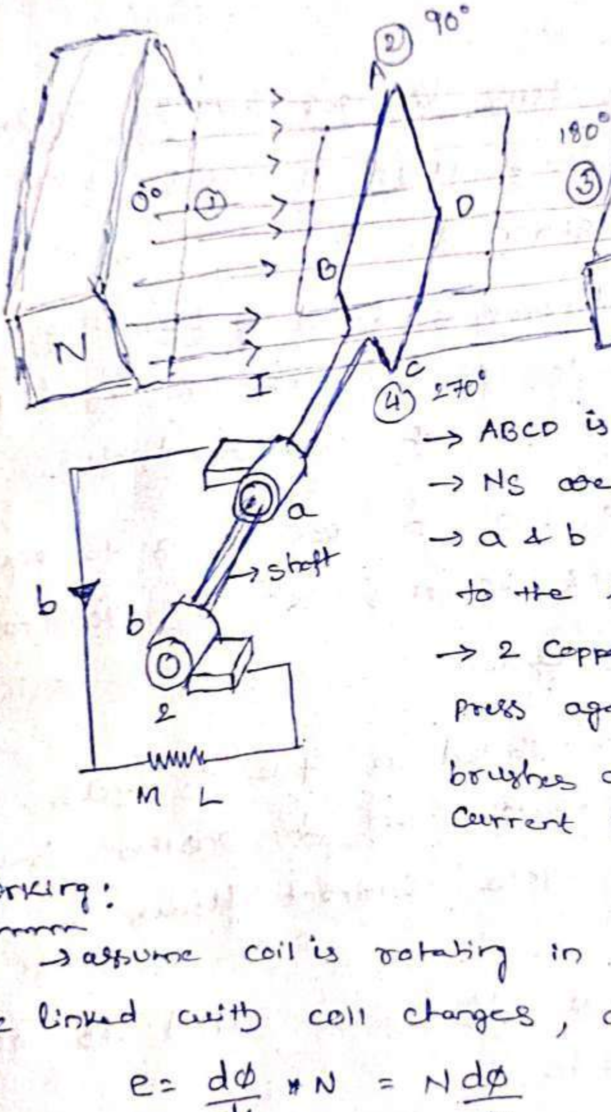
DC- Generators → Unit - (2)

principle

It is a machine which converts mechanical energy i/p into electrical energy. O/p of DC Generator is DC electrical. Whenever a rotating conductor is placed in a stationary magnetic field, a dynamically induced emf is induced in a conductor. If conductor ends is short circuited then current flows through a conductor.



→ ABCD is a rotating conductor
→ NS are stationary magnetic poles
→ a & b are slip rings connected to the shaft.
→ 2 copper or carbon brushes press against the slip rings, brushes are used to collect current from the conductor.

Working:

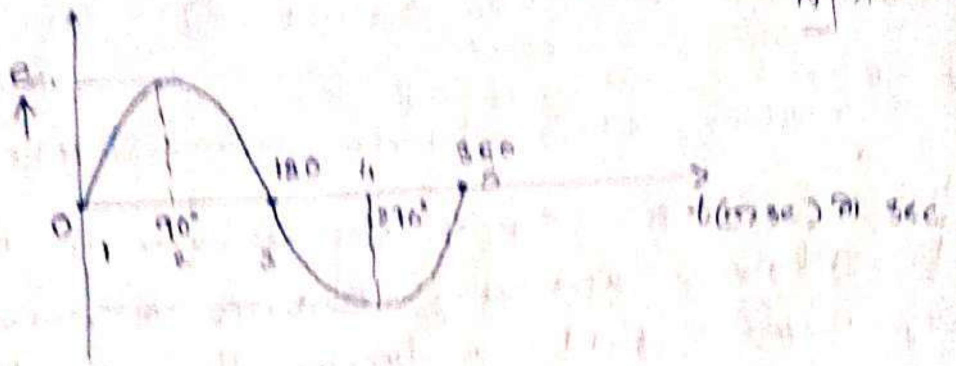
→ assume coil is rotating in clock wise direction, flux linked with coil changes, an emf is induced

$$e = \frac{d\phi}{dt} * N = N\frac{d\phi}{dt}$$

If coil sides AB & CD are parallel to magnetic lines, no emf is induced.

If $\theta = 90°$ or $270°$, Maximum flux is cut by conductor, an emf is induced.

If $\theta = 0$ or $180°$ emf is zero.



from 0° to 90°, rate of change of flux linkages increases hence emf also increases. (from 0 to 90° or position 1 to 2).

from 90° to 180°, flux linkages cut by conductor decreases, resultant emf also decreases seen from position 2 to position 3.

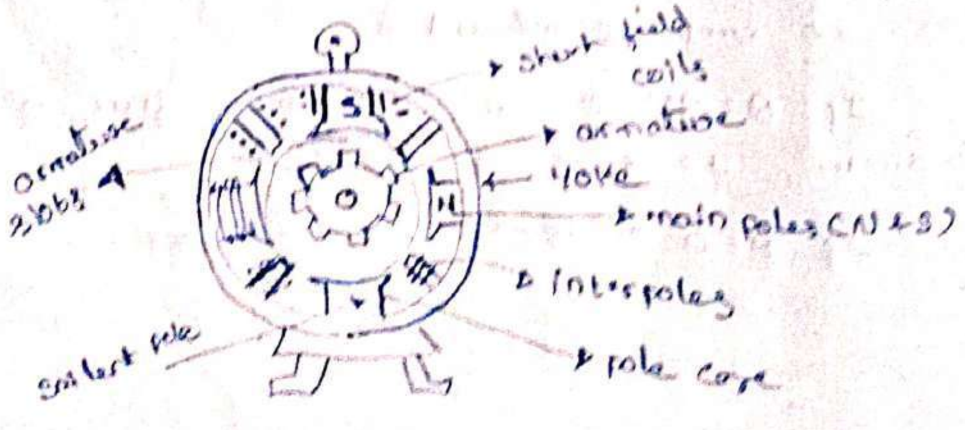
Direction of induced emf is found by flemming's right hand rule. From 0 to 90° or position from 1 to 3 indicates 1st half position of coil revolution.

From θ = 180° to 270° or position 3 to position (4) emf increases & emf decreases at θ = 270° to θ = 360° completely another 1/2 cycle.

The 2 half cycles called as +ve 1/2 cycle, current flows from A-B-M-L-C-D & another half cycle called -ve 1/2 cycle, current flows from D-C-L-M-B-A.

(1) +ve & (1) -ve 1/2 cycles called as one revolution. or one cycle.

<u>Construction details of Generator</u>



Yoke → known as magnetic frame.

→ stationary part of machine, which produces a magnetic flux from main poles.

→ Acts as 2 purposes

① to cover the whole machine

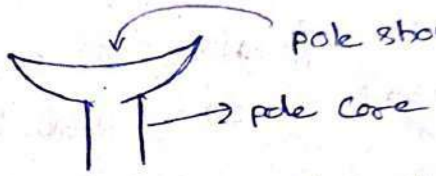
② provide the mechanical support

→ for small machines it is made up of Iron, for larger machines it is made up of cast steel. because weight is main factor, to reduce weight steel is preferrable.

poles:

It consists of pole core, pole shoes & pole coils.

→ pole core & pole coils forms the magnetic field.



→ end of pole core it is formed as shoe type to reduce the air gap b/w the stator & rotor.

→ if pole core is wounded with copper wire then it is known as pole coils.

interpoles

also called as commutating poles

→ used to improve the commutation.

→ These are made up of thick conductor with few turns wounded on that conductor.

→ It is carries full armature current.

Armature

→ Rotating part of machine is armature

→ Consists of armature core & armature winding

→ Armature core consists of some slots to carry armature windings. this core rotates in magnetic field.

→ If armature rotates in magnetic field, hysteresis & eddy current losses takes place in the form of heat.

Commutator

→ It is a current collecting device which an AC induced emf into unidirectional emf. All the ends of armature coils are seriesly connected to each other & its ends are welded to commutator.

Brushes:

→ collects the current from commutator.
→ made up of carbon or graphite.
→ these are rectangular shape placed in brush holders.

Bearings:

→ used to reduce the friction & noise b/w the stator & rotor bearings are provided to the rotor shaft.
→ For small machines, ball bearings are used
→ For large " roller bearings are used.

Armature windings

→ classified as 2 types
① open coil winding: (2) closed coil winding

The ends of the windings are in open circuit until an external source or load is connected.

② closed winding

→ preferred for dc machines.
→ The ends of windings are completely short circuited or closed.

these are again classified as

ⓐ ring winding

Armature core consists of ring made with windings are arranged by providing laminations. The ends of ring windings are connected to commutator advantages

→ no crossing of winding each other
→ seems simple
→ same winding used for 2, 4, 6 & 8 poles machines

disadvantages

→ uneven flux linking with the coil.
→ Emf is small compared to drum winding
Here emf is half of the drum winding.
→ Insulation of winding is difficult.
→ maintainence cost is high.

(b) Drum winding

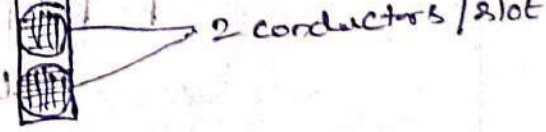
→ conductors are placed in armature slots & are connected one to another by front & back end connectors.
these are classified as

(i) single layer winding

An armature consists of one slot, only one winding is used in the slot. or
only one conductor is used in one slot. Here a coil has one side.

(ii) double layer winding

Here 2 coils are placed in one slot or 2 conductors are used in one slot.



→ Here one coil is on upper part of pole & another part is bottom part of pole.
→ used in medium sized machines.
→ uper sides of coils are numbered as 1, 3, 5, 7 & lower coil sides are numbered as 2, 4, 6, 8.

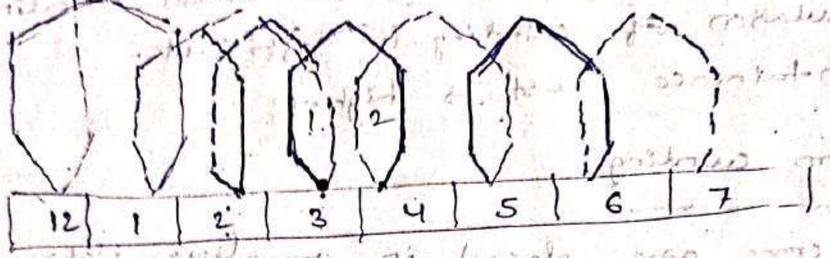
advantages

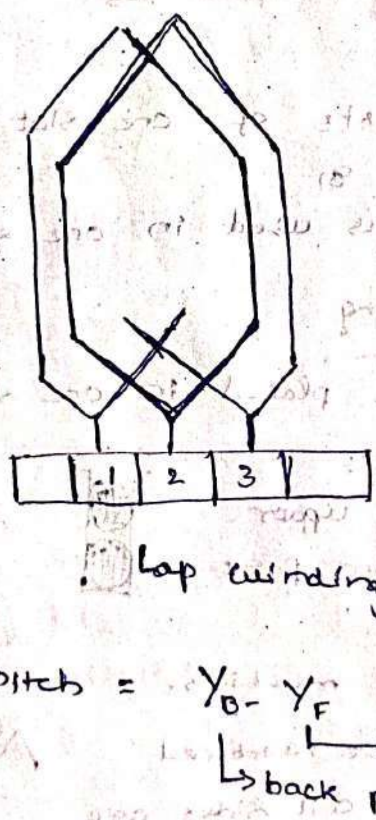
→ for higher ratings machines using 2 coils per slot reduces the size
→ Commutation is improved
→ EMF O/P is high.

double layer winding is again classified as 2 types based on connections.

(I) lap winding

In this, single coil is used or single turn coils is preferable. Here finishing end of coil is connected to commutator & starting end of coil is located or situated under the same pole.





Lap winding

One pole pitch = $Y_B - Y_F$ → front pitch, → back pitch

$\Rightarrow Y_B = \frac{Z}{P} = \frac{\text{no. of conductors}}{\text{no. of poles}}$

$\Rightarrow Y_B = Y_F \pm 2m$ where $m = 1, 2, 3$ → simplex, duplex, triplex

$\Rightarrow Y_B > Y_F \Rightarrow Y_B = Y_F + 2m$

$Y_B < Y_F \Rightarrow Y_B = Y_F - 2m$

⇒ average pitch $Y_A = \frac{Y_F + Y_B}{2} = \frac{Z}{P}$

⇒ no. of parallel paths $A = P$

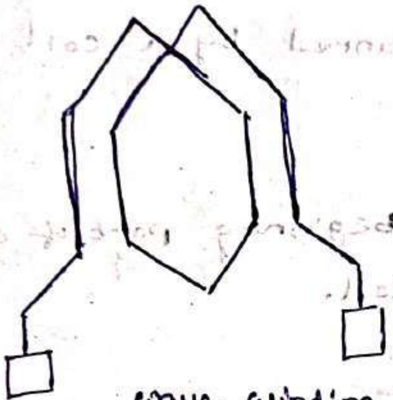
Wave winding: It is a series winding.

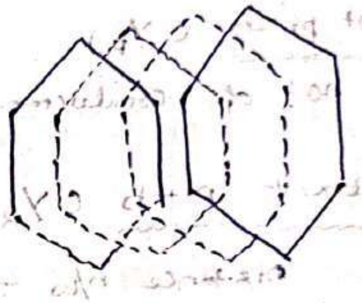
1 set of coils carry current in one direction & another set of coils carry current in opposite direction. which are connected in series.

→ Both Y_B & Y_F are odd & of same sign.

→ $Y_R = Y_F + Y_B = \frac{Z \pm 2}{P}$

→ no. of ||el paths equal to 2 or A = 2





Important definitions

Pole pitch Distance b/w the 2 adjacent poles
or
no. of conductors divided by no. of poles.

$$\text{Pole pitch} = \frac{\text{no. of Conductors / slot}}{\text{no. of poles}}$$

Example: 48 Conductors per slot, consists of 4 poles. Pole pitch = 48/4 = 12.

Coil span (Y_S) or coil pitch

⇒ also called as pole span. It is a distance b/w the 2 sides of a coil.

⇒ coilspan or pole span or coil pitch $Y_S = \frac{\text{no. of slots}}{\text{no. of poles}}$

coilspan = 180°

⇒ If coil span or pole span is equal one pole pitch then it is called full pitched.

Pitch of a winding

Distance b/w the 2 successive Conductors or distance b/w the 2 begining Conductors.

lap winding $Y = Y_B - Y_F$

wave " $Y = Y_B + Y_F$

Back pitch :

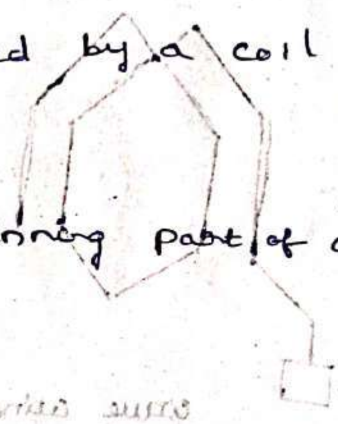
no: of Conductors spanned (→ spreading) by a coil on back end. It is denoted as Y_B.

front pitch (Y_F)

no: of conductors spanned by a coil on front end.

Resultant pitch (Y_R)

Distance b/w the beginning part of one coil to the beginning part of next coil.



emf equation of Generator

$$E_g = \frac{\phi Z N}{60} \times \left(\frac{P}{A}\right)$$

↳ generated emf

Let ϕ = flux/pole in wb

Z = no: of conductors or total no: of Conductors

Z = no: of slots × no: of Conductors/slot

P = no: of poles

A = no: of parallel path

N = no: of revolutions / minute

⇒ we know that average emf / conductor

$$e = N\frac{d\phi}{dt} \quad ; \quad N = \text{no: of turns} = 1$$

$$e = \frac{d\phi}{dt}$$

⇒ Total flux cut / pole $d\phi = \phi P$ wb

no: of revolutions per minutes

1 rpm = 60 rps
60 rps = N rpm
rps = $\frac{1}{60}$

60 rps = 1 rpm.

60 rps = N rpm

$dt = 1\text{ rps} = \frac{N}{60}$ rpm

60 rps = N rpm
1 rpm = 60

N = 1

$e = \frac{d\phi}{dt} = \frac{\phi P}{\frac{N}{60}}$

1 rpm = 60 rps
N rpm = 60 rps

$1 rps = \frac{N}{60} rpm$

N rpm = 60 rps
1 rps =

N rpm = 60 rps

$1 rpm = \frac{60}{N} rps$

rpm = 60 rps
N rpm = 60 rps

$1 rps = \frac{60}{N} rps$

$1 rpm = \frac{60}{N} rps$

$$e = \frac{d\phi}{dt} = \frac{P\phi}{\frac{60}{N}} = \frac{NP\phi}{60} \rightarrow (1)$$

⇒ Also they are Z/A Conductors Connected in series in each parallel path

above equation (1) becomes

$$E_g = e = \frac{NP\phi}{60} * \frac{Z}{A} = \boxed{\frac{\phi ZN}{60} * \frac{P}{A}}$$

For lap winding (no. of parallel path (A) = no. of poles)

A = P

For wave winding

no. of parallel paths A = 2

$$E_g = \frac{\phi ZN}{60} * \frac{P}{2}$$

Problems: A dc generator has armature emf 100V, usefull flux/pole is 20 mwb & speed is 800 rpm. Calculate generated emf (i) with same flux (20 mwb) & speed is 1,000 rpm (ii) with flux/pole is 24 m wb & a speed of 900 rpm.

sol. given armature emf $E_1 = 100V$,

let E_2 be the generated emf $E_2 = ?$

Speed $N_1 = 800$ rpm.

→ we know that induced emf is proportional to flux/pole & speed.

$$E = N\phi$$

$$\frac{E_2}{E_1} = \frac{N_2\phi_2}{N_1\phi_1}$$

(i) $\phi_2 = 20$ mwb, $\phi_1 = 20$ mb

$N_2 = 1000$ rpm $N_1 = 800$ rpm

$$E_2 = E_1 * \left[\frac{N_2\phi_2}{N_1\phi_1}\right] = 100 * \frac{1000 * 20 * 10^{-3}}{800 * 20 * 10^{-3}} = 125\,V$$

(ii) $\phi_2 = 24$ mWb, $N_2 = 900$ rpm

$\phi_1 = 20$ mwb, $N_1 = 800$ rpm

$$E_2 = E_1 * \left[\frac{N_2\phi_2}{N_1\phi_1}\right] = 100 * \frac{900 * 24 * 10^{-3}}{800 * 20 * 10^{-3}} = 135\,V$$

(Q) (2) calculate voltage induced in armature of a 4 pole lap wound dc machine having 728 conductors & running at 1800 rpm. The flux/pole is 30 m wb.

sol E_g or $E = \frac{\phi Z N}{60} * \frac{P}{A}$

given poles $P = 4$, connection is lap wound so parallel paths = no. of poles i.e $A = P = 4$

Conductors $Z = 728$, speed $N = 1800$ rpm, $\phi = 30$ m wb

$$E = \frac{30 * 10^{-3} * 728 * 1800}{60} * \frac{4}{4} = ?$$

(Q) use above problem data find voltage induced in armature having wave wound dc machine.

sol Poles = $P = 4$, $\phi = 30$ m wb, conductors $Z = 728$, speed $N = 1800$ rpm, connection is wave wound no. of parallel paths is $A = 2$

$$E_g \text{ or } E = \frac{\phi Z N}{60} * \frac{P}{A} = \frac{30 * 10^{-3} * 728 * 1800}{60} * \frac{4}{2} =$$

(Q) A 4 pole lap wound armature has 144 slots with 2 coil sides per slot, each is having 2 turns. If flux per pole is 20 m wb & armature rotates at 720 rpm. what is induced voltage sol no: of poles P = 4, flux/pole = 20 m wb, speed N = 720 rpm

Connection is lap wound, parallel path A = P = 4

no: of slots = 144 slots

no: of coils per slot = 2

no: of turns per coil = 2

Total no: of Conductors = no: of slots * no: of coils * no: of turns

Z = 144 * 2 * 2 = 576

For wave wound no: of parallel paths

A = P = 4

induced emf Eg or $E = \frac{\phi Z N}{60} \times \frac{P}{A} = \frac{20 \times 10^{-3} \times 576 \times 720}{60} \times \frac{4}{4}$

Eg = 138.24 Volt

(2) An 8 pole dc generator has 500 conductors, usefull flux 0.05 wb. what will be generated emf. If it is lap connected, runs at 1200 rpm. what must speed required to produce same emf. if it is wave wound.

sol no: of poles P = 8, conductors Z = 500, flux ϕ = 0.05

Eg = ? (i) lap connected A = P = 8, N = 1200 rpm

$E_g = \frac{\phi Z N}{60} \times \frac{P}{A} = \frac{0.05 \times 500 \times 1200}{60} \times \frac{8}{8} = 500V$

(ii) speed required to produce same emf if it is wave wound.

For wave wound no: of parallel paths A = 2

P = 8 Eg = 500V, N = ?, ϕ = 0.05, Z = 500

$E_g = \frac{\phi Z N}{60} \times \frac{P}{A} \Rightarrow \boxed{\frac{E_g \times 60 \times A}{\phi \times Z \times P} = N}$

$N = \frac{500 \times 60 \times 2}{0.05 \times 500 \times 8} = 300 rpm$

(3) An 8 pole lap wound armature rotated at 350 rpm is required to generate 260V, usefull flux/pole is 0.05 wb. It armature has 120 slots. calculate no: of conductors/slot & determine the actual value of flux required to generate same voltage.

Connection is lap wound.

sol: no. of parallel paths A = P = 8, N = 350 rpm

Generated voltage or emf Eg or E = 260 V, ϕ = 0.05 wb,

no. of slots = 120. Conductors Z = ?

$$E = \frac{\phi Z N}{60} * \frac{P}{A} \Rightarrow Z = \frac{E * 60 * A}{\phi N P} = \frac{260 * 60 * 8}{350 * 0.05 * 8}$$

Z = no. of Conductors / slot * no. of slots

891.4 = no. of Conductors / slot * 120

no. of Conductors / slot $= \frac{891.4}{120} = 7.42 \simeq 8$ $\left[\frac{15600}{17.5} = 891.4 \right.$

$\Rightarrow$ actual value of flux required to generate same voltage is

$$E = \frac{\phi Z N}{60} * \frac{P}{A} \Rightarrow \boxed{\phi = \frac{E * 60 * A}{P * Z * N}}$$

$$\phi = \frac{260 * 60 * 8}{8 * 350 * 8} = \_\_\_\_$$

Armature reaction

The effect of magnetic field set up by armature current on main field flux of poles of generator.

The armature reaction has 2 effects on main field flux.

① weakens the main field flux called de-magnetisation

② creates a distortions in main field flux called cross magnetisation.

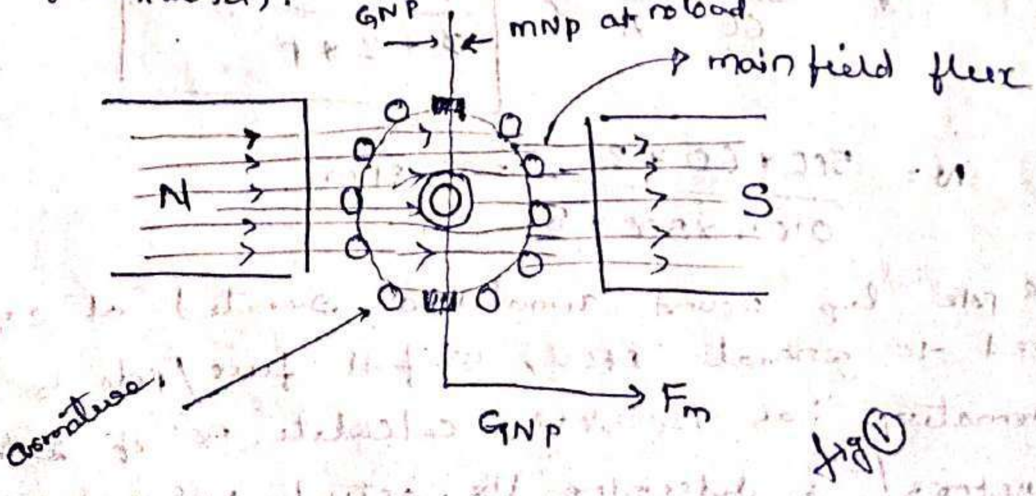


fig ①

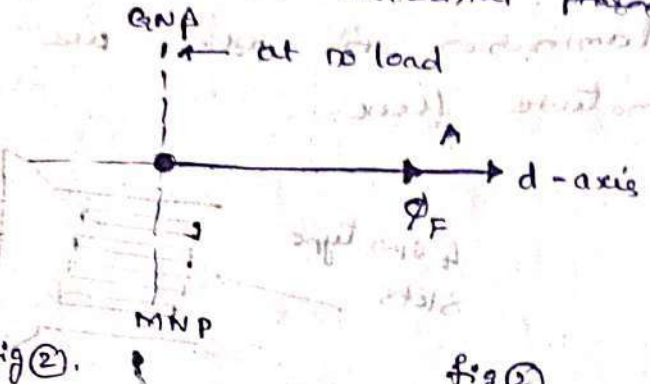
→ Reduction of magnetic flux leads to reduction of voltage & torque

→ distortions in main field flux leads to increase iron losses, poor Commutation, Sparking at brushes.

Considered a 2 pole machine shown in fig①. Let us assume there is no armature Currents at no load. main field flux is on horizontal plane OA. shown in fig②

⇒ so at no load

GNP → Geometrical neutral plane & MNP (magnetic neutral plane) exactly coincide. shown in fig②.



fig②

⇒ If DC machine is loaded, armature winding recieves armature Current.

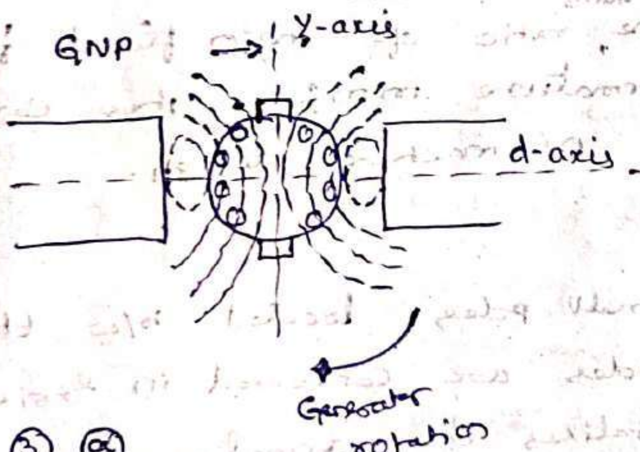
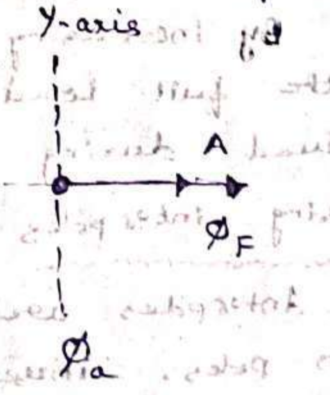


fig ③ ⓐ



fig③ ⓑ

This armature Current set up an armature flux ϕ_a shown in vertical axis shown in fig③ⓑ, here armature rotates in clockwise direction for generator.

⇒ If armature flux ϕ_a cross the main field flux (ϕ_F) then it is called cross magnetization. effect.

⇒ If armature flux ϕ_a opposes the main field flux ϕ_F then it is called de-magnetization effect. Here total flux / pole reduces from no load to full load.

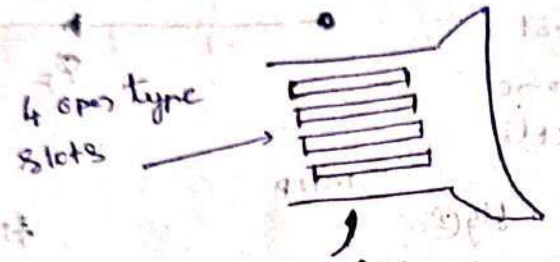
Cross magnetisation can be minimised using

→ using high reluctance pole tips

By flattening the pole faces, so that air gap is increased, this leads to increase reluctance.

→ Reducing the armature flux

→ By providing more reluctance & by providing a lamination on poles, we can reduce the armature flux.



→ Strenthing the main field flux

By increasing the turns ratio of main field flux to the full load armature mmf., this can be achieved during the DC machine design.

→ using interpoles

Interpoles are small poles, located b/w the main poles. These poles are connected in series with armature neutralises the armature mmf. this improves the commutation.

→ using Compensating windings

→ also called as auxillary windings.

→ these are arranged with main field winding slots.

→ Currents in compensating or auxillary winding should be completely opposite to the armature winding currents.

→ Both currents gets neutralised, maintains a uniform distribution of flux.

De-magnetising ampere turn per pole

Armature flux de-magnetises the main field flux (or) reduces the main field flux. So we require an extra ampere-turns to increase the main field flux. It can be calculated.

no: of turns = Half the no: of Conductors

Z = total no: of Conductors,
I = Current in each armature Conductor

$I = \frac{I_a}{2}$ for wave winding

$I = \frac{I_a}{P}$ for lap winding

total no: of Conductors $= \frac{4\theta_m}{360} \times Z$

Here 2 conductors becomes one turn

$\therefore$ total no: of turns $= \frac{2\theta_m}{360} \times ZI$

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

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

Cross magnetising Ampere-turns / pole AT_c/P

AT_c/pole = Total no: of Conductors/pole − De-magnetizing Conductors/pole

AT_c/pole =

⇒ we know that demagnetising Conductors/pole $= \frac{2\theta_m}{360} \times Z$

Total no: of Conductors/pole $= \frac{Z}{P}$

⇒ Cross magnetising Conductors/pole $= \frac{Z}{P} - Z \times \frac{2\theta_m}{360}$

$= Z\left[\frac{1}{P} - \frac{2\theta_m}{360}\right]$

Cross magnetising ampere-~~turns~~ Conductors/pole $= ZI\left[\frac{1}{P} - \frac{2\theta_m}{360}\right]$

Cross-magnetising amp-turns / pole = $ZI\left[\frac{1}{2P} - \frac{\theta_m}{360}\right]$

We know that one turn = 2 conductors

$1T = 2Z$

Problem

Connection is wave wound, no: of poles : 8, no: of Conductors Z = 480. Armature Current Ia = 250A. Find de-magnetising & cross magnetising amp-turns / pole. if brushes are shifted by 6° electrical from GNA.

Sol $P = 8$, $Z = 480$, $I_a = 250A$

$\theta_e = 6°$

$AT_d / \text{pole} = ?$, $AT_c/\text{pole} = ?$

$I = \frac{I_a}{A} = \frac{I_a}{\text{no: of IIel paths}}$

$$\theta_{mec} = \frac{2\theta_e}{\text{no: of poles}}$$

⇒ (1) de-magnetising ampere-turns / pole = $\frac{\theta_m}{360} * ZI$

for wave winding connection

Current in each conductor $I = \frac{I_a}{2} = \frac{250}{2} = 125A$

$\theta_{mech} = \frac{2*6°}{8} = 1.5$

$AT_d / \text{pole} = \frac{1.5}{360} * 480 * 125 = ?$

⇒ Cross magnetising ampere-turns / pole.

$AT_c / \text{pole} = ZI\left[\frac{1}{2P} - \frac{\theta_m}{360}\right]$

$= 480 * 125\left[\frac{1}{8 \times 2} - \frac{1.5}{360}\right]$

$= ?$

(6) A 300KW, 500V, 6 pole lap wound generator has 70 slots with 12 conductors / slot. If brushes are shifted to 3.33 mechanical degrees. Ignore shunt field current. Find demagnetising & cross magnetising amp-turns

, connection is lap wound $A = P$

O/p of generator is 300KW = P_{out}

Voltage $V = 500V$

Poles $P = 6$, no: of slots = 70, no: of conductors/slot = 12

brush angle in mechanical $\theta_m = 3.33°$

⇒ Demagnetising amp-turn/pole = ?

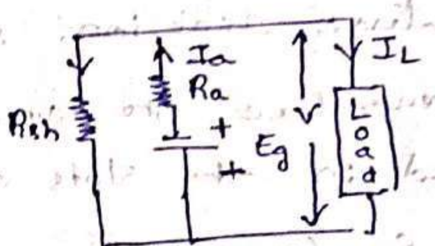
⇒ Cross magnetising amp-turn/pole = ?

⇒ $I_a = I_L + I_{sh}$

$= I_L + V/R_{sh}$

neglect shunt resistance

$I_a = I_L + \frac{V}{R_{sh}} = I_L + 0$



⇒ $P_{out} = VI_L$

$300 * 10^3 = 500 * I_L$

$I_L = \frac{300 * 10^3}{500} = 600A$

$I_a = 600 + 0 = 600a$

⇒ Demagnetising amp-turns/pole: $AT_d/\text{pole} = ZI * \frac{\theta_m}{360°}$

for lap wound

Current in each conductor $I = \frac{I_a}{A} = \frac{I_a}{\text{no: of parallel paths}}$

$I = \frac{I_a}{P} = \frac{600}{6} = 100A$

Z ⇒ no: of slots × no: of conductors/slot

$= 70 * 12 = 840$ conductors

$AT_d/\text{pole} = 840 * 100 * \frac{3.33}{360} =$

⇒ cross magnetising amp-turns/pole $AT_c/\text{pole} = ZI\left[\frac{1}{2P} - \frac{\theta_m}{360}\right]$

$= 840 \times 100\left[\frac{1}{2 * 6} - \frac{3.33}{360°}\right] =$

Compensating winding

Due to armature reaction, flux distribution of wave badly distorted. In the absence of compensating windings these flux oscillating b/w backward & forward.

If this emf exceeds the break down voltage a spark will spread all over the commutator. This leads to short circuit of armature. This happens when coils are located b/w main poles & sudden increase in loads increases the emf. All this is due to armature reaction. So this windings are used to neutralize the armature reaction. These are placed in the slots of main field windings.

So compensating winding is connected in series with armature winding. Other cross magnetising effect causes sparking at the commutator.

Let Z_c = no. of compensating conductors/pole
Z_a = no. of armature conductors/pole
I_a = Armature current

$$Z_c I_a = Z_a \left(\frac{I_a}{A}\right)$$

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

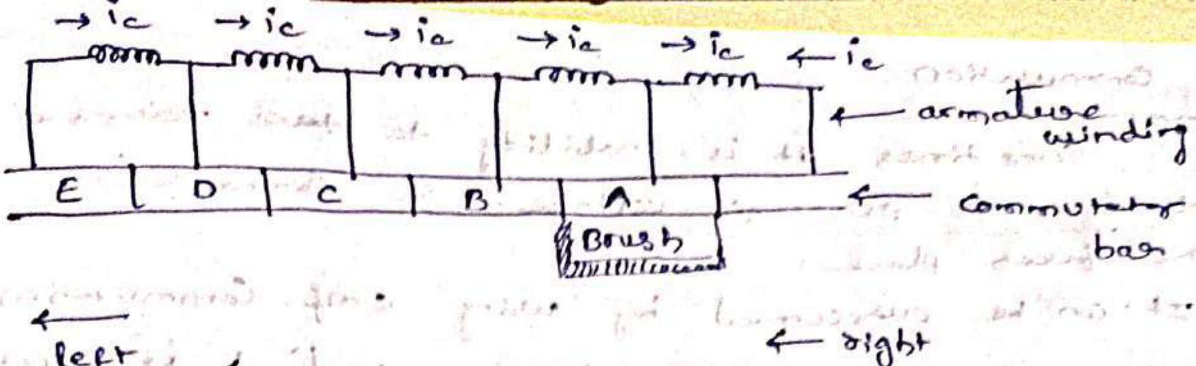
Commutation

It is the process of reversing the armature current by means a commutator & brushes.

Importance of Commutation

① Converting a.c current in armature into dc current
② also used to reverse the direction of current.
③ It maintains rotor mmf stationary in space.

Commutation period => $T_c = \dfrac{\text{width of brush}}{\text{peripheral position of commutator}}$



→ depending upon the reversal of Current, Commutation is of 3 ways.

① Straight Line Commutation

→ also called linear Commutation
→ Current density is uniform over the brush contact. so brush losses is minimum.

② Over Commutation or accelerated Commutation

Change of Current at end of Commutation period is zero.

→ also called as accelerated Commutation

③ Under Commutation

Reversal of Current change is very fast at end of Commutation period.

→ also called as Retarded Commutation.
→ sparking takes place only at trailing edge.

Methods to improve Commutation

① Resistance Commutation

In this high resistance Carbon or graphite brushes are used in place of Copper brushes.

→ Copper brushes have 2 problems.
① due to low resistance, Commutation is poor
② needs to replace brushes frequently.

→ Carbon brushes or graphite brushes are self lubricant, so they offer less friction & last for long time.

→ If low resistance, Current is directly flows through the coil.
→ If high resistance, Current flows brushes & some part to coil.

EMF Commutation

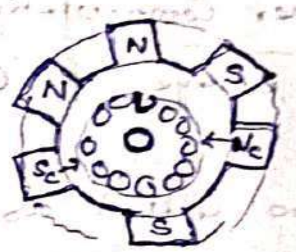
Some times it is inability to take reversal of current due to reactance voltage. So Commutation failure takes place.

It can be overcomed by using emf Commutation. Here an equal amount Emf is generated & is opposite direction to reactance voltage becomes nullified. this is done by (i) Brush shifting

In this method, brushes are partly shifted beyond the Magnetic neutral axis, as result reactance voltage can be reduced.

(ii) using Commutation poles

→ also called as interpoles.
→ located b/w main poles.
→ Commutating pole windings are connected in series with armature winding.



→ this poles generates an emf exactly opposite to reactance voltage.

N, S → main poles
Nc, Sc → Commutating Poles.

→ Emf of interpoles magnitude is opposite to the emf of reactance voltage magnitude.

Equalizer Connection

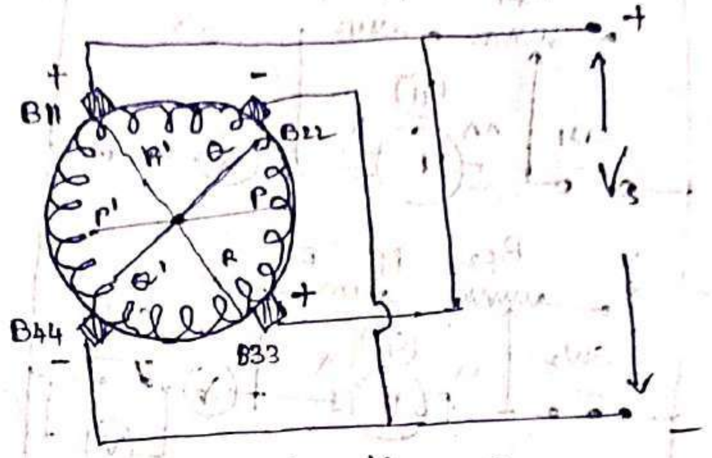
This Connection is arises when there is a lap winding. In lap winding induced emf in parallel path are unequal due to

(i) differences in air gap
(ii) Improper arrangement of field windings

→ above 2 causes finally leads to circulating Currents.
→ These circulating Currents at brushes & commutator leads to sparking.
→ finally Commutation failure takes place.
→ To overcome the circulating Currents, a ~~high~~ low resistance Copper Conductors are Connected across the armature winding.

→ These are arranged in the form of ring: will bypass
the circulating currents.

→ due to the potential difference exist b/w the armature winding + equalizer windings these circulating currents becomes diverted.



equalizer Connections.

parallel operations of DC Generators

Many of power plants found to have several smaller generators serving in parallel instead using single unit. Here all units run at a time or few units keeping running parallel.

parallel operation provides

① Reliability
② Continuity of service
③ High efficiency
④ Repair is quite easy
⑤ Easy maintainence.

To achieve the parallel operations following Conditions must satisfied

ⓐ Generators must have equal ratings
ⓑ Polarities of generators must have same
ⓒ load characteristics should be same.
ⓓ Voltages should be identical,
ⓔ Generators that are driven by Primemovers should speed must be same.

Procedure to get parallel of generators

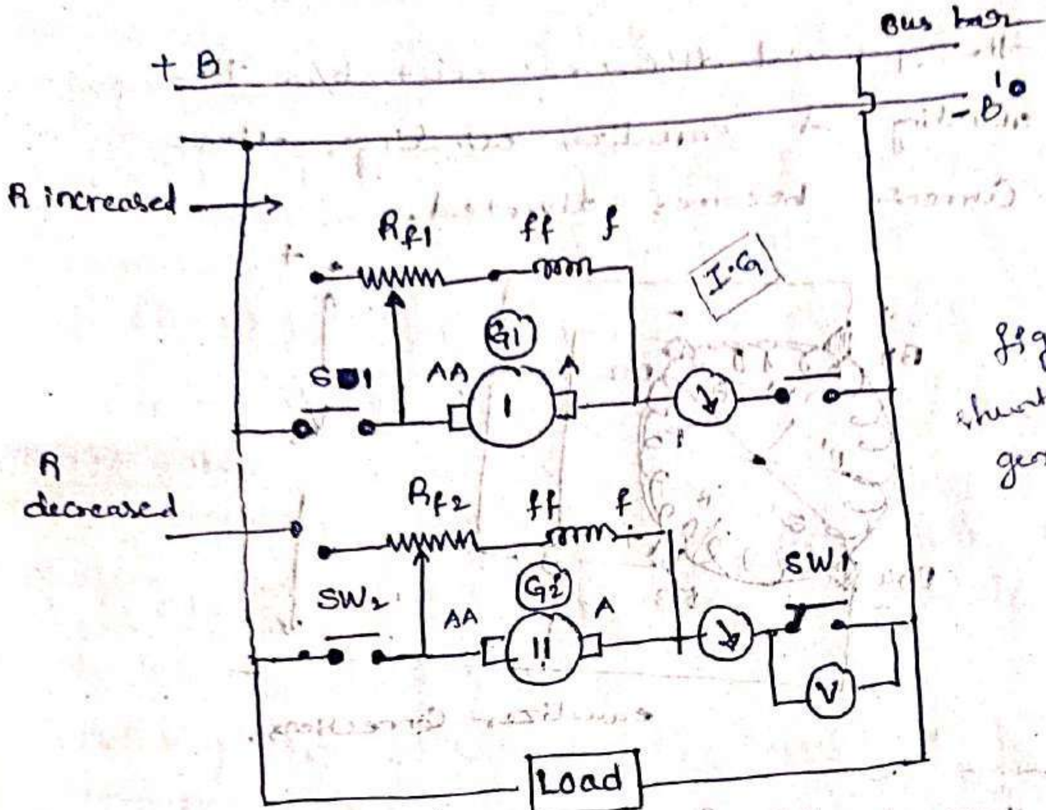


fig: shunt generators is parallel

→ Generators +ve & -ve terminals are exactly connected to bus bar terminals.

→ If polarity of incoming generator is not same then a short circuit will when switch SW1 is closed.

→ short circuit leads to block out of plant.

→ Before paralleling it is necessary to check the reverse polarities any.

→ Shunt generator ① is connected across the bus bar BB'. For keeping 2nd generator in ||el with 1st generator the following procedure is followed.

(1) Bring the 2nd generator speed to its rated value using prime mover.

(2) After bringing 2nd generator speed then close switch SW2. then circuit is completed.

(3) Connect a voltmeter across switch SW1.

(4) Excitation of 2nd generator is adjusted till the voltmeter across SW1 reads zero.

DC- Motors (1-8) pages

DC Motor Converts an DC electric supply into Mechanical one.

Motor Converts an electrical energy into Mechanical energy.

So i/p to motor is electrical & o/p of motor is Mechanical.

Unit-II
DC-motors

Principle of DC motor

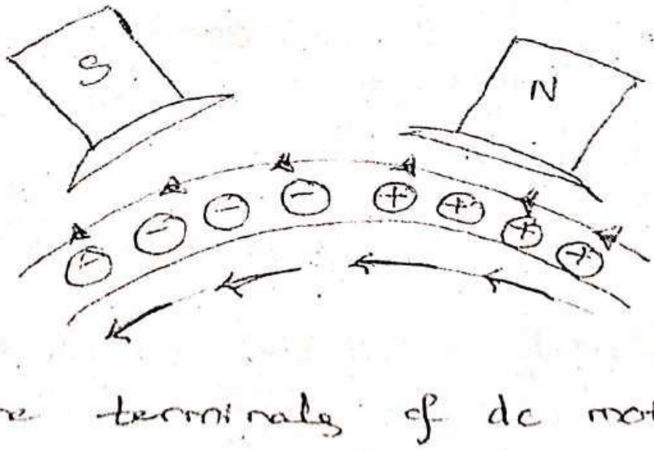
Whenever a Current Carrying Conductor is placed in a stationary magnetic field, the Conductor experiences a Mechanical force.

The direction of force is given by flemmings left rule

$$\boxed{F = BIl}$$

So its Construction is similar to d.c generator.

Working of DC motor



when the terminals of dc motor are Connected to d.c supply, field magnets gets excited develops N & S poles.

Here armature Conductors Carry Currents. (2)

Conductors under N-pole Carry Current in one direction.

Conductors under S-pole Carry Current in opposite direction to the N-pole.

Such Conductors are placed in a stationary magnetic field, the Conductors experiences a mechanical force.

The Mechanical force acting on each Conductor tends to rotate in the armature in anticlock-wise direction.

When Conductor moves from one side of brush to another side of brush, Current in Current becomes reversed. The Conductor shifted to another pole by maintain direction of force remains constant.

Force experienced by the Conductor is given as $\boxed{F = BIl}$ Newtons. Unit-II DC-motors

B = flux density in wb/m²
I = Current in Amps
l = length of Conductor

Back emf or Counter emf

When a Conductor Cuts the stationary magnetic field, an emf is induced in the Conductor.

This induced emf in motor is Called as back emf or Counter emf.

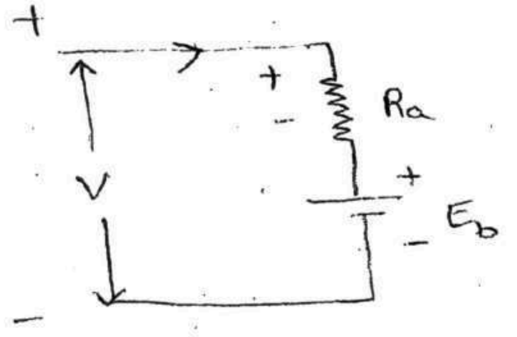
The back emf developed by the motor must oppose the supply voltage using lenzs law.

Back emf

$$E_b = \frac{\phi Z N}{60} * \frac{P}{A} \longrightarrow (1)$$

ϕ = flux/pole in webers
Z = no. of conductors
N = speed of motor
P = no. of poles
A = no. of parallel paths
E_b = back emf

Equivalent circuit of motor



$$V - I_a R_a - E_b = 0$$

$$\boxed{V = E_b + I_a R_a} \rightarrow (2)$$

$$I_a = \frac{V - E_b}{R_a} \text{ Amps}$$

R_a = armature voltage
$V - E_b$ = net voltage in armature

Back emf of motor depends on
(1) Armature speed (2) Armature current
(3) Armature resistance.

$$\boxed{N\, E_b \propto \frac{1}{I_a}}$$

if E_b is less than supply voltage $E_b < V$

Speed of motor is high, E_b also high but I_a is small

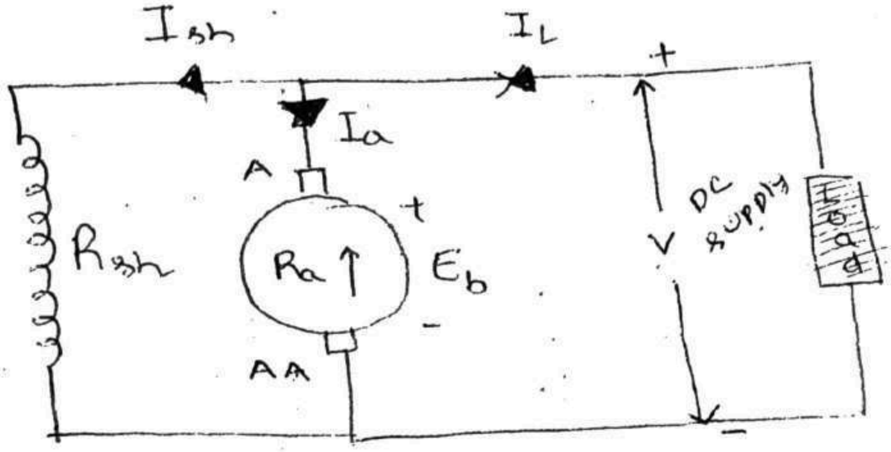
$N\uparrow$ speed, $E_b\uparrow$ back emf, $I_a\uparrow$ armature current

Speed of motor is low, E_b is less I_a is high

$N\downarrow$, $E_b\downarrow$, $I_a\uparrow$

Voltage equation of DC motor

$V - I_aR_a - E_b = 0$



I_L = line Current

I_a = armature Current

I_{sh} = shunt field Current

R_{sh} = shunt field Current

$V =$

Unit - II

DC-motors

$V = E_b + I_a R_a$

$I_a = \dfrac{V - E_b}{R_a}$ → voltage equation of motor

Losses in DC - motor

these are classified as

1. Copper losses or winding losses (I^2R)
2. Core loss or Iron losses
3. Brush losses
4. Mechanical losses
5. stray - load losses

① Copper losses or Cu losses or winding losses

These losses occur due to the presence of resistance in winding. whenever a Current flowing through winding, these losses occur in terms of heat liberated.

Magnetic losses or core or Iron losses

Core or Iron losses are due to hysteresis & eddy current losses.

These losses are constant during no load & loading condition. these are 20% of full load losses

Brush losses

These losses occurs b/w the copper commutator & carbon brushes. These losses produces a power losses at the contacts of brushes.

Mechanical losses

these losses are associated with the mechanical parts. Mechanical losses consists of frictional & windage losses. These losses occurs due to wearout of bearings.

These losses are overcomed by reducing the friction b/w the stator & rotor by providing air cooling inside it.

stray losses

The above all losses are stray losses. These are miscellaneous losses. these losses are very difficult to determine.

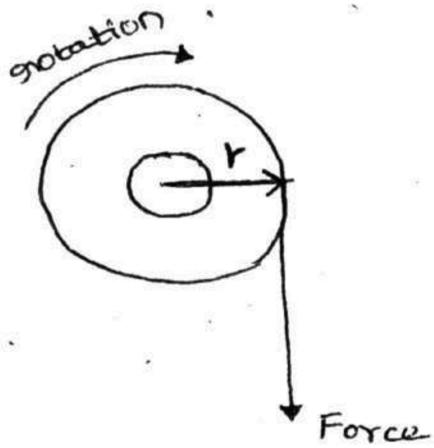
Efficiency of DC machine or motor

The efficiency of dc motor is the ratio of o/p power to the i/p power

It is denoted as 'η'

$$\text{Efficiency } \eta = \frac{o/p}{i/p} * 100 = \frac{o/p}{o/p + \text{Total losses}} * 100$$

Torque Equation of DC motor



1 rev = N rpm

$\frac{1}{N}$ rev = 1 rpm

Unit - II

DC motors

It is the product of force & radius. Consider a wheel of radius (r) in meter, circumferential force (F) Newtons. Let the force (F) causes the wheel to rotate (N).

$$\boxed{Torque = F * r} \quad N\text{-}m$$

(r → distance)

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

Work done per revolution = Force * distance

distance = circumference of a circle = $2\pi r$

$$\boxed{W = F * 2\pi r}$$

Power developed $P = \frac{\text{Work done}}{\text{time}} = \frac{F * 2\pi r}{\text{time for 1 rev}}$

$$P = \frac{F * 2\pi r}{\frac{60}{N}}$$

rpm = 60

rps = $\frac{60}{N}$

$$P = (F * r) * \frac{2\pi N}{60} = T * \omega$$

$$\boxed{P = T * \omega} \text{ watts}$$

T = Torque in Newton meter

ω = angular speed in rad/sec

Torque developed by DC motor is obtained Electrical power supplied to it & mechanical power produced by it. It is called as armature torque.

Gross Mechanical torque is $E_b I_a$

Power in armature = armature torque * ω

$$E_b I_a = T * \omega$$

$$E_b I_a = T_a * \frac{2\pi N}{60}$$

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

$$\left(\frac{\phi Z N}{60} * \frac{P}{A}\right) I_a = T_a * \frac{2\pi N}{60}$$

$$T_a = \frac{60}{2\pi N}\left(\frac{\phi Z N}{60}\right) * \left(\frac{P}{A}\right) I_a$$

$$= \frac{1}{2\pi} * \frac{\phi Z P}{A} * I_a$$

$$\boxed{T_a = \frac{0.159\, \phi * I_a * Z * P}{A}}$$

T is propotional to ϕI_a.

Speed Control of dc motor

We know that back emf developed by motor

$$E_b = \frac{\phi Z N}{60} * \frac{P}{A} \longrightarrow ①$$

Voltage equation of motor is

$$V = E_b + I_a R_a$$

$$E_b = V - I_a R_a \longrightarrow ②$$

By varying flux or field, speed of motor is controlled.

Changing in flux (ϕ) can be obtained by changing field current.

$$\phi = \frac{di}{dt}$$

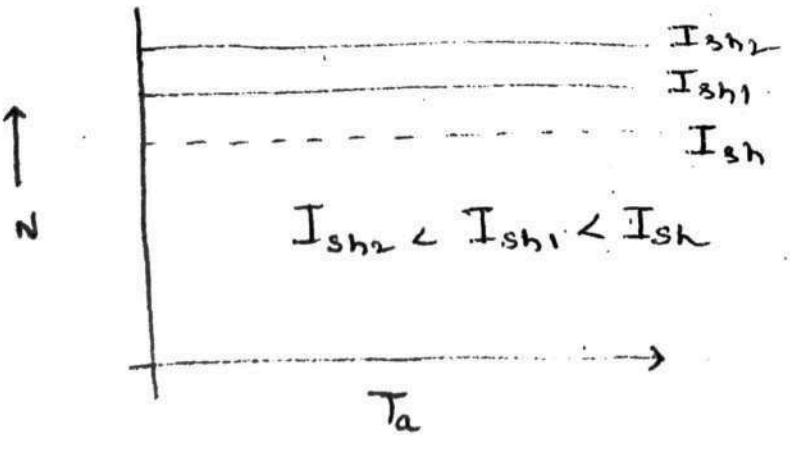
Field current is varied by varying the field resistance or ~~[illegible]~~ which is connected in series with shunt field winding.

By varying the field resistance, field current varied if field current varies then flux also varies finally speed of motor varies.

By increase the field resistance, flux of motor decreases, current through motor decreases as a result motor speed increases.

$$N = \frac{R}{\phi}$$

If I_{sh} is less means, field Resistance is maximum, Rheostat carries small amount of current. I^2R losses will be small.



Speed - Torque

$$\frac{\phi Z N}{60} * \frac{P}{A} = (V - I_a R_a)$$

$$N = \frac{60 * A * (V - I_a R_a)}{\phi * Z * P}$$

$$\boxed{N = \frac{(V - I_a R_a)}{K_b * \phi}} \rightarrow (3)$$

$$\boxed{K_b = \frac{Z * P}{60 * A}}$$

$$\boxed{\frac{A * 60}{Z * P} = \frac{1}{K_b}}$$

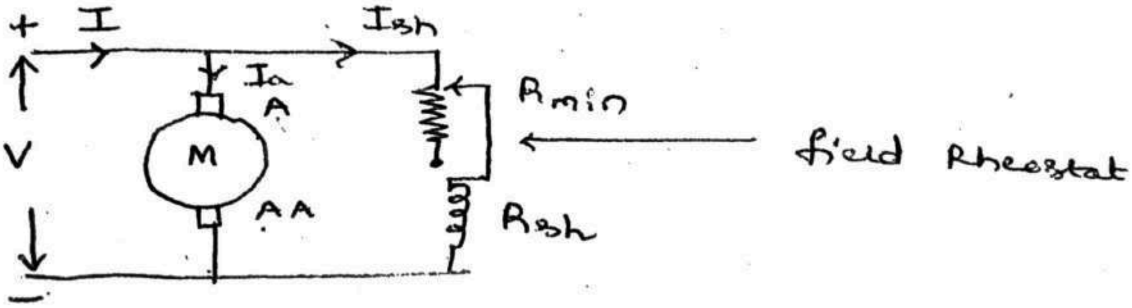
Equation (3) indicates speed of dc motor

V = supply voltage
I_a = armature Current
R_a = armature resistance
ϕ = flux

They are 3 methods of speed Control

→ (1) By varying armature resistance (R_a)
→ (2) By varying flux (ϕ) [field Control]
→ (3) By varying applied voltage (Voltage Control)

Speed Control of dc motor using field or flux Control method



$$\boxed{e = \phi N}$$

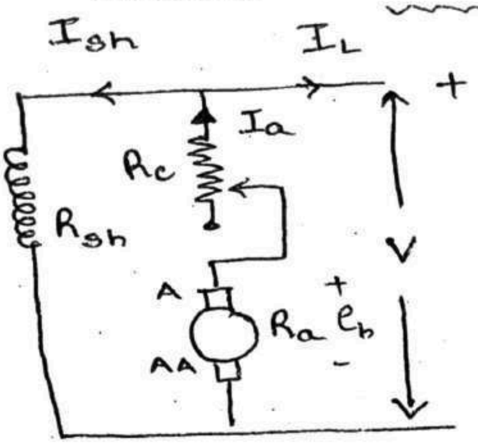
we know that induced emf of machine

$e = \phi N$

$N = \frac{1}{\phi}$ By maintaining e is constant

Rheostatic

~~[illegible]~~ Controlled or ~~Voltage~~ ~~[illegible]~~ method



$V - I_aR_c - I_aR_a - e_b = 0$

$e_b = V - I_a(R_a + R_c)$

$\Rightarrow$

$e_b - I_aR_a - I_aR_c - V = 0$

$-V - I_a(R_a + R_c) + e_b = 0$

$e_b = V$

We know that

Induced emf $e = N\phi$

where N = speed in rpm

ϕ = flux in webers

Unit - II DC-motors

This method is based on by varying the Voltage across armature of motor, then back emf of the motor also varies & hence speed of motor is Controlled.

This is done by inserting a variable resistor or Controller resistor (R_c) is Connected in series with armature of motor.

We know that back emf of motor is

$e_b \propto N\phi \Rightarrow N = \frac{e_b}{\phi}$ Let ϕ = constant = 1

$\therefore N = e_b$

$V - I_aR_a \propto N$

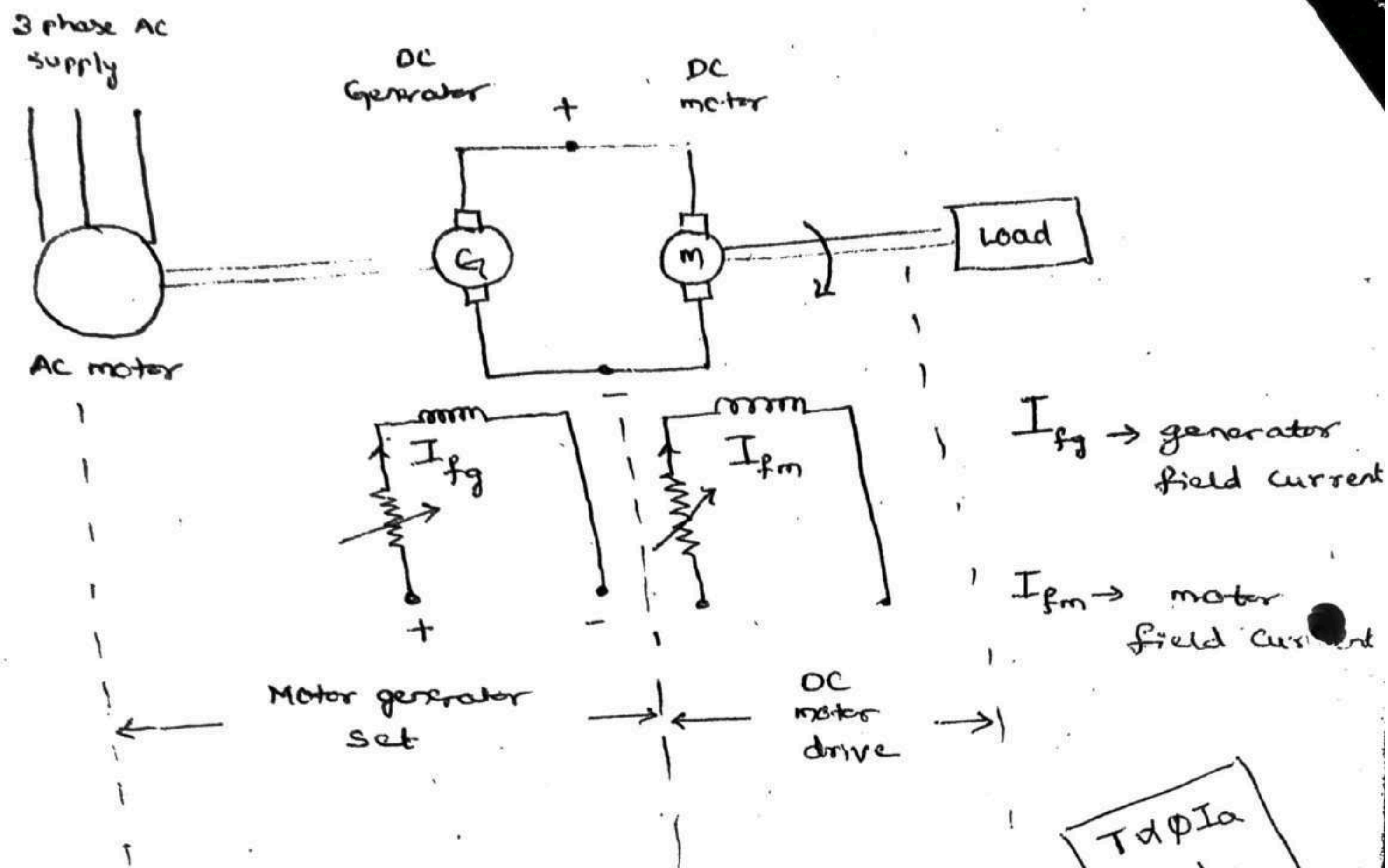
$V - I_a(R_a + R_c) \propto N$

$V = IR$, $V = e_b$

$R = \frac{V}{I} = \frac{e_b}{I}$

As Controller resistance R_c is zero, Current through motor is maximum, but Voltage drop across motor is zero. Then speed of motor reduces.

Speed Control of dc motor using Armature voltage



fig①: Ward-Leonard drive

$T \propto \phi I_a$

$T \propto \frac{1}{N}$

Speed of dc motor is achieved by varying applied voltage.

The principle is based on Ward-Leonard system.

In above s/m, (M) is main dc motor whose speed is to be Controlled, G is a separately excited dc generator.

The dc generator is driven by either 3 phase Induction motor or synchronous motor.

By changing Generator field Current, Generator voltage is changed. This changed voltage is applied to main dc motor (M).

By maintaining motor field Current I_{fm} is Constant so that motor flux ϕ_m also remains Constant.

The generator field Current I_{fg} is varied such that armature voltage changes from zero to (7) rated value. The speed will change from zero to base speed.

Since the speed control is carried out with rated Current & Constant flux of motor, a Constant torque upto base speed is obtained. Since power is propotional to speed, it increases with speed. Hence from armature voltage control method constant torque and variable power drive is obtained from speed.

Problems

Unit-II

DC-motors

A 4 pole dc motor takes 50A armature current. The armature has lap connected 480 conductors. The flux/pole is 20 m wb. Calculate gross torque developed motor.

Sol Poles $P=4$, $I_a = 50A$, no. of Conductors $Z = 480$

Armature has lap connected

no. of parallel paths (A) = no. of poles (p)

$A = P$

$A = P = 4$

Gross torque developed motor

$$T_g = 0.159 * \phi * I_a * \frac{ZP}{A} = 0.159 * 20 * 10^{-3} * 50 * 480 * 4/4$$

$= 76.394$ N-m

Problem A 220V dc motor has armature resistance $R_a = 0.75\Omega$, Armature Current $I_a = 30A$, to certain load. Calculate induced emf in motor?

sol $V = 220V$, $I_a = 30A$, $R_a = 0.75$

$$-E_b + V + I_aR_a = 0$$

$$\boxed{V = E_b + I_aR_a}$$

$$220V = E_b + 30 * 0.75$$

$$E_b = 220 - 30 * 0.75 = 197.5\,V$$

so'

Problem no: of poles in d.c motor has 4 poles Connected in lap. The flux/pole is 30 m wb. No: of armature Conductors is 250. when Connected to 230V supply it draws armature Current 40A. Calculate back emf & speed at which motor is running. Assume armature resistance 0.6 Ω.

sol no: of poles $P = 4$.

given armature winding is Connected in lap

$A = P = 4$

supply voltage $V = 230V$, no: of Conductors $Z = 250$

$\phi = 30\,m\,wb = m = 30 * 10^{3}\,wb$, $I_a = 40A$,

Back emf $E_b = ?$, speed of motor $N = ?$

$$V = E_b + I_aR_a$$

$$E_b = V - I_aR_a = 230 - (40 * 0.6) = 206\,V$$

we know that back emf developed by motor

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

$$\frac{E_b * 60 * A}{\phi Z P} = N \Rightarrow \frac{206 * 60 * 4}{30 * 10^{-3} * 250 * 4} = N$$

$$N = 1648\ rpm$$

Applications of DC Generators (G5)

(1) DC shunt generators are used for supp[lying] Constant loads. These is also used for charging batteries.

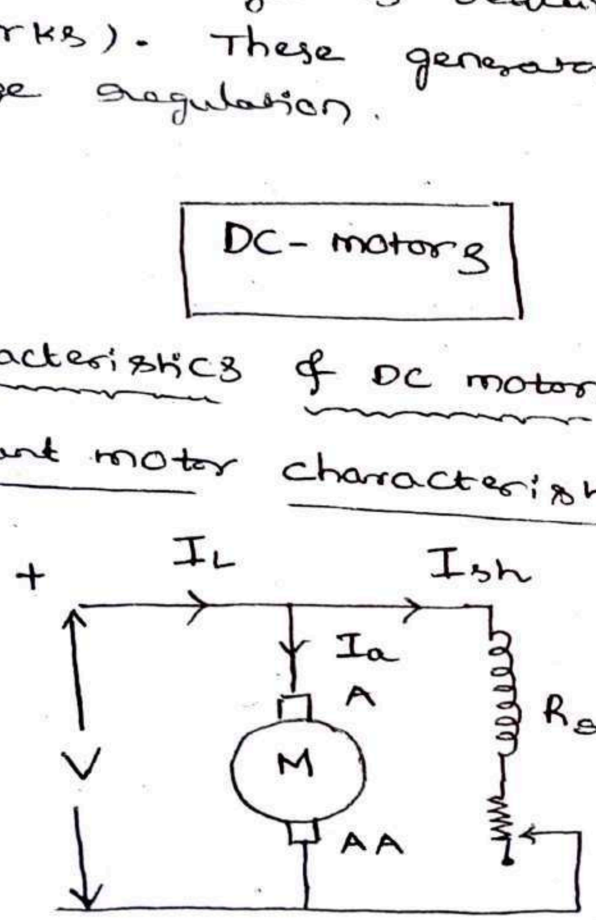
(2) Series generators are generally used as boosters for adding a voltage ~~diff~~ in transmission line to reduce voltage drop

(3) Compound generators are used where Constant voltage is required in dc n/ws. (networks). These generators maintains good Voltage regulation.

DC- motors   unit-(II)

characteristics of DC motors (G5- M6) pages

(1) shunt motor characteristics



fig(1)

In this connection, field winding is connecte across the armature of the motor.

Since supply given to the motor is constant so field current is constant, hence flux is constant

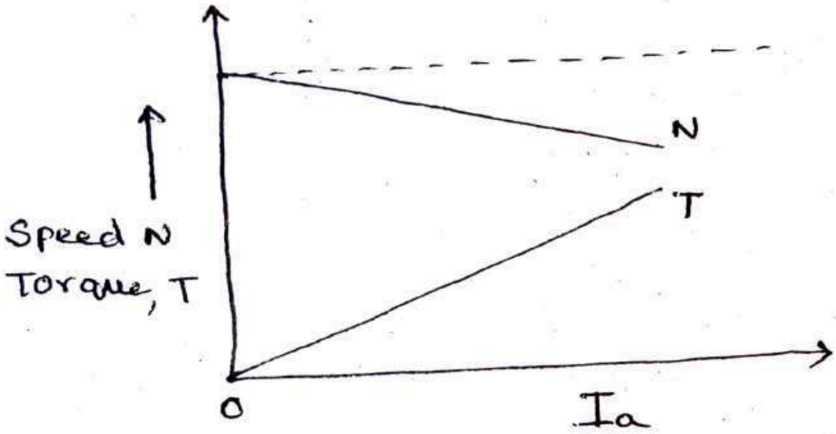
the supply or line current I_L, (M1)
...ature current I_a, field current I_{sh}

$$I_L = I_a + I_{sh}$$

since I_{sh} & ϕ are nearly constant

$$N = K_1 (V - I_a R_a)$$

K_1 is constant



T vs Ia

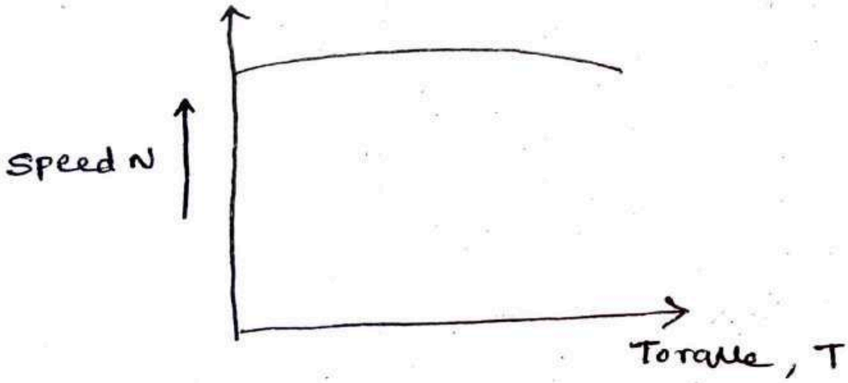
T vs N

Ia vs N

Unit - II DC-motors DC-generators

$T \propto \phi I_a$

$T \propto \frac{1}{N}$



since ϕ is nearly constant for shunt motor

$$T \propto I_a$$

(a) Torque & armature current T/Ia characteristics is called as electrical characteristics

(b) Speed (N) & armature current (Ia)

(c) Speed (N) & Torque (Ta) also known as Mechanical characteristics

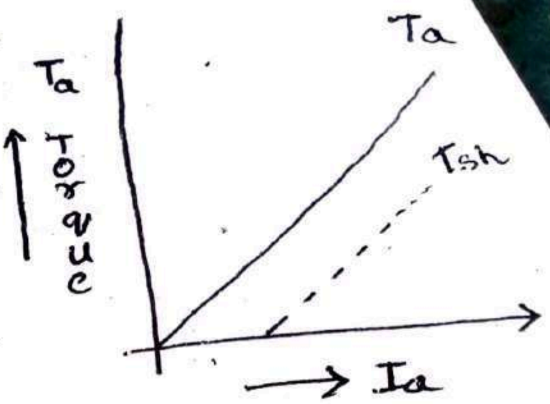
(a) T / Ia characteristics

we know that $T_a \propto \phi I_a$

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

assume ϕ is Constant

$T_a \propto I_a$



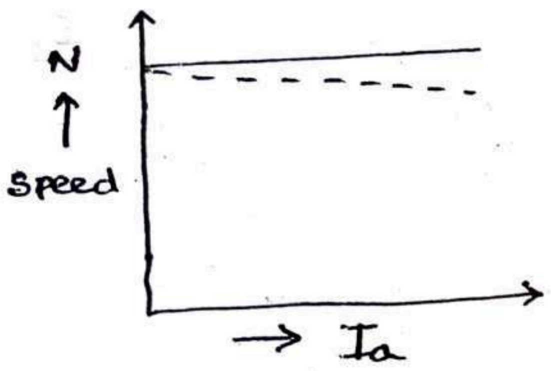
electrical characteristics are straight from origin

(b) speed vs Armature characteristics

If ϕ is assumed constant then

$N \propto E_b$. E_b is practically Constant

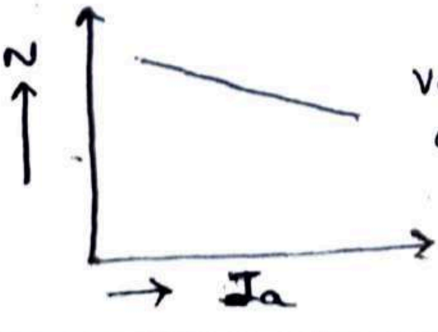
so speed is also Constant



E_b & ϕ decreases, if load increases as a result speed somewhat decreases.

The drop in speed varies from 5-15% of full load speed. As a result slightly have drooping shown in dotted line

(c) speed vs Armature torque Ia



This curve is obtained by the values N & Ia for various armature current

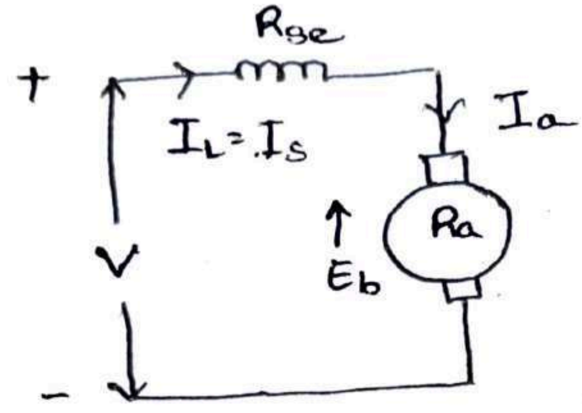
$N \uparrow \; T_a \downarrow$

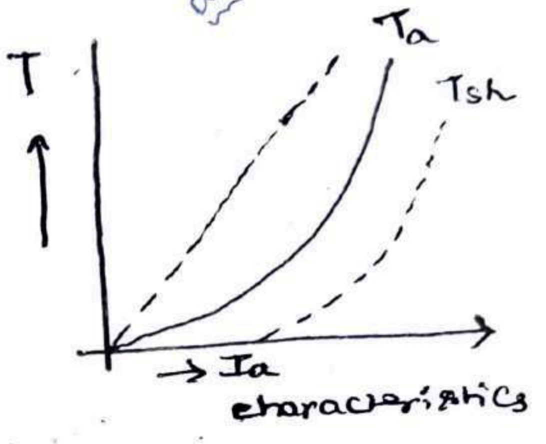
...acteristics of series motors

(M2)

Unit - II DC-motors

...ue Vs Armature Current





we know that $T_a \propto \phi I_a$

if flux induced is due to Armature Current. so $\phi \propto I_a$ upto saturation point

$$T_a \propto I_a * I_a \Rightarrow T \propto I_a^2$$

Unit-(II) DC-motors

At light loads ϕ is low so I_a is also low. But I_a increases, T_a also increases.

T/I_a Curves is parabola upto saturation. After saturation ϕ is almost independent of I_a. So $T_a \propto I_a$, T/I_a characteristics is straight line.

Before saturation motor develops torque is square of current.

(b) Speed Vs Armature Current

$$E_b \propto N\phi \qquad \phi \propto I_a$$

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

Neglect E_b since speed variations is very small for various load Currents.

With increased I_a, ϕ also increases

$\therefore$ speed $N \propto \frac{1}{\phi}$

If the load is heavy, I_a is large so speed is very low.

If load current is low, I_a is also low, ϕ is also low

$N \propto \frac{1}{\phi}$ ϕ = low means

Speed N becomes dangerous (over speed) so series motor never start without some mechanical load.

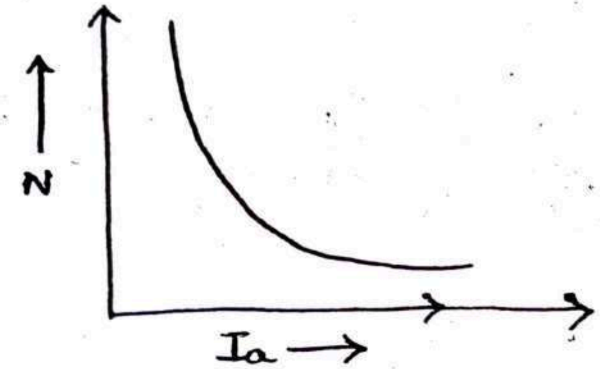
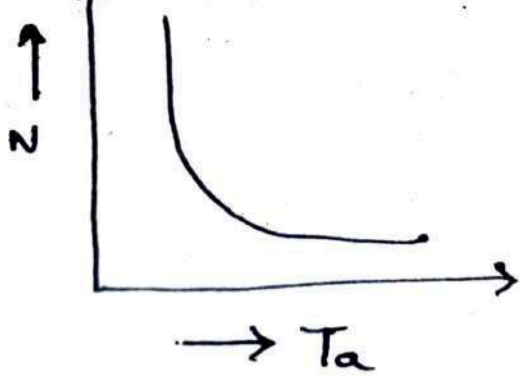


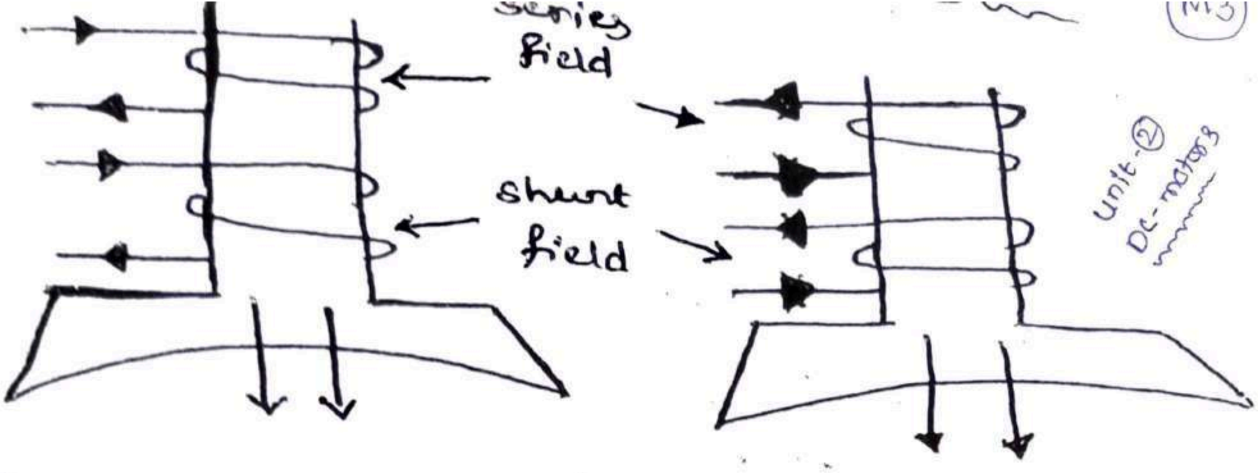
fig shows N/Ia characteristics

(c) Speed Vs armature torque (Mechanical characteristics)

when speed is low, Torque is high
if speed is high, Torque is low



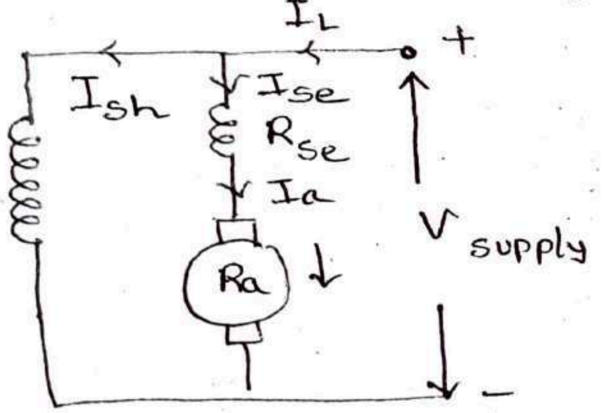
(M3)



Compound motors have both series & shunt field windings. If series field aids the shunt field excitation then it is Cummulative. If series field opposes the shunt field then it is called Differentially.

DC-motors
Unit-2

Characteristics of Cummulative Compound motors



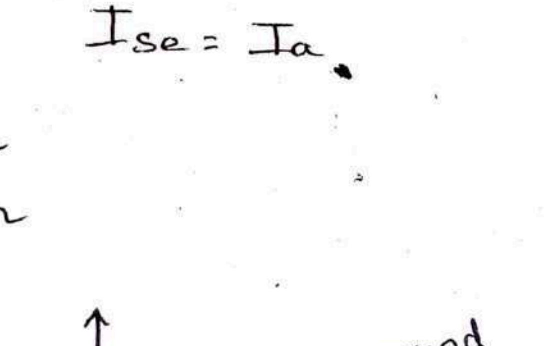
I_L = line line Current = I_s (supply Current)

$$I_L = I_s$$

$$I_{se} = I_a$$

$$I_L = I_{se} + I_{sh}$$
$$= I_a + I_{sh}$$

ⓐ T_a vs I_a characteristics.



As load on motor increases, Series field increases but shunt field becomes Constant

Load ↑, Series field ↑, Shunt field Constant

As a result total flux (ϕ) increases

$T_a \propto \phi I_a$

Torque of Cummulative motor > shunt motor Tor[que]

(b) N / Ia characteristics

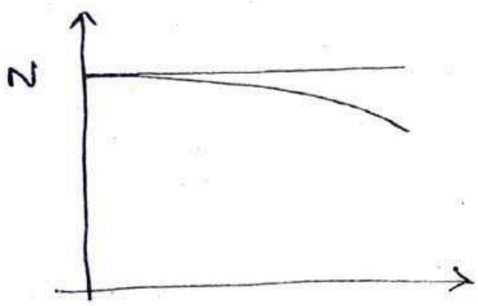
$N \propto \frac{1}{T}$

$N \propto \frac{1}{\phi}$

Load on motor increases, flux also increases since Ia increases, Speed (N) decreases

Load ↑, ø ↑, N ↓

Speed in Cummulative motor < Shunt motor Speed.

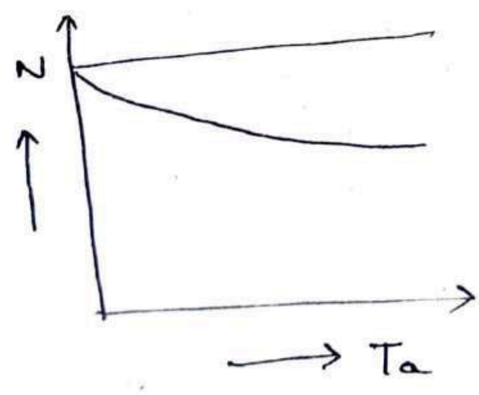


So for Cummulative motor Torque (Ta) is greater than Ta (Torque) of shunt motor

(iii) N / Ta

$T \propto \phi I_a$

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



Load ↑
flux ↑
Ia ↑
} Torque ↑

$T \propto \frac{1}{N}$

T ↑ N ↓

...cations of DC motors

(M4)

Shunt motor is used for constant speed applications. Series motors is used in starting heavy loads, also suitable for high load variations.

(a) Shunt motors

Used for Constant speed applications such as lathes, Centrifugal pumps, machine tools, blowers, fans

(b) Series motors using in railway traction, cranes, electric railways, Conveyors, hoist, trolley cars

(c) Compound motors

For intermittent high torque loads

For shears, punches, hoists, stamping process, Elevators, Conveyors.

Unit-(2) DC-motors

Three Point Starter

We know that Voltage of dc motor is

$$V = E_b + I_a R_a$$

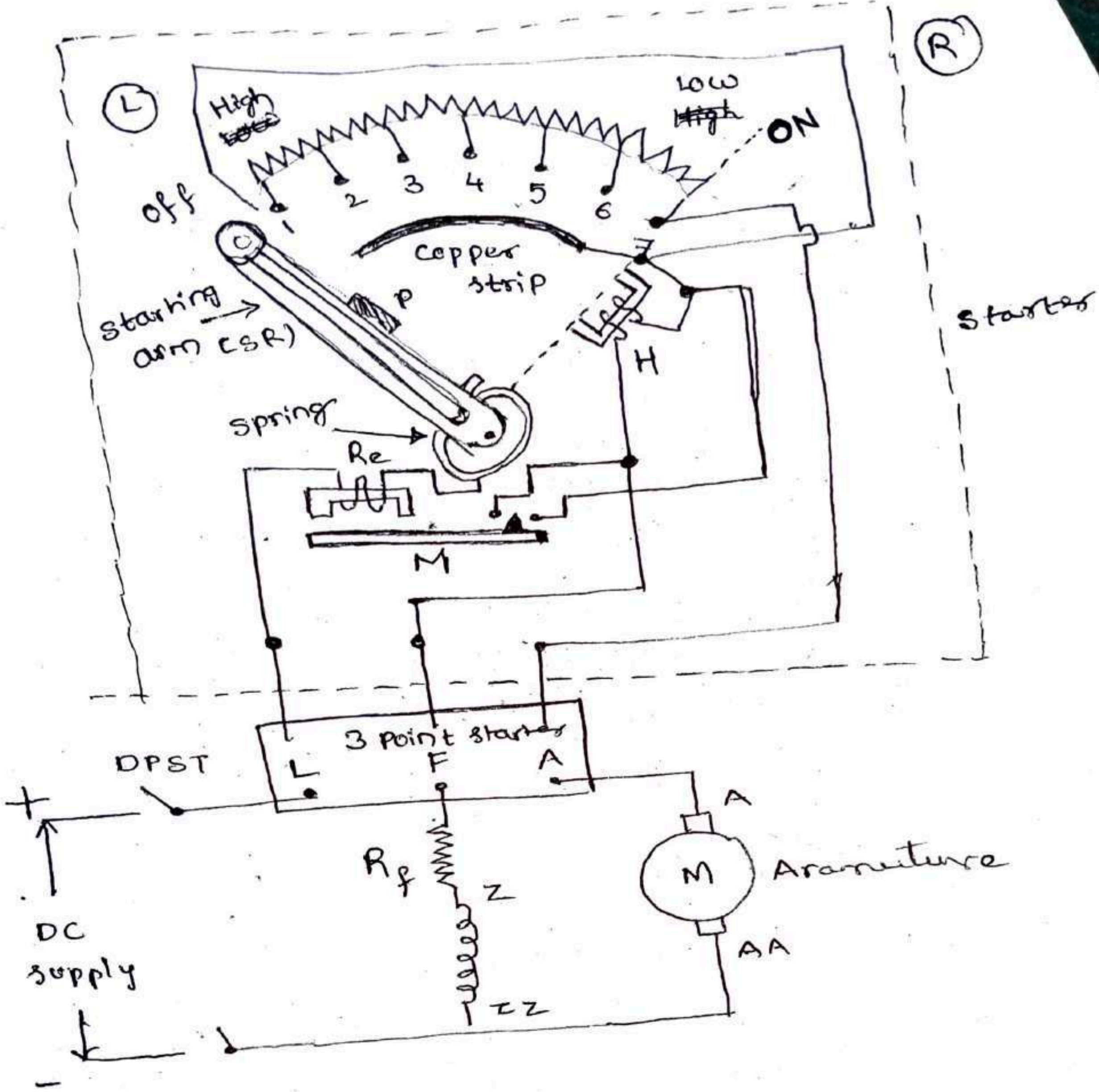
$$\frac{V - E_b}{R_a} = I_a \longrightarrow \text{Current drawn by motor}$$

V = supply voltage, E_b = back emf

R_a = Armature resistance

When motor is rest, E_b is zero. When we apply full voltage, armature draws very high currents to avoid high starting Current a series resistance is Connected to the armature of motor.

fig shows 3 point starter



→ It Consists of 3 terminals. shown in above These are indicated as Line (L), field (F) & Armature (A).

→ when motor is in normal operation, starting arm (SR), over load coil (Re) & Hold on coil (H) which holds to starting arm. during its full running position.

Starting the motor

By DPST switch, starting arm SR is moved slowly from left to Right. when arm contact with stud 1, field circuit & armature connected in series with starting resistance Rc.

As the ~~####~~ arm is moved further, (M5)
stance R_S is gradually cut off till the motor
attains its rated speed.

The spring Re in the starter is used to restore the arm (SR) to off position. When the arm the electromagnetic H is energised & acts as as magnetic to the hold starting arm untill the field current flow through the Hold on coil.

In case of failure of power or sudden disconnection of supply, Hold on coil becomes de-energised & releases the arm as a result immediately comes to starting position (off) by the action of spring force (Re).

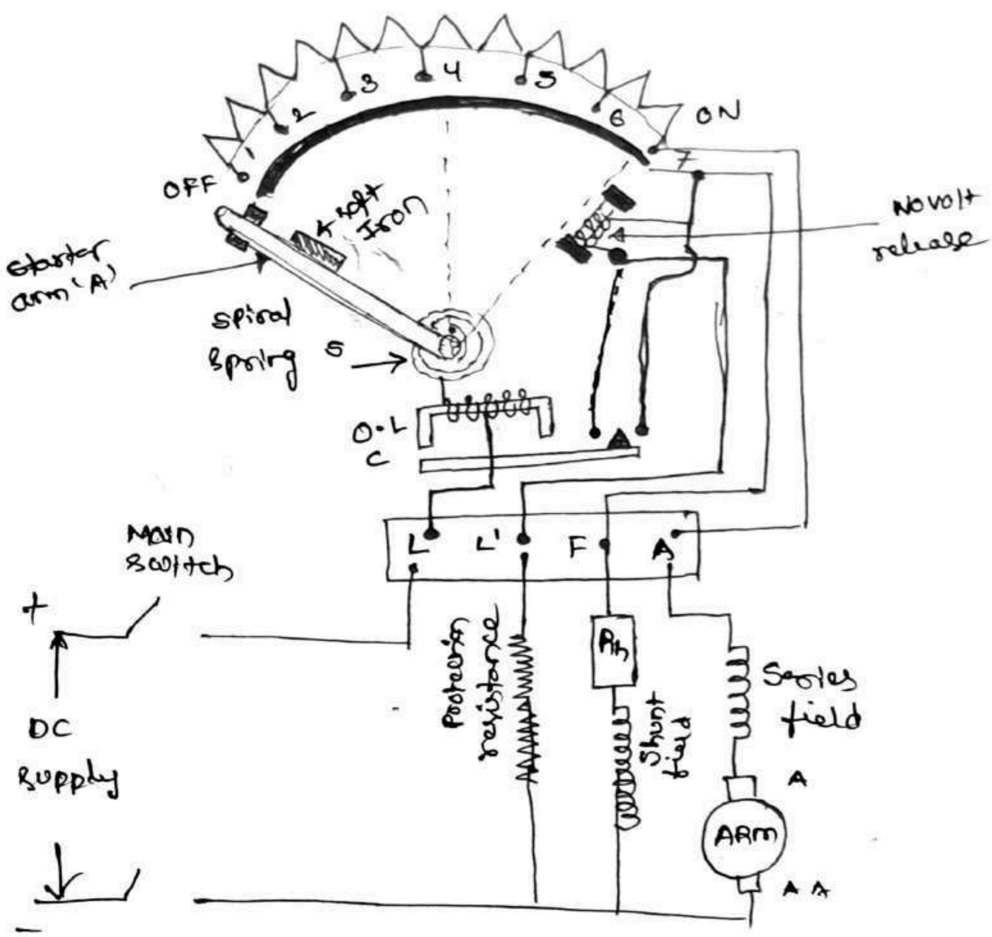
Over current release or over load coil also consists of an electromagnet connected to line supply. If armature current exceeds its preset value, then Rod (m) gets magnetised & lifted up as a results it short circuits the electromagnet. Hence the starting arm (SR) will be released comes to its orginal back position by spring action.

DC-motor 8

Unit-(2)
DC-motors

Four - Point starter

O.L.C
Over load coil.



4 Point starter

→ No volt release coil is connected in series with shunt field & field rheostat.

→ If starting arm is at stud (1), line current divides into 3 sections

1. passes through starting resistance, armature & series field.
2. 2nd part passes through shunt field.
3. 3rd part " " no volt release coil.

→ Here shunt field avoids the restoration of arm to pullback to off position.

→ Before starting dc motor, field circuit is kept closed. Rheostat in series with shunt field is kept at zero or minimum position. Similarly starting resistance in series with armature is kept at maximum value.

For stopping the motor, line switch is opened instead ②
of throwing back the starting arm.

Also for stopping the motor, entire field resistance is Cut off & allow the motor speed falls below the normal speed then opened the line switch.

Testing of dc machines

To determine the efficiency of a d.c machine we need to perform 3 test

① Direct method :

→ suitable for a small machines
→ used to measure efficiency & losses.
→ The machine is completely done by full load. applied to machine.

② Indirect method

→ suitable to find the efficiency & losses in shunt & Compound motor.
→ losses Can be determined without loading machine.
→ It fails to provide the temperature raise during light load Conditions.

③ Regenerative method

→ requires 2 identical machines of same rating.
→ one machine acting as motor & other acting as generator.
→ this requires small power to test large machines for long duration.
→ efficiency, temperature raise, losses Can be find out through this test.

For stopping the motor, line switch is opened instead of throwing back the starting arm.

~~[struck out]~~.

Also for stopping the motor, entire field resistance is cut off & allow the motor speed falls below the normal speed then opened the line switch.

Testing of dc-machines

To determine the efficiency of a d.c machine we need to perform 3 test

① Direct method :

→ suitable for a small machines
→ used to measure efficiency & losses.
→ The machine is ~~[struck out]~~ completely done by full load applied to machine.

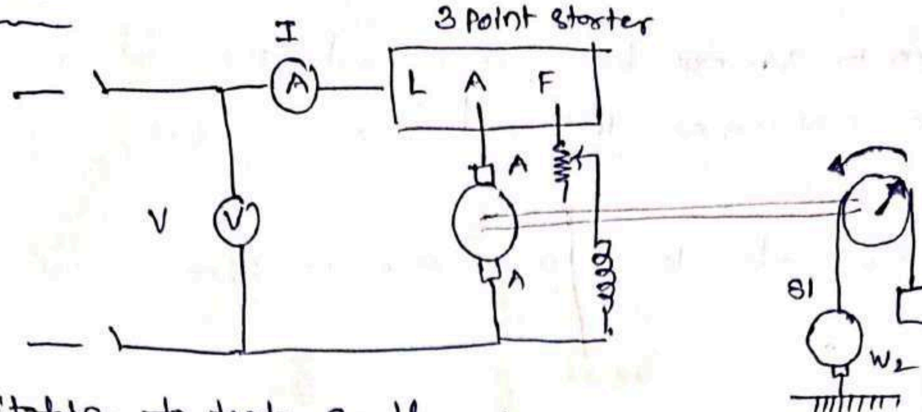
② Indirect method

→ suitable to find the efficiency & losses in shunt & compound motor.
→ losses can be determined without loading machine.
→ It fails to provide the temperature raise during light load conditions.

③ Regenerative method

→ requires 2 identical machines of same rating.
→ one machine acting as motor & other acting as generator
→ this requires small power to test large machines for long duration.
→ efficiency, temperature raise, losses can be find out through this test.

Brake test



→ suitable to test small motors.

→ By applying brake to the pulley which is mounted to the shaft of the motor & this pulley is a water cooled one.

→ Brake band consists of 2 ends, one end is connected to spring through the earth or ground.

→ another end of band is connected to suspended weight (W_1).

→ Difference in weight W1 & spring balance reading W_2 gives force applied on the pulley.

Let W1 be suspended weight in (kg)
W_2 be spring reading which reads the weight in kg.

Net amount of force acting on pulley is
$= 9.81(W_1 - W_2)$ newtons.

if (r) is the radius pulley in meter
N is motor speed in rpm

Then shaft torque developed by motor is

$T_{sh} = 9.81(W_1 - W_2) * r$ N-m

Motor o/p power $= T_{sh} * 2\pi N$ watt

$= 9.81(W_1 - W_2) * r * 2\pi N$

motor i/p power $= VI$

$$\eta\% = \frac{o/p}{i/p} = \frac{9.81(W_1 - W_2) * r * 2\pi N}{VI}$$

Drawbacks of the test

→ o/p of motor cannot be determined accurately

→ fails to determine internal losses & efficiency of large machines.

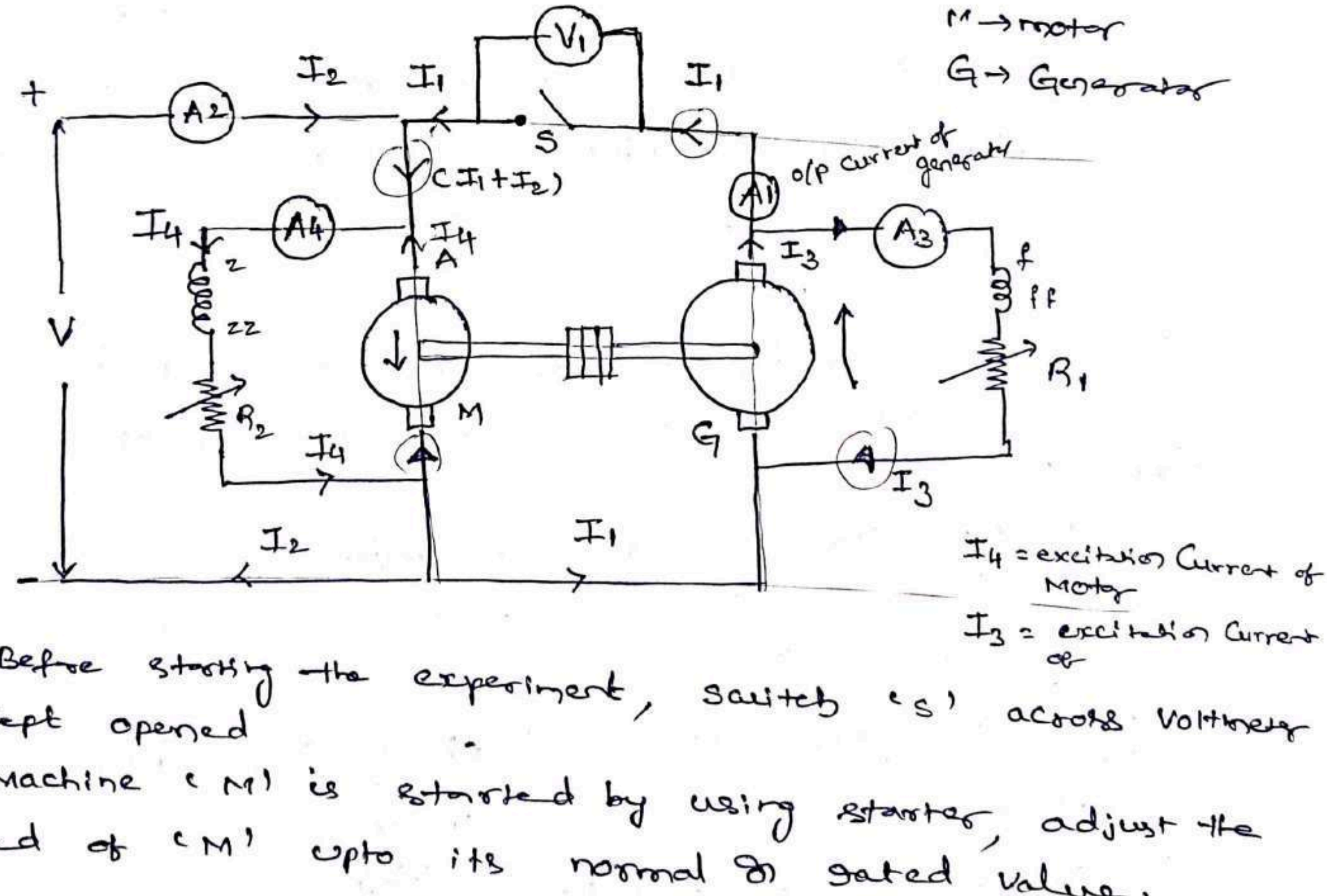
→ not suitable to test the large machines.

Re-generative & Hopskinson's test

→ Also called as Back-Back test
→ This test is carried on 2 identical shunt machines.
→ It is a full load test.
→ Both machines are mechanically coupled & are electrically adjusted.
→ one act as a motor & other act as a generator.
→ electrical o/p of generator is used in supplying a greater i/p to the motor.

Conditions to be needed

① 2 shunt machines of identical ratings is needed
② 2 shunt machines connected in parallel
③ field on ① motor is weakened & other is strengthened.
④ field weakened acting as a motor & field strengthen acting as a generator.



I_4 = excitation current of Motor
I_3 = excitation current of

→ Before starting the experiment, switch 'S' across Voltmeter is kept opened
→ Machine 'M' is started by using starter, adjust the speed of 'M' upto its normal or rated value.
→ Machine 'M' coupled to the Machine 'G' generates voltage is read by Voltmeter.
→ Adjust the voltage of Machine 'G' by varying the field Rheostat untill the Voltmeter attains zero reading.

→ Zero reading in voltmeter indicates the magnitude & polarity is same to that of supply mains.

→ If voltmeter attains zero then close the switch 'S'.

Motor i/p = $V(I_1+I_2)$, I_2 is Current from main supply.

Generator o/p = VI_1. → ①

So electrical o/p of generator & small power from mains is taken by motor develops Mechanical power.

→ assume both machines have same efficiency:

$\eta_m = \frac{o/p}{i/p}$ ⇒ o/p of motor = $\eta_m * V(I_1+I_2) = \eta V(I_1+I_2)$

o/p of generator = η_g * i/p = η_g * o/p of motor

i/p to generator is o/p of motor = $\eta * V(I_1+I_2)$

o/p of generator = $\eta * \eta V(I_1+I_2) = \eta^2 V(I_1+I_2)$ → ②

from ① & ② we get ⇒ equating ① & ②

{ o/p of generator = o/p of mot

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

$\eta = \sqrt{\frac{I_1}{I_1+I_2}}$

⇒ efficiencies of both machines are different because of their armature Currents & excitation Currents is different.

Let R_a = armature of each resistance

I_3 = excitation Current of generator

I_4 = " " " motor.

Armature Copper losses	Shunt Copper losses
motor	motor
⇒ $I_a^2 R_a = (I_1+I_2-I_4)^2 R_a$	⇒ VI_4
⇒ Generator	Generator
$I_a^2 R_a = (I_1+I_3)^2 R_a$	⇒ VI_3

power drawn from supply is VI_2

⇒ total Generator & motor losses is equal to i/p power supplied by mains.

⇒ Stray losses of the machine is obtained by subtracting armature & shunt Copper losses from i/p power

⇒ stray losses = i/p Power from mains − total losses of both machines

$$= VI_2 - \left[(I_1+I_3)^2 R_a + (I_1+I_2-I_4)^2 R_a + VI_3 + VI_4 \right] = W$$

above is stray losses for 2 machines.

stray losses per 2 machines ↗

stray losses per one machine = $W/2$.

For generator

$\eta = \frac{o/p}{i/p} = \frac{o/p}{o/p + T.L}$

Total losses = $(I_1+I_3)^2 R_a + VI_3 + \frac{W}{2} = W_g$

$o/p = VI_1 \Rightarrow \boxed{\eta_g = \frac{VI_1}{VI_1 + W_g}}$

For motor

Total losses = $(I_1+I_2-I_4)^2 R_a + VI_4 + W/2 = W_m$

$i/p = V(I_1+I_2) \Rightarrow \boxed{\eta_m = \frac{V(I_1+I_2) - W_m}{V(I_1+I_2)}}$ $\quad \eta_m = \frac{o/p}{i/p} = \frac{i/p - T.L}{i/p}$

Advantages

→ power required is small

→ temperature raise also observed in the form of losses

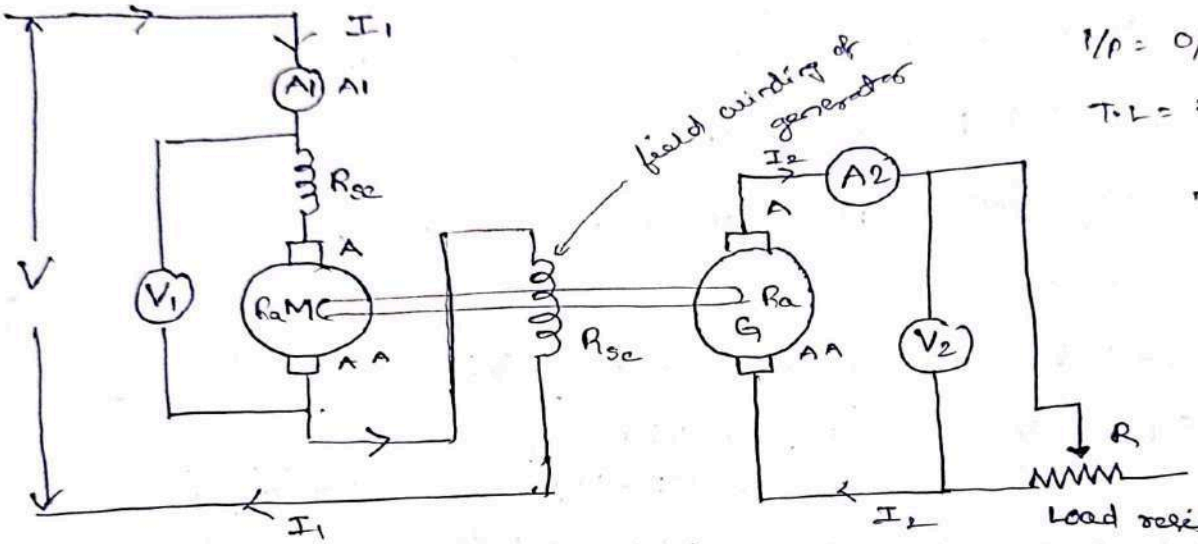
→ Commutation qualities also observed.

Disadvantages

→ requires 2 identical machines

field test → for series motor

→ requires 2 machines to perform this test.
→ These 2 machines are coupled to each other
→ one machine acts as a motor & other acts as generator.
→ Iron & frictional losses of both machines are made equal by (I) Joining the field winding of generator in series with armature of motor
(II) Both machines makes to run at equal speeds.



I/p = O/p + T.L
T.L = I/p − O/p
↓ motor ↓ Gener

⇒ Vary load resistance until the motor current reaches to full load value indicated by ammeter (A1).

⇒ Let V = supply voltage, I_1 = motor current
V_2 = terminal voltage of generator, I_2 = load current

Motor i/p or intake of whole set $= VI_1$

O/p of generator $= V_2 I_2$

Total losses = motor i/p − Generator O/p $= VI_1 - V_2 I_2 = W_t$

Armature & field Cu losses $= I_1^2 (R_a + 2R_{se}) + I_2^2 R_a = W_{cu}$

R_a = armature resistance of each machine
R_{se} = series field resistance of each machine.

stray losses = $W_t - W_{cu}$ = Total losses − Cu losses

stray losses above is for above 2 machines.

" " per machine = $\frac{W_t - W_{cu}}{2}$

Motor efficiency

Motor i/p = $V_1 I_1$

Motor losses = armature Cu losses + field Cu losses + Stray losses

$= I_1^2 R_a + I_1^2 R_{se} + W_s = W_m$

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

$$\eta_m = \frac{o/p}{i/p} = \frac{i/p - \text{motor losses}}{i/p} = \frac{V_1 I_1 - W_m}{V_1 I_1}$$

Generator efficiency (η_g)

Here generator o/p is wasted & it is not fed back to the motor, so generator efficiency will be small use.

Generator o/p = $V_2 I_2$

field Cu loss = $I_1^2 R_{se}$ i/p = o/p + T·L

armature Cu loss = $I_2^2 R_a$

Stray loss = W_s

Total losses = $I_1^2 R_{se} + I_2^2 R_a + W_s = W_g$

$$\eta_g = \frac{o/p}{i/p} = \frac{V_2 I_2}{o/p + T\cdot L} = \frac{V_2 I_2}{V_2 I_2 + W_g}$$

Retardation test

→ Also called as running down test

→ used to find stray losses in shunt machines.

→ By knowing the armature & field Cu losses we calculate the efficiency.

→ Allow the machine to run above the normal speed then supply is cut off from the armature. by maintaining its field constant.

Now the kinetic energy of armature is used to meet the rotational losses.

Kinetic energy ⇒ $K \cdot E = \frac{1}{2} I \omega^2$

where I = moment of inertia of armature
ω = angular velocity

Rotational losses W = rate of change of K·E

$$W = \frac{d}{dt}(K \cdot E) = \frac{d}{dt}\left(\frac{1}{2} I \omega^2\right) = I\omega \cdot \frac{d\omega}{dt}$$

case i To find $\frac{d\omega}{dt} = \frac{dN}{dt}$

① Voltmeter is connected across the armature, acts as a speed indicator because $E \propto N$.

→ If supply cutt off, armature speed slowly falls as a result voltmeter reading slowly falls down.

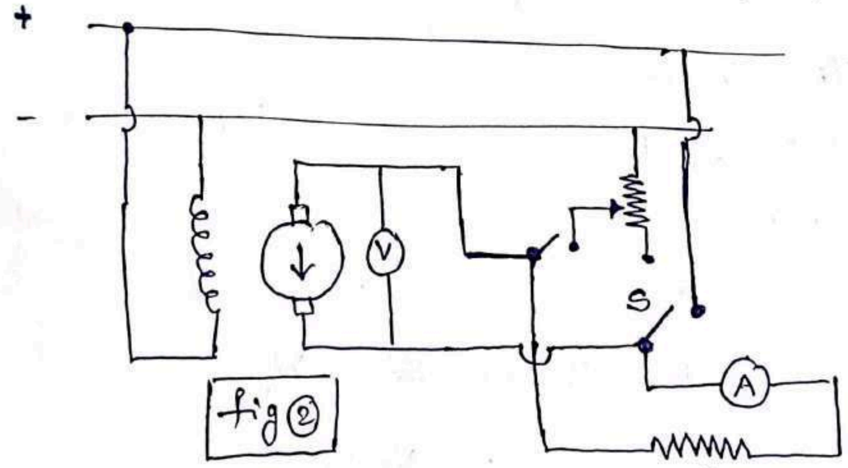
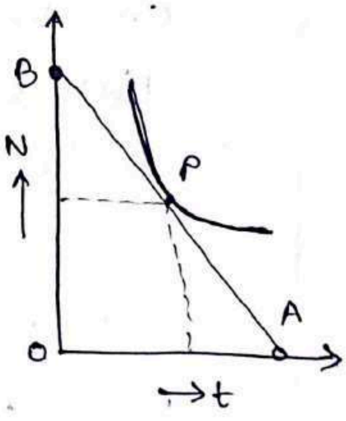


fig ②



Let AB → indicate tangent to normal speed

$$\frac{dN}{dt} = \frac{OB \text{ in rpm}}{OA \text{ in sec}} =$$

$$W = I\omega \cdot \frac{d\omega}{dt} = I\left(\frac{2\pi N}{60}\right) * \frac{d}{dt}\left(\frac{2\pi N}{60}\right) = I\left(\frac{2\pi}{60}\right)^2 \frac{dN^2}{dt}$$

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

$$W = 0.011\, I N \frac{dN}{dt}$$

Case ii To find the moment of inertia

(a) To Calculate (I)

Adding a fly wheel of known moment of inertia to the shaft & draw the slow down curve.

Because of fly wheel machine slow down time is longer. For any speed $\frac{dN}{dt_1}$ & $\frac{dN}{dt_2}$ are determined.

Losses in both machines would be same

$$W = \left(\frac{2\pi}{60}\right)^2 I \cdot N \left(\frac{dN}{dt_1}\right) \rightarrow \text{1st case}$$

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

equating (1) & (2) cases

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

$$\frac{dN}{dt_1} \Big/ \frac{dN}{dt_2} = \frac{I + I_1}{I} \Rightarrow I = I_1 * \frac{dN/dt_2}{dN/dt_1 - dN/dt_2}$$

$$I = I_1 \frac{dt_1}{dt_2 - dt_1} \text{ or } I_1 \frac{t_1}{t_2 - t_1}$$

(b) 2nd method → where I is eliminated

In this method an electrical torque is added by means of resistance acts as a retarding torque. This retarding torque making it slow down. shown in fig (2)

Let W' be the additional power loss $= I_a^2 (R_a + R)$ or $V I_a$

$$W = \left(\frac{2\pi}{60}\right)^2 I \cdot N \frac{dN}{dt_1}$$

$$W + W' = \left(\frac{2\pi}{60}\right)^2 I \cdot N \cdot \frac{dN}{dt_2}$$

} Both cases dN is same

$$\frac{W + W'}{W} = \frac{dt_1}{dt_2} \Rightarrow \therefore W = W' * \frac{dt_2}{dt_1 - dt_2} = W' * \frac{t_2}{t_1 - t_2}$$

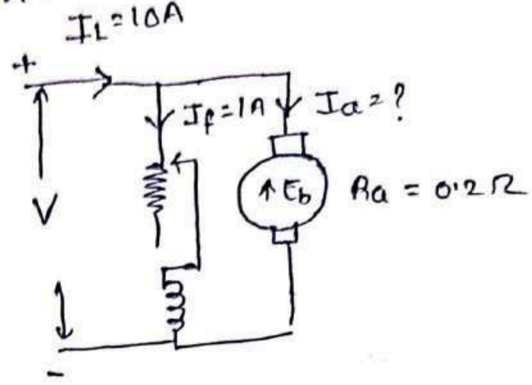
$\frac{dN}{dt_1}$ = rate change of speed without extra load

$\frac{dN}{dt_2}$ = " " " " with extra electrical load.

DC-motors - problems

Swinburne's test

A 500V, DC shunt motor takes 4A on no load, the armature resistance of 0.2 Ω, field current 1A, Determine its o/p & efficiency when i/p current is 10A.



Voltage = 500V, line current or no load current $I_L = 4A$, $R_a = 0.2\Omega$

⇒ given field current I_f or $I_{sh} = 1A$.

No load Condition

field Current = 1A

No load armature Current ⇒ $I_{a0} = I_{L0} - I_f$ $\quad$ $I_L = I_f + I_a$

$J_{a0} = 4 - 1 = 3A$ $\quad$ $I_a = I_L - I_f$

$V - I_{a0}R_a - E_b = 0 \Rightarrow E_{b0} = V - J_{a0}R_a = 500 - 3 * 0.2 = 499A$

⇒ No load Cu losses $= I_{a0}^2 R_a = 3^2 * 0.2 = 1.8W$

⇒ Motor i/p = Motor o/p + Total losses

VI_L = Motor o/p + (Constant losses + Cu losses)

Constant losses $W_c = ?$ Let motor $o/_p = 0$

Constant losses W_c = Motor i/p − Cu losses

$= VI_L - I_{a0}^2 R_a = (500 * 4) - (1.8)$

$= 1990W$

on - load Condition

load Current $I_L = 10A$

armature Current on load $I_a = I_L - I_f = 10 - 1 = 9A$

⇒ Back emf $E_b = V - I_a R_a = 500 - (9 * 0.2) = 498V$

⇒ Cu losses on load $= J_a^2 R_a = 9^2 * 0.2 = 16.2W$

Total losses $= W_c + I_a^2 R_a$

$W_c = VI_L - J_a^2 R_a = (500 * 10) - (16.2) = 1998\ w$

Motor o/p = Motor i/p − T.L $= (500 * 10) - (1998 + 16.2) = 2986W$

$$\eta_m = \frac{o/p}{i/p} = \frac{2986}{5000} * 100 = 60\%.$$

III unit

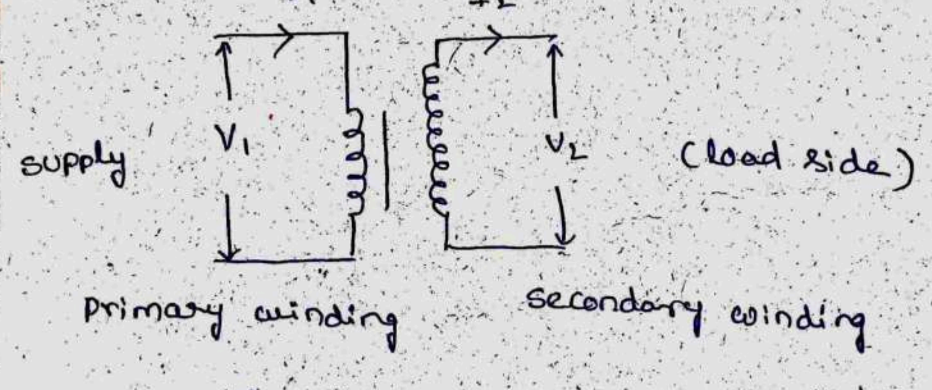
AC- machines

single phase transformers

DC generators generates Constant DC voltage. To increase or decrease the Constant dc voltage is not achieved. The voltages in case A.C can be changed. To avoid the above voltage values changing problem we go for using AC voltages. this change can be done by using AC machines Best example Converting voltages from high to low or low to high voltage is done by a device Called Transformer.

Definition of transformer

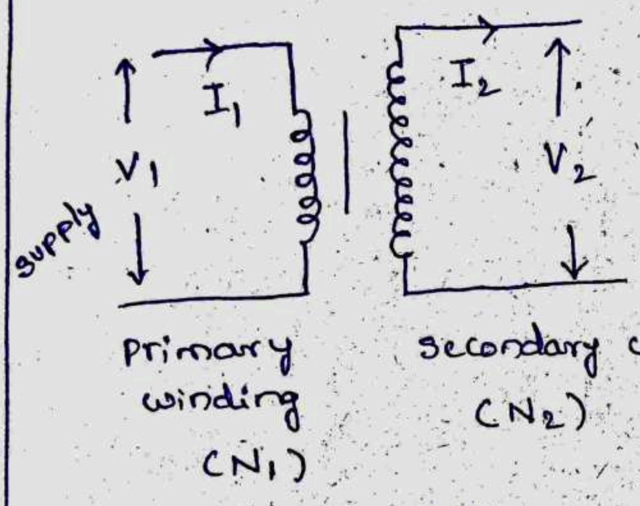
It is a static device which transforms voltage or current in one circuit to another circuit without changing frequency.



supply is given to primary side & Load is Connected to secondary side.

According to voltages, it is classified as 2 types (1) step up (2) step down transformer

Step up transformer



$N_1 \rightarrow$ no. of turns in primary

$N_2 \rightarrow$ no. of turns in secondary

$\boxed{N_1 < N_2} \rightarrow$ step up transformer

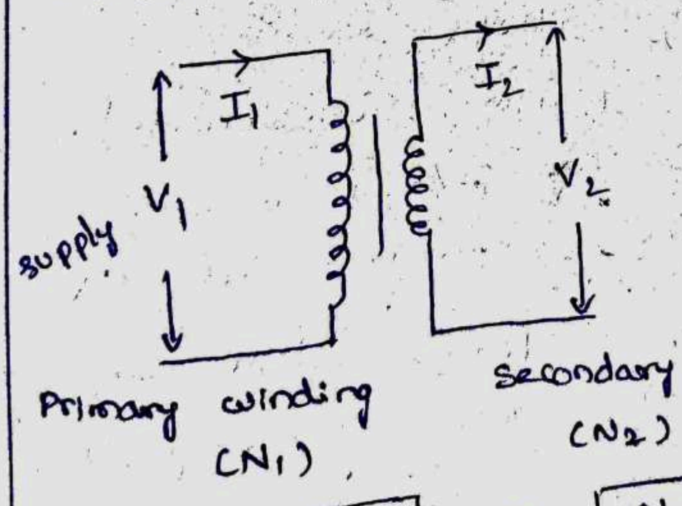
If no. of turns in primary is less than the no. of turns in 2ndary is step up transformer

or

No. of turns in secondary is greater than No. of turns in primary

$\boxed{N_2 > N_1} \rightarrow$ step up transformer,

Step down transformer



$\boxed{N_1 > N_2}$ or $\boxed{N_2 < N_1}$

step down transformer.

Principle of Operation

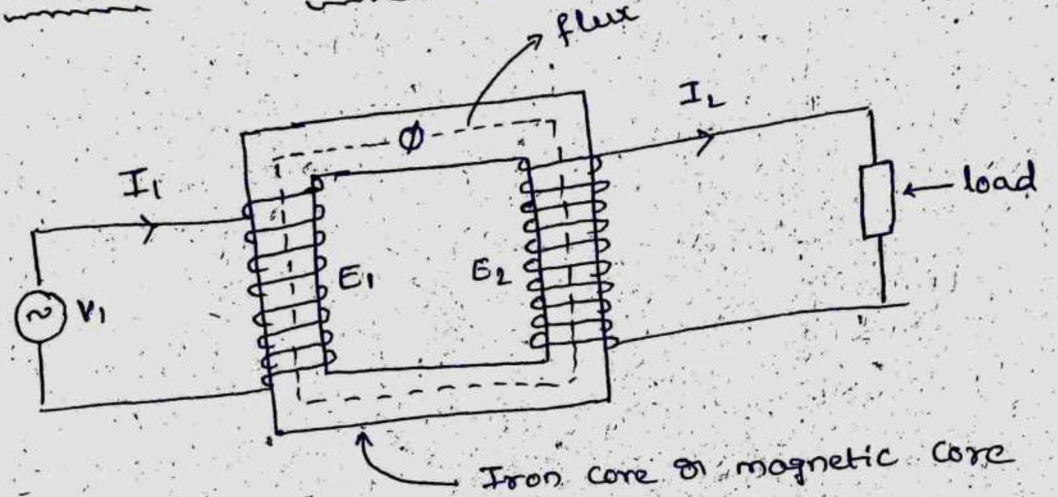


fig: Connection type of transformer

→ It consists of magnetic or Iron core & 2 different windings wounded over the core.

→ Here windings forms an electrical circuit & Core forms the magnetic circuit

Principle

The basic principle of transformer depends on mutal induction b/w the 2 circuits.

If one winding (primary) is connected to the supply of AC, alternating flux ϕ is established in the core due to the current in primary.

Alternating flux in primary links with the other winding secondary. The alternating flux in 2ndary induces an emf in secondary.

If 2ndary winding is closed or short circuited by load, a secondary current will flow.

Finally we conclude that energy in one circuit is transfored to other circuit by maintaining I/p & O/p frequency is constant.

Constructional details

They are 3 important parts
① primary winding ② secondary winding
③ Transformer core.

primary winding → supply part is Connected to primary side is called as primary winding
secondary winding → Load part is Connected to secondary side is Called as secondary winding.

Transformer Core

The outer part of transformer is core. The core is made up of Iron. It is Commonly Connected b/w the primary & secondary windings.

Sometimes the core is made up of silicon steel since to reduce the hysteresis losses.

The Core is made up of some laminated stampings which are insulated each other by varnising metal oxide to reduce eddy eddy current losses.

The thickness of laminating stamping are 0.3 to 0.5mm.

Again Transformer core are classified as 2 types.
ⓐ Core type ⓑ shell type

ⓐ Core type

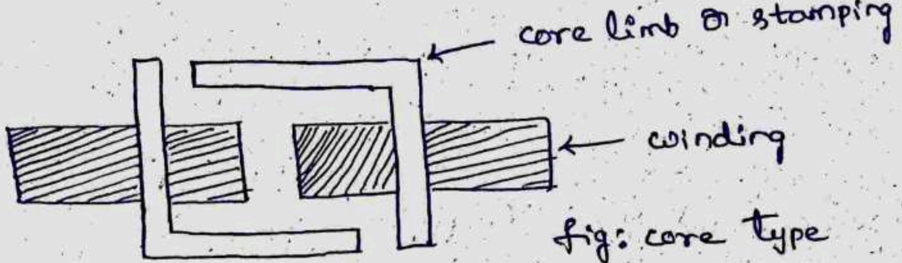


fig: core type

A part of core is sourrounding by the windings.
or
windings sourrounds the core.

It has 2 limbs which is made up of L-shape. For each L' shape limb a core sourrounds the winding.

Coils are usually cylindrical type

→ For high ratings, stepped core with cylindrical type coils are used

→ For smaller ratings, either square or rectangular core with rectangular type coils are used.

Shell type transformer

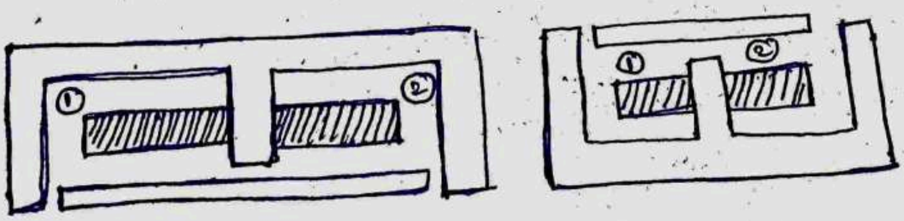


fig: shell types transformer

In this core sourrounds the winding.
Here 2 windings are carried by a central limb.

The cores are in the shape of E + one shape stampings. Therefore no: of limbs is three.

It has 2 parallel magnetic paths.

Transformer tank

The outer part of machine is tank. It is a metallic container which can be used for placing a core & windings. The tank is filled transformer oil.

Transformer oil

It is a mineral oil. It provides coolings to transformer core & windings during loading conditions.

It also acts a insulation b/w tank & core & windings.

Conservator

It is a drum located at the top of transformer which contains transformer oil. It is connected to tank by means of pipe. During loading & unloading conditions oil gets contraction & expansion in the space of conservator.

Breather

It is a cylindrical tube consists of a silica gel with cobalt. The purpose is to extract fresh air which is used to cool core & winding inside the tank.

Emf equation of a transformer

Let V_1 be the A.C voltage applied at the primary side having the frequency f.

because of primary voltage current flows through the primary side induces a flux (ϕ) in primary side.

→ sinusoidal flux in primary can be represented as

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

→ where ϕ_m = maximum sinusoidal flux

The flux in primary induces an emf in (e_1) primary winding

we know that induced emf

$$e_1 = -N_1 \frac{d\phi}{dt}$$

e_1 = primary induced emf

N_1 = no. of turns in primary

$$e_1 = -N_1 \frac{d(\phi_m \sin\omega t)}{dt}$$

$$= -N_1 \omega \phi_m \cos\omega t$$

$\omega = 2\pi f$

$$= -2\pi f N_1 \phi_m \cos\omega t$$

$$e_1 = 2\pi f N_1 \phi_m \sin(\omega t - 90) = 2\pi f N_1 \phi_m$$

$$e_1 = e_{m1} = 2\pi f N_1 \phi_m$$

rms value of induced emf E_1

$$E_1 = \frac{e_{m1}}{\sqrt{2}} = \frac{2\pi f N_1 \phi_m}{\sqrt{2}}$$

$$\boxed{E_1 = 4.44 f N_1 \phi_m}$$

$$E_2 = 4.44 f N_2 \phi_m$$

E_1 = induced emf in primary

E_2 = induced emf in secondary

N_1, N_2 } no. of turns in primary & secondary

Transformation ratio $K = \frac{V_2}{V_1} = \frac{N_2}{N_1} = \frac{I_1}{I_2} = \frac{E_2}{E_1}$

Losses & efficiency of transformer

Losses in transformer as classified as

(1) core losses & Iron losses (2) Copper losses

The above 2 losses reduces system efficiency & increases the temperature

Core losses.

These losses are due to alternating flux in transformer core. These losses additionally generates hysteresis & eddy current losses.

(W_h) Hysteresis loss = $K_h f * B_m^{1.6}$ watt/m³

(W_e) Eddy current loss = $K_e * B_m^2 f^2 * t^2$ watt/m³

above losses are determined open circuit test

$W_h = K_h * f * B_m^{1.6}$

$W_e = K_e * t^2 * B_m^2 f^2$

Iron losses = Hysteresis + Eddy current losses

Hysteresis is minimised by using high steel having more silicon content &

Eddy current losses is minimised by using thin laminations on core

② Copper Losses

These losses are due to ohmic resistance. These losses occur in both primary + secondary. These are determined from short circuit losses.

Copper losses $P_{cu} = I^2 R$

Copper losses vary as square of load current.

Total losses = iron losses + Copper losses

$= P_i + P_c$

among 90% of total losses are due to copper losses only.

Efficiency of transformer

the efficiency of transformer is defined as it is the ratio of o/p power to i/p power in KW

$$\text{Efficiency } (\eta) = \frac{o/p}{i/p} = \frac{o/p}{o/p + \text{Total losses}}$$

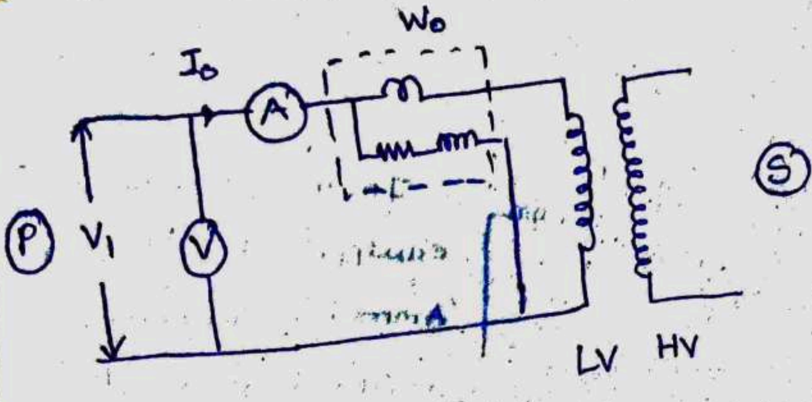
$$\eta = \frac{(x)\ \text{full load VA} * \text{p.f}}{(\text{full load VA})(x) + (P_i + x^2 P_{cu})}$$

Transformer tests

% efficiency + % regulation at various power factors, loads are determined from 2 test ① open circuit (2) short circuit test.

open circuit or No load test

from this we measure core losses.



(P) → primary side (supply)
(S) → secondary side (load side) → open

L.V → low voltage winding
HV → High voltage winding

Here measuring equippments like voltmeter (V), ammeter (A), wattmeter are taken at LV side.

Here rated voltage of LV winding is applied to primary & secondary left opened. Applied voltage is measured by voltmeter & no load current is measured by ammeter. No load or Iron losses is measured by Wattmeter (W_o). So iron losses is constant during no load or loading.

Iron losses, P_i = Watt meter reading = W_o

No load Current I_o = ammeter reading

Applied voltage = Voltmeter reading = V_o

P/P power $W_o = V_o I_o \cos\phi_o$

$\cos\phi_o$ = No load p.f

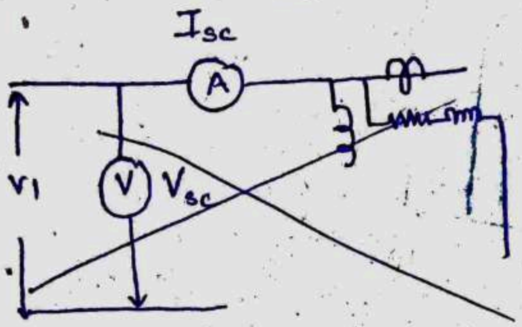
$$\cos\phi_o = \frac{W_o}{V_o I_o}$$

$I_W = I_o \cos\phi_o$, $I_m = I_o \sin\phi_o$

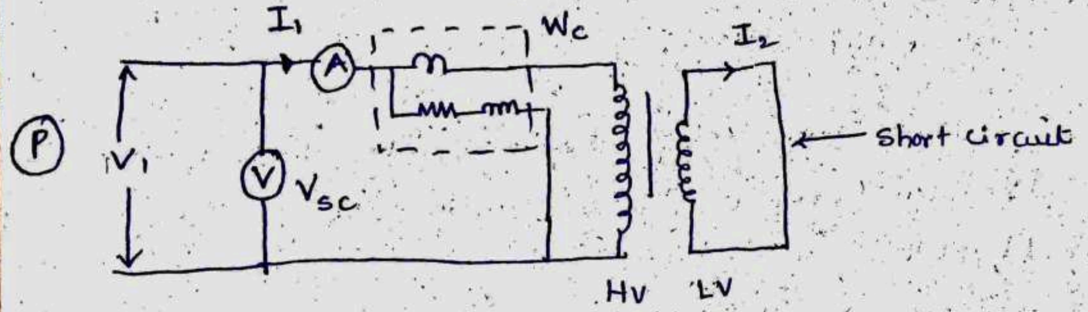
I_W → working Component

I_m → magnetising Component

Short circuit test



- In this test measuring equippments Voltmeter, Ammeter, wattmeter are Connected at High voltage winding side & Low voltage winding secondary is short circuited by using thick wire.



Here rated current of High Voltage winding is applied to the primary. Due to Current in Primary (I_1) induces a Current in secondary I_2.

$$\frac{I_1}{I_2} = \frac{N_2}{N_1}$$

Here voltmeter reads short circuit voltage V_{sc},

Ammeter reads primary rated current I_1,

wattmeter reads full load cu losses $= W_s$

full load Cupper losses $= i_1^2 R_{01}$

$$P_c = I_1^2 R_{01}$$

$$\boxed{R_{01} = \frac{P_c}{I_1^2}}$$

R_{01} is the equivalent resistance of t/former refer to primary.

During no load conditions Cu losses is small & during loading conditions Cu losses is almost doubles. So Cu losses are also called variable losses

equivalent impedance refer to primary $Z_{01} = \frac{V_{sc}}{I_1}$

Total or equivalent reactance refer to primary

$$X_{01} = \sqrt{Z_{01}^2 - R_{01}^2}$$

full load Copper losses $P_c = V_{sc} I_1 \cos\phi_{sc}$

$$\cos\phi_{sc} = \frac{P_c}{V_{sc} I_1}$$

Problem

A 20KVA transformer has 200 turns on primary & 40 turns on secondary. Primary is connected to 1000V, 50Hz supply. Determine
(i) 2ndary voltage on open circuit
(ii) Current flowing through 2 windings on full load
(iii) maximum value of flux.

Sol

rating of transformer = 20KVA,
No. of turns in primary $N_1 = 200$
No. of turns in secondary $N_2 = 40$
Frequency $f = 50Hz$; primary voltage $V_1 = 1000V$
$I_1 = ?$, $I_2 = ?$, secondary voltage $V_2 = ?$

① secondary voltage, V_2

we know that transformation ratio

$$K = \frac{V_2}{V_1} = \frac{N_2}{N_1} = \frac{E_2}{E_1} = \frac{I_1}{I_2}$$

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

$$V_2 = V_1 * \frac{N_2}{N_1} = 1000 * \frac{40}{200} = 200\,V$$

(ii) Current flowing through primary I_1.

$$I_1 = \boxed{\frac{\text{KVA rating of transformer}}{\text{Primary Voltage}}} = \frac{20 * 1000}{1000} = 20\,A$$

Current flowing through secondary I_2.

$$I_2 = \frac{\text{KVA rating}}{\text{secondary voltage}} = \frac{20 * 1000}{200} = 100\,A$$

(iii) Maximum value of flux ϕ_m = ?

$$\boxed{E_1 = 4.44 * \phi_m * f * N_1}$$

$$\phi_m = \frac{E_1}{4.44 * 50 * 200} = 22.52\ mwb$$

problem

② single phase transformer has frequency 50 Hz having no load ratio is $\frac{6600}{300}$ V. If maximum value of flux is 0.09 Weber, find the number of turns in each windings.

sol frequency $f = 50\,Hz$, Primary voltage $V_1 = 6600\,V$

secondary voltage $V_2 = 300\,V$, flux $\phi_m = 0.09\,wb$

find number of turns N_1 & N_2

No load ratio = $\frac{6600}{300} = \frac{V_2}{V_1}$

sol

we know that Emf equation of transformer

$E_1 = 4.44 * f * \phi_m * N_1$

$300 = 4.44 * 50 * 0.09 * N_1$

$$K = \boxed{\frac{V_2}{V_1} = \frac{E_2}{E_1} = \frac{I_1}{I_2} = \frac{N_2}{N_1}}$$

$N_2 = \frac{300}{4.44 * 50 * 0.09}$

$N_2 = 15$

$N_1 = \frac{V_2}{4.44 * f * \phi_m} = \frac{300}{4.44 * 50 * 0.09} = 330$

problem ③ A 6600/440 V single phase 600 KVA transformer has 1200 primary turns find
① Transformation ratio (II) secondary turns
(III) Voltage/turn (IV) secondary current when supplied a load 400 KW at 0.8 p.f lagging.

sol given

$V_1 = E_1 = 6600$

$V_2 = E_2 = 440$

transformer rating = 600 KVA

primary turns $N_1 = 1200$

secondary voltage $E_2 = 440V$

① $K = ?$ (II) Secondary turns = ? (II) secondary current $I_2 = ?$

(IV) voltage/turn = ?

① transformation ratio

$$K = \frac{V_2}{V_1} = \frac{440}{6600} = 0.066$$

(ii) secondary turns

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

$$\therefore N_2 = \frac{V_2}{V_1} * N$$

$$N_2 = \frac{440}{6600} * 440 = 80$$

(iii) Voltage / turn =

$$V = \frac{\text{Primary Voltage } V_1}{\text{primary turns } N_1} = \frac{6600}{1200} = 5.5\,V$$

(iv) secondary Current (I_2) when it supplies load 400kW at 0.8 p.f

$$\cos\phi_2 = 0.8$$

$$P = V_2 I_2 \cos\phi_2$$

$$400 * 1000 = 440 * I_2 * 0.8$$

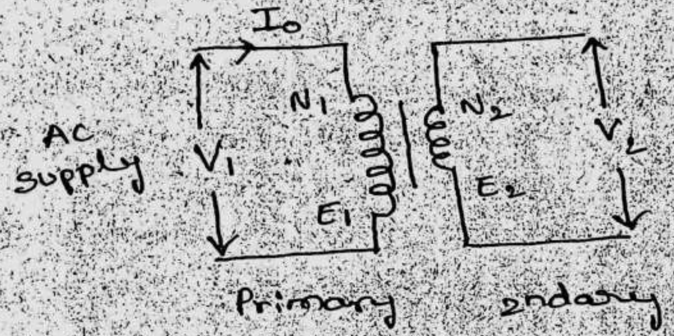
$$I_2 = \frac{400 * 1000}{440 * 0.8} = 1136.36\,A$$

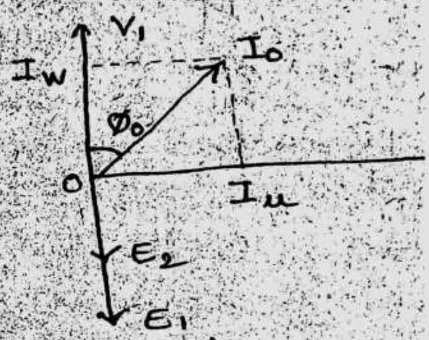
Single phase transformers

(T1-T15) pages

Transformer Operation — No load

Primary is connected to ac supply & secondary winding is left open, then the transformer is said to be on no-load.





vector diagram

Let V_1 be the primary supply voltage
I_0 be the no load primary current
This I_0 establishes a flux 'ϕ' in the core.
No load input power

$$W_0 \text{ or } P_0 = V_1 I_0 \cos\phi$$

I_0 has 2 components

① Active or working or wattful component (I_w) which is inphase with supply V_1.
It supplies Iron losses & small amount of copper losses in primary.

$$I_w = I_0 \cos\phi_0$$

(2) Magnetising or Reactive or wattless component (I_μ) which is in quadrature with supply V_1. and its function to establish a flux in core.

$$I_\mu = I_0 \sin\phi_0$$

Total primary no load Current. (T2)

$$I_0 = \sqrt{I_\omega^2 + I_\mu^2}$$

Unit - III transformers

Important points to be remember

(1) No load primary Current I_0 is very small Compared to full load primary Current.

(II) As primary no load Current I_0 is very small Cu (copper) losses in primary on no load is negligible.

Problems on No-load

A 2200/250 V transformer takes 0.5A at a power factor 0.3 on open circuited. Find magnetising & working Components of no load primary Current.

sol

Primary voltage $V_1 = 2200\,V$

2ndary voltage $V_2 = 250\,V$

No load Current $I_0 = 0.5\,A$

No load Power factor $\cos\phi_0 = 0.3 \Rightarrow \cos^{-1}(0.3)$ $\phi_0 = 72.54$

find I_μ (Magnetising Component) = ?

I_w (working Component) = ?

(1) $I_\mu = I_0 \sin\phi_0 = 0.5 * \sin(72.54) = 0.476\,A$

(2) $I_w = I_0 \cos\phi_0 = 0.5 * 0.3 = 0.15\,A$

(Q) no load Current of t/former is 15A having power factor of 0.2 when Connected to 460V, 50Hz supply. If primary winding has 550 turns Calculate (i) I_μ (II) iron loss (III) maximum value of flux ϕ_m

Given data

no load current $I_0 = 15A$

p.f $\cos\phi_0 = 0.2$ ↪ $\phi_0 = \cos^{-1}(0.2) = 78.4$

$V_1 = 460V = E_1$

Primary winding $N_1 = 550$

(i) $I_\mu = I_0 \sin\phi = 15 * \sin(78.4) = 14.7 A$

(ii) Iron loss $W_0 = V_1 I_0 \cos\phi_0$

$= 460 * 0.5 * 0.2 = 138 W$

(iii) maximum value of flux (ϕ_m)

$E_1 = 4.44 * \phi_m * f * N_1$

$$\phi_m = \frac{E_1}{4.44 * f * N_1} = \frac{460}{4.44 * 50 * 550} = 3.77 \text{ m web}$$

(Q) Find (i) active component I_w (ii) Reactive component I_μ (iii) no load current I_0 at a power factor 0.25 lagging having 230V/115 V If i/p power on no load to high voltage winding is 70W.

sol. given data

Primary voltage $V_1 = 230V$

2ndary voltage $V_2 = 115V$

No load I/P power W_0 or $P_0 = 70 W$

Power factor $\cos\phi_0 = 0.25$

$\phi_0 = \cos^{-1}(0.25) = 75.52$

(i) Active component

$I_w = I_0 \cos\phi_0$

$I_0 = ?$

(T3)

Transformer on load

When 2ndary is loaded, secondary current set up (I_2). Here secondary winding is connected to load, secondary current flows through load.

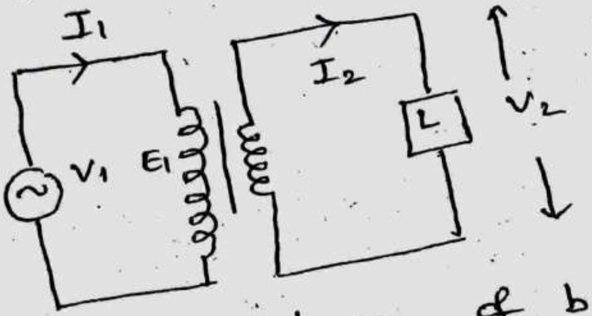


fig shows transformer with load on secondary

Magnitude & phase of both V_2 & I_2 depends on the type of load.

* If load is Resistive
  I_2 is inphase with V_2
* If load is inductive
  I_2 lags the voltage V_2 by 90
* If load is Capacitive
  I_2 leads the voltage V_2 by 90°

III - unit Transformers

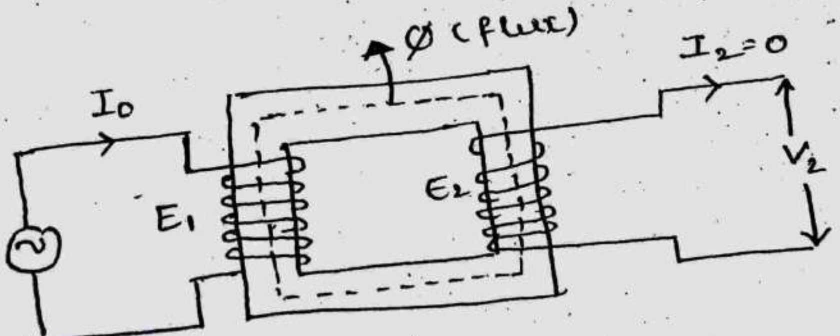


fig shows transformer under no load

Primary current flows through the primary winding set up a flux in core.

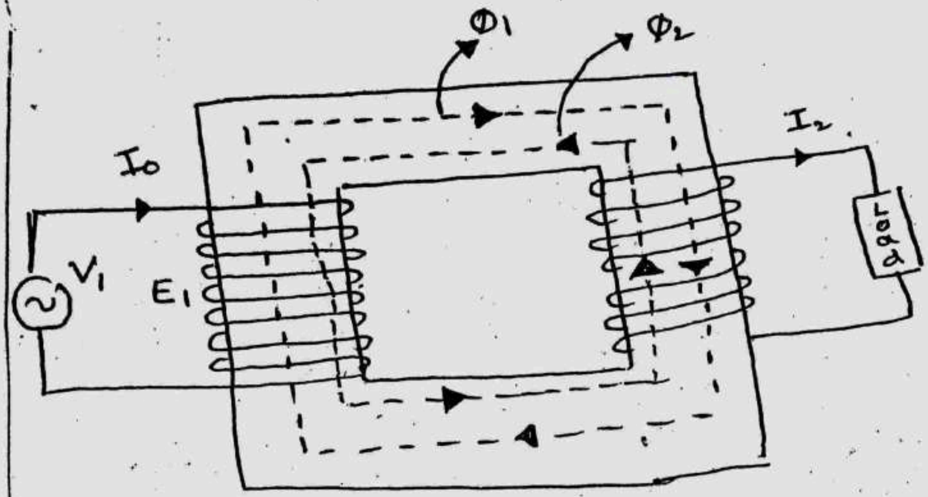


fig shows transformer under load condition

Secondary Current I_2 establishes a flux ϕ_2. This flux ϕ_2 opposes the flux (ϕ_1) & decrease the no load flux. Hence primary induced emf E_1 reduces & more current flows through primary.

Let the additional primary current be I_2'. It is known as load component of primary current. This current is opposite or antiphase with I_2. I_2' establishes a flux ϕ_2' which is opposite to direction of ϕ_2. Hence ϕ_2' & ϕ_2 cancels each other. It is shown in fig ①

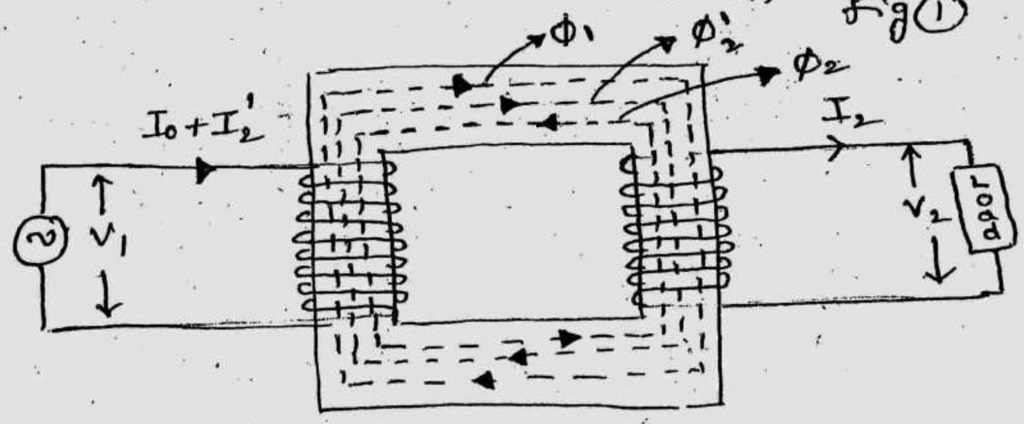


fig ①

Let N_1 → no. of turns in primary
I_1 → Primary current or no load
N_2 → no. of turns in secondary

(T4)

$I_2 \rightarrow$ secondary current

$I_2' \rightarrow$ Load component of primary current

$$\frac{N_2}{N_1} = \frac{I_1}{I_2} = K \longrightarrow (1)$$

During loading condition on secondary, secondary current I_2 creates an additional current in primary side, this is given as I_2'. $I_0 = I_2'$

$$N_2 I_2 = N_1 I_1$$

$$N_2 I_2 = N_1 I_2'$$

$$I_2' = \frac{N_2}{N_1} * I_2 = K * I_2$$

III - unit Transformers

During loading or unloaded condition, flux passing through the core is constant.

Extra no need

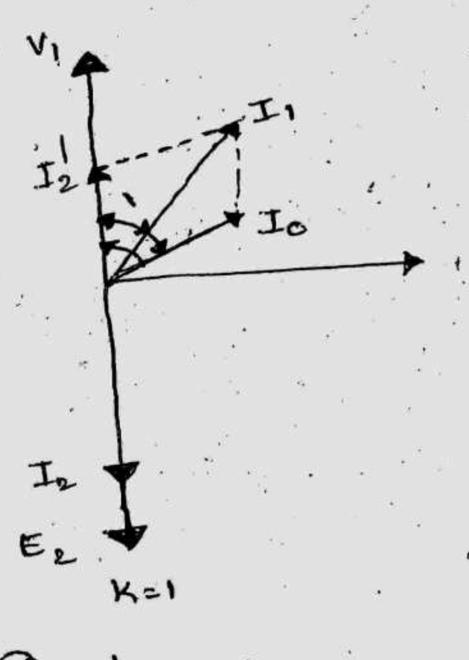


fig (a) phasor diagram for non inductive load (Resistive load)

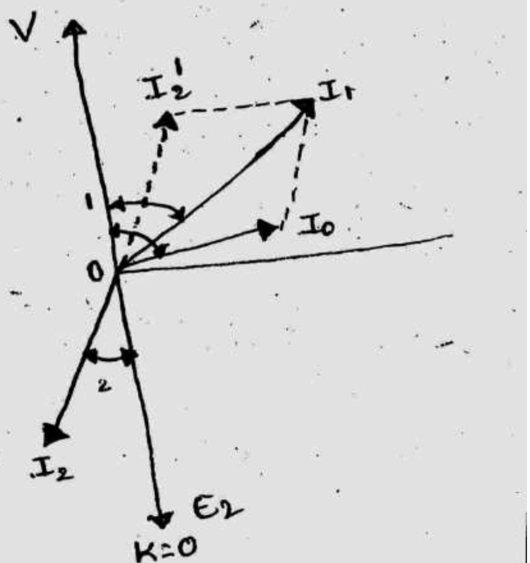


fig (b) phasor diagram for inductive load.

(T4)

I_2 → secondary current

I_2' → Load Component of Primary Current

$$\frac{N_2}{N_1} = \frac{I_1}{I_2} = K \rightarrow (i)$$

During loading condition on secondary secondary current I_2 creates an additional current in primary side, this is given as I_2'. $I_0 = I_2'$

$$N_2 I_2 = N_1 I_1$$

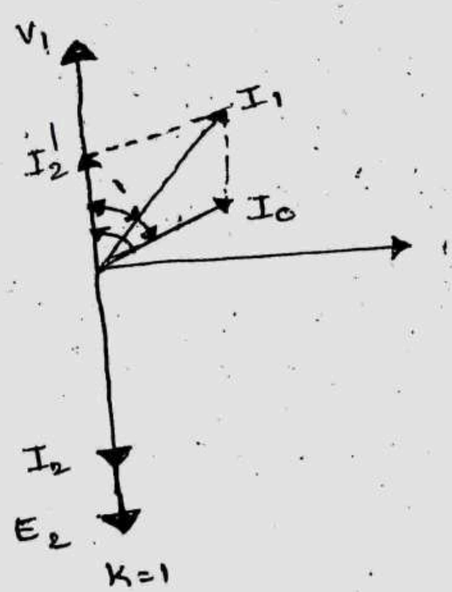
$$N_2 I_2 = N_1 I_2'$$

$$I_2' = \frac{N_2}{N_1} * I_2 = K * I_2$$

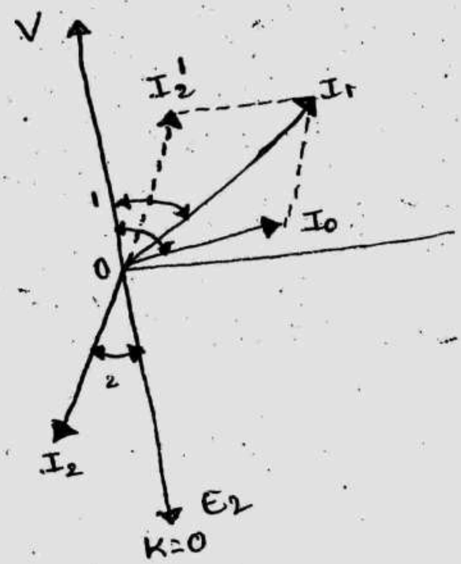
III - unit Transformers

During loading or unloaded condition, flux passing through the core is constant.

Extra no need



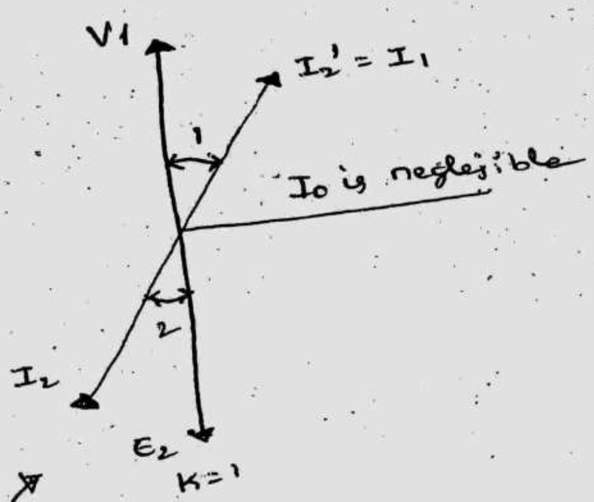
fig(a) phasor diagram for non inductive load (Resistive load)



fig(b) phasor diagram for inductive load.

from fig (a) I_2 is in phase with E_2. It causes primary component of load current I_2' which is antiphase with I_2 & is equal in magnitude.

Total primary current I_1 is the sum of I_2' & I_0. I_1 lags behind voltage at an angle ϕ_1.



from fig (b)

Here I_2 lag E_2 by ϕ_2. Current I_2' is in antiphase with I_2.

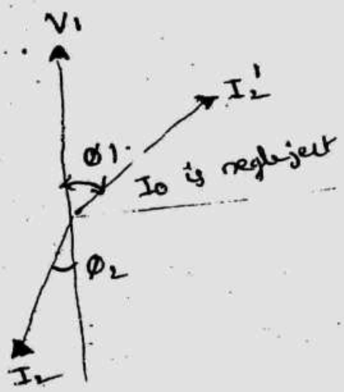
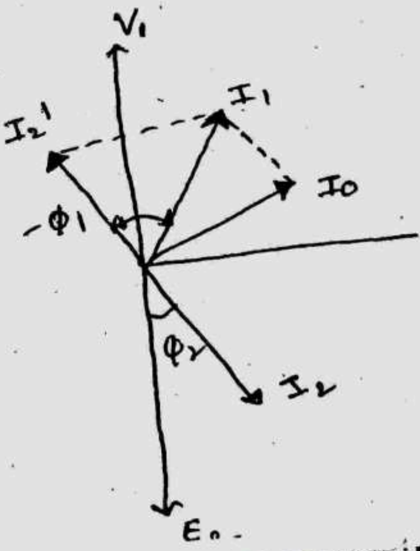


fig (c) shows that $\phi_1 > \phi_2$, neglect I_0 then $\phi_1 = \phi_2$

$$N_1 I_2' = N_2 I_1 = N_1 I_2$$

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

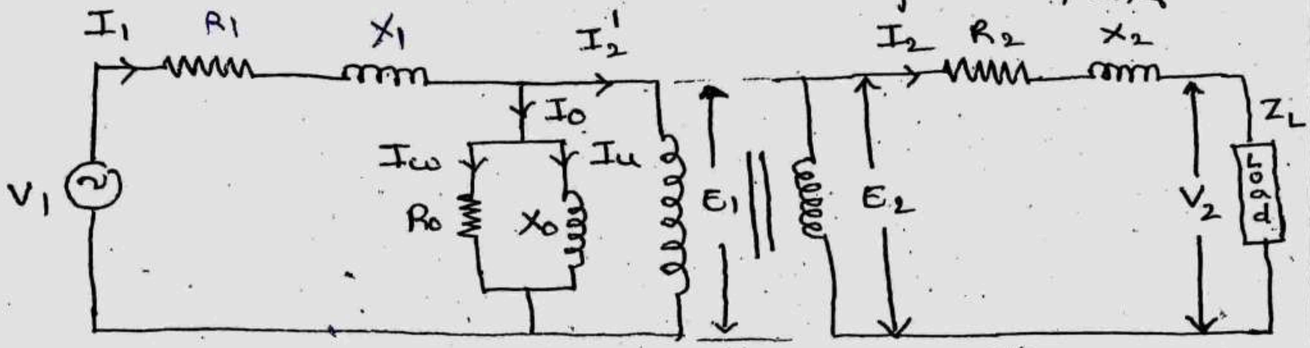


...ary winding in V

" " ondary winding in Y

Equivalent circuit of transformer (T5)

An equivalent circuit is used to evaluate or describe s/m behaviour using equations. fig① shows equivalent circuit of transformer



→ During no load condition, transformer draws no load current (I_0) in primary side. No load current I_0 * produce flux & core losses in core.

→ Iron loss component is represented by (R_0) non inductive resistance & magnitude magnitising current by X_0.

III-unit Transformer

Both R_0 & X_0 are connected in parallel with primary winding. R_0 & X_0 branch is called as no load branch or exciting branch.

R_1, X_1 → Primary Resistance & reactance in Ω
R_0, X_0 → No load Resistance & reactance in Ω
I_1 → Full load primary current in Amp
I_0 → No load " " in Amp
I_2' → Load component of primary current in Amp
I_w → working component
I_μ → Magnetising component
E_1 → induced emf in primary winding in V
E_2 → " " " ...ondary winding in V

R_2, X_2 → 2ndary winding resistance & reactance in Ω

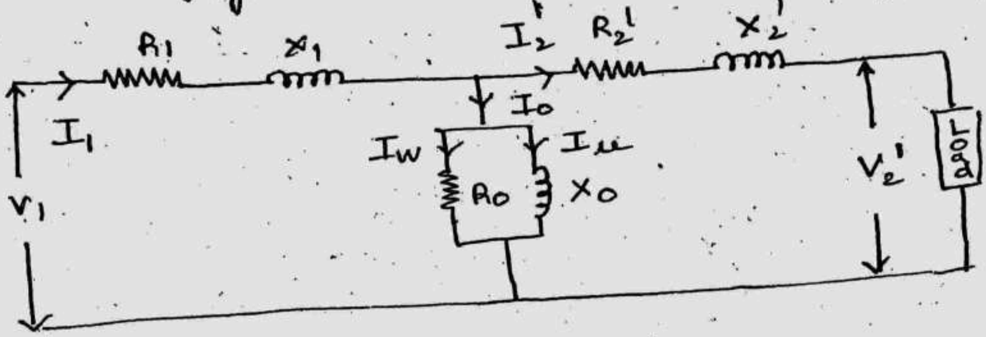
Z_L = load impedance

I_2 = full load 2ndary current in Amp

K = transformation ratio

<u>Equivalent circuit refer to primary</u> (exact of equ. ckt)

If all the 2ndary parameters are transferred to primary side is shown in given fig



While transferring the 2ndary parameters to primary side, Resistances, reactances are divided by K^2,

voltages are divided by K

Currents are multiplied by K

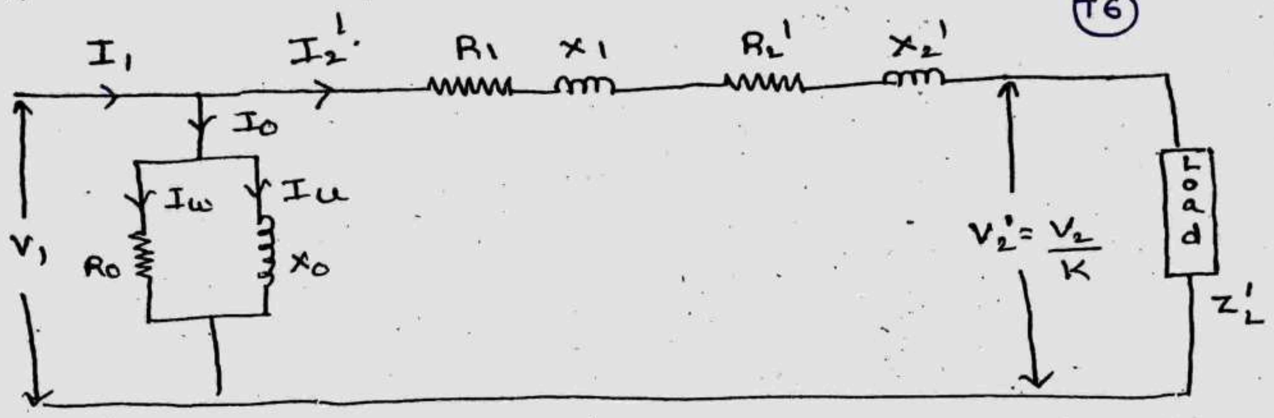
The circuit is called as exact equivalent circuit of transformer.

$$R_2' = \frac{R_2}{K^2}, \quad X_2' = \frac{X_2}{K^2}, \quad V_2' = \frac{V_2}{K}, \quad I_2' = K I_2$$

$$R_0 = \frac{V_1}{I_W}, \quad X_0 = \frac{V_2}{I_\mu} \quad Z_L' = \frac{Z_L}{K^2}$$

Approximate equivalent circuit is drawn as

(T6)



fig② approximate equivalent circuit

no load current is just 3% of rated primary current. so $I_2' = I_1$. so exciting branch or no load branch is transferred to left side of circuit shown in above fig②.

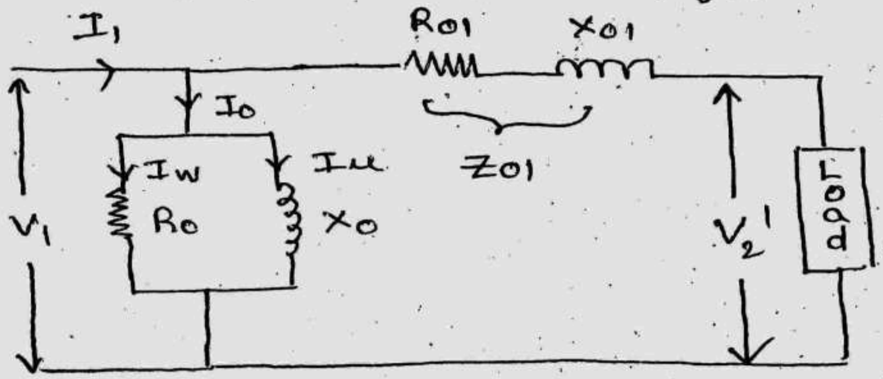
Combined all resistances in figure②

$$R_{01} = R_1 + R_2' = R_1 + \frac{R_2}{K^2}$$

similarly add all reactances in fig②

$$X_{01} = X_1 + X_2'$$

then above above fig② is redrawn as



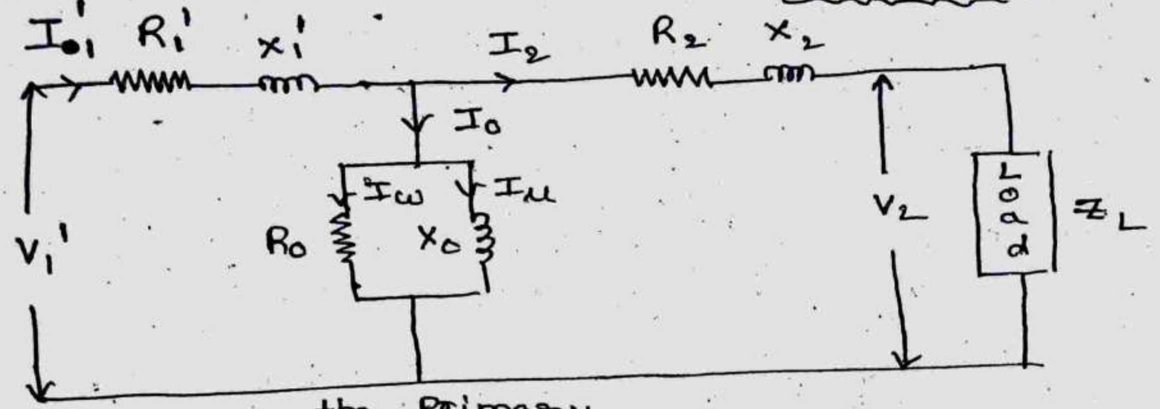
$$Z_{01} = R_{01} + jX_{01}$$

$$|Z_{01}| = \sqrt{R_{01}^2 + X_{01}^2}$$

fig③ shows all parameters referred to primary

III - unit Transformers

equivalent circuit refer to secondary

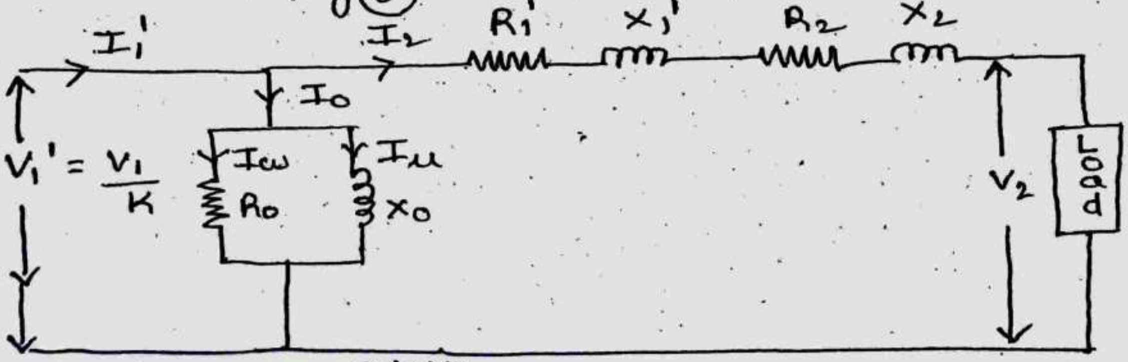


the Primary

fig④ If all parameters are transferred to secondary shows shown in figure④

I_1', R_1', x_1', V_1' are the transferring parameters of primary side is transferred to endary side.

While transferring primary parameters to secondary all the resistances, reactances are divided by K^2 & voltages is divided by K, Current is multiplied by K. The circuit is called approximate equivalent circuit shown in fig⑤



fig⑤ approximate equivalent circuit.

$R_1' = R_1 / K^2$, $x_1' = x_1 / K^2$, $V_1' = \frac{V_1}{K}$, $I_1' = I_1 K$

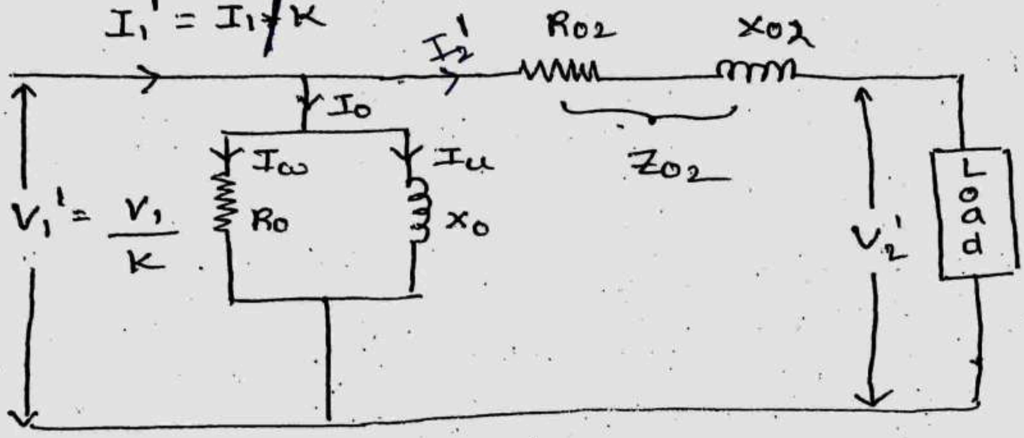
$R_0 = \frac{V_1}{I_w}$, $X_0 = \frac{V_2}{I_\mu}$

Combined all resistances in fig⑤ (T7)

$R_{02} = R_1' + R_2$

$X_{02} = X_1' + X_2$

Then above fig is re-drawn as



fig⑥ all parameters referred to secondary

unit-③ Transformers

$Z_{02} = R_{02} + jX_{02}$

$|Z_{02}| = \sqrt{R_{02}^2 + X_{02}^2}$

III - unit Transformers

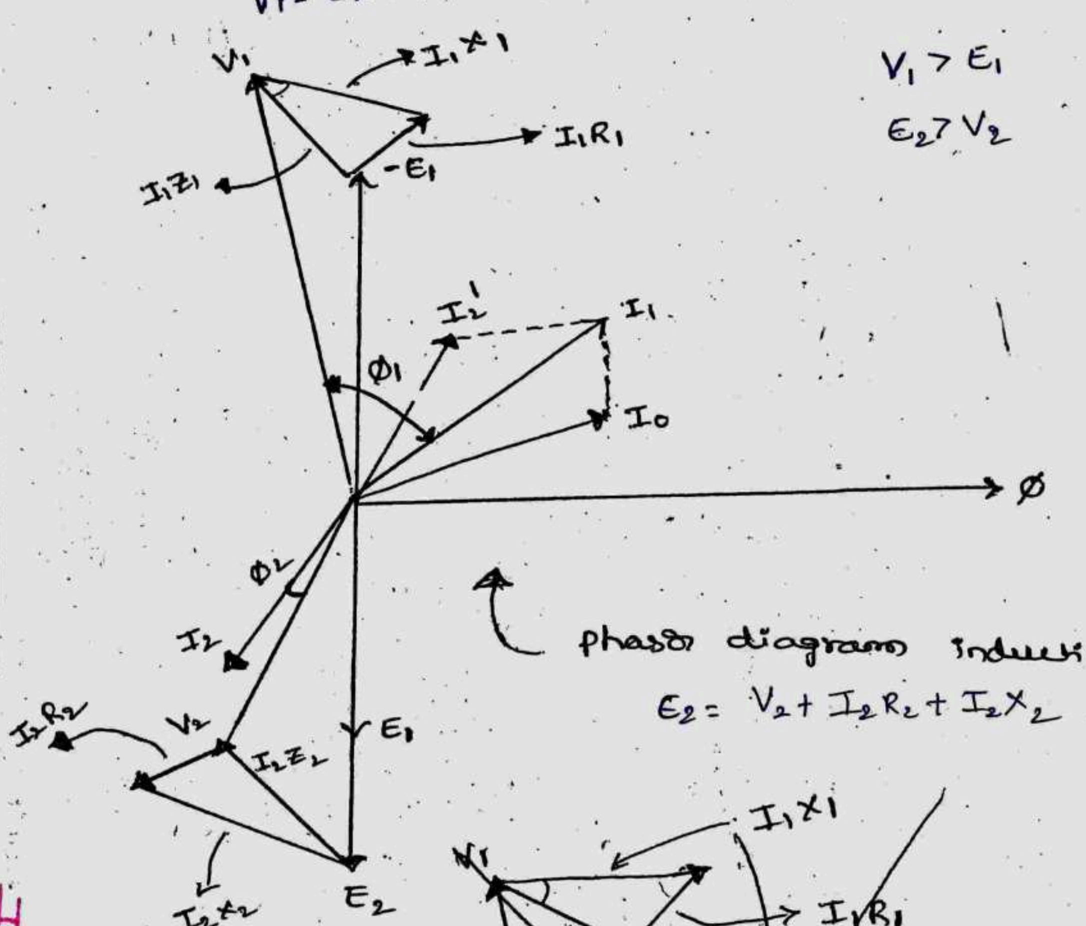
Phasor diagrams

fig⑦ shows phasor diagrams of pratical transformer for inductive load (lagging power factor)

Both E_1 & E_2 lags the mutal flux by 90°

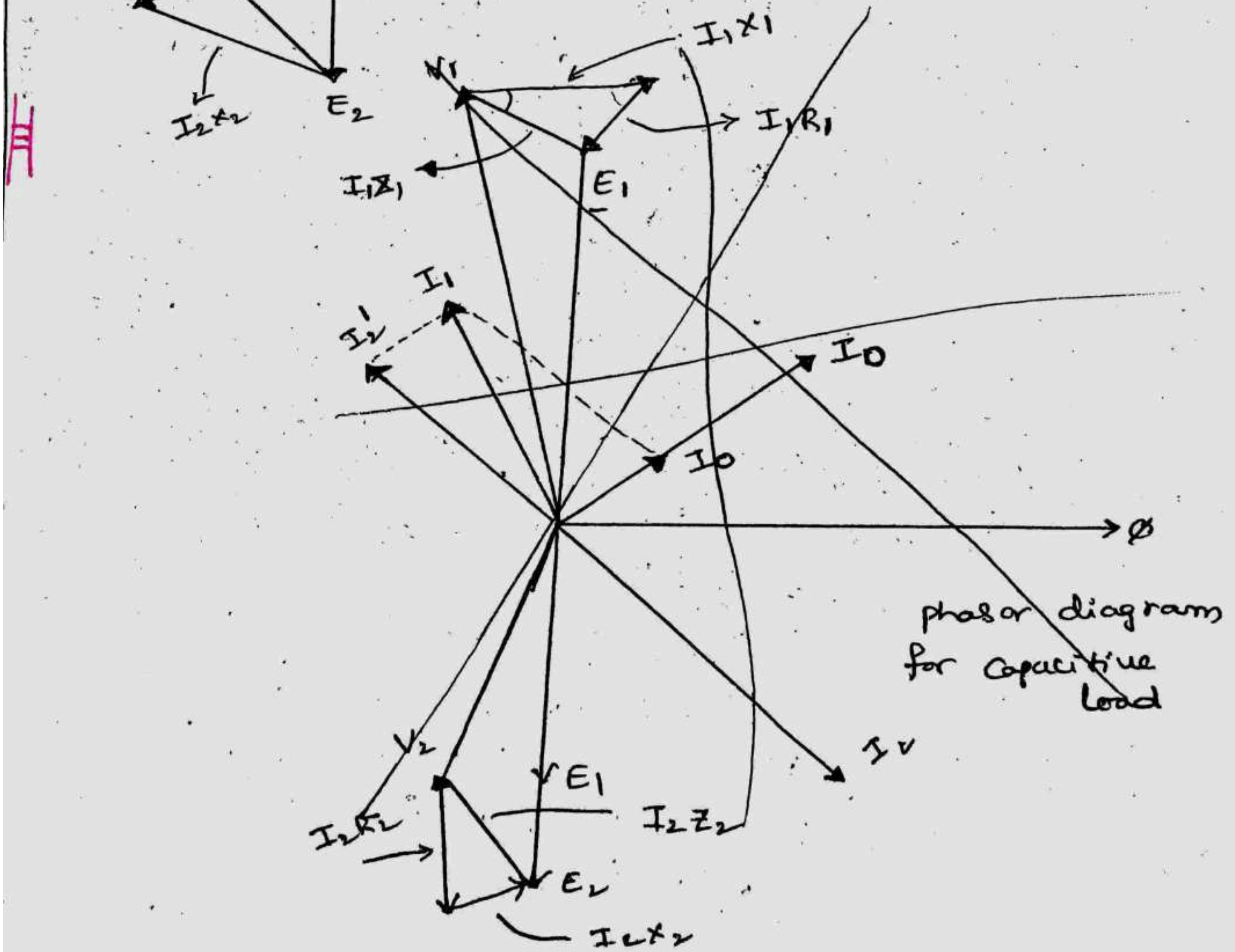
the load component of primary current I_2' neutralises the de-magnetising current I_2

$V_1 = E_1 + I_1R_1 + I_1X_1$



phasor diagram inductive load

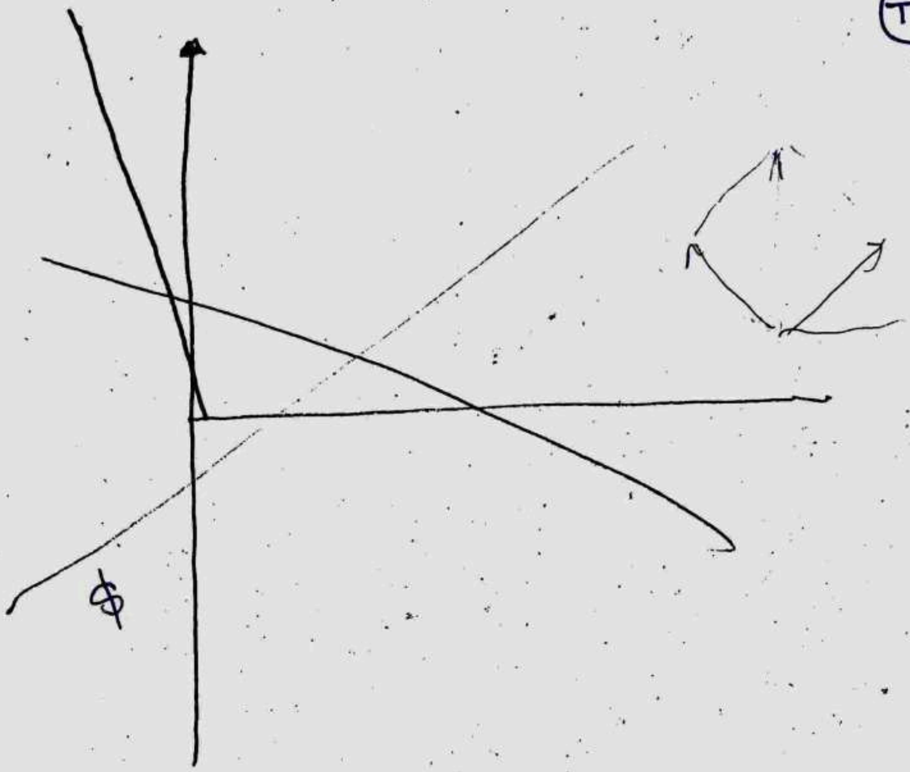
$E_2 = V_2 + I_2R_2 + I_2X_2$

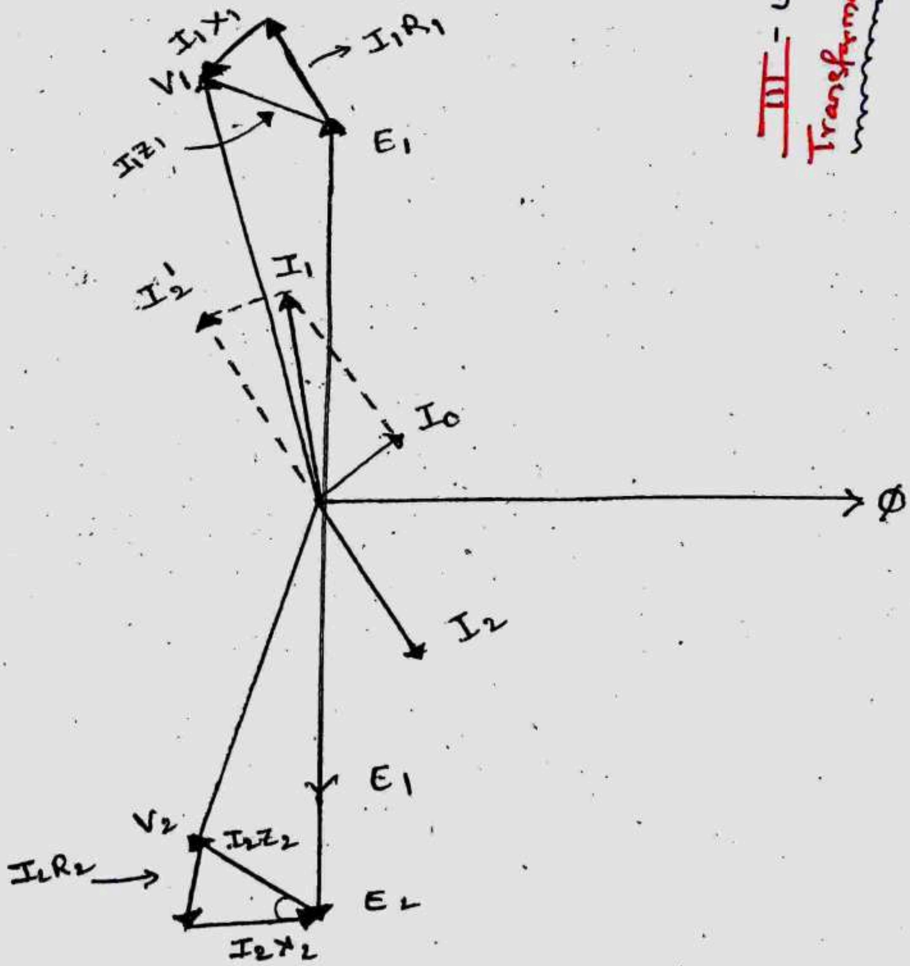


phasor diagram for capacitive load

for Capacitive loading phasor diagram

(T8)





III - unit Transformers

Losses in Transformer

Efficiency of a Transformer

Transformer efficiency $\eta = \dfrac{\text{O/P power}}{\text{I/P power}}$

$$\eta = \frac{O/P}{O/P + \text{Total losses}} = \frac{O/P}{O/P + \text{iron losses} + \text{copper losses}}$$

O/P power $= V_2 I_2 \cos\phi$

where V_2 = secondary terminal voltage on load

I_2 = " current at load

$\cos\phi$ = Power factor at load

Iron losses is derived from O.C test it is given as $P_i = W_o$

Copper losses is derived from S.C test it is given as $P_{cu} = W_{sc}$ at full load

Let x be % load of the transformer

$$\therefore \text{transformer efficiency } \eta = \frac{x * V_2 * I_2 * \cos\phi}{x V_2 I_2 \cos\phi + P_i + x^2 P_c}$$

at $x = 100\%$ full load

$x = 50\%$ at ½ load

(or)

$$\eta = \frac{x * KVA * \cos\phi}{x * KVA * \cos\phi + P_i + x^2 P_{cu}}$$

Regulation of transformer

(T9)

Proper operation of electrical apparatus depends on the rated voltage. During transformer on loading, the o/p voltage varies we have to maintain the o/p voltage with variations.

Definition

It is defined as reduction of terminal voltage from NO load to full load terminal voltage

$$\% \text{ Regulation} = \frac{V_2 - V_{2(F.L)}}{V_2} * 100$$

$$= \frac{V_{2\,N.L} - V_{2\,F.L}}{V_{2\,N.L}} * 100$$

III - unit Transformers

N·L → No load
F·L → full load

Regulation for ideal transformer is 0%.

$$\% \text{ Regulation} = \frac{\text{Voltage drop}}{V_1} * 100 = \frac{I_1 R_{01} \cos\phi \pm I_1 X_{01}}{V_1}$$

$$\% \text{ Reg} = \frac{I_1 R_{01} \cos\phi \pm I_1 X_{01} \sin\phi}{V_1} * 100$$

+ → lagging
− → leading

for unity power factor $\% \text{ Reg} = \frac{I_1 R_{01}}{V_1} * 100$

Problem

Data from open & short circuit test Conducting on 15KVA V_1 450/120V V_2, 50HZ transformer are:

O.C test

$$V_1 = V_{oc} = 120V$$
$$I_1 = I_o = 4.2A$$
$$W_i = 80W$$

} read on low voltage sid

Short circuit test

$$V_1 = V_{sc} = 9.65\,V$$
$$I_1 = I_{sc} = 22.2A$$
$$W_{cu} = W_{sc} = 120W$$

} read on High voltage sid

Calculate: (I) draw its equivalent circuit refer to primary (II) Efficiency, (III) (η) efficiency at ½ load and 0.8 lag p.f Voltage regulation for 0.8 lag p.f

Sol

$$KVA = 15$$
$$V_1 = 450,\ V_2 = 120$$
$$K = \frac{V_2}{V_1} = 0.266$$

$$\frac{V_2}{V_1} = \frac{I_1}{I_2} = \frac{I_o}{I_1} = 0.266$$
$$\therefore I_o = I_1 * 0.266$$

No load Primary Current.

$$I_o = I_o * K = 4.2 * 0.266 = 1.12A$$

Primary voltage $V_1 = 450V$.

$$W_i = W_o = 80W$$
$$W_i = V_1 I_o \cos\phi$$
$$80 = 450 * 1.12 * \cos\phi_o$$
$$\cos\phi_o = 0.159$$
$$\phi_o = \cos^{-1}(0.159) = 80.9$$
$$\sin\phi_o = \sin(80.9) = 0.987$$

(T10)

∴ **Working Component (I_ω)**

$$I_\omega = I_0 \cos\phi_0$$

$$= 1.12 * 0.159 = 0.178 \text{ A}$$

Magnetising Component (I_μ)

$$I_\mu = I_0 \sin\phi_0 = 1.12 * 0.987 = 1.1 \text{A}$$

$$R_0 = \frac{V_1}{I_\omega} = \frac{450}{0.178} = 2530\,\Omega \quad \Big| \quad X_0 = \frac{V_1}{I_\mu} = \frac{450}{1.1} = 409\,\Omega$$

S.C test

$V_1 = 450$ (P), $V_2 = 120$ V (S)

instruments reads on primary side, so we can consider a wattmeter reads primary side

$V_{sc} = 9.65$, $I_{sc} = 22.A$, $W_{sc} = P_{cu} = 120$ W copper losses.

$$Z_{01} = \frac{V_{sc}}{I_{sc}} = \frac{9.65}{22.2} = 0.435\,\Omega$$

$$I_{sc}^2 R_{01} = W_{sc} \Rightarrow (22.2)^2 * R_{01} = 120 \text{ w}$$

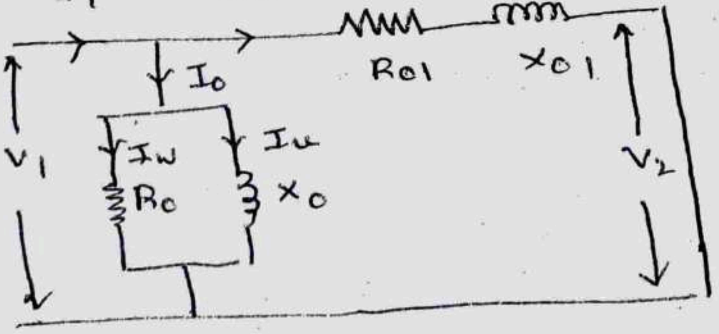
$$R_{01} = 0.243\,\Omega \checkmark$$

$$Z_{01} = \sqrt{R_{01}^2 + X_{01}^2}$$

$$X_{01}^2 = Z_{01}^2 - R_{01}^2 \Rightarrow X_{01} = \sqrt{Z_{01}^2 - R_{01}^2} = 0.36 \checkmark$$

III - unit Transformers

① approximate equivalent circuit



(11)

Efficiency $\eta = \frac{o/p \text{ power}}{i/p \text{ power}}$ p.f = $\cos\phi = 0.8$

o/p Power = KVA * p.f
= 15 * 1000 * 0.8
= 12000 W

i/p Power = o/p power + Total losses

Total losses = iron losses + Copper losses
= (80 + 120) = 200 W

i/p Power = 12000 + 200 = 12,200 W

$\eta = \frac{12000}{12,200} * 100 = 98.36\%$

(b) Voltage regulation

$\% \text{ Reg} = \frac{\text{Voltage drop}}{i/p \text{ voltage}} * 100$

Voltage drop = $I_1 (R_{01} \cos\phi_0 + X_{01} \sin\phi_0)$

full load Current $I_1 = \frac{KVA}{V_1} = \frac{15 * 10^3}{450} = 33.3 A$

Voltage drop = $33.33 (0.243 * 0.8 + 0.361 * 0.6)$
= 13.69 V

$\cos\phi = 0.8$

$\phi = \cos^{-1}(0.8) =$

$\sin($ $) = 0.6$

% Regulation = $\frac{13.69}{450} * 100$
= 3.04 %

(T 11)

(iii) Efficiency at ½ load

$x = 1/2$

Iron losses = 80W

Cu losses = $x^2 * W_{sc}$

$= (1/2)^2 * 120 = 30W$

III - unit Transformer

Total losses = 80 + 30 = 110W

o/p power = $x * KVA * \cos\phi$

$= (1/2) * 15000 * 0.8 = 6000\,W$

$$\eta\,\% = \frac{o/p\ power}{i/p\ power} = \frac{6000}{o/p + T.L} = \frac{6000}{6000 + 110W} * 100$$

= 98.19 %

Problem ② Rating of transformer is 40KVA having Primary & 2ndary resistances are 10Ω & 0.02Ω at 6600/250 V. Equivalent leakage reactance referred to primary winding is 35Ω. Find full load regulations at various power factors ① unity (ii) 0.8 lag (iii) 0.8 leading

sol

transformer rating = 40 KVA

Primary resistance $R_1 = 10\Omega$

2ndary resistance $R_2 = 0.02\Omega$

leakage reactance referred to primary $X_{01} = 35\Omega$

Primary voltage $V_1 = 6600$,

2ndary Voltage $V_2 = 250V$

∴ Transformation ratio $K = \frac{V_2}{V_1} = \frac{250}{6600} = 0.0378$

Equivalent resistance refer to primary

$$R_{01} = R_1 + R_2' = R_1 + \frac{R_2}{K^2} = 10 + \frac{0.02}{0.0378} = 24\,\Omega$$

we know that % voltage Regulation refer to primary

$$\%\ \text{Regulation} = \frac{I_1(R_{01}\cos\phi \pm X_{01}\sin\phi)}{V_1} * 100$$

Here + for lagging
− for leading

(i) % Regulation for unity Power factor

$\cos\phi = 1$

$\phi = \cos^{-1}(1) = 0$

$\sin\phi = \sin(0) = 0$

Primary Current $I_1 = \frac{\text{KVA rating}}{\text{Primary voltage}} = \frac{KVA}{V_1}$

$$I_1 = \frac{40*1000}{6600} = 6.06\,A$$

$$\%\ Reg = \frac{I_1(R_{01}\cos\phi + X_{01}\sin\phi)}{V_1} * 100$$

$$= \frac{6.06[24*1 + 35*0]}{6600} = \frac{6.06*24}{6600} * 100$$

$\%\ Reg = 2.203$

(ii) % Regulation for 0.8 lagging p.f

$\cos\phi = 0.8$

$\phi = \cos^{-1}(0.8) = 36.86$

$\sin(36.86) = 0.6$

Primary Current $I_1 = 6.06\,A$

(T 13)

Predetermination of efficiency & Regulation

In order to determine efficiency & Regulation we need the data of open circuit & short circuit test. From these data we can predetermine the efficiency & regulation at various power factors & various load are obtained.

Example Find the regulation, efficiency of transformer at various loads & power factors from the given data of O.C & S.C test conducted on 1 KVA rating having primary voltage 200V & secondary voltage 110V.

III - unit Transformers

O.C test : $V_0 = 110V$, $I_0 = 1.2A$, $W_0 = 55.2W$

S.C test : $V_{sc} = 10.2V$, $I_{sc} = 5A$, $W_{sc} = 50W$

sol from O.C test

$$W_0 = V_0 I_0 \cos\phi$$

$$\rightarrow \cos\phi = W / V_0 I_0 = \frac{55.2}{110 * 1.2} = 0.418$$

unit-(3) Transformers

$$\rightarrow \phi = \cos^{-1}(0.418) = 65.29$$

$$\rightarrow \therefore \sin\phi = \sin(65.29) = 0.908$$

→ working component current } $I_W = \boxed{I_0 \cos\phi} = 1.2 * 0.418 = 0.50$

→ Magnetising Current $I_\mu = \boxed{I_0 \sin\phi} = 1.2 * 0.908 = 1.08A$

→ No load resistance $\boxed{R_0 = \frac{V_0}{I_\omega}} = \frac{110}{0.50} = 220\Omega$

(T14)

→ No load reactance $\boxed{X_0 = \frac{V_0}{I_\mu}} = \frac{110}{1.08} = 101.85\ \Omega$

Short circuit test

$V_{sc} = 9.8$, $I_{sc} = 5A$, $W_{sc} = 50W$

$V_1 = 200V$, $V_2 = 110V$

→ $\boxed{K = \frac{V_2}{V_1}} = \frac{110}{200} = 0.55$

→ $W_{sc} = I_{sc}^2 R_{02}$

$\boxed{R_{02} = \frac{W_{sc}}{I_{sc}^2}} = \frac{50}{(5)^2} = 2\ \Omega$

$\boxed{Z_{02} = \frac{V_{sc}}{I_{sc}}} = \frac{10.2}{5} = 2.04$

→ $\boxed{Z_{02} = \sqrt{R_{02}^2 + X_{02}^2}}$ $X_{02} = \sqrt{Z_{02}^2 - R_{02}^2}$

$X_{02} = \sqrt{Z_{02}^2 - R_{02}^2}$

→ $X_{02} = \sqrt{(2.04)^2 - (2)^2} = 0.401$

→ $R_{01} = \frac{R_{02}}{K^2} = R_2'$ ⇒ $\boxed{R_{01} = \frac{R_{02}}{K^2}} = \frac{2}{(0.55)^2} = 6.611$

→ $\boxed{X_{01} = X_2' = \frac{X_{02}}{K^2}} = \frac{0.401}{(0.55)^2} = 1.325$

(T14)

efficiency $\eta = \frac{x * KVA * \cos\phi}{x * KVA * \cos\phi * W_o + x^2 W_{sc}} * 100$

where x = load i.e 0.25, 0.50, 0.75, 100%

W_o = iron losses, W_{sc} = copper losses

$\cos\phi = 0.2, 0.4, 0.6, 0.8, 1$

similarly % Regulation is

$$\% \text{Reg} = \frac{x * I_{sc}(R_{o2}\cos\phi \pm X_{o2}\sin\phi)}{V_2}$$

+ → lagging

− → leading

$W_o = 55.2$

$W_{sc} = 50$

III - unit Transformers

> At load x = 25% or $x = 0.25$, efficiency & regulation is

* $x = 0.25$, $\cos\phi = 0.2 \Rightarrow \phi = \cos^{-1}(0.2) = 78.46$

$\sin\phi = \sin(78.46) = 0.979$

* efficiency $\eta = \frac{0.25 * 1 * 1000 * 0.2}{0.25 * 1 * 1000 * 0.2 * 55.2 + (0.25)^2 * 50}$

$= \frac{0.05 * 1000}{0.05 + 55.2 + 3.125} = \frac{50}{50 + 55.2 + 3.125} = 0.46$

$= 46\%$ at $\cos\phi = 0.2$

$\% \text{Regulation} = \frac{0.25 * 5(2 * 0.2 + 0.4 * 0.979)}{110}$

$= \frac{1.25(0.4 + 0.36)}{110} = 0.899$

lead 0.042

at $\cos\phi = 0.4$, $\sin\phi = \sin(66.42) = 0.916$

$\phi = \cos^{-1}(0.4) = 66.42$

% Regulation at $\cos\phi = 0.4$ } $= \frac{1.25\,(2*0.2 + .4*0.916)}{110} * 100$

$= 0.870$, lead (0.038)

at unity power factor % Reg is

$\cos\phi = 1$

$\phi = \cos^{-1}(1) = 0$, $\sin\phi = \sin(0) = 0$

$= \frac{1.25\,(2*0.2 + 0)}{110} * 100$

$= 0.45$

Efficiency at load 50%

$x = 50\% = 0.5$, $\cos\phi = 0.2$

efficiency $\eta = \frac{x * KVA * \cos\phi}{(x * KVA * \cos\phi) + W_o + x^2 W_{sc}} * 100$

$= \frac{0.5 * 1 * 1000 * 0.2}{(100 + 55.2 + (0.5)^2 * 50)} * 100 = 59.630$

% Regulation at $\cos\phi = 0.4$, $\sin\phi = 0.9165$

$= \frac{x * I_{sc}\,(R_{o2}\cos\phi \pm X_{o2}\sin\phi)}{V_2} * 100$

$= \frac{0.5 * 5\,(2 * 0.4 + (0.4 * 0.9165))}{110}$

$= \frac{2.5\,(0.8 + 0.3666)}{110} = 2.69$, lead (-)0.2d → 0.985

(T15)

at $\cos\phi = 1$, $\sin\phi = 0$

% regulation

$$\frac{0.5 * 5(0.8)}{110} = 0.909$$

at $\cos\phi = 0.2$, $\sin\phi = 0.9797$

% regulation $= \frac{2.5(0.4)}{110} = 0.18$

Efficiency at load $x = 100\%$ or $x = 1$ at $\cos\phi = 0.2$

$$\eta = \frac{x * KVA * \cos\phi}{x * KVA * \cos\phi + W_0 + x^2 W_{sc}} * 100$$

$$= \frac{1 * 1 * 1000 * 0.2}{200 + 55.2 + 50} * 100 = 65.5\%$$

III - unit Transformers

% Regulation at load $x = 1$, $\cos\phi = 0.2$

$\phi = \cos^{-1}(0.2) = 78.46$, $\sin\phi = \sin(78.46) = 0.9797$

$$\% \text{Reg} = \frac{x I_{sc}(R_{02}\cos\phi \pm X_{02}\sin\phi)}{V_2} * 100$$

$$= \frac{5(2 * 0.2 + 0.4 * 0.9797)}{110} * 100 = 3.59$$

lag = 3.59, lead 0.0369

$\cos\phi = 0.4$, $\sin\phi = 0.91651$

$$\% \text{Reg} = \frac{5(2 * 0.4 + 0.4 * 0.91651)}{110} * 100 = 5.30$$

lead 1.97

$\cos\phi = 0.6$, $\sin\phi = 0.8$

$$\%\,Reg = \frac{5(2*0.6 + 0.4*0.8)}{110}$$

% Reg = 6.909, lead 4

$\cos\phi = 0.8$ $\sin\phi = 0.6$

% Reg = 8.3 lag

lead 6.18

$\cos\phi = 1$ $\sin\phi = 0$

$$\frac{5(2)}{110} \quad 9.09$$

As load increases, efficiency increases

As Power factor increases, regulation increases

load	p.f	efficiency	regulation
↑	↑	↑	↓

transformers → problems

Performance of single phase T/f having 200/400 V, 50Hz has following data.

(I) O.C test : 200V, 0.7A, 70 W on L.V side

(II) S.C test : 15V, 10A, 85W on H.V side → Reads on H.V

→ calculate 2ndary voltage V_2 while delivering 5KW of power at 0.8 P.f lag, primary voltage V_1=200V.

Given primary voltage $V_1 = 200 = E_1$

2ndary voltage $V_2 = 400 = E_2$

O.C test : $V_0 = 200V$, $I_0 = 0.7$, $W_i = 70W$

S.C test : $V_{sc} = 15V$, $I_{sc} = 10A$, $W_{cu} = 85W$

$\frac{E_2}{E_1} = \frac{V_2}{V_1} = \frac{400}{200} = 2 = K$

from O.C test

$I_{\omega} = I_0 \cos\phi_0$

$W_i = V_1 I_0 \cos\phi$

$\cos\phi = \frac{70}{200 * I_0} \Rightarrow I_0 = \frac{70}{200 * \cos\phi}$

$\Rightarrow \cos\phi = \frac{70}{200 * 0.7} = 0.5$

$\Rightarrow \sin\phi = 0.866$

$I_{\omega} = I_0 \cos\phi = 0.7 * 0.5 = 0.35$

$I_{\mu} = I_0 \sin\phi = 0.7 * 0.866 =$

$I_{\mu} = 0.606 A$

$\Rightarrow R_0 = \frac{V_1}{I_{\omega}} = \frac{200}{0.35} = 571.4 \Omega$

$\Rightarrow X_0 = V_1 / I_{\mu} = \frac{200}{0.606} = 330 \Omega$

from S.C test

$V_{sc} = 15V$, $I_{sc} = 10A$, $W_{cu} = 85W$

given all parameters refer to primary.

$R_{01} = ?$ $X_{01} = ?$, $Z_{01} = ?$

(I) $Z_{02} = \frac{V_{sc}}{I_{sc}} = \frac{15}{10} = 1.5$

(II) $W_{cu} = I_{sc}^2 * R_{02} = 85$

$R_{02} = 85/(10)^2 = 0.85 \Omega$

(III) $X_{02} = \sqrt{Z_{02}^2 - R_{02}^2}$

$X_{02} = \sqrt{(1.5)^2 - (0.85)^2} = 1.24 \Omega$

(IV) $Z_{01} = \frac{Z_{02}}{K^2} = \frac{1.5}{(2)^2} = 0.375$

(V) $R_{01} = \frac{R_{02}}{K^2} = \frac{0.85}{(2)^2} = 0.21 \Omega$

(VI) $X_{01} = \sqrt{Z_{01}^2 - R_{01}^2} = \sqrt{(0.375)^2 - (0.21)^2}$

$X_{01} = 0.31$

⇒ given o/p of t/former is 5KW at 0.8 P.f lagg $\cos\phi_2 = 0.8$

$V_2 I_2 \cos\phi_2 = 5 * 1000$

$I_2 = \frac{5*1000}{400*0.8} = 15.6 A$, V_2 = N.L 2ndary voltage = 400

⇒ 2ndary voltage at full load ($V_{2(FL)}$)

or Total voltage drop in 2ndary

$= I_2 (R_{02} \cos\phi_2 + X_{02} \sin\phi_2) =$

$= 15.6 (0.85 * 0.8 + 1.24 * 0.6) = 22.2V$

⇒ 2ndary voltage drop

$V_2 = V_{2(N.L)} - V_{2(F.L)} = 400 - 22.2V$

$V_2 = 377.84$

⇒ % Voltage regulation rough

$$= \frac{V_{2(N.L)} - V_{2(F.L)}}{V_{2(N.L)}} * 100$$

$$= \frac{400 - 22.2V}{400} * 100 = 94.46$$

$$\% Reg = \frac{\text{2ndary total voltage drop } (V_2 FL)}{V_{2(N.L)}} * 100$$

$= 5.5\%$

(I)

(A) A 230/460V t/former has Primary resistance $R_1 = 0.2\Omega$, $X_1 = 0.5\Omega$. Corresponding values for 2ndary are $R_2 = 0.75\Omega$, $X_2 = 1.8\Omega$. Find ① 2ndary terminal voltage V_2, supplying a load of 10A at 0.8 p.f lag, find its voltage regulation.

Sol given $V_1 = 230$, 2ndary voltage on no load $V_2 = 460V$

$\Rightarrow K = \frac{V_2(N.L)}{V_1} = \frac{460}{230} = 2$, $I_2 = 10A$, $\cos\phi_2 = 0.8$

$R_1 = 0.2\Omega$, $X_1 = 0.5\Omega$, $R_2 = 0.75\Omega$, $X_2 = 1.8\Omega$

% Regulation refer to 2ndary = $\frac{I_2(R_2\cos\phi_2 + X_2\sin\phi_2)}{V_{2(N.L)}} * 100$

$I_2(R_2\cos\phi_2 + X_{02}\sin\phi_2)$ = Total voltage drop in 2ndary or 2ndary voltage at full load.

$\Rightarrow$ Convert all the parameters of Primary to 2ndary side

Equivalent resistance refer 2ndary $R_{02} = R_2 + K^2R_1$

" reactance " " $X_{02} = X_2 + K^2X_1$

$R_{02} = 0.75 + (2)^2 * 0.2 = 0.75 + 0.8 = 1.55\Omega$

$X_{02} = 1.8 + (2)^2 * 0.5 = 1.8 + 2 = 3.8\Omega$

$\Rightarrow$ 2ndary voltage drop at full load = $I_2(R_{02}\cos\phi_2 + X_{02}\sin\phi_2)$

given $\cos\phi_2 = 0.8$, $\sin\phi_2 = 0.6$, $I_2 = 10A$

$V_{2(F.L)} = 10(1.55 * 0.8 + 3.8 * 0.6) = 35.2V$

$\Rightarrow$ % voltage regulation = $\frac{\text{2ndary voltage drop at full load}}{\text{2ndary voltage at No load}} * 100$

$\frac{V_{2(F.L)}}{V_{2(N.L)}} * 100 = \frac{35.2}{460} * 100 = 7.65\%$.

Theirfore 2ndary voltage drop $V_2 = V_{2(N.L)} - V_{2(F.L)}$

$V_2 = 460 - 35.2 = 424.8V$

Condition for maximum efficiency (η_{max})

efficiency is maximum if Cu losses P_{cu} = Iron losses P_i

let Cu losses $P_{cu} = I_1^2 R_{01}$

let Iron losses P_i = Hysteresis + Eddy Current losses

$= W_h + W_e$

⇒ Now Considered at primary i/p side

Input $= V_1 I_1 \cos\phi_1$

Efficiency $\eta = \frac{o/p}{i/p} = \frac{i/p - T.L}{i/p}$ $i/p = o/p + T.L$, $o/p = i/p - T.L$

Total losses = Iron losses + Cu losses $= P_i + I_1^2 R_{01}$

$$\eta = \frac{V_1 I_1 \cos\phi_1 - P_i - I_1^2 R_{01}}{V_1 I_1 \cos\phi_1} = 1 - \frac{P_i}{V_1 I \cos\phi_1} - \frac{I_1^2 R_{01}}{V_1 I_1 \cos\phi_1}$$

$$\eta = 1 - \frac{P_i}{V_1 I_1 \cos\phi_1} - \frac{R_{01} * I_1}{V_1 \cos\phi_1} \longrightarrow (1)$$

differentiating equation (1) w.r.to I_1 we get

$$\frac{d\eta}{dI_1} = 0 + \frac{P_i}{V_1 \cos\phi_1 I_1^2} - \frac{R_{01}}{V_1 \cos\phi_1}$$ $\frac{d\eta}{dI_1} = 0$

$$0 = 0 + \frac{P_i}{V_1 \cos\phi_1 I_1^2} - \frac{R_{01}}{V_1 \cos\phi_1}$$

$$\frac{P_i}{V_1 I_1^2 \cos\phi_1} = \frac{R_{01}}{V_1 \cos\phi_1} \Rightarrow \frac{P_i}{I_1^2} = R_{01}$$

$$P_i = I_1^2 R_{01}$$

$\therefore P_i = P_{cu} = I_1^2 R_{01}$

$\frac{d}{dx}$

$\frac{d}{dI_1}\left(\frac{1}{I_1}\right) =$

$\frac{d}{dI_1}(I_1^{-1}) =$

$= n x^{n-1}$

$= -1 I_1^{-1-1}$

$= -I_1^{-2}$

$= -\frac{1}{I_1^2}$

⇒ Load KVA at $\eta_{max} = x^2 * KVA * \sqrt{\frac{\text{Iron losses}}{x^2 * \text{Cu losses}}}$

x = Full load KVA or ½ load KVA

$= x^2 * KVA * \sqrt{\frac{P_i}{x^2 P_{cu}}}$

⇒ Load in KW at $\eta_{max} = x^2 * KVA * P.f * \sqrt{\frac{P_i}{x^2 P_{cu}}}$

(3)

(6). A 25KVA, 2500/250 V 1-phase transformer has Iron losses = 960W full load Cu losses = 1500 watts. calculate at what load maximum efficiency occurs & find the value of maximum efficiency at unity power factor.

full load = x^2 = 1

Sol KVA rating = 25

$V_1 = 2500$, $V_2 = 250V$, Iron losses $P_i = 960W$, $P_{cu} = 1500$ watt

Load KVA at maximum efficiency $= x^2 * KVA * \sqrt{\frac{P_i}{x^2 P_{cu}}}$

x = full load = 100% = 1

$= 25 * \sqrt{\frac{960}{1 * 1500}} = 20$ KVA

(ii) maximum efficiency at unity p.f is

$\eta_m = \frac{O/P}{I/P} \Rightarrow O/P = \frac{x * KVA * P.f}{x * KVA * P.f + T.L}$ $= 1 * 25 * 1 = 25$ KVA

at maximum efficiency $P_i = P_{cu} = 960$ W

Total losses $= P_i + P_{cu} = 960 + 960 = 1920$ KW

$\eta_{max} = \frac{25 * 1000}{1000 * 25 + 1920} = 92.86\%$

(6) A 250/500V, 50Hz T/f primary resistance & reactance are 0·175Ω, 0·375Ω & 2ndary resistance & reactances are $R_2 = 780Ω$ $X_2 = 265Ω$. Determine voltage regulation, losses, efficiency delivering 6KVA at 0·8 P.f leading at rated voltage.

sol

$V_1 = 250V$, 2ndary voltage at no load $V_{2(N.L)} = 500V$, $f = 50Hz$

$R_1 = 0·175Ω$, $R_2 = 780Ω$, $X_1 = 0·375Ω$ & $X_2 = 265Ω$,

$\cos\phi_2 = 0·8$

$\sin\phi_2 = 0·6$

⇒ transformation ratio $K = \frac{V_{2(N.L)}}{V_1} = \frac{500}{250} = 2$

① % Regulation $= \frac{V_{2(N.L)} - V_{2(F.L)}}{V_{2(N.L)}} * 100$

[illegible] ⇒ $I_2(R_{02}\cos\phi_2 + X_{02}\sin\phi_2)$ = 2ndary voltage drop at full load $V_{2(F.L)}$

⇒ Convert all primary parameters into 2ndary side

$R_{02} = R_2 + K^2R_1 = 780 + (2)^2 * 0·175 = 780 + 0·7 = 780·7Ω$

$X_{02} = X_2 + K^2X_1 = 265 + (2)^2 * 0·375 = 265 + 1·5 = 266·5Ω$

⇒ 2ndary voltage drop $V_{2(F.L)} = 12(780·7*0·8 + 0·6 * 266·5) = 9406·8$

$V_2 = 5575·9$

given $6*1000 = V_2 I_2 \cos\phi_2$

$\frac{6*1000}{500*[redacted]} = I_2 ⇒ 12A$

losses = ohmic losses $= I_2^2 R_{02} = (12)^2 * 780·7 = 112·42 KW$

% efficiency $\eta = \frac{o/p}{i/p} = \frac{V_2 I_2 * \cos\phi_2}{o/p + T.L} = \frac{500*12*0·8}{(500*12*0·8) + 112·42}$

$\eta = \frac{4800}{4800 + 112·42} * 100 = 97·71$

Sumpner's Test

(1)

→ Also called as back-back test & Regenerative test & heat loss test

→ This test is suitable for conducting full load on large transformers.

→ This test requires 2 transformers of same KVA ratings:- . .

→ Here primaries of 2 t/fs are connected in parallel & are connected to supply.

→ 2 t/f's 2ndaries are connected in series with polarities in phase opposition. with primaries.

→ Their phase opposition are identified using a voltmeter connected in 2ndaries side.

→ If voltmeter indicates zero means, their 2ndaries are in phase opposition. Otherwise voltage reads by voltmeter.

→ If voltmeter reads any value, these are not in phase opposition, just by interchange 2ndary terminals we get a phase opposition.

Procedure to conduct test

→ By opening the secondary side SPST switch open & [redacted] apply rated voltage across primary side.

→ wattmeter W_1 reads only iron losses in primary side.

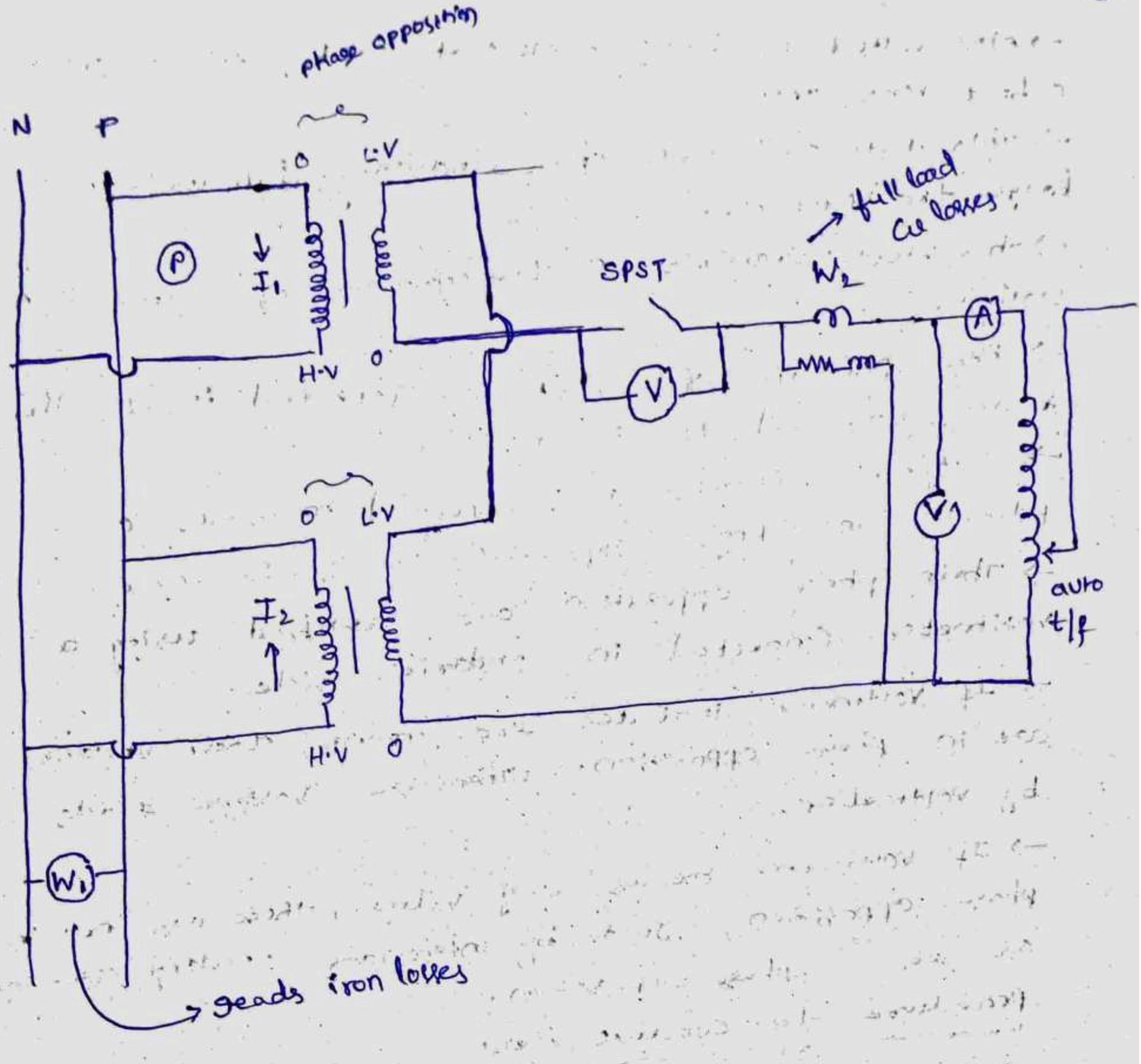
→ By closing SPST switch on 2ndary side apply rated current to the 2ndary side.

→ wattmeter W_2 reads full load Cu losses on 2ndary side.

→ from Iron & Cu losses we determine efficiency, % Regulation at any load & p.f are predetermined.

→ power loss in this test are twice & doubles the single phase T/former.

②



$$\% \eta = \frac{o/p}{i/p} = \frac{o/p}{o/p + T.L} = \frac{x * \text{rating of t/f} * \cos\phi}{x * \text{rating of t/f} * \cos\phi + T.L} * 100$$

Total losses (T.L) = $W_i + x^2 W_{cu}$ where x = load %.

$$\% \text{Reg} = \frac{x * I_{sc} \left(R_{02} \cos\phi \pm X_{02} \sin\phi \right)}{V_2 (N.L)} * 100$$

+ = lag

− = lead

③

Advantages of sumpner test

→ Higher capacity of t/former can be tested without using actual load.

→ power required is very small

→ Also used to find Cu losses, iron losses, efficiency & regulation at any desired load & desired p.f

→ It is also used to measure temperature rise at any load.

Disadvantages of sumpner test

→ Requires 2 identical t/formers of same ratings.

Separation of losses in 1-phase transformer ①

→ we know that induced emf of transformer

$e = 4.44 * f * \phi_m * N$

N → no. of turns & is fixed, only frequency & flux in that is going to be changes

$e \propto f \phi_m \Rightarrow \phi_m = \frac{e}{f}$

⇒ During no load, induced emf $e \simeq V$.

$\phi_m \propto \frac{V}{f}$

⇒ To maintain flux in core constant, we maintain V/f ratio constant. Here separation of iron losses is performed at various frequencies to maintain V/f ratio constant.

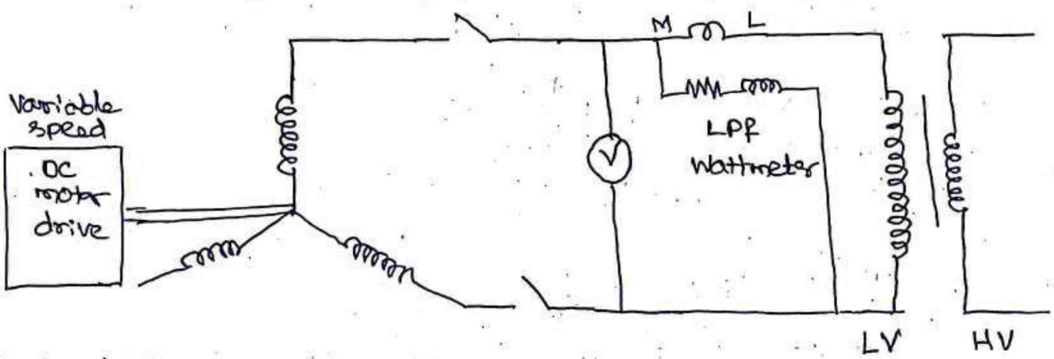
Requirements to carry out test

→ requires an alternator, which is driven by DC motor

→ A 2 winding transformer which is of single phase

→ L.V winding of t/former is connected to any 2 phases of 3 phase stator of alternator

→ H.V winding of t/former is kept open



→ A LPF wattmeter connected across the LV side of transformer.

Procedure for conducting test

① close DPST switch, allow motor to run at constant speed say N_1 having frequency (f).

$N_1 = \frac{120f}{P} \Rightarrow f = \frac{N_1 * P}{120}$

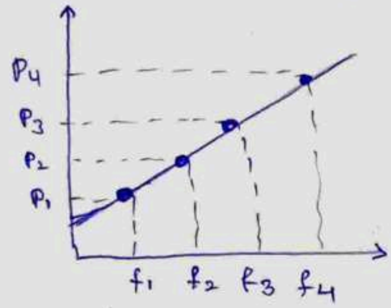
② Adust the field of alternator untill a voltmeter reads a LV winding voltage

(2)

$V_1 = f_1 * \frac{\text{Rated L.V side voltage of T/f}}{\text{Rated supply frequency}}$.

→ measure the speed of motor as N_2, corresponding voltage $V_2 = f_2 * \frac{V}{f}$

→ procedure is repeated for variable speed & note down voltage, wattmeter reading & calculate frequency



For core losses of sinusoidal i/p

total core losses = Hysteresis + Eddy current losses

P_c or W_i or $W_c = W_h + W_e$

$W_h = P * B_{max}^{1.6} * f$ & $W_e = Q B_{max}^2 * f^2$

P, Q are constants & we calculate hysteresis & eddy current losses.

$W_i = W_h + W_e = P * B_{max}^{1.6} * f + Q B_{max}^2 * f^2 = f(P B_{max}^{1.6} + Q B_{max}^2 * f)$

$\frac{W_i}{f} = P B_{max}^{1.6} + Q B_{max}^2 * f$

⇒ we know that $B_{max} = \frac{\phi_m}{A}$ which is constant one, Hence

$W_h = K_1 * f$
$W_e = K_2 * f^2$ } Hence iron losses are separated

or

$W_h = K_h * f$
$W_e = K_e * f^2$

or

$$\boxed{W_i = K_1 * f + K_2 * f^2}$$

where $K_1 = P B_{max}^{1.6} = (K_h)$

$K_2 = Q B_{max}^2 = (K_e)$

Iron losses of transformer core at normal flux density was ③ measured at frequency 30Hz & 50Hz, results are being 30W & 54W. Calculate (i) Hysteresis loss & (ii) eddy current loss.

total core loss in a transformer

$\Rightarrow W_i = W_h + W_e = P B_{max}^{1.6} * f + Q B_{max}^2 * f^2$

if flux density is constant

$\Rightarrow W_i = K_h * f + K_e * f^2 \longrightarrow ①$

$K_h = K_1 \rightarrow$

$K_e = K_2 \rightarrow$

At $f = 30Hz$, $W_i = 30W$

$\Rightarrow 30 = K_h * 30 + K_e * (30)^2 \longrightarrow ②$

$30 = 30 * K_h + 900 * K_e$

At $f = 50Hz$, $W_i = 54W$

$54 = K_h(50) + K_e(50)^2$

$54 = 50K_h + 2500 K_e \longrightarrow ③$

solve equations ② & ③ we get

$K_h = 0.88$, $K_e = 4 * 10^{-3} = 0.004$

$\Rightarrow$ Hysteresis losses & eddy current losses at $f = 50Hz$ is

$W_h = 0.88 * 50 = 44W$ since $W_h = K_h * f$

$W_e = K_e * f^2 = (0.004) * (50)^2 = 10W$

$W_i = W_h + W_e = 44 + 10 = \underline{54W}$

$\Rightarrow$ Hysteresis losses & eddy current losses at $f = 30Hz$ is

$W_h = K_h * f = 0.88 * 30 = 26.4W$

$W_e = K_e * f^2 = 0.004 * (30)^2 = 3.6$

$W_i = W_h + W_e = 26.4 + 3.6 = \underline{30W}$

A 440V, 50Hz transformer has total iron losses are 2500W at normal voltage & frequency. When applied voltage & frequency were 220V, 25Hz, iron losses are found to be 850W. Calculate Hysteresis & eddy current losses at normal voltage & normal frequency.

for case ① details

$V = 440V$

$f = 50Hz$

Iron losses $W_i = 2500W$

for case (ii) details

$V = 220V$

$f = 25Hz$

$W_i = 850W$

Hysteresis losses $W_h = K_h * f$ at $f = 50Hz$ $W_i = 2500W$ (4)

$W_h = K_h * 50 = 50 * K_h$; $W_e = K_e * f^2 = K_e * 2500$

$\boxed{W_i = W_h + W_e} \Rightarrow 2500 = 50 * K_h + 2500 * K_e \longrightarrow (1)$

⇒ At $f = 25Hz$, Iron losses is 850 W

$\boxed{W_i = W_h + W_e} \Rightarrow 850W = K_h * f + K_e * f^2$

$850 = K_h * 25 + K_e * 625 \longrightarrow (11)$

$50K_h + 2500 * K_e = 2500$

$25K_h + 625 * K_e = 850$

$K_h = 18$, $K_e = 0.64$

⇒ At normal frequency, Hysteresis & eddy Current losses are

$W_h = K_h * f = 18 * 50 = 900W$

$W_e = K_e * f^2 = 0.64 * (50)^2 = 1600W$

$W_i = W_h + W_e = 900 + 1600 = 2500W$

(6) Transformer is Connected to 1000V, 50HZ supply, Core losses is 1000W, Hysteresis loss is 650W & eddy Current loss is 350W. If applied Voltage is raised to 2000V, f is 100Hz. find new core losses.

Sol

At 1000V, $f = 50HZ$ $W_i = 1000W$ $W_h = 650W$, $W_e = 350W$

Hysteresis losses $W_h = K_h * f = 650 = K_h * 50 \Rightarrow \boxed{K_h = 13}$

⇒ Now applied Voltage is raised to 2000V, new frequency $f = 100Hz$ then Core losses = ?

$W_i = W_h + W_e$

$= K_h * f + K_e * f^2$

$= (13) * (100) + (0.14)(100)^2$

$W_i = 2700W.$

$\boxed{W_e = K_e * f^2}$

$350 = K_e * 2500$

$\boxed{K_e = 0.14}$

$\%Z^2 = \sqrt{(\%R)^2 + (\%X^2)}$

$\%X = \sqrt{(\%Z)^2 - (\%R)^2} = \sqrt{4^2 - 1.8^2}$

$\%X = 3.57\%$

$\%X = \%R =$ Cu loss

full load Current

$$\boxed{I_1 = \frac{KVA\ rating}{V_1}} = \frac{50,000}{3300} = 15.2$$

$$\%R = \frac{R_{01} I_1 * 100}{V_1}$$

$$1.8 = \frac{R_{01} I_1 * 100}{V_1}$$

$$\frac{1.8 * 3300}{15.2 * 100} = R_{01} \Rightarrow R_{01} = 3.91\Omega$$

$$\%Z = \frac{I_1 Z_{01}}{V_1} * 100$$

$$\boxed{Z_{01} = \frac{\%Z * V_1}{I_1 * 100}}$$

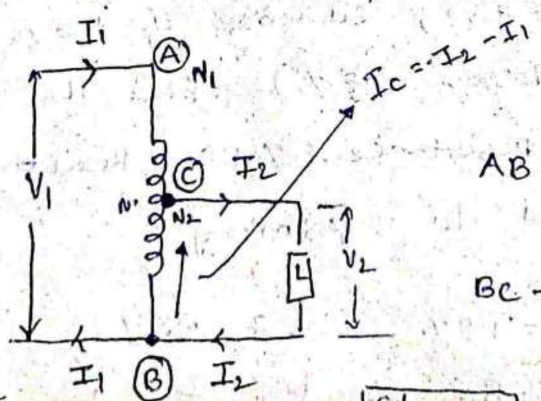
$$X_{01} = \frac{3.57 * 3300}{100 * 15.2} = 7.76\Omega$$

$$Z_{01} = \frac{4 * 3300}{100 * 15.2} = 8.7\Omega$$

Auto transformer

A transformer which consists of only one winding which is common to both primary & secondary.

fig (a)



AB → Primary winding having N1 turns

BC → 2ndary winding having N_2 turns

Step down

Step up

→ These windings are not electrically separated, operation is similar to 2 winding transformer.

→ It is used where the transformation ratio differs from unity ($K \neq 1$)

→ One winding is used in Auto transformer So Copper losses are very less Compare to 2 winding transformer.

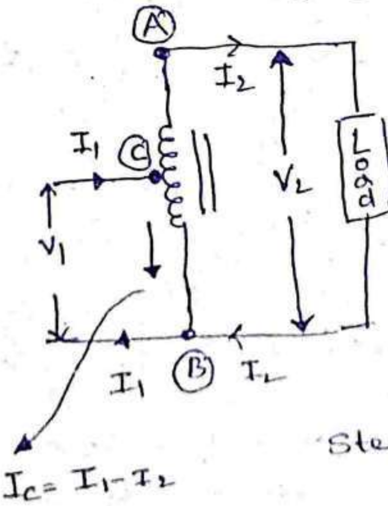
Neglecting iron losses & No load current

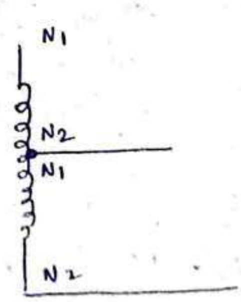
$$\frac{V_2}{V_1} = \frac{N_2}{N_1} = \frac{I_1}{I_2} = K$$

→ Current in section BC is due to the difference b/w Current I_2 & I_1

In I_2 is greater than I_1. $(I_2 - I_1)$

→ O/p is similar to 2 winding transformer, Efficiency & Voltage regulation is more superior than 2 winding transformer.





Step up

Saving of Copper

→ Weight of copper is propotional to the product of current & number of turns

⇒ Wt of Cu in (AC) $\propto (N_1 - N_2) I_1$
Wt of Cu in (BC) $\propto N_2 (I_2 - I_1)$ } from fig (1) W_a

Total weight of copper in Auto transformer

$$\propto (N_1 - N_2) I_1 + N_2 (I_2 - I_1)$$

⇒ In 2 winding transformer wt of Cu is

wt of Cu in primary $\propto N_1 I_1$
wt of Cu in 2ndary $\propto N_2 I_2$ } W_o

Total weight of copper $\propto N_1 I_1 + N_2 I_2$

∴ $\dfrac{\text{wt of Cu in Auto t/former}}{\text{wt of Cu in 2 winding transformer}} = \dfrac{(N_1 - N_2) I_1 + N_2 (I_2 - I_1)}{N_1 I_1 + N_2 I_2}$

$$= \frac{I_1 (N_1 - 2N_2) + N_2 I_2}{N_1 I_1 + N_2 I_2} = \frac{I_1 N_1 \left(1 - \frac{2N_2}{N_1}\right) + N_2 I_2}{N_1 I_1 + N_2 I_2}$$

$$= \frac{I_1 N_1}{N_1 I_1} \left[\frac{\left(1 - \frac{2N_2}{N_1}\right) + \frac{N_2 I_2}{N_1 I_1}}{1 + \frac{N_2 I_2}{N_1 I_1}} \right] = 1 - \frac{\frac{2N_2}{N_1} + 1}{1 + \frac{N_2}{N_1} * \frac{I_2}{I_1}} = 1 - \frac{2K}{1 + K * \frac{1}{K}}$$

$$\boxed{\frac{N_2}{N_1} = K, \quad \frac{I_1}{I_2} = K}$$

$$= 1 - \frac{2K}{2} = 1 - K$$

$\frac{2 - 2K}{2}$

$\frac{2(1-K)}{2}$

Now

wt of Copper in Auto transformer
$= (1-K) *$ weight of Copper in 2 winding transformer

$$\boxed{W_a = W_o (1 - K)}$$

W_a = weight of Cu in auto transformer
W_o = weight of Cu in ordinary or 2 winding transformer

saving = $W_o - W_a$

$= W_o - (1-K)W_o = KW_o$

Saving of Cu in auto transformer

= K * (wt of Cu in 2 winding t/former)

→ so. power transformed is inductively when i/p is (1-K) * i/p

→ Power transfored is conductively from source to load. (K * i/p power)

Problem

Auto transformer supplies load is 3KW at 115 volts at unity power factor. If applied primary voltage is 230 V. Calculate power transferred to load. (a) inductively (b) conductively also Calculate saving of Cu in auto-transformer (W_a). ~~The primary voltage is 500V~~ & 2ndary ~~voltage is 400V~~ & 2ndary

$\frac{I_2}{I_2}$ Current I_2 is 100A.

Sol $V_2 = 115V$, $V_1 = 230V$, i/p put power = 3KW

Power Transfered inductively

$= i/p (1-K) = 3000(1-0.5) = 1.5KW$

$K = \frac{115}{230} = 0.5$ ⇒ power transferred Conductively

$= K * i/p \text{ power} = 0.5 * 3000$

$= 1.5 KW$

(b) $\frac{I_1}{I_2} = K$ ⇒ $I_1 = 0.5 * 100 = 50A$

Saving of Cu = $K * W_o = 0.5 W_o$

Conversion of 2 winding Transformer into auto transformer

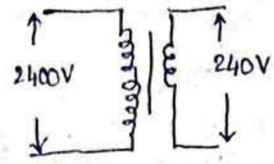


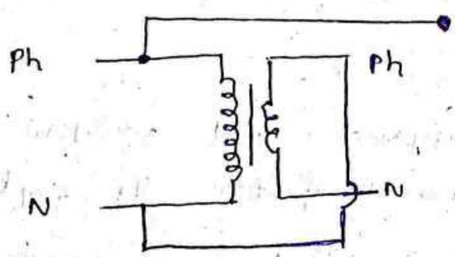
fig ①

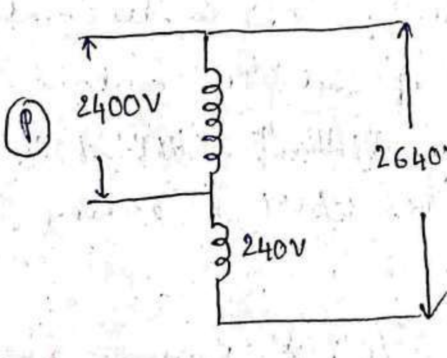
fig ① shows a 2 winding transformer.

A 2 winding t/former is Converted into auto transformer either step up or step down.

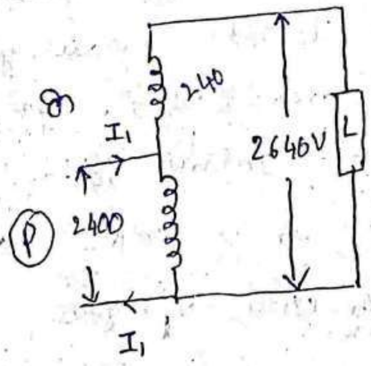
It is based on polarities.

→ If we employ **additive** polarity b/w h.v & l.v sides we get a step up transformer





or



If we use subtractive polarity b/w h.v & l.v sides we get a step down transformer

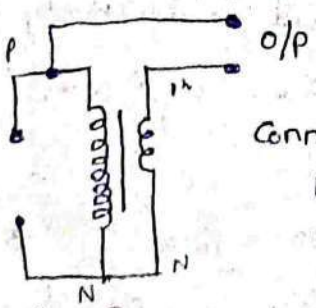
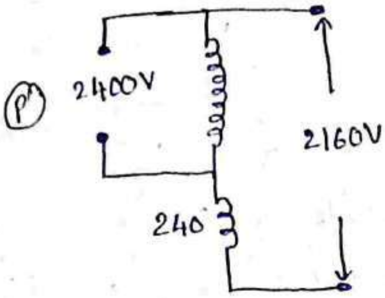


fig (b)

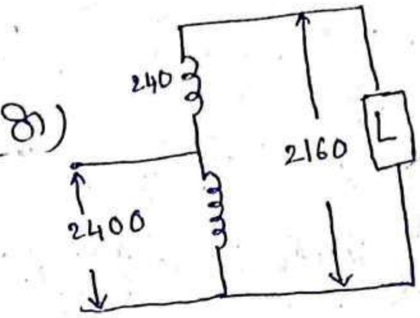
Connection for subtractive Polarity is shown fig (b)

(28)

(P)



(Or)



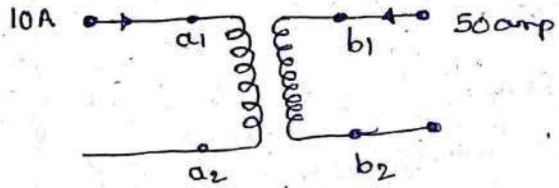
fig(b) → (1)   fig(b) → (2)

step down auto transformer

$V_2 = 2400 - 240 = 2160\,V$.

Example

An 11500/2300 V transformer is rated at 100 KVA as a 2 winding t/former. If 2 windings are connected in series to form an auto-transformer what will be the possible voltage ratio.



11500/2300V

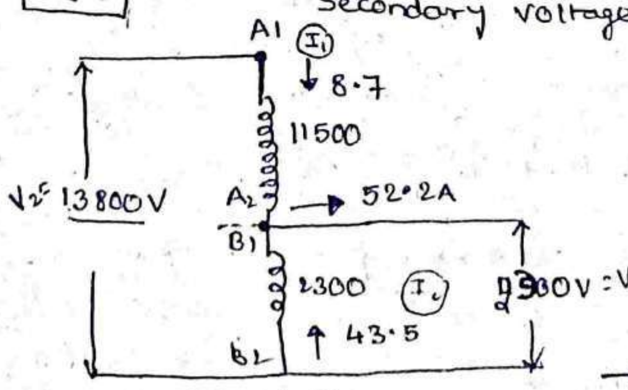
→ Rated Current at 11500 V winding (HV)

$$= \frac{\text{KVA rating}}{\text{Primary Voltage}} = \frac{100 * 1000}{11500} = 8.7\,A$$

→ Rated Current at 2300 winding (LV)

$$= \frac{\text{KVA Rating}}{\text{Secondary voltage}} = \frac{100 * 1000}{2300} = 43.5\,A$$

fig(1)

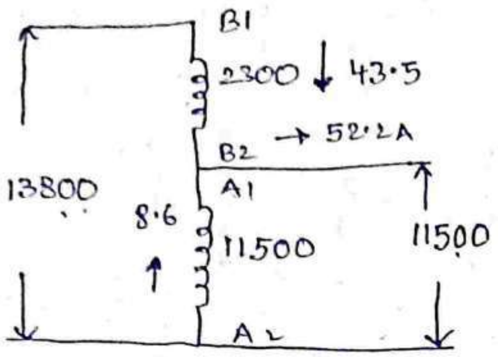


13800/2300

Here HV side the rating is 13800 A

LV side the rating is 2300

→ Possible voltage ratio = $\frac{13800}{2300}$



HV side rating is 13800

LV side rating is 11500.

possible voltage rating is 13800/11500

13800/11500

fig ②

$V_1 = 2300 \quad V_2 = 13800$

from fig① i/p current at winding $(A_1-A_2) = 8.7$

⇒ KVA rating = Primary voltage * primary current

$= 13800 * 8.7 = 120$ KVA

o/p current (I_2) = $\frac{\text{KVA rating}}{V_2} = \frac{120*1000}{2300} = 52.2$ Amp

⇒ Current in winding (B_1-B_2) =

Difference b/w o/p current (I_2) & i/p current (I_1).

$\frac{13800}{2300} = \frac{V_1}{V_2}$

$= 52.2 - 8.7 = \underline{43.5}$ A

The Rated current at winding B_1-B_2 is 43.5A

from fig ②

$V_2 = 13800, \ V_1 = 11500$

Transformation ratio = $\frac{13800}{11500} = 1.2$

KVA rating = Primary voltage * Primary current

$= 13800 * 43.5 = 600$ KVA

o/p current (I_2) = $\frac{\text{KVA rating}}{V_2} = \frac{600*1000}{11500} = 52.2$ Amp

Current in winding $A_1-A_2 = I_2 - I_1 = 52.2 - 43.5$
$= 8.7$ A

Parallel operation of single phase transformers

→ A single t/former is enough to meet the required load demand.

→ The same amount of load can be meet by connecting an another transformer to present one can also meet the same load.

Another transformer can be arranged in parallel with previous one then load can be shared by 2 transformers.

→ Adding one transformer in parallel with existing involves a cost

But having some advantages transformers operating in parallel.

Advantages of using one or more transformers are

* 2 transformers operating in parallel increases the system reliability.

* If one fails to operate, other one supply power to load i.e continuity of supply is possible

* Depending on power demand, transformers can be switched on & switched off.

Conditions satisfied for parallel operation of transformers

* T/formers must have equal voltage ratio's i.e primaries of 2 T/formers are connected to same source or voltage

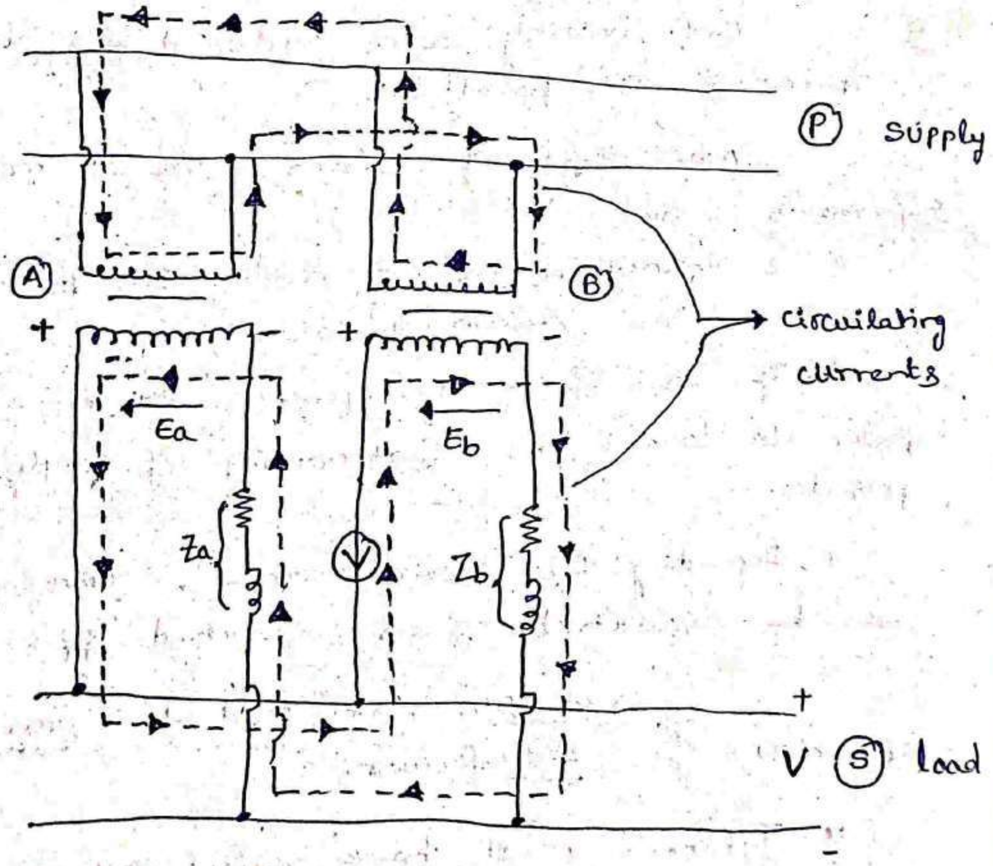
2ndaries of 2 T/formers are must have equal voltage magnitudes

* leakage impedance should be inversely proportiona

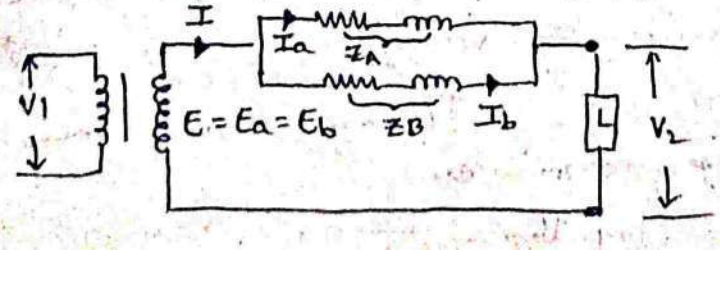
to their KVA ratings

$$Z = \frac{1}{KVA}$$

* Ratio of leakage reactance to leakage resistance of equivalent circuit should be same for all t/formers.
* Polarities of t/formers on 2ndary must be same.
  This is check by connecting a voltmeter across the 2ndaries of any one T/former.
  → Polarities are correct, if voltmeter shows zero (V=0)



Ideal Case (No load operation)



No load 2ndaries voltages of A & B T/former is given as

E_a & E_b

→ if $E_a - E_b = 0$ or $E_a = E_b$

There is no circulating current exist.

→ if $E_a \neq E_b$ or unequal then circulating currents exists in secondary

$$i_c = \frac{E_a - E_b}{Z_A + Z_B}$$

Also if E_a & E_b are out of phase, magnitudes of 2ndaries also changes results large circulating currents, increases ohmic losses will reduces efficiency of T/former

It is recommanded that

I_c circulating currents must be less than 10% of rated current.

I_c < 10% of rated current

I_c & E_a are same

I_c & E_b are opposite

$$E_a + I_a Z_A = E_b - I_b Z_B$$

$$E + I_A Z_A = E - I_B Z_B$$

we know that t/former secondary voltage

$V = E +$

$$\boxed{V = E - I_A Z_A = E - I_B Z_B}$$

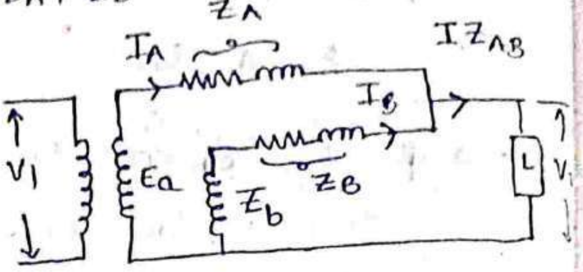
$$I_A Z_A = I_B Z_B$$

$$I_A = I_B \frac{Z_B}{Z_A}, \quad I_B = I_A \frac{Z_A}{Z_B}$$

this for on no load operation

$$I_c = \frac{I_A - I_B}{Z_A + Z_B} = \frac{E_A - E_B}{Z_A + Z_B}$$

On- load operation



$$I_c = \frac{E_A - E_B}{Z_A + Z_B}$$

fig (1) on load operation

$$I = I_A + I_B$$

$$I = I_B\left(1 + \frac{Z_B}{Z_A}\right) = I_B\left(\frac{Z_A + Z_B}{Z_A}\right)$$

$$I_B = I * \frac{Z_A}{Z_A + Z_B}$$

$$I_A = I * \frac{Z_B}{Z_A + Z_B}$$

Multiplying V_2 on both sides we get

$$V_2 I_B = V_2 * I * \frac{Z_A}{Z_A + Z_B}$$

$$S_B = S * \frac{Z_A}{Z_A + Z_B}$$

$$V_2 I_A = V_2 * I * \frac{Z_B}{Z_A + Z_B}$$

$$S_A = S * \frac{Z_A}{Z_A + Z_B}$$

Unequal Voltage ratio's

from (1)st fig we say that

Voltage ratio's of 2 transformers are different, their 2ndary Voltages are unequal.

let $E_A, E_B \rightarrow$ no load 2ndary emf's of t/f (A) & B

Z_L = load impedance across 2ndary

we know that $I_c = \frac{E_A - E_B}{Z_A + Z_B}$

we know that secondary voltages of 2 transformers

$$V_2 = E_A - I_A Z_A = E_B - I_B Z_B = I Z_L$$

$E_A = V_2 + I_A Z_A$, $E_B = V_2 + I_B Z_B$, $V_2 = I Z_L$

$V_2 = I Z_{AB}$

$E_A = I_A Z_A + (I_A + I_B) Z_L \longrightarrow$ (a)

$E_B = I_B Z_B + (I_A + I_B) Z_L \longrightarrow$ (b)

$$V_2 = (I_A + I_B) Z_L$$

$E_A - E_B = I_A Z_A - I_B Z_B \longrightarrow$ (c)

$$I_A = \frac{(E_A - E_B) + I_B Z_B}{Z_A} \longrightarrow (d)$$

substitute equation (d) in equation (b)

$$E_B = I_B Z_B + \left[\left\{\frac{(E_A - E_B) + I_B Z_B}{Z_A}\right\} + I_B\right] Z_L$$

$E_B Z_A$

$$E_B = \frac{I_B Z_B * Z_A + \{(E_A - E_B) + I_B Z_B + I_B Z_A\} Z_L}{Z_A}$$

$$E_B Z_A = I_B Z_B * Z_A + (E_A - E_B) Z_L + I_B Z_B Z_L + I_B Z_A Z_L$$

$$= I_B Z_B * Z_A + (E_A - E_B) Z_L + I_B Z_L (Z_A + Z_B)$$

$$E_B Z_A = I_B [Z_A Z_B + Z_L (Z_A + Z_B)] + (E_A - E_B) Z_L$$

$$E_B Z_A - (E_A - E_B) Z_L = I_B (Z_A + Z_B + Z_L (Z_A + Z_B))$$

$$I_B = \frac{E_B Z_A - (E_A - E_B) Z_L}{Z_A Z_B + Z_L (Z_A + Z_B)}$$ ✓ imp

$$I_A = \frac{E_A Z_B + (E_A - E_B) Z_L}{Z_A Z_B + Z_L (Z_A + Z_B)}$$ ✓ imp

now

$$I = I_A + I_B$$

$$I = \frac{E_A Z_B + Z_A E_B}{Z_A Z_B + Z_L (Z_A + Z_B)}$$ ✓ imp

divide num by $Z_A Z_B$ & denomin by $Z_A Z_B * Z_L$

If Z_A & Z_B are small compared to Z_L

Neglect $Z_A Z_B$

$$I = \frac{\frac{E_A Z_B}{Z_A Z_B} + \frac{E_B Z_A}{Z_A Z_B}}{1 + \frac{Z_L}{Z_B} + \frac{Z_L}{Z_A}}$$

~~$I_A = \frac{E_A Z_B + (E_A - E_B)}{Z_L (Z_A + Z_B)}$~~

$$I_A = \frac{E_A Z_B}{Z_L (Z_A + Z_B)} + \frac{E_A - E_B}{Z_A + Z_B}$$

$I =$

divide num

$$I_B = \frac{E_B Z_A}{Z_L(Z_A+Z_B)} - \frac{(E_A-E_B)}{(Z_A+Z_B)}$$

$V_2 = E_A - I_A Z_A$

$V_2 = E_B - I_B Z_B$

$= E_B + I_A Z_B$

Total Current

$$I = I_A + I_B$$

$$\boxed{I_B = I - I_A}$$

∴ circulating currents in secondary on no load is given as

$$I_C = \frac{E_A - E_B}{Z_A + Z_B} \quad \text{when } E_A > E_B$$

under load conditions, circulating currents

$$\boxed{I_C = \frac{E_A - E_B}{Z_A + Z_B + \frac{Z_A Z_B}{Z_L}}} = \frac{Z_L(E_A - E_B)}{Z_L(Z_A+Z_B) + Z_A Z_B}$$

from given equation

$$\boxed{E_A - E_B = I_A Z_A - I_B Z_B} \longrightarrow (1)$$

Total Current

$$I = I_A + I_B \Rightarrow \boxed{I_B = I - I_A}$$

Substitute I_B in equ (1)

$$E_A - E_B = I_A Z_A - (I - I_A) Z_B$$

$$E_A - E_B = I_A Z_A + I_A Z_B - I Z_B$$

$$= I_A (Z_A + Z_B) - I Z_B$$

$$\boxed{I_A = (E_A - E_B) + I Z_B \big/ Z_A + Z_B}$$

$I_A + I_B = I$

$$\boxed{I_A = I - I_B} \rightarrow (b)$$

Substitute equation (b) in equation (1)

$E_A - E_B = (I - I_B) Z_A - I_B Z_B$

$E_A - E_B = I * Z_A - I_B Z_A - I_B Z_B$

$E_A - E_B = I * Z_A - I_B (Z_A + Z_B)$

$I_B (Z_A + Z_B) = I * Z_A - (E_A - E_B)$

$$\boxed{I_B = \frac{I * Z_A - (E_A - E_B)}{Z_A + Z_B}}$$

∴ terminal voltage

$$V_2 = I * Z_L = \frac{E_A Z_B + E_B Z_A - I Z_A Z_B}{Z_A + Z_B}$$

⇒ The value of V_2 may also found as

$V_2 = E_A - I_A Z_A$

$I_A Z_A = E_A - V_2$

$$I_A = \frac{(E_A - V_2)}{Z_A} = (E_A - V_2) Y_A$$

$$I_B = \frac{(E_B - V_2)}{Z_B} = (E_B - V_2) Y_B$$

$V_2 = I * Z_L$

$$\boxed{I = \frac{V_2}{Z_L} = V_2 Y_L}$$

$I = I_A + I_B = V_2 Y_L$

$$V_2 = \frac{E_B Y_B + E_A Y_A}{Y_L + Y_A + Y_B}$$

— x —

if load is given in KVA then V_2 is

$S = V_2 I \Rightarrow I = \frac{S}{V_2}$

$$V_2 = \frac{E_A Z_B + E_B Z_A - I Z_A Z_B}{Z_A + Z_B}$$

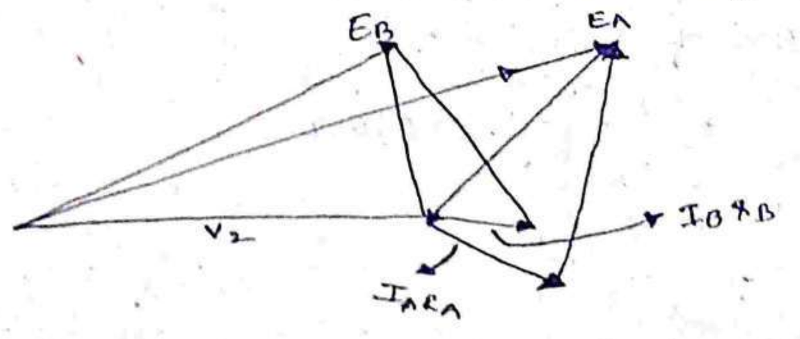
$$V_2 = \frac{E_A Z_B + E_B Z_A - S \frac{Z_A Z_B}{V_2}}{Z_A + Z_B}$$

$$V_2 = \frac{V_2 (Z_B E_A + E_B Z_A) - S Z_A Z_B}{V_2 (Z_A + Z_B)}$$

$$V_2^2 (Z_A + Z_B) = V_2 (Z_B E_A + E_B Z_A) - S Z_A Z_B$$

If I_A & I_B known from V_2

$V_2 = E_A - I_A Z_A$ & $V_2 = E_B - I_B Z_B$



Problem KVA of (A) = 500, KVA of (B) = 250 KVA

Two transformers (A) & (B) operating in parallel supply a common load 750 KVA at 0.8 p.f lag. Their open circuit voltages are 405 & 415 V. T/former (A) has resistance 1% & reactance 5%. T/former (B) has resistance 1.5% & reactance 4%. Find (a) cross current in secondaries on no load (b) load shared by each T/former

Sol

T/former (A)	T/former (B)
$E_A = 405$	$E_B = 415$
$R_A = 1\%$, $X_A = 5\%$, KVA = 500	$R_B = 1.5\%$, $X_B = 4\%$
load Current in KVA = 750	KVA = 250 KVA
	Let V_2 be assumed as 400

$I_A R_A = 1\%$ of V_2

$$R_A = \frac{1}{100} * \frac{V_2}{I_A}$$

$$I_A = \frac{\text{T/f (A) KVA}}{V_2} = 750$$

$$I_A = \frac{\text{T/f (A) KVA}}{V_2} = \frac{500 * 1000}{400} = 1250\,A$$

$$R_A = \frac{1}{100} * \frac{400}{1250} = 0.0032$$

$$R_A = \frac{1}{100} * \frac{V_2}{\left(\text{load KVA + T/f (A) KVA}\right)}$$

$$X_A = \frac{5}{100} * \frac{V_2}{I_A}$$

$I_A X_A = 5\%$ of V_2

$$X_A = \frac{5}{100} * \frac{V_2}{I_A} = 0.016\,\Omega$$

$I_B R_B = 1.5\%$ of V_2

$$I_B = \frac{\text{Rating of T/f (B)}}{V_2} = \frac{250 * 1000}{400} = 625\text{A}$$

$$\boxed{R_B = \frac{1.5}{100} * \frac{V_2}{I_B}} = \frac{1.5}{100} * \frac{400}{625} = 0.0096$$

$I_B X_B = 4\%$ of V_2

$$\boxed{X_B = \frac{4}{100} * \frac{V_2}{I_B}} = 0.0256$$

$Z_A = 0.0032 + j0.016$, $Z_B = 0.0096 + j0.0256$

$= 0.063 \angle 78.5°$ $= 0.0275 \angle 69.4$

$Z_A + Z_B = 0.0436 \angle 72.9°$

Let Z_L be the load impedance, with terminal V_2

$$\frac{V_2^2}{Z_L} = \text{load} \angle -\phi = 750 * 10^3 \angle -36.86$$

$$\frac{V_2^2}{\text{load} \angle -\phi} = Z_L \Rightarrow Z_L = \frac{(400^2)}{750 * 10^3 \angle -36.86}$$

$$Z_L = 0.213 \angle 36.86 = 0.1706 + i\,0.128$$

(a) Circulation currents on no load

$$I = \frac{E_A - E_B}{Z_A + Z_B} = \frac{(405 - 415)}{0.0436 \angle 72.9} = -229.3 \angle -72.9$$

(b) load current shared by each t/former

$$I_A = \frac{E_A Z_B + (E_A - E_B) Z_L}{Z_A Z_B + Z_L(Z_A + Z_B)}$$

$$= 970\angle -35^\circ$$

$$I_B = \frac{E_B Z_B - (E_A - E_B) Z_L}{Z_A Z_B + Z_L(Z_A + Z_B)} = 875\angle 42.6$$

. load shared by each t/former

$S_A = V_2 * I_A = 400 * 970\angle -35 = 388\angle -35^\circ$ KVA

$\cos\phi_A = \cos(-35) = 0.81$

$S_B = V_2 * I_B = 400 * 875\angle 42.6 = 350\angle 42.6$ KVA

$\cos\phi_B = \cos(42.6) = 0.736$

imp imp

2 T/formers have following

	(A)	(B)
Rated current	200 A	600 A
Per unit Resistance	0.02	0.025
" " Reactance	0.05	0.06
No load emf	245V	240V

Calculate terminal voltage & supply load impedance (0.025 + j0.1)

sol

given impedance in per unit is converted into Ω

$$Z_A = Z_{pu} * \frac{emf(A)}{\text{Rated current}}$$

$\Rightarrow Z_A = (0.02 + 0.025i) * \frac{245}{200}$

$Z_A = 0.066\angle 68.2$

$= 0.0245 + 0.06128i$

$$Z_B = Z_{B(pu)} * \frac{Emf(B)}{\text{Rated Current of } T/f(B)}$$

$$= (0.025 + j0.06) * \frac{240}{600} = 0.026 \angle 67.3 = 0.010 + j0.023$$

Also $Z_L = (0.25 + j0.1) = 0.269 \angle 21.8 =$

$$Z_A + Z_B = 0.066 \angle 68.2 + 0.026 \angle 67.3$$

$$= 0.0919 \angle 67.94$$

2ndary terminal voltage

$$V_2 = I Z_L$$

$$I = \frac{E_A Z_B + E_B Z_A}{Z_A Z_B + Z_L (Z_A + Z_B)} = 855 \angle -24.8$$

$$V_2 = 855 \angle -24.8 * 0.269 \angle 21.8$$

$$= 229.99 \angle -3$$

(6) load of $(2 + j1.5) = 2.5 \angle 36.86$

$Z_A = 0.15 + j0.5$

$Z_B = 0.1 + j0.6$

$E_A = 207 \angle 0°$

$E_B = 205 \angle 0°$

find power o/p & p.f of each T/former

Sol

$$I_A = \frac{E_A Z_B + (E_A - E_B) Z_L}{Z_A Z_B + Z_L (Z_A + Z_B)}$$

$$I_A = 42.26 \angle -38.9 = 32.89 - j26.55$$

$$I_B = \frac{E_B Z_A - (E_A - E_B) Z_L}{Z_A Z_B + Z_L (Z_A + Z_B)}$$

$$= 33.56 \angle -42.9 = 24.58 - j22.84$$

Now

$$V_2 = I Z_L$$

$$= (I_A + I_B) Z_L$$

$$= 189.4 \angle -3.9$$

$V_2 = I Z_L$
$= (42.26 + 33.56)$

P.f of T/f (A) = $-3.9 - (-\phi_A) =$
P.f of T/f (B) =

$\cos\phi_A =$

$$P_A = 189.4 * 33.56 *$$

$$\phi_A = -3.9 - (-38.9) = 35$$

$$\phi_B = -3.9 - (-42.9) = 39$$

$$P_A = V_2 * I * \cos\phi_A = (189.4) *$$

$$P_B = V_2 * I * \cos\phi_B$$

C H A P T E R 33

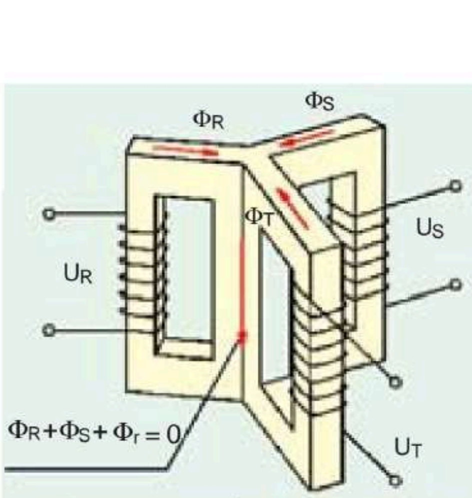
TRANSFORMER: THREE PHASE

Learning Objectives

- Three-phase Transformers
- Three-phase Transformer Connections
- Star/Star or Y/Y Connection
- Delta-Delta or Connection
- Wye/Delta or Y/ Connection
- Delta/Wye or /Y Connection
- Open-Delta or V-V Connection
- Power Supplied by V-V Bank
- Scott Connection or T-T Connection
- Three-phase to Two-Phase Conversion and vice-versa
- Parallel Operation of 3-phase Transformers
- Instrument Transformers
- Current Transformers
- Potential Transformers

Three phase transformers are used throughout industry to change values of three phase voltage and current. Three phase power is the most common way in which power is produced.

33.1. Three-Phase Transformer



Three phase transformer inner circuits

Large scale generation of electric power is usually 3-phase at generated voltages of 13.2 kV or somewhat higher. Transmission is generally accomplished at higher voltages of 110, 132, 275, 400 and 750 kV for which purpose 3-phase transformers are necessary to step up the generated voltage to that of the transmission line. Next, at load centres, the transmission voltages are reduced to distribution voltages of 6,600, 4,600 and 2,300 volts. Further, at most of the consumers, the distribution voltages are still reduced to utilization voltages of 440, 220 or 110 volts. Years ago, it was a common practice to use suitably interconnected three single-phase transformers instead of a single 3-phase transformer. But these days, the latter is gaining popularity because of improvement in design and manufacture but principally because of better acquaintance of operating men with the three-phase type. As compared to a bank of single-phase transformers, the main advantages of a 3 phase transformer are that it occupies less floor space for equal rating, weighs less, costs about 15% less and further, that only one unit is to be handled and connected.

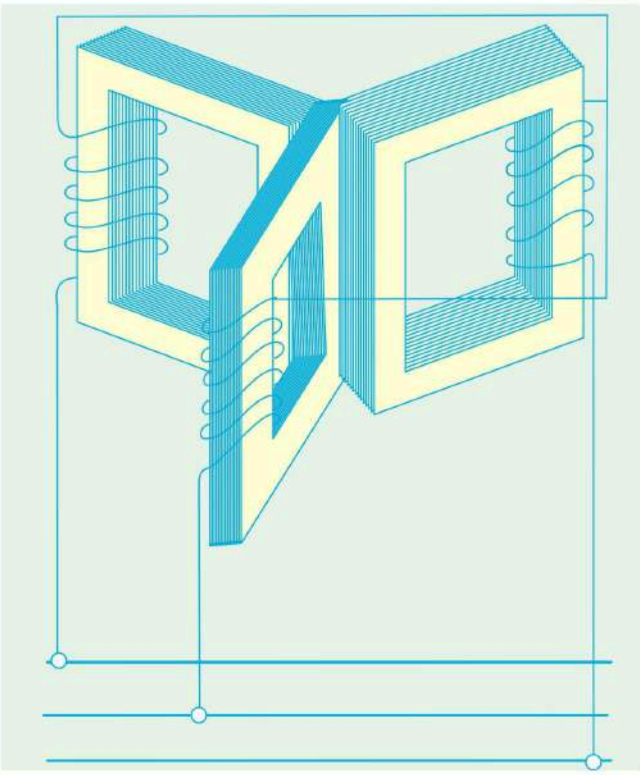


Fig. 33.1

Like single-phase transformers, the three-phase transformers are also of the core type or shell type. The basic principle of a 3-phase transformer is illustrated in Fig. 33.1 in which only primary windings have been shown interconnected in star and put across 3-phase supply. The three cores are 120° apart and their empty legs are shown in contact with each other. The centre leg, formed by these three, carries the flux produced by the three-phase currents I_R, I_Y and I_B. As at any instant $\boldsymbol{I_R + I_Y + I_B} = 0$, hence the sum of three fluxes is also zero. Therefore, it will make no difference if the common leg is removed. In that case any two legs will act as the return for the third just as in a 3-phase system any two conductors act as the return for the current

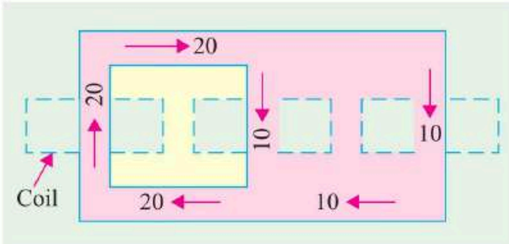


Fig. 33.2 (*a*)

in the third conductor. This improved design is shown in Fig. 33.2 (*a*) where dotted rectangles indicate the three windings and numbers in the cores and yokes represent the directions and magnitudes of fluxes at a particular instant. It will be seen that at any instant, the amount of 'up' flux in any leg is equal to the sum of 'down' fluxes in the other two legs. The core type transformers are usually wound with circular cylindrical coils.

In a similar way, three single-phase shell type transformers can be combined together to form a 3-phase shell type unit as shown in Fig. 33.2(*b*). But some saving in iron can be achieved in constructing a single 3-phase transformer as shown in Fig. 33.3. It does not differ from three single-phase transformers put side by side. Saving in iron is due to the joint use of the magnetic paths between the coils. The three phases, in this case, are more independent than they are in the core type transformers, because each phase has a magnetic circuit independent of the other.

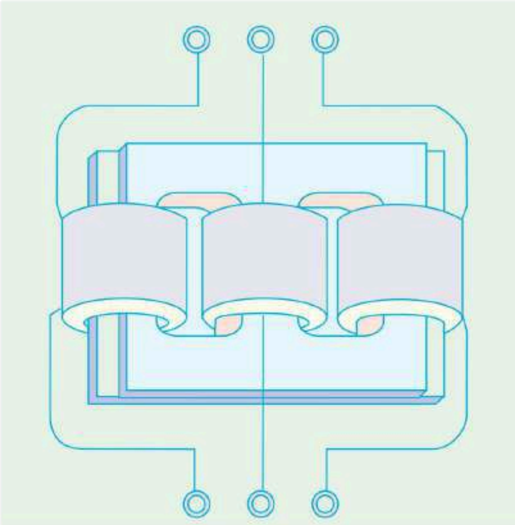


Fig. 33.2 (*b*)

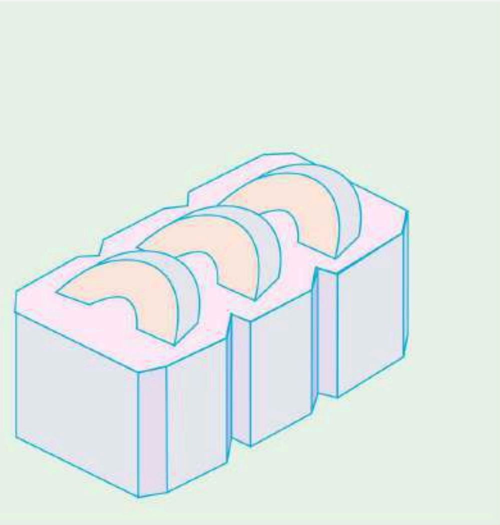
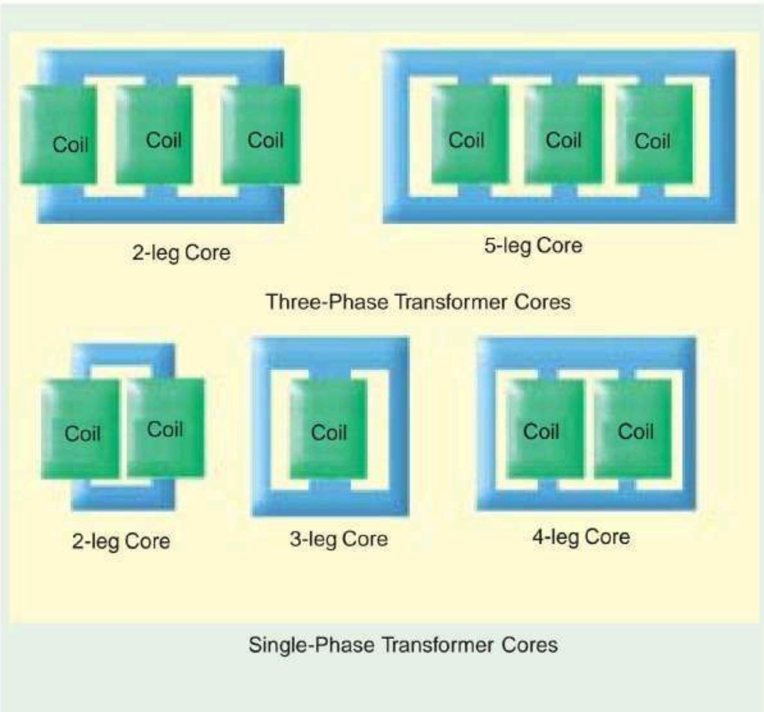


Fig. 33.3



One main drawback in a 3-phase transformer is that if any one phase becomes disabled, then the whole transformer has to be ordinarily removed from service for repairs (the shell type may be operated open

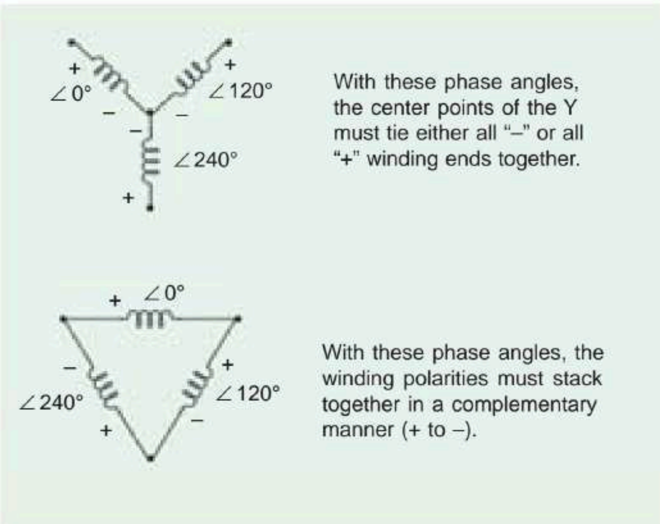
Δ or Vee but this is not always feasible). However, in the case of a 3-phase bank of single-phase transformers, if one transformer goes out of order, the system can still be run open-Δ at reduced capacity or the faulty transformer can be readily replaced by a single spare.

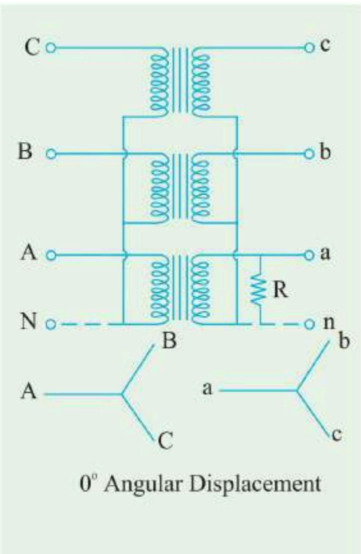
33.2. Three-phase Transformer Connections

There are various methods available for transforming 3-phase voltages to higher or lower 3-phase voltages *i.e.* for handling a considerable amount of power. The most common connections are (*i*) $Y-Y$ (*ii*) $\Delta-\Delta$ (*iii*) $Y-\Delta$ (*iv*) $\Delta-Y$ (*v*) open-delta or $V-V$ (*vi*) Scott connection or $T-T$ connection.

33.3. Star/Star or *Y/Y* Connection

This connection is most economical for small, high-voltage transformers because the number of turns/phase and the amount of insulation required is minimum (as phase voltage is only $1/\sqrt{3}$ of line voltage). In Fig. 33.4 a bank of 3 transformers connected in *Y* on both the primary and the secondary sides is shown. The ratio of line voltages on the primary and secondary sides is the same as the transformation ratio of each transformer. However, there is a phase shift of 30° between the phase voltages and line voltages both on the primary and secondary sides. Of course, line voltages on both sides as well as primary voltages are respectively in phase with each other. ***This connection works satisfactorily only if the load is balanced.*** With the unbalanced load to the neutral, the neutral point shifts thereby making the three line-to-neutral (*i.e.* phase) voltages unequal. The effect of unbalanced loads can be illustrated by placing a single load between phase (or coil) *a* and the neutral on the secondary side. The power to the load has to be supplied by primary phase (or coil) *A*. This primary coil *A* cannot supply the required power because it is in series with primaries *B* and *C* whose secondaries are open. Under these conditions, the primary coils *B* and *C* act as very high impedances so that primary coil *A* can obtain but very little current through them from the line. Hence, secondary coil *a* cannot supply any appreciable power. In fact, a very low resistance approaching a short-circuit may be connected between point *a* and the neutral and only a very small amount of current will flow. This, as said above, is due to the reduction of voltage E_{an} because of neutral shift. In other words, under short-circuit conditions, the neutral is pulled too much towards coil *a*. This reduces E_{an} but increases E_{bn} and E_{cn} (however line voltage E_{AB}, E_{BC} and E_{CA} are unaffected). On the primary side, E_{AN} will be





0° Angular Displacement

Fig. 33.4

practically reduced to zero whereas E_{BN} and E_{CN} will rise to nearly full primary line voltage. This difficulty of shifting (or floating) neutral can be obviated by connecting the primary neutral (shown dotted in the figure) back to the generator so that primary coil *A* can take its required power from between its line and the neutral. It should be noted that if a single phase load is connected between the lines *a* and *b*, there will be a similar but less pronounced neutral shift which results in an overvoltage on one or more transformers.

Another advantage of stabilizing the primary neutral by connecting it to neutral of the generator is that it eliminates distortion in the secondary phase voltages. This is explained as follows. For delivering a sine wave of voltage, it is necessary to have a sine wave of flux in the core, but on account of the characteristics of iron, a sine wave of flux requires a third harmonic component in the exciting current. As the frequency of this component is thrice the frequency of the circuit, at any given instant, it tends to flow either towards or away from the neutral point in all the three transformers. If the primary neutral is isolated, the triple frequency current cannot flow. Hence, the flux in the core cannot be a sine wave and so the voltages are distorted. But if the primary neutral is earthed *i.e.* joined to the generator neutral, then this provides a path for the triple-frequency currents and e.m.fs. and the difficulty is overcome. Another way of avoiding this trouble of oscillating neutral is to provide each of the transformers with a third or tertiary winding of relatively low kVA rating. This tertiary winding is connected in Δ and provides a circuit in which the triple-frequency component of the magnetising current can flow (with an isolated neutral, it could not). In that case, a sine wave of voltage applied to the primary will result in a sine wave of phase voltage in the secondary. As said above, the advantage of this connection is that insulation is stressed only to the extent of line to neutral voltage *i.e.* 58% of the line voltage.

33.4. Delta-Delta or Δ – Δ Connection

This connection is economical for large, low-voltage transformers in which insulation problem is not so urgent, because it increases the number of turns/phase. The transformer connections and voltage triangles are shown in Fig. 33.5. The ratio of transformation between primary and secondary line voltage is exactly the same as that of each transformer. Further, the secondary voltage triangle *abc* occupies the same relative position as the primary voltage triangle *ABC* *i.e.* there is no angular displacement between the two. Moreover, there is no internal phase shift between phase and line voltages on either side as was the case in $Y - Y$ connection. This connection has the following advantages :

1. As explained above, in order that the output voltage be sinusoidal, it is necessary that the magnetising current of the transformer must contain a third harmonic component. In this case, the third harmonic component of the magnetising current can flow in the Δ-connected transformer primaries without flowing in the line wires. The three phases are 120° apart which is $3 \times 120 = 360°$ with respect to the third harmonic, hence it merely circulates in the Δ. Therefore, the flux is sinusoidal which results in sinusoidal voltages.

2. No difficulty is experienced from unbalanced loading as was the case in $Y - Y$ connection. The three-phase voltages remain practically constant regardless of load imbalance.

3. An added advantage of this connection is that if one transformer becomes disabled, the system can continue to operate in open-delta or in $V - V$ although with reduced available capacity. The reduced capacity is 58% and not 66.7% of the normal value, as explained in Art. 33.7.

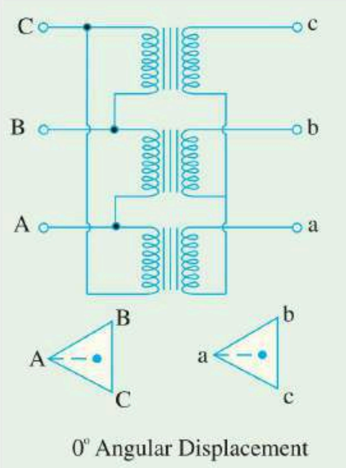


Fig. 33.5

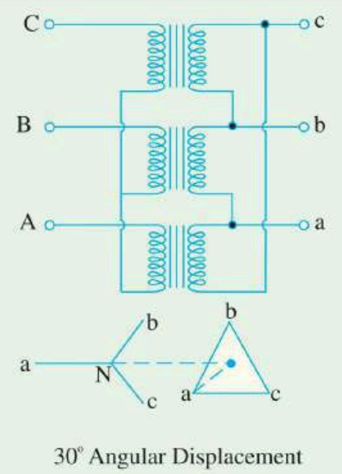


Fig. 33.6

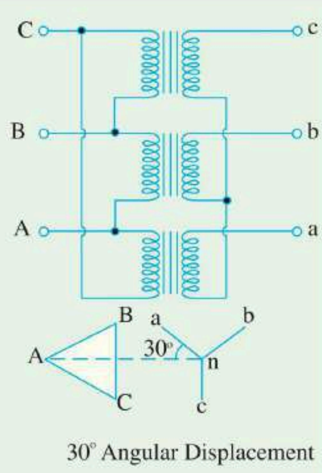


Fig. 33.7

33.5. Wye/Delta or Y/Δ Connection

The main use of this connection is at the substation end of the transmission line where the voltage is to be stepped down. The primary winding is *Y*-connected with grounded neutral as shown in Fig. 33.6. The ratio between the secondary and primary line voltage is $1/\sqrt{3}$ times the transformation ratio of each transformer. There is a 30° shift between the primary and secondary line voltages which means that a $Y-\Delta$ transformer bank cannot be paralleled with either a $Y-Y$ *or* a $\Delta-\Delta$ bank. Also, third harmonic currents flows in the Δ to provide a sinusoidal flux.

33.6. Delta/Wye or Δ/Y Connection

This connection is generally employed where it is necessary to step up the voltage as for example, at the beginning of high tension transmission system. The connection is shown in Fig. 33.7. The neutral of the secondary is grounded for providing 3-phase 4-wire service. In recent years, this connection has gained considerable popularity because it can be used to serve both the 3-phase power equipment and single-phase lighting circuits.

This connection is not open to the objection of a floating neutral and voltage distortion because the existence of a Δ-connection allows a path for the third-harmonic currents. It would be observed that the primary and secondary line voltages and line currents are out of phase with each other by 30°. Because of this 30° shift, it is impossible to parallel such a bank with a $\Delta - \Delta$ or $Y - Y$ bank of transformers even though the voltage ratios are correctly adjusted. The ratio of secondary to primary voltage is $\sqrt{3}$ times the transformation ratio of each transformer.

Example 33.1. *A 3-phase, 50-Hz transformer has a delta-connected primary and star-connected secondary, the line voltages being 22,000 V and 400 V respectively. The secondary has a star-connected balanced load at 0.8 power factor lagging. The line current on the primary side is 5 A. Determine the current in each coil of the primary and in each secondary line. What is the output of the transformer in kW ?*

Solution. It should be noted that in three-phase transformers, the *phase* transformation ratio is equal to the turn ratio but the terminal or line voltages depend upon the method of connection employed. The Δ/Y connection is shown in Fig. 33.8.

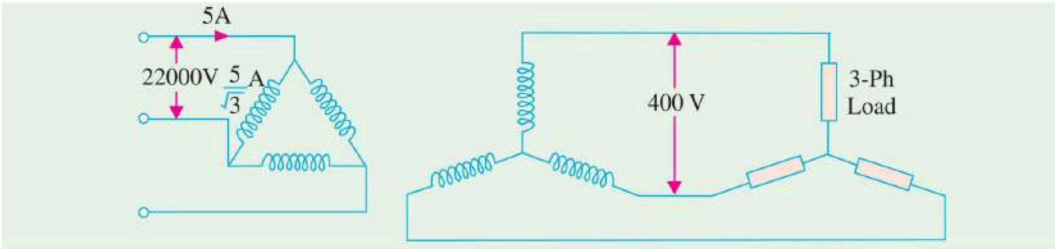


Fig. 33.8

Phase voltage on primary side	= 22,000 V
Phase voltage on secondary side	$= 400/\sqrt{3}$
∴ K	$= 400/22{,}000 \times \sqrt{3} = 1/55\sqrt{3}$
Primary phase current	$= 5/\sqrt{3}$ A
Secondary phase current	$= \dfrac{5}{\sqrt{3}} \div \dfrac{1}{55\sqrt{3}} = 275$ A
Secondary line current	= **275 A**
∴ Output	$= \sqrt{3} V_L I_L \cos\phi = \sqrt{3} \times 400 \times 275 \times 0.8 =$ **15.24 kW.**

Example 33.2. *A 500-kVA, 3-phase, 50-Hz transformer has a voltage ratio (line voltages) of 33/11-kV and is delta/star connected. The resistances per phase are : high voltage 35 Ω, low voltage 0.876 Ω and the iron loss is 3050 W. Calculate the value of efficiency at full-load and one-half of full-load respectively (a) at unity p.f. and (b) 0.8 p.f.* **(Electrical Machinery, Madras Univ. 1985)**

Solution. Transformation ratio $K = \dfrac{11{,}000}{\sqrt{3} \times 33{,}000} = \dfrac{1}{3\sqrt{3}}$

Per phase $R_{02} = 0.876 + (1/3\sqrt{3})^2 \times 35 = 2.172\ \Omega$

Secondary phase current $= \dfrac{500{,}000}{\sqrt{3} \times 11{,}000} = \dfrac{500}{11\sqrt{3}}$ A

Full-load condition

Full load total Cu loss $= 3 \times (500/11\sqrt{3})^2 \times 2.172 = 4{,}490$ W; Iron loss = 3,050 W

Total full-load losses = 4,490 + 3,050 = 7,540 W; Output at unity p.f. = 500 kW

∴ F.L. efficiency = 500,000/507,540 = 0.9854 or **98.54%**; Output at 0.8 p.f. = 400 kW

∴ Efficiency = 400,000/407.540 = 0.982 or **98.2%**

Half-load condition

Output at unity p.f.= 250 kW

Cu losses $= (1/2)^2 \times 4{,}490$ = **1,222 W**

Total losses = 3,050 + 1,122 = 4,172 W

Three-phase transformer

$\therefore$ $\eta = 250{,}000/254{,}172 = 0.9835 =$ **98.35 %**

Output at 0.8 p.f. $= 200$ kW $\therefore$ **$\eta = 200{,}000/204{,}172 = 0.98$ or 98%**

Example 33.3. *A 3-phase, 6,600/415-V, 2,000-kVA transformer has a per unit resistance of 0.02 and a per unit leakage reactance of 0.1. Calculate the Cu loss and regulation at full-load 0.8 p.f. lag.* **(Electrical Machines-I, Bombay Univ. 1987)**

Solution. As seen from Art. 27 – 16, $\% R = \%\text{ Cu loss} = \dfrac{\text{Cu loss}}{VA} \times 100$

Now, $\% R = 0.02 \times 100 = 2\%$ $\quad \therefore \quad 2 = \dfrac{\text{Cu loss}}{2{,}000} \times 100 \quad \therefore$ Cu loss = **40 kW**

Now, percentage leakage reactance $= 0.1 \times 100 = 10\%$

$$\text{Regn.} = v_r \cos\phi + v_x \sin\phi = 2 \times 0.8 + 10 \times 0.6 = \mathbf{7.6\%}$$

Example 33.4. *A 120-kVA, 6,000/400-V, Y/Y 3-ph, 50-Hz transformer has an iron loss of 1,600 W. The maximum efficiency occurs at 3/4 full load.*

Find the efficiencies of the transformer at

(*i*) *full-load and 0.8 power factor* (*ii*) *half-load and unity power factor*

(*iii*) *the maximum efficiency.* **(Elect. Technology Utkal Univ. 1987)**

Solution. Since maximum efficiency occurs at 3/4 full-load, Cu loss at 3/4 full-load equals iron loss of 1,600 W.

Cu loss at 3/4 F.L. $= 1{,}600$ W; Cu loss at F.L. $= 1{,}600 \times (4/3)^2 = 2{,}845$ W

(*i*) F.L. output at 0.8 p.f. $= 120 \times 0.8 = 96 \text{ kW} = 96{,}000$ W

Total loss $= 1{,}600 + 2{,}845 = 4{,}445$ W

$\therefore$ $\eta = \dfrac{96{,}000}{100{,}445} \times 100 =$ **95.57 %**

(*ii*) Cu loss at 1/2 full-load $= (1/2)^2 \times 2{,}845 = 710$ W

Total loss $= 710 + 1{,}600 = 2310$ W

Output at 1/2 F.L. and u.p.f. is $= 60 \text{ kW} = 60{,}000$ W; $\eta = \dfrac{60{,}000}{62{,}310} \times 100 =$ **96.57%**

(*iii*) Maximum efficiency occurs at 3/4 full-load when iron loss equals Cu loss.

Total loss $= 2 \times 1{,}600 = 3{,}200$ W

Output at u.p.f. $= (3/4) \times 120 = 90 \text{ kW} = 90{,}000$ W

Input $= 90{,}000 + 3{,}200 = 93{,}200$ W $\therefore \eta = \dfrac{90{,}000}{93{,}200} \times 100 =$ **96.57%**

Example 33.5. *A 3-phase transformer, ratio 33/6.6-kV, Δ/Y, 2-MVA has a primary resistance of 8 Ω per phase and a secondary resistance of 0.08 ohm per phase. The percentage impedance is 7%. Calculate the secondary voltage with rated primary voltage and hence the regulation for full-load 0.75 p.f. lagging conditions.* **(Elect. Machine-I, Nagpur, Univ. 1993)**

Solution. F.L. secondary current $= \dfrac{2 \times 10^6}{\sqrt{3} \times 6.6 \times 10^3} = 175$ A

$K = 6.6/\sqrt{3} \times 33 = 1/8.65$; $R_{02} = 0.08 + 8/8.65^2 = 0.1867\ \Omega$ per phase

Now, secondary impedance drop per phase $= \dfrac{7}{100} \times \dfrac{6{,}600}{\sqrt{3}} = 266.7$ V

$\therefore$ $Z_{02} = 266.7/175 = 1.523\ \Omega$ per phase

$$X_{02} = \sqrt{Z_{02}^2 - R_{02}^2} = \sqrt{1.523^2 - 0.1867^2} = 1.51\ \Omega/\text{phase}$$

Drop per phase $= I_2\,(R_{02}\cos\phi + X_{02}\sin\phi) = 175\,(0.1867 \times 0.75 + 1.51 \times 0.66) = 200$ V

Secondary voltage/phase $= 6,600/\sqrt{3} = 3,810$ V $\quad\therefore\quad V_2 = 3,810 - 200 = 3,610$ V

$\therefore$ Secondary *line* voltage $= 3,610 \times \sqrt{3} =$ **6,250 V**

%regn. $= 200 \times 100/3,810 =$ **5.23 %**

Example 33.6. *A 100-kVA, 3-phase, 50-Hz 3,300/400 V transformer is Δ-connected on the h.v. side and Y-connected on the l.v. side. The resistance of the h.v. winding is 3.5 Ω per phase and that of the l.v. winding 0.02 Ω per phase. Calculate the iron losses of the transformer at normal voltage and frequency if its full-load efficiency be 95.8% at 0.8 p.f. (lag).*

(A.C. Machines-I, Jadavpur Univ. 1989)

Solution. F.L. output $= 100 \times 0.8 = 80$ kW; Input $= 80/0.958 = 83.5$ kW

Total loss $=$ Input $-$ Output $= 83.5 - 80 = 3.5$ kW

Let us find full-load Cu losses for which purpose, we would first calculate R_{02}.

$$K = \frac{\text{secondary voltage/phase}}{\text{primary voltage/phase}} = \frac{400/\sqrt{3}}{3,300} = \frac{4}{33\sqrt{3}}$$

$$R_{02} = R_2 + K^2 R_1 = 0.02 + (4/\sqrt{3} \times 33)^2 \times 3.5 = 0.037\ \Omega$$

Full-load secondary phase current is $I_2 = 100,000/\sqrt{3} \times 400 = 144.1$ A

Total Cu loss $= 3\,I_2^2 R_{02} = 3 \times 144.1^2 \times 0.037 = 2,305$ W

Iron loss $=$ Total loss $-$ F.L. Cu loss $= 3,500 - 2,305 =$ **1,195 W**

Example 33.7. *A 5,000-kVA, 3-phase transformer, 6.6/33-kV, Δ/Y, has a no-load loss of 15 kW and a full-load loss of 50 kW. The impedance drop at full-load is 7%. Calculate the primary voltage when a load of 3,200 kW at 0.8 p.f. is delivered at 33 kV.*

Solution. Full-load $\quad I_2 = 5 \times 10^6/\sqrt{3} \times 33,000 = 87.5$ A

Impedance drop/phase $= 7\%$ of $(33/\sqrt{3}) = 7\%$ of 19 kV $= 1,330$ V

$\therefore\quad Z_{02} = 1,330/87.5 = 15.3\ \Omega$/phase; F.L. Cu loss $= 50 - 15 = 35$ kW

$\therefore\quad 3\,I_2R_{02} = 35,000;\quad R_{02} = 35,000/3 \times 8.75^2 = 1.53\ \Omega$/phase

$\therefore\quad X_{02} = \sqrt{15.3^2 - 1.53^2} =$ **15.23 Ω**

When load is 3,200 kW at 0.8 p.f.

$I_2 = 3,200/\sqrt{3} \times 33 \times 0.8 = 70$ A; drop $= 70\,(1.53 \times 0.8 + 15.23 \times 0.6) = 725$ V/phase

$$\therefore\quad \%\ \text{regn.} = \frac{725 \times 100}{19,000} = 3.8\ \%$$

Primary voltage will have to be increased by 3.8%.

$\therefore$ Primary voltage $= 6.6 + 3.8\%$ of $6.6 = 6.85$ kV $=$ **6,850 V**

Example 33.8. *A 3-phase transformer has its primary connected in Δ and its secondary in Y. It has an equivalent resistance of 1% and an equivalent reactance of 6%. The primary applied voltage is 6,600 V. What must be the ratio of transformation in order that it will deliver 4,800 V at full-load current and 0.8 power factor (lag) ?* **(Elect. Technology-II, Magadh Univ. 1991)**

Solution. Percentage regulation

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

$= 1 \times 0.8 + 6 \times 0.6 = 4.4\%$

Induced secondary e.m.f. (line value)

$= 4,800 + 4.4\%$ of $4,800 = 5,010$ V, as in Fig. 33.9.

Secondary phase voltage

$= 5,010/\sqrt{3} = 2,890$ V

Transformation ratio

$K = 2,890/6,600 =$ **0.437.**

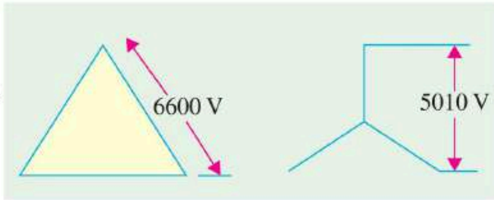


Fig. 33.9

Example 33.9. *A 2000-kVA, 6,600/400-V, 3-phase transformer is delta-connected on the high voltage side and star-connected on the low-voltage side. Determine its % resistance and % reactance drops, % efficiency and % regulation on full load 0.8 p.f. leading given the following data :*

S.C. test ; H.V. data : 400 V, 175 A and 17 kW

O.C. test; L.V. data : 400 V, 150 A and 15 kW **(Basic Elect., Machines Nagpur Univ. 1993)**

Solution. From S.C. test data, we have

Primary voltage/phase $= 400$ V; Primary current/phase $= 175/\sqrt{3} = 100$ A

$$\therefore \quad Z_{01} = \frac{400}{101} = 3.96\ \Omega$$

$$I_1^2 R_{01} = \frac{17000}{3} \text{ or } R_{01} = 0.555\ \Omega;\ X_{01} = \sqrt{3.96^2 - 0.555^2} = 3.92\ \Omega$$

$$\% R = \frac{I_1 R_{01}}{V_1} \times 100 = \frac{101 \times 0.555}{6,600} \times 100 = \mathbf{0.849}$$

$$\% X = \frac{I_1 X_{01}}{V_1} \times 100 = \frac{101 \times 3.92}{6,600} \times 100 = \mathbf{6}$$

$$\% \text{ regn} = v_r \cos\phi - v_x \sin\phi = 0.49 \times 0.8 - 6 \times 0.6 = -2.92\%$$

Full-load primary line current can be found from

$$\sqrt{3} \times 6,600 \times I_1 = 2000 \times 1,000;\ I_1 = 175 \text{ A}$$

It shows that S.C. test has been carried out under full-load conditions.

Total losses $= 17 + 15 = 32$ kW; F.L. output $= 2,000 \times 0.8 = 1600$ kW

$$\eta = 1,600/1,632 = 0.98 \text{ or } \mathbf{98\%}$$

Example 33.10. *A 3-ph, delta/star connected 11,000/440 V, 50 Hz transformer takes a line current of 5 amp, when secondary Load of 0.8 Lagging p.f. is connected. Determine each coil-current and output of transformer.* **(Amravati Univ. 1999)**

Solution. Due to delta/star connections the voltage ratings of the two sides on per phase basis are :

Primary coil rating = 11,000 V, Secondary coil rating $= \dfrac{440}{\sqrt{3}} = 254$ volts

Primary coil-current $= 5/\sqrt{3} = 2.887$ amp

Each coil is delivering equal volt. amps.

Since three phase volt – amps $= 3 \times 11,000 \times 5/\sqrt{3}$

$= 95266$

Volts amps/phase $= 31755$

This corresponds to the secondary coil-current of I_2, given by

$$I_2 = \frac{31755}{254} = 125 \text{ amp. This is shown in Fig. 33.10.}$$

Total Output of transformer, in kVA = 31,755

Since, the p.f. given is 0.8 lagging.

The total output power in kW $= 31{,}755 \times 0.80 =$ **25.4 kW**

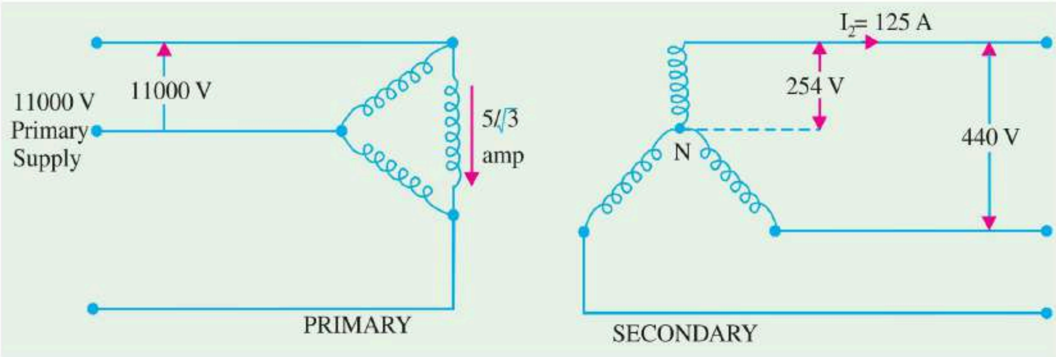


Fig. 33.10. Transformer coil currents

Example 33.11. *A load of 1000 kVA at 0.866 p.f. lagging is supplied by two 3 phase transformers of 800 kVA capacity operating in parallel. Ratio of transformation is same : 6600/400 V, delta/star. If the equivalent impedances referred to secondary are (0.005 + j.015) ohm and (0.012 + j 0.030) ohm per phase respectively. Calculate load and power factor of each transformer.*

(Amravati Univ. 1999)

Solution. Total load $= 1000$ kVA

$\cos\phi = 0.866$ Lag, $\phi = 30°$ lag

Total power output $= 866$ kW

Secondary current with star connection,

$$I_2 = \frac{1000}{\sqrt{3} \times 440} \times 1000 = \mathbf{1312.2\ amp}$$

If the two transformers are identified as *A* and *B*, with their parameters with subscripts of *a* and *b*, we have :

$$\dot{\mathbf{Z}}_a = 0.005 + j\,0.015 = 0.0158 \angle 71.56° \text{ ohm}$$

$$\dot{\mathbf{Z}}_b = 0.012 + j\,0.030 = 0.0323 \angle 68.2° \text{ ohm}$$

$$\dot{\mathbf{Z}}_a + \dot{\mathbf{Z}}_b = 0.017 + j0.045 = 0.0481 \angle 69.3° \text{ ohm}$$

$\dot{\mathbf{I}}_{2a}$ = secondary current of transformer *A*

$\dot{\mathbf{I}}_{2b}$ = secondary current of transformer *B*

$$\dot{\mathbf{I}}_{2a} = \frac{\dot{\mathbf{Z}}_b}{\dot{\mathbf{Z}}_b + \dot{\mathbf{Z}}_a} \times \dot{\mathbf{I}}_2 = \frac{0.0323 \angle 68.2°}{0.0481 \angle 69.3°} \times 1312 \angle -30°$$

$$= 88.1 \angle -31.1°$$

$$\dot{\mathbf{I}}_{2b} = \frac{\dot{\mathbf{Z}}_a}{\dot{\mathbf{Z}}_a + \dot{\mathbf{Z}}_b} \times \dot{\mathbf{I}}_2 = \frac{0.0158 \angle 71.56°}{0.0481 \angle 69.3°} \times 1312 \angle -30°$$

$$= 43.1 \angle -27.74°$$

For Transformer *A*

Load $= 3 \times 254 \times 881 \times 10^{-3} = 671.3$ kVA

Power factor = cos 31.1° lag = 0.856 lag

For Transformer *B*

Load = $3 \times 254 \times 431 \times 10^{-3} = 328.4$ kVA

Power factor = cos 23.74° lag = 0.885 lag

Check : Total kW gives a check.

1000 kVA at 0.866 lag means 866 kW.

Output, in kW, of transformer A = 671.3×0.856 = **574.6 kW**

Output in kW of transformer B = 328.4×0.885 = **290.6 kW**

Sum of these two outputs = 574.6 + 290.6 = **865.2 kW**

Note. Total kVAR also gives a check.

Depending on leading or lagging p.f., appropriate sign (+ *ve* or − *ve*) must be assigned to the kVAR-term.

Tutorial Problem No. 33.1

1. A 3-phase, star-connected alternator generates 6,360 V per phase and supplies 500 kW at a p.f. 0.9 lagging to a load through a step-down transformer of turns 40 : 1. The transformer is delta connected on the primary side and star-connected on the secondary side. Calculate the value of the line volts at the load. Calculate also the currents in (*a*) alternator windings (*b*) transformer primary windings (*c*) transformen secondary windings. **[476 V (*a*) 29.1 A (*b*) 16.8 A (*c*) 672 A]**

2. A 11,000/6,600 V, 3-ϕ, transformer has a star-connected primary and a delta-connected secondary. It supplies a 6.6 kV motor having a star-connected stator, developing 969.8 kW at a power factor of 0.9 lagging and an efficiency of 92 per cent. Calculate (*i*) motor line and phase currents (*ii*) transformer secondary current and (*iii*) transformer primary current.

[(*a*) Motor ; $I_L = I_{ph}$ = 126.3 A (*b*) phase current 73 A (*c*) 75.8 A]

33.7. Open-Delta or $V - V$ connection

If one of the transformers of a $\Delta - \Delta$ is removed and 3-phase supply is connected to the primaries as shown in Fig. 33.11, then three equal 3-phase voltages will be available at the secondary terminals on no-load. This method of transforming 3-phase power by means of only two transformers is called the open − Δ or $V - V$ connection.

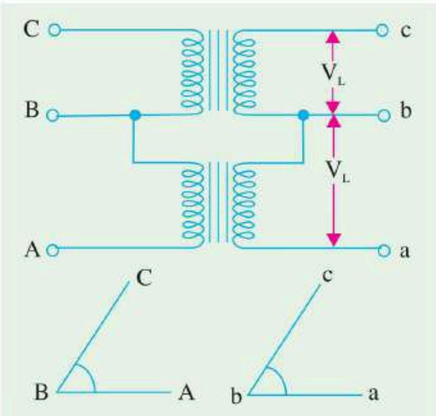


Fig. 33.11

It is employed :

1. when the three-phase load is too small to warrant the installation of full three-phase transformer bank.

2. when one of the transformers in a $\Delta - \Delta$ bank is disabled, so that service is continued although at reduced capacity, till the faulty transformer is repaired or a new one is substituted.

3. when it is anticipated that in future the load will increase necessitating the closing of open delta.

One important point to note is that the total load that can be carried by a $V - V$ bank is *not* two-third of the capacity of a $\Delta - \Delta$ bank but it is only 57.7% of it. That is a reduction of 15% (strictly, 15.5%) from its normal rating. Suppose there is $\Delta - \Delta$ bank of three 10-kVA transformers. When one transformer is removed, then it runs in $V - V$. The total rating of the two transformers is 20 kVA. But the capacity of the $V - V$ bank is not the sum of the transformer kVA ratings but only 0.866 of it *i.e.* $20 \times 0.866 = 17.32$ (or $30 \times 0.57 = 17.3$ kVA). The fact that the ratio of V-capacity to Δ-capacity is $1/\sqrt{3}$ = 57.7% (or nearly 58%) instead of $66\frac{2}{3}$ per cent can be proved as follows :

As seen from Fig. 33.12 (*a*)

$$\Delta - \Delta \text{ capacity} = \sqrt{3} \cdot V_L \cdot I_L = \sqrt{3} \cdot V_L (\sqrt{3} \cdot I_S) = 3V_L I_S$$

In Fig. 33.12 (*b*), it is obvious that when $\Delta - \Delta$ bank becomes $V - V$ bank, the secondary line current I_L becomes equal to the secondary phase current I_S.

$$\therefore \quad V - V \text{ capacity} = \sqrt{3} \cdot V_L I_L = \sqrt{3}\, V_L \cdot I_S$$

$$\therefore \quad \frac{V - V \text{ capacity}}{\Delta - \Delta \text{ capacity}} = \frac{\sqrt{3} \cdot V_L I_S}{3 V_L I_S} = \frac{1}{\sqrt{3}} = 0.577 \text{ or } 58 \text{ per cent}$$

It means that the 3-phase load which can be carried ***without exceeding the ratings*** of the transformers is 57.7 per cent of the original load rather than the expected 66.7%.

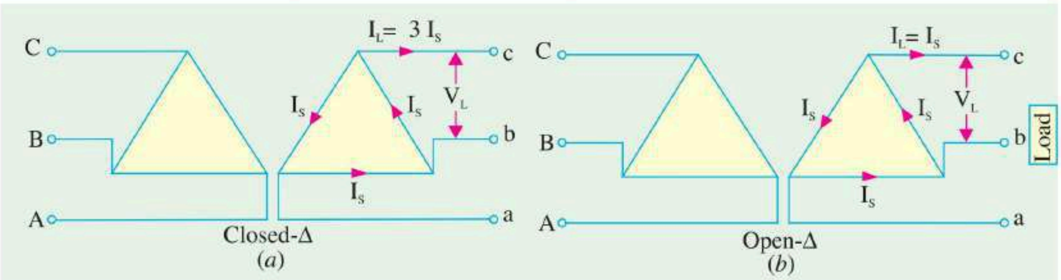


Fig. 33.12

It is obvious from above that when one transformer is removed from a $\Delta - \Delta$ bank.

1. the bank capacity is reduced from 30 kVA to $30 \times 0.577 = 17.3$ kVA and not to 20 kVA as might be thought off-hand.
2. only 86.6% of the rated capacity of the two remaining transformers is available (*i.e.* $20 \times 0.866 = 17.3$ kVA). In other words, ratio of *operating* capacity to *available* capacity of an open-Δ is 0.866. This factor of 0.866 is sometimes called the ***utility factor***.
3. each transformer will supply 57.7% of load and not 50% when operating in $V - V$ (Ex. 33.13).

However, it is worth noting that if three transformers in a $\Delta - \Delta$ bank are delivering their *rated load** and one transformer is removed, the overload on *each* of the two remaining transformers is 73.2% because

$$\frac{\text{total load in } V - V}{VA/\text{transformer}} = \frac{\sqrt{3} \cdot V_L I_S}{V_L I_S} = \sqrt{3} = 1.732$$

This over-load may be carried temporarily but some provision must be made to reduce the load if overheating and consequent breakdown of the remaining two transformers is to be avoided.

The disadvantages of this connection are :

1. The average power factor at which the *V*-bank operates is less than that of the load. ***This power factor is actually 86.6% of the balanced load power factor.*** Another significant point to note is that, except for a balanced unity power factor load, the two transformers in the $V - V$ bank operate at different power factors (Art. 33.8).

2. Secondary terminal voltages tend to become unbalanced to a great extent when the load is increased, this happens even when the load is perfectly balanced.

It may, however, be noted that if two transformers are operating in $V - V$ and loaded to rated capacity (in the above example, to 17.3 kVA), the addition of a third transformer increases the total capacity by $\sqrt{3}$ or 173.2% (*i.e.* to 30 kVA). It means that for an increase in cost of 50% for the third transformer, the increase in capacity is 73.2% when converting from a $V - V$ system to a $\Delta - \Delta$ system.

* In Ex. 33.13, the three transformers are not supplying their rated load of $20 \times 3 = 60$ kVA but only 40 kVA.

33.8. Power Supplied by $V - V$ Bank

When a $V - V$ bank of two transformers supplies a balanced 3-phase load of power factor $\cos \phi$, then one transformer operates at a p.f. of $\cos(30° - \phi)$ and the other at $\cos(30° + \phi)$. Consequently, the two transformers will not have the same voltage regulation.

$\therefore \quad P_1 = \text{kVA} \cos(30° - \phi)$ and $P_2 = \text{kVA} \cos(30° + \phi)$

(i) When $\phi = 0$ *i.e.* load p.f. = 1

Each transformer will have a p.f. = $\cos 30° = 0.866$

(ii) When $\phi = 30°$ *i.e.* load p.f. = 0.866.

In this case, one transformer has a p.f. of $\cos(30° - 30°) = 1$ and the other of $\cos(30° + 30°) = 0.866$.

(iii) When $\phi = 60°$ *i.e.* load p.f. = 0.5

In this case, one transformer will have a p.f. = $\cos(30 - 60°) = \cos(-30°) = 0.866$ and the other of $\cos(30° + 60°) = 0$. It means that one of the transformers will not supply any load whereas the other having a p.f. = 0.866 will supply the entire load.

Example 33.12. *What should be the kVA rating of each transformer in a V – V bank when the 3-phase balanced load is 40 kVA ? If a third similar transformer is connected for operation, what is the rated capacity ? What percentage increase in rating is affected in this way ?*

Solution. As pointed out earlier, the kVA rating of each transformer has to be 15% greater.

$\therefore$ kVA/trasformer $= (40/2) \times 1.15 = \mathbf{23}$

$\Delta - \Delta$ bank rating $= 23 \times 3 = 69$; Increase $= [(69 - 40)/40] \times 100 = \mathbf{72.5\%}$

Example 33.13. *A Δ – Δ bank consisting of three 20-kVA, 2300/230-V transformers supplies a load of 40 kVA. If one transformer is removed, find for the resulting V – V connection*

(i) *kVA load carried by each transformer*
(ii) *per cent of rated load carried by each transformer*
(iii) *total kVA rating of the V-V bank*
(iv) *ratio of the V-V bank to Δ – Δ bank transformer ratings.*
(v) *per cent increase in load on each transformer when bank is converted into V-V bank.*

Solution. *(i)* As explained earlier in Art. 33.7, $\dfrac{\text{total kVA load in } V - V \text{ bank}}{VA/\text{transformer}} = \sqrt{3}$

$\therefore$ kVA load supplied by *each* of the two transformers $= 40/\sqrt{3} = \mathbf{23.1\ kVA}$

Obviously, each transformer in V - V bank does not carry 50% of the original load but 57.7%.

(ii) per cent of rated load $= \dfrac{\text{kVA load/transformer}}{\text{kVA rating/transformer}} = \dfrac{23.1}{20} = \mathbf{115.5\ \%}$

carried by each transformer.

Obviously, in this case, each transformer is overloaded to the extent of 15.5 per cent.*

(iii) kVA *rating* of the V - V bank $= (2 \times 20) \times 0.866 = \mathbf{34.64\ kVA}$

(iv) $\dfrac{V - V \text{ rating}}{\Delta - \Delta \text{ rating}} = \dfrac{34.64}{60} = 0.577$ or **57.7%**

---

* Overloading becomes 73.2% only when full rated load is supplied by the $\Delta - \Delta$ bank (*i.e.* $3 \times 20 = 60$ kVA in this case) before it becomes $V - V$ bank.

As seen, the rating is reduced to 57.7% of the original rating.

(*v*) Load supplied by each transformer in $\Delta - \Delta$ bank = 40/3 = 13.33 kVA

∴ Percentage increase in load supplied by each transformer

$$= \frac{\text{kVA load/transformer in } V - V \text{ bank}}{\text{kVA load/transformer in } \Delta - \Delta \text{ bank}} = \frac{23.1}{13.3} = 1.732 = \mathbf{173.2\ \%}$$

It is obvious that each transformer in the $\Delta - \Delta$ bank supplying 40 kVA was running underloaded (13.33 *vs* 20 kVA) but runs overloaded (23.1 *vs* 20 kVA) in $V - V$ connection.

Example 33.14. *A balanced 3-phase load of 150 kW at 1000 V, 0.866 lagging power factor is supplied from 2000 V, 3-phase mains through single-phase transformers (assumed to be ideal) connected in (i) delta-delta (ii) Vee-Vee. Find the current in the windings of each transformer and the power factor at which they operate in each case. Explain your calculations with circuit and vector diagrams.*

Solution. (*i*) Delta-Delta Connection

$$\sqrt{3}\ V_L I_L \cos\phi = 150{,}000$$

$$\sqrt{3} \times 1000 \times I_L \times 0.866 = 150{,}000 \therefore I_L = 100 \text{ A}$$

∴ Secondary line current = 100 A; secondary phase current = $100/\sqrt{3}$ = **57.7 A**

Transformation ratio = 1000/2000 = 1/2

∴ Primary phase current = 57.7/2 = **28.85 A**

(*ii*) Vee-Vee Connection

Let I be the secondary line current which is also the phase current in $V - V$ connection. Then

$$\sqrt{3} \times 1000 \times I \times 0.866 = 150{,}000 \quad \therefore \quad I = 100 \text{ A}$$

∴ Secondary phase current = **100 A**; primary phase current = 100 × 1/2 = **50 A**

Transformer power factor = 86.6 per cent of 0.866 = **0.75 (lag).**

Example 33.15. (*a*) *Two identical 1-phase transformers are connected in open-delta across 3-phase mains and deliver a balanced load of 3000 kW at 11 kV and 0.8 p.f. lagging. Calculate the line and phase currents and the power factors at which the two transformers are working.*

(*b*) *If one more identical unit is added and the open delta is converted to closed delta, calculate the additional load of the same power factor that can now be supplied for the same temperature rise. Also calculate the phase and line currents.* **(Elect. Machinery-I, Madras Univ. 1987)**

Solution. (*a*) If I is the line current, then

$$\sqrt{3} \times 11{,}000 \times I \times 0.8 = 3{,}000{,}000 \qquad \mathbf{I = 197\ A}$$

Since, this also represents the phase current,

∴ Secondary phase current = **197 A**; Transformer p.f. = 86.6 per cent of 0.8 = **0.693**

(*b*) Additional load = 72.5 per cent of 3000 = **2175 kW**

Total load = 3000 + 2175 = 5175 kW

Now, $\sqrt{3} \times V_L I_L \cos\phi$ = 5,175,000 or $\sqrt{3} \times 11{,}000 \times I_L \times 0.8$ = 5,175,000

∴ I_L = **340 A;** phase current = $340/\sqrt{3}$ = **196 A**

Example 33.16. *Two transformers connected in open delta supply a 400-kVA balanced load operating at 0.866 p.f. (lag). The load voltage is 440 V. What is the (a) kVA supplied by each transformer ? (b) kW supplied by each transformer ?* **(Elect. Machines-I, Gwalior Univ. 1991)**

Solution. As stated in Art 33.7, the ratio of operating capacity to available capacity in an open-Δ is 0.866. Hence, kVA of each transformer is one-half of the total kVA load divided by 0.866.

(*a*) kVA of each transformer $= \dfrac{(400/2)}{0.866} =$ **231 kVA**

(*b*) As stated in Art 33.8, the two transformers have power factors of cos (30° − φ) and cos (30° + φ).

$\therefore \quad P_1 = \text{kVA} \cos(30° - \phi) \text{ and } P_2 = \text{kVA}\cos(30 + \phi)$

Now, load p.f. $= \cos\phi = 0.866; \quad \phi = \cos^{-1}(0.866) = 30°$

$\therefore \quad P_1 = 231 \times \cos 0° =$ **231 kW**; $P_2 = 231 \times \cos 60° =$ **115.5 kW**

Obviously, $P_1 + P_2$ must equal $400 \times 0.86 = 346.5$ kW

Tutorial Problem No. 33.2

1. Three 1100/110-V transformers connected delta-delta supply a lighting load of 100 kW. One of the transformers is damaged and removed for repairs. Find

(*a*) What currents were flowing in each transformer when the three transformers were in service ?

(*b*) What current flows in each transformer when the third is removed ? and

(*c*) The output kVA of each transformer if the transformers connected in open Δ supply the full-load with normal heating ?

[(*a*) primary = 30.3 A; secondary 303 A (*b*) primary = 30.3 $\sqrt{3}$A ; secondary = 303$\sqrt{3}$A (*c*) 33.33 kVA] ***(Elect. Machines-I, Gwalior Univ. Apr. 1977)***

33.9. Scott Connection or *T* - *T* Connection

This is a connection by which 3-phase to 3-phase transformation is accomplished with the help of two transformers as shown in Fig. 33.13. Since it was first proposed by Charles *F*. Scott, it is frequently referred to as Scott connection. This connection can also be used for 3-phase to 2-phase transformation as explained in Art. 33.10.

One of the transformers has centre taps both on the primary and secondary windings (Fig. 33.13) and is known as the ***main*** transformer. It forms the horizontal member of the connection (Fig. 33.14).

The other transformer has a 0.866 tap and is known as ***teaser*** transformer. One end of both the primary and secondary of the teaser transformer is joined to the centre taps on both primary and secondary of the main transformer respectively as shown in Fig. 33.14 (*a*). The other end *A* of the teaser primary and the two ends *B* and *C* of the main transformer primary are connected to the 3-phase supply.

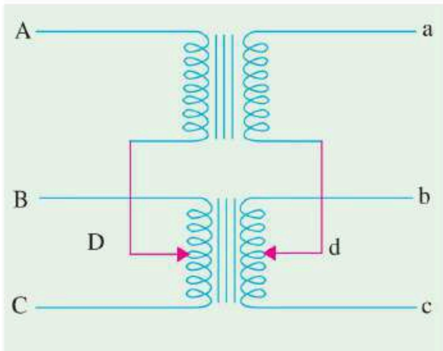


Fig. 33.13

The voltage diagram is shown in Fig. 33.14 (*a*) where the 3-phase supply line voltage is assumed to be 100 V and a transformation ratio of unity. For understanding as to how 3-phase transformation results from this arrangement, it is desirable to think of the primary and secondary vector voltages as forming geometrical T_S' (from which this connection gets its name).

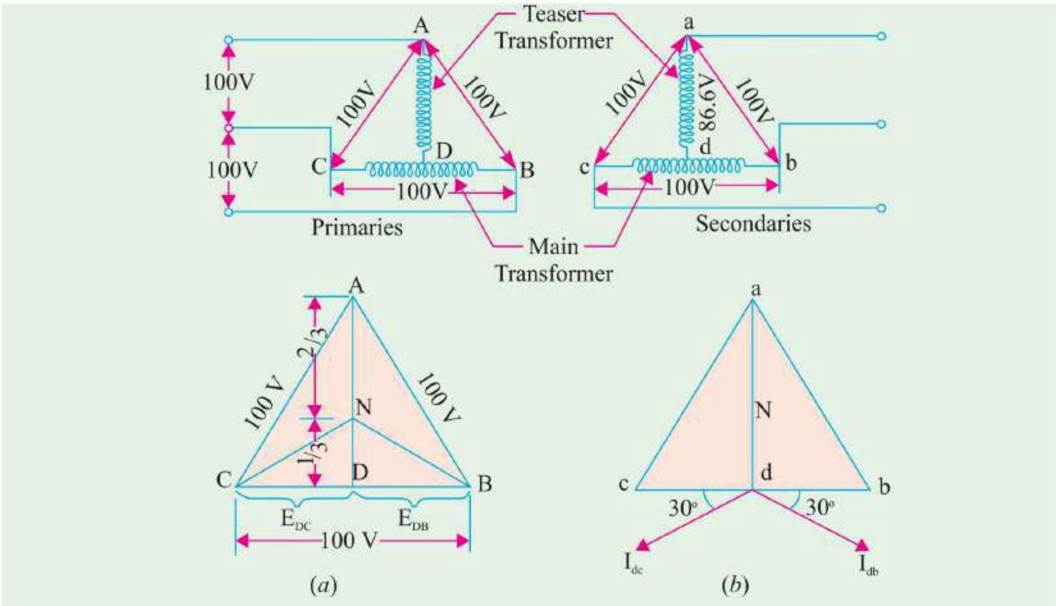


Fig. 33.14

In the primary voltage T of Fig. 33.14 (a), E_{DC} and E_{DB} are each 50 V and differ in phase by 180°, because both coils DB and DC are on the same magnetic circuit and are connected in opposition. Each side of the equilateral triangle represents 100 V. The voltage E_{DA} being the altitude of the equilateral triangle is equal to $(\sqrt{3}/2) \times 100 = 86.6$ V and lags behind the voltage across the main by 90°. The same relation holds good in the secondary winding so that abc is a symmetrical 3-phase system.

With reference to the secondary voltage triangle of Fig. 33.14 (b), it should be noted that for a load of unity power factor, current I_{db} lags behind voltage E_{db} by 30° and I_{dc} leads E_{dc} by 30°. In other words, the teaser transformer and each half of the main transformer, all operate at different power factors.

Obviously, the full rating of the transformers is not being utilized. The teaser transformer operates at only 0.866 of its rated voltage and the main transformer coils operate at cos 30° = 0.866 power factor, which is equivalent to the main transformer's coils working at 86.6 per cent of their kVA rating. Hence the capacity to rating ratio in a T–T. connection is 86.6% — the same as in $V - V$ connection if two identical units are used, although heating in the two cases is not the same.

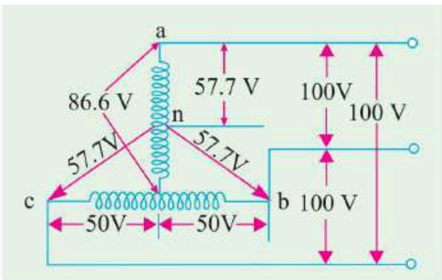


Fig. 33.15

If, however, both the teaser primary and secondary windings are designed for 86.6 volts only, then they will be operating at full rating, hence the combined rating of the arrangement would become $(86.6 + 86.6)/(100 + 86.6) = 0.928$ of its total rating.* In other words, ratio of kVA utilized to that available would be 0.928 which makes this connection more economical than open-Δ with its ratio of 0.866.

* Alternatively, VA capacity available is $= V_L I_L + (0.866\ V_L) I_L = 1.866\ V_L I_L$ where I_L is the primary line current. Since 3-phase power is supplied, volt-amperes actually utilized $= 1.732\ V_L I_L$. Hence, ratio of kVA actually utilized to those available is $= 1.732\ V_L I_L / 1.866\ V_L I_L = 0.928$.

Fig. 33.15 shows the secondary of the $T-T$ connection with its different voltages based on a nominal voltage of 100 V. As seen, the neutral point *n* is one third way up from point *d*. If secondary voltage and current vector diagram is drawn for load power factor of unity, it will be found that

1. current in teaser transformer is in phase with the voltage.
2. in the main transformer, current leads the voltage by 30° across one half but lags the voltage by 30° across the other half as shown in Fig. 33.14 (*b*).

Hence, when a balanced load of p.f. = cos ϕ, is applied, the teaser current will lag or lead the voltage by Φ while in the two halves of the main transformer, the angle between current and voltage will be $(30° - \Phi)$ and $(30° + \Phi)$. The situation is similar to that existing in a $V-V$ connection.

Example 33.17. *Two T-connected transformers are used to supply a 440-V, 33-kVA balanced load from a balanced 3-phase supply of 3300 V. Calculate (a) voltage and current rating of each coil (b) kVA rating of the main and teaser transformer.*

Solution. (*a*) Voltage across main primary is 3300 V whereas that across teaser primary is $= 0.866 \times 3300 = 2858$ V.

The current is the same in the teaser and the main and equals the line current.

$\therefore \quad I_{LP} = 33,000/\sqrt{3} \times 3300 = 5.77$ A —Fig. 33.16

The secondary main voltage equals the line voltage of 440 V whereas teaser secondary voltage $= 0.866 \times 440 = 381$ V.

The secondary line current, $I_{LS} = I_{LP}/k = 5.77/(440/3300) = 43.3$ A as shown in Fig. 33.16.

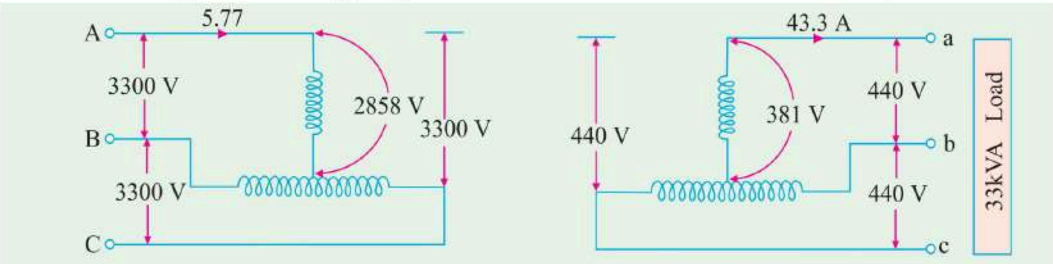


Fig. 33.16

(*b*) Main kVA $= 3300 \times 5.77 \times 10^{-3} =$ **19 kVA**

Teaser kVA $= 0.866 \times$ main kVA $= 0.866 \times 19 =$ **16.4 kVA**

33.10. Three-phase to Two-phase Conversion and *vice-versa*

This conversion is required to supply two-phase furnaces, to link two-phase circuit with 3-phase system and also to supply a 3-phase apparatus from a 2-phase supply source. For this purpose, Scott connection as shown in Fig. 33.17 is employed. This connection requires two transformers of different ratings although for interchangeability and provision of spares, both transformers may be identical but having suitable tappings.

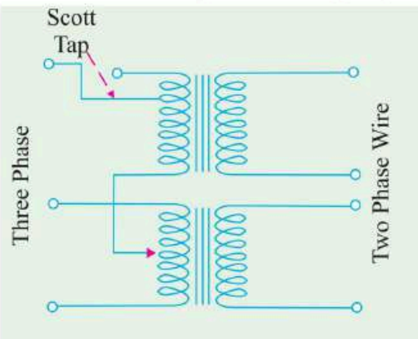


Fig. 33.17

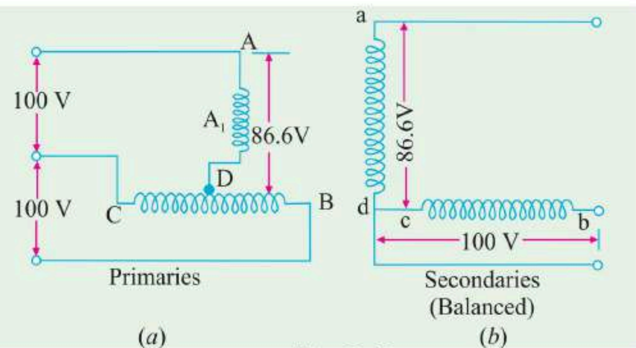


Fig. 33.18

If, in the secondaries of Fig. 33.14 (*b*), points *c* and *d* are connected as shown in Fig. 33.18 (*b*), then a 2-phase, 3-wire system is obtained. The voltage E_{dc} *is 86.6 V but* E_{Cb} = 100 V, hence the

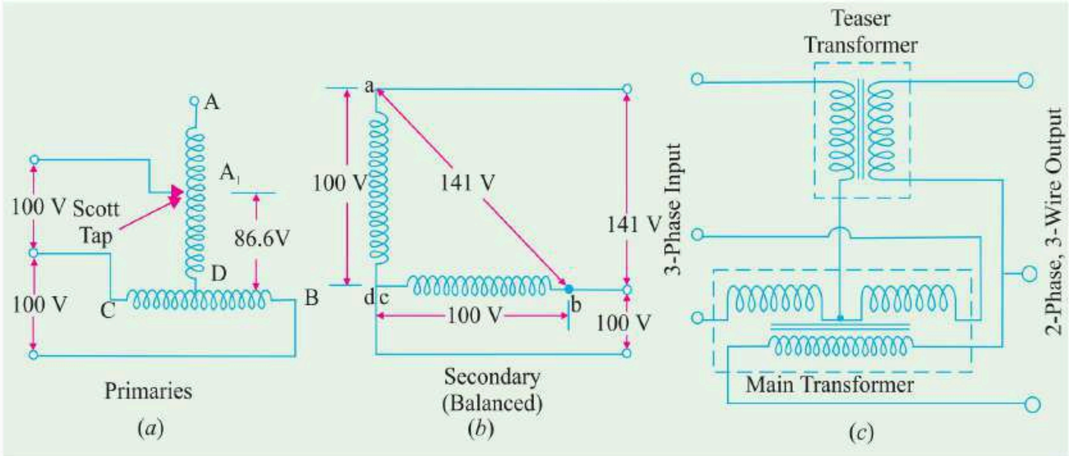


Fig. 33.19

resulting 2-phase voltages will be unequal. However, as shown in Fig. 33.19 (*a*) if the 3-phase line is connected to point A_1, such that DA_1 represents 86.6% of the teaser primary turns (which are the same as that of main primary), then this will increase the volts/turn in the ratio of 100 : 86.6, because now 86.6 volts are applied across 86.6 per cent of turns and not 100% turns. In other words, this will make volts/turn the same both in primary of the teaser and that of the main transformer. If the secondaries of both the transformers have the same number of turns, then secondary voltage will be equal in magnitude as shown, thus resulting in a symmetrical 2-phase, 3-wire system.

Consider the same connection drawn slightly differently as in Fig. 33.20. The primary of the main transformer having N_1 turns is connected between terminals *CB* of a 3-phase supply. If supply line voltage is *V*, then obviously $V_{AB} = V_{BC} = V_{CA} = V$ but voltage between *A* and *D* is $V \times \sqrt{3}/2$. As said

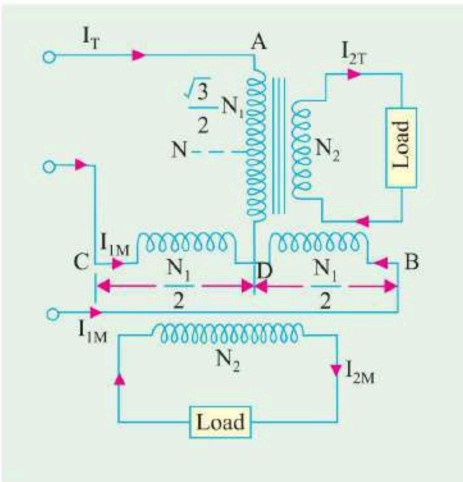


Fig. 33.20

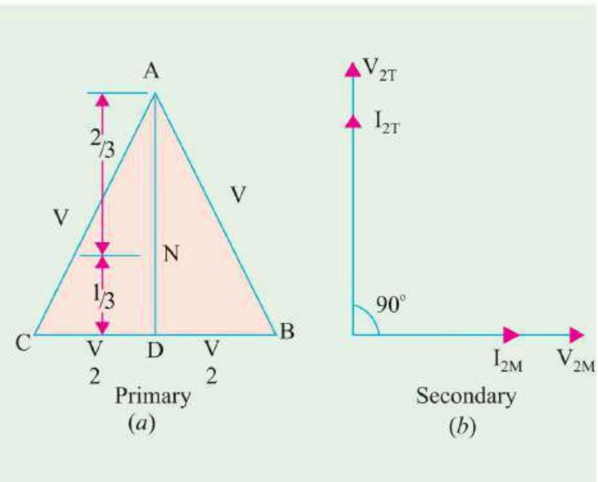


Fig. 33.21

above, the number of turns between *A* and *D* should be also $(\sqrt{3}/2)\ N_1$ for making volt/turn the same in both primaries. If so, then for secondaries having equal turns, the secondary terminal voltages will be equal in magnitude although in phase quadrature.

It is to be noted that point D is not the neutral point of the primary supply because its voltage with respect to any line is not $V/\sqrt{3}$. Let N be the neutral point. Its position can be determined as follows. Voltage of N with respect to A must be $V/\sqrt{3}$ and since D to A voltage is $V \times \sqrt{3}/2$, hence N will be $(\sqrt{3}V/2 - V/\sqrt{3})$ = 0.288 V or 0.29 V from D. Hence, N is above D by a number of turns equal to 29% of N_1. Since 0.288 is one-third of 0.866, hence N divides the teaser winding AD in the ratio 2 : 1.

Let the teaser secondary supply a current I_{2T} at unity power factor. If we neglect the magnetizing current I_0, then teaser primary current is $I_{1T} = I_{2T} \times$ transformation ratio.

$\therefore \quad I_{1T} = I_{2T} \times N_2/(\sqrt{3}N_1/2) = (2/\sqrt{3}) \times (N_2/N_1) \times I_{2T} = 1.15\,(N_2/N_1)\,I_{2T} = 1.15\,KI_{2T}$ where $K = N_2/N_1$ = transformation ratio of ***main*** transformer. The current is in phase with star voltage of the primary supply (Fig. 33.21).

The total current I_{1M} in each half of the primary of the ***main*** transformer consists of two parts :

(i) One part is that which is necessary to balance the main secondary current I_{2M}. Its value is

$$= I_{2M} \times \frac{N_2}{N_1} = KI_{2M}$$

(ii) The second part is equal to one-half of the teaser primary current *i.e.* $\frac{1}{2}I_{1T}$. This is so because the main transformer primary forms a return path for the teaser primary current which divides itself into two halves at mid-point D in either direction. The value of each half is $= I_{1T}/2 = 1.15\,KI_{2T}/2 = 0.58\,KI_{2T}$.

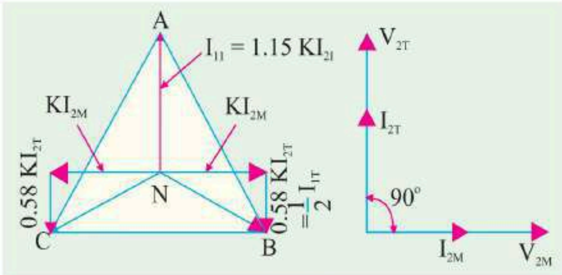


Fig. 33.22

Hence, the currents in the lines B and C are obtained vectorially as shown in Fig. 33.22. It should be noted that as the two halves of the teaser primary current flow in opposite directions from point D, they have no magnetic effect on the core and play no part at all in balancing the secondary ampere-turns of the main transformer.

The line currents thus have rectangular components of KI_{2M} and 0.58, KI_{2T} and, as shown in Fig. 33.22, are in phase with the primary star voltages V_{NB} and V_{NC} and are equal to the teaser primary current. Hence, the three-phase side is balanced when the two-phase load of unity power factor is balanced.

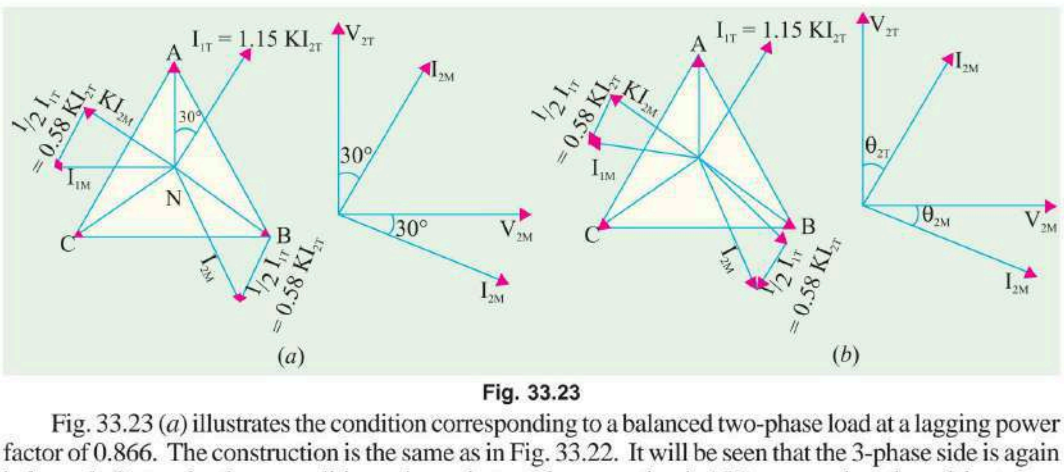


Fig. 33.23

Fig. 33.23 (*a*) illustrates the condition corresponding to a balanced two-phase load at a lagging power factor of 0.866. The construction is the same as in Fig. 33.22. It will be seen that the 3-phase side is again balanced. But under these conditions, the main transformer rating is 15% greater than that of the teaser, because its voltage is 15% greater although its current is the same.

Hence, **we conclude *that if the load is balanced on one side, it would always be balanced on the other side.***

The conditions corresponding to an unbalanced two-phase load having different currents and power factors are shown in Fig. 33.23 (*b*). The geometrical construction is similar to those explained in Fig. 33.22 and 33.23 (*a*).

Summarizing the above we have :

1. Teaser transformer primary has $\sqrt{3}/2$ times the turns of main primary. But volt/turn is the same. Their secondaries have the same turns which results in equal secondary terminal voltages.

2. If main primary has N_1 turns and main secondary has N_2 turns, then main transformation ratio is N_2/N_1. However, the transformation ratio of teaser is

$$N_2/(\sqrt{3}N_1/2) = 1.15\ N_2/N_1 = 1.15\ K$$

3. If the load is balanced on one side, it is balanced on the other side as well.

4. Under balanced load conditions, main transformer rating is 15% greater than that of the teaser.

5. The currents in either of the two halves of main primary are the vector sum of KI_{2M} and 0.58 KI_{2T} (or $\frac{1}{2}I_{1T}$).

Example 33.18. *Two transformers are required for a Scott connection operating from a 440-V, 3-phase supply for supplying two single-phase furnaces at 200 V on the two-phase side. If the total output is 150 kVA, calculate the secondary to primary turn ratio and the winding currents of each transformer.*

Solution. Main Transformer

Primary volts $= 440$ V ; secondary volts = 200 V $\therefore \dfrac{N_2}{N_1} = \dfrac{200}{440} = \dfrac{1}{2.2}$

Secondary current $= 150{,}000/2 \times 200 =$ **375 A**

$\therefore$ Primary current $= 375 \times 1/_{2.2} =$ **197 A**

Teaser Transformer

Primary volts $= (\sqrt{3}/2 \times 440) = 381$ V : Secondary volts = 200 V

$$\frac{\text{secondary turns}}{\text{primary turns}} = \frac{200}{381} = \frac{1}{1.905} \text{ (also teaser ratio} = 1.15 \times 1/2.2 = 1/1.905)$$

Example 33.19. *Two single-phase furnaces working at 100 V are connected to 3300-V, 3-phase mains through Scott-connected transformers. Calculate the current in each line of the 3-phase mains when the power taken by each furnace is 400-kW at a power factor of 0.8 lagging. Neglect losses in the transformers.* **(Elect. Machines-III, South Gujarat Univ. 1988)**

Solution. Here $K = 100/3{,}300 = 1/33$ (main transformer)

$$I_2 = \frac{400{,}000}{0.8 \times 100} = 5{,}000\text{A (Fig. 33.24); Here } I_{2T} = I_{2M} = I_2 = 5{,}000 \text{ A}$$

As the two-phase load is balanced, the 3-phase side is also balanced.

Primary phase currents are $= 1.15\ KI_2 = 1.15 \times (1/33) \times 5{,}000 = 174.3$ A

Since for a star-connection, phase current is equal to line current,

$\therefore$ Line current = **174.3 A**

Note. We have made use of the fact that since secondary load is balanced, primary load is also balanced. If necessary, I_{1M} can also be found.

I_{1M} is the vector sum of (*i*) KI_{2M} and (*ii*) $\frac{1}{2}\,I_{1T}$ or 0.58 KI_{2T}.

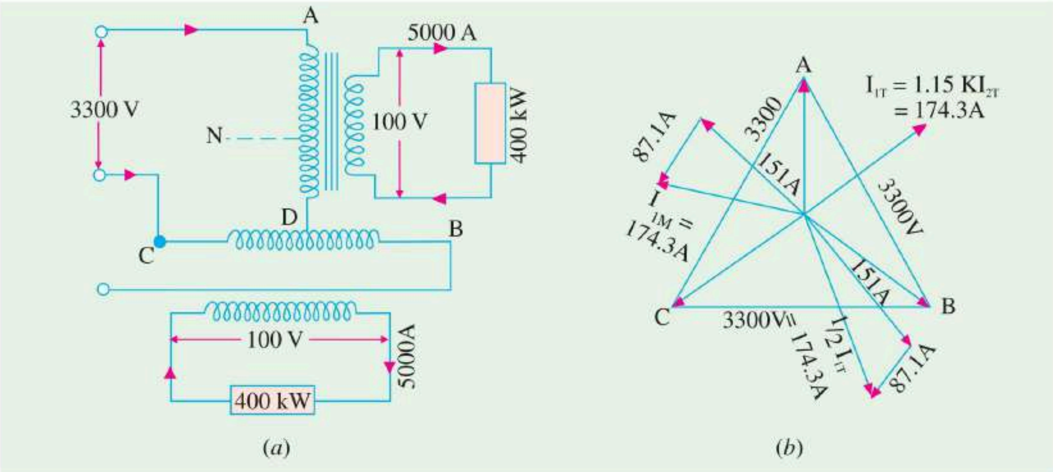


Fig. 33.24

Now, KI_{2M} = (1/33) × 5,000 = 151 A and 0.58 $KI_2 = \frac{1}{2}\,I_{1T}$ = 174.3/2 = 87.1 A

∴ $I_{1M} = \sqrt{151^2 + 87.1^2}$ = **174.3 A**

Example 33.20. *In a Scott-connection, calculate the values of line currents on the 3-phase side if the loads on the 2-phase side are 300 kW and 450 kW both at 100 V and 0.707 p.f. (lag) and the 3-phase line voltage is 3,300 V. The 300-kW load is on the leading phase on the 2-phase side. Neglect transformer losses.* **(Elect. Technology, Allahabad Univ. 1991)**

Solution. Connections are shown in Fig. 33.25 (*a*) and phasor diagram in Fig. 33.25 (*b*).

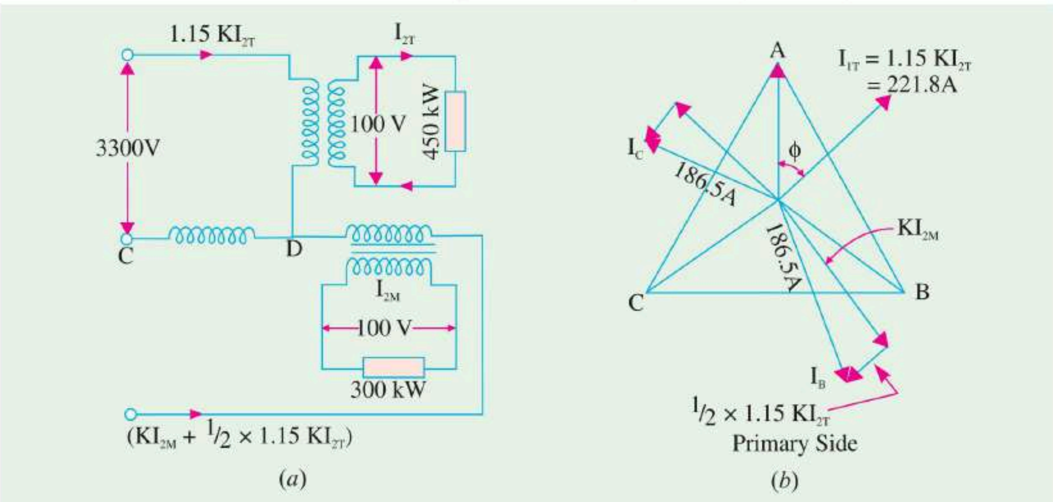


Fig. 33.25

Here, K = 100/3,300 = 1/33

Teaser secondary current is I_{2T} = 450,000/100 × 0.707 = 6360 A

Teaser primary current is I_{1T} = 1.15 KI_{2T} = 1.5 × (1/33) × 6360 = 221.8 A

As shown in Fig. 33.25 (*b*), main primary current I_{1M} has two rectangular components.

(*i*) KI_{2M} where I_{2M} is the secondary current of the main transformer and

(*ii*) Half of the teaser primary current $\frac{1}{2}I_{1T} = \frac{1}{2}\times 1.15\ KI_{2T} = 0.577\ KI_{2T}$

Now $KI_{2M} = \frac{1}{33}\times\frac{300,000}{100\times 0.707} = 128.58$ A ; Also $\frac{1}{2}I_{1T} = \frac{1}{2}\times 221.8 = 110.9$A

Main Primary current $= \sqrt{128.58^2 + 110.9^2} = 169.79$A

Hence, the 3-phase line currents are **221.8 A** in one line and **169.79 A** in each of the other two.

Example 33.21. *Two electric furnaces are supplied with 1-phase current at 80 V from a 3-phase, 11,000 V system by means of two single-phase Scott-connected transformers with similar secondary windings. When the load on one furnace is 500 kW (teaser secondary) and on the other 800 kW (secondary of main transformer) what current will flow in each of the 3-phase lines (a) at unity power factor and (b) at 0.5 power factor ? Neglect phase displacement in and efficiency of, the transformers.* **(Electrical Engineering, Madras Univ. 1987)**

Solution. The connections are shown in Fig. 33.26 and the phasor diagrams for unity and 0.5 p.f. are shown in Fig. 33.27 (*a*) and (*b*) respectively.

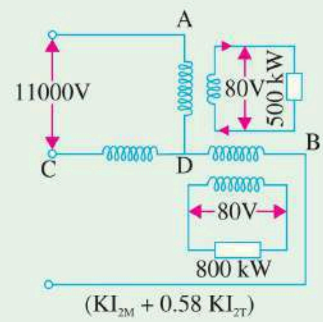


Fig. 33.26

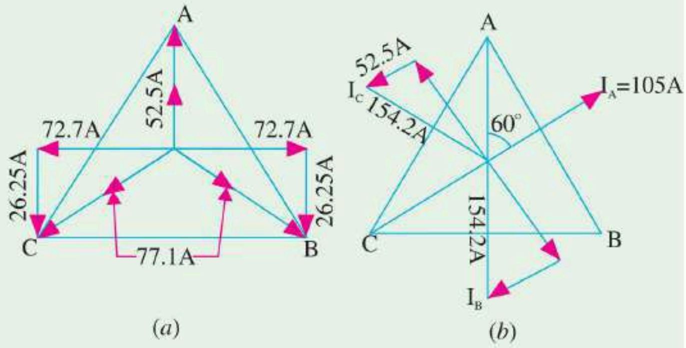


Fig. 33.27

Here, $K = 80/11,000 = 2/275$

(*a*) Unity p.f.

With reference to Fig. 33.27 (*a*), we have $I_{2T} = 500,000/80 \times 1 = 6,250$ A

Teaser primary current $I_{1T} = 1.15\ KI_{2T} = 1.15 \times (2/275) \times 6,250 = 52.5$ A

For the main transformer primary

(*i*) $KI_{2M} = \frac{2}{275}\times\frac{800,000}{80\times 1} = 72.7$ A (*ii*) $\frac{1}{2}\times I_{1T} = 52.5/2 = 26.25$ A

Current in the primary of the main transformer is $= \sqrt{72.7^2 + 26.25^2} = 77.1$ A

Hence, one 3-phase line carries **52.5 A** whereas the other 2 carry **77.1 A** each [Fig. 33.27 (*a*)].

(*b*) 0.5 p.f.

With reference to Fig. 33.27 (*b*) we have $I_{2T} = 500,000/80 \times 0.5 = 12,500$ A

Teaser primary current $I_{1T} = 1.15 \times (2/275) \times 12,500 = 105$ A

For the main transformer primary

(i) $$KI_{2M} = \frac{2}{275} \times \frac{800{,}000}{80 \times 0.5} = 145.4 \text{ A (ii) } \frac{1}{2} I_{1T} = 105/2 = 52.5 \text{ A.}$$

Current in the primary of the main transformer is $= \sqrt{145.4^2 + 52.5^2} = 154.2$ A.

Hence, one 3-phase line carries **105 A** and the other two carry **154.2 A** each.

Note : Part (*b*) need not be worked out in full because at 0.5 p.f., each component current and hence the resultant are doubled. Hence, in the second case, answers can be found by multiplying by a factor of 2 the line currents found in (*a*).

Example 33.22. *Two furnaces are supplied with 1-phase current at 50 V from a 3-phase, 4.6 kV system by means of two 1-phase, Scott-connected transformers with similar secondary windings. When the load on the main transformer is 350 kW and that on the other transformer is 200 kW at 0.8 p.f. lagging, what will be the current in each 3-phase line ? Neglect phase displacement and losses in transformers.* **(Electrical Machinery-II, Bangalore Univ. 1991)**

Solution. Connections and vector diagrams are shown in Fig. 33.28.

$$K = 50/4{,}600 = 1/92; I_{2T} = 200{,}000/50 \times 0.8 = 5{,}000 \text{ A}$$

$$I_{1T} = 1.15\, KI_{2T} = 1.1 \times (1/92) \times 5{,}000 = 62.5 \text{ A}$$

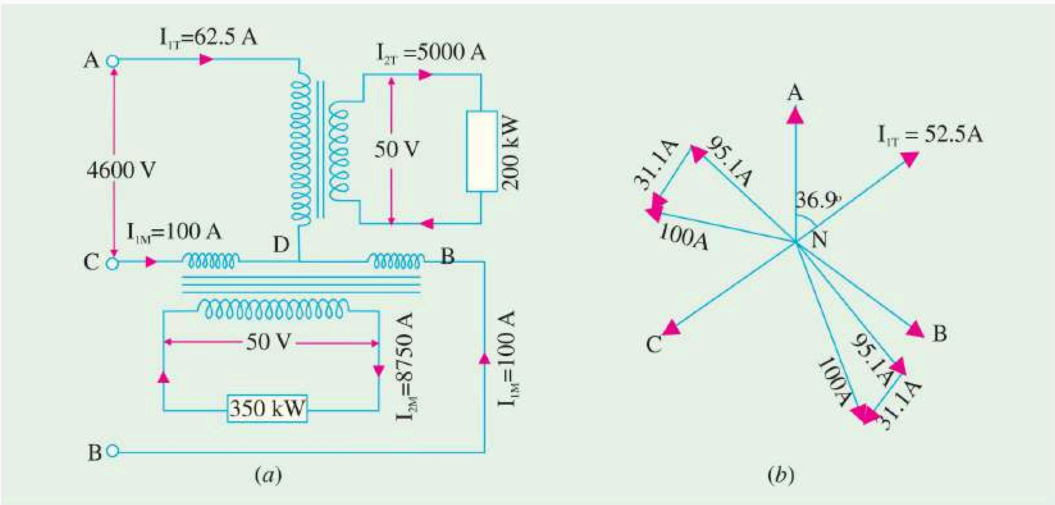


Fig. 33.28

As shown in Fig. 33.28 (*b*), main primary current I_{1M} has two rectangular components.

(i) KI_{2M} where $I_{2M} = 350{,}000/50 \times 0.8 = 8{,}750$ A $\therefore KI_{2M} = 8{,}750/92 = 95.1$ A

(ii) $(1/2)\, I_{1T} = 62.5/2 = 31.3$ A $\quad \therefore \quad I_{1M} = \sqrt{95.1^2 + 31.3^2} = 100$ A

$\therefore$ Current in line A = **62.5 A;** Current in line B = **100 A;** Current in line C = **100 A.**

Example 33.23. *Two single-phase Scott-connected transformers supply a 3-phase four-wire distribution system with 231 volts between lines and the neutral. The h.v. windings are connected to a two-phase system with a phase voltage of 6,600 V. Determine the number of turns in each section of the h.v. and l.v. winding and the position of the neutral point if the induced voltage per turn is 8 volts.*

Solution. As the volt/turn is 8 and the h.v. side voltage is 6,600 V, the h.v. side turns are = 6,600/8 = **825** on both transformers.

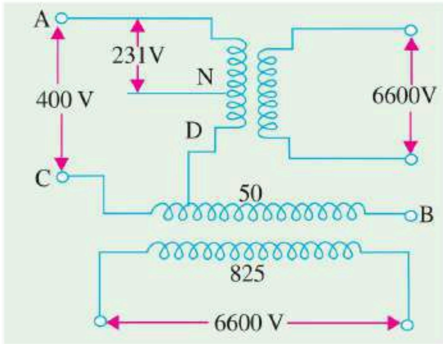


Fig. 33.29

Now, voltage across points B and C of main winding

= line voltage = $231 \times \sqrt{3} = 400$ V

No. of turns on the l.v. side of the main transformer = 400/8 = **50**

No. of turns on the l.v. side of teaser transformer = $\sqrt{(3/2)} \times$ mains turns

$= \sqrt{3} \times 50/2 =$ **43** (whole number)

The neutral point on the 3-phase side divides teaser turns in the ratio 1 : 2.

$\therefore$ Number of turns between A and $N = (2/3) \times AD$

$= (2/3) \times 43 =$ **29**

Hence, neutral point is located on the 29th turn from A downwards (Fig. 33.29).

Example 33.24. *A Scott-connected (2 to 3-phase) transformer links a 6,000 V, 2-phase system with a 440 V; 3-phase system. The frequency is 50 Hz, the gross core area is 300 cm², while the maximum flux density is to be about 1.2 Wb/m². Find the number of turns on each winding and the point to be tapped for the neutral wire on the 3-phase side. If the load is balanced on the one side of such a transformer, find whether it will also be balanced on the other side.* **(London Univ.)**

Solution. Use the transformer voltage equation 1,

$E = 4.44 fN \Phi_x$ volt

Gross core area = 300 cm^2

Assuming net iron = 0.9 of gross area, and considering the h.v. side, we have

$6000 = 4.44 \times 50 \times N_1 \times 1.2\,(300 \times 0.9 \times 10^{-4})$

$N_1 =$ **834**

Hence, h.v. sides of both transformers have 834 turns each.

Now $K = 440/6000 = 11/150$

$\therefore$ Turns on the *l*.v. side of main transformer

$N_2 = 834 \times 11/150 =$ **61**

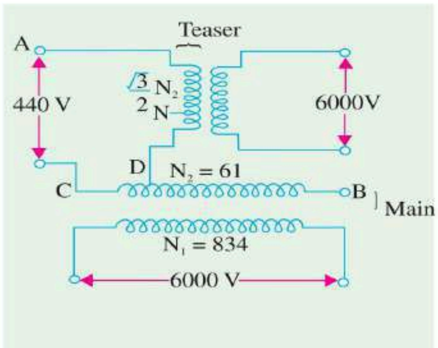


Fig. 33.30

Turns on the *l*.v. side of teaser = $(\sqrt{3}/2) \times 61 =$ **53**

With reference to Fig. 33.30, number of turns in $AN = 53 \times 2/3 =$ **35**

Example 33.25. *A 2-phase, 4-wire, 250 V system is supplied to a plant which has a 3-phase motor load of 30 kVA. Two Scott-connected transformers supply the 250 V motors. Calculate (a) voltage (b) kVA rating of each transformer. Draw the wiring connection diagram.*

Solution. *(a)* Both the main and the teaser have the same voltage rating as the supply voltage *i.e.* 250 V. The current in the main and the teaser coils is the same as the supply current and is

$$= \frac{\text{Total kVA}}{2 \times \text{Line voltage}} = \frac{30,000}{2 \times 250} = 60 \text{ A arcsin } \theta$$

On the three-phase side, current is the same in all coils and is equal to the load line current $= 30,000/\sqrt{3} \times 250 = 69.3$ A

Load voltage on main secondary = line voltage = 250 V

Load voltage on teaser secondary = $0.866 \times 250 = 216.5$ V

Hence, voltage rating of main transformer is **250/250** whereas that of teaser transformer is **250/216.5.**

The current rating of main transformer is **60/69.3** and it is the same for the teaser transformer.

(*b*) The volt-amp rating of the teaser primary as well as secondary is the same *i.e.* $60 \times 250 \times 10^{-3} = 69.3 \times 216.5 \times 10^{-3} =$ **15 kVA**

The main volt-ampere rating of secondary is = $250 \times 69.3 \times 10^{-3} =$ **17.3 kVA**

Incidentally, if two identical transformers are used for providing inter-changeability, then both must be rated at 17.3 kVA. In that case, a total capacity of 34.6 kVA would be required to provide a 30 kVA load.

The wiring connections are shown in Fig. 33.31.

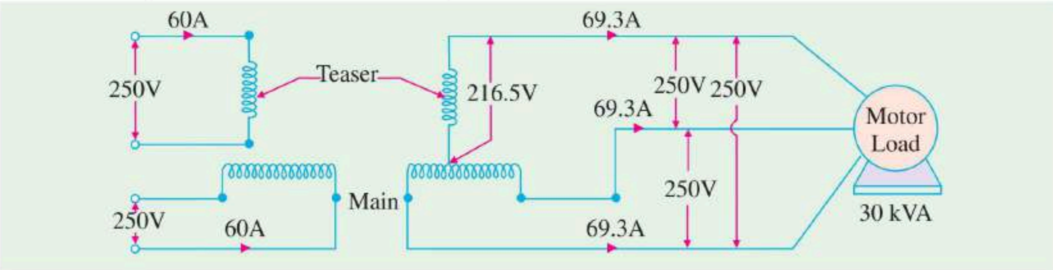


Fig. 33.31

Tutorial Problem No. 33.3

1. A Scott-connected transformer is fed from a 6,600-V, 3-phase network and supplies two single-phase furnaces at 100 V. Calculate the line currents on the 3-phase side when the furnaces take 400 kW and 700 kW respectively at 0.8 power factor lagging. **(Elect. Machines II, Indore Univ. 1977)**

[With 400 kW on teaser, line currents are 87. 2 A; 139 A; 139 A]

2. Two 220-V, 1-phase electrical furnaces take loads of 350 kW and 500 kW respectively at a power factor of 0.8 lagging. The main supply is at 11-kV, 3-phase, 50 Hz. Calculate current in the 3-phase lines which energise a Scott-connected transformer combination. **(Elect. Machines, Madras Univ. 1978)**

[With 350 kW on teaser line currents are : 45.7 A ; 61.2 A; 61.2 A]

3. Two electric furnaces are supplied with 1-phase current at 80 V from 3-phase, 11,000-V supply mains by means of two Scott-connected transformers with similar secondary windings. Calculate the current flowing kW respectively in each of the 3-phase lines at U.P.P. when the loads on the two transformers are 550 kW of 800 kW.

[With 550 kW on teaser, line currents are : 57.5 A; 78.2; 78.2 A] (Electrical Machines-I, Madras University, 1977)

33.11. Parallel Operation of 3-phase Transformers

All the conditions which apply to the parallel operation of single-phase transformers also apply to the parallel running of 3-phase transformers but with the following additions :

1. The voltage ratio must refer to the terminal ***voltage of primary and secondary***. It is obvious that this ratio may not be equal to the ratio of the number of turns per phase. For example, if V_1, V_2 are the primary and secondary terminal voltages, then for Y/Δ connection, the turn ratio is $V_2/(V_1/\sqrt{3}) = \sqrt{3}V_2/V_1$.

2. The phase displacement between primary and secondary voltages must be the same for all transformers which are to be connected for parallel operation.

3. The phase sequence must be the same.

4. All three transformers in the 3-phase transformer bank will be of the same construction either core or shell.

Note. (*i*) In dealing with 3-phase transformers, calculations are made for one phase only. The value of equivalent impedance used is the equivalent impedance per phase referred to secondary.

(*ii*) In case the impedances of primary and secondary windings are given separately, then primary impedance must be referred to secondary by multiplying it with (transformation ratio)^2.

(*iii*) For Y/Δ or Δ/Y transformers, it should be remembered that the voltage ratios as given in the questions, refer to terminal voltages and are quite different from turn ratio.

Example 33.26. *A load of 500 kVA at 0.8 power factor lagging is to be shared by two three-phase transformers A and B of equal ratings. If the equivalent delta impedances as referred to secondary are (2 + j6) Ω for A and (2 + j5) Ω for B, calculate the load supplied by each transformer.*

Solution. $$\mathbf{S_A} = \mathbf{S}\frac{\mathbf{Z_B}}{\mathbf{Z_A}+\mathbf{Z_B}} = \mathbf{S}\frac{1}{1+(\mathbf{Z_A}/\mathbf{Z_B})}$$

Now $S = 500\,(0.8 - j0.6) = (400 - j300)$

$$\mathbf{Z_A/Z_B} = (2+j6)/(2+j5) = 1.17 + j\,0.07;\ \mathbf{Z_B/Z_A} = (2+j5)/(2+j6) = 0.85 - j\,0.05$$

$$\mathbf{S_A} = (400 - j300)/(2.17 + j0.07) = 180 - j\,144.2 = 230.7\angle -38.7°$$

$$\cos\phi_A = 0.78 \text{ lagging}$$

$$\mathbf{S_B} = (400 - j\,300)/(1.85 - j0.05) = 220.1 - j\,156 = 270\angle -40°28' \ \therefore\ \cos\Phi_B = \mathbf{0.76\ lagging.}$$

Example 33.27. *State (i) the essential and (ii) the desirable conditions to be satisfied so that two 3-phase transformers may operate successfully in parallel.*

A 2,000-kVA transformer (A) is connected in parallel with a 4,000 kVA transformer (B) to supply a 3-phase load of 5,000 kVA at 0.8 p.f. lagging. Determine the kVA supplied by each transformer assuming equal no-load voltages. The percentage voltage drops in the windings at their rated loads are as follows :

Transformer A	*resistance 2% ;*	*reactance 8 %*
Transformer B	*resistance 1.6 % ;*	*reactance 3 %*

(Elect. Engineering-II, Bombay Univ. 1987)

Solution. On the basis of 4,000 kVA

$$\%\,\mathbf{Z}_A = (4{,}000/2{,}000)\,(2+j8) = (4 + j16) = 16.5\angle 76°$$

$$\%\,\mathbf{Z}_B = (1.6 + j3);\ \%\,Z_A + \%\,Z_B = (5.6 + j16) = 19.8\angle 73.6°$$

$$\mathbf{S} = 5{,}000\angle -36.9° = (4{,}000 - j\,3{,}000)$$

Now $$S_B = \mathbf{S}.\frac{\mathbf{Z_A}}{\mathbf{Z_A}+\mathbf{Z_B}} = 5{,}000\angle -36.9° \times \frac{16.5\angle 76°}{19.8\angle 73.6°}$$

$$= 5{,}000\angle -36.9° \times 0.832\angle 2.4° = 4{,}160\angle -34.5° = (3{,}425 - j\,2{,}355)$$

$$S_A = \mathbf{S} - \mathbf{S_B} = (4{,}000 - j\,3{,}000) - (3{,}425 - j\,2355)$$

$$= (575 - j\,645) = 864\angle -48.3°$$

$$\cos\phi_B = \cos 34.5° = 0.824 \text{ (lag)};\ \cos\phi_A = \cos 48.3° = \mathbf{0.665\ (lag).}$$

Example 33.28. *A load of 1,400 kVA at 0.866 p.f. lagging is supplied by two 3-phase transformers of 1,000 kVA and 500 kVA capacity operating in parallel. The ratio of transformation is the same in both : 6,600/400 delta-star. If the equivalent secondary impedances are (0.001 + j 0.003) ohm and (0.0028 + j0.005) ohm per phase respectively, calculate the load and power factor of each transformer.* **(Elect. Engg-I, Nagpur Univ. 1993)**