss =

FL output at u.p.f. = 25 x Half F.L. Unityp.r.

cu loss = 400 x (1/2/ = 100 W. Iron loss remains constant at 350 W. Total loss = 350 -450 w.

Half-load output at u.p.f. = 12.5 kW

Example 320. and p: be the iron andcopper losses ofa transformeronfull•load.findthe ratio OfP, and pz such that efficiency occurs at full-load.

Sec. B, Summer 1992)

Solution. If P: is theCu loss atfull-load, its valueat 75% offull.load is—p: At maximum efficiency, it equals the ironloss pa which remains constantthroughout. Hence, at maximum

efficiency.

p, 9P2/16 or P/Pz-9/t6.

Example 32.61. A 11000/230 V, 150-kVA. I-phase, transformer has core loss Of1.4 kW and EL Cu loss OfI kW Determine

(i) rhe WA loadfor max efficiency and value Of efficiency at unity p.f.

(io rhe efficiency at halfEL 0.8p.f. leading (Basic Elect-Machine,NagpurUniv. 1993)

Solution. (i) Load WA correspondingto maximumefficiency is

Since Cu loss equals iron = F.L. kVA × loss at maximum efficiency, totul loss output = 160 x I = 160 kW

= 160/162.8 -0.982 or 9K2%

(ii) Cu lossat half full-load = 1.6k $(1/2)^2$ = 0.4 kW Total loss= 1.44 0.4 = 1.8 kW

HalfEL. output at 0.8 p.f.= (150/2) × 0.8 = 60 kW FAIiciency = 60/(60 + 1.8) = 0.97 or 97%

Example 32.62. A 5-kVA. 2,30QQ30-u 50•Hz transformer was testedfor the iron losses 'With normal excitation and Cu losses atfull-loud and these werefound to be 40 W and 112 W 'espectively.

Calculate the efficiencies Of the transformer at 0.8 powerfactorfor thefollowing WA 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 $= 112 \times (1.25/5)^2 = 7$ W

Total loss $= 40 + 7 = 47$ W Output $= 1.25 \times 0.8 = 1$ kW $= 1{,}000$ W

$\eta = 100 \times 1{,}000/1{,}047 =$ **95.51 %**

(ii) Cu loss at 2.5 kVA $= 112 \times (2.5/5)^2 = 28$ W

Total loss $= 40 + 28 = 68$ W

Output $= 2.5 \times 0.8 = 2$ kW

$\eta = 2{,}000 \times 100/2{,}068 =$ **96.71%**

(iii) Cu loss at 3.75 kVA

$= 112 \times (3.75/5)^2 = 63$ W

Total loss $= 40 + 63 = 103$ 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 $= 5 \times 0.8 = 4$ kW

$\eta = 4 \times 100/4.142 =$ **96.34 %**

(v) Cu loss at 6.25 kVA

$= 112 \times (6.25/5)^2 = 175$ W

Total loss $= 125$ W $= 0.125$ kW ; Output $= 6.25 \times 0.8 = 5$ kW

$\eta = 5 \times 100/5.215 =$ **95.88 %**

(vi) Cu loss at 7.5 kVA $= 112 \times (7.5/5)^2 = 252$ W

Total loss $= 292$ W $= 0.292$ kW ; Output $= 7.5 \times 0.8 = 6$ kW

$\eta = 6 \times 100/6.292 =$ **95.36 %**

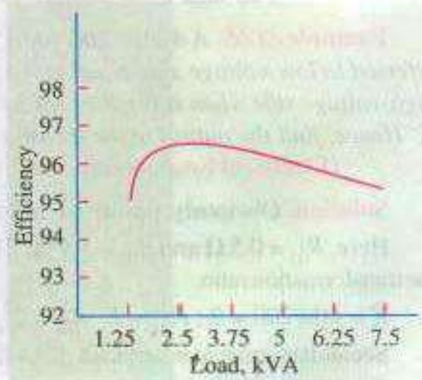


Fig. 32.57

The curve is shown in Fig. 32.57.

Example 32.63. 2ffl-kVA transformer has an efficiency Of ar full load. the mat. efficiency Occurs ar three quarters offull-load. calculate the efficiency at half Assume negligible magnetizing current and p.f. O,8 at all loads. (Elect. Punjab UniV. Jan. 1991)

Solution. As given. the transformerhas a EL efficiency of98 % pr.

El..output = 200x0.8= 160kW ; EL. input- 60/0.98 =163.265 kW

F.L.tosses = 163.265- 160=3.265kW ELoutput = 25XO.8=20kW- 20,OOOW

Full-load = 20,000 x 100/(20.000 464.4)= 9-7.' %

Example 32.6*. A 4-kVA. V, I-phase transfonnerhasequivalent n•sistance and œacrance referred ro low-voltage side equal to O, 512 1.5 Q respectively Find the terminal voltage On the high-voltage side When supplies 3/41/1full-load a/ powerfactor OfO.8, the supply voltage being 220 V. Hence, find the output transformer and its efficiency ifthe corelosses are 100 W.

(Electrical Engineering : Bombay Univ. 1985'

Solution. Obviously, primary is the side and the secondary. the high voltage side.

Here, ROI Q and = I S These 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 (X4X 3/4)/400 7SA

Total drop as referred to transformer secondary is

Terminal voltageon high-voltage side under givenloadconditionis = 400-39=361 v culoss =
Iron loss 100 W

= 212SW output = (4 x 3/4) x 0.8 = 2.4 kW

Input = 2.400+212.5-2,612.5 w n-2.400x 100/2,612.5 = 91.87

Example 32.66. A 20•kVA, 440/220 V, 50 Hz transformer has iron loss W. The Cu isfound be When delivering halffull-load curt-em. Determine efficiency when

Assumingalagging factor

deliveringfull-load current at 0.8 lagging and /ii) the percent offull-load When the efficiency Will be marimum. (Electrutechnique•ll, MS. Univ., Baroda 1987)

Hence. efficiency would be maximum at90 % ofEL

Example 32.67. Consider a 4-kVA. 200/400 V Mingle-phase transformer supplying full-load current at 0.8 lagging powerfactor. The QC-IS. C. test results are as follows :

O.C.test : 200 V, O.SA. 70B' (I.V. side)

S.C. test 20M 10 A 60 V: Side'

Calculate efficiency, secondary voltage and current into primary at the above load.

Calculate the load at unity powerfactor corresponding to marimum efficiency iEleci. Machines Nagpur Univ. 1993È

Solution. Full-toad. = 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 +

EL. n -3.2/3.33=0.960r96 %

Example 32.68. A 600 WA. I-phase transformer has an efficiency of92 % both atfu[l-loadand half-load at unity powerfactor. Determine its efficiency at 60 % offull-load at O.S powerfactor lag.

Sec. B,

x ICO

2

(x x WA) x cos + W, + .rWcu where x represents percentage Of full-load W, is iron loss and Wcu is full-load Cu loss,

At EL u.p.r. Here x =

W/+ -52.174kW

Atha1fFL UPE Her-ex=

*100;

= 85.9%

has an efficiency Of92 % atfull-load and also at half-load. Determine its efficiency When it operates at p.j: and 60 Of load. (Electric. Machines. Kerala Univ. 1987)

Solulion. The fact that efficiency is the same 92 % atbotb full-load and half-load Will help us to find the iron and copper losses.

At full-load

Output -600 kW ;

SinevCu loss becoloes one-fourthof its EL. value, hence x +y/4 - 26. l Solving for-rand y. we get 17.4kW ; y =

At 60 full-load cu 0.62 x34.s= 1253 kW ; Total loss- 17.4+ 12.53-29.93 kW

=360kW •02360/389.93=0.965or 96.5

Example 32.70. The maximum efficiency Ofa /OO-kVA, Single phase transformer is and occurs at offull load at 8 If rhe leakage impedance of transformer is find the voltage regulation al rated load Of O. 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 kW

Culossat full-load = $0.65/0.8^2$ = I kW

Cu loss 1 00

x 100-lx

IOO

% age regn, = + 5 0.6)

Example 32.71. A 10WA, 5(YW440- single phase transformerhas eddyCurrent and hysteresis losses of I 0.5 and 0.6 per cent ofoutput onfull What "'ill be rhe percentage losses if the transformer is used on 50-11: system keeping the full-load current consJont ?

Assume unity powerfactor operation. Compare thefull load efficienciesfor rhe nvo cases.

(Elect. Machines, B, 1991

Solution. We know that El = 4.44 f When both excitation voltage and frequency are doubled, flux remains unchanged.

FL. output at upf 10kVA x I 10kW

FL Cu loss 1.5 x 10/100 = 0.1SkW : Eddy current loss

= 0.5 x = 0.05 kW : Hysteresis loss = 0.6 x

Now, full-load current is kept constant but voltage is increased from 5000 V to 10.000 V. Hence, output will be doubled to 20 kW. Dueto constant current, Cu loss would also remain constant.

New = 0.15 kW, % cu loss

Now, eddy curœntloss

New eddy current loss -0.05 IOO- 1 %

Now, = 0.06x (50/25) - 0.12 kW, %

at 0.8 p.f. a/ normal voltage

Solution.

Example 32.73. A single phake transformer is rated at IOO•kVA, 2300/230-V. 50 HZ. The maximumflux density in the core is l. 2 Wb/m^2 and the net cross-sectional areo Ofthe core is O. $04"1^2$.

Determine

(a) The number ofprimary and Secondary turns needed.

(b) [f the mean length Of the magnetic circuit is 2.5 m and the*elative permeability is 1200, determine the magnetising current. Neglect theßurrent drawn for the core loss.

(c) On short-circuit with full-load current flowing, the power input is 1200 W and an opencircuit With rated voltage, the power input was 400 W. Determine the efficiency of the transformer at 75 % offull-load With 0.8 p.f lag.

(d) Ifthe same transformer is connected to a supply thefrequency

(i.e.. 100 Whar is effect on ifs efficiency ? (Elect. Engg„ Bombay U"is. 19tB)

—9.21 A

Output— 100 x (3/4)

(d) When frequency is doubled. iron loss isincœased because

(i) hysteresis loss is doubled—

(ii) eddy current loss is quadrupled — We Hence. efficiency will decrease

what is rhe power-factor ar Which rhe regulation will•v' : '(i/ Zero; (ii) positive-maximum ? (b Ifits maximum efficiency occurs atfull-load (at unity p.f, what Will be efficiency under these conditions ?

Solution : Approximate perceptage regulation is given, in thi' case, by the relationship

I 5.4 sin O.

la) Regulation :

(i' If regulation is zero. negative sign must be applicable. This happens at leadings p.f.

Corresponding pf. = leading

= 18.44" leading

(ii) For maximum positive regulation, lagging p.f_ is a must. From phasordiagram, the can be obtained.

Corresponding tan 5.4/1.8

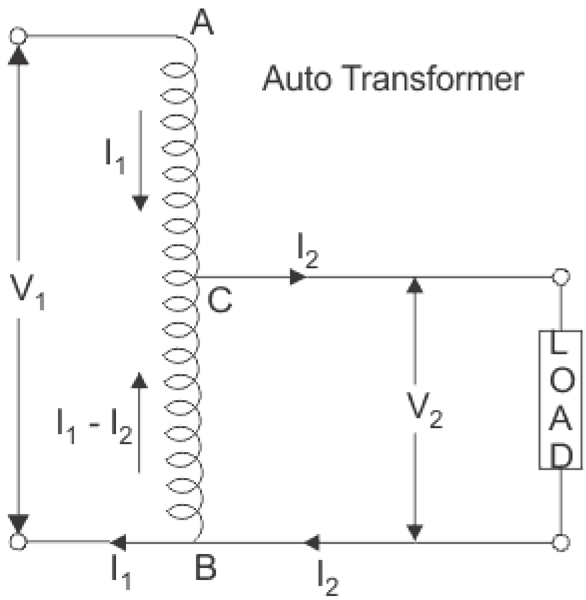
% Voltage regulation = 1.8cos4+5.4sin 0=5.7 % (b) Efficiency : Maximum efficiency occurs at such a Iron losses =

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,

$$\frac{V_1}{N_1} X N_2\ and\ from\ the\ figure\ above,\ this\ voltage\ is\ V_2$$

$$Hence,\ \frac{V_1}{N_1} X N_2 = V_2$$

$$\Rightarrow \frac{V_2}{V_1} = \frac{N_2}{N_1} = Constant = K$$

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,
$(N_1 - N_2)I_1 + N_2(I_2 - I_1)$

$$\Rightarrow N_1I_1 - N_2I_1 + N_2I_2 - N_2I_1$$

$$\Rightarrow N_1I_1 + N_2I_2 - 2N_2I_1$$

$$\Rightarrow 2N_1I_1 - 2N_2I_1 (Since,\ N_1I_1 = N_2I_2)$$

$$\Rightarrow 2(N_1I_1 - N_2I_1)$$

In similar way it can be proved, the weight of copper in two winding transformer is proportional to,
$N_1I_1 - N_2I_2$

$$\Rightarrow 2N_1I_1 \qquad (Since,\ in\ a\ transformer\ N_1I_1 = N_2I_2)$$

$N_1I_1 + N_2I_2$

$\Rightarrow 2N_1I_1$ (Since, in a transformer $N_1I_1 = N_2I_2$)

Let's assume, W_a and W_{tw} are weight of copper in auto transformer and two winding transformer respectively,

$$Hence,\ \frac{W_a}{W_{tw}} = \frac{2(N_1I_1 - N_2I_1)}{2(N_1I_1)}$$

$$= \frac{N_1I_1 - N_2I_1}{N_1I_1} = 1 - \frac{N_2I_1}{N_1I_1}$$

$$= 1 - \frac{N_2}{N_1} = 1 - k$$

$$\therefore W_a = W_{tw}(1-k)$$

$$\Rightarrow W_a = W_{tw} - kW_{tw}$$

∴ 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 event.

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.

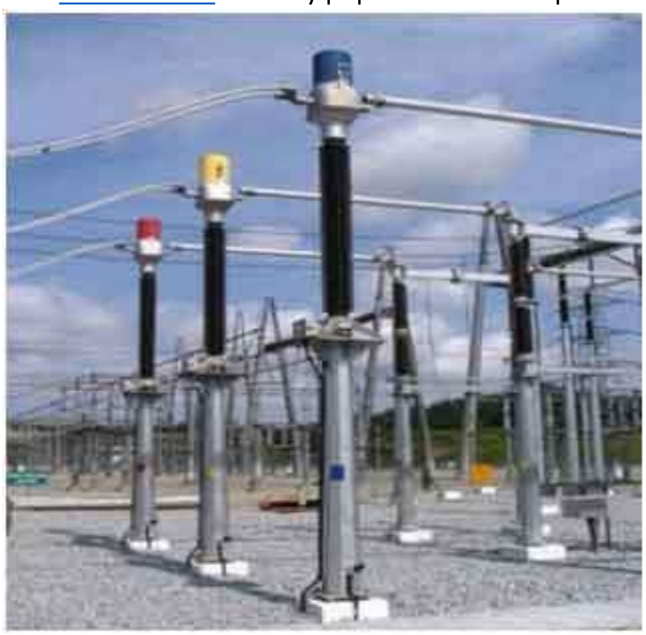
3. **Auto transformer** is used as variac in laboratory or where continuous variable over broad ranges are required.

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

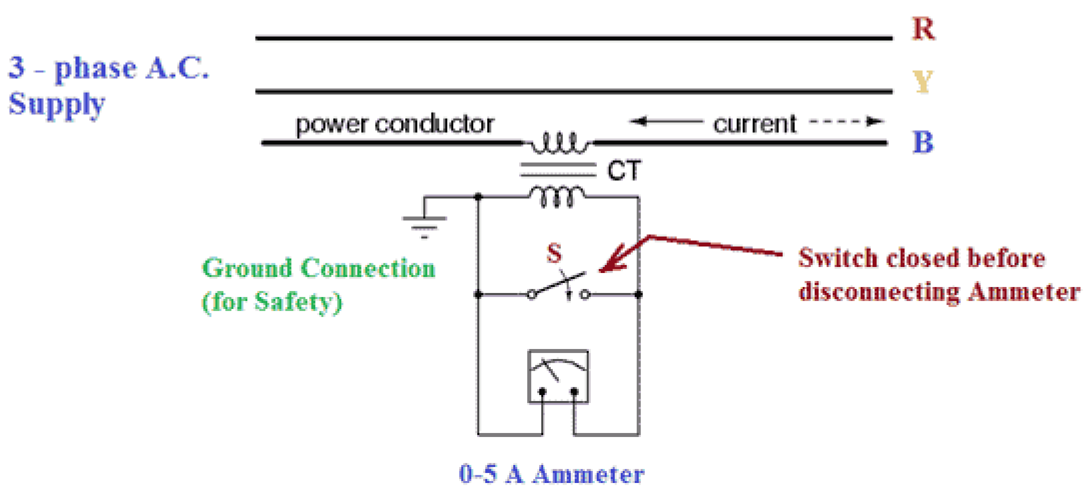
Instrument transformers are of two types –

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.



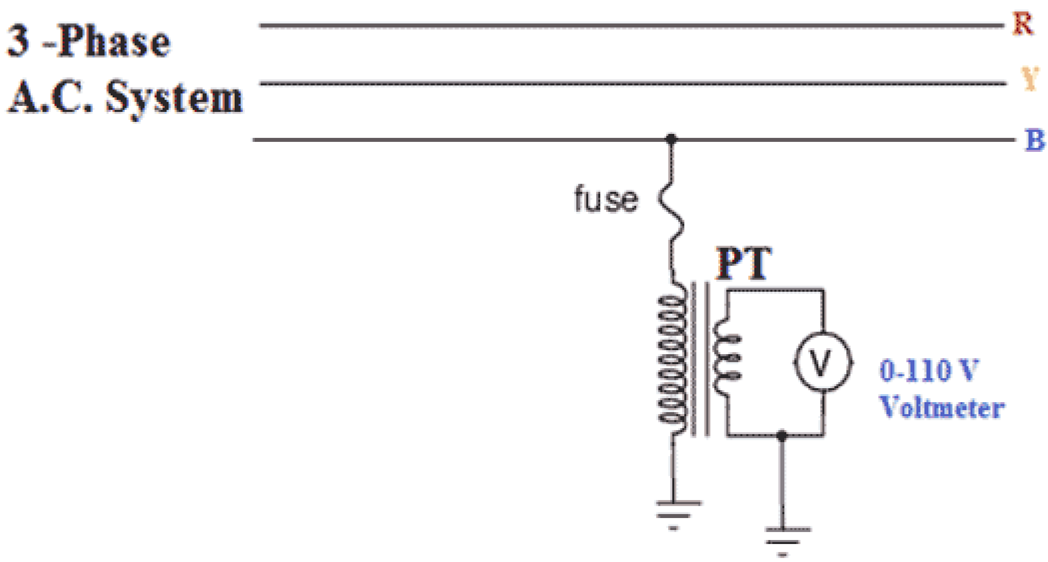
Current Transformer (C.T.)

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.