KIITPOLYTECHNIC

LECTURE NOTES

ON

ELECTRICAL MACHINE

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CONTENTS

DC GENERATORS

Principle of Operation of a D.C. Generator

All the generators work on a principle of dynamically induced e.m.f. This principle nothing but the Faraday’s law of electromagnetism induction. It states that, ‘whenever the number of magnetic lines of force i.e. flux linking with a conductor or a coil changes, an electromotive force is set up in that conductor or coil.’ The change in flux associated with the conductor can exist only when there exists a relative motion between a conductor and the flux. The relative motion can be achieved by rotating conductor with respect to flux or by rotating flux with respect to a conductor. So a voltage gets generated in a conductor, as long as there exists a relative motion between conductor and the flux.

Such an induced e.m.f. which is due to the physical movement of coil or conductor with respect to flux or movement of flux with respect to coil or conductor is called dynamically induced e.m.f.

Key Point:

So a generating action requires following basic components to exist,

i) The conductor or a coil

ii) The relative motion between conductor and flux.

In a particular generator, the conductors are rotated to cut the magnetic flux, keeping flux stationary. To have a large voltage as the output, the numbers of conductors are connected together in a specific manner, to form a winding. This winding is called armature winding of a d.c. machine. The part on which this winding is kept is called armature of a d.c. machine. To have the rotation of conductors, the conductors placed on the armature are rotated with the help of some external device. Such an external device is called a prim mover. The commonly used prim movers are diesel engines, steam engines, steam turbines, water turbines etc. The necessary magnetic flux is produced by current carrying winding which is called field winding. The direction of the induced e.m.f. can be obtained by using Fleming’s right hand role.

Single Loop DC Generator

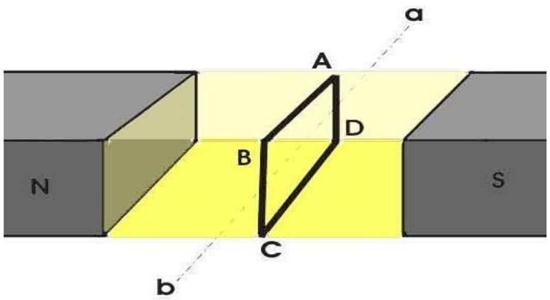


Figure: Single Loop Generator

In the figure above, a single loop of conductor of rectangular shape is placed between two opposite poles of magnet.

Let's us consider, the rectangular loop of conductor is ABCD which rotates inside the magnetic field about its own axis ab. When the loop rotates from its vertical position to its horizontal position, it cuts the flux lines of the field. As during this movement two sides, i.e. AB and CD of the loop cut the flux lines there will be an emf induced in these both of the sides (AB and BC) of the loop.

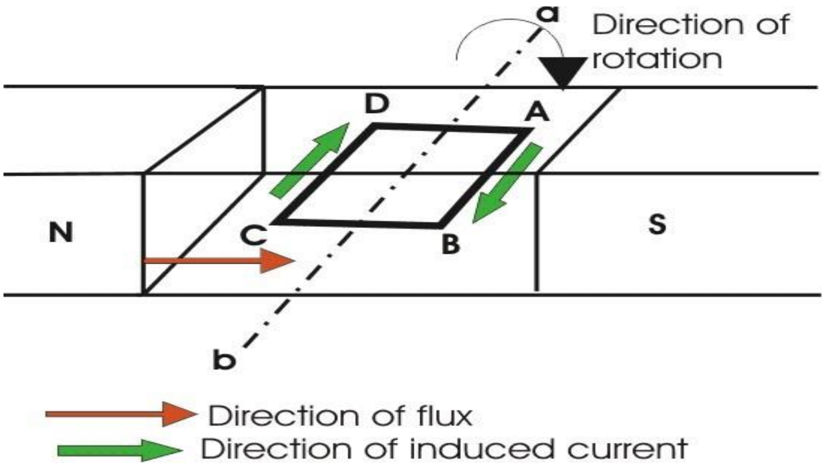


Figure: Single Loop Generator

As the loop is closed there will be a current circulating through the loop. The direction of the current can be determined by Flemming's right hand Rule. This rule says that if you stretch thumb, index finger and middle finger of your right hand perpendicular to each other, then thumbs indicates the direction of motion of the conductor, index finger indicates the direction of magnetic field i.e. N - pole to S - pole, and middle finger indicates the direction of flow of current through the conductor.

Now if we apply this right hand rule, we will see at this horizontal position of the loop, current will flow from point A to B and on the other side of the loop current will flow from point C to D.

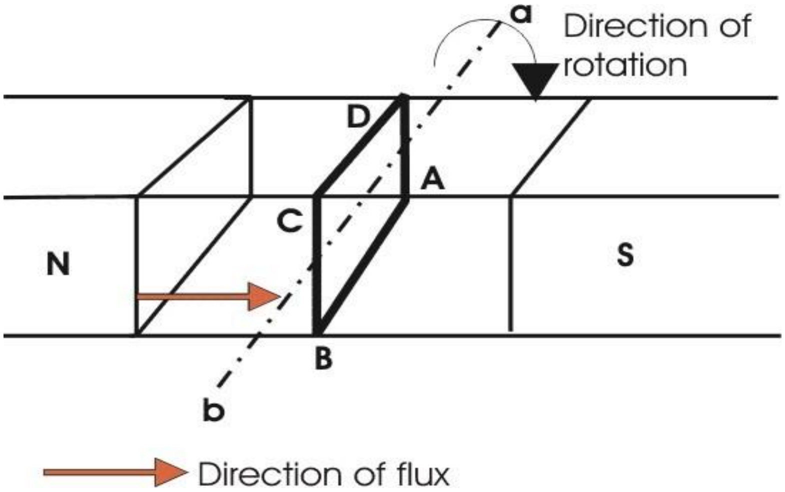


Figure: Single Loop Generator

Now if we allow the loop to move further, it will come again to its vertical position, but now upper side of the loop will be CD and lower side will be AB (just opposite of the previous vertical position). At this position the tangential motion of the sides of the loop is parallel to the flux lines of the field. Hence there will be no question of flux cutting and consequently there will be no current in the loop. If the loop rotates further, it comes to again in horizontal position. But now, said AB side of the loop comes in front of N pole and CD comes in front of S pole, i.e. just opposite to the previous horizontal position as shown in the figure beside.

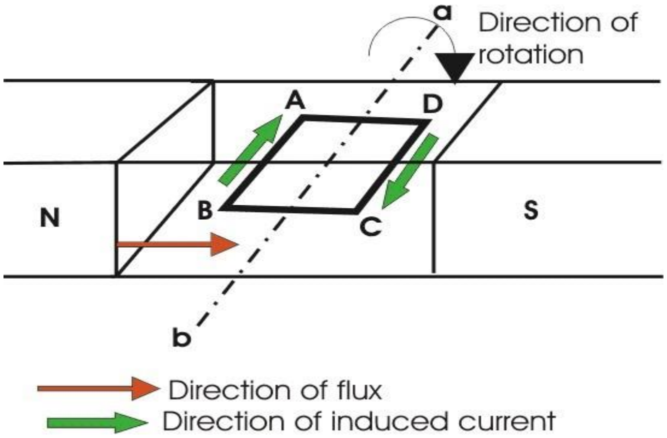


Figure: Single Loop Generator

Here the tangential motion of the side of the loop is perpendicular to the flux lines, hence rate of flux cutting is maximum here and according to Flemming's right hand Rule, at this position current flows from B to A and on other side from D to C. Now if the loop is continued to rotate about its axis, every time the side AB comes in front of S pole, the current flows from A to B and when it comes in front of N pole, the current flows from B to A. Similarly, every time the side CD comes in front of S pole the current flows from C to D and when it comes in front of N pole the current flows from D to C.

If we observe this phenomena in different way, it can be concluded, that each side of the loop comes in front of N pole, the current will flow through that side in same direction i.e. downward to the reference plane and similarly each side of the loop comes in front of S pole, current through it flows in same direction i.e. upwards from reference plane. From this, we will come to the topic of principle of DC generator. Now the loop is opened and connected it with a split ring as shown in the figure below. Split ring are made out of a conducting cylinder which cuts into two halves or segments insulated from each other. The external load terminals are connected with two carbon brushes which are rest on these split slip ring segments.

Working Principle of DC Generator

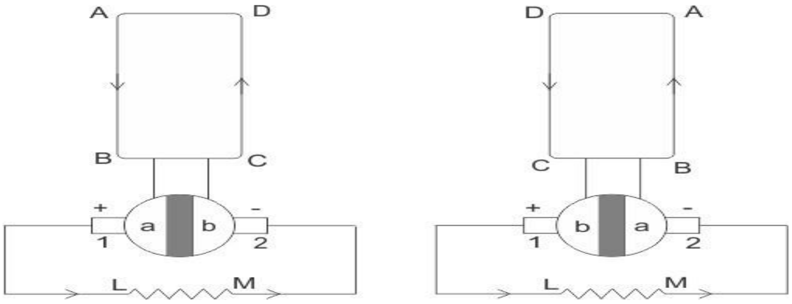


Fig: Commutation action

It is seen that in the first half of the revolution current flows always along ABLMCD i.e. brush no 1 in contact with segment a. In the next half revolution, in the figure the direction of the induced current in the coil is reversed. But at the same time the position of the segments a and b are also reversed which results that brush no 1 comes in touch with the segment b. Hence, the current in the load resistance again flows from L to M. The wave from of the current through the load circuit is as shown in the figure. This current is unidirectional.

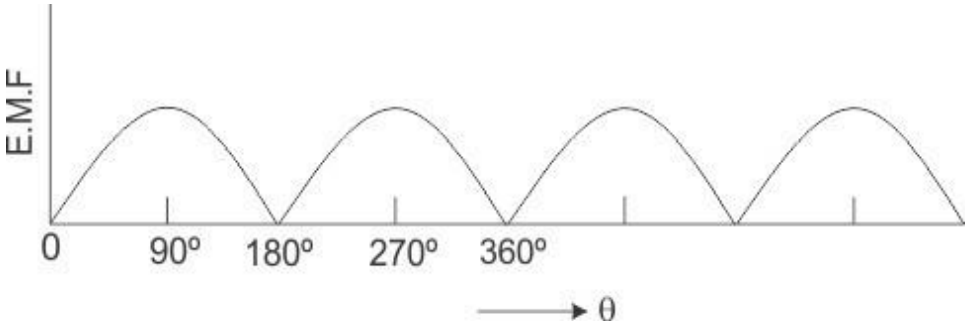


Fig: Output waveform of generator

This is basic working principle of DC generator, explained by single loop generator model. The position of the brushes of DC generator is so arranged that the change over of the segments a and b from one brush to other takes place when the plane of rotating coil is at right angle to the plane of the lines of force. It is so become in that position, the induced emf in the coil is zero.

Construction of a DC Machine:

A DC generator can be used as a DC motor without any constructional changes and vice versa is also possible. Thus, a DC generator or a DC motor can be broadly termed as a DC machine. These basic constructional details are also valid for the construction of a DC motor. Hence, let’s call this point as construction of a DC machine instead of just 'construction of a DC generator.

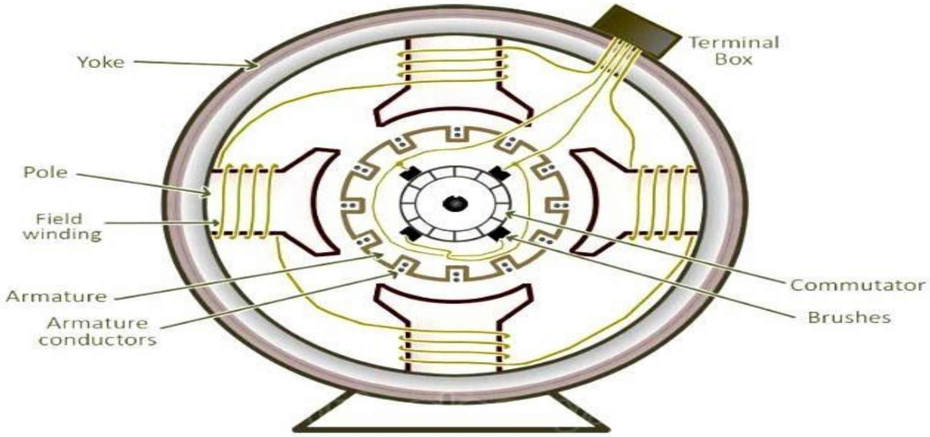


Figure 1: constructional details of a simple 4-pole DC machine

The above figure shows constructional details of a simple 4-pole DC machine. A DC machine consists of two basic parts; stator and rotor. Basic constructional parts of a DC machine are described below.

1. **Yoke:** The outer frame of a dc machine is called as yoke. It is made up of cast iron or steel. It not only provides mechanical strength to the whole assembly but also carries the magnetic flux produced by the field winding.

2. **Poles and pole shoes:** Poles are joined to the yoke with the help of bolts or welding. They carry field winding and pole shoes are fastened to them. Pole shoes serve two purposes; (i) they support field coils and (ii) spread out the flux in air gap uniformly.

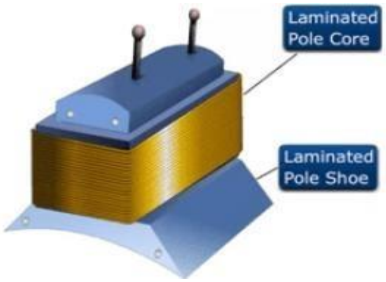


Figure 2: Pole Core and Poles Shoes representation

3. **Field winding:** They are usually made of copper. Field coils are former wound and 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.

4. **Armature core:** Armature core is the rotor of a dc machine. It is cylindrical in shape with slots to carry armature winding. The armature is built up of thin laminated circular steel disks for reducing eddy current losses. It may be provided with air ducts for the axial air flow for cooling purposes. Armature is keyed to the shaft.

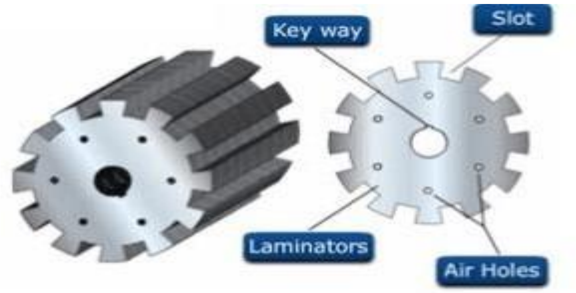


Figure 3: Armature of DC machine

5. **Armature winding:** It is usually a former wound copper coil which rests in armature slots. The armature conductors are insulated from each other and also from the armature core. Armature winding can be wound by one of the two methods; lap winding or wave winding. Double layer lap or wave windings are generally used. A double layer winding means that each armature slot will carry two different coils.

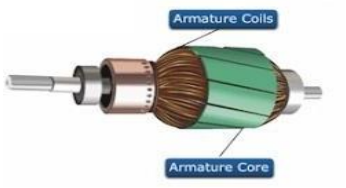


Figure 4: Armature Winding/coil of DC machine

6. **Commutator and brushes:** Physical connection to the armature winding is made through a commutator-brush arrangement. The function of a commutator, in a dc generator, is to collect the current generated in armature conductors. Whereas, in case of a dc motor, commutator helps in providing current to the 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 shaft. Brushes are usually made from carbon or graphite. They rest on commutator segments and slide on the segments when the commutator rotates keeping the physical contact to collect or supply the current.

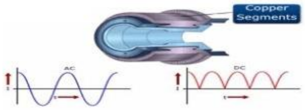


Figure 5: Commutator of DC machine

Emf Equation of a DC Generator

As the armature rotates, a voltage is generated in its coils. In the case of a generator, the emf of rotation is called the Generated emf or Armature emf and is denoted as Er = Eg. In the case of a motor, the emf of rotation is known as Back emf or Counter emf and represented as Er = Eb. The expression for emf is same for both the operations. I.e., for Generator as well as for Motor

Derivation of EMF Equation of a DC Machine – Generator and Motor

Let,

- **P** – Number of poles of the machine
- **ϕ** – Flux per pole in Weber.
- **Z** – Total number of armature conductors.
- **N** – Speed of armature in revolution per minute (r.p.m).
- **A** – Number of parallel paths in the armature winding.

In one revolution of the armature, the flux cut by one conductor is given as

$$\text{Flux cut by one conductor} = P\varphi \quad \text{wb} \ldots \ldots (1)$$

Time taken to complete one revolution is given as

$$t = \frac{60}{N} \quad \text{seconds} \quad \ldots \ldots . (2)$$

Therefore, the average induced e.m.f in one conductor will be

$$e = \frac{P\varphi}{t} \quad \ldots \ldots . (3)$$

Putting the value of (t) from Equation (2) in the equation (3) we will get

$$e = \frac{P\varphi}{60/N} = \frac{P\varphi N}{60} \quad \text{volts} \quad \ldots \ldots . (4)$$

The number of conductors connected in series in each parallel path = Z/A.

Therefore, the average induced e.m.f across each parallel path or the armature terminals is given by the equation shown below.

$$E = \frac{P\varphi N}{60} \text{ x } \frac{Z}{A} = \frac{PZ\varphi N}{60\ A} \quad \text{volts} \quad \text{or}$$

$$E = \frac{PZ\varphi n}{A} \quad \ldots \ldots (5)$$

Where n is the speed in revolution per second (r.p.s) and given as

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

For a given machine, the number of poles and the number of conductors per parallel path (Z/A) are constant. Hence, the equation (5) can be written as

$$E = K\varphi n$$

Where, K is a constant and given as

$$K = \frac{PZ}{A}$$

Therefore, the average induced emf equation can also be written as

$$E \propto \varphi n \quad \text{or}$$

$$E = K_1 \varphi N$$

Where K_1 is another constant and hence induced emf equation can be written as

$$E \propto \varphi N \quad \text{or}$$

$$E \propto \varphi \omega$$

Where ω is the angular velocity in radians/second is represented as

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

Thus, it is clear that the induced emf is directly proportional to the speed and flux per pole. The polarity of induced emf depends upon the direction of the magnetic field and the direction of rotation. If either of the two is reverse the polarity changes, but if two are reversed the polarity remains unchanged.

This induced emf is a fundamental phenomenon for all the DC Machines whether they are working as a generator or motor.

If the machine DC Machine is working as a Generator, the induced emf is given by the equation shown below.

$$E_g = \frac{PZ\varphi N}{60\,A} \quad \text{volts}$$

Where $\mathbf{E_g}$ is the **Generated Emf**

If the machine DC Machine is working as a Motor, the induced emf is given by the equation shown below.

$$E_b = \frac{PZ\varphi N}{60\,A} \quad \text{volts}$$

In a motor, the induced emf is called **Back Emf ($\mathbf{E_b}$)** because it acts opposite to the supply voltage.

Types of DC Generators – Separately Excited and Self Excited

The DC generator converts the electrical power into electrical power. The magnetic flux in a DC machine is produced by the field coils carrying current. The circulating current in the field windings produces a magnetic flux, and the phenomenon is known as Excitation. DC Generator is classified according to the methods of their field excitation.

By excitation, the DC Generators are classified as Separately excited DC Generators and Self-excited DC Generators. There is also Permanent magnet type DC generators. The self-excited DC Generators are further classified as Shunt wound DC generators; Series wound DC generators and Compound wound DC generators. The Compound Wound DC generators are further divided as long shunt wound DC generators, and short shunt wound DC generators.

The field pole of the DC generator is stationary, and the armature conductor rotates. The voltage generated in the armature conductor is of alternating nature, and this voltage is converted into the direct voltage at the brushes with the help of the commutator.

The detailed description of the various types of generators is explained below.

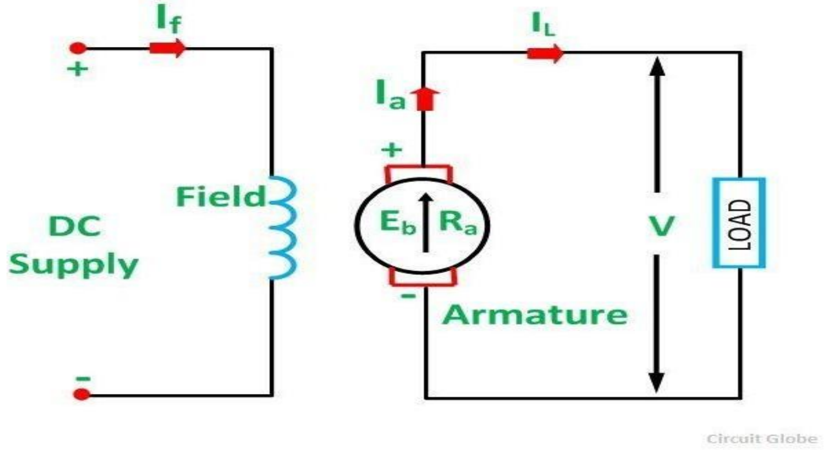
Permanent Magnet type DC Generator

In this type of DC generator, there is no field winding is placed around the poles. The field produced by the poles of these machines remains constant. Although these machines are very compact but are used only in small sizes like dynamos in motorcycles, etc. The main disadvantage of these machines is that the flux produced by the magnets deteriorates with the passage of time which changes the characteristics of the machine.

Separately Excited DC Generator

A DC generator whose field winding or coil is energized by a separate or external DC source is called a separately excited DC Generator. The flux produced by the poles depends upon the field current with the unsaturated region of magnetic material of the poles. i.e. flux is directly proportional to the field current. But in the saturated region, the flux remains constant.

The figure of self-excited DC Generator is shown below.



Separately Excited DC Generator

Here,

$I_a = I_L$ where I_a is the armature current and I_L is the line current.

Terminal voltage is given as

$$V = E_g - I_a R_a \quad \ldots\ldots(1)$$

If the contact brush drop is known, then the equation (1) is written as

$$V = E_g - I_a R_a - 2v_b \quad \ldots..(2)$$

The power developed is given by the equation shown below.

$$\text{Power developed} = E_g I_a \quad \ldots \ldots..(3)$$

$$\text{Power output} = VI_L = VI_a \quad \ldots \ldots..(4)$$

Power output is given by the equation (4) shown above.

Self Excited DC Generator

Self-excited **DC Generator** is a device, in which the current to the field winding is supplied by the generator itself. In self-excited DC generator, the field coils mat be connected in parallel with the armature in the series, or it may be connected partly in series and partly in parallel with the armature windings.

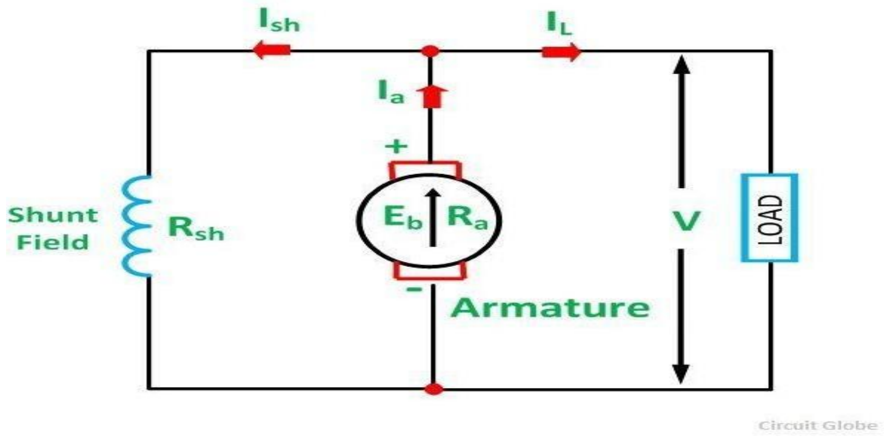
The self-excited DC Generator is further classified as

1. Shunt Wound Generator
2. Series Wound Generator
3. Compound Wound Generator

1. Shunt Wound Generator

In a **shunt wound generator,** the field winding is connected across the armature winding forming a parallel or shunt circuit. Therefore, full terminal voltage is applied across it. A very small field current I_{sh}, flows through it because this winding has many turns of fine wire having very high resistance R_{sh} of the order of 100 ohms.

The connection diagram of shunt wound generator is shown below.



Shunt Wound DC Generator

Shunt field current is given as

$$I_{sh} = \frac{V}{R_{sh}}$$

Where R_{sh} is the shunt field winding resistance.

The current field I_{sh} is practically constant at all loads. Therefore, the DC shunt machine is considered to be a constant flux machine.

Armature current is given as

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

Terminal voltage is given by the equation shown below.

$$V = E_g - I_a R_a$$

If the brush contact drop is included, the equation of the terminal voltage becomes

$$V = E_g - I_a R_a - 2v_b$$

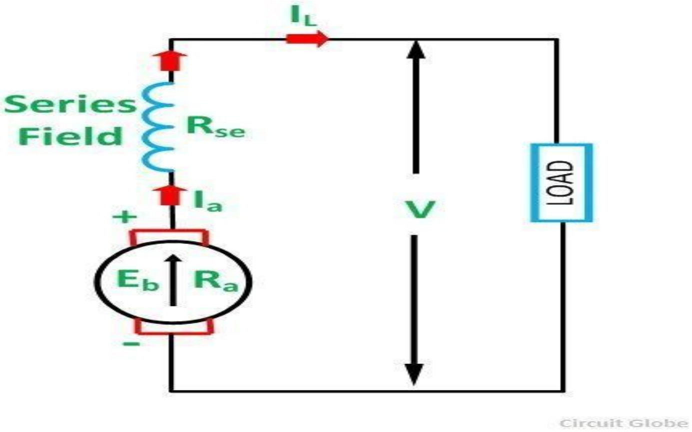
$$\text{Power developed} = E_g I_a$$

$$\text{Power output} = V I_L$$

2. Series Wound Generator

A **series-wound generator** the field coils are connected in series with the armature winding. The series field winding carries the armature current. The series field winding consists of a few turns of wire of thick wire of larger cross-sectional area and having low resistance usually of the order of less than 1 ohm because the armature current has a very large value.

Its convectional diagram is shown below.



Series Wound DC Generator

Series field current is given as

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

R_{se} is known as the series field winding resistance.

Terminal voltage is given as

$$V = E_g - I_aR_a - I_{se}R_{se}$$

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

If the brush contact drop is included, the terminal voltage equation is written as

$$V = E_g - I_a(R_a + R_{se}) - 2V_b$$

$$\text{Power developed} = E_gI_a$$

$$\text{Power output} = VI_L = VI_a$$

The flux developed by the series field winding is directly proportional to the current flowing through it. But it is only true before magnetic saturation after the saturation flux becomes constant even if the current flowing through it is increased.

3. Compound Wound Generator

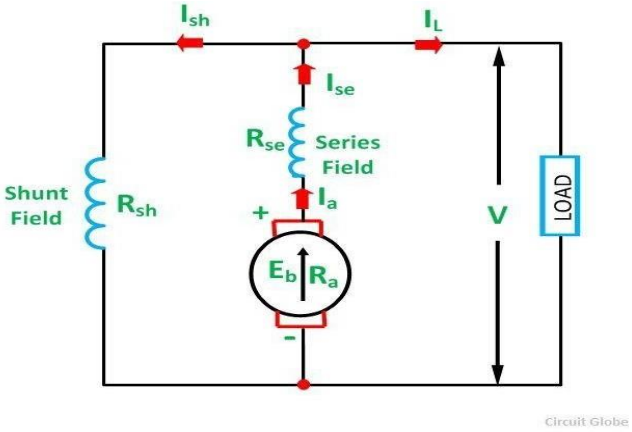
In a Compound Wound Generator, there are two sets of the field winding on each pole. One of them is connected in series having few turns of thick wire, and the other is connected in parallel having many turns of fine wire with the armature windings. In other words, the generator which has both shunt and series fields is called the compound wound generators.

If the magnetic flux produced by the series winding assists the flux produced by the shunt winding, then the machine is said to be **cumulative compounded**. If the series field flux opposes the shunt field flux, then the machine is called the **differentially compounded**.

It is connected in two ways. One is a long shunt compound generator, and another is a short shunt compound generator. If the shunt field is connected in parallel with the armature alone then the machine is called the short compound generator. In long shunt compound generator, the shunt field is connected in series with the armature. The two types of generators are discussed below in details.

Long Shunt Compound Wound Generator

In a long shunt wound generator, the shunt field winding is parallel with both armature and series field winding. The connection diagram of long shunt wound generator is shown below



Long Shunt Compound Wound Generator

Shunt field current is given as

$$I_{sh} = \frac{V}{R_{sh}}$$

Series field current is given as

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

Terminal voltage is given as

$$V = E_g - I_aR_a - I_{se}R_{se} = E_g - I_a(R_a + R_{se})$$

If the brush contact drop is included, the terminal voltage equation is written as

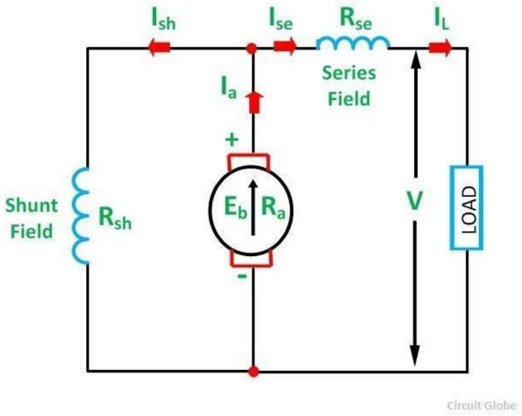
$$V = E_g - I_a (R_a + R_{se}) - 2V_b$$

$$\text{Power developed} = E_g I_a$$

$$\text{Power output} = V I_L$$

Short Shunt Compound Wound Generator

In a Short Shunt Compound Wound Generator, the shunt field winding is connected in parallel with the armature winding only. The connection diagram of short shunt wound generator is shown below.



Short Shunt Compound Wound Generator

Series field current is given as

$$I_{se} = I_L$$

Shunt field current is given as

$$I_{sh} = \frac{V + I_L R_{se}}{R_{sh}} = \frac{E_g - I_a R_a}{R_{sh}}$$

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

Terminal voltage is given as

$$V = E_g - I_a R_a - I_L R_{se}$$

If the brush contact drop is included, the terminal voltage equation is written as

$$V = E_g - I_a R_a - I_L R_{se} - 2V_b$$

$$\text{Power developed} = E_g I_a$$

$$\text{Power output} = V I_L$$

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 Compound Wound generator.

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

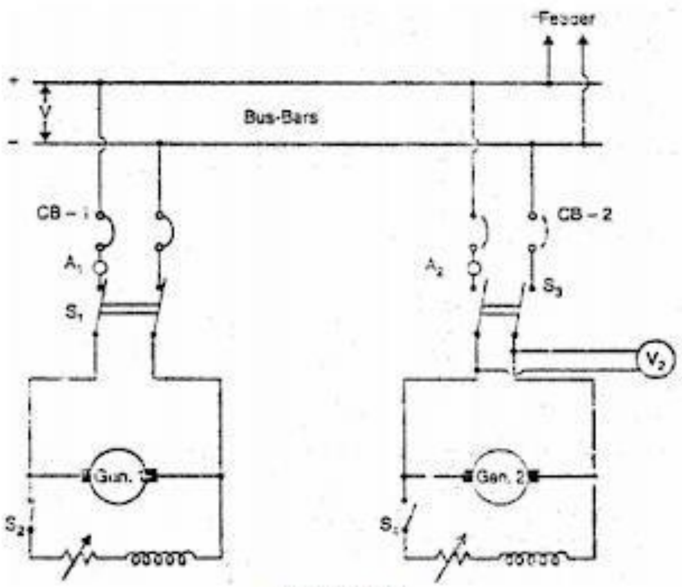


Fig. (3.15)

Parallel operation of shunt generators

(i) The prime mover of generator 2 is brought up to the rated speed. Now switch S4 in the field circuit of the generator 2 is closed.

(ii) Next circuit breaker CB-2 is closed and the excitation of generator 2 is adjusted till it generates a voltage equal to the bus-bars voltage.This is indicated by voltmeter V2.

(iii) Now the generator 2 is ready to be paralleled with generator 1. The main switch S3 is closed, thus putting generator 2 in parallel with generator 1. Note that generator 2 is not supplying any load because it's generated e.m.f. is equal to bus-bars voltage.The generator is said to be “floating” (i.e., not supplying any load) on the bus-bars.

(iv) If generator 2 is to deliver any current, then it's generated voltage E should be greater than the bus-bars voltage V. In that case, the current supplied by it is I = (E - V)/Ra where Ra is the resistance of the armature circuit. By increasing the field current (and hence induced e.m.f. E), the generator 2 can be made to supply the proper amount of load.

(v) The load may be shifted from one shunt generator to another merely by adjusting the field excitation. Thus if generator 1 is to be shut down, the whole load can be shifted onto generator 2 provided it has the capacity to supply that load. In that case, reduce the current supplied by generator 1 to zero (This will be indicated by ammeter A1) open C.B.-1 and then open the main switch S1.

Load Sharing of two generators:

The load sharing between shunt generators in parallel can be easily regulated because of their drooping characteristics.The load may be shifted from one generator to another merely by adjusting the field excitation.Let us discuss the load sharing of two generators which have unequal no-load voltages.

Let E_1, E_2 = no-load voltages of the two generators

R_1, R_2 = their armature resistances

V = common terminal voltage (Bus-bars voltage)

then $I_1 = (E_1 - V)/R_1$ and $I_2 = (E_2 - V)/R_2$

Thus the current output of the generators depends upon the values of E1 and E3.These values may be changed by field rheostats.The common terminal voltage (or bus-bars voltage) will depend upon

(i) the e.m.f.s of individual generators and

(ii) the total load current supplied.

It is generally desired to keep the bus bars voltage constant. This can be achieved by adjusting the field excitations of the generators operating in parallel.

Compound Generators in Parallel:

Under-compounded generators also operate satisfactorily in parallel but over compounded generators will not operate satisfactorily unless their series fields are paralleled. This is achieved by connecting two negative brushes together as shown in Fig. (3.16) (i). The conductor used to connect these brushes is generally called equaliser bar. Suppose that an attempt is made to operate the two generators in Fig. (3.16) (ii) in parallel without an equalizer bar. If, for any reason, the current supplied by generator 1 increases slightly, the current in its series field will increase and raise the generated voltage.

This will cause generator 1 to take more load. Since total load supplied to the system is constant, the current in generator 2 must decrease and as a result, its series field is weakened. Since this effect is cumulative, the generator 1 will take the entire load and drive generator 2 as a motor. Under such conditions, the current in the two machines will be in the direction shown in Fig. (3.16) (ii). After machine 2 changes from a generator to a motor, the current in the shunt field will remain in the same direction, but the current in the armature and series field will reverse.

Thus the magnetising action, of the series field opposes that of the shunt field. As the current taken by the machine 2 increases, the demagnetizing action of series field becomes greater and the resultant field becomes weaker. The resultant field will finally become zero and at that time machine 2 will short circuit machine 1, opening the breaker of either or both machines.

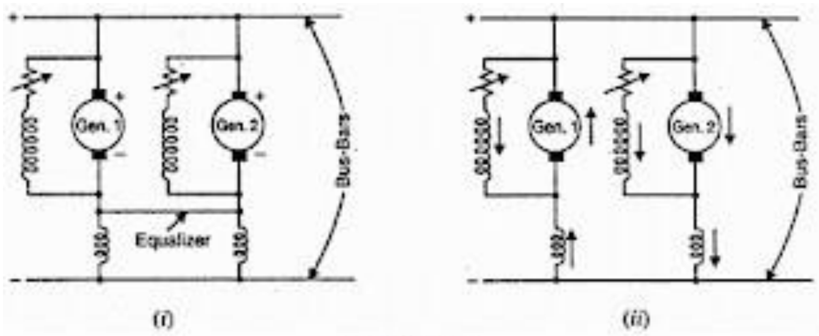


Fig. (3.16)

Fig: Parallel operation of compound generators

When the equalizer bar is used, a stabilizing action exists? And neither machine tends to take the entire load. To consider this, suppose that current delivered by generator 1 increase. The increased current will not only pass through the series field of generator 1 but also through the equalizer bar and series field of generator 2.Therefore, the voltage of both the machines increases and the generator 2 will take a part of the load.

PARALLEL OPERATION OF DC SERIES GENERATOR

The interesting thing about the parallel operation of DC series generator is that DC series generators are not usually employed for supply of power. Instead DC series motors are arranged in parallel to operate as DC series generators during Electric Braking.

- Series generators are rarely used in industry for supplying loads. Some applications like electric braking may employ them and operate two or more series generates in parallel.
- The excitation of the machine I increase, increasing the load current delivered. As the total current is I the current supplied by machine II reduces, so also its excitation and induced emf.

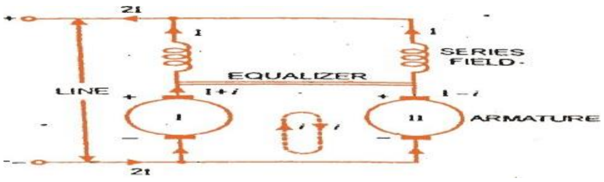


Fig: Parallel operation of Series generators

- Thus machine I takes greater and greater fraction of the load current with machine II shedding its load. Ultimately the current of machine II becomes negative and it also loads the first machine.
- Virtually there is a short circuit of the two sources, the whole process is thus highly unstable. One remedy is for a problem as this is to make the two fields immune to the circulating current between the machines.
- With the equalizer present, a momentary disturbance does not put the two machines out of action.
- A tendency to supply a larger current by a machine strengthens the field of the next machine and increases its induced emf . This brings in stable conditions for operation rapidly.

Use of Equalizer Bars:

Here comes the use of equalizer bars in the parallel operation of DC series generators. The possibility of reversal of either machine can be prevented by preventing the flow of circulating current produced due to inequalities of induced emfs of the machines through the series field winding.

- This Aim can be achieved by connecting a heavy copper bar of negligible resistance across the two machines as shown in the figure.
- Now the circulating current does not affect the field winding, but it get confined to the armature and the equalizing bars.
- Now if the armature current increases, the terminal voltage drop occurs and the original condition is restored.

Cross connection of Field windings:

If the field coils are cross-connected when the series motors are connected in parallel, then any increase in the current of the armature of generator 1, the increased current flows occurs through the field coil of generator 2. This increases the electromotive force of generator, which opposes the change in load sharing trying to stabilize the operation of the two generators at the original operating condition itself. Thus it will give more positive and better operation than equalizer connection.

DC MOTOR

WORKING PRINCIPLE OF A DC MOTOR

The DC motor is the device which converts the direct current into the mechanical work. It works on the principle of Lorentz Law, which states that “the current carrying conductor placed in a magnetic and electric field experience a force”. And that force is called the Lorentz force. The Fleming left-hand rule gives the direction of the force.

Fleming Left Hand Rule

If the thumb, middle finger and the index finger of the left hand are displaced from each other by an angle of 90°, the middle finger represents the direction of the magnetic field. The index finger represents the direction of the current, and the thumb shows the direction of forces acting on the conductor.

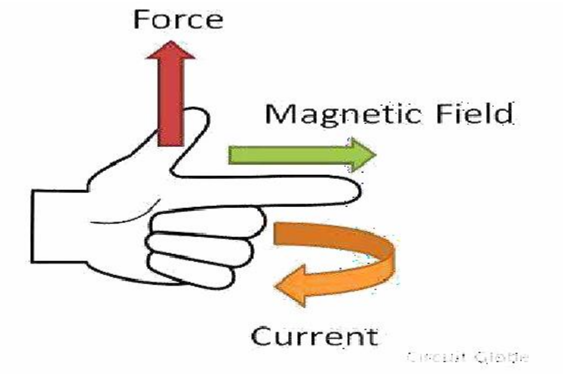


Fig: Flemings left hand rule

The formula calculates the magnitude of the force,

$$F = BIl \quad \text{newton}$$

Before understanding the working of DC motor first, we have to know about their construction. The armature and stator are the two main parts of the DC motor. The armature is the rotating part, and the stator is their stationary part. The armature coil is connected to the DC supply.

The armature coil consists the commutators and brushes. The commutators convert the AC induces in the armature into DC and brushes transfer the current from rotating part of the motor to the stationary external load. The armature is placed between the north and south pole of the permanent or electromagnet.

For simplicity, consider that the armature has only one coil which is placed between the magnetic field shown below in the figure A. When the DC supply is given to the armature coil the current starts flowing through it. This current develops their own field around the coil. Figure B shows the field induces around the coil.

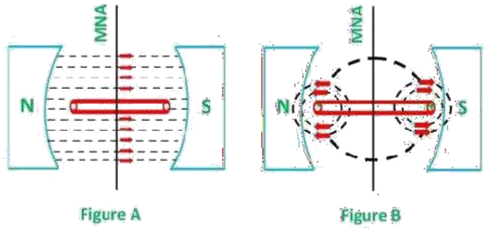


Figure A

Figure B

Fig: magnetic field induces around the coil.

By the interaction of the fields (produces by the coil and the magnet), resultant field develops across the conductor. The resultant field tends to regain its original position, i.e. in the axis of the main field. The field exerts the force at the ends of the conductor, and thus the coil starts rotating.

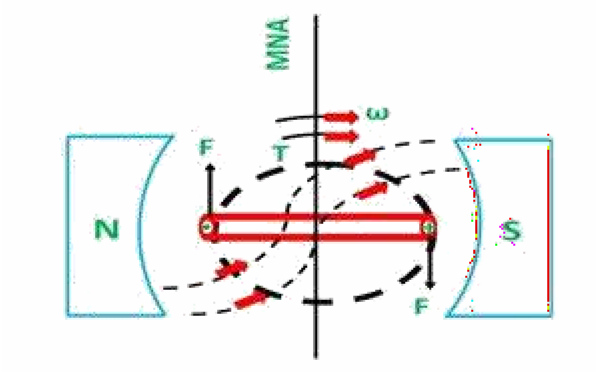


Figure C

Fig: Field produced due to poles alone

Let the field produces by the main field be F_m, and this field rotates in the clockwise direction. When the current flows in the coil, they produce their own magnetic field says F_r. The field F_r tries to come in the direction of the main field. Thereby, the torque act on the armature coil.

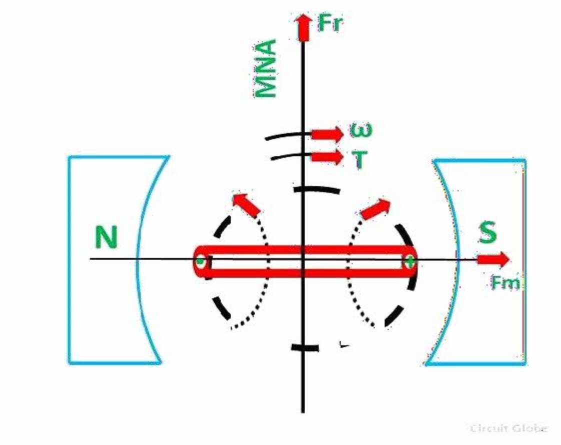


Fig: Field produced due to conductors alone

The actual DC motor consists a large number of armature coils. The speed of the motor is directly proportional to the number of coils used in the motor. These coils are kept under the impact of the magnetic field.

The one end of the conductors are kept under the influence of north pole, and the other end is kept under the influence of the South pole. The current enters into the armature coil through the north pole and move outwards through the south pole. When the coil moves from one brush to another, at the same time the polarity of the coil also changes. Thus, the direction of the force or torque acting on the coil remains same.

The torque induces in the coil become zero when the armature coil is perpendicular to the main field. The zero torque means the motor stops rotating. For solving this problem, the number of armature coil is used in the rotor. So if one of their coils is perpendicular to the field, then the other coils induce the torque. And the rotor moves continuously.

Also, for obtaining the continuous torque, the arrangement is kept in such a way that whenever the coils cut the magnetic neutral axis of the magnet the direction of current in the coils become reversed. This can be done with the help of the commutator.

Back Emf and its Significance in DC Motor

When a dc voltage V is applied across the motor terminals, the armature starts rotating due to the torque developed in it.

As the armature rotates, armature conductors cut the pole magnetic field, therefore, as per law of electromagnetic induction, an emf called ***back emf*** is induced in them.

The back emf (also called counter emf) is given by

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

where, P=number of poles of dc motor

Φ= flux per pole

Z=total number of armature conductors

N=armature speed

A=number of parallel paths in armature winding

As all other parameters are constant, therefore, $E_b \propto N$

As per Lenz's law, "the induced emf always opposes the cause of its production". Here, the cause of generation of back emf is the rotation of armature. Rotation of armature is due to armature torque. Torque is due to armature current and armature current is due to supply dc voltage V. Therefore, the ultimate cause of production of E_b is the supply voltage V.

Therefore, back emf is always directed opposite to supply voltage V.

Significance of back emf in dc motor

(1) As the back emf opposes supply voltage V, therefore, supply voltage has to force current through the armature against the back emf, to keep armature rotating. The electric work done in overcoming and causing the current to flow against the back emf is converted into mechanical energy developed in the armature.

It follows, therefore, that energy conversion in a dc motor is only possible due to the production of back emf.

Mechanical power developed in the armature = EbIa

(2) Back emf makes dc motor a self-regulating motor i.e Eb makes motor to adjust Ia automatically as per the load torque requirement. Lets see how.

From the motor figure,

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

V and Ra are fixed, therefore, armature current Ia dpends on back emf, which in turn depends on speed of the motor.

(a) when the motor is running at no-load, small torque (Ta=KIa) is required by the motor to overcome friction and windage. Therefore, a small current is drawn by the motor armature and the back emf is almost equal to the supply voltage.

(b) If the motor is suddenly loaded, the load torque beomes greater than the armature torque and the motor starts to slow down. As motor speed decreases, back emf decreases and therefore, armature current starts increasing. With increasing Ia , armature torque increases and at some point it becomes equal to the load torque. At that moment, motor stops slowing down and keeps running at this new speed.

(c) If the load on the motor is suddenly reduced, the driving torque becomes more than the load torque and the motor starts accelerating. As the motor speed increases, back emf increases and therefore, armature current decreases. Due to this reducing armature current, armature developed torque decreases and at some point becomes equal to the load torque. That point onwards, motor will stop accelerating and will start rotating uniformly at this new slightly increased speed.

So, this shows how important is back emf in dc motor. Without back emf, the electromagnetic energy conversion would not have been possible at the first place.

Power Equation of a D.C. Motor

The voltage equation of a d.c. motor is given by,

$$V = E_b + I_a R_a$$

Multiplying both sides of the above equation by I_a we get,

$$V I_a = E_b I_a + I_a^2 R_a$$

This equation is called power equation of a d.c. motor.

VI_a = Net electrical power input to the armature measured in watts.

$I_a^2R_a$ = Power loss due the resistance of the armature called armature copper loss.

So difference between VI_a and $I_a^2R_a$ i.e. input - losses gives the output of the armature.

So E_b Ia is called electrical equivalent of gross mechanical power developed by the armature.

This is denoted as P_m.

$\therefore$ Power input to the armature - Armature copper loss = Gross mechanical power developed in the armature.

Condition for Maximum Power

For a motor from power equation it is known that,

P_m = Gross mechanical power developed = E_b Ia

$= VIa - I_a^2Ra$

For maximum P_m, $dP_m/dI_a = 0$

$\therefore \quad 0 = V - 2I_aRa$

$\therefore \quad I_a = V/2Ra$ i.e. $I_aRa = V/2$

Substituting in voltage equation,

$$V = E_b + I_aRa = E_b + (V/2)$$

$\therefore \quad E_b = V/2$ ....Condition for maximum power

Key Point : This is practically impossible to achieve as for this, current required is much more than its normal rated value. Large heat will be produced and efficiency of motor will be less than 50 %.

TORQUE EQUATION OF A DC MOTOR

When a DC machine is loaded either as a motor or as a generator, the rotor conductors carry current. These conductors lie in the magnetic field of the air gap. Thus, each conductor experiences a force. The conductors lie near the surface of the rotor at a common radius from its centre. Hence, a torque is produced around the circumference of the rotor, and the rotor starts rotating.

When the machine operates as a generator at a constant speed, this torque is equal and opposite to that provided by the prime mover. When the machine is operating as a motor, the torque is transferred to the shaft of the rotor and drives the mechanical load. The expression is same for the generator and motor.

When the current carrying current is placed in the magnetic field, a force is exerted or it which exerts turning moment or torque F x r. This torque is produced due to the electromagnetic effect, hence is called **Electromagnetic torque.** The torque which is produced in the armature is not fully used at the shaft for doing the useful work. Some part of it where lost due to mechanical losses. The torque which is used for doing useful work in known as the shaft torque.

Since,

$$V = E_b + I_a R_a \quad \ldots\ldots..(1)$$

Multiplying the equation (1) by I_a we get

$$VI_a = E_b I_a + I_a^2 R_a \quad \ldots\ldots..(2)$$

Where,

VI_a is the electrical power input to the armature.

$I^2{}_a R_a$ is the copper loss in the armature.

We know that,

Total electrical power supplied to the armature = Mechanical power developed by the armature + losses due to armature resistance

Now, the mechanical power developed by the armature is Pm.

$$P_m = F_b I_a \ldots\ldots.(3)$$

Also, the mechanical power rotating armature can be given regarding torque T and speed n.

$$P_m = \omega T = 2\pi\, nT \quad \ldots\ldots.(4)$$

Where n is in revolution per seconds (rps) and T is in Newton-Meter.

Hence,

$$2\pi\, nT = E_b I_a \quad \text{or}$$

$$T = \frac{E_b I_a}{2\pi n}$$

But,

$$E_b = \frac{\varphi ZNP}{60\ A}$$

Where N is the speed in revolution per minute (rpm) and

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

Where, n is the speed in (rps).

Therefore,

$$E_b = \frac{\varphi ZnP}{A}$$

So, the torque equation is given as

$$T = \frac{\varphi ZP}{2\pi A} . I_a$$

For a particular DC Motor, the number of poles (P) and the number of conductors per parallel path (Z/A) are constant.

$$T = K\varphi I_a$$

Where,

$$K = \frac{ZP}{2\pi A} \quad \text{or}$$

$$T \propto \varphi I_a \ldots \ldots (5)$$

Thus, from the above equation (5) it is clear that the torque produced in the armature is directly proportional to the flux per pole and the armature current. Moreover, the direction of electromagnetic torque developed in the armature depends upon the current in armature conductors. If either of the two is reversed the direction of torque produced is reversed and hence the direction of rotation. But when both are reversed, and direction of torque does not change.

Shaft Torque

In a DC Motor whole of the electromagnetic torque (T) developed in the armature is not available on the shaft. A part of it is lost to overcome the iron and mechanical (friction and windage) losses. Therefore, shaft torque (T_{sh}) is somewhat less than the torque developed in the armature.

Definition: Thus, in the case of DC motors, the actual torque available at the shaft for doing useful mechanical work is known as **Shaft Torque.** It is so called because it is available on the shaft of the motor. It is represented by the symbol T_{sh}. The output of the motor is given by the equation shown below where T_{sh} is the shaft torque in r.p.s and the N is the rotation of the motor in r.p.m. The shaft torque is expressed as

$$Output = T_{sh} \times 2\pi N$$

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

$$T_{sh} = \frac{Outputs\ in\ watts}{2\pi N/60}\ N - m\ in\ r.p.m$$

$$T_{sh} = \frac{60}{2\pi}\frac{Output}{N} = 9.55\frac{Output}{N}\ N - m\ in\ r.p.s$$

The difference between the armature torque and the shaft torque ($T_a - T_{sh}$) is known as the lost torque and is due to the formation of the torque.

Brake Horse Power (B.H.P)

In the case of the motor, the mechanical power available at the shaft is known as Brake Horse Power. If T_{sh} is the shaft torque in Newton Meter and N is the speed in r.p.m then,

$$\text{Useful output power} = \omega T_{sh} = \frac{2\pi N T_{sh}}{60} \quad \text{watts}$$

$$\text{Output in B.H.P} = \frac{2\pi N T_{sh}}{60 \text{ x } 735.5} \quad \ldots\ldots(1)$$

The output brake horsepower is given by the equation (1) shown above.

TYPES OF DC MOTOR

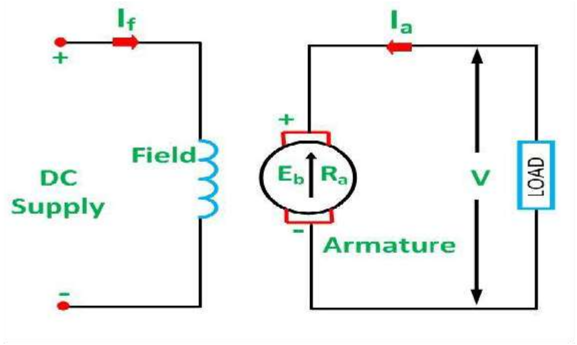
A Direct Current Motor, DC is named according to the connection of the field winding with the armature. Mainly there are two types of DC Motors. First, one is Separately Excited DC Motor and Self-excited DC Motor. The self-excited motors are further classified as Shunt wound or shunt motor, Series wound or series motor and Compound wound or compound motor.

The dc motor converts the electrical power into mechanical power is known as dc motor. The construction of the dc motor and generator are same. But the dc motor has the wide range of speed and good speed regulation which in electric traction.The working principle of the dc motor is based on the principle that the current carrying conductor is placed in the magnetic field and a mechanical force experience by it.

The DC motor is generally used in the location where require protective enclosure, for example, drip-proof, the fireproof, etc. according to the requirements. The detailed description of the various types of the motor is given below.

Separately Excited DC Motor

As the name signifies, the field coils or field windings are energized by a separate DC source as shown in the circuit diagram shown below.



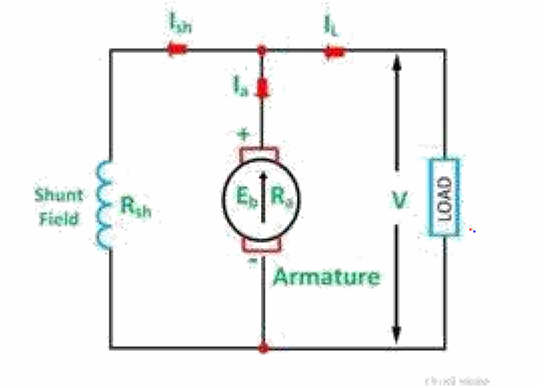
Separately Excited DC Motor

Self Excited DC Motor

As the name implies self-excited, hence, in this type of motor, the current in the windings is supplied by the machine or motor itself. Self-excited DC Motor is further divided into shunt wound, and series wound motor. They are explained below in detail.

Shunt Wound Motor

This is the most common types of DC Motor. Here the field winding is connected in parallel with the armature as shown in the figure below.



Shunt Wound DC Motor

The current, voltage and power equations for a shunt motor are written as follows.

By applying KCL at the junction A in the above figure.

The sum of the incoming currents at A = Sum of the outgoing currents at A.

$$I = I_a + I_{sh} \dots\dots\dots (1)$$

Where,

I is the input line current

Ia is the armature current

Ish is the shunt field current

Equation (1) is the current equation.

The voltage equations are written by using Kirchhoff's voltage law (KVL) for the field winding circuit.

$$V = I_{sh}R_{sh} \; \dots\dots..(2)$$

For armature winding circuit the equation will be given as

$$V = E + I_aR_a \; \dots\dots\dots(3)$$

The power equation is given as

Power input = mechanical power developed + losses in the armature + loss in the field.

$$VI = P_m + I_a^2R_a + I_{sh}^2R_{sh} \; \dots\dots\dots.(4)$$

$$VI = P_m + I_a^2R_a + VI_{sh}$$

$$P_m = VI - VI_{sh} - I_a^2R_a = V(I - I_{sh}) - I_a^2R_a$$

$$P_m = VI_a - I_a^2R_a = (V - I_aR_a)I_a$$

$$P_m = EI_a \dots\dots\dots(5)$$

Multiplying equation (3) by Ia we get the following equations.

$$VI_a = EI_a + I_a^2R_a \dots\dots\dots(6)$$

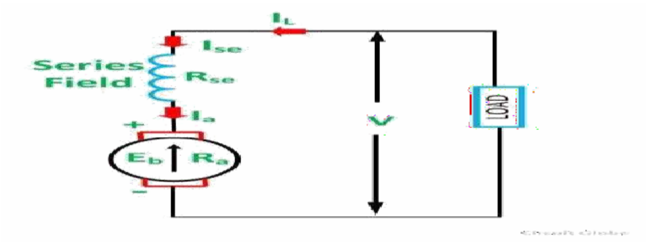
$$VI_a = P_m + I_a^2R_a \dots\dots\dots(7)$$

Where,

VI_a is the electrical power supplied to the armature of the motor.

Series Wound Motor

In the series motor, the field winding is connected in series with the armature winding. The connection diagram is shown below.



Series Wound Motor

By applying the KCL in the above figure

$$I = I_{se} = I_a$$

Where,

I_{se} is the series field current

The voltage equation can be obtained by applying KVL in the above figure

$$V = E + I\,(R_a + R_{se}) \ldots \ldots \ldots (8)$$

The power equation is obtained by multiplying equation (8) by I we get

$$VI = EI + I^2\,(R_a + R_{se}) \ldots \ldots \ldots (9)$$

Power input = mechanical power developed + losses in the armature + losses in the field

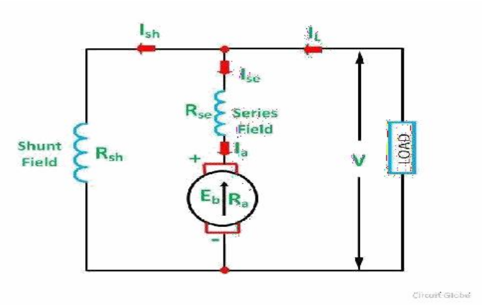
$$VI = P_m + I^2R_a + I^2R_a \ldots \ldots \ldots (10)$$

Comparing the equation (9) and (10), we will get the equation shown below.

$$P_m = EI \ldots \ldots \ldots (11)$$

Compound Wound Motor

A DC Motor having both shunt and series field windings is called a **Compound Motor**. The connection diagram of the compound motor is shown below.



Compound Motor

The compound motor is further subdivided as **Cumulative Compound** Motor and **Differential Compound** Motor. In cumulative compound motor the flux produced by both the windings is in the same direction, i.e.

$$\varphi_r = \varphi_{sh} + \varphi_{se}$$

In differential compound motor, the flux produced by the series field windings is opposite to the flux produced by the shunt field winding, i.e.

$$\varphi_r = \varphi_{sh} - \varphi_{se}$$

The positive and negative sign indicates that direction of the flux produced in the field windings.

CHARACTERISTICS OF DC MOTORS

Generally, three characteristic curves are considered important for DC motors which are,

(i) Torque vs. armature current,
(ii) (ii) Speed vs. armature current and
(iii) (iii) Speed vs. torque.

These are explained below for each type of DC motor. These characteristics are determined by keeping the following two relations in mind.

$$\mathbf{T_a \propto \phi . I_a} \text{ and } \mathbf{N \propto E_b/\phi}$$

These above equations can be studied at - emf and torque equation of dc machine. For a DC motor, magnitude of the back emf is given by the same emf equation of a dc generator i.e. $Eb = P\phi NZ / 60A$. For a machine, P, Z and A are constant, therefore, $N \propto Eb/\phi$

Characteristics Of DC Series Motors

Torque Vs. Armature Current (T_a-I_a)

This characteristic is also known as electrical characteristic. We know that torque is directly proportional to the product of armature current and field flux, $Ta \propto \phi.Ia$. In DC series motors, field winding is connected in series with the armature, i.e. Ia = If. Therefore, before magnetic saturation of the field, flux ϕ is directly proportional to Ia. Hence, before magnetic saturation Ta α Ia2. Therefore, the Ta-Ia curve is parabola for smaller values of Ia.

After magnetic saturation of the field poles, flux ϕ is independent of armature current Ia. Therefore, the torque varies proportionally to Ia only, $T \propto Ia$.Therefore, after magnetic saturation, Ta-Ia curve becomes a straight line.

The shaft torque (Tsh) is less than armature torque (Ta) due to stray losses. Hence, the curve Tsh vs Ia lies slightly lower.

In DC series motors, (prior to magnetic saturation) torque increases as the square of armature current, these motors are used where high starting torque is required.

Speed Vs. Armature Current (N-Ia)

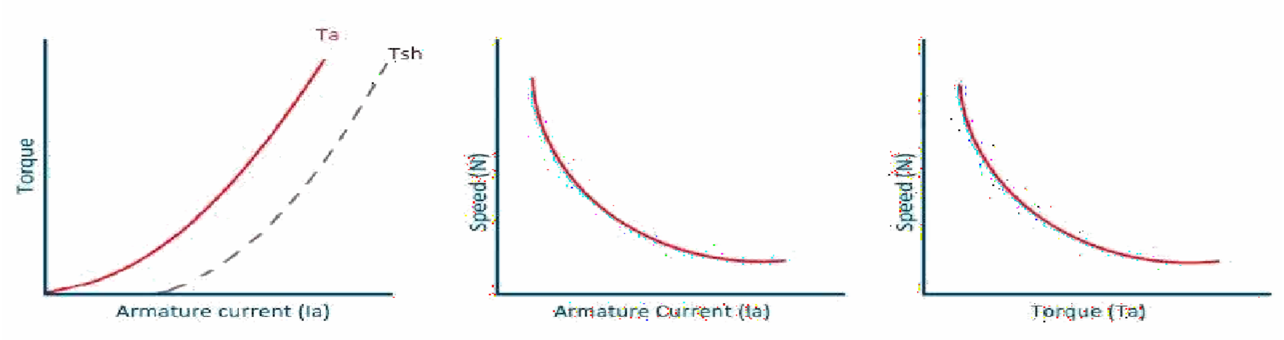
We know the relation, N ∝ Eb/ɸ

For small load current (and hence for small armature current) change in back emf Eb is small and it may be neglected. Hence, for small currents speed is inversely proportional to ɸ. As we know, flux is directly proportional to Ia, speed is inversely proportional to Ia. Therefore, when armature current is very small the speed becomes dangerously high. That is why a series motor should never be started without some mechanical load.

But, at heavy loads, armature current Ia is large. And hence, speed is low which results in decreased back emf Eb. Due to decreased Eb, more armature current is allowed.

Speed Vs. Torque (N-Ta)

This characteristic is also called as mechanical characteristic. From the above two characteristics of DC series motor, it can be found that when speed is high, torque is low and vice versa.



Characteristics of DC series motor

Characteristics Of DC Shunt Motors

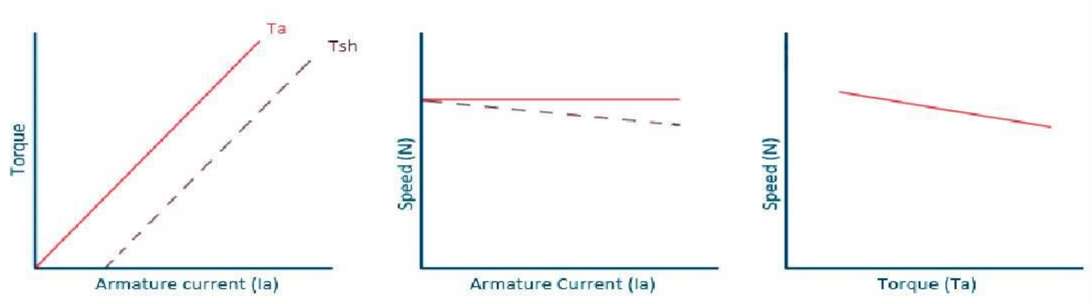
Torque Vs. Armature Current (Ta-Ia)

In case of DC shunt motors, we can assume the field flux ɸ to be constant. Though at heavy loads, ɸ decreases in a small amount due to increased armature reaction. As we are neglecting the change in the flux ɸ, we can say that torque is proportional to armature current. Hence, the Ta-Ia characteristic for a dc shunt motor will be a straight line through the origin.

Since heavy starting load needs heavy starting current, shunt motor should never be started on a heavy load.

Speed Vs. Armature Current (N-Ia)

As flux ɸ is assumed to be constant, we can say N ∝ Eb. But, as back emf is also almost constant, the speed should remain constant. But practically, ɸ as well as Eb decreases with increase in load. Back emf Eb decreases slightly more than ɸ, therefore, the speed decreases slightly. Generally, the speed decreases only by 5 to 15% of full load speed. Therefore, a shunt motor can be assumed as a constant speed motor. In speed vs. armature current characteristic in the following figure, the straight horizontal line represents the ideal characteristic and the actual characteristic is shown by the dotted line.



Characteristics of DC shunt motor

Characteristics Of DC Compound Motor

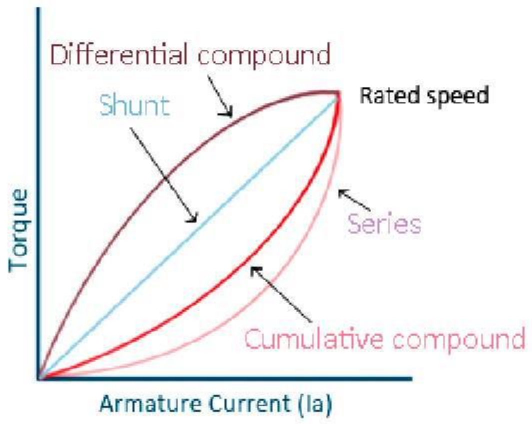
DC compound motors have both series as well as shunt winding. In a compound motor, if series and shunt windings are connected such that series flux is in direction as that of the shunt flux then the motor is said to be cumulatively compounded. And if the series flux is opposite to the direction of the shunt flux, then the motor is said to be differentially compounded. Characteristics of both these compound motors are explained below.

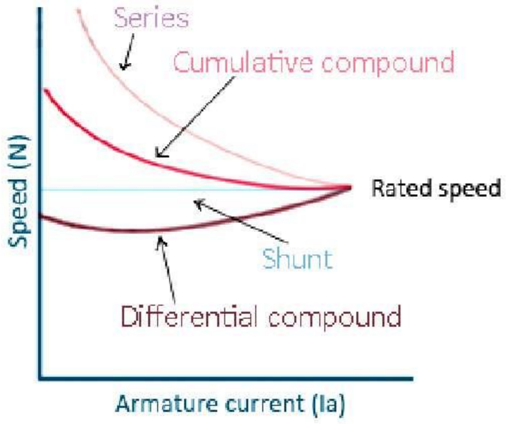
(a) Cumulative compound motor

Cumulative compound motors are used where series characteristics are required but the load is likely to be removed completely. Series winding takes care of the heavy load, whereas the shunt winding prevents the motor from running at dangerously high speed when the load is suddenly removed. These motors have generally employed a flywheel, where sudden and temporary loads are applied like in rolling mills.

(b) Differential compound motor

Since in differential field motors, series flux opposes shunt flux, the total flux decreases with increase in load. Due to this, the speed remains almost constant or even it may increase slightly with increase in load ($N \propto E_b/\phi$). Differential compound motors are not commonly used, but they find limited applications in experimental and research work.





SPEED CONTROL OF DC MOTOR:

The dc motor converts the mechanical power into dc electrical power. One of the most important features of the dc motor is that their speed can easily be control according to the requirement by using simple methods. Such type of control is impossible in an AC motor.

The concept of the speed regulation is different from the speed control. In speed regulation, the speed of the motor changes naturally whereas in dc motor the speed of the motor changes manually by the operator or by some automatic control device. The speed of the DC Motor is given by the relation shown below.

The equation (1) that the speed is dependent upon the supply voltage V, the armature circuit resistance R_a and the field flux ϕ, which is produced by the field current.

$$N = \frac{V - I_a R_a}{k\varphi} \quad \ldots\ldots\ldots\ldots (1)$$

For controlling the speed of DC Motor, the variation in voltage, armature resistance and field flux is taken into consideration. There are three general methods of speed control of a DC Motor. They are as follows.

1. Variation of resistance in the armature circuit.This method is called Armature Resistance or Rheostatic control.
2. Variation in field flux.This method is known as Field Flux Control.
3. Variation in applied voltage.This method is also known as Armature Voltage Control.

The detailed discussion of the various method of controlling the speed is given below.

Armature Resistance Control of DC Motor

Shunt Motor

The connection diagram of a shunt motor of the armature resistance control method is shown below. In this method, a variable resistor R_e is put in the armature circuit. The variation in the variable resistance does not effect the flux as the field is directly connected to the supply mains.

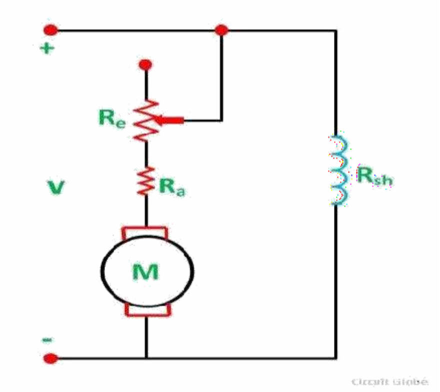


Fig: Connection diagram of a shunt motor of the armature resistance control method

The **speed current characteristic** of the shunt motor is shown below.

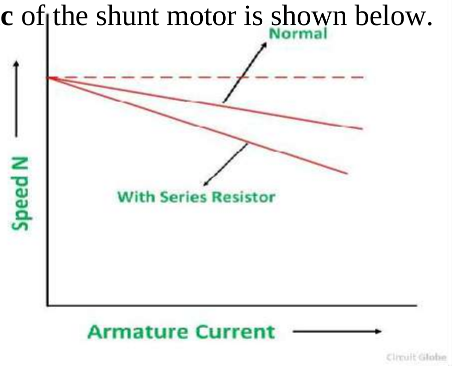


Fig: Speed current characteristic of the shunt motor

Series Motor:

Now, let us consider a connection diagram of speed control of the DC Series motor by the armature resistance control method.

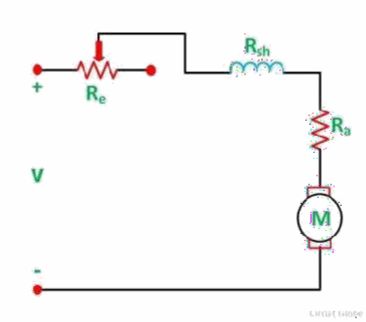


Fig: Diagram of speed control of the DC Series motor

By varying the armature circuit resistance, the current and flux both are affected. The voltage drop in the variable resistance reduces the applied voltage to the armature, and as a result, the speed of the motor is reduced.

The **speed–current characteristic** of a series motor is shown in the figure below.

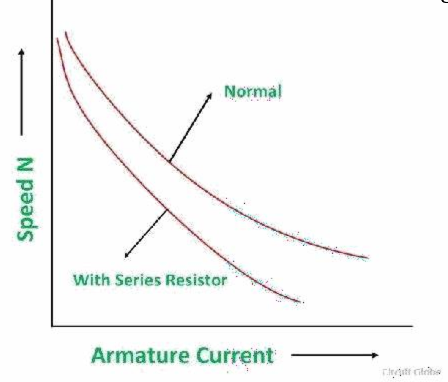


Fig: Speed–current characteristic of a series motor

When the value of variable resistance Re is increased, the motor runs at a lower speed. Since the variable resistance carries full armature current, it must be designed to carry continuously the full armature current.

Disadvantages of Armature Resistance Control Method

- A large amount of power is wasted in the external resistance Re.
- Armature resistance control is restricted to keep the speed below the normal speed of the motor and increase in the speed above normal level is not possible by this method.
- For a given value of variable resistance, the speed reduction is not constant but varies with the motor load.
- This speed control method is used only for small motors.

Field Flux Control Method of DC Motor

Flux is produced by the field current. Thus, the speed control by this method is achieved by control of the field current.

Shunt Motor

In a Shunt Motor, the variable resistor R_C is connected in series with the shunt field windings as shown in the figure below. This resistor R_C is known as a **Shunt Field Regulator.**

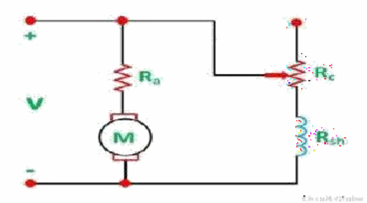


Fig: Shunt Field Regulator

The shunt field current is given by the equation shown below.

$$I_{sh} = \frac{V}{R_{sh} + R_C}$$

The connection of RC in the field reduces the field current, and hence the flux is also reduced. This reduction in flux increases the speed, and thus, the motor runs at speed higher than the normal speed. Therefore, this method is used to give motor speed above normal or to correct the fall of speed because of the load.

The **speed-torque curve** for shunt motor is shown below.

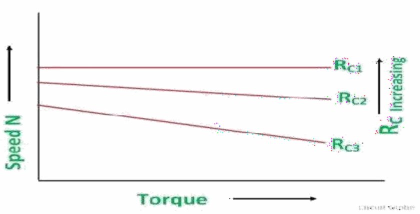


Fig: speed-torque curve for shunt motor

Series Motor

In a series motor, the variation in field current is done by any one method, i.e. either by a diverter or by a tapped field control.

By Using a Diverter:

A variable resistance R_d is connected in parallel with the series field windings as shown in the figure below.

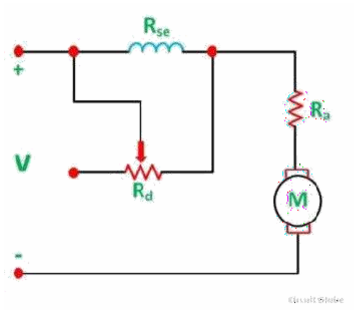


Fig: Diverter is connected in parallel with the series field windings

The parallel resistor is called a Diverter. A portion of the main current is diverted through a variable resistance R_d. Thus, the function of a diverter is to reduce the current flowing through the field winding. The reduction in field current reduces the amount of flux and as a result the speed of the motor increases.

Tapped Field Control:

The second method used in a series motor for the variation in field current is by tapped field control. The connection diagram is shown below.

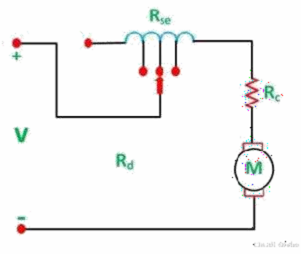


Fig: Tapped Field Control

Here the ampere turns are varied by varying the number of field turns. This type of arrangement is used in an electric traction system. The speed of the motor is controlled by the variation of the field flux. The speed-torque characteristic of a series motor is shown below.

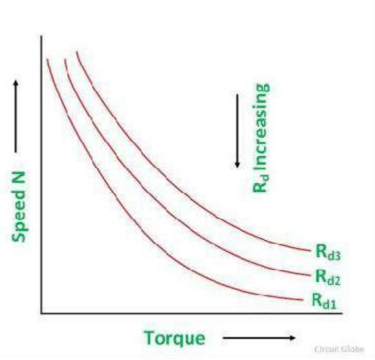


Fig: Speed-torque characteristic

Advantages of Field Flux Control

The following are the advantages of the field flux control method.

- This method is easy and convenient.
- As the shunt field is very small, the power loss in the shunt field is also small.

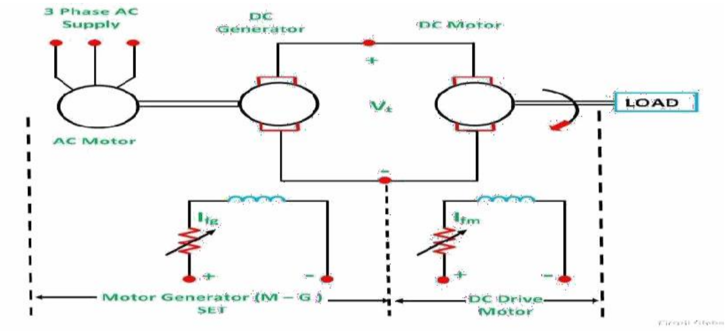
The flux cannot usually be increased beyond its normal values because of the saturation of the iron. Therefore, speed control by flux is limited to the weakening of the field, which gives an increase in speed. This method is applicable over only to a limited range because if the field is weakened too much, there is a loss of stability.

Armature Voltage Control of DC Motor

In armature voltage control method the speed control is achieved by varying the applied voltage in the armature winding of the motor. This speed control method is also known as **Ward Leonard Method**, which is discussed in detail under the topic Ward Leonard Method or Armature Voltage Control.

Ward Leonard Method Of Speed Control Or Armature Voltage Control

Ward Leonard Method of speed control is achieved by varying the applied voltage to the armature. This method was introduced in 1891. The connection diagram of the Ward Leonard method of speed control of a DC shunt motor is shown in the figure below.



In the above system, M is the main DC motor whose speed is to be controlled, and G is a separately excited DC generator.The generator G is driven by a 3 phase driving motor which may be an induction motor or a synchronous motor. The combination of AC driving motor and the DC generator is called the **Motor-Generator (M-G) set.**

The voltage of the generator is changed by changing the generator field current. This voltage when directly applied to the armature of the main DC motor, the speed of the motor M changes. The motor field current I_{fm} is kept constant so that the motor field flux ϕ_m also remains constant. While the speed of the motor is controlled, the motor armature current Ia is kept equal to its rated value.

The generated field current I_{fg} is varied such that the armature voltage $V_t$changes from zero to its rated value. The speed will change from zero to the base speed. Since the speed control is carried out with the

Need of Starters for DC Motors

The dc motor has no back EMF. At the starting of the motor, the armature current is controlled by the resistance of the circuit. The resistance of the armature is low, and when the full voltage is applied at the standstill condition of the motor, the armature current becomes very high which damage the parts of the motor.

Because of the high armature current, the additional resistance is placed in the armature circuit at starting. The starting resistance of the machine is cut out of the circuit when the machine gains it speeds. The armature current of a motor is given by

$$I_a = \frac{V - E}{R_a} \quad \ldots\ldots\ldots \quad (1)$$

Thus, I_a depends upon E and R_a, if V is kept constant. When the motor is first switched ON, the armature is stationary. Hence, the back EMF E_b is also zero. The initial starting armature current I_{as} is given by the equation shown below.

$$I_{as} = \frac{V - 0}{R_a} = \frac{V}{R_a} \quad \ldots\ldots\ldots\ldots (2)$$

Since, the armature resistance of a motor is very small, generally less than one ohm. Therefore, the starting armature current I_{as} would be very large. **For example** – if a motor with the armature resistance of 0.5 ohms is connected directly to a 230 V supply, then by putting the values in the equation (2) we will get.

$$I_{as} = \frac{V}{R_a} = \frac{230}{0.5} = 460 \quad \text{Ampere}$$

This large current would damage the brushes, commutator and windings.

As the motor speed increases, the back EMF increases and the difference (V – E) go on decreasing. This results in a gradual decrease of armature current until the motor attains its stable speed and the corresponding back EMF. Under this condition, the armature current reaches its desired value. Thus, it is found that the back EMF helps the armature resistance in limiting the current through the armature.

Since at the time of starting the DC Motor, the starting current is very large. At the time of starting of all DC Motors, except for very small motors, an extra resistance must be connected in series with the armature. This extra resistance is added so that a safe value of the motor is maintained and to limit the starting current until the motor has attained its stable speed.

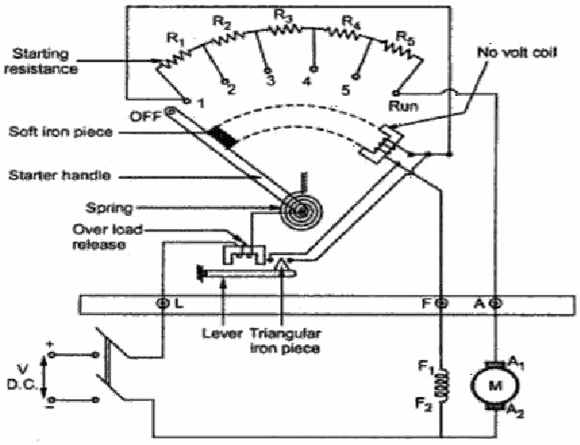
The series resistance is divided into sections which are cut out one by one, as the speed of the motor rises and the back EMF builds up. The extra resistance is cut out when the speed of the motor builds up to its normal value.

3 POINT STARTER

3 Point Starter is a device whose main function is starting and maintaining the speed of the DC shunt motor. The 3 point starter connects the resistance in series with the circuit which reduces the high starting current and hence protects the machines from damage. Mainly there are three main points or terminals in 3 point starter of DC motor. They are as follows

- **L** is known as Line terminal, which is connected to the positive supply.
- **A** is known as the armature terminal and is connected to the armature windings.
- **F** or **Z** is known as the field terminal and is connected to the field terminal windings.

The **3 Point DC Shunt Motor** Starter is shown in the figure below



3 point Starter

It consists of a graded resistance R to limit the starting current. The handle H is kept in the **OFF** position by a spring S. The handle H is manually moved, for starting the motor and when it makes contact with resistance stud one the motor is said to be in the **START** position. In this initial start position, the field winding of the motor receives the full supply voltage, and the armature current is limited to a certain safe value by the resistance (R = R1 + R2 + R3 + R4).

Working of 3 Point Starter

The starter handle is now moved from stud to stud, and this builds up the speed of the motor until it reaches the **RUN** position. The Studs are the contact point of the resistance. In the RUN position, three main points are considered. They are as follows.

- The motor attains the full speed.
- The supply is direct across both the windings of the motor.
- The resistance R is completely cut out.

The handle H is held in RUN position by an electromagnet energised by a **no volt trip coil (NVC)**. This no volt trip coil is connected in series with the field winding of the motor. In the event of switching OFF, or when the supply voltage falls below a predetermined value, or the complete failure of supply while the motor is running, NVC is energised. The handle is released and pulled back to the OFF position by the action of the spring. The current to the motor is cut off, and the motor is not restarted without a resistance R in the armature circuit. The no voltage coil also provides protection against an open circuit in the field windings.

The No Voltage Coil (NVC) is called **NO-VOLT** or **UNDERVOLTAGE** protection of the motor. Without this protection, the supply voltage might be restored with the handle in the RUN position. The full line voltage is directly applied to the armature. As a result, a large amount of current is generated.

The other protective device incorporated in the starter is the overload protection. The **Over Load Trip Coil (OLC)** and the **No Voltage Coil (NVC**) provide the overload protection of the motor. The overload coil is made up of a small electromagnet, which carries the armature current. The magnetic pull of the Overload trip coil is insufficient to attract the strip P, for the normal values of the armature current

When the motor is overloaded, that is the armature current exceeds the normal rated value, P is attracted by the electromagnet of the OLC and closes the contact aa thus, the No Voltage Coil is short-circuited, shown in the figure of 3 Point Starter. As a result, the handle H is released, which returns to the OFF position, and the motor supply is cut off.

To stop the motor, the starter handle should never be pulled back as this would result in burning the starter contacts. Thus, to stop the motor, the main switch of the motor should be opened.

Drawbacks of a 3 Point Starter

The following drawbacks of a 3 point starter are as follows:-

- The 3 point starter suffers from a serious drawback for motors with a large variation of speed by adjustment of the field rheostat.
- To increase the speed of the motor, the field resistance should be increased. Therefore, the current through the shunt field is reduced.
- The field current may become very low because of the addition of high resistance to obtain a high speed.
- A very low field current will make the holding electromagnet too weak to overcome the force exerted by the spring.
- The holding magnet may release the arm of the starter during the normal operation of the motor and thus, disconnect the motor from the line. This is not a desirable action.

Hence, to overcome this difficulty, the 4 Point Starter is used.

4 POINT STARTER

A 4 Point Starter is almost similar in functional characteristics like 3 Point Starter. In the absence of back EMF, the 4 Point Starter acts as a current limiting device while starting of the DC motor. 4 Point Starter also acts a protecting device.

The basic difference in 4 Point Starter as compared to 3 Point Starter is that in this a holding coil is removed from the shunt field circuit. This coil after removing is connected across the line in series with a current limiting resistance R. The studs are the contact points of the resistance represented by 1, 2, 3, 4, 5 in the figure below. The schematic connection diagram of a 4 Point Starter is shown below.

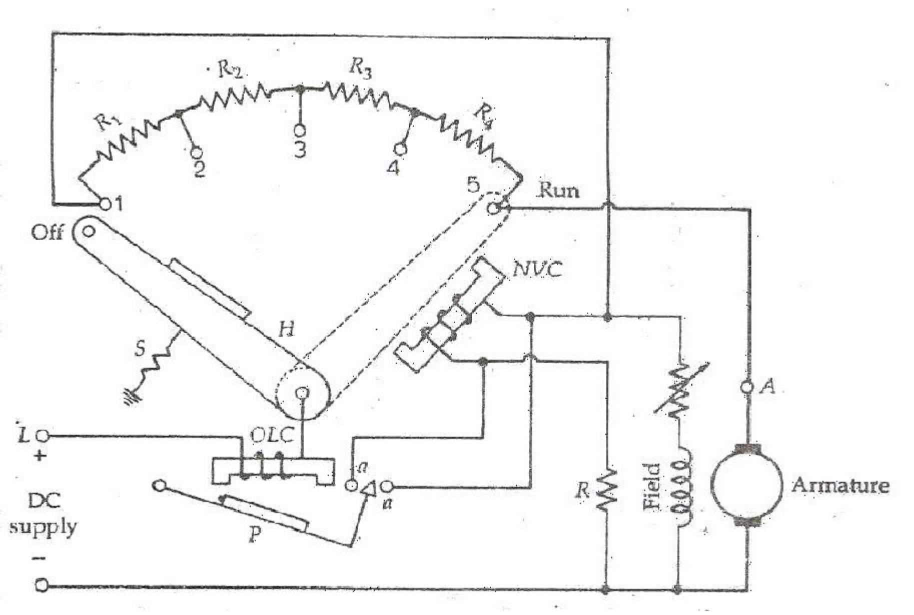


Fig: 4 Point Starter

The above arrangement forms three parallel circuits. They are as follows:-

- Armature, starting the resistance and the shunt field winding.
- A variable resistance and the shunt field winding.
- Holding coil and the current limiting resistance.

With the above three arrangements of the circuit, there will be no effect on the current through the holding coil if there is any variation in speed of the motor or any change in field current of the motor. This is because the two circuits are independent of each other.

The only limitation or the drawback of the 4 point starter is that it cannot limit or control the high current speed of the motor. If the field winding of the motor gets opened under the running condition, the field current automatically reduces to zero. But as some of the residual flux is still present in the motor, and we know that the flux is directly proportional to the speed of the motor. Therefore, the speed of the motor increases drastically, which is dangerous and thus protection is not possible. This sudden increase in the speed of the motor is known as High-Speed Action of the Motor.

Nowadays automatic push button starters are also used. In the automatic starters, the ON push button is pressed to connect the current limiting starting resistors in series with the armature circuit. As soon as the full line voltage is available to the armature circuit, this resistor is gradually disconnected by an automatic controlling arrangement.

The circuit is disconnected when the OFF button is pressed. Automatic starter circuits have been developed using electromagnetic contactors and time delay relays. The main advantage of the automatic starter is that it enables even the inexperienced operator to start and stop the motor without any difficulty.

LOSSES IN DC MACHINE

The losses that occur in a DC Machine is divided into five basic categories. The various losses are Electrical or Copper losses (I^2R losses), Core losses or Iron losses, Brush losses, Mechanical losses, Stray load losses. These losses are explained below in detail.

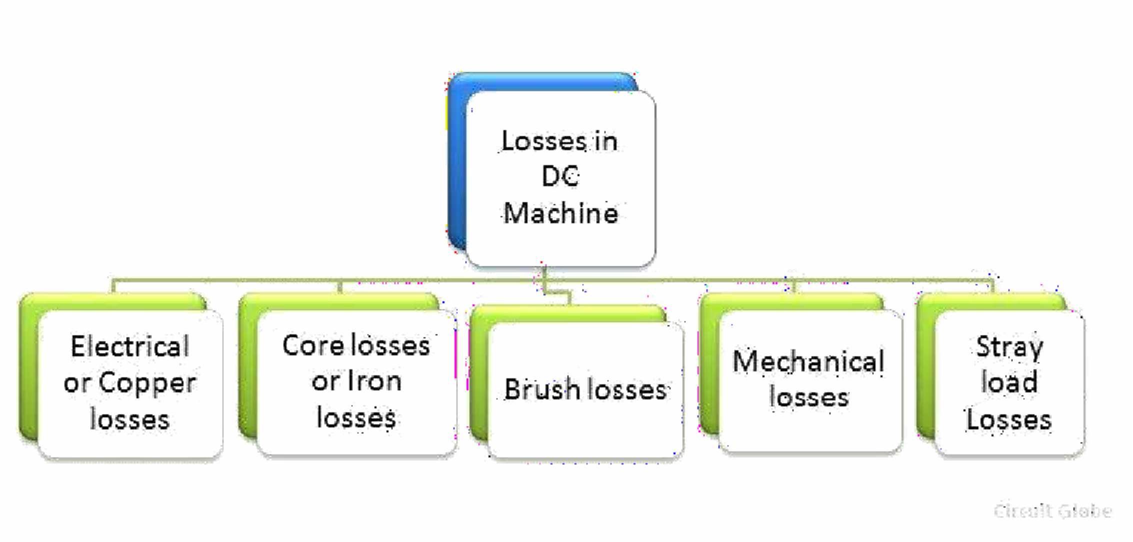


Fig: Classification of losses in DC machnes

Electrical or Copper Losses in dc machine

These losses are also known as Winding losses as the copper loss occurs because of the resistance of the windings. The ohmic loss is produced by the current flowing in the windings. The windings that are present in addition to the armature windings are the field windings, interpoles and compensating windings.

Armature copper losses = $I_a^2R_a$ where I_a is armature current, and Ra is the armature resistance. These losses are about 30 percent of the total full load losses.

In shunt machine, the Copper loss in the shunt field is $I^2_{sh}R_{sh}$, where I_{sh} is the current in the shunt field, and R_{sh} is the resistance of the shunt field windings. The shunt regulating resistance is included in R_{sh}.

In a series machine, the copper loss in the series windings is $I_{se}^2 R_{se}$, where, I_{se} is the current through the series field windings, and R_{se} is the resistance of the series field windings.

In a Compound machine, both the shunt and the series field losses occur. These losses are almost 20 percent of the full load losses.

Copper losses in the interpole windings are written as $I_a^2 R_i$ where R_i is the resistance of the interpole windings.

Copper loss in the compensating windings if any is $I_a^2 R_c$ where R_c is the resistance of compensating windings.

Magnetic Losses or Core Losses or Iron Losses in dc machine

The core losses are the hysteresis and eddy current losses. These losses are considered almost constant as the machines are usually operated at constant flux density and constant speed. These losses are about 20 percent of the full load losses.

Brush Losses in dc machine

Brush losses are the losses taking place between the commutator and the carbon brushes. It is the power loss at the brush contact point. The brush drop depends upon the brush contact voltage drop and the armature current Ia. It is given by the equation shown below.

The voltage drop occurring over a large range of armature currents, across a set of brushes is approximately constant If the value of brush voltage drop is not given than it is usually assumed to be about 2 volts. Thus, the brush drop loss is taken as $2I_a$.

Mechanical Losses in dc machine

The losses that take place because of the mechanical effects of the machines are known as mechanical losses. Mechanical losses are divided into bearing friction loss and windage loss. The losses occurring in the moving parts of the machine and the air present in the machine is known as Windage losses. These losses are very small.

Stray Losses in dc machine

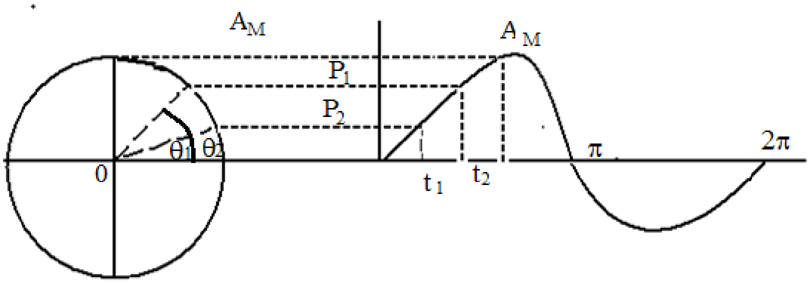
These losses are the miscellaneous type of losses. The following factors are considered in stray load losses.

- The distortion of flux because of armature reaction.
- Short circuit currents in the coil, undergoing commutation.

These losses are very difficult to determine. Therefore, it is necessary to assign the reasonable value of the stray loss. For most machines, stray losses are taken by convention to be one percent of the full load output power.

AC CIRCUIT

Phasor or Vector Representation of Alternating Quantity :→



An alternating current or voltage, (quantity) in a vector quantity which has magnitude as well as direction. Let the alternating value of current be represented by the equation e = E_m Sin wt. The projection of E_m on Y-axis at any instant gives the instantaneous value of alternating current. Since the instantaneous values are continuously changing, so they are represented by a rotating vector or phasor. A phasor is a vector rotating at a constant angular velocity

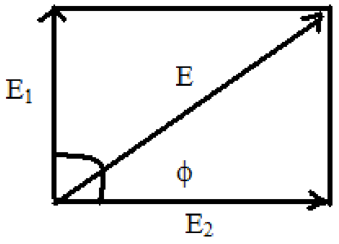
At $t_1, e_1 = E_{m_1} \sin wt_1$

At $t_2, e_2 = E_{m_2} \sin wt_2$

Addition of two alternating Current :→

Let $e_1 = E_{m_1} \sin wt$

$e_2 = E_{m_2} \sin(wt - \phi)$



The sum of two sine waves of the same frequency is another sine wave of same frequency but of a different maximum value and Phase.

$$e = \sqrt{e_1^2 + e_2^2 + 2e_1 e_2 \cos\phi}$$

Phasor Algebra :→

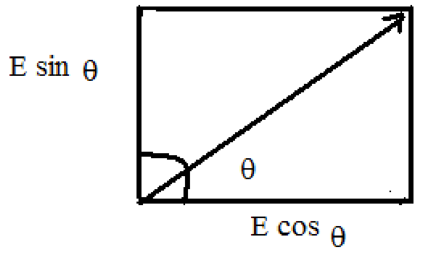
A vector quantity can be expressed in terms of

(i) Rectangular or Cartesian form

(ii) Trigonometric form

(iii) Exponential form

(iv) Polar form



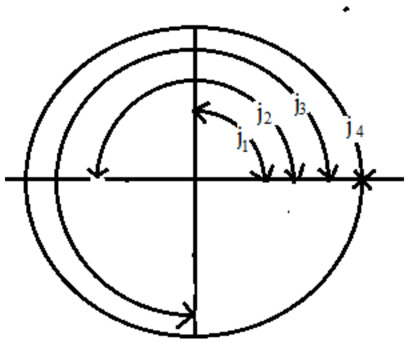
$$E = a + jb$$
$$= E(\cos\theta + j\sin\theta)$$

Where a = E cos θ is the active part

b = E sin θ is the reactive part

$\theta = \tan^{-1}\left(\frac{b}{a}\right)$ = Phase angle

$$j = \sqrt{-1}(90^o)$$
$$j^2 = -1(180^o)$$
$$j^3 = -j(270^o)$$
$$j^4 = 1 \ \ (360^o)$$



(i) Rectangular for :-

$$E = a \pm jb$$
$$\tan\theta = b/a$$

(ii) Trigonometric form :-

$$E = E(\cos\theta \pm j\sin\theta)$$

(iii) Exponential form :-

$$E = Ee^{\pm j\theta}$$

(iv) Polar form :-

$$E = E/ \pm e \qquad (E = \sqrt{a^2 + b^2})$$

Addition or Subtration :-

$$E_1 = a_1 + jb_1$$
$$E_2 = a_2 + jb_2$$
$$E_1 \pm E_2 = (a_1 + a_2) \pm (b_1 + b_2$$
$$\phi = \tan^{-1}\left(\frac{b_1 + b_2}{a_1 + a_2}\right)$$

Multiplication : -

$$E_1 \times E_2 = (a_1 + ja_1) \pm (a_1 + jb_2)$$
$$= (a_1a_2 - b_1b_2) + j(a_1a_2 + b_1b_2)$$

$$\phi = \tan^{-1}\left(\frac{a_1b_2 + b_1a_2}{a_1a_2 - b_1b_2}\right)$$

$$E_1 = E_1\angle\theta_1$$

$$E_2 = E_2\angle\theta_2$$

$$E_1 \times E_2 = E_1E_2 \quad \angle\phi_1 + \phi_2$$

Division :-

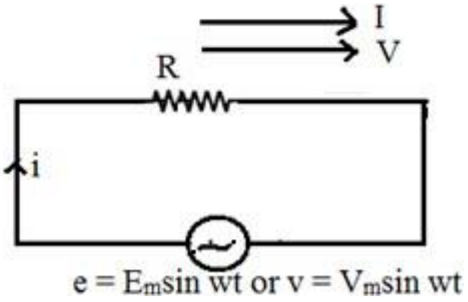
$$E_1 = E_1\angle\theta_1$$

$$E_2 = E_2\angle\theta_2$$

$$\frac{E_1}{E_2} = \frac{E_1\angle\theta_1}{E_2\angle\theta_2} = \frac{E_1}{E_2}\angle\theta_1 - \theta_2$$

A.C. through Pure Resistance :→

Let the resistance of R ohm is connected across to A.C supply of applied voltage



$e = E_m \sin wt$ ------------------------- (1)

Let ‘I’ is the instantaneous current .

Here $e = iR$

$\Rightarrow i = e/R$

$i = E_m \sin wt / R$----------------------- (2)

By comparing equation (1) and equation (2) we get alternating voltage and current in a pure resistive circuit are in phase

Instantaneous power is given by

P = ei

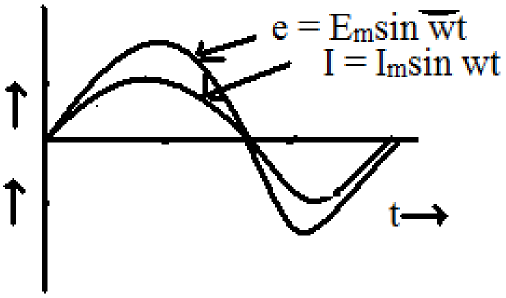
$= E_m \sin wt \,.\, I_m \sin wt$

$= E_m I_m \sin^2 wt$

$$= \frac{E_m I_m}{2} . 2\sin^2 wt$$

$$= \frac{E_m}{\sqrt{2}} . \frac{I_m}{\sqrt{2}} . (1 - \cos 2wt)$$

$$P = \frac{E_m}{\sqrt{2}} . \frac{I_m}{\sqrt{2}} - \frac{E_m}{\sqrt{2}} . \frac{I_m}{\sqrt{2}} . \cos 2wt$$



i.e. $P = \frac{V_m}{\sqrt{2}} . \frac{I_m}{\sqrt{2}} - \frac{V_m}{\sqrt{2}} . \frac{I_m}{\sqrt{2}} . \cos 2wt$

Where $\frac{V_m}{\sqrt{2}}.\frac{I_m}{\sqrt{2}}$ is called constant part of power.

$\frac{V_m}{\sqrt{2}}.\frac{I_m}{\sqrt{2}}\cos 2wt$ is called fluctuating part of power.

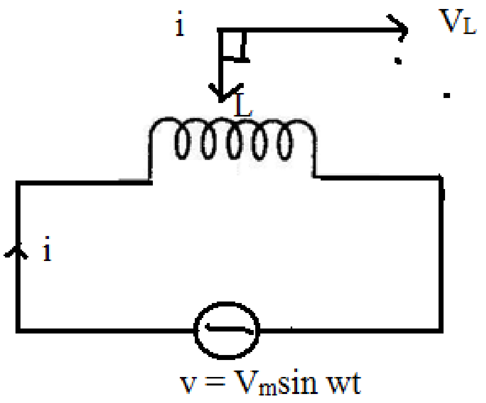
The fluctuating part $\frac{V_m I_m}{2}.\cos 2wt$ of frequency double that of voltage and current waves.

Hence power for the whole cycle is $P = \frac{V_m}{\sqrt{2}}.\frac{I_m}{\sqrt{2}} = V_{rms}.I_{rms}$

$$\boxed{\Rightarrow P = VI \text{ watts}}$$

A.C through Pure Inductance :→

Let inductance of ‘L’ henry is connected across the A.C. supply

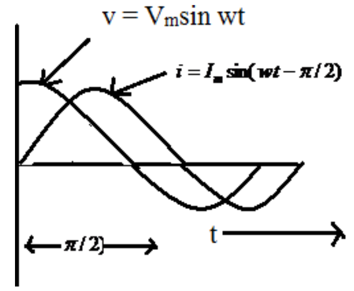


$v = V_m \sin wt$ -------------------------- (1)

According to Faraday’s laws of electromagnetic inductance the emf induced across the inductance

$$V = L\frac{di}{dt}$$

$\frac{di}{dt}$ is the rate of change of current



$$V_m \sin wt = L\frac{di}{dt}$$

$$\frac{di}{dt} = \frac{V_m \sin wt}{L}$$

$$\Rightarrow di = \frac{V_m}{L}\sin wt.dt$$

Integrating both sides,

$$\int di = \int \frac{V_m}{L}\sin wt.dt$$

$$i = \frac{V_m}{L}\left(-\frac{\cos wt}{w}\right)$$

$$i = -\frac{V_m \cos wt}{wL}$$

$$i = -\frac{V_m}{wL}\cos wt$$

$$i = -\frac{V_m}{wL}\sin\left(wt - \frac{\pi}{2}\right)$$

$$= -\frac{V_m}{X_L}\sin\left(wt - \frac{\pi}{2}\right) \quad [\because X_L = 2\pi fL = wL]$$

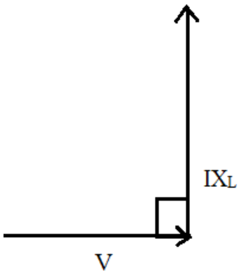
Maximum value of i is $I_m = \frac{V_m}{X_L}$ when $\sin\left(wt - \frac{\pi}{2}\right)$ is unity.

Hence the equation of current becomes $i = I_m \sin(wt - \pi/2)$

So we find that if applied voltage is rep[resented by $v = V_m \sin wt$, then current flowing in a purely inductive circuit is given by

$$i = I_m \sin(wt - \pi/2)$$

Here current lags voltage by an angle π/2 Radian.



Power factor = cos ϕ

= cos 90°

= 0

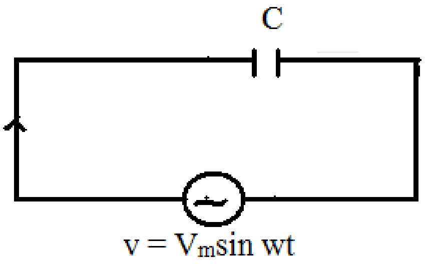
Power Consumed = VI cos ϕ

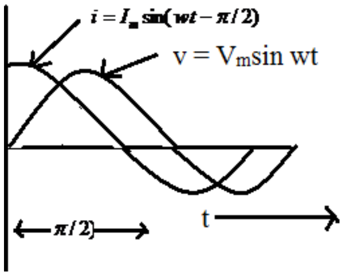
= VI × 0

= 0

Hence, the power consumed by a purely Inductive circuit is zero.

A.C. Through Pure Capacitance : →





Let a capacitance of ‘C” farad is connected across the A.C. supply of applied voltage

$$v = V_m \sin wt \text{-----------------------------------} (1)$$

Let ‘q’ = change on plates when p.d. between two plates of capacitor is ‘v’

$$q = cv$$

$$q = cV_m \sin wt$$

$$\frac{dq}{dt} = c\frac{d}{dt}(V_m \sin wt)$$

$$i = cV_m \sin wt$$

$$= wcV_m \cos wt$$

$$= \frac{V_m}{1/wc} = \cos wt$$

$$= \frac{V_m}{Xc} = \cos wt$$ [$\therefore X_c = \frac{1}{wc} = \frac{1}{2\pi fc}$ is known as capacitive reactance in ohm.]

$$= I_m \cos wt$$

$$= I_m \sin(wt + \pi/2)$$

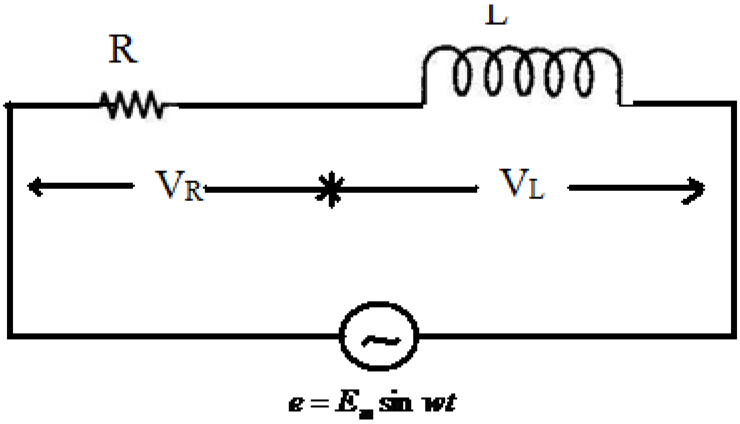
Here current leads the supply voltage by an angle π/2 radian.

Power factor = cos ϕ
= cos 90° = 0

Power Consumed = VI cos ϕ
= VI × 0 = 0

The power consumed by a pure capacitive circuit is zero.

A.C. Through R-L Series Circuit : →



The resistance of R-ohm and inductance of L-henry are connected in series across the A.C. supply of applied voltage

$e = E_m \sin wt$ ----------------------------(1)

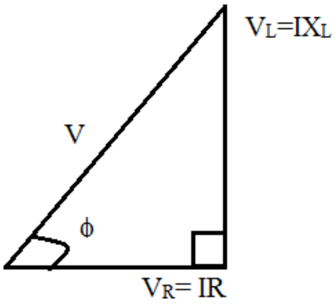
$$V = V_R + jV_L$$

$$= \sqrt{V_R^2 + V_L^2}\angle\phi = \tan^{-1}\left(\frac{X_L}{R}\right)$$

$$= \sqrt{(IR)^2 + (IX_L)^2}\angle\phi = \tan^{-1}\left(\frac{X_L}{R}\right)$$

$$= I\sqrt{R^2 + X_L^2}\angle\phi = \tan^{-1}\left(\frac{X_L}{R}\right)$$

$$V = IZ\angle\phi = \tan^{-1}\left(\frac{X_L}{R}\right)$$



Where $Z = \sqrt{R^2 + X_L^2}$

$= R + jX_L$ is known as impedance of R-L series Circuit.

$$I = \frac{V}{Z\angle\phi} = \frac{E_m \sin wt}{Z\angle\phi}$$

$$I = I_m \sin(wt - \phi)$$

Here current lags the supply voltage by an angle ϕ.

Power Factor :→ It is the cosine of the angle between the voltage and current.

OR

It is the ratio of active power to apparent power.

OR

It is the ratio of resistance to inpedence .

Power :→

$$= v.i$$

$$= V_m \sin wt . I_m \sin(wt - \phi)$$

$$= V_m I_m \sin wt . \sin(wt - \phi)$$

$$= \frac{1}{2} V_m I_m \; 2 \sin wt . \sin(wt - \phi)$$

$$= \frac{1}{2} V_m I_m \; [\cos\phi - \cos 2(wt - \phi)]$$

Obviously the power consists of two parts.

(i) a constant part $\frac{1}{2} V_m I_m \cos\phi$ which contributes to real power.

(ii) a pulsating component $\frac{1}{2} V_m I_m \cos(2wt - \phi)$ which has a frequency twice that of the voltage and current. It does not contribute to actual power since its average value over a complete cycle is zero.

Hence average power consumed

$$= \frac{1}{2} V_m I_m \cos\phi$$

$$= \frac{V_m}{\sqrt{2}} . \frac{I_m}{\sqrt{2}} \cos\phi$$

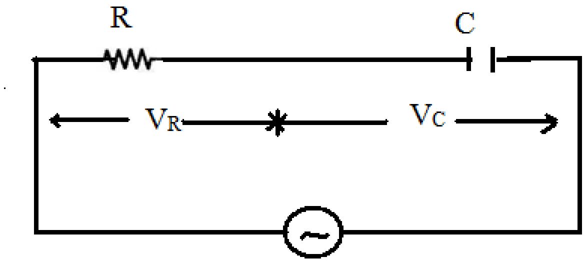
$$= VI \cos\phi$$

Where V & I represents the r.m.s value.

A.C. Through R-C Series Circuit : →

The resistance of ‘R’-ohm and capacitance of ‘C’ farad is connected across the A.C. supply of applied voltage

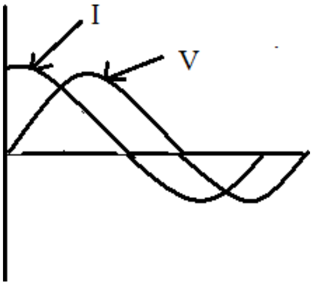
$e = E_m \sin wt$ ------------------------------(1)



$$V = V_R + (-jV_C)$$
$$= IR + (-jIX_C)$$
$$= I(R - jX_C)$$
$$V = IZ$$

Where $Z = R - jX_C = \sqrt{R^2 + X_C^2}$ is known as impedance of R-C series Circuit.

$$Z = R - jX_C$$
$$= \sqrt{R^2 + X_C^2}$$
$$\angle -\phi = \tan^{-1}\left(\frac{X_C}{R}\right)$$

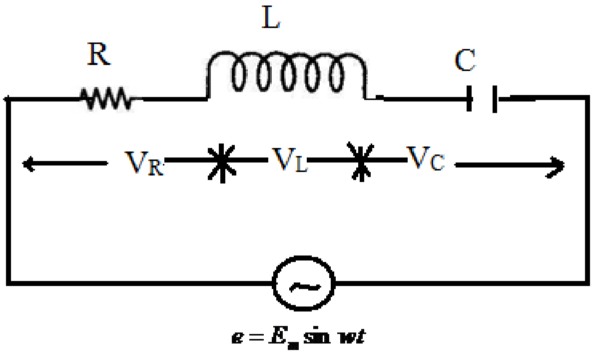


$$V = IZ\angle -\phi$$
$$\Rightarrow I = \frac{V}{Z\angle -\phi}$$
$$= \frac{E_m \sin wt}{Z\angle -\phi}$$
$$= \frac{E_m}{Z\angle}\sin(wt + \phi)$$
$$\Rightarrow I = I_m \sin(wt + \phi)$$

Here current leads the supply voltage by an angle ‘ϕ’.

A.C. Through R-L-C Series Circuit : →

Let a resistance of ‘R’-ohm inductance of ‘L’ henry and a capacitance of ‘C’ farad are connected across the A.C. supply in series of applied voltage



$e = E_m \sin wt$ --------------------------------- (1)

$$
\begin{aligned}
e &= \vec{V}_R + \vec{V}_L + \vec{V}_C \\
&= V_R + jV_L - jV_C \\
&= V_R + j(V_L - V_C) \\
&= I_R + j(IX_L - IX_C) \\
&= I[R + j(X_L - X_C)] \\
&= I\sqrt{R^2 + (X_L - X_C)^2} \quad \angle \pm \phi = \tan^{-1}\left(\frac{X_L - X_C}{R}\right) \\
&= IZ\angle \pm \phi
\end{aligned}
$$

Where $Z = I\sqrt{R^2 + (X_L - X_C)^2}$ is known as the impedance of R-L-C Series Circuit.

If $X_L > X_C$, then the angle is +ve.

If $X_L < X_C$, then the angle is -ve.

Impedance is defined as the phasor sum of resistance and net reactance

$$
e = IZ\angle \pm \phi
$$

$$
\Rightarrow I = \frac{e}{Z\angle \pm \phi} IZ\angle \pm \phi \quad = \frac{E_m \sin wt}{Z\angle \pm \phi} \quad = I_m \sin(wt \pm \phi)
$$

(1) If $X_L > X_C$, then P.f will be lagging.

(2) If $X_L < X_C$, then, P.f will be leading.

(3) If $X_L = X_C$, then, the circuit will be resistive one. The p.f. becomes unity and the resonance occurs.

REASONANCE

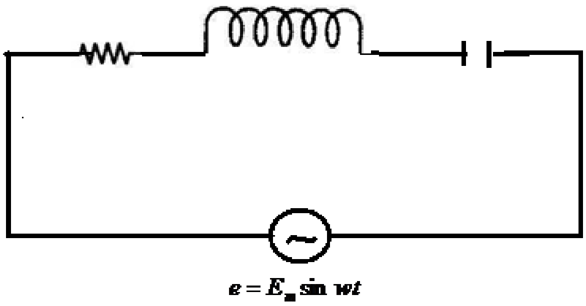
It is defined as the resonance in electrical circuit having passive or active elements represents a particular state when the current and the voltage in the circuit is maximum and minimum with respect to the magnitude of excitation at a particular frequency and the impedances being either minimum or maximum at unity power factor

Resonance are classified into two types.

(1) Series Resonance

(2) Parallel Resonance

(1) Series Resonance :- Let a resistance of ‘R’ ohm, inductance of ‘L’ henry and capacitance of ‘C’ farad are connected in series across A.C. supply



$$e = E_m \sin wt$$

The impedance of the circuit

$$Z = R + j(X_L - X_C)]$$

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

The condition of series resonance:

The resonance will occur when the reactive part of the line current is zero

The p.f. becomes unity.

The net reactance will be zero.

The current becomes maximum.

At resonance net reactance is zero

$$X_L - X_C = 0$$

$$\Rightarrow X_L = X_C$$

$$\Rightarrow W_o L = \frac{1}{W_o C}$$

$$\Rightarrow W_o^2 LC = 1$$

$$\Rightarrow W_o^2 = \frac{1}{LC}$$

$$\Rightarrow W_o = \frac{1}{\sqrt{LC}}$$

$$\Rightarrow 2\pi f_o = \frac{1}{\sqrt{LC}}$$

$$\Rightarrow f_o = \frac{1}{2\pi\sqrt{LC}}$$

Resonant frequency $(f_o) = \frac{1}{2\pi} \cdot \frac{1}{\sqrt{LC}}$

Impedance at Resonance

$Z_0 = R$

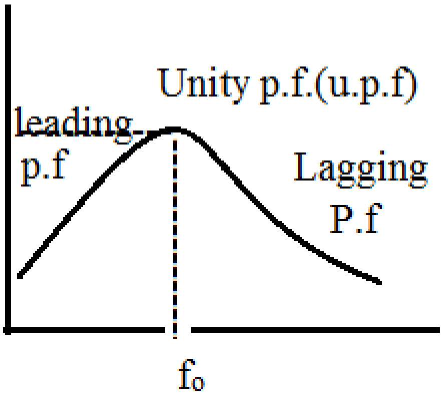
Current at Resonance

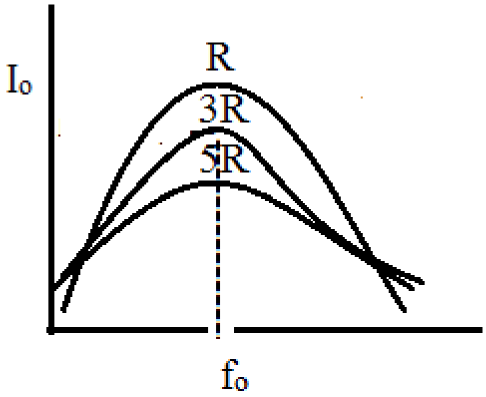
$$I_o = \frac{V}{R}$$

Power factor at resonance

$$p.f. = \frac{R}{Z_o} = \frac{R}{R} = 1 \qquad [\because Z_o = R]$$

Resonance Curve :-





At low frequency the X_c is greater and the circuit behaves leading and at high frequency the X_L becomes high and the circuit behaves lagging circuit.

If the resistance will be low the curve will be stiff (peak).

- If the resistance will go oh increasing the current goes on decreasing and the curve become flat.

Band Width :→

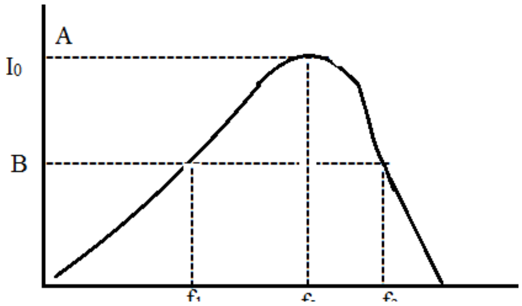
At point 'A' the power loss is I_0^2R.

The frequency is f_0 which is at resonance.

At point 'B' the power loss is $\frac{I_0^2R}{2}$.

The power loss is 50% of the power loss at point

'A"/



Hence the frequencies corresponding to point 'B' is known as half power frequencies f_1 & f_2.

f_1 = Lower half power frequency

$$f_1 = f_0 - \frac{R}{4\pi L}$$

F_2 = Upper half power frequency

$$f_2 = f_0 + \frac{R}{4\pi L}$$

Band width (B.W.) is defined as the difference between upper half power frequency ad lower half power frequency.

B.W. = $f_2 - f_1 = \frac{R}{2\pi L}$

Selectivity : →

Selectivity is defined as the ratio of Band width to resonant frequency

Selectivity = $\frac{B.W.}{f_0} = \frac{R}{2\pi L}$ $\quad Selectivity = \frac{R}{2\pi f_o L}$

Quality Factor (Q-factor) :→

It is defined as the ratio of 2π × Maximum energy stored to energy dissipated per cycle

Q-factor $= \frac{2\pi \times \frac{1}{2} L I_0^2}{I^2 RT}$

$$= \frac{\pi L \left(\sqrt{2} I\right)^2}{I^2 RT}$$

$$= \frac{\pi L.2I^2}{I^2 RT}$$

$$= \frac{\pi L.2I^2}{I^2 RT}$$

$$= \frac{2\pi L.}{RT}$$

$$\boxed{\text{Quality factor} = = \frac{2\pi f_0 L.}{R}}$$

$$\overset{\Upsilon}{\underset{\leq}{,}} Q = \frac{1.}{I} = f_0 / \overset{\infty}{f}$$

Quality factor is defined as the reciprocal of power factor.

$$\boxed{\text{Q factor} = = \frac{1.}{\cos\phi}}$$

It is the reciprocal of selectivity.

Q-factor Or Magnification factor $= \frac{\text{Voltage across Inductor.}}{\text{Voltage across resistor}}$

$$= \frac{I_0 X_L}{I_0 R}$$

$$= \frac{X_L}{R}$$

$$= \frac{2\pi f_0 L}{R} = \frac{W_0 L}{R}$$

$$\boxed{\text{Q- factor} = = \frac{W_0 L}{R}}$$

Q-factor factor $= \frac{\text{Voltage across Capacotor.}}{\text{Voltage across resistor}}$

$$= \frac{I_0 X_c}{I_0 R}$$

$$=\frac{X_C}{R}$$

$$=\frac{1}{2\pi f_0 C}=\frac{1}{2\pi f_0 CR}$$

$$\boxed{\text{Q-factor}=\frac{1}{W_0 CR}}$$

$$Q^2=\frac{W_0 L}{R}\times\frac{1}{W_0 CR}$$

$$Q^2=\frac{1}{R^2 C}$$

$$Q=\sqrt{\frac{1}{R^2}}$$

$$\boxed{Q=\frac{1}{R}\sqrt{\frac{L}{C}}}$$

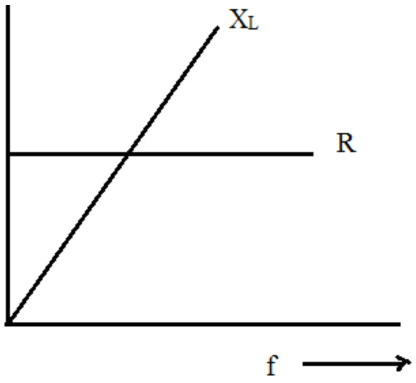
Graphical Method :→

(1) Resistance is independent of frequency It represents a straight line.

(2) Inductive Reactance $X_L = 2\pi fL$

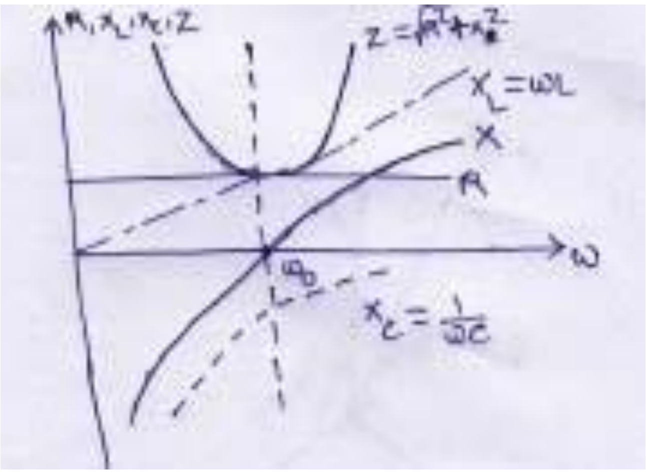
It is directly proportional to frequency. As the frequency increases , X_L increases

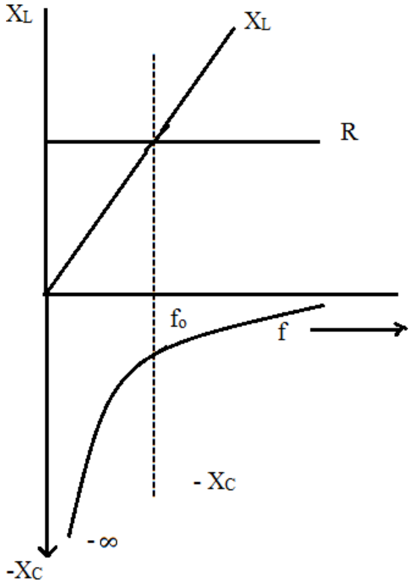
(3) Capacitive Reactance $X_C = \; = \frac{1}{2\pi fC}$



It is inversely proportional to frequency. As the frequency increases, X_C decreases.

When frequency increases, X_L increases and X_C decreases from the higher value.



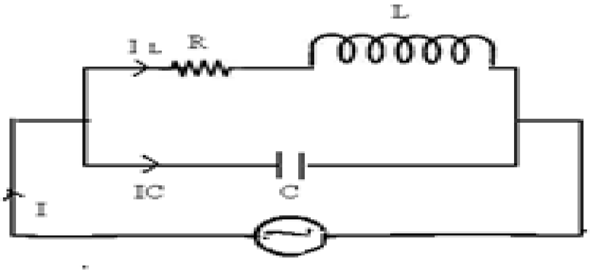


At a certain frequency. $X_L = X_C$

That particular frequency is known as Resonant frequency.

Variation of circuit parameter in series resonance:

(2) Parallel Resonance :- Resonance will occur when the reactive part of the line current is zero.



At resonance,

$I_C - I_L \sin\phi = 0$

$I_C = I_L \sin\phi$

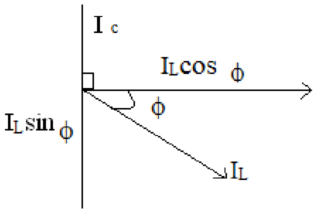
$$\Rightarrow \frac{V}{X_C} = \frac{V}{\sqrt{R^2 + X_L^2}} \sin\phi$$

$$\Rightarrow \frac{V}{X_C} = \frac{V}{\sqrt{R^2 + X_L^2}} \times \frac{X_L}{\sqrt{R^2 + X_L^2}}$$

$$\Rightarrow \frac{1}{X_C} = \frac{X_L}{R^2 + X_L^2}$$

$$\Rightarrow R^2 + X_L^2 = X_L . X_C$$

$$\Rightarrow Z^2 == X_L . X_C = W_0 L \times \frac{1}{W_0 C}$$



$$Z^2 = \frac{L}{C}$$

$$\Rightarrow R^2 + X_L{}^2 = \frac{L}{C}$$

$$\Rightarrow R^2 + (2\pi f_0 L)^2 = \frac{L}{C}$$

$$\Rightarrow R^2 + 4\pi^2 f_0^2 L^2 = \frac{L}{C}$$

$$\Rightarrow 4\pi^2 f_0^2 L^2 = \frac{L}{C} - R^2$$

$$\Rightarrow f_0^2 = \frac{1}{4\pi^2 f_0^2 L^2} = \left(\frac{L}{C} - R^2\right)$$

$$\Rightarrow f_0 = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{R^2}{L^2}}$$

f_0 = Resonant frequency in parallel circuit.

Current at Resonance = $I_L \cos\phi$

$$= \frac{V}{\sqrt{R^2 + X_L{}^2}} \cdot \frac{R}{\sqrt{R^2 + X_L{}^2}}$$

$$= \frac{VR}{R^2 + X_L^2}$$

$$= \frac{VR}{Z^2}$$

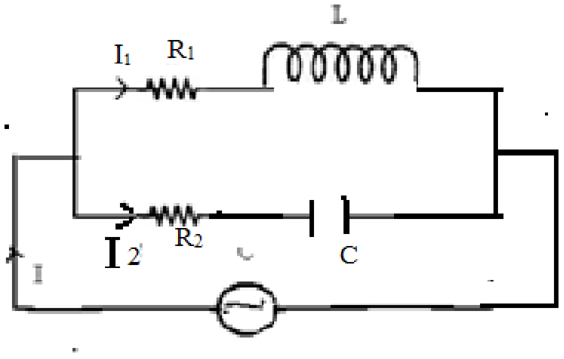
$$= \frac{VR}{L/C} = \frac{V}{L/RC}$$

$$= \frac{\text{V}}{\text{Dynamic Impedence}}$$

L/RC → Dynamic Impedance of the circuit.

or, dynamic impedances is defined as the impedance at resonance frequency in parallel circuit.

Parallel Circuit :→



The parallel resonance condition:

When the reactive part of the line current is zero.
The net reactance is zero.
The line current will be minimum.
The power factor will be unity

Impedance $Z_1 = R_1 + jX_L$

$Z_2 = R_2 - jX_C$

Admittance $Y_1 = \frac{1}{Z_1} = \frac{1}{R_1 + jX_L}$

$$= \frac{(R_1 + jX_L)}{(R_1 + jX_L)(R_1 - jX_L)}$$

$$= \frac{R_1 + jX_L}{R_1^2 + X_L^2}$$

$$Y_1 = \frac{R_1}{R_1^2 + X_L^2} - j\frac{X_L}{R_1^2 + X_L^2}$$

Admittance $Y_2 = \frac{1}{Z_2} = \frac{1}{R_1 + jX_C}$

$$= \frac{(R_2 + jX_C)}{(R2_1 - jX_C)(R_2 + jX_C)}$$

$$= \frac{R_2 + jX_L}{R_2^2 + X_C^2}$$

$$Y_2 = \frac{R_2}{R_2^2 + X_C^2} + j\frac{X_C}{R_2^2 + X_C^2}$$

Total Admittance Admittance $\left(\frac{1}{Z}\right) = \frac{1}{Z_1} + \frac{1}{Z_2}$

$$\Rightarrow Y = Y_1 + Y_2$$

$$\Rightarrow Y = \frac{R_1}{R_1^2 + X_L^2} - j\frac{X_L}{R_1^2 + X_L^2} + \frac{R2}{R_2^2 + X_C^{\ 2}} + j\frac{X_C}{R_2^2 + X_C^2}$$

$$\Rightarrow Y = \frac{R_1}{R_1^2 + X_L^2} + \frac{R2}{R_2^2 + X_C^2} - j\left[\frac{X_L}{R_1^2 + X_L^2} - \frac{X_C}{R_2^2 + X_C^2}\right]$$

At Resonance,

$$\frac{X_L}{R_1^2 + X_L^2} - \frac{X_C}{R_2^2 + X_C^2} = 0$$

$$\Rightarrow \frac{X_L}{R_1^2 + X_L^2} = \frac{X_C}{R_2^2 + X_C^2}$$

$$\Rightarrow X_L\left(R_2^2 + X_C^2\right) = X_C\left(R_1^2 + X_L^2\right)$$

$$\Rightarrow 2\pi fL\left[R_2^2 + \frac{1}{4\pi^2 f^2 C^2}\right] = \frac{1}{2\pi fC}\left(R_1^2 + 4\pi^2 f^2 L^2\right)$$

$$\Rightarrow 2\pi fLR_2^2 + \frac{L}{2\pi fC^2} = \frac{R_1^2}{2\pi fC} + \frac{2\pi fL^2}{C}$$

$$\Rightarrow \frac{L}{2\pi f C^2} - \frac{R_1^2}{2\pi f C} = \frac{2\pi f L^2}{C} - 2\pi f L R_2^2$$

$$\Rightarrow \frac{1}{2\pi f C}\left(\frac{L}{C} - R_1^2\right) = 2\pi f L\left(\frac{L}{C} - R_2^2\right)$$

$$\Rightarrow 4\pi^2 f^2 LC = \frac{\frac{L}{C} - R_1^2}{\frac{L}{C} - R_2^2} = \frac{L - CR_1^2}{L - CR_2^2}$$

$$\Rightarrow 4\pi^2 f^2 = \frac{1}{LC}\left(\frac{L - CR_1^2}{L - CR_2^2}\right)$$

$$\Rightarrow f^2 = \frac{1}{4\pi^2 LC}\left(\frac{L - CR_1^2}{L - CR_2^2}\right)$$

$$\Rightarrow f = \frac{1}{2\pi\sqrt{LC}}\sqrt{\left(\frac{L - CR_1^2}{L - CR_2^2}\right)}$$

$$\Rightarrow f = \frac{1}{2\pi}\sqrt{\left(\frac{L - CR_1^2}{L^2C - LC^2R_2^2}\right)}$$

f is called Resonant frequency.

If $R_2 = 0$

Then $f = \frac{1}{2\pi}\sqrt{\frac{L - CR_1^2}{L^2C}}$

$$= \frac{1}{2\pi L}\sqrt{\frac{L - CR_1^2}{C}}$$

$$= \frac{1}{2\pi L}\sqrt{\frac{L}{C} - R_1^2}$$

$$= \frac{1}{2\pi}\sqrt{\frac{L}{L^2C} - \frac{R_1^2}{L^2}}$$

$$\boxed{f = \frac{1}{2\pi}\sqrt{\frac{L}{LC} - \frac{R_1^2}{L^2}}}$$

If R_1 and $R_2 = 0$, then

$$f = \frac{1}{2\pi}\sqrt{\frac{L}{L^2C}}$$

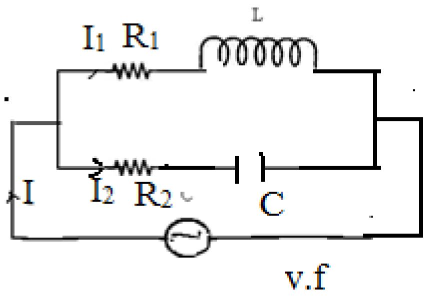
$$\boxed{f = \frac{1}{2\pi}\sqrt{\frac{1}{LC}} = \frac{1}{2\pi\sqrt{LC}}}$$

Comparison of Series and Parallel Resonant Circuit :→

Item	**Series ckt (R-L-C)**	**Parallel ckt (R– L and C)**

❖ Impedance at Resonance	Minimum	Maximum
❖ Current at Resonance	Maximum= $\frac{V}{R}$	Minimum= $\frac{V}{(L/CR)}$
❖ Effective Impedance	R	$\frac{L}{CR}$
❖ P.f. at Resonance	Unity	Unity
❖ Resonant Frequency	$\frac{1}{2\pi\sqrt{LC}}$	$\frac{1}{2\pi}\sqrt{\frac{1}{LC}-\frac{R^2}{L^2}}$
❖ It Magnifies	Voltage	Current
❖ Magnification factor	$\frac{WL}{R}$	$\frac{WL}{R}$

Parallel circuit :→



$$Z_1 = R_1 + jX_L = \sqrt{R_1^2 + X_L^2}\angle\phi_1$$

$$Z_2 = R_1 - jX_C = \sqrt{R2_1^2 + X_C^2}\angle-\phi_2$$

$$I_1 = \frac{V}{Z_1\angle\phi_1} = \frac{V}{Z_1}\angle-\phi_1 = I_1\angle-\phi_1$$

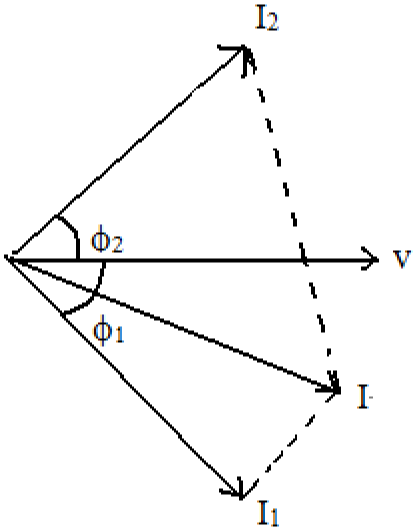
Where $\frac{V}{Z_1} = VY_1$

Here Y_1 → Admittance of the circuit

Admittance is defined as the reciprocal of impedence.

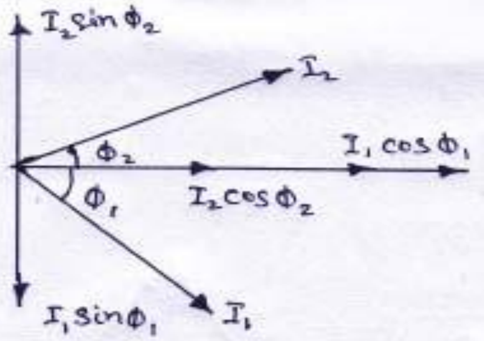
$$I_1 = VY_1 = \frac{v}{R_1 + jX_L}$$

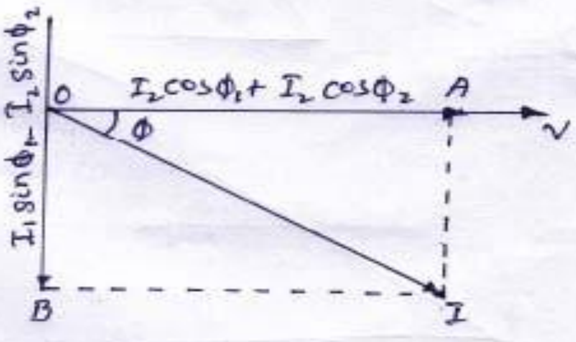
$$I_2 = \frac{V}{Z_2\angle -\phi 2_1} = \frac{V}{Z_2}\angle\phi 1 = VY_2\angle\phi = I2\angle\phi 2$$



$$I = \sqrt{I_1^2 + I_2^2 + 2I_1I_2\cos(\phi 1 + \phi 2)}$$

$$I = I_1\angle -\phi 1 + I_2\angle\phi 2$$





The resultant current “I” is the vector sum of the branch currents I_1 & I_2 can be found by using parallelogram low of vectors or resolving I_2 into their X

– and Y- components (or active and reactive components respectively) and then by combining these components.

Sum of active components of I_1 and I_2 = $I_1 \cos \phi_1 + I_2 \cos \phi_2$
Sum of the reactive components of I_1 and I_2 = $I_2 \sin \phi_2 - I_1 \sin \phi_1$

EXP – 01 :

A 60Hz voltage of 230 V effective value is impressed on an inductance of 0.265 H

(i) Write the time equation for the voltage and the resulting current. Let the zero axis of the voltage wave be at t = 0.
(ii) Show the voltage and current on a phasor diagram.
(iii) Find the maximum energy stored in the inductance.

Solution :-

$$V_{\max} = \sqrt{2}V = \sqrt{2} \times 230V$$

$$f = 60\text{Hz}, \quad W = 2\pi f = 2\pi \times 60 = 377 rad/s.$$

$$x_l = wl = 377 \times 0.265 = 100\wedge \quad .$$

(i) The time equation for voltage is $V(t) = 230\sqrt{2} \sin 377t.$

$$I_{\max} = V_{\max}/x_l = 230\sqrt{2}/100. = 2.3\sqrt{3}$$

$$\phi = 90^o\ (lag).$$

QCurrente quation is.

$$i(t) = 2.3\sqrt{2}\sin(377t - \pi/2)$$

or $= 2.3\sqrt{2}\cos 377t$

(ii) Iti

(iii) or $E_{\max} = \frac{1}{2} LI^2_{\max} = \frac{1}{2} \times 0.265 \times (2.3\sqrt{2})^2 = 1.4J$

Example -02 :

The potential difference measured across a coil is 4.5 v, when it carries a direct current of 9 A. The same coil when carries an alternating current of 9A at 25 Hz, the potential difference is 24 v. Find the power and the power factor when it is supplied by 50 v, 50 Hz supply.

Solution :

Let R be the d.c. resistance and L be inductance of the coil.

$$R = V/I = 4.5/9 = 0.5\wedge$$

With a.c. current of 25Hz, z = V/1.

$$\frac{24}{9} = 2.66\wedge$$

$$x_l = \sqrt{Z^2 - R^2} = \sqrt{2.66^2 - 0.5^2}$$

$$= 2.62\wedge$$

$$x_l = 2\pi \times 25 \times L$$

$$x_l = 0.0167\wedge$$

At 50Hz

$$x_l = 2.62 \times 2 = 5.24\wedge$$

$$Z = \sqrt{0.5^2 + 5.24^2}$$

$$= 5\,.06\,\wedge$$

I = 50/5.26 = 9.5 A

P = I^2/R = 9.5^2 × 0.5 = 45 watt.

Example – 03 :

A 50- µf capacitor is connected across a 230-v, 50 – Hz supply. Calculate

(a) The reactance offered by the capacitor.

(b) The maximum current and

(c) The r.m.s value of the current drawn by the capacitor.

Solution :

(a) $x_l = \frac{1}{wc} = \frac{1}{2\pi \text{ fe}} = \frac{1}{2\pi \times 50 \times 50 \times 10^{-6}} = 63.6\wedge$

(c) Since 230 v represents the r.m.s value

Q$I_{rms} = 230 / x_l = 230 / 63.6 = 3.62\,A$

(b) $I_m = I_{r.m.s} \times \sqrt{2} = 3.62 \times \sqrt{2} = 5.11A$

Example – 04 :

In a particular R – L series circuit a voltage of 10v at 50 Hz produces a current of 700 mA. What are the values of R and L in the circuit ?

Solution :

(i) $Z = \sqrt{R^2 + (2\pi \times 50L)^2}$

$$= \sqrt{R^2 + 98696L^2}$$

$$V = 1z$$

$$10 = 700 \times 10^{-3} \sqrt{(R^2 + 98696L^2)}$$

$$\sqrt{(R^2 + 98696L^2)} = 10 / 700 \times 10^{-3} = 100 / 7$$

$R^2 + 98696L^2 = 10000/49$ --------------------(I)

(ii) In the second case $Z = \sqrt{R^2 + (2\pi \times 75L)^2}$

Q$10 = 500 \times 10^{-3} \sqrt{R^2 + 222066L^2)} = 20$

$$\sqrt{R^2 + 222066L^2)} = 20$$

$R^2 + 222066L^2 = 400$ ----------------------------------- (II)

Subtracting Ea.(I) from (ii), we get,

$222066L^2 - 98696L^2 = 400 - (10000 / 49)$

$\Rightarrow 123370L^2 = 196$

$\Rightarrow L^2 = \frac{196}{123370}$

$\Rightarrow L = \sqrt{\frac{196}{123370}} = 0.0398H$ = 40 mH.

Substituting this value of L in equation (ii) we get $R^2 + 222066L^2 (0.398)^2 = 400$

$\Rightarrow R = 6.9\wedge$.

Example – 04 :

A 20∧ resistor is connected in series with an inductor, a capacitor and an ammeter across a 25 –v, variable frequency supply. When the frequency is 400Hz, the current is at its Max^m value of 0.5 A and the potential difference across the capacitor is 150v. Calculate

(a) The capacitance of the capacitor.

(b) The resistance and inductance of the inductor.

Solution :

Since current is maximum, the circuit is in resonance.

$x_l = V_C / 1 = 150 / 0.5 = 300\wedge$

(a) $x_l = 1/2\pi fe \Rightarrow 300 = 1/2\pi \times 400 \times c$

$\Rightarrow c = 1.325 \times 10^{-6} f = 1.325\mu f$.

(b) $x_l = x_l = 150 / 0.5 = 300\wedge$

2π × 400 × L =300

⇒L = 0.49H

(c) At resonance,

Circuit resistance = 20+R

⇒ V/Z = 2510.5

⇒ R = 30∧

Single Phase Transformers

Introduction

The transformer is a device that transfers electrical energy from one electrical circuit to another electrical circuit. The two circuits may be operating at different voltage levels but always work at the same frequency. Basically transformer is an electro-magnetic energy conversion device. It is commonly used in electrical power system and distribution systems. It can change the magnitude of alternating voltage or current from one value to another. This useful property of transformer is mainly responsible for the widespread use of alternating currents rather than direct currents i.e., electric power is generated, transmitted and distributed in the form of alternating current. Transformers have no moving parts, rugged and durable in construction, thus requiring very little attention. They also have a very high efficiency as high as 99%.

Single Phase Transformer

A transformer is a static device of equipment used either for raising or lowering the voltage of an a.c. supply with a corresponding decrease or increase in current. It essentially consists of two windings, the primary and secondary, wound on a common laminated magnetic core as shown in Fig 1. The winding connected to the a.c. source is called primary winding (or primary) and the one connected to load is called secondary winding (or secondary). The alternating voltage V1 whose magnitude is to be changed is applied to the primary.

Depending upon the number of turns of the primary (N1) and secondary (N2), an alternating e.m.f. E2 is induced in the secondary. This induced e.m.f. E2 in the secondary causes a secondary current I2. Consequently, terminal voltage V2 will appear across the load.

If V2 > V1, it is called a step up-transformer.

If $V2 < V1$, it is called a step-down transformer.

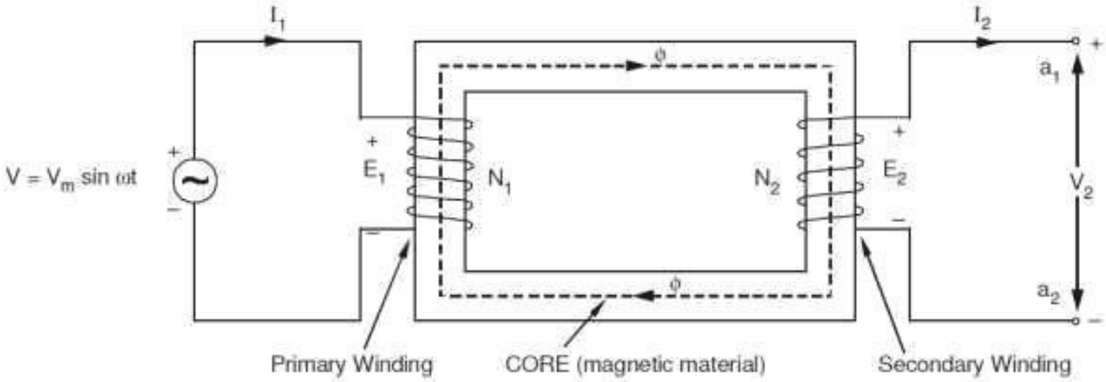


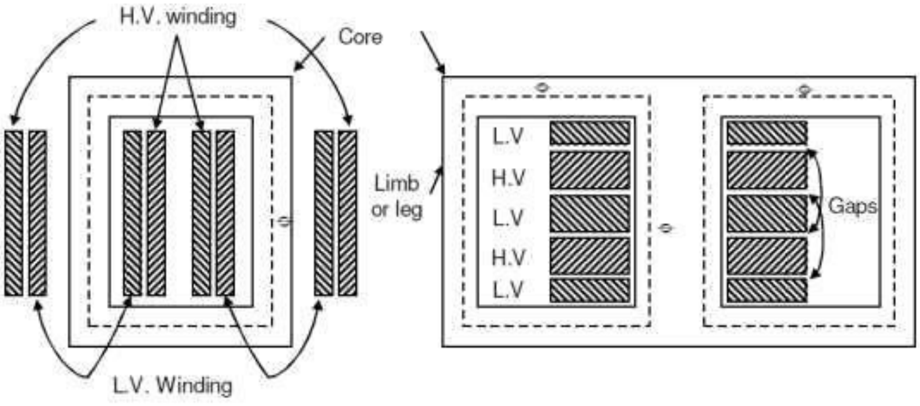
Fig. 2.1 Schematic diagram of single phase transformer

Constructional Details

Depending upon the manner in which the primary and secondary windings are placed on the core, and the shape of the core, there are two types of transformers, called (a) core type, and (b) shell type.

Core-type and Shell-type Construction

In core type transformers, the windings are placed in the form of concentric cylindrical coils placed around the vertical limbs of the core. The low-voltage (LV) as well as the high-voltage (HV) winding are made in two halves, and placed on the two limbs of core. The LV winding is placed next to the core for economy in insulation cost. Figure 2.1(a) shows the cross-section of the arrangement. In the shell type transformer, the primary and secondary windings are wound over the central limb of a three-limb core as shown in Figure 2.1(b). The HV and LV windings are split into a number of sections, and the sections are interleaved or sandwiched i.e. the sections of the HV and LV windings are placed alternately.



(a) Core Type **(b) Shell Type**

Fig: 2.1 Core type & shell type transformer

Core

The core is built-up of thin steel laminations insulated from each other. This helps in reducing the eddy current losses in the core, and also helps in construction of the transformer. The steel used for core is of high silicon content, sometimes heat treated to produce a high permeability and low hysteresis loss. The material commonly used for core is CRGO (Cold Rolled Grain Oriented) steel. Conductor material used for windings is mostly copper. However, for small distribution transformer aluminum is also sometimes used. The conductors, core and whole windings are insulated using various insulating materials depending upon the voltage.

Insulating Oil

In oil-immersed transformer, the iron core together with windings is immersed in insulating oil. The insulating oil provides better insulation, protects insulation from moisture and transfers the heat produced in core and windings to the atmosphere. The transformer oil should possess the following qualities:

(a) High dielectric strength,
(b) Low viscosity and high purity,
(c) High flash point, and
(d) Free from sludge.

Transformer oil is generally a mineral oil obtained by fractional distillation of crude oil.

Tank and Conservator

The transformer tank contains core wound with windings and the insulating oil. In large transformers small expansion tank is also connected with main tank is known as conservator. Conservator provides space when insulating oil expands due to heating. The transformer tank is provided with tubes on the outside, to permits circulation of oil, which aides in cooling. Some additional devices like breather and Buchholz relay are connected with main tank. Buchholz relay is placed between main tank and conservator. It protect the transformer under extreme heating of transformer winding. Breather protects the insulating oil from moisture when the cool transformer sucks air inside. The silica gel filled breather absorbs moisture when air enters the tank. Some other necessary parts are connected with main tank like, Bushings, Cable Boxes, Temperature gauge, Oil gauge, Tapings, etc.

rinciple of Operation

When an alternating voltage V1 is applied to the primary, an alternating flux ϕ is set up in the core. This alternating flux links both the windings and induces e.m.f.s E1 and E2 in them according to

Faraday’s laws of electromagnetic induction. The e.m.f. E1 is termed as primary e.m.f. and e.m.f. E2 is termed as secondary e.m.f.

Clearly, $E_1 = -N_1 \frac{d\phi}{dt}$

and $E_2 = -N_2 \frac{d\phi}{dt}$

$$\therefore \quad \frac{E_2}{E_1} = \frac{N_2}{N_1}$$

Note that magnitudes of E2 and E1 depend upon the number of turns on the secondary and primary respectively.

If N2 > N1, then E2 > E1 (or V2 > V1) and we get a step-up transformer. If N2 < N1, then E2 < E1

(or V2< V1) and we get a step-down transformer.

If load is connected across the secondary winding, the secondary e.m.f. E2 will cause a current I2 to flow through the load. Thus, a transformer enables us to transfer a.c. power from one circuit to another with a change in voltage level.

The following points may be noted carefully

(a) The transformer action is based on the laws of electromagnetic induction.

(b) There is no electrical connection between the primary and secondary.

(c) The a.c. power is transferred from primary to secondary through magnetic flux.

There is no change in frequency i.e., output power has the same frequency as the input power.

(e) The losses that occur in a transformer are:

(a) ***core losses***—eddy current and hysteresis losses

(b) ***copper losses***—in the resistance of the windings

In practice, these losses are very small so that output power is nearly equal to the input primary power. In other words, a transformer has very high efficiency.

E.M.F. Equation of a Transformer

Consider that an alternating voltage V1 of frequency f is applied to the primary as shown in Fig.2.3. The sinusoidal flux ϕ produced by the primary can be represented as:

$\phi=\phi m \sin\omega t$

When the primary winding is excited by an alternating voltage V1, it is circulating alternating current, producing an alternating flux ϕ.

ϕ - Flux

ϕm - maximum value of flux N1

- Number of primary turns N2 -

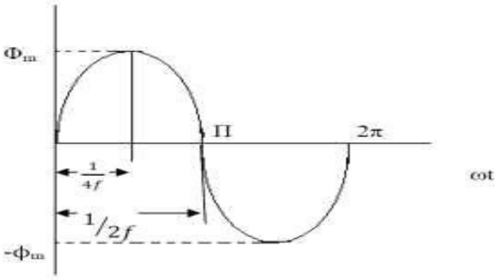
Number of secondary turns

f - Frequency of the supply voltage

E1 - R.M.S. value of the primary induced e.m.f

E2 - R.M.S. value of the secondary induced e.m.f

The instantaneous e.m.f. e1 induced in the primary is -



From Faraday’s law of electromagnetic induction -

$$\text{Average e.m.f per turns} = \frac{d\phi}{dt}$$

$d\phi$ = change in flux
dt = time required for change in flux

The flux increases from zero value to maximum value ϕm in 1/4f of the time period that is in 1/4f seconds.

The change of flux that takes place in 1/4f seconds = $\phi m - 0 = \phi m$

webers **Voltage Ratio**

$$\frac{d\phi}{dt} = \frac{dt}{1/4f} = 4f\phi_m \; w_b/\text{sec.}$$

Since flux ϕ varies sinusoidally, the R.m.s value of the induced e.m.f is obtained by multiplying the average value with the form factor

$$\text{Form factor of a sinwave} = \frac{\text{R.m.s value}}{\text{Average value}} = 1.11$$

R.M.S Value of e.m.f induced in one turns = $4\phi_m f \times 1.11$ Volts.

= $4.44\phi_m f$ Volts.

R.M.S Value of e.m.f induced in primary winding = $4.44\phi_m f$ N1Volts.

R.M.S Value of e.m.f induced in secondary winding = $4.44\phi_m f$ N2Volts.

The expression of E_1 and E_2 are called e.m.f equation of a transformer

$$\boxed{\begin{array}{l} V_1 = E_1 = 4.44\phi_m f N_1 \text{Volts.} \\ V_2 = E_2 = 4.44\phi_m f N_2 \text{Volts.} \end{array}}$$

Voltage transformation ratio is the ratio of e.m.f induced in the secondary winding to the e.m.f induced in the primary winding.

$$\frac{E2}{E1} = \frac{4.44\phi mf\, N2}{4.44\phi mf\, N1}$$

$$\boxed{\frac{E2}{E1} = \frac{N2}{N1} = K}$$

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

$$E_2 = KE_1 \qquad \text{where } K = \frac{N2}{N1}$$

1. If N2>N1 i.e. K>1 we get E2>E1 then the transformer is called step up transformer.

2. If N2< N1 i.e. K<1 we get E2< E2 then the transformer is called step down transformer.

3. If N2= N1 i.e. K=1 we get E2= E2 then the transformer is called isolation transformer or 1:1 Transformer

Current Ratio

Current ratio is the ratio of current flow through the primary winding (I1) to the current flowing through the secondary winding (I2). In an ideal transformer -

Apparent input power = Apparent output power.

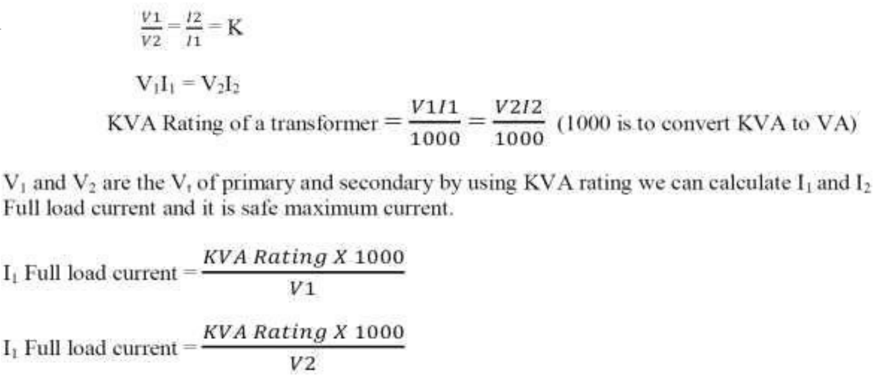
$$V1I1 = V2I2$$

$$\frac{I1}{I2} = \frac{V2}{V1} = \frac{N2}{N1} = \text{K}$$

Volt-Ampere Rating

i) The transformer rating is specified as the products of voltage and current (VA rating).

ii) On both sides, primary and secondary VA rating remains same. This rating is generally expressed in KV



$$\frac{V1}{V2} = \frac{I2}{I1} = \text{K}$$

$$V_1I_1 = V_2I_2$$

$$\text{KVA Rating of a transformer} = \frac{V1I1}{1000} = \frac{V2I2}{1000} \quad \text{(1000 is to convert KVA to VA)}$$

V_1 and V_2 are the V_t of primary and secondary by using KVA rating we can calculate I_1 and I_2 Full load current and it is safe maximum current.

$$I_1 \text{ Full load current} = \frac{KVA\ Rating\ X\ 1000}{V1}$$

$$I_1 \text{ Full load current} = \frac{KVA\ Rating\ X\ 1000}{V2}$$

Transformer on No-load

a) Ideal transformer

b) Practical transformer

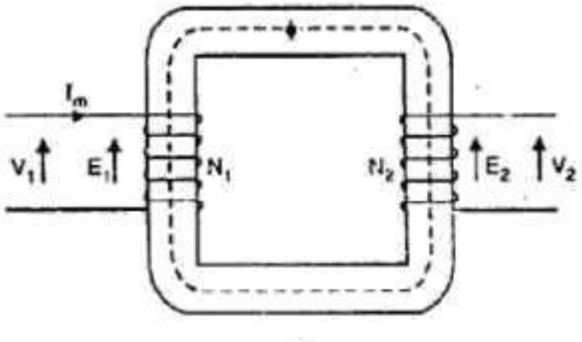
a) Ideal Transformer

An ideal transformer is one that has

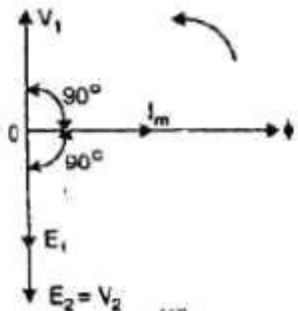
(i) No winding resistance
(ii) No leakage flux i.e., the same flux links both the windings

(iii) No iron losses (i.e., eddy current and hysteresis losses) in the core

Although ideal transformer cannot be physically realized, yet its study provides a very powerful tool in the analysis of a practical transformer. In fact, practical transformers have properties that approach very close to an ideal transformer.



(i)



(ii)

Consider an ideal transformer on no load i.e., secondary is open-circuited as shown in *Fig.2.4 (i)*. under such conditions, the primary is simply a coil of pure inductance. When an alternating voltage V1 is applied to the primary, it draws a small magnetizing current Im which lags behind the applied voltage by 90°. This alternating current Im produces an alternating flux ϕ which is proportional to and in phase with it. The alternating flux ϕ links both the windings and induces e.m.f. E1 in the primary and e.m.f. E2 in the secondary. The primary e.m.f. E1 is, at every instant, equal to and in opposition to V1 (Lenz's law). Both e.m.f.s E1 and E2 lag behind flux ϕ by 90°.However, their magnitudes depend upon the number of primary and secondary turns. *Fig. 2.4 (ii)* shows the phasor diagram of an ideal transformer on no load. Since flux ϕ is common to both the windings, it has been taken as the reference phasor. The primary e.m.f. E1 and secondary e.m.f. E2 lag behind the flux ϕ by 90°. Note that E1 and E2 are in phase. But E1 is equal to V1 and 180° out of phase with it.

$$\boxed{\frac{E2}{E1} = \frac{V2}{V1} = K}$$

Phasor Diagram

i) Φ (flux) is reference

ii) Im produce ϕ and it is in phase with ϕ, V1 Leads Im by 90˚

E1 and E2 are in phase and both opposing supply voltage V1, winding is purely inductive
So current has to lag voltage by 90˚.

iii) The power input to the transformer

P = V1.I1. cos (90˚)................... (cos90˚ = 0)

P= 0 (ideal transformer)

***b)i) Practical Transformer* on no load**

A practical transformer differs from the ideal transformer in many respects. The practical transformer has (i) iron losses (ii) winding resistances and (iii) Magnetic leakage

(i) **Iron losses**. Since the iron core is subjected to alternating flux, there occurs eddy current and hysteresis loss in it. These two losses together are known as iron losses or core losses. The iron losses depend upon the supply frequency, maximum flux density in the core, volume of the core etc. It may be noted that magnitude of iron losses is quite small in a practical transformer.

(ii) **Winding resistances.** Since the windings consist of copper conductors, it immediately follows that both primary and secondary will have winding resistance. The primary resistance R1 and secondary resistance R2 act in series with the respective windings as shown in Fig. When current flows through the windings, there will be power loss as well as a loss in voltage due to IR drop. This will affect the power factor and E1 will be less than V1 while V2 will be less than E2.

Consider a practical transformer on no load i.e., secondary on open-circuit as Shown in Fig 2.5.

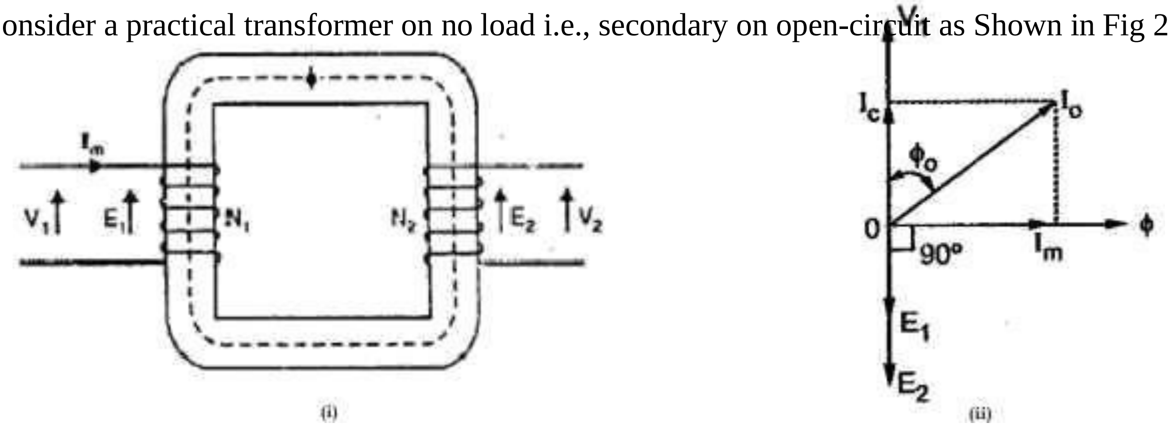


Fig: 2.5 Phasor diagram of transformer at noload

Here the primary will draw a small current I0 to supply -

(i) The iron losses and
(ii) A very small amount of copper loss in the primary.

Hence the primary no load current I0 is not 90° behind the applied voltage V1 but lags it by an angle ϕ0 < 90° as shown in the phasor diagram. No load input power, W0 = V1 I0 cos ϕ0

As seen from the phasor diagram in Fig.2.5 (ii), the no-load primary current I0

(i) he component Ic in phase with the applied voltage V1. This is known as active or working or iron loss component and supplies the iron loss and a very small primary copper loss.

$$I_c = I_0 \cos \phi_0$$

The component Im lagging behind V1 by 90° and is known as magnetizing component. It is this component which produces the mutual flux ϕ in the core.

$$I_m = I_0 \sin \phi_0$$

Clearly, Io is phasor sum of Im and Ic,

$$I_o = \sqrt{Im^2 + Ic^2}$$

$$\text{No load P.F., } \cos\phi o = \frac{Ic}{Io}$$

The no load primary copper loss (i.e. Io^2R1) is very small and may be neglected.

Therefore, the no load primary input power is practically equal to the iron loss in the transformer i.e., No load input power, W0 = V1Iocosϕo = Pi = Iron loss

***b) ii)Practical Transformer* on Load**

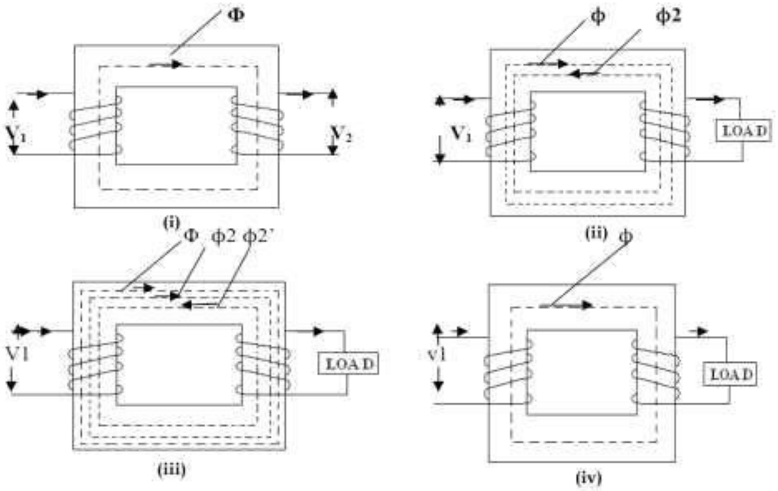


Fig: 2.6

At no load, there is no current in the secondary so that V2 = E2. On the primary side, the drops in R1 and X1, due to I0 are also very small because of the smallness of I0. Hence, we can say that at no load, V1 = E1.

i) When transformer is loaded, the secondary current I2 is flows through the secondary winding. Already Im magnetizing current flow in the primary winding fig. 2.6(i).

ii) The magnitude and phase of I2 with respect to V2 is determined by the characteristics of the load. a) I2 in phase with V2 (resistive load)
b) I2 lags with V2 (Inductive load)
c) I2 leads with V2 (capacitive load)

iii) Flow of secondary current I2 produce new Flux ϕ2 fig.2.6 (ii)

iv)Φis main flux which is produced by the primary to maintain the transformer as constant magnetising component.

v) Φ2 opposes the main flux ϕ, the total flux in the core reduced. It is called demagnetising Ampere- turns due to this E1 reduced.

vi) To maintain the ϕ constant primary winding draws more current (I2') from the supply (load component of primary) and produce ϕ2' flux which is oppose ϕ2 (but in same direction as ϕ), to maintain flux constant flux constant in the core fig.2.6 (iii).

vii) The load component current I2' always neutralizes the changes in the load.

viii) Whatever the load conditions, the net flux passing through the core is approximately the same as at no-load. An important deduction is that due to the constancy of core flux at all loads, the core loss is also practically the same under all load conditions fig.2.6 (iv).

$$\boxed{\Phi_2 = \phi_2' \quad N_2I_2 = N_1I_2' \quad I_2' = \frac{N2}{N1} X I_2 = KI_2}$$

Phasor Diagram

i) Take (ϕ) flux as reference for all load

ii) The no load I_o which lags by an angle ϕo. Io $=\sqrt{Ic^2 + Im^2}$.

ii) The load component I2', which is in anti-phase with I2 and phase of I2 is decided by the load.

iii) Primary current I1 is vector sum of Io and I2'

$$\vec{I_1} - \vec{I_o} + \vec{I_2'}$$

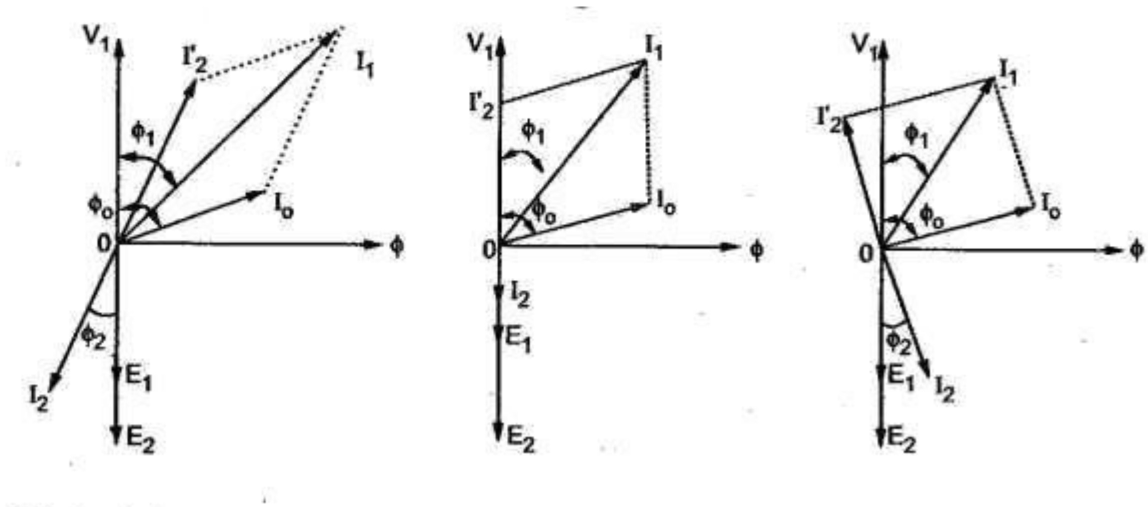
$$I_1 = \sqrt{Io^2 + I2'^2}$$

a) If load is Inductive, I2 lags E2 by ϕ2, shown in phasor diagram fig 2.7 (a).

b) If load is resistive, I2 in phase with E2 shown in phasor diagram fig. 2.7 (b).

c) If load is capacitive load, I2 leads E2 by ϕ2 shown in phasor diagram fig. 2.7 (c).

For easy understanding at this stage here we assumed E2 is equal to V2 neglecting various drops.



(a) Inductive load **(b) Resistive load** **(c) Capacitive load**

Fig: 2.7.a

$$\vec{I_1} - \vec{I_0} + \vec{I_2'}$$

$$I_1 \cong I_2' \qquad I_1 = \sqrt{Io^2 + I2'^2}$$

Balancing the ampere – turns

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

$$\frac{I1}{I2} = \frac{N2}{N1} = K$$

Now we going to construct complete phasor diagram of a transformer (shown in Fig: 2.7.b)

Effect of Winding Resistance

In practical transformer it process its own winding resistance causes power loss and also the voltage drop.

R1 – primary winding resistance in ohms.
R2 – secondary winding resistance in ohms.

The current flow in primary winding make voltage drop across it is denoted as I1R1 here supply voltage V1 has to supply this drop primary induced e.m.f E1 is the vector difference between V1 and I1R1.

$$\vec{E_1} = \vec{V_1} - \vec{I_1R_1}$$

Similarly the induced e.m.f in secondary E2, The flow of current in secondary winding makes voltage drop across it and it is denoted as I2R2 here E2 has to supply this drop. The vector difference between E2 and I2R2

$$\vec{V_2} = \vec{E_2} - \vec{I_2R_2}$$ (Assuming as purely resistive drop here)

Equivalent Resistance

1) It would now be shown that the resistances of the two windings can be transferred to any one of the two winding.

2) The advantage of concentrating both the resistances in one winding is that it makes calculations very simple and easy because one has then to work in one winding only.

3) Transfer to any one side either primary or secondary without affecting the performance of the transformer.

The total copper loss due to both the resistances

$$\begin{aligned}\text{Total copper loss} &= I_1^2R_1 + I_2^2R_2\\ &= I_1^2\left[R_1 + \frac{I2^2}{I1^2}\right]\\ &= I_1^2\left[R_1 + \frac{1}{K}R_2\right]\end{aligned}$$

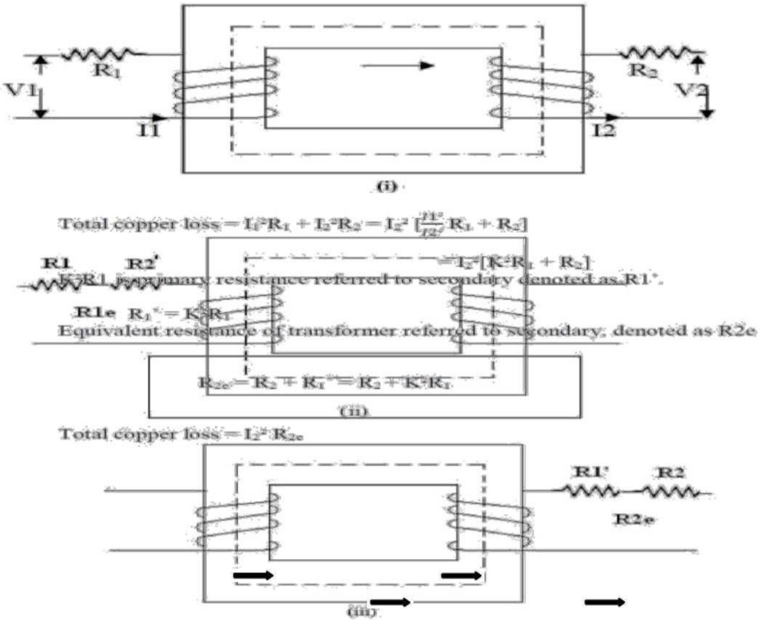
$\frac{R2}{K^2}$ is the resistance value of R_2 shifted to primary side and denoted as R_2'.
R_2' is the equivalent resistance of secondary referred to primary

$$\boxed{R_2' = \frac{R2}{K^2}}$$

Equivalent resistance of transformer referred to primary fig (ii)

$$\boxed{R_{1e} = R_1 + R_2' = R_1 + \frac{R2}{K^2}}$$

Similarly it is possible to refer the equivalent resistance to secondary winding.



Total copper loss = $I_1^2R_1 + I_2^2R_2 = I_2^2\,[\frac{I1^2}{I2^2}R_1 + R_2]$

$= I_2^2[K^2R_1 + R_2]$

K^2R1 is primary resistance referred to secondary denoted as R1'.

$R_1' = K^2R_1$

Equivalent resistance of transformer referred to secondary, denoted as R2e

$R_{2e} = R_2 + R_1' = R_2 + K^2R_1$

Total copper loss = $I_2^2\,R_{2e}$

Note:

i) When a resistance is to be transferred from the primary to secondary, it must be multiplied by K², it must be divided by K² while transferred from the secondary to primary.

High voltage side low current side high resistance side Low voltage side high current side low resistance side

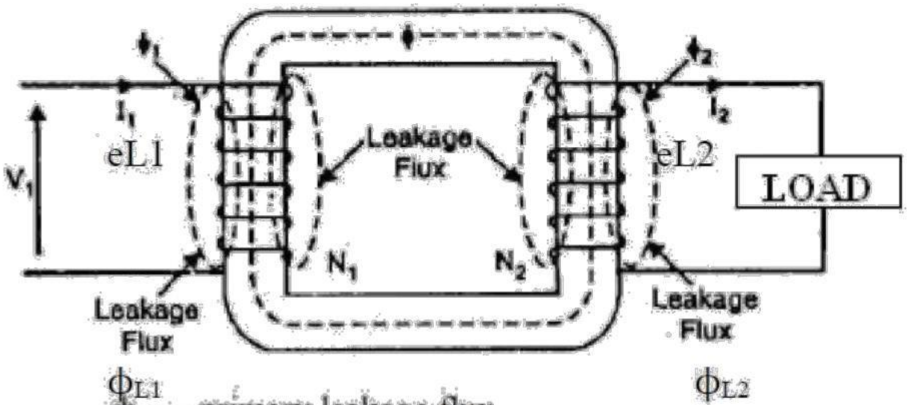
Effect of Leakage Reactance

i) It has been assumed that all the flux linked with primary winding also links the secondary winding. But, in practice, it is impossible to realize this condition.

ii) However, primary current would produce flux ϕ which would not link the secondary winding. Similarly, current would produce some flux ϕ that would not link the primary winding.

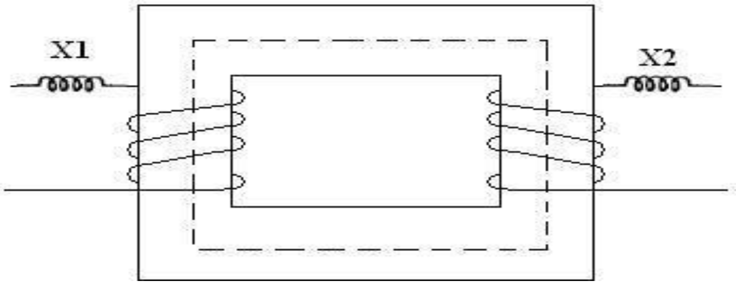
iii) The flux $\phi L1$ complete its magnetic circuit by passing through air rather than around the core, as shown in fig.2.9. This flux is known as primary leakage flux and is proportional to the primary ampere – turns alone because the secondary turns do not links the magnetic circuit of $\phi L1$. It induces an e.m.f eL1 in primary but not in secondary.

iv) The flux $\phi L2$ complete its magnetic circuit by passing through air rather than around the core, as shown in fig. This flux is known as secondary leakage flux and is proportional to the secondary ampere– turns alone because the primary turns do not links the magnetic circuit of $\phi L2$. It induces an e.m.f eL2 in secondary but not inprimary.



ϕ_{L1} – primary leakage flux
ϕ_{L2} – secondary leakage flux
e_{L1} – self induced e.m.f (primary)
e_{L2} –self induced e.m.f (secondary)

Equivalent Leakage Reactance



Similarly to the resistance, the leakage reactance also can be transferred from primary to secondary. The relation through K^2 remains same for the transfer of reactance as it is studied earlier for the resistance

X1 – leakage reactance of primary.
X2 - leakage reactance of secondary.
Then the total leakage reactance referred to primary is X1e given by

$$X_{1e} = X_1 + X_2'$$

$$X_2' = \frac{X2}{K^2}$$

The total leakage reactance referred to secondary is X_{2e} given by

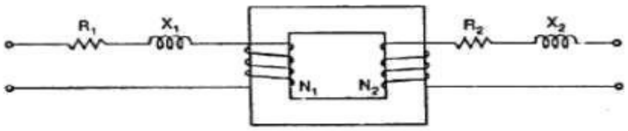
$$X_{2e} = X_2 + X_1'$$
$$X_1' = K^2X_1$$

$$\boxed{\begin{aligned} X_{1e} &= X_1 + X_2' \\ X_{2e} &= X_2 + X_1' \end{aligned}}$$

Equivalent Impedance

The transformer winding has both resistance and reactance (R1, R2, X1,X2).Thus we can say that the total impedance of primary winding isZ1 which is,

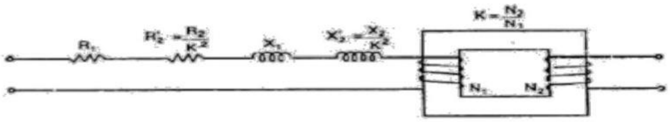
Z1 = R1 + jX1 ohms
On secondary winding,
Z2 = R2 + jX2 ohms



Individual magnitude of Z1 and Z2 are

$$Z_1 = \sqrt{R1^2 + X1^2}$$
$$Z_2 = \sqrt{R2^2 + X2^2}$$

Similar to resistance and reactance, the impedance also can be referred to any one side,



Z_{1e}= total equivalent impedance referred to primary

$$Z_{1e} = R_{1e} + jX_{1e} = Z_1 + Z_2' = Z_1 + \frac{Z2}{K^2}$$

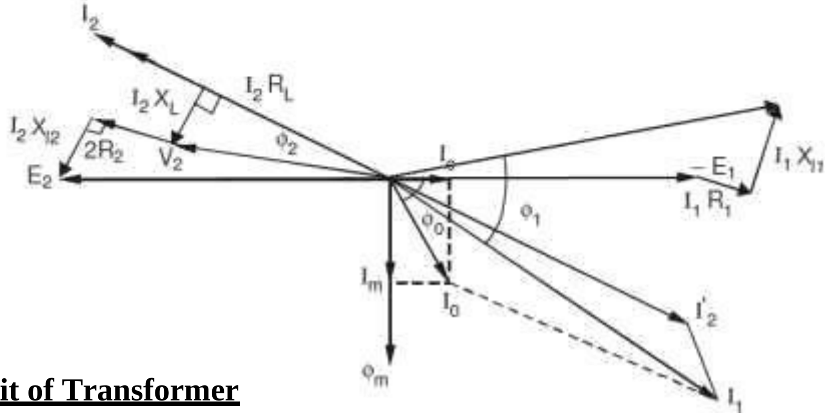
Complete Phasor Diagram of a Transformer *(for Inductive Load or Lagging pf)*

We now restrict ourselves to the more commonly occurring load i.e. inductive along with resistance,

which has a lagging power factor. For drawing this diagram, we must remember that

$$\overline{V_2} = \overline{E}_2 - \overline{I}_2\,(R_2 + j\,X_{l2})$$

and $$\overline{V_1} = -\,\overline{E}_1 + \overline{I}_2\,(R_1 + j\,X_{l1})$$



Equivalent Circuit of Transformer

No load equivalent circuit

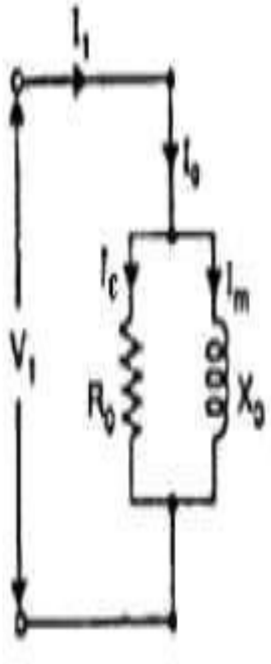
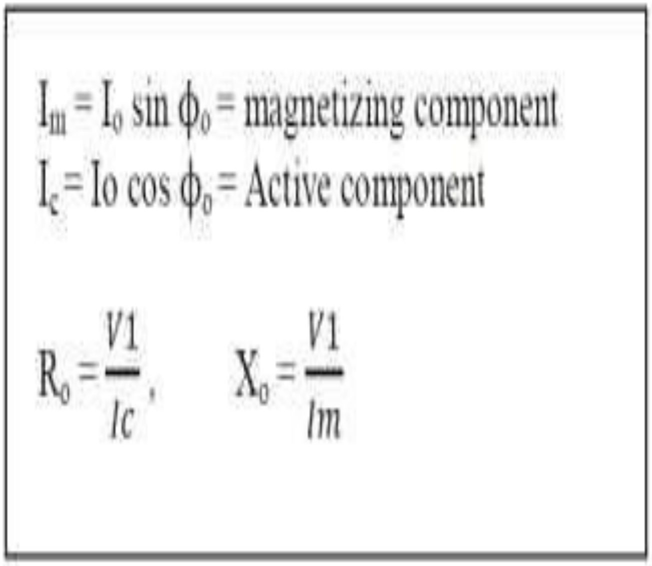


Fig:11



$I_m = I_0 \sin\phi_0$ = magnetizing component

$I_c = I_0 \cos\phi_0$ = Active component

$$R_0 = \frac{V1}{Ic}, \qquad X_0 = \frac{V1}{Im}$$

i) Im produces the flux and is assumed to flow through reactance Xo called no load reactance while Ic is active component representing core losses hence is assumed to flow through the resistance R0

ii) Equivalent resistance is shown in fig.2.12.

iii) When the load is connected to the transformer then secondary current I2 flows causes voltage drop across R2 and X2. Due to I2, primary draws an additional current.

$$I_2' = \frac{I2}{K}$$

I1 is the phasor addition of Io and I2'. This I1 causes the voltage drop across primary resistance R1 and reactance X1.

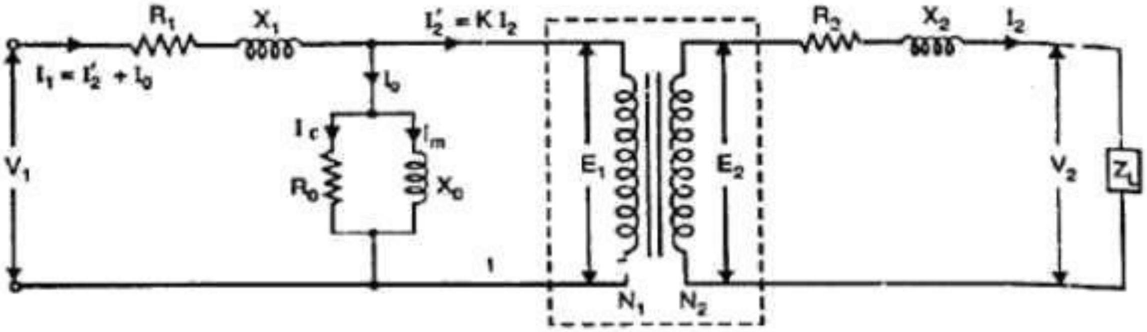


Fig: 2.12

To simplified the circuit the winding is not taken in equivalent circuit while transfer to one side.

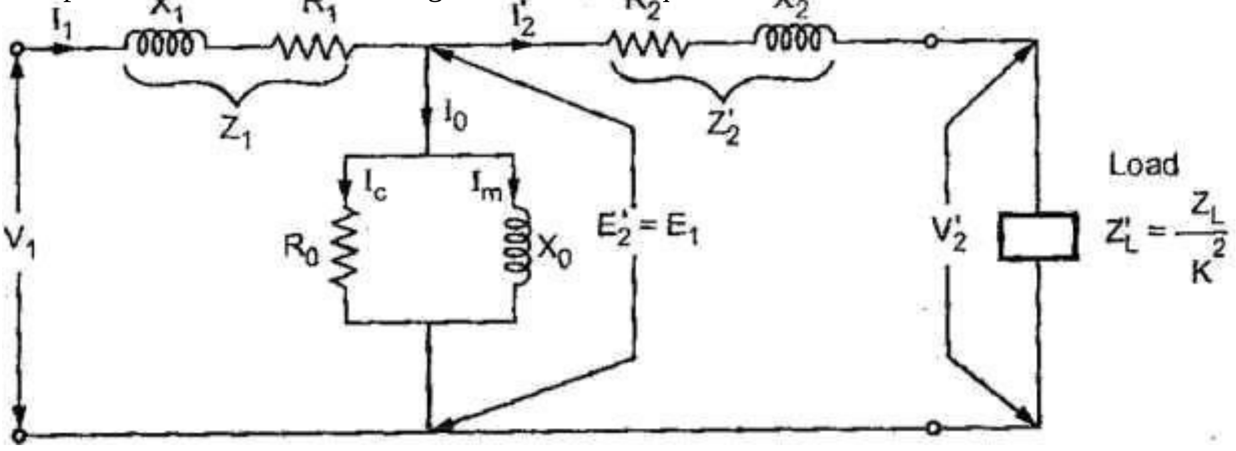


Fig: 2.13

Exact equivalent circuit referred to primary

Transferring secondary parameter to primary -

$$\boxed{R_2' = \frac{R2}{K^2}, X_2' = \frac{X2}{K^2}, Z_2' = \frac{Z2}{K^2}, E_2' = \frac{E2}{K'}, I_2' = KI_2, K = \frac{N2}{N1}}$$

High voltage winding	low current	high impedance
Low voltage winding	high current	low impedance

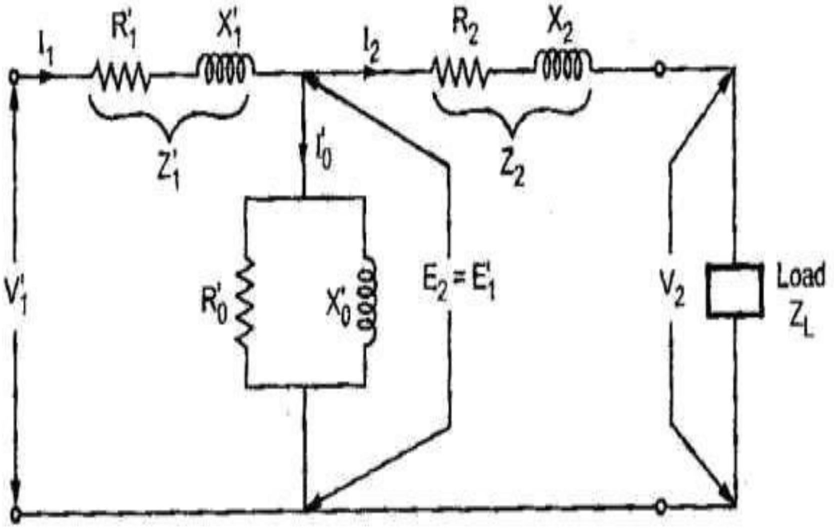


Fig: 2.14

Exact equivalent circuit referred to secondary

$$R_1' = R_1K^2,\ X_1' = K^2X_1\ ,\ E_1' = KE_1$$

$$Z_1' = K^2Z1\ ,\ I_1' = \frac{I1}{K'},\ I_o = \frac{Io}{K}$$

Now as long as no load branch i.e. exciting branch is in between Z1 and Z2’, the impedances cannot be combined. So further simplification of the circuit can be done. Such circuit is called approximate equivalent circuit.

Approximate Equivalent Circuit

i) To get approximate equivalent circuit, shift the no load branch containing Ro and Xo to the left of R1 and X1.

ii) By doing this we are creating an error that the drop across R1 and X1 to Io is neglected due to this circuit because simpler.

iii) This equivalent circuit is called approximate equivalent circuit Fig: 2.15 & Fig: 2.16.

In this circuit new R1 and R2' can be combined to get equivalent circuit referred to primary R1e,similarly

X1 and X2' can be combined to get X1e.

$$R_{1e} = R_1 + R_2' = R_1 + \frac{R2}{K^2}$$

$$X_{1e} = X_1 + X_2' = X_1 + \frac{X2}{K^2}$$

$$Z_{1e} = R_{1e} + jX_1E, \qquad R_o = \frac{V1}{Ic}, \quad \text{and } X_o = \frac{V1}{Im}$$

$$I_c = I_o \cos\phi_o, \quad \text{and } I_m = I_o \sin\phi_o$$

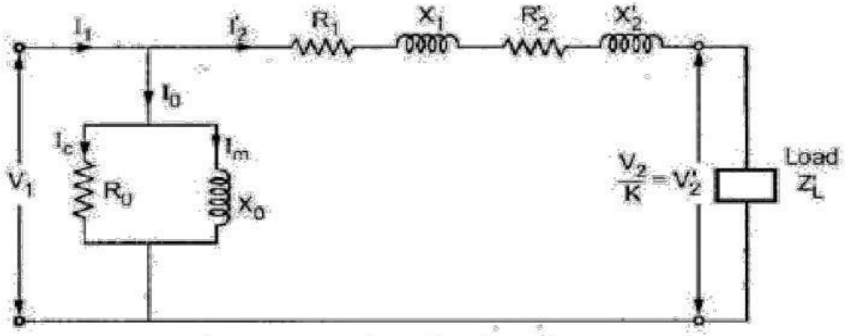
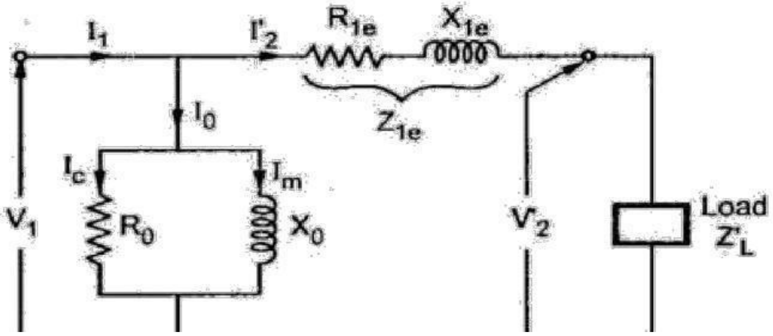
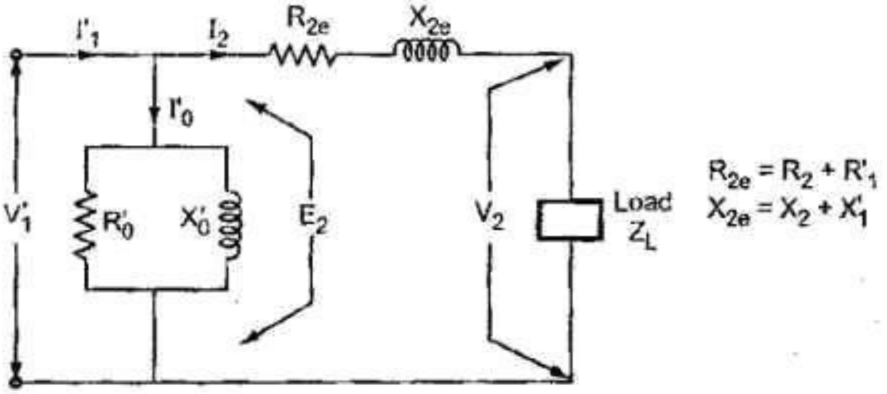


Fig:2.15Approximate equivalent circuit referred to primary



Approximate Voltage Drop in a Transformer



$$\vec{E_2} = \overrightarrow{I_2R_{2e}} + \overrightarrow{I_2X_{2e}} + \vec{V_2} = \vec{V_2} + \vec{I_2}(R_{2e} + jX_{2e}), \quad \vec{E_2} = \vec{V_2} + \overrightarrow{I_2Z_{2e}}$$

Fig. 2.17

Primary parameter is referred to secondary there are no voltage drop in primary. When there is no load,

I2 = 0 and we get no load terminal voltage drop in

V2o = E2 = no load terminal voltage

V2 = terminal voltage on load

For Lagging P.F.

i) The current I2 lags V2 by angle ϕ2

ii) Take V2 as reference

iii) I2R2e is in phase with I2 while I2 X2e leads I2 by 90˚

iv) Draw the circle with O as centre and OC as radius cutting extended OA at M.

as OA = V2 and now OM = E2.

v) The total voltage drop is AM = I2Z2e.

vi) The angle α is practically very small and in practice M&N are very close to each other. Due to this the approximate voltage drop is equal to AN instead of AM

AN – approximate voltage drop

To find AN by adding

AD& DN AD = AB cosϕ

= I2R2e cosϕ DN = BL

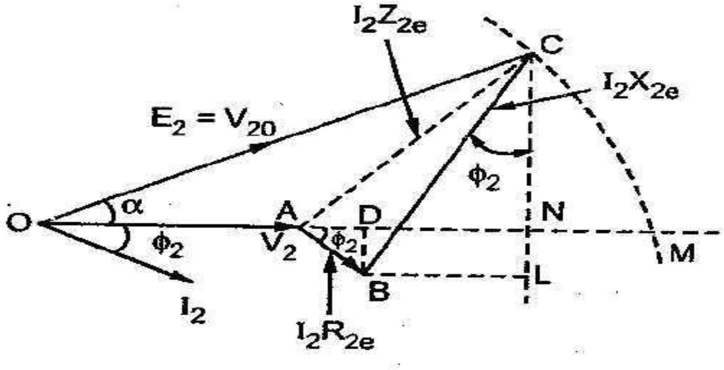
sinϕ = I2X2e sinϕ

AN = AD + DN = I2R2e cosϕ2 + I2X2e sinϕ2

Assuming: ϕ2 = ϕ1 = ϕ

Approximate voltage drop = I2R2e cosϕ+I2X2e sinϕ (referred to secondary)

Similarly: Approximate voltage drop = I1R1e cosϕ+I1X1e sinϕ (referred to primary)

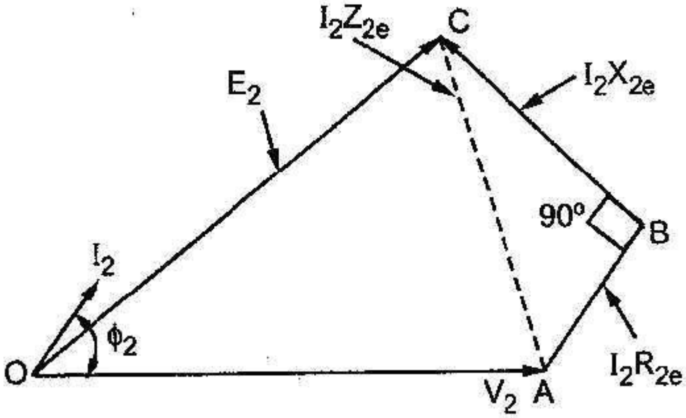


For Leading P.F Loading

I2 leads V2 by angle ϕ2

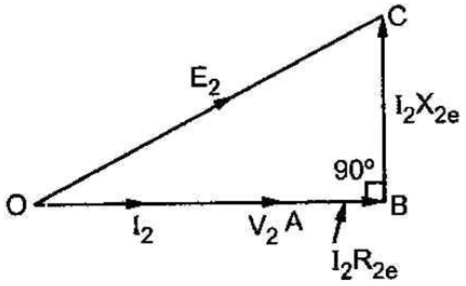
Approximate voltage drop = I2R2e cosϕ - I2X2e sinϕ (referred to secondary)

Similarly: Approximate voltage drop = I1R1e cosϕ - I1X1e sinϕ (referred to primary)


I_2Z_{2e}
C
E_2
I_2X_{2e}
90°
B
I_2
ϕ_2
O
V_2
A
I_2R_{2e}

For Unity P.F. Loading

Approximate voltage drop = I2R2e (referred to secondary) Similarly: Approximate voltage drop = I1R1e (referred to primary)



Cosϕ = 1
Sinϕ = 0

Fig: 2.20

Approximate voltage drop = E2 – V2

= I2R2e cosϕ ± I2X2e sinϕ (referred to secondary)

= I1R1e cosϕ ± I1X1e sinϕ (referred to primary)

Losses in a Transformer

The power losses in a transformer are of two types, namely;

1. Core or Iron losses
2. Copper losses

These losses appear in the form of heat and produce (i) an increase in Temperature and (ii) a drop in efficiency.

Core or Iron losses (Pi)

These consist of hysteresis and eddy current losses and occur in the transformer core due to the alternating flux. These can be determined by open-circuit test.

Hysteresis loss = kh f $Bm^{1.6}$ watts /m^3

Kh – hysteresis constant depend on material f - Frequency

Bm – maximum flux density

Eddy current loss = Ke f^2 Bm^2t^2 watts /m^3

Ke – eddy current constant

t - Thickness of the core

Both hysteresis and eddy current losses depend upon

(i) Maximum flux density Bm in the core

(ii) Supply frequency f. Since transformers are connected to constant-frequency, constant voltage supply, both f and Bm are constant. Hence, core or iron losses are practically the same at all lods.

Iron or Core losses, Pi = Hysteresis loss + Eddy current loss = Constant losses (Pi)

The hysteresis loss can be minimized by using steel of high silicon content .Whereas eddy current loss can be reduced by using core of thin laminations.

Copper losses (Pcu)

These losses occur in both the primary and secondary windings due to their ohmic resistance. These can be determined by short-circuit test. The copper loss depends on the magnitude of the current flowing

through the windings.

$$\text{Total copper loss} = I_1^2R_1 + I_2^2R_2 = I_1^2(R_1 + R_2') = I_2^2(R_2 + R_1')$$

$$\boxed{\text{Total loss} = \text{iron loss} + \text{copper loss} = Pi + Pcu}$$

Efficiency of a Transformer

Like any other electrical machine, the efficiency of a transformer is defined as the ratio of output power (in watts or kW) to input power (watts or kW) i.e.

Power output = power input – Total losses

Power input = power output + Total losses

= power output + Pi + Pcu

$$\text{Efficiency} = \frac{power\ output}{power\ input}$$

$$\text{Efficiency} = \frac{power\ output}{power\ input + Pi + Pcu}$$

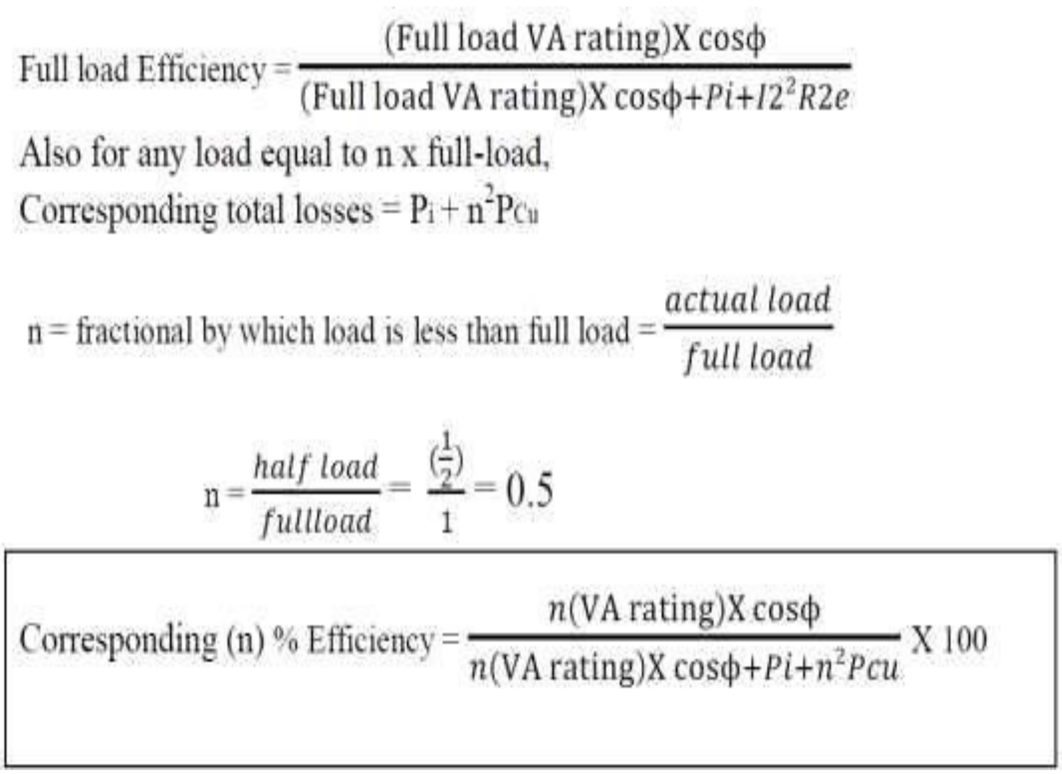
Power output = $V_2I_2 \cos\phi$. $\cos\phi$ = load power factor

Transformer supplies full load of current I_2 and with terminal voltage V_2

Pcu = copper losses on full load = $I_2^2 R_{2e}$

This is full load efficiency and I2 = full load current.

We can now find the full-load efficiency of the transformer at any p.f. without actually loading the transformer.



$$\text{Full load Efficiency} = \frac{(\text{Full load VA rating})\text{X} \cos\phi}{(\text{Full load VA rating})\text{X} \cos\phi + Pi + I2^2R2e}$$

Also for any load equal to n x full-load,

Corresponding total losses = $P_i + n^2P_{Cu}$

$$\text{n} = \text{fractional by which load is less than full load} = \frac{actual\ load}{full\ load}$$

$$\text{n} = \frac{half\ load}{fullload} = \frac{(\frac{1}{2})}{1} = 0.5$$

$$\boxed{\text{Corresponding (n) \% Efficiency} = \frac{n(\text{VA rating})\text{X} \cos\phi}{n(\text{VA rating})\text{X} \cos\phi + Pi + n^2Pcu} \text{ X } 100}$$

TESTING OF TRANSFORMERS

Testing of Transformer

The testing of transformer means to determine efficiency and regulation of a transformer at any load and at any power factor condition.

There are two methods

i) Direct loading test

ii) Indirect loading test

a. Open circuit test

b. Short circuit test

i) Load test on transformer

This method is also called as direct loading test on transformer because the load is directly connected to the transformer. We required various meters to measure the input and output reading while change the load from zero to full load. Fig. 2.22 shows the connection of transformer for direct load test. The primary is connected through the variac to change the input voltage as we required. Connect the meters as shown in the figure below.

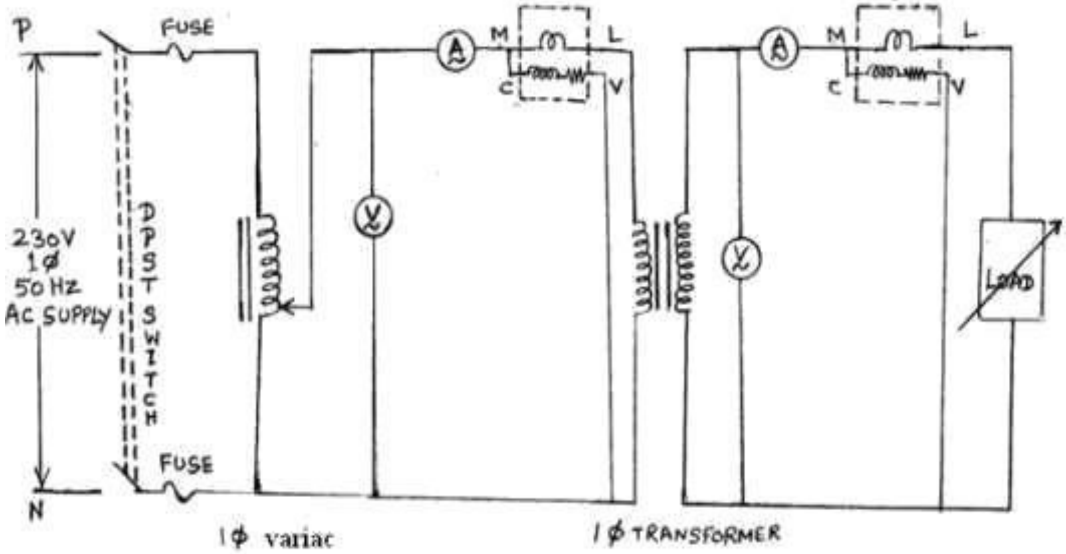


Fig: 2.22

The load is varied from no load to full load in desired steps. All the time, keep primary voltage V1 constant at its rated value with help of variac and tabulated the reading. The first reading is to be noted on no load for which I2 = 0 A and W2 = 0W.

Calculation

From the observed reading

W1 = input power to the transformer

W2 = output power delivered to the load

$$\boxed{\% \eta = \frac{W2}{W1} X 100}$$

The first reading is no load so $V2 = E_2$

The regulation can be obtained as

$$\% R = \frac{E2-V2}{} X 100$$

The graph of % η and % R on each load against load current IL is plotted as shown in fig. 2.23.

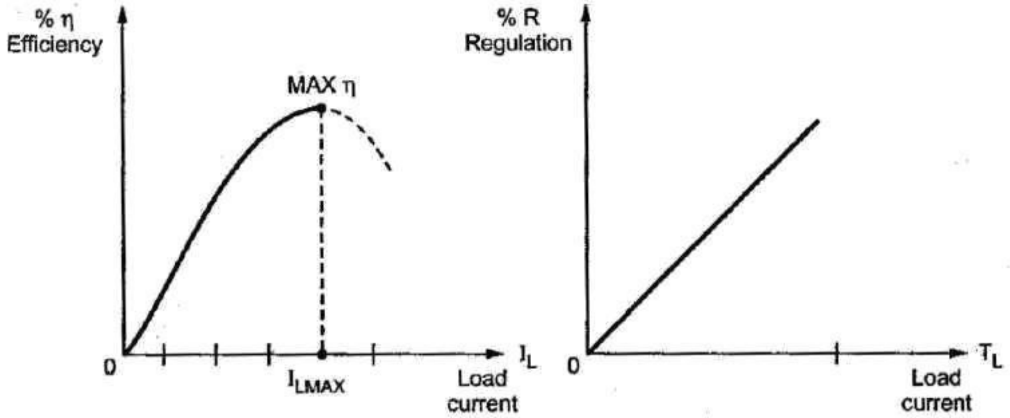


Fig: 2.23

<u>Advantages:</u>

1) This test enables us to determine the efficiency of the transformer accurately at any load.

2) The results are accurate as load is directly used.

<u>Disadvantages:</u>

1) There are large power losses during the test.

2) Load not avail in lab while test conduct for large transformer.

ii) a. <u>Open-Circuit or No-Load Test</u>

This test is conducted to determine the iron losses (or core losses) and parameters R0 and X0 of the transformer. In this test, the rated voltage is applied to the primary (usually low-voltage winding) while the secondary is left open circuited. The applied primary voltage V1 is measured by the voltmeter, the no load current I0 by ammeter and no-load input power W0 by wattmeter as shown in Fig.2.24.a. As the normal rated voltage is applied to the primary, therefore, normal iron losses will occur in the transformer core. Hence wattmeter will record the iron losses and small copper loss in the primary. Since no-load current I0 is very small (usually 2-10 % of rated current). Cu losses in the primary under no-load condition are negligible as compared with iron losses. Hence, wattmeter reading practically gives the iron losses in the transformer. It is reminded that iron losses are the same at all loads.

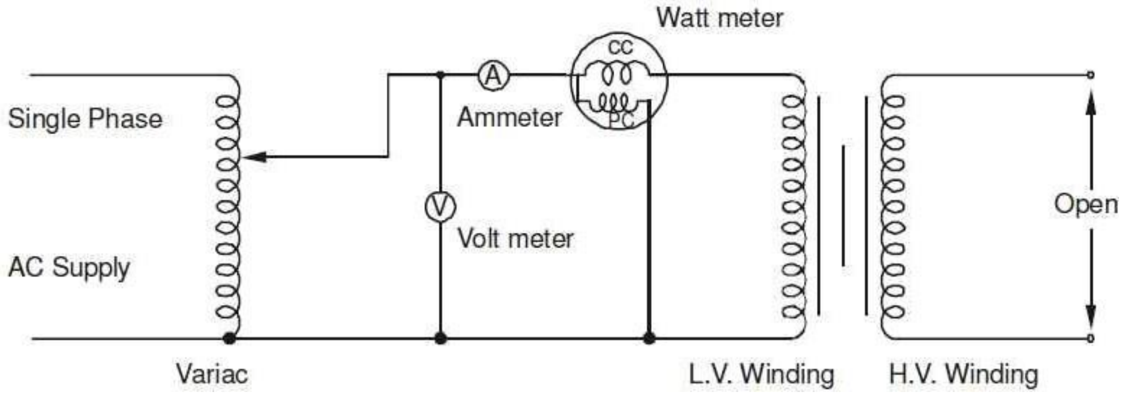


Fig: 2.24.a

Iron losses, P_i = Wattmeter reading = W_0
No load current = Ammeter reading = I_0
Applied voltage = Voltmeter reading = V_1

Input power, $W_0 = V_1 I_0 \cos \phi_0$

No - load p.f., $\cos\phi = \frac{Wo}{Vo\,Io}$ = no load power factor

$I_m = I_o \sin \phi_o$ = magnetizing component
$I_c = I_o \cos \phi_o$ = Active component

$R_o = \frac{Vo}{Ic}\ \Omega, \quad X_o = \frac{Vo}{Im}\ \Omega$

Under no load conditions the PF is very low (near to 0) in lagging region. By using the above data we can draw the equivalent parameter shown in Figure 2.24.b.

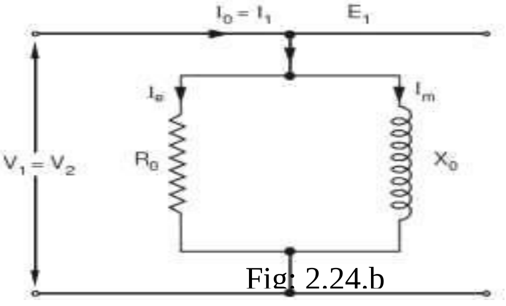
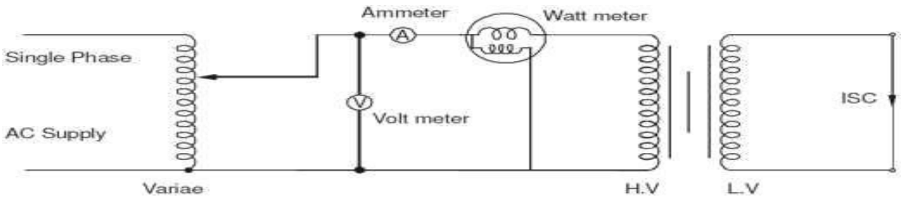


Fig: 2.24.b

Thus open-circuit test enables us to determine iron losses and parameters R0 and X0 of the transformer

ii) b. Short-Circuit or Impedance Test

This test is conducted to determine R1e (or R2e), X1e (or X2e) and full-load copper losses of the transformer. In this test, the secondary (usually low-voltage winding) is short-circuited by a thick conductor and variable low voltage is applied to the primary as shown in Fig.2.25. The low input voltage is gradually raised till at voltage VSC, full-load current I1 flows in the primary. Then I2 in the secondary also has full-load value since I1/I2 = N2/N1. Under such conditions, the copper loss in the windings is the same as that on full load. There is no output from the transformer under short-circuit conditions. Therefore, input power is all loss and this loss is almost entirely copper loss. It is because iron loss in the core is negligibly small since the voltage VSC is very small. Hence, the wattmeter will practically register the full load copper losses in the transformer windings.



Auto-transformers

The transformers we have considered so far are two-winding transformers in which the electrical circuit connected to the primary is electrically isolated from that connected to the secondary. An auto-transformer does not provide such isolation, but has economy of cost combined with increased efficiency. Fig.2.26 illustrates the auto-transformer which consists of a coil of NA turns between terminals 1 and 2, with a third terminal 3 provided after NB turns. If we neglect coil resistances and leakage fluxes, the flux linkages of the coil between 1 and 2 equals NA ɸm while the portion of coil between 3 and 2 has a flux linkage NB ɸm. If the induced voltages are designated as EA and EB, just as in a two winding transformer,

$$\frac{\bar{E}_A}{\bar{E}_B} = \frac{N_A}{N_B}$$

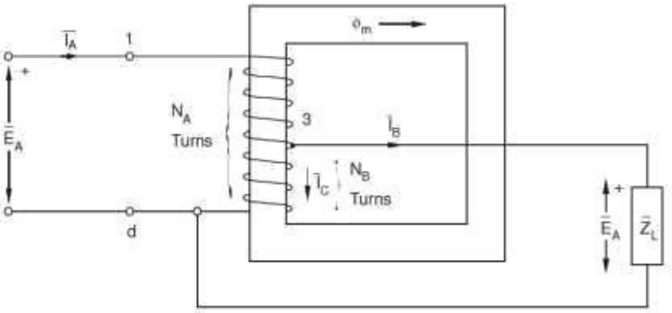


Fig: 2.2

Neglecting the magnetizing ampere-turns needed by the core for producing flux, as in an ideal transformer, the current *IA* flows through only (*NA* – *NB*) turns. If the load current is *IB*, as shown by

Kirchhoff's current law, the current *IC* flowing from terminal 3 to terminal 2 is (I*A* - *IB*). This current flows through *NB* turns. So, the requirement of a net value of zero ampere-turns across the core demands that

$$(N_A - N_B)\,\bar{I}_A + (\bar{I}_A - \bar{I}_B)\,N_B = 0$$

or

$$N_A\,\bar{I}_A - N_B\,\bar{I}_B = 0$$

Hence, just as in a two-winding transformer,

$$\frac{\bar{I}_A}{\bar{I}_B} = \frac{N_B}{N_A}$$

Consequently, as far as voltage, current converting properties are concerned, the autotransformer of Figure: 26 behaves just like a two-winding transformer. However, in the autotransformer we don't need two separate coils, each designed to carry full load values of current.

Parallel Operation of Transformers

It is economical to install numbers of smaller rated transformers in parallel than installing bigger rated electrical power transformers. This has mainly the following advantages,

To maximize electrical power system efficiency: Generally electrical power transformer gives the maximum efficiency at full load. If we run numbers of transformers in parallel, we can switch on only those transformers which will give the total demand by running nearer to its full load rating for that time. When load increases, we can switch none by one other transformer connected in parallel to fulfill the total demand. In this way we can run the system with maximum efficiency.

To maximize electrical power system availability: If numbers of transformers run in parallel, we can shut down any one of them for maintenance purpose. Other parallel transformers in system will serve the load without total interruption of power.

To maximize power system reliability: if any one of the transformers run in parallel, is tripped due to fault of other parallel transformers is the system will share the load, hence power supply may not be interrupted if the shared loads do not make other transformers over loaded.

To maximize electrical power system flexibility: There is always a chance of increasing or decreasing future demand of power system. If it is predicted that power demand will be increased in future, there must be a provision of connecting transformers in system in parallel to fulfil the extra demand because, it is not economical from business point of view to install a bigger rated single transformer by forecasting the increased future demand as it is unnecessary investment of money. Again if future demand is decreased, transformers running in parallel can be removed from system to balance the capital investment and its return.

Conditions for Parallel Operation of Transformers

When two or more transformers run in parallel, they must satisfy the following conditions for satisfactory performance. These are the conditions for parallel operation of transformers.

- ***Same voltage ratio of transformer.***
- ***Same percentage impedance.***
- ***Same polarity.***
- ***Same phase sequence.***

- ***Same Voltage Ratio***

Same voltage ratio of transformer

If two transformers of different voltage ratio are connected in parallel with same primary supply voltage, there will be a difference in secondary voltages. Now say the secondary of these transformers are connected to same bus, there will be a circulating current between secondary's and therefore between primaries also. As the internal impedance of transformer is small, a small voltage difference may cause sufficiently high circulating current causing unnecessary extra I2R loss.

Same Percentage Impedance

The current shared by two transformers running in parallel should be proportional to their MVA ratings. Again, current carried by these transformers are inversely proportional to their internal impedance. From these two statements it can be said that, impedance of transformers running in parallel are inversely proportional to their MVA ratings. In other words, percentage impedance or per unit values of impedance should be identical for all the transformers that run in parallel.

Same Polarity

Polarity of all transformers that run in parallel, should be the same otherwise huge circulating current that flows in the transformer but no load will be fed from these transformers. Polarity of transformer means the instantaneous direction of induced emf in secondary. If the instantaneous directions of induced secondary emf in two transformers are opposite to each other when same input power is fed to both of the transformers, the transformers are said to be in opposite polarity. If the instantaneous directions of induced secondary e.m.f in two transformers are same when same input power is fed to the both of the transformers, the transformers are said to be in same polarity.

Same Phase Sequence

The phase sequence or the order in which the phases reach their maximum positive voltage, must be identical for two parallel transformers. Otherwise, during the cycle, each pair of phases will be short circuited.

The above said conditions must be strictly followed for parallel operation of transformers but totally identical percentage impedance of two different transformers is difficult to achieve practically, that is why the transformers run in parallel may not have exactly same percentage impedance but the values would be as nearer as possible.

Why Transformer Rating in kVA?

An important factor in the design and operation of electrical machines is the relation between the life of the insulation and operating temperature of the machine. Therefore, temperature rise resulting from the losses is a determining factor in the rating of a machine. We know that copper loss in a transformer depends on current and iron loss depends on voltage. Therefore, the total loss in a transformer depends on the volt-ampere product only and not on the phase angle between voltage and current i.e., it is independent of load power factor. For this reason, the rating of a transformer is in kVA and not kW.

SINGLE-PHASE INDUCTION MOTORS

INTRODUCTION:

There are two basic reasons for the use of single-phase motors rather than 3-phase motors.

1. For reason of economy, most houses, offices and also rural areas are supplied with single phase a.c, as power requirements of individual load items are rather small.
2. The economics of the motor and its branch circuit.
   - Fixed loads requiring not more than 0.5KW can generally be served most economically with single phase power and a single phase motor.
   - Single phase motors are simple in construction, reliable, easy to repair and comparatively cheaper in cost and therefore, find wide use in fans, refrigerators, vacuum cleaners, washing machines, other kitchen equipment, tools, blowers, centrifugal pumps, small farming appliances etc.

Because of above reasons motors of comparatively small ratings (mostly in fractional KW ratings) are manufactured in large number to operate on single phase ac at standard frequencies. An indication of the number of such motors can be had from the fact that the sum of total of all fractional kilowatt motors in use today far exceeds the total of integral kilowatt motors of all types.

TYPES OF SINGLE-PHASE MOTOR:

The Single phase motors may be of the following types:

1. **Single-phase Induction Motors:**
   - A. Split-phase motors
     - (i) Resistance-start motor
     - (ii) Capacitor-start motor
     - (iii) Permanent-split (single-value) capacitor motor
     - (iv) Two-value capacitor motor.
   - B. Shaded-pole induction motor.

C. Reluctance-start induction motor.
D. Repulsion-start induction motor.

2. **Commutator-Type, Single-Phase Motors:**
   A. Repulsion motor.
   B. Repulsion-induction motor.
   C. A.C series motor.
   D. Universal motor.
3. **Single-phase Synchronous Motors:**
   A. Reluctance motor.
   B. Hysteresis motor.
   C. Sub-synchronous motor.

SINGLE-PHASE INDUCTION MOTORS

Applications and Disadvantages:

Applications:

- Single phase induction motors are in very wide use in industry especially in fractional horse-power field.

  They are extensively used for electrical drive for low power constant speed apparatus such as machine tools, domestic apparatus and agricultural machinery in circumstances where a three-phase supply is not readily available.
- Single phase induction motors sizes vary from 1/400 kw to 1/25 kw are used in toys, hair dryers, vending machines etc.
- Universal motor is widely used in portable tools, vacuum cleaners& kitchen equipment.

Disadvantages:

Though these machines are useful for small outputs, they are not used for large powers as they suffer from many disadvantages and are never used in cases where three-phase machines can be adopted.

The main disadvantages of single-phase induction motors are:

1. Their output is only 50% of the three-phase motor, for a given frame size and temperature rise.

2. They have lower power factor.
3. Lower efficiency.
4. These motors do not have inherent starting torque.
5. More expensive than three-phase motors of the same output.
6. Low overload capacity.

CONSTRUCTION OF SINGLE PHASE INDUCTION MOTOR:

Single phase induction motor is very simple and robust in construction. The stator carries a distributed winding in the slots cut around the inner periphery. The stator conductors have low resistance and they are winding called Starting winding is also mounted on the stator. This winding has high resistance and its embedded deep inside the stator slots, so that they have considerable inductance. The rotor is invariably of the squirrel cage type. In practice, in order to convert temporarily the single phase motor into two-phase motor, auxiliary conductors are placed in the upper layers of stator slots. The auxiliary winding has a centrifugal switch in series with it. The function of the switch is to cut off the starting winding, when the rotor has accelerated to about 75% of its rated speed. In capacitor-start motors, an electrolytic capacitor of suitable capacitance value is also incorporated in the starting winding circuit.

The main stator winding and auxiliary (or starting) winding are joined in parallel, and there is an arrangement by which the polarity of only the starting winding can be reversed. This is necessary for changing the direction of rotation of the rotor.

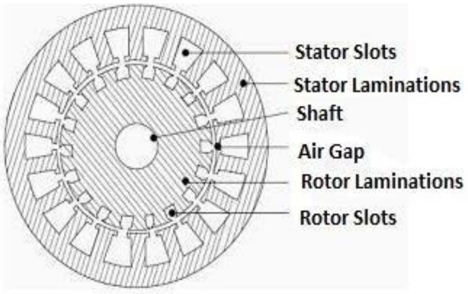


Fig: 1.41

A 1-phase induction motor is similar to a 3-phase squirrel cage induction motor in physical appearance. The rotor is same as that employed in 3-phase squirrel cage induction motor. There is uniform air gap between stator and rotor but no electrical connection between them.

Although single phase induction motor is more simple in construction and is cheaper than a 3-phase induction motor of the same frame size, it is less efficient and it operates at lower power factor.

WORKING OF SINGLE-PHASE INDUCTION MOTOR:

A single phase induction motor is inherently not self-staring can be shown easily.

Consider a single phase induction motor whose rotor is at rest. Let a single phase a.c. source be connected to the stator winding (it is assumed that there is no starting winding). Let the stator be wound for two poles.

When power supply for the stator is switched on, an alternating current flows through the stator winding. This sets up an alternating flux. This flux crosses the air gap and links with the rotor conductors. By electromagnetic induction e.m.f.'s are induced in the rotor conductors. Since the rotor forms a closed circuit, currents are induced in the rotor bars. Due to interaction between the rotor induced currents and the stator flux, a torque is produced. It is readily seen that if all rotor conductors in the upper half come under a stator N pole, all rotor conductors in the lower half come under a stator S pole. Hence the upper half of the rotor is subjected to a torque which tends to rotate it in one direction and the lower half of the rotor is acted upon by an equal torque which tends to rotate it in the opposite direction. The two equal and opposite torques cancel out, with the result that the net driving torque is zero. Hence the rotor remains stationary. Thus the single phase motor fails to develop starting torque.

This argument holds good irrespective of the number of stator poles and the polarity of the stator winding. The net torque acting on the rotor at standstill is zero.

If, however, the rotor is in motion in any direction when supply for the stator is switched on, it can be shown that the rotor develops more torque in that direction. The net torque then, would have non-zero value, and under its impact the rotor would speed up in its direction.

The analysis of the single phase motor can be made on the basis of two theories:

i. Double revolving field theory, and
ii. Cross field theory.

1.51 DOUBLE REVOLVING FIELD THEORY:

This theory makes use of the idea that an alternating uni-axial quantity can be represented by two oppositely-rotating vectors of half magnitude. Accordingly, an alternating sinusoidal flux can be represented by two revolving fluxes, each equal to half the value of the alternating flux and each rotating synchronously in opposite direction.

As shown in figure: (a) let the alternating flux have a maximum value of ϕ_m. Its component fluxes A and B will each equal to $\phi_m/2$ revolving in anti-clockwise and clockwise directions respectively.

After some time, when A and B would have rotated through angle +Θ and – Θ, as in figure: (b), the resultant flux would be

$$= 2*\frac{\phi_m}{2}\cos\frac{2\Theta}{2} = \phi_m \cos\Theta$$

After a quarter cycle of rotation, fluxes A and B will be oppositely-directed as shown in figure: (c) so that the resultant flux would be zero.

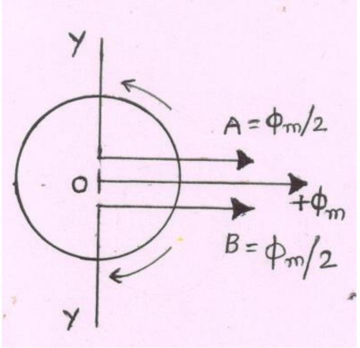


Fig: 1.51(a)

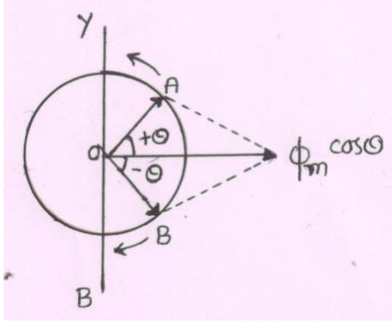


Fig: 1.51(b)

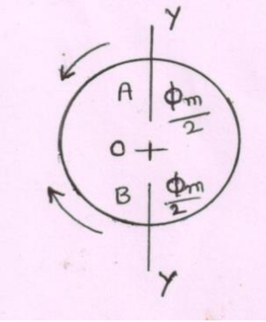


Fig:1.51 (c)

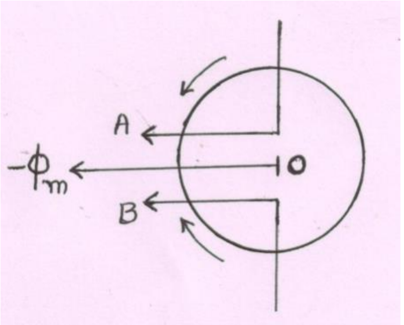


Fig: 1.51 (d)

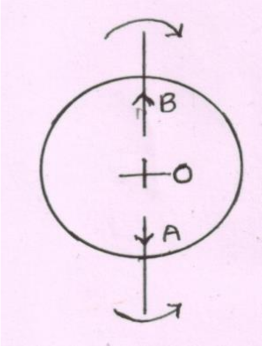


Fig: 1.51(e)

After half a cycle, fluxes A and B will have a resultant of $-2*\frac{\phi_m}{2} = -\phi_m$. After three quarters of a cycle, again the resultant is zero, as shown in figure: (e) and so on. If we plot the values of resultant flux against ϴ between limits $ϴ=0^0$ to $ϴ=360^0$, then a curve similar to the one shown in figure: (f) is obtained. That is why an alternating flux can be looked upon as composed of two revolving fluxes, each of half the value and revolving synchronously in opposite directions.

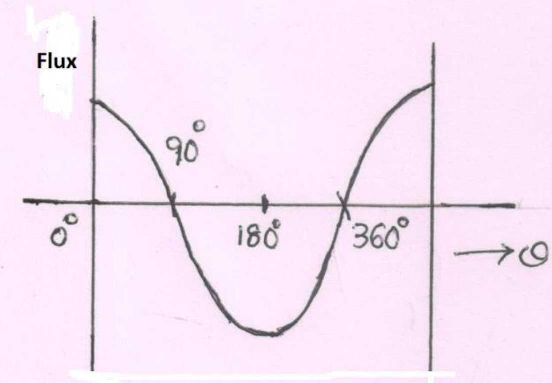


Fig: 1.51(f)

It may be noted that if the slip of the rotor is S with respect to the forward rotating flux (i.e. one which rotates in the same direction as rotor) then its slip with respect to the backward rotating flux is (2-S).

Each of the two component fluxes, while revolving round the stator, cuts the rotor, induces an e.m.f. and this produces its own torque. Obviously, the two torques (called forward and backward torques) are oppositely-directed, so that the net or resultant torques is equal to their difference as shown in fig: (g)

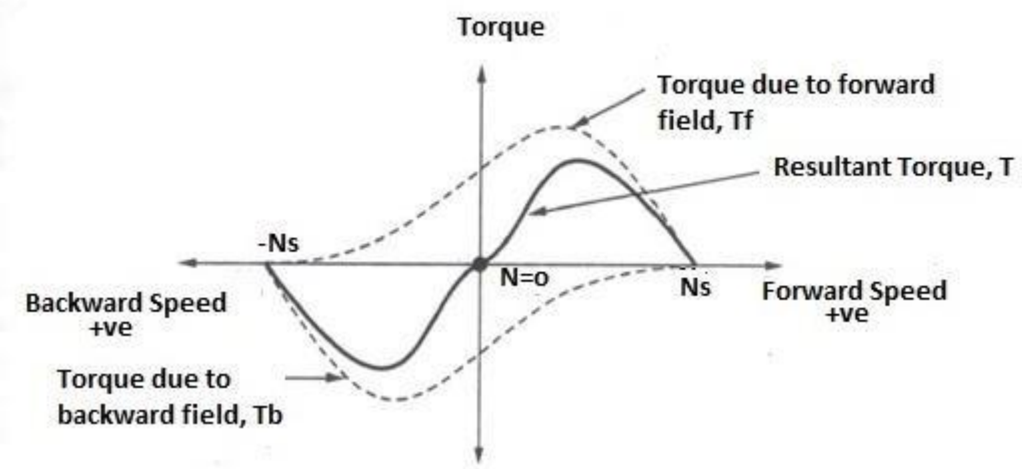


Fig: 1.51(g) Torque-Speed characteristics

Now, power developed by a rotor is $P_g = \left(\frac{1-S}{S}\right) I_2^2 R_2$

If N is the rotor r.p.s., then torque is given by , $T_g = \frac{1}{2\Pi N} \left(\frac{1-S}{S}\right) I_2^2 R_2$

Now, $N = N_s (1-S)$

Therefore, $T_g = \frac{1}{2\Pi N_s} \frac{I_2^2 R_2}{S} = k \frac{I_2^2 R_2}{S}$

Hence, the forward and backward torques are given by

$$T_f = k \frac{I_2^2 R_2}{S} \quad \text{and} \quad T_b = -k \frac{I_2^2 R_2}{(2-S)}$$

or $T_f = \frac{I_2^2 R_2}{S}$ synch. Watt and $T_b = -\frac{I_2^2 R_2}{(2-S)}$ synch. Watt

Total torque **T** = $T_f + T_b$

Fig: (g) shows both torques and the resultant torque for slips between zero and +2. At standstill, S=1 and (2-S) =1. Hence, T_f and T_b are numerically equal but, being oppositely directed, produce no resultant torque. That explains why there is no starting torque in a single-phase induction motor.

However, if the rotor is started somehow, say, in the clockwise direction, the clockwise torque starts increasing and, at the same time, the anticlockwise torque starts decreasing. Hence, there is a certain amount of net torque in the clockwise direction which accelerates the motor to full speed.

EQUIVALENT CIRCUIT:

The equivalent circuit of a single phase induction motor can be developed on the basis of two revolving field theory. To develop the equivalent circuit it is necessary to consider standstill or blocked rotor conditions.

The motor with a blocked rotor merely acts like a transformer with its secondary short circuited and its equivalent circuit will be as shown in fig: 1.6 (a), E_m being e.m.f. induced in the stator.

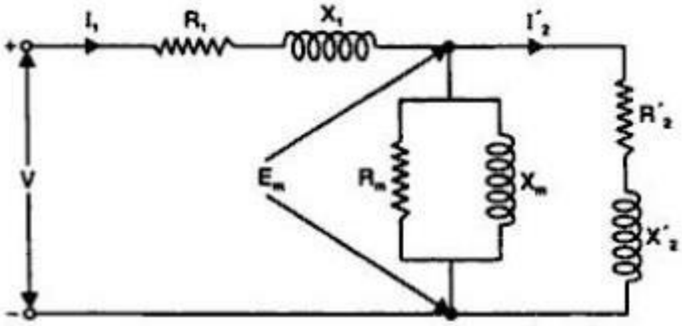


Fig:1.6 (a) Equivalent Circuit of a Single Phase Induction Motor

The motor may now be viewed from the point of view of the two revolving field theory. The two flux components induce e.m.f. E_{mf} and E_{mb} in the respective stator winding. Since at standstill the two oppositely rotating fields are of same strength, the magnetizing and rotor impedances are divided into two equals halves connected in series as shown in figure:1.6(b)

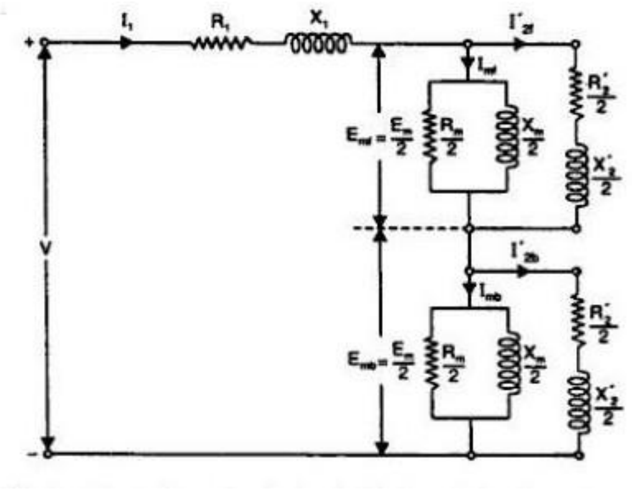


Fig:1.6 (b) Equivalent Circuit of Single Phase Induction Motor at Standstill on the basis of Two Revolving Field Theory

When the rotor runs at speed N with respect to forward field, the slip is S w.r.t. forward field and (2-S) w.r.t. backward field and the equivalent circuit is as shown in fig:1.6(c)

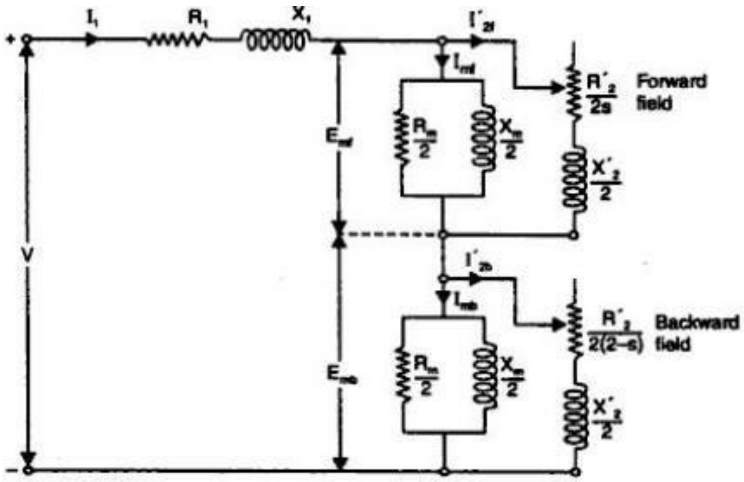


Fig:1.6 (c) Equivalent Circuit of a Single Phase Induction Motor Under Normal Operating Conditions

If the core losses are neglected the equivalent circuit is modified as shown in fig:1.6(d). The core losses, here, are handled as rotational losses and subtracted from the power converted into mechanical power; the amount of error thus introduced is relatively small.

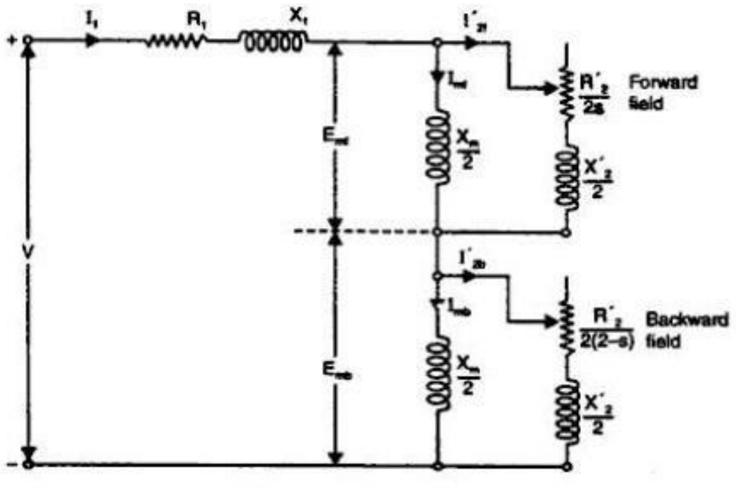


Fig:1.6 (d) Approximate Equivalent Circuit of a Single Phase Induction Motor Under Normal Operating Conditions

STARTING METHODS OF SINGLE-PHASE INDUCTION MOTORS:

A single-phase induction motor with main stator winding has no inherent starting torque, since main winding introduces only stationary, pulsating air-gap flux wave. For the development of starting torque, rotating air-gap field at starting must be introduced. Several methods which have been developed for the starting of single-phase induction motors, may be classified as follows:

a) Split-phase starting.
b) Shaded-pole starting.
c) Repulsion-motor starting and
d) Reluctance starting.

A single-phase induction motor is commonly known by the method employed for its starting. The selection of a suitable induction motor and choice of its starting method, depend upon the following:

(i) Torque-speed characteristic of load from standstill to the normal operating speed.
(ii) The duty cycle and
(iii) The starting and running line-current limitations as imposed by the supply authorities.

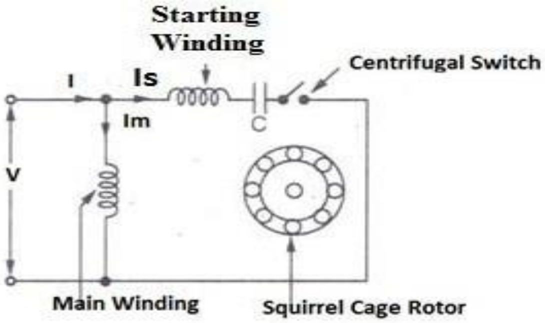
Capacitor split-phase motors (or) Capacitor start motors:

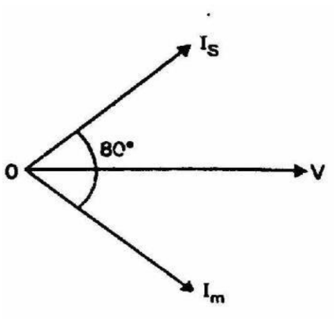
The capacitor split-phase motor is identical to a resistor split-phase motor except that the starting winding has as many turns as the main winding. Moreover, a capacitor C is connected in series with the starting winding as shown in figure: 1.72(a).The value of capacitor is so chosen that I_S leads I_m by about 80° (i.e., $\phi \sim 80°$) which is considerably greater than 25° found in resistor split-phase motor [See figure: 1.72(b).Consequently, starting torque ($T_s = k\, I_m\, I_S \sin\phi$) is much more than that of a split-phase motor Again, the starting winding is opened by the centrifugal switch when the motor attains about 75% of synchronous speed. The motor then operates as a single-phase induction motor and continues to accelerate till it reaches the normal speed.

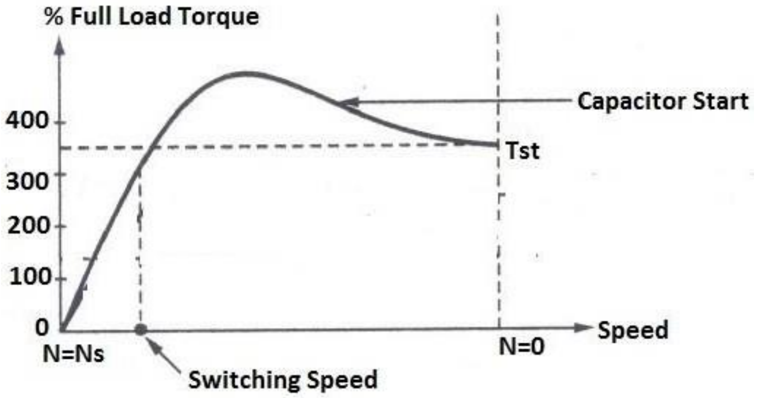
Characteristics

(i) Although starting characteristics of a capacitor-start motor are better than those of a resistor split-phase motor, both machines possess the same running characteristics because the main windings are identical.

(ii) The phase angle between the two currents is about 80° compared to about 25° in a resistor split-phase motor. Consequently, for the same starting torque, the current in the starting winding is only about half that in a resistor split-phase motor. Therefore, the starting winding of a capacitor start motor heats up less quickly and is well suited to applications involving either frequent or prolonged starting periods.







Applications:

Since the motors possess high-starting torque, these motors are used for

a. Refrigerators
b. Air-conditioners
c. Compressors
d. Reciprocating pumps
e. Other loads requiring high-starting torques.

The power rating of such motors lies between 120 W and 750W.

Capacitor-Start and Capacitor-Run motors:

This motor is identical to a capacitor-start motor except that starting winding is not opened after starting so that both the windings remain connected to the supply when running as well as at starting. Two designs are generally used.

(i) In one design, a single capacitor C is used for both starting and running as shown in fig: 1.73(a).This design eliminates the need of a centrifugal switch and at the same time improves the power factor and efficiency of the motor.

(ii) In the other design, two capacitors C1 and C2 are used in the starting winding as shown in fig: 1.73(b).. The smaller capacitor C1 required for optimum running conditions is permanently connected in series with the starting winding. The much larger capacitor C2 is connected in parallel with C1 for optimum starting and remains in the circuit during starting. The starting capacitor C1 is disconnected when the motor approaches about 75% of synchronous speed. The motor then runs as a single-phase induction motor.

Characteristics

(i) The starting winding and the capacitor can be designed for perfect 2-phase operation at any load. The motor then produces a constant torque and not a pulsating torque as in other single-phase motors.

(ii) Because of constant torque, the motor is vibration free.

Applications:

a. Hospitals
b. Studios and
c. Other places where silence is important.

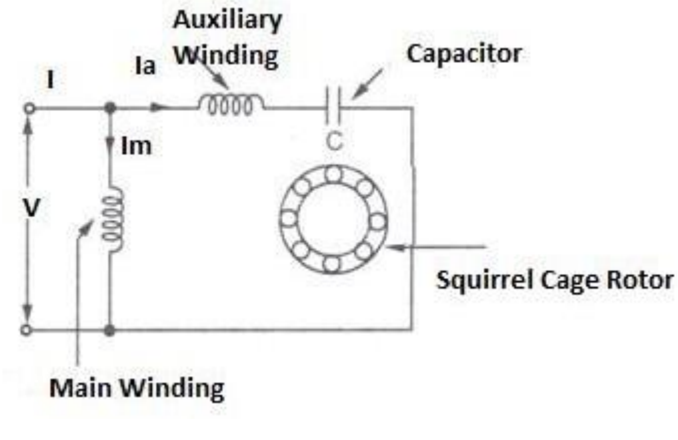


Fig: 1.73(a)

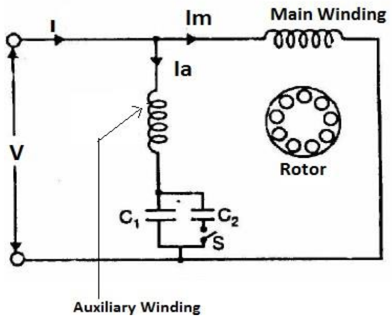
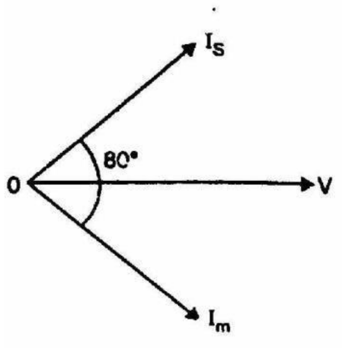


Fig: 1.73 (b)



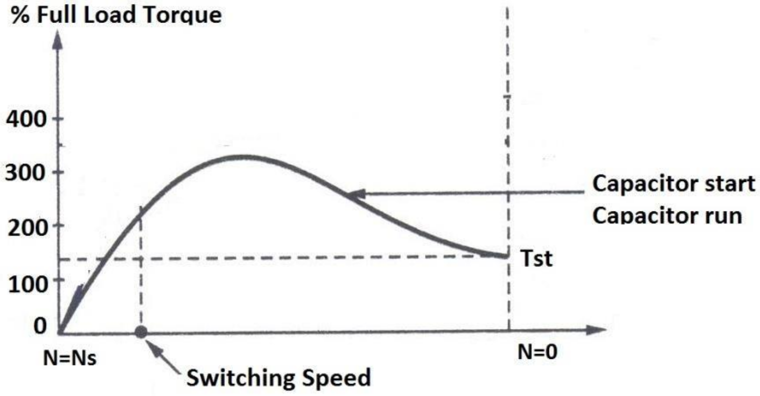


Fig: 1.73 (c) **Fig:** 1.73 (d)

The power rating of such motors lies between 100 to 400 watts

Capacitor-run motors:

This motor is also called permanent split capacitor motor. The same capacitor is kept permanently in series with auxiliary winding both at starting and under running conditions as illustrated in figure: 1.74 (a). There is no centrifugal switch. At a particular desired load, the capacitor and auxiliary winding can be so designed as to result in 90^0 time-phase displacement between the two winding currents. In such a case, the motor would operate as a balanced two phase induction motor, backward rotating flux would, therefore, be absent and the motor would have improved efficiency and better operating power factor. Since backward rotating field can be reduced to zero, the pulsating torque due to interaction between forward and backward rotating fields is absent and this results in a quiet motor.

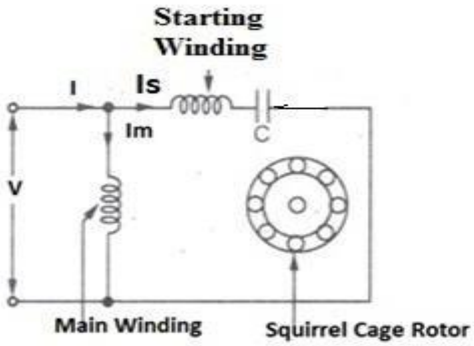


Fig: 1.74 (a)

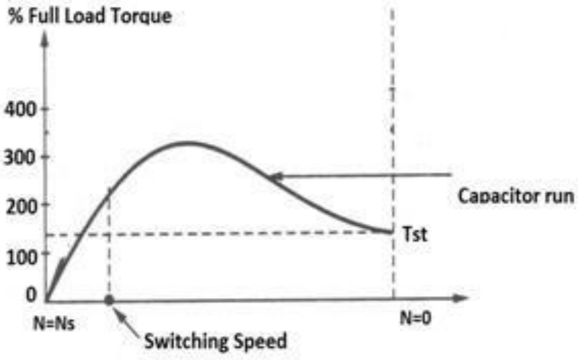


Fig: 1.74 (b)

In these motors, the value of permanent capacitor is so chosen as to obtain a compromise between the best starting and running conditions. A typical torque-speed characteristic is shown in fig: 1.74 (b)

These motors are used where quiet operation is essential as in

a. Offices
b. Class rooms
c. Theaters
d. Ceiling fans, in which the value of capacitance varies from 2 to 3µF.

Shaded-Pole Motor:

The shaded-pole motor is very popular for ratings below 0.05 H.P. (~40 W) because of its extremely simple construction. It has salient poles on the stator excited by single-phase supply and a squirrel cage rotor as shown in figure: 1.8(a). A portion of each pole is surrounded by a short-circuited turn of copper strip called shading coil.

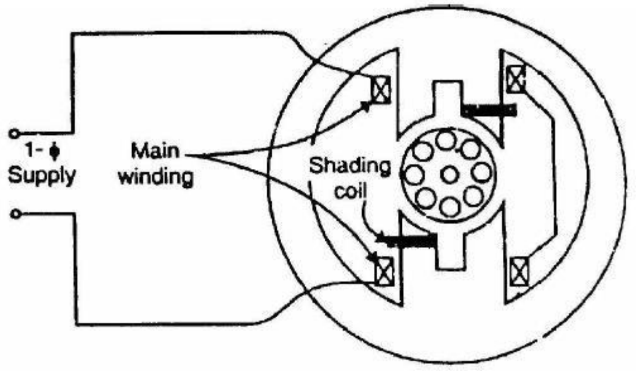


Fig: 1.8(a)

The operation of the motor can be understood by referring to figure: 1.8(b) which shows one pole of the motor with a shading coil.

(i) During the portion OA of the alternating-current cycle [See figure: 1.8(b)(i)], the flux begins to increase and an e.m.f. is induced in the shading coil. The resulting current in the shading coil will be in such a direction (Lenz's law) so as to oppose the change in flux. Thus the flux in the shaded portion of the pole is weakened while that in the unshaded portion is strengthened as shown in figure: 1.8(b)(ii)

(ii) During the portion AB of the alternating-current cycle, the flux has reached almost maximum value and is not changing. Consequently, the flux distribution across the pole is uniform [See figure: 1.8(b)(iii)] since no current is flowing in the shading coil. As the flux decreases (portion BC of the alternating current cycle), current is induced in the shading coil so as to oppose the decrease in current. Thus the flux in the shaded portion of the pole is strengthened while that in the unshaded portion is weakened as shown in figure: 1.8(b)(iv)

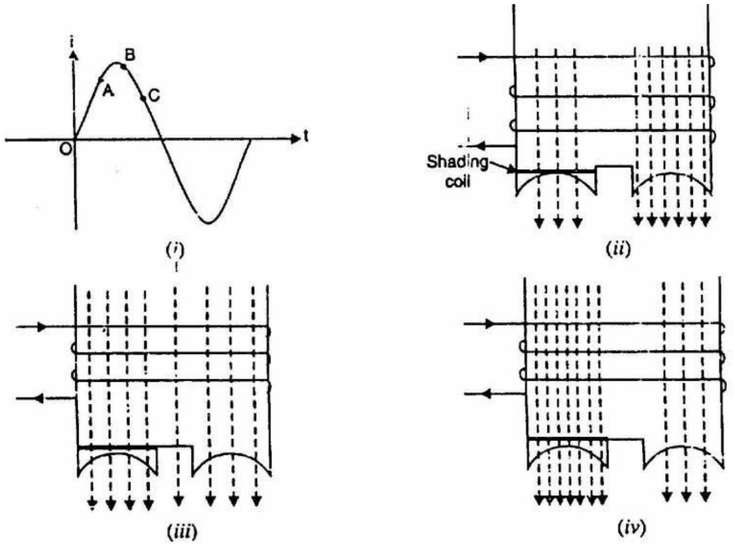


Fig: 1.8(b)

(iii) The effect of the shading coil is to cause the field flux to shift across the pole face from the unshaded to the shaded portion. This shifting flux is like a rotating weak field moving in the direction from unshaded portion to the shaded portion of the pole.

(iv) The rotor is of the squirrel-cage type and is under the influence of this moving field. Consequently, a small starting torque is developed. As soon as this torque starts to revolve the rotor, additional torque is produced by single-phase induction-motor action. The motor accelerates to a speed slightly below the synchronous speed and runs as a single-phase induction motor.

Characteristics

(i) The salient features of this motor are extremely simple construction and absence of centrifugal switch.

(ii) Starting torque, efficiency and power factor are very low

Applications:

These motors are only suitable for low power applications e.g., to drive:

a. small fans
b. Toys
c. Hair driers
d. Desk fans etc.

The power rating of such motors is upto about 30 W.

A.C. SERIES MOTOR (or) UNIVERSAL MOTOR:

A d.c. series motor will rotate in the same direction regardless of the polarity of the supply. One can expect that a d.c. series motor would also operate on a single-phase supply. It is then called an a.c. series motor. However, some changes must be made in a d.c. motor that is to operate satisfactorily on a.c. supply. The changes effected are:

(i) The entire magnetic circuit is laminated in order to reduce the eddy current loss. Hence an a.c. series motor requires a more expensive construction than a d.c. series motor.

(ii) The series field winding uses as few turns as possible to reduce the reactance of the field winding to a minimum. This reduces the voltage drop across the field winding.

(iii) A high field flux is obtained by using a low-reluctance magnetic circuit.

(iv) There is considerable sparking between the brushes and the commutator when the motor is used on a.c. supply. It is because the alternating flux establishes high currents in the coils short-circuited by the brushes. When the short-circuited coils break contact from the commutator, excessive sparking is produced. This can be eliminated by using high-resistance leads to connect the coils to the commutator segments.

Construction:

The construction of an a.c. series motor is very similar to a d.c. series motor except that above modifications are incorporated [See figure:1.91]. such a motor can be operated either on a.c. or d.c. supply and the resulting torque-speed curve is about the same in each case. For this reason, it is sometimes called a universal motor.

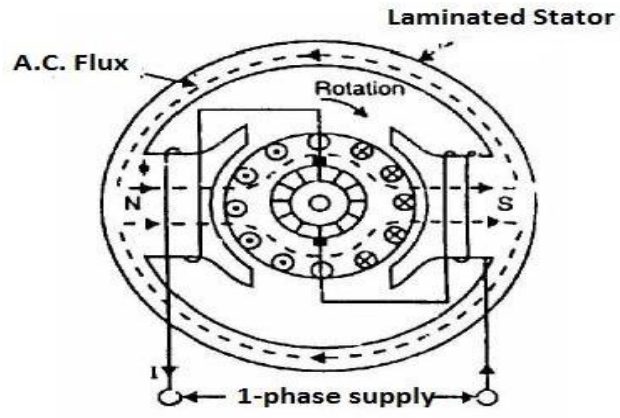


Fig: 1.91

Operation

When the motor is connected to an a.c. supply, the same alternating current flows through the field and armature windings. The field winding produces an alternating flux □ that reacts with the current flowing in the armature to produce a torque. Since both armature current and flux reverse simultaneously, the torque always acts in the same direction. It may be noted that no rotating flux is produced in this type of machines; the principle of operation is the same as that of a d.c. series motor.

Characteristics

The operating characteristics of an a.c. series motor are similar to those of a d.c. series motor.

(i) The speed increases to a high value with a decrease in load. In very small series motors, the losses are usually large enough at no load that limits the speed to a definite value (1500 - 15,000 r.p.m.).

(ii) The motor torque is high for large armature currents, thus giving a high starting torque.

(iii) At full-load, the power factor is about 90%. However, at starting or when carrying an overload, the power factor is lower.

Applications

The fractional horsepower a.c. series motors have high-speed (and corresponding small size) and large starting torque. They can, therefore, be used to drive:

a) high-speed vacuum cleaners

b) sewing machines
c) electric shavers
d) drills
e) Machine tools etc.

ALTERNATOR - CONSRUCTION AND WORKING PRINCIPLE

Synchronous generator or AC generator is a device which converts mechanical power in the form of A.C.

It works on the principle of ELECTRO MAGNETIC INDUCTION and it is also called as

Alternator

An alternator consists of armature winding and field magnet, but the difference between the alternator and DC generator is that in the DC generator armature rotates and the field system is stationary. This arrangement is the alternator is just reverse of it there the armature is stationary called as stator and field system is rotating called as Rotor.

For generating EMF, three things are essential:

1) Magnetic field
2) System of conductors
3) Relative motion between those two.

The conductors are mounted on the stators and the field poles are mounted on the Rotor core Relative motion between the stator conductors and the field is brought about rotating the field system.

The rotor is coupled mechanically to a suitable print mover. When the prime mover runs, the rotor core also rotates and the field flux is cut by the stationary stator conductors and emf's are induced in them.

If a load is connected across the stator terminals electric power would be delivered to it.

ADVANTAGES OF STATIONARY ARMATURE

The generated power can be easily taken out from the stator.

There is no possibility of the armature conductors flying of, when the machine runs at high speed since they are housed in the stator slots.

There is no difficulty in insulating the armature (stationary) winding for very high voltages, i.e, as high as 30000v or more.

Two slip rings are required for the supply of DC energy required for rotor field excitation. Since exciting current is to be supplied at low voltage, there is no difficulty in insulating them.

Rotating field is competitively light and can run with high speeds.

DIFFERENCES:-

S.No.	STATIONARY FIELD SYSTEM	ROTATING FIELD SYSTEM
1	4 slip rings are required.	100 slip rings are required.
2	Heavy armature current passes through slip rings.	Very low field current passes through slip rings.
3	More sparking at slip rings.	No sparking at slip rings.
4	Armature supply is taken through slip rings.	Armature supply is taken through fixed connections.
5	Capacity is limited to 30KVA.	It can be designed to any capacity.
6	Voltage is limited to 440v.	Voltage is up to 33KV is generated.
7	Low efficiency.	High efficiency.
8	More maintenance.	Less maintenance.

CONSTRUCTION:-

An alternator consists of mainly two parts

1. Stator
2. Rotor

1. Stator:-

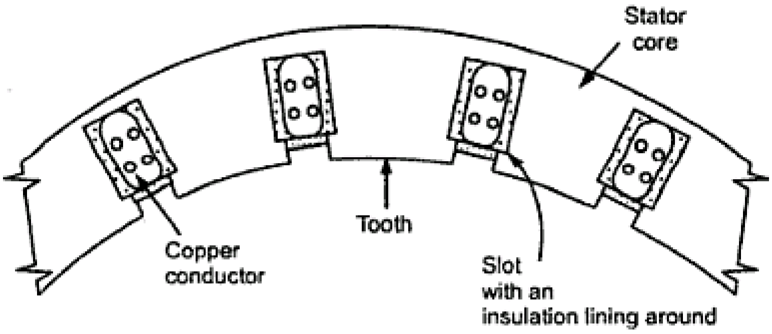


Fig 2.1

The armature core is supported by the stator frame and is built up of laminations of special magnetic iron or steel iron alloy the core is laminated to minimize the loss due to

Eddy currents.

The laminations are stamped out in complete rings or segments. The laminations are insulated from each other and have space between them for allowing the cooling air to pass through.

The inner periphery of the stator is slotted and copper conductors which are joined to one another constituting armature winding housed in these slots. The other ends of the winding are brought out are connected to fixed terminal from which the generator power can be taken out.

Different shapes of the armature slots are shown in the fig.

The wide open type slot also used in DC machines has the advantage of permitting easy installation of form-wound colis and there easy removal in case of repair but it has the disadvantage of distributing the air gaps flux into bunches that produce ripples in the wave of generated EMF.

The semi closed type slots are better in this respect but do not allow the use of form wound coils.

The fully closed slots donot disturb the air gap flux but they try to increase the inductance of the windings. The armature conductors have to be threaded through, there by increasing the initial labour and cost of the winding. Hence, these are rarely used.

2. <u>Rotor</u>:-

Depending upon the type of application, these are classified into two types

1) Salient-pole or projecting pole type
2) Non silent-pole or round rotor or cylindrical rotor

Salient-pole or projecting pole type

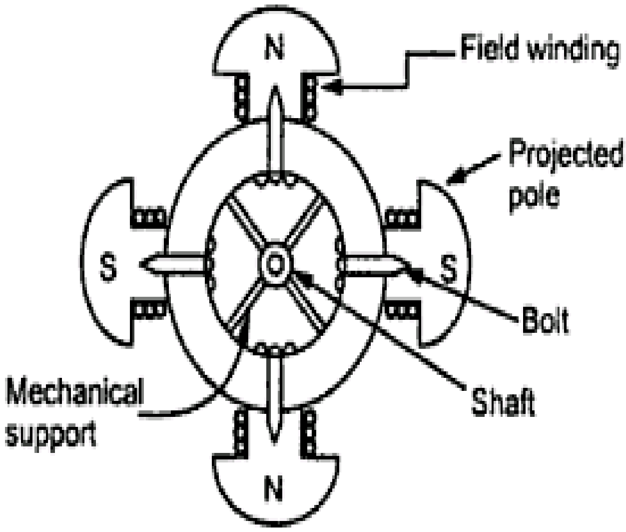


Fig 2.2

- It is used for and medium speed alternators used in hydro and diesel power generating station.
- The poles are made of laminated sheets and fixed to the rotor by dove tail joint.
- Short circuited damper bars are placed in the slots provided on the pole surfaces.
- These are used to prevent hunting and to provide starting torque in synchronous motors.
- The field coils are placed on the poles as shown in the figure

Key features:-

- It has non-uniform air gap.
- The diameter of the rotor is more than of the cylindrical rotor.
- The no. of holes is higher than that of the non salient-pole rotor
- Axial length is less.
- The prime mover speed is less and is driven in hydal turbines
- These generators are used in hydro electric stations so these are called as hydro generators.

Non-Salient pole type (or) Cylindrical type (or) Round rotor:

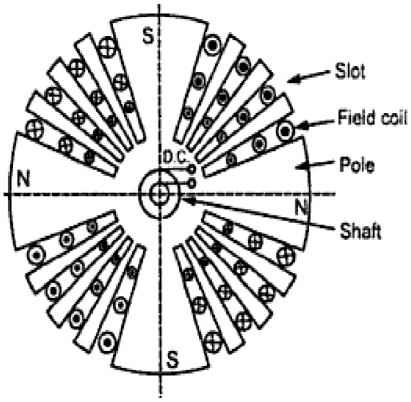


Fig 2.3

- Slots are provided in between the poles and these slots are placed with field winding Conductors.

Features :-

- No. of poles are less when compared to salient pole type.
- Diameter is less
- Axial length is more
- Air gap is uniform
- Prime mover speed is more and is driven in thermal turbines.
- These are used in thermal stations so, these are called as turbo Generators.

Electrical Engineering Materials

Contents:

- Classification of materials
- Conducting materials
- Semi-conducting materials
- Insulating materials
- Magnetic materials
- Special purpose material

Classification of material:

The material are classified into following types

1. **Conducting material** –The material in which electric current flow easily . Example: copper , brass etc.2
2. **Insulating material -** The material in which electric current cannot flow .Example: wood glass .
3. **Semiconducting material** – The material whose property lies between insulating and conducting material. Example: silicon, gallium.

Classification of material on the basis of atomic theory

- Conducting material.
- Insulating material.
- Semiconducting material.

Conducting material:

The materials which conduct electricity due to free electrons when an electric potential difference is applied across them are known as conducting materials.

Gold, silver, copper, aluminum are the examples of conducting materials.

Insulating material:

The material which does not allow the electricity to pass through them is known as an electrical insulating material.

The material which does not allow the electricity to pass through them is known as an electrical insulating material. The material which does not allow the electricity to pass through them is known as an electrical insulating material

glass wool, polystyrene, plastic, wood fiber, and plant fiber are the example of insulating material.

Semiconducting material.

The material whose property is lies between insulating and conducting material. examples of semiconductors are **silicon, germanium, gallium arsenide**

Energy band theory

The range of energies possessed by the electrons of the same orbit of different atoms in a solid is known as energy band

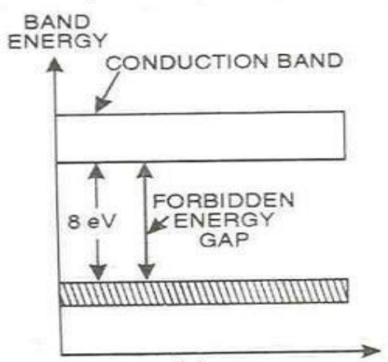
Types of energy bands.

- Valence band
- Conduction band
- Forbidden energy band

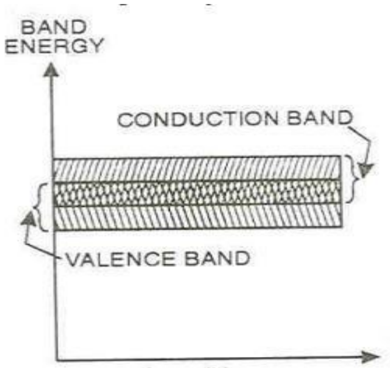
Classification of materials on the basis of energy band:

Insulators- insulators are those materials in which we cannot pass the electric current easily. The valence band of these substances is full whereas the conduction band is completely empty. The forbidden energy gap between valence band and conduction band is very large (8ev) as shown in the fig (a). Therefore a large amount of energy, i.e. a very high electric field is required to push the valence electrons to the conduction band.

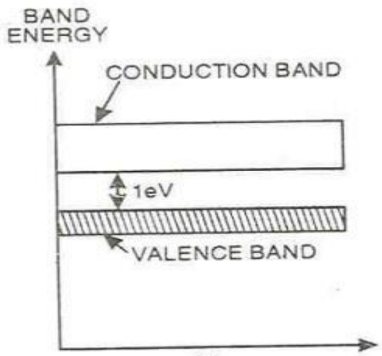
Conductors:- conductors are those materials which offers least resistance to electric current. The valence band of these substances overlaps the conduction band as shown in fig (b). Due to this overlapping, a large number of free electrons are available for conduction. This is the reason, why a slight potential difference applied across them causes a heavy flow of current through them. **Semiconductors:**
semiconductors are those materials whose resistivity lies between conductors and insulators . The valence band of these substances is almost filled, but the conduction band is almost empty. The forbidden energy gap between valence and conduction band is very small (1ev) as shown in fig (c). Therefore comparatively a smaller electric field is required to push the valence electrons to the conduction band.



(a)



(b)



(c)

CONDUCTING MATERIAL

Conductor – conductor are those material which permit the flow of energy .

ELECTRICAL PROPERTY –

1. Resistivity must be low .
2. Conductivity must be good .
3. Temp. Co-efficient of resistance must be low .

MEC HANICAL PROPERTY

1. Resistance to corrosion.
2. Ductility.
3. It should withstand stress and strain .

ECONOMICAL FACTOR

1. Low in cost.
2. Easy available.
3. Easy to manufacture.

RESISTANCE: The property of material by which it opposes the flow of electric current through it is called resistance.

RESISTANCE DEPEND UPON VARIOUS FACTOR

1. It directly proportional to length of conductor.
2. It inversely proportional to area of conductor.
3. It depends upon the nature of material.

4. It depends upon temp. R=p l\A The unit of resistance is OHM .

SPECIFIC RESISTANCE OR RESISTIVITY

The resistance offered by 1 meter length of conductor of the material having an area of one square meter . R=p L\A L =1m , A = 1m square p=find p=RA\L= ohm * 1\1= ohm meter THE unit of specific resistance is ohm meter .

FACTOR EFFECTING RESISTIVITY

- Temperature
- Alloying
- Mechanical stressing

EFFECT OF TEMPERATURE – Resistivity of material depend upon temp. changes . The resistance of all pure metal increase with increase in temp

EFFECT OF ALLOYING –

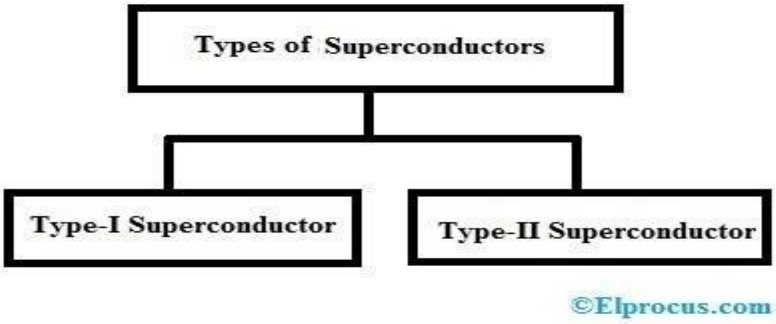
Alloying is a process of adding of impurities in the metals and non metals in small amount . By alloying we can change alloying and mechanical strength of conductor .

EFFECT OF MECHANICAL STREESING When material is subjected to mechanical stresses its resistivity changes due to mechanical distortion on crystal structure of material . The main limitation of mechanical stressing is reduction in the conductivity of material .

SUPERCONDUCTOR -Superconductor are those material which shows zero resistance at a particular temp. The temp. at which this occurs is called super conducting transition temperature . Transition temp. of few metal is given below –

Types of Superconductors

Superconductors are classified into two types namely type-I & type-II.



Type-I Superconductor

This kind of superconductor includes basic conductive parts and these are utilized in different fields from electrical cabling to microchips on the computer. These types of superconductors lose their superconductivity very simply when it is placed in the magnetic field at the critical magnetic field (Hc). After that, it will become like a conductor. These types of semiconductors are also named as soft superconductors due to the reason of loss of superconductivity. These superconductors obey the Meissner effect completely. The **superconductor examples** are Zinc and Aluminum.

Type-II Superconductor

This kind of superconductor will lose their superconductivity slowly but not simply as it is arranged within the exterior magnetic field. When we observe the graphical representation between magnetization vs. the magnetic field, when the second type semiconductor is placed within a magnetic field, then it will lose its superconductivity slowly.

APPLICATION OF SUPER CONDUCTOR

- Electrical machines
- Transmission and distribution line
- Electromagnet
- Computers

CLASSIFICATION OF CONDUCTING MATERIAL :

- Low resistivity material
- High resistivity material

LOW RESITIVITY MATERIAL

1. Low resistance temp. Coefficient
2. Sufficient mechanical
3. Ductility
4. Resistance to corrosion
5. Density

APPLICATON OF LOW RESITIVITY MATERIAL -It is used in house wiring, as conductor for transmission and distribution, motor and transformer.

HIGH RESITIVITY MATERIAL

1. High resistivity
2. Low temp. Co-efficient
3. High melting point
4. High ductile
5. Corrosion resistance
6. High mechanical strength

APPLICATION – These are used for making heating element, electric bulb, electric iron etc.

PROPERTIES AND APPLICATION OF LOW RESISTIVITY MATERIAL

- **SILVER**– silver is at top in all conductor material. It is high electrical conductivity & corrosion resistance.

PROPERTY –

1. It is high ductile & malleable.
2. It has highest electrical and thermal conductivity.
3. Its melting point 960 C
4. Its density is 10.5 g /cc.
5. Low surface contact resistance

APPLICATION – it is used to making contact of relay, thermal overload devices.

GOLD

Gold is a precious and costly metal. It is having good conductivity. Gold is having highest malleability and ductility among all metals. Due to high cost, its practical use is limited to precious instruments used for research.

PROPERTIES –

1. It is high ductile and malleable.
2. It offers high resistance of corrosion.
3. Its melting point is 1063 C.
4. Its boiling point is 2970 C .

APPLICATION – It is used for making contacts of highly sensitivity devices .Due to its high cost its use is limited.

COPPER

The extensively used, high conductivity material as conductor for electrical machines or equipment is copper. Malleability, weld ability and solder ability are most important properties of copper. Copper in pure form is having good conductivity. But the conductivity of standard grade copper is reduced due presence of impurities.

PROPERTIES –

1. It is radish in color.
2. It is ductile and malleable in nature.
3. It is low contact resistance.
4. Its melting point is 1083 C.
5. Its boiling point is 2320 C.
6. Its density is 8.9 g /cc.
7. Its tensile strength is 8.15 tones/cm square.

APPLICATION – It is used for making electrical wires, cables , winding of transformer and machine .

TYPES OF COPPER

- Hard drawn copper
- Annealed copper

DIFFERENCE BETWEEN HARD DRAWN COPPER AND ANNEALED COPPER

Hard drawn copper	Annealed copper
1. It is made by drawing copper into conductor in cold condition.	1. It is made by increasing temp. of hard drawn copper to a specific value then cool at room temp.
2. It is very hard	2. It is comparatively soft .
3. Its tensile strength is 8.15 tones/cm square	3. Its tensile strength is 4.5 tones/cm square.
4 It is less flexible.	4. It is more flexible.
5. It is used for making commutator segments.	5. It is used for making winding in transformer.

ALUMINIUM-

Aluminum is an element which is a silver-white, light weight, soft, non-magnetic and ductile metal. Aluminum is the third most abundant element. It is widely available in India & most commonly used material Its conductivity is next to copper .

PROPERTIES –

1. It is silver white color .
2. It is ductile and malleable .
3. It offer high resistance to corrosion .
4. Its specific gravity is 2.7 .
5. Its melting point is 655 C .
6. Its boiling point is 1800 C .
7. It is softer then copper .

APPLICATION – It is used in flexible electric wires , overhead transmission , electronics kit , household items .

LOW RESITIVITY COPPER ALLOYS

The following properties are required in **high resistivity or low conductivity conducting material**–

- High resistivity.
- High melting point.
- High mechanical strength.
- High ductility, so that can be drawn in the form of wire easily.
- High corrosion resistance mean free from oxidation.
- Low cost.
- Long life or durable.
- High flexibility.

BRASS – it is an alloy of copper and zinc containing 60% of copper and 40% zinc.

• PROPERTIES –

1. It is high tensile strength .
2. It is lower conductivity than copper .
3. It can attain any shape if pressed .
4. It can be easily drawn into wires .

5. Its melting point is about 890 C .

6. Its specific gravity is 3.3 .

APPLICATION – It is used as a current carrying material on plug point , socket outlets , switches , lamp holders .

BRONZE

Its color is radish yellow in color and it is alloy of copper and tin . It contain 84% copper and 8 to 16% OF tin.

PROPERTIES –

1. It is found in two types i.e. cadmium bronze and silicon bronze.

2. It has good conductivity but less than copper

3. It is free from corrosion .

APPLICATION – It is used for conducting commutator or segments .

PLATINUM

Platinum is among the most stable metals with high resistivity .

PROPERTIES –

1. It is a grayish white metals .

2. It is malleable and ductile .

3. Its melting point is 1775 C .

4. Its specific gravity is 21.4 g/cc .

5. It is high tensile strength .

APPLICATION –

1. it is used as heating element in ovens .

2. it is used in thermocouple .

3. It is used as grid for vacuum tubes

MERCURY

Mercury is silvery white metal .

PROPERTIES – 1. Its specific gravity is 13.55 g/cc .

2. It remain in liquid state at room temperature

3. Its boiling point is 358 C .

4. it is highly poisonous metal .

5. It is heavy white silver metal .

6. oxidation takes place beyond 300 C in contact with air .

APPLICATION – It is used in thermometers , fluorescent tubes , mercury arc rectifier .

LEAD

It is bluish gray colored metal

. **PROPERTIES** –

1. It is a hard and soft metal with high specific gravity.

2. It is high malleable.

3. Lead is corrosion resistant metal.

APPLICATION – It is used in lead acid battery, soldering wires, cable sheathes , protective glass in computers .

Tungsten

- It’s Very hard metal.
- Its Resistivity is twice to aluminum.
- It has high tensile strength.
- It can be drawn in the form of very thin wire.
- It oxidize very quickly in the presence of oxygen.
- It can be used up to 2000ºC in the atmosphere of inert gases (Nitrogen, Argon etc.) without oxidation.

Properties of Tungsten

- Specific weight : 20 gm/cm^3
- Resistivity : 5.28 μΩ -cm
- Temperature coefficient of resistance : 0.005 / ºC
- Melting point : 3410ºC
- Boiling point : 5900ºC
- Thermal coefficient of expansion: 4.44×10^{-9} / ºC

Uses of Tungsten

1. Used as filament for incandescent lamp.
2. As electrode in X- ray tubes.
3. The great hardness, high melting and boiling points make it suitable for use as electrical contact

material in certain applications. It is having high resistance for destructive forces produces during operation of electrical contacts.

Carbon

Carbon in widely used in electrical engineering. Electrical carbon materials are manufactured from graphite and other forms of carbon.

Properties of Carbon

- Resistivity : 1000 – 7000 μΩ – cm
- Temperature coefficient of resistance : – 0.0002 to – 0.0008 /^{o}C
- Melting point : 3500^{o}C
- Specific gravity : 2.1gm /cm^3

Uses of Carbon

Carbon is having following applications in electrical Engineering

1. Used for making pressure sensitive resistors, which are used in automatic voltage regulators.
2. Used for manufacturing the carbon brushes, which are used in DC machines. These carbon brushes improve the commutation as well as reduce the wear and tear.
3. For making filament of incandescent lamp.
4. For making electrical contacts.
5. For making resistors.
6. For making battery cell elements.
7. Carbon electrodes for electric furnaces.
8. Arc lighting and welding electrodes.
9. Component for vacuum valves and tubes.
10. For makings parts for telecommunication equipment.

What is Bundled Conductor?

bundled conductor to those conductors which form from two or more stranded conductors, bundled together to get more current carrying capacity.

- It use two or more stranded conductors per phase. It also, increase the current carrying capacity of the system, a bundle conductor also contributes various facilities to the electrical transmission system.
- A bundled conductor reduces the reactance of the electric transmission line.

- It also reduces voltage gradient, corona loss, radio interference, surge impedance of the transmission lines.

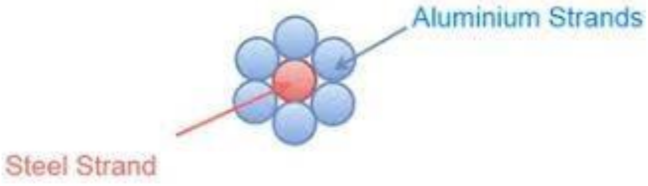
  By making bundle conductor, the geometric mean radius (GMR) of the conductor increased.
- As the self GMR of the conductor increases, the inductance of the conductor decreases. Theoretically, there is an optimum sub-conductor spacing in bundle conductor that will give minimum voltage gradient on the surface of bundle conductor.
- The optimum spacing between sub-conductors for reducing voltage gradient is eight to ten times of the diameter of the conductor.
- It is a conductor made up of two or more sub conductor per phase in close proximity and is used as one phase conductor . For voltage more than 220KV ,it is preferable to use more than one conductor per phase which i9s known as bundle conductor .
- **PROPERTY** –
- 1. Reduce corona loss .
- 2. Reduce reactance .
- 3. Reduce surge impedance .
- 4. It reduce radio interference .

APPLICATION It is used for transmission purpose as it helps in obtaining better voltage regulation and efficiency by reducing the inductance and skin effect present in the power lines .

Stranded Conductor

- The stranded conductor usually has a central wire which is surrounded by the layers of wires. These layers consists of 6, 12, 18, …. wires succe.ssively. Thus the total strands are 7, 13, 19. ....Such a stranded conductor with 37 strands.

- A stranded conductor is consists of several thin wires of small cross sectional area called strands



Stranded Conductor

As shown in figure above, at the center of stranded conductor, a steel conductor is used , which provide the high tensile strength to conductor. In the outer layers of **stranded conductor**, we use aluminum conductors, which provide the conductivity to stranded conductor.

Basic, reason of using stranded conductor is to make the conductor flexible. If we use a single solid conductor. It does not have sufficient flexibility and it is difficult to coil a solid conductor. Hence, it becomes difficult to transport a single solid conductor of long length over the distance. To eliminate this drawback, conductor is formed by using several thin wires of small cross section. These thin wires are called strands. By making the conductor stranded, it becomes flexible. Which makes **stranded conductor** suitable to be coiled easily to transport it over long distance.

INSULATING MATERIAL

The material which cannot allow passing electric current.

CHARCTERSTIC OF GOOD INSULATING MATERIAL

1. IT should have high resistance.
2. The leakage current through the material should be minimum.
3. It should have good heat dissipation capability.
4. It should have high mechanical strength to withstand vibrations.
5. It should have small dielectric loss.
6. It should also have small thermal expansion to prevent mechanical strength .
7. It should be non ignitable.
8. It should be resistant to oils, liquids, gas fumes.

SELECTION OF INSULATING MATERIAL

Properties of the material

. • Ease of shaping.

- Material availability.
- Cost factor.

GENERAL PROPERTY OF INSULATING MATERIAL

- Electrical property
- Thermal property

. • Mechanical property & physical property

- Chemical property
- Visual properties

ELECTRICAL PROPERTY

- Resistivity (insulation resistance)
- Dielectric strength
- Dielectric loss
- Dielectric constant

THERMAL PROPERTY

- Heat resistance
- Thermal resistance and thermal conductivity

MECHANICAL & PHYSICAL PROPERTY –

- Tensile strength
- Compressive strength
- Brittleness
- Porosity
- Density

CHEMICAL PROPERTY –

- Chemical resistance
- Hygroscopicity
- Solubility
- Radiation resistance
- Moisture permeability

VISIUAL PROPERTY –

- Appearance
- Colour
- Crystalline

CLASSIFICATION OF INSULATING MATERIAL -

According to substance and material it is classified as

(a) Solids: mica, asbestos, ceramic, glass

(b)Liquids: mineral oil, synthetic varnishes etc

(c) Gases: air, hydrogen, argon etc

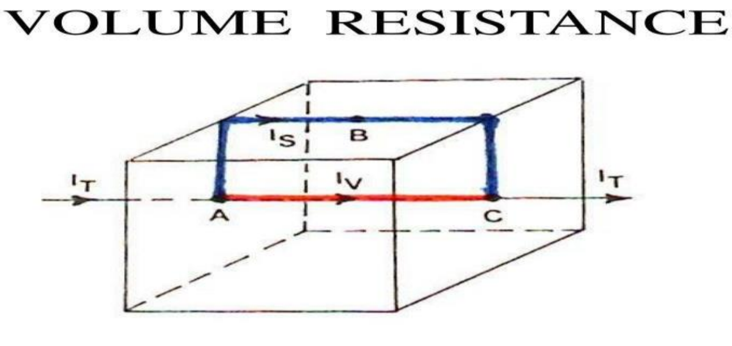
ELECTRICAL PROPERTIES OF INSULATING MATERIALS

Insulation resistance: Insulation resistance is defined as the resistance to current leakage through and over the surface of the insulation material surrounding a conductor.

Types of insulation resistance-

- VOLUME insulation resistance-
- SURFACE insulation resistance-

VOLUME insulation resistance-The resistance offered to current Iv which flow through the material is called volume resistance, as from A-C, shown in fig below.



SURFACE INSULATION RESISTANCE-

The resistance offered to current which flows over the surface of insulating material is called SURFACE insulation resistance. As from A-B and then from B-C as shown in above fig.

Di-electric strength: It is the maximum voltage which when applied to an insulating material without destructing its insulating properties is known as di-electric strength. Every electrical apparatus is designed to operate within a defined range of voltage.

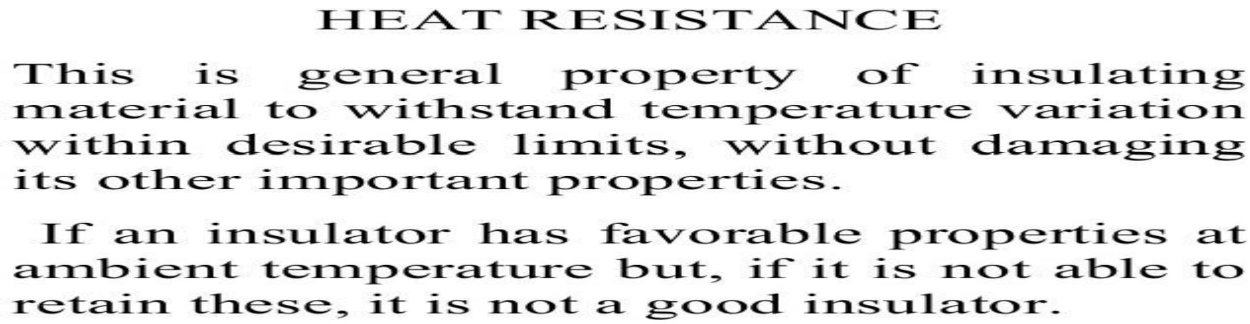
DIELECTRIC CONSTANT

The dielectric constant of a substance is the ratio of the permittivity of the substance to the permittivity of the free space.

Mathematically dielectric constant is:

$k= \epsilon 0/\epsilon$here,

- κ is the dielectric constant
- ϵ is the permittivity of the substance
- $\epsilon 0$ is the permittivity of the free space



HEAT RESISTANCE

This is general property of insulating material to withstand temperature variation within desirable limits, without damaging its other important properties.

If an insulator has favorable properties at ambient temperature but, if it is not able to retain these, it is not a good insulator.

CLASSIFICATION ON THE BASIS OF OPERATING TEMPERATURE:

Heat generated due to I^2R losses and di electric losses will be dissipated through the insulator itself. How effective this flow of heat takes place depends upon the thermal conductivity of the insulator. An insulator with better thermal conductivity will not allow temperature rise because of effective heat transfer through it to the atmosphere.

CHEMICAL PROPERTY –

- solubility
- chemical resistance
- weather ability

Solubility: In certain application insulation can be applied only after it is dissolved in some solvents. In such cases the insulating material should be solube in certain appropriate solvent. If the insulating material is soluble in water then moisture in the atmosphere will always be able to remove the applied insulation and cause break down.

CHEMICAL RESISTANCE:

Presence of gases, water, acids, alkalies and salt affects different insulators differently. Chemically a material is a better insulator if it resist chemical action.

WEATHERABILITY:

Insulators come in contact with atmosphere both during manufacture or operation. The contact of insulation with atmosphere is often so complete that even the less chemically aggressive atmosphere can prove a threat to the smooth running of apparatus.

HYGROSCOPICITY:

The property of insulating material by virtue of which it absorbs moisture. The insulating material should be non-hygroscopic. The absorption of moisture reduces the resistivity of the insulator.

Mechanical property:

Mechanical

strength Porosity

Density

Brittleness

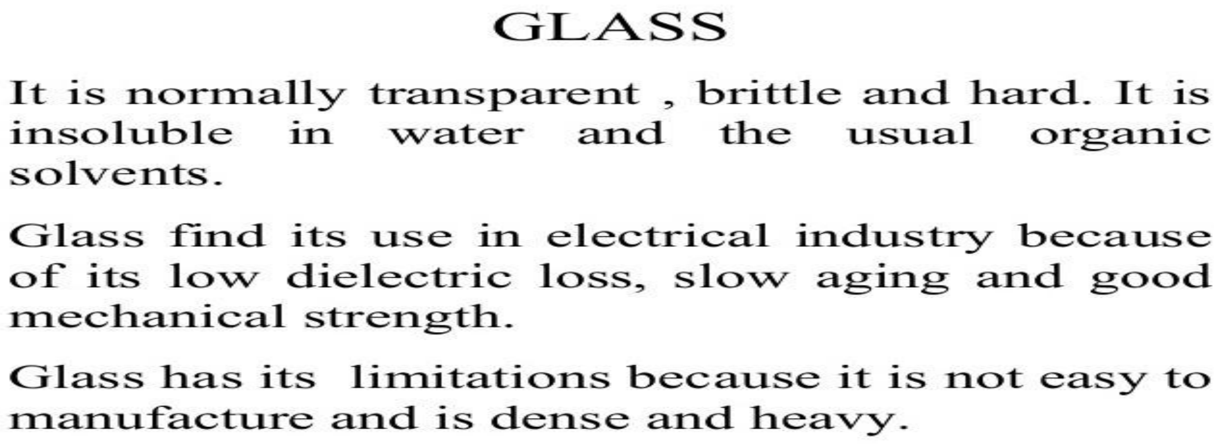
Mechanical strength:

The insulating material should have high mechanical strength to bear the mechanical stresses and strain during operation. Temperature and humidity are the main factor which reduces the mechanical strength of insulating materials**.**

POROSITY:

A material having very small holes in it is called a porous material. Insulator absorbs moisture. If it is porous which reduces its resistivity as will as mechanical strength. Porous materials are impregnated with varnish or resin to fill their pores which makes them non-pores thus better insulating material.

BRITTLENESS: The insulating material should not be brittle. Otherwise insulator may fracture easily due to stress.

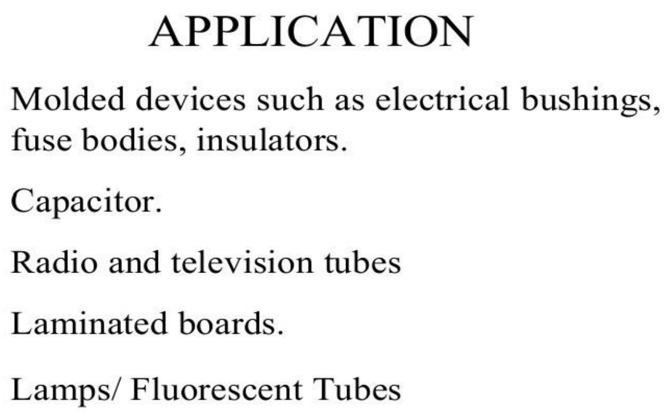


GLASS

It is normally transparent , brittle and hard. It is insoluble in water and the usual organic solvents.

Glass find its use in electrical industry because of its low dielectric loss, slow aging and good mechanical strength.

Glass has its limitations because it is not easy to manufacture and is dense and heavy.



APPLICATION

Molded devices such as electrical bushings, fuse bodies, insulators.

Capacitor.

Radio and television tubes

Laminated boards.

Lamps/ Fluorescent Tubes

Magnetic Material

Magnetic Field: The magnetic field is an imaginary line of force around a magnet which enables other ferromagnetic materials to get repelled or attracted towards it.The magnetic field lines are formed due to various reasons like orbital movement of electrons, current flowing in a conductor etc.

Magnetic Flux Density(B)

When a substance is subjected to the magnetic field H, then the density of magnetic field lines that pass through the substance per square meter is known as **Magnetic Flux Density**. It is given by

$$B = \mu \times H \text{ (Tesla or weber /m}^2\text{)}$$

Where μ is called the **Permeability** and is defined as the degree to which a substance gets magnetized.The value of permeability in vacuum is given by

$$m = 4px\ 10^{-7} (H/m)$$

Classification of Magnets

Depending on the above explained properties of magnets, magnets can be classified as:

- Diamagnetic
- Para-magnetic
- Ferro-magnetic

Diamagnetic Substance

Diamagnetic Substances are repelled by magnets due to the fact that they produce negative magnetization. **The net magnetic moment is zero in diamagnetic substance** because when an external field is applied to a diamagnetic substance then the magnetic moment of electrons is aligned to the opposite direction of the applied field. Every element in the periodic table possess the property of diamagnetism, but few elements like Cu, Al_2O_3, Si, Zn have stronger diamagnetic property.

Paramagnetic Substance

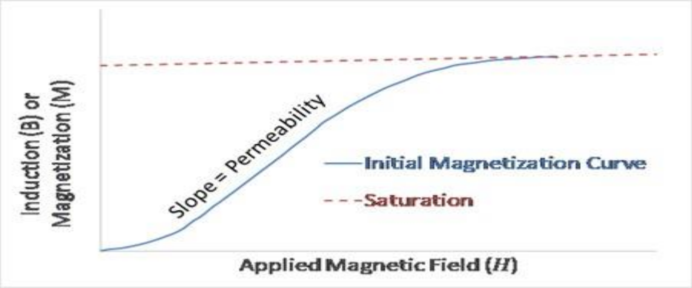
In Paramagnetic material, there exists a little magnetic moment since the net magnetic moment is not cancelled out completely. The magnetic moments in paramagnetic material are randomly aligned and when they are subjected to an external magnetic field, these magnetic moments align themselves in the direction of the applied magnetic field H. **Example** of paramagnetic materials include Al, Cr, Mo,Ti,Zr.

Ferromagnetic Substance

Unlike diamagnets or paramagnets, those materials which tend to remain magnetized even when the magnetic field is removed exhibits ferromagnetism. **This phenomenon is also**

known as Hysteresis and the plot between variations of magnetism with magnetic field is called **Hysteresis Loop**. However at one point or temperature the ferromagnetic materials tend to lose its magnetic properties. This temperature or point is known as **Curie point or Curie temperature**.

Magnetization Curve:



- When a magnetic material is placed into a magnetic field $(\vec{H})$, it's magnetic dipoles will align to create a response magnetization $(\vec{M})$, which will combine with the applied field to generate a magnetic induction $(\vec{B})$. If the response were linear, it would be an easy calculation. However, the response is nonlinear, resulting in hysteresis curves when the applied magnetic field is cycled.

- The magnetization curve of a magnetic material is as descriptive of a material's magnetic properties as its stress-strain curve is descriptive of its mechanical properties. Just as key tensile properties can be found on a stress-strain curve, key magnetic properties can also be found on the magnetization curve.

- The first thing to note is that there are two types of magnetization curves generated in response to an applied field. **M-H** curves focus on the internal response of the magnetic material, while **B- H** curves focus on the magnetic induction. Therefore, it is important to know what type of curve you are looking at when trying to determine magnetic properties.
- Figure 1 shows schematically what happens when a magnetic field (H) is applied to a magnetic material. As the field increases in strength, the magnetic moment of the material ($(\vec{M})$ increases $(\vec{B})$ as well, as the magnetic dipoles begin to align with the applied magnetic field. That is, the material is becoming **magnetically polarized**. Since M is increasing, the corresponding magnetic

  induction increases as well. Eventually, when the magnetic dipoles are fully aligned with the field, $(\vec{M})$ can increase no more. This is known as the **saturation magnetization**.
- The slope of the magnetization curve is the **magnetic permeability (μ)** of the material. Note, however, that the initial magnetization is usually not a straight line! This means that the magnetic permeability will vary depending on the magnetic field strength. Often, test labs will therefore report 3 values of permeability. These will be the initial (low slope), intermediate (maximum slope), and the final (lower slope again). Since the longest, linear part of the curve is

the maximum slope, this would often be considered to be the default permeability.

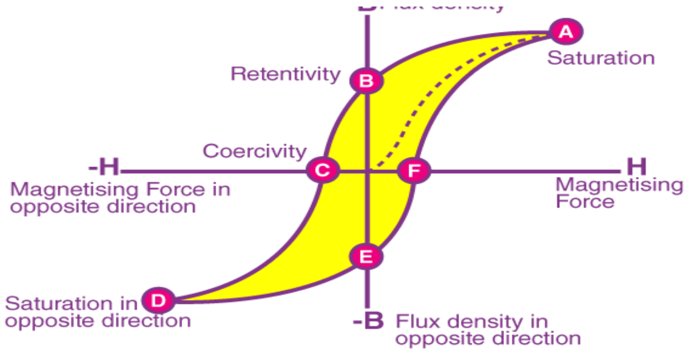
Hysteresis Loop

Hysteresis Loop Definition

A curve, or loop, plotted on B-H coordinates showing how the magnetization of a ferromagnetic material varies when subjected to a periodically reversing magnetic field, is known as Hysteresis Loop.

Hysteresis Loop

The hysteresis loop shows the relationship between the magnetic flux density and the magnetizing field strength. The loop is generated by measuring the magnetic flux coming out from the ferromagnetic substance while changing the external magnetizing field.



Looking at the graph, if B is measured for various values of H and if the results are plotted in graphic forms then the graph will show a hysteresis loop.

- The magnetic flux density (B) is increased when the magnetic field strength(H) is increased from 0 (zero).
- With increasing the magnetic field there is an increase in the value of magnetism and finally reaches point A which is called saturation point where B is constant.
- With a decrease in the value of the magnetic field, there is a decrease in the value of magnetism. But at B and H are equal to zero, substance or material retains some amount of magnetism is called retentivity or residual magnetism.
- When there is a decrease in the magnetic field towards the negative side, magnetism also decreases. At point C the substance is completely demagnetized.
- The force required to remove the retentivity of the material is known as Coercive force (C).
- In the opposite direction, the cycle is continued where the saturation point is D, retentivity point is E and coercive force is F.
- Due to the forward and opposite direction process, the cycle is complete and this cycle is called the hysteresis loop.

Advantages of Hysteresis Loop

1. A smaller region of the hysteresis loop is indicative of less loss of hysteresis.

2. Hysteresis loop provides a substance with the importance of retentivity and coercivity. Therefore the w ay to select the right material to make a permanent magnet is made simpler by the heart of machines.

3. Residual magnetism can be calculated from the B-H graph and it is, therefore, simple to choose material for electromagnets.

Retentively and Coercivity

When a ferromagnetic material is magnetized by applying the external magnetizing field, after magnetization if we remove the external magnetizing field the material will not relax back to its zero magnetization position.

Receptivity

The amount of magnetization present when the external magnetizing field is removed is known as retentivity.

- It is a material's ability to retain a certain amount of magnetic property while an external magnetizing field is removed.
- The value of B at point b in the hysteresis loop.

Coercivity

The amount of reverse(-ve H) external magnetizing field required to completely demagnetize the substance is known as coercivity of substance. The value of H at point c in the hysteresis loop.

Curie point: The temperature above which a ferromagnetic substance loses its ferromagnetism and becomes paramagnetic.

Eddy Current: Eddy currents are loops of electrical current induced within conductors by a changing magnetic field in the conductor according to Faraday's law of induction. Eddy currents flow in closed loops within conductors, in planes perpendicular to the magnetic field.

Magneto-striction:

When a ferromagnetic material is magnetized a small amount of change occurs in dimension of the material which causes small extension, reducing the cross section of the crystal.

When the material is subjected to the rapid alternating magnetic field, extension and contraction of the material takes place and this phenomenon is called as Magneto-striction.

All ferromagnetic materials are classified into 2 categories.

- Soft magnetic material
- Hard magnetic material

Soft magnetic material:

- The material which have sharply rising magnetization curve, relatively small and narrow hysteresis loop and small energy loss during cyclic magnetization is known as Soft magnetic material.
- It is used for construction of cores for electro-machines and switch-gear parts
- It should have high permeability

- It is easier for soft magnet material to get saturation as orientation take place easily.

Hard magnetic material:

- The magnetic material which have gradually rising magnetizing curve, large hysteresis loop area and large energy loss during each cycle of magnetization is known as Hard magnetic material
- It is also used for making permanent magnet.
- The desired property required for making permanent magnet are high saturation value, high coercive force and high residual magnetism.
- In hard magnet is difficult to orient the domain as compare to soft magnet material ,therefore it is difficult to magnetized hard magnet
- It is used for the construction of core of transformer , electromagnet of electric motor

Soft Magnet	**Hard Magnet**
Magnetization and demagnetization is easy	Magnetization and demagnetization is difficult
A soft magnet can be produced by heating and gradual cooling	A hard magnet can be produced by heating and sudden cooling
The hysteresis loop area is small, retentivity and coercivity is also small	The hysteresis loop area is large, retentivity and coercivity is also high
Soft magnets are temporary magnets	Hard magnets are permanent magnets
Examples: Ferrous-nickel alloy, Ferrites Garnets	Examples: Steel, carbon steel, chromium steel, tungsten

Induction Motor

Construction:

The induction motor mainly divided in to two parts.

(1) Stator (2) Rotor

In case of D. C. Motor basically it is divided into two main parts (i) Yoke (ii) Armature. Yoke is outer & stationary part, similarly the outer portion of the induction motor is known as stator. It is also stationary part of the induction motor. The stator of the induction motor is cylindrical in shape.

The inner part of D. C. Motor i.e., armature is rotating in nature. Similarly the rotating part of the induction motor is known as rotor. The rotor lies inside the stator. It is cylindrical in shape.

Rotor is divided into two types.

(i) Squirrel cage Rotor

(ii) Phase wound Rotor or Slip ring Rotor,

Figure shows the disassembled view of an induction motor with squirrel cage rotor.

(a) Stator (b) Rotor (c) bearing shields (d) Fan (e) Ventilation grill (f) terminal box.

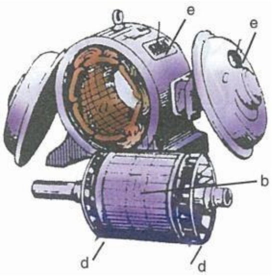


Fig 1.1

Similarly figure shows the disassembled view of a slip ring motor (a) stator (b) rotor (c) bearing shields (d) Fan (e) Ventilation grill (f) Terminal box (g) Slip ring (h) brushes & brush holder.

Production of Rotating Magnetic Field:

When 3 – phase stationary coils are fed with 3 – phase supply, a uniformly rotating magnetic flux of constant magnitude will produce.

It will now be shown that when three – phase winding displaced in space by 120^0, are fed by three phase currents, displaced in time by 120^0, they produce a resultant magnetic flux, which rotates in space as if actual magnetic poles were being rotated mechanically.

The principle of a 3 – phase, two pole stator having three identical windings placed 120^0 space degree apart as shown in fig – 1.2. The flux due to three phase windings is shown in fig 1.3.

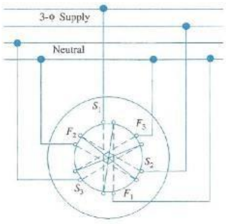


Fig 1.2

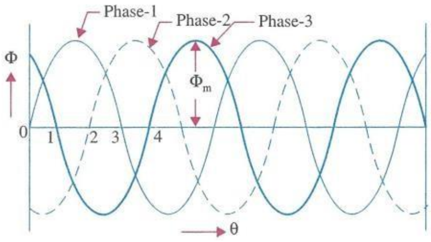


Fig 1.3

Let the maximum value of flux due to any one of the three phases be ϕ_m. The resultant flux ϕ_r, at any instant is given by the vector sum of the individual fluxes ϕ_1, ϕ_2 and ϕ_3 due to three phases. Considering values of ϕ_r at four instants i.e. 1/6th time period apart corresponding to points marked 0, 1, 2 & 3.

Proof :

Case – 1 : Resultant flux at origin i.e. when $\theta = 0^0$ At that time $\phi_1 = 0$,

$\phi_2 = \phi m \text{ Sin} < -120^0 = -\frac{\sqrt{3}}{2}\phi m$ $\phi_3 = \phi m \text{ Sin} < -240^0 = -\frac{\sqrt{3}}{2}\phi m.$

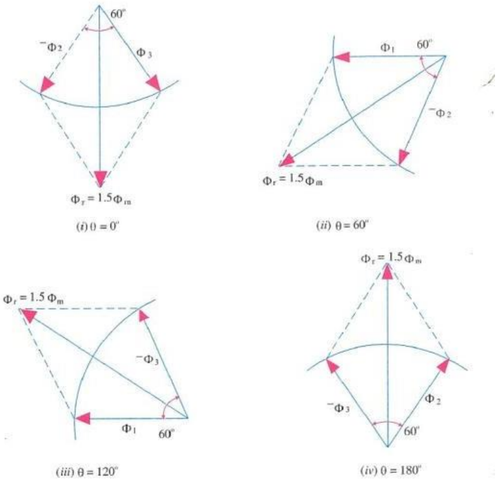


Fig 1.4

Resultant flux ϕ_r :

As per law of parallerogram

$$\phi_r^2 = \phi_2^2 + \phi_3^2 + 2\,\phi_2 \cdot \phi_3 \cdot \cos 60^0$$

$$\Rightarrow \phi_r^2 = \left(\frac{\sqrt{3}}{2}\phi_m\right)^2 + \left(\frac{\sqrt{3}}{2}\phi_m\right)^2 + 2.\ \frac{\sqrt{3}}{2}\phi_m \cdot \frac{\sqrt{3}}{2}\phi_m\ \frac{1}{2}$$

$$\Rightarrow \phi_r^2 = \frac{\phi_m^2}{4} + \frac{3}{4}\phi_m^2 + \frac{3}{4}\phi_m^2$$

$$\Rightarrow \phi_r^2 = \frac{9}{4}\phi_m^2$$

$$\Rightarrow \phi_r = \frac{3}{2}\phi_m$$

$$\Rightarrow \phi_r = 1.5\ \phi_m$$

Case – II : When $\theta = 60^0$

Therefore $\phi_1 = \phi_m \text{ Sin} < 60^0 = \frac{\sqrt{3}}{2}\phi_m$

$\phi_2 = \phi_m \text{ Sin} < -120^0 + 60^0 = \phi_m \text{ Sin} < -60^0 = \dfrac{-\sqrt{3}}{2}\phi_m$

and $\phi_3 = \phi_m \text{ Sin} < -240^0 + 60^0 = \phi_m \text{ Sin} < -180 = 0$

case – III When $\theta = 120^0$

$\phi_1 = \phi_m \text{ Sin} < 120^0 = \dfrac{\sqrt{3}}{2}\phi_m$

$\phi_2 = \phi_m \text{ Sin} < -120^0 + 120^0 = \phi_m \text{ Sin} < 0^0 = 0$

$\phi_3 = \phi_m \text{ Sin} < -240^0 + 120^0 = \phi_m \text{ Sin} < -120^0 = \dfrac{-\sqrt{3}}{2}\phi_m$

ϕ_r can be calculated as earlier

Similarly $\phi_r = 1.5\phi_m$

Case – IV When $\theta = 180^0$

$\phi_1 = \phi_m \text{ Sin} < 180^0 = 0$

$\phi_2 = \phi_m \text{ Sin} < -120^0 + 180^0 = \phi_m \text{ Sin} < 60^0 = \dfrac{\sqrt{3}}{2}\phi_m$

$\phi_3 = \phi_m \text{ Sin} < -240^0 + 180^0 = \phi_m \text{ Sin} < -60^0 = \dfrac{-\sqrt{3}}{2}\phi_m$

Similarly ϕ_r can be calculated as earlier $\phi_r = 1.5\ \phi_m$

Hence from the above four cases we can draw a conclusion that the resultant flux (ϕ_r) inside the stator winding at any time = 1.5 ϕm and the resultant flux (ϕ_r) rotates around the stator at syncronous speed.

https://www.youtube.com/watch?v=DANGZvHOgj0&list=PLbRMhDVUMngcDrGXlt-hX-ekpldUlC2b6&index=39

How the rotor rotates :

The rotor lies inside the stator. There is an air gap in between the stator and rotor. The stator slots are provided with three Phase winding.

When three phase stator windings are fed by a 3-phase supply then a rotating magnetic flux of constant magnitude will produce.

This rotating flux passes through air gap and cuts the stationary conductors on the rotor . There is also a 3-phase rotor winding on the rotor. The stator and rotor windings act as primary and secondary windings of a 3-phase transformer. The air gap acts as core of the transformer. The fluxes passes from stator to rotor winding through induction principle.

The rotating flux produces an emf in the rotor winding. The rotor winding is closed circuit. Hence current will flow in the rotor conductors. When current will flow it will produce the flux in the air gap. The flux in the rotor winding interacts with the flux in the stator winding there by producing a torque, which is responsible for the rotation of the rotor.

Slip(s) :

The rotor never succeeds in catching up with the stator field. It is really did so, then there would be no relative speed between the two, hence no rotor emf, no rotor current and so no torque to maintain rotation. That in why the rotor runs at a speed which is always less than the speed of the stator field.

The difference between synchronous speed N_s to the actual speed of the totor N_r is known as slip speed.

Slip speed = $N_s - N_r$.

Slip (s) or % of Slip (s) = $\frac{N_s - N_r}{N_s} \times 100$

$\Rightarrow S = \frac{N_s - N_r}{N_s}$

$\Rightarrow N_s - N_r = SN_s$

$\Rightarrow N_s - SN_S = N_r$

$\Rightarrow N_s(1-S) = N_r$

Therefore Rotor speed $N_r = N_s$ (1-S)

Frequency of Rotor Current :

When the rotor is stationary, the frequency of rotor current is the same as the supply frequency. But when the rotor starts revolving, then the frequency depends upon the relative speed. Let the frequency of the rotor current be f'.

Hence $N_s - N_r == \frac{120 f'}{P}$

As Ns = $= \frac{120 f}{P}$

$$\Rightarrow \frac{N_s - N_r}{N_s} = \frac{120 f'}{P} \times \frac{P}{120 f}$$

$$\Rightarrow S = \frac{f'}{f}$$

Therefore $f' = Sf$

Hence Rotor frequency = slip x supply frequency

Torque of an Induction Motor :

The torque of an induction motor is the torque produced at the rotor. Hence $T=T_r$ where T_r is the rotor torque.

In case of D.C. motor torque = Armature Torque = T_a

$$T_a = 0.159 \phi Z I_a \left(\frac{P}{A}\right) \text{ N·m}$$

There fore $T_a = K\phi I_a$

[Where 0.159, Z, P and A are all constants)

Where ϕ is the flux produced by the filed winding which is pulsating in nature.

Similarly in case of an induction motor the torque is also proportional to the product of flux produced in stator and rotor current.

However there is another factor which is to be taken is power factor. Because in this case both flux and current are alternating in nature.

Therefore $T_r \propto \phi I_2 \cos \phi_2$

Where I_2 – Rotor Current

ϕ - flux produced in the stator.

ϕ_2 – The phase angle between rotor emf and rotor current (E_2 and I_2)

As $\phi \propto E_2$

Therefore $T_r = T \propto E_2 I_2 \cos \phi_2$

$$T = K E_2 I_2 \cos \phi_2$$

Starting Torque :

The torque developed by the motor at the instant of starting is called starting torque.

Let E_2 = Rotor emf per phase at stand still

R_2 = Rotor resistance / phase

X_2 = Rotor reactance / phase at stand still

$Z_2 = \sqrt{R_2^2 + X_2^2}$ = Rotor impedance / phase at stand still

Then $I_2 = \frac{E_2}{Z_2} = \frac{E_2}{\sqrt{R_2^2 + X_2^2}}$, $\cos \phi_2 = \frac{R_2}{Z_2} = \frac{R_2}{\sqrt{R_2^2 + X_2^2}}$

Stand still or starting torque $T_{st} = K E_2 I_2 \cos \phi_2$

Or $T_{st} = K E_2 \cdot \frac{E_2}{\sqrt{R_2^2 + R_2}} \cdot \frac{R_2}{\sqrt{R_2^2 + R_2}} = \frac{K E_2^2 R_2}{R_2^2 \quad R_2}$

+

If supply voltage V remains constant, then the flux ϕ and hence E_2 remain constant.

Therefore $T_{st} = K_1 \frac{R_2}{R_2^2 + X_2^2}$

$$\Rightarrow T_{st} = K_1 \frac{R_2}{Z_2^2}$$

Starting Torque of a Squirrel – cage Induction Motor :

The resistance of a squirrel cage motor is fixed and small as compared to its reactance which is very large especially at the start because at stand still, the frequency of the rotor currents equal the supply frequency. Hence the starting current I_2 of the rotor, though very large in magnitude, laggs by a very large angle E_2, with the result that the starting torque per ampere is very poor. Hence, such motors are not useful where the motor has to start against heavy loads.

Starting Torque of a slip-ring motor :

The starting torque of such motor is increased by improving its power factor by adding external resistance in the rotor circuit from the star connected rheostat, the rheostat resistance being progressively cut out as the motor gathers speed. Addition of external resistance, however increases the rotor impedance and so reduces the rotor current. At first, the effect of improved power factor predominates the current–decrearing effect of impedance. Hence, starting torque is increased. But after a certain point, the effect of increased impedance predominates the effect of improved power factor and so the torque starts decreasing.

Condition for maximum starting Torque :

As starting torque $T_{st} = \frac{K_2 R_2}{R_2^2 + X_2^2}$

From mathematics we know that differentiation of a maximum quantity = 0

D (T_{st}) = 0, when T_{st} = Maximum starting Torque

Therefore $\frac{d(T_{st})}{dR_2} = 0$

$$\Rightarrow \frac{d}{dR_2}\left(\frac{K_2 R_2}{R_2^2 + X_2^2}\right) = 0$$

$$\Rightarrow K_2 \frac{d}{dR_2}\left(\frac{R_2}{R_2^2 + X_2^2}\right) = 0$$

$$\Rightarrow \frac{d}{dR_2}\left(\frac{R_2}{R_2^2 + X_2^2}\right) = 0$$

$$\Rightarrow \frac{\left(R_2^2 + X_2^2\right)\cdot\frac{d}{dR_2}\cdot R_2 - R_2\frac{d}{dR_2}\left(R_2^2 + X_2^2\right)}{\left(R_2^2 + X_2^2\right)^2} = 0$$

$$\Rightarrow R_2^2 + X_2^2 \cdot 1 - R_2\left(2R_2 + 0\right) = 0$$

$$\Rightarrow R_2^2 + X_2^2 - 2R_2^2 = 0$$

$$\Rightarrow X_2^2 = R_2^2$$

$$\Rightarrow R_2 = X_2$$

Hence the starting torque will be maximum when Rotor resistance = Rotor Reactance.
https://www.youtube.com/watch?v=YzY3RoOKdnY&list=PLbRMhDVUMngcDrGXlt-hX-ekpldUlC2b6&index=38

Rotor EMF and Rotor reactance under running condition :

Rotor EMF : Let E_2 = Stand still rotor EMF / phase

X_2 = Stand still rotor reactance / phase

When rotor starts rotating, the relative speed between rotor and rotating flux in the stator starts decreasing.

$$\text{Slip (s)} = \frac{N_s - N_r}{N_s}$$

The rotor induced emf is directly proportional to this relative speed

i.e. $E_r \propto (N_s - N_r) E_2$

$\Rightarrow E_r = K (N_s - N_r) E_2$

$$\Rightarrow E_r = \frac{N_s - N_r}{N_s} \cdot E_2$$

Therefore $E_r = SE_2$

Rotor Reactance :

The frequency of the rotor current

$f_r = sf$

Therefore $X_r = 2\pi s f_r L$

$\Rightarrow X_r = 2\, \pi s f L$

$\Rightarrow X_r = S\,(2\pi f L)$

Therefore $X_r = S\, X_2$

Torque under running conditions :

As we know that starting torque $T_{st} = KE_2I_2 \cos \phi_2$

Therefore $T_{st} \propto E_2\, I_2 \cos \phi_2$

So the torque under running condition $T_r \propto E_r\, I_r \cos \phi_r$

Where E_r = Rotor EMF/Phase under running condition

I_r = Rotor Current/Phase under running condition

$A_s\, E_r \propto \phi$

Therefore $T_r \alpha \phi I_r \cdot \cos \phi_r$

$I_r = \dfrac{E_r}{Z_r}$ But $Z_r = R_2 + j\,X_r = R_2 + j\,SX_2$

$\text{Cos}\,\phi_r = \dfrac{R_2}{\sqrt{R_2^2 + (SX_2)^2}}$ and $I_r = \dfrac{SE_2}{\sqrt{R_2^2 + (SX_2)^2}}$

Therefore running torque $T_r \,\alpha\, E_r I_r$ as ϕ_r

Therefore $T_r \,\alpha\, \phi \dfrac{SE_2}{\sqrt{R_2^2 + (S\cdot X_2)^2}} \cdot \dfrac{R_2}{\sqrt{R_2^2 + (S\cdot X_2)^2}}$

$\Rightarrow$ $T_r \,\alpha\, \phi \dfrac{SE_2R_2}{R_2^2 + (S\cdot X_2)^2}$

$\Rightarrow$ As $E_2 \,\alpha\, \phi$

Otenu $T_r \,\alpha\, \dfrac{SE_2^2R_2}{R_2^2 + (S\cdot X_2)^2}$

Therefore $T_r = \dfrac{K_1SE_2^2R_2}{R_2^2 + (S\cdot X_2)^2}$

Torque under stand still condition :

Nr = 0 at stand still condition

$S = \dfrac{N_S - 0}{N_S} = 1$

Therefore torque under stand still condition

$Tr = \dfrac{K_1E_2^2R_2}{R_2^2 + X_2^2}$

Condition for maximum Torque under running condition :

The torque of a rotor under running condition

$T_r = \dfrac{K_1SE_2^2R_2}{R_2^2 + (S\cdot X_2)^2}$

The conditions for maximum torque may be obtained by differentiating the above equation w.r.t slip (s) and then putting it equal to zero.

Let $Y = \frac{1}{T_r}$ (For to make the differentiation easy)

Therefore $Y = \frac{R_2^2 + (SX_2)^2}{K_1 S E_2^2 R_2}$

$$\Rightarrow Y = \frac{R_2}{K_1 S E_2^2} + \frac{S X_2^2}{K_1 E_2^2 R_2}$$

For maximum torque under running condition $\frac{dY}{dS} = 0$

$$\Rightarrow \frac{d}{dS}\left(\frac{R_2}{K_1 S E_2^2}\right) + \frac{d}{dS}\left(\frac{S X_2^2}{K_1 E_2^2 R_2}\right) = 0$$

$$\Rightarrow \frac{d}{dS}\left(\frac{R_2}{S E_2^2}\right) + \frac{d}{dS}\left(\frac{S X_2^2}{E_2^2 R_2}\right) = 0$$

$$\Rightarrow \frac{\frac{dR_2}{dS} \cdot S E_2^2 - R_2 \frac{d}{dS}\left(S E_2^2\right)}{\left(S E_2^2\right)^2} + \frac{\frac{d}{dS}\left(S E_2^2\right) \cdot E_2^2 R_2 - \frac{d}{dS} E_2^2 R_2 \cdot \left(S X_2^2\right)}{\left(E_2^2 R_2\right)^2} = 0$$

$$\Rightarrow \frac{0 - \cdot E_2^2 R_2}{S^2 E_2^4} + \frac{X_2^2 E_2^2 R_2 - 0}{E_2^4 R_2^2} = 0$$

$$\Rightarrow \frac{-R_2 E_2^2}{S^2 E_2^4} + \frac{X_2^2}{E_2^2 R_2} = 0$$

$$\Rightarrow \frac{R_2}{S^2 E_2^2} = \frac{X_2^2}{E_2 R_2}$$

$$\Rightarrow \frac{R_2}{S^2} = \frac{X_2^2}{R_2}$$

$$\Rightarrow R_2^2 = S^2 X_2^2$$

Therefore $\boxed{R_2 = SX_2}$

Hence the torque under running condition will be maximum when $R_2 = SX_2$

As the torque under running condition

$$T_r = \frac{K_1 S E_2^2 R_2}{R_2^2 + (SX_2)^2}$$

Putting the value $R_2 = SX_2$

Therefore $T_r = T_r\,(\text{max}) = \frac{K\,SE_2^2 \cdot SX_2}{(SX_2)^2 + (SX_2)^2}$

$$\Rightarrow T_r\,(\text{max}) = \frac{KS^2E_2^2X_2}{2S^2X_2^2} = \frac{K\,E_2^2}{2X_2}$$

Hence $\boxed{T_r\,(\text{max}) = \frac{K\,E_2^2}{2X_2}}$

Relation between full load Torque and Maximum Torque :

As Torque $(T) = \frac{K_1\,SE_2^2\,R_2}{R_2^2 + (SX_2)^2}$

E_2 is practically constant

Hence $T = \frac{K_2\,SR_2}{R_2^2 + (SX_2)^2}$

Therefore $T \;\alpha\; \frac{SR_2}{R_2^2 + (SX_2)^2}$

Taking full load slip as S_f at full load torque T_f

Therefore $T_f \;\alpha\; \frac{S_f R_2}{R_2^2 + (SX_2)^2}$ .... (I)

As $T_{max} = \frac{K\,E_2^2}{2X_2}$

$T_{max} \;\alpha\; \frac{1}{2X_2}$ .... (II)

$$\frac{(i)}{(ii)} = \frac{T_f}{T_{max}} = \frac{S_f R_2}{R_2^2 + (S_f X_2)^2} \times \frac{2X_2}{1}$$

$$\frac{T_f}{T_{max}} = \frac{2S_f R_2 X_2}{R_2^2 + (S_f X_2)^2}$$

Dividing X_2^2 on both side

$$\Rightarrow \frac{T_f}{T_{max}} = \frac{2S_f \frac{R_2}{X_2}}{\frac{R_2^2}{X_2^2} + S_f^2}$$

Taking $\frac{R_2}{X_2} = a$

$$\Rightarrow \frac{T_f}{T_{max}} = \frac{2aS_f}{a^2 + S_f^2}$$

In general $\frac{\text{operating Torque}}{\text{Maximum Torque}} = \frac{2as}{s^2 + a^2}$

s – operating slip

Relation between starting Torque and Maximum Torque :

As $T_{st} = K \frac{R_2}{R_2^2 + X_2^2}$

$$\Rightarrow T_{st} \; \alpha \; \frac{R_2}{R_2^2 + X_2^2} \text{ ....(i)}$$

But $T_{max} \; \alpha \; \frac{1}{2X_2}$ ………………….. (ii)

$$\frac{(i)}{(ii)} \Rightarrow \frac{T_{st}}{T_{max}} = \frac{R_2}{R_2^2 + X_2^2} \times \frac{2X_2}{1}$$

$$\Rightarrow \frac{T_{st}}{T_{max}} = \frac{2R_2X_2}{R_2^2 + X_2^2}$$

$$\Rightarrow \frac{T_{st}}{T_{max}} = \frac{\frac{2R_2X_2}{X_2^2}}{\frac{R_2^2}{X_2^2} + \frac{X_2^2}{X_2^2}}$$

$$\Rightarrow \frac{T_{st}}{T_{max}} = \frac{\frac{2R_2}{X_2}}{\left(\frac{R_2}{X_2}\right)^2 + 1}$$

$$\Rightarrow \boxed{\frac{T_{st}}{T_{max}} = \frac{2a}{a^2+1}}$$

Relation between Torque and slip :

$$\text{As Torque (T)} = \frac{KSE_2^2 R_2}{R_2^2 + (SX_2)^2}$$

Taking Torque in Y axis and slip in X axis

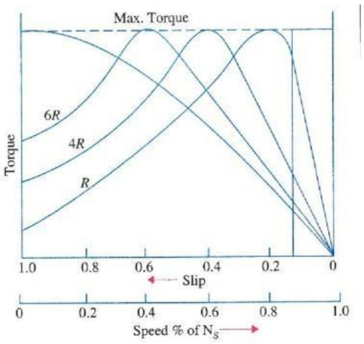


Fig. 1.5

At origin i.e. S = 0, torque T = 0

Therefore the curve starts from origin. At normal speed, closed to synoronism that is when N_r is very near to N_s, then slip is very nearly equal to zero.

Therefore $SX_2 << R_2$

$$\Rightarrow T \propto \frac{SE_2^2 R_2}{R_2^2} \qquad \{\text{Neglecting } (SX_2)^2\}$$

(Taking supply voltage constant so E_2 is also constant)

$$\Rightarrow T \propto \frac{S}{R_2}$$

For a particular induction motor R_2 is constant.

Hence $T \propto S$

Therefore low valve of slip, torque is directly proportional to slip. Hence the curve is straight line for low valve of slip.

As slip increases the torque also increases and becomes maximum when = $R_2 = SX_2$

$$\text{i.e. } S = \frac{R_2}{X_2}$$

As the slip further increases (SX_2) becomes higher compare to R_2.

Hence R_2 can be neglected in compare to (SX_2)

$$\Rightarrow T\alpha \frac{S}{(SX_2)^2}$$

$$\Rightarrow T\alpha \frac{1}{SX_2^2}$$

Taking X_2 is constant for a particular induction motor

Therefore $T \ \alpha \ \frac{1}{S}$

So beyond the point of maximum torque any further increase in slip, results in decrease of torque.

Method of standing of Induction Motor

The operation of the squirrel cage induction motor is similar to transformer having short circuited on the secondary side.

Due to short circuited on the rotor circuit it will take heavy current when it is directly switched on. Generally when direct switched, take five to seven times of their full load current. This initial excessive current is objectionable, because it will produce large line voltage drop.

Hence it is not advisable to start directly motors of rating above 5 KW. But the starting torque of an induction motor can be improved by increasing the resistance of the rotor circuit. This is easily feasible in the case of slip ring induction motor but not in the case of squirrel cage motors. However, in their case, the initial in rush of current is controlled by applying a reduced voltage to the stator during the starting period, full normal voltage being applied when the motor has run up to speed.

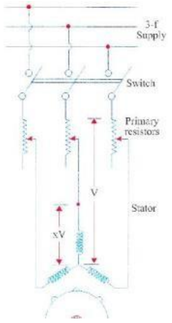
Method of Starting of Squirrel Cage Motor :

(1) Resistors Method

(2) Star – Delta Method

(3) Auto transformer Method

In the above methods, the supply voltage to the squirrel cage motor is reduced during starting.



1) Resistor Method :

In this method the resistors are connected in series with the stator phases, to give reduced voltage to the stator winding.

When resistors are connected in series with the stator phases, the current in the stator phases will reduce. If the voltage applied across the motor terminals is reduced by 50%, starting current is reduced by 50%.

Fig 1.6

When the motor starts running the resistances in the circuit is gradually cut out and full voltage is applied to the stator circuit. This method is useful for the smooth starting of small machines only.

2) Star – Delta Starter :

This method is used in the case of motors which are built to run normally with a delta connected stator winding. It consists of a two way switch which connects the motor in star for starting and then in delta for normal running.

At starting, when star connected, the applied voltage over each motor phases is reduced by afactor $\frac{1}{\sqrt{3}}$. Hence during starting, when motor is star connected it takes $\frac{1}{\sqrt{3}}$ times as much as starting current.

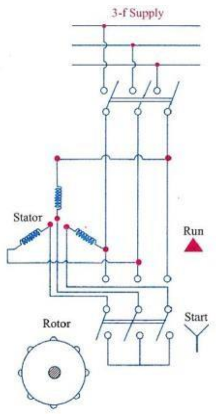


Fig 1.7

When the motor catches the speed 80% of its normal speed switch is changed to delta positions at that time $V_L = V_{ph}$.

Auto Transformer Method :

This starter is popularly known as auto starter in auto transformer the secondary side gets less voltage in compare to primary side.

As shown in the figure, at starting condition, a reduced voltage is applied across the mo terminals. When the motor catches the speed 80% of its normal speed, connections are changed to running position, then full supply voltage is applied across the motor.

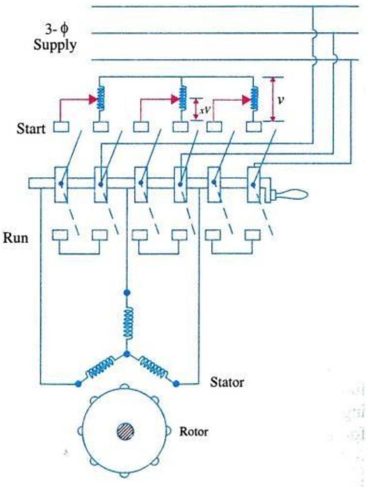


Fig 1.8

Most of the auto starters are provided with 3 – sets of taps so as to reduced the voltage to 80, 65 or 50 percent of line voltage.

Slip ring Motor :

Rotor Rheostat Method :

These motors are practically always started with full line voltage applied across the stator terminals. The value of starting current is adjusted by introducing a variable resistance in the rotor circuit.

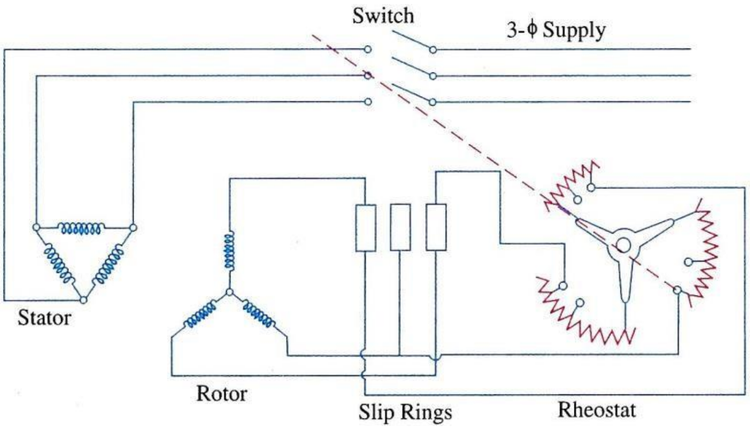


Fig 1.9

The controlling resistance is in the form of a rheostat, connected in star, the resistance being gradually cut – out of the rotor circuit, as the motor gathers speed

Speed Control of Induction Motor :

The speed of an induction motor can be changed under two main headings.

(i) Control from stator side

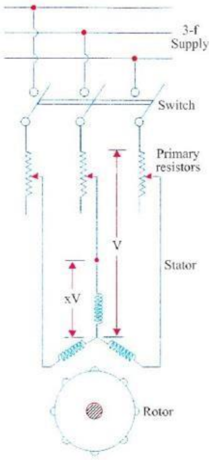
(ii) Control from Rotor side

(i) Control from stator side :

(a) By changing the applied voltage

(b) By changing the applied frequency

(c) By changing the no of stator poles.



(ii) Control from Rotor side :

(a) Rotor Rheostatic Control

(b) Cascade operation

(c) By injecting emf in the rotor circuit

Fig 1.10

By changing applied voltage :

This method is the easiest way for controlling speed of an induction motor. But this method is rarely used for the following reasons.

(i) A large change in voltage is required for a small change in speed.

(ii) Due to the connection of resistances in the stator phases, large power loss occurs at the resistors.

When the resistances are added in the stator circuit, voltage across the stator phase decreases.

As torque (T) = $\frac{KV^2R_2}{R_2^2 + X_2^2}$

$\Rightarrow$ Torque $T = K_1 V^2$

$\Rightarrow T \alpha V^2$

The torque depends on the supply voltage on the stator terminals, when V will decrease T will decrease hence speed will decrease.

By Charging the number of stator poles :

This method is easily applicable to squirrel cage motors because the squirrel cage rotor adopts it self to any reasonable number of stator poles.

The change in number of stator poles is achieved by having two more entirely independent stator windings in the same slots. Each winding gives a different number of poles and hence different synchronous speed.

Rotor Rheostatic Control :

This method is applicable to slip ring motors alone. The motor speed is reduced by introducing an external resistance in the rotor circuit.

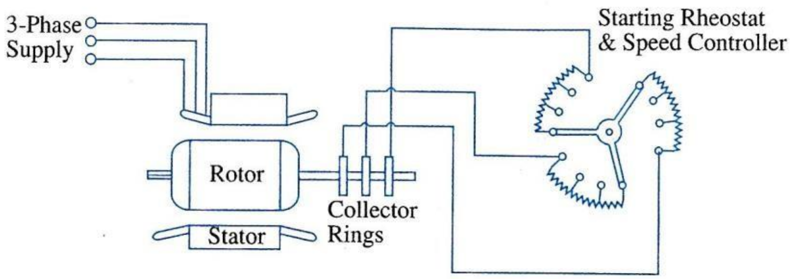


Fig 1.11

For this purpose the rotor starter may be used.

As torque (T) α $\frac{S}{R_2}$

By increasing the motor resistance torque will decrease. Hence speed will decrease.

Motor Enclosures :

Enclosed and semi-enclosed motors are practically identical with open motors in mechanical construction and in their operating characterstics. Many different types of frames or enclosures are available to suit particular requirements. Some of the common type of enclosures are given below.

(i) Totally enclosed, Non ventilated type.
(ii) Splash – Proof type
(iii) Totally enclosed, Fan cooled type.
(iv) Cowl covered motor
(v) Protected Type
(vi) Drip – Proof Motors
(vii) Self (Pipe) Ventilated Type
(viii) Separately (Forced) Ventilated Type.

Induction Generator :

When the rotor of an induction motor runs faster than its synchronous speed at that time the induction motor runs as a generator called Induction generator. It converts the mechanical energy it receives into electrical energy is released by the stator.

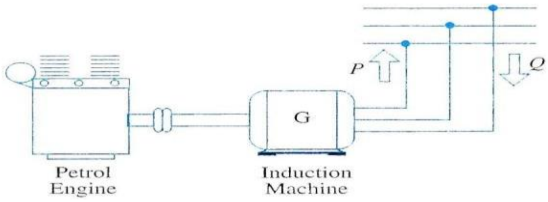


Fig 12

Figure shows a ordinary squirrel cage induction motor which is driven by a petrol engine and is connected to a 3 – phase line. As soon as motor speed exceeds its synchronous speed, it starts delivering active power P to the 3 – phase line. However, for creating its own magnetic field, it absorbs reactive power Q from the line to which it connected.

-0-