GOVERNMENT OF TAMILNADU
DIRECTORATE OF TECHNICAL EDUCATION
CHENNAI – 600 025
STATE PROJECT COORDINATION UNIT

Diploma in Electrical and Electronics Engineering

Course Code: 1030

M – Scheme

e-TEXTBOOK

on

ELECTRICAL MACHINES - I

for

III Semester DEEE

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DIPLOMA IN ELECTRICAL AND ELECTRONICS ENGINEERING

M - SCHEME

Course Name: Diploma in Electrical and Electronics Engineering

Subject Code: 1030 **Semester: III**

Subject Title: ELECTRICAL MACHINES I

RATIONALE:

- This subject is classified under core technology group which intends to teach the facts, concepts, principles of electrical machines, such as DC generators, DC motors, single & three phase transformers and DC electrical source (battery).
- Student will be able to analyze the characteristics of DC generators and motors, Transformers, battery & Qualitative parameters of these static and dynamic machines. These machines are used in transmission, distribution and utilization systems.
- Knowledge gained by students will be helpful in study of technological subjects such as utilization of electrical energy, switchgear & protection, manufacturing processes & maintenance of electrical machines.

OBJECTIVES:

Students will be able to:

1. Know the constructional details & working principles of dc machines and transformers.
2. Evaluate the performance of dc generators, motors & transformers.
3. Decide the suitability of dc generator, motor & transformer for particular purpose.
4. Write the specifications of dc machines & transformers as per requirement.
5. Know the constructional details, working principle, testing and capacity of battery

DETAILED SYLLABUS
1030 – ELECTRICAL MACHINES - I
(M - SCHEME)

Unit-1 D C GENERATORS **(Page No: 4-46)**

Review of electromagnetic induction – Faraday's laws – Fleming's right hand rule – Principle of operation of D.C. generators – Construction of D.C. generators – Field system– Types of armature windings – Principles of lap and wave windings – EMF equation – Types of D.C. generators – Building up of voltage of D.C. Shunt generators — No load characteristics of Shunt generator – Determination of critical field resistance – Causes of failure to build-up voltage and remedy – Load characteristics of series and shunt generators – load characteristics of cumulatively and differentially compounded generators – Applications – Problems in above topics – armature reaction – methods of compensating armature reaction – process of commutation – sparking in commutators – methods of improving commutation.

Unit -2 DC MOTORS **(Page No: 47-78)**

Principle of operation of D.C. Motors – Fleming's left hand rule – Construction – Back emf – Torque equation – Types of motors – Torque-current, Speed-current, Speed-Torque characteristics of different motors – Speed control of DC motors – Field control and armature control– necessity of Starters– 3 Point and 4 Point starters – losses in D.C. Machines – Testing of D.C. machines - Predetermination of efficiency of motor and generator by Swinburne's test – Problems in above topics – Applications of D.C. Motors.

Unit -3 **SINGLE PHASE TRANSFORMERS** **(Page No: 79-129)**

Principle of operation – Constructional details of core, shell type transformers – coil assembly – EMF Equation – Voltage ratio – Transformer on No load – Transformer on load – Current ratio – Phasor diagram on no load and on load at different power factors – O.C. test, S.C. test – Determination of equivalent circuit constants– Determination of voltage regulation and efficiency – Condition for maximum efficiency – All day efficiency – Problems on the above topics - polarity test– Parallel operation of single phase transformers– Auto transformer – principle – saving of copper – applications.

Unit -4 THREE PHASE TRANSFORMERS (Page No: 130-162)

Three phase Transformer construction – Types of connections – Star-star, Star-Delta, Delta-Star, Delta-delta connections – Scott connection - V connection of transformer – Parallel operation of three phase transformers –grouping of transformers– Conditions – Phasing out test – Pairing of transformer - Load sharing of transformers with equal and unequal ratings –Cooling of transformers – Various cooling arrangements – Transformer accessories – conservator – breather – explosion vent – Bucholz relay–ON load and OFF load tap changer – Transformer oil tester – Acidity test –- Earthing – Measurement of earth resistance.

Unit -5 STORAGE BATTERIES **(Page No: 163-177)**

Classification of cells –construction – chemical action and physical changes during charging , discharging - internal resistance and specific gravity of lead acid, nickel iron and nickel cadmium cells – indication of fully charged and discharged battery –defects and their remedies – capacity – methods of charging – maintenance – applications.

1.1 INTRODUCTION

DC generator is a machine which converts mechanical energy into electrical energy with the magnetic field as the coupling medium. It works on the principle of Faraday's law of electromagnetic induction.

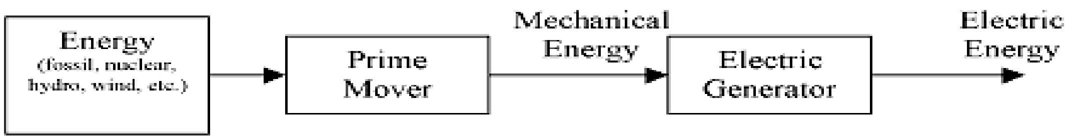


Fig.1.1

In all electrical machines including transformer magnetic field is used as a coupling medium for energy conversion and transfer. Hence it is very important for us to know the basic concepts of electromagnetism before going into the details of Faraday's law of electromagnetic induction.

1.1.1 BASICS OF ELECTROMAGNETISM:

Magnet and Magnetism:

A substance that attracts pieces of iron and steel is called a magnet and this property of the material is called magnetism.

Magnetic field:

The magnetic field is the area around a magnet in which there exists a magnetic force.

Magnetic flux:

Magnetic flux is the number of magnetic lines of forces emanating from a magnetic material. It is represented by ϕ and its unit is Weber (Wb).

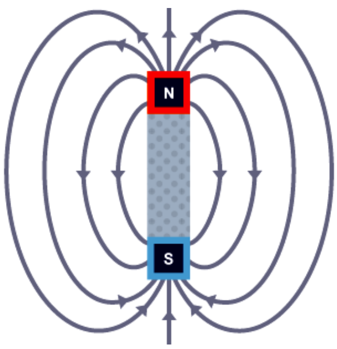


Fig.1.2 Magnetic Flux around a Magnet

Magnetic flux density:

The magnetic flux density is the flux per unit area at right angle to the flux. It is represented by **B** and its unit is Wb/m^2 or Tesla.

$$B = \frac{\phi}{A}$$

Permeability:

It is defined as the ability in which the magnetic material forces the magnetic flux through a given medium. It is represented by a letter μ and its unit is Henries per meter. (H/m)

$$\mu = \mu_o \ \mu_r ;$$

Where μ_o is the permeability of free space or air and

μ_r is the relative permeability of the medium with respect to air,

$$\mu_o = 4\pi \text{ x } 10^{-7} \text{ H/m}$$

Magnetic permeability is the opposite of magnetic reluctance.

Reluctance:

It is the property of a material which opposes the establishment of magnetic flux in it.

It is represented by S and its unit is AT/Wb

$$S = MMF / \phi \ ; \ S = l / \mu A \ ;$$

Magneto motive force MMF:

In an electric circuit an electromotive force is required to produce current flow. In magnetic circuits magneto motive force is required for the flow of flux. It is found that a product of number of turns in the winding and the current flowing in. It is a measure of how much excitation is applied. This product is called magneto motive force.

The force which causes the magnetic flux in a magnetic circuit is called magneto motive force. The unit of MMF is Ampere Turns.

$$MMF = NI$$

Coulomb's law of magnetic force:

When two isolated poles are placed nearer to each other, they experience a force.

First law:

Like poles repel each other while unlike poles attract each other.

Second law:

The force between two magnetic poles is directly proportional to the product of their pole strength and inversely proportional to the square of the distance between their centers.

$$F \alpha \ m_1 \ m_2 / d^2$$

where m_1 & m_2 represents the magnetic field strength of the two poles and

d represents the distance between the two poles.

Magnetic effects of electric current:

When an electric current flows through a conductor, magnetic field is set up all along the length of the conductor. The magnetic effects of electric current are:

i. The greater the current flow the conductor, the stronger is the magnetic field and vice versa.

ii. The magnetic field near the conductor is stronger and becomes weaker and weaker as we move away from the conductor.

iii. Magnetic lines of force around the conductor will be either clockwise or anticlockwise, depending upon the direction of current. Right Hand Thumb Rule is used to determine the direction of magnetic field around the conductor.

iv. The shape of the magnetic field depends upon the shape of the conductor.

Right Hand Thumb Rule:

Hold the conductor in the right hand with the thumb pointing in the direction of current as shown in the figure. Then the fingers will point the direction of the magnetic field around the conductor.

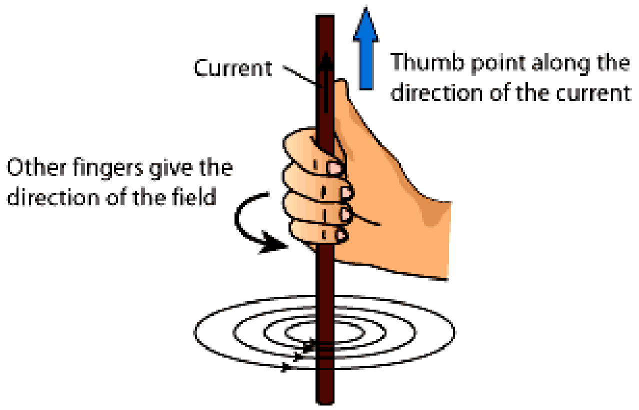


Fig.1.3 Right Hand Thumb Rule

Cross and Dot notation :

Cross and Dot notation can be used to indicate the direction of current flow. In figure 1.4, current flowing away from observer is indicated by cross. The cross is based on the tail of an arrow moving away from the observer. Figure 1.4 also shows that current flowing towards an observer and is indicated by a dot. The dot is based on the point of an arrow moving towards the observer.

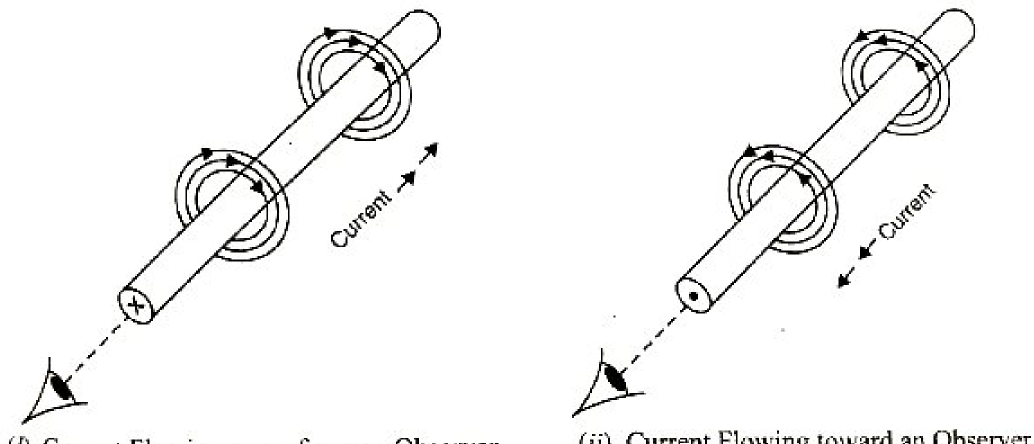


Fig.1.4

1.2 Faraday's laws of electromagnetic induction

DC generator works on the principle of Faraday's law of electromagnetic induction.

Faraday's experiment:

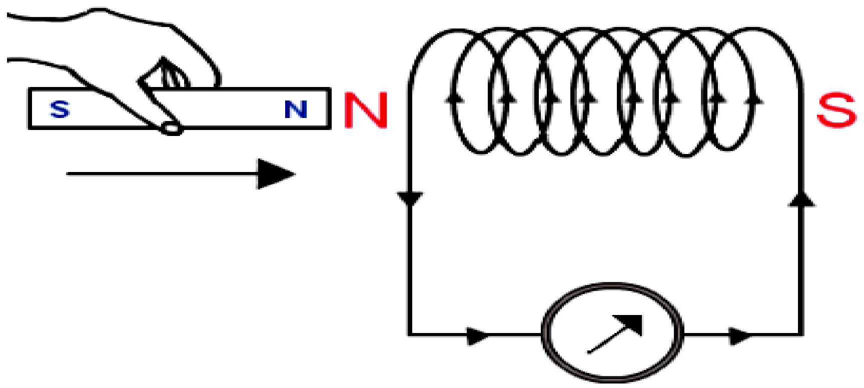


Fig.1.5

Consider a coil C of several turns connected to a central zero galvanometer as shown in figure 1.5. If a permanent magnet is moved towards the coil it will be observed that the galvanometer shows deflection in one direction. If the magnet is moved away from coil, the galvanometer again shows deflection but in opposite direction. Deflection of galvanometer indicates there is a current flow through the coil. For the current to flow, there must be an EMF in the coil. Hence it is concluded that when magnetic flux linking a conductor or coil changes an EMF is induced in it.

Faraday's laws of electromagnetic induction:

First law :

Whenever the magnetic flux linking a conductor or coil changes, an EMF is induced in it.

Second law:

The magnitude of the EMF induced in a conductor or coil is directly proportional to the rate of change of flux linkage. Here the minus sign of the RHS represents the Lenz's law.

induced emf $e \propto d\phi/dt$

$$e = -N\, d\phi/dt$$

Direction of induced EMF and current:

The direction of induced EMF and current can be determined by one of the following two methods 1.Lenz's law 2.Fleming's right hand rule.

Lenz's law:

The induced current will flow in such a direction so as to oppose the cause that produces it. In this case, the cause for the induced current is the increasing magnetic flux linking the coil. Therefore the induced current will set up magnetic flux that opposes the increase in flux through the coil.

1.3Fleming's right hand rule:

This law is used to find the direction of the induced EMF of DC generator. Hold the fore finger, middle finger and thumb of the right hand so that they are at right angles to one another. If the fore finger points in the direction of magnetic field, thumb in the direction of motion of conductor then the middle finger will point the direction of induced current.

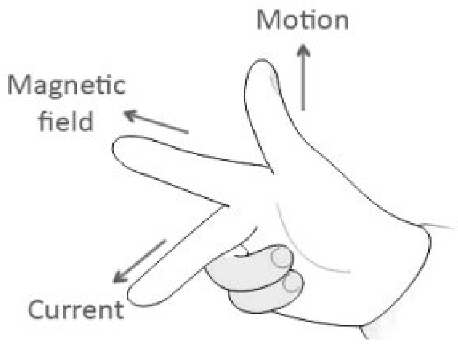


Fig.1.6

Faradays law states that whenever a conductor cuts the magnetic flux or magnetic flux cuts the conductor, an EMF is induced in the conductor.
Therefore the essential components of a generator are

i. Magnetic field.
ii. Conductor or a group of conductors
iii. Motion of conductor with respect to magnetic field.(prime mover)

For the generation of induced EMF there should be a relative motion between the conductor and the magnetic field. i.e. either the magnetic field should be moved while conductor is being stationary or the conductor is made to move in a stationary magnetic field.

When the magnetic flux linking a conductor changes, an EMF is induced in the conductor. This can be done in two ways.

1) Dynamically induced EMF:

If the conductor is moved in a stationary magnetic field then the EMF induced is called dynamically induced EMF. Example: DC generator.

2) Statically induced EMF:

If the conductor is stationary and the magnetic field is moving or changing then the induced EMF is called statically induced EMF. Example: Transformer and ac generator (alternator).

1.4 Working Principle of DC Generator:

The method of producing emf in a simple loop generator is explained in the fig.1.7.

Fig 1.7 shows a single loop of copper coil ABCD moving in a magnetic field. The two ends of the coil are joined to two slip rings 'S_1' and 'S_2'. These slip rings are insulated from each other. Two collecting brushes press against the slip rings. The brushes collect the current induced in the coil and supply it to the external load.

When the coil rotates inside the magnetic field the flux linked with the coil changes and hence emf is induced in the coil, which is proportional to the rate of change of flux linkages. Assume the coil is rotating in clock wise direction. When the plane of the coil is at right angles to the flux lines i.e. in position 1 (where $\theta = 0^0$) the flux linked with the coil is maximum, but the rate of change of flux linkages is minimum. Because in this position coil does not cut any flux lines. Therefore no emf is induced in the coil at position 1.

When the coil moves to position 4 (where ɵ = 90^0) the coil plane is horizontal to the flux line, the flux linked with the coil is minimum, but the rate of change of flux linkages is maximum. Therefore maximum emf is induced in the coil at position 3.

When again the plane of the coil from horizontal to right angles to the flux lines i.e. position 4 to position 7 (where ɵ = 90^0 to 180^0) the flux linked with the coil gradually increases, but the rate of change of flux linkages is minimum. Because in this position coil does not cut any flux lines. Therefore no emf is induced in the coil at position 7.

Now if the coil moves from position 7 to 10 (180^0 to 270^0), the emf induced in the coil is in the reverse direction. Therefore at position 7, the emf induced is -ve maximum. Then the coil moves from position 10 to position 1, (270^0 to 360^0) the flux linked with the coil gradually increases, but the rate of change of flux linkages decreases. The emf induced is zero at position 1. Thus the emf induced in the coil is an alternating emf(AC) as shown in fig.1.7.

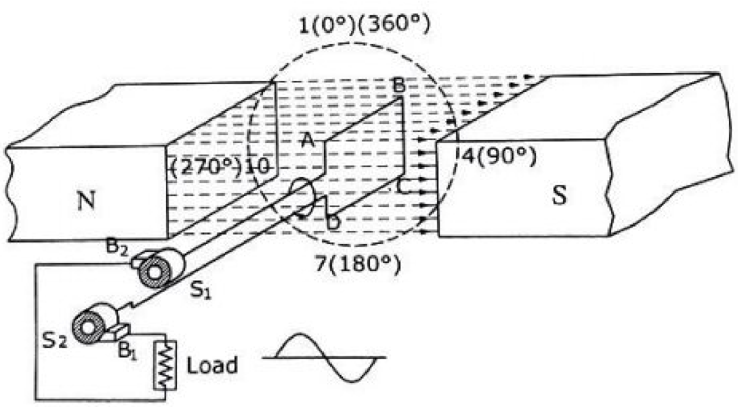
Conversion of AC to DC:

If the slip rings are replaced by split rings, the alternating emf will become unidirectional current (DC). The split rings are made out of conducting cylinder which is cut into two segments insulated from each other by thin sheet of mica. The coil ends are joined to these segments. Carbon brushes rest on the segments.

Fig 1.8 shows the connection of coil ends with slip rings a&b. In the first half revolution, current flows along ABLMCD in the brush no. 1which is in contact with the segment 'a' which acts as the positive end of emf while the segment 'b' acts as the negative end.

In the next half revolution, the direction of current in the coil has reversed as shown in fig 1.8. But at the same time, the positions of segments a and b have also been reversed. The segment 'a' is coming in contact with brush no.2 and becomes negative end of induced emf. Again the current in the load resistance flows in the same direction i.e., from L to M. Hence the current is unidirectional current. The AC induced in the coil is converted into unidirectional current due to rectifying action of the split rings (also called as commutator)

The unidirectional current is shown in fig. To minimize the ripple in DC current the number of coils in the armature should be increased.



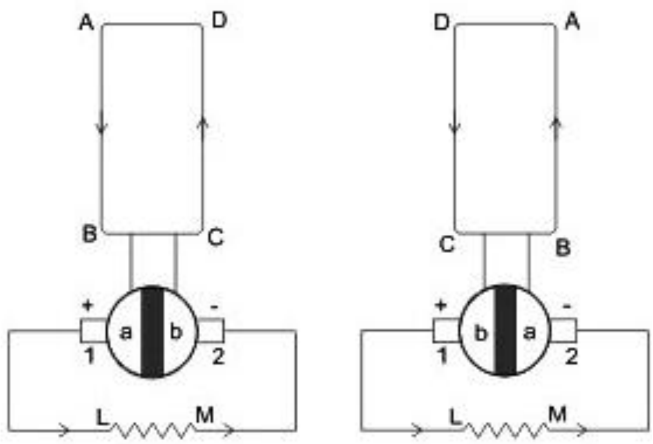
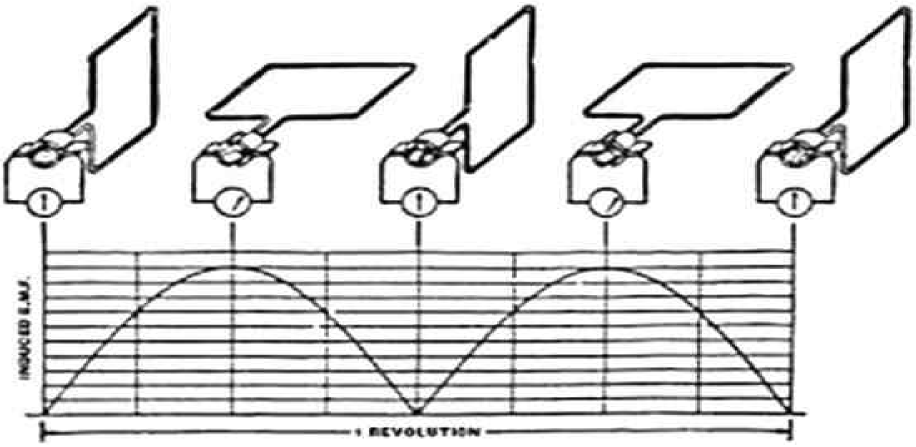


Fig.1.7

Fig.1.8



(*figure shown here is only for understanding purpose)

1.5Construction of a DC Generator

A DC generator can be used as a DC motor without any constructional changes and vice versa is also possible. Thus a DC generator and DC motor can be broadly termed as a DC machine. Fig.1.9 shows the constructional details of a simple 4 pole DC machine. It consists of two basic parts.

i) Stator and

ii) Rotor.

Major constructional parts of a DC machines are:

1. Yoke
2. Poles and pole shoes
3. Field winding
4. Armature core
5. Armature winding
6. Commutator and brushes.

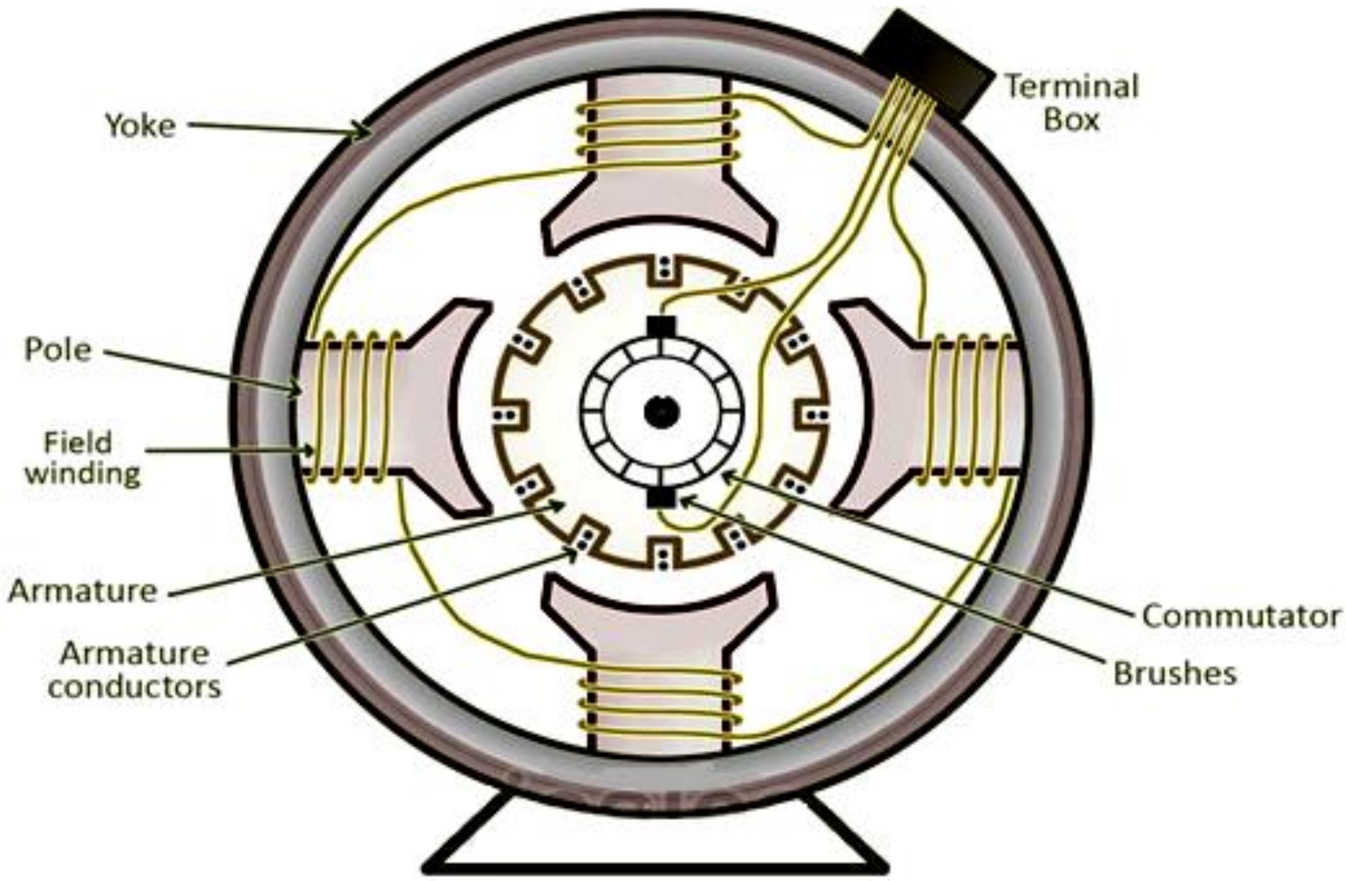


Fig.1.9

Yoke:

The outer frame of a DC machine is called yoke. It is made up of cast iron or steel. It provides mechanical strength to the whole assembly and it carries the magnetic field produced by the field windings.

Poles and Pole shoes:

Poles are joined to the Yoke with the help of bolts and welding. They carry field winding and pole shoes are fastened to them. Pole shoes serves two purposes. They support field coils and spread out the flux in the air gap uniformly.

Field winding:

They are usually made up of copper field coils and are former wound. They are placed on each pole and are connected in series. They are wound in such a way that when energized they form alternate North and South poles.

Armature Core:

Armature core is in the rotor of the DC machine. It is cylindrical in shape with slots to carry armature winding. As the armature core is also a conducting material, an emf is induced in the core. This emf produces a circulating currents(called as eddy currents) in the core and it leads to power loss called as eddy current loss. So the armature core is laminated(laminations reduces the effective area considerably thereby increasing the resistance which in turn decreases the eddy currents) to reduce eddy current losses. Air ducts are provided for the axial flow of air and is used for cooling purpose. Armature core is keyed to the shaft.

Armature winding:

It is usually former wound copper coil which is placed in armature slots. The armature conductors are insulated from each other and also from the armature core. Armature winding can be wound by the following one or two methods.

i) Lap winding

ii) Wave winding

Double layer lap and wave winding are generally used. Double layer winding means that each armature slot will carry two different coils.

Commutator and brushes:

Physical connection to the armature winding is made through a commutator and brush arrangement. A commutator is a mechanical rectifier which converts the alternating voltage generated in the armature winding into direct voltage across the brushes.

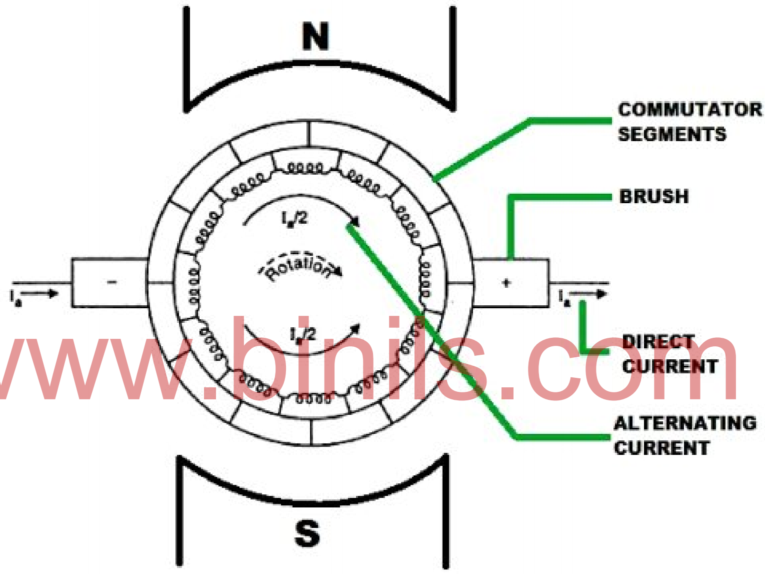


Fig.1.10

Fig. 1.10shows the commutator and brushes arrangement. The function of a commutator in DC generator is to collect the current generated in armature conductor (whereas in case of DC motor commutator helps in providing current to line armature conductors).

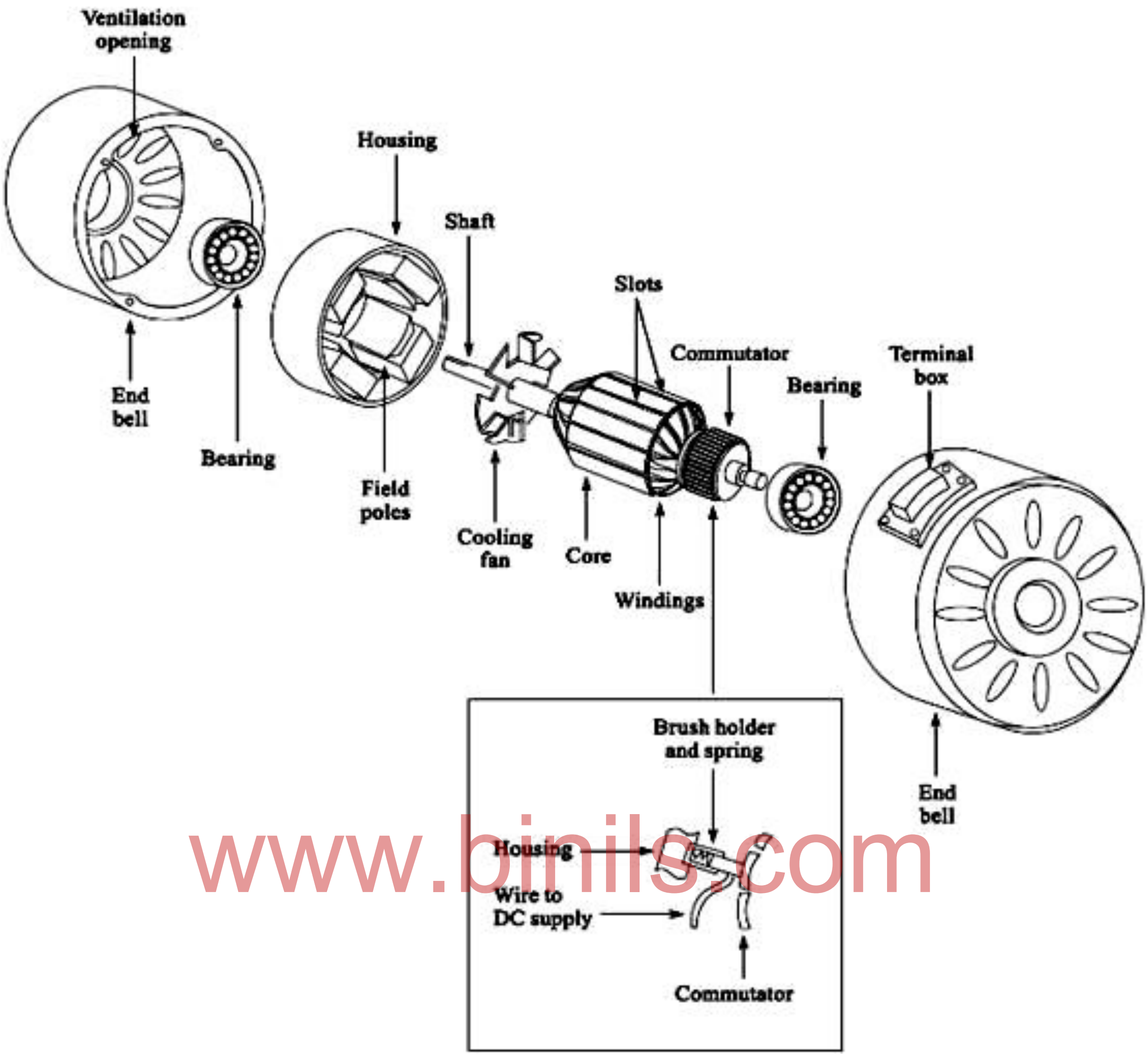
A commutator consists of a set of copper segments which are insulated from each other. The number of segments is equal to the number of armature coils. Each segment is connected to an armature coil and the commutator is keyed to the line shaft.

Brushes are usually made from carbon or graphite and they rest on commutator segment and slide on the segments when the commutator rotates.

In a DC generator field coils produces an electromagnetic field and the armature conductors are rotated into the field. Thus an electromagnetically induced EMF is generated in the armature conductors.

The direction of induced current is given by Fleming's right hand rule.

Parts of DC Generator



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1.6 Field system

The magnetic field required for the operation of a d.c. generator is produced by an electromagnet. This electromagnet carries a field winding which produces required magnetic flux when current is passed through it.

Note : The field winding is also called exciting winding and current carried by the field winding is called an exciting current.

Thus supplying current to the field winding is called excitation and the way of supplying the exciting current is called method of excitation.

There are two methods of excitation used for d.c. generators,

1. Separate excitation 2. Self- excitation

Depending on the method of excitation used, the d.c. generators are classified as,

1. Separately excited generators 2. Self excited generators

In separately excited generators, a separate external d.c. supply is used to provide exciting current through the field winding.

The d.c. generators produces d.c. voltage. If this generated voltage itself is used to excite the filed winding of the same d.c. generator, it is called self - excited generator.

1.7 TYPES OF ARMATURE WINDINGS:

The basic types of armature windings are:

a) Lap winding.
b) Wave winding.

Further based on the number of layers wound on the armature slot it is classified as:

a) Single layer winding.
b) Double layer winding.

1.8 Principles of lap & wave winding:

a) Pole pitch:

It is defined as the distance between two adjacent poles in terms of number of armature conductors or slots i.e. number of armature conductors or slots per pole.

Eg: number of conductors=48; number of poles=4

Pole pitch= 48/4= 12 slots/pole

b) Coil:

Two conductors AB&CD along with their end connection constitute one coil of the armature windings.

c) Coil span/ Coil pitch Y_s:

It is the distance measured in terms of armature slots or conductors between two sides of a coil. If the coil span is equal to the pole pitch, then it is called full pitched winding and if the coil span is less than the pole pitch, then it is called as fractional pitched or short chorded windings.

d) Back pitch Y_b:

It is defined as the distance in terms of number of armature conductors in which a coil advances on the back of the armature. (far end of the commutator)

e) Front pitch Y_f :

It is defined as the number of armature conductors spanned by a coil on the front of the armature (or) distance in terms of number of armature conductors between the second conductor of one coil and the first conductor of the next coil.

f) Commutator pitch Y_c:

The distance between the two coil sides of a coil connected to the commutator segments.

Single layer winding:

If the winding is made such in a way that each slot has one coil side of a coil, then it is called as single layer winding.

Double layer winding:

If the winding is made in such a way that each slot has coil sides of two different coils, then it is called double layer winding.

1.8.1 Lap winding [parallel connection]:

In lap winding the finishing end of one coil and the starting end of adjacent/next coil of the same pole group are connected to one/same commutator segment. As the adjacent/next coil sides are over lapped one over the other it is called as lap winding. It is used in DC machines having high-current, low- voltage rating.

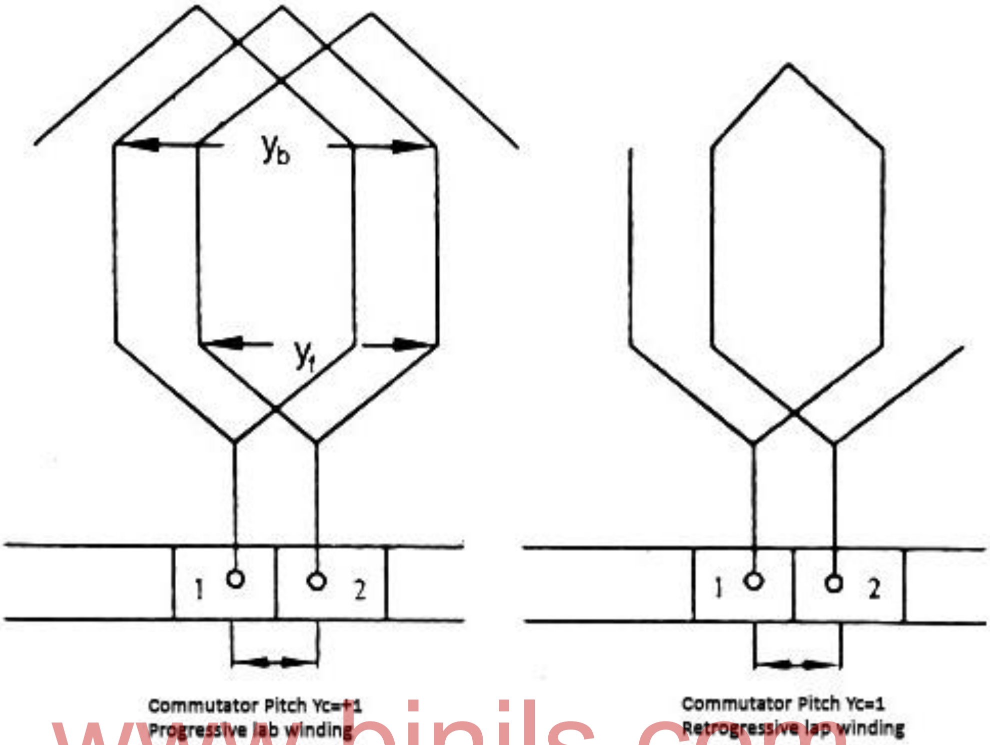


Fig.1.11

Characteristics of lap winding:

1) In lap winding the number of parallel paths is equal to the number of poles i.e. A=P.
2) The number of brushes is equal to the number of poles.
3) The back pitch Y_b & front pitch Y_f should be odd one.
4) The difference between Y_b& Y_f is : Y_b- Y_f=2
5) Commutator pitch Y_c=+1 for progressive winding
4 Y_c=-1 for retrogressive winding
6) Average pitch YA= Y_B+ Y_f/2=Z/P

1.8.2 Wave winding:

In wave winding each coil under a pole pair is connected in series with another coil occupying similar position under the next pole pair. It is used in DC machines of low current and high voltage (500-600v) range.

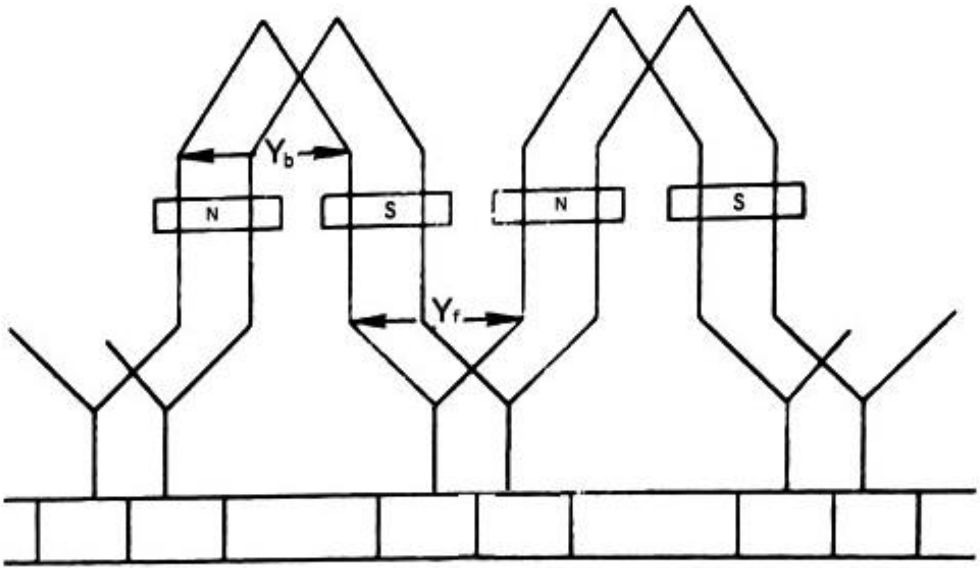


Fig.1.12

Characteristics of Wave Winding:

1) Y_b and $Y_f$should be odd one
2) Back pitch is equal to front pitch $Y_b= Y_f$
3) No. of parallel paths A=2
4) Commutator pitch Y_c= no. of segments+1/ no. of pair of poles
5) Average pitch $Y_a= Y_b+ Y_f/2=Z+2/P$

Development of Winding Diagram for 24 slots 4 pole single layer lap winding:

The given a winding is a single layer lap winding. Hence in each slot one coil side is placed. Therefore total number of conductors will be 24 x 1 = 24 conductors.

pole pitch=no. of slots/no. of poles=24/4=6

$Y_b+ Y_f/2=Z/P$----------------------------1

$Y_b- Y_f=2$----------------------------------2

$Y_b+ Y_f/2=24/4;Y_b+ Y_f=12$------------3

3+4, $Y_b+ Y_f=12$

(+) $Y_b- Y_f= 2$

$2Y_b=14$

$Y_b=7$

$Y_f=5$

S. NO	BACK SIDE [Y_b=7]	FRONT SIDE [Y_f=5]
01.	1+7=8	8-5=3
02.	3+7=10	10-5=5
03.	5+7=12	12-5=7
04.	7+7=14	14-5=9
05.	9+7=16	16-5=11
06.	11+7=18	18-5=13
07.	13+7=20	20-5=15

08.	15+7=22	22-5=17
09.	17+7=24	24-5=19
10.	19+7=26(2)	26-5=21
11.	21+7=28(4)	28-5=23
12.	23+7=30(6)	30-5=25(1)

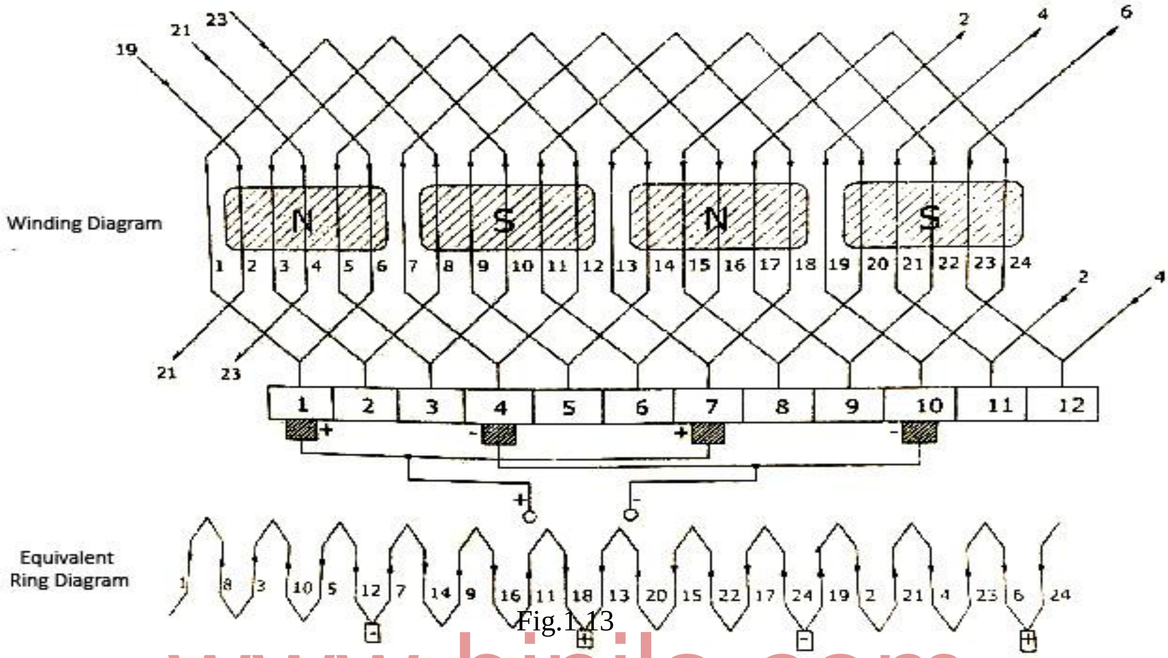


Fig.1.13

Development of Winding Diagram for 24 slots 4 pole single layer wave winding:

Y_b=Y_f = pole pitch, but pole pitch (or) Y_b (or) Y_f should be odd one

S. NO	BACK SIDE [Y_b=7]	FRONT SIDE [Y_f=7]
01.	1+7=8	8+7=15
02.	15+7=22	22+7=29(5)
03.	5+7=12	12+7=19
04.	19+7=26(2)	2+7=9
05.	9+7=16	16+7=23
06.	23+7=30(6)	6+7=13
07.	13+7=20	20+7=27(3)
08.	3+7=10	10+7=17
09.	17+7=24	24+7=31(7)
10.	7+7=14	14+7=21
11.	21+7=28(4)	4+7=11
12.	11+7=18	18+7=25(1)

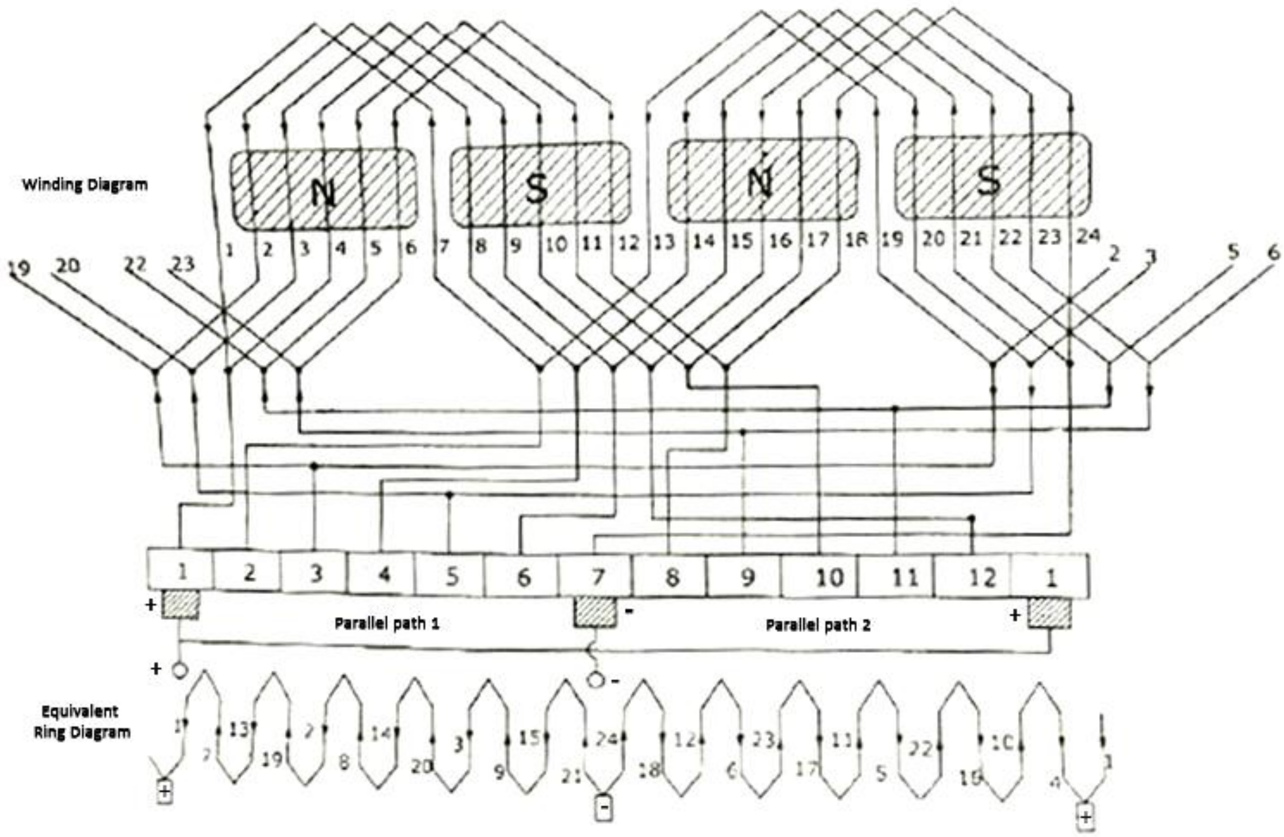


Fig.1.1

1.9 EMF equation of DC generator:

In a DC generator when armature conductor cuts the flux an EMF is induced as per Faraday's laws of electromagnetic induction. The EMF induced is based on the factors mentioned below.

Let	P	=	Number of poles in the generator
	ϕ	=	Flux per pole
	Z	=	Number of armature conductors
	N	=	Speed of rotor in RPM
	A	=	Number of parallel paths in armature
	E_g	=	EMF generated in any of the parallel path in armature.

Average EMF generated per conductor $= E_g$ Volts

Flux cut by the conductor in one revolution of the armature $d\phi$ $= P\phi$ Webers

Number of revolutions made in 1 minute $= N$

number of revolutions made in 1 second = N/60

Time taken to complete one revolution = 60/N

Average EMF generated per conductor = $P\phi/60/N$
= $\phi NP/60$ Volts

EMF generated by Z number of conductors = $Z^* \phi NP/60$
= $\phi ZNP/60$ Volts

EMF generated per parallel path = $P\phi ZN/60A$ Volts

1.10 Types of DC generator:

Types of a DC generator based on way in which the field are excited generator are classified into

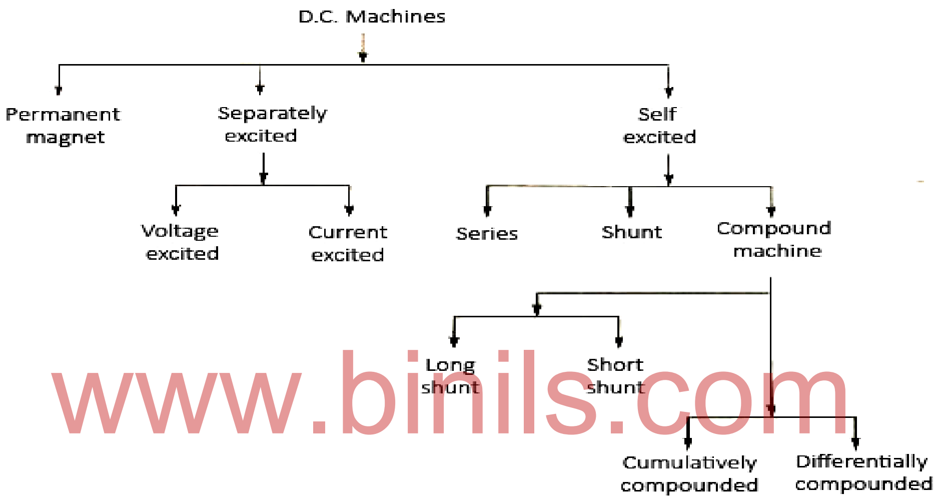


Fig.1.15

1.10.1 Separately excited generator:

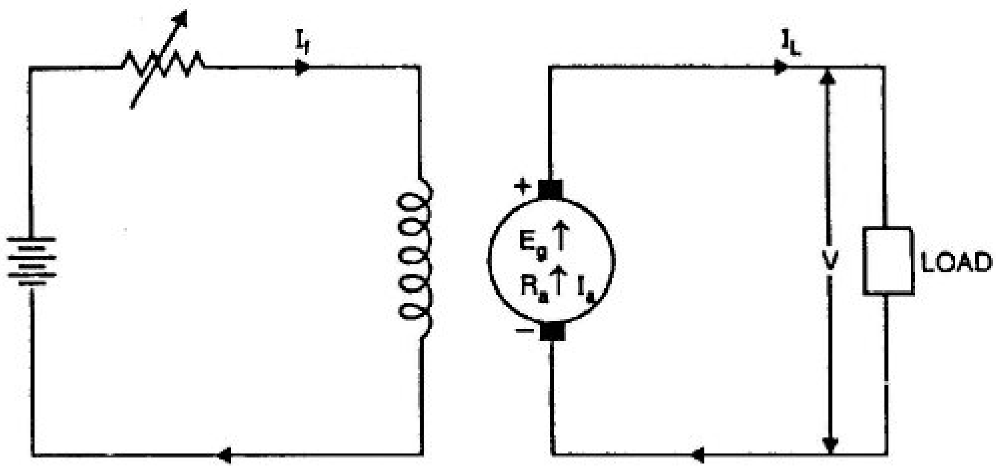


Fig. 1.16

Separately excited DC generator is a DC generator whose field magnetic winding is excited from an independent external DC source (eg: battery)

1.10.2 Self - excited DC generator:

A DC generator whose field magnet winding is supplied current from the output of the generator itself is called a self-excited generator.

There are three types of self-excited generator depending upon the manner in which the field windings is connected to the armature winding namely

i) Series generator,
ii) Shunt generator,
iii) Compound generator.

Series Generator:

In series wound generator, the field winding a connected in series with armature winding, fig.1.17, shows the connection of series wound generator, since the field of series wound generator. Since the field winding carries the whole of load current, it has a few turns of thick wire having low resistance. Series generators are used for specific purposes.

Eg: boosters, in this type the voltage increases as the load increases

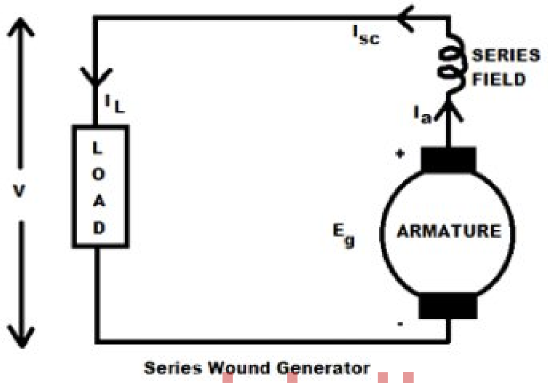


Fig.1.17

Armature current $I_a = I_{se} = I_L$
Terminal voltage $V=E_g-I(R_a+R_{se})$
Power developed in armature$=E_gI_a$
Power delivered to the load$=VI_a$ or VI_L

Shunt generator:

In shunt generator, the field winding is connected in parallel with armature winding. Here terminal voltage is applied across field winding. The shunt winding has many turns of fine wire having high resistance. Therefore only a small part of armature current flows through shunt field winding and rest flows through the load.

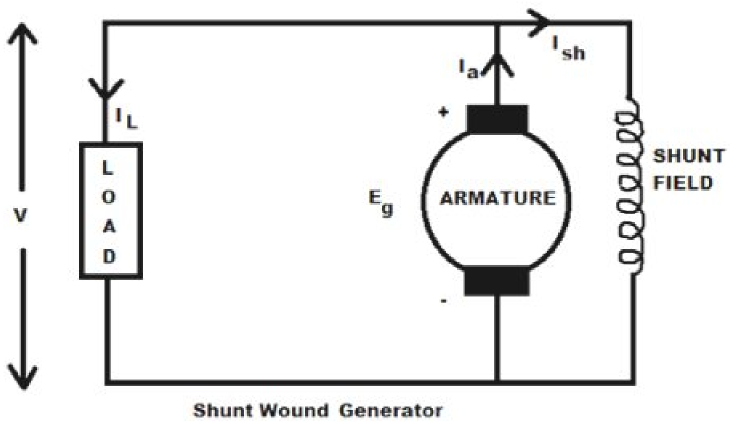


Fig.1.18

Fig.1.18 shows the connections of dc shunt generator. Shunt generators are used for lighting and power supply purposes. These are also used for charging batteries.

Shunt field current $I_{sh}=V/R_{sh}$
Arm current, $I_a=I_L+I_{sh}$
Terminal voltage $V=E_g-I_aR_a$
Power developed in armature$=E_gI_a$
Power delivered to load$=VI_L$

Compound generator:

In a compound wound generator, there are two sets of field windings on each pole, one is in series and other is in parallel with the armature. There are two types of compound wound generator.

i) Short shunt:

In this, only shunt field winding is in parallel with the arm winding as shown in fig.1.19

Series field current, $I_{se}=I_L$
Shunt field current, $I_{sh} = V+I_{se}\ R_{se}/R_{sh}$
Terminal voltage $V=E_g-I_aR_a-I_{se}R_{se}$
Power developed in armature$=E_gI_a$
Power delivered to load$=VI_L$

ii) Long shunt:

In this, shunt field winding is in parallel with both series field and armature winding as shown in fig.1.19

Series field current, $I_{se}=I_a+I_L+I_{sh}$
Shunt field current, $I_{sh}=V/R_{sh}$
Terminal voltage, $V=E_g-I_a(R_a+R_{se})$
Power developed in armature$=E_g\ I_a$
Power delivered to load$=VI_L$

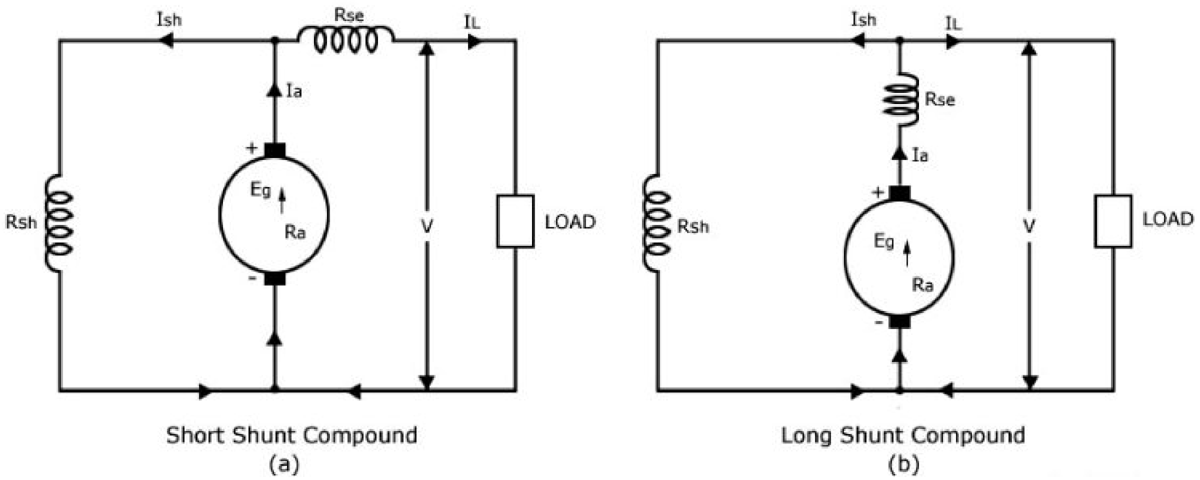


Fig.1.19

In this type of DC generator, the field is produced by the shunt as well as series winding. The shunt field is stronger than the series field. If the magnetic flux produced by the series winding assists the flux produced by the shunt field winding, the generator is said to be **Cumulatively Compounded** generator.

If the series field flux opposes the shunt field flux, the generator is said to be **Differentially Compounded.**

1.11 Building up of EMF in DC self-excited shunt generator:

In self-excited DC generator the field current is initially zero, as the voltage generated is zero at the time of starting. But the core material of the field will have some residual magnetism, which helps in generating process of the EMF. When the armature is rotated, this residual magnetism induces a small EMF in the armature called Residual voltage. This EMF is shown as**oa** in fig. This small EMF produces a field current equal to **ob'**. Now the flux produced by the field winding increases. This increased Flux increases the EMF to b'c and this increased EMF once again increases the field current to od', which in turn increases the EMF to d'e. This process is cumulative.

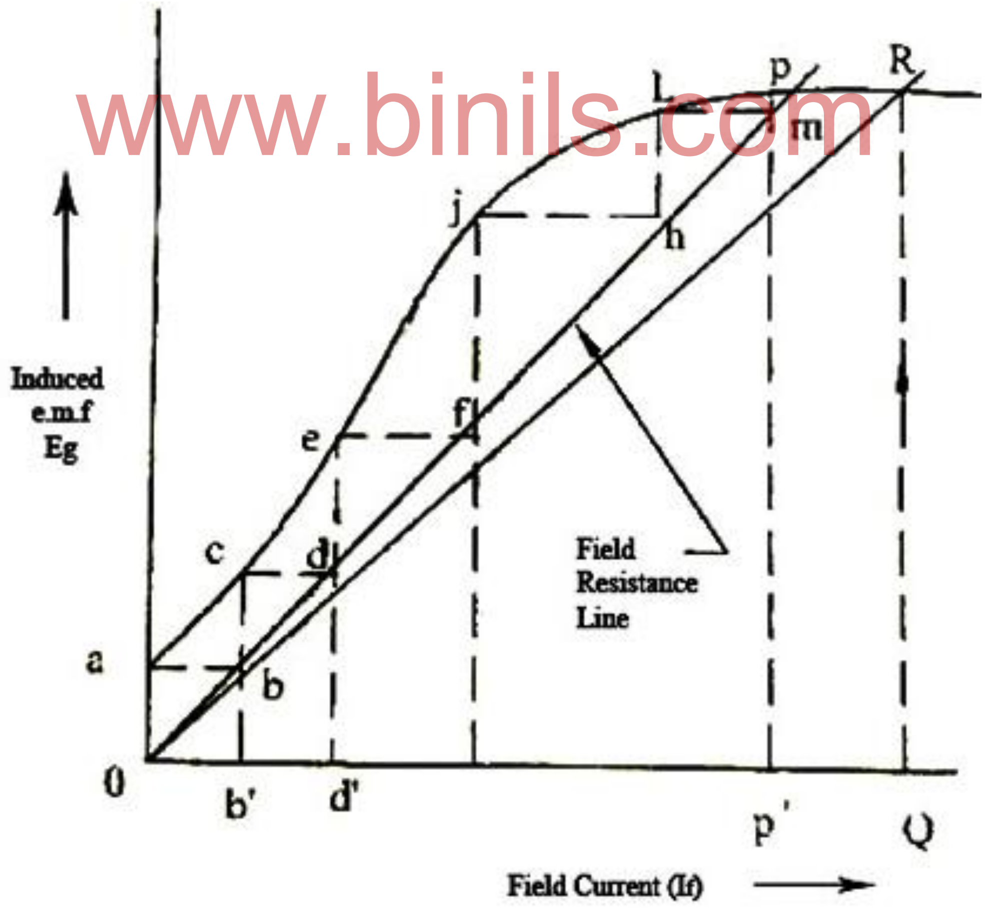


Fig.1.20

The curve obtained during this process is shown in fig.1.20. This curve cuts the field resistance line at point P as shown in figure. Beyond the point P the EMF will not be increased even the field current is increased. It is due to the saturation of magnetic poles. Thus the building up of EMF in DC shunt generator goes up until the curve cuts the field resistance line. At point P maximum EMF will be induced.

If we reduce the field resistance, the slope of the resistance line OR decreases. Hence maximum building up of EMF goes up to R in the EMF curve.

If the field resistance is increased further, the slope of the field resistance line will be increased, thereby decreasing the maximum induced EMF.

1.12 NO LOAD CHARACTERISTICS OF SHUNT GENERATOR:

As the name implies, this characteristic curve shows the performance of DC shunt generator under no load condition. That means load current is equal to zero. The curve drawn between the generated EMF and the field current is called no load characteristics. No load characteristics is also known as magnetic characteristics or open circuit characteristics.

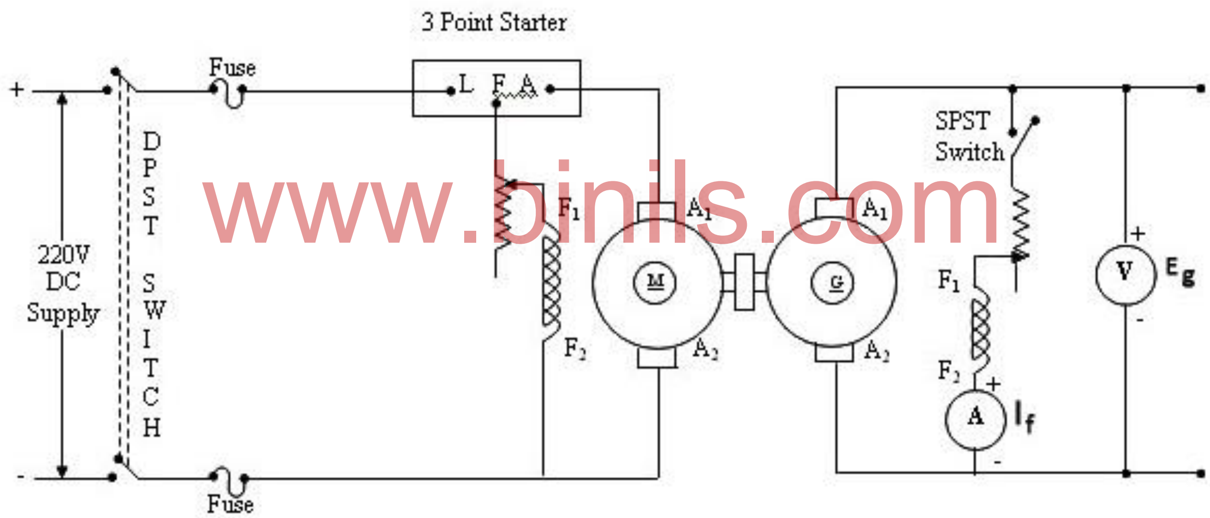


Fig.1.21

Fig.1.21 shows the experimental setup of no load characteristics. In this experiment the prime over (i.e. the motor) coupled to the generator is started with the help of a three point starter. Then the Motor is made to run at rated speed by adjusting the field rheostat of motor. When the generator runs at its rated speed field circuit is disconnected by opening the switch S. The reading of voltmeter across the armature gives residual voltage. Then the switch is closed and the field current through the field winding is increased from zero and the EMF induced for each value of field current is noted. now the characteristic curve is drawn between induced EMF and field current.

The induced EMF of DC generator is given by $E_g = P\phi ZN/60A$ Volts

If speed is constant the above equation becomes $E_g = K\phi$

Where K is constant

Hence the EMF is directly proportional to the field current. i.e. $E_g \alpha \phi$

But $\phi \alpha I_f$

Therefore $E_g \alpha I_f$

Field current increases along the straight line as shown in fig1.22.

If the field current is increased beyond the certain level the field magnets gets saturated. Therefore the induced EMF will not increase in linear proportion to the field current. Instead it increases along the curve CD as shown in fig.1.22.

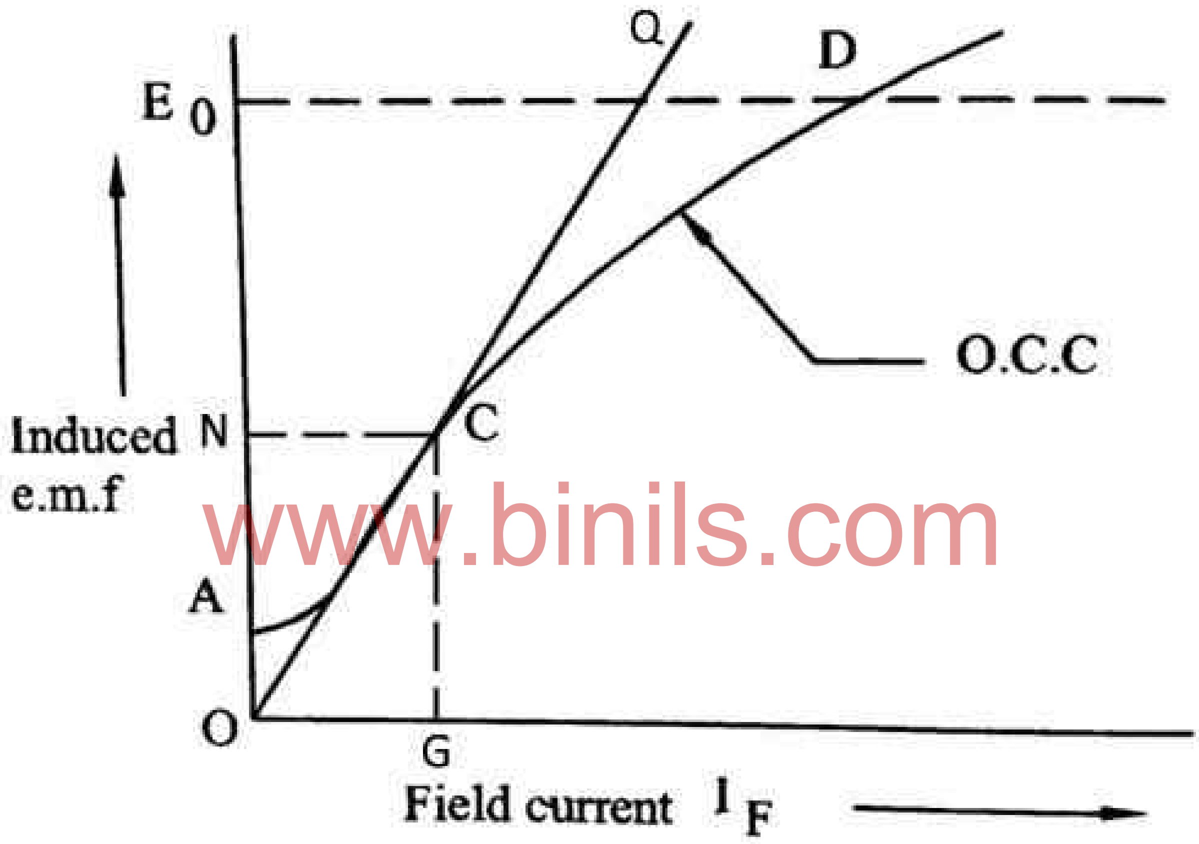


Fig.1.22

1.13 Critical field resistance:

The field circuit resistance plays a major role in building up of EMF in DC generator.

If the value of field resistance is too large then it will not allow sufficient field current to flow through the field winding to build up EMF. Therefore the field circuit resistance must be smaller than a value called Critical field resistance.

Critical field resistance is defined as the highest value of resistance of the shunt field circuit , with which a DC generator can build up its voltage.

Beyond this value of resistance, the generator fails to build up voltage. The value of field resistance represented by the slope of the tangent to the OCC curve is known as critical field resistance for the given speed.

The value of critical field resistance is calculated by drawing a tangential line to the no load characteristics curve as shown in fig. 1.22. The slope of this tangential line gives the value of critical field resistance.

In the curve shown in fig.1.22 draw a tangent line OQ on the no load characteristics curve.

Select a point C on the curve. Now the value of critical resistance is given by the slope of the curve.i.e. Critical field resistance = voltage represented by the tangent /current represented by the tangent

Critical field resistance = ON/OG   Ohms

Condition for buildup of EMF of a self - excited DC generator:

1. There must be some residual magnetism in the generator poles.

2.The field coil should be connected such that the flux produced by the exciting current flowing through them must be in the same direction of residual magnetic flux.

3. In DC shunt generator, the field resistance must be less than that of critical field resistance.

4. In DC series generator, the external load resistance should be less than the critical field resistance.

1.14 CAUSES OF FAILURE TO BUILD UP EMF AND REMEDY:

1) No residual magnetism:

While starting a DC generator there must be some residual magnetism in the magnetic poles of the generator. Otherwise the generator will not produce EMF.

2) Reversal of field connections:

Due to residual magnetism, there exists small voltage called residual voltage in the generator. This voltage produces a field current in the field winding. If the field winding connections are reversed, then the field flux destroy the residual magnetic flux. Hence the generator fails to build up voltage.

3) High Field resistance:

i. For DC shunt generator, if the field resistance is higher than the critical field resistance then the generator fails to build up the voltage.

ii. For DC series generator, if the load resistance is higher than the critical field resistance then the generator fails to build up the voltage.

4) Other factors:

Open circuit or short circuit in the field or armature circuit, loose brush connections or contacts, dirty or severely pitted commutator.

Remedies

i. At the time of starting of generator, if the poles have no residual magnetism or the field winding connections are reversed then the field winding must be connected to a DC source for a short period to magnetize the poles. This process is called as " **Flashing of field**".

ii. In case of DC shunt generator check the value of field resistance and ensure that its value is less than the critical field resistance and in case of DC series generator ensure that the initial value of the load resistance is less than the critical field resistance.

iii. Ensure that there is

a. No open or short circuit in the armature and field circuit.

b. No loose brush connections or contacts.

c. No dirt or pits in the commutators segments.

1.15 LOAD CHARACTERISTICS OF DC SERIES GENERATOR

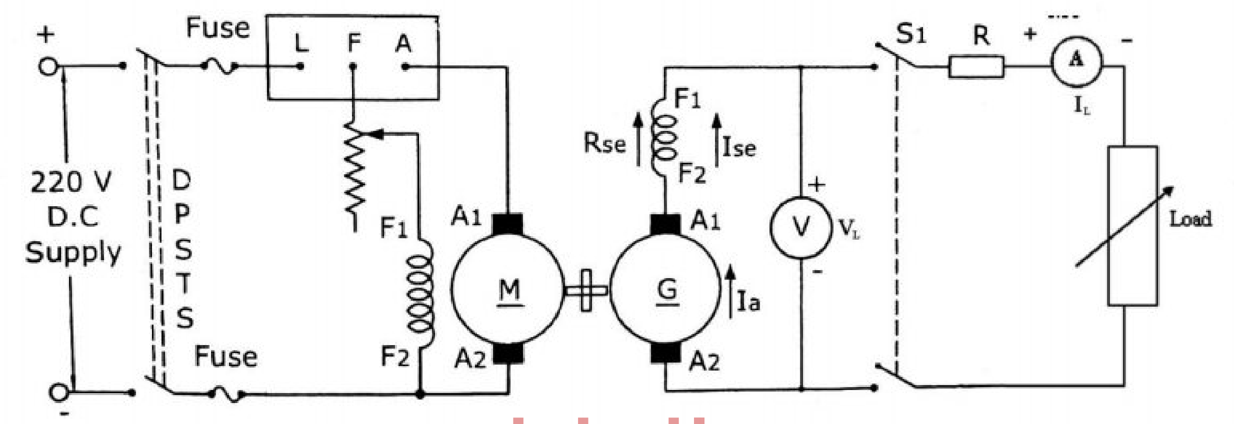


Fig.1.23

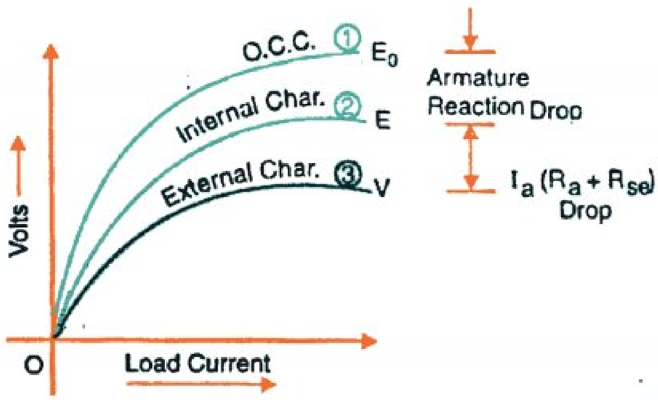


Fig.1.24

fig.1.23 shows the connections of a series wound generator. since there is only one current (which flows through the whole machine), the load current is the same as the exciting (field) current. Load characteristics shows the behavior of the generator under different load conditions.

The generator is started with the help of a prime-mover and is allowed to run at its rated speed. The load is adjusted step by step and the corresponding terminal voltage and load currents are noted. For each reading calculate the emf induced in the generator by using the formula:

$$E = V + I_a(R_a + R_{se})$$

At no load, the induced emf is zero as the field current is zero. When the load current increases, the field current also increases, which in turn increases the flux. Hence the terminal voltage and emf are also increased. So the series generator has a rising characteristics. After saturation of the field, even though the load current increases, the voltage is not increased.

(i) Internal characteristics:

Curve 2 shows the total or internal characteristics of a series generator. It gives the relation between the generated emf E and armature current on load. Due to armature reaction, the flux in the machine will be less than the flux at no- load. Hence, emf E generated under load conditions will be less than the emf E_0generated under no-load conditions. Consequently, internal characteristics curve lies below the O.C.C curve.The difference between them representing the effect of armature reaction.

(ii) External characteristics:

Curve 3 shows the External characteristics of a series generator. It gives the relation between terminal voltage V and load current I_L .

$$V = E - I_a(R_a + R_{se})$$

Therefore, external characteristics curve will lie below the internal characteristics curve by an amount equal to ohmic drop [Ra+Rse] in the machine as shown in fig. 1.23.

1.16 CHARACTERISTICS OF DC SHUNT GENERATOR:

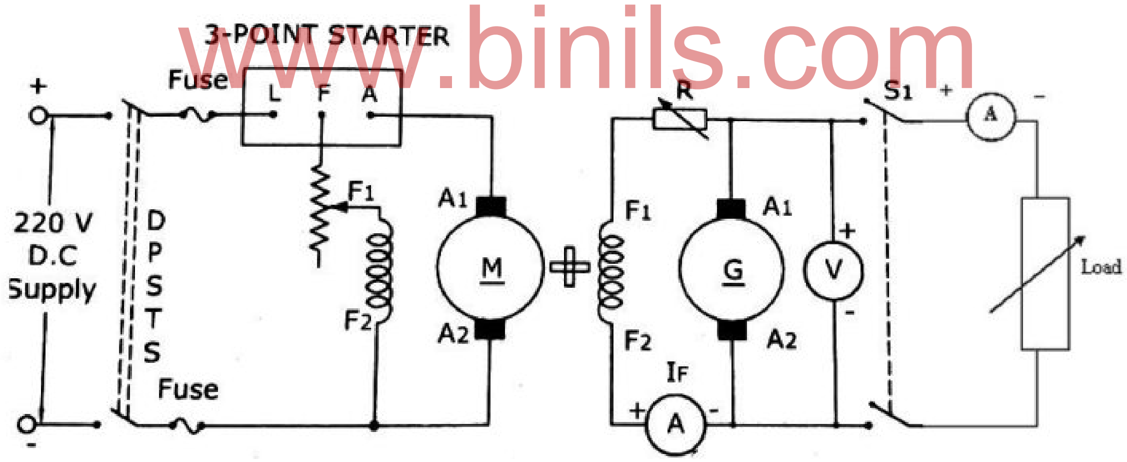


Fig.1.25

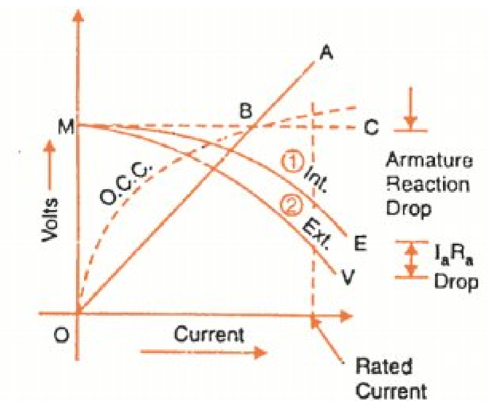


Fig.1.26

Fig.1.25 shows the connections of a shunt wound generator. The armature current I_a splits up into two parts, a small fraction I_{sh} flowing through shunt field winding while the major part I_L goes to the external load.

The generator is started with the help of a prime-mover and is allowed to run at its rated speed. At no load, the induced emf is not zero even if the field current is zero. This small voltage is due to the residual magnetism in the field winding.

Adjust the field current until the generator induces the rated voltage. Then the load is adjusted step by step and the corresponding terminal voltage and load currents are noted. For each reading, calculate the emf induced in the generator by using the formula:

$$E = V + I_aR_a$$

When the load current increases above the full load current, the voltage is reduced and Hence the terminal voltage and emf are also increased. So the series generator has a rising characteristics. After saturation of the field, even though the load current increases, the voltage is not increased.

(i). Internal characteristics:

When the generator is loaded, flux per pole is reduced due to armature reaction. Therefore, emf E generated on load is less than the emf generated at no - load, As a result, the Internal characteristics (E vs Ia) drops down slightly as shown in fig. 1.26.

(ii). External characteristics:

Curve 2 of fig. 1.26 shows the External characteristics of a shunt generator. It gives the relation between terminal voltage V and load current I_L .

$$V = E - I_aR_a ;$$

$$= E - (I_L + I_{sh}) R_a.$$

Therefore, external characteristics curve will lie below the internal characteristics curve by an amount equal to drop in the armature circuit [i.e. (I_L + Ish) Ra] as shown in fig. 1.26.

1.17 CHARACTERISTICS OF COMPOUND GENERATOR:

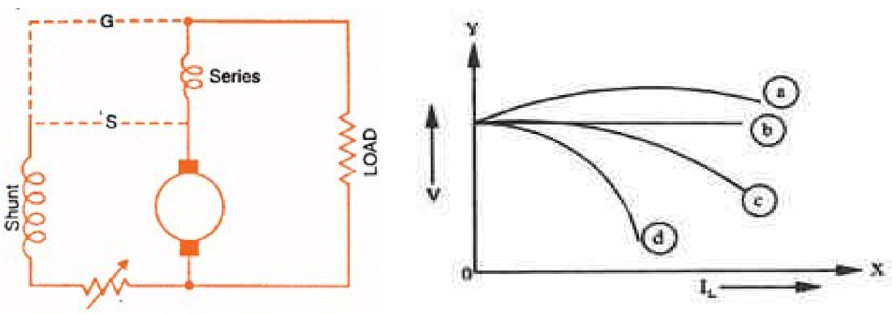


Fig.1.27

In a compound generator, both series and shunt excitation are combined as shown in fig. 1.27. The shunt winding can be connected either across the armature only (short - shunt connection S) or across armature plus series field (long shunt connection G). The compound generator can be cumulatively compounded or differentially compounded generator. The latter is rarely used in practice. Therefore, we shall discuss the characteristics of cumulatively compounded generator. It may be noted that external characteristics of long and short shunt compound generators are almost identical.

External characteristics:

Fig.1.27 shows the external characteristics of a cumulatively compounded generator. The series excitation aids the shunt excitation. The degree of compounding depends upon the increase in series excitation with the increase in load current.

(i). If series windings turns are so adjusted that with the increase in load current, the terminal voltage increases, it is called over compounded generator. In such a case, as the load current increased, the series field mmf increases and tends to increase the flux and hence the generated voltage is greater than the I_aR_a drop so that instead of decreasing, the terminal voltage increases as shown by curve A of fig. 1.27.

(ii). If series winding turns area so adjusted that with the increases in load current, the terminal voltage substantially remains constant, it is called flat - compounded generator. The series winding of such a machine has lesser number of turns than the one in over compounded machine and, therefore, does not increase the flux as much for a given load current. Consequently, the full load voltage is nearly equal to the no-load voltage as indicated by curve B in fig. 1.27.

(iii). If series field winding has lesser number of turns than for a flat - compounded machine, the terminal voltage falls with increase in load current as indicated by curve C in fig. 1.27. Such a machine is called under - compounded generator.

iv). In differential compound generator the series field flux opposes the shunt field flux. Therefore when the generator is loaded, the terminal voltage of the generator falls rapidly as shown in the curve d of fig. 1.27.

Compounding level can be adjusted by a diverter in parallel to the series field.

1.18 Applications of DC generators:

DC Shunt generator

Since the output voltage of DC Shunt generator are almost constant or can be kept constant, they are used in

i) Ordinary lighting

ii) Electroplating

iii) Exciters for Alternator

iv) Battery charging

DC Series generator

The series generator has a rising voltage characteristics. Hence they are used as

i) Boosters

ii) Supply to arc lamps

DC Compound generator

i) Flat compounded generators are used in to supply power for offices, hostels and lodges etc.

ii) Over compound generators are used to compensate the voltage drop in feeders.

iii) Differential compound generators are used to supply DC welding machines.

Power stages in a DC generator:

The various power stages in a DC generator are represented diagrammatically in Fig. 1.28.

A - B = Iron and frictional losses

B - C = Copper losses

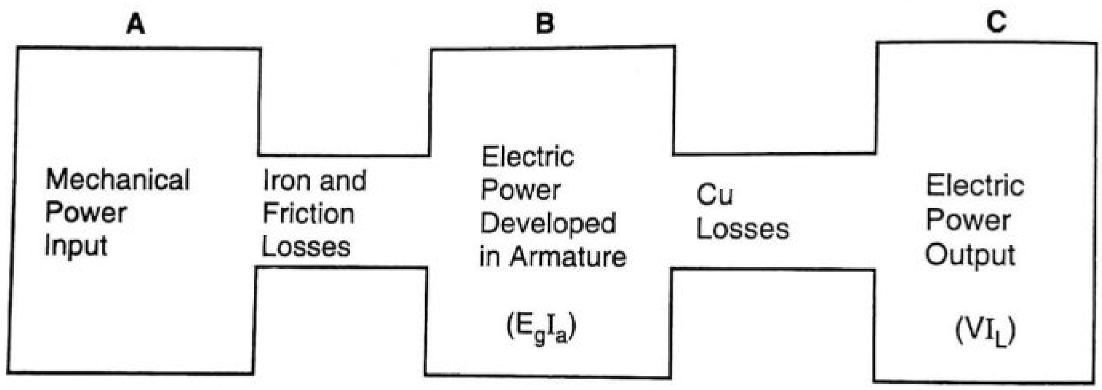


Fig.1.28

i. Mechanical Efficiency, η_m =B/A

= (E_g I_a)/ Mechanical power input

ii. Electrical Efficiency, η_e= C / B

= (VI_L) / (E_g I_a)

iii. Commercial or overall efficiency, η_c = C / A

= (VI_L) / Mechanical power input

Clearly $\eta_c = \eta_m \times \eta_e$

Unless otherwise stated, commercial efficiency is always understood.

Now, Commercial efficiency, η_c = C / A

= Output power / Input power

= (Input power - Losses) / Input power

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

These losses occur in DC machines due to the current flow in the windings(also called as I^2R losses). It is dissipated as heat ($H= I^2Rt$)

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 = $I^2_{sh} R_{sh}$

Where I_{sh} = current in the shunt field winding; R_{sh} = resistance of shunt field winding

Series field copper losses = $I^2_{se} R_{se}$

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 thinlaminations 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

a) Friction loss e.g bearing friction, brush friction etc.
b) 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

i) Constant losses
ii) Variable losses

i) 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 :

a) Iron loss
b) Mechanical loss
c) Shunt field loss

ii) Variable losses

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

a) Armature Copper loss $I_a^2 R_a$
b) Series field copper loss $I^2_{se} R_{se}$

1.19 SOLVED PROBLEMS

1. A 4 pole generator having a simplex wave wound armature has 51 slots, each slot containing 20 conductors, what will be the voltage generated in the machine , when drives at 1500 RPM assuming the flux per pole to be 7 mWb.

Given data:

No. of poles = 4

Flux $\Phi = 7 \times 10^{-3}$ Wb

No. of conductors Z = 51x20 = 1020

Speed N = 1500RPM

No. of parallel path A(Since wave winding) = 2

To find:
Generated voltage E_g

Solution:

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

$$E_g = \frac{4x7x10^{-3}x\ 1020x\ 1500}{60x2}$$

Generated voltage E_g = 357 Volts.

2. A 6 pole wave connected armature has 300 conductors and runs at 1000 rpm. The emf generated is 600 Volts. Find the useful flux per pole.

Given data:
No. of poles =6
No. of parallel path A= 2
No. of Conductor Z = 300
Speed N= 1000 rpm
Emf Generated E_g = 600 volts

To find:
Flux per pole

Solution:

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

$$\Phi = \frac{E_g 60A}{PNZ} \text{ volts}$$

$$= \frac{600\ x\ 60\ x\ 2}{6x300x1000}$$

$$= 0.04 \text{ Wb}$$

Flux per pole = 0.04 Wb

3. A lap connected DC generator has 8 poles and 120 slots with 8 conductors in each slot. If the flux per pole is 0.04 Wb. Find
a. The EMF generated when the speed is 600 RPM and
b.What should be the speed of rotation if the induced EMF is to be 500 Volts?

Given data:
No. of poles =8
Conductor per slot = 8
No. of slots = 120
Flux per pole Φ = 0.04Wb.

To find:
(a) EMF generated when the speed is 600 RPM
(b) The speed when voltage generated is 500 Volt

Solution:
A=P since lap winding

Case – I

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

$= \frac{8 \times 0.04 \times 120 \times 8 \times 600}{60 \times 8}$ volts .

= 384 Volts

EMF generated when the speed is 600 RPM = 384 Volts

Case – II

$N = \frac{E_g 60A}{P\Phi Z}$ RPM

$= \frac{500 \times 60 \times 8}{8 \times 0.04 \times 960}$

= 781.25 rpm

The speed when voltage generated is 500 Volt = 781.25 rpm

4. A long shunt DC compound generator delivers 110KW at 220 volts if R_a= 0.01 ohms, R_{se} = 0.002 ohms and shunt field as a resistance of 110ohms calculate the value of induced emf.

Given data:

Long Shunt DC compound generator
Output Power P= 110KW
Terminal Voltage V_T = 220Volts
Armature resistance R_a = 0.01ohms
Series field resistance R_{se} = 0.002 ohms
Shunt field resistance R_{sh}= 110ohms

To find:

Induced EmfE_g

Solution:

Output power P= Terminal voltage V_Tx Load current I_L
Load current $I_L = P/V_T$
= 110 x 1000/220
= 500A

Shunt field current $I_{sh} = V_T / R_{sh}$
= 220/110
= 2A

Armature current $I_a = I_L + I_{sh}$
= 500 + 2
= 502 A

Total resistance = $R_a + R_{se}$
= 0.01 + 0.002
= 0.012ohms

Induced voltage $E_g = V_T + I_L(R_a + R_{se})$

$= 220 + (502 \times 0.012)$
$= 226.024$ Volts

Induced voltage E_g = 226.024 Volts

5. A 25 KW compound generator works on full load with a terminal voltage of 220 volt. The armature series and shunt field resistance are 0.1 Ω and 0.05Ω respectively, calculate the generated emf when the generator is connected as a short shunt machine.

Given data:
Output power P = 25 Kw
Terminal voltage $V_T = 220$volt
Armature resistance $R_a = 0.1\ \Omega$
Series field resistance $R_{se} = 0.05\Omega$
Shunt field resistance $R_{sh} = 110\ \Omega$

To find:
Emf generated for short shunt machine

Solution:
Load current $I_L = P/ V_T$
$= 25 \times 10^3 / 220$
$= 113.64$A
In short shunt machine
Series field current $I_{se} = I_L = 113.64$A
Voltage drop in series field $V_{se} = I_{se} \times R_{se}$

$= 113.64 \times 0.05$
$= 5.682$ Volts

Voltage across shunt field $V_{sh} = V_T + V_{se}$
$= 220 + 5.682$
$= 225.682$V
Shunt field current $I_{sh} = V_{sh} / R_{sh}$
$= 225.682 / 110$
$= 2.052$A
Armature current $I_a = I_L + I_{sh}$
$= 113.64 + 2.052$
$= 115.692$A
Armature voltage drop $= I_aR_a$
$= 115.692 \times 0.1$
$= 11.5692$V
Emf generated $E_g = V_T + I_aR_a + I_{se} R_{se}$
$= 220 + 11.5692 + 5.682$
$= 237.25$Volts

Generated Emf E_g = 237.25 Volts

6. A 6 pole lap wound DC shunt generator has the following particulars:
Flux per pole = 0.05web; No. of turns of the armature winding = 200 turns
Resistance of the armature winding = 0.5ohms; Armature current = 40A.

Calculate the terminal voltage when running at 1000rpm

Given data:
Flux per pole Φ = 0.05web
No. of turns of the armature winding N= 200 turns
Resistance of the armature winding R_a= 0.5ohms
Armature current I_a= 40A
No. of poles = 6
No. of conductors Z= 400 conductors (Tx2)
Speed N= 1000rpm

To find:
Terminal voltage V_T

Solution:

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

$$= \frac{0.05 x 400 x 1000 x 6}{60 x 6}$$

= 333.33 Volts.
Armature resistance = 0.5 ohm
Therefore Armature drop = IaRa
= 40 x 0.5 =20 Volts.
Terminal Voltage, V = (E_g – IaRa)
= (333.33 – 20)
Terminal voltage = 313.33 Volts.

7. A 4 pole shunt generator with a shunt field resistance of 100ohms and armature resistance of 1 ohm has 378 wave connected conductors the flux per pole is 0.02wb if a load resistance of 10 ohm is connected across the armature terminals and generator is driven at 1000 rpm, calculate the power absorbed by the load.

Given data:
No. of poles = 4
Rsh = 100 ; Ra = 1; No. of armature conductors Z = 378 (wave assume A=2)
Flux per pole Φ = 0.02wb. speed N = 1000rpm R_L = 10ohms

To find:
Power absorbed by the load.

Solution:

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

$$= \frac{4 x 0.02 x 378 x 1000}{60 x 2} \text{ volts}$$

E_g = 252 Volts.

In shunt generator $V_T = V_{sh}$
Load current $I_L = V_T / R_L$
= (V_T / 10) A
Shunt field current $I_{sh} = V_T / R_{sh}$
= (V_T/100)A

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

$= (V_T/10) + (V_T/100)$

$=11V_T/100$ Amps.

$V_T = E_g - (I_aR_a)$

$= 252 - (1x\ 11V_T/100)$

$V_T = 229$ volts

Load current $= V_L/R_L$

$= 227/10$

$= 22.7A$

Power absorbed by load $= V_T \times I_L$

$= 227 \times 22.7$

$= 5153$ Watts.

Power absorbed by load = 5153 Watts.

8. A separately excited generator when running at 1000 rpm supplies 200A at 125 volts, what will be the load current when speed drops to 800 rpm, if field current I_f is unchanged given that the armature resistance is 0.04ohms and brush drop is equal to 2 volts.

Given data:

Speed N =1000 rpm

Load current I_L= 200A

Terminal voltage V = 125 volts

Armature resistance = 0.04 ohms.

Brush drop = 2 volts

To find:

Load current I_L, when speed drops to 800 rpm.

Solution:

Emf is proportional to speed

$$\frac{E_{g1}}{E_{g2}} = \frac{N_1}{N_2}$$

The load resistance $R_L = V_L/I_L$

$=125/200$

$= 0.625$ohms

Generated EMF E_{g1}= V+ I_aR_a + brush drop

$= 125 + (200 \times 0.04) + 2$

$= 135$ volts

Speed N_1 = 1000rpm

(At speed N_2 800 rpm) Generated EMF $E_{g2} = E_{g1} \times N_2 / N_1$

$=135 \times 800/1000 \quad = 108$ volts.

If I is the new load current the terminal voltage V_T is given by

$V_T =108 - (0.04 \times I) - 2$

$= 106 - 0.04\ I$

Therefore $I_L = V_T/R_L$

$I_L= (106 - 0.04\ I_L)/0.625$

$I_L = 159.4A$

Load current I_L, when speed drops to 800 rpm = 159.4A

9. An 8 pole dc shunt generator with 778 wave connected armature conductor and running at 500rpm supplies a load of 12.5 ohms resistance at terminal voltage of 50v the armature resistance is 0.24 Ω and the field resistance is 250 Ω. Find the armature current the induced e.m.f and the flux per pole.

Given data:

Pole p =8
Terminal voltage = 50V.
Armature resistance = 0.24Ω
Field resistance = 250Ω
Speed = 500rpm
Conductor = 778 (wave connected)

To find:

Armature current, the induced e.m.f and flux per pole.

Solution:

Load current $I_L = V_T/R_L$

$= 250/12.5$

$=20$ A

Shunt current $I_{sh} = V_{sh}/R_{sh}$

$= 1$ A

Armature current $I_a = I_L + Ish$

$= 20 + 1 = 21A$

Induced e.m.f. $E_g = V_T + I_a R_a$

$= 250 + (21x\ 0.24)$

$=255.04$Volts

$E_g = \frac{P\Phi ZN}{60A}$ Volts

$255.04 = \frac{8 \times \Phi x778x500}{60x2}$

$\Phi = 0.0098$ Wb

Armature current I_a= 21A
Induced e.m.f. E_g = 255.04 Volts
Flux per pole Φ = 0.0098 Wb

10. A DC generator delivers a load current of 100A at 500V. The resistances of armature and series field are 0.02 ohm and 0.05 ohm respectively. Calculate the generated emf allowing 1 volt per brush for contact drop.

Given Data:

DC series Generator Load current (I_L)	= 100A
Terminal voltage (V)	= 500 Volt
Armature Resistance (R_a)	= 0.02 ohm
Series field resistance (R_{se})	= 0.05 ohm
Brush drop/brush	= 1 volt.

To find:

Generated emf (E_g).
Solution:

Generated EMF $E_g = V + I_a(R_a+R_{se})$ + Brush drop.
In series generator = $I_a = I_{se} = I_L$
Brush drop for 2 brushes = 2 x 1 = 2 Volt.
Generated EMF (E_g) = 500 + 100 (0.02+0.05) + 2
= 509 Volts

Generated EMF (E_g) =509 volts.

11. A long shunt dynamo running at 1000 rpm supplies 22KW at shunt field a terminal voltage of 220V. The resistance of the armature, shunt and series field is 0.05 ohm, 110ohm, and 0.06 ohm respectively. The overall efficiency at the above load is 88% Find a) Cu loss b) Iron and friction losses.

Given data:
Speed N = 1000 rpm
Output power = 22 KW
Terminal Voltage = 220V
R_a = 0.05ohm R_{sh} = 110ohm R_{se} = 0.06 ohm overall η = 88%

To find
a) Cu loss b) Iron and friction losses.

Solution:
Shunt Field current (I_{sh}) = V/R_{sh} = 220/110 = 2 Amps.

Load current (I_L) = $\frac{\text{load power}}{\text{Terminal voltage}} = \frac{22 \times 10^3}{220}$ = 100 Amps

Armature current (I_a) = $I_L + I_{sh}$ = 100 + 2 = 102 amps.

Series field copper loss = $I^2_{se} R_{se}$ = 102 x 0.06 = 624.3 Watts.

$I_{se} = I_a$ in long shunt compound generator

Shunt field copper loss = $I^2_{sh} R_{sh} = 2^2 \times 110$ = 440 Watts

Armature copper loss = $I^2_a R_a$ = $102^2 \times 0.05$ = 520.2 watts

Total copper loss = 520.2 + 220 + 624.3 = 1584.5 Watts.

Output = 22000 watts

Input = $\frac{\text{output}}{\text{Efficiency}} = \frac{22000}{0.88}$ = 25000 watts.

Total losses = input power – output power = 25000 – 22000
= 3000 watts

Iron and friction losses = Total losses – Total Cu losses
= 3000 – 1584.5
=1415.5 Watts.

Total copper loss = 1584.5 Watts
Iron and friction losses = 1415.5 Watts

12. A shunt generator delivers 450A at 230V, the resistance of the shunt field and armature are 50 ohms and 0.03 ohms respectively, calculate the generated EMF.

Given Data:

I_L = 450A **V= 230volts** **R_{sh} = 50ohms** **R_a= 0.03ohms**

To find:

Generated EMF

Solution:

$I_{sh} = V_{sh} / R_{sh}$

$= 230/ 50$

$= 4.6A$

$I_a = I_L + I_{sh}$

$= 450+4.6$

$= 454.6$ A

Armature voltage drop $I_aR_a = 454.6 \times 0.03$

$= 13.6$ V

Generated EMF $E_g = V + I_aR_a$

$= 230 + 13.6$

$= 243.6$ volts

Generated EMF E_g = 243.6 volts

13. A 4 pole D.C generator is delivering 20A to load of 10Ω. If the armature resistance is 0.5Ω and the shunt field resistance is 50Ω, calculate the induced e.m.f and the efficiency of the machine. Allow a drop of 1V per brush.

Given data:

No of poles, P =4

Load current, I_L= 20A

Armature resistance, R_a = 0.5Ω

Shunt field resistance, R_{sh} =50 Ω

Load resistance, R_L = 10Ω

To find:

Calculate the induced e.m.f and the efficiency of the machine.

Solution:

Terminal voltage $V_T = I_L \times R_L$

$= 20 \times 10 = 200V$

Shunt field current $I_{sh} = V_T/R_{sh}$

$=200/50$

$= 4A$

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

$= 20 + 4$

$= 24$ A

Armature drop $I_a R_a = 24 \times 0.5 = 12V$

Brush drop = 2x1 = 2V

Induced Emf, $E_g = V_T + I_a R_a$ + Brush drop

$= 200 + 12 + 2$

$= 214$ V

Since iron and friction losses are not given. Only electrical efficiency of the machine can be found out.

Total power generated in the armature = 214 x 24 = 5,136W

Useful output = 200 x 20

= 4000W

$$\% \text{ Efficiency} = \frac{\text{useful out put}}{\text{Total power}} \times 100$$

$$= \frac{4000}{5,136} \times 100$$

= 77.9 %

Induced Emf, E_g = 214 Volts

% Efficiency = 77.9 %

1.20 Armature reaction in DC generators:

In DC machines, a main flux is produced by magnetic field poles and is responsible for the production of EMF in the armature winding. However, current flowing through armature winding also creates a flux called as armature flux. This flux will distort or weaken the main flux. The distortion and weakening of main flux takes place both in generators and motors. The effect of armature flux on main flux distribution in the air gap is called as armature reaction.

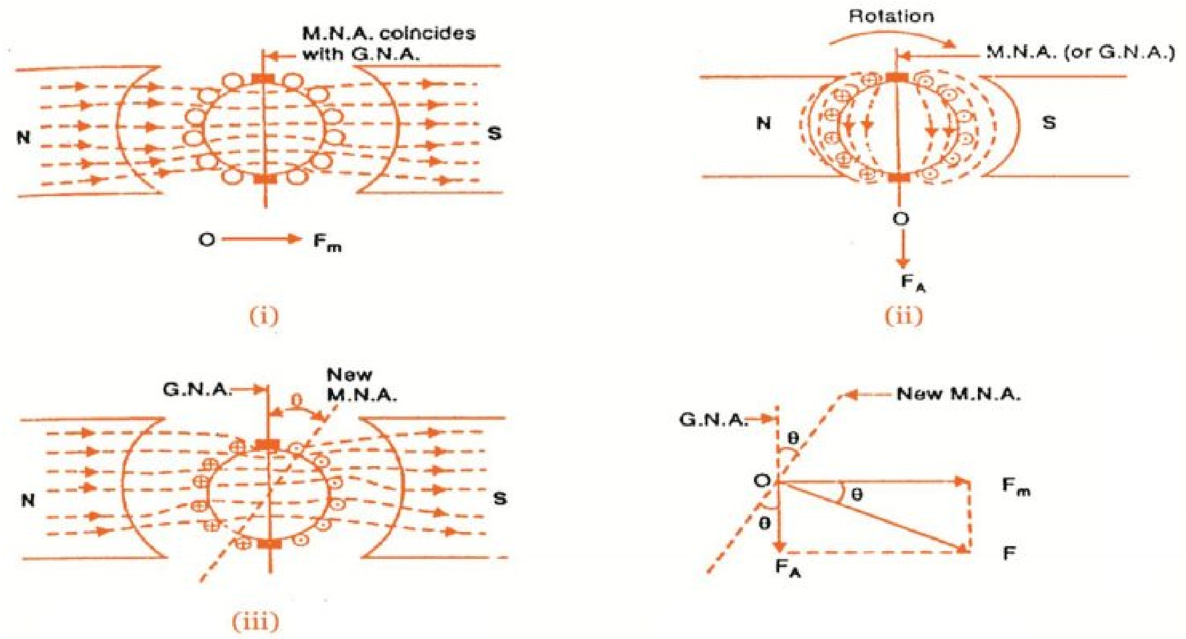


Fig.1.29

The armature mmf produces two undesirable effects on the main flux:

1. Net reduction in the main flux called as demagnetizing effect.

2. Distortion of the main field flux along the air gap periphery called as cross magnetizing effect. Cross magnetizing leads to sparking in the brushes.

MNA - Magnetic neutral axis

MNA may be defined as the axis along which no EMF is generated in the armature conductors as they move parallel to the flux lines. It is perpendicular to the magnetic flux lines. Brushes are always placed along MNA because reversal of currents in the armature conductors takes place along the axis.

GNA - Geometrical Neutral axis

GNA may be defined as the axis which bisects the angle between two centers of the adjacent poles. It is perpendicular to the stator field axis.

Armature reaction

Consider, no current in flowing in the armature conductors and only the field winding is energized as shown in Fig.i of Fig 1.29 . In this case, magnetic flux lines due to the field poles are uniform and symmetrical to the polar axis. The magnetic neutral axis coincides with the Geometrical neutral axis GNA.

Fig.ii shows armature flux lines due to the armature current. It is along the MNA.

When the machine is running, both the armature flux and field flux will be present at a time. The armature flux superimposes with the main field flux and hence disturbs the main field flux as shown in fig.iii. Under the leading pole tips the field flux and armature flux act in opposite direction. Therefore the net flux decreases. Under the trailing pole tips the armature flux and main field flux act in the same direction. Therefore the net flux increases.

Therefore the total flux acting in the generator is reduced which inturn decreases the induced emf in a loaded generator.

The resultant magnetic flux F_r is shown in the fig.4 The effect of armature reaction is to shift the axis of the resultant mmf acting in the direction of rotation of armature.

Due to this MNA gets shifted in the same direction by some angles. to make 90^0 with the resultant flux. Now the MNA is advanced from GNA. This effect goes on increasing and armature current increases with increase of load.

The emf induced in any coil of the armature will be zero, when it crosses the MNA axis. There the brushes are to be shifted in the direction of rotation are fixed on the MNA axis to collect the current. If the brushes are not shifted to MNA axis then the brushes short circuit the coil, which has emf induced in it. This emf produces sparking on the brushes as well as on the commutator segments. Therefore to avoid sparking the brushes are to be shifted in the direction of rotation for generator and against the direction of rotation motor But it is impossible to shift the brushes in the MNA axis.

1.21 Methods of compensating armature reaction:

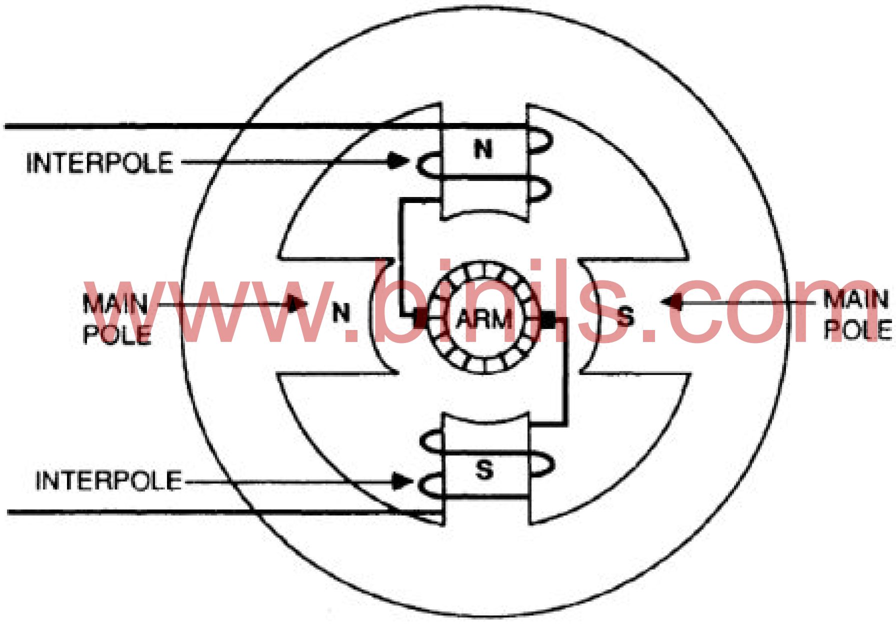
1. Increasing the air gap length:

By increasing the air gap length, the ratio between the main MMF and armature MMF may be increased. This reduces the armature reaction effect. But this is suitable only for small machines.

2. Interpoles or commutating poles:

By providing small magnetic poles called interpoles between the main poles at the MNA, the armature reaction effect may be reduced.

The coils provided around these poles are wound with thick copper wires and connected in series with armature as shown in fig. Also the mmf produced by the interpole winding act opposite to the armature reaction mmf and neutralizes it. The polarity of the interpole must be same as that of the main pole and just ahead in the direction of rotation. Interpoles are long but narrow in shape to avoid saturation.



Interpole wiring for a two-pole DC motor.

Fig.1.29

3. Compensating winding

By providing compensating winding on the pole faces, the effect of armature reaction may be reduced. In high capacity generator, a separate winding in wound in the slots provided on the pole faces of the main field system and connected in series with the armature in such a way that the current flow through these windings is in opposite direction to the armature current as shown in fig. to compensate the effect of armature reaction. Hence the current flowing through the compensating winding produces mmf which opposes the armature reaction mmf. By suitable choice and distribution of the turns in the compensating winding it is possible to neutralize the armature reaction effect completely.

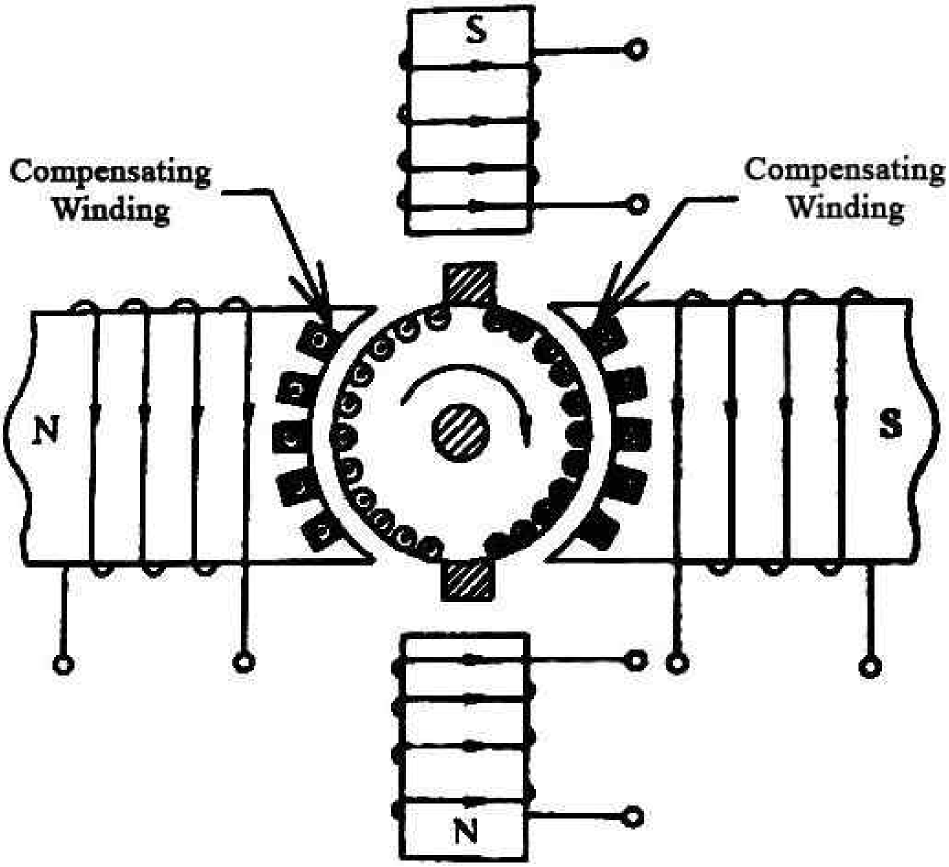
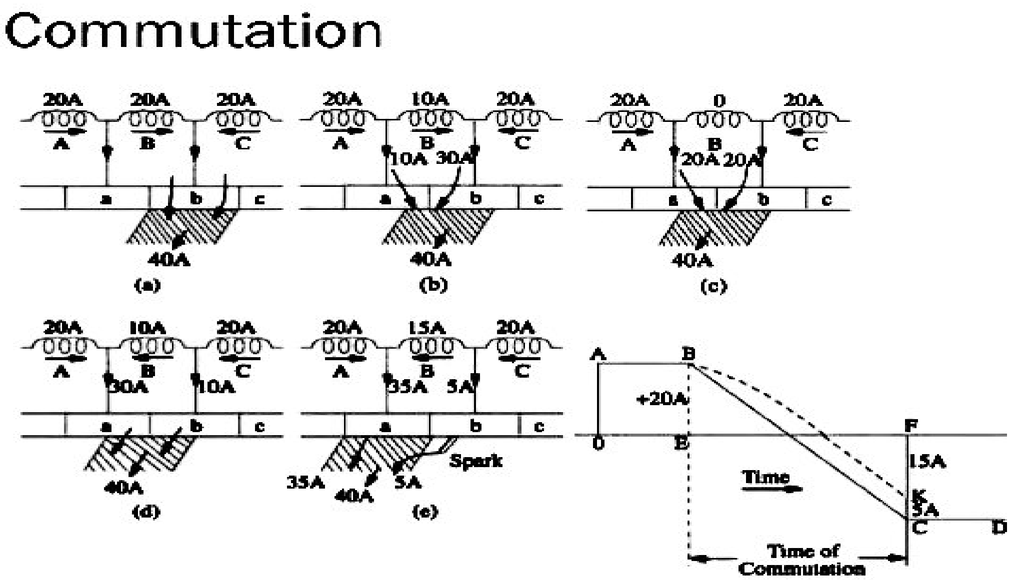


Fig.1.30

1.22 Commutation:

In DC machines commutators are used to convert alternating emf into unidirectional emf. The armature current flows in one direction when the armature conductors are under north pole and it flows in opposite direction when they are under south pole. This reversal of current takes place along magnetic neutral axis or brush axis. **The process of reversal of the current in the short circuited armature coil when it crosses the brush Axis or magnetic neutral axis is called as commutation.**

The period during which the coil remains short circuited is known as commutation period.



In figure (a), the brush in commutator segment b 20 from coil b and 20 amps from C gets commutated and 40 amps current flows through the B segment and brush.

In figure (b), as the segment moves the coil current in b reduces to 10 amps coil current in C remains as 20 amps segment a provide 10 amp and segment A & B provides 30amps. Totally 40 amp flows through the brush.

In figure (c), as the segment moves future the current in coil b becomes zero segment A and B provides 20 amps each and as a result 40 Amps and flow through the brush.

In figure (d), as the segment moves further the current in coil b is reversed to 10 amp segment a provides 30 amps and b provide 10 amps totally 40 amps current flows through brush.

In figure S as the segment moves further, the current in coil b is reversed to 15 amps segment a provides 35 amps and b provide 5amps so due to incomplete commutation the 5 amps flows I as a spark to the brush the commutation is not within the commutation period....

1.23 Sparking in commutator

Causes of sparking when the current reversal takes place in the coil an EMF is induced in it. this EMF opposes the causes producing it so that the reversal of current so current is not reversed completely which leads to sparking.

1.24 Methods of improving commutation

1. High resistance carbon brush

The current from the coil C tends to flow through coil b. And avoid the path through segment b thus the commutation is improved and the sparking is reduced

2. Interpoles or commutating poles:

By providing small magnetic poles called interpoles between the main poles at the MNA, the armature reaction effect may be reduced.

The coils provided around these poles are wound with thick copper wires and connected in series with armature as shown in fig.1.29.The coil undergoing commutation cuts the flux and has the emf induced in it. This induced emf acts in the direction opposite to the self - induced emf in the coil undergoing commutation. Since the self-induced emf is also proportional to armature current sparkless commutation is obtained. The polarity of the interpole must be same as that of the main pole and just ahead in the direction of rotation. Interpoles are long but narrow in shape to avoid saturation.

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.

2.1 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

$$F = BIl\sin\theta \text{ Newtons}$$

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.

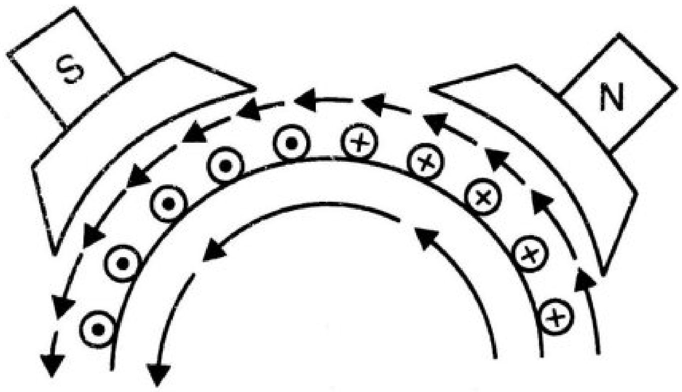


Fig.2.1

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.

2.2 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.

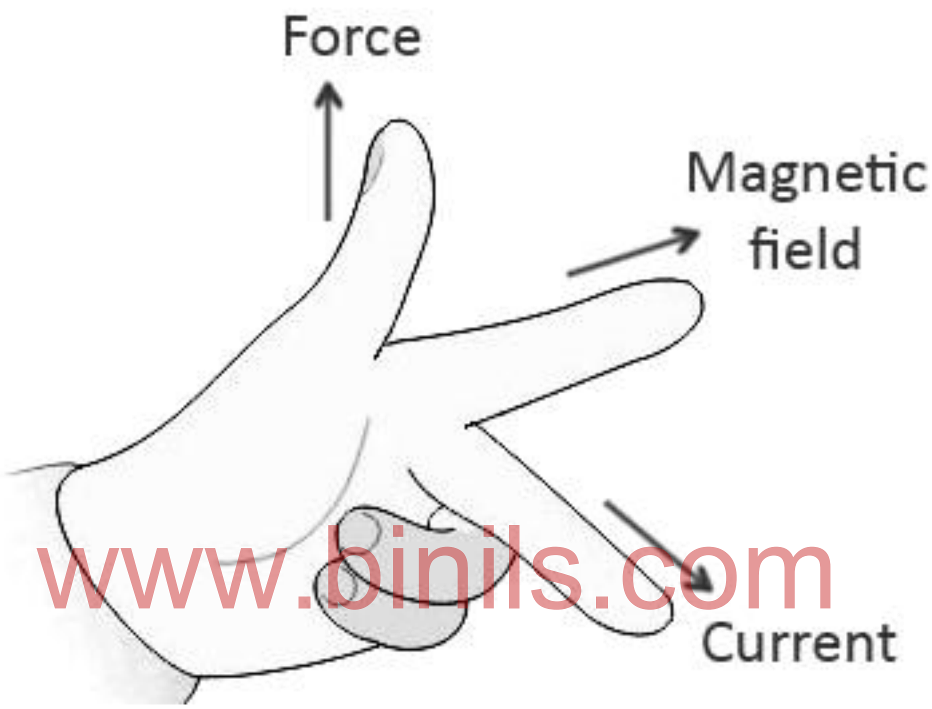


Fig.2.2

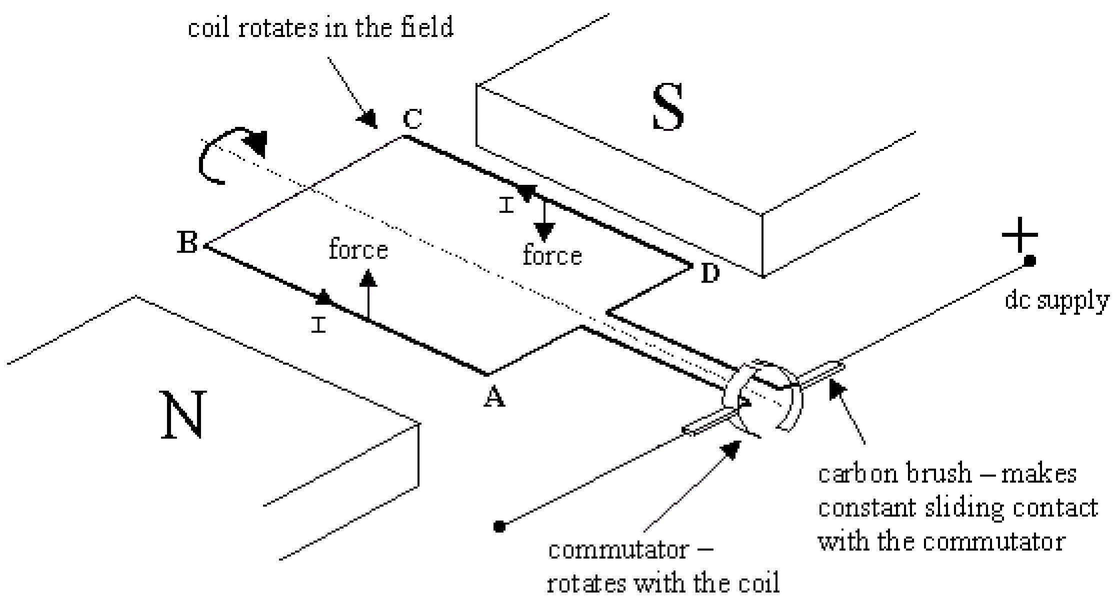


Fig.2.3

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.

2.3 CONSTRUCTION OF DC MOTOR:

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

2.4 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

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

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.

2.5 TORQUE EQUATION:

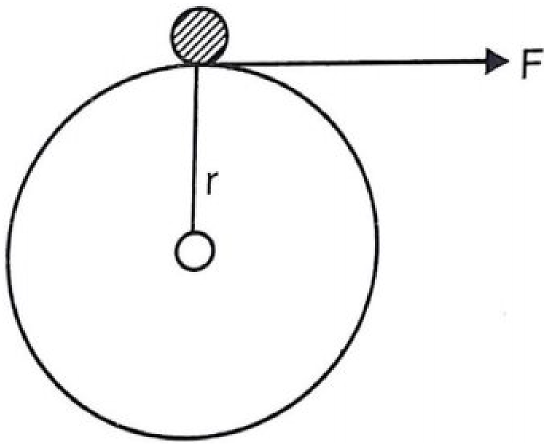


Fig.2.4

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) $= F \times r$ 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) $\quad E_b I_a = \frac{2\pi N T_a}{60}$

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

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

we know that,

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

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

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

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

9.81 Newton = 1 kg

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

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

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.

$$T \; \alpha \; \Phi \; I_a$$

2.6 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 $V=Eg + I_aR_a$

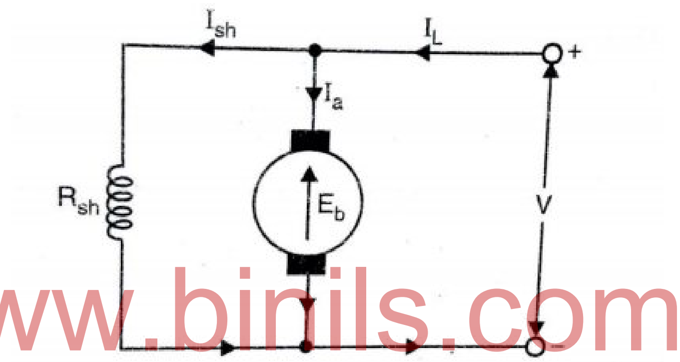


Fig.2.5

Series-wound motor:

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

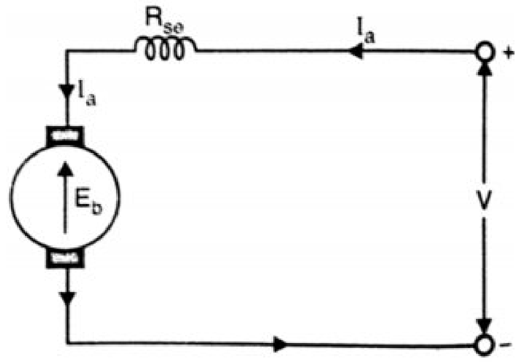


Fig.2.6

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.

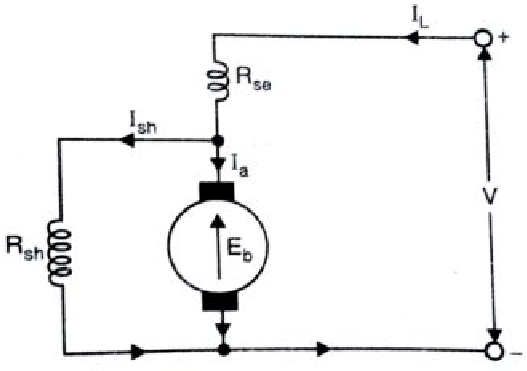


Fig.2.7

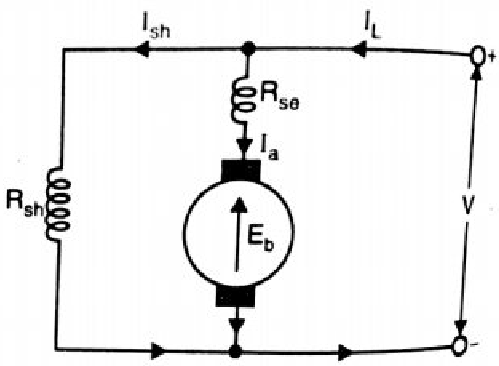


Fig.2.8

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 $T \alpha \Phi I_a$

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.

$T \alpha I_a$

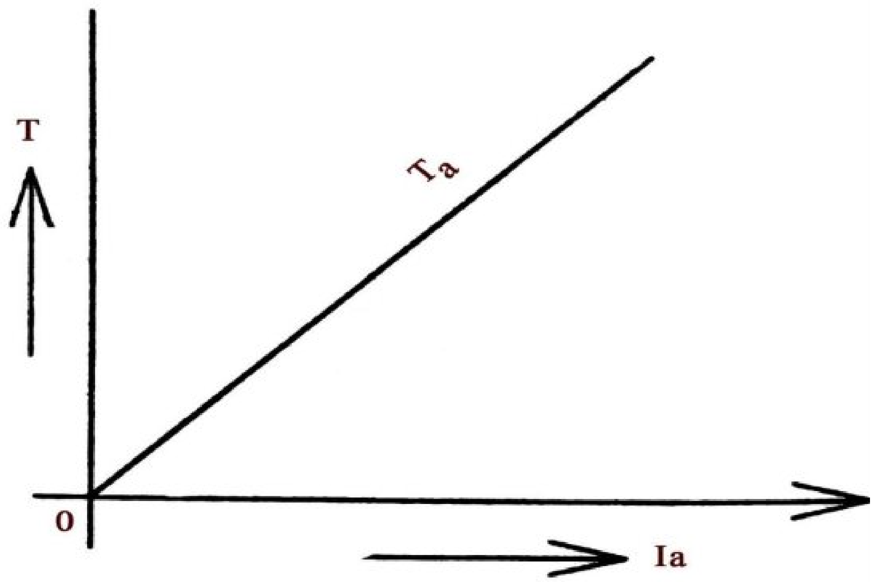


Fig.2.9

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

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

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

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

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 α $(V - I_aR_a)$.

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.

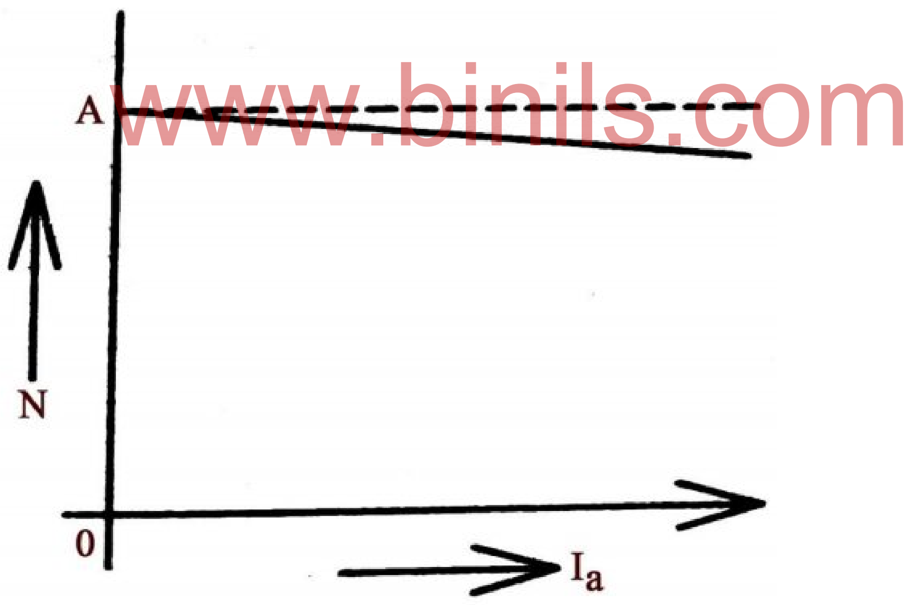


Fig.2.10

3) SPEED Vs TORQUE CHARACTERISTICS

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

Torque, T α I_a ------2

I_aα 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.

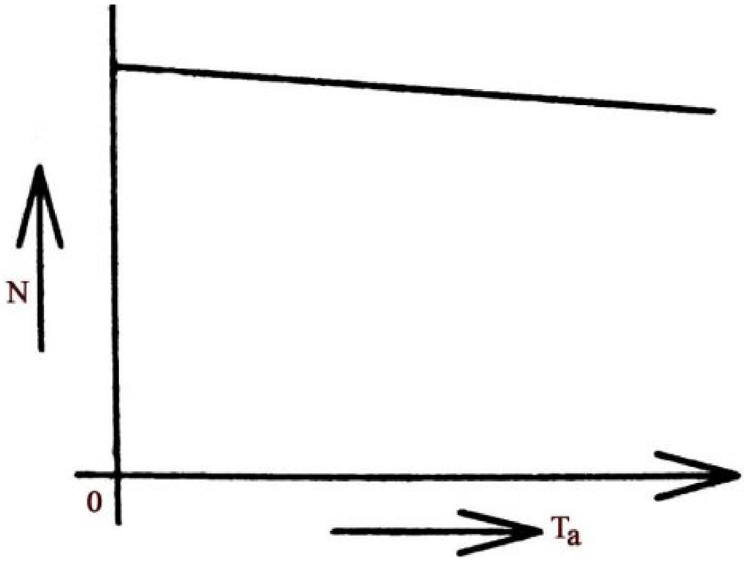


Fig.2.11

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.

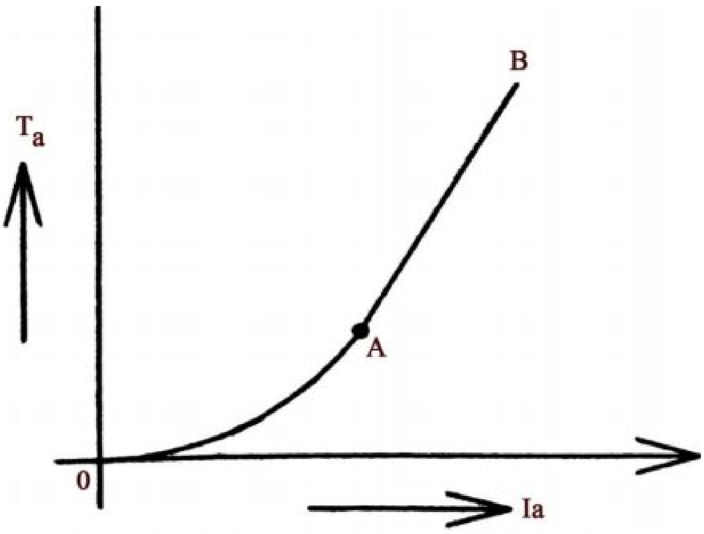


Fig.2.12

2) SPEED Vs ARMATURE CURRENT CHARACTERISTICS

In series motor I_aR_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.

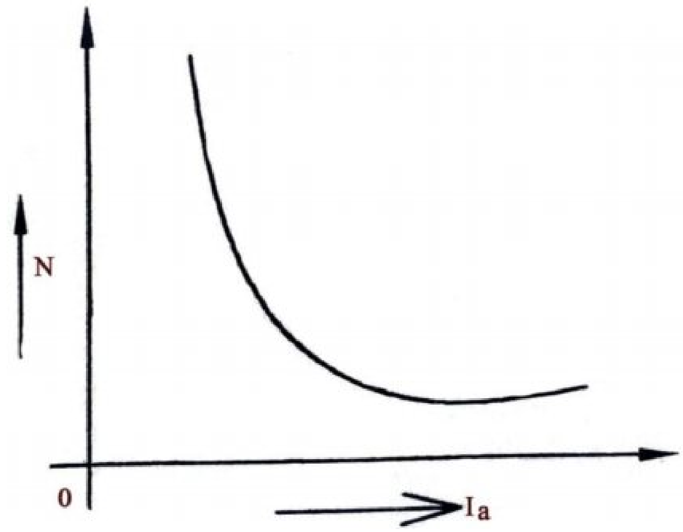


Fig.2.13

3) SPEED Vs TORQUE CHARACTERISTICS

In series motor $N \alpha V/\Phi$ ------1

$T \alpha \Phi I_a$

$T \alpha \Phi^2$ (since $I_a \alpha \Phi$)

$\Phi^2 \alpha T$

$\Phi \alpha \sqrt{T}$ ------2

By putting 2 in 1 $N \alpha V/\sqrt{T}$

$N \alpha 1/\sqrt{T}$ (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

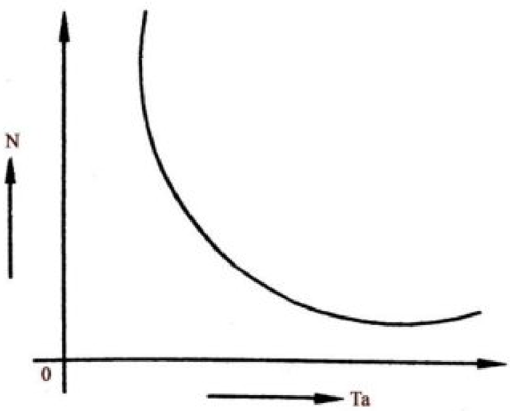


Fig.2.14

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 $T \alpha \Phi I_a$). 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.

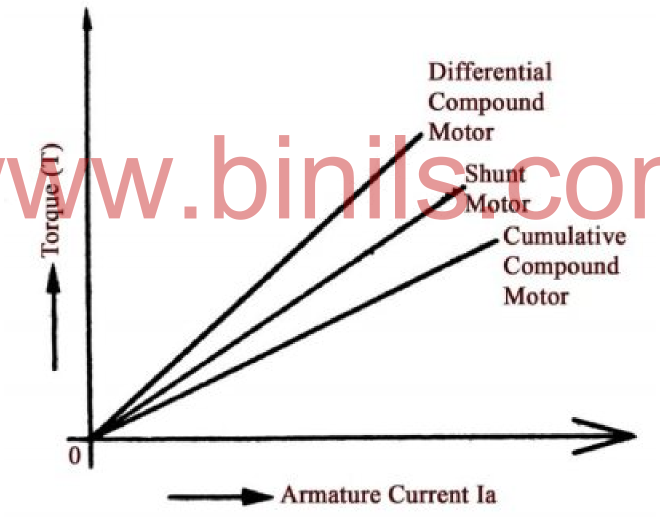


Fig.2.15

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 ($N \alpha 1/\Phi$) 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.

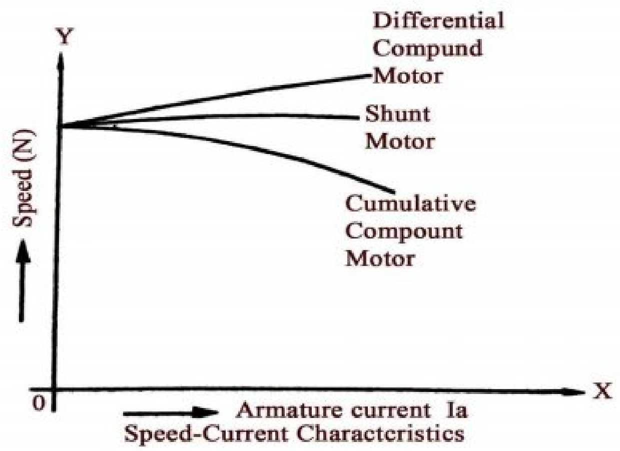


Fig.2.16

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.

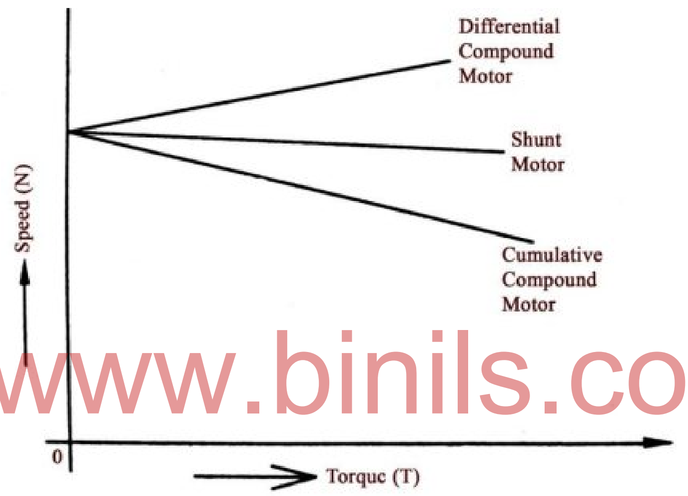


Fig.2.17

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

$$N \alpha E_b$$

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

$$E_b = V\text{-}I_a (R_a + R_c)$$

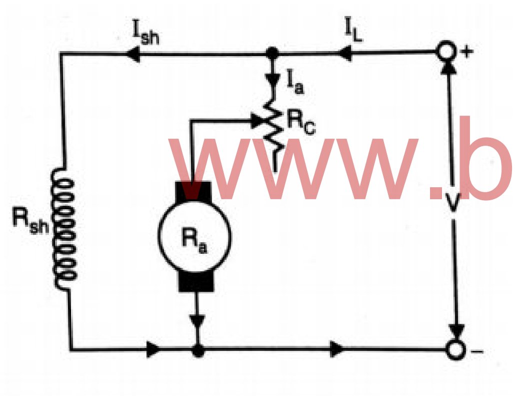


Fig.2.18

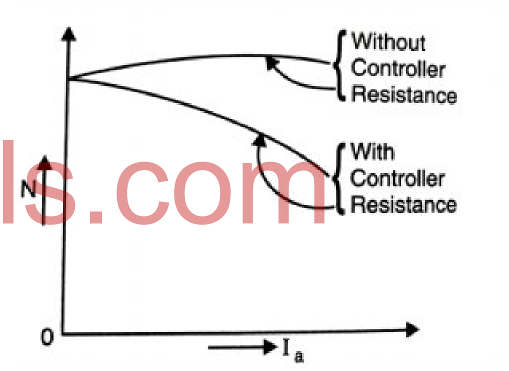


Fig.2.19

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.

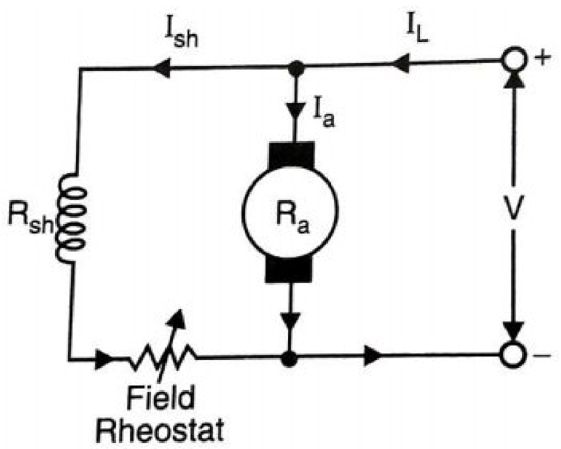
4. This method results in poor speed regulation.

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.



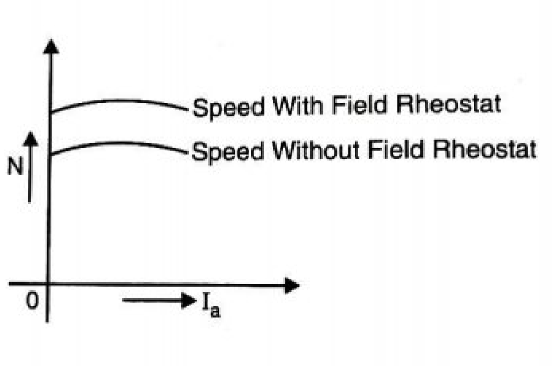


Fig.2.20

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

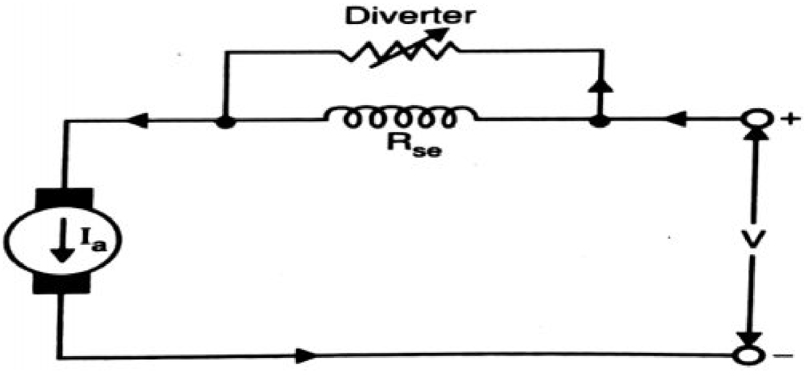


Fig.2.22

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:

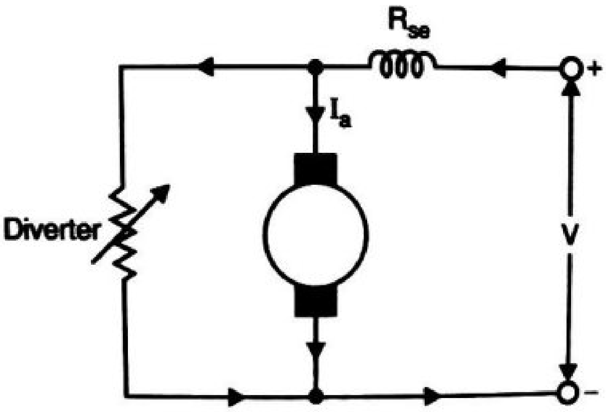


Fig.2.23

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:

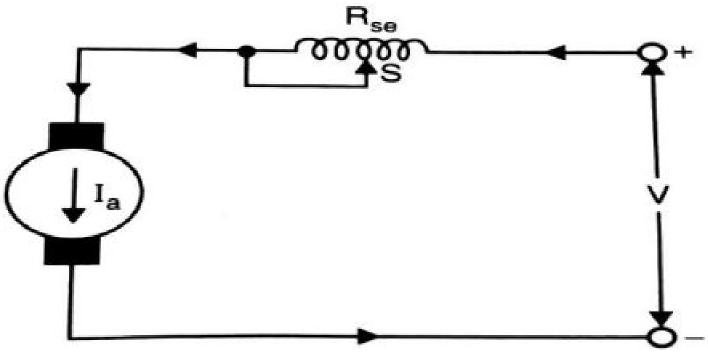


Fig.2.24

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:

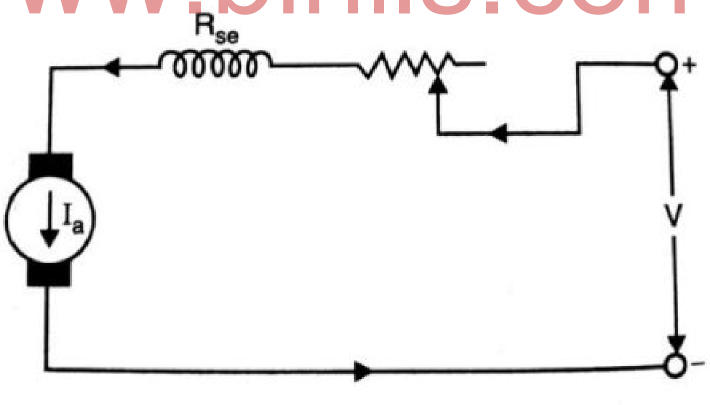


Fig.2.25

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 since $H=I^2Rt$.

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).

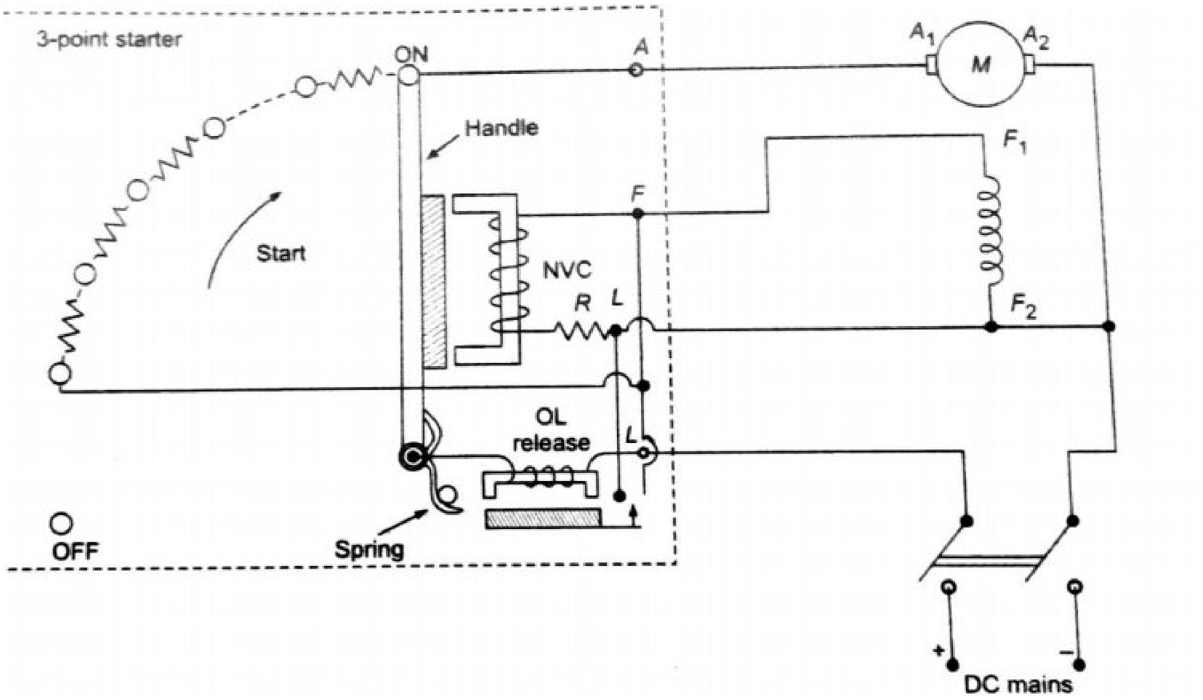


Fig.2.26

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.

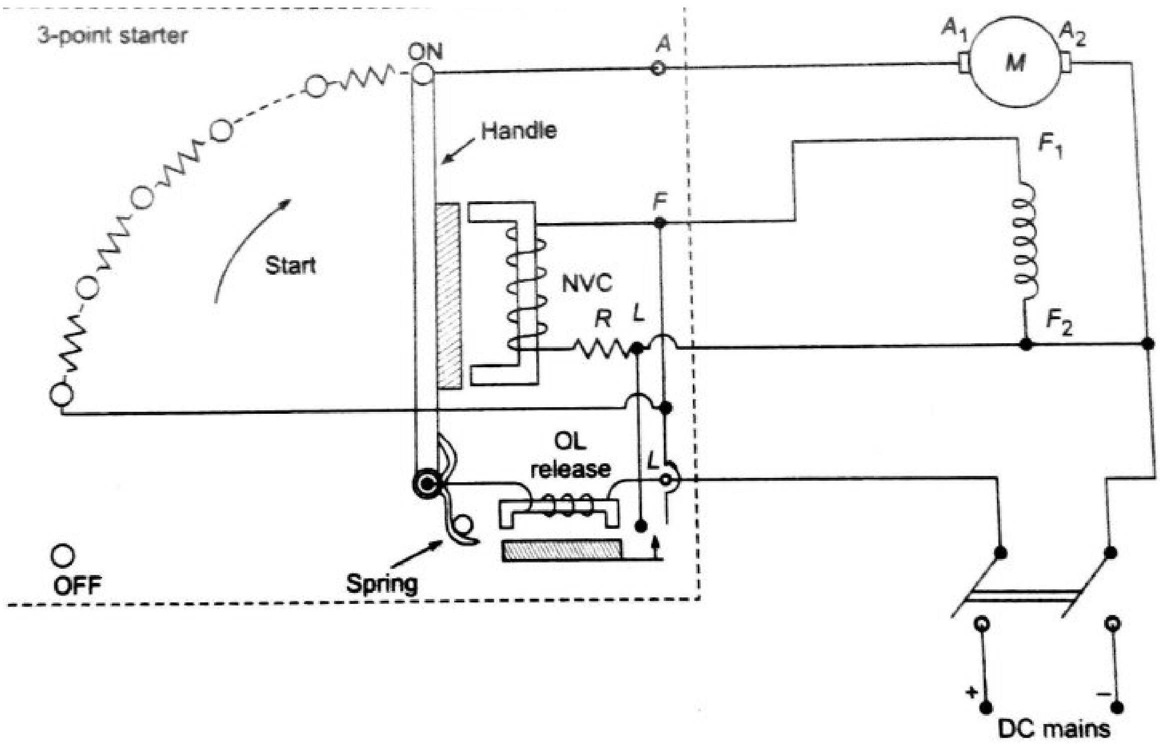


Fig.2.27

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.

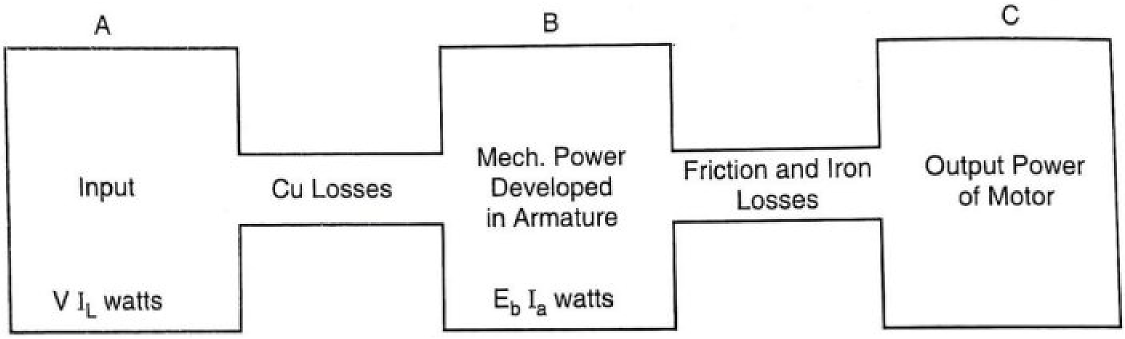


Fig.2.28

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

(iv) Copper losses

(v) Magnetic losses

(vi) 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 = $I^2_{sh} R_{sh}$

Where Ish= current in the shunt field winding; R_{sh}= resistance of shunt field winding

Series field copper losses = $I^2_{se} R_{se}$

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 $I^2_{se} R_{se}$

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=$(I_o - I_{sh})^2$ x R_{eff}

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

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

Input power=VI_L

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

Constant loss= W_c

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

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

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 $\Phi = 30 \times 10^{-3}$ web
For wave wound parallel path A = 2

To find:
Torque T_a in Kg m

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

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 $E_b = V - (I_aR_a)$

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

Also Back Emf $E_b = \frac{\Phi ZNP}{60\,A}$

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

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

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 $E_{b1} = (V - I_{a1} R_a) = 220 - (50 \times 0.2) = 210$ Volts

Back Emf when torque is doubled $E_{b2} = (V - I_{a2} R_a) = 220 - (100 \times 0.2) = 200$ 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

$= \frac{2\pi NT}{60}$

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

= 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 = $245.25 \times 20 \times 10^{-2}$

= 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 = $I_{ao}^2 R_a$

= 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 = $I_a^2 R_a = 44.04^2 \times 1$
= 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.

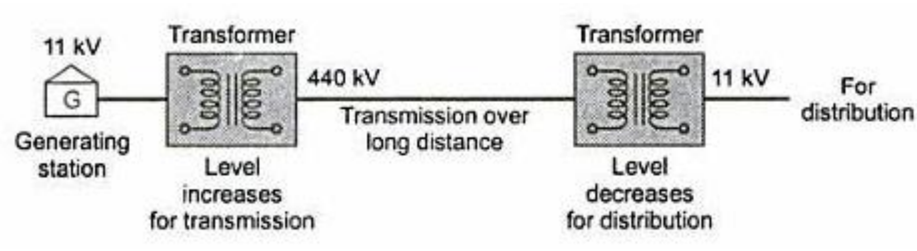


Fig 3.1 Use of transformer in transmission system

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.

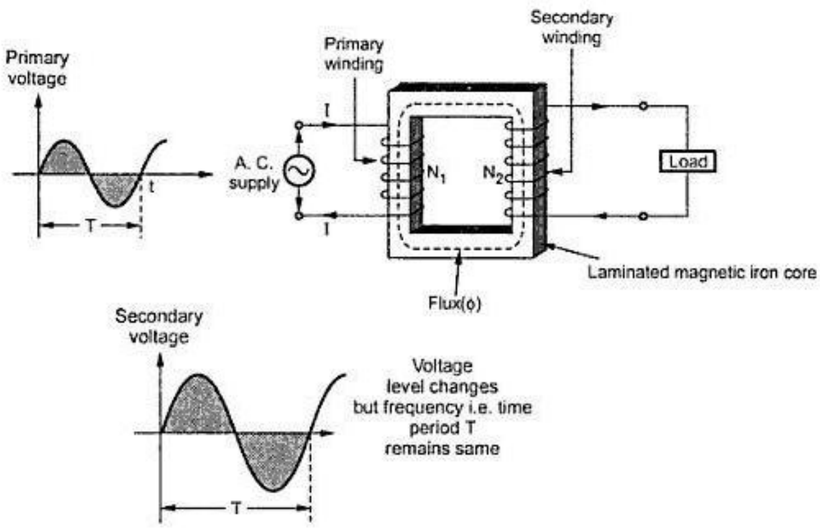


Fig 3.2 Basic Transformer

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

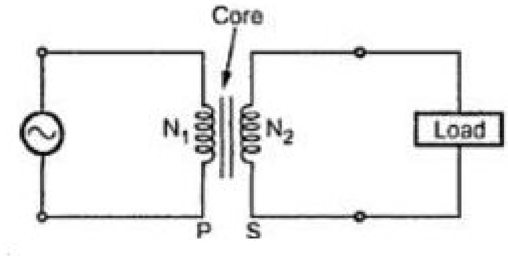


Fig 3.3 Symbolic Representation

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).

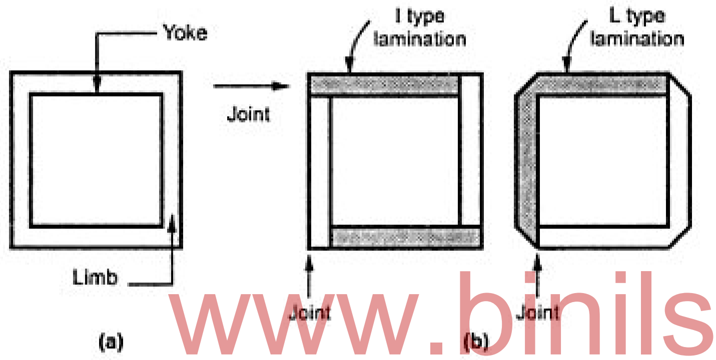


Fig 3.4

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.

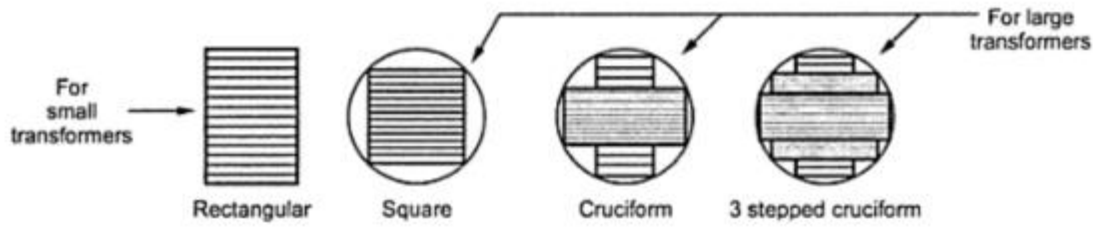


Fig 3.5

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.

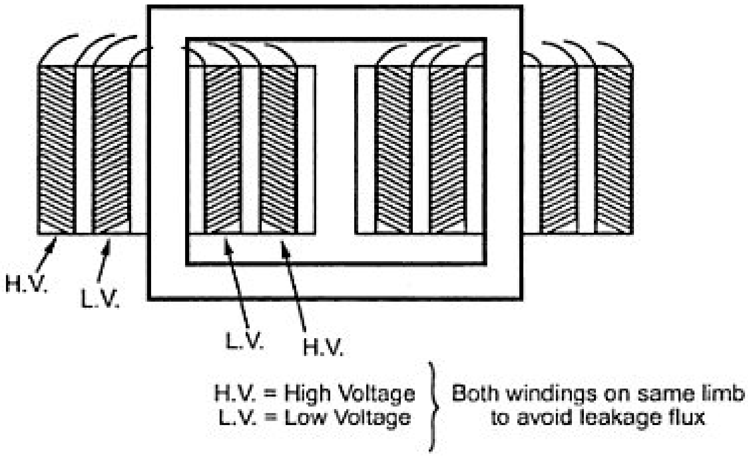


Fig 3.6

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.

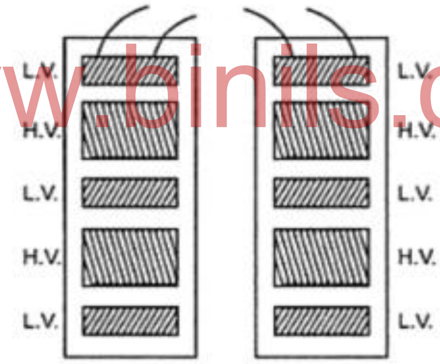


Fig 3.7

3.2.2 Core Type Transformer:

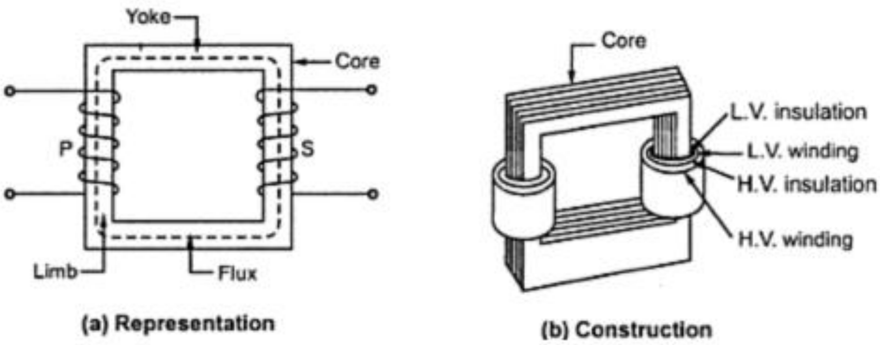


Fig 3.8

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:

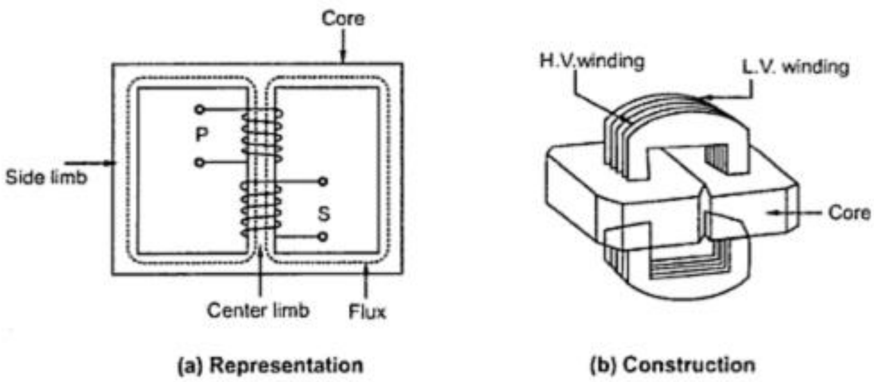


Fig 3.9

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 X A

f = Frequency of a.c input in Hz

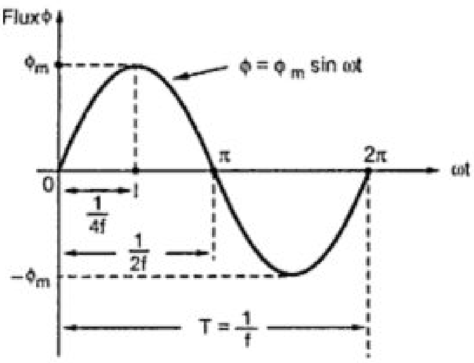


Fig 3.10

As shown in Fig. 3.10 flux increases from its zero values to maximum value Φm in one quarter of the cycle.

$$i.e.\ in\ \frac{1}{4f} seconds$$

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

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.

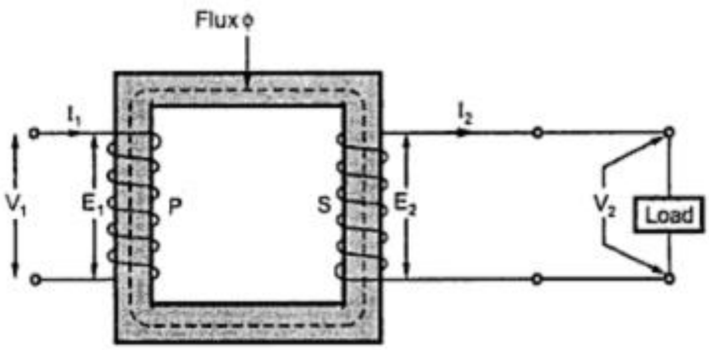


Fig 3.11

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,

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

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.

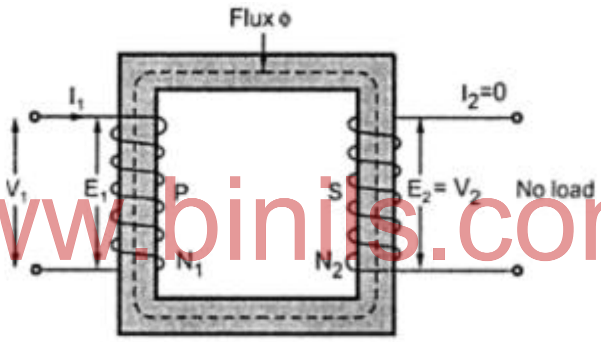


Fig 3.12

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.

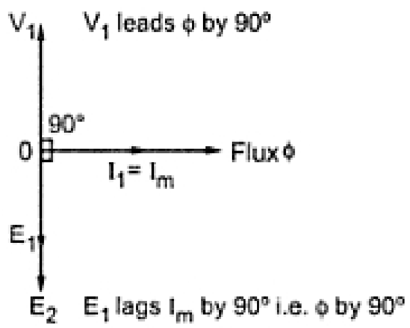


Fig 3.13

It can be seen that flux Φ is reference. I_m produces Φ hence in phase with Φ. V_1 leads 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 $V_1 I_1 \cos (V_1 \wedge I_1)$ 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

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

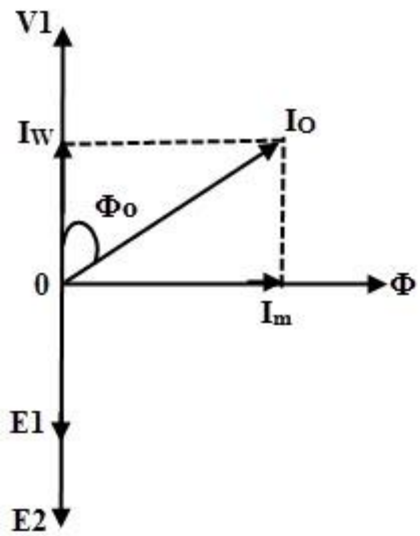


Fig 3.14

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.

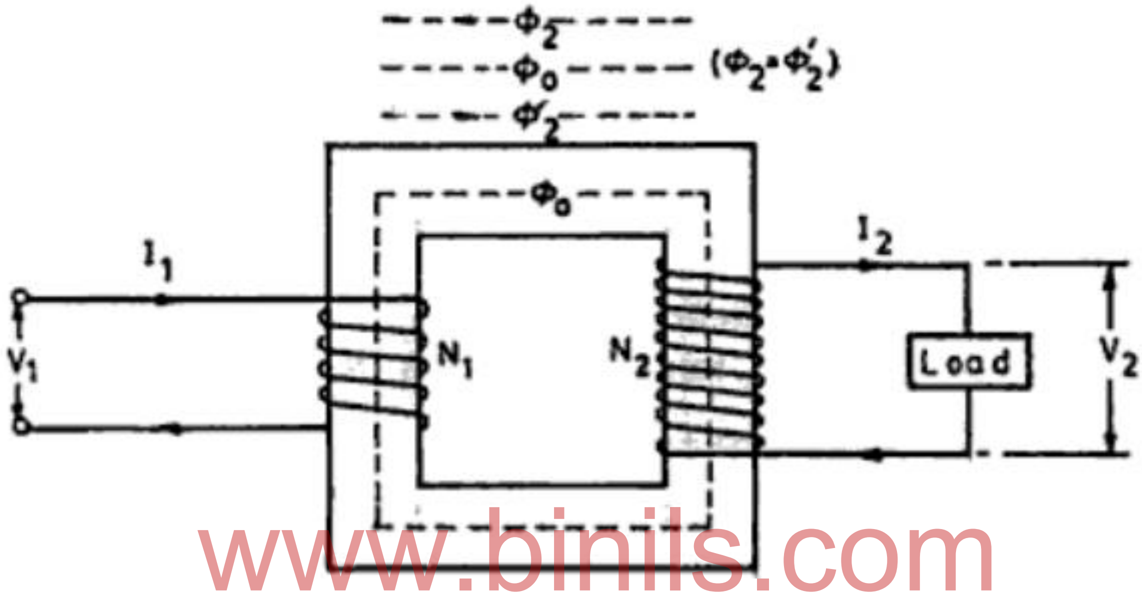


Fig. 3.15

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, $\emptyset_2 = \emptyset_2'$

∴ $N_2 I_2 = N_1 I_2'$

i.e $I_2' = \frac{N_2}{N_1} \times I_2 = K I_2$ ∵ $\frac{N_2}{N_1} = K$

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 secondary current I2.

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

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

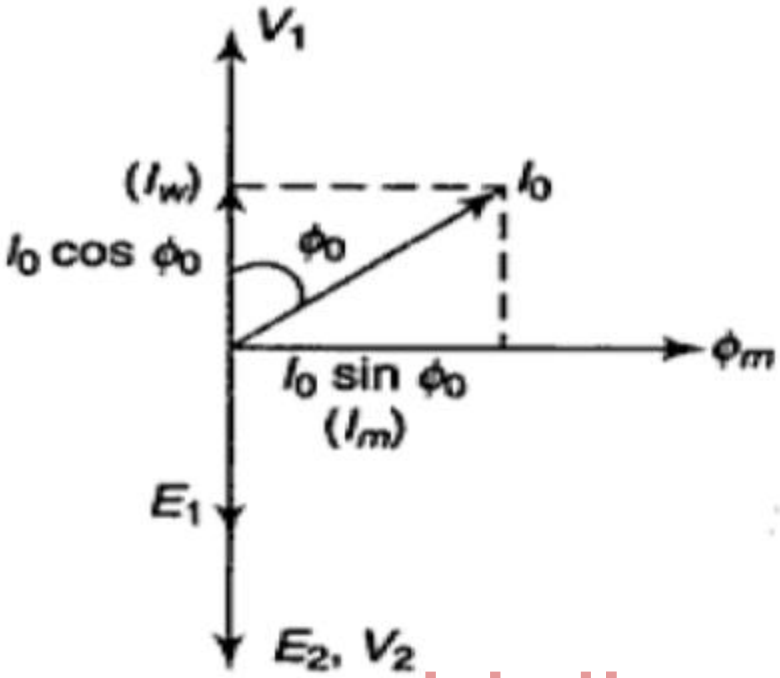


Fig. 3.16 Phasor diagram under no-load condition

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

The magnitude of the no-load current is given by,

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

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

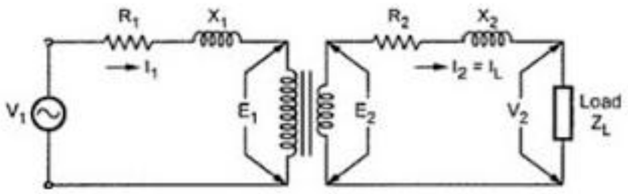


Fig 3.17

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^o

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

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

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

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^o

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

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

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

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, $\cos\Phi_2 = 1$

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^o. 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 $\cos\Phi_1$ is primary power factor. Remember that I_1X_1 leads I_1 direction by 90^o and $I_2 X_2$ leads I_2 by 90^o as current through inductance lags voltage across inductance by 90^o. The phasor diagram is shown in the Fig.3.18

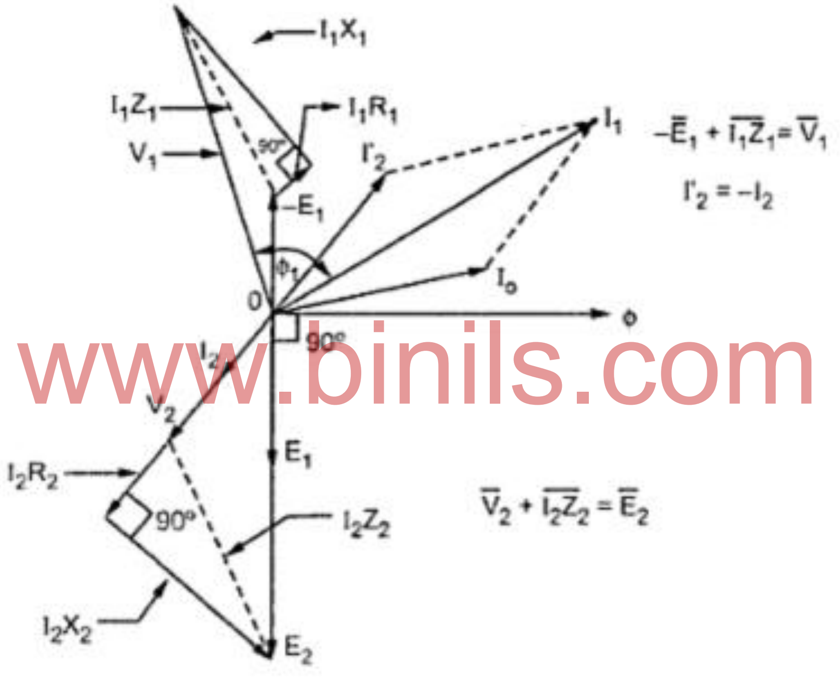


Fig 3.18

Lagging Power Factor Load, $\cos \Phi_2$

As load power factor is lagging $\cos\Phi_2$, 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^o and I_1X_1 leads I_1 by 90^o.

The complete phasor diagram is shown in the Fig. 3.19

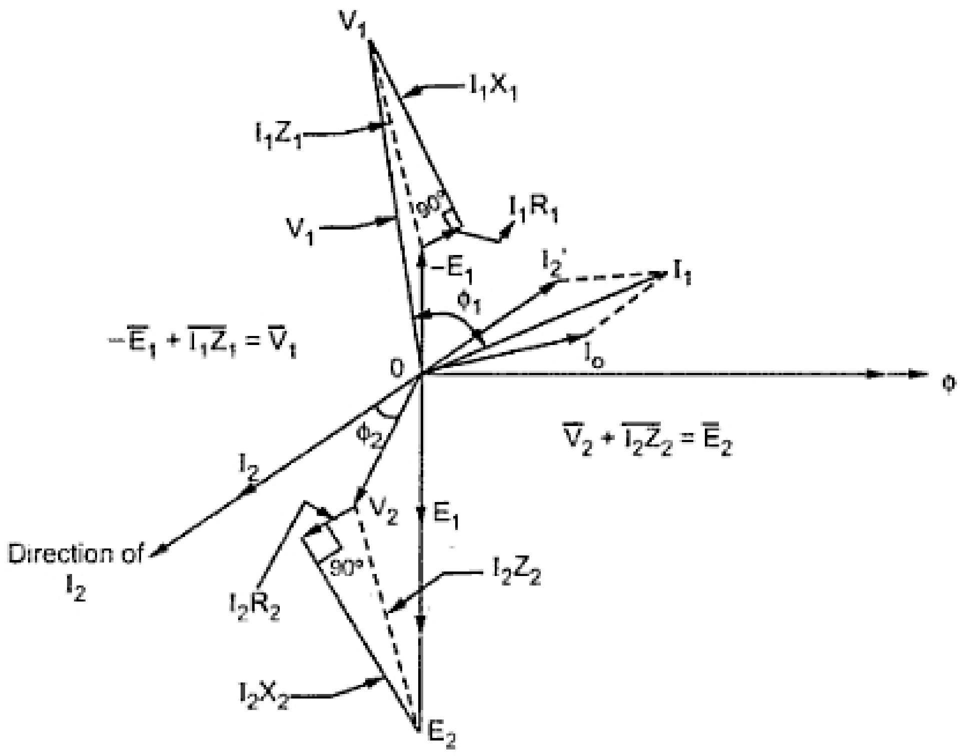


Fig3.19

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

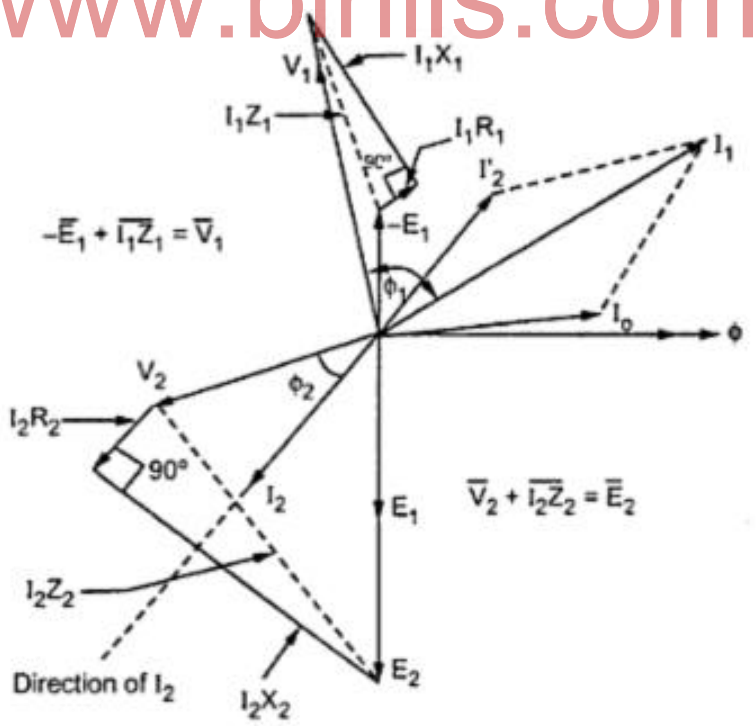


Fig 3.20

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 $X_o = V_1/I_m$

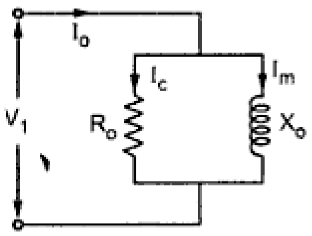


Fig 3.21

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.

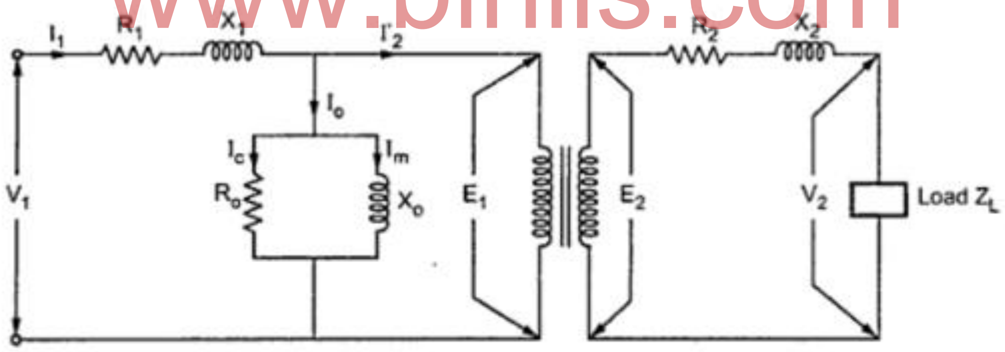


Fig 3.22

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,

$R_2' = R_2/K^2$, $X_2' = X_2/K^{2\prime}$, $Z_2' = Z_2/K^2$

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

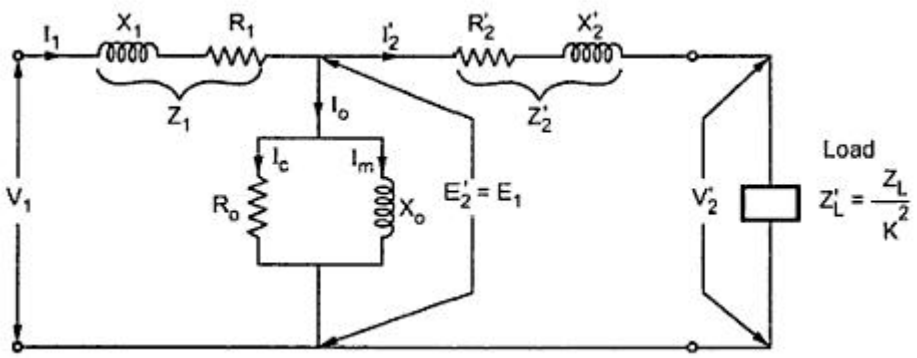


Fig 3.23

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.

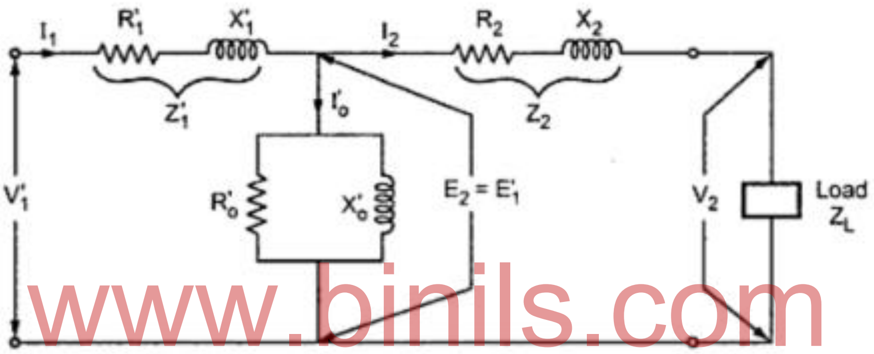


Fig 3.24

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.

Approximate Equivalent Circuit

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.

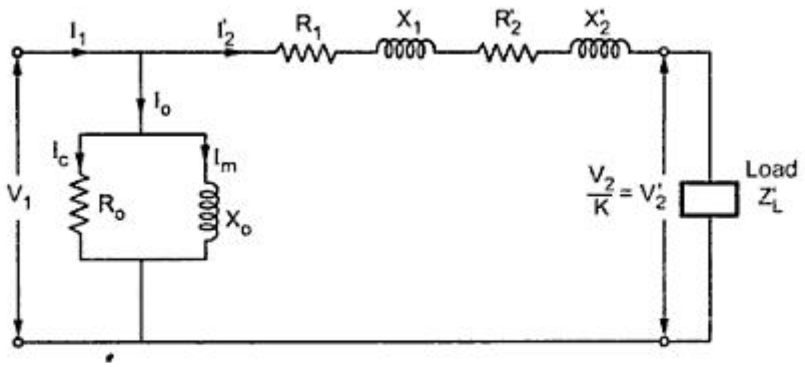


Fig 3.25

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.

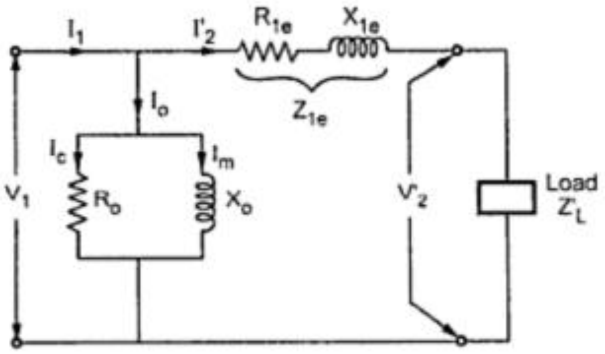


Fig 3.26

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

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

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

$R_o = V_1/I_c$ and $X_o = V_1/I_m$

$I_c = I_o \cos\Phi_o$ 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.

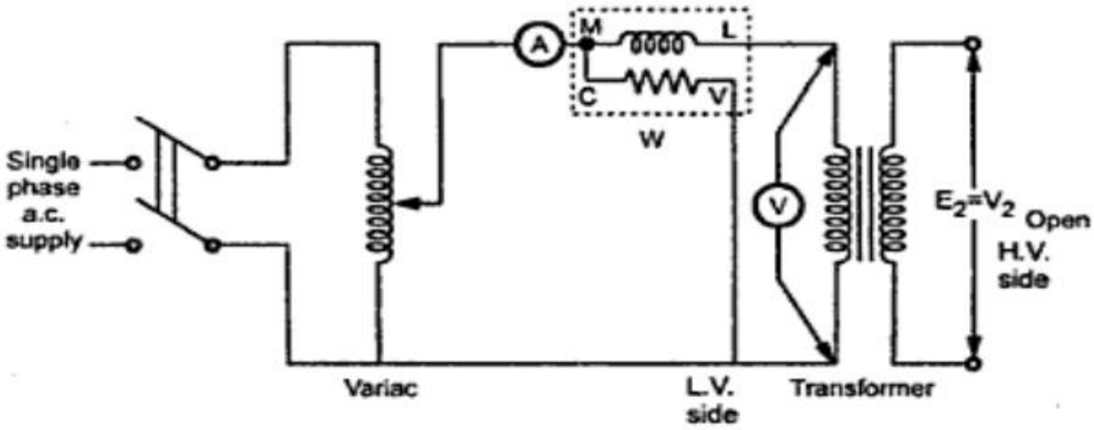


Fig.3.27 Experimental Circuit for O.C. Test

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,

$W_0 = V_0 I_0 \cos\emptyset_0$

$$\therefore \qquad \cos\emptyset_0 = \frac{W_0}{V_0 I_0} = No\ load\ power\ factor$$

Once $\cos\emptyset_0$ is known we can obtain,

$I_W = I_0 \cos\emptyset_0$

and

$I_m = I_0 \sin\emptyset_0$

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.

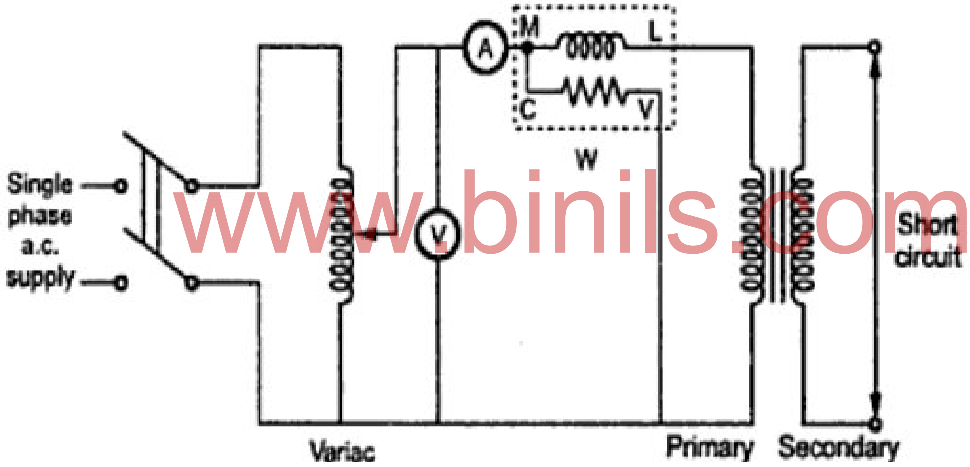


Fig.3.28 Experimental circuit for S.C. Test

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,

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

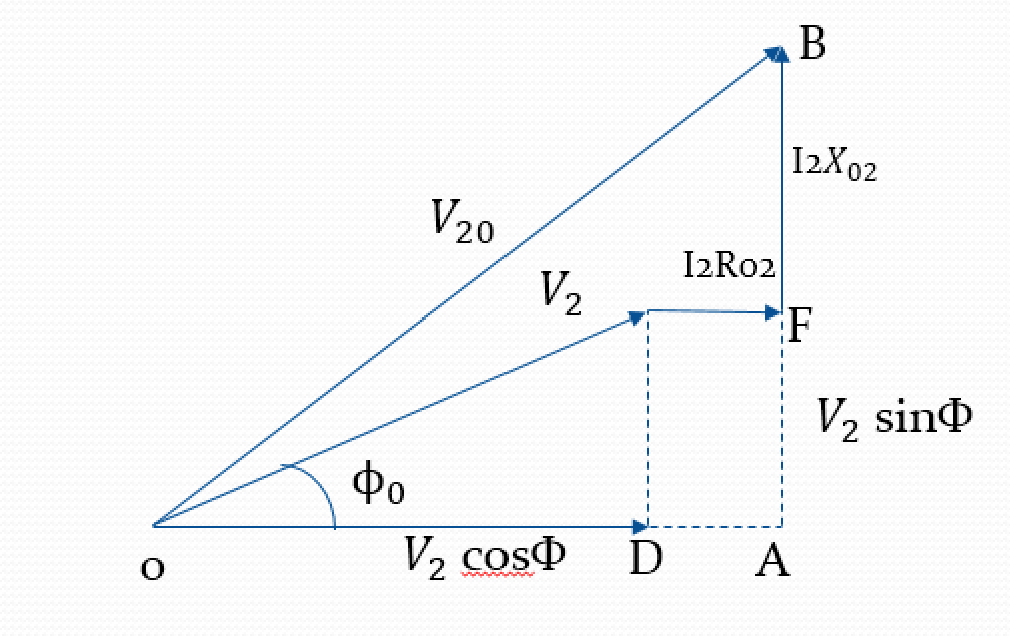
$$\%\,Voltage\ Regulation = \frac{V_{20} - V_2}{V_2} \times 100$$

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

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 = $\sqrt{OA^2 + AB^2}$

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

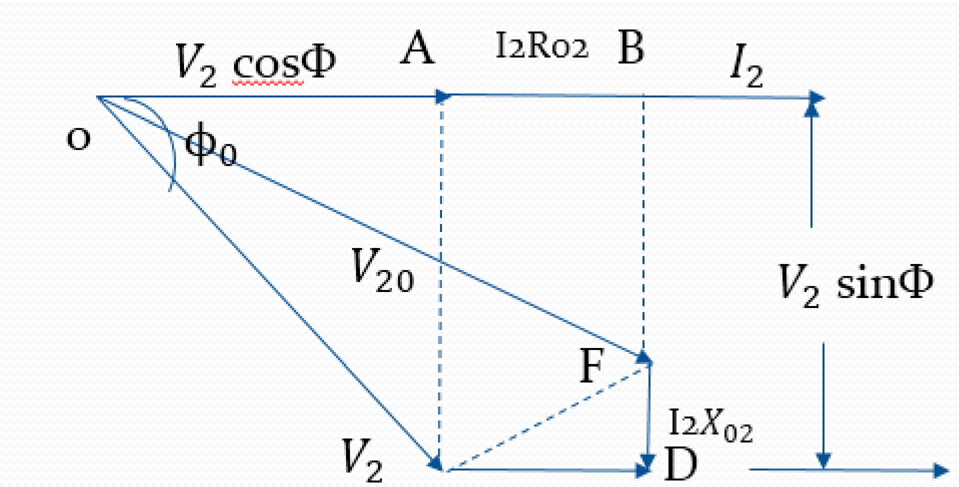
Where OB= V_{20} ; OD = $V_2\ cos\emptyset_0$; DA = I_2R_{02}; AF = $V_2\ sin\emptyset_0$; FB = I_2X_{02}

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

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 = $\sqrt{OB^2 + BF^2}$

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

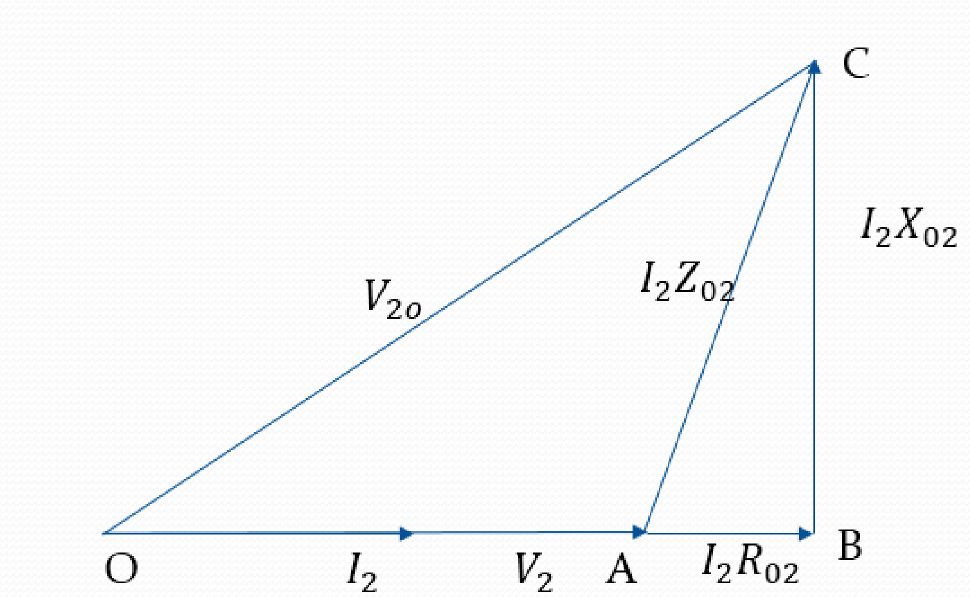
Where OF= V_{20} ; OA = $V_2\ cos\emptyset_0$; AB = I_2R_{02}; BD = $V_2\ sin\emptyset_0$; FD = I_2X_{02}

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

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 = $V_2I_2Cos\Phi$

Where $Cos\Phi$ = Load power factor

The transformer supplies full load of current I2 and terminal voltage V2

P_{cu} =Copper lossess on full load = $I_2^2R_{02}$

$$\therefore\ \eta = \frac{V_2I_2\cos\emptyset_2}{V_2I_2\cos\emptyset_2 + P_i + I_2^2R_{02}}$$

But V_2I_2 = VA rating of a Transformer

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

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

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,

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

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

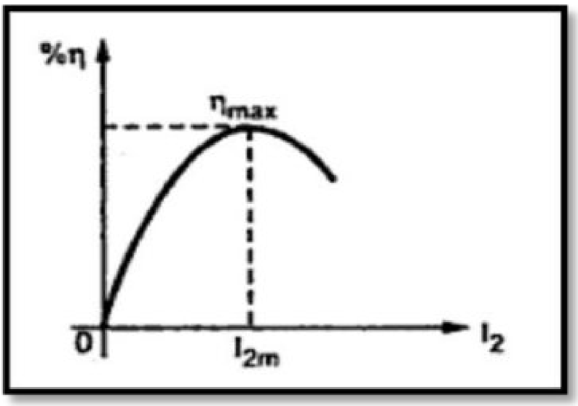


Fig.3.29

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

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

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

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

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

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

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

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

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

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.

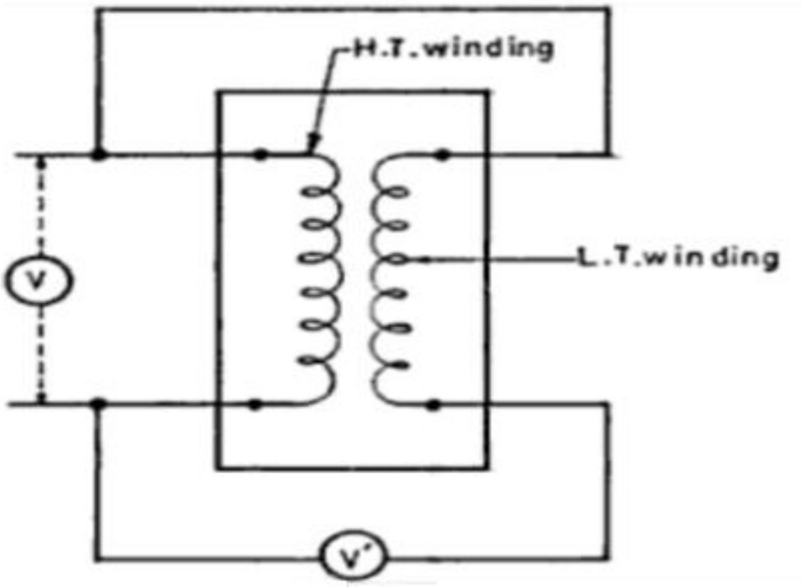


Fig.3.30

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*

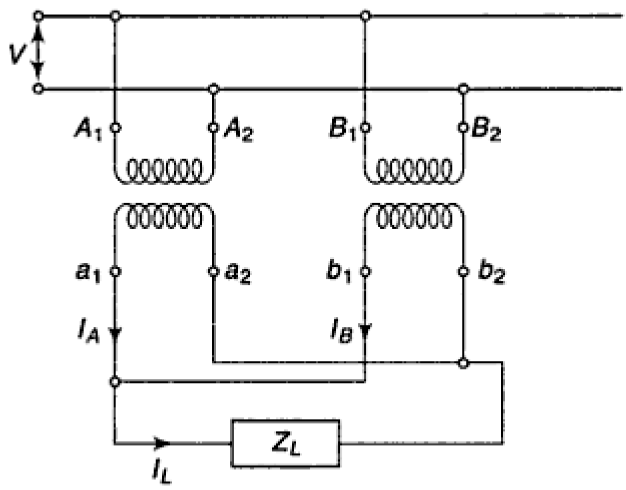


Fig.3.31 Two Single Phase Transformer in Parallel

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

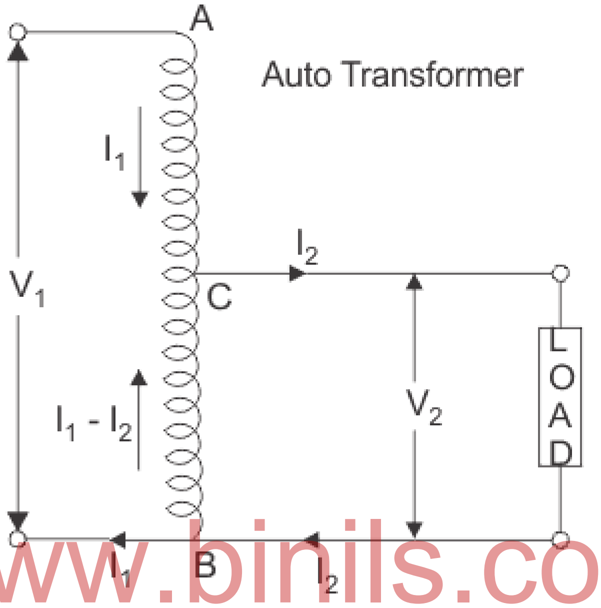


Fig.3.32 Autotransformer

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.

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

$$Weight\ of\ copper\ in\ auto-transformer$$

$$= weight\ of\ copper\ in\ section\ LS + weight\ of\ copper\ in\ section\ MS$$

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

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

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

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

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

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

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

$$\therefore \; Saving\ in\ copper = W_0 - W_a = W_0 - (1-K)W_0 = KW_0$$

$$\therefore \; Saving\ in\ copper = K \times Weight\ of\ copper\ in\ ordinary\ transformer$$

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 :			**To Find :**
Rated power	=	40 KVA	Secondary voltage on open circuit (E_2)=?
Number of primary turns(N_1)	=	400	Current flowing through the two windings (I_1 and I_2)=?
Number of secondary turns (N_2)	=	100	Maximum value of flux ($\emptyset_{max}$)= ?
Supply voltage (V_1)	=	2000V	
Supply frequency	=	50Hz	

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

To Find :

Number of primary turns (N_1) =?

Number of secondary turns (N_2) =?

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

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

Supply frequency = 50Hz

Cross –sectional area = 60cm^2

Number of primary turns (N_1) = 500

Number of secondary turns (N_2) = 100

To Find :

Transformation ratio (K) = ?

E.m.f induced in secondary winding =?

Maximum value of flux (B_{max}) =?

Solution:

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

$= \dfrac{100}{500}$

$= 0.2$

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 :

Supply frequency	=	50Hz
primary voltage (V_1)	=	6600
secondary volatge (V_2)	=	600
Maximum value of flux (B_{max})	=	1.4 Wb/m^2
cross-sectional area of the iron core	=	0.02 m^2

To Find :

Number of primary turns (N_1) =?

Number of secondary turns (N_2) =?

Solution:

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

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

$= 1.4 \times 0.02$

$= 0.028$ Wb

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

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

$$= 965 \text{ turns}$$

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

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

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

$$= 97 \text{ turns}$$

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 :

primary voltage (V_1) = 3300

secondary volatge (V_2) = 300

No-load current (I_o) = 0.6A

No –load power (W_o) = 60W

To Find :

Power factor of No-load current (cosϕ)=?

Magnetising current component (I_m) =?

Iron loss component (I_w)= ?

Solution:

From power equation $W_0 = V I_0 cos\emptyset_0$

$$cos\emptyset_0 = \frac{W_0}{V I_0}$$

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

$$= 0.33 \text{ (lagging)}$$

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

No-load current (I_o) = 1.5 A

Iron loss component (I_w) or $I_0 \cos\emptyset_0$ 0.4 A

To Find :

No-load input power (W_0) =?

Power factor of No-load current (cosϕ)=?

Magnetising current component (I_m) =?

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) $= I_0 \sin\emptyset_0$

$= 1.5 \times 0.964$

$= 1.446A$

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 :

At O.C. test

$V_0 = 200V$

$I_0 = 0.6\ A$

$W_0 = 60W$

$V_{sc} = 15\ V$

$I_{sc} = 9A$

$W_{sc} = 80W$

To Find :

$R_0 = ?$

$X_0 = ?$

$I_m = ?$

$I_w = ?$

R_{01} and $R_{02} = ?$

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 $sin\emptyset_0$, = Sin (60^0)

= 0.866

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

= 0.6 x 0.866

= 0.5196A

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

= 0.6 x 0.5

= 0.3 A

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

$= \frac{200}{0.3}$

= 666.66Ω

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

$= \frac{200}{0.5196}$

= 384.91Ω

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}	=	$\frac{V_s}{I_s}$
	=	$\frac{15}{9}$
	=	1.666Ω
X_{02}	=	$\sqrt{{Z_{02}}^2 - {R_{02}}^2}$
	=	$\sqrt{1.666^2 - 0.9876^2}$
	=	1.3417Ω
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 :

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} = ?

To Find : see last column above.

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) $= I_0 \sin\emptyset_0$

$= 6.2 \text{ x } 0.957$

$= 5.9334$A

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

$= 6.2 \text{ x } 0.29$

$= 1.8$A

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 $\cos\emptyset_0$ $= 0.8$

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

$= 36.86^0$

$= \text{Sin}\,(36.86^0)$

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

V_{sc} = 50 V

To Find :

Full load regulation at 0.7 P.f. lag=?

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

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

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

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

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

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

= 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 P_{cu} = 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 lossP_{cu} = 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	=	$\frac{Output\ power\ in\ KWh}{Output\ power\ in\ KWh + total\ losses/day}$

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

$$= 0.9068 \text{ or } 90.68\%$$

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.

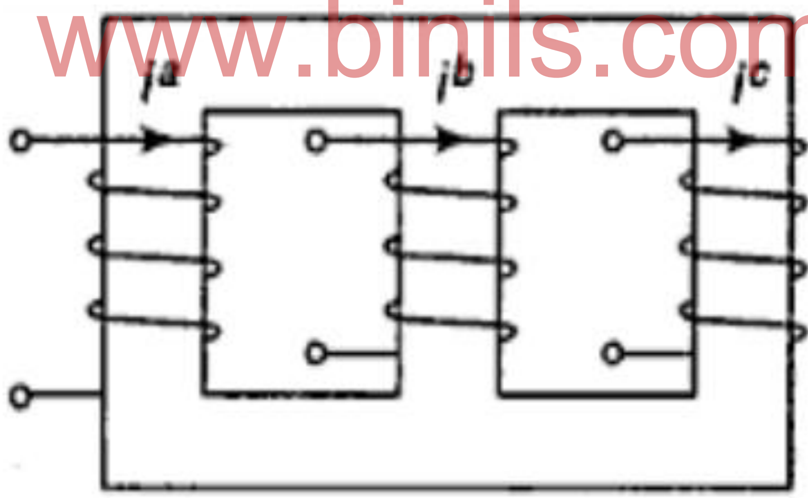


Fig.4.1 Three phase core type transformer

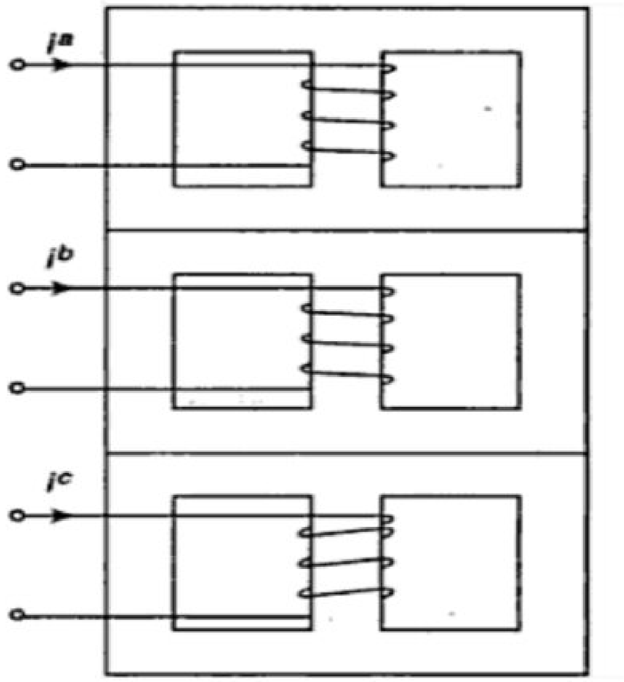


Fig.4.2 Shell Type Three phase Transformer

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)**

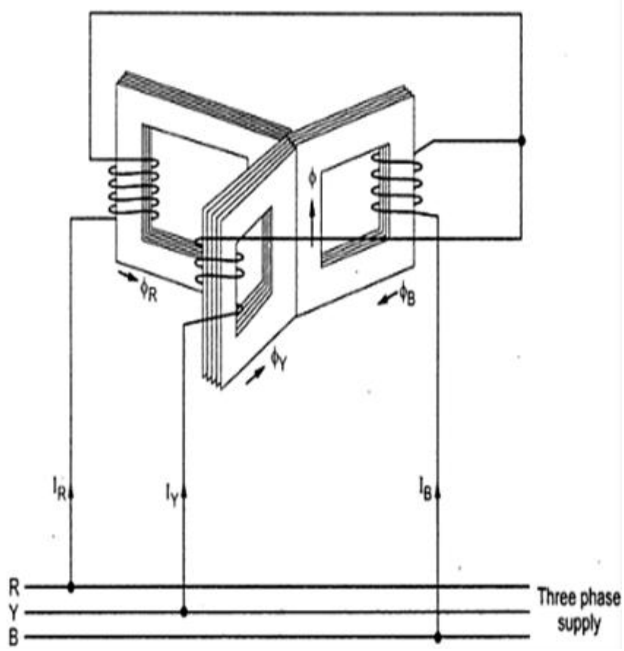


Fig. 4.3 Three Phase Transformer Connection

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.

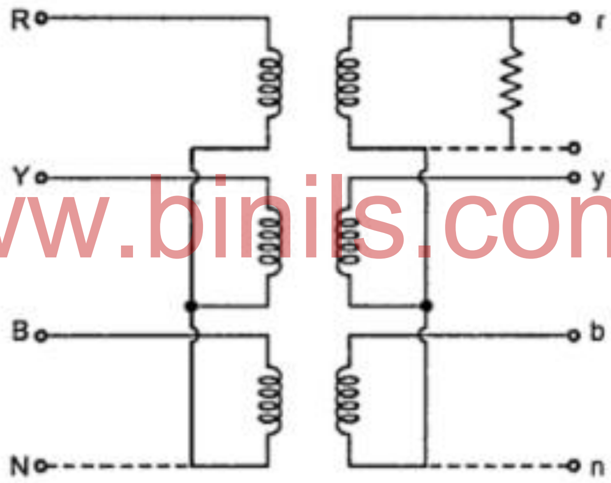


Fig 4.4

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

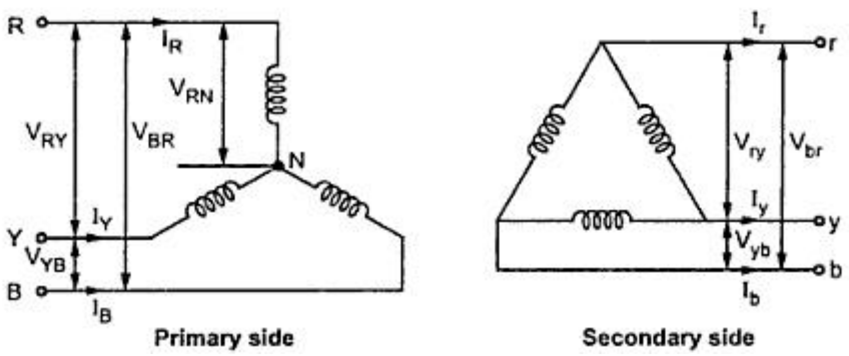


Fig 4.5

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

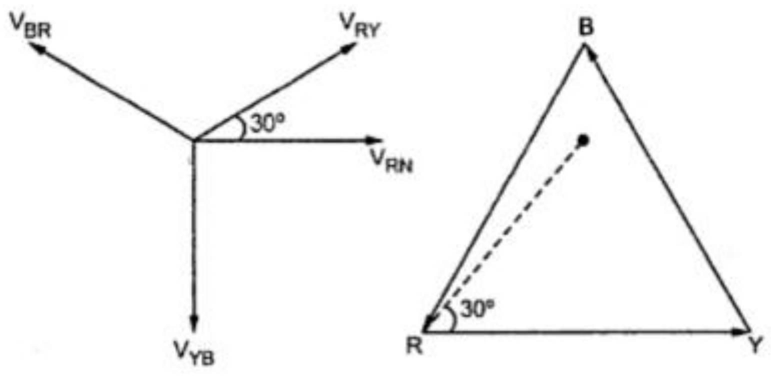


Fig 4.6

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

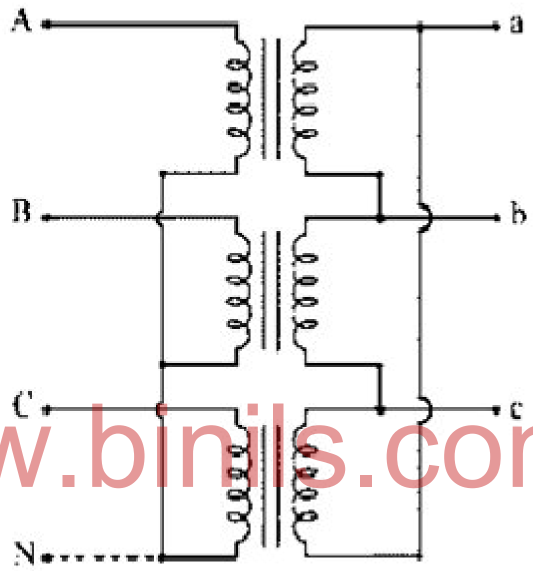


Fig 4.7

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.

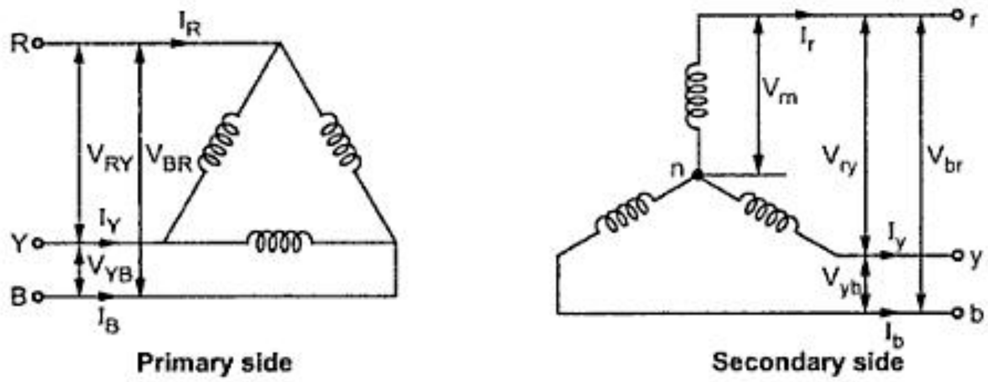


Fig 4.8

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

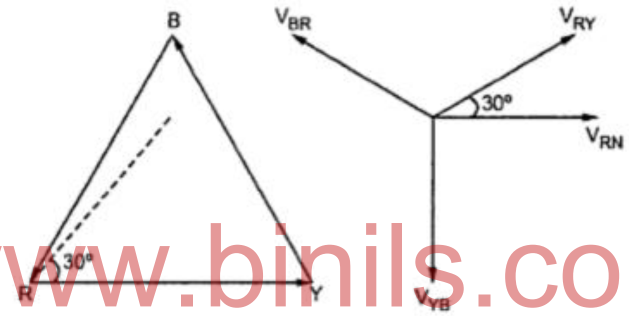


Fig 4.9

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

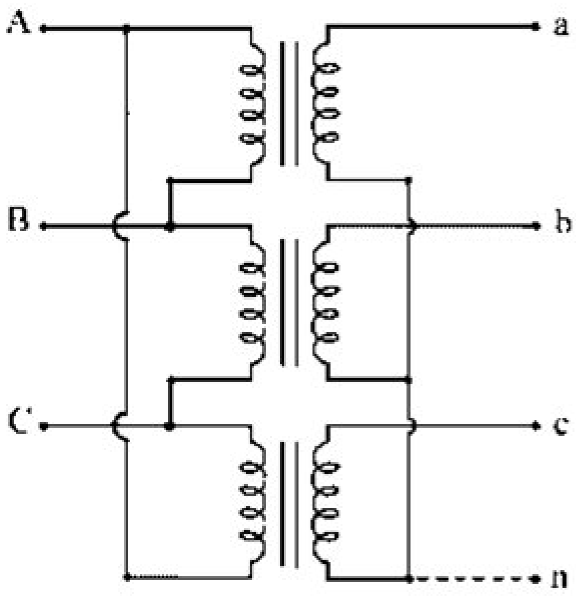


Fig 4.10

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

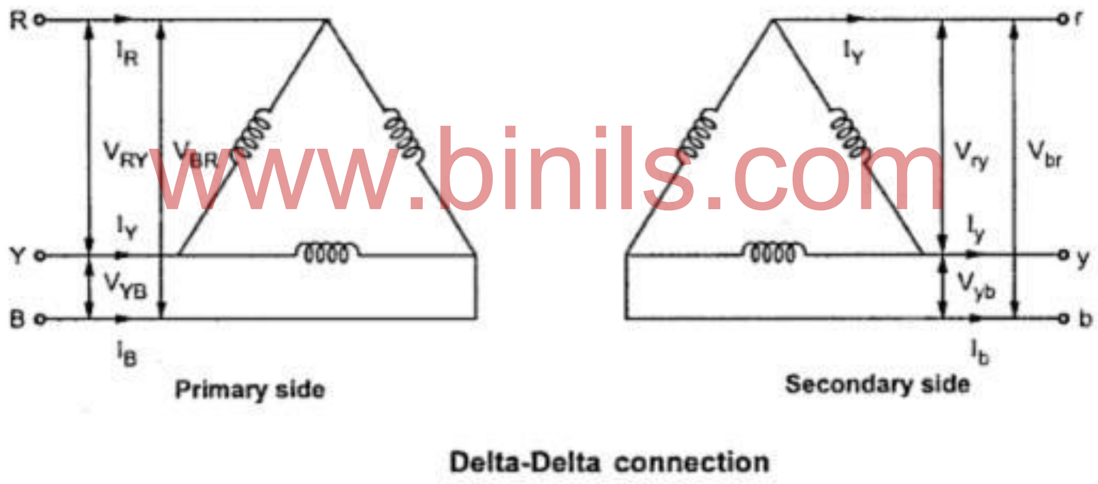


Fig 4.11

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

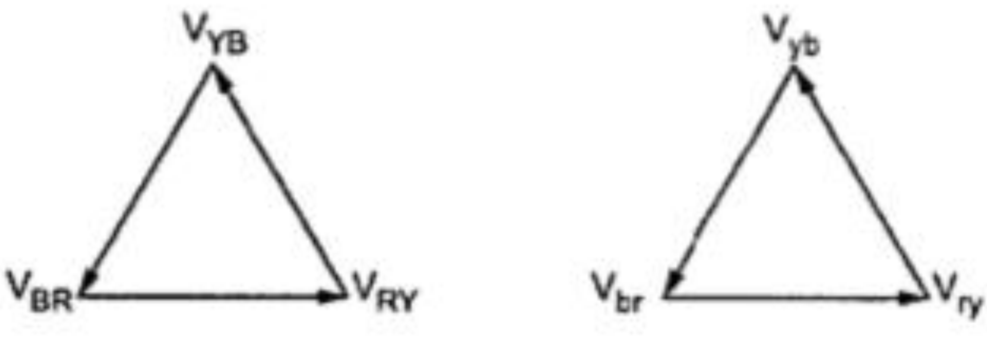


Fig 4.12

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

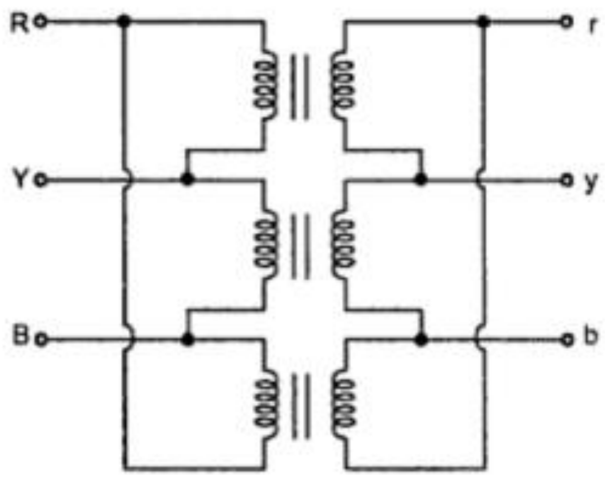


Fig 4.13

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.

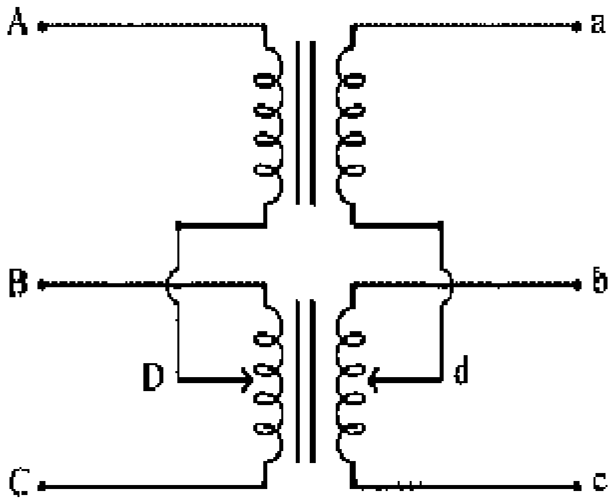


Fig 4.14

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).

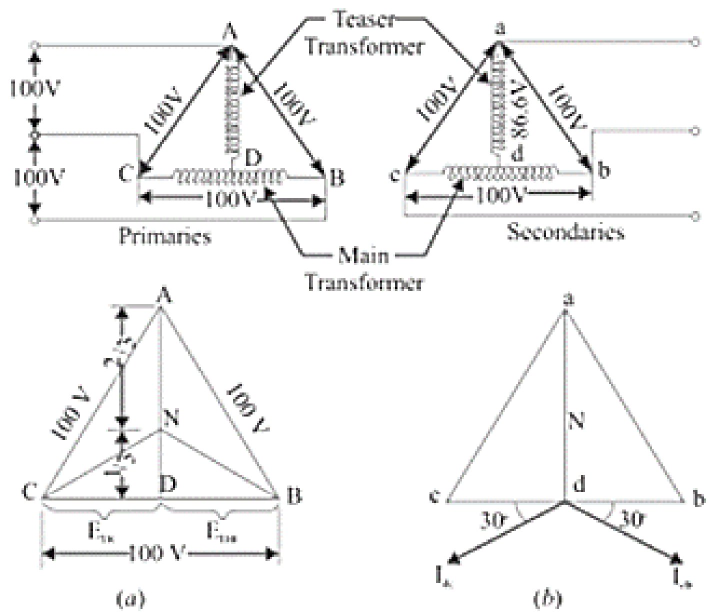


Fig 4.15

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.

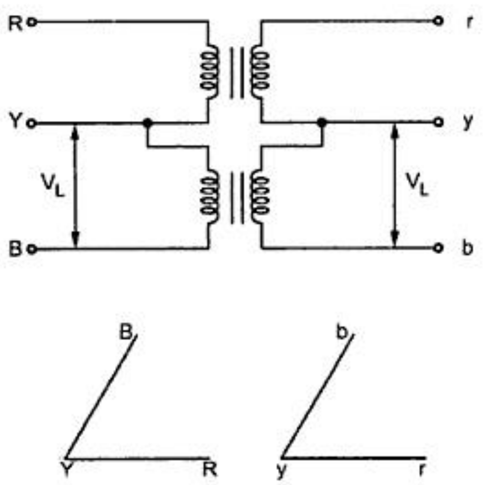


Fig 4.16

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.

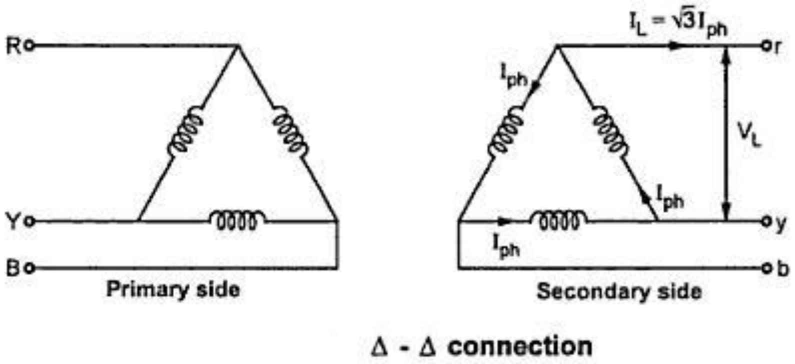


Fig 4.17(a)

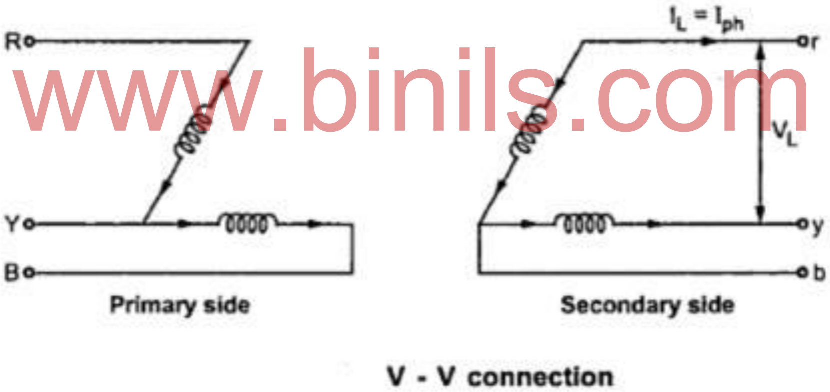


Fig 4.17 (b)

It can be seen from the Fig. 4.17(a)

Δ - Δ capacity = $\sqrt{3}$ VL IL = $\sqrt{3}$ VL ($\sqrt{3}$ 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 = $\sqrt{3}$ VL IL = $\sqrt{3}$ 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,

$$\frac{\text{V-V capacity}}{\Delta\text{-}\Delta \text{ capacity}} = \frac{\sqrt{3}\, V_L I_{ph}}{3\, V_L I_{ph}} = \frac{1}{\sqrt{3}} = 0.557 \approx 58\ \% \qquad \dots \text{(iii)}$$

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^2R 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.

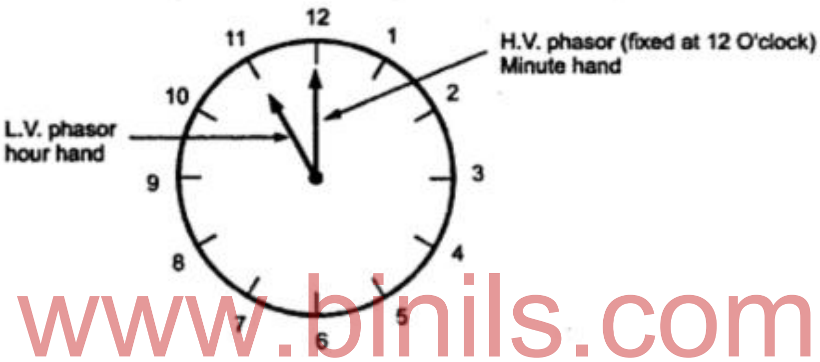


Fig 4.18

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^o phase displacement (Yy6, Dd6, Dz6)

Group 3 : 30^o lag phase displacement (Dy1, Yd1, Yz1)

Group 4 : 30^o 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

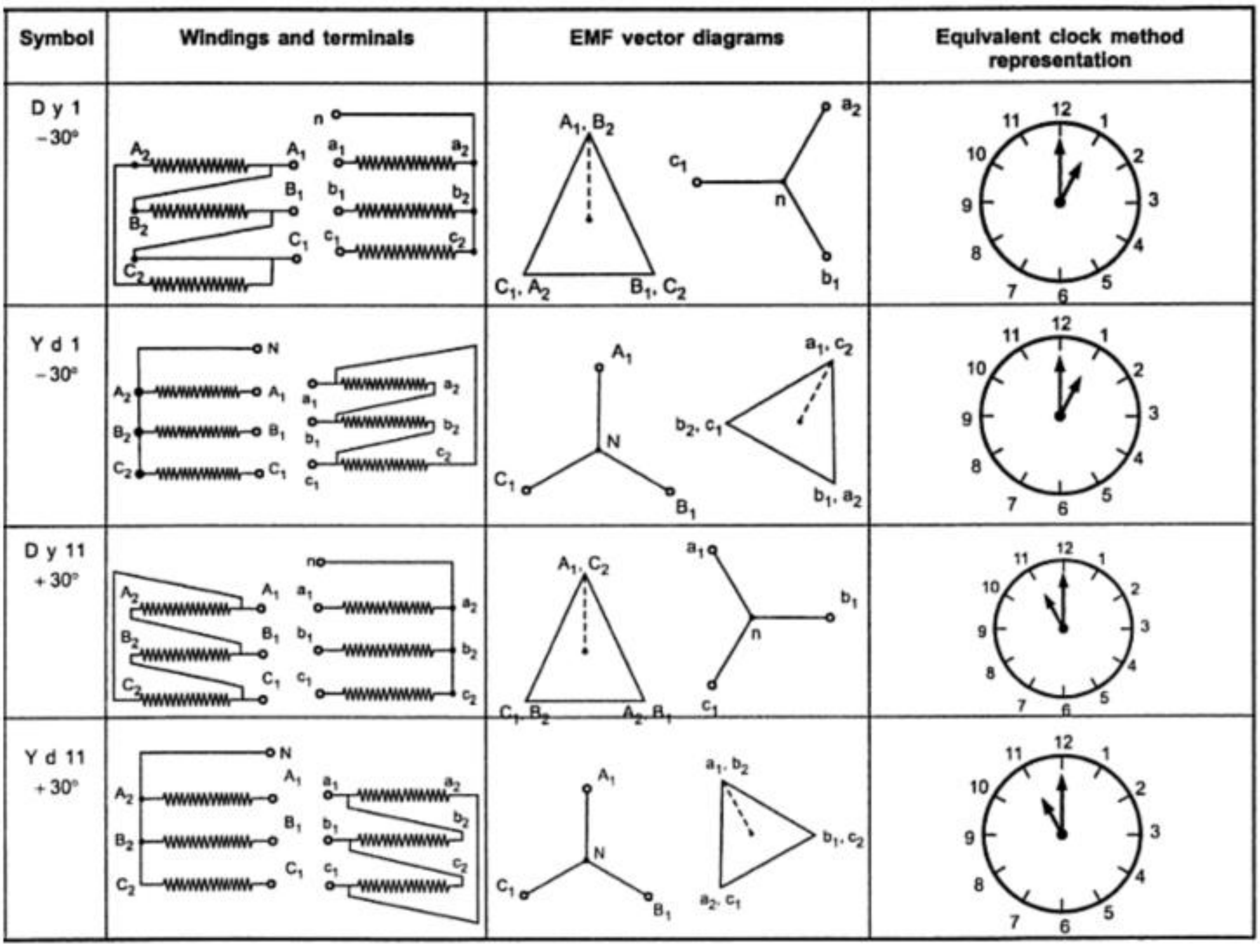


Fig 4.19

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

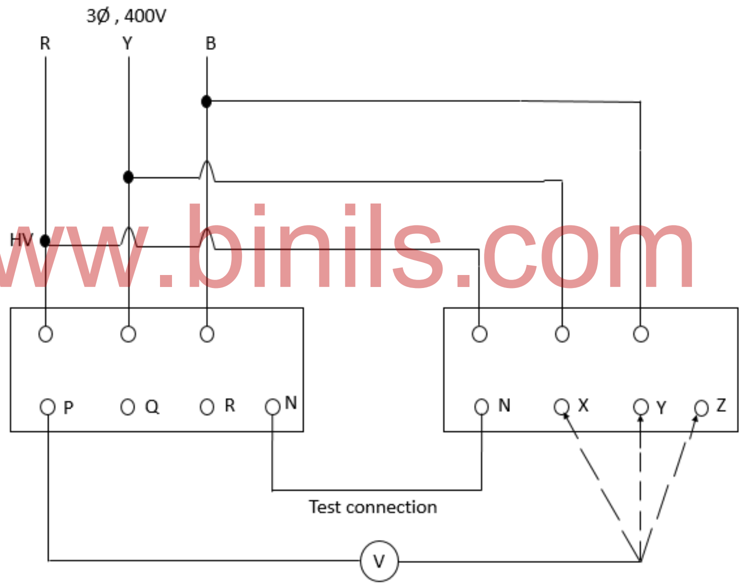


Fig 4.20

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.

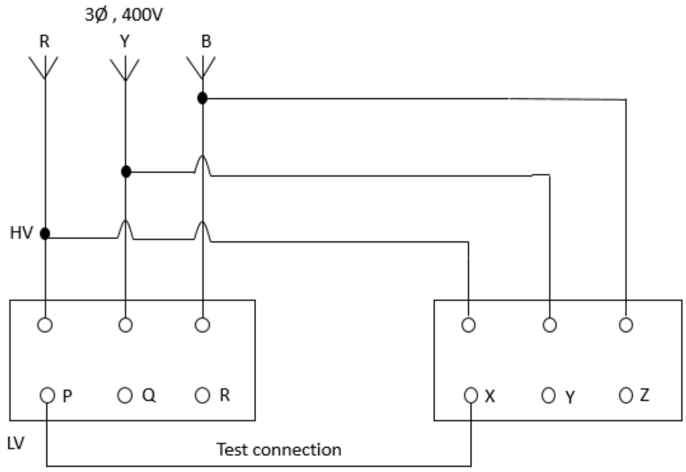


Fig 4.21

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

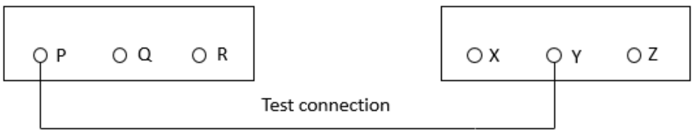


Fig 4.22

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

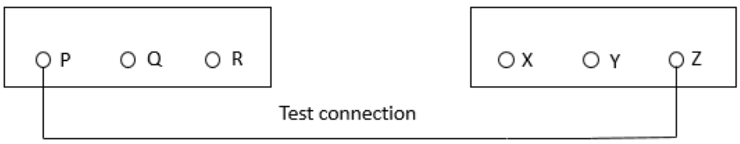


Fig 4.24

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

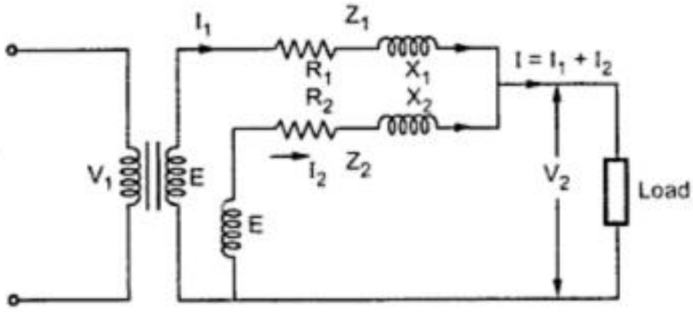


Fig 4.25

If we neglect magnetizing components, the two transformers are represented as shown in the Fig. 4.26.

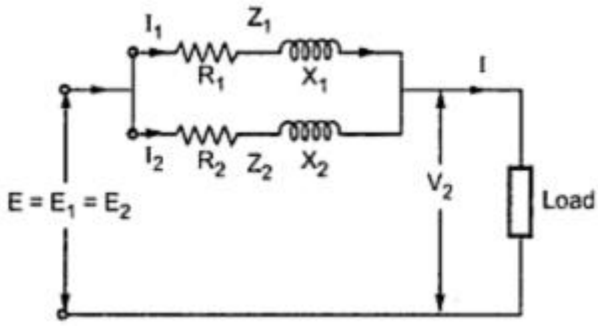


Fig 4.26

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.

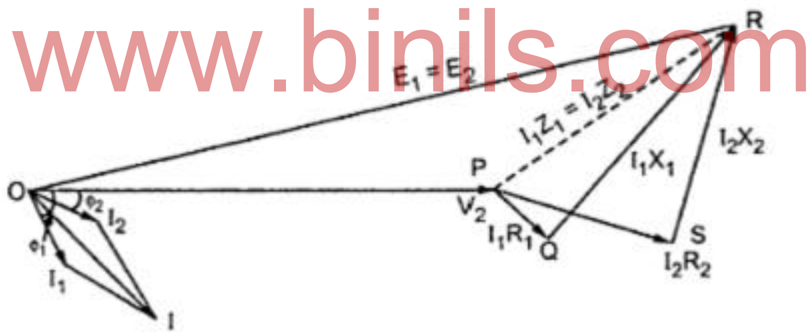


Fig 4.27

Z1 and Z2 are in parallel therefore the equivalent impedance is given by,

$1/Z_{eq} = 1/Z_1 + 1/Z_2$ $\quad\quad$ $Z_{eq} = Z_1 Z_2 /(Z_1 + Z_2)$

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.

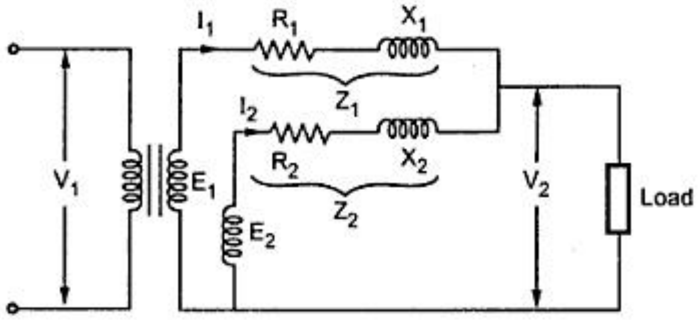


Fig 4.28

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, $I_L = I_1 + I_2$

$V_2 = I_L Z_L = (I_I + I_2) Z_L$

$E_1 = (I_1 + I_2) Z_L + I_I Z_1$ ....(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),

$$E_2 = I_2 Z_2 + \left[\left\{ \frac{(E_1 - E_2) + I_2 Z_2}{Z_1} \right\} + I_2 \right] Z_L$$

∴ $I_2 = (E_2 Z_1 - (E_1 - E_2)Z_L) / (Z_1 Z_2 + Z_L (Z_1 + Z_2))$

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,

$$I_1 + I_2 = (E_1 Z_2 + E_2 Z_1) / (Z_1 Z_2 + Z_L (Z_1 + Z_2)) \quad \text{.............(c)}$$

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.

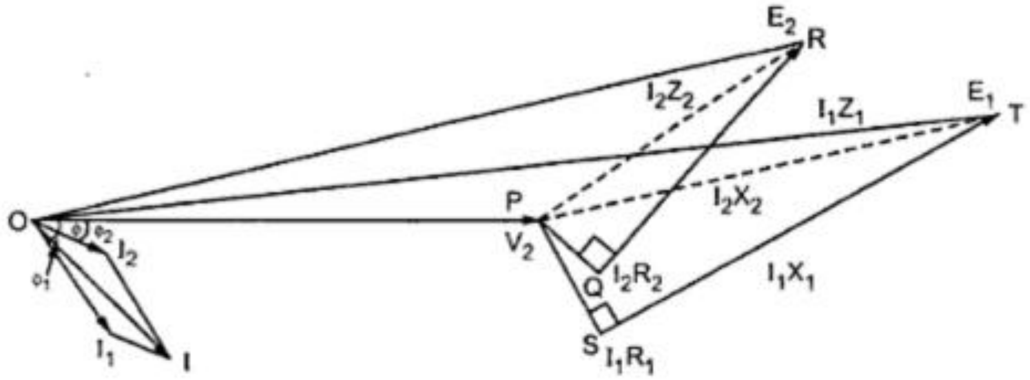


Fig 4.29

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.

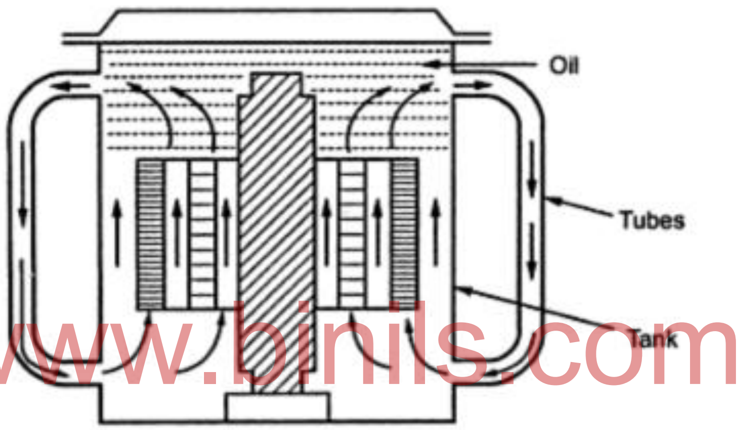


Fig 4.30

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.

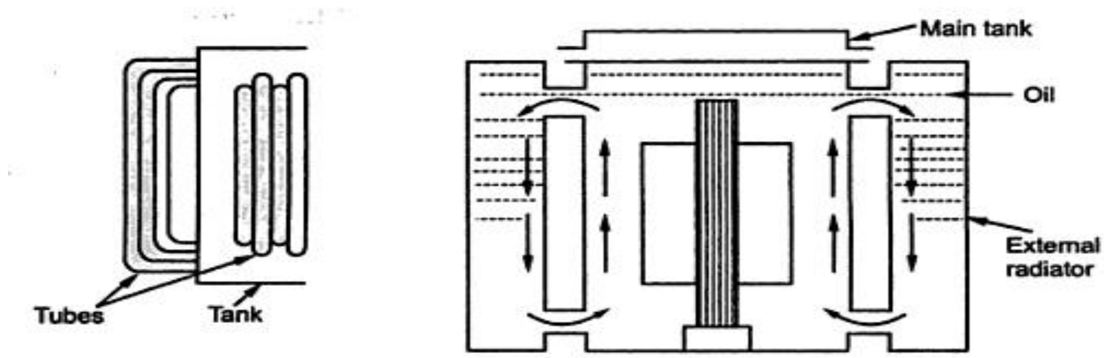


Fig 4.31

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

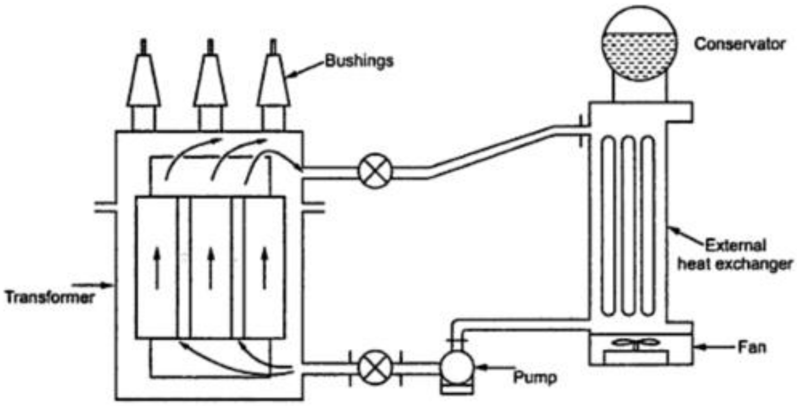


Fig 4.32

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

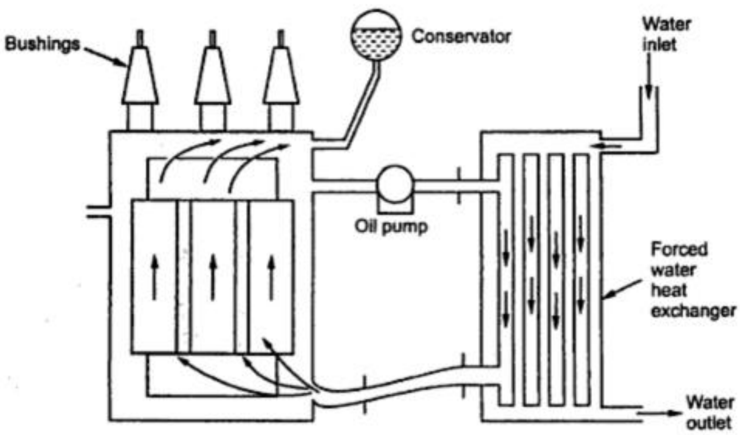


Fig 4.33

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.

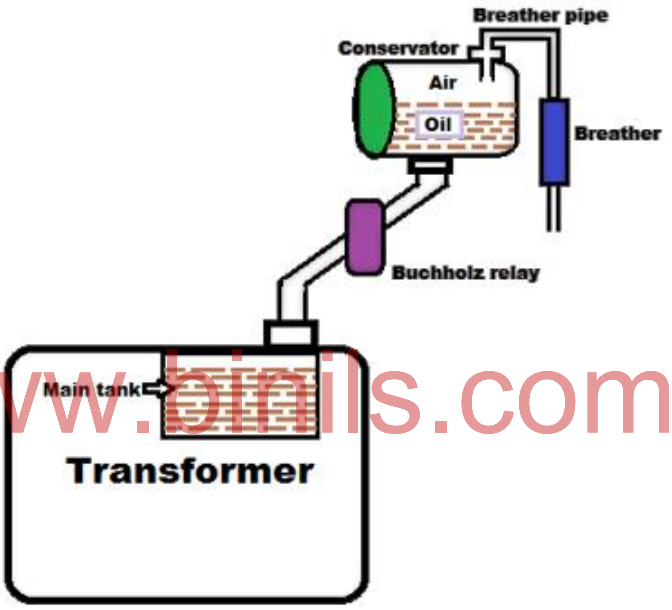


Fig 4.34

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.

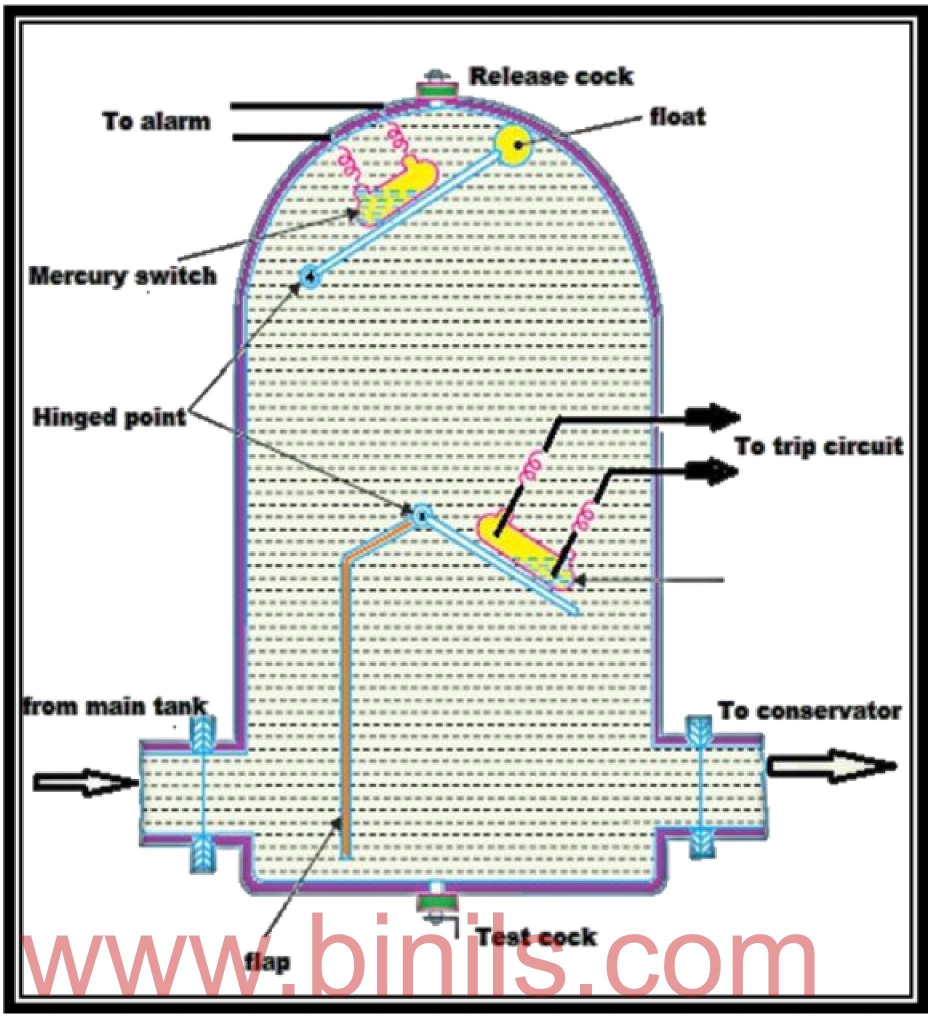


Fig.4.35 Buchholz Relay

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.

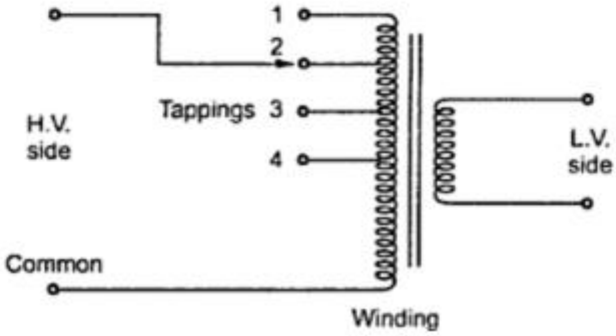


Fig 4.36

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

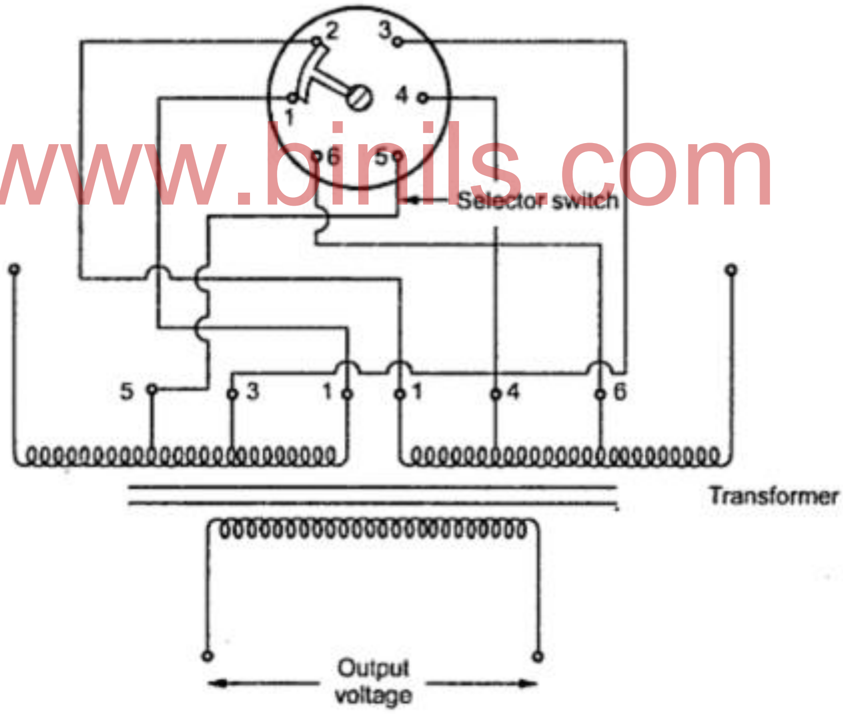


Fig 4.37

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.

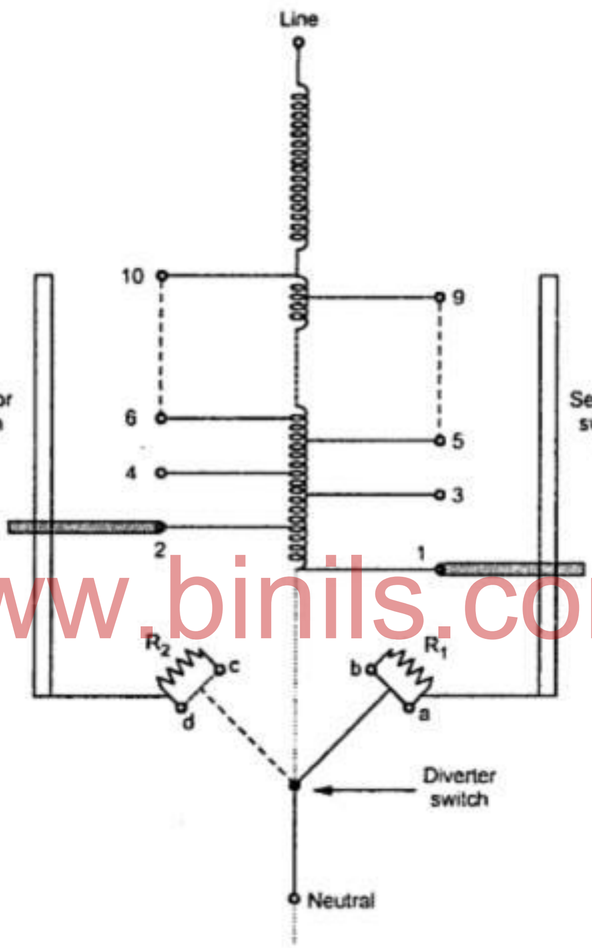


Fig 4.38

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.

4.11 Transformer Oil Tester:

The dielectric breakdown strength of transformer oil is one of the most reliable tests for ascertaining the condition of transformer oil. The BDV test should be conducted when the sample is cold and not hot oil gives a higher BDV, thus misleading the investigation.

In the testing equipment there is a test cub. This has two electrodes in the form of spheres (13 mm diameter). The sphere gap should be exactly 4mm. by the side of the test cup screws have been provided and we can adjust the gap suitably by using the screws. Also there is a step up transformer. The test electrodes are connected across the secondary terminals as shown in fig.4.39

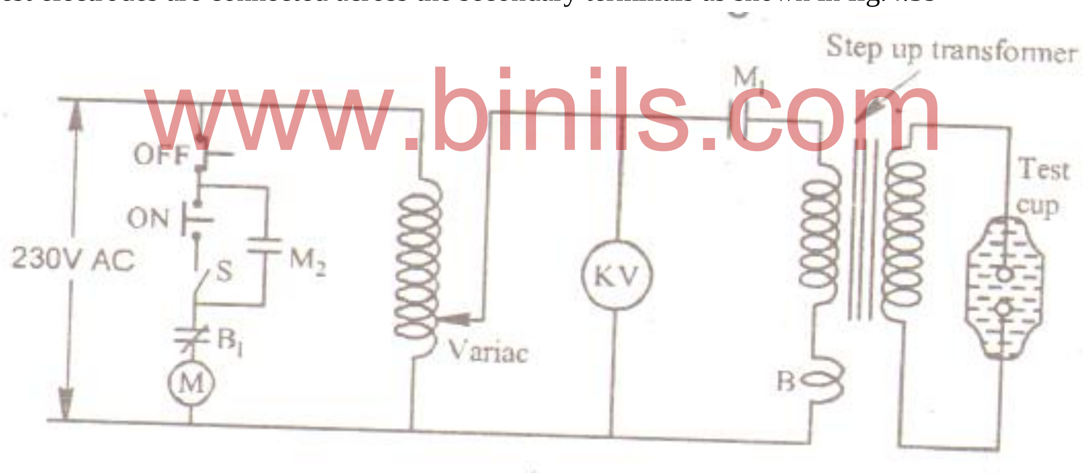


Fig.4.39 Transformer oil tester

The primary winding of the transformer is supplied through a variac. By operating this variac we can gradually increase the test voltage as required.

It has been so arranged that the contact "s" will be closed only when the variac output is zero volts.

The test cup is filled with sample of oil. The level of the oil should be at least 1 cm above the level of the electrodes. The cup is then covered with a clean glass plate and allowed to rest for 5 minutes. So that any air bubble that may be present will disappear.

When the ON button is momentarily pressed, the coil "M" is energized. Main contact M_1 closes connecting the output of the variac to the primary winding of the step up transformer. The contact S is in closed condition as the variac is in minimum output position.

The sealing contact M_2 closes. Now the no load current has no effect on the coil B to open the normally closed contact B. the test voltage is increased uniformly at a rate of 1 KV per second of the specified value.

The voltmeter connected is calibrated to show the HV side voltage. A good sample of oil withstands 22 KV for one minute. So the variac is again adjusted so that the voltage increases from 22 to 33 KV at the same uniform before.

When breakdown occurs in the oil across the electrodes there is a corresponding surge in the primary winding and the coil B and then B_1 immediately opens.

Now the coil M is de energized and the contact M_1 opens disconnecting the primary from output of the variac. The breakdown voltage is that voltage is that voltage at which sustained arcing takes place.

The reading of the voltmeter should be noted at the time to breakdown.

Acidity of Transformer Oil:

Acidity in transformer oil is objectionable as it leads to corrosion on the metal parts of the transformer immersed in the oil. Oxygen may be present inside the transformer due to air remaining in oil, air pockets trapped in the windings etc.

The oxygen reacts with the transformer oil and oxidizes it. Such oxidation produces organic acids and sludge. Metals particularly copper encourage the oxidation of oil without undergoing any chemical change in itself. The operating temperature of the transformer rises due to this chemical reaction.

Therefore, the transformer oil should be checked for acidity once in a year in the case of power transformer and once in two years in the case of distribution transformer. The prescribed limits for acidity are as follows.

1. When the acidity is less than 0.2mg\ KOH\g, the oil is in good condition (neutralization N_0 = 0.2)

2. If the index is between 0.2 and 0.5 no action need be taken if the oil is satisfactory in all the other aspects.

3. If the index is between 0.5 and 1 the oil should be kept under observation and filtered if necessary.

4. When the index exceeds 1, the oil should be removed and purified.

4.12 Acidity Test:

The acidity index is determined by using the portable acidity testing kit. The kit contains the following.

a. Two polythene bottles containing 100ml each of ethyl alcohol and sodium Carbonate solution

b. An indicator bottle containing universal indicator as supplied by the BDH division of Glaxo laboratories

c. Four clean glass test tubes.

d. Three graduated droppers (1.1ml-one, 1ml-two)

e. Colour chart calibrated with neutralization number.

Testing procedure:

1.1ml of the transformer oil to be tested is accurately pipette into a clean and dry test tube.1ml of **ethyl alcohol** is added with this and the mixture is gently shaken. After an interval of about one minute 1ml of **sodium carbonate solution** is added.

After shaking the test tube again, five drops of the universal indicator are added. The resulting mixture develops a colour. From this colour the acidity can be determined by comparing with the standard chart supplied with the kit as given below.

Colour observed	Neutralization number(Mgm/KOH/gm)
Orange	1.0
Yellowish orange	0.8
Yellow	0.6
Greenish yellow	0.4
Olive green	0.3
Parrot green	0.2
Ultramarine	0.1
Prussian blue	0.05
Indigo	0.00

4.13 Earthing

Earthing means direct electrical connection of all metallic non-current carrying parts of electrical equipment, such as metal frame, motor body etc. to earth. Earthing classified as

1. System earthing
2. Equipment earthing

Earthing of neutral in power houses and substations belongs of the first category. The purpose of system earthing is to protect the eqipments in the system from lightning, earth fault etc. earthing of non-current carrying metal parts of electrical equipment is known as equipment earthing (ex . transformer tank, motor frame). Equipment earthing ensures safety.

If there is accidental contact between a live conductor and the frame due to failure of insulation between them, no fault current will flow if the frame is not earthed the equipment will continue to function normally.

If somebody touches the frame of the equipment with barefoot they will get shock. But if the frame of the equipment is earthed, the voltage of that parts with respect to earth does not rise to dangerously higher value.

Thus severe shock is prevented. Earth fault can operate fuse or circuit breaker because of sufficient earth fault current. a thick strip of copper should connect the frame to the ground and the earth electrode should offer minimum resistance to current flow.

4.14.1 Methods of Earthing

1. Direct earthing system

In this system, the parts of an installation to be earthed are connected directly to the ground. Thus the system neutral can be grounded effectively or non-effectively. In effectively grounded system, the neutral is grounded directly and hence it is called solid grounding.

2. Multiple earthed neutral system

In this system the parts of an installation to be earthed are connected to ground as in direct earthing system. But these parts are also connected to an neutral conductor of the supply system.

3. Earth leakage circuit breaker system

In this system, the parts of an installation which are to be protected are connected to an earth electrode through the coil of an earth leakage circuit breaker. It protects the installation by disconnecting the faulty circuit.

4.15 Measurement of Earth Resistance:

Earth resistance can be measured directly by earth resistance tester. it essentially consists of a hand driven DC generator, rectifier, metering system etc.

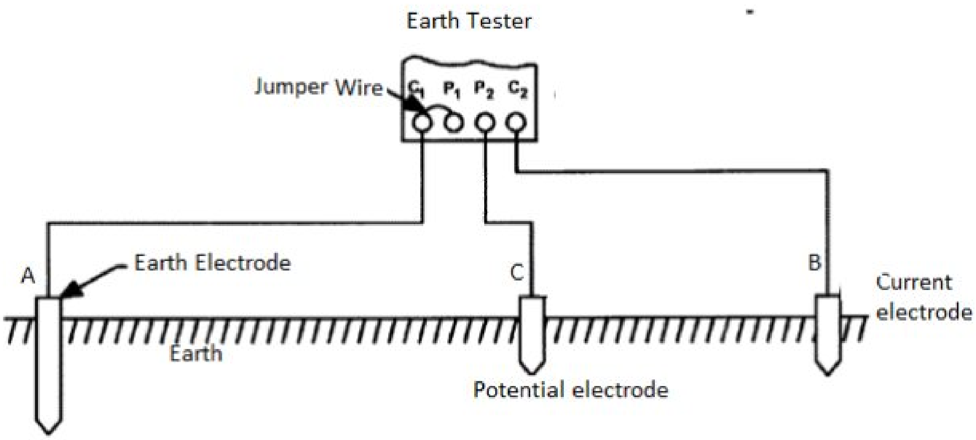


Fig 4.40

The DC voltage generated is converted in to AC and then applied to earth in order to avoid electrolytic action. The current coil is energised by the earth current. The pressure coil gets the voltage drop caused by the earth current its energisation. These two coils are forming an ohm meter.

The earth tester also works nearly on the same principle of a megger. The earth resistance of the electrode A in Fig can be measured directly with the help of an earth tester

C and B are two auxiliary electrodes of 15-20 mm diameter and 40 cm long bars. The electrode B is planted at a distance of approximately 25 M from A and C is fixed centrally between A&B. Rotate the handle of the generator at normal speed and note the meter reading.

Two more readings are taken by shifting C at a distance of 3 meters on either side of its central position. The instrument should indicate nearly constant readings in the three position. If it does not B should be moved away from A by approximately 6 meters and the experiment must be repeated till constant readings are obtained. This value is the resistance of the electrode A to earth.

PART-A

1. What are the four main connections of 3-phase transformer?
2. Write any one advantage of using 3 phase transformer.
3. How a 3 phase transformer can be constructed?
4. Draw the star-star connection of 3 phase transformer.
5. Draw the star-delta connection of 3 phase transformer.
6. Draw the delta-delta connection of 3 phase transformer.
7. Draw the delta-star connection of 3 phase transformer.
8. Expand ONAN in cooling of transformer.
9. Expand ONAF in cooling of transformer.
10. Expand OFAF in cooling of transformer.
11. Expand OFWF in cooling of transformer.
12. Mention any two methods of cooling a transformer.
13. Mention any two protective devices in an power transformer.
14. Which material is used in breather?
15. What is the color of silica gel under dry condition?
16. What is the color of silica gel under wet condition?
17. What is the working principle of Buchholz relay?
18. Mention the two methods of tap changing in a transformer?
19. What type of tap changing method is used in distribution transformer?
20. What is mean by earthing?
21. What are the methods of earthing?
22. What is the purpose of earthing?

PART-B

1. What are the advantages of 3-phase transformer?
2. Draw the diagram of V-V connection of 3-phase transformer.
3. Draw the diagram of Scott connection of 3-phase transformer.
4. Name the four protective devices in a transformer
5. Explain the purpose of the explosion vent fitted to the transformer tank.
6. What is the need for tap changing in transformers? What are the types of tap changing?
7. Explain why the transformer is rated in KVA?
8. Write short notes about Breather.
9. Write short notes about Conservator Tank.

PART-C

1. Explain in detail three phase transformer groups with neat diagrams.
2. Explain Star-star connection of three phase transformer with neat diagrams and write the advantage and disadvantages.
3. Explain Star-Delta connection of three phase transformer with neat diagrams and write the advantage and disadvantages.
4. Explain Delta-star connection of three phase transformer with neat diagrams and write the advantage and disadvantages.
5. Explain Delta-Delta connection of three phase transformer with neat diagrams and write the advantage and disadvantages
6. Explain in detail Scott (T-T) connection of three phase transformer with neat diagrams.
7. Explain in detail open delta (V-V) connection of three phase transformer with neat diagrams
8. Explain the methods of cooling of large power transformers
9. Draw and explain the function of Buchholz relay.
10. Explain in detail about load sharing of transformer with equal voltage rating.
11. Explain in detail about load sharing of transformer with unequal voltage rating.
12. Explain in detail Transformer Oil Tester.
13. Explain ON-LOAD tap changer with neat sketch.
14. Explain OFF-LOAD tap changer with neat sketch.
15. Explain about Acidity test.
16. Explain the measurement of earth resistance.

UNIT V- STORAGE BATTERIES

Introduction

Alessandro Giuseppe Antonio Anastasio Volta (Italian pronounced as Alessandro vɔlta) was an Italian physicist, chemist, and a pioneer of electricity and power who is credited as the inventor of the electrical battery and the discoverer of methane. He invented the Voltaic pile in 1799. The **voltaic pile** was the first electrical battery that could continuously provide an electric current to a circuit. With this invention Volta proved that electricity could be generated chemically by the principle that an emf can exist between two plates of different metals immersed in an electrolyte. He made a simple cell, named after him, the **Voltaic Cell**. It consisted of a glass jar containing dillute H_2So_4 with copper and zinc plates immersed in it. An e.m.f. of 0.8V was developed across the two plates with copper plate as positive electrode. The voltaic pile then enabled a rapid series of discoveries including the electrical decomposition (electrolysis) of water into oxygen and hydrogen by William Nicholson and Anthony Carlisle (1800) and the isolation of the chemical elements sodium , potassium , calcium , boron , barium and magnesium by Humphry Davy.

5.1 Classification of Cells

1. Primary Cell
2. Secondary Cell or Accumulator
   a) Lead – acid Cell
   b) Nickel – Cadmium and Nickel – Iron Cells

5.1.1 Primary Cell

Primary cells can only transform chemical energy into electrical energy and the cell can be re-activated only by renewal of the active materials. Leclanche cell, Voltaic cell, Mercury cell and the well known dry cell, all come under the primary cell group. They suffer from the drawbacks of small capacity and short life. Moreover, the chemical action is not reversible and when one cell loses its action it has to be discarded (particularly the handy dry cell of the modern day).

5.1.2 Secondary Cell

In a secondary cell or accumulator, the electrode materials can be re-activated i.e., the chemical action can be reversed. This means the chemical action is converted into electrical energy when the cell is discharging. The electrical energy is converted into a chemical change or action when the cell is being charged.

Secondary cells may be divided into two types: (a) the lead-acid cell in which lead plates covered with compounds of lead are immersed in dilute sulphuric acid, (b) the nickel cadmium and the nickel-iron cells. The above cells will be seen in greater detail.

5.2 Lead Acid Cell Construction

This type is very familiar to everyone. Since the positive and negative plates are both made of lead (alloy) and the electrolyte is dilute H2So4, it is known as lead-acid cell. The chemical substances that combine to store electrical energy are called active materials. Lead peroxide (Pbo_2) a brown chocolate colour, fairly hard but brittle substance is the active material in the positive plate. With full charge, the negative plate is just lead but it is spongy and porous in nature. The dilute H_2So_4 is made up of 3 parts of water to one part of acid. Under fully charged condition the specific gravity of the electrolyte is about 1.21.

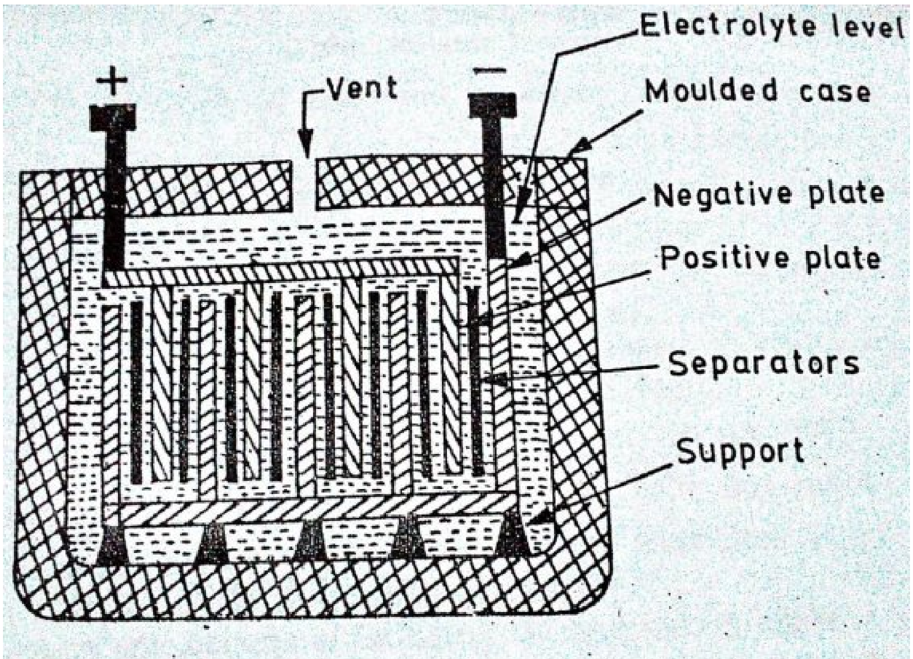


Fig. 2.1 Lead acid battery

The capacity of a cell depends on the amount of active material in the plate. The plate area is increased by arranging a number of a plates in parallel. The positive and negative plates are kept interleaved inside the container. Separators are there in between every positive and negative plate to prevent accident short circuit. Treated wood or perforated hard rubber can be used as separators. A simple sketch of a battery (assembly of cells) is shown in fig. 2.1.

The plates of a lead acid battery are prepared in two methods namely Plante process and Faure process.

(a) Plante Plates:

Plates are obtained by charging and discharging a number of times; the forming process being accelerated by the use of suitable chemicals. The effective plates area is increased by arranging in the plate large number of thin vertical laminations strengthened at intervals by horizontal binding ribs. See fig.2.2.

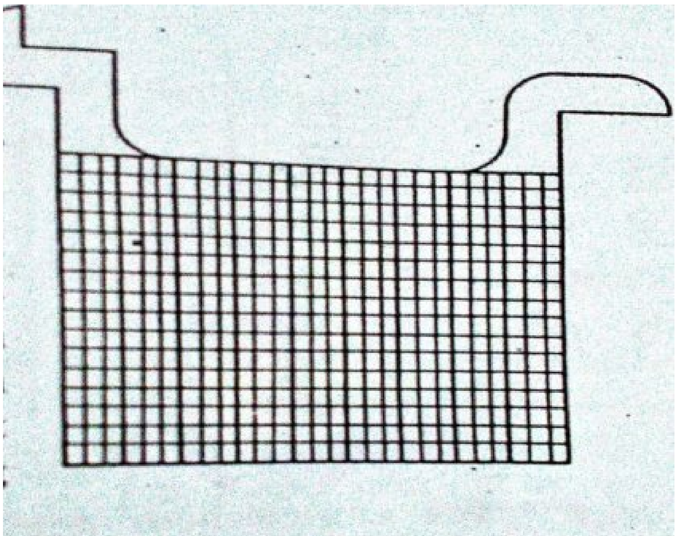


Fig. 2.2. Plante Plate

In another method, spirals of corrugated lead ribbons are inserted into a large number of circular holes in a frame work of lead antimony alloy. See fig. 2.3.

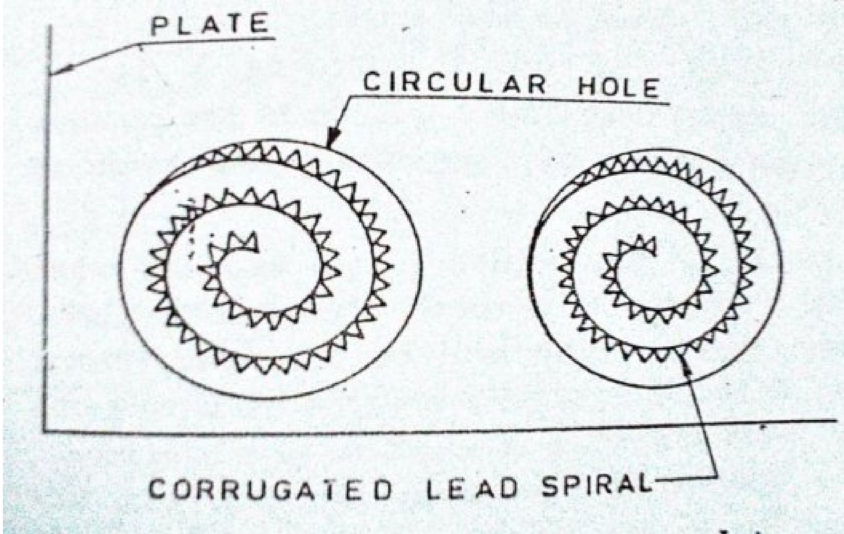


Fig. 2.3. Improved plante plate

(b) Faure Plates:

The plates made in this process are also known as pasted plates. The plates are made of lead-antimony grids into which the active material is pressed as a paste. For positive plates the paste is obtained by mixing red lead ($PbSO_4$) and sulphuric acid. After forming the positive and negative plates with pasting process the plates are immersed in dilute H_2So_4 and given one charged to get perfect set of plates. See fig. 2.4.

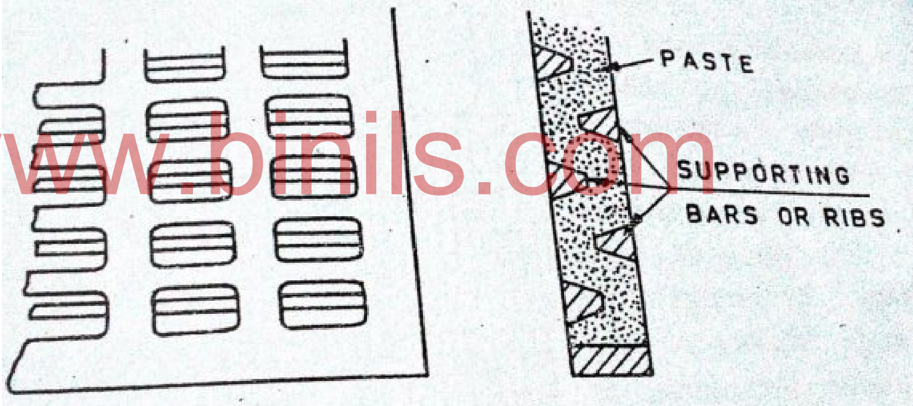


Fig. 2.4. Pasted plate

For a given ampere-hour capacity, the pasted plates are very light in weight(about 1/3 of formed plates) and hence they of cheaper in cost. However they active materials from pasted plates may peel-off and fall(shedding) due to mechanical vibrations. So the best choice will be to use positive plates made by forming process and negative plates made of pasted (Faure) process.

The active material on the positive plates expands when subjected to chemical changes. As a result, the positive plates will bend or buckle. This buckling will be less with formed plates. The tendency to buckle is usually reduced by having odd number of negative plates and even number of positive plates; one plate less than negative as shown in fig. 2.5. In this arrangement, both sides of all positive plates are actively engaged in chemical action and hence less chances for buckling.

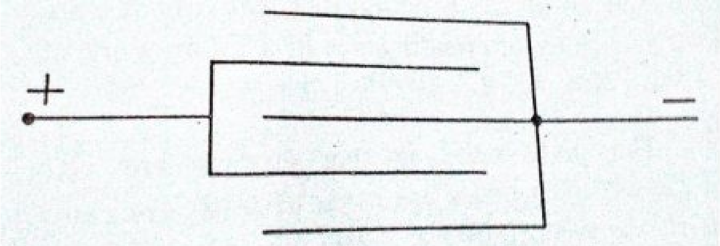


Fig. 2.5. Plate arrangement

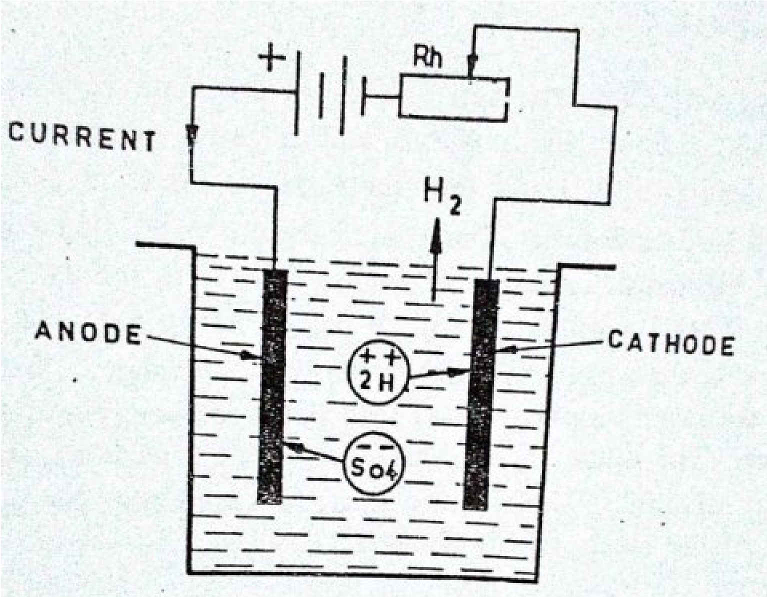


Fig. 2.6. Chemical action while charging.

The assembly of plates is immersed in dilute H_2So_4 in glass or vulcanized hard rubber containers. Holes are provided for each cell in the battery for allowing gases formed during chemical action escape. The plate assembly rests on insulated support blocks.

5.3.1 Chemical Action in Lead-Acid Cell:

When two lead plates are just immersed in dilute sulphuric acid nothing happens except that the H_2So_4 brakes into H_2++ molecules having 2 unit of positive charge and SO_4— molecules having 2 unit of negative charge. These molecules with electric charges wander freely.

5.3.1.1 Charging:

When a charging dc potential is applied, the positive electrode (anode) attracts the negative sulphate ions. The negative sulphate ions move up anode, give up there electrons react with water to form sulphuric acid and nascent oxygen as indicated by the equation -

$$SO_4^{--} + H_2O \longrightarrow H_2SO_4 + O$$

The nascent oxygen then attacks the lead anode to give lead peroxide.

$$2O + Pb \longrightarrow PbO_2$$

Thus the anode is changed to lead peroxide.

The positive hydrogen ions move to cathode, give up there positive charge, react with sulphate ions to from H2So4 and leave the cathode as spongy lead.

$$H_2 + PbSO_4 \rightarrow Pb + H_2SO_4$$

Thus, after charge, the specific gravity has gone up due to production of H_2SO_4. The positive plate is PbO_2 and negative plate is Pb.

5.3.1.2 Discharge:

During discharge, the positive hydrogen ions travel towards the positive electrode PbO2 and after their charges have been fully neutralized by the absorption of electrons from this electrode, the hydrogen atoms combine with lead peroxide and sulphuric acid to form lead sulphate and water.

$$H_2 + PbO_2 + H_2SO_4 \longrightarrow PbSO_4 + H_2O$$

The negative SO_4—ions travel towards the negative electrode (Pb) and after giving up their surplus electrons they combine with lead to form lead sulphate.

$$Pb + SO_4 \rightarrow PbSO_4$$

Since water is formed during discharge, the sp. Gravity of the electrolyte decreases. The charging and discharging of the cell can be represented by a single reversible equation given below.

Pos plate	neg plate		positive plate	negative plate
		charge →		
$PbO_2 + 2H_2SO_4 + Pb$		← discharge	$PbSO_4 + 2H_2O + PbSO_4$	

The actions during charge and discharge are summarized as follows:

5.3.2 Physical Changes While Charging:

1. The anode becomes chocolate brown in colour (PbO_2), and cathode becomes grey.
2. Sp.gravity of electrolyte is increased.
3. Potential difference across plate increases.
4. Energy is absorbed in the cell.

5.3.3 Physical Changes While Discharging:

1. Both anode and cathode become $PbSO_4$ which is slightly white in colour.
2. Due to formation of water the Specific gravity is lowered.
3. Voltage of the cell drops.
4. The cell gives out energy.

5.4.1 Internal resistance of a Battery

The internal resistance of a battery is defined as the opposition to the flow of current within the battery. Due to internal resistance some voltage will be dropped inside the battery. Hence the internal resistance of the cell must be kept minimum. to reduce the internal resistance, the size of the plates may be increased. If the plates size increased, the cell will become too big to handle. Hence in practice multiply the number of plates inside the cell. All the positive plates are joined together and all the negative plates are joined together.

5.4.2 specific gravity of lead acid

The specific gravity of electrolyte is measured with the help of hydrometer. During charging, water is absorbed hence the specific gravity of electrolyte increases. During discharging water is formed hence the specific gravity of electrolyte reduces. The specific gravity of electrolyte for a fully charged lead acid cell is about 1.21 and the specific gravity of fully discharged cell is about 1.18

5.5.1 Nickel Iron Cell:

It is one of the few types of accumulators using an alkali as the electrolyte; hence the name alkali cell. Like lead acid cell there is one set of positive plates. The positive plates are made up nickel hydroxide enclosed in finely perforated steel tubes or pockets. The electrical conductivity of these plates are raised by adding flakes of pure nickel or graphite. These tubes or pockets are assembled in nickel coated steel plates.

The negative plates are made up of iron oxide with a little mercuric oxide to increase electrical conductivity. The mixture is enclosed in perforated steel pockets also assemble in nickel plated steel plates. The electrolyte is a 20% solution of potassium hydroxide (KOH) also called caustic potash specific gravity 1.15 to 1.2. A small quantity(1%) of lithium hydroxide is also added to increase the cell capacity. The electrolyte does not undergo any chemical reaction and hence the spare quantity required is less. The positive and negative plates are separated by ebonite rods to prevent short circuit. Each cell is placed in a sheet-steel container and several such cells are arranged in a non-metallic(hard-rubber) rectangular box to form a battery.

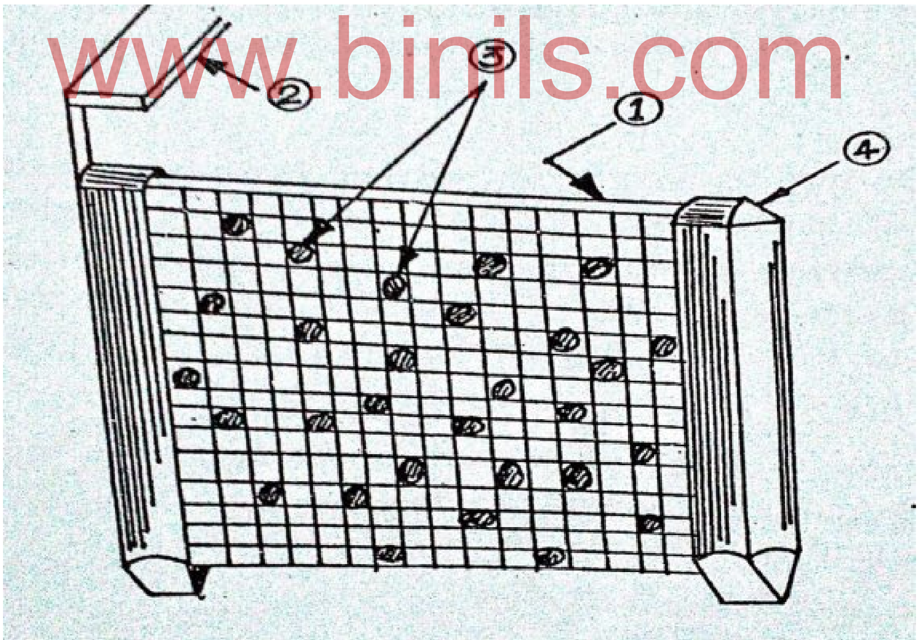


Fig. 2.8 A positive plate (Ni-Fe cell)

1. Plate
2. Plate connecting strap
3. Pockets
4. Plate support

5.5.1.1. CHEMICAL REACTION:

With full charge, the active material on the positive plates appeared to be a hydroxide of nickel having the formula Ni(OH)3. The active material on negative plate is just iron. During discharge, the positive plate active material on negative is converted into the lower hydroxide

Ni(OH)2 and the iron is converted into iron hydroxide. A single reversible chemical equation can be written thus :

Positive plate   negative plate   positive plate   negative plate

$$2Ni[OH]_3 + KOH + Fe \underset{discharge}{\overset{Charge}{\rightleftharpoons}} 2Ni[OH]_2 + KOH + Fe[OH]_2$$

Sometimes the active material may be taken as $Ni[OH]_4$ and the equation written as

Positive Plate   negative plate   positive plate   negative plate

$$Ni[OH]_4 + KOH + Fe \underset{discharge}{\overset{charge}{\rightleftharpoons}} 2Ni[OH]_2 + KOH + Fe[OH]_2$$

5.5.2 Nickel-Cadmium Cell:

This cell is very similar to nickel iron cell except that cadmium is substituted in place of iron in negative plates. A little iron is mixed to cadmium to prevent the active material from caking and losing its porosity. The electrolyte is potassium hydroxide [KOH]. The reversible chemical reaction during discharge and charge are written below:

Positive plate   negative plate   positive plate   negative plate

$$2Ni[OH]_3 + KOH + Cd \underset{discharge}{\overset{charge}{\rightleftharpoons}} 2Ni[OH]_2 + KOH + Cd[OH]_2$$

The above reactions are exactly similar to those of nickel iron cell except that cadmium finds place instead of iron. The discharge and charge characteristics are the same for both nickel-iron and nickel-cadmium cells.

Characteristics of Nickel-Iron and Nickel Cadmium Cells:

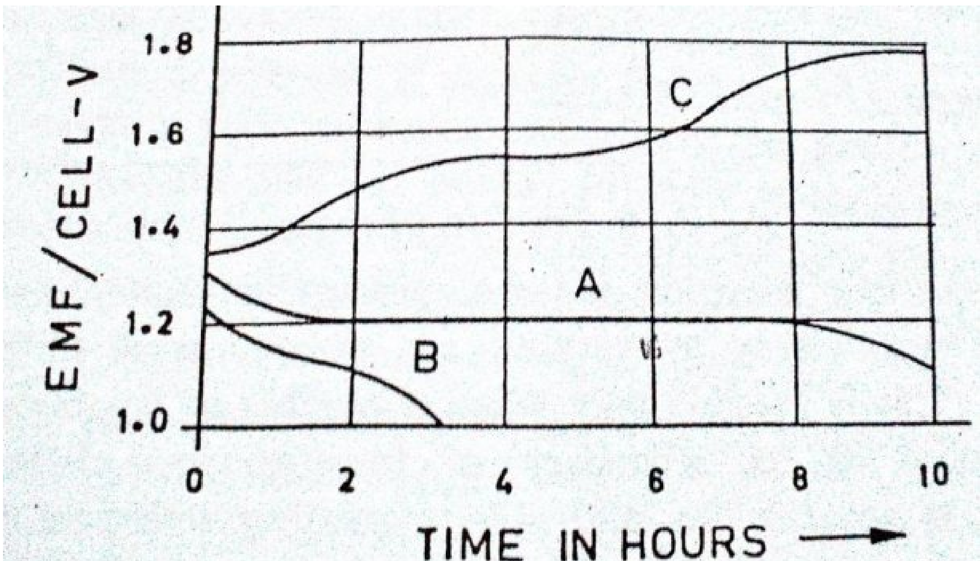


Fig.2.9 Characteristics of Alkaline Cell

Curve A represents the terminal voltage of an alkaline cell for a 10-hour discharge rate. Curve B shows the p.d. variation for a 3-hour discharge rate. Since no change takes place in respect of the electrolyte, the number of ampere hours obtainable from an alkaline battery is less affected by the discharge rate. Curve 'C' shows the rise of terminal voltage when cell is charged at the rate of 1.5 times the 10 hour discharge .

Advantages of alkaline cells:

1) Alkaline cells have plates of high mechanical strength and hence cells can withstand considerable vibrations.
2) They are free from sulphating and hence can be left in any state of charge without damage for several days.
3) They can withstand high charge currents.
4) They are not affected by corrosive liquids and fumes.

Disadvantages:

1) Internal resistance per cell is high and hence the charging voltage is much higher than the terminal voltage.
2) The e.m.f. per cell is nearly 1.4V when fully charged and decreases rapidly to 1.3V and then very slowly to 1.1 or 1.0V on discharge. The discharge voltage per cell is much smaller compared to 2V of lead-acid cells. Hence more number of cells are obtain a required battery voltage.
3) The cost is higher compared to lead-acid cell.

Uses:

Nickel iron and nickel cadmium cells are ideally suited for traction work such a driving of electric factory trucks, mine locomotives and miners lamps. In view of several specific advantages listed before, Ni-fe cells are used for train lighting schemes.

5.6.1 Indication of a fully charged lead – acid cell:

A battery can be checked for full charge from the following indications:

a) Gassing: When a cell is fully charged, gas is freely liberated from both plates. Cathode liberates hydrogen and anode liberates oxygen. The electrolyte shows a slight milky appearance.
b) Voltage: The terminal voltage of a fully charged lead – acid cell is around 2.1V which remains steady and shows no sign of variation once fully charge is given.
c) Specific gravity of the electrolyte: The specific gravity of the electrolyte is measured with a hydrometer. The value is about 1.21 when fully charged.
d) Colour of plates: On full charge the +ve plates are in dark brown chocolate colour and –ve plates appear in slate grey colour. However, the observation for colour cannot be had when the battery container is hard or any other non-transparent material.

5.6.2 Indication of a fully discharged lead – acid cell:

1. when the cell is fully discharged, both the plates becomes lead sulphate ($Pb\,SO_4$) which is whitish incolour.

2. During discharging, due to formation of water, specific gravity of the electrolyte decreases.

3. The voltage of the cell is decreased.

5.7 Defects and remedies:

The common troubles with a lead-acid battery and the remedial measures are summed up as follows:

(i) **Sulphation:** White hard crystals of lead sulphate form over both plates in an under charged cell and also in a cell lying idle for several days. When sulphation is present, the ampere – hour capacity is reduced.

The sulphation, if slight can be removed by charging and discharging at 1/3rd the normal rate and repeating the process. If the sulphation is hard the remedy is to empty the tank completely, fill it with distilled water, charge at normal rate till the specific gravity is measured to be 1.21. Such process is repeated till all the sulphate is removed.

(ii) **Buckling of plates:** Buckling refers to vertical bending of plates in the cell. This occurs when the cell is discharged or charged at very high current than normal rate. Due to severe chemical reaction, non-uniform heating of plates occurs and as a result the plates bend or buckle. Buckling may cause internal short circuit and shedding of active material (lead peroxide).

The defect is overcome by straightening the buckled plates after taking out the plates from the assembly. The grid surfaces should be refilled with new paste of the active material.

(iii) **Shedding:** Falling of active material due to violent vibration or due to buckling of plates is called shedding. The accumulation of fallen material may cause short circuiting of plates.

The fallen material is removed after emptying the container. After washing with clean water, the container is filled with fresh electrolyte and the pasted plate assembly is reintroduced into the electrolyte.

5.8 Capacity:

The capacity of a battery is the amount of electricity (electric charges) which can be obtained from it. It is expressed in ampere-powers (Ah). The ampere-hour capacity is found by multiplying the value of the constant current taken from the battery by the number of hours it will supply this current before its voltage drop to 1.8 V per cell. The voltage of a fully charged cell is 2V.

The normal capacity of lead cell is taken as number of ampere hours it can give on a 10 hours discharge at constant current before its p.d. falls to about 1.8 V.

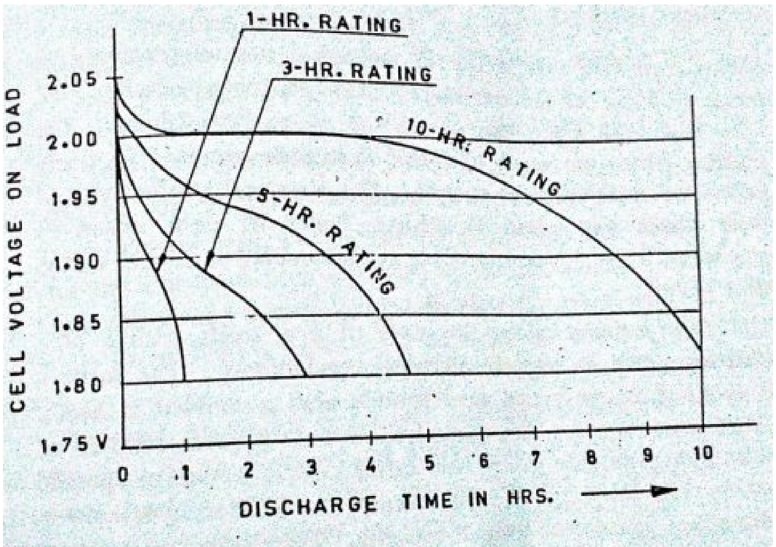


Fig. 2.7. Discharge Characteristics.

When a cells is discharged with large current, it can supply only for a short duration. Therefore the product amp.× hours (Ah) will be less for quick discharge.

5.8.1 Ampere-Hour Efficiency:

For a battery, the ampere hour efficiency is the ratio of ampere hours obtainable during discharge to the ampere hour required to restore the battery to original condition. Mathematically discharge Ah=output amps × time of discharge; charge Ah=charging current × time of charge

$$\text{Ah - efficiency} = \frac{\text{discharge current} \times \text{discharge hours}}{\text{charging current} \times \text{charging hours}}$$

For a lead acid battery, Ah efficiency is around 90%

5.8.2 Watt-Hour Efficiency:

It is the ratio of watt-hours of energy delivered by battery to the watt-hour supplied by source during charging, i.e., w.h. efficiency

$$= \frac{\text{Discharge(current} \times \text{time} \times \text{voltage)}}{\text{Charge(current} \times \text{time} \times \text{volts)}}$$

Since Ah efficiency does not take into account the varying voltage of charge and discharge, the Ah efficiency is higher than watt-hour efficiency.

5.9 Charging Methods:

In certain installations batteries are kept 'floating' on the line and are allowed to get charged when the system load is light. When the system fails or when the system supply is insufficient to meet the connected load the batteries discharge and keep up the supply to load. For other types of services batteries may be removed for charging in any one of the methods described below.

The charging methods are –

1. The constant current system

2. The constant-voltage system

5.9.1 Constant- Current System:

In this method, the charging current is kept constant by varying the supply voltage to overcome the increased back e.m.f. of the cells. In olden days motor-generator sets were employed for charging the cells. In that case the current was kept constant by adjusting generator excitation. Today metal rectifiers are used in bridge configuration with suitable filter circuits to obtain ripple-free d.c. voltage. with such d.c. supplies, the constant current can be obtained by suitably varying the series rheostat. The charging current is usually kept low to ensure that there is no excess gassing during final stages of charging and also that the cell temperature does not exceed 45*C . This method takes longer charging time.

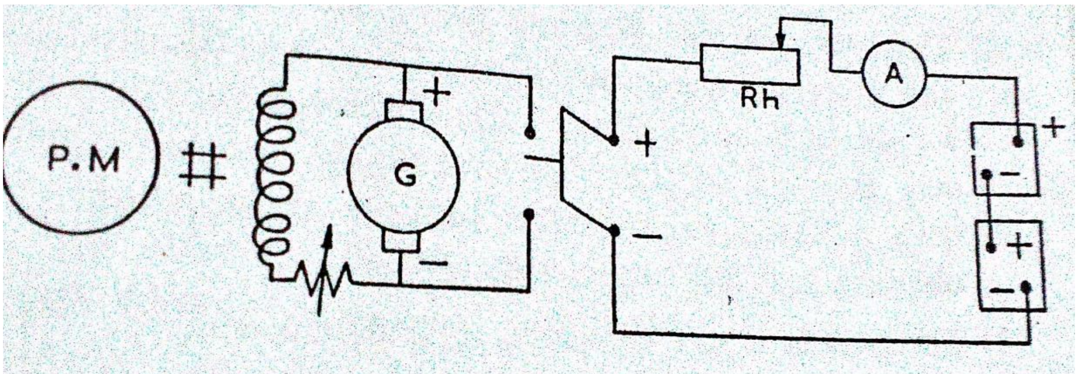


Fig. 2.10 Constant current charing

5.9.2 Constant - Voltage System:

In this method, the source voltage is not adjusted. This is the most common method of charging employed in battery charging shops. The batteries are connected in parallel to the d.c. source and the charging voltage is maintained constant. The charging current is high in the beginning when the battery is discharged condition and it gradually decreases as battery picks up charge. This is a relatively quick method of charging. However, as the initial charging current is high the life of the battery is reduced.

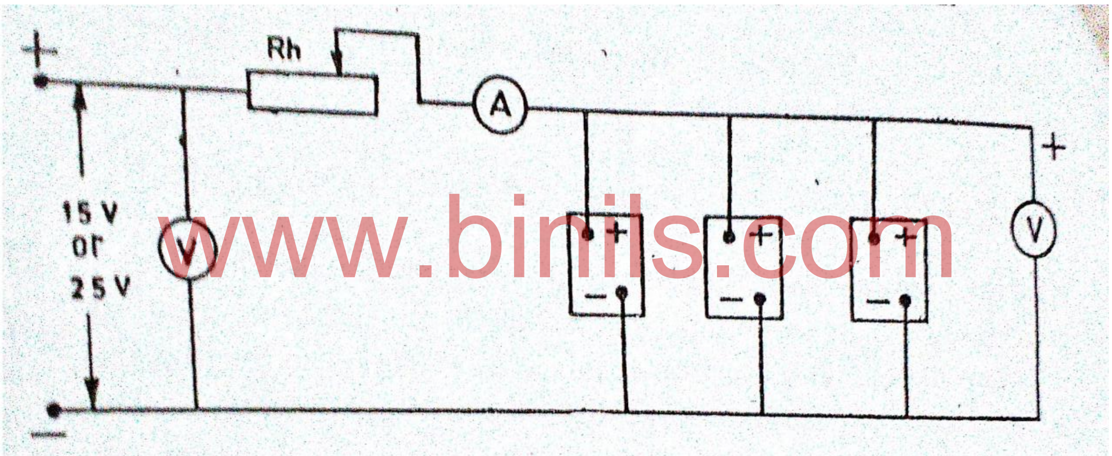


Fig. 2.11 Constant voltage charging

5.9.3 Trickle Charging:

A charging cell may lose its charge slightly when kept idle for a brief period or when kept in floating conditions. A low current charge is given to such cells occasionally to compensate for the slight loss of charge. This charging action is called trickle charging. Any conventional charging circuit can be used for trickle charging. A simple trickle charge circuit is given in fig. 2.12

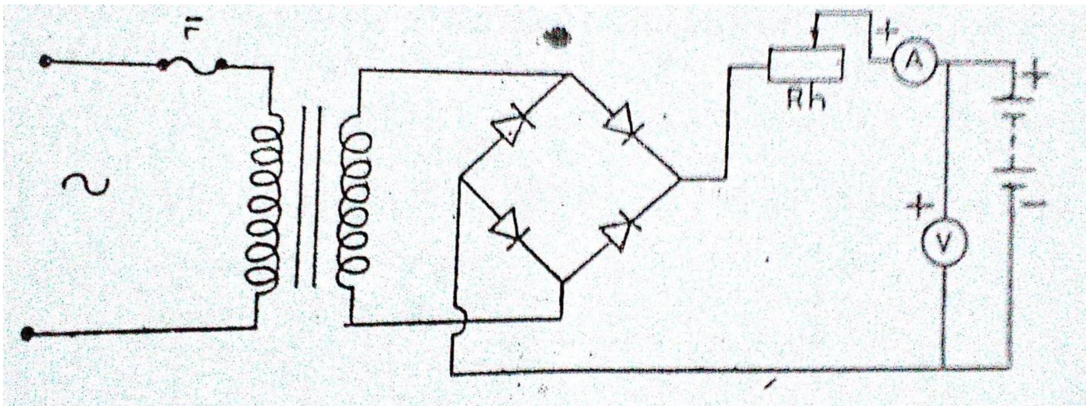


Fig.2.12 Trickle charge

Sometimes provision for d.c. regulation may be available continuously by varying a.c. voltage input to bridge rectifier. This is possible only when a number of tapping points are provided on the secondary of transformers. When tap changing is adopted, the d.c. side regulating resistance is not necessary.

5.10 Care and maintenance of lead - acid battery:

From the charging and discharging equations we had seen that both the plates become lead sulphate under discharged state. When the discharged battery is recharged insufficiently, not all lead sulphate is converted to lead peroxide and lead. When some sulphate is left out, it sticks to the plates in a crystalline form. It has a high resistance and reduces the porosity of the plates. Hence, the acid has greater difficulty in penetrating into the active material, when the cell is charged next time. The main problem in maintaining a lead-acid battery is overcoming this sulphation.

The major precautions to be taken in the maintenance of a lead-acid battery are listed below:

1. The cells should be recharged as soon as possible after discharge. Sulphation will occur readily in a discharged battery.
2. The charging and discharging rates specified by the manufacturer shall not be exceeded.
3. The p.d. of each cell and specific gravity of electrolyte shall be recorded and watched for abnormality.
4. The level of the electrolyte must be kept above the top of the plates and the loss of water by evaporation and decomposition during gassing should be made up by the addition of distilled water. The adding of distilled water may be done while the cells are gassing so that it will mix thoroughly with electrolyte.
5. The cells should be given a periodic overcharge at about half the normal rate and prolonged until the cells are gassing freely and until the half-hourly reading of the voltage do not show any further increase. This condition ensures the complete removal of any white sulphate and restores the whole of the active material to its normal conditions.
6. If a battery is in a relatively light duty, it is advisable to discharge it occasionally through an artificial load at its normal rate and then immediately recharge it.
7. If the battery is used as a standby source to give emergency lighting etc., it should be connected across a d.c. supply so as to receive a continuous trickle charge (making up the loss due to idle conditions).
8. The temperature of the cells should not exceed 45°C, otherwise the plates may get damaged quickly.

5.11 Applications:

The **applications** of nickel-iron cells were given already. They are exclusively used where mechanical vibrations are severe. In all other places lead-acid batteries are very popular on account of their higher voltage per cell and cheapness in cost. The applications of lead-acid batteries are given:

1. In automobiles for supplying lighting loads and to start the engine.
2. In power stations an array of batteries supply a d.c. 110V for operating relays in emergencies.
3. In mines they provide electrical source for lighting.
4. In engine driven alternator sets batteries provide d.c. source for excitation.
5. As a source of d.c. power for electroplating, batteries are very popular.
6. As source of lighting power in portable lamps and as a power source in portable public address (mic. Set) systems.

Example 2.1:

A charged cell was completely discharged in 12 hours, the discharge current being constant at 5A. The average terminal voltage during discharge was 1.95V. A charging current of 4A maintained constant for 18 hours was required to restore the cell to its initial state of charge the average terminal voltage being 2.2V. Calculate (a) the ampere- hour efficiency and (ii) the watt- hour efficiency.

Solution:

a) Output of cell in ampere hours = 5x12 = 60Ah.
   Input to cell, in ampere hours = 4x18 = 72 Ah.
   Ampere hour efficiency = 60/72 =0.833 or 83.33%
b) Output of cell, in watt hours = 1.95x12x5 = 117Wh.
   Input to cell, in watt hours = 2.2x18x4 = 158.4Wh.
   Watt hour efficiency = 117/158.4 = 0.739 or 73.9%

Example 2.2:

A terminal voltage of approximately 120V is to be maintained by a group of alkaline cell in series. The initial and final values of the e.m.f. per cell are 1.3V and 1.15V respectively. The internal resistance per cell is 0.01Ω and the discharge current is 10A. Calculate the initial and final number of cells required in series.

Solution:

Initial terminal voltage/cell = initial e.m.f – voltage drop/cell due to internal Resistance.

= 1.3 – (0.01x10) = 1.2V

Initial number of cells required = 120/1.2 = 100

Final terminal voltage/cell = 1.15 – (0.01x10) = 1.05V

Final number of cells required = 120/1.05 = 114

Example 2.3:

A 6-cell,12V battery is to be charged at a constant rate of 10A from a 24V d.c. supply. If the e.m.f of each cell at the beginning and end of the charge is 1.9V and 2.4V, what should be the value of maximum and minimum resistance connected in series with battery?

Solution :

Total back emf of battery during charging = 6x1.9 = 11.4V

Net driving voltage = charging voltage – back emf

= 24 – 11.4 = 12.6V

Resistance required at beginning of charge = Net Voltage/Charging current

= 12.6/10 = 1.26Ω

At the end of charging, emf per cell raises to 2.4V

Then total back emf of battery = 6X2.4 = 14.4V

Net driving voltage = 24 – 14.4 = 9.6V

Resistance required at end of charging process = 9.6/10 = 0.96 Ω

The scheme of connection is given below.

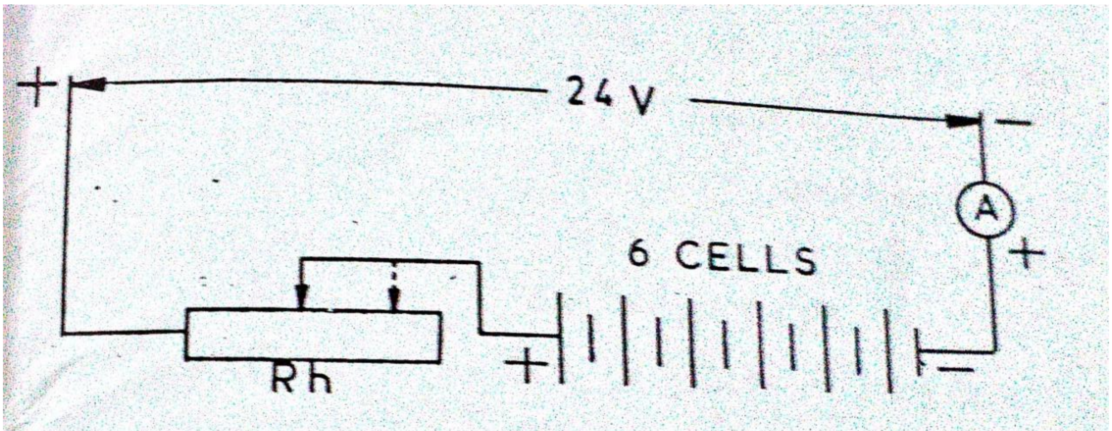


Fig 2.13

Example 2.4:

A battery having an emf of 110V and an internal resistance of 0.2Ω is connected in parallel with another battery with emf of 100V and internal resistance of 0.25 Ω. These two in parallel are placed in series with a regulating resistor of 5Ω and connected across 220V mains. Calculate the magnitude and direction of current in each battery and total current takes from the mains.

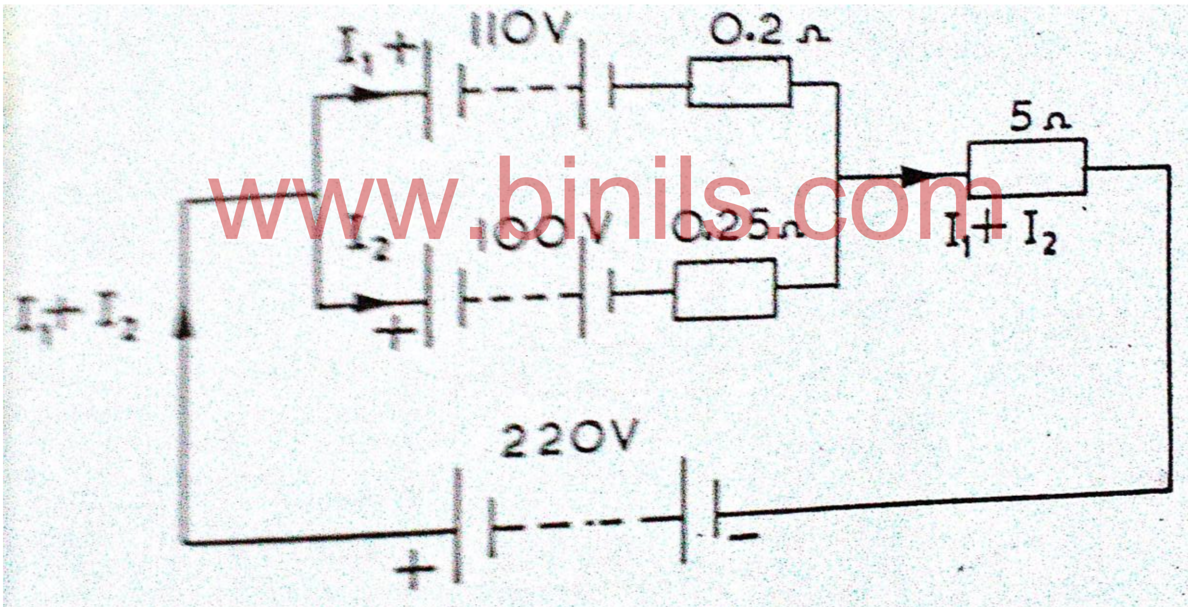


Fig. 2.14

Solution:

Assume , I_1 and I_2 to be the branch currents

Then total mains current = $I_1 + I_2$ as shown.

In top closed loop, going clockwise,

$110 + 0.2I_1 – 0.25I_2 – 100 = 0$

$0.2I_1 – 0.25I_2 = - 10$ ------------- (1)

In bottom closed loop,

$100 + 0.25I_2 + 5(I_1+I_2) – 220 = 0$

$5I_1 – 5.25I_2 = 120$ ----- (2)

Eqn. (1)x25 gives $5I_1 – 6.25I_2 = -250$ -----(3)

(3) – (2) gives $-11.5I_2 = - 370$

$I_2 = 370/11.5 = 32.2A$

Substituting in eqn. (2),

$$5I_1 + 5.25(32.2) = 120$$

$$5I_1 = 120 – 169.1$$

$$I_1 = - 9.82A$$

Initially we had assumed that current in the 110V battery to be a charging current. Now we get a minus sign. This means the actual current direction is reverse of what we assumed. It is a discharge current of 9.82A.

The current drawn from 220V mains $= I_1 + I_2$

$= - 9.82 + 32.2 = 22.38A.$

The currents are marked correctly in fig.2.15.

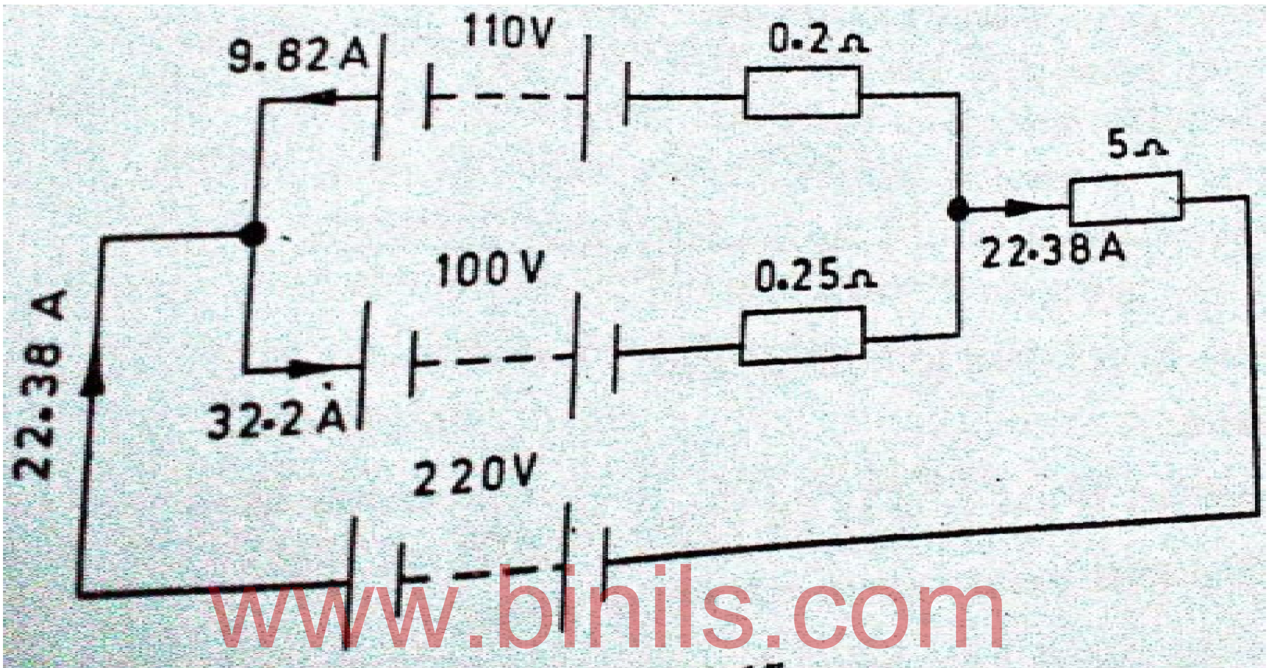


Fig. 2.15

MODEL QUESTIONS

1. Discuss the chemical actions taking place in a lead acid cell, during charging and discharging.
2. How is it decided that a storage battery is run down and requires charging? How do you know the charging is complete?
3. Discuss the various factors that affect the capacity of a lead acid battery.
4. Mention the various applications of a battery.
5. With neat diagrams describe the construction of a lead cell.
6. Describe briefly the trickle charging.
7. Briefly describe the testing and maintenance procedures for a lead acid battery.
8. Explain one charging circuit suitable for charging a lead-acid cell.
9. List out the advantages and disadvantages of a lead acid cell.
10. Explain the terms ampere hour efficiency and watt hour efficiency with reference to secondary cell.
11. Describe the construction of a Nickel Iron cell.
12. List out the troubles in lead-acid cell and mention the remedy for each.
13. An alkaline cell is discharged at a constant current of 1.4A for 21 Hrs 30 mins, the average terminal voltage being 1.2V. A charging current of 3A maintained for 12h is required to bring the cell back to the initial state of charge. The average charging potential is maintained at 1.4V. Calculate the ampere-hour and watt-hour efficiencies.