SAKUNTALA SUDARSHAN
INSTITUTE OF TECHNOLOGY (POLYTECHNIC)

LECTURE NOTES

ON

## ENERGY CONVERSION–I

BRANCH- ELECTRICAL ENGG
SEMESTER - 6TH

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Lecture In Electrical Engineering

DCGENERATOR

Anelectricalgeneratorisamachinewhichconvertsmechanicalenergy(orpower)into electrical energy (or power).

Theenergyconversionisbasedontheprinciple Of the production Of dynamically (or motionally)inducede.m.f.Asseenfromfig.26. I , whenever a conductor cuts magnetic flux. dynamically induced em-f. is produced in it accordingtoFaraday'sLawsofElectromagnetic Induction. This em-f. causes a current to now if the conductor circuit is closed.
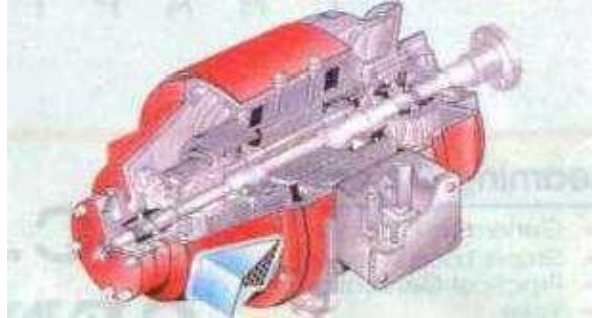
Hence,twobasicessentialpartsOf anelectricalgeneratorareamagneticfieldand(ii)a conductor or conductors which can so move as to cut the flux.

CONSTRUCTION:-

Infig.26.Iisshownasingle-turnrectangularcoilABCDrotatingaboutitsownaxisina

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

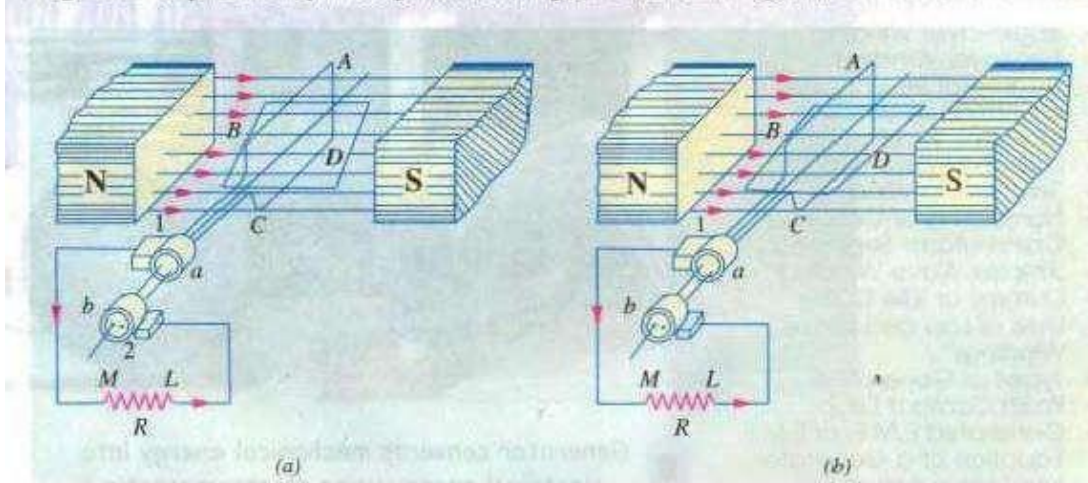Fig. 26.1

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

arejoinedtotwo slip-rings'a'and•b'whichareinsulatedfromeach Otherand fromthe-centralshaft.Two collectingbrushes(ofcarbon orcopper)pressagainsttheslip-rings.Their function is to collect the current induced in the coil and to convey il to the external load resistance R.

Therotatingcoilmaybccalled•armature'andthemagnetsas'fieldmagnets.

Working

Imagine the coil to be rotating in clock-wise direction (Fig. 26.2). As the coil assumes successivepositionsinthefield.thefluxlinkedwithitEhanges.Hence.ane.m.f.isinducedin it which is

proportionaltotherate Ofchange Offluxlinkages(e=NdcÞdt).WhentheplaneOf thecoilis 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 CDdo 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.Letustakethisno-e.m.f.orverticalpositionofthecoilasthestartingposition.Theangle of rotation or time will be measured from this position.
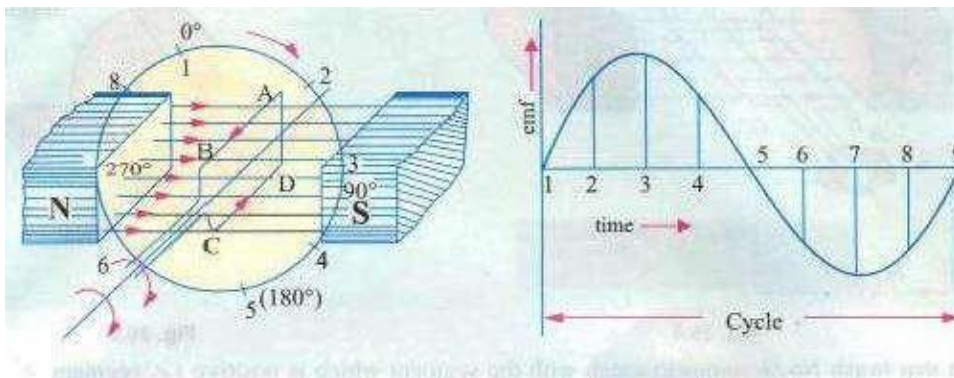

Fig.26.2   Fig,26.3

As the coil continues rotating further, the rate Of change Of flux linkages (andhence induced e_mf.init)increases.tillposition3isreachedwhere6 =90^0.Here,thecoilplaneishorizontal i.e. parallel to the lines Of flux. As seen. the flux linkedwith the coil is minimum butrate ofchangeOf'laxlinkagesismaximum.Hence,maximume.m.f.isinducedinthecoilwhenin this position (Fig. 26.3).

Inthenextquarter revolutioni.e.from900to1800,thefluxlinkedWiththecoilgradually increnses 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 firsthalf 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 givesitsdirectionfromAtoBand Cto D.Hence,the directionof currentflowisABMLCD(fig. 26. l). The current through the load resistance R flows from M to L during the first half revolution of the coil.

Inthenexthalfrevolutioni.e. fromISVto360.the variationsinthemagnitudeofaresimilar 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 fromDto CandBtoAasshowninFig.26.1Hence,thepathOf currentflowisalongDUMBA 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 continuouslyflowsinoneandthe samedirection.Itshouldbenoted thatalternatingcurrent not only reverses its direction, it does noteven 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 replacedbysplit-rings(Fig.26.4).Thesplit-ringsaremadeoutof aconductingcylinderwhich iscutinto twohalvesorsegmentsinsulatedfromeachotherbya thinsheetof micaorsome other insulating material (Fig. 26.5).

Asbefore. thecoil endsarejoinedtothesesegmentsonWhichrestthecarbonor brushes. It isseenIFig. 26,6thatinthefirst halfrevolutioncurrentflowsalong BMNI_CDJ i:e. thebrush NO. I in contact with segment'a' acts as the positive end of the supply and •b' the negative end.InthenexthalfrevolutionIFig.26.6(b)l.thedirectionOf theinducedcurrentinthe coil has reversed. But at the same time, the positions of segments 'a' and 'b' have also reversed with the
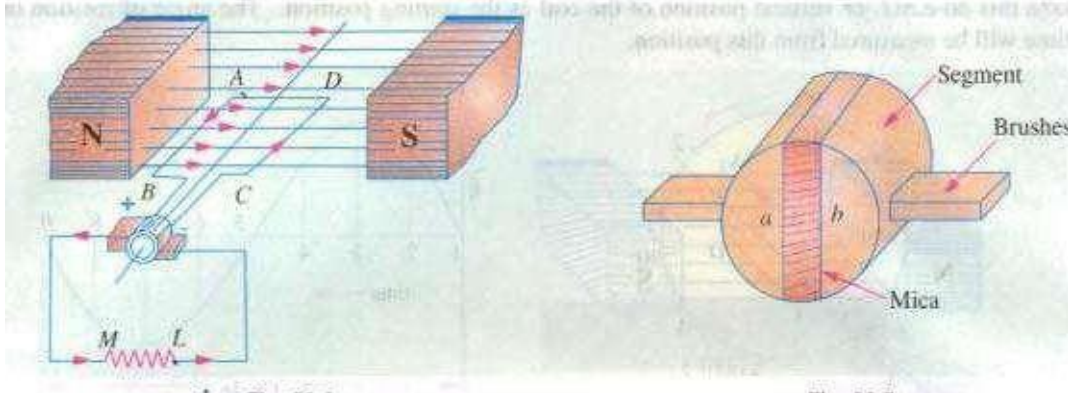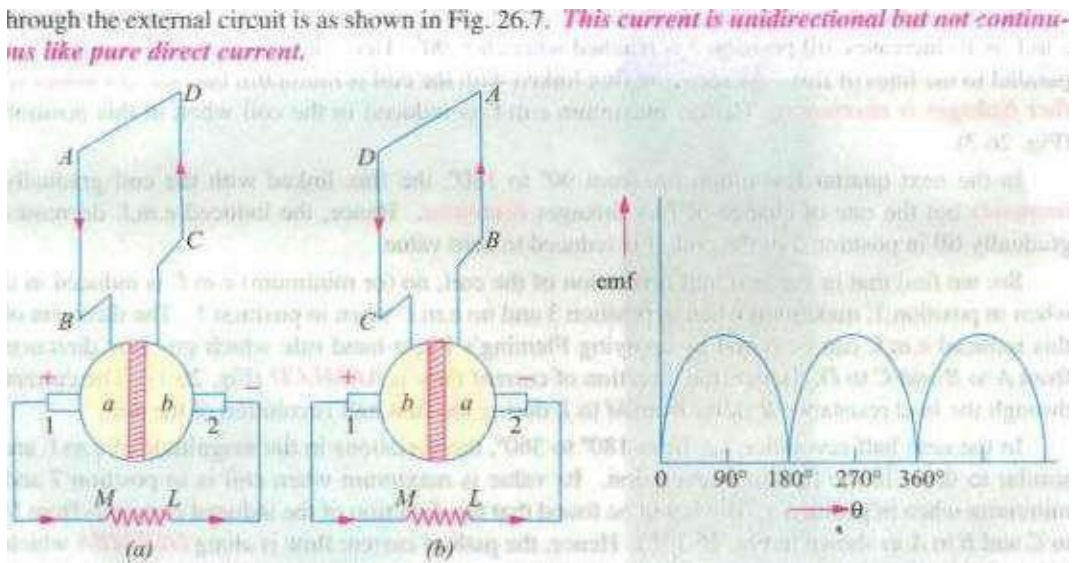
Fig. 26.4   Fig. 26.5 result that brush No. I comes in touch with the segment which is positivei.e.segmentinthiscase.Hence.currentinthe loadresistanceagainflowsfromMto

hrough the external circuit is as shown in Fig. 26.7. *This current is unidirectional but not continuus like pure direct current.*

emf

0   90° 180° 270° 360°

→ θ

(a)   (b)

L. The Waveform of the current through the external circuit is as shown in Fig. 26.7. This currentshouldbe notedthatthepositionofbrushesissoarrangedthatthechangeoverOf segments•a'andfromonebrushtothe other takesplacewhentheplaneof therotatingcoil is at right angles to the plane of the lines of It is so because in that position. the induced e.m.f.inthecoiliszero.

Anotherimportantpointworthrememberingisthatevennowthecurrentinducedin thecoil sides is alternating as before. It is only clue to the rectifying action of the split-rings (also calledcommutator)that itbecomesunidirectional intheexternal Circuit. Hence. itshouldbe clearly undEr• stood that in the armature Of a generator. the induced voltage is alternating.
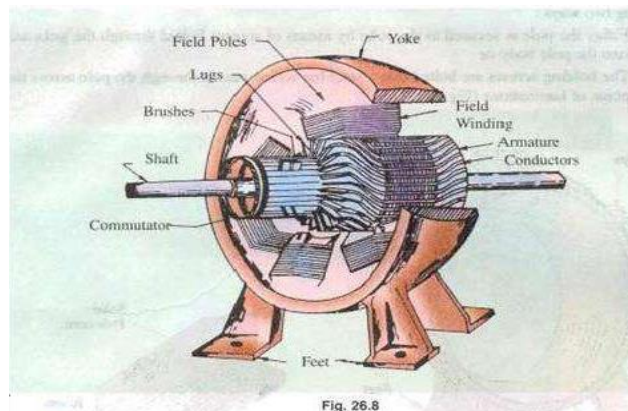
Generator-

Fig. 26.8

4

26.5. PoleCoresandPoleShoes

The field ConsistorpoleCoresandpoleshoes.ThepoleshoesSCñretwo purposes

(i) theyspreadoutthefluxintheairgapandalso,Oflargercross-section,reducethe reluctanceOfthemagneticpath• ii)theysupiX3rtthe excitingcoils(orfieldcoils)asshown infig.26.14.

TherearetwomaintypesOf poleconstruction.

(a)   ThepolecoreitselfmayasolidpiecemadeoutOf eithercastironOr caststeelbut 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)   Inmoderndesign.thecompleteNecoresandpoleshoesarebuiltofthinlaminations of annealed steel which aœ rivetted together under hydraulic pressure (Fig. 26_11). The thickness Of laminations varies from I mmto 0.25 mm- The laminated poles may be secured to the yoke in any of the following two Ways:

(i) Eitherthepoleissecured tothe yokebymeansofscrewsboltedthroughthe yoke and into the pole body or

(ii) Theholdingscrewsareboltedintoabarwhichpasses throughthepole across the plane of laminations (Fig. 26.12).
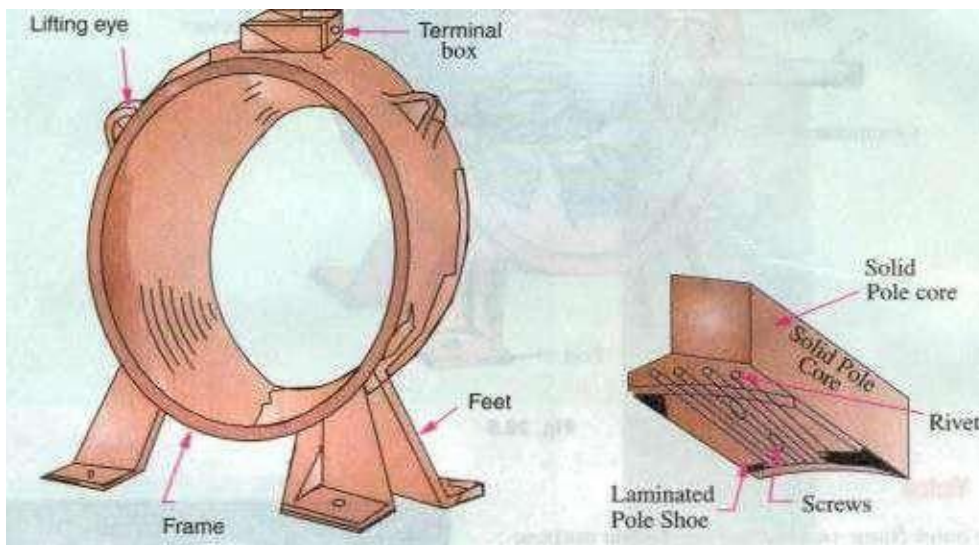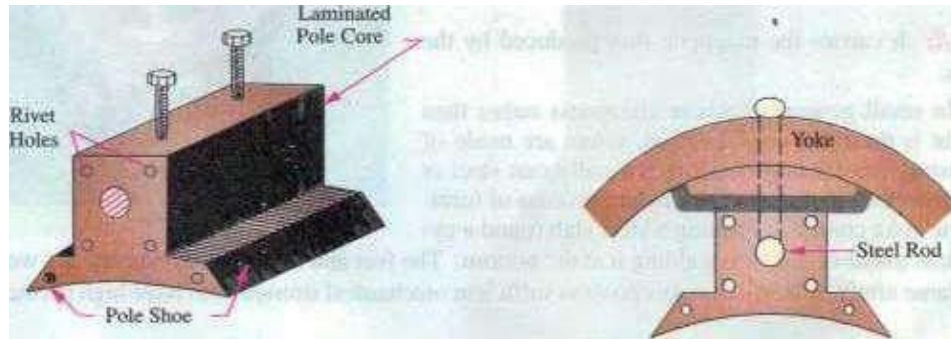
Fig.26,9   Fig.26.10

26.6. polecoas

The field coils or pole coils, which consist of copper wire or strip. are former-wound for the correctdimension(Fig.26.13).Then.theformerisremovedandwoundcoilisputintoplace over the core as shown in Fig. 26.14.

Whencurrentispassedthroughthesecoils,theyelectromagnetisethepoleswhichproduce thenecessary flux that is cut by revolving armature conductors.

26.7. ArmatureCore

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 provideapathofvery lowreluctanceto thefluxthroughthearmaturefromatv-poletoaS- pole.

It is cylindrical or drum-shiped and is built up of usually circular sheet steel discsorlaminations approximately0.5mmthick(Fig.26.15).Itiskeyedtotheshaft.

Theslotsareeitherdie-cutorpunchedon theouterperipheryOfthediscand thekeywayis located on the inner ꞁiameter asshown. 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.
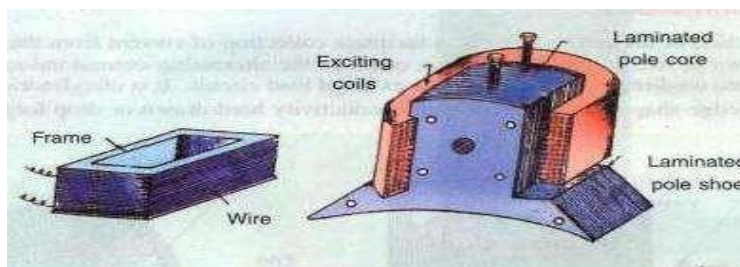

Fig.26.13   Fig.26.14

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 assembledtogether. Hence. thecircularlaminations.insteadofbeingcut out inonepiece, arecutinnumber Ofsuitablesectionsorsegmentswhichform partofa completering(Fig. 26.17).
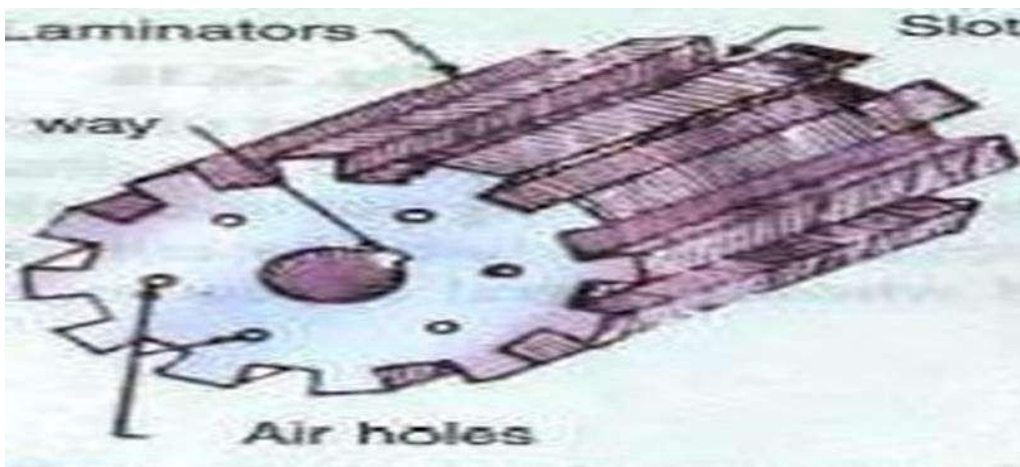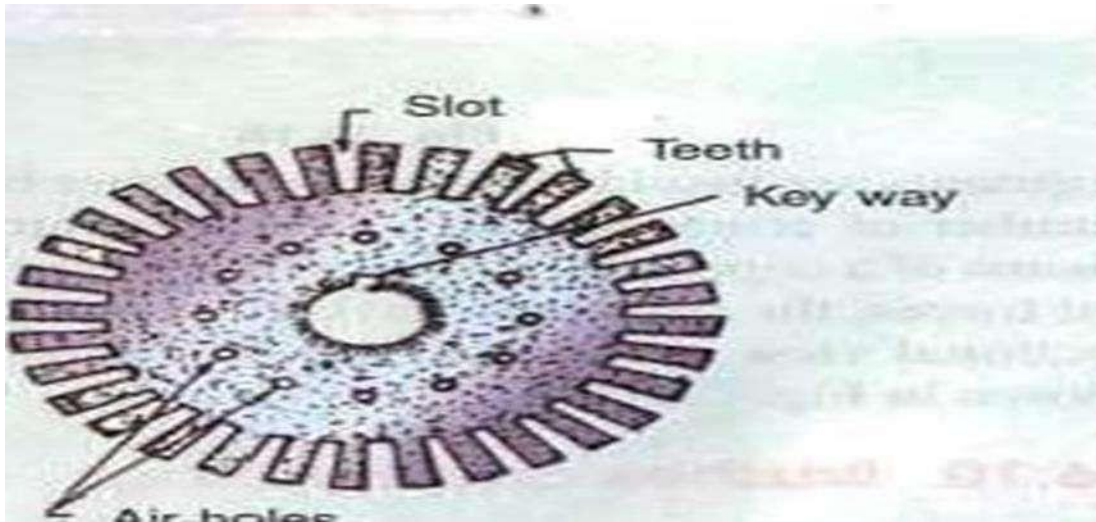
A complete circular lamination is made up Of four or six or even eight segmental laminations. Usually. two keyways are notched in each segmentanaaredove-tailedorwedge-shapedto make the laminations self-locking in position,

Thepurposeofusinglaminationsistoreducethe 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.

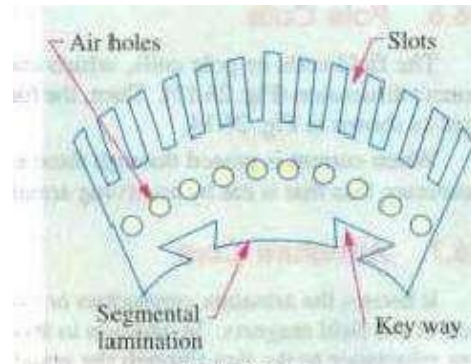Fig. 26.17

s and are then pulled into their proper shape

26.8. ArmatureWindings

Thearmaturewindingsareusuallyformer-wound.

These are first wound in the form of nat rectangular coils and are then pulled into their in a coilpuller.VariousconductorsOfthecoilsareinsulatedfromeachother.Theconductorsare 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 conductorsintounidirectionalcurrentintheexternalloadcircuit.Itisof cylindricalstructure and is built up of wedge-shaped segrtients of high•conductivity hard-drawn or drop forged copper. These
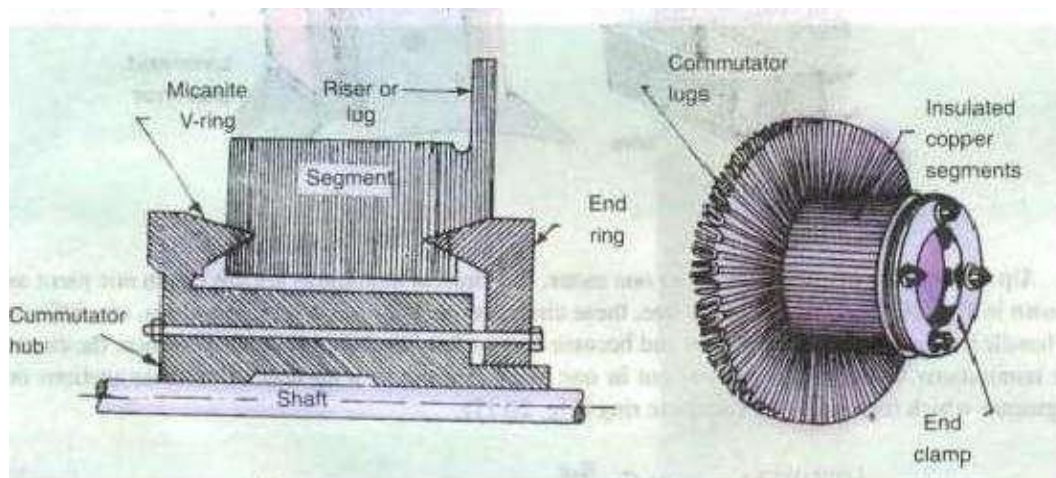

Fig. 26.18

Fig. 26.19

segmentsareinsulatedfromeachOtherby thinlayersOftliiea. ᴸThenumberOfsegmentsis 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 Topreventthemfromflyingoutunder theactionofcentrifugal 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. Brushesand•Bearings

The brushes   function is to collect current from commutator.areusuallymadeOfcarbonorgraphiteandarein 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.thebrush-holderismounteda spindleandthe brusheseanslideintherectangular-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 collectedfrom the commutator_

Flexible

Bearing

Fig. 26.20
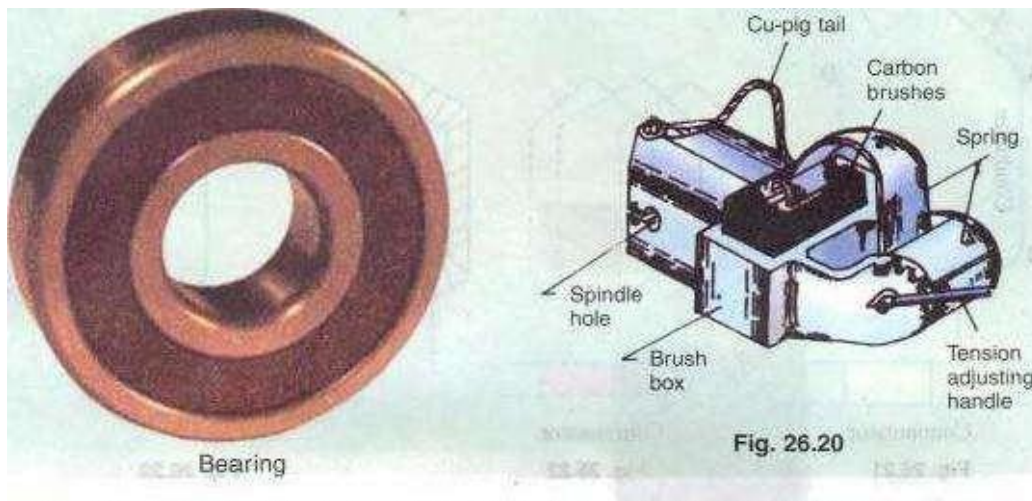
Because Oftheirreliahility, hall-bearings are frequently eniployed. though for heavýdutieS, rollerbearingsarepreferable.Theballandrollersaregenerallypackedinhardoilforquieter operation and for reduced bearing wear, sleeve bearingé are used which are lubricated by ring oilers fed from Oil reservoir in the bearing bracket.

26.11. ArmatureWindings

NOW,WeWilldiscussthewindingOfanactualarmature.Butbeforedoingthis,the meaning OfthefollowingtermsusedinconnectionWitharmaturewindingshouldbeclearlykept inmind,

26.12. Pole-pitch

Itmaybevariouslydefinedas:

(i) TheperipheryOfthe armaturedividedbythenumberofpolesorthegeneratori.e.the distance between two adjacent poles.

(ii) ItisequaltothenumberOfarmature

• conductorsand4poles,thepolepitehis48/412.

26.13. Conductor

ThelengthOfaWirelyinginthemagneticfieldandinwhichane.mf.isinduced,iscalleda 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 multiturncoil (Fig. 26.22). A single-turncoil will have twoconductors. Buta multi-turncoilmayhavemanyconductorsper coilside,InFig,2622,forexample.eachcoil side has 3 conductors, The
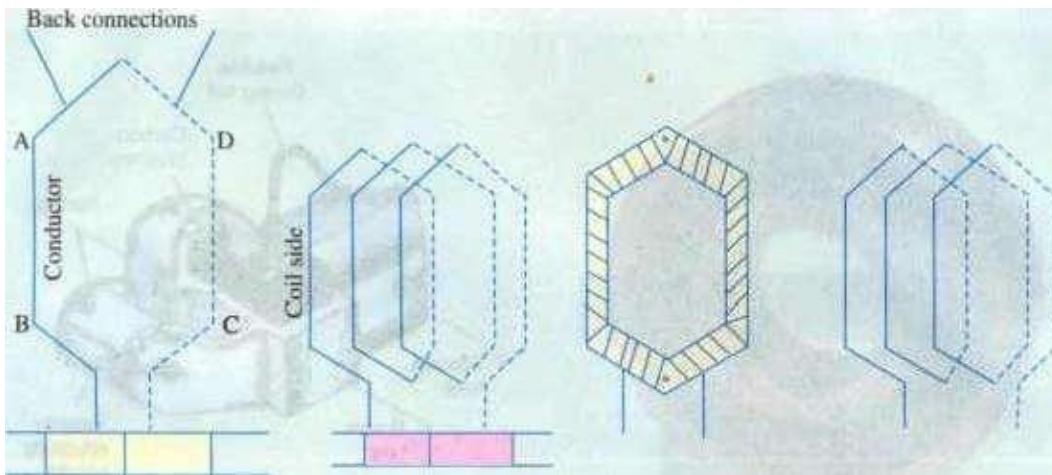
Cornmutator   Commutator

Fig.26.21   Fig.26.22   Fig.26.23

groupofwiresorconductors constitutingacoilsideof amulti-turncoiliswrappedwitha tape as a unit (Fig. 26.23) and is placed in the armature slot. It may noted that since the beginningandtheendOf each coilmustbeconnected toa commutator bar.thereareas many commutaror bars as coils for both the lap and wave windings (see Example 26. I).

Thesideofacoil(I-turnormultiturn)is.illedawindingelement.Obviously,thenumberof winding

elements is twice the number of coils.

26.15. Col-spmorCoil-pitchCYs)

It is the distance, measured in terms of armature slots for armature conductors) between two sides ofacoil.Itis,infact,theperipheryofthearmature 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 underoppositepoles,hencetheinducede.rn.fs.in them are additive. Therefore, maximum e.m.f. is induced in the coil as a Whole. itbeing 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 coilspanis36/4=9 slots.Ifnumberofslotsis35,thenYs=35/4=8 becauseitiscustomaryto drop
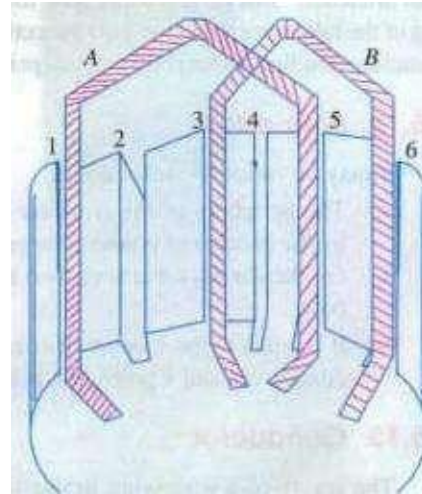
If the coil span is less than the   pitch(asinCoilFig.26.24 B

where coil pitch is 314th of the pole pitch), then the

windingisfractional-pitchea_LInthiscase,thereisaphasedifferencesidesofthe
        Hence,thetotale_m.f.roundthecoilWhichisthevectorsumofe.m.fs.inAhetwo coil sides, is less in this caseas compared to that in the first case.

26.16. Pitchofa Winding(Y)

In general, it may be defined as the distance round the armature between two successive conductorswhichdirectlyconnected together.Or,itisthedistancebetweenthe beginnings Of two consecutive turns.

$-Y_F$ —for lap winding

$+Y_F$ —-„.forwavewinding

Inpractice.coil-pitchesaslowaseight-tenthsofa polepitchareemployedwithoutmuch 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. BackPitch

Thedistance,measuredintermsofthearmature conductors,whichacoiladvancesonthe back of the armature is called back pitch and is denoted by YR

Asscenfromfig_26_28,elementlisconnected on the backOf thearmature toelement 8. Hence. $Y_B = (8 - 1) = 7$.

26.18. FrontPitch(Yr)

The number of armature conductors or elements spanned by a coil on the front (or commutatorendof anarmature'is calledthefrontpitchandisdesignatedbyAgaininFig. 26.28.element8isconnectedtoelemcnt3onthefrontOfthearmature,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)betweenthesecondconductorofone coilandthefirst conductorofthe nextcoil 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
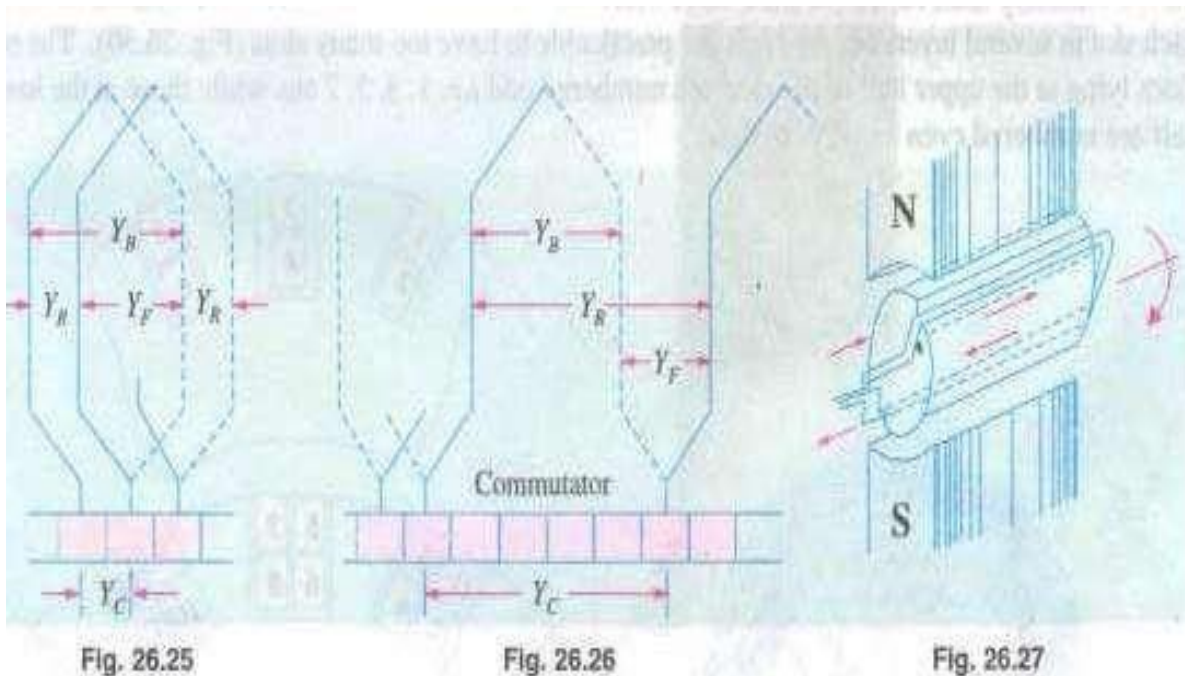
26.19. ResultantPitch

Itisthedistancebetweenthebeginningofonecoilandthebeginningofthenextcoiltowhich 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 statedintermsOfarmature conductors.arealsosometimesgiven intermsOfarmatureslots or commutator bars because commutator is, after all, an image Of the winding.

26.20. Cornmutator Pitch (Y_C)

It is the distance (measured in commutator bars or segments)between the segments to which thetwo 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 $Y_F$whereasforwavewindingitisthe sum of $Y_B$and Yr Obviously, commutator pitch is equal to the

Commutator
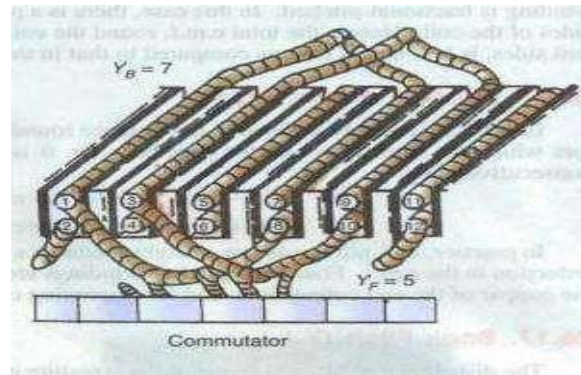
number of bars between coil leads. In general, equals the 'plex• of the lap-wound armature. Hence,itisequall,2,3,4etc.forsimplex-.duplex,triplex—andquadruplexetc.lap-windings. Fig. 26.28

26-21.Single-layerWinding

Itisthatwindinginwhichoneconductoror one coilsideisplacedineacharmatureslotas shown in Fig. 26.27. Such a winding is not much used.

26.22. Two-layerWinding

In this of winding, there are two conductors or coil sides Ixr slot arranged in two layers. Usually, one side of every coil liesin the upper half of one slot and other side lies in the lower half of some other slotal a distance of approximatelyone 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 6or 8 coil sides are used in each slot in several layers because it is not practicable to have too manyslots(fig.26.30).Thecoilsideslyingattheupperhalfoftheslots arenumberedoddi.e.I ,3.5,7etc.whilethoseatthelower

halfarenumberedeveni.e.2,4.6,8etc.
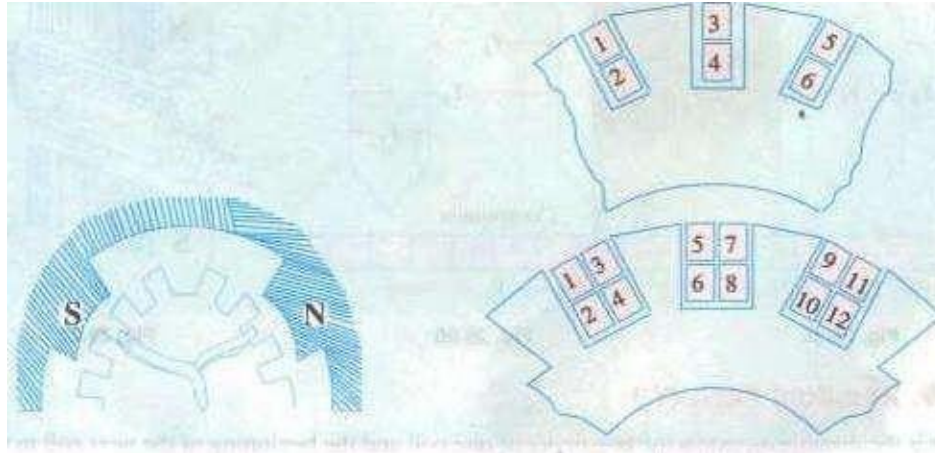
Fig.26.29   Fig.26.30

26.23. DegreeofRe-entrantOfanArmatureWinding A

winding is Saidto be Single re-entrant if on tracing through it once, all armature conductors areincludedonreturningtothestartingpoint.Itis double re-entrant if only half the conductors are included in tracing through the winding once and so On,

26.24. MultiplexWinding

Multiplex Winding

Insuch windings. there are several sets ofcompletely closed and independentwindings. If there is only one set of closed winding, it is called simplex wave winding. If there are two such windingsonthesamearmature,itiscalledduplex 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 multiplicityincreases,thenumberOfparallelpathsinthearmatureincreasesthereby increasing thecurrent rating but decreasing the voltage rating.

26.25. LapandWaveWindings

Twotypesofwindingsmostlyemployedfordrum-typearmaturesareknownasLapWinding 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.

Lap winding
Lapwinding
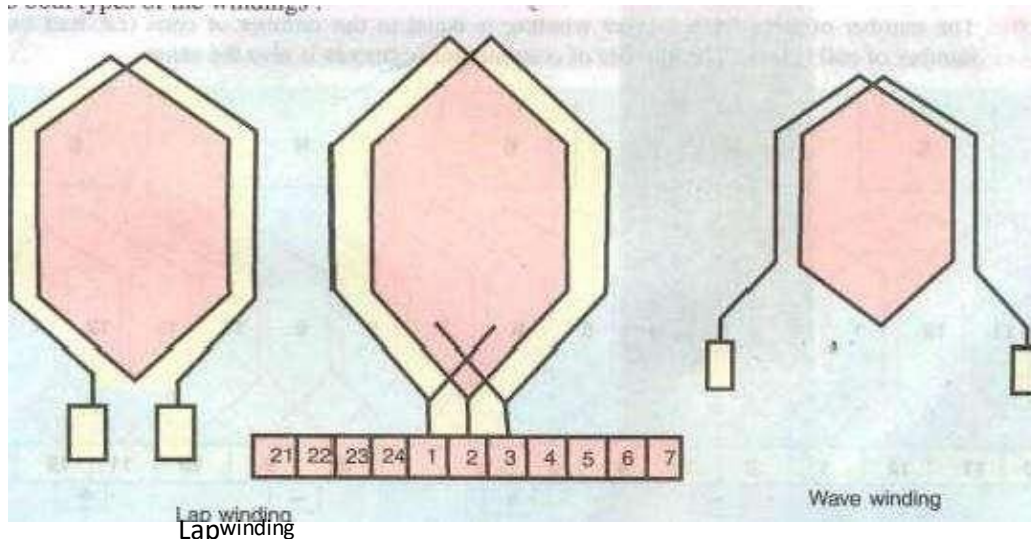
Wave winding

Eachwindingcanbearrangedprogressivelyorretrogressivelyandconnectedinsimplex, 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. windingsshouldbefull-pitched.Thisresultsinincreasede.m.f,roundthecoils.Forpur-

poses.fractional-pitchedwindingsaredeliberatelyused(Art_26.15).

(inBothpitchesshouldbe odd,otherwiseitwouldbe difficulttoplacethe coils(whichare former-wound)properlyonthearmature. Forexmaple,ifYBand YFwerebotheven, theall thecoilSidesandconductorswouldlieeitherintheupperhalfOftheslots Orin thelower

half.Hence.itwouldbecomeimpossibleforoneAidèxsfthecoilintheupperhalf.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 numberOfconductors)becausethefrontendsÃ'fconductorsarejoinedtothesegmentsin

Thewindingmustcloseuponitselfi.e.ifwestartfrotnûgivenpointandmovefromonecoi] to•another, then all conductors should he traversed and we should reach the same poinragain Withoutabreakor discontinuityiobetween.

26.26. SimplexLap-winding*

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It is shown in fig: 26-25 which employs single-turn coils. In lapwinding, the finishing end of onecoilisconnected toa commutator segmentandto thestartingend ofthe adjacentcoil situatedunderthesamepoleandsoon,tillandthecoilshavebeenconnected.Thistype Of winding derives its name from the fact it doubles or laps hack With its succeeding cods.

Followingpointsregardingsimplexlapwindingshouldbe

1. Thebackandfrontpitchesare•odd•andOfoppositeSign.ButtheyCannotThey differby2OrSomemultiplethereof.

2. Bothandshouldbenearlyequaltoapolepitch.

3. TheaveragepitchYA=.Itequglspolepitch=z

4. pitch=±I(Inkeneral,=±m)

S.ResultantpitchYRiseven,beingthearithmeticaldifferenceoftwooddnumbers,i.e.,=

6. Thenumberofslotsfor a2-layerwindingisequaltothenumberbfcoils (i.e. half the

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

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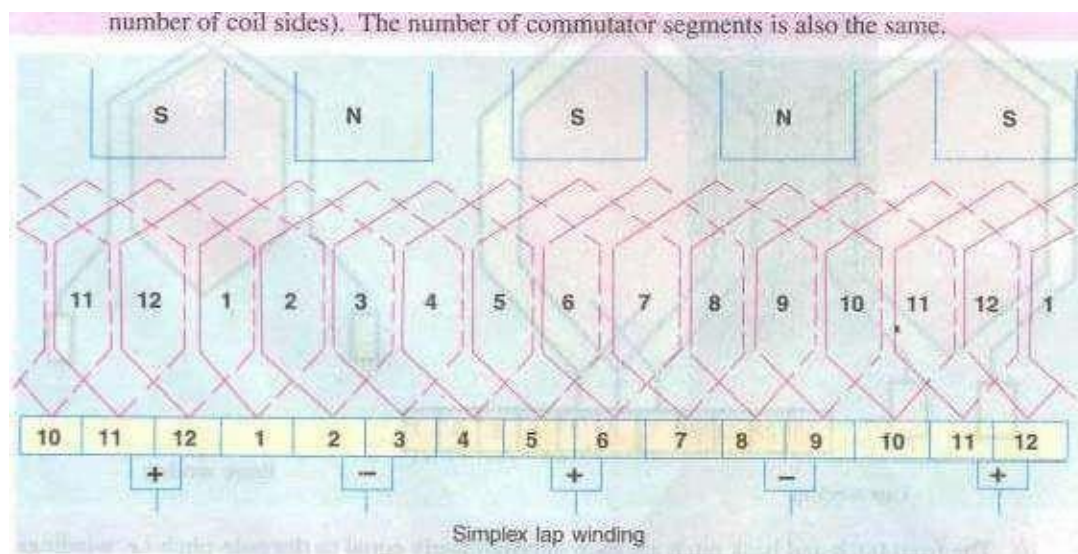
However, where heavy currents are necessary, duplex or triplex lap windings are used. The duplex lap winding is obtained by placing two similar windings on the same armature and connecting the even-numbered commutator bars to one winding and the odd-numbered ones to the second winding. Similarly.

in triples Winding. there would three Windings, cach connected to   thirdofthe commututor bars,

7. Thenumberofpárallelpathsinthearmaturewheremisthe multiplicityofthe winding and P the number of poles.

Takingthefirstcondition.wehaveYo= $Y_F \pm 2$.

(a)IfYB>YF i.e. =YF•2, thenWegeta progressiveorright-handedwindingi.e.awinding whichprogresses inthe clockwise directionas seenfrom the commutator end.othis case, obviously,

$Y_C = + 1.$

(b) If YB < YF i.e. YF —2, then we geta or left-handed winding i.e. one which advancesintheanti-clockwisedirectionWhenseenfromthecommutator side.InthisCase, Yc+ $-1.$

(c)Hence,itisobviousthat

$$Y_F = \frac{Z}{P} - 1$$
$$Y_B = \frac{Z}{P} + 1$$ for progressive SQindingûild

$$Y_F = \frac{Z}{P} + 1$$
$$Y_B = \frac{Z}{P} - 1$$ — +1

forretrogfesgivewinding

Obviously,upmustbeevento makethewindingpossible.

26.27. NumberingOfCoilsandCommutatorSegments

Inthed.c.WindingdiagramstofolloW.weWillnumberthecoilsonly(notindividualturns). 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,theof the seg mentswill bethesameasthatof theuppersideconnected to it.

Example26.1.Drawadevelopeddiagramofasimple2-laýerlap-windingfor"-pole generator With 16 coilÅ. Hence, point out the chamcteristics Of a lap-winding.

(Elect.Engineering,MadrasUniv.1981)

Solution.Thenumberofcommutatorsegments=16

NumberOfconductorsor coilsides16x232:polepitch32/4=8

Nowrememberingthat(i)YBandYF havetobe Oddand(ii)havetodifferby2,Wegetfor a progressive winding YB = 9 ; YF — —7 (retrogressive winding Will result if YR 7 and YF = —9).Obviously,commutatorpitchYc— $-1.$

(Otherwise,asshowninAn.26.26,forprogressivewinding

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

TheSimplewindingtableisgivenasunder.

BeckConnections   FrontConnections

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

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

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Back	Front
21 to (21 + 9) = 30	→ 30 to (20 − 7) = 23
23 to (23 + 9) = 32	→ 32 to (32 − 7) = 25
25 to (25 + 9) = 34 = (34 − 32) = 2	→ 2 to (34 − 7) = 27
27 to (27 + 9) = 36 = (36 − 32) = 4	→ 4 to (36 − 7) = 29
29 to (29 + 9) = 38 = (38 − 32) = 6	→ 6 to (38 − 7) = 31
31 to (31 + 9) = 40 = (40 − 32) = 8	→ 8 to (40 − 7) = 33 = =(33-32)=1

Thewindingendsherebecausewecomebacktothe conductorfromwherewestarted.

We will now discuss the developeddiagram whichis one thatis obtainedby imagining the armaturesurfacetobe removedandthenlaidoutflatsothattheslotsandconductors 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 numberisalso1The backendisjoinedattheback to theI+10th coilsideinthelowerhalf 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 26.32travelling 9coil sides to the rightatthe back and 7 to the left at the

frontwecompletethewinding,thus includingeverycoilsideoncetillwereachthecoilside I from where we started. Incidentally,itshould be noted thatall 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 flowdownwards(as shown),then thesewillnowupwardsinconductorsunder theinfluence 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.
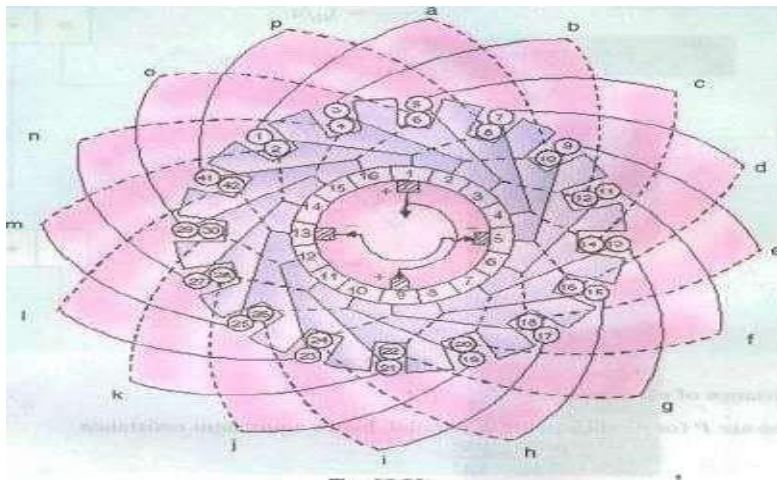

Fig.26.33

Divisionofconductorsintoparallelpathsisshownseparatelyintheschematicdiagramof Fig.

26.34. Obvi0LLsIy,   ifisthetotalcurrentsuppliedbytheEenerator,thencurrent carried by each parallel path is

Summarizingtheseconclusions,wehave

    1.   Thetotalnumberofbrushesisequaltothenumberofpoles.

    2.   Thereareasmanyparallelpathsinthearmatureasthe 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.   Thee.m.f.betweenthe+veand—vebrushesisequa/tothee.m.f-generated in any one of the parallel paths. If Z is the total number of armature conductors

andpthe numberofpoles,thenthe numberofarmatureconductors(connectedin series) in any parallel path is Z"

Resistanceofeachpath—<u>PIZ</u>

ThereareP(orA)such pathsinparallel,henceequivalentresistance

5 Ifisthetotalarmaturecurrent.thencurrentper parallelpath(orcarriedbyeach conductor) is a/P.

26.28. SimplexWaveWinding•

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 underthenextpoleofopposite'polarity(asconductors3and 12).Conductor NO.12isthen connected to conductorNo. 5 underthe original polebutwhichisalittleremovedfrom 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.Asimplexwavewindinghastwopaths.aduplexA',eave Windingfourpaths and a triplex paths etc.
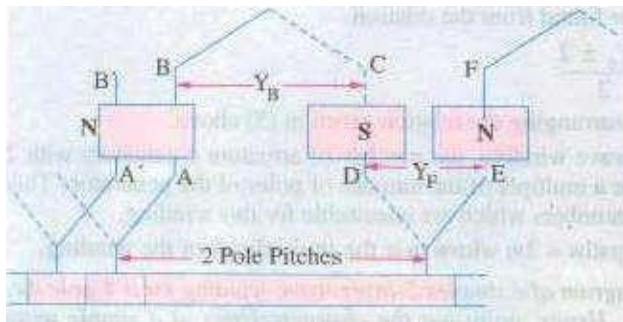
AsshowninFig.26.35.conductorAB Lis connected to CD lying under S- pole and then to EF under the next N•p01e, In this way, the winding, progresses, passing successively under every N-pole and S-pole till it returns to a conductor A 'B' lying under the original pole. Because the winding progresses in one direction

roundthearmatureinseriesof•waves',it isknownaswaveWinding.

Fig.26.35If.afterpassingonceroundthearmature.thewindingfallsinaslottotheleft 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.thengoingonceround thearmature,theWindingendsatWhichmostbeatTheupper

halfoftheslotatthe leftorTight.Countingintermsof conductors,itmeansthatABand A'B' differ by two conductors (although they diner by one slot).

Fromtheabove, following Ofpoles,then orcoilSides

$$Y_B = \text{back pitch}$$
$$Y_F = \text{front pitch}$$ nearly equal to polepitch

wecandeducethe relations.IfP—No. totalNo.Ofconductors

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

Sincep $$Y_A \times P = Z \pm 2 \qquad Y_A = \frac{Z \pm 2}{P}$$ isalwaysevenand alwaysbeeven.Put

...s even and $Z = $ PYR ± 2, hence Z must alw...

inanotherway. Z it

meansthat mustaneveninteger.

Theplussignwillgiveaprogressivewindingandthenegativesignaretrogressivewinding. Points to Note :

1.BothpitchesYBandYFareoddandofthesamesign.

2.Backandfrontpitchesare nearlyequaltothepolepitchandunaybe equalordifferby2, in which case. they are respectively one more or one less than the average40itch. 3.Resultant pitch YR

$$= Y_F + Y_B.$$

4.Commutatorpitch, $Y_C = Y_A$ (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.Theaveragepitch which must be an integer is given by which

Itisclearthat10hean thereisarestrictionon $$Y_A = \frac{Z \pm 2}{P} = \frac{\frac{Z}{2} + 1}{P/2} = \frac{\text{No. of Commutator bars} \pm 1}{\text{No. of pair of poles}}$$ integer. the.alue

ofZWithZ=32.thiswinding i'.impossiblefor4-polcmachine(thoughlapwindingis possible). Valuesor Z = 30 or 34 would be perfectly ah-ight_

i.aNCcanbefoundfromtherelation,PYA±2

Thisrelationhasbeenfoundbyrearrangingtherelationgivenin(5)above.

7. rtisobviousfrom (5)thatfor awavewinding,thenumberofarmatureconductorswith 2 eitheraddedorsubtractedmustbe amultipleofthenumberofpolesofthegenerator.This restriction eliminates many even numbers which are unsuitable for this winding.

S.Thénumberofarmatureparallelpaths=2mwheremisthemultiplicityofthewinding.

Example 26.2. Draw a developeddiagram Ofa simplei *-layer wave-winding for* a 4-pole dc. generatorWith30armatureconductors.Henée,pointOutthecharacteristicsOfa simple wave

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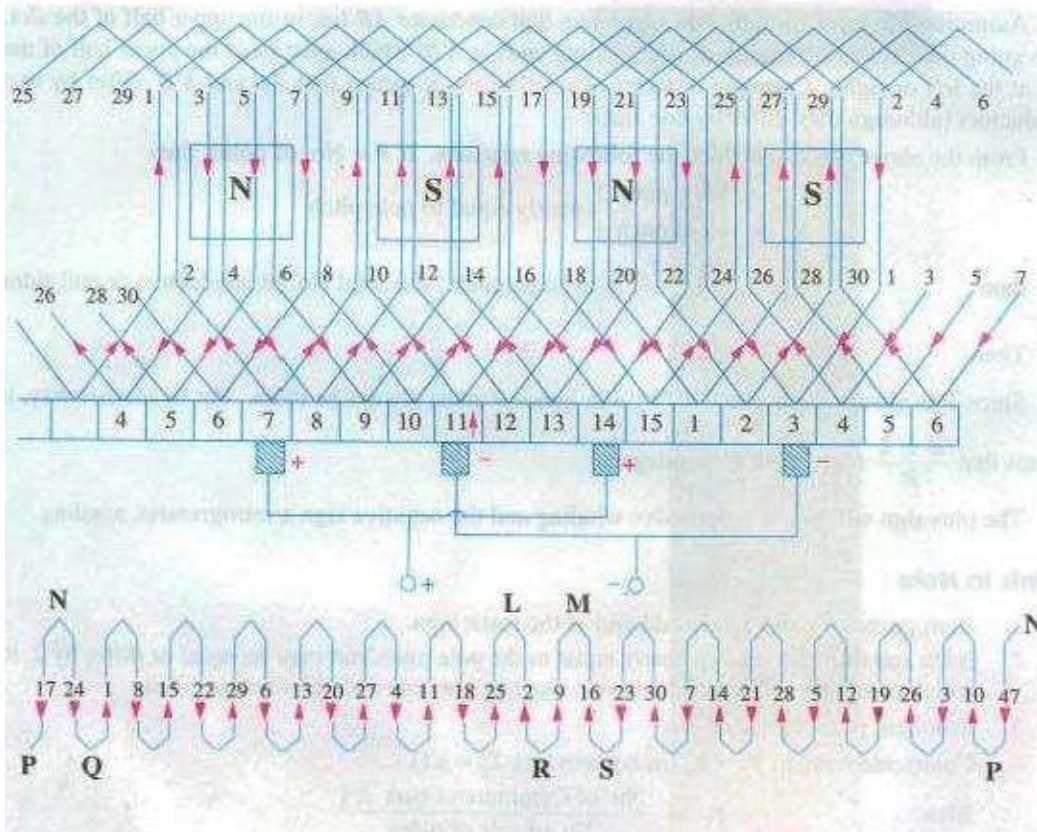

Fig.26.36

Asshowninfig.26.36and26.37,conductor No.5istakentoconductorNo.54 7 12atthe 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.ContinuingthisWay,wecomebackNO.5fromwhereWestarted.Hence.thewinding Closes itself.

IfwetakeS,thenthepitcheswouldbe: Yn9 and YF7orYb=7and YF9.Incidentally,ifYA =Ycistakenas 7,art-nature VillrotateinonedirectionandifYc=8,itWillrotateinthe Opposite direction.

———————————————

Thesimplewindingtableisasunder;

      BackConnections   FrontConnections

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

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

stage.

BrushPosition

Location of brush position in wave-winding is slightly difficult. In Fig. 26.36 conductors are supposed to be moving from left to right over the poles_By applying Fleming's Right-hand rule. the directions of the induced e.m.fs in various armature conductors can be found. The directions shown in the figure have been found in this manner. In the lower part of Fig. 26.36 is shown the equivalent ring or spiral diagram which is very helpful in understanding the formation of various parallel paths in the armature. It is seen that the winding is electrically divided into two portions. One portion consists of conductors lying between points N and L and the other of conductors lying

betweenN 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 the back and not at the commutator end of the armature, the

negativebrushhastwoalternativepositionsi.e,eitheratpointPorQ.Thesepoints on the equivalent diagram correspond to commutator segments NO. 3 and ll.

Now,wewillfindthepositionof thepositivebrush.Itisfoundthattherearetwomeeting 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 fixesthepositionofthepositivebrush.whichshouldbeplacedintouchwithcommutator segment No. 7. We find that for one position Of the brush, there are two alternative positions for the —ve brush.

Takingthe-evebrushatpointRandnegativebrushat pointp,thewindingisseentobe 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 trendofe.m.fs.intheOtherconductor"scomprisingthispath.Similarly,inpath2.thee.m.f. inconductor2 isinpositionto thedirectionOf e.rn.fs.inthepathas awhole.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.
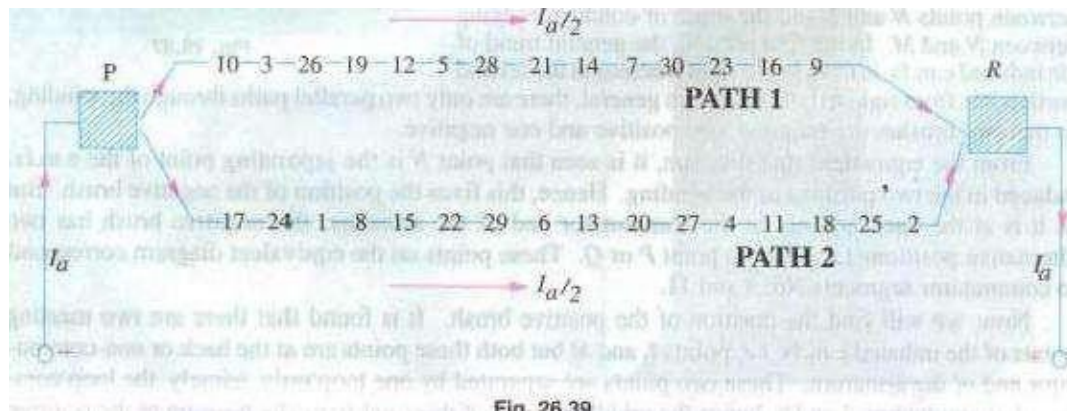

Fig.26Æ

Again, take the case of conductors 2and 9situated between points L and M. Since the armatureconductorsareincontinuousmotion overthepolefaces,theirpositionsasshown 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
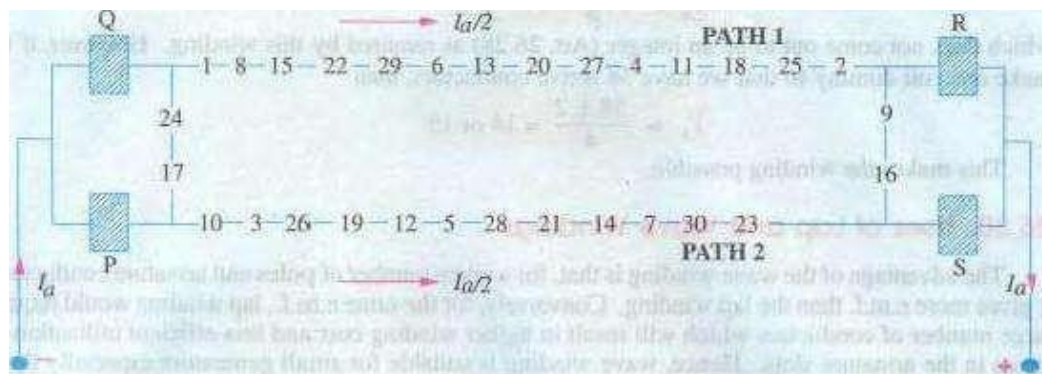
Fig. 26.40

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 thesecondpositivebnlShifused,shouldbein touchwith bothsegments14and15.

Ilmaybenotedthatifbrushesareplaced inboth alternativepositionsforbothpositiveand negative (i.e. if in 4 brushes are used, two -eve and two —ve), then the effect is merely to shortcircuitthe looplying betweenbrushes of the same polarity. This is shown inFig. 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.

Summarizingtheabovefacts,weget

▌Only two brushes are necessary. though their number may beequal tothe number of poles. ▮The number of paths through the armature winding is two irrespective Ofthe number ofgeneratorpoles.Thatigwhythiswindingissometimescalled•two-circuit'or •series'

▮.Thegeneratore.m.f.isequaltothee.m.f.inducedinanyoneofthe twoparallelpaths.•If eavisthee.m.f.induced/conductor,thengeneratore.nl.f.isEx"2.

▮.Theequivalentarmatureresistanceisnearlyone-fourthOfthetotalresistanceOf the armature winding,

5. If is the total armature current, then current carried byeachpathorconductorisobviously1/2whateverthe number of poles.

26.29. DummyorIdleCoils

These are used with wave-winding and are resorted to when therequirementsofthewindingarenotmetby thestandard armature punchings available in armature- winding shops. These dummy coils do not influence the electrical characteristics Of the winding because they are not connectedtothecommutator.Theyareexactlysimilarto 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.supposenumberOfarmatureSlotsis15,eachcontaining4sidesandthenumber of poles is 4. For a simplex wave-windings, Dummy coils

$$\underline{60\pm2}$$

4whichdoesnotcomeouttobeaninteger(Art.26.28)asrequiredbythiswinding. However, if we make one coil dummy so that we have 58 active conductors. then

$$\underline{58\pm2}$$

—14or154

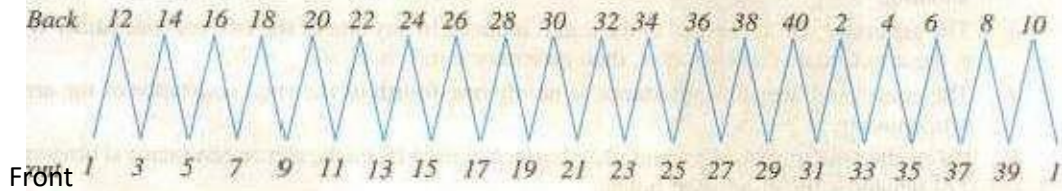Thismakesthewindingpossible.

26.30. UsesOfLapandWaveWindings

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 windingwouldrequirelargenumberOfconductorswhichwillresultinhigherwindingcost andlessefficientutilizationofspaceinthearmatureslots.Hence,wavewindingissuitable for small generators especially those meant for 500-600 V circuits.

Another advantage is that in Wave winding. equalizing connections are not necessary whereasinalapwindingtheydefinitelyare.ItissobecauseeachOf the twopaths contains conductorslyingunderallthepoleswhereasinlap-woundarmatures,each ofthePparallel 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 setup a circulating currentthatproduces sparking at brushes.
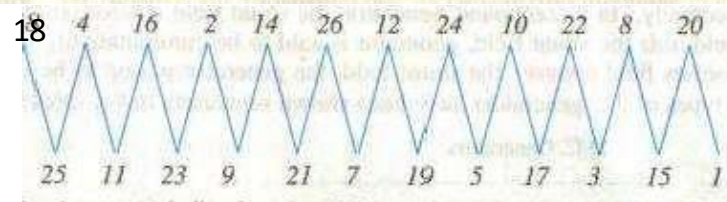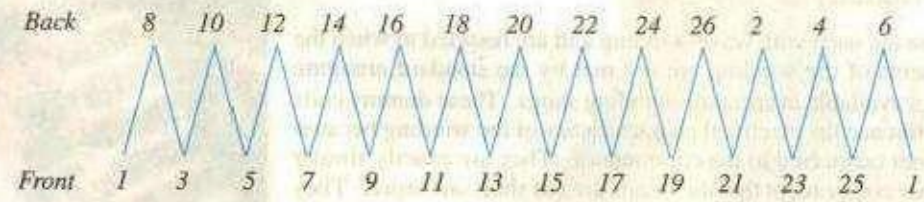
However, when large currents are required, it is necessary to use lap winding, because it gives more parallel paths.

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

(a) 1. Write down the winding

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)

Back 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 2 4 6 8 10

Front 1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39 1

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

Back   8   10   12   14   16   18   20   22   24   26   2   4   6

Front 1   3   5   7   9   11   13   15   17   19   21   23   25   1

18   4   16   2   14   26   12   24   10   22   8   20

25   11   23   9   21   7   19   5   17   3   15   1

simplex wave winding for a 4-pole d.c. machine with 28 conductors ? Explain

Tutorial Problem No. 26.1

2. With a simplex 2-layer Wave winding having 26 conductors and 4-poles. write down the Winding table. What will be the front and back pitches of the winding ?

[Hint : $Y_F = 7$ and $Y_B = 5$]

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

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•p01edc. generator has 5(H) armature conductors, and a useful flux Of O.05 Wb per pole. What Will be the e.m.f. generated if it is lap-connected and runs at 4200 rpm ? What must be the speed at which is to be driven produce the same it is Wave-wound?

[U.P.Technical Univ. 2001)

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

$E = \phi \ (N/60) \ (P/a)$

$= 0.05 \times 500 \times 20 \times 1,$

$= 500$ 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.

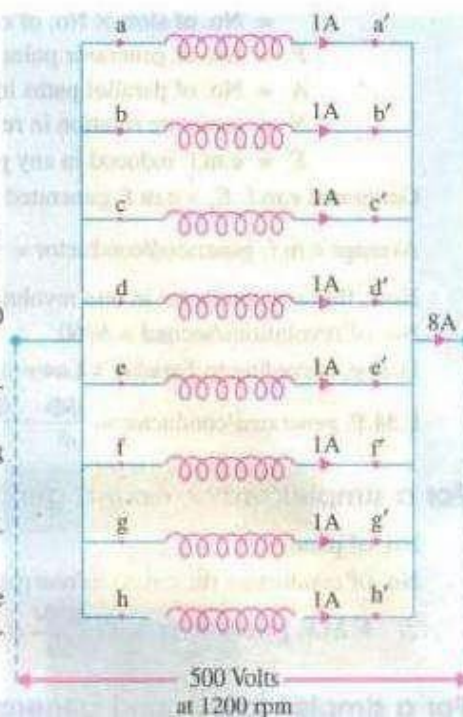Additional Explanation. Assume 1 amp as the current per conductor.

(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 the prime, mover.

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

Solution. The generator is shown in Fig. 26.64.

220/110=2 A

    1-   100A.

=102A

    220v

    Drop in series field winding=102x   =6.12V

-1022xo.05=520.2W

Series field loss—0.06=624.3W Shunt field loss=4k110=440 w

Example 26.28. A long-shunt compound-wound generator gives 240 volts at EL output of 100A. The resislances of various windings of the 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 and friction losses 10101 SOO W. Calculate EL efficiency of the machine.i Electrical Machinery-I, Indot•e Univ. 1989)

    output240x

Total armature circuit resistance= 0.1+0.02+0.0250.145n

    240/100=2ÅA   2.4=102.4A

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

Shunt field copper loss=2.4x240=576W

    Iron loss=   W; Friction loss 500W

24.000

    Total loss=1,521   -087= 87%

24.0001597

DCMOTOR

MotorPrinciple

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 magneticfield.itexperiencesamechanicalforecwhosedirectionisgivenbyFleming'sLeft- 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.
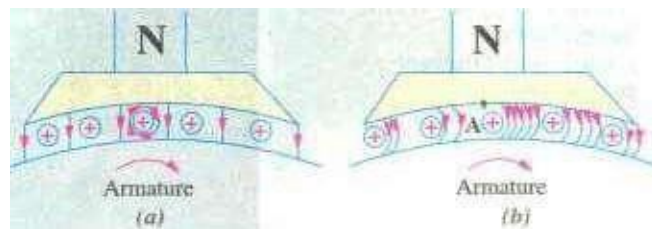
of Motor are supplied with current from the supply mains. they expenencc a force tending to rotate the armature. Armature conductors under At-pole arc assumed carry current downwards(Crosses)andthoseunderS-poles,tocarrycurrentupwards(dots).Byapplying Fleming's Left•harud Rule, the direction of the force on Fig.

eachconductor canfound.Itisshownbysmallarrowsplacedaboveeachconductor.ItWill be seen thåteach conductor can be found. Itwill be seen thateach 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.Byrevetsingcurrentineachconductorasitpassesfromonepoletoanother, ithelps to develqpa continuous and unidirectional torque.

29.2. CornparisonOfGeneratorandMotorAction

As said above, the same d-c. machine can be used. at least theoretical iy, interchangeably as a generator or as a motor.Whenoperatingasagenerator,it is driven by a mechanical machine and it develops voltage which in turn produces acurrentflowinanelectriccircuit.Whenoperatingas amotor.itissuppliedbyelectricFig. 29.2currentanditdevelopstorquewhichinturnproducesmechanicalrotation.

Armature (a)   Armature (b)

Lelusfirstconsideritsoperationas ageneratorandseehowexactlyandthroughwhich agency, mechanical power is converted into electric power.

InFig.29.2panofageneratorwhosearmatureisbeingdrivenclockwisebyitsprimenlover is shown.

Fig,29.2 (a) represents the fields set up independently by the main poles and the armature conductorslikeAinthefigure. TheresultantfieldormagneticlinesonfluxareshowninFig. 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 rubberbandOf a catapult produces a mechanical force on the stone piece. ItWill he seenthatthis forceisinadirectionopposite to that Ofarmaturerotation.Hence,itisknownasbackward force or magnetic drag on the conductors. It is against this drag action on all armat•uœconductorthattheprimemoverhastowork.TheWOEkdonein overcomingthis oppositionisconvertedintoelectricenergy. Therefore. itshouldbeclearlyunderstoodthal it is only through the instrumentality of this magnetic drag that energy conversion is possible in a d.c.

generator.

Next,supposethalthe aboved.c.machineisun•coupledfromitsprimemoverandthat

current is sent through the armature conductols under a N.polc in the downward direction as shown in Fig. 29.3 The conduclorswillagainexperiencea forec in the anticlockwise direction ('Fleming's Left hand RAIle)_
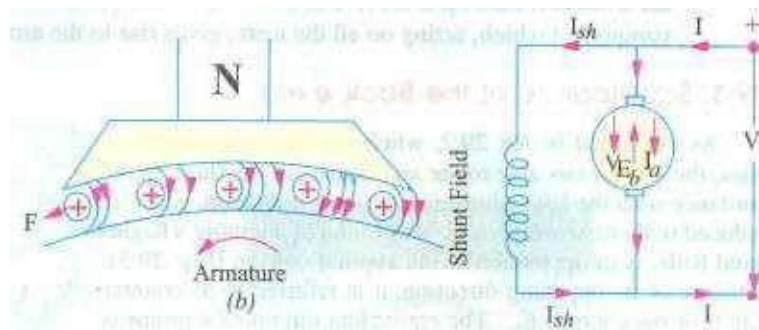
Hence.themachineWill

N

Shunt Field

I_{sh} I +

$VE_b I_a$

V

I_{sh} I

F   Armature
(b)

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

Startrolatinganticiockwise.therebydevelopingÆitorquewhichcanproducemechanical 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 whatis theequivalentofthatdragin thecase Ofamotor? Well,i'i'thehacke.rn,f.Itisexplained in this manner.

Assoonasthearmaturestartsrotating.dynamically(ormotionally)inducede.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 counterItsvalueistheSameasthe motionally induced e.mf in the
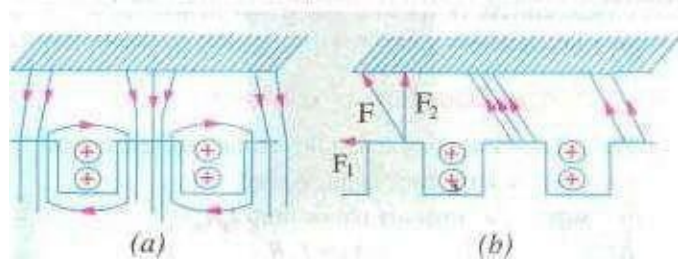
generator i.e. 14, ('ÞZ'V'x (P/A) volts. The applied voltage Vhas to be forcecurrent through thearmature-conductors againstthisbacke_m.f.Eh.Theelectricworkdoneinovercoming this opposition is convened into mechanical energy developed in the armature. Therefore.it is obvious that bulfor the pro. auction 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 slottedarmature.thetorque isnotdue tomechanicalforceontheconductorsthemselves, but due to tangential pull on the armature teeth as shown in Fig. 29.4.

It is seen fig. 29.4 thatthe main flux is concentrated in the form of tufts at the armature teethwhilethearmatureisshownbythedotted linesembracingthearmatureslots.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. Hutforthe presence ofthisopposition,therewouldsimplyt-,cnoenergyconversion.Jngenerators.opposition is provided by magnetic drag whereasin 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.

-armaturefluxonthemainflux,asshowninFig.29.4   istwo-fold,

Itincreasesthefluxon theleft-handsideof theteeth anddecreasesiton theright-hand side, thus making the distribution Of flux density across the tooth section unequal.

(ii)itinclinesthedirectionOflinesOfforce in theair-gapsothatthey arenotradial but are disposedinamannershowninFig.29.4Thepullexertedbythepoleson theteeth 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 comIN)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. SignificanceoftheBacke.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.isinducedinthemwhosedirection,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,VhastodrivelaagainsttheoppositionFig,29.5of Eh.The powerrequired to overcome thig opposition is Eh/n.
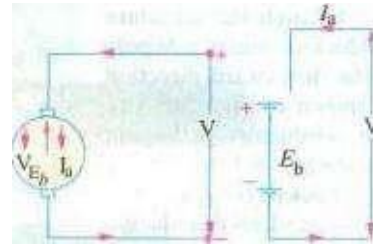
Inthecaseofa cell.(hispoweroveraninter,'aloftimeisconvertedinto chemicalenergy, but in the present case, it is converted into mechanical energy.

Itwill beseenthatI   Netvolta½ $\frac{V - V_b}{}$

n'

Resistance   Ra

RistheresistanceOf thearmature circuit.Aspointed outabove,Eh=CÞZV(P/A)volt where N is in r.p.s.

Backe_m.f_depends,amongotherfaclors.uponthearmatuœspeed.Ifspeedishigh.Ebis 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 likeagovernori.e,,itmakesamotorself-regulating so that it draws as much as is just necessary.
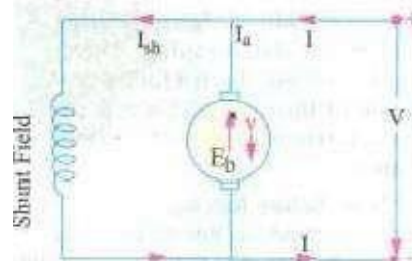
29.4. VoltageEquationOfaMotor

ThevoltageVappliedacrossthemotorarmaturehas to overcome the back e.m.f. Ebund in supply the armature ohmic drop

Thisisknownasvoltageequationofamotor.Now,multiplyingbothsidesby,Weget As

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

V   =Eectricalinputtothearmature

Eh/o=ElectricalequivalentOfmechanicalpowerdevelopedinthearmatureI:R,=Culoss in the armature

Hence.outOf thearunatureinput,someiswastedin I^2R lossandtherestis convertedinto me—chanical power within the armature.

ltmayalsobenotedthatmotorefficiencyisgivenbytheratioofpowerdevelopedbythe arma-turetoits inputi.e.EBIJVla=E*/V.Obviously.higherthevalueofEbcomparedtoV.higher the motor efficiency.

29.5. ConditionforMaximumPower

Thegrossmechanicalpowerdevelopedhyamotorispm=la—I:Ra.

Differentiatingbothsideswithtolaandequatingthe resultto zero.wegetv—2/aRa-OAs and

Thusgrossmechanicalpowerdevelopedbyamotoris maximumWhenbacke.tn_f.isequal 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-

Example29.1.A220-Vdc.machinehasanarmatureresistanceOfOS thefull-load

armature ture current is 20 A, find the induced e.m.f. when the machine acts as (i) generator (ii) motor is20A,find actsas

(Electrical Technology-1, Bombay Univ. 1987)
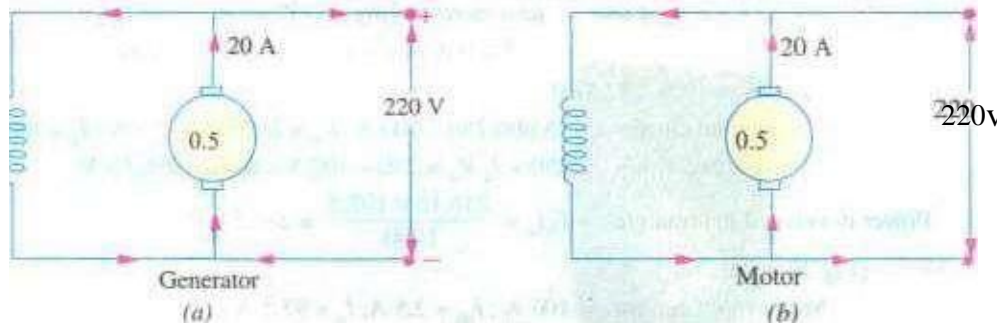

Fig.29.7

Solution.AsshowninFig.29.7,themachineisassumedtobeshunt•connected.Ineach ease,shuntcurrentisconsiderednegligiblebecauseitsvalueisnotgiven.

AsGenerator[Fig. V

Example 29.2. A separately excited D, C. generaror has armature circuit resistance OfO. I Ohmandthe brush-dropis2 V.Whenrunningat1000 r.p.m.,itdeliversaof100Aat250V 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 =262X700/1000=183.4VIfisthenewcurrent. —2— =2.5

•Thisgives 96.77amp.

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

Solution.

Forlo-IOOamp.andE 183.4v,RL-1.714ohms.

Example 29.3. A shuntmotorhasarmatureresistanceOf 0.8nandfield resistance Of

200 Determinethebacke.m.f.Whengivinganoutputof7.46kWat85pert-ent efficiency,

Solution.Motorinput $7.46x10^3/0.85W$

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

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

∴ E_b = 440 − (17.75 × 0.8) = **425.8 V**
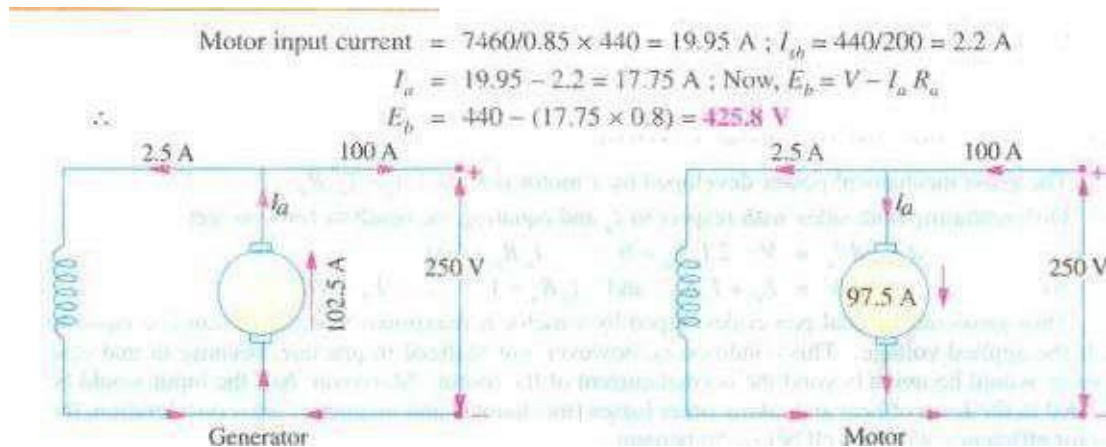

Fig.29.8(a)   Fig.29.8(b)

Example29.4.A25-kW.dc.shuntgeneratorhas *rmature and* fieldresistancesof0.06Qand 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,PunjabUniv„June1991

Solution.AsGenerator(Fig.29.8(a)/

outputcurrent=25 ,000/250 =100A I_{sh} = 250/100 = 2.5 A ; I_a = 102.5A

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

256.15x102.5

Powerdevelopedinarmature

As Motor (Fig

Motorinputcurrent

244.15v

Powerinarmature= kW

Example shunt generator With terminal voltage of 200 volts delivering 12 amps the load200ohms.isdrivenat1000Calculatethefluxperpole inthemachine.Ifthemachinehasto be run as 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.CurrentdistributionsduringtwoactionsareindicatedinFig.29.9(a)andAsa

generator,13 amp

12amp5amp

Supply

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

Fig.2"

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

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

ForaLap-wound $P = a$ armature,

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

Asamotor, $I_a = 4$ amp

Giving N $E_b = 200-4\times2—192V$
$= \phi ZN/60$

0.4237532 $N = \dfrac{60 \times 192}{0.42375 \times 32}$

=850 r.p,m.

l. What do you understand by the term 'back c,rn.f.• Ad.e_ supplyhasanarmatureresistance of O. IS Q, Calculate

      (a)TheOfhacke,m.f.whenthearmaturecurrentis120A.

      ThevalueofarmaturecurrentwhenthehackＩis4414V.

2.   Ad.c.motorconnectedto460-VsupplyutkesanarmaturcCurrentOf120Aon full load. If the circuit has a of 0.25 Q, calculate the value of the back c.m.f. at

3.   thisload.|•130VIA4•poled:c_motortakesanarmaturecurrentOf150Aat
resislance 440V.Ifitsarmaturecircuithasaof O.ISQ.whatwillthevalueOfbackc.rn.f,at thisload?1417.5VI

29.6. Torque

Bythetermtorque ismeanttheturningortwistingmomentofaforceaboutanaxis.Itis 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 acircumfcrentialforceofFNewtonwhichCausesi' to rotate at N r.p.rn. (Fig. 29.10).
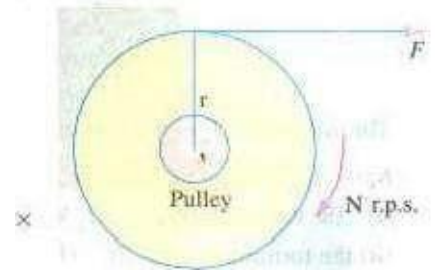
    Then torque   =ExrNewton-metre(N-m)

Work done by this force in one revolution

=Forcedistance= Fx2rtrJoulePowerdeveloped=F x 2 rtrx N Joulusecond or Watt

Now2lt.'VAngularvelocityinradian/secondandF

—Torquer

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

Moreover, m = 2 wV/60 rad's

2It,'V

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

29.7. ArmatureTorqueOfaMotor

LetTabethetorquedevelopedbythearmatureofa motorrunningatNr.p.s•IfisinMM, thenpowerdevelopedTuxNwatt

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

29.4) — $E_b I_a$ Watt

In the case of a series motor,

Windings carry full armature Current

(b) For shunt motors, Φ is practically constant, hence $T_a \propto I_a$

As seen from (iii) above

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

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

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

29.8. Shaft Torque

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

The torque Which is available for doing useful work is known as Shaft torque It is so called because it is available at the shaft_ The motor output is given by Output x 2πN Watt provided Tsh is in N-m and N in r.p,s.

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

The difference
and is due to
motor.
$$= \frac{\text{Output in watts}}{2\pi N / 60} \text{ N-m } - N \text{ in r.p.m.}$$
$$= \frac{60}{2\pi} \frac{\text{output}}{N} = 9.55 \frac{\text{Output}}{N} \text{ N-m.}$$

(Ta—T,h) is known as lost torque iron and friction losses of the

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

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

Example 29.6. A dc. motor takes an armature current Of at 480V! The armature circuit resistance is 0.2Ω 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.SecB.1989)

Solution. Eh 480—110 xo.2—458V,

0.05x864xN6

60

        N   636c p.m.

T.=0.159xo.05

Example 29.7. A 25CL •a-pole, wave-wound Series motor has 782 conductors on its armature.IfhasarmatureandseriesfieldresisianceOf0.75Ohm.Themotor takesa currvnt A.Estimateitsspeedandgmsstorquedevelopedifithasaperpoleof25mWb.

(Elect.Engg.•ll,poneUniv.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. *its* 1993) Solution. A given d_c. machine develops the Same e.m.f. in its armature conductors whetherrunningasageneratororusa motor,Onlydifferenceis thatthisarmaturee.m.f.is known as back

e.m.f.Whenthemachineisrunningasamotor.

Mechanicalpowerdevelopedinthearm   50=12.500W

T.—9.55   9.55x250   79.0N-m.

Example29.9.Determinedevelopedandshafttorque   of220-V,4-poleseriesmotorwith800 conductors Wove-connectedsupplying load0/82kW by taking45Afrom the mains. Theflltv per pole is 25 m Wh and its armature circuit resistance is 0.6 Q.

(Elect.MachineAMIEsec.BWinter1991)

.N2/500=200/210

Example29.11.-500-V.37.3kW.1000 r.p.m.d,c.shuntmotorhas *n full-load* anefficiencyOJ 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.   MotorinputW $= 37,300/0.9 = 41,444$
$= 41,444/500 = $ **82.9** A

F.l.linecurrent=41.444/S(.WJ

 =356N-m

IfRistheStarterresistance(whichisinserieswitharmature),then

Example29.12.A"-pole.220-Vshuntmotor has540lap-woundconductor.rakes32Afrom 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.   =31AV

1020

,ÞZNP

Now.   217.2=

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

T.9.55x<u>outputinwatts</u>=9.55x<u>595</u>=66.5N-m

804.4

Example29.13Findtheleadandfull-loadspeedsforafour-pole,220-V.and20-kW.shunt motor having thefollowing data :

Field—current=5amp,armatureresistance=   Ohm.

Fluxperpole0.04Wb.numberofarmature-conductors =160,livo-citèuitwave-connection, full load current = 95 amp. No load current 29 A. Neglect armature reaction.

(BharathitbasanUniv.April1997)

Solution.ThemachinedrawsasupplycurrentOf9ampatnoload.OutOf this,5ampsare 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.resultingintodecreaseinspeedunderloadcomparedtothatatNo-Load. : E., = — 4 x 0.04 = volts

Substitutingthis.

004x160x

No-Loadspeed.No—1030.5r.p.m.

ArmaturecurrentA,Ea —90x0.04216.4V(216.4/219.84)x1030.5=1014.4rpm.

F•ample 29. i 3Armature Ofa 6-pole. 6-circuit D.C. shunt motor takes   AataspeedOf350 r.p.m_ Theflux per pole is 80 milli-webers. the number Ofarmature rums is 600. and   ofthetorque islostinwindage.frictionandiron-loss.Calculatethebrake-horse- power.

(ManonmaniamSundaranarUniv.NOV.1998)

Solution. Number of armature turns = 600

Therefore,Z=NumberOfarmatureconductors=1200IfelectromagnetictorquedevelopedisTNw — m.

Armature'X'Wer   T   Tx2'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=560x $100/36.67$ —6108-5 Nw—m, Since 3% of this torque is required for overcoming different loss-terms,

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

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

Net output in kW=592536.6710-3—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 of pole-flux and the armature current is 50 Amps. (Bharathiar Univ. April 1998)

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

T=0.1590 $ZL_{,,}$ p/a Nw-m Two paths in parallel for a 4-pole case means a wave winding.

T 0.159X(24x774x50x4/2

=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 Of 40 Amps.

g Bharathiar Univ. April 1998)

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

Input Power=x5=2500 watts field copper-loss=500x2.5=1250 watts

Neglecting armature copper-loss at no load (since it comes out to be 2.5^2 x0.15 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 40A 10 load:

Output delivered 500x40x $10^{-3} = 20 \text{ kW}$

Losses: Fieldcopper-loss=1250watts

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

(c)NO load losses = 1250 watts

Totallosses   kW

GeneratorEfficiency(20/22.771)x100%=87.83%

Extensionto theQuestion: AtBiharspeedshouldthe Generatorbérun,iftheshunt-fieldis not changed, in the above case ? Assume that the motor was running 600 r,p.m, Neglect armature'

Solution.Asamotoronno-load.

$$E_{b0} = 500 - I_a r_a = 500 - 0.15 \times 2.5 = 499.625 \text{ V}$$
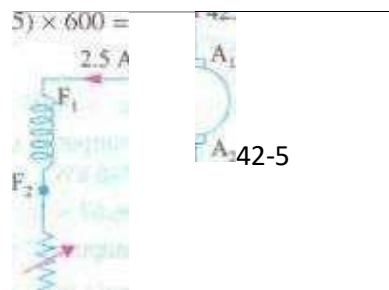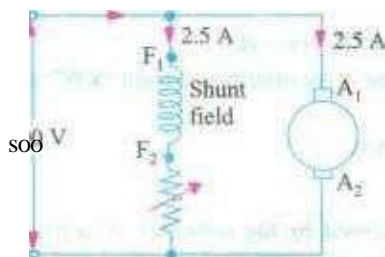
AsaGeneratorWithanarmatureculTentOf42.5A.

$$E_{b0} = -500 + 42.5 \times o.15 - 506.375V$$

Since,the terminalvoltageissameinboththecases.shuntfieldcurrentremainsas2.5 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)608.1r.p.m. 23

A   40 A

5) × 600 =

2.5 A

A_42-5

(a) Motor at no load   (b)Generatorloaded

Fig. 29.11

Note.Alternativetothisslightincreaseinthespeedistoincreasefieldcurrentwiththe help of decreasing the rheostatic resistance in the field-circuit.

Example 29.13 A dc. series motor takes 40 A at 220 V and runs at 800 r.p.m - If the armature and field res/stance are 0.2Q and O. I Q respectively and the iron and friction are O.SW find the torque developed in the armature. What Will be the output Of the motor ?

Solution. Armature torque is given by $T_a = 9.55 \dfrac{E_b I_a}{N}$ N-m is given by
Ta=9.55

$E_b = V - I_a (R_a + R_{se}) = 220 - 40 (0.2 + 0.1) = 208$ V

$T_a = 9.55 \times 208 \times 40/800 = $ **99.3 N-m**

Cut oss in armature and series-field resistance = $40^2 \times 0.3 = 480$ W

resistance=$40^2$0.3

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

power input = 220 40 = 8.800 W

        Motor output 8.800-   7.820W=7.82 **kW**

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 if its efficiency is 80Whal size is the motor pulley if the lathe pulley has a diameter of 24 cm .

(Elect. Technology-II, 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 = IW

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

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
10 cm speed and diameter of the lathe pulley.

        N,xD,or

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

The field resistance is 0.3Q; 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'

800

Solution. Total input

Now   Iron+

Friction losses

Output

$= 9 \times 55 \times \dfrac{6580}{488} = 128.8$ N-m

$E_b = V - I_a R_a = 200 - 45(0.5 + 0.3) = 164$ V

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

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

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

Losses $= 800$ W ; Total losses $= 1,620 + 800 = 2,420$ W

Output $= 9,000 - 2,420 = 6,580$ W

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

$\quad$ F x O.205 = 128.8 $\qquad$ 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. $\qquad E_b = V - I_a R_a - \text{brush drop} = 240 - (50 \times 0.1) - 2 = 233$ V

Also $\qquad I_a = 50$ A

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

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

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

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

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

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

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

$\therefore \quad$ Rotational losses $= 11,650 - 11,190 = 460$ W

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

$\therefore \qquad$ Efficiency $= \dfrac{11,190}{12240} \times 100 = 91.4$ %

Example 29.17. A 460-V series motor runs at 500 rpm. taking a current of 40 A. Calculate the speed and percentage change in torque if load is reduced so the is taking 30 A. Total resistance Of the armature and field circuits is 0.8 Assume, i71Lx is proportional to the field current.

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

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

$\therefore \quad T_1 \propto 40^2$ and $T_2 \propto 30^2$ $\quad \therefore \quad \dfrac{T_2}{T} = \dfrac{9}{16}$ T,

Example 29.18. A 460-1'.'55.95 750 r.p.m. shunt motor drives a load having a moment of inertia Of 252.8 kg-m². Find approximate time to attain full speed When starting from against full-load torque if starting current varies between 1.4 and .8 times full-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 inertia 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 of 40 A when running at full-load. The moment of inertia of the rotating system is 7.5 kg-m². If the starring current is .2 rimes full-load current. calculate (a) full•load torque fbj the time required for 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.2 x 356-71.2 N.m

NOW, torque ⌐ dt 4.41 second

29.9. Speed Of a D.C. Motor

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

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

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

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

Itshowsthatspeedisdirectlyproportionalto back can-f.Ebandinversely10 to the flux Φ

Now

$N \propto E_b/\Phi$, on

ForSeriesMotor

Let N_1 = Speedin Φ_1 the1stcase:la,armaturecurrentinthe1stcase=

tluxlpole in the first I_{a2}, Φ_2 cwse

=correspondingquantitiesinthe2ndcase.

Then. using the above relation, we get

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

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

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

ForShuntMotor

Inthiscasethesameequationapplies.

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

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

29.10. SpeedRegulation

Thetermspeedregulationreferstothe changeinspeedOfamotorWith changeinapplied 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 isreducedfrom ruled value ro zero, expressed a.s percent Of the rated load speed.

%speedregulation $=$ NLspeed—FLspeedx

F.Lsrwed

29.11. TorqueandSpeedofaD.C.Motor

Itwillbeprovedthatthoughtorqueofa motorisadmittedlyafunction offluxandarmature 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

..Art27.7

Itisseenfromabovethatincreaseinwoulddecreasethespeedbutincreasethe armature torque. It cannot be so because torque aluays tends to produce rotation. If torque increases,motorspeedmustincreu•eratherthandecrease.Theapparentinconsistency betweentheabovetwoequationscanbe reconciledinthefollowingWay:

Supposethatthefluxof amotorisdecreasedbydecreasingthefieldcurrent,Then, following sequence of events take place

l.Backe.m_f_Eb,VCÞ/K)dropsinstantly(thespeedremainsconstantbecause ofinertiaof the heavy armature).

2.Dueto decreaseinEh,isincreasedbecausel.=(V—Moreover.asmallreductioninflux produces a proportionately large increase in armature current.

3.Hence,theequation Taasmalldecreaseinismorethancounterbalanced byalarge increase in with the result that there is a net increase in To.

4•Thisincreaseinraproducesanincreaseinmotorspeed.

It is seen from above that with the applied voltage V held constant, motor speed varies inverselyastheflux.However,itispossibletoincreaseand,attime,increxsethespeed provided $I_a$is held constant as is actually done in a d.c. servomotor.

Example29.20.A4-poleseriesmotorhas944wave-connectedarmatureconductors.Ata 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.   SeeAPart11June1991

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

209—0.159 x34.6*10-3*944x1,(4/2);la=20.1A

asgiveninArt.

10-3x944xNx2

Example29.21.A25thV' shuntmotorruns at1000r.p.m.atno-loadandtakes84. Thetotal armature and shuntfield resistances are respectively 0.2£2 and 250 Q. Calculate the speed when loaded and raking 50 A. Assume the

—240.2V

2402

1000   248.6

Example29.22.Adc.seriesmotoroperates at800r.p.m.withalinecurrentof100 Afrom Example

29.23. A 230- Vd.c. shunt motorhas an armature resistance OfO_5 Q andfieldresistanceOf115QAtnoload.thespeedis1.200r.p,m.andthe armature current 2.5 A On application Of rated load. the speed drops to J, 120 r.p.m. Determinerhelinecurrentandpowerinputwhenrhe motordeliversratedload.(Elect. 'Iëchnoloxy, Kerala Univ. 1988b

1986]

Solulion.

LinecurrentdrawnbymotorPowerinputatratedload

Esample 29.24. A belt-driven shunt generator running 300 r.p.m. on 220- V *bus* bars continuesto runasa motorWhen thebelfbreaks,thentakingkW.WhatWillbeitsspeed? Given armature resistance = 0.025 resistance = 60 and contact drop under each brush =

I V. Ignore armature reaction.   (Elect.Machines(E-3)AMIEsec-cWinter1991)
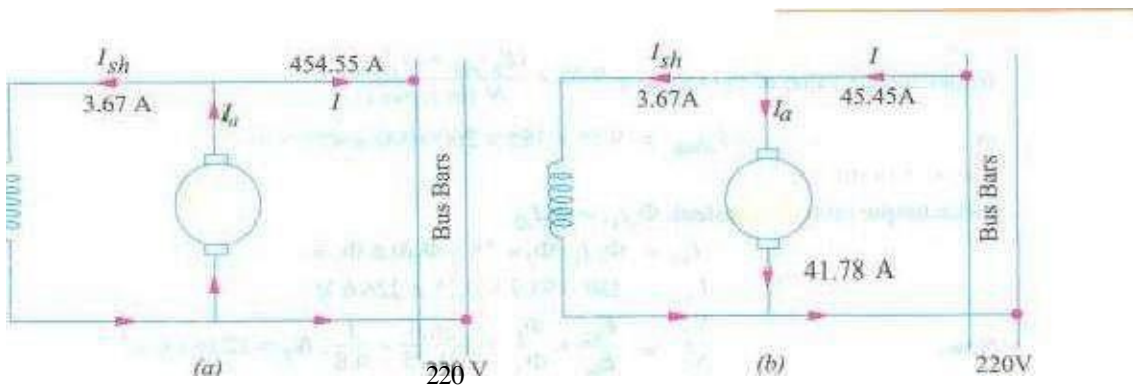
Solution. As Generator [Fig. 29.12 Load current.

Fig.29.12

AsMotor[Fig.29.12 (b)]

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

A

8 A; $I_a R_a = 41.78 \times 0.025 = 1.04$ V; E_{b2}

—45.45—3.67 $\dfrac{N_2}{N_1} = \dfrac{E_{b2}}{E_{b1}} \times \dfrac{\Phi_1}{\Phi_2}$; since $\Phi_1 = \Phi_2$ —41.78A;   -220—

1.04-2XI—216.96V $\dfrac{N_2}{200} = \dfrac{216.96}{233.45}$; $N_2 = 279$ r.p.m.

because   isconstant

300

Example 29.25. A dc. shunt machine generates 250, V on open circuital 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 speed of machine 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—　　　　Em250-0.5x 32485V

It is given that When armature runs at 1000 it generates 250V. When it generates V, it must be running at a speed = 1000 x 248.5/250 = 994 rpm.

ze,　　　　　　　　NO = 994 r.p.m_　　　　　　　　Hence,

When in Loaded　　　　　　　　　　　　　　　　　994

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

N=960 r.p.m.

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

Example 29.26.

A 250-V shunt motor giving /'1-92kW 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.
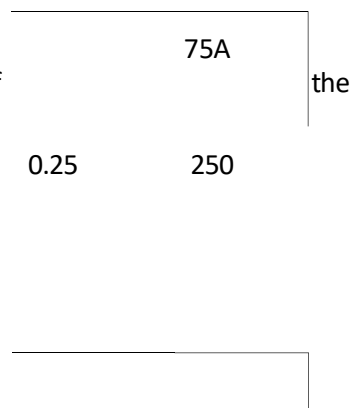
œleet.Engg.AMIETE'NewScheme) 1990 solution. Eh,- $250 - 75 \times 0.25 = 231.25 V$, as in Fig.29.13.

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

Instantaneous value of back e.m.f. —231.250.8=185v

=260A

Fig.29.13

75A

0.25　　　250

the

1030

Instantaneousvalueof the torque =

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

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

SteadyConditiorrs

Sincetorqueremains constant,

$$\text{nstant}, \Phi_1 I_{a1} = \Phi_2 I_{a2}$$
$$I_{a2} = \Phi_1 I_{a1}/\Phi_2 = 75 \times \Phi_1/0.8 \ \Phi_1 = 93.7 \text{ A}$$
$$E_{b2} = 250 - 93.7 \times 0.25 = 226.6 \text{ V}$$
$$\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{\Phi_1}{\Phi_2} = \frac{226.6}{231.25} \times \frac{1}{0.8} ; \ N_2 =$$

Now. 1225 r.p.m.

Example29.27.A220-V, dc. shunt field resistance is 100 armatureterminalswhen10AwerepassedthmughtorqueinAt-mand(c)efficiency.The normal input Of the motor is 8 k W.

V, d.c. shunt motor takes 4 A at no-load when runningat700r.p.m. The The resistance of armature at standstill gives adropof6voltsacross I A were passed through it. Calculate (a)speedonload

(Electrotechnies-n;MS.Univ.Baroda1988j

Solution. 200/100=2 A

EL.Powerinput

-40-2-38A;Ra=6/lO-O.6Ç2

— 198.8V; 1772V

;N—623.9r.p.m.

700 198.8

T.9.559.55x1772x 38/623.9=103N-m

N.L.powerinput=200 x4-800W; x06—2.4W

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

Total EL. losses 797.6 866.4 = 1664 W: output=83M)-16646336WELMotorefficiency= 0.792 or 79.2 %

Example 29.28. The input 23m V, dc. shunt motor is //kW. Calculate(a) the torque developed(h)theefficiency(e)thespeedatthisload. Theparticularsthemolorareas follows :

No-loadcurrent=SA;No-loadspeed=r.p.m.

Arm.resistance= £2;shuntfieldresistance=110£2.

Solution. No—load input — No-loadarmatureCuloss

ConstantlossesWheninputisIIkW.

Inputcurrent Arm.Culoss

Total loss

Output

Efficiency

(c) Backe.rn.f.atno-load
Backe.rn.f.atgivenload

SpeedN

Elect. Technology ;
BombayUniversity1988'-
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;
   Armaturecurrent=2=
   A

=482x05.-—1,152w;

=Arm.Culoss+Constant
losses=1152+1095.5=
2248W

=11.000-2,248—s,752w 8,752x

220-13x0.5)218.5V

=196v

     196/218.5=
     r.p.m.

196x48

-87.1N.m

Example 29.29. The armature circuit resistance a 18.65 kW 250- V series motor is O. / the brushvoltagedropis3V,and theseriesfieldresistanceis0.05.Whenthemotor takes 80 A, speed is

600r.p.m.Calculatethespeedwhenrhecurrentis $100\,A$ (Elect.

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

Solution.

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

Since   80/100

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

474 r.p.m.

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

Example A 220-volt d. c. series motor is running at a speed of 800 p.p.m. and draws 100 A_ Calculateatwhatspeedrhemotor "'illrunwhendevelopinghalfthetorq"e.Totalmsistance

Of the armature andfieldis0.1Ohm. Assume that the magnetic circuit is unsaturated.

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

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

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

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

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

Solution.

Since field is unsaturated,

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

29.12. MotorCharacteristics

ThecharacteristicCurvesOfamotorare thosecurveswhichshowrelationshipsbetweenthe following quantities.

    l.   andarmatureCurrent   characteristic.Itis *nown as electrical* Characteristic

    2.   Speedandarmaturecurrenti.e.M/acharacteristic.

    3.   Speed and torque i.e.   characteristic.Itisalsoknownasmechanicalchargcteristic.It can be found from (I) and (2) above.

Whilediscussing•notorcharacteristics,thetòllowingtworelationsshouldalwaysbekeptin mind:

$T_a \propto \Phi I_a$andN $\propto$ —

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 Ia 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 Ia 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.
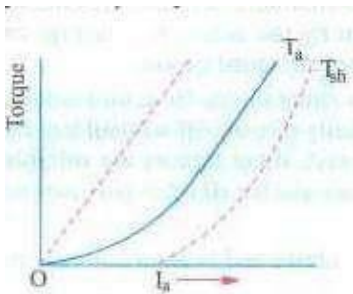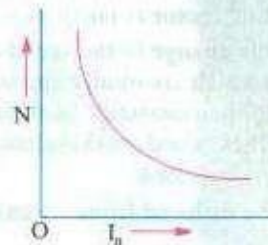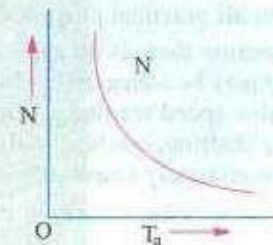

Fig,29.14   Fig.29.15   fig.29.16

2.   MI.Characteristics.VariationsofSIEedcanbededucedfromthefGrrnula:

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

Change in Eh, for various load currents is small and hence may be neglected for the time being. With increased Ia, 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

1. Characteristic

Assuming CΦ 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' I ssumcd constant, then N E,_As E his also practically Constant. speed is, for most purposes. constant (Fig. 29.18).

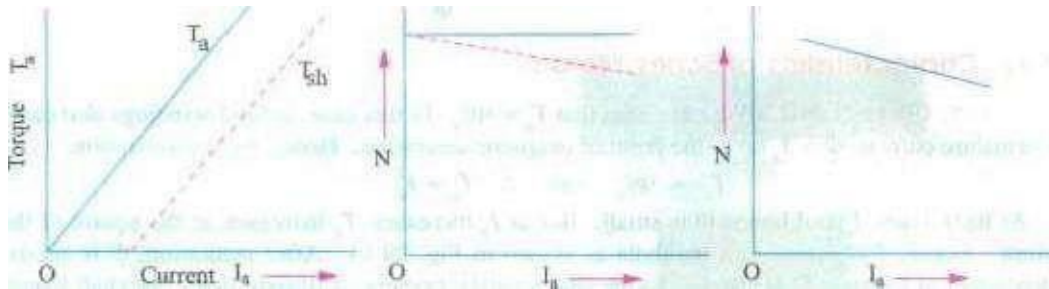
Fig.29.17   Fig.29.18   Fig.29.19

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 functioning as load equalizer), it is employed where there Fig. 29.20 are sudden temporary loads as in rolling mills. The fly-wheel supplies its stored kinetic energy when motor slows down due to sudden heavy load. And when due to the removal Of load motor speeds up, it gathers up its kinetic energy.

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

'b) Differential—compound Motors

Since series field opposes the shunt field; the flux is decreased as load is applied to the motor. This results in the motor speed remaining almost constant Or even increasing With increase in load (because, N 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.
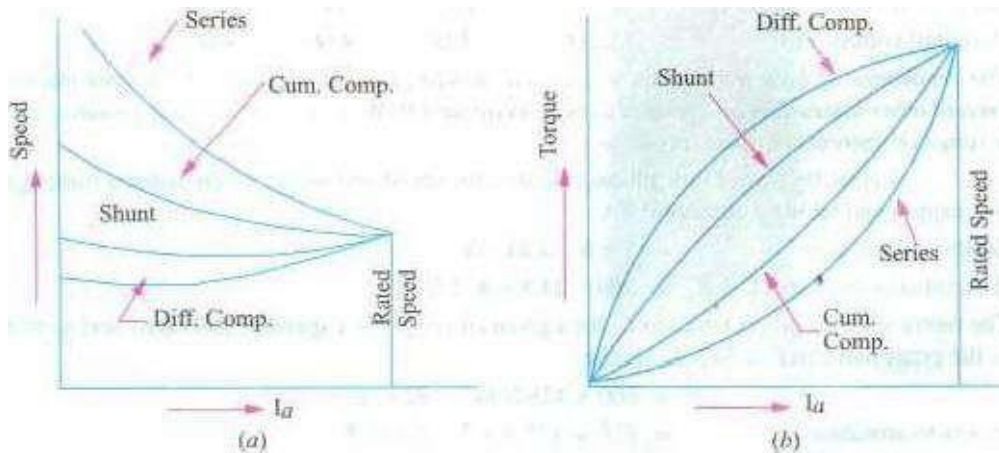
Fig.29Æi

Example29—32. The following results were obtained fmm a static torque a series *motor :*

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 Of 460 V. Resistance and field winding is 0.5Q. Ignore imn and friction losses.

Solution. Taking the case When input current is 20

A, we have

Motor input = 460x20 = 9.200W Field

and armature Cu loss

= 202xos = 200w

Ignoring iron and friction losses.

output = $9,200 - 200 = 9,000$ w

Now.   Tahx21t,V = Output in watts.

$128.8 \times 2\pi \times N$ = 9,000 0 100 200 300 400 sooN-9,000/21tx128.8 Torque(NW.m)

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

Similar calculations for Other values Of current are Fig.29.22 tabulated below:

Current (A)	20	30	40	50
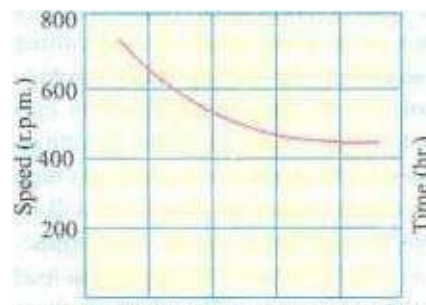
Input(W)loss (W)	9.200	13,800	18.400	23.0001,250
Output(W)	9.200	13,350	11.600	21.850
Speed(r.p.m.)	667	551	480	445
Torque(N-tn)	128.8	2305	349.8	4692

Fromthesevalues,thespeed/torquecurve canbedrawnasshowninFig.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.Calculatetheinpuitvthemotorwhen thesupplyvolraýeis5mV.assumingthatpower required for fan varies as the cube Of the speed. For the purpose Of obtaining the magnetisationcharacteristics.themotorwasrunning asaself-excitedgeneratoral600r.p.m. and the relationship between the tenninal voltage and the load current was found ro be asfollows :

loadcurrent(A)710.51427.5lèrminalvoltage(V)347393434458

TheresistanceOfboth thearmatureandfieldwindingsOfthe motoris3.5Q andthe 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.Letus.bywayofillustration.calculatethespeedandoutputwhenmotorisrunning off a supply and taking a current of IA.

      SeriesVoltagedrop   7x3.5-24SV

      Generatedorbacke.tn.f.Eh=   —24.5=475—5V

ThemotorspeedisproponionaltoEh fora givencurrent.Foraspeedof 600 r.p.m.anda current

Of7A.thegeneratede_m.fis347V.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

ThesecalculationsarerepeatedfortheothervaluesOfCurrentinthefollowingtable.

Inputcurrrent(A)			14	27.5
Seriesdrop(V)	24.5	36.7	49	96.4
Backe.m.f.(V)	475s	463.3	451	403.6

F. at 600 r.p.m. (V)	347	393	434	458
SpeedN(r.p.m.)	823	707	623	528
Armaturepower(W)	3329	4870	6310	1 1.100
MotoroutputW)	2.879	4.420	5.860	10.65
Powerrequiredbyfan(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 currentisplotted.Sincemotoroutputequalstheinpul tofan.hence theintersectionpointof these curves gives the value of motor Input current under the given conditions.

Inputcurrentcorresponding   tointersection point = 12A

∴   Motor input = 500 × 12 = **6,000 W**

29.16. Performance Curves

(a) Shunt Motor

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

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

The efficiency curve is usually of the same shape for all electric motors and generators. The shape of efficiency curve and the point of maximum efficiency can be varied considerably by the designer, though it is advantageous to have an efficiency curve which is 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 underno-loadconditionsgoesto
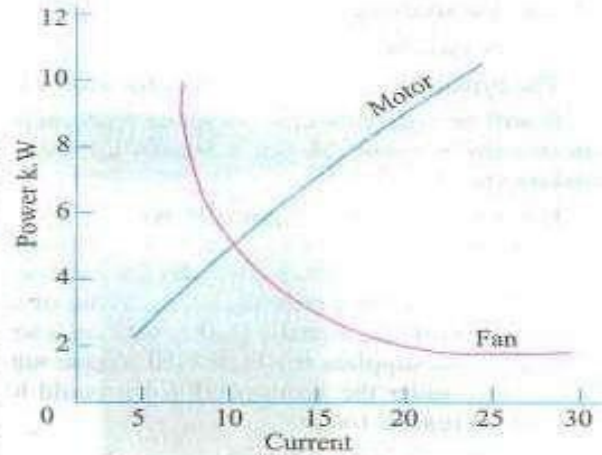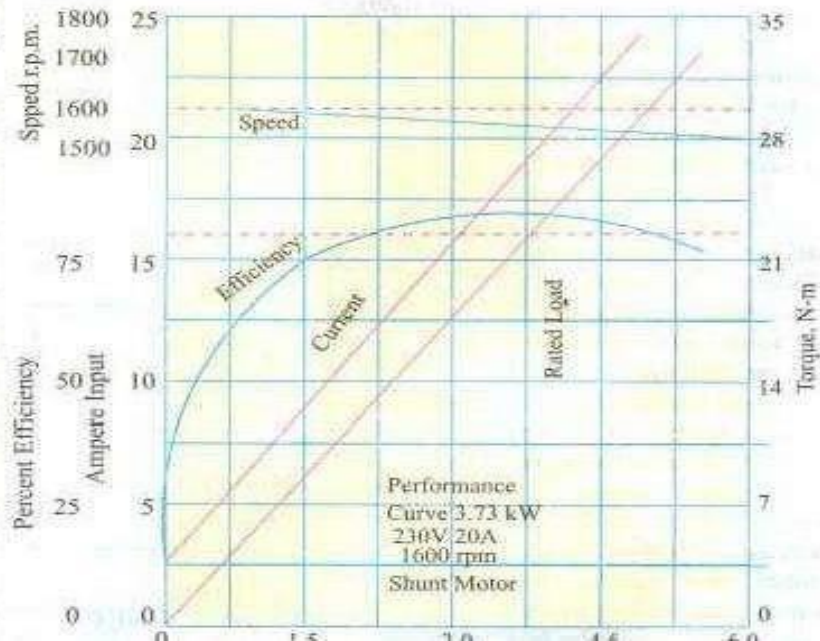
4.5

meetthevariouslosses   kWoutput
occuring

withinthemachine.   Fig.29.24

Fig. 29.23

As compared to other motors. a shunt motor is said to have a lower starting torque. this shouldnotbctaken of meanthat 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 excessofcurrentinputsovernormalvaluesthantheshuntmotorsandthatconsequentlythe depreciation on the motor

Willberelativelyless.Forexample. iftwicefuliloadtorqueisrequiredat Start, then shunt motor draws $I_a \propto \sqrt{T_a}$) whe twicethefull-loadcurrentIaorwhereas series motor draws only $T_a \propto I_a^2$ or $I_a \propto$ approximately oneandahalftimesthefill/loadcurrent

Theshuntmotoriswidelyusedwithloadsthatrequireessentiallyconstantspeed butwhere high starting torques are not needed- Such loads include centrifugal pumps. fans. winding reels conveyors and machine tools etc.

(b'SeriesMotor

ThetypicalperformancecurvesaseriesmotorareshowninFig.29.25.

Itwillbeseenthatdropinspeedwithincreasedloadismuchmoreptominentinseriesmotor than in a shunt motor. Hence, a series motor is not suitable for applications requiring a Substantially constant svxed.

Foragivencurrenginput,the siartingtorquedevelopedbyaseriesmotorisgreaterthanthat 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 thehugestarling torque. thereisanotheruniquecharacteristicofseriesmotorswhichmakes 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 inputcurrent.Supposethat insteadOfaseriesmotor.a shuntmotorisusedtodrive a Street car. When the ear ascends a grade, the shunt motor maintains the speed for car at approximatelytheSame value it had on the level ground. but the motor tends to take an excessive current. A series motor. however. automatically slowsdownonsuchagrade because Of increased current demand, and so it 600 develops more torque atreduced speed. The drop in speed permits the motor

Performance
3.73 kW. 115V
40 A Series Motor

todevelopalargetorque300WithhutamoderateincreaseofpowerHence.underthe same load conditions. rating of the series motor would bc less than for a shunt motor,
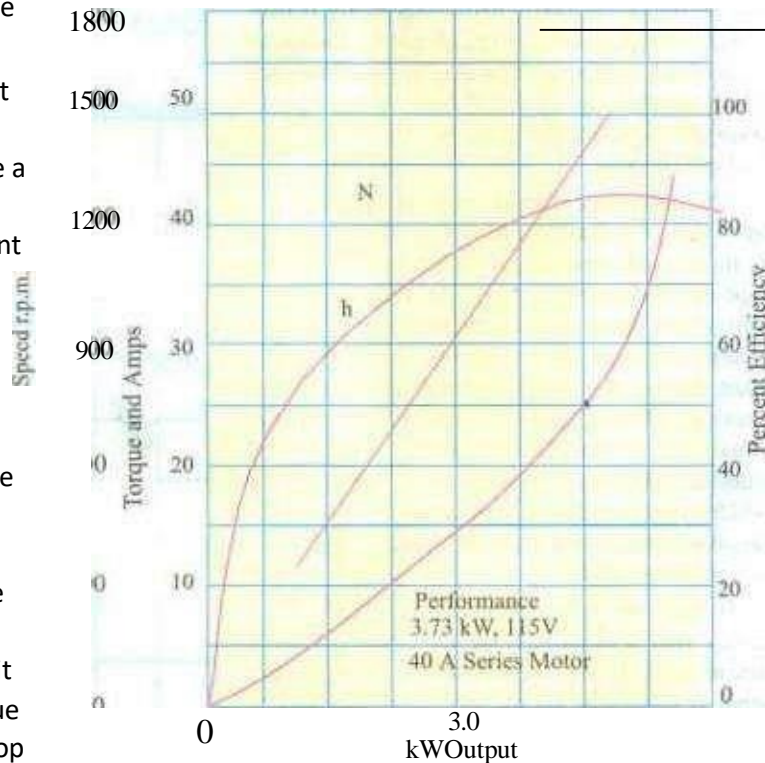
Fig.2925

29.17. ComparisonOfShuntandSeriesMotors

(a) Shunt Motors

ThedifferentcharacteristicshavebeendiscussedinArt.

29.14.Itisclearthati")speedofashuntmotoris sufficiently constant.

(h) fortheSameCurrentinput,itsstartingtorqueisnota high as that of series motor. Hence. it is used.

(i) When the speed to be maintained approximately constantfromNLtoF.Li.e.fordrivingalineofshafting etc. ij When it is required to drive the load at various speeds. any onc speed being kept constantforrelativelylongperiodi.e.forindividualdrivingofsuchmachinesaslathes.The shunt regulator enables the required speed to be obtained easily and economically.

Shunt Motors

SummaryorApplications

Typeofmotor	Characterivtic•	Applicatio
Shunt	Approximately constant speed Adjustable speed Mediumstartingtorque(Up to IS EL. torque)	Fordrivingconstantspeedlinc shafting Lathes Centrifugalpumps Machine tools Blowers and fans Reciprocatingpumps
Series	Variable speed AdjustablevariyingSlxed High Starting torque	Fortractionwork[e. ElectriclocomotivesRapidtransit systems Trolley. ears etc. Cranesandhoists Conveyors
Comulalive Compound	Variable speed Adjustablevaryingspeed High starting torque	Forintermittenthightorqueloads For shears and punches Elevators Conveyors Heavyplaners Heavyplaners Rollingmills:Icemachines:Printing presses; Air compressors

(b) SeriesMotors

TheoperatingcharacteristicshavebeendiscussedinArt29.13.Thesemotors l.havea relatively huge starting torques.

2. havegoodacceleratingtorque

3. havelowspeedhighloadsanddangerouslyhighspeedatlowloads.Hence,such motors used

l.whenalargestartingtorquerequiredi.e.fordrivinghoists,cranes.tramsetc.

2. whenthemotorcanbedirectlycoupledto a load such as a fan whose torque increases with

3. ifconstancyofspeedisnotessential,then. infact.thedecreaseofspeedwithincrease Ofload hastheadvantagethatthepowerabsorbedbythe 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. aseriesmotorsh0uldnotusedwherethereisapossibilityoftheloaddecreasingto a Very small Thus, it should not be used for driving centrifugal pumps or for a belt-drive Of any kind.

SeriesMotors

29.18. LossesandEfficiency

Thelossestakingplaceinthemotorare thesameasingenerators.Theseare(i)Coplrrlosses (ii)Magneticlcvsse_sandiiii•Mechanicallosses,

Theconditionformaximumpowerdevelopedbythemotoris

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

TheConditionformaximumefficiencyisthatarmatureCulossesareequaltoconstant losses. (Art. 26.39).

29.19. PowerStages

Thevariousstagesofenergytransformationinamotorandalsothevariouslossesoccurring in it are shown in the now diagram of Fig. 29.26.

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

c

11m=-h

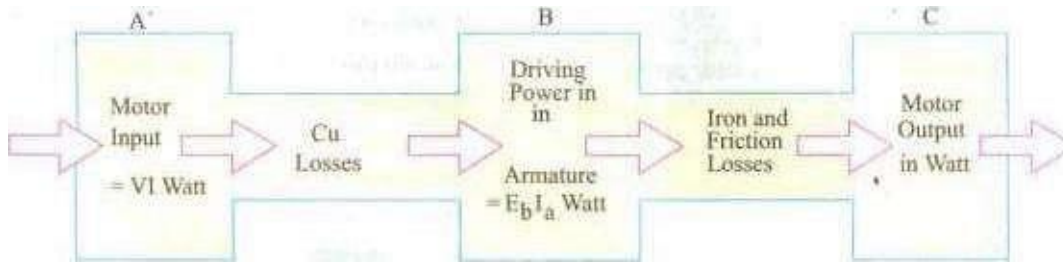Theefficiencycurveforamotor issimilarinshapetothatforagenerator(Art.24ß5).

Fig.2926

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

Example 29.34, One' of the r,vo similar 50th V' *hunt machines* A and B running light takes 3 A. When A is mechanically coupled to B. the input to A is 33A with B unexcited and 4.5A When B is separately-excited ro generate 500V Calculate the friction and windage loss and core loss of each machine. Machinery-I, Madras Univ. 1985

Solution. When running light. machine input is used to meet the following losses (i' armature Cu loss shunt Cu loss ' iii' iron loss and mechanical tosses i.e. friction and windage losses. Obviously, these no-load losses fcu• each machine equal 500X3 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 05A more current Friction and windage loss of B 500 x 0.5 250 W

(b) With B excited

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

A draws, 4.5—3 = I.5A more current.

Iron and mechanical losse• of B = ISX500 750 W

    Iron   of B = 750-250   W

Example A 220 Shunt motor has an am-alary resistance Of 0.2 ohm and field resistance of The motor draws 5 Aal 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 = 3^2k   W

∴ Constant or standing losses of the motor = 1100   1098

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

WHence.totalmotorlosses=1098+500=1598W

Motorinputonload-220x52=11,440W;output—11,440-1598=9842W

=955xoutputhV=9.55x9842/1436   N-m

Example 29—V'. 250 Vshunt motor on no runs 1000 and takes 5 amperes. Armature and shuntfieldresistancesare0.2and250ohmsrespectivelyCalculate'hespeedwhen *loaded* taking current Of50 A. The armature r•ection weakens thefield by   *3%.*

(Elect.Engg.-lNagpurUniv.1993) Sol

2402

     1000   24920.97q

Example29.37.A500Vt}.c.shuntmotortakesa currentOf5 AOnno-loadTheresislaneesOf 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-Londcondition

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

Arm.Cu $_1 loss = 3^2 \times 0.22 = 2$ W; Motor input $= 500 \times 5 = 2500$ W

osses = 2500-2=2498 W

Constant

Itisassumedthattheselossesremainconstantunder allloadconditions. I

.o:ad condition

$^{(a)}$Motorcurrent   100A;Ia=$100 - 2 = 98$ A; $E_b = 500 - (98 \times 0.22)$=478.44V

Example29—39.Adc.shuntmachineWhilerunningasgeneratordevelopsavoltageOf250 V at J000 on no-load. armature resistance Of 0.5£2 andfield resistance Of 250 When the machinerunsusmotor:inpultoitatno-loadis4.4 250 V.Calculatethespeedandefficiency 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 250V al 1000 r.p.m. If this machine wasrunningasmotorat1000 r.p.m..itwill.obviously,haveabacke.m.f.of250Vproduced in its armature. Hence N, = r.p.m. and Eh, 250 V.

Whenitrunsasamotor.drawing40A.thebacke.m.f.inducedinitsarmatureisEb2 =

$$250 - (40 - 1) \times 0.5 = 230.5 \text{ V}; \text{ Also } \Phi_2 = 0.96\ \Phi_1, N_2 = ?$$

UsingtheaboveequationWe have

1000

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

Emciencv

No-loadinputrepresentsmotorlosseswhichconsistsof(a)armatureCuRaWhichisvariable.

(b)constant lossesW,whichconsistsofjii shuntCuloss(iibmagneticlossesand'iii' mechanical losses.

No-loadinput or total losses 250 x 4

WArm.cul

oss=W,W,=   =995.5W

Whenmotordrawsalinecurrentof 40A,itsarmaturecurrentis(40—I=39Aculoss= 760.5W:Totallosses-760.541756W

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

-8.244xIOW10.ooo=82..wrt

Example29.40.ThearmatureWindingOfa4-poie•,250Vdc.shuntmotor islapconnected. There are 120 slots, each slot containing8 conductors. The is 20 mWb and current taken by motoris25A.Theresistanceof armatureandfieldcircuitareO.Iand125respeclively.Ifthe rotational losses amount 10 be 810 Wfind,

(i)grosstorque(ii)usefultorqueand   efficiency.(Elect.MachinesNagpurUniv. 1993)

Soil"ion.   -(23x0.1)-247.7V

20X IO-3 X960X,V4

NOW,A   247.7 = 60   (4)—:N—773r.p.nL

247.7X23

GrosstorqueorarmaturetorqueT.9.55   9.55x=70.4N-m

773

Rotationallosses=810W:Totalmotorlosses=810+500+53=1363W

Motorinput=250x25=6250W;Motoroutput- 6250 -1363-4887W

T_{sh} =9.55xoutputiN=9.55x4887/773-60-4N-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'motorhasatotalof 620 conductors arranged in two parallel paths and yielding an armature circuit resistance OfO. 2 Q

Whenitdelivers raredpower a'ratedspeed. itdraws a line currentOf 74.8A anda field currentOf   3 L Calculate (i'theflu.xperpolethetorquedeveloped   (iii)lherotationallosses expressed as a percentage ofpower.

Solution.

(i) Now.

fArmatureTorque,

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

Outpul14,920W;Rotationallosses=15.483—

14.920=   W $I = 230 \times 74.8$

(iv) Motorinput-   -17.204W:Total   17204-14.920W

LossesexpressedaspcteentageOfpowerinput=2284/17,204= O.133or 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 resistameare0.5Qand250£2respectively.A,'outputpowerwillrheefficiency bemaximum ?Isitpossibleobtainthisoutputfrom themachine?MS.Univ.Baroda1985) Solution.

When loaded lightly

Totalmotorinput(Ortotalno-loadlosses)=250x 5= 1.250W

fieldCu10ss = 250* 1 =250 W;

Ironlossesandfrictionlosses=1250 —250— 8=992 WTheselosseswouldbeassumed constant.

Letbcthefull-loadarmaturecurrent,then armatureinputis=(250xWELoutput=7.46x 1000=7.460W The losses in the armature :

(i)Ironandfrictionlosses=992W

(ii) ArmatureCuloss   =la:*0.05w   2501.—_7,460 $992 + I^2 \times 0.5$

O   =365A

ELinputcurTent=36.5+I= 37.5A;Motorinput= 250x37SW EL

output = 7,460 W

FLefficiency100/250x375-79.6%NOW.efficiencyismaximumWhenarmatureCuloss equals Constant loss.

i.e.   1.242Worla=49.84A

Armatureinput250x49.8412.460W

ArmatureCuloss49.84^{2}x0.51242W;Ironandfrictionlosses=992W

Armatureoutput   10.226 w

Outputpower=10,226W=10.226kW

Astheinputcurrentformaximumefficiencyisbeyondthefull-loadmotorcurrent,itis never realiscd in practice.

Input

Example29.45.A50-h.p.(373kW),460-Vd.c.shuntmotorrunninglighttakesacurrentof 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.

Determinewhenthemotorisrunningatfullload

(ijrhecurrentinput(iithespeed Determinethearmaturecurrentatwhichefficiencyis gnat- imam. Ignore the effect ofarmature reaction.1991)

Solution.   460/270=1.7

When running light

I_a=4—1.7=2.3A;ArmatureCuloss —2.3^2*0.31.5W(negligible)

No-loadarmatureinput=460x2.3=1,058W

AsarmatureCulossisnegligible,hence1,058Wrepresentsiron.frictionandwindage losses which will assumed to be constant.

Letfull-loadarmatureinputcurrentbe/Then

Armatureinput=   IW;ArmatureCuloss   x0.3W

=   38.358=0la=88.5A

fijCurrentinput=88.5+1.7=90.2A

=660x433.5/459a=624r.p.m.

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

Tutorial Problems 29.3

A4-POle250—V.   motora   armatureWith

(a) the   torque(b)thesreed

(b) theoutpattorqueand(d) theefficiency.ifthemotor currentis50AThe 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)173.5N-rn(b)   r.p.m.(c)   N.m(d)86.9%]

2. no-load,ashunttyotor takes5Aat250V.resistancesofthefieldand armaturecircuits 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%.Itisthatwindage.frictionandeddycurrentJossesareindependentofthe current and speedl

SINGLEPHASETRANSFORMER

.WorkingPrincipleOfaTransformer

A transformer is a static (or stationary) piece ofapparatus by means of which electric power in onecircuitistransformedintoelectric 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 consistsOf twoinductivewhichareelectricallyseparatedbatmagneticallylinkedthrougha path of low reluctance as in Fig. 32.1. The two coils possess high mutual inductance. If One coil isConnectedtoaalternatingvoltage,analtematingfluxissetupinthelaminatedcore. most of which is linked the other coil in which it produces mutually-induced e.m,f.facCording to Faraday's Laws Of Electromagneticcoil circuitis closed,a current flows initandsoelectricenergyistransrewed(entirelymagnetically)fromthefirsttothesecond coil. The firstcoil,inwhichelectric energy is fedfrom thea.c. supply mains,is calledprimary windingandtheotherfromwhichenergyisdrawnout,iscalledsecondarywinding.Inbrief. a tKånsformer is a device that
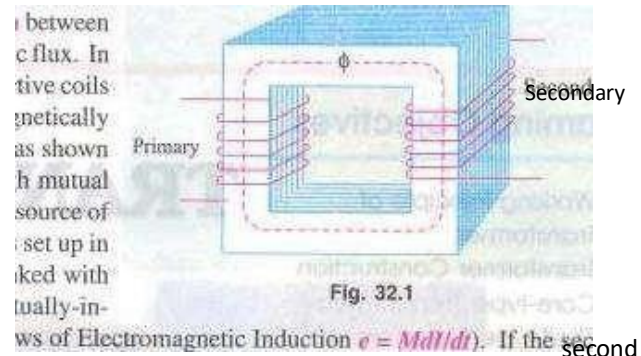
1. transferselectricpowerfromonecircuittoanother 2:

it does so without a change of frequency

3.   itaccomplishesthisbyelectromagneticinductionand

4.   wherethetwoelectriccircuitsareinmutualinductiveinfluenceof eachother.

32.2.TransformerConstructionIroncore

Thesimpleelementsofatransformerconsistof two coilshavingmutualinductanceanda 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 mediumforVoltsinsulatingthecoreanditswindingsfromitscontainersuitablebushings (eitherofporcelain,oil-filledorcapacitor-type)for ondaryinsulatingandbringingoutthe terminals of windings

1118

from "0/120

typesofPrincipleottransformer

the core is constructed of transformer sheet steel laminations assembled to provide continuousmagneticpath Withaminimumofair-gapincluded.Thesteelusedisofhigh silicon content, sometimes heat treated

Fig. 32.2   toproduceahighpermeabilityandalowhysteresislossatthe

usual operating flux densities. The eddy current loss laminatingthecore,thelaminationsbeinginsulatedfrom 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 frequencyOf25Hr..Thecorelaminations(inthestrips)
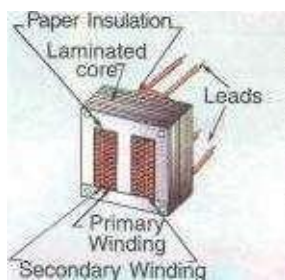
arejoinedasshownin   Fig.32.2.Italternatelayers are staggered in order to gapsrightthroughthecross-section of the are said to be 'imbricated'.

isseen avoidthe core.

Constructional/y,thegeneraltypes,distinguishedfromeach other merely by the manner in which the primary

Core-typetransformerandsecondarycoilsareplacedaround 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,

Intheso-calledcoretype transformers,thewindingssurroundaaryWindingconsiderable par/ ofthe core whereas in shell-type transformers. the core

in Fig. 32.3 (*a*) and (*b*) respectively.
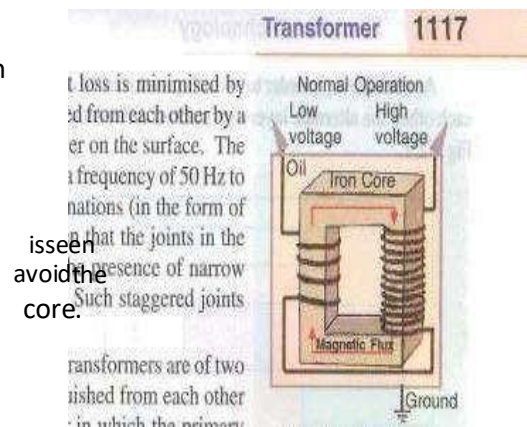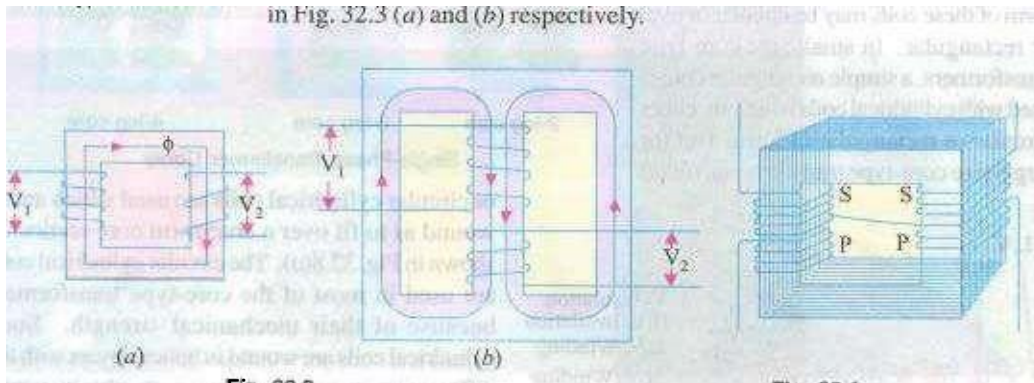
Fig.32.3

Shell-Typetransformersurroundsaconsiderableportionofrhewindings 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 actualconstruction,thesearealwaysinterleavedtoreduceleakagellux_AsshowninFig. 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„
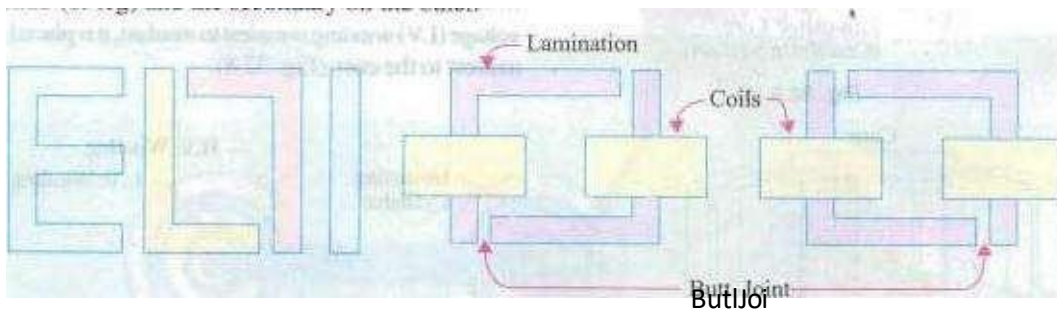

Fig.32.5   Fig.32.6

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.Theassemblyofthecompletecore for the two types of transformers is shown in Fig. 32.6 and Fig. 32.7.

Assaidabove,inordertoavoidhighreluctanceatthejointswherethelaminationsare buttedagainst each other, the alternate layersare stackeddifferently to eliminatethesejointsas shown in Fig. 32.6and
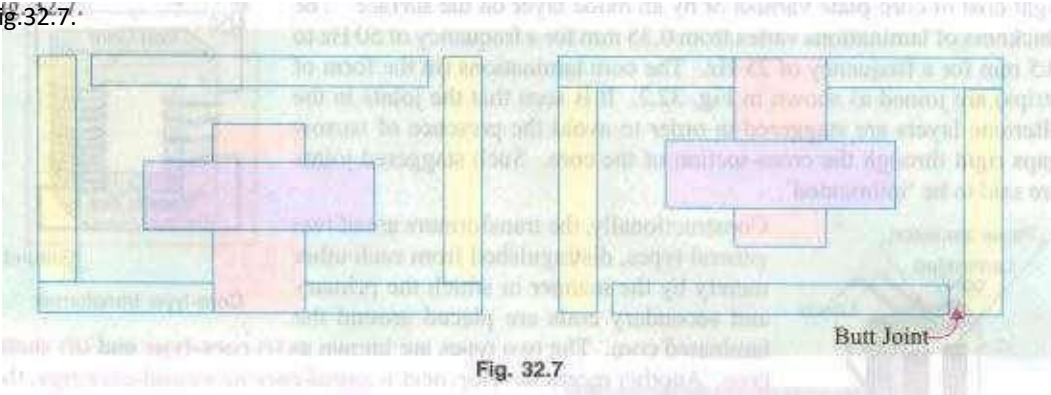
Fig.32.7.

Butt Joint

Fig. 32.7

Because oflaminations and insulation, the net oreffective   area is reduced. due allowanceforwhichhastobe made(Ex.32.6).'tisfoundthat.ingeneral,thereductionin coresectional areadueto thepresence ofpaper, surface oxide etc. is of the order of 10% approximately.

Aspointedoutabove. rectangularcoresWith ᵉᶜᵗᵃⁿᵍᵘˡᵃʳcylindrical coilscanbeusedforsmall- 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. squarecores may be used as shown in Fig. 329 (b) where circlesrepresentthetubularformercarryingthe coils.Obviously.aconsiderableamountof useful space is still wasted. A common improvementon 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 coreplatesarenecessary.notonlygiveshighspacefactorbutalsoresultsinreducedlength 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.
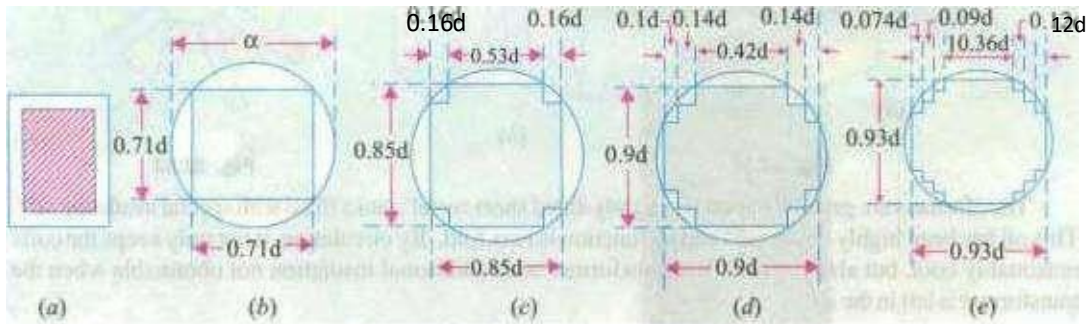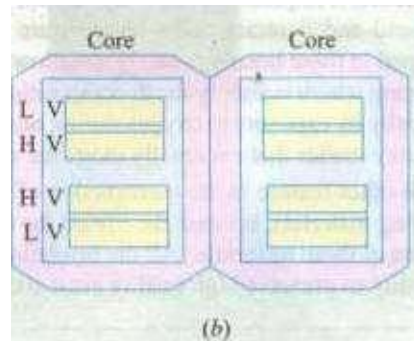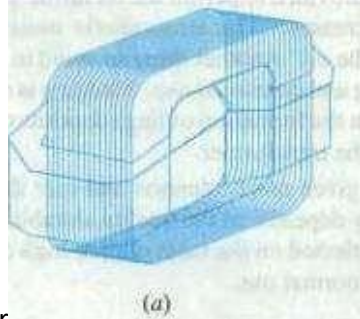
Fig. 32.9

32.4. Shell-type Transformers

In these case also, the coils are form-would but are multi-layer disc type usually wound in the Inthesecasealso,the coilsareform-wouldbutaremulti-layerdiscformofpancakes.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.Ashell-typetransformermayhaveasimple

rectangular   formas showninFig.32.oritmayhavedistributedformasshowninFig.32.II. Fig. 32.10

A very commonly-used shell-type transformer is the one known as Berry Transformer—so calledafterthenameofitsdesignerandiscylindricalinform.Thetransformercore consists Of laminations arranged in groups which radiate outfrom 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 rigidmechanicalbracinginOldertopreventmovementandpossibleinsulationdamage. bracingreducesvibrationandtheobjectionablenoise—ahummingsound-duringoperation.

The spiral-core transformer employs the newest development in   construction. The core is a sembledofacontinuousstrip orribbonof transformersteelwoundintheformof 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 higheroperatingfluxdensitiesWithlowerloss^{per}kg.Theuseofhigherfluxdensityœduees the weight per WA. Hence, the advantages ofsuch construction are

re (i) a relatively more rigid core (ii) lesser weight and size per kVA rating (iii) lower iron losses at higher operating flux densities and (iv) lower cost of manufacture.

(a)   (b)   li

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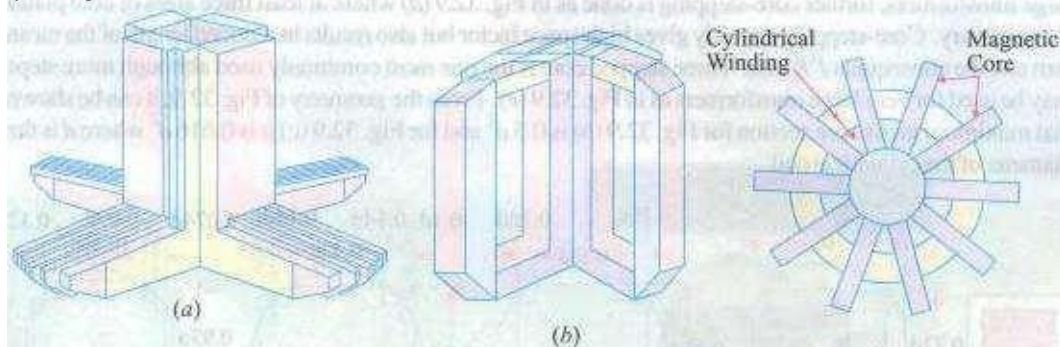
a relatively more rigid   (ii) lesser weight and size per kVA rating (iiö lower iron losses athigher

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 notonlykeepsthe coilsreasonablycool,butalsoprovidesthetransformerwithadditional 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 ishighlydetrimentalfromtheinsulationviewpointbecauseitlowersthedielectricstrengthOf the Oil considerably. The importanceofavoiding moisture in the transformer Oil is clearfrom the fact anaddition Of 8 parts of Water inI 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 inthe formationOf large deposits ofdark and heavy matter thateventually 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.durabilityandhandling ofthesematerials.Alltheinsulatingmaterialsareselected

onthebasisof theirhighqualityandabilitytopreservehighqualityevenaftermanyyears 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 PYROCLORisbeingeOensivelyusedbecauseitpossessesremarkablestabilityasadielectric 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 manydesignsOfthe-SC,their-sizeandconstnlction dependingonthevoltageOftheleads. For moderate voltages, porcelain bushings are Lsed to insulate the leadsas they come out through the tank. In general,they look almostlike the insulators used on the transmission lines. Inhigh voltage installations, Oil-filled orcapacitor—^{type}bushings areemployed.

Thechoiceofcoreor shell-typeconstruction isusuallydetermined bycost,becausesimilar characteristics can be obtained withboth types. For very high-voltage transformers or formultiwindingdesign,shelltypeconstmctionispreferredbymanymanufacturers.Inthis 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.

Anothermeansofclassifyingthetransformersisaccordingtothetypeofcoolingemployed. Thefollowing types are in common use :

[a]oil-Aled self-cooled   (b) oil-filled Wafer-cooled   (c' áir-biast type

Smallandmediumsizedistributiontransformers-socalledbecauseoftheiruseon 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 tanksare usually smooth-surfaced, but for largersizes. the cases are frequently corrugated or flutedtogetgreaterheatradiationareawithoutincreasingtheCubicalcapacityOfthe tank. Still larger sizes are provided With radiators or pipes.

Construction Of very large self-cooled transformers isexpensive,a more economical form OfConstructionforsuch largetransformersisprovidedintheoil-immersed,water-cooled type. As before, the windings and the cote are immersed in the Oil, but there is mounted neartheSurface ofoil,acoolingcoilthmughâh'hichcoldWateriskeptcirculating.Theheat

iscarriedawaybythiswater.ThelargesttransformerssuchasthoseusedWithhigh-voltage transmission lines; are constructed in this

Oil-filled transformers are bail t for outdoor duty and as these require no housing Other thantheirown.agreatsavingistherebyeflCcted.Thesetransformersrequireonlyperiodic inspection.

For voltages below 25.000 V. transformers can bc built for cooling by means of an air-blast. Thetransformerisnotimmersedinoil.batishousedinathinsheet-metalboxopen atboth ends through which air is blown from the bottom to the top hy means of a fan or blower.

32.5.ElementaryTheoryofanIdealTransformer

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 woundonaloss-freecore.Itmay, however, be notedthai iv is impoçsible

[10]realizesuchatransformerinpractice,yetrorcani•enience, willstartwithsucha former
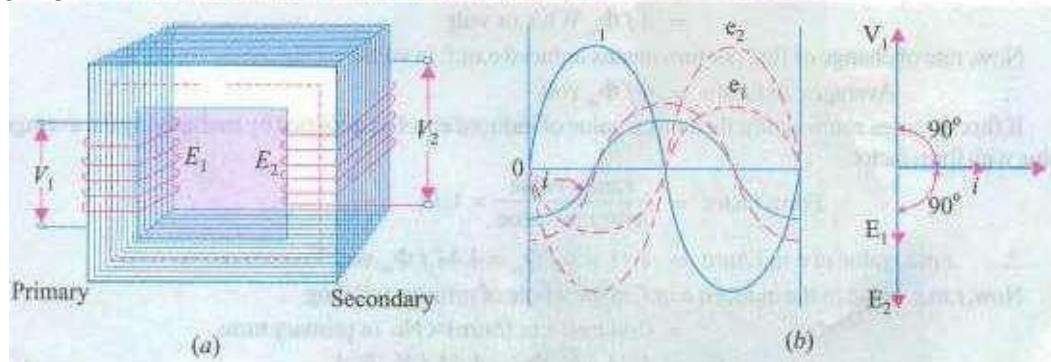

Fig.32.13

Consideranidealtransformer[Fig.32.13whosesecondaryisopenandwhoseprimaryis 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 analternatingfluxOwhichis. at all times, pmportional to the cun-ent OLssuming permeabilityofthemagnetic circuittobeconstant)hence. is in phase with it. This changing flux islinked bothwith the and the
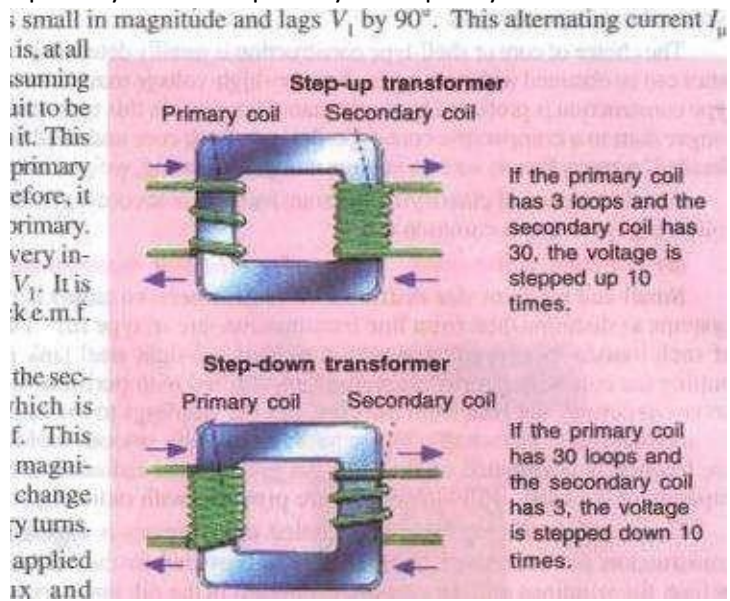
secondarywindings.Therefore,itproducesself-inducede.m.f,intheprimaryThisself-induced e.m.f. Et is. at every inStant, equal to and in to VI. It is also known as Counter e.m.f.orbacke.oftheprimary.

Similarly, there is pnxiuced in the secondary an induced e.tn.f. E2 which is known as mutuallyinducedc-m.f.Thise.m.f.isantiphasewithV,anditsmagnitudeisproportional to the rate of change Of flux and the numberof secondary turns

TheinstantaneousvaluesOfappliedvoltage.inducede.m.fs.fluxandmagnetisingcurrent are shown by sinu-Step-up transformersoidal wavesinFig. 32.13 fig. 32.13

(c) showstheVectorialrepœsentationOftheeffectivevaluesOftheabovequantities.

32.6.E.M.F.EquationOfaTransformer

Let   NI=No.Ofturnsinprimary Nk

= No. ofturns in secondary

= Maximum flux in core in w&rs

f =Frequencyofa.c,inputinHz

Asshowninfig.32.14,flux $= \dfrac{\Phi_m}{1/4f}$ increasesfromitszerovalueto maximum value 4'nin one quarter $4f\Phi_m$ Wb/s   ofthecyclei.e.in1/4/second.

Average rate of change of flux =
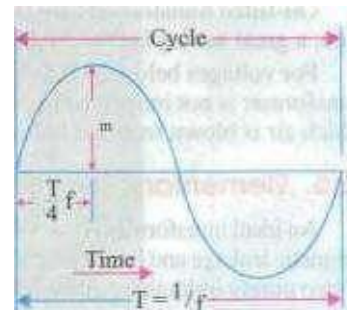
Fig.3214

=   orvolt

Now.rateofchangeoffluxperturnmeansinducede_m-f_involts_ Avetagee.rn.f./turn =

4fcbm volt

Iffluxvariessinusoidallythenr.m.s.valueofinducede.m.f.isobtainedbymultiplying theaverage valuewith formfactor. rm. S. value

Formfactor=-1.11

average value

       rms.valueofe.m.f]turn=1.11x4   4.44   volt

Now.r.ms.valueoftheinducede.m.f.inthewholeofprimarywinding

=(inducede.tn.fjturn)xNo.ofprimarytums

Hence.currentsaræintheinverseratioofthe(voltage)transformationratio.

Example 32.1. The [2]maximumflux density:tn die core ofa 250/3000-Võlts,SO-Hzsingle-Þhasetransformeris1.2Wb,4n.Ifthee.m.j:perfurnis8volt,determine(i) primaryand secondary turns areg core.

(ElectricalEngg.-l,NagpnrUniv.1991)

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

       (ii) We may use = — 4.44   Bm A

       3000   4.44x50x375xL2xA;A=0.03m2.

Example32.2.TheofaIOO-kVA.11000/550V:_50-HZ„I-ph,Copé typetransformerhasa 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.By1991)

       Solution.   1.3

       11,000=   x   1060

       550=   xL3X0.036:N2=53

       =   1060=53

e.m.f.}tum=   10.4Vor550/53=104v

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

Example323.Asingle-phasetransformerhas400primaryand1000secondary   turns.The netcross-sectionalareaofthecoreis   60cm^2.Iftheprimarywindingbeconnecteda   50-Hz supply ar 520V. calculate (i) the peak value density in the core (ìi) the voltage induced in

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

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

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

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

the secondary Winding. (Elect. Engg-E. rune Unh'. 1989) Example 32.4, '4 25-kVA transformerhas500 turnsonthe primaryand50turns onthe second. arywinding. The primary is connected to 3000-1' SO-Hz supply. Find the full-load primary and secondary currenfs,the secondarye.nt.f:and themaximumfluxinthecore.Neglectleakagedrops 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.perturnonprimaryside=30/500—6Secondary e.m.f. r

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

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

SolutionMaximumvalueoffluxhastwengivenas0.05Wb.

(ii) e.m.f.perturn   4.44f

=4.44x50 x0.05=11.1volts

(i)Calculationsfornumtvofturnsontwosides

Voltagephaseondelta-connectedprimarywinding11000volts

Voltageperphaseonstar-connectedsecondarywinding550/1.732= 317.5voltsT1= numberofturnson primary, per phasevoltage perphase}e.m.f. turn

T.numberofturnsonsecondary.perphasevoltageperphase/e.m.f.perturn317.5/11.1- 28.6

Note:Generally,Low-voltage-turnscalculatedfirst.thefigureisroundedofftonext higlEr even integer. _In this case. itbe 30. Theo. number Of turns on primary side is calculated by turns-ratio.

Inthiscase,

This. however, reduces the flux and results into less saturation. This, in fact, is an elementaryaspectinDesign-calculationsfortransformers.(Explanationisaddedhere only to overcome a doubt whether a fraction is acceptable as a number ofL.V. turns).

(ii) Full load   andL.V.phasecurrents:

Output per phase =

H.V.phase-current

L.V.phase-current=

Example32.6.Asingle{phasetranžformerhas500turnsintheprimaryandturnsin 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.

(BharathinrUniversityNovember199T

,Solution.Fromthe

(i) Peakfluxdensity, ^{2}0

$^{(ii)}$Wtageinducedinsecondaryis from tmnsformationratioorturnsratio

m.f. equation for transformer,
$$500 = 4.44 \times 50 \times \phi_m \times 500$$
$$\phi_m = 1/222 \text{ Wb}$$
$$B_m = \phi_m / (80 \times 10^{-4}) = 0.563 \text{ wb/m}$$

obtained

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

$V = 500 \times 1200/5$

V2—500k12CW500=1200volts

Example32.7.A25kVA.single•phasetrttnSfOñ7ier41ås250rurnSonprimàrÿ *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.. (ìì) maximumflux in the core.

(BharathiarUniv.April   1998)

Solution.= Secondary   If V_2 voltagerating,=secondarye.m.f.' V_2

1500 — 250 , giving V2 = 240 volts

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

(iiibIf0misthemaximumcore-fluxinWb;

1500=4.44x   givingÇ=O.027Wbor27mWb

1130

Example 32.8. A asingle-phase,50"z, core-type transformer has Square cores of20cm side. Permissible maximumflux-density is"Wb/m^2. Calculate number of 'urns per Limb on•heHighandlarw•volrogesidesforu3000/220Vratio.ManonmnniumSundaranar cniv.April1998)

Solution. E-MF. equation gives the number of turns required on the two sides. We shall firstcalculatetheL.V.-turns,round thefigureoffto thenexthigherevennumber,sothat given maximum

fluxdensityisnotexceeded.WiththecorrectednumberofL.V.turns,calculateH.V.-turns   by transformation ratio. Further, there are two Limbs. Each Limb accommodates half-LV. and halfH.V]

Windingfromtheview-pointofreducingleakagereactance.

StartingwithcalculationforLV.tums,Ty

         4.44x50xt(20x20x   Tz=220

=220/8.0=24.77

Select

=26x3000/220=354,selectingthenearesteveninteger. of H.V.

turns on each Limb = /

NumberOfLV.turnsoneachLimb=13

32.8. TransformerwithLossesbutnoMagneticLeakage

Wewillconsidertwocases(i)whensucha transformerisOnno loadand(i"whenitis loaded.

32.9. TransformeronNo-load

Intheabovediscussion.weassumedidealtransformeri.e.OneinwhichthereWereno losses   and copperlosses. But practical conditions require that certain modificationsbemadeintheforegoingtheory.Whenanactualtransformerisputon load. there iviroiiloššin the core andcopperlossin the Windings (both primary and secondary) and these losses arenot entirely negligible.

Evenwhenthetransformerison   no-load,theprimaryinputcurrentisnotwhollyreactive. Theprimary input current under nozload conditions hastosupply (i) iron losses in the core

i.e. hysteresis loss and 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 under m-load Conditions. No-load Condition pf an actual transformer is shown vectorially in Fig. 32.16.

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,

I_w = 10 COS ϕ_0

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

Iosin4)o

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

primary current. It is

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

2.   Owing to the fáét that the permeability of the 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 Which is responsible for shift in the known as hysteresis' angle advance.

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

(h) A 2200/250-1" transformer takes Aata p.f Of 0.3 on open circuit. Find magnetising and working components of no-load primary current.
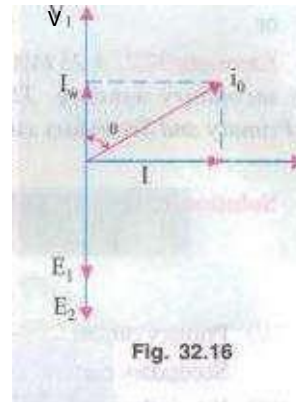
Solution.   Iron-losscurrent

no-load input in watts   400-—   =0.182Aprimaryvoltage200

        Magnetising component   — 0.182)? 0.672 A

Thetwocomponentsareshowninfig.295.

Example32.10.ASingle-phasetransfoññèr/tas500turnsonthe primaryandJ4tJturnson thesecondarywinding.The•neonlengthOfrhemagneticpathinrheiron coreis150cm and the joints are *quivalent*'o an air-gap ofO. When a p.d. V is applied to the primary maximum flux density is 1.2Wb/m^2. Calculate (a/ the cross-sectional areaof the core (b) no-loadsecondaryvoltage(c)rheno-loadcurrentdrawnbytheprimary(d)powerfactor 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

Thisisthenetcross-sectionalarea.However,thegrossareawouldbeaboutforthe insulation between laminations.

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

∴NL,secondaryvoltage-KEI

750

80.0001=955

        Totalforgiven=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/   1.196A

Volumeofiron=lengthxarea=

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

Total iron loss

IronlosscomponentOf no-loadprimarycurrentisIw=526.5/3000—O.176A

1.196^2+0.1762 —0.208 A

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

        32.10. TransformeronLoad   10

magnitude and phase of 12 with respect 'o V: is determined by the teristics ofthe Current',isinWithV,ifloadisnon-inductive,itlagsifloadisinductiveanditieadsifloadis cal•live.

Thesecondarycurrentsetsupitsownandhenceits ownfluxwhichisinoppositionto 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. thetwo canceleachotherout.So.wefindthatthemagneticeffectsofsecondarycurrent 12areimmediatelyneutralizedbytheadditional primarycurrentl:'whichisbroughtinto 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 $\qquad \Phi_2 = \Phi_2' \quad \therefore \quad N_2 I_2 = N_1 I_2' \quad \therefore \quad I_2' = \dfrac{N_2}{N_1} \times I_2 = K I_2$

Hence, when transformer is on load, the primary winding has two currents in it; one is I_0 and the other is I_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'*
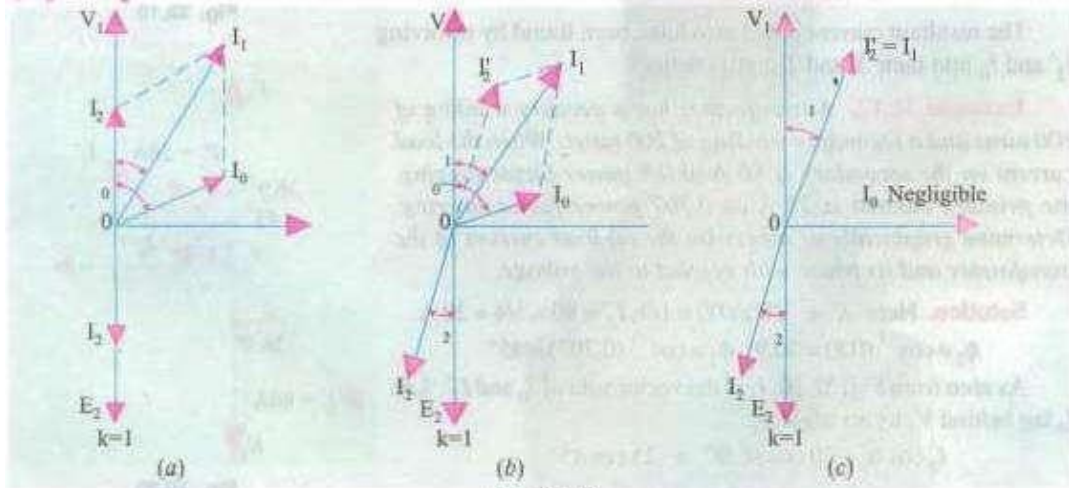
Fig. 32.18

Hence,whatevertheloadconditions.thenetfluxpassingthroughisapproximatelyofcore fluxatallloads,thecoreloss

In Fig. 32.18 are shown the vector diagrams fora loaJtransformer when load is non-inductiveandWhenitis.inductive(asimilardiagramcouldbedrawnforcapacitiveload). Voltage transformation ratio ofunity is assumed so thatprimary vectorsare equal to the

secondaryvectors.Withreferencetofig.32.1812issecondarycurrentinphasewithE2 (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.

InFig.32.18(b)vectorsaredrawnfor aninductiveload.Here12lagsEa(actuallyby 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

Itwillbeobserved isslightly greater than ϕ_2. But if we neglect I_0 a that Butifwe neglect 10 Moreover.under this assumption ascomparedt042' asinFig.32.18then

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

NIG =

Itshowsthatunderfull-loadconditions,theratioof primaryandsecondarycurrentsis constanL This important relationship is made the basis of current transformer—a transformer whichis usedwithalow-range ammeter for measuring currents incircuits Where the direct connection Of the ammeter is impracticable.

Fig.3220

$$E_1 = V_1 - I_1 R_1 \qquad \text{...vector difference}$$
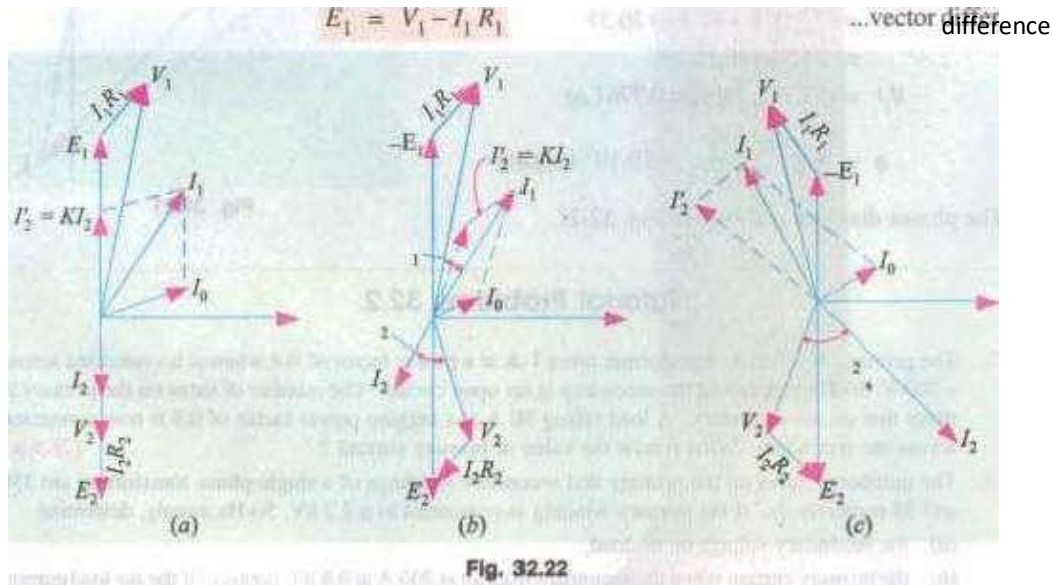
Fig. 32.22

Thevectordiagramsfornon-inductive,inductiveandcapacitiveloadsareshowninFig. 32.22(a),(b)and(c)respectively.

32.12. EquivalentResistance

In Fig. 32.23 a transformer is shown whose primary and secondary windings have resistancesofRIandR:respectively.Theresistanceshavebeenshownexternaltothe windings.

It would now be shown that the resistances of the two windings can be transferred to any one of the two windings. The advantage of concentrating both the resistances in one winding is that it makes calculations very simple and easy because one has then to work in one winding only. It will be proved that a resistance of R: 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 12^2Ra, This loss is supplied by primary which takes a current of ll. 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 refetïcdto 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.
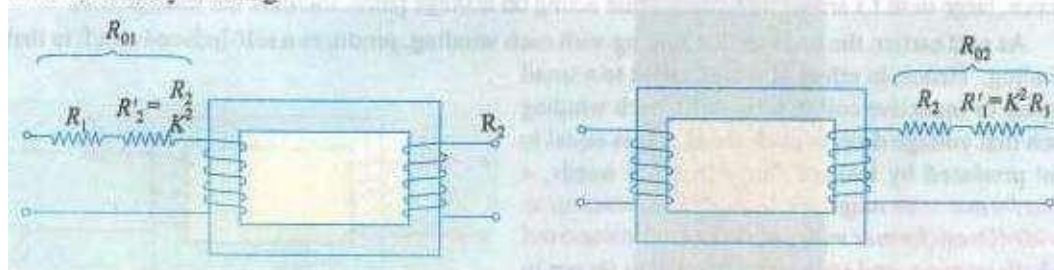

Fig. 32.24   Fig. 32.25

the referred to primary and may be designated as It is

to be noted that

La 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.totaltransformerresistanceasreferredtosecondaryis,

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

* Actually $I_2 \# 2/I_2' = I/K$ and not $I_2 \# 2/I_1$. However, if J_0 is neglected, then $I_2' = I_1$.

Note:(tisimportanttorememberthat

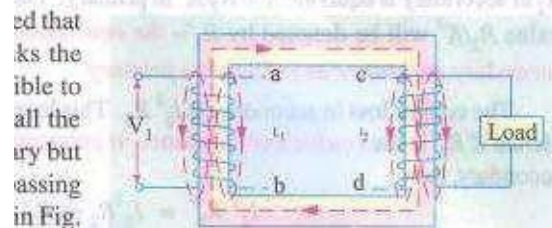(a)Whenshiftinganyprimaryresistance tothesecondary,*nut/iplyitby(bWhen shifting secondary resistance to the primary, divide it hy R.

(CJhowever.whenshiftinganyvoltage from one.inding toanother

32.13. MagneticLeakage

Intheprecedingdiscussion.ithasbeen assumed that all the flux linked with primary winding also links the secondary winding. But, in practice, it is impossible to realize this condition. Itis found,however,thatall the flux linkedwithprimary does not linkthesecondarybutpartofiti.e_OLcompletesitsmagneticcircuitbypassingthroughair than around the core, as shown in Fig. 32.26. This leakage flux is produced when the m.m.f.duetoprimaryampere-turnsexistingbetueenpoints,aandFig.32.26b,actsalong 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.secondaryampere-turns(orm.m.f.)actingacrosspointscanddsetupleakage flux Φ_{L_1} 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). .

Atno load and lightloads. theprimary and secondary ampere-turns are small,hence leakagefluxes   are   negligible.ButWhenloadisincreased.bothprimaryandsecondary windings carry huge currents. Hence. large m.m.f.s areSetupwhich,while acting on leakage paths, increase the leakageflux.

Assaidearlier,theleakagefluxlinkingwitheachwinding,producesa self-inducede,m.f. in that winding. Hence, in effect, it is equivalent toasmallchokerorinductivecoilinserieswith each winding such that voltage drop in each series coil is equal to that produced by leakage flux. In other words, a transformer With
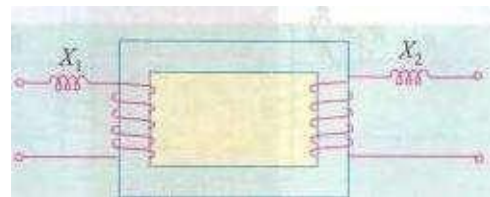
magneticleakageisequivalenttoanidealtransformerWithinductivecoilsconnecredin both primary and secondary circuils as shown in

Fig.32.27suchthattheinternale.rn.f.ineachinductiveFig.32.27coilisequaltothatdue to the corresponding leakage flux in the actual transformer.

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

ThetermsX,andXïareknownasprimaryandsecondaryleakagereactance-srespectively.

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 contributestothe transferofenergyfromtheprimarytothesecondarywinding.

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 fluxeswould result. These leakage fluxes areminimisedbysectionalizingandinterleavingtheprimaryandsecondarywindingsasin Fig. 32.6 or Fig. 32.8.

32.14. TransformerwithResistanceandLeakageReactance

InFig.32.28theprimaryandsecondarywindingsOfatransformerWithreactances 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,secondaryimpedanceisgivenby The resistance   and leakage reactance Of each winding is responsibleforsomevoltagedropineach winding.Inprimary,theleakagereactancedropis
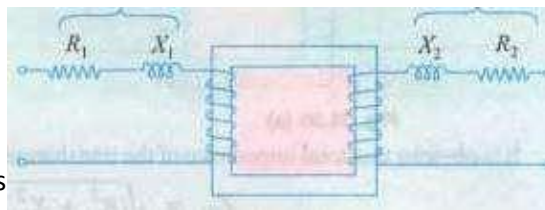
Similarly,thereare12R2and'2X2dropsinsecondarywhichcombinewithV:togiveEl.

Thevectordiagramforsuchatransformerfor differentkindsofloadsisshowninfig. 32.29.Inthesediagrams,vectorsforresistivedropsaredrawnparalleltocurrentvectors 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.
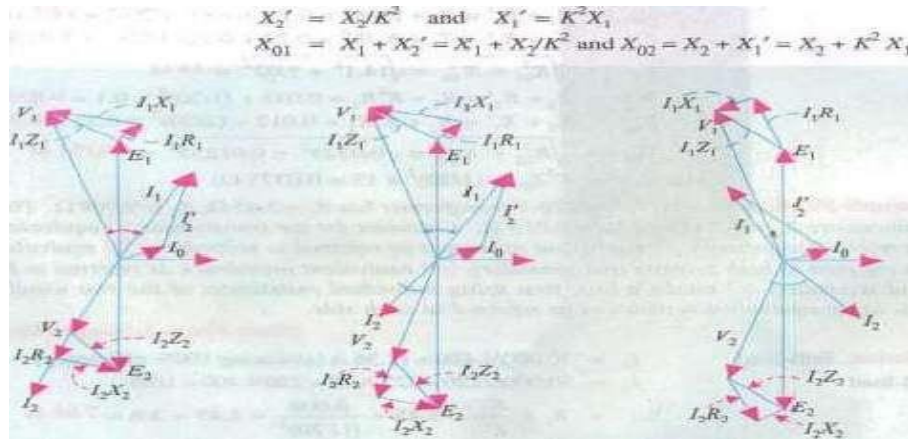
$$X_2' = X_2/K^2 \quad \text{and} \quad X_1' = K^2 X_1$$
$$X_{01} = X_1 + X_2' = X_1 + X_2/K^2 \quad \text{and} \quad X_{02} = X_2 + X_1' = X_2 + K^2 X_1$$

Fig.32.29

It is obvious that total impedance of the transformer as referred to primary is given by

32.30(a)

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

Fig.32.30(b)

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

Example 32.15. A 30 kVA, 2400/120-V, 50-Hz transformer has a high voltage winding resistance Of 0.1 and a leakage reactance of 0.22Q. 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.

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

$$R_{01} = R_1 + R_2' = R_1 + R_2/K^2 = 0.1 + 0.035/(1/20)^2 = \textbf{14.1}\ \Omega$$

$$X_{01} = X_1 + X_2' = X_1 + X_2/K^2 = 0.22 + 0.12/(1/20)^2 = \textbf{5.02}\ \Omega$$

$$Z_{01} = \sqrt{R_{01}^2 + X_{01}^2} = \sqrt{14.1^2 + 5.02^2} = \textbf{15}\ \Omega$$

(ii)

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

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

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

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

Example 32.16. *A 50-kVA, 4,400/220-V transformer has $R_1 = 3.45\ \Omega$, $R_2 = 0.009\ \Omega$. The values of reactances are $X_1 = 5.2\ \Omega$ and $X_2 = 0.015\ \Omega$. Calculate for the transformer (i) equivalent resistance as referred to primary (ii) equivalent resistance as referred to secondary (iii) equivalent reactance as referred to primary (iv) equivalent reactance as referred to secondary (v) equivalent impedance as referred to both primary and secondary (vi) total Cu loss, first using individual resistances of the two windings and secondly, using equivalent resistances as referred to each side.*

Solution. Full-load

Full-load $I_1 = 50,000/4,400 = 11.36$ A (assuming 100% efficiency)

(i) $I_2 = 50,000/2220 = 227$ A; $K = 220/4,400 = 1/20$

(ii) $R_{01} = R_1 + \dfrac{R_2}{K^2} = 3.45 + \dfrac{0.009}{(1/20)^2} = 3.45 + 3.6 = \textbf{7.05}\ \Omega$

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

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

Also Cu 10»

32.16. Total Approximate Voltage Drop in a Transformer

When the transformer is on no-load then V_1 is approximately equal to E_1. Hence $E_2 = KE_1 = KV_1$. Also, $E_2 = {}_0V_2$: where ${}_0V_2$ is secondary terminal voltage on no-load, hence no-load secondary terminal voltage is KV_1. The secondary voltage on load is V_2.
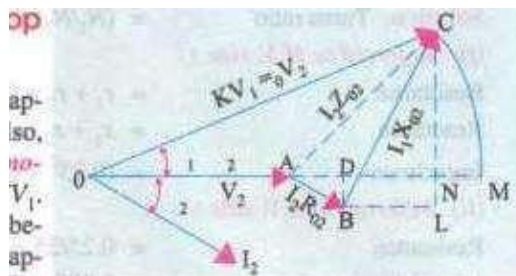

Fig. 32.35

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

The difference between the two is I_2 as shown in Fig. 32.35. The approximate voltage drop of the transformer as referred to secondary is found thus :

W'th O as the centre and radius OC draw an arc cutting OA produced at M. The total voltage drop I_2Z_{02} = AC = AM which is approximately equal to AN. From B draw BD perpendicular on OA produced.

Draw CN to OM and draw BL parallel to OM.

Approximate voltage drop

= AN = AD + DN

$+I_2X_{02}\sin$

$$= I_2R_{02}\cos\phi$$

$\phi_1 = \phi_2 = \phi \text{ (approx)}.$

where

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

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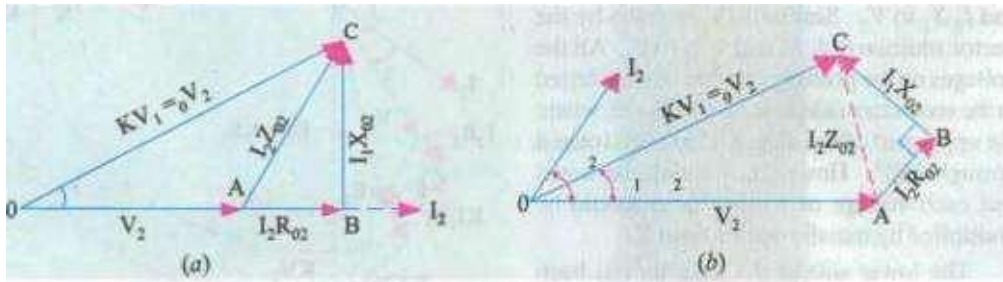
Fig. 32.36

The approximate voltage drop for leading power factor becomes $(I_2R_{02}\cos\phi \pm I_2X_{02}\sin\phi)$

In general, approximate voltage 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 $(I_1R_{01}\cos\phi \pm I_1X_{01}\sin\phi)$

% voltage drop in secondary

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

$$= \frac{100 \times I_2R_{02}}{{}_0V_2}\cos\phi \pm \frac{100\,I_2\,X_{02}}{{}_0V_2}\sin\phi$$

$$= v_r\cos\phi \pm v_s\sin\phi$$

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

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

32.17. Exact Voltage Drop

With reference to Fig. 32·35, it is to be noted that exact voltage drop is AM and not AÑ, If we add the quantity NM to 'W, we will get the exact value of the voltage drop.

Considering

Considering the right-angled triangle OCN, we get

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

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

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

$\therefore$ For a *lagging* power factor, exact voltage drop is

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

For a *leading* power factor, the expression becomes

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

In general, the voltage drop is

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

Percentage drop is the right-angled triangle OCN, we get

$$\frac{00}{20v/} \quad (12Ro,co.\pm \quad \sin \quad \cos \quad \sin$$

2

$$= (v_2 COS \pm v_2 sinO) + (1/200)(vx \quad V_2 sinO)$$

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)

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

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

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

$$\text{age} = 460 - 35.2 = 424.8\,\text{V}$$

Solution.

Voltage drop

∴ Secondary terminal voltage =

Example 32.22. Calculate the regulation ofa transformer in which the percentage resistancedropsis1.0%andpercentagereactancedropis5.0%whenthepowerfactoris (a)0.8lagging(b)unityand(c)0.8leading.(ElectricalEngineering,BannrasHinduUniv. 1988)

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

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

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

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

Example32.23.Atransformerhasareaciancedropof5%andaresistancedmpofFindthe

lagging power factoratwhichthe voltageregulationis maximum and the value of 'hi' regulation,

(Elect.FAEgg. PunjabUniv.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 $\dfrac{d\mu}{d\phi} = -v_r$

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

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

Solution.Thepercentagevoltageregulation(p)isgivenby sine. v

coso

— vrsin   vs cos = O

635^0Now,cos=0.45andsin=0.892

Maximumpercentageregulation=(2.5x0.45)+(5x 0.892)5$85

Maximumpercentageregulationis5.585andoccursatapowerfactorof0Æ5(lag).

Example 32.24. Calculate the percentage voltage drop for a transformer with a percentageresistanceof2.5%and.'reactance of5%ofrating500kVAwheniris delivering 400kVA at lagging, 'Elect. Machinery-I,

(%R)IcosO•Solution.   %drop

WhereIfisthefull-loadcutTCntand/theactual current. In

the present case,

32.18. EquivalentCircuit

The transformer shown diagrammatically in Fig. 32.37 (a) can be resolved into an equivalentcircuitinwhichtheresistance andleakagereactanceof thetransformerare

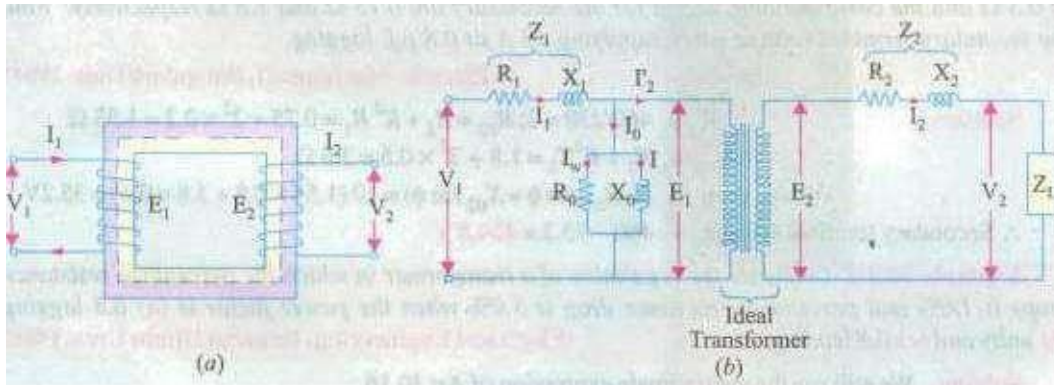imaginedtobeexternaltothewindingwhoseonlyfunctionthen istotransformthe voltage (Fig. 32.37 (b)). The no-load

Fig. 32.37

current10issimulatedbypureinductanceXo takingthemagnetisingcomponentIganda 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.ThevalueofXo=El/IoandofRo=ItisclearthatElandE,arerelatedtoeachotherby expression

Tomaketransformercalculationssimpler,itispreferabletotransfervoltage,currentand impedance

cithertothe primaryOrtothesecondary.Inthatcase. wewouldhavetoworkin onewinding only which is more convenient.

Theprimaryequi ofthesecondaryinducedvoltageisE2'E2jK=El.

Similarly.primaryequivalentOfsecondaryterminalorOutputvoltageisV,'V2/KPrimary equivalentofthe secondary current is 12' = K12.

Fortransferringsecondary impedance to primary K^a is used.
$$R_2' = R_2/K^2, \; X_2' = X_2/K^2, \; Z_2' = Z_2/K^2$$

ThesamerelationshipisLisedforshiftinganexternalloadimpedancetothe primal)'.

ThesecondarycircuitisshowninFig.32.38(O)and itsequivalentprimaryvaluesareshown infig.
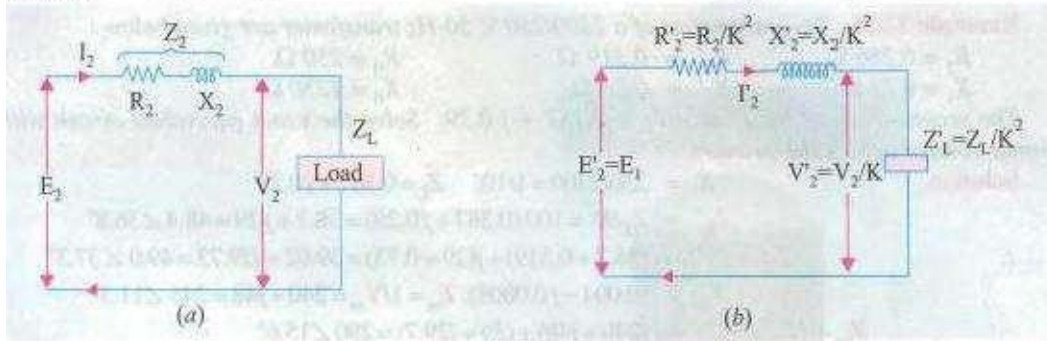
Fig. 32.38

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

The total equivalent circuit of the transformer is obtained by adding in the in Fig. 32.39. This is known as the exact equivalent circuit but it presents a somewhat harder circuit problem to solve. A simplification can be made by transferring the exciting circuit across the terminals as in Fig. 32.40 or in Fig. 32.41 (a). It should be noted that in this case $X_0 = V_1/I_\mu$.
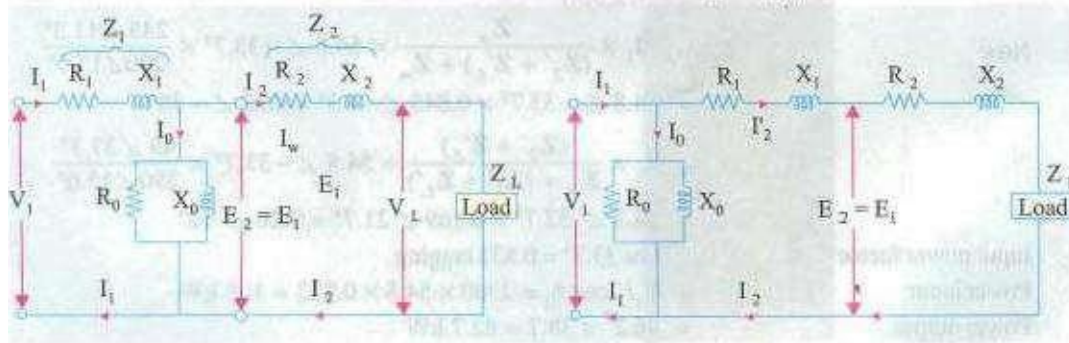
Fig. 32.39   Fig. 32.40

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

$$Z = Z_1 + Z_m \| (Z_2' + Z_L') = \left(Z_1 + \frac{Z_m (Z_2' + Z_L')}{Z_m + (Z_2' + Z_L')} \right)$$

where $Z_2' = R_2' + jX_2'$ and Z_m = impedance of the exciting circuit.

can be made by transferring the exciting circuit aero:'S the terminals as in

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

$$V_1 = I_1 \left[Z_1 + \frac{Z_m (Z_2' + Z_L')}{Z_m + (Z_2' + Z_L')} \right]$$

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

Example 32.25. *The parametres of a 2300/230 V, 50-Hz transfomer are given below :*

$$R_1 = 0.286\ \Omega \qquad R_2' = 0.319\ \Omega \qquad R_0 = 250\ \Omega$$
$$X_1 = 0.73\ \Omega \qquad X_2' = 0.73\ \Omega \qquad X_0 = 1250\ \Omega$$

The secondary load impedance $Z_L = 0.387 + j\,0.29$. *Solve the exact equivalent circuit with normal voltage across the primary.*
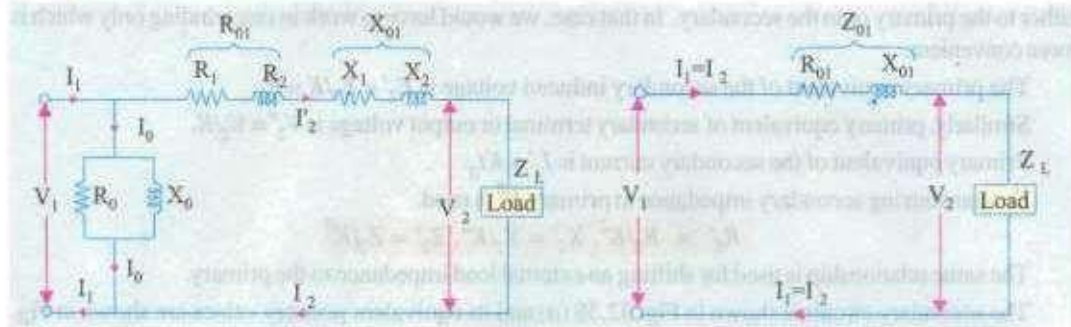
Solution.

$$K = 230/2300 = 1/10; \qquad Z_L = 0.387 + j\,0.29$$

$$Z_L' = Z_L/K^2 = 100\,(0.387 + j\,0.29) = 38.7 + j\,29 = 48.4\ \angle 36.8°$$

$$\therefore \quad Z_2' + Z_L' = (38.7 + 0.319) + j(29 + 0.73) = 39.02 + j\,29.73 = 49.0\ \angle 37.3°$$

$$Y_m = (0.004 - j\,0.0008); \quad Z_m = 1/Y_m = 240 + j\,48 = 245\ \angle 11.3°$$

$$Z_m + (Z_2' + Z_L') = (240 + j\,48) + (39 + j\,29.7) = 290\ \angle 15.6°$$

$$\therefore \quad I_1 = \cfrac{V_1}{Z_1 + \cfrac{Z_m(Z_2' + Z_L')}{Z_m(Z_2' + Z_L')}} = \left[\cfrac{2300\ \angle 0°}{0.286 + j\,0.73 + 41.4\ \angle 33°}\right]$$

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

Now

$$I_2' = I_1 \times \frac{Z_m}{(Z_2' + Z_L') + Z_m} = 54.8\ \angle -33.7° \times \frac{245\ \angle 11.3°}{290 \angle 15.6°}$$

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

$$I_0 = I_1 \times \frac{(Z_2' + Z_L')}{Z_m + (Z_2' + Z_L')} = 54.8\ \angle -33.7° \times \frac{49\ \angle 37.3°}{290 \angle 15.6°}$$

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

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

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

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

Example 32.26. *A transformer has a primary winding with a voltage-rating of 600 V. Its* transformer has a primary winding With a voltage-ratingOf 600 V. secondary-voltage rating is 1080 V With an additional tap a! 720 V. An 8 kW resistive load is connected acrossIOSO-Voutputterminals.Apurelyinductiveloadof10k VAisconnectedacross the

tapping point and common second00' terminal so as get 720 V. Calculate the primary currentandits power-factor Correlateifwiththeexistingsecondaryloads.Neglectlosses and magnetizing current. (Nagpur University, Winter 1999)

Solution.LoadsareconnectedasshowninFig.32142.

8000

$=7.41$atunityp,f.

1080

$=10000/720=13.89$atzerolaggingp.f.

These arereflected on to the primary sides with appropriate raùos ofturms, with correspondingpowerfactors.Iftheconespondingtransformedcurrentsarerepresented by theabovesymbols modified by

$$I'_{r_2} = 7.41 \times 1080/600 = 13.34 \text{ A at unity p.f.}$$
$$I'_{L_2} = 13.89 \times 720/600 = 16.67 \text{ A at zero lag. p.f.}$$

Hence,

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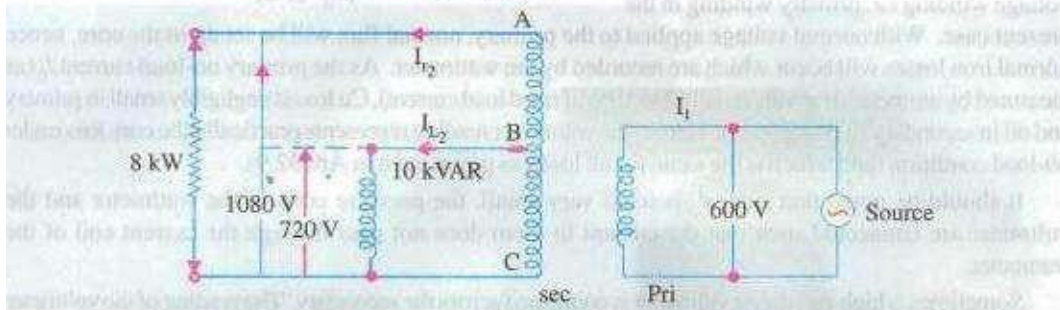

Fig. 32.42

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 unity p.f, and I OkVAR lagging s = P+iQ = g-j10kVA S = Power—

factor =

$$(8^2 + 10^2)^{0.5} = 12.8 \text{ kVA}$$

Primary current = 12.8 x $\cos\phi = 8/12.8 = 0.625 \text{ lag}$ 1000/600 = 21.33A

32.19. Transformer Tests

As shown in Ex 32.25. the performance of a transformer can be calculated on the basis of its equivalent

circuit which contains (Fig. 32.41) four main parameters, the equivalent resistance Rot as referred to primary (or secondary R02), the equivalent leakage reactance as referred to primary (or secondary x02), the core-loss conductance Go (or resistance Roj und the magnetiSing susceptance BO (or reactanceXoj.These constants or parameters can be easily 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-circuit tests of a transformer.

Small transformer

32.20. Open-circuitorNo-loadTest

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

Onewindingofthetransformer —whicheverisconvenientbut usuallyhighvollageWinding — 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 recordedbythewattmeter.Astheprimaryno-loadcurrent10[as]measuredbyammeter) is small (usually 2 to ofrated load cunænl), Cu loss is negligibly small in primaryand 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).
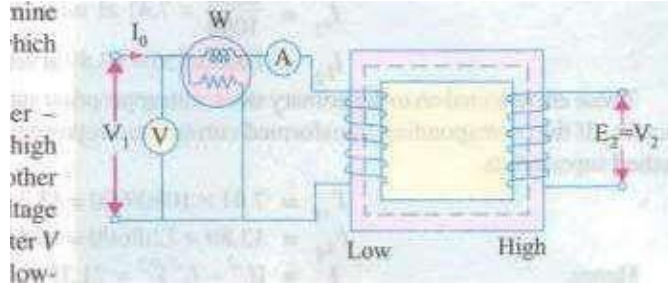
It should be noted that since is itself very small. the pressure coils Of the wattmeter and thevoltmeterareconnectedsuchthattheinthemdoesnotpassthroughthe culTentcoil Of the

Sometimes,connectedacrossthesecondary.ThereadingOfthevoltmetergivesthe induced e-m.f. in thesecondary winding._ Thishelps to find transformation ratio K.

Theno-loadvector diagramisshowninFig.32.16.IfWisthewattmeterreading(infig. 32,435.

W=VIlocos$0:.cosOo=VWVl/o

        =Iosin$o.   and

Or since the current is practically all-exciting current when a is on no-load (i.e. 10 and as thevoltagedropinprimaryleakageimpedanceishencetheexcitingadmittanceYOofthe transformer is given by 10 V, Yo or Yo = WV,.

        The exciting conductance Go is given by   VI^{2}GoorGO=

The exciting susceptance = (Y0^2— G)

Example.3227.Inno-loadrestofsingle-phasetransformer,thefollowingtesrdatawere obtained :

Primaryvoltage:220V :Secondaryvolt"ge: *110 V.* primarycurrent:0.5 A;Powerinput: 30 W.

Findthefollowing :

(i'Theturnsratio(inthemagtierisingcomponouofno-loadeurrent(iii'itsworking(orloss) component ii the iron loss.

Resistanceoftheprimarywinding=0.6ohm.

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

Solution.

(iiij　　Gcos.-O.5x0.273—O.1365A

PrimaryCuloss=0:52x0.6£0.15w Ironloss=30-0.15=29.85w

Example32.28.'5WA200/1000V50single-phasefransfOrmeÈgaveresults. SC.

O)Calculatetheparametersoftheequivalentcircuitrcferred10the Lside.

(ii) Calculafe'heoutputsecondaryvoltagedelivering3kWprimarybeing200V,Find(he percènrakg regulation also.

(NagpurUniversity,November19%)

Solution.(i)Shuntbranchparametersfrom O.C.test(L.V.side):

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

AllthesearereferredtoLV.side.

(ii)Series.hranchparametersfromS.Ctest(H.Vside):

SincetheS.C.testhasbeenconducted　　　fromH.V.side,theparameterswillrefertoH.V. side.TheyshouldbeconvertedtotheparametersreferredtoL.V. sidebytransforming them suitably.

FromS.C.Testreadings,

ThesearereferredtoH,V'side.

Equivalentcircuitcanbedrawn withRoundXmcalculated.tboveandr,andXl.sabove. L V.

Current at rated load= 5000/200 = 25 A

LN.　　lagging=18.75A

3222Short-CircuitorImpedanceTest

This is an economical method for determining the following : iii EAuivalent irnrrdance   orG), leakage reactance (Xo, or Xo:) and total resistance(orR,z)ofthetransformeras referred to the winding in which the meaSuring irwtruments are placed.
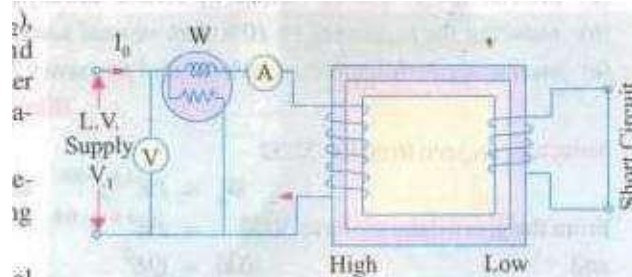
(iiiCulossatfullload(andatanydesired load). 'This loss is used in calculating the efficiency ofthe transformer liii' KnowingZo,orZo:,the totalvoltage dropinthe transformerasreferredFig.32.45toprimaryorsecondarycanbecalculatedand hence regulation Ofthe transformerdetermin

In this test. one winding, usually the low-voltage winding, issolidly short-circuited by a thickconductor(or throughanammeterWhichmayservetheadditionalOfindicatingrated load curtrnt) as shown in FIE, 32.45.
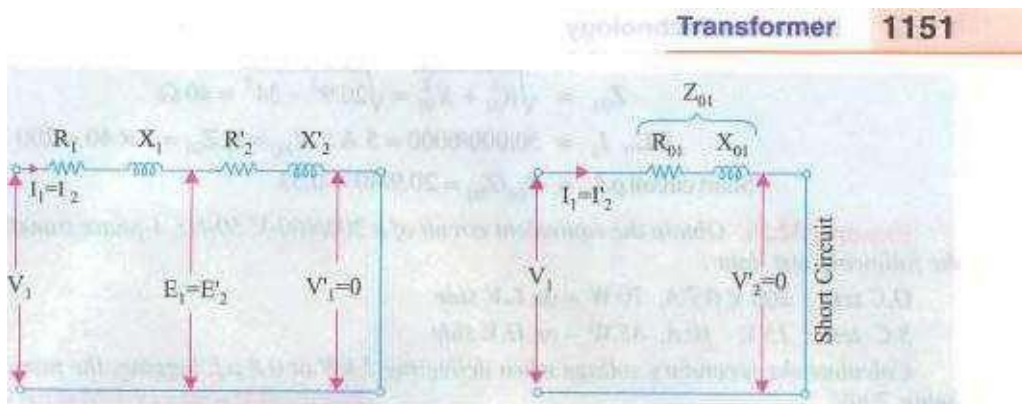
Fig.32.46

A low voltage (usually 5 to   arnormalprimaryvoltage)atcorreclfrequency(thoughforCu 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 Þ produced is also a small percentage of its normal value (Art. 32.6), Hence. core losses are very small With the result that the wattmeter reading 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 $\quad W = I_1^2 R_{01}$

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

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

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.
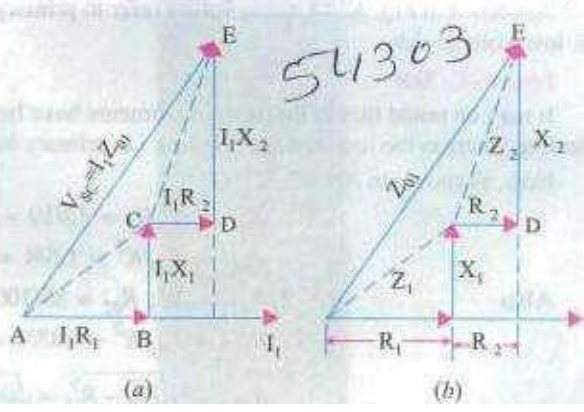
If R, can be measured, then knowing R_{01}, we can find R_2' $R_0 - R_1$. The

1^2R loss for the whole transformer i.e. both primary Cu loss and secondary Cu loss, The equivalent circuit of the tramsformer under shon-ciœuit 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 $\quad \therefore \quad \eta = \dfrac{5000 \times 0.8 \times 100}{4000 + 149.4} = \textbf{96.42\%}$

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

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

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

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

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. Such á transformer is mainly œquired for isolation.

Transformer1161

RatedCurrent=13amp

230

Co-lossesatratedload120watts.fromSC.test

Core losses 100Watts,fromO.C.test

Atfull load. VAoutput - — 3000

At 0.8 lag p. Poweroutput

Required efficiency =

FromS.C.test.

Approximatev01tageregulation

13.51

Intermsofthevoltageregulation=230x100% -5.874%

Example32.49.A10kVA,500/250V.single-phasetransformerhasitsmaximumefficiencyof 94% When delivering Estimate its efficiency when delivering ifs full-load output p.f. of 0.8 lagging. (Nagpur UniveÑty, November 1998'

Solution.Ratedoutputagunityp.f.=10000W.Hence,ofratedOutput=9,000W Input

with efficiency =

Losses=

Atmaximumefficiency,variablecopper-loss=constant=Core $574/2 = 287$ W loss=574/2

Atratedcurrent,Letthe copper-losspcwalls

At90%loadwithunityp.f..thecopper-lossisexpressedas0.90^2xPi.

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

ofcalculationofvoltage-magnitudes,approximavfOrrnuJaforvoltageregulationcanbeused. For the present case of 0.8 lagging p.f.

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

230+43.5 (0.316x

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

ItmeansthatH.V.sideterminalvoltagemust2410forkeeping230Vatthespecifiedload.

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

With Lagging p.f., sign is retained. With leading poWer-factor. the —ve sign is applicable. For the voltage-regulation to be zero. only leading Bf. condition can prevail. sinO

=nix-0.0792/0316=0.25

=140.cos4=0.97 leading

Corresponding sin o=Sin 0.243

H.V. terminal voltage required is 23mV to maintain 230 Vat since regulation condition is under discussion.

Example 32.51. A 5kVA. 2200 Q 20 single-phase transformer has the following parameters.

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

LV: 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 LV. 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 on H.V. side can be obtained after transformation.

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

Total winding resistance ref. to L.V. side = $r_1' + r_2 = (220/2200)^2 \times 3.4 + 0.028$

Total winding-leakage-reactance ref. to L.V. side = $x_1' + x_2$

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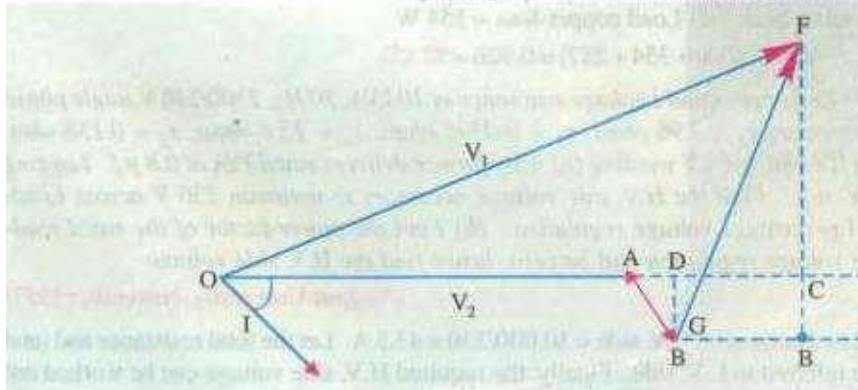

Fig. 32.53(c)

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

$QA = V_2 = 220$ volts, $I = 22.73$ A at lagging phase angle of 36.87°

$AB = Ir$, $AD = Ir \cos \phi = 22.73 \times 0.062 \times 0.80 = 1.127$ V

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

Rated

OC = 220+1.127+1.80 = 222.93 volts

BD = 'rsin4' = O. 85N

VF = xco. = 2.40V

CF = 240-0.85 = 155v

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

Required terminal voltage of H.V. side - VI-222935(2200/220)=2229g5volts

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

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

(Nagpur University April 1999)

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

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

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

And Constant core-loss = 65 W

From S.C. test, Z = 15/10 = 1.5 ohms

$$R = 75/100 = 0.75 \text{ ohm}$$
$$x = \sqrt{1.5^2 - 0.75^2} = {=130} \quad \begin{vmatrix} 1.52 - \\ 0.752 \end{vmatrix} \text{ ohms}$$

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/ 6575)

= 0.966 - 966%

Full load voltage regulation at 0.80 lagging p.f.

Thus, due to loading, H.M side voltage will drop by 16.14 volts (i.e. terminal voltage for the load will be 383.86 volts), when EV. side is energized by 200-V source.

32.25. Percentage Resistance, Reactance and 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)Percentageimpedanceatfull-load

It may be noted that percentage resistance, reactanceandimpedancehavethesamevalue whether referred to primary or secondary.

=1.648+5.87=7.52%

Example32.57.AiràhsformerhascoppeNossofand reactance-drop of3.5% when tested at full-load. Calculate its full-load regulation at (i) (ii) 0.8 pl. Laggingand(iii)0.8p'.Leading.(Bharathithasan Univ. April 1997'

Solution.Thetest-dataatfull-loadgivesfollowing parameters :

p.a.resistance=0.015,p.o.reactance—0.035

(t)ApproximateVoltage—Regulationatunityp.f.fullload

=0.015cos040.035sin4'

=0.015perunit=1.5%

(ii)   ApproximateVoltage—Regulationat0.80Laggingp.r.
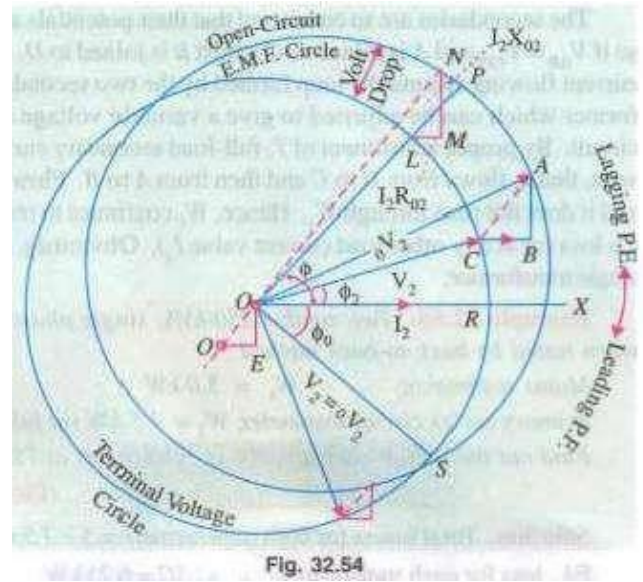
(iii)   ApproximateVoltageRegulation

$= (0.015 \times 0.8) + (0.035 \times 0.6) = 0.033$ 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 $= -0.9\%$ at0.8

Fig. 32.54

32.26. KappRegulationDiagram

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,secondaryterminalvoltagenotonlydependsonthe loadbuton powerfactoralso(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.

FordrawingKappregulationdiagram,itisnecessarytoknowtheequivalentresistanceand reactance as referred to secondary i.e. R02 and x02_ If is the secondary load current, then

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secondaryterminalvoltageOnloadV2.isobtainedbysubtracting12and12x02voltage 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 theload current and is taken as the reference vector, CB represents 12 Rm and is parallel to 012,AB represents I_2x02 and is drawn at right angles to CB. Vector OC obviously represents and is drawn at rightanglestoCB. Vector OCobviously represents secondary terminal voltage Since 12 isconstant, the drop triangle ABC remains constant in sizz It is seen that end point C ofV:liesonanother circlewhosecentreis O'.Thispoint(Yliesatadistance of12venicallylow 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 ofcosthen aradius OLP is drawn inclined at an angle of with OX. LM = 12 and is drawn horizontal MN=12x02 andisdrawnperpendicularto 1M.Obviously,ONisnoloadvoltageov:.Now,ON OP ov2. Similarly. OLis V2. The voltage drop-op-OL=LP.

$$\frac{OP - OL}{OP} \times 100 = \frac{LP}{OP} \times$$

Hence.percentageregulation•downis—   100

Itisseenthatfor findingvoltagedrop.triangleI-MNneednotbedrawn.butsimplytheradius 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 angleof00leading,thefallbecomeszero;henceV,= ov2.Foranglesgreaterthansecondary terminal voltage V: greater than oV_2

The Kapp diagram is very helpful in determining the variation of regulation with the radii of the circles. diagram has to be drawn on a very large scale, if sufficiently accurate results are

32.27. Sumpner Of Back-to-Back Test

This test provides data for finding regulation. efficie1EY and heating conditions and is employed only similar transformers are available.

is loaded on the other are connected to supply. The from the supply is that ne œssary for the losses of both transfOrmers rEgligibly small in the control

As shown in Fig. 3255. primaries two transformers are connected across the same a.c. supply. With open, the wattmeter WI reads the for the two .ra1VSfornErs.

Fig. 32.55

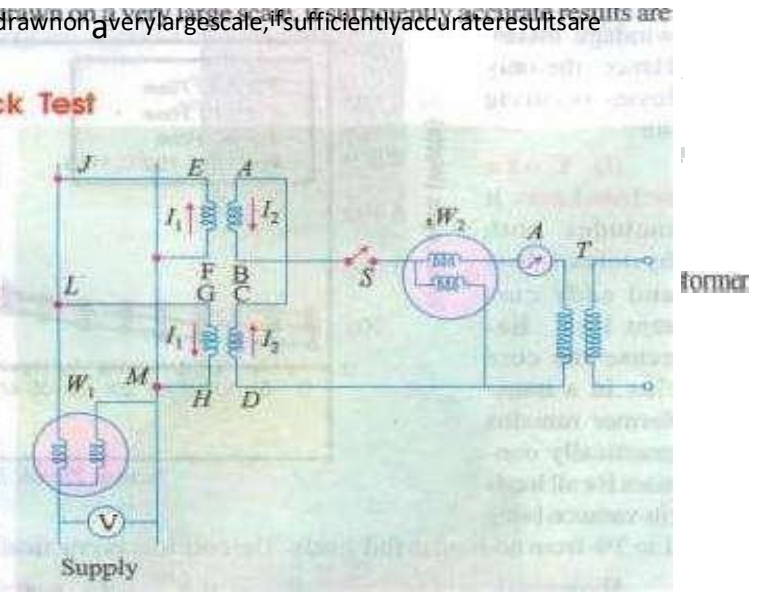power factor but it has the disadvantage that since the lengths of the sides of the impedance triangle are small as compared to The secondaries are so connected that their potentials are in opposition to each other. This would so if VAB = vCD and A is joined to C whilst B is joined to D. In that case, there would be no secondary current flowing around the loop formed by the two secondaries. Tis an auxiliary low-voltage transformer which can be adjusted to given variable voltage and hence current in the secondary loop circuit. By proper adjustment of T, full-load secondary current can be made to flow as shown. It is seen, that 12 flows from D to C and then from A to B. Flow of is confined to the loop FEJLGHMF and it does not pass through WI. Hence, W, continues to read the core loss and W2 measures full-load Cu loss (or at any other load current value 12). Obviously, the power taken in is twice the losses of a single transformer.

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

Mains WI = 5.0 kW

Primary series circuit Wattmeter, W2 ___ Z-5kW 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

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

(i) **Core or Iron Loss:** It includes both hysteresis loss and eddy current loss. Because the core flux in a transformer remains practically con-
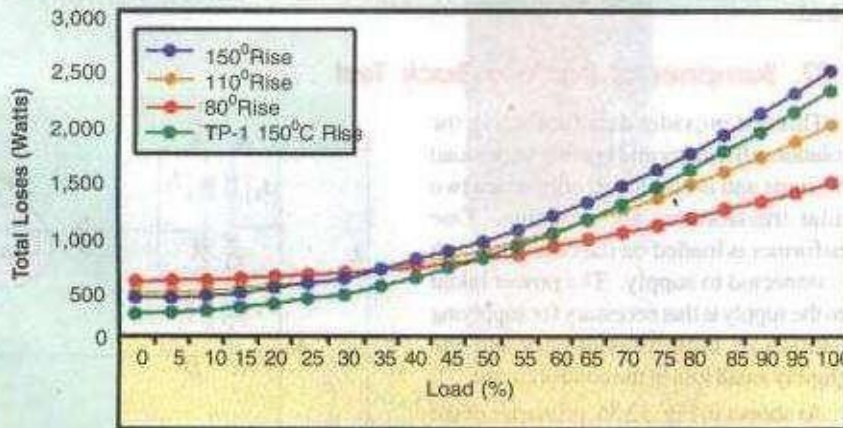
Stant for all loads   Typical 75 kVA Transformer Losses NS, Load

(its   tx•ing

I to 3% from no-load to full-load). The core loss is practically the same at all loads.

Wh= $\eta B_{max}^{1.6} f$

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

(ii) Copper loss. This loss is   resistance

$= 11^2 R_1 + R_{ot} + $ It is clear that Cu loss ik proportional to (current/or kVA. In other words, Cu loss at half the full-load is one-fourth of that at full-toad.

The value Of CUIOSS 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 particularloadandpowerfactorisdefinedastheoutputdividedbytheinput—thetwobeing measured in the same units (either watts or kilowatts)

$$Efficiency = \frac{Output}{Input}$$

But a transformer being ahighly efficient piece ofequipment, has very small loss, hence it is imppracticål to to measure transformer, efficiency by measuring input and output. These quantitiesarenearlyofthe samesire,Abettermethod istodeterminethelossesandthen to calculate theefficiency from

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

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

Ou!pyt

It may be noted here that efficiency is based on power output in watts and not in volt-amperes,althoughlossesareproportionaltoVA. Hence;at anyvolt-ampere load. theefficiency depends on power factor, beingmaximum at a power factorofunity.

Efficiency can be computed by determiningcore from testandCu lossfromtheshort-circuittest,

32.30. ConditionforMaximumEfficiency

culoss

Forntobemaximum.

The output current cormsrxmding to maximum efficiency is $1_2 = \sqrt{(W_i/R_{02})}$ It is this value of the output current which will make the Cu loss equal to the iron losg. 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
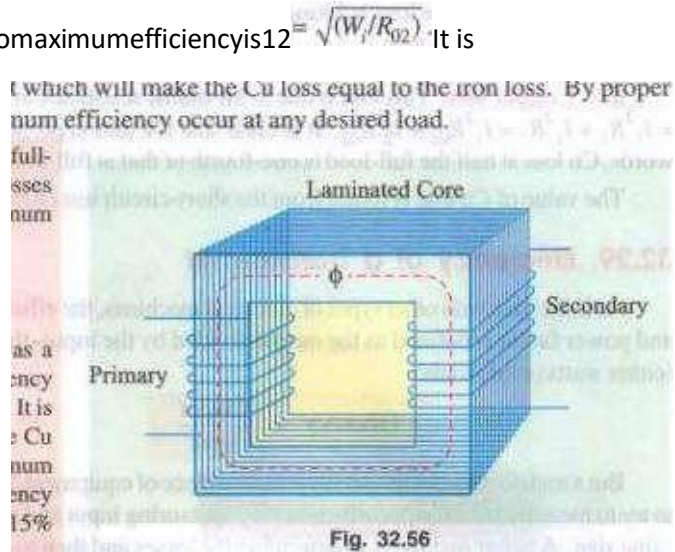
Fig. 32.56

-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 at any load is given by

where x

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

(i) full load (ii) half full-load.

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

(Elect.Engg.&Electronic.BangaloreUniv.1990 and

Similar example in U.P.TechnicalUniversity 2001)

Total loss =

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

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

output at u.p.f. = 12.5 kW

Example 320.   and p: be the iron and copper losses of a transformer on full•load. find the ratio Of P, and pz such that   efficiency occurs at   full-load.

Sec. B, Summer 1992)

Solution. If P: is the Cu loss at full-load, its value at 75% of full.load is—p: At maximum efficiency, it equals the iron loss pa which remains constant throughout. 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 Of 1.4 kW and EL Cu loss Of I kW Determine

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

(i or he efficiency at half EL 0.8 p.f. leading (BasicElect-Machine, NagpurUniv. 1993)

Solution.(i) Load WA corresponding to maximum efficiency is

Since Cu loss equals iron $= F.L. kVA \times$ loss at maximum efficiency, totul loss output =160 xI=160 kW

=160/162.8-0.982 or 9K2%

(ii) Cu loss at half full-load $= 1.6 k (1/2)^2 = 0.4$ kW Total loss=1.440.4= 1.8kW Half EL.

output at 0.8 p.f.= ($0/2) \times 0.8 = 60$ kW 150/2) FAliciency =

Example 32.62. A 5-kVA.2,30 QQ30-u50•Hz transformer was tested for the iron losses' With normal excitation and Cu losses at full-loud and these were found to be 40 W and 112 W 'espectively.

Calculate the efficiencies Of the transformer at 0.8 power factor for the following 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
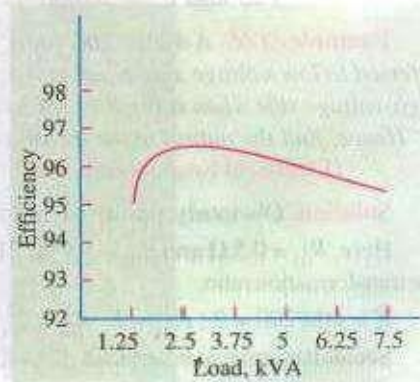
$\eta = 6 \times 100/6.292 = $ **95.36 %**

Fig. 32.57

Thecurveisshowninfig.32.57.

Example32.63.2ffl-kVAtransformerhasanefficiencyOfarfullload.themat.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.Asgiven.thetransformerhasaELefficiencyof98%   pr.

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

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

Full-load=20,000x100/(20.000464.4)=9-7.'%

Example32.6*.A4-kVA.V,I-phasetransfonnerhasequivalentn•sistanceandœacrance referredrolow-voltagesideequaltoO,5121.5QrespectivelyFindtheterminalvoltageOn

1165

the high-voltage side When supplies 3/4 1/1 full-load a/power factor Of O.8, the supply voltage being 220 V Hence, find the output transformer and its efficiency if the core losses are 100W.

(Electrical Engineering : Bombay Univ. 1985'

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

Here, ROIQ and =IS 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 (X4X3/4)/4007SA

Total drop as referred to transformer secondary is

Terminal voltage on high-voltage side under given load condition is =400-39=361 v culoss= Iron loss 100 W

=212SW   output=(4x3/4)x0.8=2.4kW

Input=2.400+212.5-2,612.5wn-2.400x100/2,612.5=91.87

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

Assuming a lagging   factor

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

Hence. efficiency would be maximum at 90% of EL

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

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

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

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

Calculate the load at unity power factor corresponding to marimum efficiency i Eleci. Machines Nagpur Univ. 1993È

Solution. Full-toad. = 4000/400 =10A

It means that S.C. test has been carried out with full Secondary flowing, Hence, 60W 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-loadatunitypowerfactor.Determineitsefficiencyat60 %offull-loadatO.Spowerfactor lag.

Sec.B,

x ICO

2

(xxWA)xcos+W, +.rWcuwherexrepresentspercentageOffull-load W,isironlossand Wcu is full-load Cu loss,

    At EL u.p.r.   Herex=

    W/+   -52.174kW

Atha1fFLUPEHer-ex=

*100;

=85.9%

hasanefficiencyOf92%atfull-loadandalsoathalf-load.DetermineitsefficiencyWhenit operates at p.j: and 60 Of load.(Electric. Machines. Kerala Univ. 1987)

Solulion.Thefactthat efficiencyisthesame 92%atbotbfull-loadandhalf-loadWill helpus to find the iron and copper losses.

At full-load

Output-600kW;

SinevCulossbecoloesone-fourthofitsEL.value,hence $x+y/4-26.$lSolvingfor-randy.we get 17.4   kW ; y=

At60full-loadcu   0.62x34.s=1253kW;Totalloss-17.4+12.53-29.93kW

    =360kW   •02360/389.93=0.965 or 96.5

Example32.70.Themaximumefficiency Ofa/OO-kVA,Singlephasetransformerisandoccurs 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,NagpurUniv.   1993)

Solution.Sincemaximumefficiency occursat80percentOffull-loadat0.8p.f..

64/0.98=65.3kW

Culossatfull-load=0.65/0.8^2=IkW Cu

loss1 00

x100-

lxIOO

%ageregn,=   +50.6)

Example32.71.A10WA,5(YW440- singlephasetransformerhaseddyCurrentandhysteresis 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 ?

Assumeunitypowerfactoroperation.Comparethefullloadefficienciesforrhenvocases.

(Elect.Machines,   B,1991

Solution.WeknowthatEl= 4.44fWhen bothexcitationvoltageandfrequencyaredoubled, flux remains unchanged.

FL.outputatupf10kVAxI10kW

FLCuloss1.5x10/100=0.1SkW:Eddycurrentloss

= 0.5x=0.05kW:Hysteresisloss=0.6x

Now, full-load current is kept constant but voltage is increased from 5000 V to 10.000 V. Hence, outputwillbedoubledto20 kW.Duetoconstantcurrent,Culosswouldalsoremain constant.

New   =0.15kW,%culoss

Now,eddycurœntloss

New eddy current loss -0.05   IOO-1%

Now, = 0.06x (50/25) - 0.12 kW, %

at 0.8 p.f.   a/normalvoltage

Solution.

Example32.73.AsinglephaketransformerisratedatIOO•kVA,2300/230-V.50   HZ. Themaximumflux density inthe core is l. 2Wb/m^{2}andthe net cross-sectional areo Ofthe core is O. 04"1^2.

Determine

(a)   ThenumberofprimaryandSecondaryturnsneeded.

(b)   [fthemeanlengthOf themagneticcircuitis2.5mand the*elativepermeabilityis 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 opencircuitWithratedvoltage,thepowerinputwas 400W.Determinetheefficiencyof the transformer at 75 % offull-load With 0.8 p.f lag.

(d)   Ifthesametransformerisconnectedtoasupplythefrequency

     (i.e..100   Whariseffectonifsefficiency?(Elect.Engg„BombayU"is.19tB)

—9.21A

Output—100x(3/4)

(d) Whenfrequencyisdoubled.ironlossisincœased   because

   (i)   hysteresislossisdoubled—

   (ii) eddycurrentlossisquadrupled—WeHence.efficiencywilldecrease

whatisrhepower-factorar Whichrheregulationwill•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:Approximateperceptageregulationisgiven,inthi'case,by therelationship I

          5.4 sin O.

la)Regulation:

(i'Ifregulationiszero.negativesignmustbeapplicable.Thishappensatleadingsp.f.

          Correspondingpf.   =   leading

=18.44"leading

    Formaximumpositiveregulation,laggingp.f_isamust.Fromphasordiagram,the can be obtained.

     Correspondingtan   5.4/1.8

%Voltageregulation=1.8cos4+5.4sin0=5.7%(b)Efficiency:Maximumefficiencyoccursat such a Iron losses =

AUTOTRANSFORMER

An **autotransformer** isakindof electricaltransformer whereprimaryandsecondary sharessamecommonsinglewinding.Sobasicallyit'saonewindingtransformer.

AutotransformerTheory

In an auto transformer, one single winding is used as primary winding as well as secondarywinding.But intwowindingstransformertwodifferentwindingsareused for primary and secondary purpose. A circuit diagram of auto transformer is shown below.

Auto Transformer
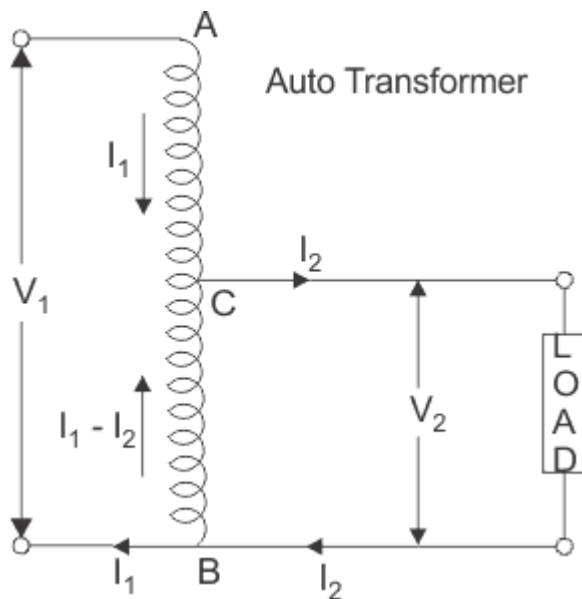
The winding AB oftotalturns N_1 is consideredas primary winding. This winding is tappedfrompoint'C'andthe portionBCisconsideredassecondary.Let'sassume the number of turns in between points 'B' and 'C' is N_2.

IfV$_1$ voltage isapplied acrossthewindingi.e.inbetween'A'and'C'.

$$So\ voltage\ per\ turn\ in\ this\ winding\ is\ \frac{V_1}{N_1}$$

Hence,thevoltageacrosstheportionBCofthewinding,willbe,

$$\frac{V_1}{N_1}XN_2\ and\ from\ the\ figure\ above,\ this\ voltage\ is\ V_2$$

$$Hence,\ \frac{V_1}{N_1}XN_2 = V_2$$

$$\Rightarrow \frac{V_2}{V_1} = \frac{N_2}{N_1} = Constant = K$$

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,
$$(N_1 - N_2)I_1 + N_2(I_2 - I_1)$$

$$\Rightarrow N_1 I_1 - N_2 I_1 + N_2 I_2 - N_2 I_1$$

$$\Rightarrow N_1 I_1 + N_2 I_2 - 2N_2 I_1$$

$$\Rightarrow 2N_1 I_1 - 2N_2 I_1 \, (Since, \ N_1 I_1 = N_2 I_2)$$

$$\Rightarrow 2(N_1 I_1 - N_2 I_1)$$

In similar way it can be proved, the weight of copper in two winding transformer is proportional to,
$$N_1 I_1 - N_2 I_2$$

$$\Rightarrow 2N_1 I_1 \qquad (Since, \ in \ a \ transformer \ N_1 I_1 = N_2 I_2)$$

$N_1 I_1 + N_2 I_2$

$\Rightarrow 2N_1 I_1 (Since, in a transformer $N_1 I_1 = N_2 I_2$)

Let's assume, W_a and W_{tw} are weight of copper in auto transformer and two winding transformer respectively,

$$Hence, \quad \frac{W_a}{W_{tw}} = \frac{2(N_1 I_1 - N_2 I_1)}{2(N_1 I_1)}$$

$$= \frac{N_1 I_1 - N_2 I_1}{N_1 I_1} = 1 - \frac{N_2 I_1}{N_1 I_1}$$

$$= 1 - \frac{N_2}{N_1} = 1 - k$$

$$\therefore W_a = W_{tw}(1 - k)$$

$$\Rightarrow W_a = W_{tw} - kW_{tw}$$

$\therefore$ Saving of copper in auto transformer compared to two winding transformer,

$$\Rightarrow W_{tw} - W_a = kW_{tw}$$

400/220KV Single Phase Transformer

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 becauseoflessohmiclossandcore lossduetoreductionoftransformermaterial.

3. Autotransformerhasbetter[voltageregulation](link)as[voltagedrop](link)in[resistance](link)and reactance of the single winding is less.

DisadvantagesofUsingAutoTransformer

1. Because of electrical conductivityof the primary and secondary windings the lower voltage circuitis liable tobe impresseduponby higher voltage. Toavoidbreakdown inthelowervoltagecircuit,itbecomesnecessaryto designthelowvoltagecircuitto withstand higher voltage.

2. The[leakageflux](link)betweentheprimaryandsecondarywindingsissmallandhencethe impedance is low. This results into severer short circuit currents under fault conditions.

3. Theconnectionson primaryandsecondarysideshavenecessarilyneedstobesame, except when using interconnected starring connections. This introduces complicationsduetochangingprimaryandsecondaryphaseangleparticularlyinthe case of delta/delta connection.

4. Becauseofcommonneutralinastar/starconnectedautotransformeritisnot 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 voltageadjustmenttappingsareprovided.Itshouldbeknownthattheprovisionof tapping on an auto transformer increases considerably the frame size of the[transformer](link).Iftherangeoftappingisverylarge,theadvantagesgainedininitial cost is lost to a great event.

ApplicationsofAutoTransformers

1. Compensating[voltagedrops](link)byboostingsupplyvoltageindistributionsystems.

2. Autotransformerswithanumberoftappingareusedforstartinginductionand synchronous motors.

3. **Autotransformer**isusedasvariacinlaboratoryorwherecontinuousvariableover broad ranges are required.

INSTRUMENTTRANSFORMER

InstrumentTransformersareusedinACsystemformeasurementofelectricalquantitiesi.e. voltage, current,power, energy, power factor,frequency. **Instrument transformers** are also used with protective relaysfor 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 costlytodesignthemeasuringinstrumentsformeasurementofsuchhighlevelvoltageand current. Generally measuring instrumentsare designed for 5 A and 110 V.

Themeasurementofsuchverylargeelectricalquantities,canbe madepossiblebyusingthe Instrument transformers with these small rating measuring instruments. Therefore these instrument transformersare very popular in modern power system.

AdvantagesofInstrumentTransformers

1. ThelargevoltageandcurrentofACPowersystemcanbemeasuredbyusing small rating measuring instrument i.e. 5 A, 110 – 120 V.

2. By using the instrument transformers, measuring instruments can be standardized.Whichresultsinreductionofcostofmeasuringinstruments. Moreeverthedamagedmeasuringinstruments canbereplaced easywith healthy standardized measuring instruments.

3. Instrument transformers provide electrical isolation between high voltage power circuit and measuring instruments. Which reduces the electricalinsulationrequirementformeasuringinstrumentsandprotectivecircuit sand also assures the safety of operators.

4. Severalmeasuringinstrumentscanbeconnectedthrougha single transformer to power system.

5. Duetolowvoltageandcurrent levelinmeasuring andprotectivecircuit,there is low power consumption in measuring and protective circuits.

**TypesofInstrumentTransformers**

Instrumenttransformersareoftwotypes−

1. CurrentTransformer(C.T.)

2. PotentialTransformer(P.T.)

CurrentTransformer(C.T.)

Current transformeris used to step down the current of power system to a lower leveltomakeit feasibletobemeasuredbysmallratingAmmeter(i.e.5Aammeter). A typical connection diagram of a current transformer is shown in figure below.

**Current Transformer (C.T.)**
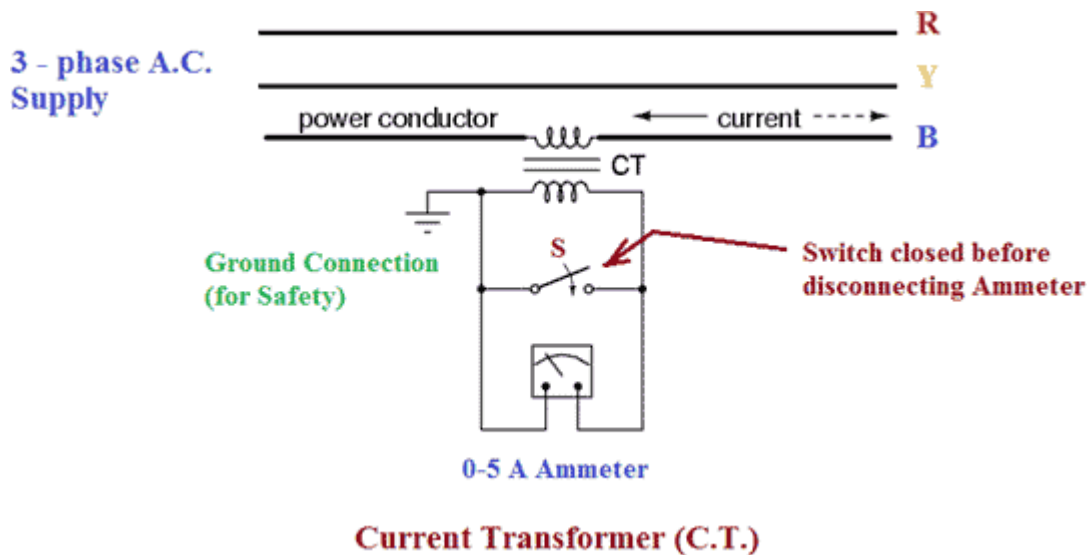
PrimaryofC.T.ishavingveryfewturns.Sometimesbarprimary isalsoused.Primary is connected in series with the power circuit. Therefore, sometimes it also called **series transformer**. The secondary is having large no. of turns. Secondary is connected directly to an ammeter. As the ammeter is having very 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 secondarywithrespecttoearth. Whichinturnsreducethechancesofinsulation breakdownandalsoprotecttheoperatoragainsthighvoltage.Moreeverbefore 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.

PotentialTransformer(P.T.)

Potential transformeris used to step down the voltage of power system to a lower level to make is feasible to be measured by small rating voltmeteri.e. 110 – 120 V voltmeter.Atypicalconnectiondiagramofa potentialtransformerisshowingfigure below.
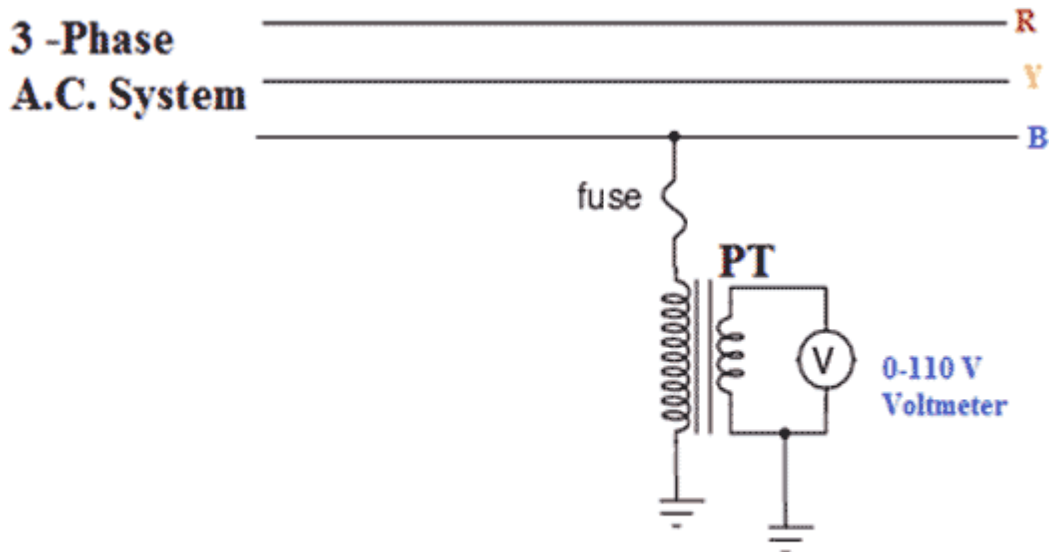
Potential Transformer (P.T.)

Primary of P.T. is having large no. of turns. Primary is connected across the line (generallybetweenonlineandearth).Hence,sometimesitisalsocalled the**parallel transformer**. Secondary of P.T. is having few turns and connected directly to a voltmeter. As thevoltmeteris having largeresistance. Hencethesecondary of aP.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.

DifferencebetweenC.T.andP.T.

Fewdifferencesbetween C.T. and P.T. are listed below–

Sl. No.	CurrentTransformer(C.T.)	PotentialTransformer(P.T.)
1	Connectedinserieswithpowercircuit.	ConnectedinParallelwithPower circuit.
2	SecondaryisconnectedtoAmmeter.	Secondaryisconnectedto Voltmeter.
3	Secondaryworksalmostinshort circuited condition.	Secondaryworksalmostinopen circuited condition.
4	Primarycurrentdependsonpower circuit current.	Primarycurrentdependson secondary burden.
5	Primary current and excitation vary overwide rangewithchangeofpower circuit current	Primary current and excitation variationarerestrictedtoasmall range.
6	Oneterminalofsecondaryisearthedto avoid the insulation break down.	Oneterminalofsecondarycan be earthed for Safety.
7	Secondaryisneverbeopencircuited.	Secondarycanbeusedinopen circuit condition.