Module 3: Electrical Machines (Transformer)

Magnetic materials

The materials which allow easy flow of magnetic flux through it are called as magnetic materials. Magnetic materials can be classified as:

Diamagnetic Materials

Diamagnetic materials repel any externally applied magnetic field. This occurs because their magnetic domains realign to oppose an externally applied magnetic field when influenced by a magnetic field. All materials show some diamagnetic properties, however, in most materials the effect is extremely weak and unnoticed. All the electrons within the atoms of diamagnetic materials are paired, therefore they do not generate their own net magnetic field.

E.g. Gold, silver, water, graphite etc.

Paramagnetic Materials

Paramagnetic materials have a small susceptibility to magnetic fields meaning that they are slightly attracted by a magnetic field. However, unlike ferromagnetic materials they do not maintain their magnetic properties once the external magnetic field is removed. Most elements are paramagnetic, however, because their attractive force is many thousands of times weaker than ferromagnetic material they are also generally considered as 'non-magnetic'.

E. g. Aluminum, Magnesium, Lithium etc.

Ferromagnetic materials

Ferromagnetic materials have some unpaired electrons in their atoms and therefore generate a net magnetic field, albeit a very weak one. This is because the individual atoms or groups of atoms, known as magnetic domains, are randomly aligned cancelling each other out. When an external magnetic field is applied to the ferromagnetic material the individual domains are forced into alignment which they maintain once the external field is removed therefore maintaining their magnetism, known as remanence. Iron, nickel and cobalt are all ferromagnetic materials. E.g. Iron, Cobalt, Nickel etc.

Comparison between various magnetic materials:

TYPES OF MAGNETIC MATERIALS

All material can be classified in terms of their magnetic behavior.

DIAMAGNETIC	PARAMAGNETIC	FERROMAGNETIC
→ The material which have a weak, negative susceptibility to magnetic fields	→ The material which have small, positive susceptibility to magnetic fields	→ The material which have a large, positive susceptibility to an external magnetic field.
→ These materials are slightly repelled by a magnetic field and they do not retain the magnetic properties when the external field is removed.	→ These materials are slightly attracted by a magnetic field and they do not retain the magnetic properties while the external field is removed.	→ These materials exhibit a strong attraction of magnetic fields and are able to retain their magnetic properties after the external field has been removed.
→ In diamagnetic materials all the electrons are paired so there is no permanent net magnetic moment per atom.	→ Paramagnetic properties are due to the presence of some unpaired electron, and from the realignment of the electron paths caused by the external magnetic field.	→ Ferromagnetic materials have some unpaired electrons so their atoms have a net magnetic moment.
→ Diamagnetic elements are: Copper, Silver and Gold. Also water, graphite, bismith.	→ Example: Aluminium, magnesium, lithium.	→ Example: Iron, Nickel, Cobalt.

Properties	Diamagnetic	Paramagnetic	
State	They can be solid, liquid or gas.	They can be solid, liquid or gas.	They are solid.
Effect of magnet.	weakly repelled by a magnet.	weakly attracted by a magnet.	Strongly attracted by a magnet.
Behaviour under non-uniform field	Tend to move from high to low region.	Tend to move from low to high field region.	Tend to move from low to high field region.
Behaviour under external field	They do not preserve the magnetic properties once the external field is removed.	They do not preserve the magnetic properties once the external field is removed.	They preserve the magnetic properties after the external field is removed.
Effect of temperature	No effect.	With the rise of temperature, it becomes a diamagnetic.	Above curie point, it become a paramagnetic
Permeability	Little less than unity.	Little greater than unity.	Very high.
Susceptibility	Little less than unity and negative.	Little greater than unity and positive	Very high and positive.

Note : Curie Temperature/Point (T_c) : It is the temperature above which certain material lose their permanent magnetic properties, to be replaced by induced magnetism.

e.g. Iron $T_c = 1043$ K

(continued)

B-H curve

Magnetic flux generated by an electromagnetic coil is the amount of magnetic field or lines of force produced within a given area and that it is called Magnetic flux density, B and the unit of flux density is Tesla, T.

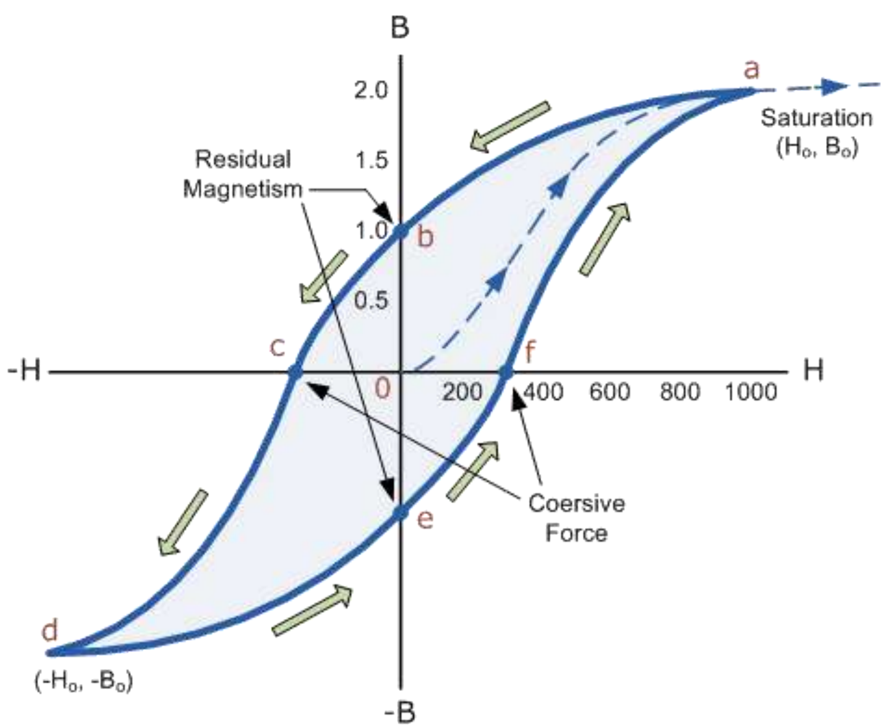
$$B = \Phi / A$$

The magnetic strength of an electromagnet depends upon the number of turns of the coil, the current flowing through the coil or the type of core material being used, and if we increase either the current or the number of turns, we can increase the magnetic field strength, symbol H.

$$H = NI / l$$

Also, we know that, B = μ H

By plotting values of flux density, (B) against the field strength, (H) we can produce a set of curvescalled MagnetizationCurves, MagneticHysteresis Curves or more commonly B-H Curves for each type of core material used.



The Magnetic Hysteresis loop above, shows the behaviour of a ferromagnetic core graphically as the relationship between B and H is non-linear. Starting with an unmagnetised core both B and H will be at zero, point 0 on the magnetisation curve.

If the magnetisation current, i is increased in a positive direction to some value the magnetic field strength H increases linearly with i and the flux density B will also increase as shown by the curve from point 0 to point a as it heads towards saturation.

Now if the magnetising current in the coil is reduced to zero, the magnetic field circulating around the core also reduces to zero. However, the coils magnetic flux will not reach zero due to the residual magnetism present within the core and this is shown on the curve from point a to point b.

To reduce the flux density at point b to zero we need to reverse the current flowing through the coil. The magnetising force which must be applied to null the residual flux density is called a "Coercive Force". This coercive force reverses the magnetic field re-arranging the molecular magnets until the core becomes unmagnetised at point c.

An increase in this reverse current causes the core to be magnetised in the opposite direction and increasing this magnetisation current further will cause the core to reach its saturation point but in the opposite direction, point d on the curve.

This point is symmetrical to point b. If the magnetising current is reduced again to zero the residual magnetism present in the core will be equal to the previous value but in reverse at point e.

Again reversing the magnetising current flowing through the coil this time into a positive direction will cause the magnetic flux to reach zero, point f on the curve and as before increasing the magnetisation current further in a positive direction will cause the core to reach saturation at point a.

Then the B-H curve follows the path of a-b-c-d-e-f-a as the magnetising current flowing through the coil alternates between a positive and negative value such as the cycle of an AC voltage. This path is called a Magnetic Hysteresis Loop.

Retentivity: The ability for a coil to retain some of its magnetism within the core after the magnetization process has stopped is called retentivity, while the amount of flux density still remaining in the core is called Residual Magnetism.

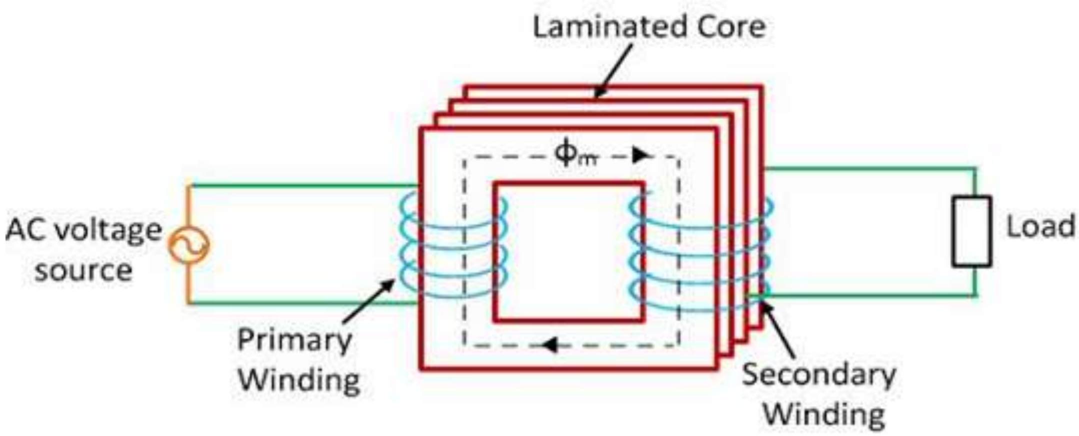
Coercive Force: The opposing magnetic intensity that must be applied to a magnetized material to remove the residual magnetism is called coercive Force

Transformer

The transformer is the static device which works on the principle of electromagnetic induction. It is used for transferring the electrical power from one circuit to another without any variation in their frequency. In electromagnetic induction, the transfer of energy from one circuit to another takes places by the help of the mutual induction.i.e. the flux induced in the primary winding is linked with the secondary winding.

Construction of an Electrical Transformer

The primary winding, secondary winding and the magnetic core are the three important of the transformer. These coils are insulated from each other. The main flux is induced in the primary winding of the transformer. This flux passes through the low reluctance path of the magnetic core and linked with the secondary winding of the transformer.



Transformer Working

The main principle of operation of a transformer is electromagnetic induction.

Consider the N1 and N2 are the numbers of the turn on the primary and the secondary winding of the transformer shown in the figure above. The voltage is applied to the primary winding of the transformer because of which the current is induced in it. The current causes the magnetic flux which is represented by the dotted line in the above figure.

The flux induces in the primary winding because of self-induction. This flux is linked with the secondary winding because of mutual induction. Thus, the emf is induced in the secondary winding of the transformer. The power is transferred from the primary winding to the secondary winding. The frequency of the transferred energy also remains same.

The produced electro-motive force can be explained with the help of Faraday's laws of Electromagnetic Induction as

$$e=N*d\Phi/dt$$

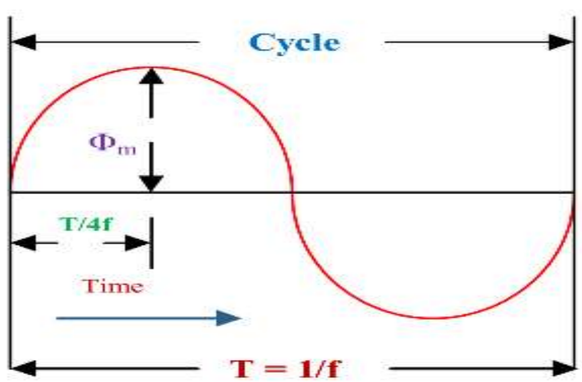
The induced emf in primary and secondary windings depends upon rate of change of flux linkages. The rate of change of flux is same for both primary and secondary; therefore induced emf in primary is proportional to number of turns of primary windings and in secondary is proportional to number of turns of secondary winding.

E.M.F. Equation of transformer

Suppose N_1 = No. of turns of primary coil & N_2 = No. of turns of secondary coil of a transformer.

Φ_m = Maximum flux in core (Webers)

= B_mx A



f= frequency of alternating current in Hz

From the figure, it has been seen that the flux Φ increases from its zero value to maximum value Φm in one quarter of the cycle i.e in 1/4 f second

$$\therefore average\ rate\ of\ change\ of\ flux = \frac{\Phi m}{1/4f}$$

$$=4\ f\ \Phi_m Wb/s\ \text{or volt}$$

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

∴ average e.m.f/ turn = 4 f Φ_m volt

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

$$\therefore \text{ From factor } = \frac{r.m.s\ value}{average\ value} = 1.11$$

∴r.m.s value of e.m.f./turn = 1.11 x 4fΦ_m = 4.44 fΦ_m volt

Now, r.m.s value of the induced e.m.f in the primary winding

∴ E_1 = (induced e.m.f/turn) x No. of primary turns

∴ E_1 = 4.44 f Φ_m N_1 (As $\Phi_m = B_m$ x A)

∴ E_1 = 4.44 f $N_1 B_m$A..................... (i)

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

∴ E_2 = (induced e.m.f/turn) x No. of Secondary turns

= 4.44 f Φ_m N_2 (As $\Phi_m = B_m$ x A)

⇒ E_2 = 4.44 f $N_2 B_m$ A.................... (ii)

It is seen from equation (i) and (ii) that $E_1 / N_1 = E_2 / N_2 = 4.44 f \Phi_m$.

From the above equation it is seen that the e.m.f/ turn is the same in both primary and secondary windings.

Voltage Transformation Ratio
.From equation (i) and (ii),we get

$\therefore E_1 / N_1 = E_2 / N_2 = 4.44 f \Phi_m = K$

Constant K is known as voltage transformation ratio.

i) If $N_2 > N_1$ i.e $K > 1$,then transformer is called step-up transformer.

ii) If $N_2 < N_1$ i.e $K < 1$,then transformer is

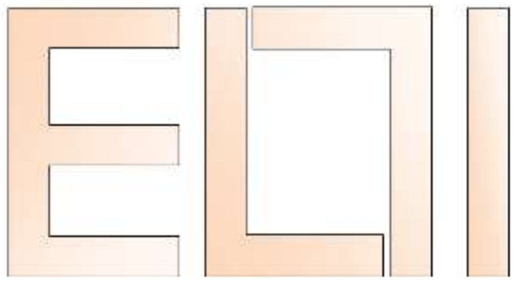
called step-down transformer.

Transformer types on basis of construction

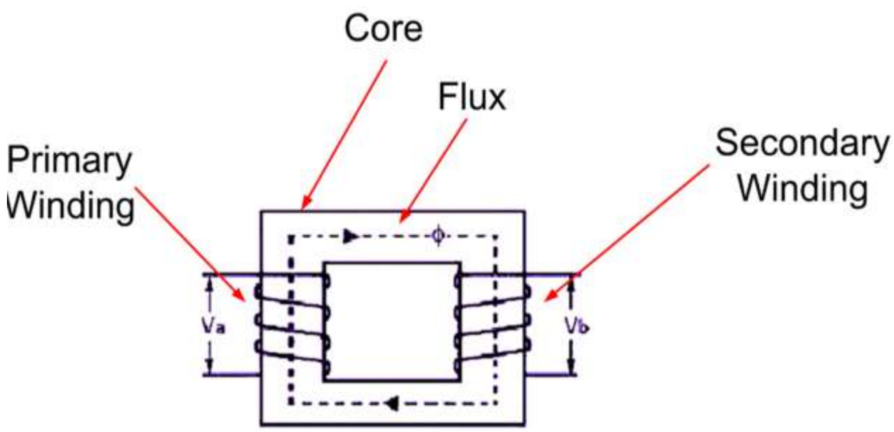
According to core construction and manner in which primary and secondary windings are placed around it, transformer can be categorized in two types:

a) Core type
b) Shell type

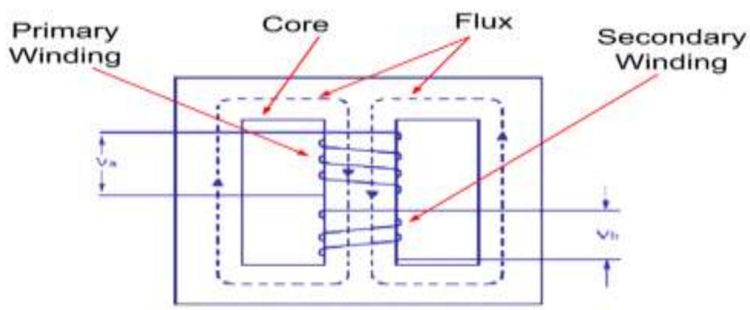
In core and shell-type transformer, the laminations are in the following types i.e. L, E, &I types respectively, which are shown in fig. To avoid high reluctance at joints, the laminations are butted each other which is shown in fig.



Core Type transformer: In **core** type transformers, winding is positioned on two limbs of the core and there is only one flux path and windings are circumventing the core.



Shell Type transformer: In shell type transformers, winding is positioned on the middle limb of the core while other limbs are utilized as the mechanical support.



Ideal transformer

An ideal transformer is an imaginary transformer which has. - no copper losses (no winding resistance) - no iron loss in core. - no leakage flux. In other words, an ideal transformer gives output power exactly equal to the input power.

In an ideal transformer, there is no power loss. Therefore, the output power is equal to the input power.

$$E_2 I_2 \cos\varphi = E_1 I_1 \cos\varphi \quad \text{or} \quad E_2 I_2 = E_1 I_1$$

OR

$$\frac{E_2}{E_1} = \frac{I_1}{I_2}$$

Since $E_l \propto N_2$ and $E_1 \propto N_1$, also E_1 is similar to V_1 and E_2 is similar to V_2

Therefore, the transformation ratio will be given by the equation shown below

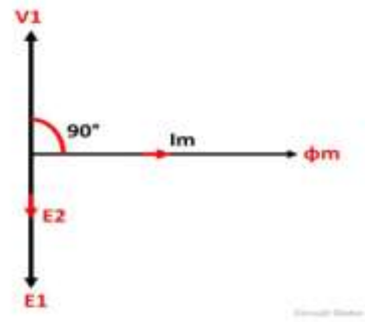
$$\frac{V_2}{V_1} = \frac{E_2}{E_1} = \frac{N_2}{N_1} = \frac{I_1}{I_2} = K$$

The primary and the secondary currents are inversely proportional to their respective turns.

Phasor diagram:

The phasor diagram of the ideal transformer is shown in the figure below. As the coil of the primary transformer is purely inductive the magnetizing current induces in the transformer lag 90º by the input voltage V_1.

The E_1 and E_2 are the emfinduced in the primary and secondary winding of the transformer. The direction of the induced emf is inversely proportional to the applied voltage.



Losses in Transformer

There are various types of losses in the transformer such as iron losses, copper losses, hysteresis losses, eddy current losses, stray loss, and dielectric losses. The hysteresis losses occur because of the variation of the magnetization in the core of the transformer and the copper loss occur because of the transformer winding resistance.

1. Iron losses: Iron losses are caused by the alternating flux in the core of the transformer as this loss occurs in the core it is also known as Core loss. Iron loss is further divided into hysteresis and eddy current loss.
   (a) Hysteresis Loss: The core of the transformer is subjected to an alternating magnetizing force, and for each cycle of emf, a hysteresis loop is traced out. Power is dissipated in the form of heat known as hysteresis loss and given by the equation shown below

$$P_h = K\eta B_{max}^{1.6} f V \quad \text{watts}$$

Where

- $K\eta$ is a proportionality constant which depends upon the volume and quality of the material of the core used in the transformer.
- f is the supply frequency
- B_{max} is the maximum or peak value of the flux density

The iron or core losses can be minimized by using silicon steel material for the construction of the core of the transformer.

(b) Eddy Current Loss: When the flux links with a closed circuit, an emf is induced in the circuit and the current flows, the value of the current depends upon the amount of emf around the circuit and the resistance of the circuit. Since the core is made of conducting material, these EMFs circulate currents within the body of the material. These circulating currents are called Eddy Currents. They will occur when the conductor experiences a changing magnetic field. As these currents are not responsible for doing any useful work, and it produces a loss (I^2R loss) in the magnetic material known as an When the flux links with a closed circuit, an emf is induced in the circuit and the current flows, the value of the current depends upon the amount of emf around the circuit and the resistance of the circuit. Since the core is made of conducting material, these EMFs circulate currents within the body of the material. These circulating currents are called Eddy Currents. They will occur when the conductor experiences a changing magnetic field. As these currents are not responsible for doing any useful work, and it produces a loss (I^2R loss) in the magnetic material known as an Eddy Current Loss. The eddy current loss is minimized by making the core with thin laminations. The eddy current loss is minimized by making the core with thin laminations.

The equation of the eddy current loss is given as

$$P_e = K_e B_m^2 t^2 f^2 V \qquad \text{watts}$$

K_e – co-efficient of eddy current. Its value depends upon the nature of magnetic material like volume and resistivity of core material, thickness of laminations, where

- B_m – maximum value of flux density in wb/m^2
- T – thickness of lamination in meters
- F – frequency of reversal of magnetic field in Hz
- V – volume of magnetic material in m^3

(a) Copper Loss or Ohmic Loss: These losses occur due to ohmic resistance of the transformer windings. If $I_1$and I_2 are the primary and the secondary current. R_1 and R_2 are the resistance of primary and secondary winding then the copper losses occurring in the primary and secondary winding will be $I_1^2R_1$ and $I_2^2R_2$ respectively.

Therefore, the total copper losses will be

$$P_c = I_1^2R_1 + I_2^2R_2$$

These losses varied according to the load and known hence it is also known as variable losses. Copper losses vary as the square of the load current.

Efficiency of transformer

The Efficiency of the transformer is defined as the ratio of useful output power to the input power. The input and output power are measured in the same unit. Its unit is either in Watts (W) or KW. Transformer efficiency is denoted by Ƞ.

$$\eta = \frac{\text{output power}}{\text{input power}} = \frac{\text{output power}}{\text{output power + losses}}$$

$$\eta = \frac{\text{output power}}{\text{output power + iron losses + copper losses}}$$

$$\eta = \frac{V_2 I_2 \mathrm{Cos}\varphi_2}{V_2 I_2 \mathrm{Cos}\varphi_2 + P_i + P_c}$$

Where,

V_2 – Secondary terminal voltage

I_2 – Full load secondary current

Cosϕ_2 – power factor of the load

Pi – Iron losses = hysteresis losses + eddy current losses

Pc – Full load copper losses = I_2^2Res

Consider, the x is the fraction of the full load. The efficiency of the transformer regarding x is expressed as

$$\eta_x = \frac{x \text{ X output}}{x \text{ X output} + P_i + x^2 P_c} = \frac{x\, V_2 I_2 \mathrm{Cos}\varphi_2}{x\, V_2 I_2 \mathrm{Cos}\varphi_2 + P_i + x^2 I_2^2 R_{es}}$$

\

The value of the terminal voltage V2 is approximately constant. Thus, for a given power factor the Transformer efficiency depends upon the load current I2. In equation (1), the numerator is constant and the transformer efficiency will be maximum if the denominator with respect to the variable I2 is equated to zero.

$$\frac{d}{dI_2} = \left(V_2\,Cos\varphi_2 + \frac{P_i}{I_2} + I_2R_{es} \right) = 0 \qquad \text{or} \qquad 0 - \frac{P_i}{I_2^2} + R_{es} = 0$$

Or

$$I_2^2R_{es} = P_i \;\ldots\ldots\ldots..(2)$$

i.e Copper losses = Iron losses

Thus, the transformer will give the maximum efficiency when their copper loss is equal to the iron loss.

From equation (2) the value of output current I2 at which the transformer efficiency will be maximum is given as

$$\eta_{max} = \frac{V_2I_2Cos\varphi_2}{V_2I_2Cos\varphi_2 + 2P_i} \qquad as\ (P_c = P_i)$$

Voltage Regulation:

At constant supply voltage, change in secondary terminal voltage from no load to full load with respect to no load voltage is called Voltage Regulation of the transformer .

$$\text{Voltage Regulation} = \frac{E_2 - V_2}{E_2}$$

Where

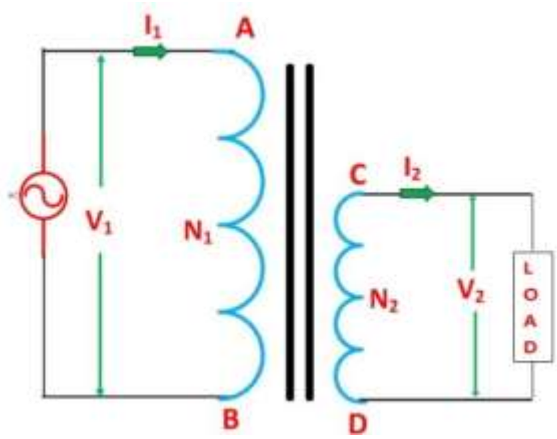
E_2 = Secondary terminal voltage at no load.

V_2 = Secondary terminal voltage at full load.

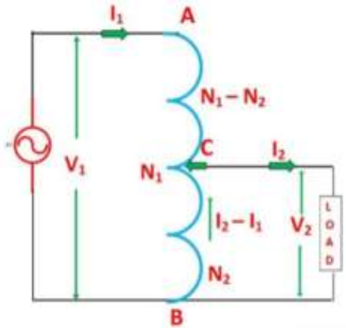
Auto-Transformer

An Auto Transformer is a transformer with only one winding wound on a laminated core. An auto transformer is similar to a two winding transformer but differ in the way the primary and secondary winding are interrelated. A part of the winding is common to both primary and secondary sides. On load condition, a part of the load current is obtained directly from the supply and the remaining part is obtained by transformer action. An Auto transformer works as a voltage regulator.

In an ordinary transformer, the primary and the secondary windings are electrically insulated from each other but connected magnetically as shown in the figure below and in auto transformer the primary and the secondary windings are connected magnetically as well as electrically. In fact, a part of the single continuous winding is common to both primary and secondary.



There are two types of auto transformer based on the construction. In one type of transformer, there is continuous winding with the taps brought out at convenient points determined by desired secondary voltage and in another type of auto transformer, there are two or more distinct coils which are electrically connected to form a continuous winding. The construction of Auto transformer is shown in the figure below.



The primary winding AB from which a tapping at C is taken, such that CB acts as a secondary winding. The supply voltage is applied across AB, and the load is connected across CB. The tapping may be fixed or variable. When an AC voltage V_1 is applied across AB, an alternating flux is set up in the core, as a result, an emf E_1 is induced in the winding AB. A part of this induced emf is taken in the secondary circuit.

Let,

- V_1 – primary applied voltage
- V_2 – secondary voltage across the load
- I_1 – primary current
- I_2 – load current
- N_1 – number of turns between A and B
- N_2 – number of turns between C and B

Neglecting no load current, leakage reactance and losses,

$V_1 = E_1$ and $V_2 = E_2$

Therefore the transformation ratio

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

As the secondary ampere-turns are opposite to primary ampere turns, so the current I_2 is in phase opposition to I_1. The secondary voltage is less than the primary. Therefore current I_2 is more than the current I_1. Therefore, the resulting current flowing through section BC is

$(I_2 – I_1)$

Now, ampere turns due to section BC = current* turns

$= (I_2 – I_1) N_2 = N_1 I_1 (1-K)$……….(i)

Ampere turns due to section AC = $I_1 (N_1 – N_2) = N_1 I_1 (1-K)$……………(ii)

Equations (i) and (ii) shows that the ampere turns due to section BC and AC balance each other which is the characteristic of transformer action.

Saving of Copper:

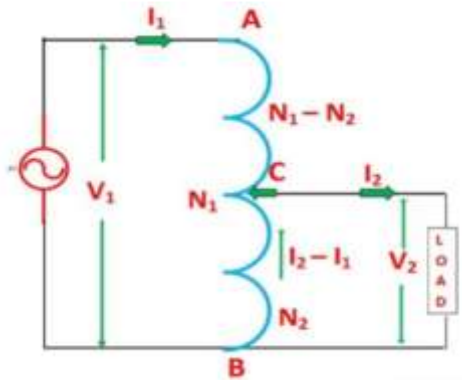
The weight of winding material (Copper) is proportional to the length and area of cross section of the conductors.

W_a = Volume of material

$W_a = (a \times L)$

- The cross section of the conductor depends on current (I) and length of conductors is proportional to the number of turns (N).
- Therefore the weight of copper is directly proportional to ampere - turns (NI).

Weight of the copper in the ordinary transformer (W_O) = $N_1I_1 + N_2I_2$



Weight of copper in the auto transformer (W_a) = Weight of copper in part AB+Weight of copper in part CB

Weight of copper in part AB= $I_1 (N_1 – N_2)$

Weight of copper in part CB = $(I_2 – I_1) N_2$

Total weight of copper in the auto transformer = $I_1 (N_1 – N_2) + (I_2 – I_1) N_2$

$= (I_1N_1 + I_2N_2 – 2N_2I_1)$

Weight of copper in auto transformer (W_a)/Weight of copper in ordinary transformer (W_O)

$= (I_1N_1 + I_2N_2 – 2N_2I_1) / (I_1N_1 + I_2N_2)$

$= (I_1N_1 + I_1N_1 – 2N_2I_1) / 2N_1I_1$ (As $N_1I_1 = N_2I_2$)

$= (2I_1N_1 / 2I_1N_1) – (2N_2I_1 / 2I_1N_1)$

$= (1) – (K)$ $\quad$ (As $K = N_2 / N_1 = I_1 / I_2$)

$= 1 – K$

Therefore $W_a = (1 – K) W_O$

Saving in Copper $= W_O – W_a$

$= W_O – (1 – K) W_O$

$= KW_O$

Therefore the saving in copper material depends on the value of K (Voltage transformation ratio). Higher value of K, more saving in copper material.

Advantages of Auto transformer:

Less costly

Better regulation

Low losses as compared to ordinary two winding transformer of the same rating.

Disadvantages of Auto transformer:

There are various advantages of the auto transformer, but then also one major disadvantage, why auto transformer is not widely used, is that

The secondary winding is not insulated from the primary winding.

If an auto transformer is used to supply low voltage from a high voltage and there is a break in the secondary winding, the full primary voltage comes across the secondary terminal which is dangerous to the operator and the equipment. So the auto transformer should not be used for interconnecting high voltage and low voltage systems.

Used only in the limited places where a slight variation of the output voltage from input voltage is required.

Applications of Auto transformer:

It is used as a starter to give up to 50 to 60% of full voltage to the stator of a squirrel cage induction motor during starting.

It is used to give a small boost to a distribution cable, to correct the voltage drop.

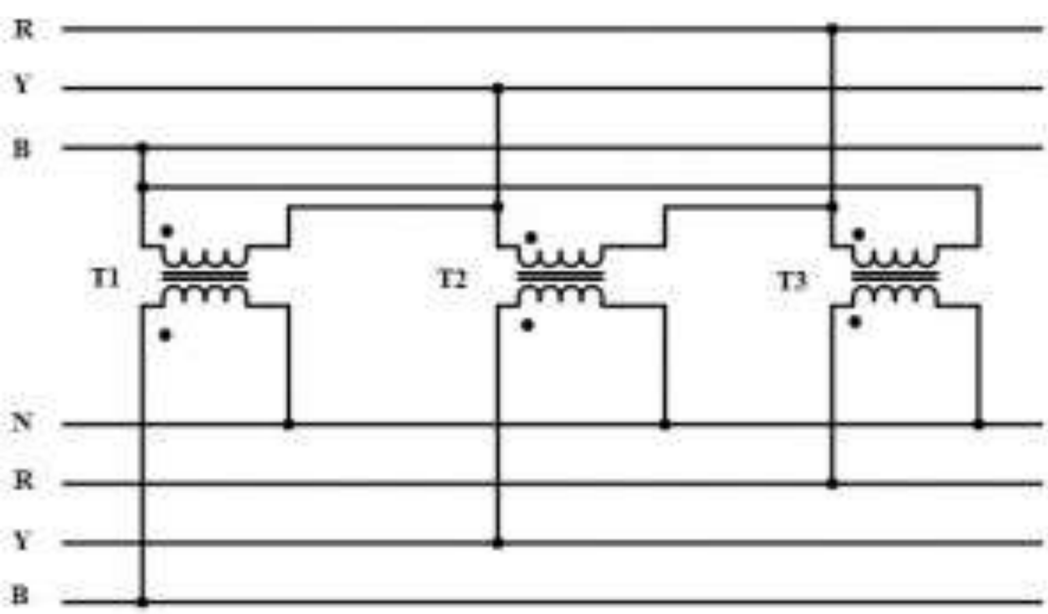
It is also used as a voltage regulator

Used in power transmission and distribution system and also in the audio system and railways.

Three Phase Transformer

Three phase transformers are used to step-up or step-down the high voltages in various stages of power transmission system. The power generated at various generating stations is in three phase nature and the voltages are in the range of 13.2KV or 22KV. In order to reduce the power loss to the distribution end, the power is transmitted at somewhat higher voltages like 132 or 400KV. Hence, for transmission of the power at higher voltages, three phase step-up transformer is used to increase the voltage. Also at the end of the transmission or distribution, these high voltages are step-down to levels of 6600, 400, 230 volts, etc. For this, a three phase step down transformer is used.

A three phase transformer can be built in two ways; a bank of three single phase transformers or single unit of three phase transformer. The former one is built by suitably connecting three single phase transformers having same ratings and operating characteristics. In this case if the fault occurs in any one of the transformers, the system still retained at reduced capacity by other two transformers with open delta connection. Hence, continuity of the supply is maintained by this type of connection. These are used in mines because easier to transport individual single phase transformers.



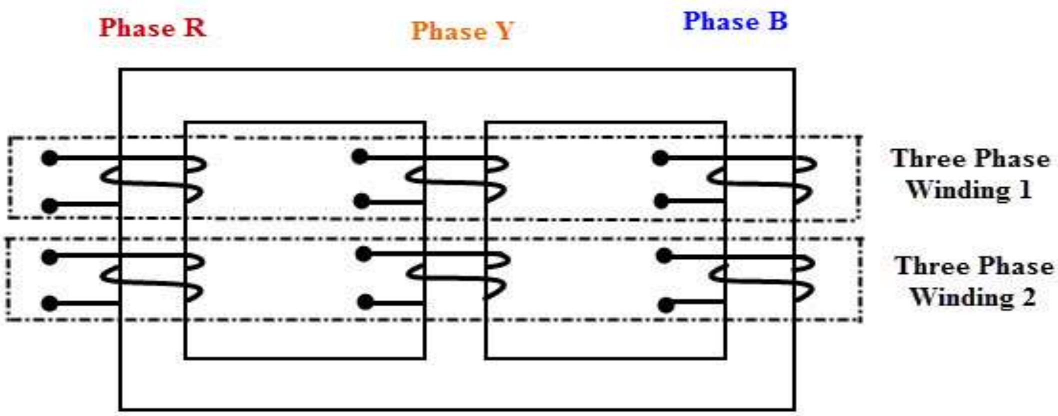
Instead of using three single phase transformers, a three phase bank can be constructed with a single three phase transformer consisting of six windings on a common multi-legged core. Due to this single unit, weight as well as the cost is reduced as compared to three units of the same rating and also windings, the amount of iron in the core and insulation materials are saved. Space required to install a single unit is less compared with three unit bank. But the only disadvantage with single unit three phase transformers is if the fault occurs in any one of the phase, then entire unit must be removed from the service.

Construction of Three Phase Transformers

A three phase transformer can be constructed by using common magnetic core for both primary and secondary windings. As we discussed in the case of single phase transformers, construction can be core type or shell type. So for a bank of three phase core type transformer, three core type single phase transformers are combined. Similarly, a bank of three phase shell type transformer is get by properly combining three shell type single phase transformers. In a shell type transformer, EI laminated core surrounds the coils whereas in core type coil surrounds the core.

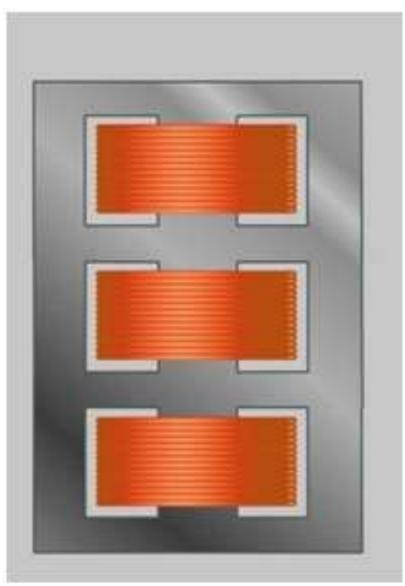
Core Type Construction

In core type three phase transformer, core is made up of three limbs or legs and two yokes. The magnetic path is formed between these yokes and limbs. On each limb both primary and secondary windings are wounded concentrically. Circular cylindrical coils are used as the windings for this type of transformer. The primary and secondary windings of one phase are wounded on one leg. Under balanced condition, the magnetic flux in each phase of the leg adds up to zero. Therefore, under normal conditions, no return leg is needed. But in case of unbalanced loads, high circulating current flows and hence it may be best to use three single phase transformers.



Shell Type Construction

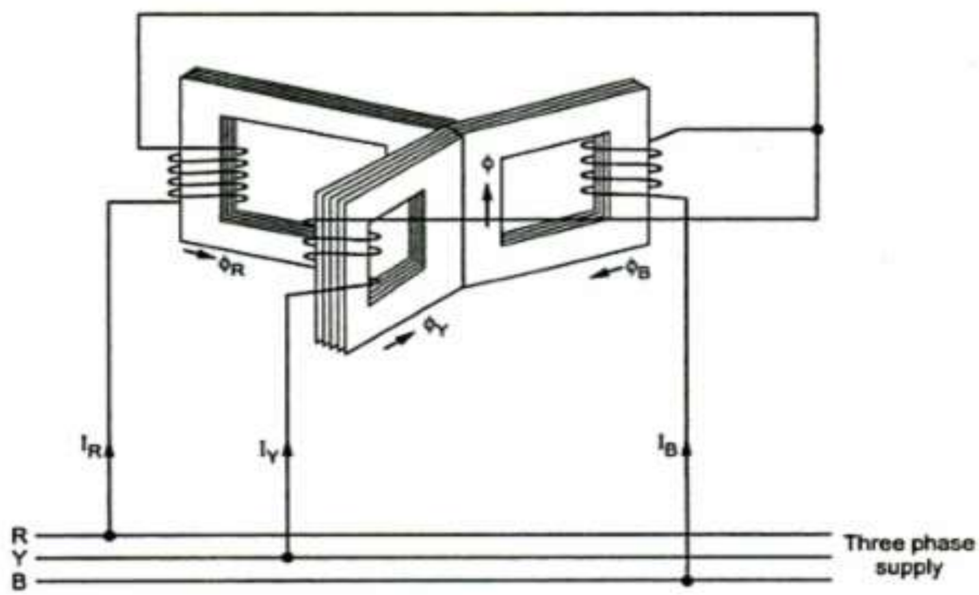
In shell type, three phases are more independent because each phase has independent magnetic circuit compared with core type transformer. The construction is similar to the single phase shell type transformer built on top of another. The magnetic circuits of this type of transformer are in parallel. Due to this, the saturation effects in common magnetic paths are neglected. However, shell type constructed transformers are rarely used in practice.



Shell Type

Working of Three Phase Transformers

Consider the below figure in which the primary of the transformer is connected in star fashion on the cores. For simplicity, only primary winding is shown in the figure which is connected across the three phase AC supply. The three cores are arranged at an angle of 120 degrees to each other. The empty leg of each core is combined in such that they form center leg as shown in figure.



Working of a transformer

When the primary is excited with the three phase supply source, the currents IR, IY and IB are starts flowing through individual phase windings. These currents produce the magnetic fluxes ΦR, ΦY and ΦB in the respective cores. Since the center leg is common for all the cores, the sum of all three fluxes are carried by it. In three phase system, at any instant the vector sum of all the currents is zero. In turn, at the instant the sum of all the fluxes is same. Hence, the center leg doesn’t carry any flux at any instant. So even if the center leg is removed it makes no difference in other conditions of the transformer.

Likewise, in three phase system where any two conductors acts as return for the current in third conductor, any two legs acts as a return path of the flux for the third leg if the center leg is removed in case of three phase transformer. Therefore, while designing the three phase transformer, this principle is used.

These fluxes induce the secondary EMFs in respective phase such that they maintain their phase angle between them. These EMFs drives the currents in the secondary and hence to the load. Depends on the type of connection used and number of turns on each phase, the voltage induced will be varied for obtaining step-up or step-down of voltages.

3-Phase Connection

Windings of a three phase transformer can be connected in various configurations as
(i) Star-Star, (ii) Delta-Delta, (iii) Star-Delta, (iv) Delta-Star.
These configurations are explained below.

Star-Star (Y-Y)

- Star-star connection is generally used for small, high-voltage transformers. Because of star connection, number of required turns/phase is reduced (as phase voltage in star connection is 1/√3 times of line voltage only). Thus, the amount of insulation required is also reduced.
- The ratio of line voltages on the primary side and the secondary side is equal to the transformation ratio of the transformers.
- Line voltages on both sides are in phase with each other.
- This connection can be used only if the connected load is balanced.

Delta-Delta (Δ-Δ)

- This connection is generally used for large, low-voltage transformers. Number of required phase/turns is relatively greater than that for star-star connection.
- The ratio of line voltages on the primary and the secondary side is equal to the transformation ratio of the transformers.
- This connection can be used even for unbalanced loading.

- Another advantage of this type of connection is that even if one transformer is disabled, system can continue to operate in open delta connection but with reduced available capacity.

Star-Delta OR wye-delta (Y-Δ)

- The primary winding is star star (Y) connected with grounded neutral and the secondary winding is delta connected.
- This connection is mainly used in step down transformer at the substation end of the transmission line.
- The ratio of secondary to primary line voltage is 1/√3 times the transformation ratio.
- There is 30° shift between the primary and secondary line voltages.

Delta-Star or delta-wye (Δ-Y)

- The primary winding is connected in delta and the secondary winding is connected in star with neutral grounded. Thus it can be used to provide 3-phase 4-wire service.
- This type of connection is mainly used in step-up transformer at the beginning of transmission line.
- The ratio of secondary to primary line voltage is √3 times the transformation ratio.
- There is 30° shift between the primary and secondary line voltages.