INTERNATIONAL INSTITUTE OF TECHNOLOGY & MANAGEMENT, MURTHAL SONEPAT
E-NOTES , Subject : Electrical Machine-I, Subject Code: 180941 , Course: Diploma , Branch : Electrical Engineering , Sem-4th
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UNIT-1

1. Introduction to Electrical Machines

In electrical engineering, electric machine is a general term for machines using electromagnetic forces, such as electric motors, electric generators, and others. They are electromechanical energy converters: an electric motor converts electricity to mechanical power while an electric generator converts mechanical power to electricity. The moving parts in a machine can be rotating (rotating machines) or linear (linear machines). Besides motors and generators, a third category often included is transformers, which although they do not have any moving parts are also energy converters, changing the voltage level of an alternating current.

Electric machines, in the form of generators, produce virtually all electric power on Earth, and in the form of electric motors consume approximately 60% of all electric power produced. Electric machines were developed beginning in the mid 19th century and since that time have been a ubiquitous component of the infrastructure. Developing more efficient electric machine technology is crucial to any global conservation, green energy, or alternative energy strategy.

1.1 Definition of motor and generator

Generator:

An electric generator is a device that converts mechanical energy to electrical energy. A generator forces electrons to flow through an external electrical circuit. It is somewhat analogous to a water pump, which creates a flow of water but does not create the water inside. The source of mechanical energy, the prime mover, may be a reciprocating or turbine steam engine, water falling through a turbine or waterwheel, an internal combustion engine, a wind turbine, a hand crank, compressed air or any other source of mechanical energy.

The two main parts of an electrical machine can be described in either mechanical or electrical terms. In mechanical terms, the rotor is the rotating part, and the stator is the stationary part of an electrical machine. In electrical terms, the armature is the power-producing component and the field is the magnetic field component of an electrical machine. The armature can be on either the rotor or the stator. The magnetic field can be provided by either electromagnets or permanent magnets mounted on either the rotor or the stator. Generators are classified into two types, AC generators and DC generators.

AC generator

An AC generator converts mechanical energy into alternating current electricity. Because power transferred into the field circuit is much less than power transferred into the armature circuit, AC generators nearly always have the field winding on the rotor and the armature winding on the stator.

AC generators are classified into several types.

- In an induction generator, the stator magnetic flux induces currents in the rotor. The prime mover then drives the rotor above the synchronous speed, causing the opposing rotor flux to cut the stater coils producing active current in the stater coils, thus sending power back to the electrical grid. An induction generator draws reactive power from the connected system and so cannot be an isolated source of power.

- In a Synchronous generator (alternator), the current for the magnetic field is provided by a separate DC current source.

DC generator

A DC generator is a machine that converts mechanical energy into Direct Current electrical energy. A DC generator generally has a commutator with split ring to produce a direct current instead of an alternating current.

Motor:

An electric motor converts electrical energy into mechanical energy. The reverse process of electrical generators, most electric motors operate through interacting magnetic fields and current-carrying conductors to generate rotational force. Motors and generators have many similarities and many types of electric motors can be run as generators, and vice versa. Electric motors are found in applications as diverse as industrial fans, blowers and pumps, machine tools, household appliances, power tools, and disk drives. They may be powered by direct current or by alternating current which leads to the two main classifications: AC motors and DC motors.

AC motor:

An AC motor converts alternating current into mechanical energy. It commonly consists of two basic parts, an outside stationary stator having coils supplied with alternating current to produce a rotating magnetic field, and an inside rotor attached to the output shaft that is given a torque by the rotating field. The two main types of AC motors are distinguished by the type of rotor used.

- Induction (asynchronous) motor, the rotor magnetic field is created by an induced current. The rotor must turn slightly slower (or faster) than the stator magnetic field to provide the induced current. There are three types of induction motor rotors, which are squirrel-cage rotor, wound rotor and solid core rotor.
- Synchronous motor, it does not rely on induction and so can rotate exactly at the supply frequency or sub-multiple. The magnetic field of the rotor is either generated by direct current delivered through slip rings (exciter) or by a permanent magnet.

DC motor:

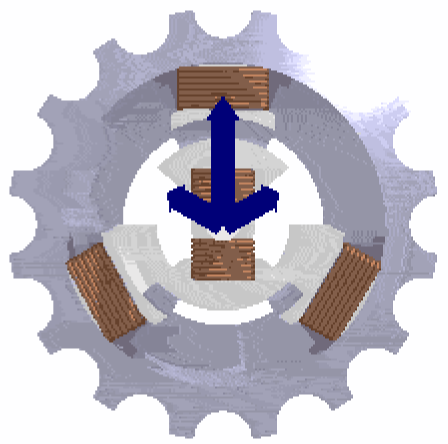
The brushed DC electric motor generates torque directly from DC power supplied to the motor by using internal commutation, stationary permanent magnets, and rotating electrical magnets. Brushes and springs carry the electric current from the commutator to the spinning wire windings of the rotor inside the motor. Brushless DC motors use a rotating permanent magnet in the rotor, and stationary electrical magnets on the motor housing. A motor controller converts DC to AC. This design is simpler than that of brushed motors because it eliminates the complication of transferring power from outside the motor to the spinning rotor. An example of a brushless, synchronous DC motor is a stepper motor which can divide a full rotation into a large number of steps

1.2 Torque development due to rotation magnetic fields.

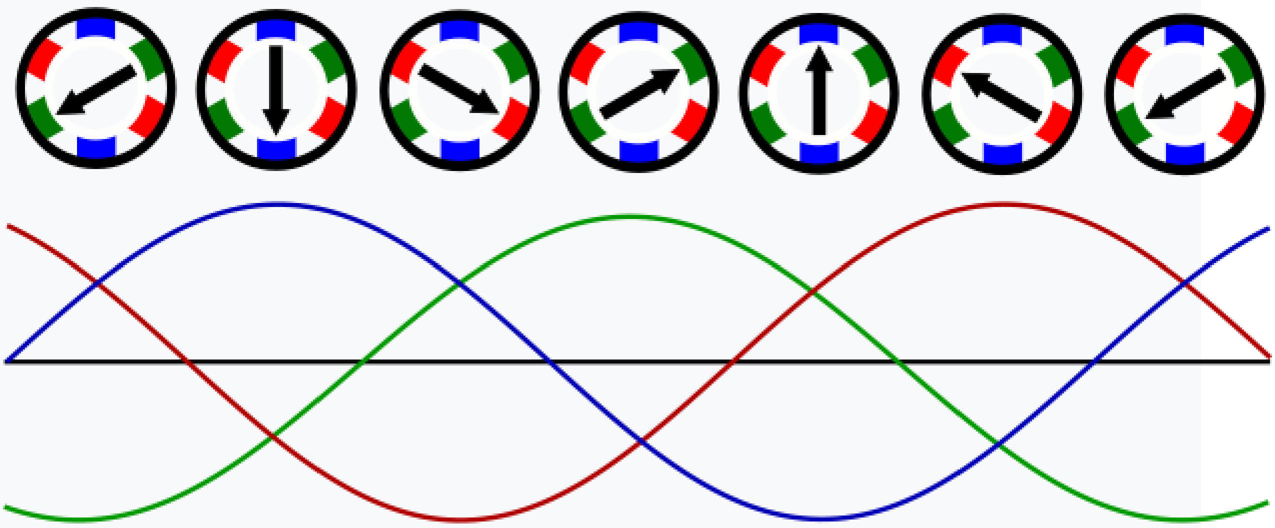
A rotating magnetic field is a magnetic field that has moving polarities in which its opposite poles rotate about a central point or axis. Ideally, the rotation changes direction at a constant angular rate. This is a key principle in the operation of the alternating-current motor.

Rotating magnetic fields are often utilized for electromechanical applications such as induction motors and electric generators. However, they are also used in purely electrical applications such as induction regulators.

A symmetric rotating magnetic field can be produced with as few as two polar wound coils driven at 90 degrees phasing. However, 3 sets of coils are nearly always used because it is compatible with a symmetric 3-phase AC sine current system. The three coils are driven with each set driven 120 degrees in phase from the others. For the purpose of this example, the magnetic field is taken to be the linear function of the coil's current.



Sine wave current in each of the three stationary coils produces three sine varying magnetic fields perpendicular to the rotation axis. The three magnetic fields add as vectors to produce a single rotating magnetic field.



Rotating 3-phase magnetic field, as indicated by the rotating black arrow

The result of adding three 120-degrees phased sine waves on the axis of the motor is a single rotating vector which remains always constant in magnitude.[1] The rotor has a constant magnetic field. The N pole of the rotor will move toward the S pole of the magnetic field of the stator, and vice versa. This magneto-mechanical attraction creates a force which will drive the rotor to follow the rotating magnetic field in a synchronous manner.

U.S. Patent 381968: Mode and plan of operating electric motors by progressive shifting; Field Magnet; Armature; Electrical conversion; Economical; Transmission of energy; Simple construction; Easier construction; Rotating magnetic field principles.

A permanent magnet in such a field will rotate so as to maintain its alignment with the external field. This effect was utilized in early alternating current electric motors. A rotating magnetic field can be constructed using two orthogonal coils with a 90 degree phase difference in their alternating currents. However, in practice such a system would be supplied through a three-wire arrangement with unequal currents. This inequality would cause serious problems in the standardization of the conductor size. In order to overcome this, three-phase systems are used where the three currents are equal in magnitude and have a 120 degree phase difference. Three similar coils having mutual geometrical angles of 120 degrees will create the rotating magnetic field in this case. The ability of the three phase system to create the rotating field utilized in electric motors is one of the main reasons why three phase systems dominate in the world electric power supply systems.

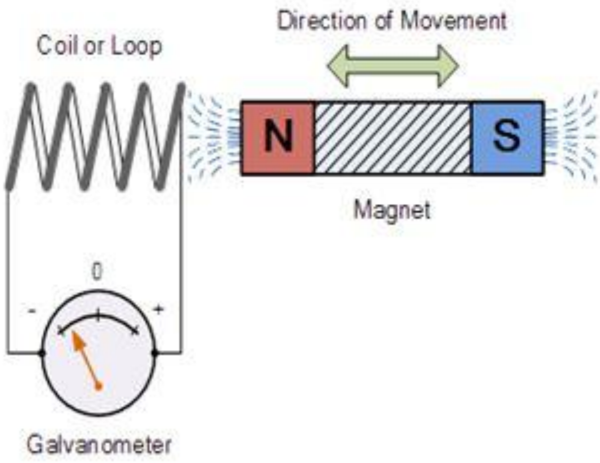
Rotating magnetic fields are also used in induction motors. Because magnets degrade with time, induction motors use short-circuited rotors (instead of a magnet) which follow the rotating magnetic field of a multicoiled stator. In these motors, the short circuited turns of the rotor develop eddy currents in the rotating field of the stator which in turn move the rotor by Lorentz force. These types of motors are not usually synchronous, but instead necessarily involve a degree of 'slip' in order that the current may be produced due to the relative movement of the field and the rotor.

1.3 Electro-magnetically induced emf.

Electromagnetic Induction or Induction is a process in which a conductor is put in a particular position and magnetic field keeps varying or magnetic field is stationary and a conductor is moving. This produces a Voltage or EMF (Electromotive Force) across the electrical conductor. Michael Faraday discovered Law of Induction in 1830. Let us now study the Electromagnetic Induction in detail

Suppose while shopping you go cashless and your parents use cards. The shopkeeper always scans or swipes the card. Shopkeeper does not take a photo of the card or tap it. Why does he swipe/scan it? And how does this swiping deduct money from the card? This happens because of the '**Electromagnetic Induction**'.

Can moving objects produce electric currents? How to determine a relationship between electricity and magnetism? Can you imagine the scenario if there were no computers, no telephones, no electric lights. The experiments of Faraday has led to the generation of generators and transformers.



The induction of an electromotive force by the motion of a conductor across a magnetic field or by a change in magnetic flux in a magnetic field is called **'Electromagnetic Induction'.**

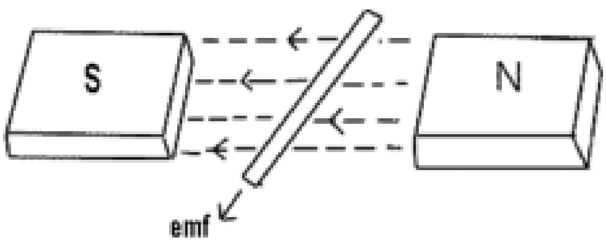
This either happens when a conductor is set in a moving magnetic field (when utilizing AC power source) or when a conductor is always moving in a stationary magnetic field.

This law of electromagnetic induction was found by **Michael Faraday.** He organized a leading wire according to the setup given underneath, connected to a gadget to gauge the voltage over the circuit. So when a bar magnet passes through the snaking, the voltage is measured in the circuit. The importance of this is a way of producing electrical energy in a circuit by using magnetic fields and not just batteries anymore. The machines like generators, transformers also the motors work on the principle of electromagnetic induction.

Browse more Topics under Magnetic Effects Of Electric Current

- Magnetic Field and Magnetic Force
- Domestic Electric Currents

Faraday's law of Electromagnetic Induction



Source: Electricaleasy

- First law: Whenever a conductor is placed in a varying magnetic field, EMF induces and this emf is called an induced emf and if the conductor is a closed circuit than the induced current flows through it.
- Second law: The magnitude of the induced EMF is equal to the rate of change of flux linkages.

Based on his experiments we now have Faraday's law of electromagnetic induction according to which the amount of voltage induced in a coil is proportional to the number of turns and the changing magnetic field of the coil.

So now, the induced voltage is as follows:

$e = N \times d\Phi dt$

where,

e is the induced voltage
N is the number of turns in the coil
Φ is the magnetic flux
t is the time

1.4 Elementary concept of an electrical machine

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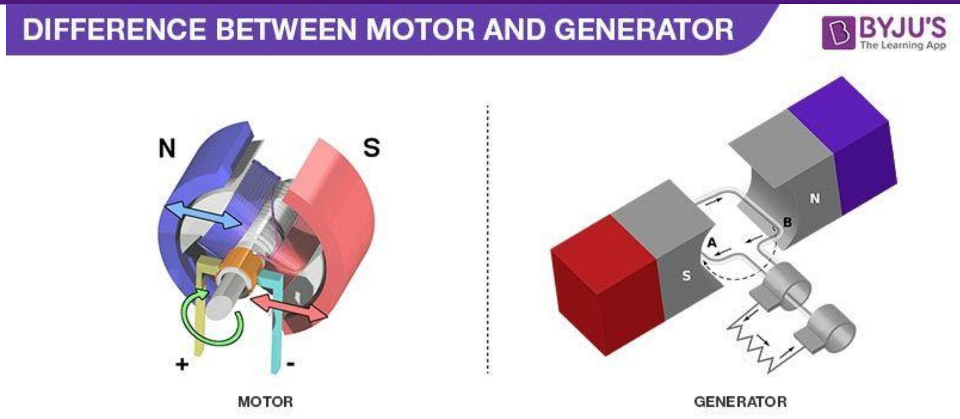
1.5 Comparison of generator and motor

Difference Between Motor and Generator



Difference between motor and generator is probably the most common question from the electricity topic of physics. In this article, the main differences between electric motor and generator are given here. The motor and generator difference given here is in tabular form for better understanding and clarity.

Before moving to the differences between a motor and generator, it is important to know what they are. Their functions, structure and other related details. To learn more about an electric motor and generator, visit the links given below.

- The Electric Motor
- The Electric Generator

Difference Between Motor and Generator

Sl. No.	Differentiating Property	Motor	Generator
1	Definition	An electric motor is a machine that converts electrical energy to mechanical energy.	An electric generator is a machine that converts mechanical energy to electrical energy.`
2	Rule	Electric motor follows Fleming's left-hand rule.	Electric generator follows Fleming's right-hand rule.
3	Principle	Motors works on the principle that a current carrying conductor experiences a force when placed in a magnetic field.	Generators work on the principle of electromagnetic induction.
4	Driving force for shaft	The shaft of an electric motor is driven by a magnetic force	The shaft of an electric generator is connected to the

		which is developed between the armature and field.	rotor which is driven by a mechanical force.
5	Current Usage	In a motor, current is supplied to the armature winding.	In a generator, current is produced in the armature winding.
6	Example	Ceiling fans, cars, etc. are all examples of motor.	In power stations, generator is used to generate electricity.

These were the main motor and generator differences that can be asked in the exams. Students aspiring for engineering courses are required to be completely get acquainted with the concepts of motors and generators. Check the articles given below to get additional information about generators and motors with their principles.

UNIT-II

2.1Principles Of D.C. Machines

D.C. machines are the electro mechanical energy converters which work from a D.C. source and generate mechanical power or convert mechanical power into a D.C. power.

2.2. Construction of d.c. Machines

A D.C. machine consists mainly of two part the stationary part called stator and the rotating part called rotor. The stator consists of main poles used to produce magnetic flux ,commutating poles or interpoles in between the main poles to avoid sparking at the Commutator but in the case of small machines sometimes the interpoles are avoided and finally the frame or yoke which forms the supporting structure of the machine. The rotor consist of an armature a cylindrical metallic body or core with slots in it to place armature windings or bars,aCommutator and brush gears The magnetic flux path in a motor or generator is show below and it is called the magnetic structure of generator or motor.
The major parts can be identified as,
1. Frame
2. Yoke
3. Poles Institute of Technology Madras
4. Armature
5. Commutator and brush gear
6. Commutating poles
7. Compensating winding
8. Other mechanical parts

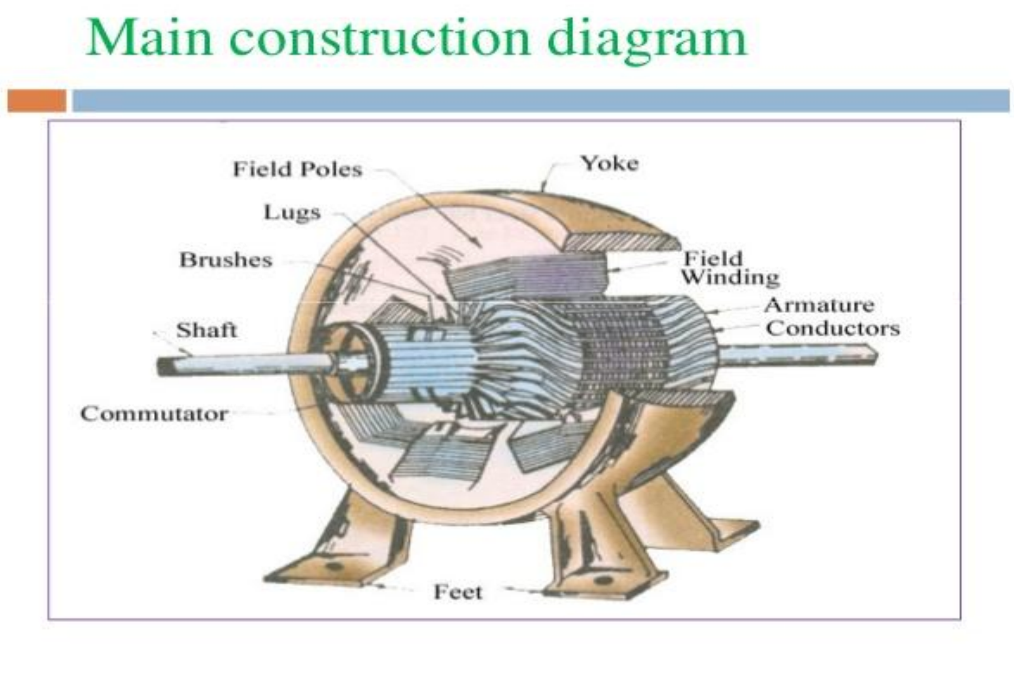


Fig.2.1: Construction Diagram of DC Machine

2.2.1 Frame

Frame is the stationary part of a machine on which the main poles and Commutator poles are bolted and it forms the supporting structure by connecting the frame to the bed plate. The ring

shaped body portion of the frame which makes the magnetic path for the magnetic fluxes from the main poles and interspoles is called frames.

2.2.2 Yoke.

Yoke was made up of cast iron but now it is replaced by cast steel. This is because cast iron is saturated by a flux density of 0.8 Web/sq.m where as saturation with cast iron steel is about 1.5 Web/sq.m. So for the same magnetic flux density the cross section area needed for cast steel is less than cast iron hence the weight of the machine too. If we use cast iron there may be chances of blow holes in it while casting. So now rolled steels are developed and these have consistent magnetic and mechanical properties.

2.2.3 End Shields or Bearings

If the armature diameter does not exceed 35 to 45 cm then in addition to poles end shields or frame head with bearing are attached to the frame. If the armature diameter is greater than 1m pedestal type bearings are mounted on the machine bed plate outside the frame. These bearings could be ball or roller type but generally plain pedestal bearings are employed. If the diameter of the armature is large a brush holder yoke is generally fixed to the frame.

2.2.4 Main poles

Solid poles of fabricated steel with separate/integral pole shoes are fastened to the frame by means of bolts. Pole shoes are generally laminated. Sometimes pole body and pole shoe are formed from the same laminations. The pole shoes are shaped so as to have a slightly increased air gap at the tips. Inter-poles are small additional poles located in between the main poles. These can be solid, or laminated just as the main poles.

These are also fastened to the yoke by bolts. Sometimes the yoke may be slotted to receive these poles. The inter poles could be of tapered section or of uniform cross section. These are also called as commutating poles or com poles. The width of the tip of the com pole can be about a rotor slot pitch.

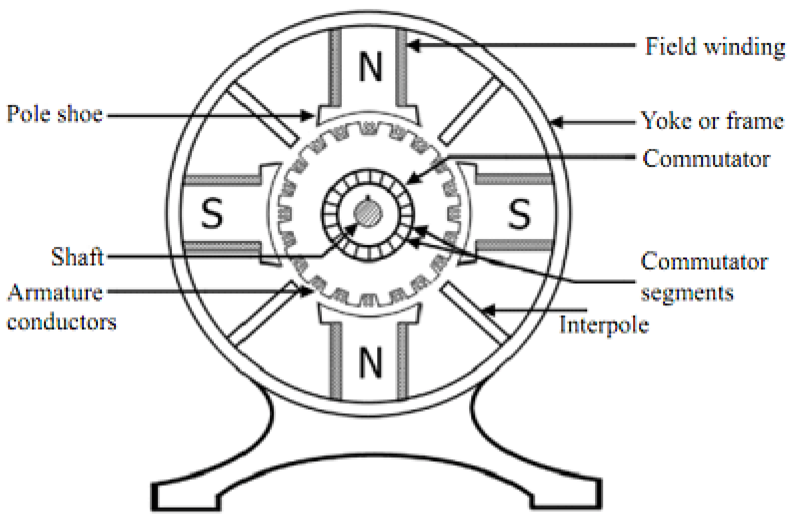


Fig.2.2: DC Machine

2.2.5 Armature

The armature is where the moving conductors are located. The armature is constructed by stacking laminated sheets of silicon steel. Thickness of this lamination is kept low to reduce eddy current losses. As the laminations carry alternating flux the choice of suitable material, insulation coating on the laminations, stacking it etc are to be done more carefully. The core is divided into packets to facilitate ventilation. The winding cannot be placed on the surface of the rotor due to the mechanical forces coming on the same. Open parallel sided equally spaced slots are normally punched in the rotor laminations. These slots house the armature winding. Large sized machines employ a spider on which the laminations are stacked in segments. End plates are suitably shaped so as to serve as ’Winding supporters’. Armature construction process must ensure provision of sufficient axial and radial ducts to facilitate easy removal of heat from the armature winding. Field windings: In the case of wound field machines (as against permanent magnet excited machines) the field winding takes the form of a concentric coil wound around the main poles. These carry the excitation current and produce the main field in the machine. Thus the poles are created electromagnetically.

Two types of windings are generally employed. In shunt winding large number of turns of small section copper conductor is of Technology Madras used. The resistance of such winding would be an order of magnitude larger than the armature winding resistance. In the case of series winding a few turns of heavy cross section conductor is used. The resistance of such windings is low and is comparable to armature resistance. Some machines may have both the windings on the poles. The total ampere turns required to establish the necessary flux under the poles is calculated from the magnetic circuit calculations.

The total mmf required is divided equally between north and south poles as the poles are produced in pairs. The mmf required to be shared between shunt and series windings are apportioned as per the design requirements. As these work on the same magnetic system they are in the form of concentric coils. Mmf ’per pole’ is normally used in these calculations. Armature winding as mentioned earlier, if the armature coils are wound on the surface of
The armature, such construction becomes mechanically weak. The conductors may fly away when the armature starts rotating. Hence the armature windings are in general pre-formed, taped and lowered into the open slots on the armature. In the case of small machines, they can be hand wound. The coils are prevented from flying out due to the centrifugal forces by means of bands of steel wire on the surface of the rotor in small groves cut into it. In the case of large machines slot wedges are additionally used to restrain the coils from flying away.

2.2.6 Commutator

Commutator is the key element which made the D.C. machine of the present day possible. It consists of copper segments tightly fastened together with mica/micanite insulating separators on an insulated base. The whole Commutator forms a rigid and solid assembly of insulated copper strips and can rotate at high speeds. Each Commutator segment is provided with a 'riser' where the ends of the armature coils get connected. The surface of the Commutator is machined and surface is made concentric with the shaft and the current collecting brushes rest on the same. Under-cutting the mica insulators that are between these Commutator segments have to be done periodically to avoid fouling of the surface of the Commutator by mica when the Commutator gets worn out.

Some details of the construction of the Commutator. Brush and brush holders: Brushes rest on the surface of the Commutator. Normally electro-graphite is used as brush material. The actual composition of the brush depends on the peripheral speed of the Commutator and the

working voltage. The hardness of the graphite brush is selected to be lower than that of the Commutator. When the brush wears out the graphite works as a solid lubricant reducing frictional coefficient. More number of relatively smaller width brushes are preferred in place of large broad brushes. The brush holders provide slots for the brushes to be placed. The connection Brush holder with a Brush and Positioning of the brush on the Commutator from the brush is taken out by means of flexible pigtail. The brushes are kept pressed on the Commutator with the help of springs. This is to ensure proper contact between the brushes and the Commutator even under high speeds of operation. Jumping of brushes must be avoided to ensure arc free current collection and to keep the brush contact drop low.

Other mechanical parts End covers, fan and shaft bearings form other important mechanical parts. End covers are completely solid or have opening for ventilation. They support the bearings which are on the shaft. Proper machining is to be ensured for easy assembly. Fans can be external or internal. In most machines the fan is on the non-Commutator end sucking the air from the Commutator end and throwing the same out. Adequate quantity of hot air removal has to be ensured. Bearings Small machines employ ball bearings at both ends. For larger machines roller bearings are used especially at the driving end. The bearings are mounted press-fit on the shaft. They are housed inside the end shield in such a manner that it is not necessary to remove the bearings from the shaft for dismantling.

2.3 Lap Winding :

This type of winding is used in dc generators designed for high-current applications. The windings are connected to provide several parallel paths for current in the armature. For this reason, lap-wound armatures used in dc generators require several pairs of poles and brushes.
In lap winding, the finishing end of one coil is connected to a commutator segment and to the starting end of the adjacent coil situated under the same pole an so on,till all the coils have been connected. This type of winding derives its name from the fact it doubles or laps back with its succeeding coils. Following points regarding simplex lap winding should be noted:
1. The back and front pitches are odd and of opposite sign. But they can't be equal.They differ by 2 or some multiple thereof.
2. Both YB and YF shpuld be nearly equal to a pole pitch.
3. The average pitch YA = (YB + YF)/2.It equals pole pitch = Z/P.
4. Commutator pitch YC = ±1.
5. Resultant pitch YR is even, being the arithmetical difference of two odd numbers i.e YR = YB - YF.
6. The number of slots for a 2-layer winding is equal to the number of coils.The number of commutator segments is also the same.

7. The number of parallel paths in the armature = mP where 'm' is the multiplicity of the winding and 'P' the number of poles.Taking the first condition, we have
YB = YF ± 2m where m=1 fo simplex lap and m =2 for duplex winding etc.
8. If YB > YF i.e YB = YF + 2, then we get a progressive or right-handed winding
i.e a winding which progresses in the clockwise direction as seen from the comutator end.In this case YC = +1.
9. If YB < size="1">F i.e YB = YF - 2,then we get a retrogressive or left-handed winding i.e one which advances in the anti-clockwise direction when seen from the commutator side.In this case YC = -1.
10. Hence, it is obvious that for

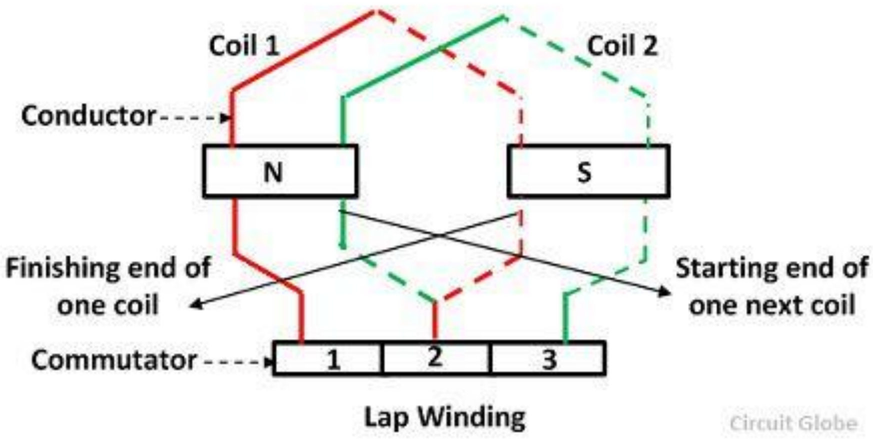


Fig.2.3: Lap Winding

2.4 Wave Winding

This type of winding is used in dc generators employed in high-voltage applications. Notice that the two ends of each coil are connected to commutator segments separated by the distance between poles. This configuration allows the series addition of the voltages in all the windings between brushes. This type of winding only requires one pair of brushes. In practice, a practical generator may have several pairs to improve commutation.
When the end connections of the coils are spread apart as shown in Figure a wave or series winding is formed. In a wave winding there are only two paths regardless of the number of poles. Therefore, this type winding requires only two brushes but can use as many brushes as poles. Because the winding progresses in one direction round the armature in a series of 'waves' it is know as wave winding. If, after passing once round the armature, the winding falls in a slot to the left of its starting point then winding is said to be retrogressive. If, however, it falls one slot to the right, then it is progressive.

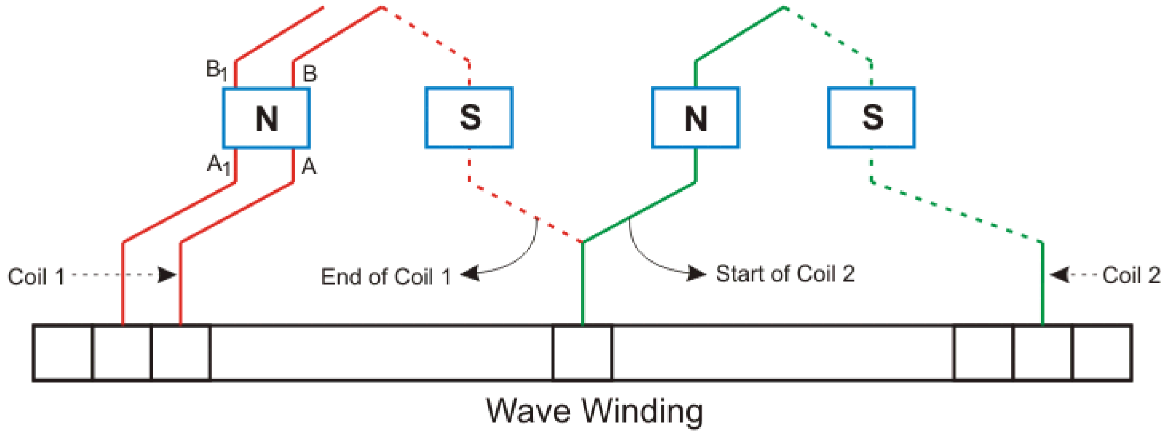


Fig.2.4: Wave Winding

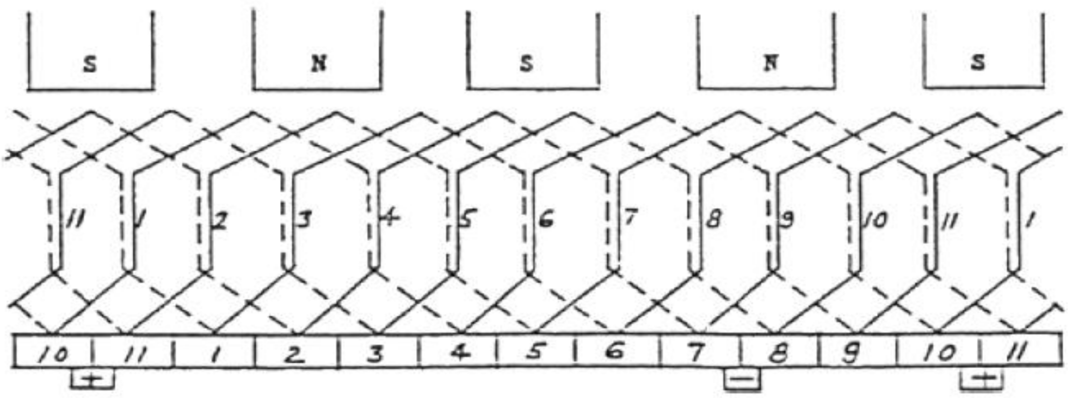


Fig.2.5: Construction Diagram of Wave Winding.

1. YF are odd and of the same sign.
2. Back and front pitches are nearly equal to the pole pitch and may be equal or differ by 2, in which case, they are respectively one more or one less than the average pitch.
3. Resultant pitch YR = YF + YB.
4. Commutator pitch, YC = YA (in lap winding YC = ±1). Also YC = (No.of commutator bars ± 1) / No.of pair of poles.
5. The average pitch which must be an integer is given by YA = (Z ± 2)/P = (No.of commutator bars ± 1)/No.of pair of poles.

6. The number of coils i.e NC can be found from the relation NC = (PYA ± 2)/2.
7. It is obvious from 5 that for a wave winding, the number of armature conductors with 2 either added or subtracted must be a multiple of the number of poles of the generator.This restriction eliminates many even numbers which are unsuitable for this winding.
8. The number of armature parallel paths = 2m where 'm' is the multiplicity of the winding.

2.5 EMF Equation

Consider a D.C generator whose field coil is excited to produce a flux density distribution along the air gap and the armature is driven by a prime mover at constant speed as shown in figure

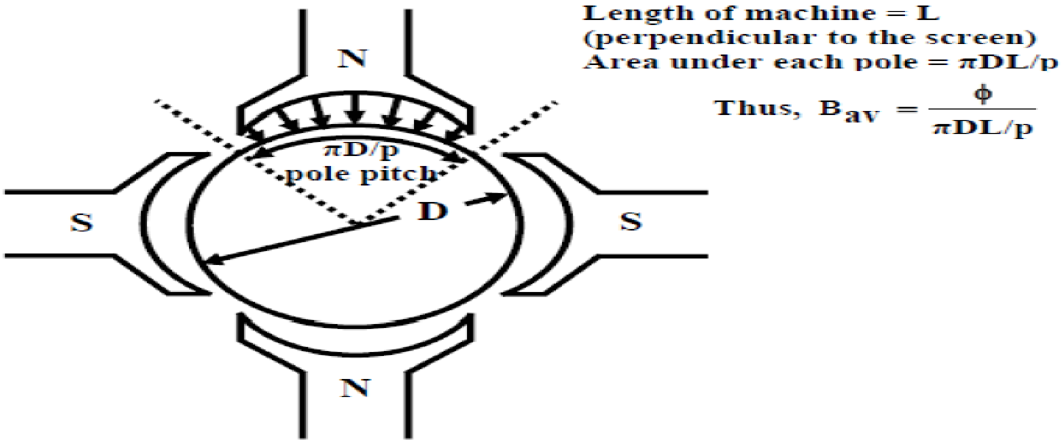


Fig.2.6: Diagram of DC Machine

Let us assume a p polar d.c generator is driven (by a prime mover) at n rps. The excitation of the stator field is such that it produces a φ Wb flux per pole. Also let z be the total number of armature conductors and a be the number of parallel paths in the armature circuit. In general, as discussed in the earlier section the magnitude of the voltage from one conductor to another is likely to very since flux density distribution is trapezoidal in nature. Therefore, total average voltage across the brushes is calculated on the basis of average flux density Bav. If D and L are the rotor diameter and the length of the machine in meters then area under each pole is . Hence average flux density in the gap is given by

EMF Equation a DC Generator

Now, for simplex wave wound generator
no. of parallel paths = A = 2

$$\therefore Eg = \frac{P\varnothing N Z}{120} \text{ volts}$$

and, for simplex lap wound generator
no. of parallel paths = A = no. of poles = P

$$\therefore Eg = \frac{P\varnothing N}{60} \frac{Z}{P} \text{ volts}$$

2.6 Armature reaction

In a unloaded d.c machine armature current is vanishingly small and the flux per pole is decided by the field current alone. The uniform distribution of the lines of force get upset when armature too carries current due to loading. In one half of the pole, flux lines are concentrated and in the other half they are rarefied. Qualitatively one can argue that during loading condition flux per pole will remain same as in no load operation because the increase

of flux in one half will be balanced by the decrease in the flux in the other half. Since it is the flux per pole which decides the emf generated and the torque produced by the machine, seemingly there will be no effect felt so far as the performance of the machine is concerned due to armature reaction. This in fact is almost true when the machine is lightly or moderately loaded.

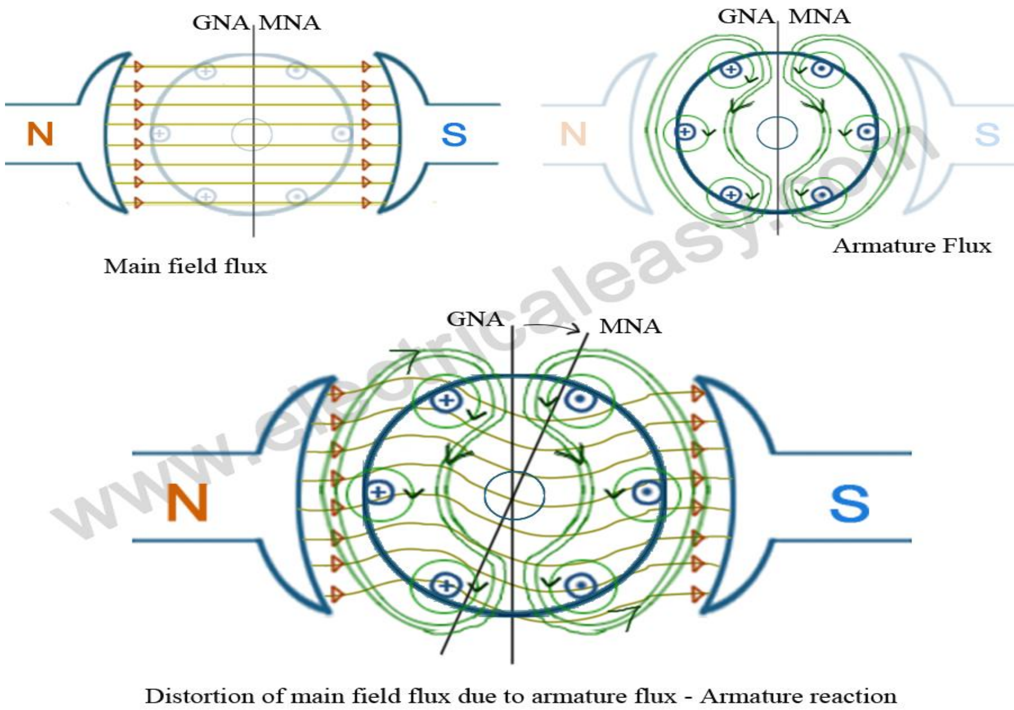


Fig.2.7: Armature Reaction of DC Machine

2.7 Methods Of Excitation

Various methods of excitation of the field windings are Separately-excited generators
Self-excited generators: series generators, shunt generators, compound generators
With self-excited generators, residual magnetism must be present in the machine iron to get the self-excitation process started. The relation between the steady-state generated emf Ea and the armature terminal voltage *Va* is$Va=Ea-IaRa$ rarefied. Qualitatively one can argue that during loading condition flux per pole will remain same as in no load operation because the increase of flux in one half will be balanced by the decrease in the flux in the other half. Since it is the flux per pole which decides the emf generated and the torque produced by the machine, seemingly there will be no effect felt so far as the performance of the machine is concerned due to armature reaction. This in fact is almost true when the machine is lightly or moderately loaded.

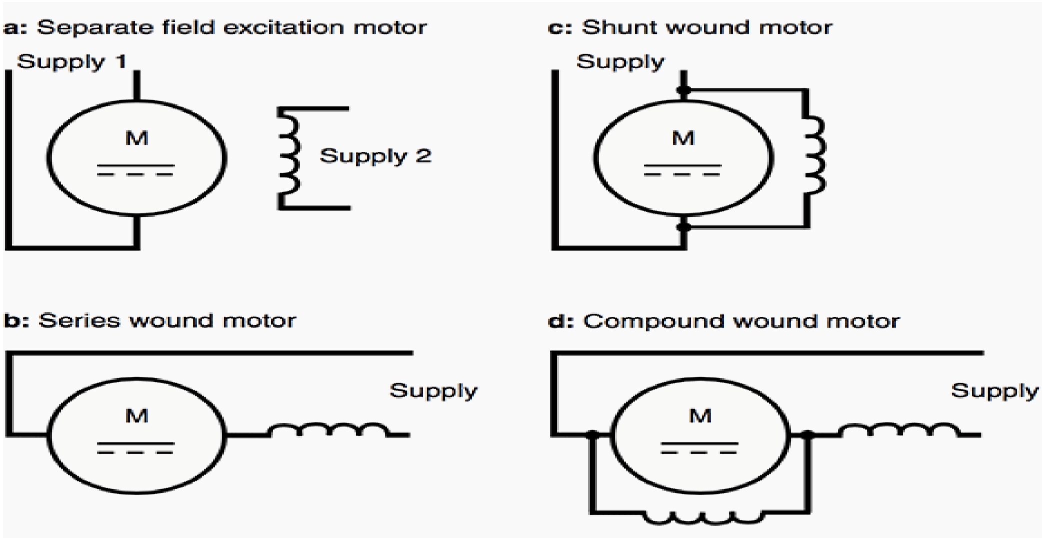


Fig.2.8: Excitation of different types of DC Machine

2.8 Commutation And Interpoles

In larger machines the commutation process would involve too much sparking, which causes brush wear, noxious gases (ozone) that promote corrosion, etc. In these cases it is common to use separate commutation interpoles. These are separate, usually narrow or seemingly vestigal pole pieces which carry armature current. They are arranged in such a way that the flux from the interpole drives current in the commutated coil in the proper direction

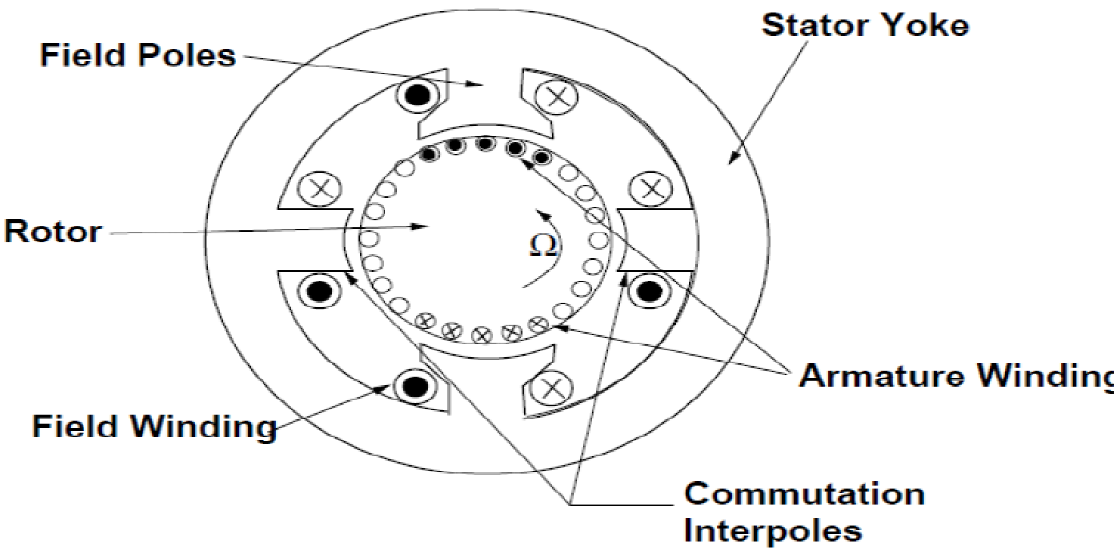


Fig.2.9: Commutator and interpole Diagram of DC Machine

Remember that the coil being commutated is located physically between the active poles and the interpole is therefore in the right spot to influence commutation. The interpole is wound with armature current (it is in series with the main brushes). It is easy to see that the interpole must have a flux density proportional to the current to be commutated. Since the speed with which the coil must be commutated is proportional to rotational velocity and so is the voltage induced by the interpole, if the right numbers of turns are put around the interpole, commutation can be made to be quite accurate.

2.9 Generator Characteristics

The three most important characteristics or curves of a D.C generator are:

2.9.1.OpenCircuitCharacteristic(O.C.C.)

This curve shows the relation between the generated emf. at no-load (E_0) and the field current (I_f) at constant speed. It is also known as magnetic characteristic or no-load saturation curve. Its shape is practically the same for all generators whether separately or self-excited. The data for O.C.C. curve are obtained experimentally by operating the generator at no load and constant speed and recording the change in terminal voltage as the field current is varied.

2.9.2. Internal or Total characteristic (E/I_a)

This curve shows the relation between the generated emf. On load (E) and the armature current (I_a). The emfE is less than E0 due to the demagnetizing effect of armature reaction. Therefore, this curve will lie below the open circuit characteristic (O.C.C.)It cannot be obtained directly by experiment. It is because a voltmeter cannot read the emf. Generated on load due to the voltage drop in armature resistance. The internal characteristic can be

obtained from external characteristic if winding resistances are known because armature reaction effect is included in both characteristics.

2.9.3. External Characteristic (V/IL)

This curve shows the relation between the terminal voltage (V) and load current (IL). The terminal voltage V will be less than E due to voltage drop in the armature circuit. Therefore, this curve will lie below the internal characteristic. This characteristic is very important in determining the suitability of a generator for a given purpose. It can be obtained by making simultaneous

2.9.4. No-load Saturation Characteristic (E0/I*f*)

It is also known as magnetic characteristic or open circuit Characteristic (*O.C.C*).It shows the relation between the no-load generated emf in armature, E0 and the field or exciting current I*f* at a given fixed speed. It is just demagnetization curve for the material of the electromagnets. Its shape is practically the same for all generators whether separately-excited or self-excited.

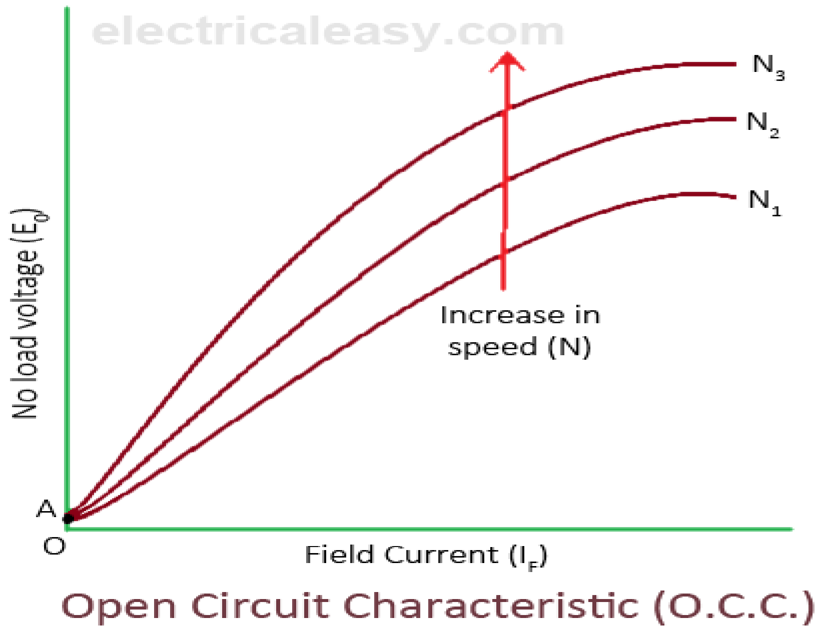


Fig.2.10: Open Circuit Characteristics of DC Machine

A typical no load saturation curve is shown in Figure.It has generator output voltage plotted against field current. The lower straight line portion of the curve represents the air gap because the magnetic parts are not saturated. When the magnetic parts start to saturate, the curve bends over until complete saturation is reached. Then the curve becomes a straight line again.

2.9.5.Separately-Excited Generator

The No-load saturation curve of a separately excited generator will be as shown in the above Figure. It is obvious that when it is increased from its initial small value, the flux and hence generated emf .E.g. increase directly as current so long as the poles are unsaturated. This is represented by straight portion in Figure. But as the flux density increases, the poles become saturated, so a greater increase I*f* is required to produce a given increase in voltage than on the lower part of the curve. That is why the upper portion of the curve bends.

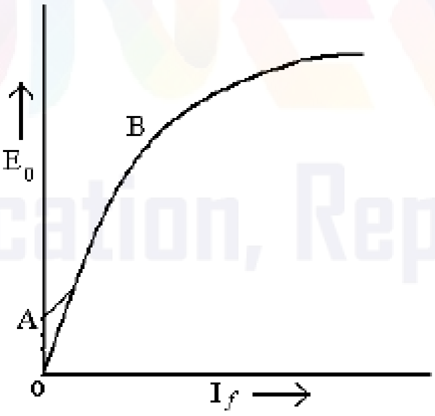


Fig.2.11: variation of voltage v/s field current

The *O.C.C* curve for self-excited generators whether shunt or series wound is shown in above Figure.Due to the residual magnetism in the poles, some emf (=OA) is generated even when I*f* =0.Hence, the curve starts a little way up. The slight curvature at the lower end is due to magnetic inertia.It is seen that the first part of the curve is practically straight.This is due to fact that at low flux densities reluctance of iron path being negligible,total reluctance is given by the air gap reluctance which is constant.Hence,the flux and consequently, the generated emfis directly proportional to the exciting current.However, at high flux densities, where μ is small,iron path reluctance becomes appreciable and straight relation between E and If no longer holds good. In other words,after point B, saturation of pole starts. However, the initial slope of the curve is determined by air-gap width.O.C.C for higher speed would lie above this curve and for lower speed, would lie below it. Separately-excited Generator Let we consider a separately-excited generator giving its rated no-load voltage of E0 for a certain constant field current. If there were no armature reaction and armature voltage drop,then this voltage would have remained constant as shown in Figure by the horizontal line 1. But when the generator is loaded, the voltage falls due to these two causes, therebygiving slightly dropping characteristics.If we subtract from E0 the values of voltage drops due to armature reaction for different loads, then we get the value of E-the emf actually induced in the armature under load conditions.Curve 2 is plotted in this way and is known as the internal characteristic.

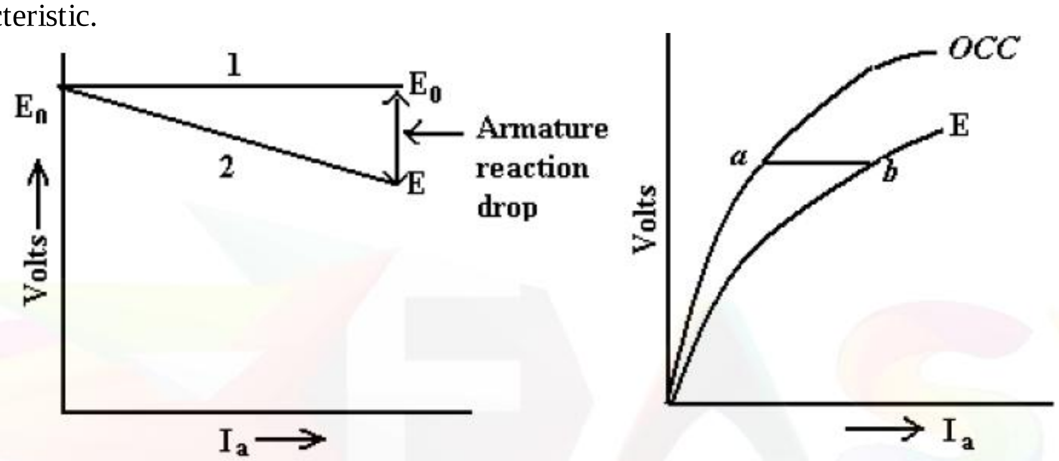


Fig.2.12: Characteristics of separately excited d.c motor

In this generator, because field windings are in series with the armature, they carry full armature current Ia. As Ia is increased, flux and hence generated emf is also increased as shown by the curve. Curve *Oa* is the *O.C.C.* The extra exciting current necessary to neutralize the weakening effect of armature reaction at full load is given by the horizontal distance *ab*. Hence, point *b* is on the internal characteristic.

2.9.6. External Characteristic (V/I)

It is also referred to as performance characteristic or sometimes voltage regulating curve. It gives relation between the terminal voltage V and the load current I. This curve lies below the internal characteristic because it takes in to account the voltage drop over the armature circuit resistance. The values of V are obtained by subtracting IaRa from corresponding values of E.This characteristic is of great importance in judging the suitability of a generator for a particular purpose.It may be obtained in two ways By making simultaneous measurements with a suitable voltmeter and an ammeter on a loaded generator or Graphically from the *O.C.C* provided the armature and field resistances are known and also if the demagnetizing effect or the armature reaction is known.

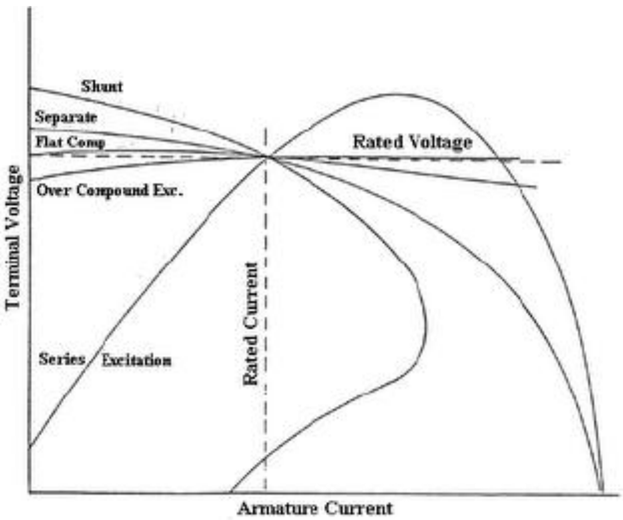


Fig.2.13: External characteristics of DC Machine

Figure above shows the external characteristic curves for generators with various types of excitation. If a generator, which is separately excited, is driven at constant speed and has a fixed field current, the output voltage will decrease with increased load current as shown. This decrease is due to the armature resistance and armature reaction effects. If the field flux remained constant, the generated voltage would tend to remain constant and the output voltage would be equal to the generated voltage minus the IR drop of the armature circuit. However, the demagnetizing component of armature reactions tends to decrease the flux, thus adding an additional factor, which decreases the output voltage.

DC MOTORS

3.1 D.C. Motor Principle

A machine that converts d.c. power into mechanical power is known as a d.c motor. Its operation is based on the principle that when a current carrying conductor is placed in a magnetic field, the conductor experiences a mechanical force. The direction of this force is given by Fleming's left hand rule and magnitude is given by; basically, there is no constructional difference between a d.c. motor and a d.c.generator. The same d.c. machine can be run as a generator or motor.

3.2 Working of D.C. Motor

When the terminals of the motor are connected to an external source of d.c. supply:
(i) The field magnets are excited developing alternate N and S poles;
(ii) The armature conductors carry currents.

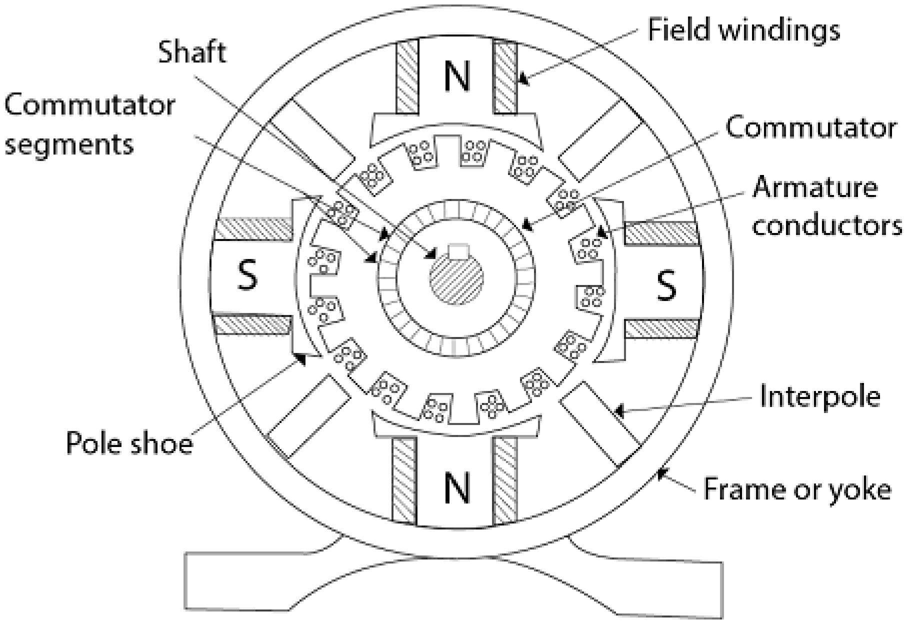


Fig.3.1: Construction Diagram of DC Motor

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

3.3 Types of D.C. Motors

Like generators, there are three types of d.c. motors characterized by the connections of field winding in relation to the armature viz.:
(i) Shunt-wound motor in which the field winding is connected in parallel with the

armature. The current through the shunt field winding is not the same as the armature current. Shunt field windings are designed to produce the necessary m.m.f. by means of a relatively large number of turns of wire having high resistance. Therefore, shunt field current is relatively small compared with the armature current.

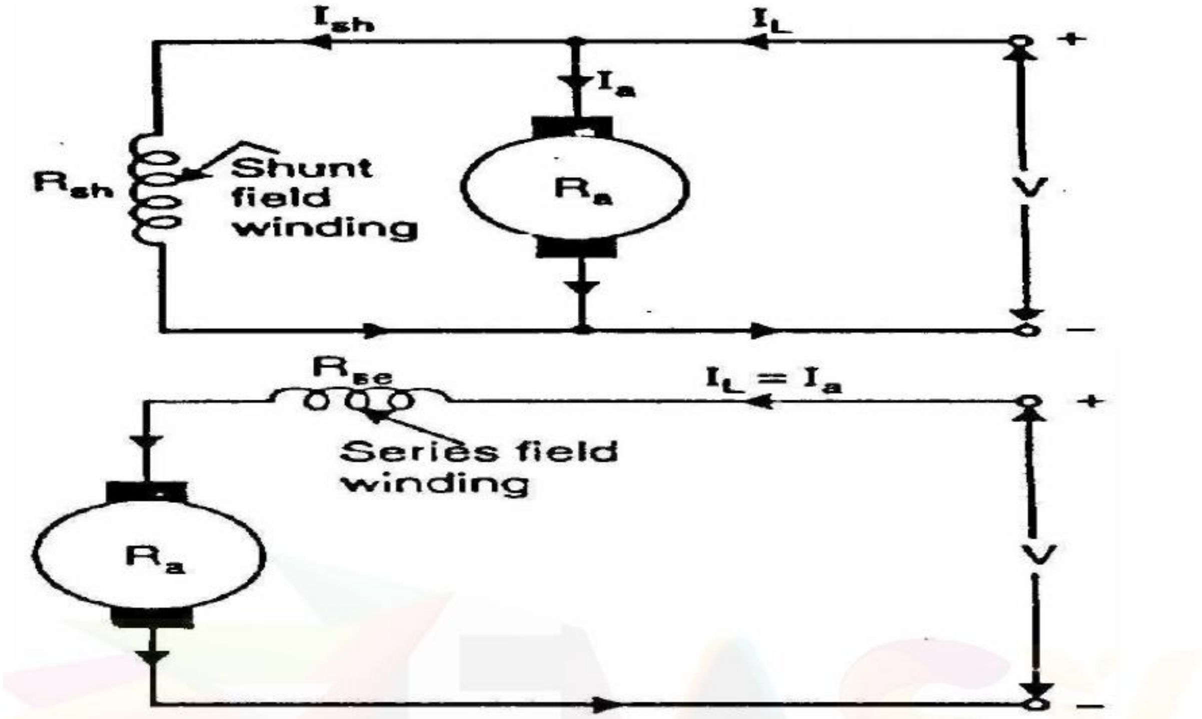


Fig.3.2: DC series and shunt Motor

(ii) Series-wound motor in which the field winding is connected in series with the armature Therefore, series field winding carries the armature current. Since the current passing through a series field winding is the same as the armature current, series field windings must be designed with much fewer turns than shunt field windings for the same m.m.f. Therefore, a series field winding has a relatively small number of turns of thick wire and, therefore, will possess a low resistance.

(iii) Compound-wound motor which has two field windings; one connected in parallel with the armature and the other in series with it. There are two types of compound motor connections (like generators). When the shunt field winding is directly connected across the armature terminals it is called short-shunt connection. When the shunt winding is so connected that it shunts the series combination of armature and series field it is called long-shunt connection.

3.4 Motor Characteristics

3.4. Torque/Speed Curves

In order to effectively design with D.C. motors, it is necessary to understand their characteristic curves. For every motor, there is a specific Torque/Speed curve and Power curve.

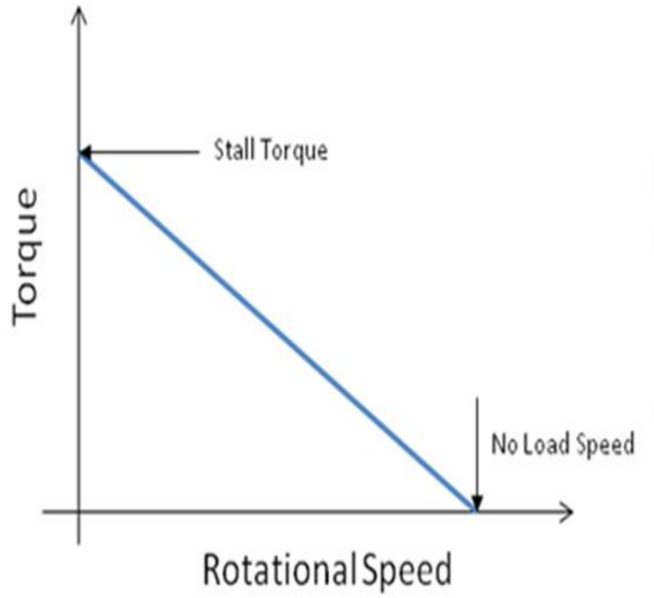


Fig.3.3: Variation of torque v/s speed of DC Motor

The graph above shows a torque/speed curve of a typical D.C. motor. Note that torque is inversely proportional to the speed of the output shaft. In other words, there is a tradeoff between how much torque a motor delivers, and how fast the output shaft spins. Motor characteristics are frequently given as two points on this graph: The stall torque represents the point on the graph at which the torque is a maximum, but the shaft is not rotating. The no load speed, is the maximum output speed of the motor (when no torque is applied to the output shaft).

The linear model of a D.C. motor torque/speed curve is a very good approximation. The torque/speed curves shown below are actual curves for the green maxon motor (pictured at right) used by students in 2.007. One is a plot of empirical data, and the other was plotted mechanically using a device developed at MIT.

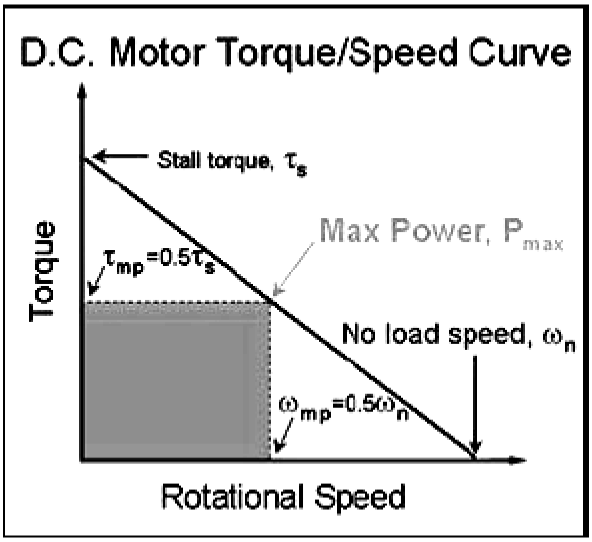


Fig.3.4: speed/torque curve of DC Motor

This corresponds to the area of a rectangle under the torque/speed curve with one Corner at the origin and another corner at a point on , and = ½ **.**

3.5 Speed Control Of Dc Shunt Motor

We know that the speed of shunt motor is given by: Where, Va is the voltage applied across the armature, N is the rotor speed and φ is the flux per pole and is proportional to the field current If. As explained earlier, armature current Ia is decided by the mechanical load present on the shaft. Therefore, by varying Va and If we can vary n. For fixed supply voltage and the motor connected as shunt we can vary Va by controlling an external resistance connected in series with the armature. If of course can be varied by controlling external field resistance Rf connected with the field circuit. Thus for. shunt motor we have essentially two methods for controlling speed, namely by:

1. Varying Armature Resistance
2. Varying Field Resistance

3.5.1Speed Control by Varying Armature Resistance

The inherent armature resistance Ra being small, speed n versus armaturecurrent (Ia) characteristic will be a straight line with a small negative slope as shown in figure.

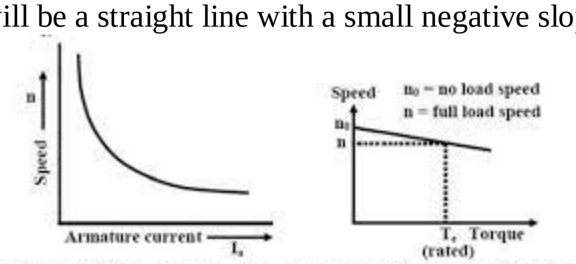


Figure 5.20(i) Speed Vs Armature Current. (ii) Speed Vs Torque Characteristics

Fig.3.5: speed/ armature resistance of DC Motor

Note that for shunt motor voltage applied to the field and armature circuit are same and equal to the supply voltage V. However, as the motor is loaded, IaRa drop increases making speed a little less than the no load speed n0. For a well designed shunt motor this drop in speed is small and about 3 to 5% with respect to no load speed. This drop in speed from no load to full load condition expressed as a percentage of no load speed is called then he rent speed regulation of the motor. It is for this reason, a d.c shunt motor is said to be practically a

constant speed motor since speed drops by a small amount from no load to full load condition.

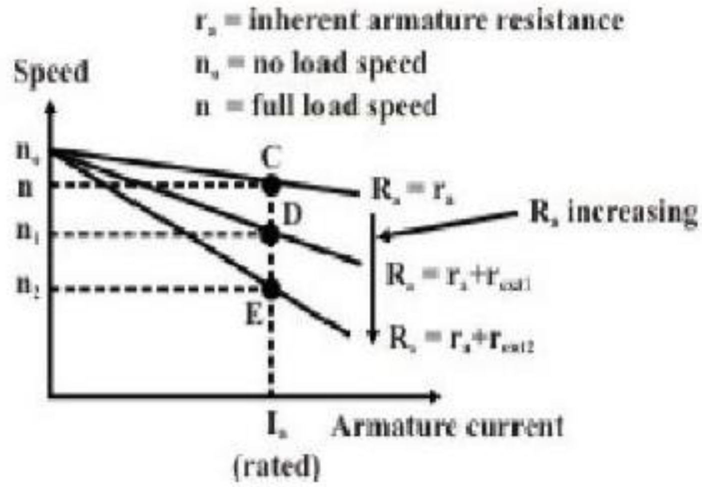


Fig.3.6: Speed / Armature current of DC Motor

From these characteristic it can be explained how speed control is achieved.

Let us assume that the load torque TL is constant and field current is also kept constant. Therefore, since steady state operation demands Te = TL, Te= kIaφ too will remain constant; which meansIa will not change. Suppose Rest = 0, then at rated load torque, operating point will be at C and motor speed will be n. If additional resistance rext1 is introduced in the armature circuit, new steady state operating speed will be n1 corresponding to the operating point D.
This same load torque is supplied at various speed. Variation of the speed is smooth and speed will decrease smoothly if Rest is increased. Obviously, this Method is suitable for controlling speed below the base speed and for supplying constant rated load torque which ensures rated armature current always. Although, this method provides smooth wide range speed control (from base speed down to zero speed), has a serious draw back since energy loss takes place in the external resistance Rest reducing the efficiency of the motor.

3.5.2 Speed Control by Varying Field Current

In this method field circuit resistance is varied to control the speed of a d.cshuntmotor. Let us rewrite .the basic equation to understand the method. If flux φ will change, hence speed will vary. To change If an external resistance is connected in series with the field windings. The field coil produces rated flux when no external resistance is connected and rated voltage is applied across field coil. It should be understood that we can only decrease flux from its rated value by adding external resistance. Thus the speed of the motor will rise as we decrease the field current and speed control above the base speed will be achieved. Speed versus armature current characteristic is shown in figure for two flux values φ and φ1. Since φ1<φ, the no load speed no' for flux value φ1 is more than the no load speed no corresponding to φ. However, this method will not be suitable for constant load torque .To make this point clear, let us assume that the load torque is constant at rated value. So from the initial steady condition, we have TL rated=Ta1= k=Ia rated .If load torque remains constant and flux is reduced to φ1, new armature current in the steady state is obtained from kI a1=TL rated . Therefore new armature current is but this fraction is less than 1. Hence new armature current will be greater than the rated armature current and the motor will be overloaded. This method

therefore, will be suitable for a load whose torque demand decreases with the rise in speed keeping the output power constant as shown in figure. Obviously this method is based on flux weakening of the main field.

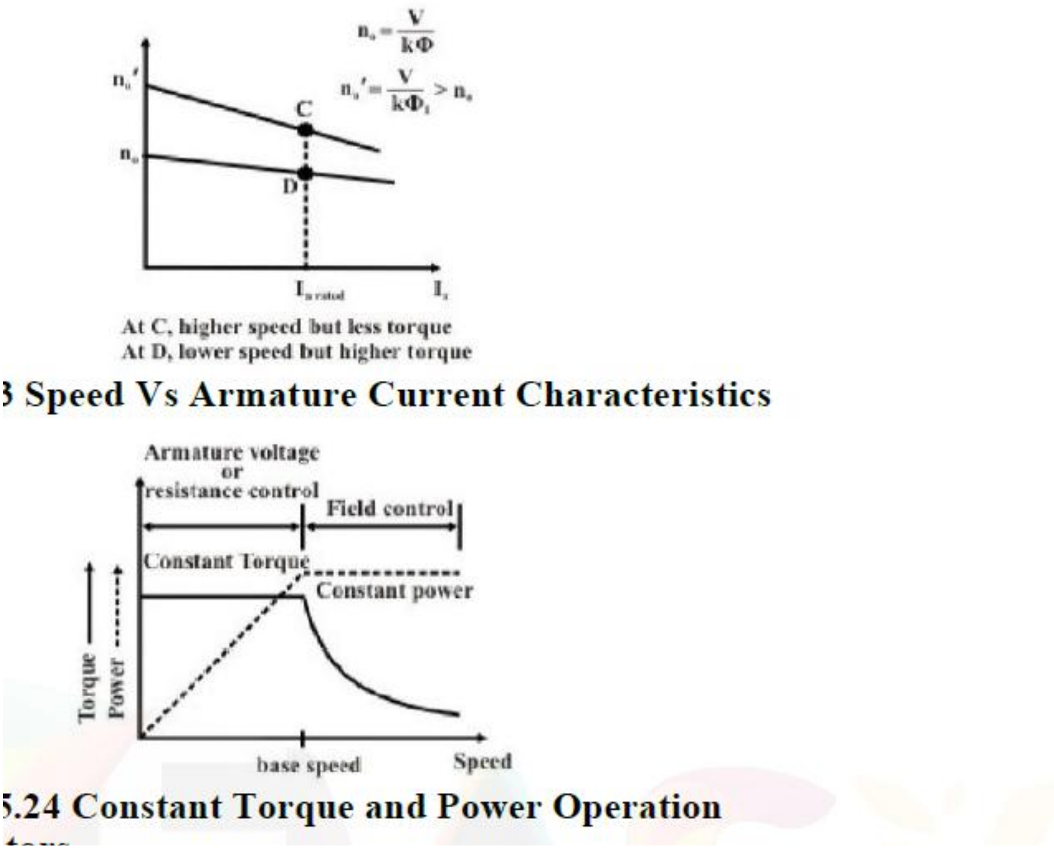


Fig.3.7: Speed Vs Armature current characteristics

3.6 Starting Of Dc Motors

The speed of the machine has to be increased from zero and brought to the operating speed. This is called starting of the motor. The operating speed itself should be varied as per the requirements of the load. This is called speed control. Finally, the running machine has to be brought to rest, by decelerating the same. This is called braking.

At the instant of starting, rotor speed n = 0, hence starting armature current is Ist=V/ra. Since, armature resistance is quite small, starting current may be quite high (many times larger than the rated current). A large machine, characterized by large rotor inertia (J), will pick up speed rather slowly. Thus the level of high starting current may be maintained for quite some time so as to cause serious damage to the brush/commutator and to the armature winding. Also the source should be capable of supplying this burst of large current. The other loads already connected to the same source, would experience a dip in the terminal voltage, every time a D.C motor is attempted to start with full voltage. This dip in supply voltage is caused due to sudden rise in voltage drop in the source's internal resistance. The duration for which this drop in voltage will persist once again depends on inertia of the motor. Hence, for small D.C motors extra precaution may not be necessary during starting as large starting current will very quickly die down because of fast rise in the back emf. However, for large motor, a starter is to be used during starting. A simple starter to limit the starting current, a suitable

external resistance R is connected in series, as shown in the figure, with the armature so that Ist=V/(R+ra) At the time of starting, to have sufficient starting torque, field current is maximized by keeping external field resistance Rf to zero value. As the motor picks up speed, the value of R is gradually decreased to zero so that during running no external

resistance remains in the armature circuit. But each time one has to restart the motor, the external armature resistance must be set to maximum value by moving the jockey manually. Now if the supply goes off, motor will come to a stop. All on a sudden, let us imagine, supply is restored. This is then nothing but full voltage starting. In other
words, one should be constantly alert to set the resistance to maximum value whenever the motor comes to a stop. This is one major limitation of a simple rheostatic starter.

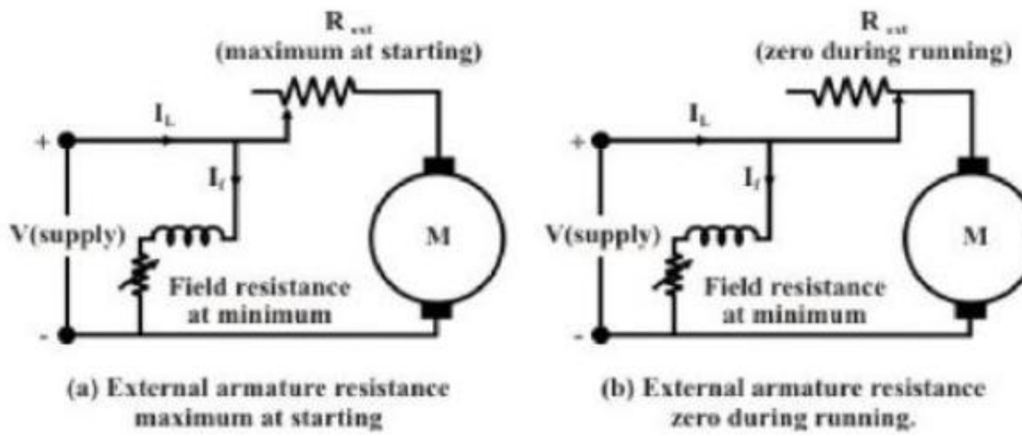


Fig.3.8: Circuit Diagram of Rheostatatic starters

3.7 Three Point Starter

A "3-point starter" is extensively used to start a D.C shunt motor. It not only overcomes the difficulty of a plain resistance starter, but also provides additional protective features such as over load protection and no volt protection. The diagram of a 3-point starter connected to a shunt motor is shown in figure. Although, the circuit looks a bit clumsy at a first glance, the basic working principle is same as that of plain resistance starter. The starter is shown enclosed within the dotted rectangular box having three terminals marked as A, L and F for external connections. Terminal A is connected to one armature terminal Al of the motor. Terminal F is connected to one field terminal F1 of the motor and terminal L is connected to one supply terminal as shown. F2 terminal of field coil is connected to A2 through an external variable field resistance and the common point connected to supply (-ve). The external armatures resistances consist of several resistances connected in series and are shown in the form of an arc. The junctions of the resistances are brought out as terminals and marked. Just beneath the resistances, a continuous copper strip also in the form of an arc is present.

There is a handle which can be moved in the clockwise direction against the spring tension. The spring tension keeps the handle in the OFF position when no one attempts to move it. Now let us trace the circuit from terminal L (supply + ve). The wire from L passes through a small electro magnet called OLRC, (the function of which we shall discuss a little later) and enters through the handle shown by dashed lines. Near the end of the handle two copper strips are firmly connected with the wire. The furthest strip is shown circular shaped and the other strip is shown to be rectangular. When the handle is moved to the right, the circular strip of the handle will make contacts with resistance terminals 1, 2 etc. Progressively. On the other hand, the rectangular strip will make contact with the continuous arc copper strip.
The other end of this strip is brought as terminal F after going through an electromagnet coil (called NVRC). Terminal F is finally connected to motor field terminal Fl.

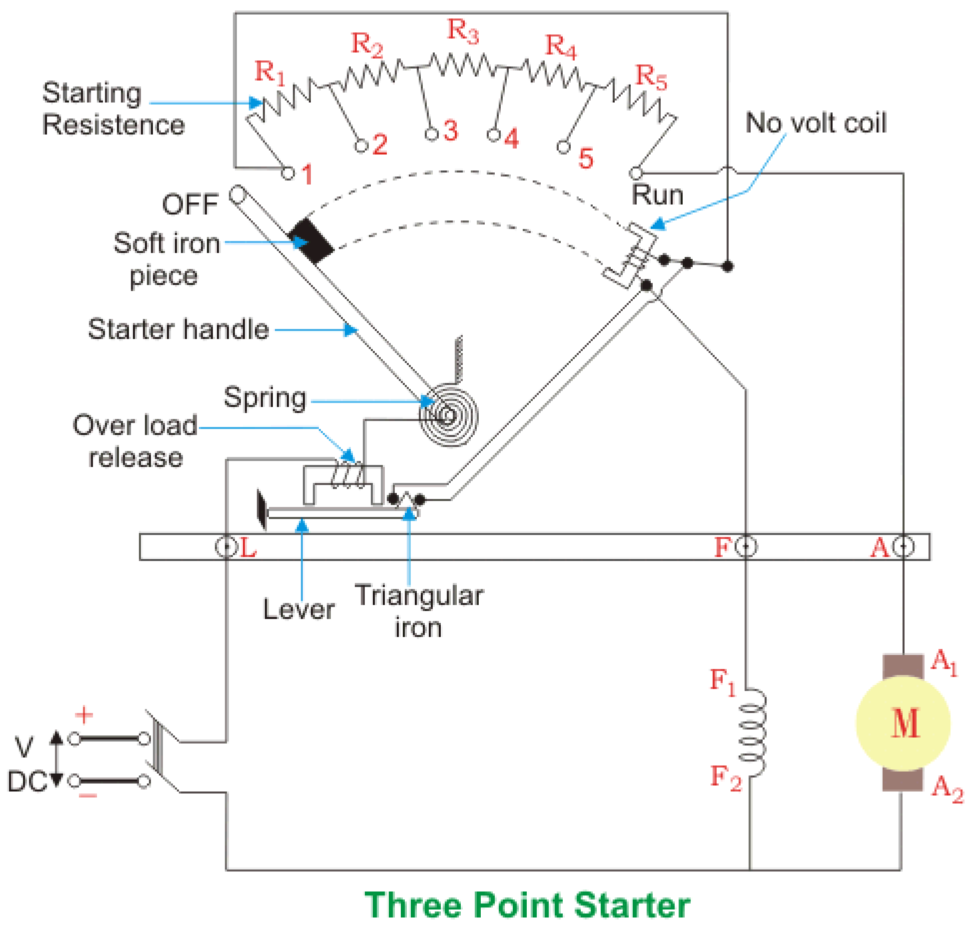


Fig.3.9: Three Point Starter of DC Motor

Working principle

In the operation of the starter, initially the handle is in the OFF position. Neither armature nor the field of the motor gets supply. Now the handle is moved to stud number 1. In this position armature and all the resistances in series gets connected to the supply. Field coil gets full supply as the rectangular strip makes contact with arc copper strip. As the machine picks up speed handle is moved further to stud number 2. In this position the external resistance in the armature circuit is less as the first resistance is left out. Field however, continues to get full voltage by virtue of the continuous arc strip. Continuing in this way, all resistances will be left out when stud number 12 (ON) is reached. In this position, the electromagnet (NVRC) will attract the soft iron piece attached to the handle. Even if the operator removes his hand from the handle, it will still remain in the ON position as spring restoring force will be balanced by the force of attraction between NVRC and the soft iron piece of the handle. The no volt release coil (NVRC) carries same current as that of the field coil. In case supply voltage goes off, field coil current will decrease to zero. Hence NVRC will be de-energized and will not be able to exert any force on the soft iron piece of the handle. Restoring force of the spring will bring the handle back in the OFF position. The starter also provides over load protection for the motor. The other electromagnet, OLRC overload release coil along with a soft iron piece kept under it, is used to achieve this. The current flowing through OLRC is the line current IL drawn by the motor. As the motor is loaded, Ia hence IL increases. Therefore, IL is a measure of loading of the motor. Suppose we want that the motor should not be over loaded beyond rated current. Now gap between the electromagnet and the soft iron piece is so adjusted that for $IL \leq Irated$ the iron piece will not be pulled up. However, if $IL \leq Irated$ force of

attraction will be sufficient to pull up iron piece. This upward movement of the iron piece of OLRC is utilized to de-energize NVRC. To the iron a copper strip is attached. During over loading condition, this copper strip will also move up and put a short circuit between two terminals B and C. Carefully note that B and C are nothing but the two ends of the NVRC. In other words, when over load occurs a short circuit path is created across the NVRC. Hence NVRC will not carry any current now and gets deenergized. The moment it gets deenergised, spring action will bring the handle in the OFF position thereby disconnecting the motor from the supply. Three point starter has one disadvantage.

3.8 Four-Point Starter

The four-point starter eliminates the drawback of the three-point starter. In addition to the same three points that were in use with the three-point starter, the other side of the line, L1, is the fourth point brought to the starter when the arm is moved from the "Off" position. The coil of the holding magnet is connected across the line. The holding magnet and starting resistors function identical as in the three point starter.

The possibility of accidentally opening the field circuit is quite remote. The four - point starter provides the no-voltage protection to the motor. If the power fails, the motor is disconnected from the line.

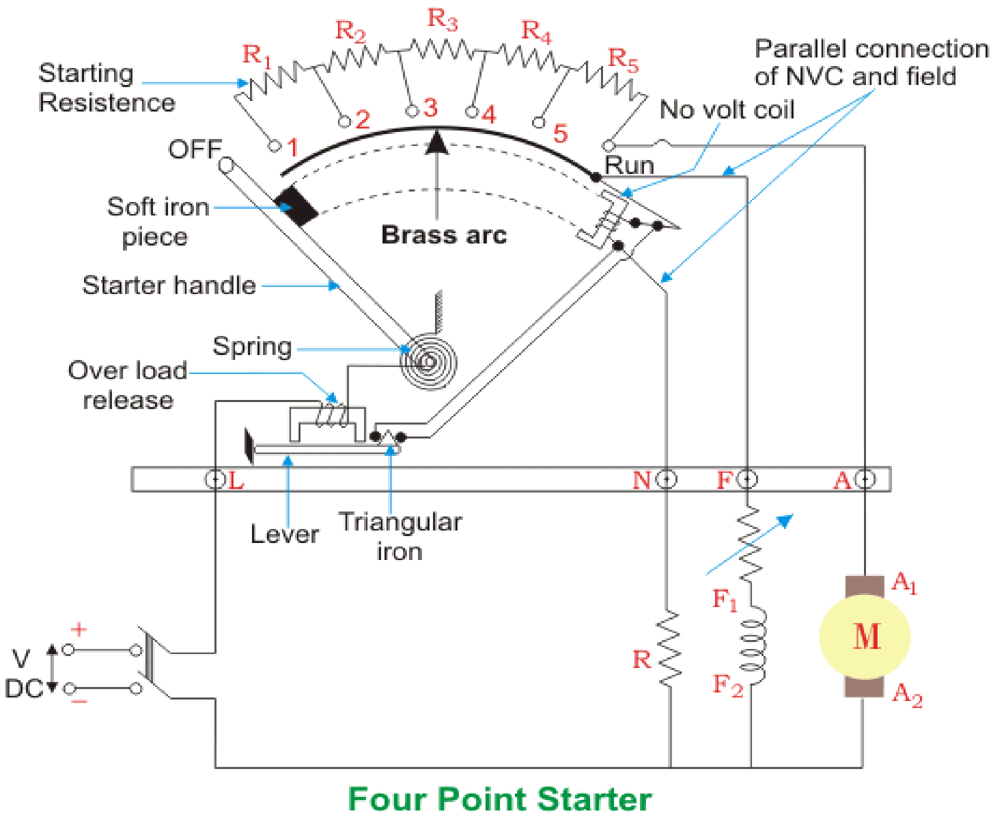
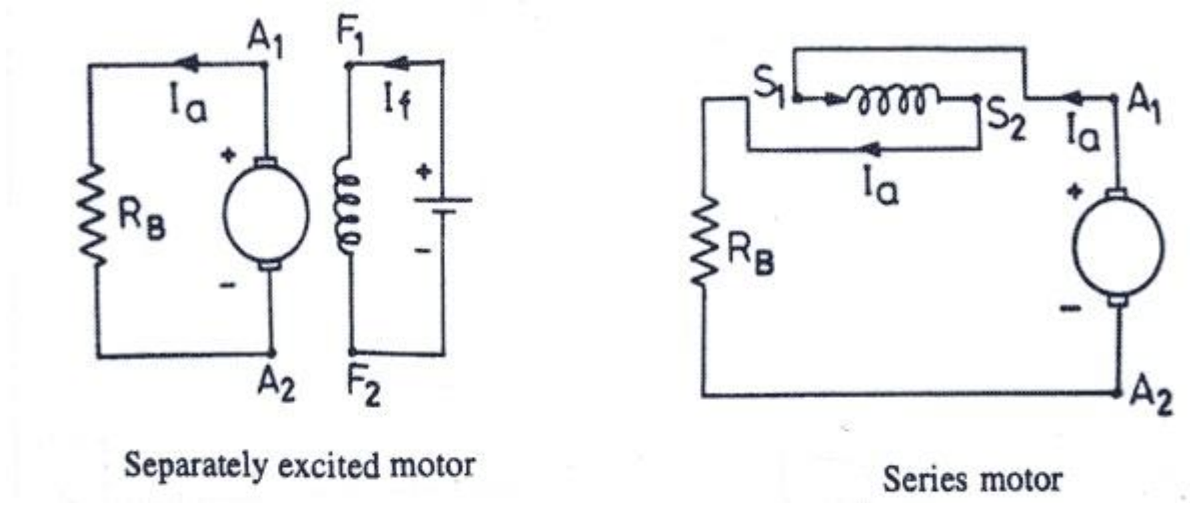


Fig.3.10: Four Point Starter of DC Motor

3.9Braking of dc motor

3.9.1 Plugging or dynamic braking

This method of braking can be understood by referring to figures 39.25 and 39.26. Here S is a double pole double throw switch. For usual motoring mode, S is connected to positions 1 and 1'. Across terminals 2 and 2', a series combination of an external resistance R_b and supply voltage with polarity as indicated is connected. However, during motor mode this part of the circuit remains inactive. To initiate braking, the switch is thrown to position 2 and 2' at $t = 0$, thereby disconnecting the armature from the left hand supply. Here at $t = 0_+$, the armature current will be $I_a = (E_b + V)/(r_a + R_b)$ as E_b and the right hand supply voltage have additive polarities by virtue.



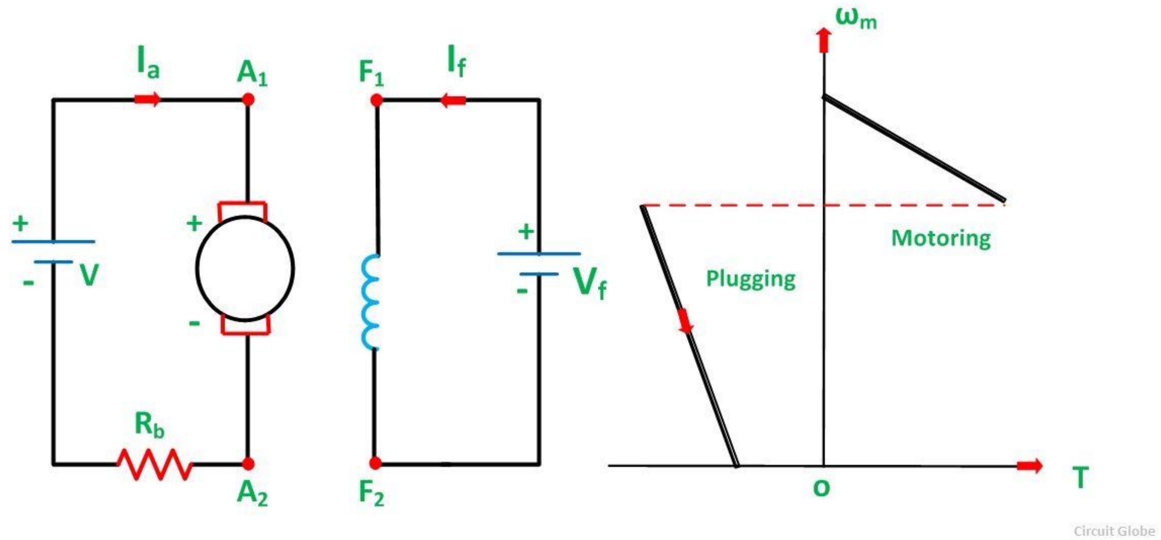


Fig.3.11: plugging and motering mode of of DC Motor

of the connection. Here also I_a reverses direction producing T_e in opposite direction to n. I_a decreases as E_b decreases with time as speed decreases. However, I_a can not become zero at any time due to presence of supply V. So unlike rheostatic braking, substantial magnitude of braking torque prevails. Hence stopping of the motor is expected to be much faster then rheostatic breaking. But what happens, if S continuous to be in position 1' and 2' even after zero speed has been attained? The answer is rather simple, the machine will start picking up speed in the reverse direction operating as a motor. So care should be taken to disconnect the right hand supply, the moment armature speed becomes zero.

3.9.2 Regenerative braking

A machine operating as motor may go into regenerative braking mode if its speed becomes sufficiently high so as to make back emf greater than the supply voltage i.e., $E_b > V$. Obviously under this condition the direction of I_a will reverse imposing torque which is opposite to the direction of rotation. The situation is explained in figures 39.27 and 39.28. The normal motor operation is shown in figure 39.27 where armature motoring current I_a is drawn from the supply and as usual $E_b < V$. Since $E_b = k\varphi\, n_1$. The question is how speed on its own become large enough to make $E_b < V$ causing regenerative braking. Such a situation may occur in practice when the mechanical load itself becomes active. Imagine the d.c motor is coupled to the wheel of locomotive which is moving along a plain track without any gradient as shown in figure 39.27. Machine is running as a motor at a speed of n_1 rpm. However, when the track has a downward gradient, component of gravitational force along the track also

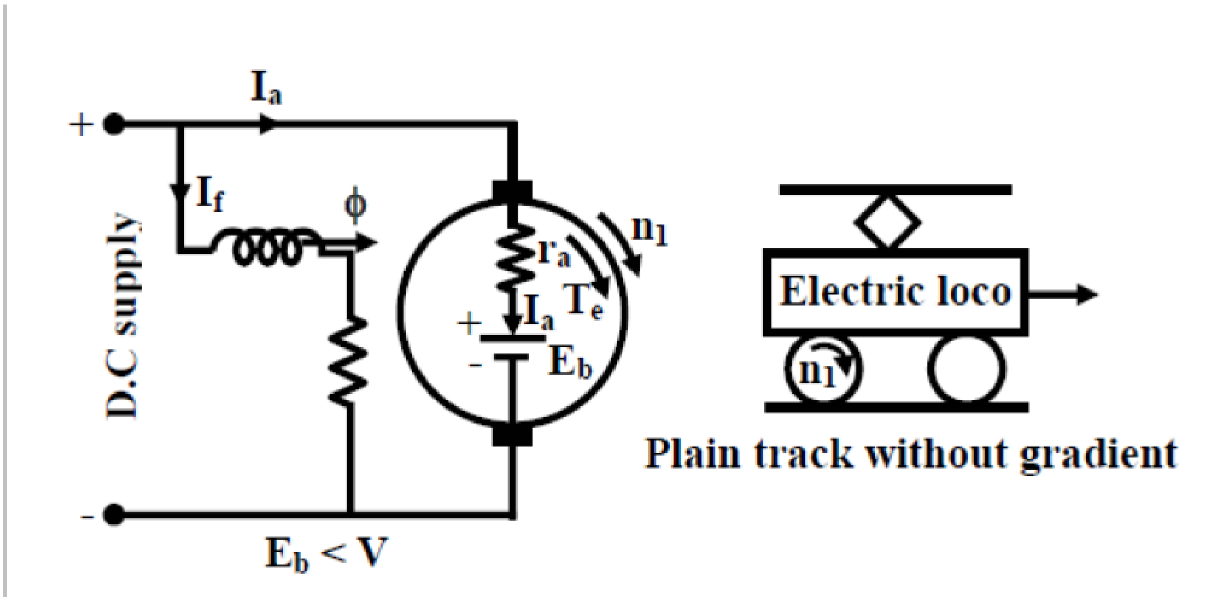


Figure 39.27: Machine operates as motor

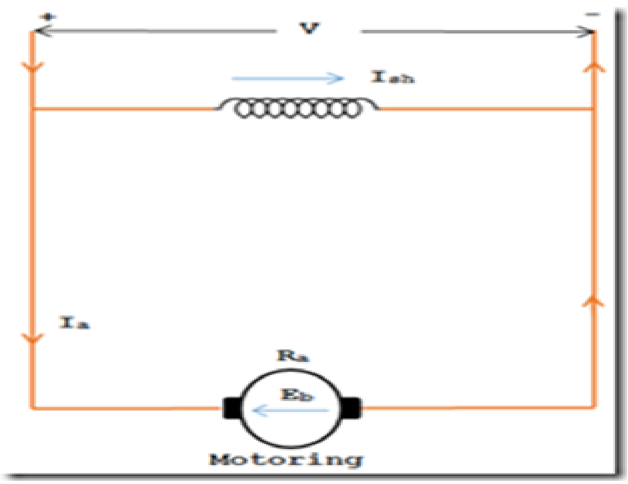


Fig.3.12: machine operates as DC Motor

appears which will try to accelerate the motor and may increase its speed to n_2 such that $E_b = k\varphi\, n_2 > V$. In such a scenario, direction of I_a reverses, feeding power back to supply. Regenerative braking here will not stop the motor but will help to arrest rise of dangerously high speed.

3.10 Swinburne's Test

For a d.c shunt motor change of speed from no load to full load is quite small. Therefore, mechanical loss can be assumed to remain same from no load to full load. Also if field current is held constant during loading, the core loss too can be assumed to remain same.
In this test, the motor is run at rated speed under *no load* condition at rated voltage. The current drawn from the supply I_{L0} and the field current I_f are recorded (figure 40.3). Now we note that:

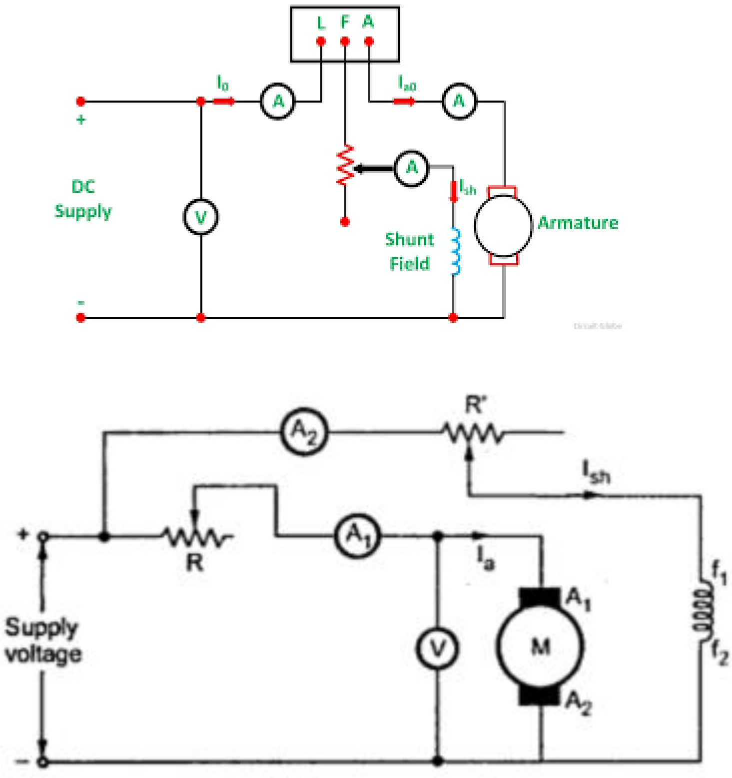


Fig.3.13: Swinburne test of DC Motor

Since the motor is operating under no load condition, net mechanical output power is zero. Hence the gross power developed by the armature must supply the core loss and friction & windage losses of the motor. Therefore,

$$P_{core} + P_{friction} = (V - I_{a0}r_a)I_{a0} = E_{b0}I_{a0}$$

Since, both P_{core} and $P_{friction}$ for a shunt motor remains practically constant from no load to full load, the sum of these losses is called constant rotational loss i.e.,

$$\text{constant rotational loss, } P_{rot} = P_{core} + P_{friction}$$

In the Swinburne's test, the constant rotational loss comprising of core and friction loss is estimated from the above equation. After knowing the value of P_{rot} from the Swinburne's test, we can fairly estimate the efficiency of the motor at any loading condition. Let the motor be loaded such that new current drawn from the supply is I_L and the new armature current is I_a as shown in figure 40.4. To estimate the efficiency of the loaded motor we proceed as follows:

$$
\begin{aligned}
\text{Input power to the motor, } P_{in} &= VI_L \\
\text{Cu loss in the field circuit } P_{fl} &= VI_f \\
\text{Power input to the armature, } &= VI_L - VI_f \\
&= V(I_L - I_f) \\
&= VI_a \\
\text{Cu loss in the armature circuit } &= I_a^2 r_a \\
\text{Gross power developed by armature } &= VI_a - I_a^2 r_a \\
&= (V - I_a r_a) I_a \\
&= E_b I_a \\
\text{Net mechanical output power, } P_{net\,mech} &= E_b I_a - P_{rot} \\
\therefore \text{ efficiency of the loaded motor, } \eta &= \frac{E_b I_a - P_{rot}}{VI_L} \\
&= \frac{P_{net\,mech}}{P_{in}}
\end{aligned}
$$

$$
\begin{aligned}
\text{Output power of the generator, } P_{out} &= VI_L \\
\text{Cu loss in the field circuit } P_{fl} &= VI_f \\
\text{Output power of the armature, } &= VI_L + VI_f \\
&= VI_a \\
\text{Mechanical input power, } P_{in\,mech} &= VI_a + I_a^2 r_a + P_{rot} \\
\therefore \text{ Efficiency of the generator, } \eta &= \frac{VI_L}{P_{in\,mech}} \\
&= \frac{VI_L}{VI_a + I_a^2 r_a + P_{rot}}
\end{aligned}
$$

The biggest advantage of Swinburne's test is that the shunt machine is to be run as motor under *no load* condition requiring little power to be drawn from the supply; based on the no load reading, efficiency can be predicted for any load current. However, this test is not

sufficient if we want to know more about its performance (effect of armature reaction, temperature rise, commutation etc.) when it is actually loaded. Obviously the solution is to load the machine by connecting mechanical load directly on the shaft for motor or by connecting loading rheostat across the terminals for generator operation. This although sounds simple but difficult to implement in the laboratory for high rating machines (say above 20 kW), Thus the laboratory must have proper supply to deliver such a large power corresponding to the rating of the machine. Secondly, one should have loads to absorb this power.

UNIT- 3
TRANSFORMER

3.1 Principle Of Operation

A transformer is a device that transfers electrical energy from one circuit to another through inductively coupled conductor. A varying current in the first or primary winding creates a varying magnetic flux in the transformer core, and thus a varying magnetic field through the secondary winding. This varying magnetic field induces a varying electromotive force EMF or voltage in the secondary winding. This effect is called mutual induction.

If a load is connected to the secondary, an electric current will flow in the secondary winding and electrical energy will be transferred from the primary circuit through the transformer to the load. In an ideal transformer, the induced voltage in the secondary winding is in proportion to the primary voltage , and is given by the ratio of the number of turns in the secondary to the number of turns in the primary as follows: By appropriate selection of the ratio of turns, a transformer thus allows an alternating current (AC) voltage to be "stepped up" by making greater than , or "stepped down" by making less than .

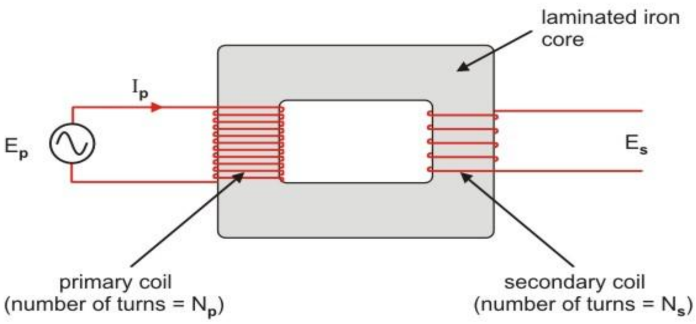


Fig3.1: Basic Diagram of Transformer

3.1.1 Basic Principle

Construction

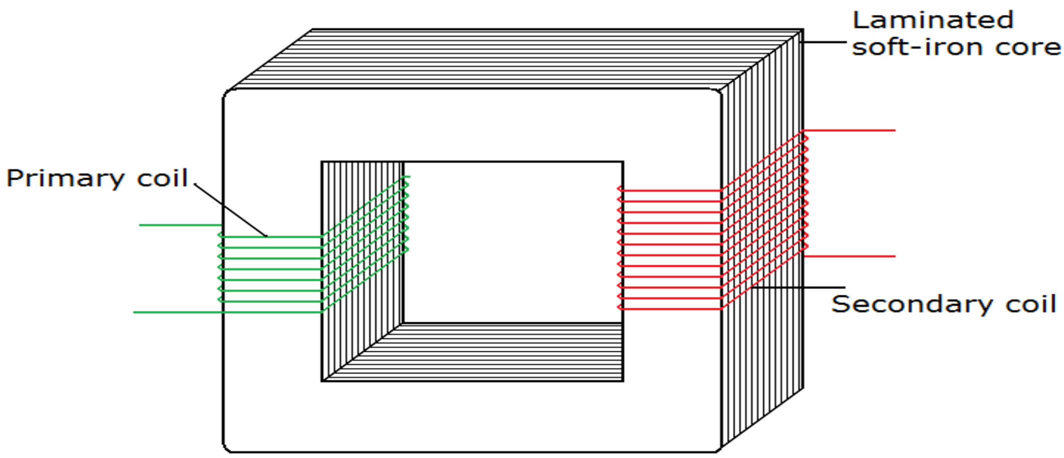


Figure 3.2 Laminated core transformer showing edge of laminations

Laminated steel cores

Transformer use at power or audio frequencies typically have cores made of high permeability Si steel. The steel has permeability many times that of free and the core thus serves to greatly reduce the magnetizing current and confine the flux to a path which closely couples the windings. Early transformer developers soon realized that cores constructed from solid iron resulted in prohibitive eddy-current losses, and their designs mitigated this effect with cores consisting of bundles of insulated iron wires. Later designs constructed the core by stacking layers of thin steel laminations, a principle that has remained in use. Each lamination is insulated from its neighbors by a thin non-conducting layer of insulation. The universal transformer equation indicates a minimum cross-sectional area for the core to avoid saturation.

The effect of laminations is to confine eddy currents to highly elliptical paths that enclose little flux, and so reduce their magnitude. Thinner laminations reduce losses, but are more laborious and expensive to construct. Thin laminations are generally used on high frequency transformers, with some types of very thin steel laminations able to operate up to 10 kHz.

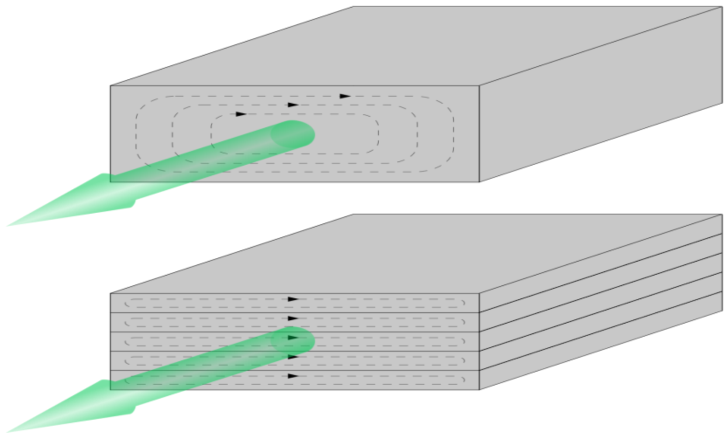


Figure 3.3 laminating the core greatly reduces eddy-current losses

One common design of laminated core is made from interleaved stacks of Eshaped steel sheets capped with shaped pieces, leading to its name of "E-I transformer”. Such a design tends to exhibit more losses, but is very economical to manufacture. The cut-core or C-core type is made by winding a steel strip around a rectangular form and then bonding the layers together. It is then cut in two, forming two C shapes, and the core assembled by binding the two C halves together with a steel strap.They have the advantage that the flux is always oriented parallel to the metal grains, reducing reluctance.

Solid cores

Powdered iron cores are used in circuits such as switch-mode power supplies that operate above mains frequencies and up to a few tens of kilohertz. These materials combine high magneticpermeancehigh bulk electrical resistivity. For frequencies extending beyond the VHF band, cores made from non-conductive magnetic ceramic materials called ferrites are common. Some radio-frequency transformers also have movable cores (sometimes called 'slugs') which allow adjustment of the coupling coefficient (and bandwidth) of tuned radio-frequency circuits.

Figure 3.4 Small toroidal core transformer

Toroidal transformers are built around a ring-shaped core, which, depending on operating frequency, is made from a long strip of silicon steel or perm alloy wound into a coil, powdered iron, or ferrite. A strip construction ensures that the grain boundaries are optimally aligned, improving the transformer's efficiency by reducing the core's reluctance. The closed ring shape eliminates air gaps inherent in the construction of an E-I core.[78] The cross-section of the ring is usually square or rectangular, but more expensive cores with circular cross-sections are also available. The primary and secondary coils are often wound concentrically to cover the entire surface of the core. This minimizes the length of wire needed, and also provides screening to minimize the core's magnetic field from generating electromagnetic.

Toroidal transformers are more efficient than the cheaper laminated E-I types for a similar power level. Other advantages compared to E-I types, include smaller size (about half), lower weight (about half), less mechanical hum (making them superior in audio amplifiers), lower exterior magnetic field (about one tenth), low off-load losses (making them more efficient in standby circuits), single-bolt mounting, and greater choice of shapes. The main disadvantages are higher cost and limited power capacity (see "Classification" above). Because of the lack of a residual gap in the magnetic path, toroidal transformers also tend to exhibit higher inrush current, compared to laminated E-I types.

Air cores

A physical core is not an absolute requisite and a functioning transformer can be produced simply by placing the windings near each other, an arrangement termed an "air-core" transformer. The air which comprises the magnetic circuit is essentially lossless, and so an air-core transformer eliminates loss due to hysteresis in the core material.[41] The leakage inductance is inevitably high, resulting in very poor regulation, and so such designs are unsuitable for use in power distribution. They have however very high bandwidth, and are frequently employed in radio-frequency applications, for which a satisfactory coupling coefficient is maintained by carefully overlapping the primary and secondary windings. They're also used for resonant transformers such as Tesla coils where they can achieve reasonably low loss in spite of the high leakage inductance.

Windings

The conducting material used for the windings depends upon the application, but in all cases the individual turns must be electrically insulated from each other to ensure that the current travels throughout every turn.For small power and signal transformers, in which currents are low and the potential difference between adjacent turns are there.

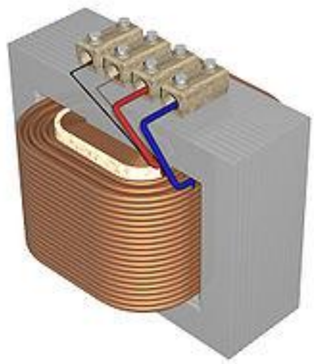


Figure 3.5 Windings are usually arranged concentrically

Different Types of Windings

After understanding the basic working principle of a transformer, it is clear that windings play a very crucial role in a transformer.

There are different transformer types available with Transformer Manufacturer Company in India that use different types of windings, such as core type transformer and shell type transformer.

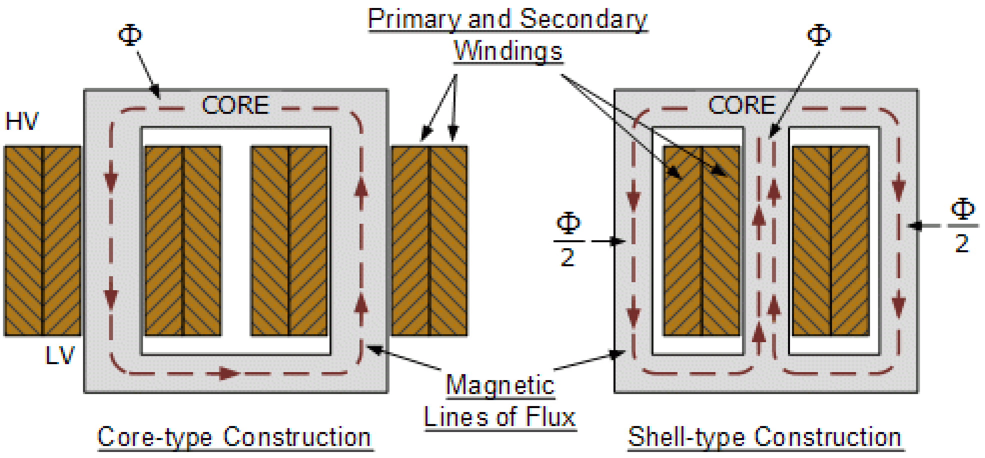


Figure 3.6 Core Type and Shell type Windings

The core type transformer is the one in which the wrapping of primary and secondary winding is done on the outside limbs. While the shell type transformer is the one in which the primary and secondary windings are placed on the inner limbs.
The core type transformer uses concentric type windings.

A low voltage winding is placed near the core, although to reduce the leakage reactance, the windings can be interlaced.

The windings used for core type transformers depends on many factors, such as current rating, limit of temperature rise, short circuit withstand capacity, transport facilities, surge voltage and many more.

Types of Windings Used in Core Type Transformers

The following mentioned windings are layered type and either rectangular or round conductor.

1. Cylindrical Windings:
   (a) Multi Layered Windings
2. Helical Windings:
   (a) Single Helical Windings
   (b) Double Helical Windings
   (c) Disc- Helical Windings
3. Multi- Layer Helical Windings
4. Cross- Over Windings
5. Disc and Continuous Disk Windings
6. Aluminum Windings

Cylindrical Windings

Cylindrical windings are windings with low voltage that use up to 6.6 kV for kVA up to 600-750 and have a current rating between 10 to 600A.

Multi Layered Cylindrical Windings

Cylindical windings are mostly used in its multi- layered form. It is used with rectangular conductors in the two- layered type as it becomes very easy to secure the lead- out ends.

The oil ducts separate the layers of the windings, this arrangement facilitated by the cooling process through oil circulation in the winding.

In multi layered cylindrical windings, circular conductors are used; they are wound on vertical strips to improve the cooling conditions. The arrangement creates oil ducts which facilitate good cooling.

These types of windings are used for high voltage ratings up to 33kV, 800 kVA and the current ratings up to 80 A.

The maximum diameter that is used in this type of winding for a bare conductor is 4mm.

Helical Windings

Helical windings are used for low voltage and high capacity transformers, where the current is higher and at the same time the winding turns are lesser.The output of transformer in this case varies from 160 to 1000 kVA from 0.23 to 15 kV.

For securing the adequate mechanical strength the cross- sectional area of the strip is made not less than 75 to 100mm square. The maximum number of strips that are used to make up the conductor in parallel is 16.

Types of helical windins:

Single Helical Windings

The winding in axial direction along a screw line with inclination is referred to as Single Helical Windings. These windings consist of only one layer of turns in each of the windings.

Double Helical Windings

The Double Helical Winding provides an advantage of reducing the eddy current loss in conductors. This is due to the reduced number of parallel conductors that are situated in a radial direction.

Disc- Helical Windings

The Disc- Helical Windings is designed in a way that the parallel connected strips are placed side to side in a radial direction so as to occupy the total radial depth of the winding.

Multi-layer Helical Windings

The Multi- Layer Helical Winding is used commonly for high voltage ratings such as 110 kV and above. These windings include several cylindrical layers concentrically that are wound and connected in series.

The outer layers of these windings are made shorter than the inner layers for distributing the capacitance uniformly. These windings basically improve the surge behavior of the transformers.

Crossover Windings

These windings are used for high voltage windings of the small transformers. The conductors of these windings are paper covered strips or round wires. The windings help reduce the

voltage between adjacent layers as they are divided into a number of coils. The coils are separated axially by a distance of 0.5-1mm. The voltages between adjacent coils must not be more than 800 to 1000V.
The inside end of the coil is connected with the output end of the adjacent one. The axial length of each coil in actuality is about 50 mm, while the spacing between the two coils is about 6 mm so that it can accommodate the blocks of insulating material. The coil width is 25 to 50 mm. Crossover winding has greater strength than cylindrical winding under normal conditions. Although, the crossover has lower impulse strength as compared to the cylindrical one. This type of winding also consumes a higher labor cost.

Disc and Continuous Disc Winding

The Disc and Continuous Disc Winding is basically used for high capacity transformers. These windings consist of numerous flat coils/ discs in a series or parallel formation. The coils of these windings are formed with the help of rectangular strips that are wound spirally from the centre outwards in a radial direction.
The conductors of these windings can be a single strip or multiple strips in a parallel formation that are wound on the flat side. This formation of the conductors makes the construction for this type of windings extremely strong. The discs are separated from each other with the help of press- board sectors that are attached to vertical strips. The vertical and the horizontal spacers for free circulation of oil provide radial and axial ducts that come in contact with each turn. The area of the conductor ranges from 4 to 50 mm square and limits for current are 12 to 600 A. The minimum oil duct width is 6 mm for 35 kV. The advantage of these windings is that they provide greater mechanical axial strength and cheapness.

Shell Type Transformer Windings

Sandwich Type Winding

The Sandwich Type Windings provide easy control over the reactance, as the nearer two coils are together on the same magnetic axis; the greater is the proportion of the mutual flux and the lesser is the leakage flux. The leakage flux can be reduced by sub- dividing the sections of the low and the high voltages. The end low voltages sections, in Sandwich Type Windings contain half the turns of the normal low voltage sections that are referred to as half coils.
For balancing the magneto-motive forces of the adjacent sections, each of the normal sections, either high or low voltage carries the same number of ampere turns. The higher the degree of subdivision of the voltages, the smaller will be the reactance.

Advantages of Shell Type Windings

The Shell Type Windings provides a lot of advantages, such as high capability of withstanding short- circuits, higher mechanical strength, higher dielectric strength, great leakage magnetic flux control, extremely efficient cooling capability, a flexible design with a compact size. All these advantages come with a highly reliable design.

Servo Star is a premium Transformer Manufacturer Company in India that provides quality transformers. Get the transformer best price for your industry, home and offices with different kinds of windings for different purposes.

Cooling

The conservator (reservoir) at top provides oil-to-atmosphere isolation. Tank walls' cooling fins provide required heat dissipation balance. Though it is not uncommon for oil-filled transformers to have today been in operation for over fifty years high temperature damages winding insulation, the accepted rule of thumb being that transformer life expectancy is halved for every 8 degree C increase in operating temperature. At the lower end of the power rating range, dry and liquid-immersed transformers are often self-cooled by natural convection and radiation heat dissipation. As power ratings increase, transformers are often cooled by such other means as forced-air cooling, force-oil cooling, watercooling, or a combinations of these.

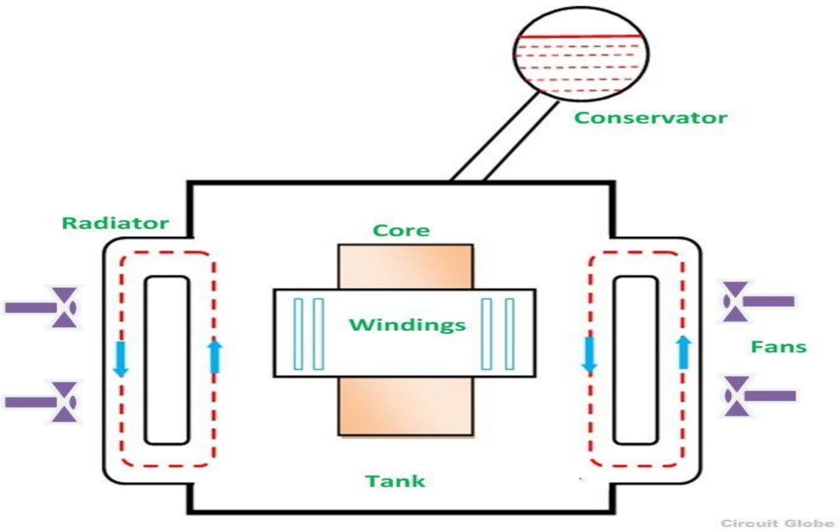


Figure 3.7 Cooling of Transformer

The dialectic coolant used in many outdoor utility and industrial service transformers is transformer oil that both cools and insulates the windings. Transformer oil is a highly refined mineral oil that inherently helps thermally stabilize winding conductor insulation, typically paper, within acceptable insulation temperature rating limitations. However, the heat removal problem is central to all electrical apparatus such that in the case of high value transformer assets, this often translates in a need to monitor, model, forecast and manage oil and winding conductor insulation temperature conditions under varying, possibly difficult, power loading conditions. Indoor liquid-filled transformers are required by building regulations in many jurisdictions to either use a non-flammable liquid or to be located in fire-resistant rooms.

3.1.2 An ideal Transformer

Ideal Transformer on Load. An ideal transformer is one which has no losses (no iron loss and no copper loss) and no leakage flux i.e. all the flux produced by the primary winding is linking with the secondary winding.

1. The resistance of their primary and secondary winding becomes zero.
2. The core of the ideal transformer has infinite permeability. The infinite permeable means less magnetizing current requires for magnetizing their core.
3. The leakage flux of the transformer becomes zero, i.e. the whole of the flux induces in the core of the transformer links with their primary and secondary winding.
4. The ideal transformer has 100 percent efficiency, i.e., the transformer is free from hysteresis and eddy current loss.

The above mention properties are not possible in the practical transformer. In an ideal transformer, there is no power loss. Therefore, the output power is equal to the input power.

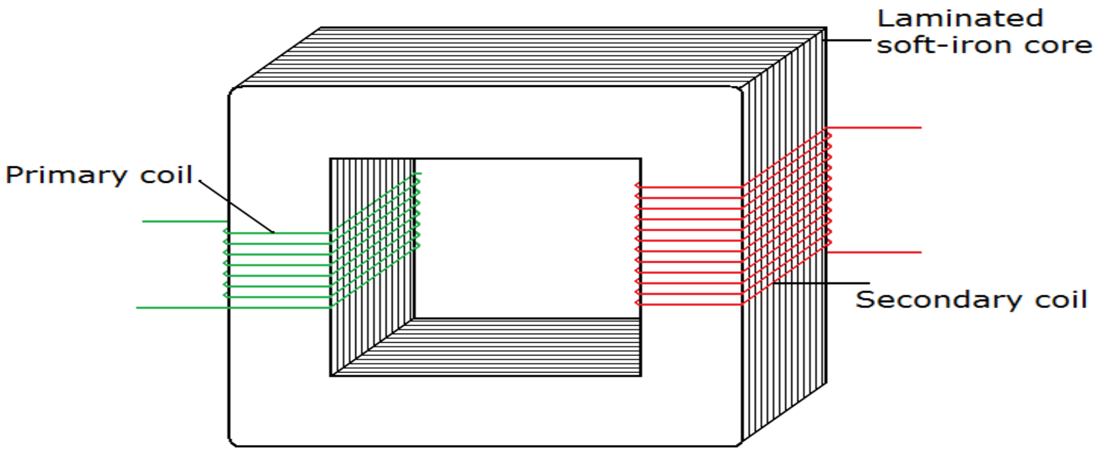


Figure 3.8 Ideal Transformer

3.1.3 Induction Law

The voltage induced across the secondary coil may be calculated from Faraday's law of induction, which states that where V_s is the instantaneous voltage, N_s is the number of turns in the secondary coil and Φ is the magnetic flux through one turn of the coil. If the turns of the coil are oriented perpendicularly to the magnetic field lines, the flux is the product of the magnetic flux density *B* and the area *A* through which it cuts. The area is constant,
being equal to the cross-sectional area of the transformer core, whereas the magnetic field varies with time according to the excitation of the primary. Since the same magnetic flux passes through both the primary and secondary coils in an ideal transformer, the instantaneous voltage across the primary winding equals

$$V_P = N_P \frac{d\Phi}{dt}.$$

Taking the ratio of the two equations for V_s and V_P gives the basic equation for stepping up or stepping down the voltage

$$\frac{V_s}{V_p} = \frac{N_s}{N_p}.$$

N_p/N_s is known as the *turns ratio*, and is the primary functional characteristic of any transformer. In the case of step-up transformers, this may sometimes be stated as the reciprocal, N_s/N_p. *Turns ratio* is commonly expressed as an irreducible fraction or ratio: for example, a transformer with primary and secondary windings of, respectively, 100 and 150 turns is said to have a turns ratio of 2:3 rather than 0.667 or 100:150. An elementary transformer consists of a soft iron or silicon steel core and two windings, placed on it. The windings are insulated from both the core and each other. The core is built up of thin soft iron or low reluctance to the magnetic flux. The winding connected to the magnetic flux. The winding connected to the supply main is called the primary and the winding connected to the load circuit is called the secondary.

Although in the actual construction the two windings are usually wound one over the other, for the sake of simplicity, the figures for analyzing transformer theory show the windings on opposite sides of the core, as shown below Simple Transformer When primary winding is connected to an ac supply mains, current flows through it. Since this winding links with an iron core, so current flowing through this winding produces an alternating flux in the core. Since this flux is alternating and links with the secondary winding also, so induces an emf in the secondary winding. The frequency of induced emf in secondary winding is the same as that of the flux or that of the s supply voltage. The induced emf in the secondary winding enables it to deliver current to an external load connected across it. Thus the energy is transformed from primary winding to the secondary winding by means of electromagnetic induction without anychange in frequency. The flux of the iron core links not only with the secondary winding but also with the primary winding, so produces self-induced emf in the primary winding: This induced in the primary winding opposes the applied voltage and therefore sometimes it is known as back emf of the primary. In fact the induced emf in the primary winding limits the primary current in much the same way that the back emf in a dc motor limits the armature current.

Transformation ratio.

The ratio of secondary voltage to primary voltage is known as the voltage transformation ratio and is designated by letter K. i.e. Voltage transformation ratio.

Current ratio.

The ratio of secondary current to primary current is known as current ratio and is reciprocal of voltage transformation ratio in an ideal transformer.

3.2 Equivalent Circuit

The electrical circuit for any electrical engineering device can be drawn if theequations describing its behavior are known. The equivalent circuit for electromagneticdevice is a combination of resistances, inductances, capacitances, voltages etc. In theequivalent circuit, (R1+jX1) and (R2+jX2) are the leakage impedances of the primary andsecondary windings respectively. The primary current I1 consists of two components.One component, I1´ is the load component and the second is no-load current Io which iscomposed of Ic and Im. The current Ic is in phase with E1 and the product of these twogives core loss. Ro represents the core loss and is called core-loss resistance. The currentIm is represented by a reactance Xo and is called magnetizing reactance. The transformermagnetization curve is assumed linear, since the effect of higher order harmonics can't berepresented in the equivalent circuit. In transformer analysis, it is usual to transfer thesecondary quantities to primary side or primary quantities to secondary side.

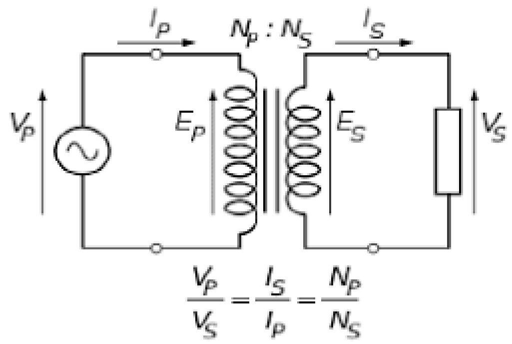


Figure 3.9 Exciting Current Neglected

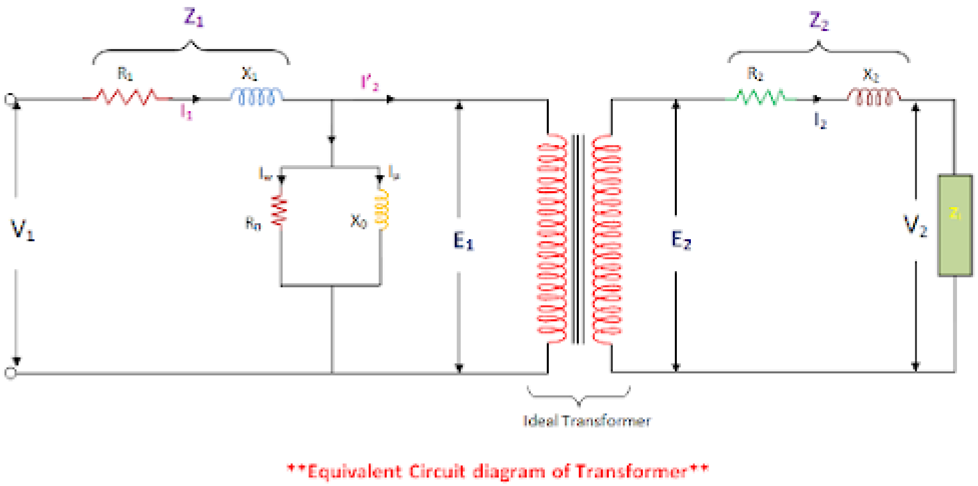


Figure 3.10 Exat Equivalent Circuit

3.3 Transformer Losses

1. Primary copper loss
2. Secondary copper loss
3. Iron loss
4. Dielectric loss
5. Stray load loss

These are explained in sequence below. Primary and secondary copper losses take place in the respective winding resistances due to the flow of the current in them. The primary and secondary resistances differ from their d.c. values due to skin effect and the temperature rise of the windings. While the average temperature rise can be approximately used, the skin effect is harder to get analytically. The short circuit test gives the value of Re taking into account the skin effect.

The iron losses contain two components - Hysteresis loss and Eddy current loss. The Hysteresis loss is a function of the material used for the core.Ph = KhB1.6f For constant voltage and constant frequency operation this can be taken to be constant. The eddy current loss in the core arises because of the induced emf in the steel lamination sheets and the eddies of current formed due to it. This again producesa power loss Pe in the lamination.wheret is the thickness of the steel lamination used. As the lamination thickness is much smaller than the depth of penetration of the field, the eddy current loss can be reduced by reducing the thickness of the lamination. Present day laminations are of 0.25 mm thickness and are capable of operation at 2 Tesla.

These reduce the eddy current losses in the core.This loss also remains constant due to constant voltage and frequency of operation. The sum of hysteresis and eddy current losses can be obtained by the open circuit test.The dielectric losses take place in the insulation of the transformer due to the large electric stress. In the case of low voltage transformers this can be neglected. For constant voltage operation this can be assumed to be a constant. The stray load losses arise out of the leakage fluxes of the transformer. These leakage fluxes link the metallic structural parts, tank etc. And produce eddy current losses in them. Thus they take place 'all round' the transformer instead of a definite place , hence the name 'stray'. Also the leakage flux is directly proportional to the load current unlike the mutual flux which is proportional to the applied voltage. Hence this loss is called 'stray load' loss.This can also be estimated experimentally.

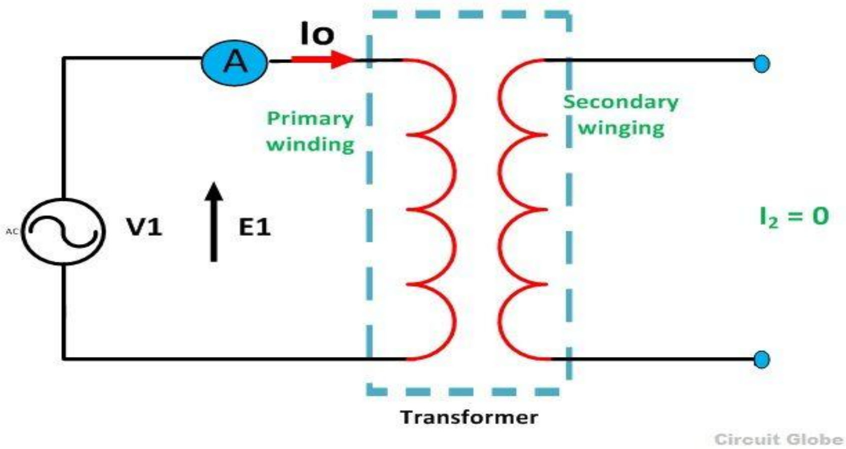


Figure 3.11 Transformer on No Load

When the primary of a transformer is connected to the source of an ac supply and the secondary is open circuited, the transformer is said to be on no load. Which will create alternating flux. No-load current, also known as excitation or exciting current has two components the magnetizing component Im and the energy component

Ie.

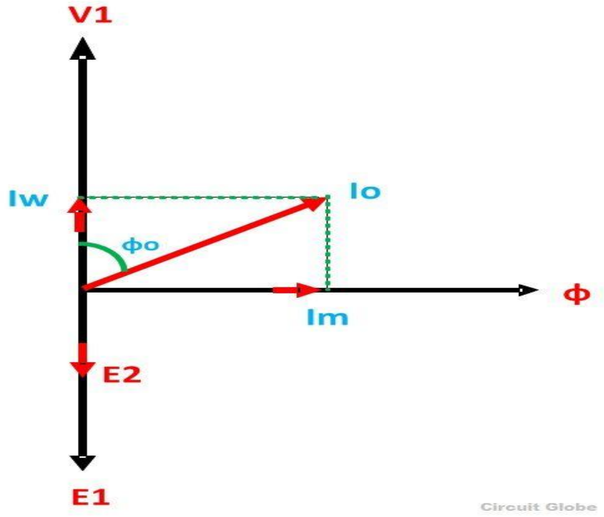


Figure 3.12 Phasor Diagram on No Load

Im is used to create the flux in the core and Ie is used to overcome the hysteresis and eddy current losses occurring in the core in addition to small amount of copper losses occurring in the primary only (no copper loss occurs in the secondary, because it carries no current, being open circuited.) From vector diagram shown in above it is obvious that

1. Induced emfs in primary and secondary windings, and lag the main flux by and are in phase with each other.
2. Applied voltage to primary and leads the main flux by and is in phase opposition to
3.Secondary voltage is in phase and equal to since there is no voltage drop in secondary side
4. is in phase with and so lags
5. is in phase with the applied voltage .
6. Input power on no load = cos where Transformer on Load

The transformer is said to be loaded, when its secondary circuit is completed through an impedance or load. The magnitude and phase of secondary current (i.e. current flowing through secondary) with respect to secondary terminals depends upon the characteristic of the load i.e. current will be in phase, lag behind and lead the terminal voltage respectively when the load is non-inductive, inductive and capacitive. The net flux passing through the core remains almost constant from noload to full load irrespective of load conditions and so core losses remain almost constant from no-load to full load .Secondary windings Resistance and Leakage Reactance In actual practice, both of the primary and have got some ohmic resistance causing voltage drops and copper losses in the windings. In actual practice, the total flux created does not link both of the primary and secondary windings but is divided into three components namely the main or mutual flux linking both of the primary and secondary windings, primary leakage flux linking with primary winding only and secondary leakage flux linking with secondary winding only.

The primary leakage flux is produced by primary ampere-turns and is proportional to primary current, number of primary turns being fixed. The primary leakage flux is in phase with and produces self inducedemf is in phase with and produces self inducedemf E given as 2f in the primary winding. The self inducedemf divided by the primary current gives the reactance of primary and is denoted by .

i.e. E = 2fπ

3.4 Transformer Tests

1 .Open-circuit or no-load test
2.Short circuit or impedance test

3.4.1 Open-circuit or No-load Test.
In this test secondary (usually high voltage) winding is left open, all metering instruments (ammeter, voltmeter and wattmeter) are connected on primary side and normal rated voltage is applied to the primary (low voltage) winding, as illustrated below

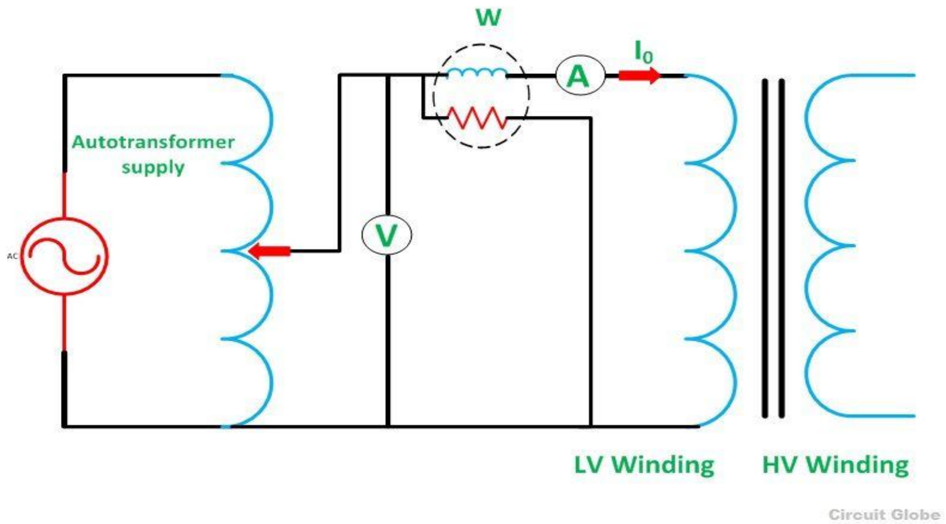


Figure 3.13 Open Circuit Test

Iron loss = Input power on no-load W0 watts (wattmeter reading) No-load current = 0 amperes (ammeter reading) Angle of lag, = /Io Ie = and Im = √o - Caution: Since no load current I0 is very small, therefore, pressure coils of watt meter and the volt meter should be connected such that the current taken by them should not flow through thecurrent taken by them should not flow through the current coil of the watt meter.

3.4.2 Short-circuit or Impedance Test.
This test is performed to determine the full-load copper loss and equivalent resistance and reactance referred to secondary side. In this test, the terminals of the secondary (usually the low voltage) winding are short circuited, all meters (ammeter, voltmeter and wattmeter) are connected on primary side and a low voltage, usually 5 to 10 % of normal rated primary voltage at normal frequency is applied to the primary, as shown in fig below.

The applied voltage to the primary, say Vs' is gradually increased till the ammeter A indicates the full load current of the side in which it is connected. The reading Ws of the wattmeter gives total copper loss (iron losses being negligible due to very low applied voltage resulting in very small flux linking with the core) at full load. Le the ammeter reading be Is.

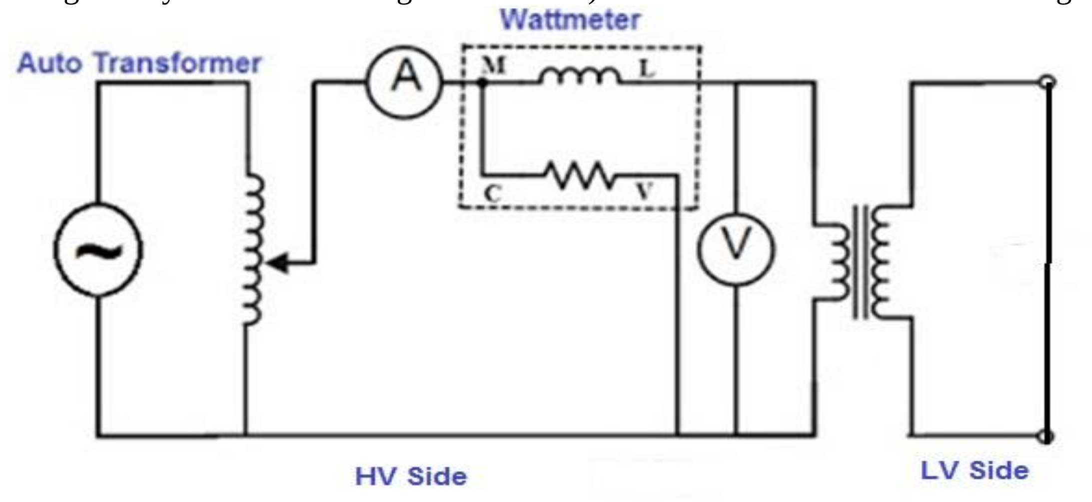


Figure 3.14 Short Circuit Test.

Equivalent impedence referred to primary= Commercial Efficiency and Allday Efficiency (a) Commercial Efficiency. Commercial efficiency is defined as the ratio of power output to power input in kilowatts.(b) All-day Efficiency**.** The all day efficiency is defined as the ratio of output in kwh to the input in kwh during the whole day. Transformers used for distribution are connected for the whole day to the line but loaded intermittently. Thus the core losses occur for the whole day but copper losses occur only when the transformer is delivering the load current. Hence if the transformer is not used to supply the load current for the whole day all day efficiency will be less than commercial efficiency. The efficiency (commercial efficiency) will be maximum when variable losses (copper losses) are equal to constant losses (iron or core losses).sign is for inductive load and sign is for capacitive load Transformer efficiency, Where x is the ratio of secondary current I2 and rated full load secondary current.

3.5 Efficiency

Transformers which are connected to the power supplies and loads and are in operation are required to handle load current and power as per the requirements of the load. An unloaded transformer draws only the magnetization current on the primary side, the secondary current being zero. As the load is increased the primary and secondary currents increase as per the load requirements. The volt amperes and wattage handled by the transformer also increases. Due to the presence of no load losses and I2R losses in the windings certain amount of electrical energy gets dissipated as heat inside the transformer.

This gives rise to the concept of efficiency. Efficiency of a power equipment is defined at any load as the ratio of the power output to the power input. Putting in the form of an expression, while the efficiency tells us the fraction of the input power delivered to the load, the deficiency focuses our attention on losses taking place inside transformer. As a matter of fact the losses heat up machine. The temperature rise decides the rating of the equipment. The temperature rise of the machine is a function of heat generated the structural configuration, method of cooling and type of loading (or duty cycle of load). The peak temperature attained directly affects the life of the insulations of the machine for any class of insulation.

The losses that take place inside the machine expressed as a fraction of the input is sometimes termed as deficiency. Except in the case of an ideal machine, a certain fraction of the input power gets lost inside the machine while handling the power. Thus the value for the efficiency is always less than one. In the case of a.c. machines the rating is expressed in terms of apparent power. It is nothing but the product of the applied voltage and the current drawn. The actual power delivered is a function of the power factor at which this current is drawn.

As the reactive power shuttles between the source and the load and has a zero average value over a cycle of the supply wave it does not have any direct effect on the efficiency. The reactive power however increases the current handled by the machine and the losses resulting from it. Therefore the losses that take place inside a transformer at any given load play a vital role in determining the efficiency. The losses taking place inside a transformer can be enumerated as below:

1. Primary copper loss
2. Secondary copper loss
3. Iron loss
4. Dielectric loss
5. Stray load loss

% Efficiency = output/ inpu×100

All day efficiency

Large capacity transformers used in power systems are classified broadly into Power transformers and Distribution transformers. The former variety is seen in generating stations and large substations. Distribution transformers are seen at the distribution substations. The basic difference between the two types arises from the fact that the power transformers are switched in or out of the circuit depending upon the load to be handled by them. Thus at 50% load on the station only 50% of the transformers need to be connected in the circuit. On the other hand a distribution transformer is never switched off. It has to remain in the circuit irrespective of the load connected. In such cases the constant loss of the transformer continues to be dissipated. Hence the concept of energy based efficiency is defined for such transformers. It is called ’all day’ efficiency. The all day efficiency is thus the ratio of the energy output of the transformer over a day to the corresponding energy input. One day is taken as duration of time over which the load pattern repeats itself. This assumption,however, is far from being true. The power output varies from zero to full load depending on the requirement of the user and the load losses vary as the square of the fractional loads. The no-load losses or constant losses occur throughout the 24 hours.

All Day Efficiency= out put power×24 ×100 /Input power×24

3.6 Voltage Regulation

With the increase in load on the transformer, there is a change in its terminal voltage. The voltage falls if the load power factor is lagging. It increases if power is leading. The change in secondary terminal voltage from full load to no load, expressed as a percentage of full load voltage is called the percentage voltage regulation of the transformer

% Regulation E- V/V x 100.

3.7 Auto Transformer

The primary and secondary windings of a two winding transformer have induced emf in them due to a common mutual flux and hence are in phase. The currents drawn by these two windings are out of phase by 180◦. This prompted the use of a part of the primary as secondary. This is equivalent to fusing the secondary turns into primary turns. The fused section need to have a cross sectional area of the conductor to carry (I2−I1) ampere! This ingenious thought led to the invention of an auto transformer. Fig. 12 shows the physical arrangement of an auto transformer. Total number of turns between A and C are T1. At point B a connection is taken. Section AB has T2 turns. As the volts per turn, which is proportional to the flux in the machine, is the same for the whole winding, V1 : V2 = T1 : T2 (76)

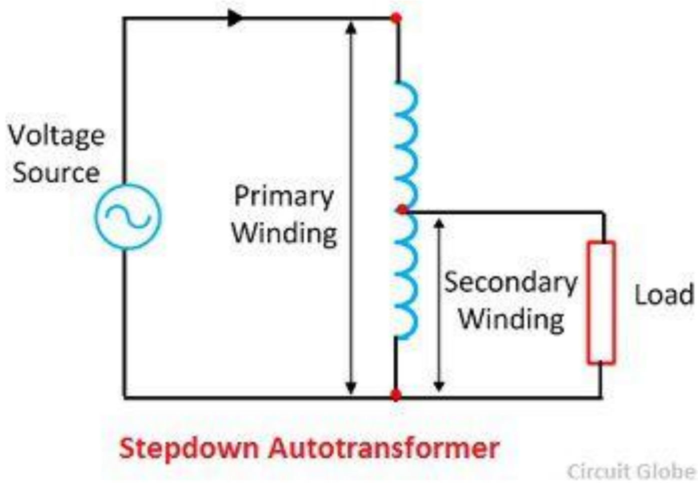


Figure 3.15 Step Down Autotransformer

For simplifying analysis, the magnetizing current of the transformer is neglected. When the secondary winding delivers a load current of I2 ampere the demagnetizing ampere turns is I2T2 . This will be countered by a current I1 flowing from the source through the T1 turns such that, I1T1 = I2T2

A current of I1 ampere flows through the winding between B and C . The current in the winding between A and B is (I2 − I1) ampere. The cross section of the wire to be selectedfor AB is proportional to this current assuming a constant current density for the whole winding. Thus some amount of material saving can be achieved compared to a two winding transformer. The magnetic circuit is assumed to be identical and hence there is no saving in the same. To quantify the saving the total quantity of copper used in an auto transformer is expressed as a fraction of that used in a two
winding transformer as,

$$\frac{copper\ in\ auto\ transformer}{copper\ in\ two\ winding\ transformer} = \frac{(T_1 - T_2)I_1 + T_2(I_2 - I_1)}{T_1I_1 + T_2I_2}$$

$$= 1 - \frac{2T_2I_1}{T_1I_1 + T_2I_2}$$

$$\text{But } T_1I_1 = T_2I_2$$

$$\therefore \text{The Ratio} = 1 - \frac{2T_2I_1}{2T_1I_1} = 1 - \frac{T_2}{T_1}$$

This means that an auto transformer requires the use of lesser quantity of copper given by the ratio of turns. This ratio therefore denotes the savings in copper. As the space for the second winding need not be there, the window space can be less for an auto transformer, giving some saving in the lamination weight also. The larger the ratio of the voltages, smaller is the savings. As T2 approaches T1 the savings become significant. Thus auto transformers become ideal choice for close ratio transformations. The savings in material is obtained, however, at a price. The electrical isolation between primary and secondary.

3.8 Rating and Specification of Transformer

Turns ratio determines output voltage relative to the input. There is often some latitude in the range, such as, say, 100–130V input and 200–260V output, that indicates indicates a forced 1:2 ratio; ex.: 123V input will produce 246V output with that particular transformer. The design/manufacturing methodology determines ratio and range of voltage latitude.

Power is about wire size and proportional heat that must be dissipated. For technical reasons this is specified in VA, or kVA, not Watts. Watts and VA are similar to speed and velocity, there is difference. Current capacity depends on the power and voltage ratings. Given power, voltage, current; you can specify any two, of the three, the third is dictated by the first two.

Specification of a transformer includes:-

- **kVA Rating** : Or you can say maximum power rating upto which the transformer can work at unity power factor.
- **Primary Voltage**: Rated Voltage on primary side.
- **Secondary Voltage**: Rated Voltage on secondary side.
- **Full load current**: Rated full load current on both HV/LV side.
- **Number of phase**: Denoted by φ. 3-φ/1-φ
- **Vector**: Special Transformers having Y-Δ/Δ-Y or Δ-Δ/Y-Y or zigzag connection are stated here. Something like "Dyn11" whuch means primary is Delta connected, secondary is Star connected with a neutral point "n" and 11 denotes phase shift i.e, secondary ...