CONTENT

SUBJECT/SUBJECT CODE-4030330 / ELECTRICAL MACHINES I

1. **NOTES OF LESSON INDEX PAGE**
2. **NOTES OF LESSON (VIDEO LINK,PPTLINK ATTACHED IN THE INDEX PAGE)**

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NOTES OF LESSON –INDEX PAGE

YEAR	SECOND YEAR	SEMESTER	IV SEMESTER
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UNIT-I-DC GENERATORS

S.NO.	TOPIC	REFER TEXT BOOK NAME	VIDEO PRESENTATION	PPT	ANY OTHER
1	Review of electromagnetic induction – Faraday's laws – Fleming's right hand rule				
2.	Principle of operation of D.C. generators Construction of D.C. generators	A Textbook of Electrical Technology - Volume II B.L. Theraja			
3.	Types of armature windings(No Winding diagram) – EMF equation(Simple problems)				
4.	Types of D.C. generators	Elements of Electrical Engineering Maria Louis			
5.	No load and load characteristics of DC generators				
6.	Causes of failure to build-up voltage and remedy	Electrical Machines Nagarath	NIL	YES	NIL
7.	armature reaction	Electrical Machines Bhattacharya			
8.	methods of compensating armature reaction				
9.	process of commutation				
10.	methods of improving commutation. Load characteristics of DC generators	Electrical Technology Edward Hughes			
11.	Applications of DC generators				

UNIT-II-DC MOTORS

S.NO.	TOPIC	REFER TEXT BOOK NAME	VIDEO PRESENTATION	PPT	ANY OTHER
1.	Principle of operation of D.C. Motors	A Textbook of Electrical Technology - Volume II B.L. Theraja	NIL	YES	E-BOOK
2.	Fleming's left hand rule				
3.	Back emf – Torque equation Types of motors				
4.	Torque-current,Speed-current, Speed-Torque characteristics of different motors	Elements of Electrical Engineering Maria Louis			
5.	Speed control of DC motors – Field control and armature control				
6.	necessity of Starters– 3 Point starter	Electrical Machines Nagarath			
7.	4 Point starters				
8.	losses in D.C. Machines				
9.	Testing of D.C. machines	Electrical Machines Bhattacharya			
10.	Predetermination of efficiency of motor and generator by Swinburne's test				
11.	Problems in above topics	Electrical Technology Edward Hughes			
12.	Applications of D.C. Motors.				

UNIT-III-SINGLE PHASE TRANSFORMER

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<tr><td>1.</td><td>Principle of operation</td><td rowspan="13">A Textbook of Electrical Technology - Volume II B.L. Theraja

Elements of Electrical Engineering Maria Louis

Electrical Machines Nagarath

Electrical Machines Bhattacharya

Electrical Technology Edward Hughes</td><td rowspan="13">NIL</td><td rowspan="13">NIL</td><td rowspan="13">E-BOOK</td></tr>
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UNIT-IV-THREE PHASE TRANSFORMER

S.NO.	TOPIC	REFER TEXT BOOK NAME	VIDEO PRESENTATION	PPT	ANY OTHER
1..	Three phase Transformer construction	A Textbook of Electrical Technology - Volume II B.L. Theraja			
2.	types of connections of transformer				
3.	Parallel operation of three phase transformers	Elements of Electrical Engineering Maria Louis			
4.	Parallel operation of three phase transformers				
5.	Grouping of transformers				
6.	Pairing of transformer				
7.	Load sharing of transformers with equal and unequal ratings	Electrical Machines Nagarath			
8.	Cooling of transformers – Various cooling arrangements Transformer accessories				
9.	Bucholz relay–ON load	Electrical Machines Bhattacharya	NIL	NIL	E-BOOK
10.	OFF load tap changer-transformer oil tester	Electrical Technology Edward Hughes			

UNIT-V- MAINTENANCE OF DC MACHINES AND TRANSFORMERS

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<tr><td>1.</td><td>Maintenance – Importance,</td><td rowspan="11">A Textbook of Electrical Technology - Volume II B.L. Theraja

Elements of Electrical Engineering Maria Louis

Electrical Machines Nagarath

Electrical Machines Bhattacharya

Electrical Technology Edward Hughes</td><td>https://www.youtube.com/watch?v=2tPrQ0XGrEc</td><td rowspan="11">NIL</td><td rowspan="11">NIL</td></tr>
<tr><td>2.</td><td>Preventive and Breakdown maintenance</td><td>https://www.youtube.com/watch?v=2i8wf_T1CYU</td></tr>
<tr><td>3.</td><td>Advantages of preventive maintenance</td><td>https://www.youtube.com/watch?v=JLDXLcooWs8</td></tr>
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<tr><td>10.</td><td>Transformer oil tester
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INTRODUCTION

A DC motor is a machine which converts electrical energy into mechanical energy. Basically there is no constructional difference between a DC motor and a DC generator. The same DC machine can be run as a generator or as a motor. DC motor has excellent torque, speed and load characteristics. Hence they are more preferred than any other motor for industrial applications.

1.1 Principle of operation of DC Motor:

Operation of DC motor is based on the principle that when a current carrying conductor is placed in a magnetic field, the conductor experiences a mechanical force. The direction of this force is given by Fleming's left hand rule and its magnitude is given by

F= BIlsinθNewtons where F= Force experienced by the conductor in Newtons,

B = Flux density in the air gap in Wb/ m^2 or Tesla I = Current carried by the conductor in amperes,

l = Length of the conductor in metres θ = Angle between the vectors B & I

From the above equation, it can be inferred that,if a conductor of length l metre, carryinga current of I amperes is placed in a uniform magnetic field offlux density B, then a force of F Newton will be experienced by that conductor.

Requirements of a DC motor:

1. Magnetic field: When the field winding is excited, it gives main flux.
2. Conductor which carries current: Armature winding is given DC voltage which produces current through the armature winding.

Working of a DC motor:

Consider a part of DC motor having multiple poles as shown in fig. 2.1. When the terminals of motor are connected to an external source of DC supply,

i) The field magnets are excited developing alternate N and S poles.

ii) The armature conductor carry currents. All conductors under N pole carry currents in one direction while all the conductors under S pole carry currents in the opposite direction.

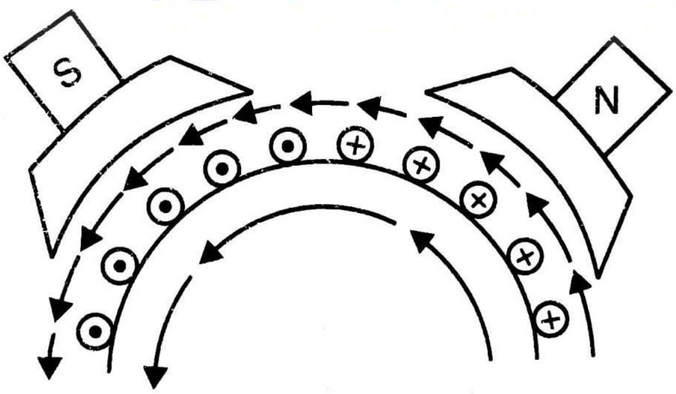


Fig.2.1

Suppose the conductors under N pole carry current into the plane of the paper and those under S pole carry currents away from the plane of the paper as shown in fig.2.1. Since each armature conductor is carrying current and is placed in the magnetic field, a mechanical force acts on it. By applying Fleming's left hand rule it is clear that the force on each conductor is tending to rotate the armature in the anticlockwise direction. All these forces add together to produce a driving torque which sets the armature rotating. When the conductor moves from one side of a brush to the other, the current in that conductor is reversed and at the same time it comes under the influence of next pole which is of opposite polarity. Consequently the direction of force on the conductor remains the same.

1.2 Fleming's left hand rule:

It is used to find the direction of force (motion of a conductor) in a DC motor. Hold the fore finger, middle finger and thumb of left hand mutually perpendicular to each other. If the fore finger represents the direction of magnetic field, the middle finger represents the direction ofcurrent then the thumb will represent the direction of motion of conductor (force). as shown in fig.2.2.

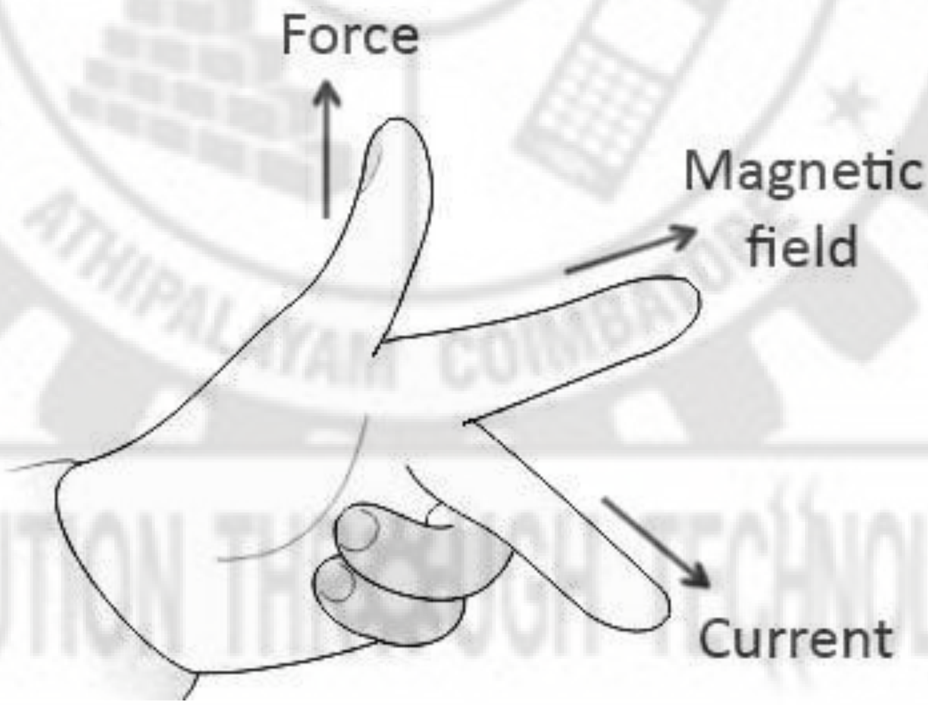


Fig.2.2

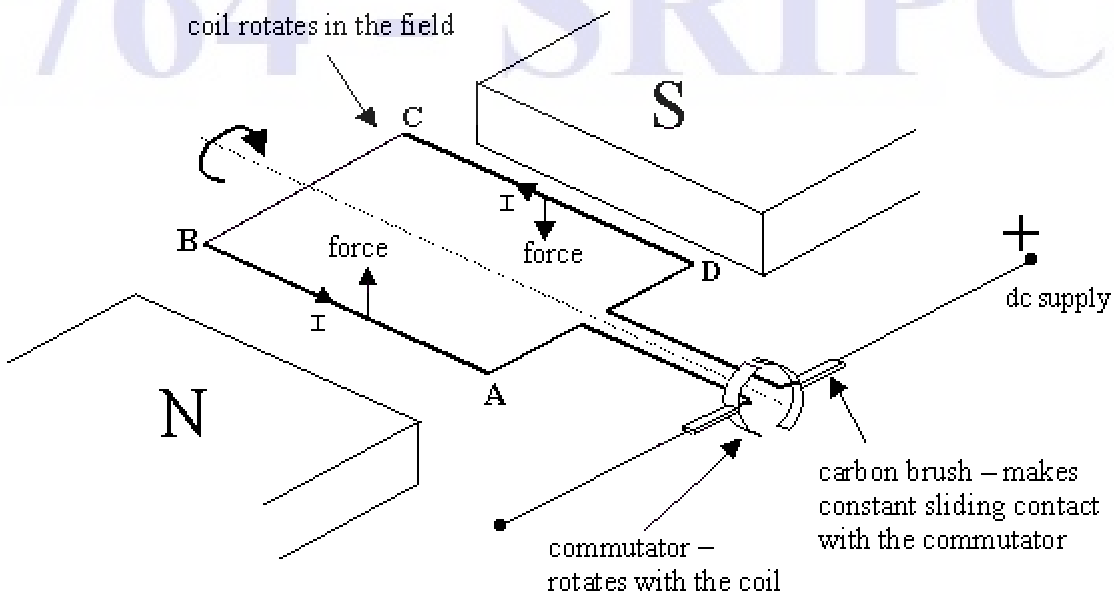


Fig.2.3

The fig 2.3. shows the direction of motion of the current carrying conductor placed in a magnetic field. According to Fleming's left hand rule,the left part of the conductor moves upwards and the right part of the coil moves downwards. As a result, the coil moves in clockwise direction.

1.3 CONSTRUCTION OF DC MOTOR:

There is no constructional difference between a DC motor and a DC generator.

1.4 BACK EMF(OR) COUNTER EMF:

When DC supply is given to DC motor its armature starts rotating. The armature rotates and cuts the static magnetic flux produced by the field magnets. Therefore an e.m.f is induced in the armature conductor as per Faraday's laws of Electromagnetic induction. By Lenz's law, this induced

e.m.f will oppose the supply voltage. Hence the e.m.f induced in the armature is called back e.m.f (or) counter e.m.f (E_b).

Back EMF induced in the armature of a DC motor $E_b = \frac{P\Phi ZN}{60A}$ volts

P – No. of poles
Φ – Flux per pole in Webers
Z - No. of conductor in the armature N – Speed of the armature in rpm
A – Number of parallel paths.
V – Supply voltage to the motor in Volts I_a – Armature current in Amperes
R_a– Armature resistance in ohms.
$I_a R_a$ is the voltage drop in the armature circuit

Consider a shunt wound motor. When a DC voltage V Volts is applied across the motor terminals, the field magnets are excited and armature conductors are supplied with current. Therefore, driving torque acts on the armature which begins to rotate. As the armature rotates, back EMF(E_b) is induced which opposes the applied voltage V. The applied voltage V has to force the current through the armature against the back EMF.

Net voltage across armature circuit = V-E_b If R_a is the armature circuit resistance then

$$I_a=(V-E_b)/R_a$$

Since V and R_a are usually fixed, the value of E_b will determine the current drawn by the motor. If the value of E_b is high, then the current drawn by the motor will be low.

From the equations of back EMF and armature current, it can be noted that , if the speed of the motor is high, then back EMF is large and hence the motor will draw less armature current and vice versa.

Significance of Back e.m.f:

1. The back e.m.f in a DC motor regulates the flow of armature current, i.e. automatically changes the armature current to meet the load requirements and it makes the motor as a self regulating one.

2. The electric work done in overcoming and causing the current to flow against back EMF is converted into mechanical energy developed in the armature. Therefore the energy conversion in a DC motor is only possible due to the production of back EMF.

1.5 TORQUE EQUATION:

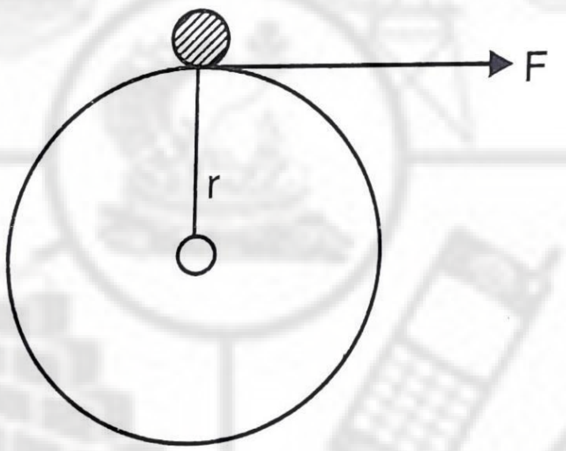


Fig.2.4

Torque is the turning moment of a force about an axis and is measured by the product of force (F) and radius (r) at right angle to which the force acts.

$$T = F \times r \text{ Newton metre}$$

Consider a pulley of radius, r metre acted upon by circumferential force of F Newton which caused it to rotate at a speed of N rpm as shown in fig.2.4.

Torque produced on the pulley (T) =F x r Newton metre

Assume T_a be the torque developed by the armature and rotates at a speed N rpm. Electrical power developed = $E_b I_a$ Watts................ (1)

Mechanical power developed in the armature $= \frac{2\pi N T_a}{60}$ (2)

The electric power is converted into mechanical power in the armature Equate (1) and (2) $E_b I_a = \frac{2\pi N T_a}{60}$

$$2\pi N\, T_a = 60 \times E_b I_a$$

$$\text{Torque } (T_a) = \frac{60 \times E_b I_a}{2\pi} \text{ Nm}$$

we know that,

$$\text{Back e.m.f } E_b = \frac{P\Phi ZN}{60A} \text{ volts}$$

$$\text{Torque } (T_a) = \frac{60 \times P\Phi ZN \times I_a}{2\pi N \times 60\, A} \text{ Nm}$$

$$T_a = \frac{P\Phi Z \times I_a}{2\pi\, A}$$

$$T_a = 0.159\, P\Phi Z\, I_a \text{ N.m}$$

$$T = \frac{0.159\ P\Phi Z\ I_a}{A}\ \text{N.m}$$

9.81 Newton = 1 kg

$$T = \frac{0.159\ P\Phi Z\ I_a}{9.81 A}\ \text{kg.m}$$

$$\boxed{T = \frac{0.0162\ P\Phi Z\ I_a}{A}\ \text{kg.m}}$$

In a particular DC motor, the number of conductors 'Z', the number of poles 'P' and the number of parallel path 'A' remains constant. Therefore the torque developed 'T' will be proportional to the product of flux and armature current Ia.

$$\boxed{T \propto \Phi I_a}$$

1.6 Types of D.C. Motors:

Like generators, there are three types of dc. Motors characterized by the connections of field winding in relation to the armature.

Shunt-wound motor:

Shunt motor is a motor in which the field winding is connected in parallel with the armature. Terminal voltage $V=E_g + I_aR_a$

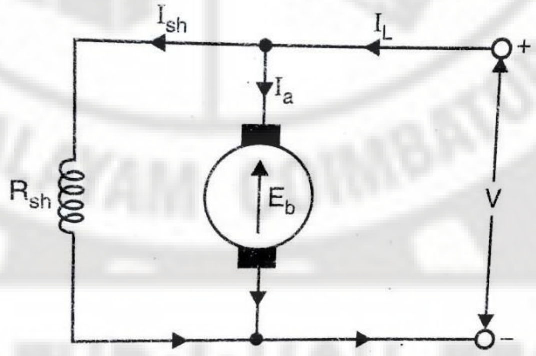


Fig.2.5

Series-wound motor:

Series motor is a motorin which the field winding is connected in series with the armature. Terminal voltage $V=E_g+ Ia(R_a+R_{se})$

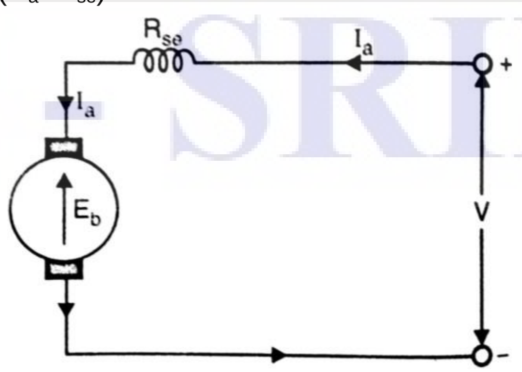


Fig.2.6

Compound-wound motor:

Compound motor has two field windings; one connected in parallel with the armature and the other in series with it. There are two types of compound motor connections. When the shunt field winding is directly connected across the armature terminals, it is called short shunt connection when the shunt field winding is so connected that it shunts the series combination of armature and series fields, it is called long shunt connection.

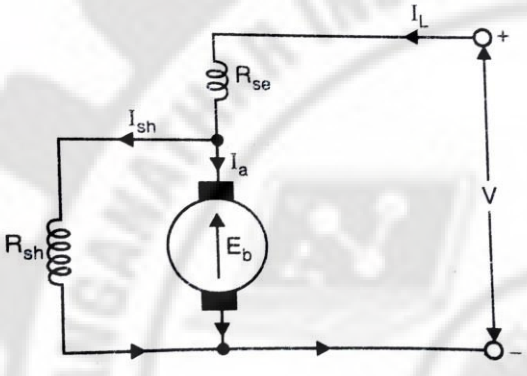


Fig.2.7

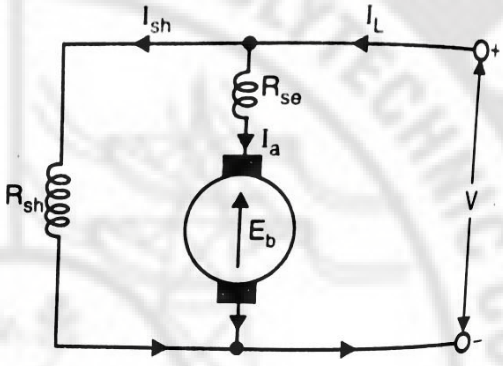


Fig.2.8

For short shunt motor:

Terminal voltage $V=E_g+I_aR_a+I_{se}R_{se}$

For long shunt motor:

Terminal voltage, $V=E_g+I_a(R_a+R_{se})$

2.7.1 DC SHUNT MOTOR CHARACTERISTICS

1) TORQUE Vs ARMATURE CURRENT CHARACTERISTICS

In a DC motor $T \propto \Phi I_a$

As the shunt field winding is connected directly to the supply voltage, the field is assumed to be constant. So the flux will also be constant. Hence torque developed in a DC shunt motor will be directly proportional to armature current I_a.

$$T \propto I_a$$

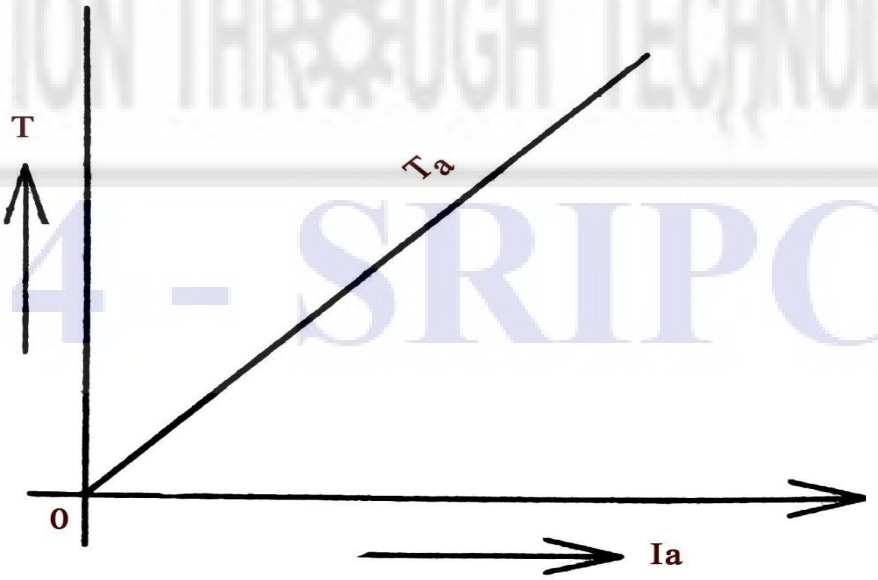


Fig.2.9

From the above Fig.2.9, it can be understood that the torque vs armature current is a linear curve.

2) SPEED Vs ARMATURE CURRENT CHARACTERISTICS

Back e.m.f $E_b = \frac{P\Phi ZN}{60A}$ volts

$E_b = V - I_aR_a$ From the above equations

$$\frac{P\Phi ZN}{60A} = V - I_aR_a$$

$$N = \frac{(V - I_aR_a) \times 60 A}{P\Phi Z}$$

$$N \propto \frac{(V - I_aR_a)}{\Phi}$$

When the supply voltage V is constant, then flux Φ also will be constant. Hence the speed is directly proportional to $(V - I_aR_a)$. i.e. $N \propto (V - I_aR_a)$.

From the above expression, it can be noted that speed of the DC shunt motor decreases with the increase in armature current due to loading. The characteristic curve is slightly drooping one as shown in Fig.2.10. But due to armature reaction the flux is weakened and the speed will increase. This increase in speed compensates the decrease in speed due to I_aR_a drop. Therefore the speed of DC shunt motor is almost constant.

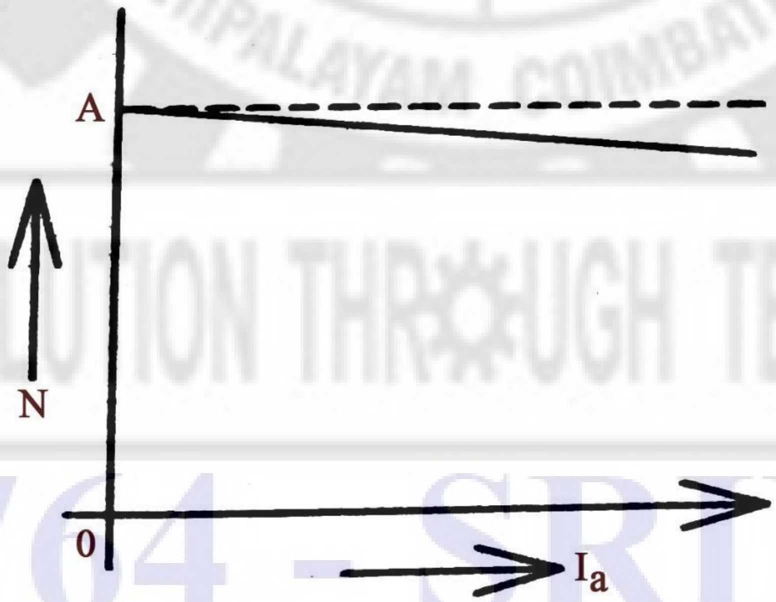


Fig.2.10

3) SPEED Vs TORQUE CHARACTERISTICS

In shunt motor Speed, $N \propto (V - I_aR_a)$ -------------- 1

Torque, $T \alpha I_a$ --------------- 2

$I_a \alpha T$

So $I_a = KT$

Now equation 1 becomes $N \alpha (V - KTR_a)$

From the above equation when the torque increases, the speed decreases as shown in Fig.2.11.

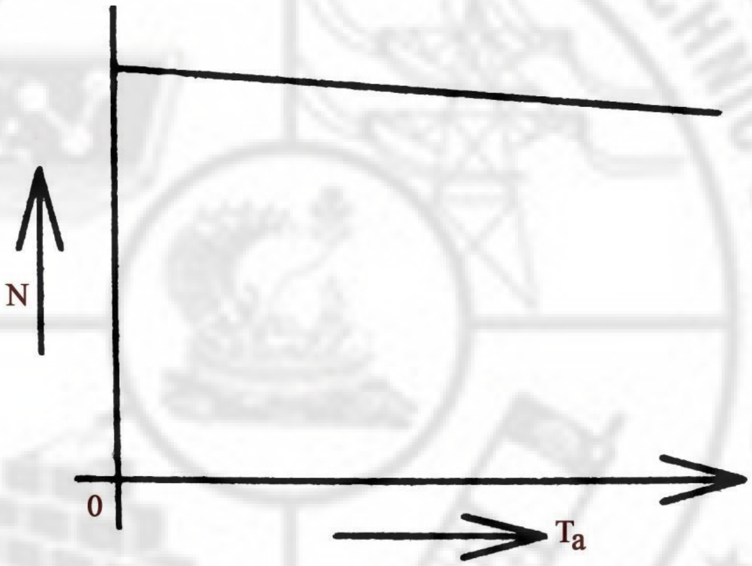


Fig.2.11

2.7.2 DC SERIES MOTOR CHARACTERISTICS

1) TORQUE Vs ARMATURE CURRENT CHARACTERISTICS

In a DC motor $T \alpha \Phi I_a$. Up to magnetic saturation $\Phi \alpha I_a$. So before saturation $T \alpha I_a^2$ and the corresponding curve is from O to A of Fig.2.12. After magnetic saturation Φ becomes constant. Hence $T \alpha I_a$ and is indicated from A to B of Fig.2.12.

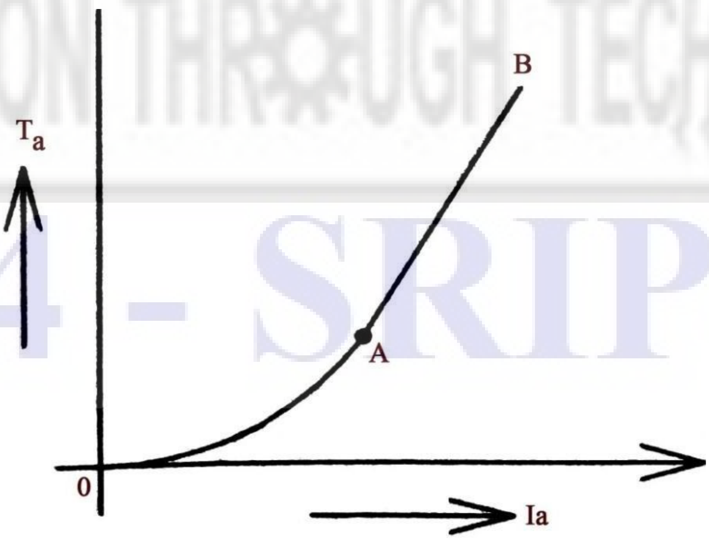


Fig.2.12

2) SPEED Vs ARMATURE CURRENT CHARACTERISTICS

In series motor $I_a R_a$ drop is very small when compared to supply voltage. Hence N =

V/Φ. On light load, the flux will be very low. When the load increases flux also increases. Hence the speed drops rapidly. So the shape of the curve will be hyperbolic as shown in Fig.2.13. After saturation flux remains constant. Therefore the speed will be constant and low at heavy loads. The series motor should be started with load only to avoid running from dangerously high speed.

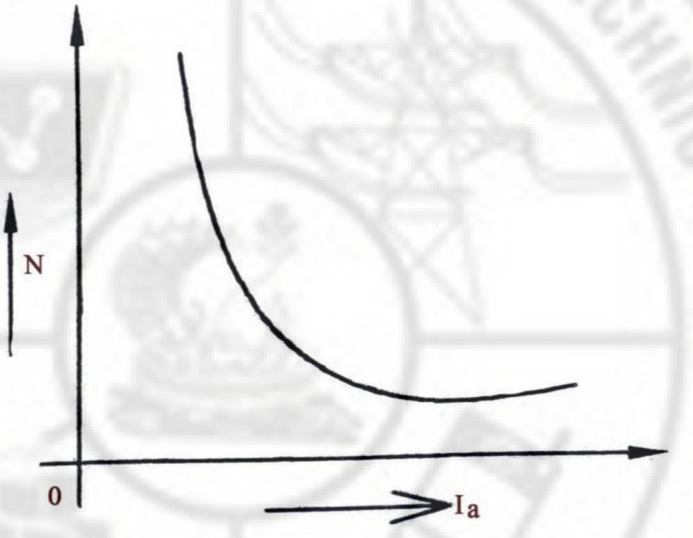


Fig.2.13

3) SPEED Vs TORQUE CHARACTERISTICS

In series motor N α V/Φ --1

T α Φ I_a

T α $Φ^2$ (since I_aα

Φ) $Φ^2$ α T

Φα √ T --2

By putting 2 in 1 N α V/√ T

N α 1/√ T (If V is kept constant)

from the above equation the speed is inversely proportional to torque and the curve is hyperbolic in shape as shown in Fig.2.14

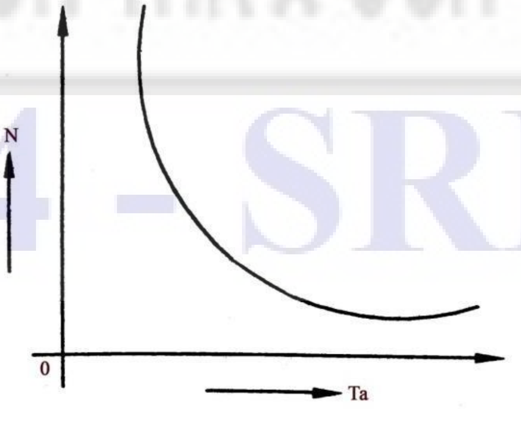


Fig.2.14

2.7.3 CHARACTERISTICS OF DC COMPOUND MOTOR

There are two types of compound motor

1) Cumulative type:

In this type the connection of the series field flux will be adding the shunt field flux.Hence the cumulative compound motor has more flux than that of shunt motor.

1) TORQUE Vs ARMATURE CURRENT CHARACTERISTICS

As the load increases, the series field increases but shunt field strength remains constant. Consequently, total flux is increased and hence the armature torque also increases (since T α Φ I_a). So the torque of cumulative compound motor is greater than that of shunt motor for given armature current due to series field as shown in Fig.2.15.

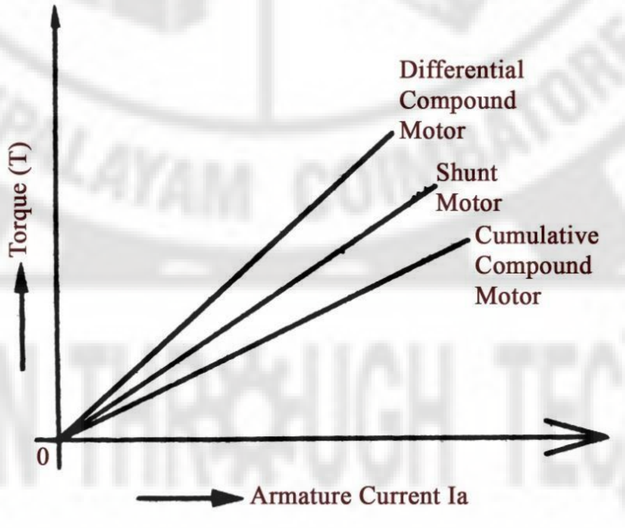


Fig.2.15

2) SPEED Vs ARMATURE CURRENT CHARACTERISTICS

As explained above, as the load increases, the flux per pole increases. Consequently, the speed of the motor falls (N α 1/Φ) as the load increases as shown in Fig.2.16. It may be noted that as the load is added, the increased amount of flux causes the speed to decrease more than does the speed of the shunt motor. Thus the speed regulation of a cumulative compound motor is poorer than that of a shunt motor.

Note: Due to shunt field, the motor has a definite no load speed and can be operated safely at no load.

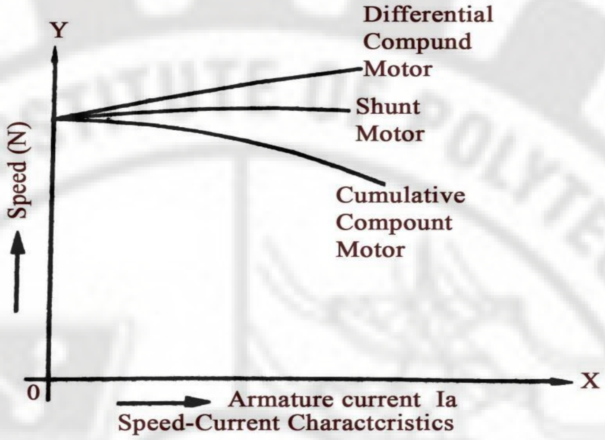


Fig.2.16

3) SPEED Vs TORQUE CHARACTERISTICS

Fig.2.17 shows that for a given armature current, the torque of a cumulative compound motor is more than that of a shunt motor but less than that of a series motor.

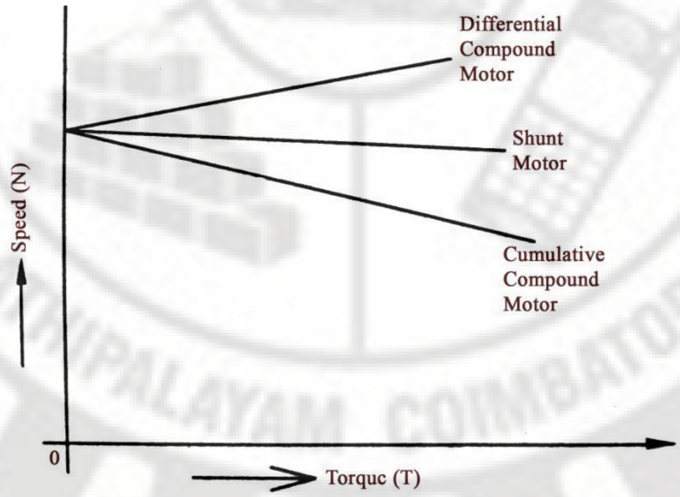


Fig.2.17

2.7.4 Differential type:

In this type the connection of the series field will be in such a way that flux produced by the series field will be opposing the flux due to shunt field. the characteristics of compound wound motor are combination of shunt and series wound Motors. Differential compound motors are rarely used due to their poor torque characteristics at heavy loads.

Speed control of DC motors:

Back EMF induced in the armature of a DC motor is given by

$$E_b = \frac{P\Phi ZN}{60A} \text{ volts}$$

Here P,Z,A are fixed $N \propto \frac{E_b}{\Phi}$

We know that $E_b = V - I_a R_a$

Now $N \propto \frac{(V - I_a R_a)}{\Phi}$

From the above equation, it can be concluded that,

i. When V increases,speed increases
ii. When flux per pole increases, speed decreases.

The following are the most common methods of controlling the speed DC motors based on the above principles

2.8 Speed control of DC shunt motor:

There are two types of speed control of DC shunt motor.
1. Armature control or resistance control method. 2.Field control method.

2.9.1 Armature control or resistance control method:

The relation between speed and supply voltage is given by

$$N \propto E_b$$

This method is based on the fact that by varying the voltage available across the armature, the back EMFand the speed of the motor can be changed. This is done by inserting a variable resistance R_c(known as controller resistance) in series with the armature as shown in fig. 2.18

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

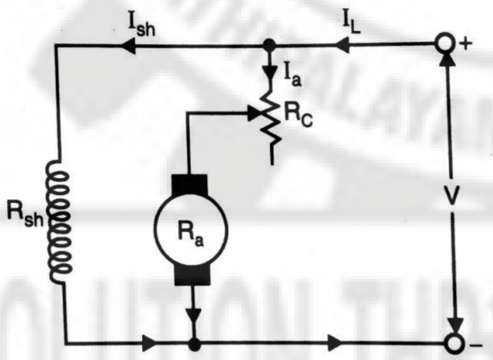


Fig.2.18

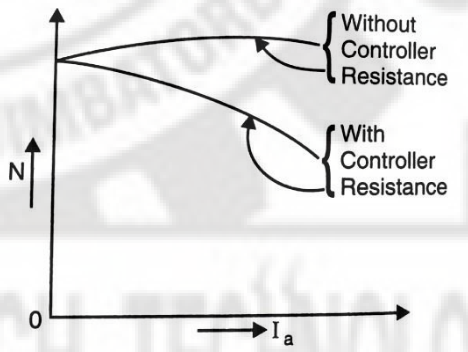


Fig.2.19

As this control resistance R_c is increased, the voltage drop across the control resistance increases and the back EMF E_b decreases and hence the speed decreases as shown in Fig.2.19. This highest speed obtainable is that corresponding to R_c=0; i.e. rated speed. Hence this method can only provide speeds below the rated speed.

Demerits:

1. This method is not widely used because of the large losses in the Rheostat and also efficiency of the motor is reduced.

2. Speeds below ratedspeed can only be obtained.

3. Requires expensive arrangements to dissipate the heat developed in the control resistance.

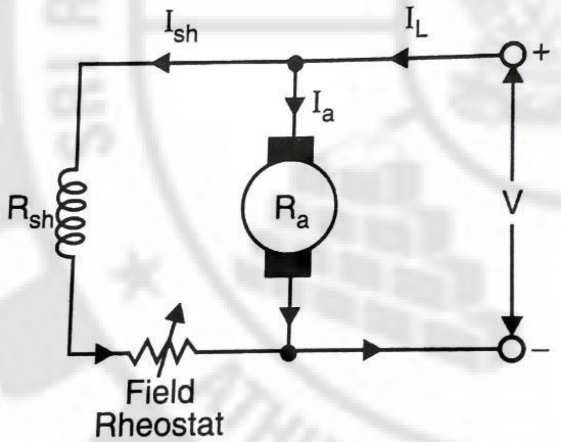
4. This method results in poor speed regulation.

Merits:

This method is suitable for constant load drives where speed variation from low speed up to rated speed are only required.

2.9.2 Field control method:

As per the speed equation, the speed is inversely proportional to the field flux. Since flux depends upon the exciting current (field current), if the current is decreased then the speed will be increased. In field control method, the air gap flux is varied by introducing a resistance in the shunt field circuits. It is the most commonly used as well as the most economic method.



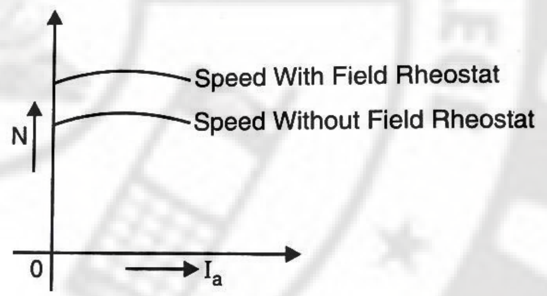


Fig.2.20

Fig.2.21

A variable resistance (rheostat) is connected in series with the shunt field of shunt or compound motor. By increasing the series resistance, the field current may be decreased and thus the field flux weakens and speed increases. In this case losses are small.

In this method we can only raise the speed of the motor above the rated speed since the flux cannot be increasedbeyond the value corresponds to the rated voltage.

Advantages :

1. Higher speeds i.e. above rated speed only can be obtained.

2. Speed control is easy, economic, convenientand efficient.

3. The speed control by this method is independent of load on the machine.

Disadvantages :

1. At high speeds,the flux will be very low and torque is also reduced.

2. There is a limit to the maximum speed obtained by this method as the weak field leads to poor commutation.

Speed control of DC series motor:

Methods of speed control in DC series motor

I. Field control method

1. Field diverter method

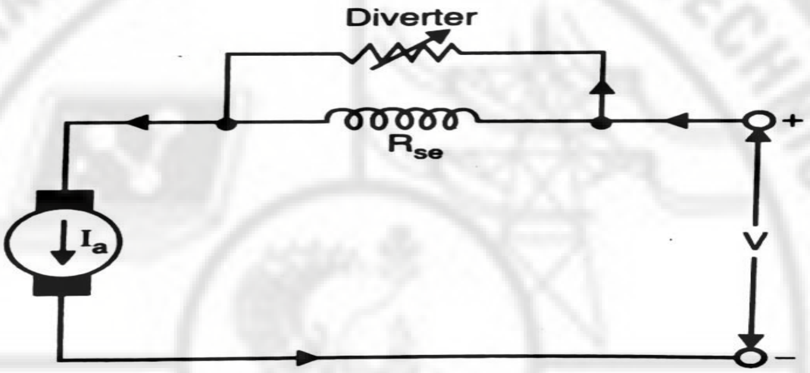


Fig.2.22

Avariable resistance called diverter is connected in parallel with the series field winding as shown in Fig.2.22. Any desired amount of current can be passed through the diverter by adjusting its resistance. The flux can be decreased and hence the speed of the motor is increased. This method can provide speed above the rated speed. The lowest speed obtained is the rated speed of the motor.

Applications:

This method is mainly used in the speed control of electric trains. By this method speed above rated only could be obtained and the power loss in the diverter is quite considerable.

Armature diverter method:

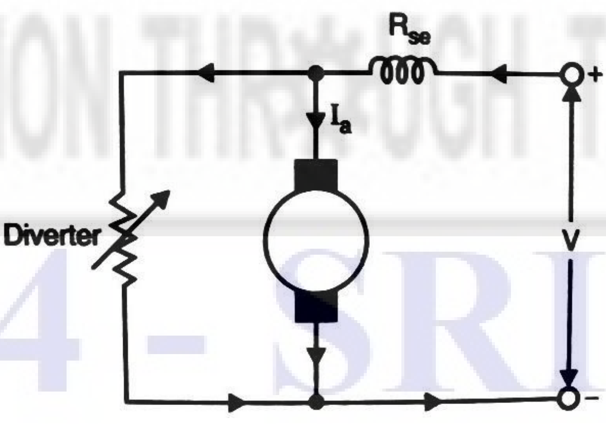


Fig.2.23

In this method, a variable resistor called armature diverter is connected across the armature as shown in Fig.2.23. By this method, the armature current is controlled to vary the speed below the rated value of the series motor. For a motor running at constant load torque, if the armature current is reduced by the armature diverter, the line current increases to meet the torque and the series field current increases. This increased field current reduces the speed. This method is costly and unsuitable for changing loads. The speed control method illustrated for DC series motor cannot be used for compound motor as this adjustments would radically change the performance characteristic of the compound motor.

Field tapping methods:

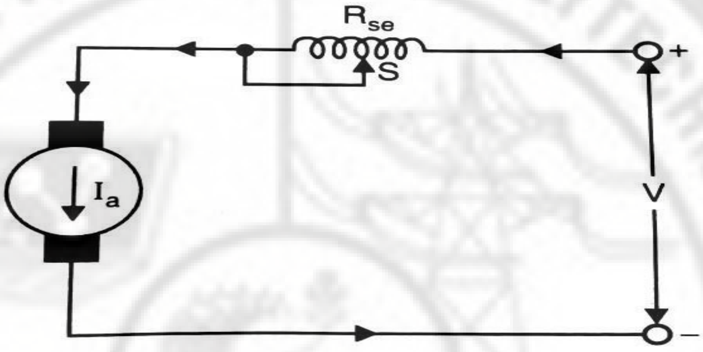


Fig.2.24

A tap changing arrangement is made on the series field winding as shown in fig.2.24 By varying the number of effective turns of the field winding, the speed can be controlled. The motor circuit should be started with all the winding included and the speed can be changed then by setting at a suitable tappings. This provision should be incorporated in the switch gear. Otherwise if the tapping is kept at lower setting and the motor is started, the motor races to a high speed at the time of starting itself which is undesirable.

Applications:

This method is used in small motors like food mixers, fans etc.

Armature resistance control method:

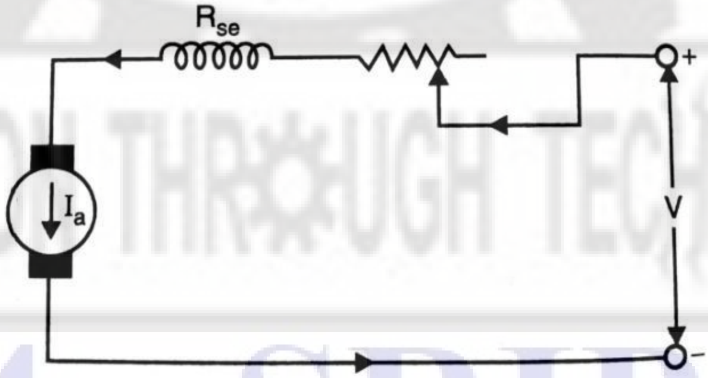


Fig.2.25

In this method a variable resistance is directly connected in series with the supply as shown in fig.2.25. This reduces the voltage available across the armature and hence the speed falls. By changing the value of variable resistance, any speed below the rated speed can be obtained. This method is mostly used to control the speed of DC series motor.

This method has following disadvantages

1. Poor speed regulation.

2. power loss in the series resistance.

In spite of these disadvantages, this method is most commonly used since it is only used intermittently when the motor is carrying full load.

2.10 Necessity of starter:

At the time of starting speed, N=0, so back EMF E_b =0, as $E_b \alpha$ N. The armature current is given by $I_a=(V-E_b)/R_a$

The current drawn by the motor from the rated supply voltage would be several times the rated currentsince, the back EMF is zero and the armature resistance maybe less than 1 Ohm. This heavy starting current leads to the following problems:

i. Heavy sparking at the brushes which may destroy the commutator and brush gear,

ii. Sudden development of large torque causes mechanical shock to the shaft, reducing its life .

iii. Insulation may get weakened due to heat produced by the high starting current $H=I^2Rt$.

since In order to avoid these problems, the starting current is limited by using

starters, which

reduces the voltage or increases the resistance I=V/R for the duration of starting period only (5- 10sec).

Types of DC motor starter:

1. 2 point starter - DC series motor.
2. 3 point starter - DC shunt motor.
3. 4 point starter DC compound motor.

2.11. 1.3 point starter:

It has

i. Three terminals namely line L, field F, armature A,
ii. Handle with soft iron keeper,
iii. Overload relay OLR and
iv. No volt release (NVR).

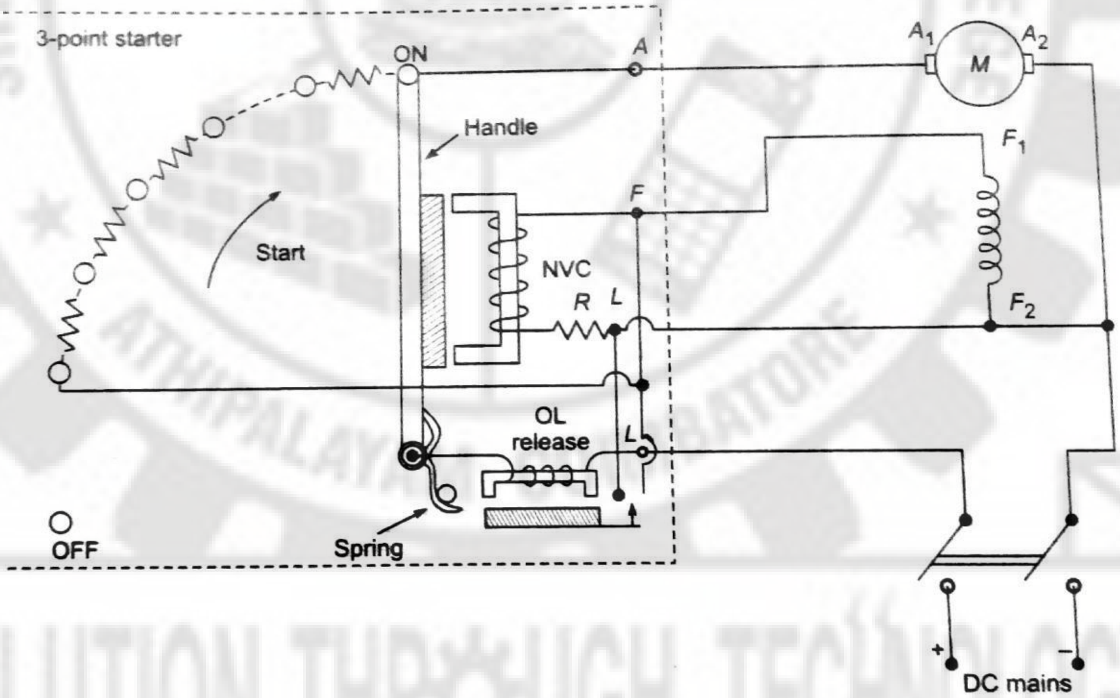


Fig.2.26

The connection diagram of a three-point starter is shown in Fig.2.26. The starter terminals to be connected to the motor are A(Armature); F(field) and L(line). The starting resistance is arranged in steps between conductingraised studs. As the starting handle is rotated about its fulcrum, it moves from one stud to the next, one resistance step is cut out, and it gets added to the field circuit. There is a short time wait at each stud for the motor to build up speed. This arrangement ensures a high average starting torque.

At start the handle is brought to stud one. The line voltage gets applied to the armature with full starting resistance in series with armature and to the field with NVC in series. Thus thestarting current is limited to a safe value and the motor starts with maximum torque. As it pick up speed the handle is moved from stud to stud (notching) to the ON position shown in Fig.2.26. The starting resistance has been fully cut out and is now included in the field circuit; being small it makes little difference in the field current. The resistance of NVC is small and forms part of the field resistance. The voltage across the armature is the line voltage. The handle is held in this position by the electromagnet excited by the field current flowing through NVC.

Two protections are incorporated in the starter.

1. NVC(No volt coil): In case of failure of field current(due to accidental or otherwise open circuiting), this coil releases the handle (held electromagnetically), which goes back to the OFF position under the spring action.

2. OLR(Over load release): The contact of this relay at armature current above a certain value (over load/ short circuit) closes the NVC ends, again bringing the handle to OFF position due to demagnetizing of NVC.

Disadvantage:

If the motor speed is controlled using field regulator the NVR gets de energized and the handle goes back to OFF position. So field control cannot be applied in 3 points starter.

2.11.2. 4 point starter:

It has

i. Four terminals namely L+, L-, F, A,

ii. Handle with soft iron keeper,

iii. Overload relay OLR and

iv. No volt release (NVR).

The connection diagram of a three-point starter is shown in Fig.2.27. The starter terminals to be connected to the motor are A(Armature); F(field); L + (line +) and L - (line -). The starting resistance is arranged in steps between conducting raised studs. As the starting handle is rotated about its fulcrum, it moves from one stud to the next, one resistance step is cut out. There is a short time wait at each stud for the motor to build up speed. This arrangement ensures a high average starting torque.

At start the handle is brought to stud one. The line voltage gets applied to the armature with full starting resistance in series with armature. Also the line voltage gets applied to the field winding. The NVC in series with a protective resistor is connected between L+ and L- terminals. Thus the starting current is limited to a safe value and the motor starts with maximum torque. As it pick up speed the handle is moved from stud to stud (notching) to the ON position shown in Fig.2.27. The starting resistance has been fully cut out. The voltage across the armature is the line voltage. The handle is held in this position by the electromagnet excited by the field current flowing through NVC.

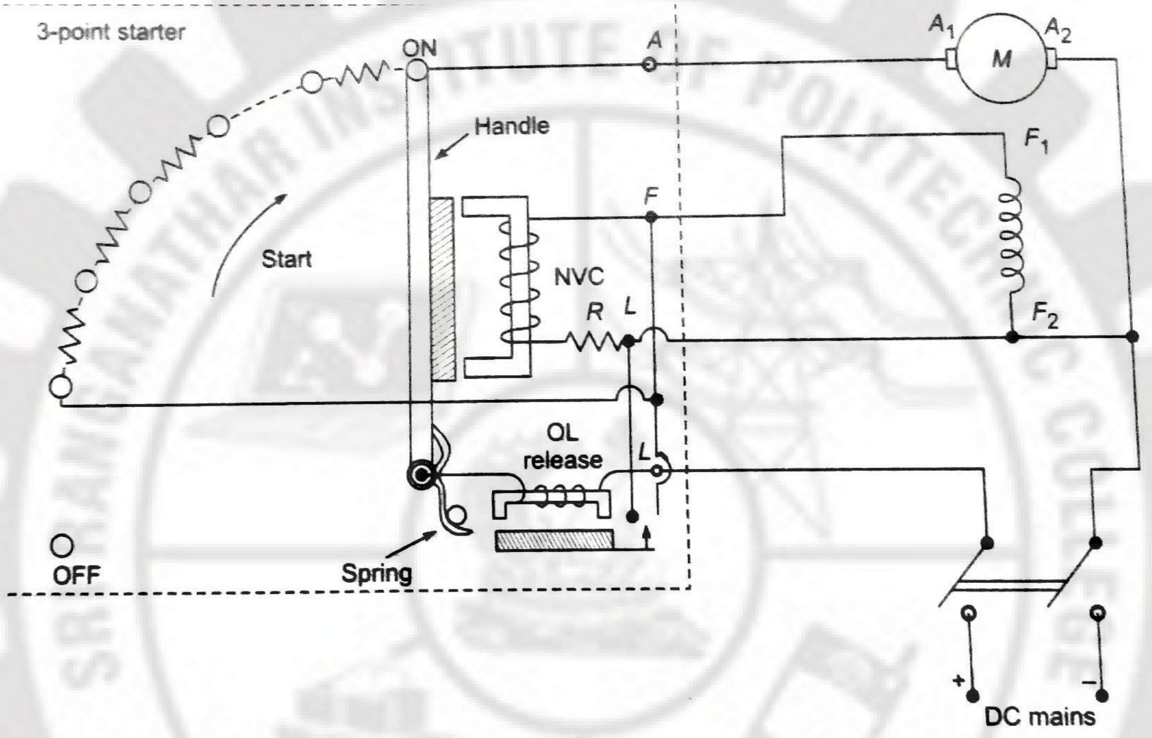


Fig.2.27

Initially the starter handle is kept in OFF position then it is gradually moved to the ON position in steps (also called as notching). At the first step, maximum resistance is connected in series to the armature which limits the starting current.

Then, as the handle is moved gradually to ON position the resistance is also gradually excluded from the circuit. The field winding is energized through NVR. By that time the motor would have reached the 80 percentage of the rated speed, which is enough to generate the required back EMF. The NVR is energized and the soft iron keeper of the handle is held by the NVR.

Two protections are incorporated in the starter.

1. NVC(No volt coil): In case of failure of field current(due to accidental or otherwise open circuiting), this coil releases the handle (held electromagnetically), which goes back to the OFF position under the spring action.

2. OLR(Over load release): The contact of this relay at armature current above a certain value (over load/ short circuit) closes the NVC ends, again bringing the handle to OFF position due to demagnetizing of NVC.

Advantage:

As the NVC is independent of the field current, even if the field regulator is used to control the speed it does not make any impact on the NVC as in the three point starter.

POWER STAGES IN DC MOTOR:

The power stages in a DC motor are represented diagrammatically in Fig. 2.28.

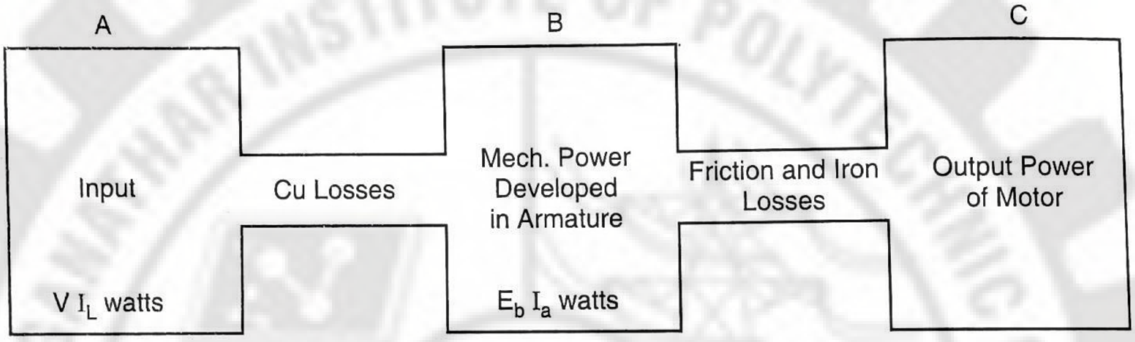


Fig.2.28

A-B = Copper losses
B - C = Iron and friction losses
i. Mechanical Efficiency, η_m= C/B

ii. Electrical Efficiency, η_e= B / A

iii. Overall efficiency, η_c= C / A

2.12. Losses in DC Machines:

The losses taking place in the DC machine (motor or generators) are

(i) Copper losses
(ii) **Magnetic losses**
(iii) **Mechanical losses**

i. Copper losses

Armature copper losses

Armature copper losses = I_a^2

R_a
Where I_a= current in the Armature winding; R_a = resistance of armature and interpoles
This loss is about 30 to 40 % of full- load losses.

Field copper losses
Shunt field copper losses = $I_{sh}^2 R_{sh}$
Where Ish= current in the shunt field winding; R_{sh}= resistance of shunt field winding

Series field copper losses = $I_{se}^2 R_{se}$
Where I_{se}= current in the series field winding; R_{sh}= resistance of series field winding.

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

ii. Iron or Core losses

These losses occur in the armature of a DC machine and are due to the rotation of armature in the magnetic field of the poles. They are of two types a) Hysteresis loss b) Eddy current loss

Hysteresis loss

Hysteresis loss occurs in the armature of the DC machine since any given part of the armature is subjected to magnetic reversals as it passes under successive poles. It is given by

Hysteresis loss $P_h = \eta B^{1.6}_{max} f V$ Watts

Where B_{max}= maximum flux density in armature in

Wb/m^2 f = frequency of magnetic reversals

V = Volume of armature core in

m^3 η = Steinmetz hysteresis coefficient

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

Eddy current loss

When armature rotates in the magnetic field of the poles, an emf is induced in it which circulates eddy currents in the armature core. The power loss due to these eddy current s is called eddy current loss. In order to reduce this loss, the armature core is built up of thin laminations insulated from each other by a thin layer of varnish.

Eddy current loss $P_e = K_e B^2_{max} f^2 t^2 V$

Watts Where K_e = Constant

B_{max}= Maximum flux density in armature core in Wb/m^2

f = Frequency of magnetic reversals

in Hz t = Thickness of lamination in m

V = Volume of armature core in m^3

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

iii) Mechanical losses:

These losses are due to friction and windage effects

c) Friction loss e.g bearing friction, brush friction etc.
d) Windage loss i.e. air friction or rotating armature.

These losses depend upon the speed of the machine. But for a given speed, they are practically constant.

Note: Iron losses and mechanical losses together are called stray losses.

The losses in the DC machines are may be subdivided into

iii) Constant losses
iv) Variable losses

iii) Constant losses

Those losses in DC machine which remain constant at all loads are known as constant losses. The constant losses in DC machine are :

d) Iron loss
e) Mechanical loss
f) Shunt field loss

iv) Variable losses

Those losses in DC which vary with load are called variable losses. The variable losses in a DC machine are :

c) Armature Copper loss $I_a^2 R_a$
d) Series field copper loss $I_{se}^2 R_{se}$

2.13 Testing of DC machines:

The main objective of testing is to find out the performance of the machine at different loads.

1) Direct method.
2) Indirect method.

2.13.1 Direct method:

- This method is suitable for small machines.
- The motor is stared without load (shunt/ compound) (or) with load (series) using a suitable starter [3 point starter – for shunt motor,2 point starter–for series motor, 4 point starter – for compound motor]
- The motor is made to run at its rated speed by adjusting the field rheostat.
- Then the load is applied in steps gradually by using a brake drum [water cooled] arrangement until the ammeter reads the rated current of the motor.
- With the help of the readings taken from the meters, the performance of the machine is calculated.

V_L	I_L	Input Power	N	Spring Balance readings		T	Output power	% Efficiency
				S1	S2			
Volts	Amps	Watts	Rpm	Kg	Kg	Kg m	Watts	%

Here

V_L = Line voltage

I_L = Line current

Input power = V_L x I_L

N = Speed
T = Torque = (S1-S2) x r x 9.81 Nm; Where r = radius of the brake drum
in m Output power= (2πNT/60) watts
% Efficiency = (Output power /Input power) x 100

2.13.2 Indirect method:

a) Swinburne 's test / no load test
b) Hopkinson 's test / regenerative method

2.14Swinburne's test:

This method is applicable to those machines in which the flux is practically constant (shunt / compound motors)

Motor is started and tested on-load.

With the help of no-load readings the efficiency of the machines can be predeterminedfor any load and for both motoring & generating actions.

No load readings:

No load Voltage V_o Volts	No load current I_o Amps	Field current I_{sh} Amps

Armature resistance R_a is measured by applying low DC voltages to the armature.

$$R_{eff} = 1.2\ R_a$$

R_{eff} is equivalent to R_a at hot conditioni.e. while running for long period No load input power= V_o x I_o Watts

No load armature copper loss=$(I_o\text{-}I_{sh})^2$ x R_{eff}

Constant loss =W_c=$(V_o \times I_o)$ - $((I_o\text{-}I_{sh})^2 R_{eff})$

Efficiency as a motor(for any load (1/4, 1/2, 3/4 and full load):

Input power=VI_L

Armature copper loss= $(I_L\text{-}\ I_{sh})^2$x R_{eff}

Constant loss= W_c

Total losses = $((I_L\text{-}\ I_{sh})^2$ x $R_{eff})+W_c$

Efficiency= [Output power/Input power] x 100

= [(Input power -Losses)/Input power]

$$= \frac{VI_L-[((I_L-I_{sh})^2 \times R_{eff})+W_c]}{VI_L}$$

Efficiency As Generator

Output Power= VI_L

Armature copper loss= $(I_L+I_{sh})^2$ x R_{eff}

Constant loss= W_c

Total loss= $((I_L+\ I_{sh})^2$ x R_{eff})+W_c

Efficiency= (output power/ input power)

$$= \frac{(VI_L)}{(VI_L+[((I_L+I_{sh})^2 \times R_{eff})+W_c]}$$

Advantages

1. It is economical and convenient as the as the power required to test a large machine is small(only no-load input power) i.e. no-load test only.
2. Efficiency can be predetermined for any load

Disadvantages

1. Iron losses are not taken into account(hysteresis + eddy current)
2. Impossible to know whether commutation would be satisfactory at full load and whether the temperature rise would be within the specified limits.

2.15 SOLVED PROBLEMS

1. A 250 V motor has an armature circuit resistance of 0.5 ohms. If the full load armature current is 25A. Find the back EMF induced in the armature.

Given data:

Armature resistance R_a = 0.5
ohms Full load armature current
I_a= 25 Amp Voltage = 220 Volts

To find:

Back EMF E_b induced at full load condition.

Solution:

E_b= V- (I_aR_a)
= 220- (25x0.5)

Back emf induced E_b= 207.5 Volts

2. Determine the value of torque in kg meter developed by the armature of a 6 pole wave wound motor having 492 conductor, 30 m web per pole when the total armature current is 40Amp.

Given data:

No of poles P = 6
No of conductors Z = 492
Armature current I_a= 40
Amps Flux per pole Φ = 30 x 10^{-3} web
For wave wound parallel path A = 2

To find:

Torque T_a in Kg m

Solution:

Torque T = $0.0162\Phi Z I_a P/A$
= 0.0162 x 30 x 10^{-3} x 492 x 40 x 6/2

Torque developed = 28.693 Kg m.

3. A 4 pole, 500 V DC shunt motor has 720 wave connected conductor on its armature. The full load armature current is 60 A & the flux per pole is 0.03 web, the armature resistance including brush contact is 0.2 Ω. Calculate the full load speed of the motor.

Given data:

No. of poles P = 4

Supply voltage = 500

Volts No. of conductors

Z = 720

No. of parallel paths A = 2 since wave

connected Full load armature current I_a=

60A

Flux per pole Φ = 0.03 web

Armature resistance including brush drop = 0.2 Ω

To find speed N

Solution:

Back Emf $E_b = V - (I_a R_a)$

$= 500 – (60 \times 0.2) = 488$ volts.

Also Back Emf $E_b = \frac{\Phi Z N P}{60 A}$

$$488 = \frac{0.03 \times 720 \times N \times 4}{60 \times 2}$$

$$N = \frac{488 \times 60 \times 2}{0.03 \times 720 \times 4}$$

Full load speed of the Motor N = 677.77 rpm.

4. The armature resistance of a 220 V shunt motor is 0.5 Ohms. The no load armature current is 2.5 A .When loaded the armature current is 50A and the speed is 1200rpm. Find the no load speed.

Given data:

Supply voltage V = 220 volts

Armature resistance R_a = 0.5

ohms

No load armature current I_{a0} = 2.5

Amps Load current I_L= 50 A

Speed at loaded condition N_1 = 1200 rpm

To find:

No load speed N_0

Solution:

$N = E_b / \Phi$

$$\frac{N_0}{N_1} = \frac{E_{b0}}{E_{b1}} \times \frac{\Phi_1}{\Phi_0}$$

Assuming $\Phi_1 = \Phi_0$ (since flux remains constant in shunt motor)

$$\frac{N_0}{N_1} = \frac{E_{b0}}{E_{b1}}$$

$E_b = V - I_aR_a$

$E_{b0} = 220 - (2.5 \times 0.5)$

$= 218.75$ Volts

$E_{b1} = 220 - (50 \times 0.5)$

$= 195$ Volts

$$N_0 = N_1 \times \frac{E_{b0}}{E_{b1}}$$

$$= 1200 \times \frac{218.75}{195}$$

$= 1346.15$ rpm

No load speed $N_0 = 1346.15$ rpm

5.A 220 V DC shunt motor runs at 500 rpm when the armature current is 50 amps. Calculate the speed, if the torque is doubled. Armature resistance is 0.2 ohms.

Given data:

Supply Voltage V = 200

Volts Speed N = 500 rpm

Armature current $I_a = 50$ A

Armature resistance $R_a = 0.2$ ohms

To find:

The speed if the torque is doubled

Solution:

$T \alpha I_a$

Case I (Normal torque) $T_1 \alpha I_{a1}$

Case II (torque is doubled) $T_2 \alpha I_{a2}$

$$\frac{T_2}{T_1} = \frac{I_{a2}}{I_{a1}}$$

$$I_{a2} = \frac{T_2}{T_1} \times I_{a1}$$

$I_{a2} = 2 I_{a1}$ (since torque is doubled $T_2 / T_1 = 2$)

= 2 x 50

= 100 Amps

Back Emf under normal torque E_{b1} = (V- I_{a1} R_a) = 220 – (50 x 0.2) = 210 Volts Back Emf when torque is doubled E_{b2} = (V- I_{a2} R_a) = 220 – (100 x 0.2) = 200 Volts

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

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

$$= \frac{200}{210} \times 500$$

N_2 = 476.19 rpm.

Speed if the torque is doubled N_2 = 476.19 rpm

6. A 20 HP DC motor has 89.3 % efficiency at rated power. What are the total losses?

Given data:

Motor rating = 20 HP

% Efficiency = 89.3 %

To find:

Total losses

Solution:

Output power = 20 HP = 20 x 746 = 14920 Watts

% Efficiency = Output power / Input power Input power = Output power / % Efficiency

= 14920 / 0.893

= 16707.72 Watts

Total losses = Input power – Output power

= 16707.72 – 14920

= 1787.72 Watts

Total losses = 1787.72 Watts

7. In a load test, on a DC shunt motor, the tensions on the two sides of the brake were 2.9 kg and 0.17 kg. Radius of the pulley was 7 cm. Input current was 2 amp at 230 volts. The

motor speed was 1500 rpm. Find the torque, power-output and efficiency.

Given data:
Input voltage V = 230 Volts
Input current I = 2 Ampere
Speed N = 1500 rpm
Spring balance readings S_1 = 2.9 kg, S_2= 0.17
kg Pulley radius = 7 cm

To find:
Torque, Power-output, Efficiency

Solution:
Torque = Force x radius

Force = $(S_1 – S_2)$ x 9.81 N
= (2.9 – 0.17) x 9.81
= 26.78 N

Torque = 26.78 x 7 x 10^{-2}
= 1.8746 N-m

Output power = (Torque x Radians/ sec) Watts

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

$$= \frac{2\pi \times 1500 \times 1.8746}{60}$$

= 294 Watts

% Efficiency = (Output power / Input power) x
100 Input power = V x I
= 230 x 2
= 460 Watts

% Efficiency = (294/ 460) x 100
= 63.9 %

Torque = 1.8746
N-m Output power = 294 Watts
% Efficiency = 63.9 %

8. The following readings are obtained when doing a load test on a DC shunt motor using a brake drum:
Spring balance reading 10 kg and 35 kg, Diameter of the drum 40 cm, Speed of the motor 950 rpm Applied voltage 200 Volts
Line current 30 A
Calculate the output power and the efficiency.

Given data:
Input voltage V = 200

Volts Line current I = 30 Ampere Speed N = 950 rpm
Spring balance readings S_1 = 35 kg, S_2 = 10 kg Brake drum diameter = 40 cm; radius = 20 cm

To find:

Power-output, Efficiency

Solution:

Force = $(S_1 – S_2)$ x 9.81
= (35 – 10) x 9.81
= 245.25 N

Torque = 245.25 x 20 x 10^{-2}
= 49.05 N-m

Output power = $\frac{2\pi NT}{60}$
= $\frac{2\pi \times 950 \times 49.05}{60}$
= 4881.64 Watts

% Efficiency = (Output power / Input power) x 100

Input power = V x I
= 200 x 30
= 6000 Watts

% Efficiency = (4881.64/ 6000) x 100
= 81.36 %

Output power = 4881.64 Watts

% Efficiency = 81.36 %

9. While conducting Swinburne's test on D.C shunt motor it takes a no load current of 4 Amps at 500V. The armature resistance is 1 ohms and the field resistance is 520 ohms. Find the efficiency of the (i) Generator when delivering 45 amps and (ii) motor when taking a current of 45 amps.

Given data:

No load current I_0 = 4 Amps
Supply voltage V = 500 Volts
Armature resistance R_a = 1 ohm Field resistance R_{sh}= 520 ohms

To find:

Efficiency of generator when delivering a current of 45 amps Efficiency of motor when taking a current of 45 amps

Solution:

No load power = V x I_o

= 500 x 4 = 2000 watts (total

loss) I_{sh} = V/ R_{sh} = 500/520 = 0.961 Amps

I_{ao} = I_o - I_{sh} = 4- 0.961 = 3.039 Amps

No load armature copper loss = $I_{ao}^2 R$

= 3.039^2 x 1

= 9.235 Watts

Constant losses W_c = No load power – No load armature copper loss

= 2000 - 9.235 = 1990.765 Watts.

When acting as a generator

When I_L = 45 amps

Output power = V x I_L = 500 x 45

= 22500 Watts

Armature copper loss = $I_a^2 R_a$

Where $I_a = I_L + I_{sh}$ = 45 + 0.961 = 45.961 Amps

$I_a^2 R_a = (45.961)^2$ x 1

= 2112.413 Watts

Total losses = Armature copper loss + Constant loss

= 2112.413 + 1990.765

= 4103.178 watts

Input power = Output power + Total losses on load

= 22500 x 4103.178

= 26603.178 Watts

% Efficiency = (Output power/ Input power) x 100

= (22500/26603.178) x 100

= 84.576 %

When acting as motor

I = 45 amps

$I_a = I_L - I_{sh}$

= 45 - 0.961

I_a= 44.04 amps

Armature copper loss = $I_a^2 R_a$= 44.04^2 x 1

= 1939.52 Watts

Total losses = Constant loss (W_C) + Armature copper loss

= 1990.765 + 1939.52
= 3930.28 Watts

Input power = V X I
= 500 X 45 = 22500 Watts
Output power = Input power – Total losses
= 22500 – 3930.28
= 18569.72 watts
% Efficiency = Output power / Input power x 100
= 18569.72/22500 x 100
= 82. 53 %

% Efficiency as a Generator = 84.576 %

% Efficiency as a motor = 82. 53 %

2.16

Applications

DC Shunt motor

A DC shunt motor has a medium starting torque. Speed regulation is about 5-15%. It is used essentially for constant speed applications requiring medium starting torques, such as centrifugal pumps, fans blowers, conveyors, machine tools, printing presses, etc.

DC Series motor

A DC series motor has very high starting torque, upto five times the full-load torque.
For drives requiring a very high starting torque, such as hoists, cranes, bridges, battery- powered vehicles and traction -type loads, the DC series motor is the obvious choice.

DC Compound motor

A compound motor has a considerably higher starting torque compared to a shunt motor and possesses, a drooping speed-load characteristic.

DC Compound motors are used for pulsating loads needing flywheel action, plunger pumps, shears, conveyors, crushers, bending rolls, punch presses, hoists, rolling mill, planning and milling machines, etc.

Exercise Problems

1. A 25 kw, 250V DC shunt generator has armature and field resistances of 0.06ohm and 100ohm respectively. Determine the total armature power developed when working (i) as a generator delivering 25 kw output and (ii) as a motor taking 25 kw input.

Answer (i) Generator-power developed in armature=26.25kw

(ii) Motor-power developed in armature=23.8kw

2. A DC motor takes an armature current of 110A at 480V. the armature circuit resistance is 0.2 ohm. The machine as 6 poles and the armature is lap connected with 864 conductors. the flux per Pole is 0.05Wb. calculate (i) the speed and (ii)the gross torque developed by the armature.

Answer (i) Speed=636 RPM

(ii) Torque=756.3 N-m

3. A 500 volt DC shunt generator motor draws a line current of 5A on light load. if armature resistance is 0.15ohm and field resistance is 200ohms, determine the efficiency of the machine running as a generator delivering a load current of 40Amps.

Answer: Generator Efficiency = 87.83%

4. A DC shunt driver centrifugal pump whose torque varies as the square of the speed. the motor is fed from a 200v supply and takes 50A when running at 1000 RPM. What resistance must be inserted in the armature circuit in order to reduce the speed to 800 RPM? the armature and field resistance of the motor of 0.1 and 100ohm respectively.

Answer: Additional resistance=1.32 ohms

5. A 250 volt shunt motor has an armature current of 20 amps when running at 1000 RPM against full load torque. the armature resistance 0.5 Ohm. what resistance must be inserted in series with the armature to reduce the speed to 500 RPM at the same torque and what will be the speed if load torque is halved with this resistance in the circuit? assume the flux to remains constant throughout and neglect contact drop.

Answer: i) Resistance must be inserted=6 ohms,

ii) Speed=771 RPM

6. The DC series motor takes 40 amp at 200V and runs at 800 RPM. If the armature and field resistance are 0.2ohm and 0.1ohm respectively. And the iron and friction losses are

0.5kw. Find the torque developed in the armature. What will be the output of the motor.

Answer: i) Torque developed in the armature T_a= 99.3N-m

ii) Motor output=7.82kw

7. The armature circuit resistance of 18.65kw, 250V series motor is 0.1ohm, the brush voltage drop is 3 volt and the series field resistance is 0.05. When the motor takes 80 amp, speed is 600 RPM. Calculate the speed when the current is 100 amp.

Answer: Speed=474 RPM

8. A shunt motor running on no load takes 5amps at 200volts. the resistance of the field circuit is 150ohms and of the armature 0.1ohms. Determine the output and efficiency of motor when the input current is 120A at 200V. State any conditions assumed.

Answer i) Output power = 21,593 Watts

ii)Efficiency 89.8%

9. A 230v DC shunt motor takes an armature current of 20 A on certain load, the armature resistance is 0.5 ohms find the resistance required in series with the armature to half the speed. If, (i) the load torque is constant, (ii). The load torque is proportional to the square of the speed.

Answer:i) Series Resistance (constant load torque) = 5.5ohms 23.5 ohms

ii) Series Resistance (load torque α Speed^2) =23.5 ohms

10. A DC series motor with unsaturated magnetic circuit and with negligible resistance when running at certain speed on a given load take 50A at 500 volts, if the load torque varies as the cube of the speed, find the resistance which should be connected in series with the machines to reduce the speed by 25% .

Answer: Series resistance = 7.89 ohms

11. A 460V series motor runs at 500 rpm taking a current of 40A, calculate the speed and % change in torque, if the load is reduced so that the motor is taking 30A. Total resistance armature and field circuit is 0.8ohms assume flux proportional to the field current.

Answer: i) speed = 680 rpm

ii) % change in torque = 43.75%

UNIT III- SINGLE PHASE TRANSFORMERS

Introduction:

The main advantage of alternating currents over direct current is that, the alternating currents can be easily transferable from low voltage to high voltage or high voltage to low. Alternating voltages can be raised or lowered as per requirements in the different stages of electrical network as generation, transmission, distribution and utilization. This is possible with a static device called transformer. The transformer works on the principle of mutual induction. It transfer an electric energy from one circuit to other when there is no electrical connection between the two circuits. Thus we can define transformer as below:

The transformer is a static device, in which an electrical power is transformed from one alternating current circuit to another with the desired change in voltage and current, without any change in the frequency.

The use of transformers in transmission system is shown in the Fig 3.1.

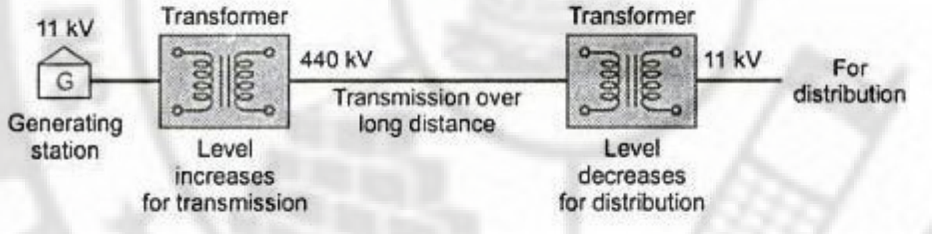


Fig 3.1 Use of transformer in transmission system

3.1 Principle Of Operation

The principle of mutual induction states that when two coils are inductively coupled and if current in one coil is changed uniformly then an e.m.f. gets induced in the other coil. This e.m.f can drive a current, when a closed path is provided to it. The transformer works on the same principle. In its elementary form, it consists of two inductive coils which are electrically separated but linked through a common magnetic circuit. The two coils have high mutual inductance. The basic transformer is shown in the Fig 3.2.

One of the two coils is connected to source of alternating voltage. This coil in which electrical energy is fed with the help of source called primary winding (P). The other winding is connected to load. The electrical energy transformed to this winding is drawn out to the load.

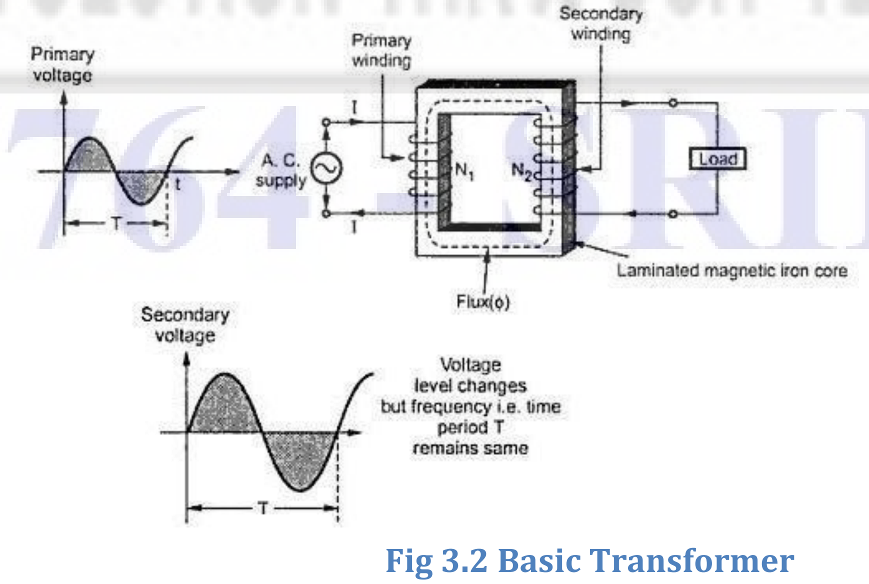


Fig 3.2 Basic Transformer

This winding is called secondary winding (S). The primary winding has N_1number of turns while the secondary winding has N_2 number of turns. Symbolically the transformer is indicated as shown in the Fig 3.3

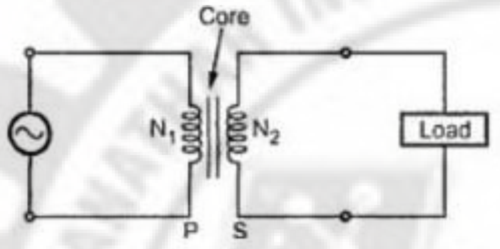


Fig 3.3 Symbolic Representation

When primary winding is excited by an alternating voltage, it circulates an alternating current. This current produces an alternating flux (Φ) which completes its path through common magnetic core as shown dotted in the Fig 3.2. Thus an alternating, flux links with the secondary winding. As the flux is alternating, according to Faraday's law of an electromagnetic induction, mutually induced e.m.f. gets developed in the secondary winding. If now load is connected to the secondary winding, this e.m.f. drives a current through it.

Thus through there is no electrical contact between the two windings, an electrical energy gets transferred from primary to the secondary.

The emf induced in the secondary winding depends upon the number of turns of the windings. If the number of turns in the secondary winding is more than that of the primary winding, the emf induced in the secondary winding will be higher than the voltage applied to the primary winding. This type of transformers are said to be step up transformers.

If the number of turns in the secondary winding is less than that of primary winding, the emf induced in the secondary winding will be less than the voltage applied to the primary winding. This type of transformers are said to be step down transformer.

Energy is transferred from the primary circuit to the secondary circuit through the medium of the magnetic field.

In brief, a transformer is a device that:

(i) Transfers electric power from one circuit to another ;
(ii) It does so without change of frequency; and
(iii) It accomplishes this by electromagnetic induction (Mutual induction).

3.2 Constructional Details of Transformer

The simple elements of a transformer consist of two coils having mutual inductance and a laminated steel core. The two coils are insulated from each other and the steel core.

Other necessary parts are:

- A suitable container for the assembled core and windings.
- A suitable medium for insulating the core and its windings from each other and from the container.
- Suitable bushings (either of porcelain, oil-filled or capacitor- type) for insulating and bringing
- Conservator tank – to top up the fall in oil level in transformer tank
- Breather – to filter the moisture entry from atmosphere to transformer.

- Oil – to transfer heat from winding/core to body to dissipate and acts as a insulator to isolate body from the winding.

In all types of transformers, there are two basic parts of Transformer

a) **Magnetic core**
b) **Windings**

3.2.1 Magnetic Core

There are two basic parts of a transformer i) Magnetic Core ii) Winding or Coils. The core of the transformer is either square or rectangular in size. It is further divided into two parts. The vertical position on which coils are wound is called limb while the top and bottom horizontal portion is called yoke of the core. These parts are shown in the Fig.3.4 (a).

Core is made up of lamination. Because of laminated type of construction, eddy current losses get minimised. Generally high grade silicon steel laminations (0.3 to 0.5 mm thick) are used. These laminations are insulated from each other by using insulation like varnish. All laminations are varnished. Laminations are overlapped so that to avoid the air gap at joints. For this generally 'L' shaped or 'I' shaped laminations are used which are shown in the Fig 3.4 (b).

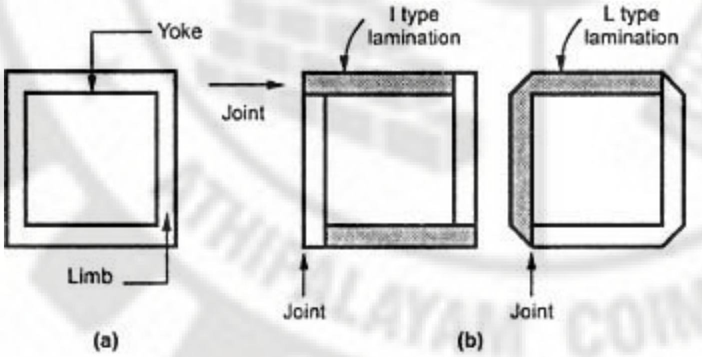


Fig 3.4

The cross-section of the limb depends on the type of coil to be used either circular or rectangular. The different cross-section of limbs, practically used are shown in the Fig. 3.5.

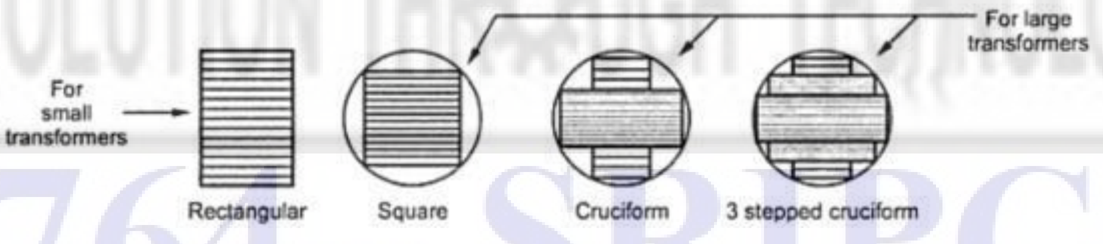


Fig 3.5

Types of Windings

The coils used are wound on the limbs and are insulated from each other. In the basic transformer shown in the Fig 3.2 the two windings wound are shown on two different limbs i.e. primary on one limb while secondary on other limb. But due to this leakage flux increases which effects the transformer performance badly. Similarly it is necessary that the windings should be very closes to each other to have high mutual inductance. To achieve this, the tow windings are split into number of coils and are wound adjacent to each other on the same limb. A very common arrangement is cylindrical coils as shown in the Fig. 3.6.

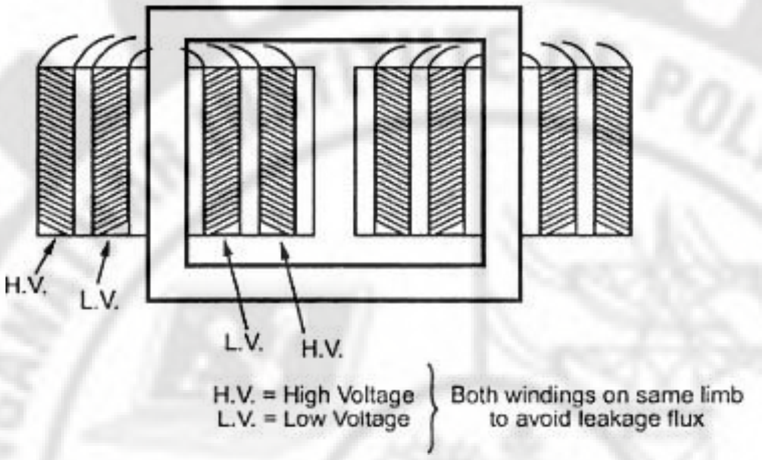


Fig 3.6

Such cylindrical coils are used in the core type transformer. Theses coils are mechanically strong. These are wound in the helical layers. The different layers are insulated from each other by paper, cloth or mica. The low voltage winding is placed near the core from ease of insulating it from the core. The high voltage is placed after it.

The other type of coils which is very commonly used for the shell type of transformer is sandwiching coils. Each high voltage portion lies between the two low voltage portion sandwiching the high voltage portion. Such subdivision of windings into small portion reduces the leakage flux. Higher the degree of subdivision, smaller is the reactance. The sandwich coil is shown in the Fig. 3.7. The top and bottom coils are low voltage coils. All the portion are insulated from each other by paper.

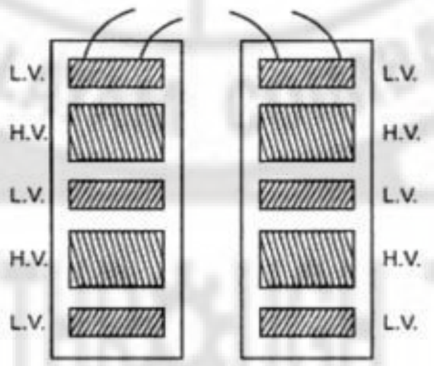


Fig 3.7

3.2.2 Core Type Transformer:

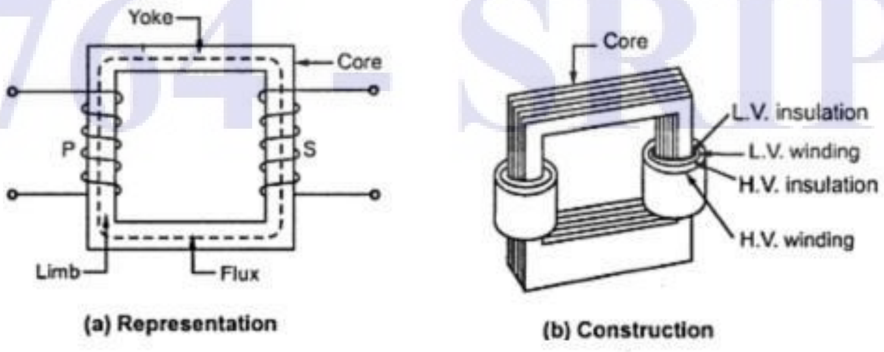


Fig 3.8

1) It has single magnetic circuit
2) Core is rectangular in shape of uniform cross-section. It consists of two vertical limbs and the horizontal yokes connecting two limbs
3) Coils used are cylindrical type
4) Coils are wound in helical layers with different layers, insulated from each other on two limbs
5) Low voltage coils is placed inside near the core while HV coils surrounds the LV coil
6) Windings are uniformly distributed over the two limbs so natural cooling is more effective
7) In order to minimize leakage flux, half the primary and half the secondary are placed concentrically on each limb

3.2.3 Shell Type Transformer:

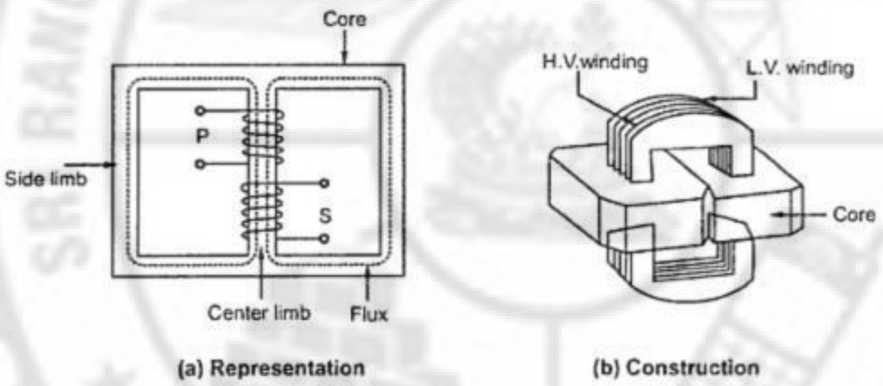


Fig 3.9

1) Magnetic circuit is divided in two or more parts
2) Core has three limbs
3) Both HV & LV windings are placed on central limb
4) Coils used are multilayer disc type or sandwich type
5) HV coils are placed between LV coils
6) LV coils are near to top and bottom of yokes
7) For low capacity shell type transformer is preferred
8) Windings are surrounded by the core so natural cooling does not exist

3.4. Emf Equation of Transformer:

Let N_1 = No. of turns in primary

N_2 = No. of turns in secondary

Φ_m = Maximum flux in core in Weber

$= B_m \times A$

f = Frequency of a.c input in Hz

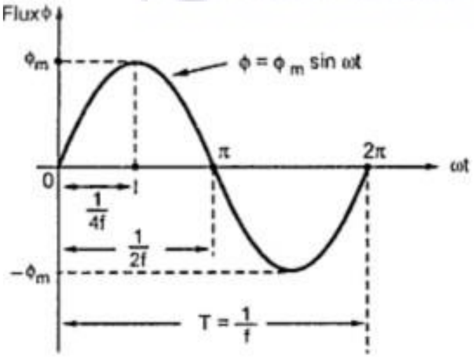


Fig 3.10

As shown in Fig. 3.10 flux increases from its zero values to maximum value Φ_m in one quarter of the cycle i.e. $\frac{1}{4f}$ seconds

$$\therefore \; Average\, rate\, of\, change\, of\, flux = \frac{\emptyset_m}{1/4f} = 4f\emptyset_m \frac{wb}{s}\, or\, volt$$

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

$$\therefore \quad Average\; e.m.f\; per\; turn = 4f\emptyset_m\; volt$$

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

$$Form\, factor = \frac{r.m.s\, value}{Average\, value} = 1.11$$

$$\therefore \quad r.m.s\, value\, of\, e.m.f\, per\, turn = 1.11 \times 4f\emptyset_m = 4.44f\emptyset_m\, volt$$

Now, r.m.s value of the induced e.m.f in the whole of primary winding = (induced e.m.f/turn) X No. of primary Turns

$$E_1 = 4.44\, fN_1\emptyset_m = 4.44fN_1B_mA$$

Similarly, r.m.s value of the e.m.f induced in secondary is

$$E_2 = 4.44\, fN_2\emptyset_m = 4.44fN_2B_mA$$

Ratio of Transformer:

Consider a transformer shown in Fig.3.11. Indicating various voltages and currents.

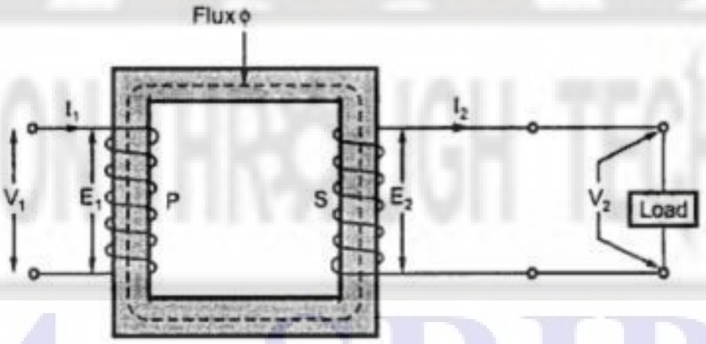


Fig 3.11

3.5 Voltage Ratio:

We know from the e.m.f equations of a transformer that

$$E_1 = 4.44\emptyset_{max} fN_1 \;\; volt$$

And

$$E_2 = 4.44\emptyset_{max} fN_2 \;\; volt$$

Taking ratio of the two equations we get,

$$\frac{E_2}{E_1} = \frac{N_2}{N_1} = K$$

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

Thus,

$$E_2 = KE_1 \qquad where\ K = \frac{N_2}{N_1}$$

If $N_2 > N_1$ i.e. K>1, we get $E_2 > E_1$ then the transformer is called step-up transformer

If $N_2 < N_1$, i.e. K<1, we get $E_2 < E_1$ then the transformer is called step-down transformer If $N_2 = N_1$, i.e. K=1, we get $E_2 = E_1$ then the transformer is called isolation transformer **Ideal Transformer on No Load**

Consider an ideal transformer on no load as shown in the Fig. 3.12. The supply voltage is and as it is V_1 an no load the secondary current $I_2 = 0$.

The primary draws a current I_1 which is just necessary to produce flux in the core. As it magnetising the core, it is called magnetising current denoted as I_m. As the transformer is ideal, the winding resistance is zero and it is purely inductive in nature. The magnetising current is I_m is very small and lags V_1 by 30^o as the winding is purely inductive. This I_m produces an alternating flux Φ which is in phase with I_m.

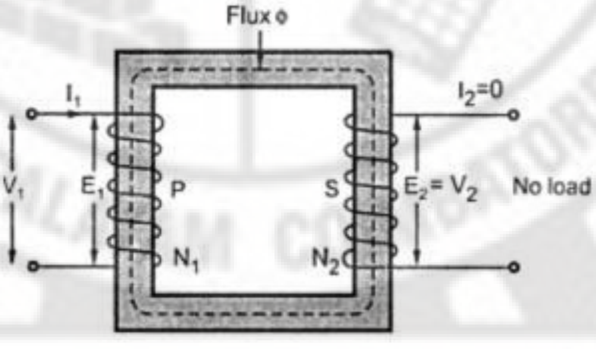


Fig 3.12

The flux links with both the winding producing the induced e.m.f.s E_1 and E_2 , in the primary and secondary windings respectively. According to Lenz's law, the induced e.m.f. opposes the cause producing it which is supply voltage V_1. Hence E_1 is in antiphase with V_1 but equal in magnitude. The induced E_2 also opposes V_1 hence in antiphase with V_1 but its magnitude depends on N_2. Thus E_1 and E_2 are in phase.

The phasor diagram for the ideal transformer on no load is shown in the Fig. .3.13.

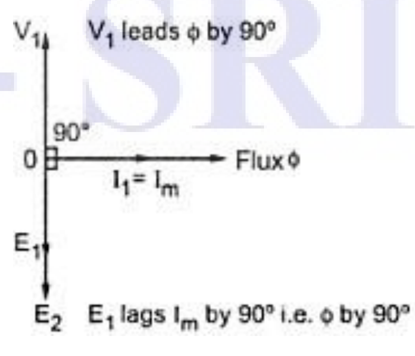


Fig 3.13

It can be seen that flux Φ is reference. I_m produces Φ hence in phase with Φ. V_1leads I_m by 90^o as winding is purely inductive so current has to lag voltage by 90^o.

E_1 and E_2 are in phase and both opposing supply voltage.

The power input to the transformer is V_1 I_1 cos (V_1 ^ I_1) i.e. V_1 I_m cos(90^o) i.e. zero. This is because on no load output power is zero and for ideal transformer there are no losses hence input power is also zero. Ideal no load p.f. of transformer is zero lagging.

3.6 Transformer on No-Load:

Actually in practical transformer iron core causes hysteresis and eddy current losses as it is subjected to alternating flux. While designing the transformer the efforts are made to keep these losses minimum by,

1. Using high grade material as silicon steel to reduce hysteresis loss
2. Manufacturing core in the form of laminations or stacks of thin lamination to reduce eddy current loss

Apart from this there are iron losses in the practical transformer. Practically primary winding has certain resistance hence there are small primary copper loss present.

Thus the primary current under no load condition has to supply the iron losses. i.e. hysteresis loss and eddy current loss and a small amount of primary copper loss. This current is denoted as I_o

Now the no load input current I_o has two components:

1. A purely reactive component I_m called magnetising component of no load current required to produce the flux. This is called wattles component.
2. An active component I_w or I_c which supplies total losses under no load condition called power component of no load current. This is called wattful component or core loss component of I_o

The total no load current Io is the vector addition of I_m and I_w

$\overline{I_0} = \overline{I_m} + \overline{I_w}$

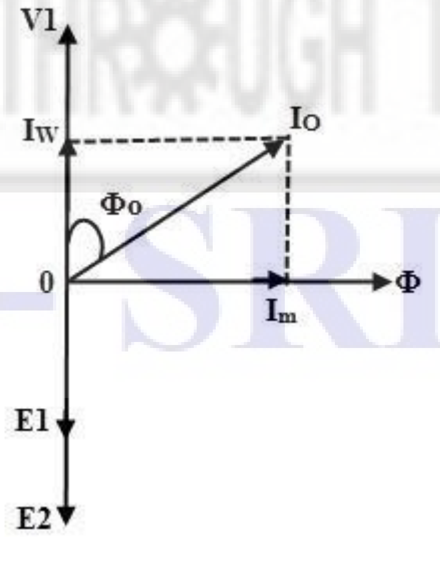


Fig 3.14

3.7 Transformer on Load:

The transformer is said to be loaded when the secondary circuit of a transformer is completed through an impedance or load. The magnitude and phase of secondary current I_2 with respect to secondary terminal voltage will depend upon the characteristics of load. i.e. current I_2 will be in phase, lag behind and lead the terminal voltage V_2 respectively when the load is purely resistive, inductive and capacitive.

The secondary current I_2 sets up its own ampere-turns ($=N_2I_2$) and creates its own flux Φ_2 opposing the main flux Φ_0 created by no-load current I_0. The opposing secondary flux Φ_2 weakens the primary flux Φ_0 momentarily hence primary counter or back e.m.f E_1 tends to be reduced. V_1 gains the upper hand over E_1 momentarily an hence causes more current to flow
In primary.

Let this additional primary current be I_2'. It is known as load component of primary current. The additional primary m.m.f $N_1 I_2'$ sets up its own flux $\emptyset_2'$ which is in opposition to $\emptyset_2$ and is equal to it in magnitude. Hence they cancel each other.

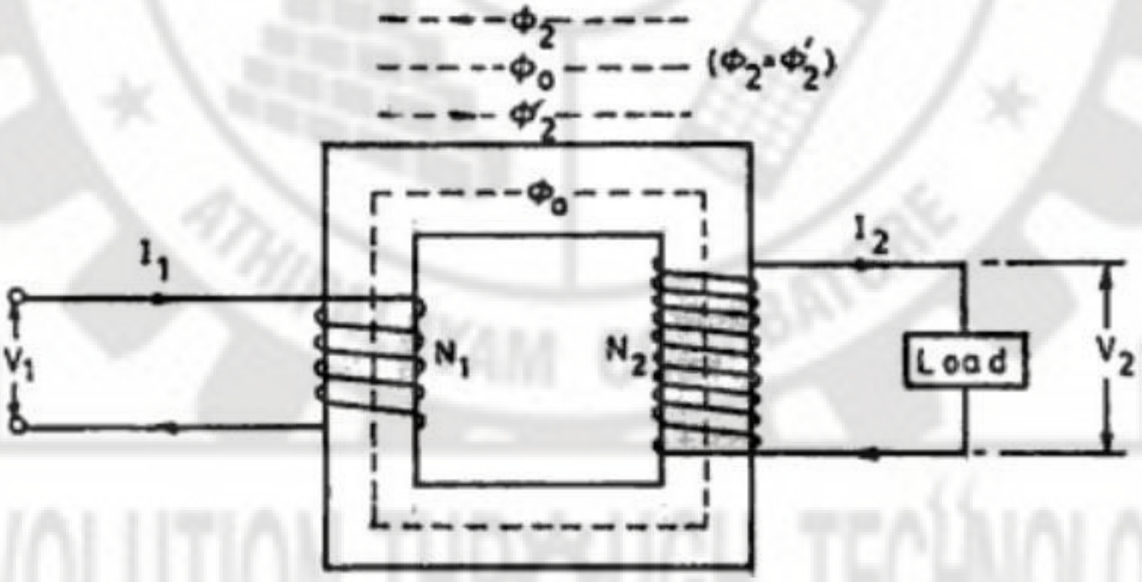


Fig. 3.15

From the above discussion it can be concluded that:

1. Whatever be the load conditions, ***the net flux passing through the core is approximately the same as at no-load***
2. *Since the core flux remains constant at all loads, the* ***core loss almost remains constant under different loading conditions.***

Since, $\emptyset_2 = \emptyset_2'$

$\therefore$ $N_2 I_2 = N_1 I_2'$

i.e $I_2' = \dfrac{N_2}{N_1} \times I_2 = K I_2$ $\quad\because \dfrac{N_2}{N_1} = K$

The total primary current is the vector sum of I_0 *and* I_2': the current I_2' is in anti-phase with I_2 and K times in magnitude.

3.8 Current Ratio:

For an ideal transformer there are no losses. Hence the product of primary voltage V1 and Primary current I1, is same as the product of secondary voltage V2 and the

$So, \quad V_1 I_1 = input\ VA \quad and \quad V_2 I_2 = output\ VA$

secondary current I2.

For an ideal transformer,

$$V_1 I_1 = V_2 I_2$$

$$\frac{V_2}{V_1} = \frac{I_1}{I_2} = K$$

3.9.1 Phasor diagram on no load

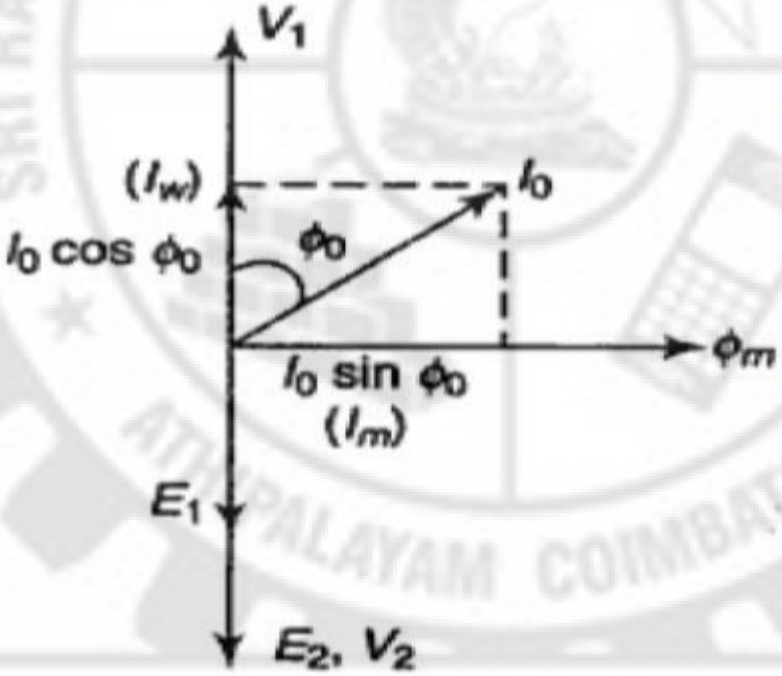


Fig. 3.16 Phasor diagram under no-load condition

In practical transformer, due to winding resistance, no load current I_o is no longer at 90^0 with respect to V_1. But it lags V_1 by angle Φ_0 which is less than 90^0. Thus $\cos\Phi_0$ is called no load power factor of practical transformer.

The Phasor diagram is shown in the Fig.3.16. It can be seen that the two components of Io are,

$$I_m = I_0 sin\emptyset_0$$

This is magnetising component lagging V1 exactly by 90^0

$$I_w = I_0 cos\emptyset_0$$

This is core loss component which is in-phase with

V_1

$$I_0 = \sqrt{I_m^2 + I_w^2}$$

The magnitude of the no-load current is given by, While $\emptyset_0 = No\ load\ primary\ power\ factor\ angle$

The total power input on no load is denoted as W_o and is given by,

$W_0 = V_0 I_0 \cos\emptyset_0 = V_0 I_w$

It may be noted that the current I_o is very small, about 3 to 5% of the full load rated current. Hence the primary copper loss is negligibly small hence I_c or I_W is called core loss or iron loss component. Hence power input W_0 on no load always represents the iron losses as copper loss is negligibly small. The iron losses are denoted as P_i and are constant for all load conditions.

$\therefore \quad W_0 = V_0 I_0 \cos\emptyset_0 = P_i = Iron\ loss$

3.9.2 Phasor Diagram or Vector Diagram On Load (Different Power Factors)

Consider a transformer supplying the load as shown in the Fig. 3.17

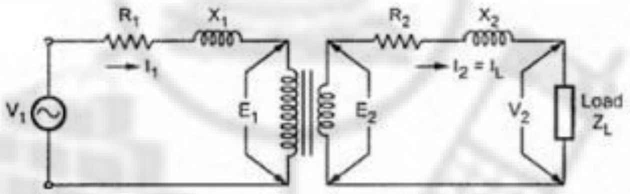


Fig 3.17

The various transformer parameters are,

R_1		=	Primary winding resistance
X_1		=	Primary leakage reactance
R_2		=	Secondary winding resistance
X_2		=	Secondary leakage reactance
Z_L		=	Load impedance
I_1		=	Primary current
I_2		=	Secondary current = I_L = Load current
now	$\bar{I}_1$	=	$\bar{I}_o + \bar{I}_2'$
where	I_o	=	No load current
I_2'		=	Load component of current decided by the load
		=	K I_2 where K is transformer component

The primary voltage V_1 has now three components,

1. $-E_1$, the induced e.m.f. which opposes V_1
2. $I_1 R_1$, the drop across the resistance, in phase with I_1
3. $I_1 X_1$, the drop across the reactance, leading I_1 by 90°

$\therefore \quad \bar{V}_1 = -\bar{E}_1 + \bar{I}_1\bar{R}_1 + \bar{I}_1\bar{X}_1$ ... phasor sum

$= -\bar{E}_1 + \bar{I}_1 (R_1 + j X_1)$

$\boxed{V_1 = -\bar{E}_1 + \bar{I}_1\bar{Z}_1}$

The secondary induced e.m.f. has also three components,

1. V_2, the terminal voltage across the load
2. $I_2 R_2$, the drop across the resistance, in phase with I_2
3. $I_2 X_2$, the drop across the reactance, leading I_2 by 90°

$\therefore \quad \bar{E}_2 = \bar{V}_2 + \bar{I}_2\bar{R}_2 + \bar{I}_2\bar{X}_2$ ... phasor sum

$\therefore \quad \bar{V}_2 = \bar{E}_2 - \bar{I}_2 (R_2 + j X_2)$

$\therefore \quad \boxed{V_2 = \bar{E}_2 - \bar{I}_2\bar{Z}_2}$

The phasor diagram for the transformer on load depends on the nature of the load power factor. Let us consider the various cases of the load power factor.

1.1 Unity power factor load, cosΦ_2 = 1

As load power factor is unity, the voltage V_2 and I_2 are in phase. Steps to draw the phasor diagram are,

1. Consider flux Φ as reference
2. E_1 lags Φ by 90°. Reverse E_1 to get $-E_1$.
3. E_1 and E_2 are inphase
4. Assume V_2 in a particular direction
5. I_2 is in phase with V_2.
6. Add $I_2 R_2$ and $I_2 X_2$ to to get E_2.
7. Reverse I_2 to get I_2'.
8. Add I_o and I_2' to get I_1.
9. Add $I_1 R_1$ and to $-E_1$ to get V_1.

Angle between V_1 and I_1 is Φ_1 and cosΦ_1 is primary power factor. Remember that I_1X_1 leads I_1 direction by 90° and I_2 X_2 leads I_2 by 90° as current through inductance lags voltage across inductance by 90°. The phasor diagram is shown in the Fig.3.18

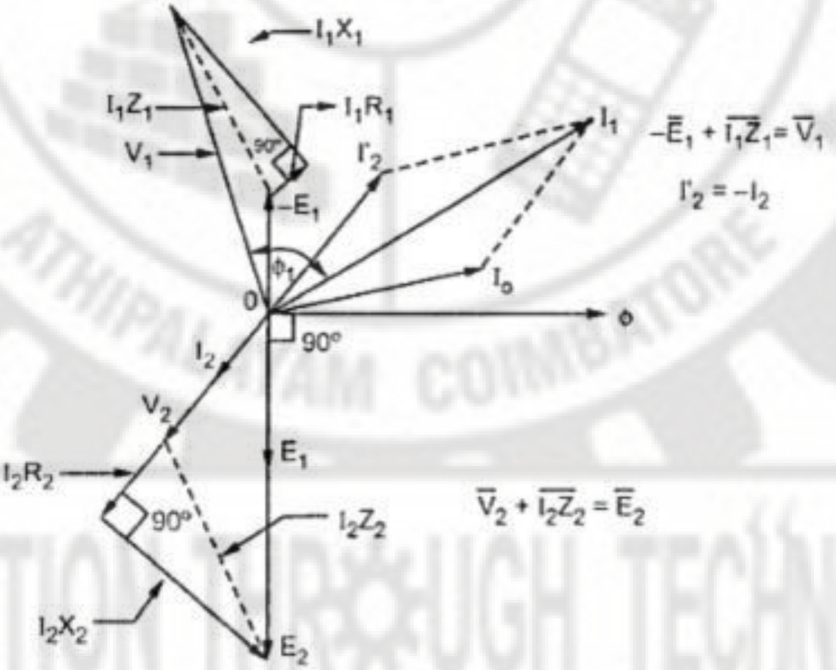


Fig 3.18

Lagging Power Factor Load, cos Φ_2

As load power factor is lagging cosΦ_2, the current I_2 lags V_2 by angle Φ_2. So only changes in drawing the phasor diagram is to draw I_2 lagging V_2 by Φ_2 in step 5 discussed earlier. Accordingly direction of I_2 R_2, I_2 X_2, I_2', I_1, I_1 R_1 and I_1X_1 will change. Remember that whatever may be the power factor of load, I_2X_2 leads I_2 by 90° and I_1X_1 leads I_1 by 90°.

The complete phasor diagram is shown in the Fig. 3.19

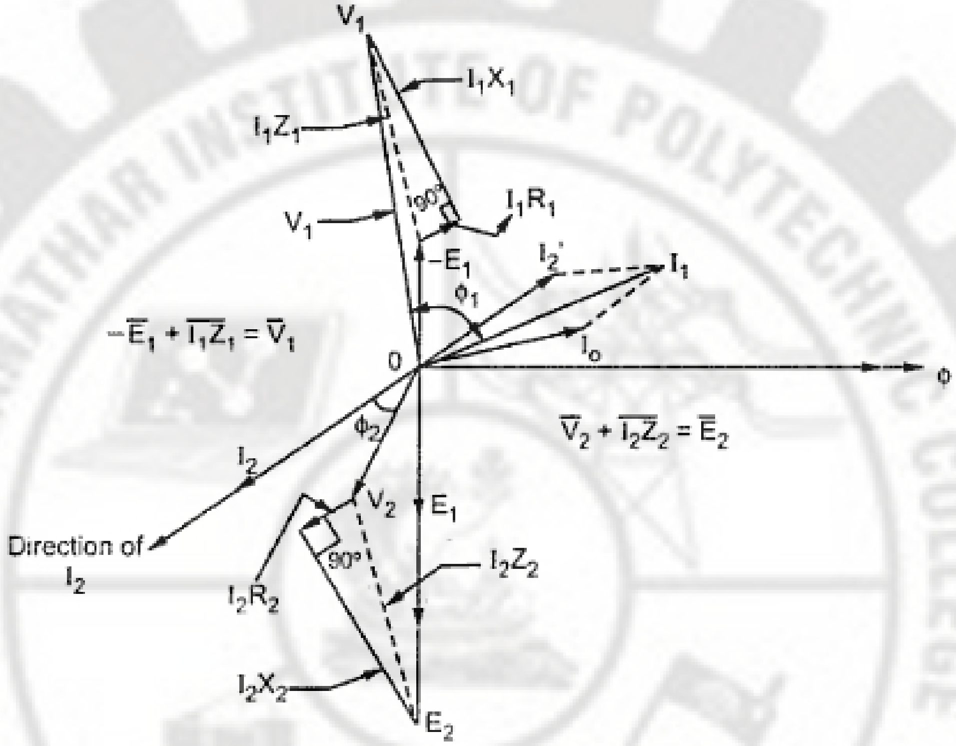


Fig3.19

Loading Power Factor Load, cos Φ_2

As load power factor is leading, the current I_2 leads V_2 by angle Φ_2. So change is to draw I_2 leading I_2 by angle Φ_2. All other steps remain same as before. The complete phasor diagram is shown in the Fig. 3.20

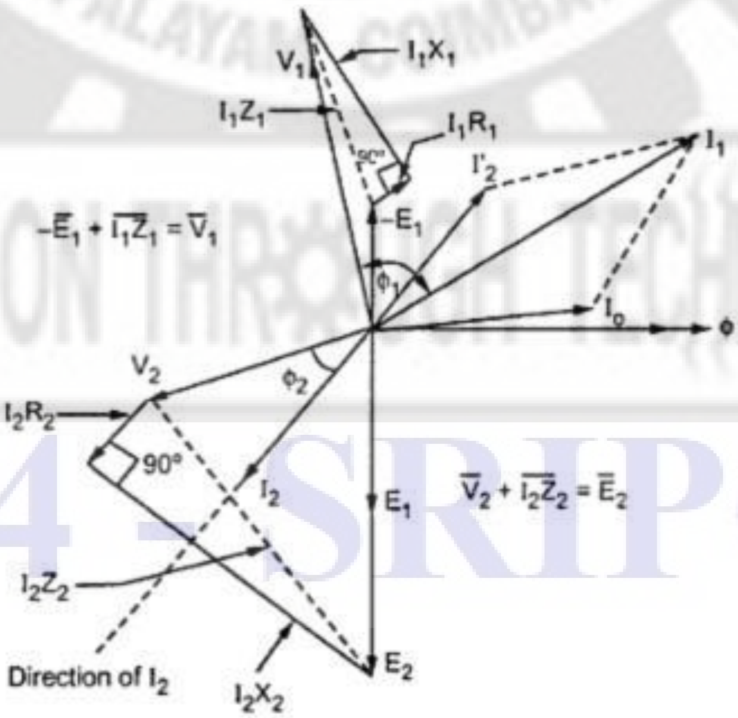


Fig 3.20

Equivalent circuit of Transformer

The term equivalent circuit of a machine means the combination of fixed and variable resistances and reactances, which exactly simulates performance and working of the machine.

For a transformer, no load primary current has two components, I_m = I_o $\sin\Phi_o$ = Magnetizing component

$I_c = I_o \cos\Phi_o$ = Active component

I_m produces the flux and is assumed to flow through reactance X_o called no load reractance while I_c is active component representing core losses hence is assumed to flow through the reactance R_o. Hence equivalent circuit on no load can be shown as in the Fig.3.21. This circuit consisting of R_o and X_o in parallel is called exciting circuit. From the equivalent circuit we can write,

$R_o = V_1/I_c$

and $X_o = V_1/I_m$

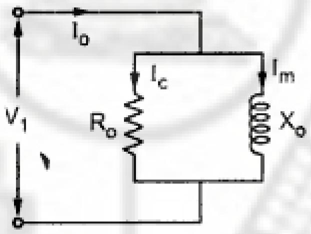


Fig 3.21

When the is connected to the transformer then secondary current I_2 flows. This causes voltage drop across R_2 and R_2. Due to I_2, primary draws an additional current $I_2' = I_2/K$. Now I_1 is the phasor addition of I_o and I_2'. This I_1 causes the voltage drop across primary resistance R_1 and reactance X_1.

Hence the equivalent circuit can be shown as in the Fig. 3.22.

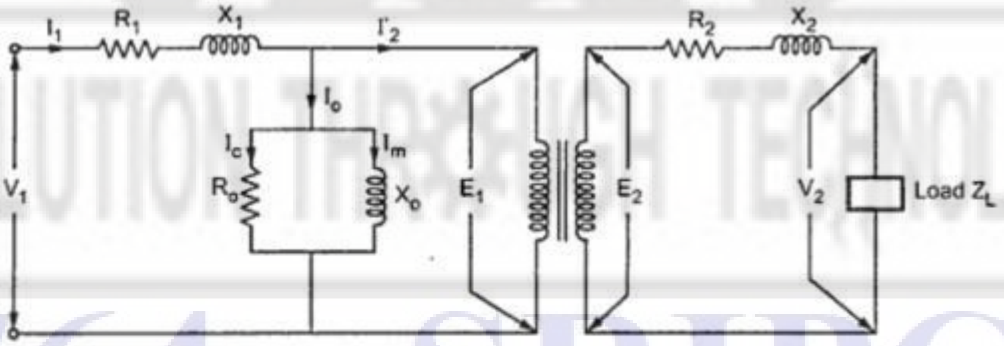


Fig 3.22

But in the equivalent circuit, windings are not shown and it is further simplified by transferring all the values to the primary or secondary. This makes the transformer calculation much easy.

So transferring secondary parameters to primary we get, $R_2' = R_2/K^2$, $X_2' = X_2/K^{2'}$, $Z_2' = Z_2/K^2$

While $E_2' = E_2/K'$ $I_2' = K\, I_2$

Where $K = N_2/N_1$

While transferring the values remember the rule that

Low voltage winding High current Low impedance High voltage winding Low current

High impedance

Thus the exact equivalent circuit referred to primary can be shown as in the Fig. 3.23

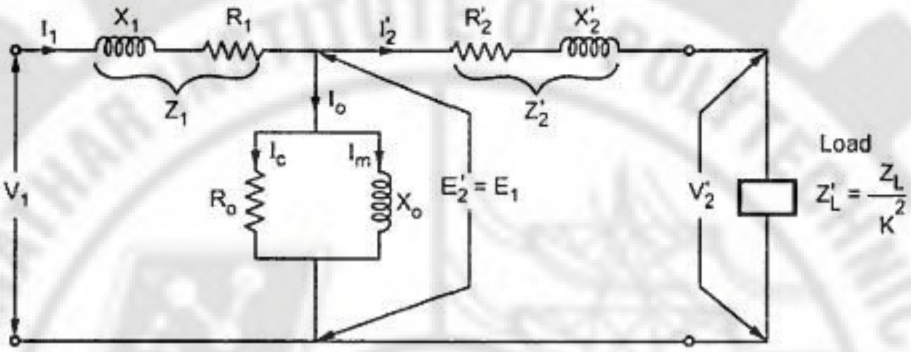


Fig 3.23

Similarly all the primary value can be referred to secondary and we can obtain the equivalent circuit referred to secondary.

$R_1' = K^2 R_1$, $X_1' = K^2 X_1$, $Z_1' = K^2$

Z_1 $E_1' = K E_1$, $I_o' = I_1 /K'$ $I_o' = I_o /K$

Similarly the exciting circuit parameters also gets transferred to secondary as $R_o'$and X_o '. The circuit is shown in the Fig.3.24.

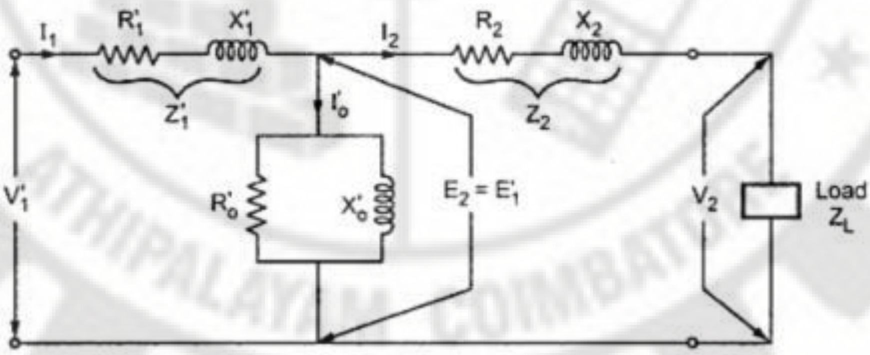


Fig 3.24

Now as long as no load branch i.e. exciting branch is in between Z_1 and Z_2', the impedances can not be combined. So further simplification of the circuit can be done. Such circuit is called approximate equivalent circuit.

<u>Approximate Equivalent Circuit</u>

To get approximate equivalent circuit, shift the no load branch containing R_o and X_o to the left of R_1 and X_1. By doing this we are creating an error that the drop across R_1 and X_1due to I_o is neglected. Hence such an equivalent circuit is called approximate equivalent circuit.

So approximate equivalent circuit referred to primary can be as shown in the Fig. 3.25.

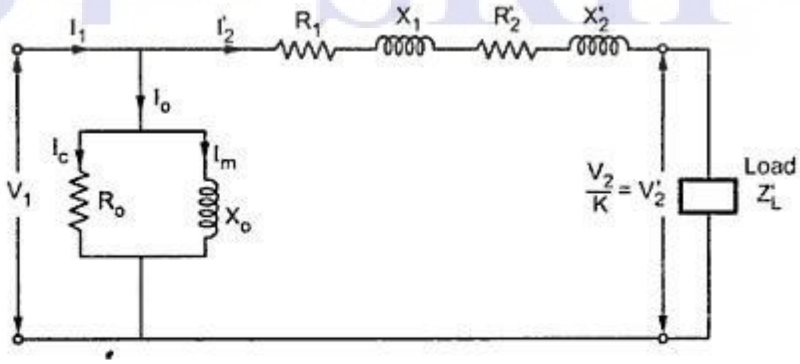


Fig 3.25

In this circuit now R_1 and R_2' can be combined to get equivalent resistance referred to primary R_{1e} as discussed earlier. Similarly $X_1$and X_1' can be combined to get X_{1e}. And equivalent circuit can be simplified as shown in the Fig. 3.26.

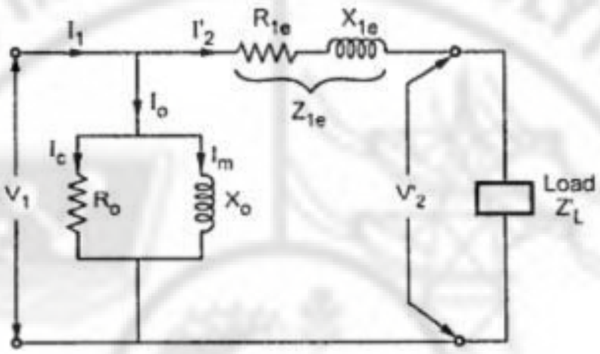


Fig 3.26

We know that, $R_{1e} = R_1 + R_2' = R_1 + R_2/K^2$

$$X_{1e} = X_1 + X_2' = X_1 + X_2/K^2$$

$$Z_{1e} = R_{1e} + j\, X_{1e}$$

$$R_o = V_1 / I_c \text{ and } X_o = V_1 / I_m$$

$$I_c = I_o \cos\Phi_o \text{ and } Im = I_o \sin\Phi_o$$

In the similar fashion, the approximate equivalent circuit referred to secondary also can be obtained.

3.10 Determination of Equivalent Circuit Constants:

The equivalent circuit parameters of a transformer are determined by conducting two tests on a transformer which are

1. ***Open Circuit Test (O.C. test)***
2. ***Short Circuit Test (S.C. Test)***

The parameters calculated from these test results are effective in determining the regulation and efficiency of a transformer at any load and power factor condition, without actually loading the transformer. The advantage of this method is that without much power loss the tests can be performed and results can be obtained.

3.10.1 Open Circuit Test (O.C. Test):

The experimental circuit to conduct O.C. test is shown in the Fig.3.27

The transformer primary is connected to a.c. supply through ammeter, wattmeter and variac. The secondary of transformer is kept open. Usually low voltage side is used as primary and high voltage side as secondary to conduct O.C.Test.

The primary is excited by rated voltage, which is adjusted precisely with the help of a variac. The wattmeter measures input power. The ammeter measures input current. The voltmeter gives the value of rated primary voltage applied at rated frequency.

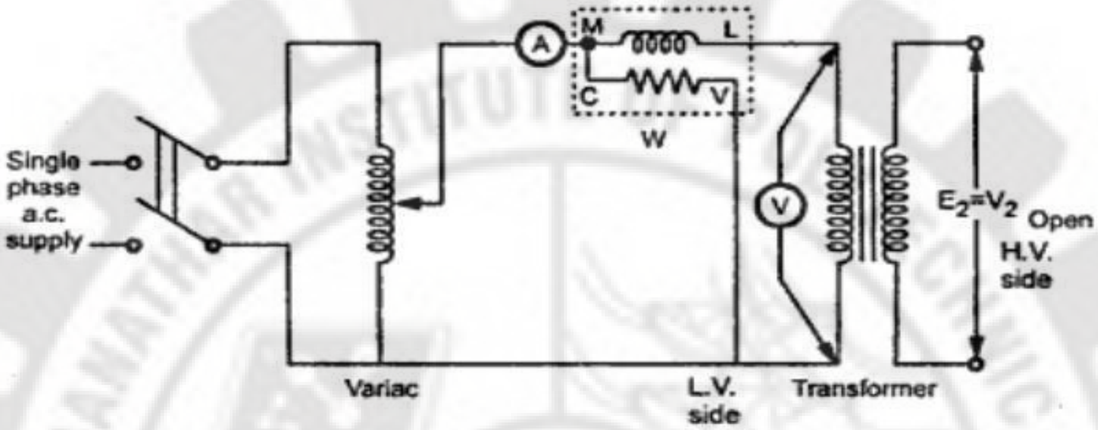


Fig.3.27 Experimental Circuit for O.C. Test

When the primary voltage is adjusted to its rated value with the help of variac, readings of ammeter and wattmeter are to be recorded.
The observation table is as follows.

No load Voltage V_o Volt	No load Current I_o Ampere	No load Power W_o Watt

Where,

V_o = Rated Voltage

I_o = Input current = No Load current

W_o = Input Power

As transformer secondary is open, it is on load. So current drawn by the primary is no load current I_o. The two components of this no load current are,

$$I_m = I_0 \sin \emptyset_0$$

$$I_W = I_0 \cos \emptyset_0$$

Where, $\cos \emptyset_0 = No\ load\ power\ factor$

And hence power input can be written as,

$$W_0 = V_0 I_0 \cos \emptyset_0$$

The transformer no load current is always very smaall, hardly 2 to 4% of its full load value. As I_2=0, secondary copper losses are zero. And I_1= I0 is very low hence copper losses on primary are also very very low. Thus the total copper losses in O.C test are negligible small.

As output power is zero and copper losses are very low, the total input power is used to supply iron losses.

This power is measured by the wattmeter i.e. W_o. Hence the wattmeter in O.C test gives iron losses which remain constant for all the loads.

∴ $W_0 = P_i = Iron\ loeeses$

Calculations: We know that,

$W_0 = V_0 I_0 \cos\phi_0$

$\therefore \quad \cos\phi_0 = \frac{W_0}{V_0 I_0} = No\ load\ power\ factor$

Once $\cos\phi_0$ is known we can obtain,

$I_W = I_0 \cos\phi_0$

and

$I_m = I_0 \sin\phi_0$

Once I_w and I_m are known we can determine exciting circuit parameters as,

$R_0 = \frac{V_0}{I_W}\ \Omega \quad and\ X_0 = \frac{V_0}{I_m}\ \Omega$

3.10.2 Short Circuit Test (S.C. Test):

In this test, primary is connected to a.c supply through variac, ammeter and voltmeter as shown in the Fig.3.28

The secondary is short circuited with the help of thick copper wire or solid link.As high voltage side is always low current side, it is convenient to connect high voltage side to supply and shorting the low voltage side.

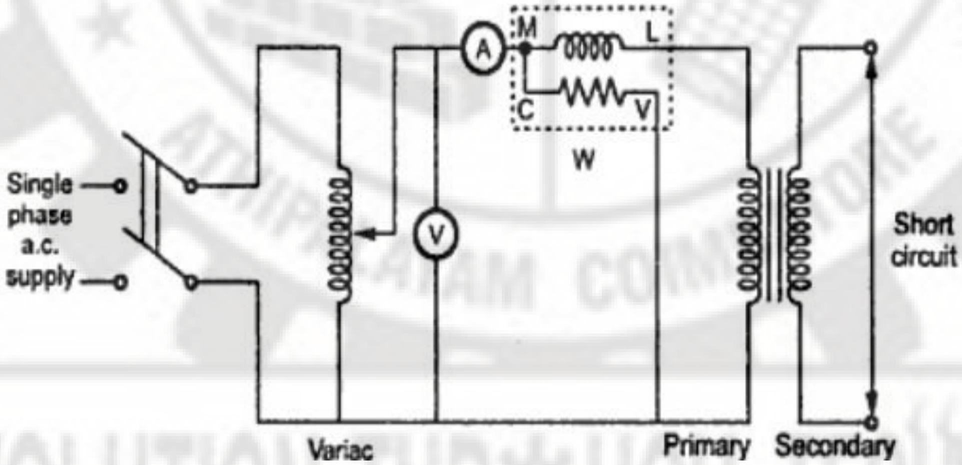


Fig.3.28 Experimental circuit for S.C. Test

As secondary is shortted, its resistance is very small and on rated voltage it may draw very large current. Such large current can cause overheating and burning of the transformer. To limit this short circuit current, primary is supplied with low voltage which is just enough to cause rated current to flow through primary which can be observed on an ammeter.

The low voltage can be adjusted with the help of variac. Hence this test is also called low volatge test or reduced voltage test. The wattmeter reading as well as voltmeter, ammeter readings are recorded. The observation table is as follows.

Short circuit Voltage V_{sc} Volt	Short circuit Current I_{sc} Ampere	Short circuit Power W_{sc} Watt

Now the cureent flowing through the winding is rated current hence the total copper loss is the full load copper loss. Now the voltage applied is low whhich is a small fraction of the rrated voltage. The iron losses are fuction of applied voltage.

So the iron losses in reduced voltage test are very small. Hence the wattmeter reading is the power loss which is equal to full load copper losses as iron losses are very low.

$\therefore \quad W_{sc} = (P_{cu})F.L = Full\, load\, copper\, loss$

Calculations:

From the S.C. test readings we can write,

$W_{SC} = V_{SC} I_{SC} \cos \emptyset_{SC}$

$\therefore \quad \cos \emptyset_{SC} = \frac{V_{SC} I_{SC}}{W_{SC}}$

$W_{SC} = I_{SC}^2 R_{01} = Copper\ loss$

$R_{01} = \frac{W_{SC}}{I_{SC}^2}$

And

$Z_{01} = \frac{V_{SC}}{I_{SC}} = \sqrt{R_{01}^2 + X_{01}^2}$

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

Thus we get the equivalent circuit parameters R_{01}, X_{01} and Z_{01}. Knowing the transformation ratio K, the equivalent circuit parameters referred to secondary also can be obtained.

3.11 Voltage Regulation Of Transformer:

Voltage drop occures in a transformer due to resistance of the winidng and leakage reactance . due to the above reasons,the secondaruy voltage under load is different from the terminal volatge under no-load conditions.

The regulation is defined as change in the magnitude of the secondary terminal voltage, when full load i.e rated load of specified power factor supplied at rated voltage is reduced to no load, with primary volatge maintained constant expresed as the percenatge of the rated terminal volatge.

Let V_{20} = Secondary terminal voltage on no-load V_2 = Secondary terminal on given load

Then mathematiclly voltage regulation at given load can be expressed as,

$$\%\,Voltage\ Regulation = \frac{No\ load\ voltage\ - load\ voltage}{Load\ volatge} \times 100$$

$$\%\,Voltage\ Regulation = \frac{V_{20} - V_2}{V_2} \times 100$$

$$The\ ratio\ of\ \left(\frac{V_{20} - V_2}{V_2}\right)\ is\ called\ per\ unit\ regulation$$

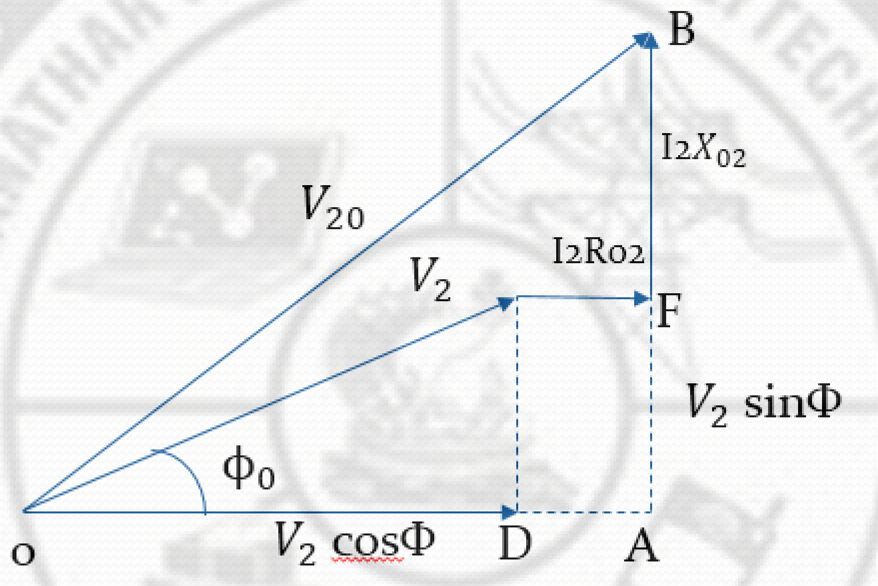
The percentage of volatge regulation depends upon the load current and load power factor. Therefore for calculating the regulation of transformer may be derived by drawing the vector diagram of transformer on load at different power factors shown in Fig

As load current I_L increases, the voltage drops tend to increase and V_2 drops more and more. In case of lagging power factor $V_2 < V_{20}$ and we get positive voltage

regulation, while for leading
power factor $V_{20} < V_2$ and we get negative voltage regulation.

Expression For Voltage Regulation:

For lagging power factor



From vector diafgram

(a) OB = $\sqrt{OA^2 + AB^2}$

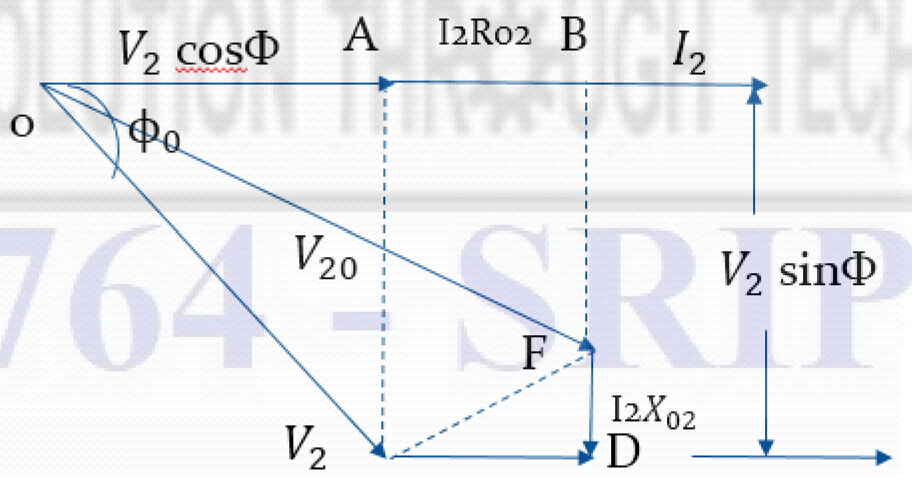
= $\sqrt{(OD + DA)^2 + (AF + FB)^2}$

Where OB= V_{20} ; OD = $V_2 \cos\emptyset_0$; DA = I_2R_{02}; AF = $V_2 \sin\emptyset_0$; FB = I_2X_{02} $V_{20} = \sqrt{(V_2 \cos\emptyset_0 + I_2R_{02})^2 + (V_2 \sin\emptyset_0 + I_2X_{02})^2}$

Then the percentage of voltage regulation canbe calculated at lagging power factor by using the formula

$$\% \, Voltage \ Regulation = \frac{V_{20} - V_2}{V_2} \times 100$$

For leading power factor



From the vector diagram

(b) OF = $\sqrt{OB^2 + BF^2}$

= $\sqrt{(OA + AB)^2 + (BD - FD)^2}$

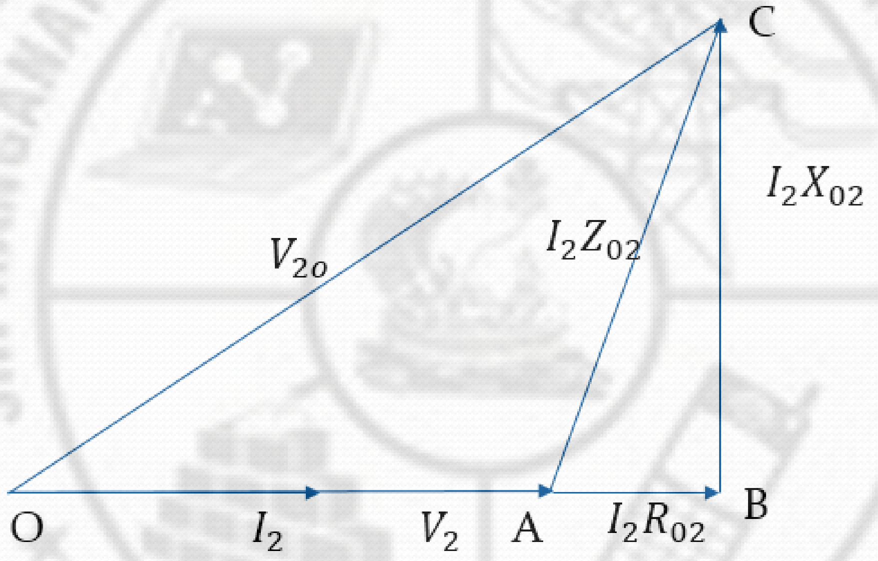
Where OF= V_{20} ; OA = $V_2 \cos\emptyset_0$; AB = I_2R_{02}; BD = $V_2 \sin\emptyset_0$; FD =

I_2X_{02} $V_{20} = \sqrt{(V_2\, cos\emptyset_0 + I_2R_{02})^2 + (V_2\, sin\emptyset_0 - I_2X_{02})^2}$

Then the percentage of voltage regulation canbe calculated at leading power factor by using the formula

$$\%\, Voltage\ Regulation = \frac{V_{20} - V_2}{V_2} \times 100$$

For unity power factor



From the vector diagram

(c) OC = $\sqrt{OB^2 + BC^2}$

= $\sqrt{(OA + AB)^2 + (BC)^2}$

Where OC= E_2 ; OA = V_2 ; AB = I_2R_{02}; BC =

I_2X_{02} $V_{20} = \sqrt{(V_2\ + I_2R_{02})^2 + (I_2X_{02})^2}$

Then the percentage of voltage regulation canbe calculated at unity power factor by using the formula

$$\%\, Voltage\ Regulation = \frac{V_{20} - V_2}{V_2} \times 100$$

The voltage regulation is defined as,

$$\%Regulation = \frac{V_{20} - V_2}{V_2} \times 100 = \frac{Total\ voltage\ drop}{V_2} \times 100$$

The regulation can be expressed as,

$$\%\, Regulation = \frac{I_2R_{02}\cos\emptyset \pm I_2X_{02}\sin\emptyset}{V_2} \times 100$$

Where,

I_2 = Full load secondary current V_2 = Secondary terminal voltage E_2 = No load secondary volatge

R_{02} = Equivalent resistance reffered to secondary X_{02} = Equivalent reacyance reffered to secondary CosΦ = Load power factor

+ sign for lagging power factor while – sign for leading power factor loads

Losses In A Transformer:

In a trnasforemr, there exists two types of losses.

1. The core gets subjected to an alternating flux, causing core losses
2. The winding carry current when transformer is loaded, causing copper losses.

Core or Iron Lossess:

Due to alternating flux set up in the magnetic core of the transformer , it undergoes a cycle of magnetization and demagnetization. Due to hystesis effect there is loss of energy in this process which is called hysteresis loss.

It is given by,

$Hysteresis\ loss = K_h B_m^{1.6} f v \quad watt$

Where,

K_h = Hystesresis constant depends on material

B_m = maximum Flux density

F = Frequency

V = volume of the core

The induced e.m.f. in the core tries to set up eddy current in the core and hence responsible for the eddy current losses. The eddy current loss is given by,

$$Eddy\ current\ loss = K_e B_m^2 f^2 t^2 \text{watt/unit volume}$$

Where,

Ke = Eddy current constant T = thickness of the core

Copper Lossess:

The copper losses are due to the power wasted in the form of I^2R loss due to the resistance of the primary and secondary windings. The copper loss depends on the magnitude of the current flowing through the winding.

$$Total\ Cu\ loss = I_1^2 R_1 + I_2^2 R_2 = I_1^2(R_1 + R'_2) = I_2^2(R_2 + R'_1) = I_1^2 R_{01} = I_2^2 R_{02}$$

The copper losses are denoted as Pcu. If the current through the windings is full load current, we get copper lossess at full load. If the load on transformer is half then we get copper losses at half load which are less than full load copper losses.

Thus copper lossess are called variable lossess. Copper losses are proportional to the square of the kVA rating

So,

$$P_{cu} \propto I^2 \propto (kVA)^2$$

Thus for trnasformer,

Total lossess = Iron lossess + Copper loss

= $P_i + P_{cu}$

3.11 Efficiency of A Transformer:

Due to the lossess in a transformer, the output power of a transformer is less than the input power supplied.

∴ Power ouput = Power input – Total lossess

∴ Power input = Power output+ Total lossess

= Power output+ Pi+Pcu

The efficiency of any device is defined as the ratio of the power output to power input. So for a transformer the efficiency can be expressed as,

$$\eta = \frac{Power\ output}{Power\ Input}$$

$$\therefore\ \eta = \frac{Power\ output}{Power\ Input + P_i + P_{cu}}$$

Now power output = $V_2 I_2 Cos\Phi$

Where CosΦ = Load power factor

The transformer supplies full load of current I2 and terminal voltage V2 P_{cu} =Copper lossess on full load = $I_2^2 R_{02}$

$$\therefore\ \eta = \frac{V_2 I_2 \cos\emptyset_2}{V_2 I_2 \cos\emptyset_2 + P_i + I_2^2 R_{02}}$$

But $V_2 I_2$ = VA rating of a Transformer

$$\therefore\ \eta = \frac{(VA\ rating) \times \cos\emptyset_2}{(VA\ rating) \times \cos\emptyset_2 + P_i + I_2^2 R_{02}}$$

$$\therefore\ \%\eta = \frac{(VA\ rating) \times \cos\emptyset_2}{(VA\ rating) \times \cos\emptyset_2 + P_i + I_2^2 R_{02}} \times 100$$

But if the transformer is subjected to fractional load then using the appropriate values of various quantities , the efficiency can be obtained.

Let n = Fractional by which load is less than full load = (Actual load/ Full load) In general for fractional load the efficecny is given by,

$$\therefore \quad \%\eta = \frac{n(VA\,rating) \times \cos\emptyset_2}{n(VA\,rating) \times \cos\emptyset_2 + P_i + n^2(P_{cu})F.L} \times 100$$

Where n= Fraction by which load is less than full load

3.12 Condition For Maximum Efficiency:

When a transformer works on a constant input voltage and frequency then efficiecny varies with the load. As load increases, the effciecny increases. At a certain load current, it achieves a maximum value. If the transformer is loaded further the efficiecny starts decreasing. The graph of efficiency against load current I_2 is shown in the Fig.3.29

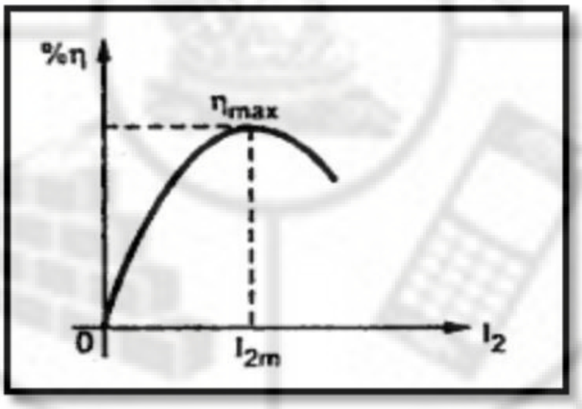


Fig.3.29

The load current at which the efficiency attains maximum value is denoted as I_{2m} and maximum efficiency is denoted as η_{max}

The efficiency is a function of load .i.e. load current I_2 assuming $\cos\Phi_2$ constant. The secondary terminal voltage V_2 is also assumed constant. So for maximum efficiency,

$$\frac{d\eta}{dI_2} = 0$$

Now

$$\eta = \frac{V_2 I_2 \cos\emptyset_2}{V_2 I_2 \cos\emptyset_2 + P_i + I_2^2 R_{02}}$$

$$\therefore \quad \frac{d\eta}{dI_2} = \frac{d}{dI_2}\left[\eta = \frac{V_2 I_2 \cos\emptyset_2}{V_2 I_2 \cos\emptyset_2 + P_i + I_2^2 R_{02}}\right] = 0$$

$$(V_2 I_2 \cos\emptyset_2 + P_i + I_2^2 R_{02}) \frac{d}{dI_2}(V_2 I_2 \cos\emptyset_2) - (V_2 I_2 \cos\emptyset_2) . \frac{d}{dI_2}(V_2 I_2 \cos\emptyset_2 + P_i + I_2^2 R_{02}) = 0$$

$$(V_2 I_2 \cos\emptyset_2 + P_i + I_2^2 R_{02})(V_2 \cos\emptyset_2) - (V_2 I_2 \cos\emptyset_2) . (V_2 \cos\emptyset_2 + 2I_2\ R_{02}) = 0$$

$$V_2^2 I_2 cos^2\emptyset_2 + P_i V_2 \cos\emptyset_2 + V_2 I_2^2 R_{02} \cos\emptyset_2 - V_2^2 I_2 cos^2\emptyset_2 - 2V_2 I_2^2 R_{02} \cos\emptyset_2 = 0$$

$$P_i V_2 \cos\emptyset_2 - V_2 I_2^2 R_{02} \cos\emptyset_2 = 0$$

$$P_i V_2 \cos\emptyset_2 = V_2 I_2^2 R_{02} \cos\emptyset_2$$

$$P_i = I_2^2 R_{02} = P_{cu}$$

So condition to achieve maximum efficiency is that, ***Copper losses= Iron losses***

3.13 All-Day (or Energy) Efficiency:

The primary of distribution transformer is connected to the line for 24 hours a day. Thus the core losses occur for the whole 24 hours whereas copper losses occur only when the transformer is on load. Distribution transformers operate well below the rated power output for most of the time.

It is therefore necessary to design a distribution transformer for maximum efficiency occurring at the average output power. The performance of a distribution transformer is more appropriately represented by all-day or energy efficiency.

Energy efficiency of a transformer is defined as the ratio of total energy output for a certain period to the total energy input for the same period. The energy efficiency can be calculated for any specific period. When the energy efficiency is calculated for a day of 24 hours it is called the all-day efficiency.

All- day efficiency is defined as the ratio of the energy output to the energy input taken over a 24-hour period.

$$\eta_{All\ day} = \frac{Energy\ output\ over\ 24\ hours}{Energy\ input\ over\ 24\ hours} \times 100$$

3.14 Polarity Test:

A polarity test is carried out to find out the terminals having the same instantaneous polarity assuming that the terminals are not marked. The connections are shown in Fig.3.30.

i. One HT and one LT terminals are joined together. A voltmeter is placed between the remaining two terminals.
ii. A convenient moderate voltage is impressed on the HT winding

If the voltage 'V' is 'greater' than the applied voltage V, then the transfer has 'additive' polarity ,If 'V' is less than V, the transformer has 'subtractive polarity'. The terminals are marked accordingly.

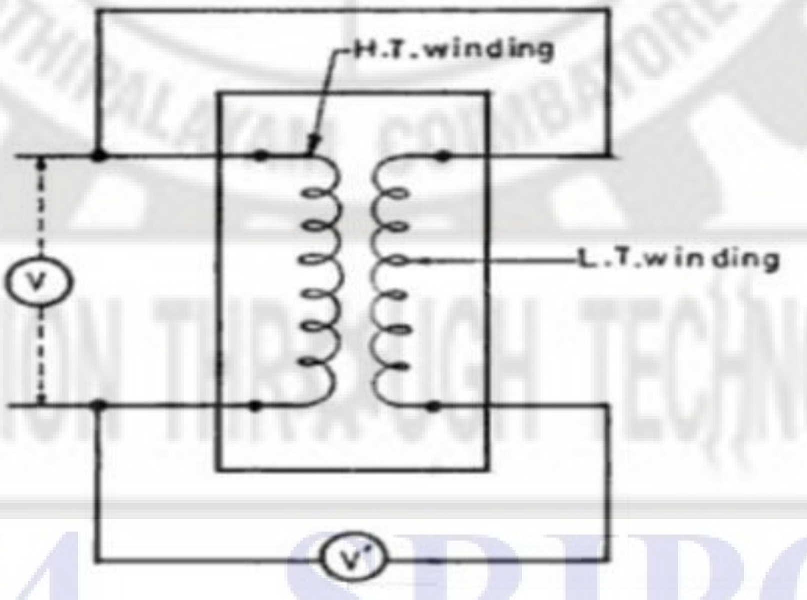


Fig.3.30

3.15 Parallel Operation of Single-Phase Transformers:

If the amount of power to be transfered is greater than the capacity of the existing transformer, it is necessary to connect two or more transformers in parallel.

Conditions for Parallel operation:

For parallel operation of transformers, the following conditions should be satisfied.

1. ***The turns ratio and the voltage ratings should be same***
2. ***Polarities of transformers should be same***
3. ***Percentage impedance of the transformers preferably be same***
4. ***Ratio of resistance to reactance preferably be same***

Advantages of Parallel operation:

1. *The total load of the circuit can be increased*
2. *If any one transformer fails to supply, the continuity of supply is maintained by the other healthy transformer*
3. *Maintenance of each transformer is carried wihtout interruption of supply*

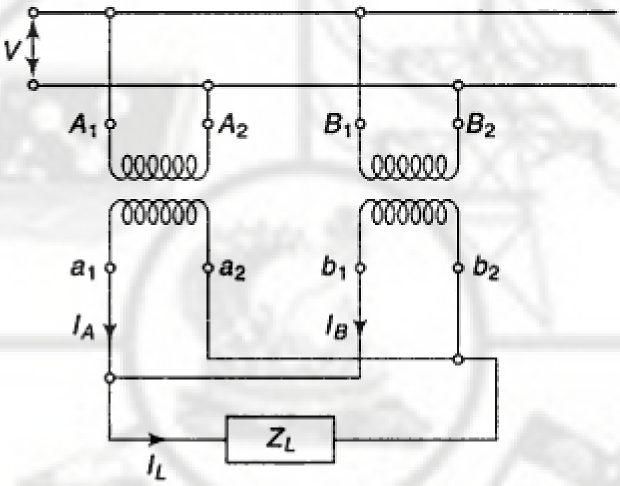


Fig.3.31 Two Single Phase Transformer in Parallel

3.16 Auto Transformer:

A transformer in which part of the winding is common to both the primary and secondary circuits is known as an Auto-Transformer. The primary is electrically connected to the secondary, as well as magnetically coupled to it.

Ref. Fig.3.32 AB is primary winding having N_1 turns and BC is secondary winding having N2 turns. If no-load current and iron losses are neglected

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

The current in the section BC is vector difference of I2 and I1. But since the two currents are practically in phase opposition, the resultant is (I2-I1) where I2>I1

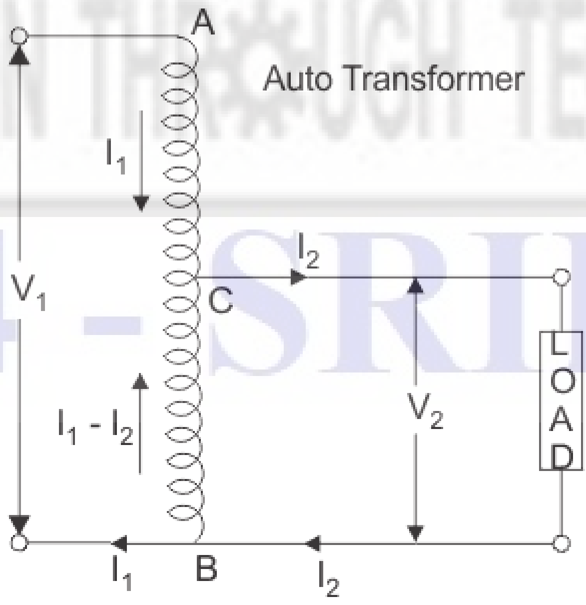


Fig.3.32 Autotransformer

3.17 Saving of Copper (In Comparison To Conventional Two Winding Transformer):

The volume and hence weight of copper is proportional to the length and area of cross-section of the conductors. But the length of conductor is proportional to the number of turns and cross-section depends on current.

Hence the weight of copper is proportional to the product of number of turns and currents to be carried.

$$\text{Weight of copper in conventional two winding transformer} \propto (N_1 I_1 + N_2 I_2)$$

$$\text{Weight of copper in auto} - \text{transformer}$$

$$= \text{weight of copper in section } LS + \text{weight of copper in section } MS$$

$$\text{But weight of copper in section } LS \propto (N_1 - N_2) I_1$$

$$\text{and weight of copper in section } MS \propto N_2 (I_2 - I_1)$$

$$\therefore \text{ Weight of copper in auto} - \text{transformer} \propto (N_1 - N_2) I_1 + N_2 (I_2 - I_1)$$

$$\therefore \frac{\text{weight of copper in auto} - \text{transformer} (W_0)}{\text{Weight of copper in ordinary transformer } (W_0)} = \frac{(N_1 - N_2) I_1 + N_2 (I_2 - I_1)}{N_1 I_1 + N_2 I_2}$$

$$= \frac{(N_1 - 2N_2) I_1 + N_2 I_2}{N_1 I_1 + N_2 I_2}$$

$$= \frac{\frac{N_1}{N_2} - 2 + \frac{I_2}{I_1}}{\frac{N_1}{N_2} + \frac{I_2}{I_1}} = \frac{\frac{1}{K} - 2 + \frac{1}{K}}{\frac{1}{K} + \frac{1}{K}}$$

$$= 1 - K \qquad \left[\because \frac{N_2}{N_1} = K, \frac{I_2}{I_1} = \frac{1}{K}\right]$$

$$\therefore \text{ Saving in copper} = W_0 - W_a = W_0 - (1 - K) W_0 = K W_0$$

$$\therefore \text{ Saving in copper} = K \times \text{Weight of copper in ordinary transformer}$$

It can be proved that power transformed = Input (1-K). The rest of the power is conducted directly from the source to the load.

Advantages:

1. Saving in conductor material and less cost
2. Power loss is reduced. So Efficiency will be high
3. Higher kVA rating
4. Lower percentage reactance hence better voltage regulation
5. Can be used for obtaining variable voltage supply

Disadvantages:

1. If there is break in the secondary winding, full voltage flows from the primary side to the secondary side load
2. Auto transformer winding need more insulation than that of two winding transformer

3.18 Applications of Auto Transformer:

1. It is used as starters for 3 phase induction motors
2. It is used in Electrical furnace
3. Three phase auto transformer are used in the interconnection of grids
4. To give smooth variation of voltage to test circuits in the laboratories
5. As a booster of supply voltage to a small- extent

Worked Examples

Example 3.1 A 40 KVA, single phase transformer has 400 turns on the primary and 100 turns on the secondary. The primary is connected to 2000 V, 50Hz supply. Determine:

(i) The secondary voltage on open circuit

(ii) **The current flowing through the two windings on full load**

(iii) **The maximum value of flux**

Given Data :

Rated power	=	40 KVA
Number of primary turns(N_1)	=	400
Number of secondary turns (N_2)	=	100
Supply voltage (V_1)	=	2000V
Supply frequency	=	50Hz

To Find :

Secondary voltage on open circuit (E_2)=?

Current flowing through the two windings (I_1 and I_2)=?

Maximum value of flux ($\emptyset_{max}$)= ?

Solution:

Secondary voltage on open circuit (E_2) or (V_2) $= E_1 \times \frac{N_2}{N_1}$

$= 2000 \times \frac{100}{400}$

= **500 V**

Primary full load current (I_1) $= \frac{Rated\ power}{V_1}$

$= \frac{40 \times 1000}{2000}$

= **20A**

Secondary full load current (I_2) $= \frac{Rated\ power}{V_2}$

$= \frac{40 \times 1000}{500}$

= **80A**

Maximum value of flux ($\emptyset_{max}$)

Using the emf equation $E_1 = 4.44\, f\, \emptyset_{max} N_1$

$\emptyset_{max} = \frac{E_1}{4.44 \times f \times N_1}$

$= \frac{2000}{4.44 \times 50 \times 400}$

= **0.0225 Wb**

Example 3.2 The no-load ratio required in a single-phase 50Hz transformer is 6600/600V.If the maximum value of flux in the core is to be about 0.08Wb, Find the number of turns in each winding.

Given Data :

Supply frequency = 50Hz

primary voltage (V_1) = 6600

secondary volatge (V_2) = 600

Maximum value of flux ($\emptyset_{max}$) = 0.08Wb

To Find :

Number of primary turns (N_1) =?

Number of secondary turns (N_2) =?

Solution:

Using relation $E_1 = 4.44\, f\, \emptyset_{max} N_1$

Number of primary turns (N_1) $= \dfrac{E_1}{4.44\, f\, \emptyset_{max}}$

$= \dfrac{6600}{4.44 \times 50 \times 0.08}$

$= 372$

$E_2 = 4.44\, f\, \emptyset_{max} N_2$

Number of secondary turns (N_2) $= \dfrac{E_2}{4.44\, f\, \emptyset_{max}}$

$= \dfrac{600}{4.44 \times 50 \times 0.08}$

$= 34$

Example 3.3 A single phase transformer is connected to a 230V, 50Hz supply. The net cross- sectional area of the core is 60cm^2 . The number of turns in the primary is 500 and in the secondary 100. Determine:

(i) Transformation ratio

(ii) E.m.f induced in secondary winding

(iii) Maximum value of flux density in the core.

Given Data :

primary voltage $E_1 = V_1$ = 230 V

To Find :

Transformation ratio (K) = ?

Supply frequency	=	50Hz	E.m.f induced in secondary winding =?
Cross –sectional area	=	$60cm^2$	Maximum value of flux (B_{max}) =?
Number of primary turns (N_1)	=	500	
Number of secondary turns (N_2)	=	100	

Solution:

Transformation ratio (k) $= \frac{N_2}{N_1}$

$= \frac{100}{500}$

$= 0.2$

Emf induced in secondary winding E_2 $= \frac{N_2}{N_1} \times E_1$

$= \frac{100}{500} \times 230$

$=$ 46V

Maximum value of flux (B_{max}) $= \frac{\emptyset_{max}}{A}$

$\emptyset_{max} = \frac{E_1}{4.44 \times f \times N_1}$

$= \frac{230}{4.44 \times 50 \times 500}$

$=$ 0.00207 Wb

$B_{max} = \frac{0.00207}{60 \times 10^{-4}}$

$=$ 0.345 Tesla or Wb/m^2

Example 3.4 A 6000/600 Volts, 50Hz, single phase transformer has a maximum flux density of $1.4Wb/m^2$ in its core. If the net cross-sectional area of the iron core is $0.02\ m^2$. Calculate the number of turns in the primary and the secondary of the transformer.

Given Data :			**To Find :**
Supply frequency	=	50Hz	Number of primary turns (N_1) =?
primary voltage (V_1)	=	6600	Number of secondary turns (N_2) =?
secondary volatge (V_2)	=	600	
Maximum value of flux (B_{max})	=	$1.4\ Wb/m^2$	
cross-sectional area of the iron	=	$0.02\ m^2$	

core

Solution:

Using relation $E_1 = 4.44\, f\, \emptyset_{max} N_1$

$\emptyset_{max} = B_{max} \times A$

$= 1.4 \times 0.02$

$= 0.028$ Wb

Number of primary turns (N_1) $= \dfrac{E_1}{4.44\, f\, \emptyset_{max}}$

$= \dfrac{6600}{4.44 \times 50 \times 0.028}$

$=$ 965 turns

$E_2 = 4.44\, f\, \emptyset_{max} N_2$

Number of secondary turns (N_2) $= \dfrac{E_2}{4.44\, f\, \emptyset_{max}}$

$= \dfrac{600}{4.44 \times 50 \times 0.028}$

$=$ 97 turns

Example 3.5 A 3300/300 V single phase transformer gives 0.6A and 60 W as ammeter and wattmeter readings when supply is given to the low voltage winding and high voltage winding is kept open, find:

(i) Power factor of No-load current

(ii) Magnetising current component

(iii) Iron loss component

Given Data :			**To Find :**
primary voltage (V_1)	=	3300	Power factor of No-load current (cosϕ)=?
secondary volatge (V_2)	=	300	Magnetising current component (I_m) =?
No-load current (I_o)	=	0.6A	Iron loss component (I_w)= ?
No –load power (W_o)	=	60W	

Solution:

From power equation $W_0 = VI_0 cos\emptyset_0$

$$cos\emptyset_0 = \frac{W_0}{VI_0}$$

$$= \frac{60}{300 \times 0.6}$$

$= 0.33$ (lagging)

Magnetising current component (I_m) $= I_0 \sin \emptyset_0$

From $cos\emptyset_0 = 0.33$

$\emptyset_0 = \cos^{-1} 0.33$

$= 70.73^0$

Therefore $sin\emptyset_0$, $=$ Sin (70.73^0)

$= 0.944$

Magnetising current component (I_m) $= I_0 \sin \emptyset_0$

= 0.6 x 0.944

= 0.5664 A

Iron loss component (I_w) $= I_0 \cos \emptyset_0$

= 0.6 x 0.33

= 0.198 A

Example 3.6 A 3300/220 V,30 KVA, single phase transformer takes a no-load current of 1.5 A when the low voltage winding is kept open. The iron loss component is equal to 0.4A find:

(i) **No-load input power**

(ii) **Power factor of no-load current**

(iii) **Magnetising component**

Given Data :

Rated power = 30 KVA

primary voltage (V_1) = 3300

secondary volatge (V_2) = 220

To Find :

No-load input power (W_0) =?

Power factor of No-load current ($\cos\phi$)=?

Magnetising current component (I_m) =?

No-load current (I_o)	=	1.5 A
Iron loss component (I_w) or $I_0 \cos\emptyset_0$		0.4 A

Solution:

No –load power W_0		=	$V_1 I_0 cos\emptyset_0$
W_0		=	3300 x 0.4
		=	1320W
		=	0.33 (lagging)
From no –load power	$cos\emptyset_0$	=	$\frac{W_0}{V_1 I_0}$
	$cos\emptyset_0$	=	$\frac{1320}{3300 \times 1.5}$
		=	0.266
From	$cos\emptyset_0$	=	0.266
	$\emptyset_0$	=	$\cos^{-1} 0.266$
		=	74.57^0
Therefore $sin\emptyset_0$	,	=	Sin (74.57^0)
		=	0.964
Magnetising current component (I_m)		=	$I_0 \sin\emptyset_0$
		=	1.5 x 0.964
		=	1.446A

Example 3.7 The following readings were obtained on O.C and S.C tests on 200/400V, 50 Hz single phase transformer.

O.C. test (L.V. Side)	**200V**	**0.6A**	**60W**
S.C. Test (H.V. Side)	**15 V**	**9A**	**80W**

Determine the equivalent circuit constants.

Given Data : | **To Find :**

At O.C. test V_0 **=** 200V | R_0 = ?

I_0	=	0.6 A	X_0 = ?
W_0	=	60W	I_m = ?
V_{sc}	=	15 V	I_w =?
I_{sc}	=	9A	R_{01} and R_{02}=?
W_{sc}	=	80W	X_{01} and X_{02} = ?

Solution:

No –load power $W_0 = V_0 I_0 cos\emptyset_0$

From no –load power $cos\emptyset_0 = \frac{W_0}{V_0 I_0}$

$cos\emptyset_0 = \frac{60}{200 \times 0.6}$

$= 0.5$

From $cos\emptyset_0 = 0.5$

$\emptyset_0 = \cos^{-1} 0.5$

$= 60^0$

Therefore $sin\emptyset_0$, $= \text{Sin}(60^0)$

$= 0.866$

Magnetising current component (I_m) $= I_0 \sin \emptyset_0$

$= 0.6 \times 0.866$

$= 0.5196A$

Iron loss component (I_w) $= I_0 \cos \emptyset_0$

$= 0.6 \times 0.5$

$= 0.3$ A

No-load resistance (R_0) $= \frac{V_0}{I_W}$

$= \frac{200}{0.3}$

$= 666.66\Omega$

No –load reactance (X_0) $= \frac{V_0}{I_m}$

$= \frac{200}{0.5196}$

$= 384.91\Omega$

At short circuit test $W_{sc} = I_s^2 R_{02}$

$R_{02} = \frac{W_s}{I_s^2}$

$= \frac{80}{9^2}$

$= 0.9876$ ohm

$Z_{02} = \frac{V_s}{I_s}$

$= \frac{15}{9}$

$= 1.666\Omega$

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

$= \sqrt{1.666^2 - 0.9876^2}$

$= 1.3417\Omega$

Transformation ratio (K) $= \frac{E_2}{E_1}$

$= \frac{400}{200}$

$= 2$

Equivalent resistance referred to primary(R_{01}) $= \frac{R_{02}}{K^2}$

$= \frac{0.9876}{2^2}$

$= 0.2469$ ohm

Equivalent reactance referred to primary(X_{01}) $= \frac{X_{02}}{K^2}$

$= \frac{1.3417}{2^2}$

$= 0.3354$ ohm

Example 3.7 The following readings were obtained from O.C and S.C tests on 30 KVA 200/2000V,50 Hz transformer.

O.C. test (L.V. Side)	**200V**	**6.2A**	**360W**
S.C. Test (H.V. Side)	**75 V**	**18A**	**600W**

Determine the equivalent circuit constants.

Given Data : **To Find :**

At O.C. test

V_0 = 200V — R_0 = ?

I_0 = 6.2 A — X_0 = ?

W_0 = 360W — I_m = ?

V_{sc} = 75 V — I_w =?

I_{sc} = 18 A — R_{01} and R_{02}=?

W_{sc} = 600W — X_{01} and X_{02} = ?

Solution:

No –load power $W_0 = V_0 I_0 cos\emptyset_0$

From no –load power $cos\emptyset_0 = \frac{W_0}{V_0 I_0}$

$cos\emptyset_0 = \frac{360}{200 \times 6.2}$

= 0.290

From $cos\emptyset_0$ = 0.290

$\emptyset_0 = \cos^{-1} 0.29$

= 73.14^0

Therefore $sin\emptyset_0$, = Sin (73.14^0)

= 0.957

Magnetising current component (I_m) = $I_0 \sin \emptyset_0$

= 6.2 x 0.957

= 5.9334A

Iron loss component (I_w) = $I_0 \cos \emptyset_0$

= 6.2 x 0.29

= 1.8A

No-load resistance (R_0) = $\frac{V_0}{I_W}$

$$= \frac{200}{1.8}$$

$$= 111.111\Omega$$

No –load reactance (X_0) $= \frac{V_0}{I_m}$

$$= \frac{200}{5.9334}$$

$$= 33.7\Omega$$

At short circuit test $W_{sc} = I_s^2 R_{02}$

$R_{02} = \frac{W_s}{I_s^2}$

$$= \frac{600}{18^2}$$

$$= 1.852\Omega$$

$Z_{02} = \frac{V_s}{I_s}$

$$= \frac{75}{18}$$

= 4.17 ohm

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

$$= \sqrt{4.17^2 - 1.852^2}$$

= 3.736 ohm

Transformation ratio (K) $= \frac{E_2}{E_1}$

$$= \frac{2000}{200}$$

= 10

Equivalent resistance referred to primary(R_{01}) $= \frac{R_{02}}{K^2}$

$$= \frac{1.852}{10^2}$$

= 0.0185 ohm

Equivalent reactance referred to primary(X_{01}) $= \frac{X_{02}}{K^2}$

$= \frac{3.736}{10^2}$

$= 0.03736$ ohm

Equivalent impedance referred to primary(Z_{01}) $= \frac{Z_{02}}{K^2}$

$= \frac{4.17}{10^2}$

$=$ 0.0417 ohm

Example 3.8 A 5 KVA, 230/110V single phase transformer has SC test data, Volt : 25, Current : 25Aand power input 100W. Calculate the voltage regulation at 0.8 p.f lagging.

Given Data :

Rated power Output P_0 **=** 5KVA

V_{sc} = 25 V

I_{sc} = 25 A

W_{sc} = 100W

To Find :

Full load regulation at 0.8 P.f. lag=?

Solution:

Transformation ratio (K) $= \frac{E_2}{E_1}$

$= \frac{110}{230}$

$= 0.478$

At short circuit test W_{sc} $= I_s^2 R_{01}$

$R_{01} = \frac{W_s}{I_s^2}$

$= \frac{100}{25^2}$

$= 0.16\ \Omega$

$Z_{01} = \frac{V_s}{I_s}$

$= \frac{25}{25}$

$=$ 1 ohm

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

$= \sqrt{1^2 - 0.16^2}$

$=$ 0.987 ohm

$R_{02} = K^2 R_{01}$

$= 0.478^2 \times 0.16$

$=$ 0.0365

$X_{02} = K^2 X_{02}$

$= 0.478^2 \times 0.987$

$=$ 0.2255 ohm

Full load current on the secondary $I_2 = \frac{output}{E_2}$

$= \frac{5 \times 1000}{110}$

$=$ 45.45 A

At 0.8 p.f lag

$E_2 = \sqrt{(V_2\,cos\emptyset_0 + I_2 R_{02})^2 + (V_2\,sin\emptyset_0 + I_2 X_{02})^2}$

From $cos\emptyset_0$ = 0.8

$\emptyset_0 = \cos^{-1} 0.8$

$= 36.86^0$

$=$ Sin (36.86^0)

Therefore $sin\emptyset_0$ = 0.6

$E_2 = \sqrt{(110 \times 0.8 + 45.45 \times 0.0365)^2 + (110 \times 0.6 + 45.45 \times 0.226)^2}$

$=$ 117.69 Volt

$\%\,Voltage\ Regulation = \frac{E_2 - V_2}{V_2} \times 100$

$$= \frac{117.69 - 110}{110} \times 100$$

$$= 6.99\%$$

Example 3.9 consider a 20 KVA, 2200/220 V, 50Hz transformer. the OC/SC test results are as follows:

O.C. test (L.V. Side)	**220V**	**4.2A**	**148W**
S.C. Test (H.V. Side)	**86 V**	**10.5 A**	**360W**

Determine the regulation at 0.8 P.f lagging at full load.

Given Data :

Rated power Output P_0 = 20KVA

V_{sc} = 86 V

I_{sc} = 10.5 A

W_{sc} = 148W

To Find :

Full load regulation at 0.8 P.f. lag=?

Solution:

Transformation ratio (K) $= \frac{E_2}{E_1}$

$$= \frac{220}{2200}$$

$$= 0.1$$

At short circuit test $W_{sc} = I_s^2 R_{01}$

$$R_{01} = \frac{W_s}{I_s^2}$$

$$= \frac{360}{10.5^2}$$

$$= 3.27\ \Omega$$

$$Z_{01} = \frac{V_s}{I_s}$$

$$= \frac{86}{10.5}$$

	=	8.19 ohm
X_{01}	=	$\sqrt{Z_{01}{}^2 - R_{01}{}^2}$
	=	$\sqrt{8.19^2 - 3.27^2}$
	=	7.51 ohm
Full load current on the primary I_1	=	$\frac{output}{E_1}$
	=	$\frac{20 \times 1000}{2200}$
	=	9.09 A
$\% Regulation$	=	$\frac{I_1 R_{01} \cos\emptyset \pm I_1 X_{01} \sin\emptyset}{V_1} \times 100$
From $cos\emptyset_0$	=	0.8
$\emptyset_0$	=	$\cos^{-1} 0.8$
	=	36.86^0
	=	Sin (36.86^0)
Therefore $sin\emptyset_0$	=	0.6
$\% Regulation$	=	$\frac{9.09(3.27 \times 0.8 + 7.51 \times 0.6)}{2200} \times 100$
	=	2.94%

Example 3.10 high voltage side short circuit test data for 20 KVA, 2300/230 V transformer are: Power = 250 W ; current = 8.7 A ; Voltage = 50V

Calculate equivalent impedance, resistance, reactance referred to H.V side. Find the transformer regulation at 0.7 lagging power factor.

Given Data :

Rated power Output P_0	=	20KVA	**To Find :**	Full load regulation at 0.7 P.f. lag=?
V_{sc}	=	50 V		

I_{sc} = 8.7 A

W_{sc} = 250W

Solution:

At short circuit test W_{sc} = $I_s^2 R_{01}$

R_{01} = $\frac{W_s}{I_s^2}$

= $\frac{250}{8.7^2}$

= 3.303 Ω

Z_{01} = $\frac{V_s}{I_s}$

= $\frac{50}{8.7}$

= 5.747 ohm

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

= $\sqrt{5.747^2 - 3.303^2}$

= 4.703 ohm

Full load current on the primary I_1 = $\frac{output}{E_1}$

= $\frac{20 \times 1000}{2300}$

= 8.696 A

$\% \, Regulation$ = $\frac{I_1 R_{01} \cos\emptyset \pm I_1 X_{01} \sin\emptyset}{V_1} \times 100$

From $cos\emptyset_0$ = 0.7

$\emptyset_0$ = $\cos^{-1} 0.7$

= 45.57^0

= Sin (45.57^0)

Therefore $sin\emptyset_0$ = 0.714

$$\% Regulation = \frac{8.696(3.303 \times 0.7 + 4.703 \times 0.714)}{2300} \times 100$$

$$= 2.14\%$$

Example 3.11 A 10KVA, 2500/250 V, single phase transformer gave the following test results:

O.C. test	**250V**	**0.8 A**	**50 W**
S.C. Test	**60 V**	**3 A**	**45W**

(i) Calculate the efficiency of half full load at 0.8 p.f

(ii) Calculate the load KVA at which maximum efficiency

occur Solution:

Full rated current $= \frac{output}{V_1}$

$$= \frac{10 \times 1000}{2500}$$

$$= 4A$$

Hence reading of wattmeter corresponding to full load current of 4A

$$= 45 \times \left(\frac{4}{3}\right)^2$$

$$= 80W$$

Full load copper loss = 80W

Full load iron loss = 50W

(i) Effeciency at half load at 0.8 p.f

$$\therefore \quad \%\eta = \frac{n(VA\ rating) \times \cos\emptyset_2}{n(VA\ rating) \times \cos\emptyset_2 + P_i + n^2(P_{cu})F.L} \times 100$$

n = Fractional by which load is less than full load = (Actual load/ Full load) =1/2 =0.5

$$= \frac{0.5 \times (10 \times 1000) \times 0.8}{0.5 \times (10 \times 1000) \times 0.8 + 50 + 0.5^2 \times 80} \times 100$$

$$= 98.3\%$$

(ii) Load KVA for maximum efficiency ,and its value

For maximum efficiency

Copper loss = Iron loss = 50W

∴ current at which maximum efficiency occurs = $\frac{50 \times 4}{80}$ = 2.5A

∴ Load KVA = $10 \times \left(\frac{2.5}{4}\right)$

= 6.25 KVA

Example 3.12 A 10KVA, 2500/250 V, single phase transformer gave the following test results:

O.C. test	**250V**	**0.8 A**	**50 W**
S.C. Test	**60 V**	**3 A**	**45W**

Compute the voltage regulation at 0.8 p.f leading

Given Data :

Rated power Output P_0 = 10KVA

V_{sc} = 60 V

I_{sc} = 3 A

W_{sc} = 45W

To Find :

Full load regulation at 0.8 P.f. lag=?

Solution:

At short circuit test W_{sc} = $I_s^2 R_{01}$

R_{01} = $\frac{W_s}{I_s^2}$

= $\frac{45}{3^2}$

= 5 Ω

Z_{01} = $\frac{V_s}{I_s}$

= $\frac{60}{3}$

= 20 ohm

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

= $\sqrt{20^2 - 5^2}$

= 19.36 ohm

Full load current on the primary I_1 = $\frac{output}{V_1}$

= $\frac{10 \times 1000}{2500}$

= 4 A

$\% Regulation$ = $\frac{I_1 R_{01} \cos\emptyset \pm I_1 X_{01} \sin\emptyset}{V_1} \times 100$

From $cos\emptyset_0$ = 0.8

$\emptyset_0$ = $\cos^{-1} 0.8$

= 36.86^0

= Sin (36.86^0)

Therefore $sin\emptyset_0$ = 0.6

$\% Regulation$ = $\frac{4(5 \times 0.8 + 19.36 \times 0.6)}{2500} \times 100$

= -1.218%

Example 3.13 Find the efficiencies of a 150KVA transformer at 75% of full load at U.P.F and 100% of Full load at p.f. of 0.8 lag. If full load copper losses are 1.6 Kw and the core losses are 1.4 KW.

Solution:

Full load copper loss = 1.6 KW

Full load iron loss = 1.4 KW

(i) Efficiency at 75% of load at Unity p.f

$\therefore \quad \%\eta = \frac{n(VA\ rating) \times \cos\emptyset_2}{n(VA\ rating) \times \cos\emptyset_2 + P_i + n^2 (P_{cu}) F.L} \times 100$

n = Fractional by which load is less than full load = (Actual load/ Full load) = 0.75

$= \frac{0.75 \times (150 \times 1000) \times 1}{0.75 \times (150 \times 1000) \times 1 + (1.4 \times 1000) + 0.75^2 \times 1.6 \times 1000} \times 100$

= 98%

Efficiency at 100% (3/4) of load at Unity p.f

∴ $\%\eta$ = $\frac{n(VA\ rating)\times\cos\emptyset_2}{n(VA\ rating)\times\cos\emptyset_2+P_i+n^2(P_{cu})F.L}\times 100$

n = Fractional by which load is less than full load = (Actual load/ Full load) = 1

= $\frac{1\times(150\times1000)\times1}{1\times(150\times1000)\times1+(1.4\times1000)+1^2\times1.6\times1000}\times100$

= 97.56%

Example 3.14 A 15 KVA, 2000/200V transformer has an iron loss of 250W and full load copper loss 350W. during the day it is loaded as follows:

No. of hours	Load	Power factor
9	1/4 load	0.6
7	Full load	0.8
6	3/4 load	1.0
2	No-load	-

Calculate the all-day

efficiency. Solution:

Rating of transformer = 15 KVA

Iron loss P_i = 250 W = 0.25 KW

Full load copper loss = 350 W = 0.35 KW

Iron loss /day = 0.25 x 24 = 6Kwh

Copper loss at 1/4 load = $\left(\frac{1}{4}\right)^2\times P_{cu}$

= $\frac{1}{16}\times 0.35$ = 0.0218KW

Copper loss for 9 hours at ¼ load

= 9 x 0.0218 = 0.196KWh

Copper loss at full load = 0.35 KW

Copper loss for 7 hours on full load

= 7 x 0.35 = 2.45 KWh

Copper loss at 3/4 load = $\left(\frac{3}{4}\right)^2\times P_{cu}$

= $\frac{9}{16}\times 0.35$ = 0.197KW

Copper loss for 6 hours at 3/4 load

= 6 x 0.197 = 1.18 KWh

Copper loss /day = 0.196 + 2.45 + 1.18 = 3.826 KWh

Total loss /day = Iron loss/day + copper loss/day

= 6 + 3.826 = 9.826 KWh

Total output /day = $\frac{1}{4} \times 15 \times 0.6 \times 9 + 15 \times 0.8 \times 7 + \frac{3}{4} \times 15 \times 1.0 \times 6$

= 20.25 + 84 + 67.5 = 171.75 Kwh

All –day efficiency = $\frac{Output\ power\ in\ KWh}{Output\ power\ in\ KWh + total\ losses/day}$

= $\frac{171.75}{171.75 + 9.826}$

= 0.9459 or 94.59%

Example 3.15 A 100 KVA transformer used for lighting has an iron loss of 800W and full load copper loss 1200W. During the day it is loaded as follows:

No. of hours	Load
4	1/2load
2	Full load
3	1/4 load

Calculate the all-day efficiency.

Solution:

Rating of transformer = 100 KVA

Iron loss P_i = 800 W = 0.8 KW

Full load copper loss = 1200 W = 1.2 KW

Iron loss /day = 0.8 x 24 = 19.2 Kwh

Copper loss at 1/4 load = $\left(\frac{1}{2}\right)^2 \times P_{cu}$

= $\frac{1}{4} \times 1.2$ = 0.3KW

Copper loss for 4 hours at 1/2 load

= 4 x 0.3 = 1.2 KWh

Copper loss at full load = 1.2 KW

Copper loss for 2 hours on full load

= 2 x 1.2 = 2.4 KWh

Copper loss at 1/4 load = $\left(\frac{1}{4}\right)^2 \times P_{cu}$

= $\frac{1}{16} \times 1.2$ = 0.075 KW

Copper loss for 3 hours at 1/4 load

= 3 x 0.075 = 0.225 KWh

Copper loss /day = 1.2 + 2.4 + 0.225 = 3.825 KWh

Total loss /day = Iron loss/day + copper loss/day

= 19.2 + 3.825 = 23.025 KWh

Total output /day = $\frac{1}{2} \times 100 \times 1.0 \times 4 + 100 \times 1.0 \times 2 + \frac{1}{4} \times 100 \times 1.0 \times 3$

= 200 + 200 + 75 = 475 Kwh

All –day efficiency = $\frac{Output\ power\ in\ KWh}{Output\ power\ in\ KWh + total\ losses/day}$

= $\frac{475}{475 + 23.025}$

= 0.9538 or 95.38%

Example 3.16 A 25 KVA distribution transformer has maximum efficiency of 96% at full load at u.p.f. the transformer is loaded as follows:

No. of hours	Load	Power factor
6	**1/2 load**	**0.8**
2	**Full load**	**1.0**
4	**1/4 load**	**1.0**
12	**No-load**	**-**

Calculate the all-day efficiency or energy

efficiency. Solution:

Output power in KW = KVA X cosϕ

= 25 x 1= 25 KW

Power input to the transformer during maximum efficiency

= $\frac{Output}{Efficiency}$

= $\frac{25 \times 1}{0.96}$

	=	26 KW
Total losses on full load	=	Input -Output
	=	26 – 25 = 1 KW
Therefore, full load copper loss	=	0.5 KW
Iron loss	=	0.5 KW

Since at maximum efficiency, core loss= copper loss

Iron loss /day	=	0.5 x 24 = 12 Kwh
Copper loss at 1/2 load	=	$\left(\frac{1}{2}\right)^2 \times P_{cu}$
	=	$\frac{1}{4} \times 0.5$ = 0.125KW

Copper loss for 6 hours at 1/2 load

	=	6 x 0.125 =0.75 KWh
Copper loss at full load	=	0.5 KW

Copper loss for 2 hours on full load

	=	2 x 0.5 = 1 KWh
Copper loss at 1/4 load	=	$\left(\frac{1}{4}\right)^2 \times P_{cu}$
	=	$\frac{1}{16} \times 0.5$ = 0.03125KW

Copper loss for 4 hours at 1/4 load

	=	4x 0.03125 = 0.125 KWh
Copper loss /day	=	0.75 + 1 + 0.125 = 1.875 KWh
Total loss /day	=	Iron loss/day + copper loss/day
	=	12 + 1.875 = 13.875 KWh
Total output /day	=	$\frac{1}{2} \times 25 \times 0.8 \times 6 + 25 \times 1.0 \times 2 + \frac{1}{4} \times 25 \times 1.0 \times 4$
	=	60 + 50 + 25 = 135 Kwh
All –day efficiency	=	$\frac{Output\ power\ in\ KWh}{Output\ power\ in\ KWh + total\ losses/day}$

$$= \frac{135}{135 + 13.875}$$

$= 0.9068$ or 90.68%

PART- A

1. What is the working principle of transformer?
2. Write the EMF equation of transformer.
3. What name is given to the coils through which current flows from the source?
4. What name is given to the coils across which load is connected?
5. Write the equation of voltage transformation ratio of transformer.
6. How is transformer rated?
7. What is the purpose of OC test?
8. What is the purpose of SC test?
9. What is the condition for maximum efficiency of a transformer?
10. What will be the polarity if two transformers are connected in parallel?
11. How can iron loss be measured?
12. How can copper loss be measured?
13. What are the various tests that give the complete parameters of the equivalent circuit of the transformer?
14. What are the types of transformer according to the construction?
15. What is the working principle of auto-transformer?
16. What type of load should be connected to a transformer for getting negative voltage regulation?
17. What type of load should be connected to a transformer for getting maximum voltage regulation?
18. Write the equation for transformation ratio of transformer.
19. Write the equation of voltage ratio of transformer.
20. Write the equation of current ratio of transformer

PART-B

1. Draw and explain the vector diagram of transformer on No-load condition.
2. What is meant by ideal transformer?
3. Draw the approximate equivalent circuit of a transformer and name the parameters.
4. Define voltage regulation of a transformer and write the expression for it.
5. What are the losses occurring in transformer?
6. Define 'All day efficiency' of a transformer.
7. What are the conditions to be satisfied for parallel operation of transformers?
8. What are the advantages of parallel operation of transformer?
9. What are the advantages of using auto transformer?
10. What are the disadvantages of using auto transformer?
11. What are the applications of auto transformer?
12. Write short notes on polarity test of single phase transformer.

PART-C

1. Derive the condition for maximum efficiency of a transformer

2. A transformer takes a current of 0.6A and absorbs 64W when primary is connected to its normal supply of 200V, 50Hz; the secondary being on open circuit. Find the magnetizing and iron loss currents.
3. A 230/2300V transformer takes no load current of 5A at 0.25p.f lagging. Find (i) the core loss and (ii) magnetizing current .
4. Draw the phasor diagram for transformer on load condition at unity p.f including the voltage drops.
5. Draw the phasor diagram for transformer on load condition at lagging p.f including the voltage drops.
6. Draw the phasor diagram for transformer on load condition at leading p.f including the voltage drops.
7. Derive, step by step, the approximate equivalent circuit of transformer.
8. Explain how the different parameters of transformer equivalent circuit are obtained by conducting OC and SC test
9. State the various losses in a transformer and explain how these losses are predetermined by OC and SC tests?
10. Derive an EMF equation of transformer.
11. Explain the construction details of single phase transformer.
12. Derive an expression of saving of copper in auto transformer.
13. Problems from above worked examples.

UNIT IV- THREE PHASE TRANSFORMERS

Introduction:

A three phase system is used to generate and transmit large of power. Three phase transformers are required to step up or step down voltages in various stages of a power system network.

Transformers for 3-phase circuits can be constructed in one of the following ways:

1. Three separate single –phase transformers are suitably connected for 3-phase operation. Such an arrangement is called a 3-phase bank of transformers.
2. A single three-phase transformer in which the cores and windings for all the three phases are combined in a single structure.

4.1 Construction of Three Phase Transformer:

The present day system is a three-phase system. The change of voltage in a three phase system is performed either by a single three phase transformer or by a three single phase transformers. **Advantages of a 3-phase unit Transformer:**

A three phase unit transformer has the following advantages over three single phase transformer bank of the same kVA rating.

1. It takes less space
2. It is lighter, smaller and cheaper
3. It is slightly more efficient

A single unit three phase transformer has a three limbed core, one limb for each phase winding. On each limb the low voltage winding is placed over the core and the high voltage winding is placed over the low voltage winding with suitable insulation between the core and low voltage winding as well as between the two windings. Fig.4.1 and Fig.4.2 shows the schematic diagram of three core type and shell type transformer respectively.

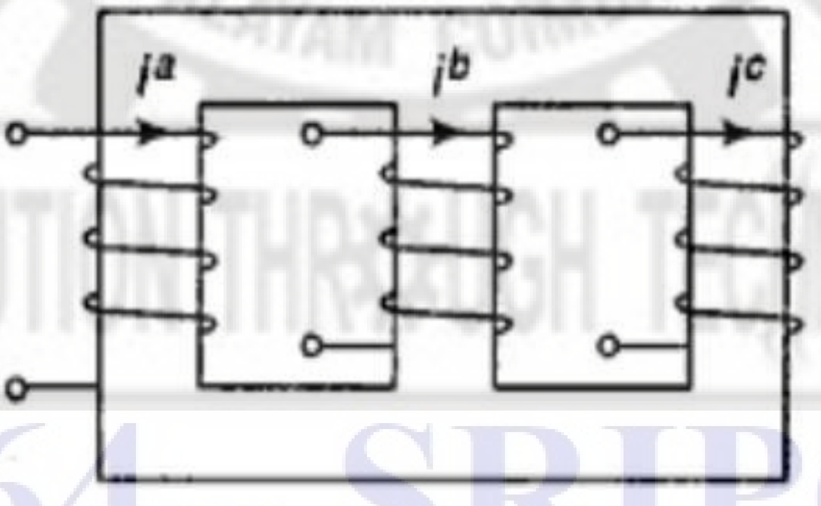


Fig.4.1 Three phase core type transformer

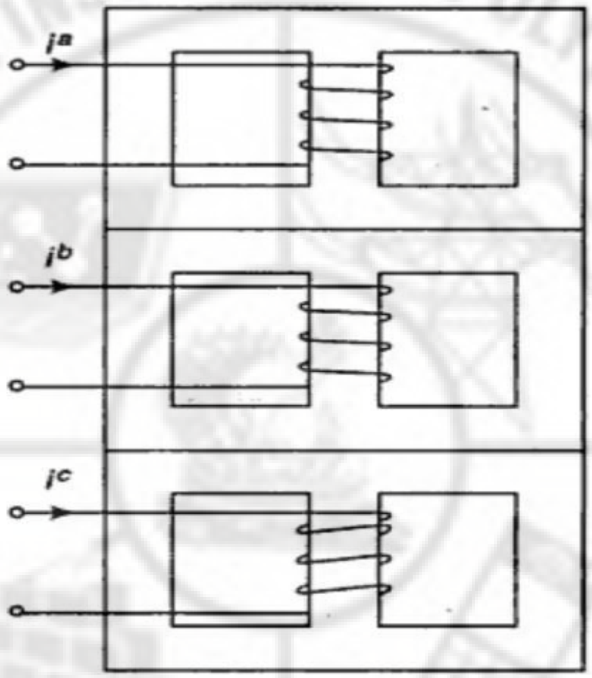


Fig.4.2 Shell Type Three phase Transformer

4.2 Three Phase Transformer Connection:

The primary and secondary winding of a three phase transformer can be connected in star or delta. Hence four main connections are possible.

1. **Star-Star** $(Y - Y)$
2. **Star-Delta** $(Y - \Delta)$
3. **Delta-Star** $(\Delta - Y)$
4. **Delta-Delta.** $(\Delta - \Delta)$
5. **Open Delta Connection (V-V)**

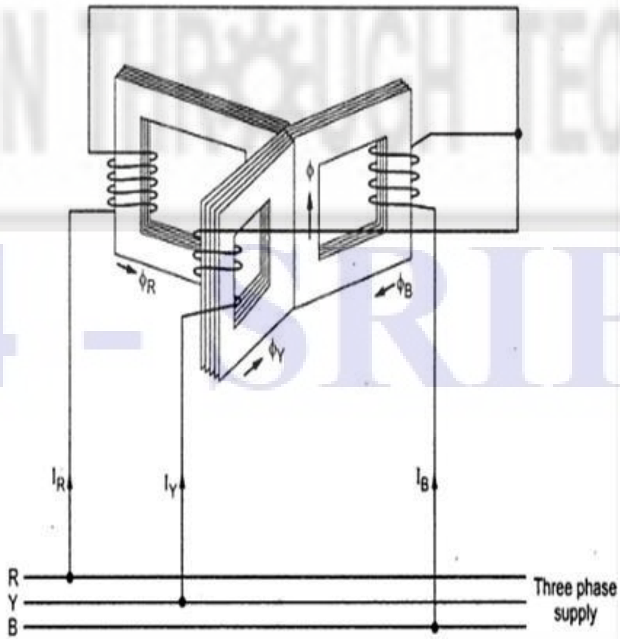


Fig. 4.3 Three Phase Transformer Connection

Factors Affecting the Choice of Connections:

Some of the factors governing the choice of connections are as follows.

1. Availability of a neutral connection for grounding, protection, or load connections.
2. Insulations to ground and voltage stress
3. Availability of a path for the flow of third harmonic currents and zero sequences currents
4. Need for partial capacity with one circuit out of service
5. Parallel operation with other transformers
6. Operation under fault conditions
7. Economic considerations

4.2.1 Star-Star Connection:

In this type of connection, both the primary and secondary windings are connected in Star as shown in the Fig. 4.4. This particular connection proves to be economical for small high voltage transformers as phase voltage is (1/√3) times that of line voltage, the number of turns per phase and the quantity of insulation required is minimum. The ratio of line voltages on the primary and secondary sides is the same as the transformation ratio of each transformer. It can be noted that there is a phase voltage shift of 30° between the phase voltages and line voltages on both primary and secondary side. The line voltages on both sides and the primary voltages are in phase with each other.

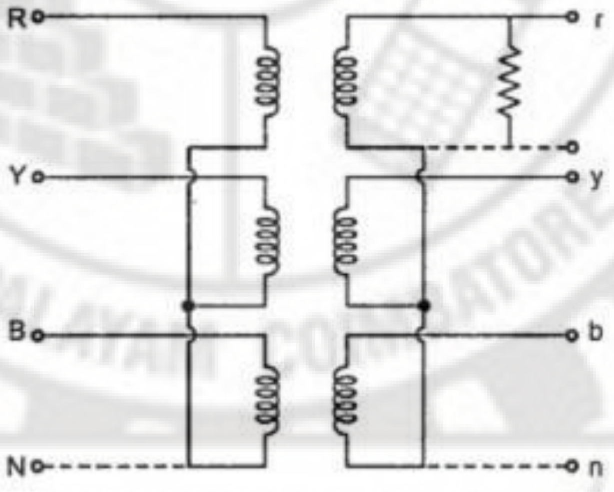


Fig 4.4

The connection of primary neutral to the neutral of generator has an add advantage that it eliminates distortion in the secondary phase voltages. If the flux in the core has sinusoidal waveform, then it will give sinusoidal waveform for the voltage. But due to characteristic of iron, a sinusoidal waveform of flux requires a third harmonic component in the exciting current. As the frequency of this component is thrice the frequency of circuit at any given constant. it will try to flow either towards or away from the neutral point in the transformer windings. With isolated neutral, the triple frequency current cannot flow so the flux in the core will not be a sine wave and the voltages are distorted.

If primary neutral is connected to generator neutral the triple frequency currents get the path to solve the difficulty. The alternative way of overcoming with this difficulty is the use of tirtiary winding of low KVA rating. These windings are connected in delta and provides a circuit in which triple frequency currents can flow. Thus sinusoidal voltage on primary will give sinusoidal voltage on secondary side.

If VL1 is the line voltage on the primary side then phase voltage on primary side is given as,

$$V_{ph1} = \frac{V_{L1}}{\sqrt{3}}$$

Advantages:

- Due to star connection, phase voltages is (1/√3) times the line voltage. Hence less number of turns are required. Also the stress on insulation is less. This makes the connection economical for small high voltage purposes.
- Due to star connection, phase current is same as line current. Hence windings have to carry high currents. This makes cross section of the windings high. Thus the windings are mechanically strong and windings can bear heavy loads and short circuit.
- There is no phase shift between the primary and secondary voltages.
- As neutral is available, it is suitable for three phase, four wire system.

DISADVANTAGES

- If the load on the secondary side unbalanced, then the performance of this connection is not satisfactory then the shifting of neutral point is possible. To prevent this, star point of the primary is required to be connected to the star point of the generator.
- Eventhough the star or neutral point of the primary is earthed, the third harmonic present in the alternator voltage may appear on the secondary side. This causes distortion in the secondary phase voltages.
- Due to the disadvantages, this connection is rare in practice and used only for small high voltage transformers.

4.2.2 Star-Delta Connection:

In this type of connection, then primary is connected in star while the secondary is connected in delta as shown in the Fig. 4.5

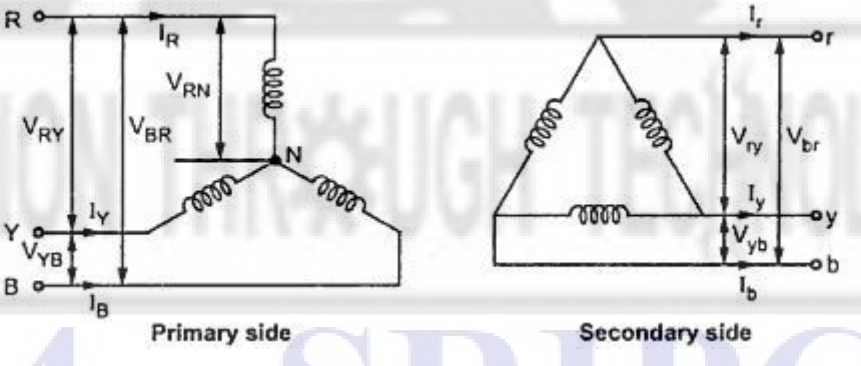


Fig 4.5

The voltages on primary and secondary sides can be represented on the phasor diagram as shown in the Fig.4.6.

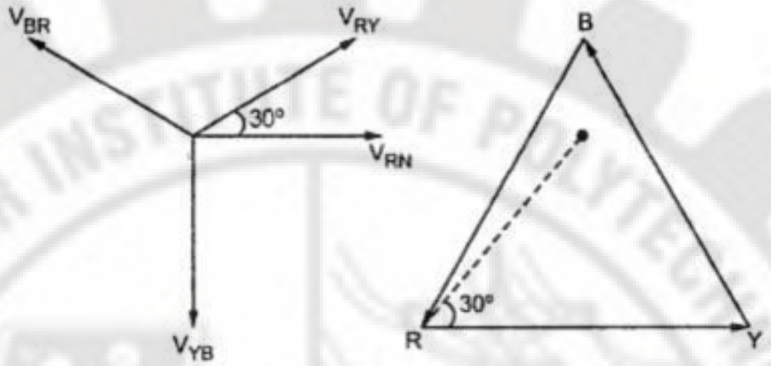


Fig 4.6

The same type of connection can be represented in another way as shown in the Fig. 4.7

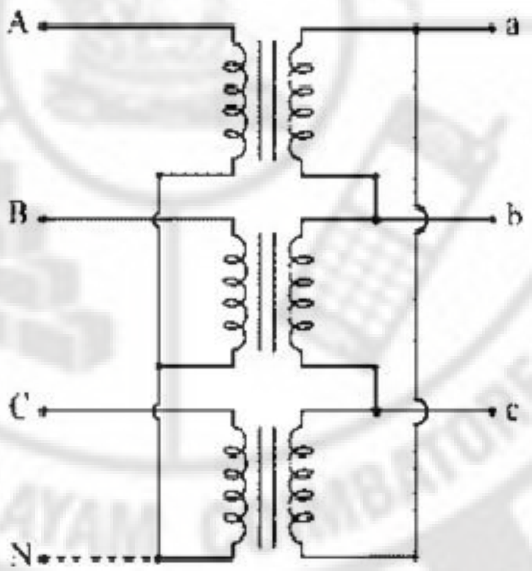


Fig 4.7

This type of connection is commonly employed at the substation end of the transmission line. The main use with this connection is to step down the voltage. The neutral available on the primary side is grounded. It can be seen that there is phase difference of 30° between primary and secondary line voltages.

The connection suffers no problems due to unbalanced load as secondaries are connected in delta. This type of transformers are commonly employed at receiving end.

Advantages

- The primary side is star connected. Hence fewer number of turns are required. This makes the connection economical for large high voltage step down power transformers.
- The neutral available on the primary can be earthed to avoid distortion.
- Large unbalanced loads can be handled satisfactory.

Disadvantages

- In this type of connection, the secondary voltage is not in phase with the primary.

Hence it is not possible to operate this connection in parallel with star-star or delta-delta connected transformer.

4.2.3. Delta –Star Connection:

In this type of connection, the primary connected in delta fashion while the secondary current is connected in star fashion as shown in the Fig.4.8.

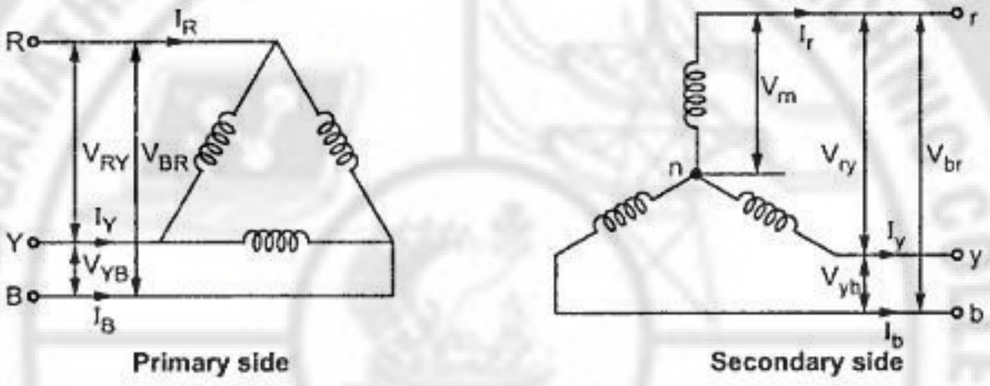


Fig 4.8

The voltage on primary and secondary side can be represented on the phasor diagram as shown in the Fig. 4.9

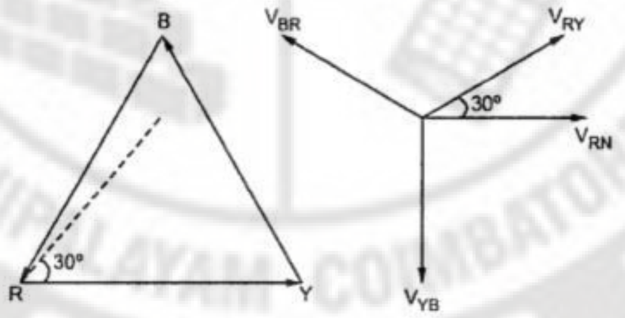


Fig 4.9

The another way of representing the same type of connection is shown in the Fig. 4.10.

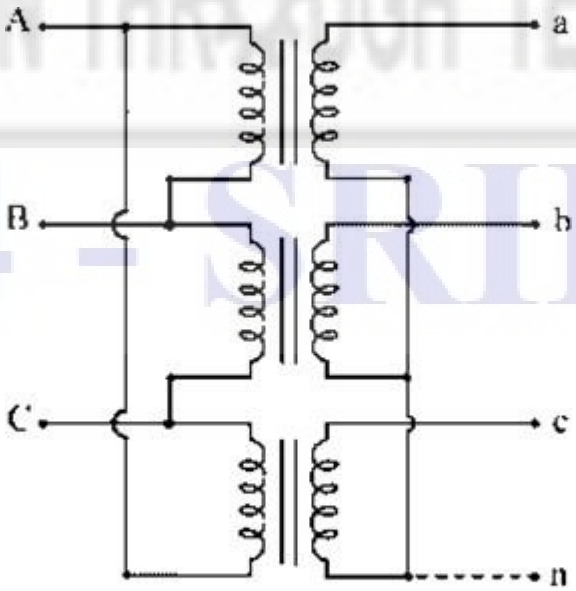


Fig 4.10

The main use of this connection is to step up the voltage i.e. at the beginning of high tension transmission system. It can be noted that there is a phase shift of 30° between primary line voltage and secondary line voltage as leading.

As secondary side is star connected, use of three phase, four wire system is possible.

Advantages

- On primary side due to delta connection winding cross-section required is less.
- On secondary side, neutral is available, due to which it can be used for 3-phase, 4 wire supply system.
- There is no distortion due to third harmonic components.
- The windings connected on star makes it economical due to saving in cost of insulation.
- Large unbalanced loads can be handled without any difficulty.

Disadvantages

- Due to phase shift between primary and secondary voltages, hence it is not possible to operate this connection in parallel with star-star or delta-delta connected transformer.

4.2.4 Delta-Delta Connection:

In this type of connection, both the three phase primary and secondary windings are connected in delta as shown in the Fig.4.11

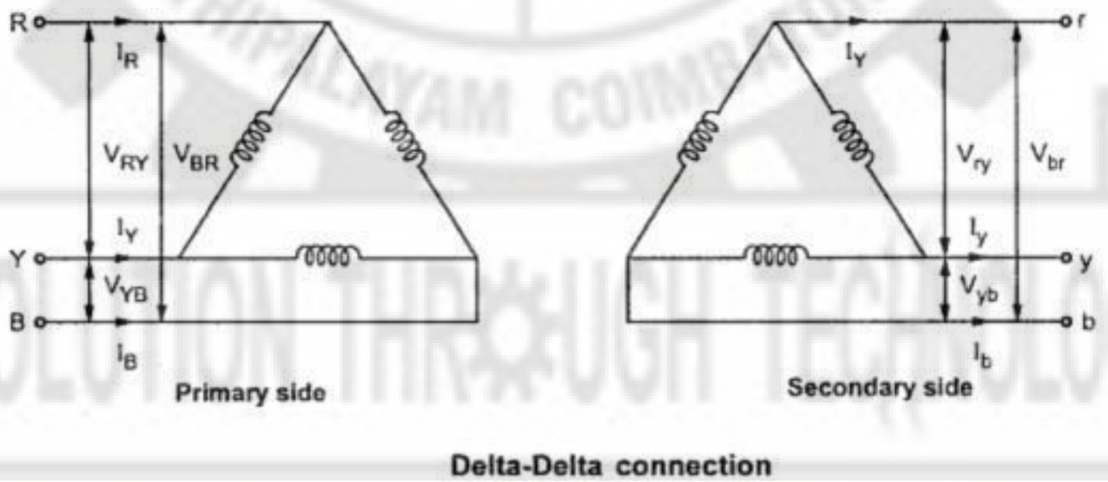


Fig 4.11

The voltages on primary and secondary sides can be shown on the phasor diagram as shown in the Fig. 4.12

Fig 4.12

The another way of representing this type of connection is shown in the Fig. 4.13

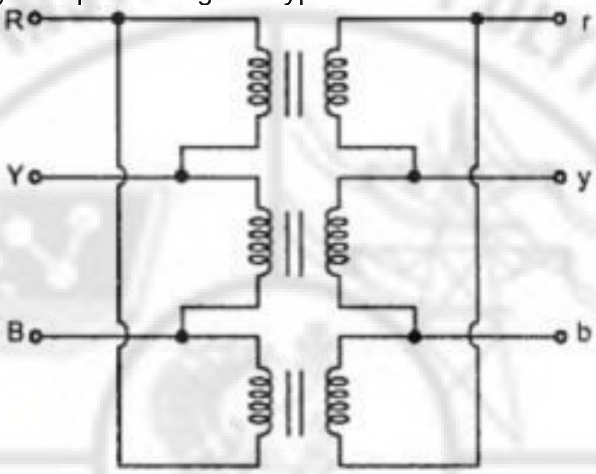


Fig 4.13

This connection proves to be economical for large low voltage transformers as it increases number of turns per phase.

Advantages

- in order to get secondary voltage as sinusoidal, the magnetizing current of transformer must contain a third harmonic component. The delta connection provides a closed path for circulation of third harmonic component of current. The flux remains sinusoidal which results in sinusoidal voltages.
- Even if the load is unbalanced the three phase voltages remains constant. Thus it allows unbalanced loading also.
- The important advantage with this type of connection is that if there is bank of single phase transformers connected in delta-delta and if one of the transformers is disabled then the supply can be continued with remaining tow transformers of course with reduced efficiency.
- There is no distortion in the secondary voltages.
- Due to delta connection, phase voltage is same as line voltage hence winding have more number of turns. But phase current is (1/√3) times the line current. Hence the cross-section of the windings is very less. This makes the connection economical for low voltages transformers.

Disadvantages

- Due to the absence of neutral point it is not suitable for three phase four wire system.

4.2.5 Scott-Connection Or T-T Connection):

Three phase to two phase conversion and vice versa is needed under the following circumstances.

1. To supply power to two phase electric furnaces
2. To inter link three phase system and two phase systems
3. To supply power to two phase apparatus from a three phase source
4. To supply power to three phase apparatus from a two phase source

The common type of connection to achieve the above conversion is generally called ***Scott- 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. 4.14 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

One of the transformers has centre taps both on the primary and secondary windings (Fig. 4.14) and is known as the main transformer. It forms the horizontal member of the connection (Fig. 4.15).

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 trans- former respectively as shown in Fig. 4.15 (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.

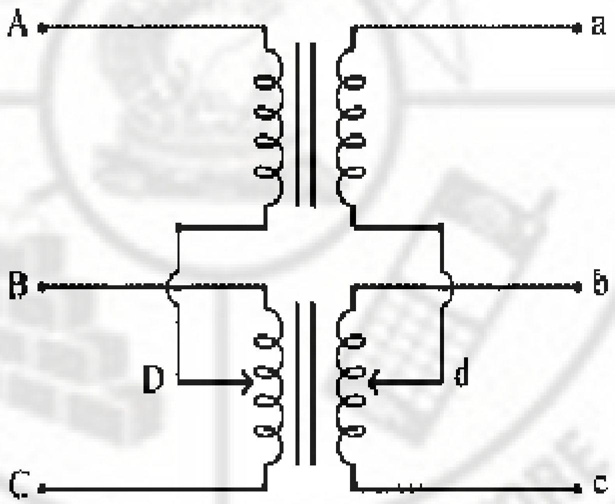


Fig 4.14

The voltage diagram is shown in Fig. 4.15 (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 (from which this connection gets its name).

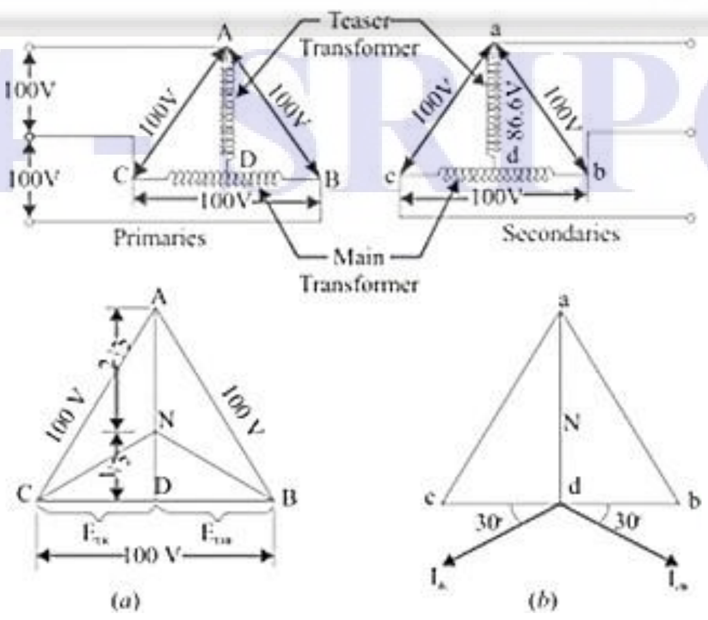


Fig 4.15

In the primary voltage T of Fig. 4.15 (a), EDC and EDB 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 EDA being the altitude of the equilateral triangle is equal to (3 / 2) ´ 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. 4.15 (b), it should be noted that for a load of unity power factor, current Idb lags behind voltage Edb by 30° and Idc leads Edc 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%.

Applications Of Scott Connection:

1. Electric furnace installations where it is desired to operate two single phase furnace together and draw a balanced load from the 3-phase supply.
2. To supply single phase loads such as electric trains which are so scheduled as to keep the load on the 3-phase system as nearly balanced as possible.
3. To link a 3-phase system with a 2-phase system with flow of power in either direction.

4.2.6 Open Delta Or V-V Connection:

In connection of three single phase transformers that if one of the transformers is unable to operate then the supply to the load can be continued with the remaining two transformers at the cost of reduced efficiency. The connection that obtained is called V-V connection or open delta connection.

Consider the Fig. 4.16 in which 3 phase supply is connected to the primaries. At the secondary side three equal three phase voltages will be available on no load.

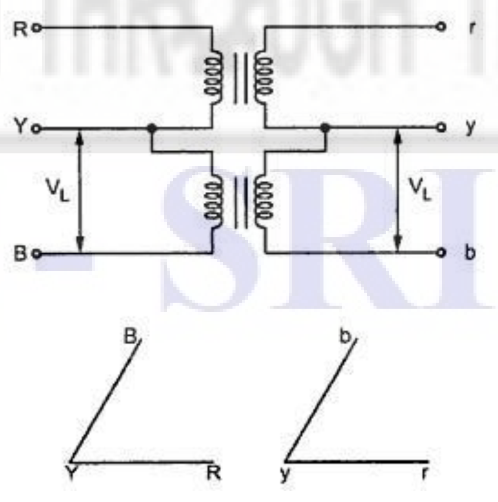


Fig 4.16

The voltages are shown on phasor diagram. The connection is used when the three phase load is very small to warrant the installation of full three phase transformer.

If one of the transformers fails in Δ - Δ bank and if it is required to continue the supply even though at reduced capacity until the transformer which is removed from the bank is repaired or a new one is installed, then this type of connection is most suitable.

When it is anticipated that in future the load increase, then it requires closing of open delta. In such cases open delta connection is preferred.

It can be noted here that the removal of one of the transformers will not give the total load carried by V - V bank as tow third of the capacity of Δ - Δ bank.

The load that can be carried by V - V bank is only 57.7% of it. it can be proved as follows.

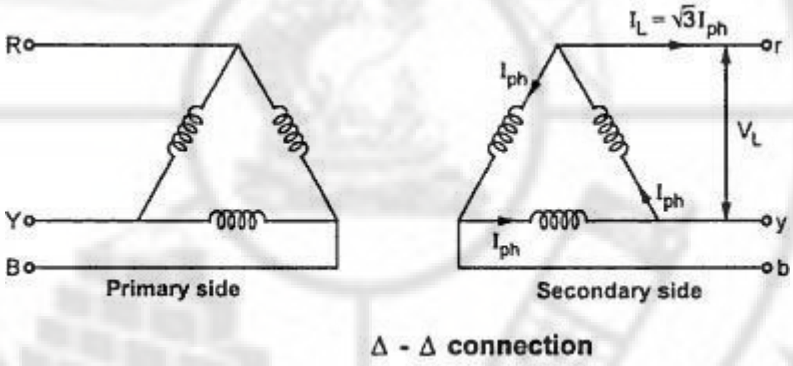


Fig 4.17(a)

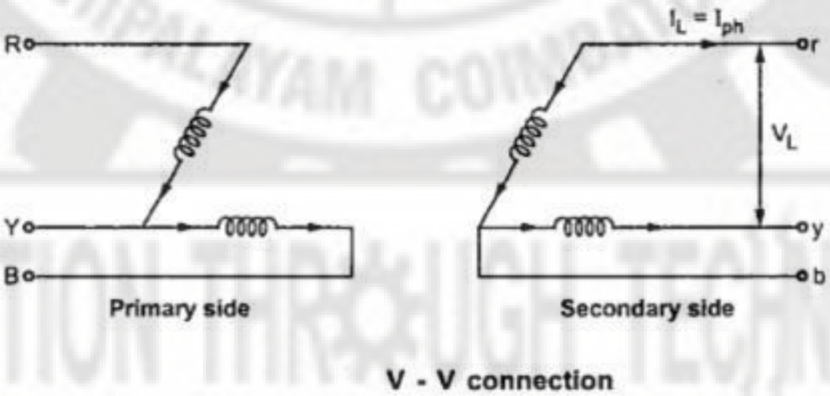


Fig 4.17 (b)

It can be seen from the Fig. 4.17(a)

Δ - Δ capacity = √3 VL IL = √3 VL (√3 Iph)

Δ - Δ capacity = 3 VL Iph... (i)

It can also be noted from the Fig. 4.17 (b) that the secondary line current IL is equal to the phase current Iph.

V- V capacity = √3 VL IL = √3 VL Iph............................ (ii)

Dividing equation (ii) by equation (i)

Thus the three phase load that can be carried without exceeding the ratings of the transformers is 57.5 percent of the original load. Hence it is not 66.7 % which was expected otherwise.

The reduction in the rating can be calculated as {(66.67 - 57.735)/(57.735)}x 100 =

15.476 Suppose that we consider three transformers connected in Δ - Δ fashion and

supplying their rated
load. Now one transformer is removed then each of the remaining two transformers will be overloaded. The overload on each transformer will be given as,

$$\frac{\text{V - V capacity}}{\Delta\text{ - }\Delta\text{ capacity}} = \frac{\sqrt{3}\, V_L I_{ph}}{3\, V_L I_{ph}} = \frac{1}{\sqrt{3}} = 0.557 \approx 58\ \% \qquad \ldots \text{(iii)}$$

This overload can be carried temporarily if provision is made to reduce the load otherwise overheating and breakdown of the remaining two transformers would take place.

Applications of Open-Delta Systems:

The open delta system is used in one of the following circumstances:

1. As a temporary measure when one transformer of a Δ-Δ system is damaged and removed for repair and maintenance.
2. To provide service in a new development area where the full growth of load may require several years. In such cases a V-V system is installed in the initial stage. This reduces the initial cost. Whenever, the need arises at a future date to accommodate the growth in the power demand, a third transformer is added for Δ-Δ operation. The addition of one transformer increases the capacity of the total bank by 73.2 %.

4.3 Parallel Operation of Three Phase Transformer and Conditions

The transformers are connected in parallel when load on one of the transformers is more than its capacity. The reliability is increased with parallel operation than to have single larger unit. The cost associated with maintaining the spares is less when two transformers are connected in parallel.

The following conditions are to be satisfied while connecting three phase transformers in parallel.

i) The transformers connected in parallel must have same polarity so that the resultant voltage around the local loop is zero. With improper polarities there are changes of dead short circuit.

ii) The relative phase displacements on the secondary sides of the three phase transformers to be connected in parallel must be zero. The transformers with same phase group can be connected in parallel.

As the phase shift between the secondary voltages of a star/ delta and delta/ star transformers is 30^o, they cannot be connected in parallel. But transformers with + $30^o$and - 30^ophase shift can be connected in parallel by reversing phase sequence of one of them.

iii) The voltage ratio of the two transformers must be same. This prevents no load circulating current when the transformers are in parallel on primary and secondary sides. As the leakage impedance is less, with a small voltage difference no load circulating current is high resulting in larger I^2 R losses.

iv) The ratio of equivalent leakage reactance to equivalent resistance preferably same for all transformers. If there is difference in this ratio, the phase angle of the two currents show divergence. One transformer will operate at higher p.f. while other transformer will operate at lower p.f. Due to this given load is not proportionately shared by them.

4.4 Three Phase Transformer Vector Groups:

According to B.S. (British Standard), transformer terminals are brought out in rows with high voltage winding on one side while low voltage winding on the other side. They are lettered from left to right facing the h.v. side. The h.v. terminals are represented with capital letters e.g. A, B, C and l.v.

terminals are represented with small letter e.g. a, b, c. If transformer has tertiary winding, then it is represented in capital letters enclosed in circles.

The neutral terminals are represented after line terminals. The two ends of each winding are designated by subscript numbers 1, 2. If there are intermediary tappings these are numbered in order of their separation from end 1 e.g. if h.v. winding on phase B has three tappings then it would be represented as B1, B2, B3, B3 , B4 , B5 with B1 and B5 forming the phase terminals.

If the voltage induced in h.v. phase B1 B2 is in the direction of B1 to B2 at a given instant, then the induced e.m.f. in the corresponding l.v. phase at the same instant will be from b1 to b2. The polyphase transformers are given some symbols to show the type of phase connection and the angle of advance turned through in passing from the vector representing the h.v. e.m.f. to that representing the
l.v. e.m.f. at the corresponding terminal.

The angle of advance can be represented by a clock face hour figure. The h.v. side phasor is considered as minute hand which is always set at 12 O'clock (zero) position and the corresponding l.v. side phasor is shown with the hour hand.

For example, if the connection is written as "Dy 11" then it represents h.v. side delta connected while l.v. side star connected 3 phase transformer. The l.v. e.m.f. vector in a given phase combination is at 11 O'clock position i.e. + 30o in advance of the 12 O'clock position of the h.v. e.m.f. position. This is represented in the Fig. 4.18.

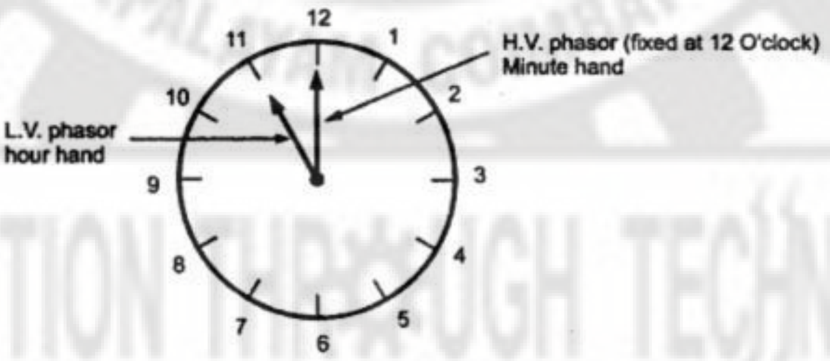


Fig 4.18

The groups into which all possible three phase transformer connections are classified are given below

:

Group 1 : Zero phase displacement (Yy0, Dd0,
Dz0) Group 2 : 180° phase displacement (Yy6,
Dd6, Dz6) Group 3 : 30° lag phase displacement
(Dy1, Yd1, Yz1)
Group 4 : 30° lead phase displacement (Dy11, Yd11, Yz11)

On the name plate of a three phase transformer, the vector group is written as Yd11, Dyn11 etc. Typical representation of the vector group could be Yd1 or Dy11 etc.

Letter Y – Represents star connected
HV Letter y – Represents star
connected LV Letter D – Represents
Delta connected HV Letter d –

Represents Delta connected LV

The third numerical figure says the angle of phase shift based on clock convention.

The minute hand is used to represent the primary phase to neutral voltage and always shown to occupy the position 12. The hour hand represents the secondary phase to neutral voltage and may, depending upon phase shift, occupy position other than 12 as shown in the figure 4.19 below

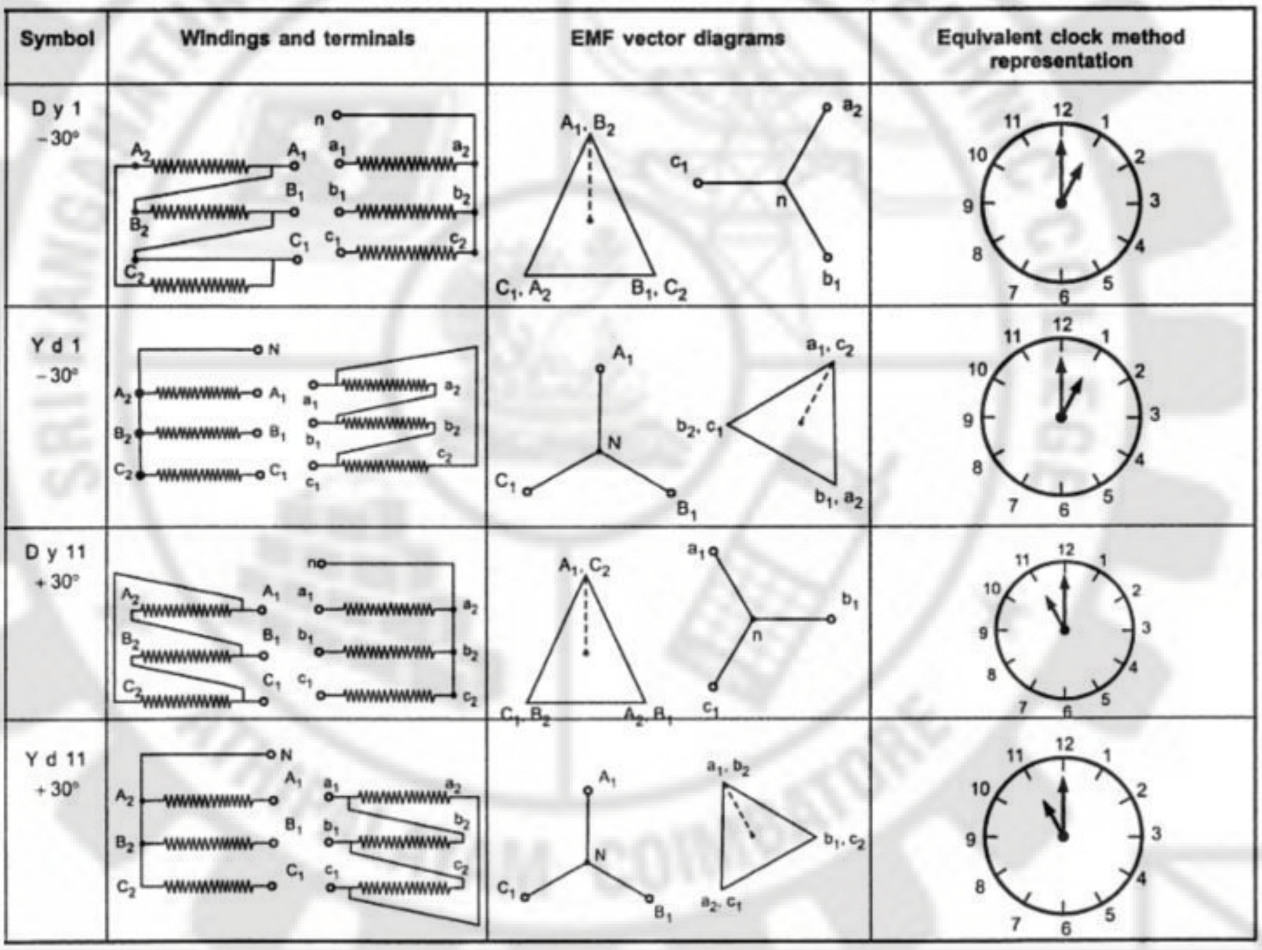


Fig 4.19

4.5 Phasing Out Test
Polarity and phasing Out:

While connecting new transformer, special care should be taken to follow the diagram of connections supplied by the manufacturer taking into account, the phase sequence of the supply. In case of three phase transformers if connections are not made in correct phase sequence, the outgoing supply may also be of wrong phase sequence. This would require breaking down of connections and remaking the high voltage cable connections.

Whether the phase rotation is clockwise or anti-clockwise, it should be the same for all the transformers that have to work in parallel. However, it is recommended that the standard phase sequences in accordance with the Indian and International Practice, namely red, yellow and blue sequence in the anti-clockwise directions should be adopted. A positive check will help in ensuring correct external connection. The simplest way is to connect two transformers in parallel on primary sides connect the secondary terminals of one transformer to its bus-bars, and it assumed, corresponds to the equivalent terminal of the second transformers to the bus-bars, which it is assumed, corresponds to the equivalent terminals of the first transformer. After ensuring that both transformers are on the same tap, voltage readings between the remaining secondary terminals of the two transformers and the bus – bars be taken. If both readings are zero, the transformers are of same polarity and phase rotation, and the connection may now be made permanent.

In case of star connected secondaries, an alternative arrangement to the secondary connections indicated above is to connect the star points to each other. (this connection may be via earth in which case, of course, none of the secondary terminals will be connected to the bus-bars before closing)

It is also possible for the voltage reading to be double of the secondary voltage which when the voltage reading happens to be across unlike phases. It is, therefore, necessary that care is taken to see the range of the voltmeter is equivalent to the sum of secondary voltage of the two transformers.

4.6 Pairing of Transformer

Pairing refers to the paralleling of transformers. While pairing of transformers the following points are to be considered.

1. The vector groups of the transformers must be same
2. Transformers from group 1 and group 2 can be paralleled by suitably changing the internal connections of one of the transformers.
3. It is also possible to connect the transformers of vector group 3 and vector group 4 by suitable changes in the external connections.
4. Transformers in either group 1 or 2 cannot be paralleled with either group 3 or group 4. The other requirements for satisfactory parallel operations are given below.

1. The turns ratio and voltage rating should be same
2. Polarities of transformer should be same.
3. Percentage Impedance of the transformers preferably same.
4. Ratio of resistance to reactance preferably same.

If the two transformer windings have been star connected, then the neutral points are connected together as shown in Fig 4.20

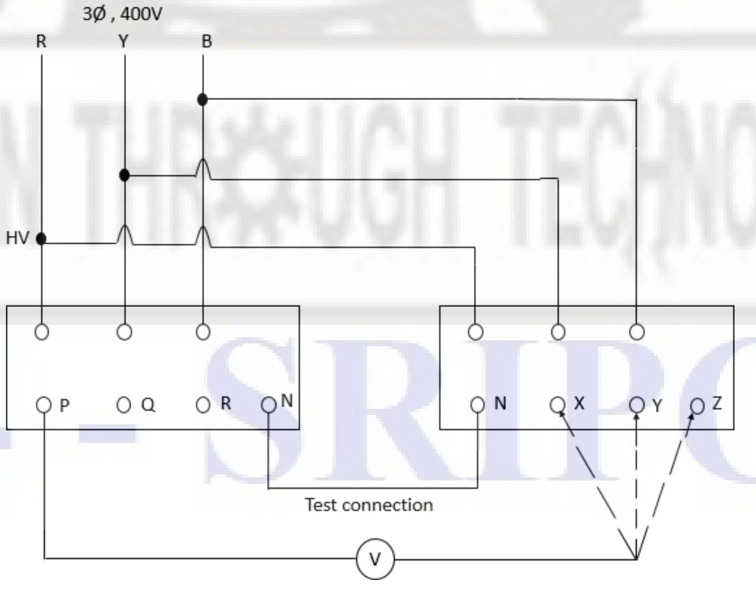


Fig 4.20

Then the transformer primary is applied with low voltage. Measure the voltage between each secondary terminal of the first transformer and second transformer by using a voltmeter.

If the polarities are similar, then the voltmeter reading will zero. Then permanent connections can be made.

For example, the voltage between the terminals (P,X), (Q,Y) and (R,Z) is zero then connect P and X,Q and Y,R and Z.

Trial – I

Two similar terminals of the secondaries are linked as shown in Fig 4.21 . A low voltage is applied to the primary.

1) Measure the voltage between Q and Y, and R and Z. If these voltages are zero connect P and X, Q and Y and R and Z

2) If the voltage between Q and Y is not zero then measure the voltage between the terminals Q and Z. If this voltage is zero, then measure the voltage between R and Y. If this voltage is also zero then connect P and X, Q and Z and R and Y.

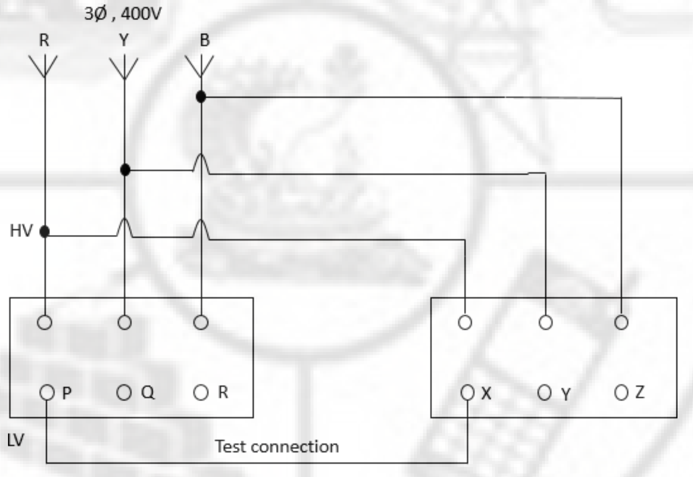


Fig 4.21

Trial –II

In the first trail the voltage between Q and Y, and between Q and Z is not zero then connect the terminals P and Y as shown in Fig 4.22

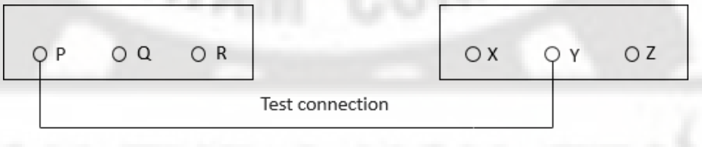


Fig 4.22

1. Now measure the voltage between Q and X. If it is zero measure the voltage between R and Z. If this is also zero. Then connect the terminals P and Y, Q and X and R and Z.
2. If the voltage between Q and X is not zero, then measure the voltage between Q and Z. If it is zero, then measure the voltage between R and X. If this is also zero then connect the terminals P and Y, Q and Z and R and X

Trail – III

In second trail, the voltage between the terminals Q and X and Q and Z are not zero, the then change the test connection as shown in Fig 4.24 i.e. connect P and Z

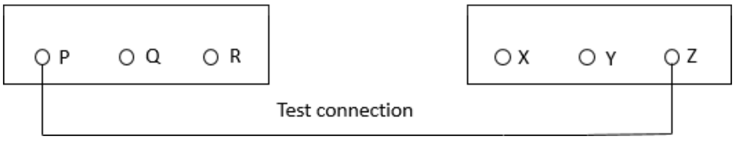


Fig 4.24

1. Now measure the voltage between the terminals Q and X, if it is zero then measure the voltage between R and Y. If it is also zero, then connect the terminals P and Z, Q and X and R and Y.

2. If the voltage between Q and X is not zero, measure the voltage between Q and Y and R and X. This voltage must be zero. Now connect the terminals P and Z, Q and Y and R and X.

4.7 Load Sharing By Two Transformers Connected In Parallel :(With Equal Voltage Ratio)

Let us now consider the case of two transformers connected in parallel having equal voltage ratios. The two transformers are having no load secondary voltage same. i.e. E1 = E2 = E. These voltages are in phase with each other. This is possible if the magnetizing currents of the two transformers are not much different. With this case the primaries and secondaries of the two transformers can be connected in parallel and no current will circulate under no load condition. This is represented in the Fig. 4.25

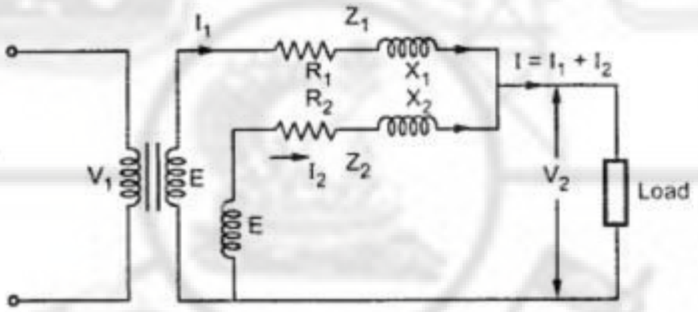


Fig 4.25

If we neglect magnetizing components, the two transformers are represented as shown in the Fig. 4.26.

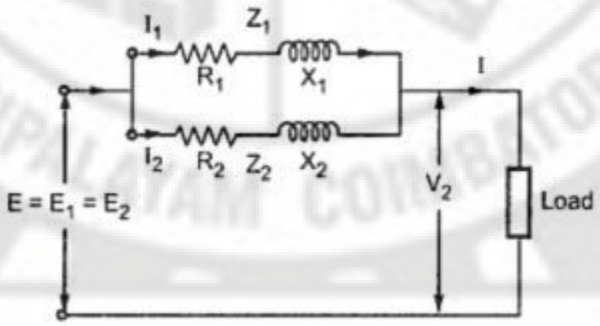


Fig 4.26

The phasor diagram under this case is shown in the Fig. 4.27. The two impedances Z1 and Z2 are in parallel. The values of Z1 and Z2 are with respect to secondary.

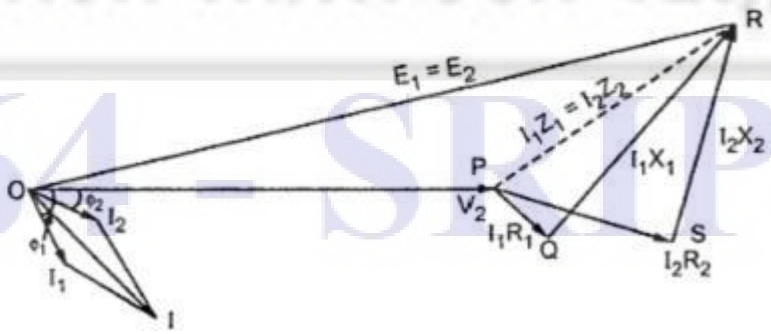


Fig 4.27

Z1 and Z2 are in parallel therefore the equivalent impedance is given by, $1/Z_{eq} = 1/Z_1 + 1/Z_2$ $Z_{eq} = Z_1 Z_2 / (Z_1 + Z_2)$

As seen from the phasor diagram $I_1 Z_1 = I_2 Z_2 = I Z_{eq}$

$I_1 = I\ Zeq/\ Z_1 = I\ Z_2 /(Z_1 + Z_2$

$)I_2 = I\ Zeq/ = I\ Z_1/(Z_1 + Z_2)$

Multiplying both terms of above equation by

voltage V_2, $V_2 I_1 = = V_2 I Z_2 /(Z_1 + Z_2)$

$V_2 I_2 = V_2 I Z_1/(Z_1 + Z_2)$

But $V_2 I \times 10^{-3}$ is Q i.e. the combined load in KVA

From this KVA carried by each transformer is calculated as,

$$Q_1 = Q \cdot \frac{Z_2}{Z_1 + Z_2} = Q \cdot \frac{1}{1 + \frac{Z_1}{Z_2}}$$

and

$$Q_2 = Q \cdot \frac{Z_1}{Z_1 + Z_2} = Q \cdot \frac{1}{1 + \frac{Z_2}{Z_1}}$$

The above expressions are useful in determining the values of Q_1 and Q_2 in magnitude and in phase.

4.7 Load Sharing By Two Transformers Connected In Parallel :(With Unequal Voltage Ratio)

Now we will consider the case of two transformers working in parallel and having unequal voltage ratio. This is shown in the Fig. 4.28.

The voltage ratios of the two transformers are not equal. The parallel operation under this case is still possible. But as seen previously there would be a circulating current under no load condition.

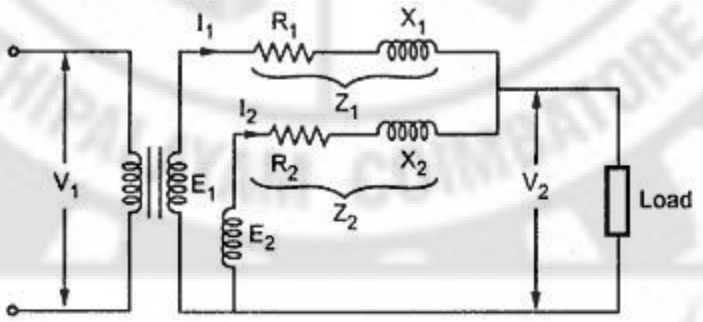


Fig 4.28

Let us consider voltage ratio of transformer 1 is slightly more than 2. So that induced e.m.f. E_1 is greater than E_2. Thus the resultant terminal voltage will be $E_1 - E_2$ which will cause a circulating current under no load condition.

$I_c = (E_1 - E_2)/(Z_1 + Z_2)$

From the circuit diagram we

have, $E_1 = V_2 + I_1 Z_1$

$E_2 = V_2 + I_2 Z_2$

Also, $I_L = I_1 + I_2$

$V_2 = I_L Z_L = (I_l + I_2) Z_L$

$E_1 =(I_1 + I_2) Z_L + I_l Z_1$ .... (a)

$E_2 =(I_1 + I_2) Z_L + I_2 Z_2$ .... (b)

Subtracting equations (a) and (b) we have,

$$E_1 - E_2 = I_1 Z_1 - I_2 Z_2$$

$$I_1 = ((E_1 - E_2) + I_2 Z_2) / Z_1$$

Subtracting this value in equation (b),

$$E_2 = I_2 Z_2 + \left[\left\{\frac{(E_1 - E_2) + I_2 Z_2}{Z_1}\right\} + I_2\right] Z_L$$

$\therefore$ $I_2 = (E_2 Z_1 - (E_1 - E_2) Z_L) / (Z_1 Z_2 + Z_L (Z_1 + Z_2))$ Similarly, $I_1 = (E_1 Z_2 + (E_1 - E_2) Z_L) / (Z_1 Z_2 + Z_L (Z_1 + Z_2))$

Adding the above equations,

$$I_1 + I_2 = (E_1 Z_2 + E_2 Z_1) / (Z_1 Z_2 + Z_L (Z_1 + Z_2)) \qquad \text{............(c)}$$

But $I_L = I_1 + I_2$

Load voltage, $V_2 = I_L Z_L$

Dividing both numerator and denominator of equation (c) by $Z_1 Z_2$,

$$I_L = \frac{\frac{E_1}{Z_1} + \frac{E_2}{Z_2}}{1 + \frac{Z_L (Z_1 + Z_2)}{Z_1 Z_2}}$$

$$I_L = \frac{\frac{E_1}{Z_1} + \frac{E_2}{Z_2}}{1 + \frac{Z_L}{Z_2} + \frac{Z_L}{Z_1}}$$

$$V_2 = I_L Z_L = \left[\frac{E_1/Z_1 + E_2/Z_2}{1 + \frac{Z_L}{Z_2} + \frac{Z_L}{Z_1}}\right] Z_L$$

$$= \frac{E_1/Z_1 + E_2/Z_2}{\frac{1}{Z_L} + \frac{1}{Z_2} + \frac{1}{Z_1}}$$

If impedances Z_1 and Z_2 are small in comparision with load impedance Z_L then product $Z_1 Z_2$ may be neglected so we get,

$$I_1 = \frac{E_1 Z_2}{Z_L (Z_1 + Z_2)} + \frac{E_1 - E_2}{Z_1 + Z_2}$$

$$I_2 = \frac{E_2 Z_1}{Z_L (Z_1 + Z_2)} - \frac{E_1 - E_2}{Z_1 + Z_2}$$

But we know that

$$(E_1 - E_2) / (Z_1 + Z_2) = I_c$$

This circulating current I_c adds to I_1 but subtracts from I_2. Hence transformer 1 gets overloaded. The transformers will not share the load according to their ratings.

The phasor diagram is shown in the Fig. 4.29.

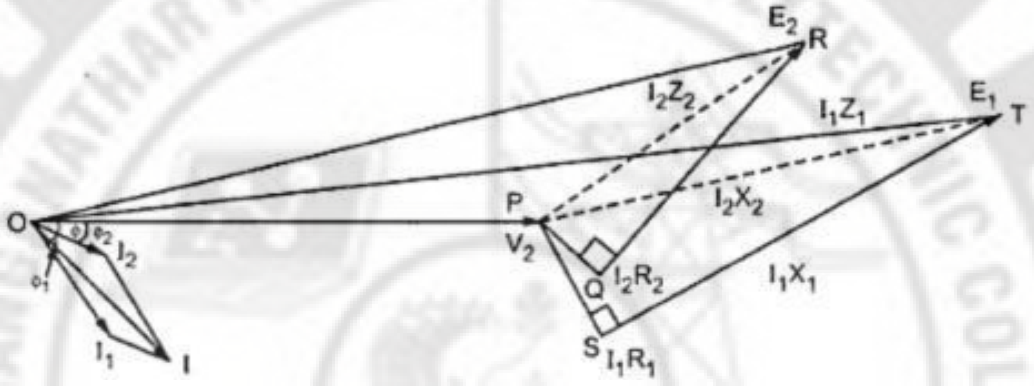


Fig 4.29

The two transformers will operate at different power factor Φ_1 and Φ_2 are the power factor angles of these two transformers whereas Φ is the combined p.f. angle.

Here E_A and E_B have the same phase but there may be some phase difference between the two due to some difference of internal connection as for the connection in parallel of a Star/Star and a Star/Delta 3 phase transformers.

4.8 Cooing of Transformer

When transformer supplies a load, two types of losses occur inside the transformer. The iron losses occur in the core while copper losses occur in the windings. The power lost due to these losses appears in the form of heat. This heat increases the temperature of the transformer.

To keep the temperature, rise of the transformer within limits, it is necessary to dissipate the heat developed to the surroundings.

A suitable coolant and cooling method is necessary for each transformer to dissipate the heat, effectively to the surroundings.

Basically there are two types of transformers, dry type transformers and oil immersed transformers. In dry type, the heat is taken to the walls of tank and dissipate to the surrounding air through convection. In oil immersed type, the oil is used as coolant. The entire assembly including core and windings is kept immersed in a suitable oil. The heat developed is transferred to the walls of tank by convection through oil. And finally heat is transferred to the surroundings from the tank walls by radiation.

The various cooling methods are designated using letter symbols which depend upon :

i) Cooling medium used and ii) Type of circulation employed The various coolants used along with their symbols are,

1. Air - A, 2. Gas - G, 3. Synthetic oil - L,
4. Mineral oil - O, 5- Solid insulation - S and 6. Water - W

There are two types of circulations which are,

1. Neutral - N and 2. Forced - F

In natural cooling, the coolant circulating inside the transformer transfers entire heat to the tank walls from where it is dissipated to the surroundings and transformers gets cooled by natural air circulating surrounding the tank walls.

In forced cooling, the coolant circulating inside the transformer gets heated as it comes in contact with windings and core. The coolant partly transfers heat to the tank walls but mainly coolant is taken to the external heat exchanger where air or water is used in order to dissipate heat of the coolant.

4.8 Various Cooling Methods or Arrangements:

4.8.1 Air Natural Type:

This method uses atmospheric air as cooling medium. The natural air surrounding the tank walls is used to carry away the heat generated, by natural convection. It is used for small low voltage transformers.

4.8.2 Air Forced Type:

In large transformers, cooling by natural air is inadequate. In such cases, the transformer is located above the air chamber and a blast of compressed air is forced on core and windings with the help of blowers or fans. This improves the heat dissipation and hence higher specific loadings are allowed in dry type transformers. This reduced the size of transformers. The air supply must be property filtered to prevent accumulation of dust particles.

4.8.3 Oil Natural Air Natural (ONAN) Cooling of Transformer:

The transformer is immersed in oil so heat generated in core and windings is passed on to oil by conduction. The heated oil transfer heat to the tank wall from where it is taken away to the surrounding air. The assembly of oil immersed transformer is shown in the

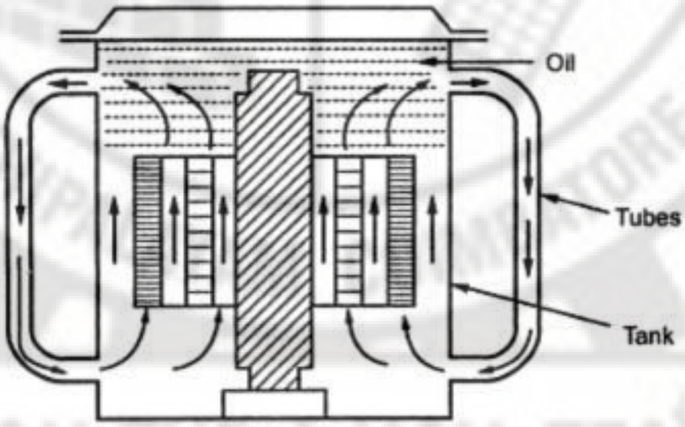


Fig.4.30.

Fig 4.30

The tubes are provided on the sides of a transformer tank. The oil in the tank is taken to the tubes. The circulation of oil through tubes causes the cooling.

The temperature rise of a transformer can be reduced by,

1. Increasing the area of heat dissipation.
2. Decreasing the cooling coefficient.

As the rating of transformer increases the plain walled tank cannot be used. It is necessary to reduce the cooling coefficient. This is achieved by use of some improved methods of cooling

The transformers upto 30 KVA use plain walled tanks. But transformer with ratings higher than 30 KVA use corrugations, fins, tubes and radiator tanks.

The Fig. 4.31 shows the tanks with the tubes and the external radiators.

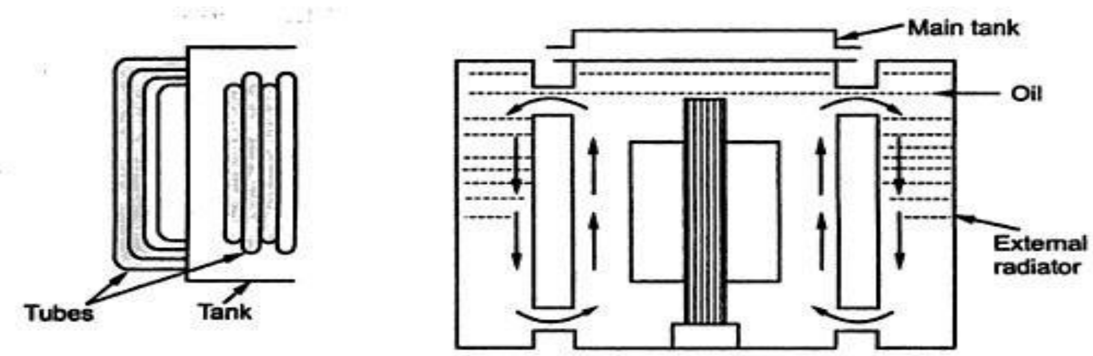


Fig 4.31

The heat developed inside the transformer is taken outside with the help of oil. The oil is cooled with the help of fins, tubes or external radiations by natural circulation of air.

4.8.4 Oil Natural Air Forced (ONAF) Cooling of Transformer:

In this method, the tank is made hollow and compressed air is blown into the hollow space to cool the transformer. The oil circulating inside takes heat to the tank walls. The method is effective and can be used for large rating transformers. Another way to force air blast is to use elliptical tubes separated from tank walls through which air is forced by fans.

4.8.5. Oil Forced Air Forced (OFAF) Cooling of Transformer:

In the external heat exchanger, the compressed air is blasted with the help of fans to cool is the oil. The advantage of this method is at low loads when losses are less there is no need to use the fans to cool the oil. The natural air is sufficient. At higher loads, both fans and pump are switched on by sensing the temperature which improves the cooling. Hence efficiency of this system is higher. The scheme is shown in the Fig. 4.32

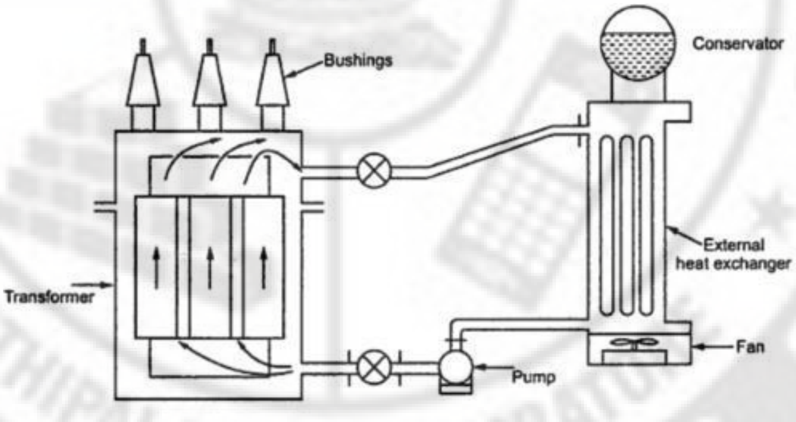


Fig 4.32

4.8.6. Oil Forced Water Forced Cooling of Transformer:

In this method, in the heat exchanger instead of air blast, water blast is used to cool the oil. The pressure oil is kept higher than water so oil mixes with water in case of leakage but water dose not mix with oil. Due to this method, smaller transformer size is sufficient as it is not necessary to employ water tubes inside the transformer tank. The method is suitable for transformers having ratings more than 30 MVA. The method is used for the transformers at hydroelectric stations as large water supply with appropriate water head is easily available. The scheme is shown in the Fig. 4.33

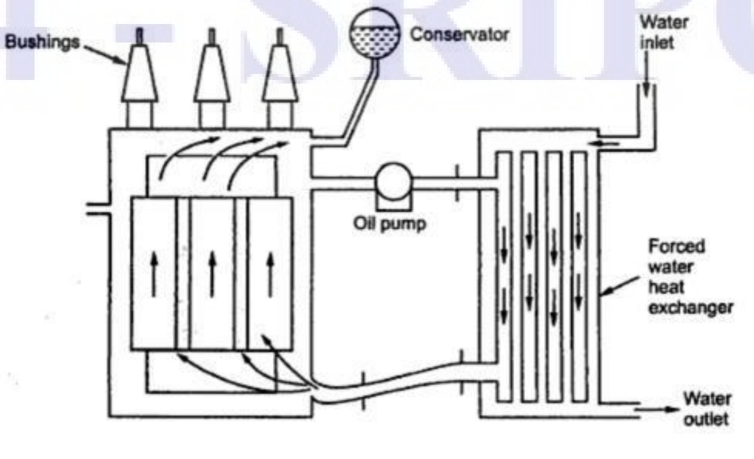


Fig 4.33

4.9. Protective Devices and Accessories:

The following are the protective devices for the transformer:

- **Conservator**
- **Breather**
- **Buchholz Relay**
- **Explosion Vent**

4.9.1 Conservator

Transformer conservator is considered as one of the important transformer accessories. As the name implies, a **transformer conservator** conserves some amount of transformer insulating oil. By definition, **transformer conservator** is an air tight metallic cylindrical drum which is fitted above the transformer main oil tank. A pipeline is provided to create a connection of transformer main tank and conservator and this pipeline usually acts as the circulating path for the insulating oil.

This conservator tank is partially filled with insulating oil. Oil is not allowed to come in contact with the atmospheric air which may contain moisture. The moisture spoils the insulating properties of oil.

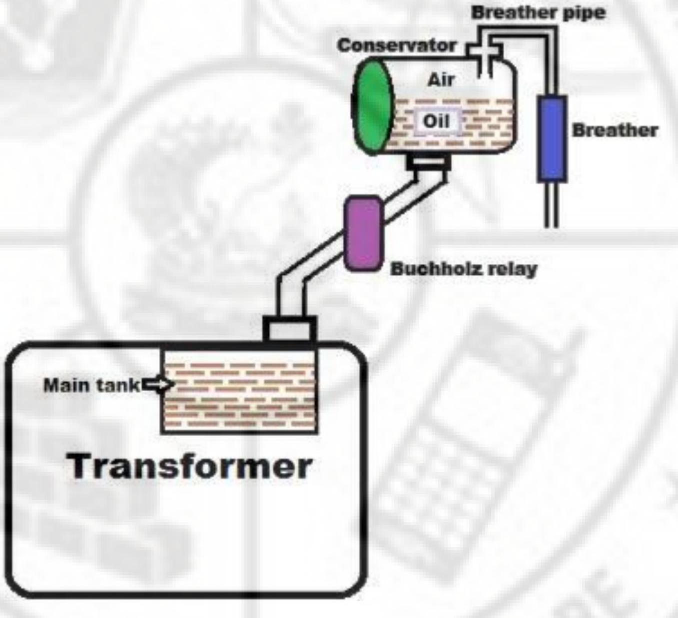


Fig 4.34

Atmospheric air may cause acidity and sludging of oil. A conservator is an air-tight metal drum placed above the level of the top of the tank and connected with it by a pipe. It is partially filled with oil.

4.9.2 Breather

When the oil expands, or contracts by the change in temperature, there is a displacement of air. When the transformer cools, the oil level goes down and the air is drawn in. This is known as breathing. The air coming in is passed through a device called breather for the purpose of extracting moisture. The breather consists of a small vessel which contains a drying a agent like silica gel crystals impregnated with cobalt chloride. It removes the moisture from the incoming air. The silica gel is blue when dry and pink when damp(moisture). Silica gel is checked regularly and dried and replaced when necessary.

4.9.3 Explosion Vent

When there is an accidental internal short circuit in the transformer, an arc is struck between the turns of the winding. Due to this heat generated by the arc and hence a very large volume of gas is produced. So the pressure in the transformer tank increases dangerously which may lead to the explosion of the transformer tank. To avoid such accidental an explosion vent is covered by a diaphram of either glass or aluminium. When the pressure in the tank increases above a critical value,

the diaphram is blown out and release the high pressure gas into the atmosphere. The hot oil may splash and cause injury to the people near the transformer tank. For this reason, the explosion vent is bent downwards.

4.9.4 Buchholz Relay:

Buchholz relay is a special type of relay which is widely used for internal protection of a transformer. This relay is mainly used in oil immersed transformer for providing protection against all types of internal faults like any insulation breakdown.

By definition, **Buchholz relay** is an oil and gas actuated relay which is located in the pipeline connecting the transformer main tank and the conservator.

Construction of Buchholz Relay:

It is a relay which is mainly connected in the pipeline between the main tank and the conservator, designed in the form of a vessel filled with oil which is dome in shape, as shown in the respective diagram which contains the total constructional details. The device can be easily subdivided into two portions inside the vessel depending on its purpose and also its structure, i.e. the upper part and the lower part.

Upper part:

The upper part contains a float which is directly connected to a hinge and a mercury switch is just kept over the float. On the other side the mercury switch is kept in such a way that the terminals of the switch when made to contact with the alarm circuit's terminal, it makes a close circuit. Thus the float is made to move up and down in the oil immersed vessel so that the terminals of the mercury switch gets connected and closing the alarm circuit for making us alert at the time of some internal faults. So the actual purpose of this upper part is to alarm us about the faults.

Lower part:

The lower part of the Buchholz relay is concerned with the detection of serious or major faults and thus completes the trip circuit to open the circuit breaker operating the transformer. It contains a hinged type flap, on which another mercury switch is kept. The mercury switch on the other side is placed in such a way that with the movement of the flap, the terminals of the switch will connect with the terminals of the Trip circuit. The flap plate is placed in just between the flow path of the oil and gas between the main tank pipe mouth and the conservator pipe mouth.

Working Principle of Buchholz Relay:

The main **working principle of buchholz relay** is depended upon the generation of hydrogen gas inside the transformer oil tank. When the transformer oil is subjected to a considerable amount of heat, then it get decomposed and produces hydrogen gas (H2). Generally, an alarm circuit and a trip circuit is connected with relay mechanism. The tripping procedure of both coils and hence the working principle of Buchholz relay is described as follows.

Working of alarm circuit:

The main reason of attaching an alarm circuitry is to alert the working personnel about the fault. If any fault occurs inside the transformer, then a huge amount of heat will be produced. So, this critical amount of heat will decompose some part of transformer oil from the main oil tank. This decomposition of oil generates a considerable amount of hydrogen gas inside the tank.

We know that hydrogen gas is lighter than the oil. As the conservator is situated at the top position of a transformer, so after generation the entire amount of gas tends to reach the conservator tank by flowing in upward direction. But as the Buchholz relay is located at the pipeline, so when flowing to the conservator, some amount of gas is also entrapped by the upper portion of Buchholz relay. More amount of heat leads to generate more amount of hydrogen gas and thus more gas will be accumulated inside the relay chamber.

When the amount of gas tends to approach a predetermined safety value, then it creates a pressure to the float which leads to tilt the float. After the movement of float, the upper mercury switch will get closed circuited and create a complete circuit for the alarm.

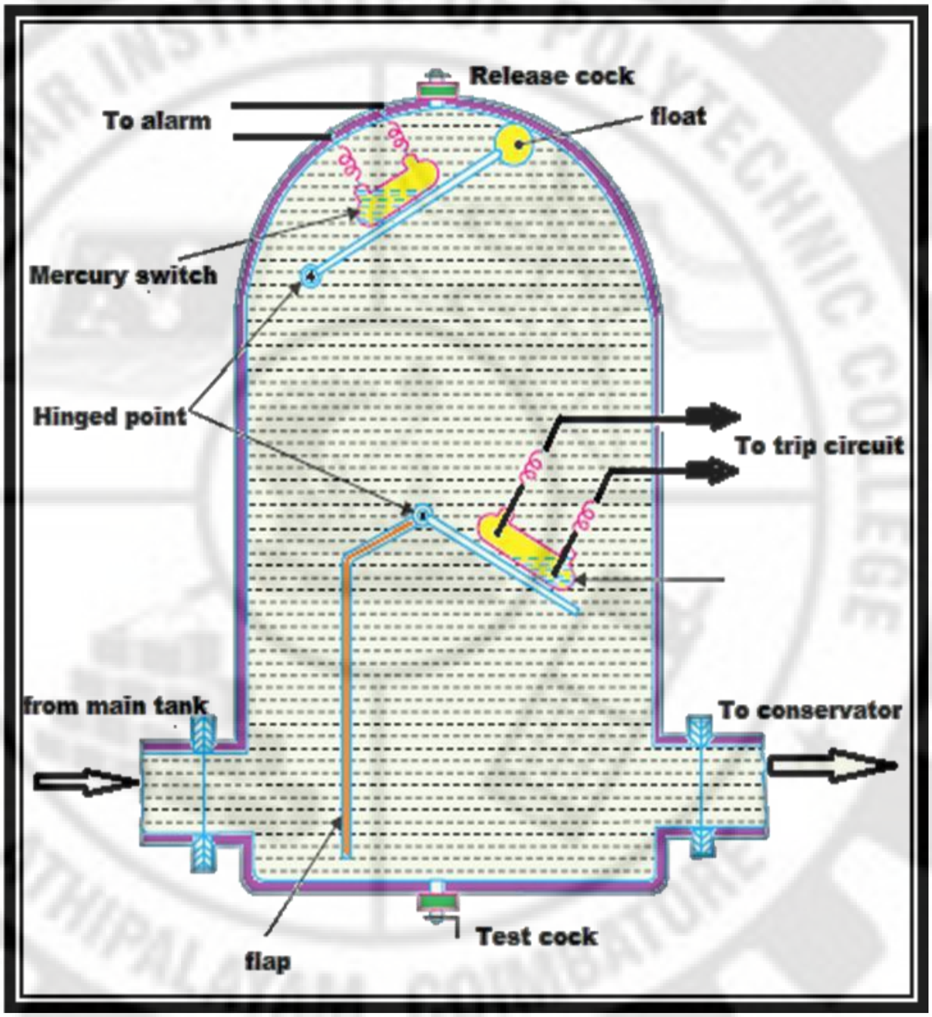


Fig.4.35 Buchholz Relay

Working of trip circuit:

When a serious fault is occurred, then a heavy amount of heat will produced inside the main tank. So, a huge amount of oil is decomposed and this leads to generate a heavy amount of hydrogen gas. The inrush of gas is much higher in that case, and when rushing upward to the conservator tank via the Buchholz relay, then a considerable amount of gas entrapped into the relay and immediately tilts the flap arrangement. After the movement of flap, the mercury switch is automatically closed and provides a closed contact for the trip circuit.

4.10. Tap Changer:

In case of power system networks, the voltage supplied by transformers can be varied by changing it s transformation ratio. This can be achieved by tappings which are provided on transformers. The tappings are the leads which are connected to various points on a transformer winding. These terminals are brought outside to permit access to the winding. Thus the number of turns present in the circuit with one tap are not same for another tap.

The turns ratio is therefore different with different tappings and hence different voltages are obtained with different tappings.

The tappings are placed either on high voltage or low voltages or sometimes on both high and low voltage windings. The Fig.4.36 shows transformer with tappings provided on high voltage winding.

When a transformer is required to give a constant load voltage despite changes in load current or supply voltage, the turn's ratio of the transformer must be altered. This is the function of a tap changer.

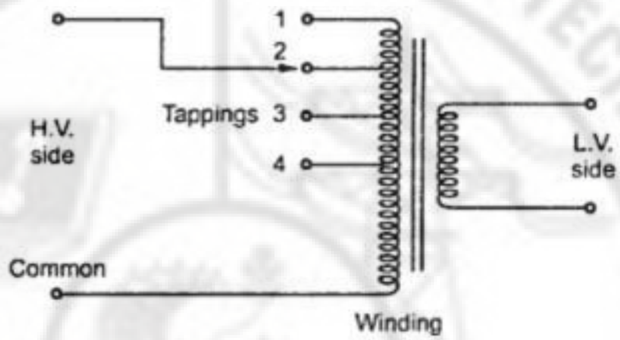


Fig 4.36

Types of Tap Changer:

- Off-load tap changer
- *On-load tap changer*

4.10.1 Off-Load Tap Changer:

In this method of tap changing, the tappings are changed when the transformer is disconnected from the supply. As per the requirement the tappings are taken out on the respective winding and the connections are brought out near the top of transformer. Manually operated selector switches are provided for change in tappings. The commonly used switches are vertical tapping switches and faceplate switches.

The off load tap changer is shown in the Fig.4.37

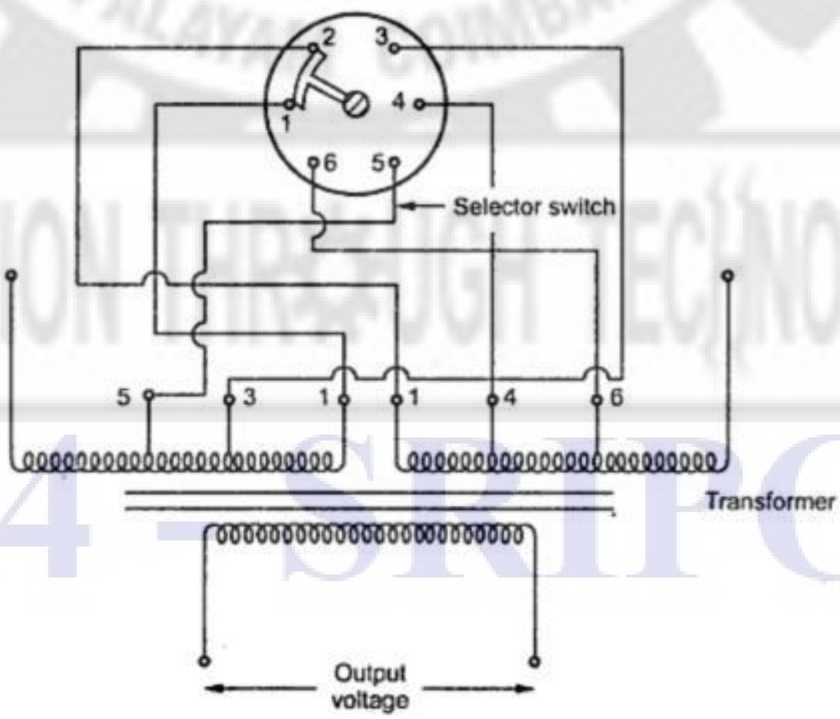


Fig 4.37

The above arrangement is normally used to get ±5 % change in the steps of ±2.5 %. It consists of an insulating base on which six brass or copper terminals are mounted. The contactor is mounted on an arm of the shaft. The central or middle part of the winding contains the taps and the taps are connected to terminals of tap changer. The shaft can be rotated from one position to another so that the selector switch is connected to adjacent pairs of stationary terminals.

Let us consider that the selector switch is at a position connecting taps 1 and 2. Hence total winding is in use. When contactor is moved one point to the left, it makes a connection between 1 and 6 thus cutting out part of the winding between taps 2 and 6. The next step connects taps 6 and 5

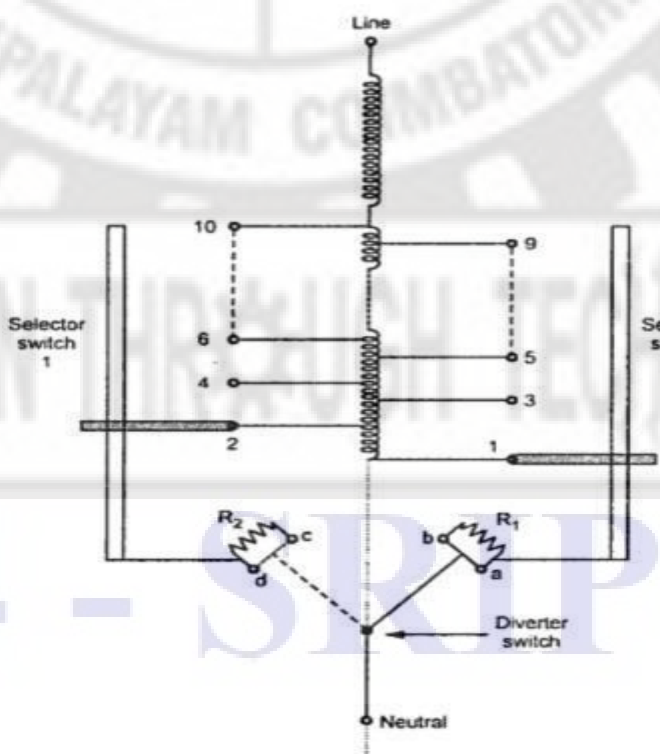
cutting out part of winding between taps 1 and 5. Thus the parts of the windings cut out gradually in steps with minimum number of turns remain in the winding with the position 5 and 6. Corresponding to each position of the selector switch different voltage regulation on positive as well as on negative side can be obtained.

4.10.2 On-Load Tap Changer:

On-load tap changers, as the name suggests, permit tap changing and hence voltage regulation with the transformer on-load. Tap changing is usually done on the HV winding for two reasons:

- Because the currents are lower, the tap changer contacts, leads, etc., can be smaller.

As the HV winding is wound outside the LV winding, it is easier to get the tapping connections out to the tap changer. Fig. shows the connections for an on-load tap changer that operates on the HV



winding of the transformer.

Fig 4.38

The selector switches 1 and 2 are provided on taps 1 and 2 respectively. The diverter switch is connecting tap 1 to the neutral terminal of the transformer winding.

If we want to change the tap from position 1 to 2 then following is the sequence of operation:

i) The resistance R_1 is short circuited as contacts a and b are closed. The load currents flows through contact a from tap. This is nothing but the running position at the tap 1.

ii) With the help of external operating mechanism, the diverter switch is moved to open the contact a. The load current now flows through resistance R_1 and contact b.

iii) The contact c closes to open the resistance R_1 when the moving contact of diverter switch continues its movement to the left. The resistance R_1 and R_2 are now connected across taps 1 and 2 so that the load current flows through these resistances to mid-point of junction of b and c.

iv) With further movement of diverter switch to the left makes contact b to open. Now the load current flows from tap 2 through resistance R_2 and contact c.

v) At last the diverter switch moves to the extreme left position which closes the contact d. This short circuits resistance R_2. The load current flows from tap 2 through contact d which is the running position of tap 2.

It can be sen that the change of tap from position 1 to 2 does not involve the movement of selector switches 1 and 2. But if is desired to have further tap change from tap 2 to tap3 then the selector switch S_2 is moved to tap 3 before the movement of diverter switch. Then then the same sequence as described above but in reverse order is to be followed and the diverter switch is moved.

As the resistances are included in the circuit there will be some loss of energy which can be reduced by keeping these resistances in circuit for minimum time as possible. For economical consideration, as the resistors are designed for short time rating, they should by kept in the circuit for minimum time. This needs some form of energy storage in driving mechanism which ensures the completion of tap change once initiated under the failure of control supply. Modern on load tap changers use springs as energy storage elements which reduce the time of resistor in a circuit to minimum. This type of tap changer is compact in size while due to high speed breaking, contact wear reduces.