MODULE 5(a)

TRANSFORMERS

Unit 5 (a): Single Phase Transformers:-

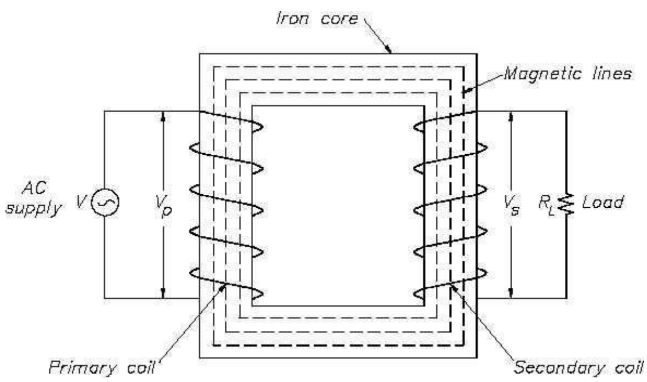
- Transformer is a static device which transfers electric energy from one electric circuit to another with the desired change in voltage and current levels without any change in power and frequency

CONSTRUCTION:

There are two basic parts of a transformer:

1) Magnetic core 2) winding

- The core of the transformer is either rectangular or square in size.
- The core is divided into i) Yoke ii)Limb
- Core is made up of silicon steel which has high permeability and low hysteresis co-efficient.
- The vertical portion on which the winding is wound is called Limb.
- The top and bottom horizontal portion is called Yoke.
- The core forms the magnetic circuit
- There are 2 windings i) Primary winding ii) Secondary winding which forms the Electric circuit. made up of conducting material like copper.
- The winding which is connected to the supply is called primary winding and having 'N_1' number of turns.
- The winding which is connected to a load is secondary winding and having 'N_2' number of turns.



TYPES OF TRANSFORMER:

Based on Construction the transformer are divided into:

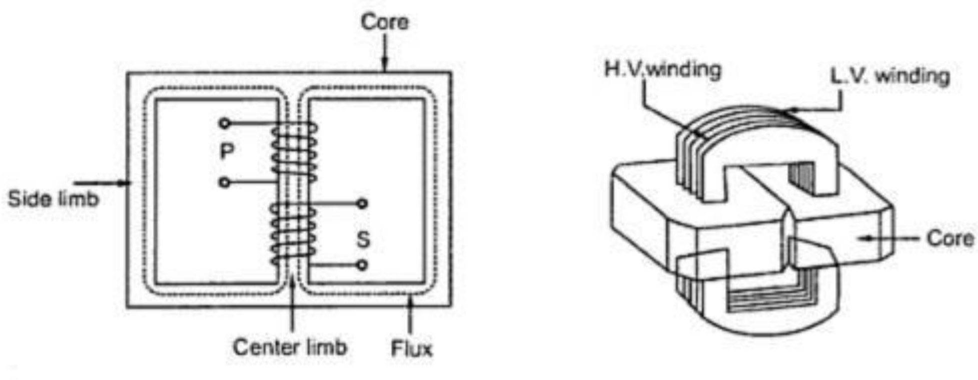
a) CORE TYPE b) SHELL TYPE.

Core type transformer:

- the **fig.1** shows the core type of transformer.
- This type of transformer has a single magnetic circuit.
- The core has 2 limbs and windings encircled the core
- The primary and secondary windings are wound on two limbs of the core .
- The core is made of very thin laminations of high grade silicon steel material to reduce the eddy current loss and Hysteresis losses in the core.

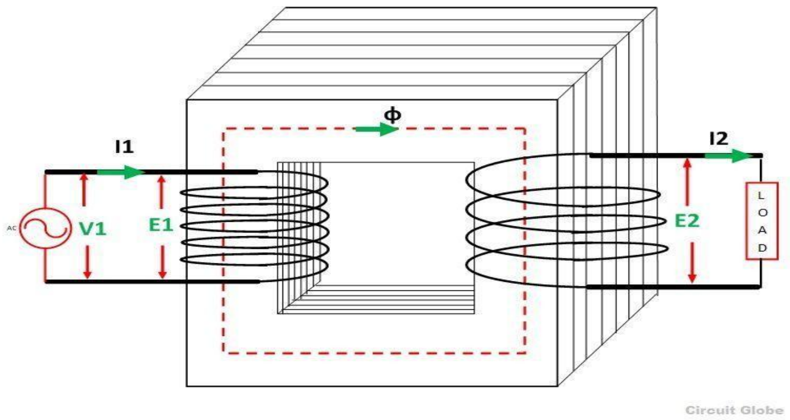
Shell type transformer:

- The fig.2 shows the shell type of transformer.
- This type of transformer has a two magnetic circuit.
- The core has 3 limbs .
- The core surrounds the windings.
- The primary and secondary windings are wound on the central limb.
- The core is made of very thin laminations of high grade silicon steel material to reduce the eddy current loss and Hysteresis losses in the core.



(a) Representation (b) Construction

WORKING PRINCIPLE: - A transformer works on the principle of mutual induction between two magnetically coupled coils



- The fig shows the general arrangement of a transformer.
- An alternating voltage applied to Primary winding it circulates an alternating current.This current produces an alternating flux in the iron core which completes its path through common magnetic core as shown in dotted line in the above fig .
- This flux induces an Emf 'E1' in primary winding.
- The flux also links secondary winding and thereby induces an emf 'E2' in Secondary.
- Thus though there is no electrical contact between the two windings, an electrical energy gets transferred from primary to secondary.

EMF EQUATION:

Principle:- Whenever a coil is subjected to alternating flux, there will be an induced emf in it and is called the statically induced emf $e = \frac{Nd\phi}{dt}$

Let N_1, N_2 be the no. of turns of the primary and secondary windings, E_1, E_2 the induced emf in the primary and secondary coils. ϕ be the flux which is sinusoidal f be the frequency in Hz

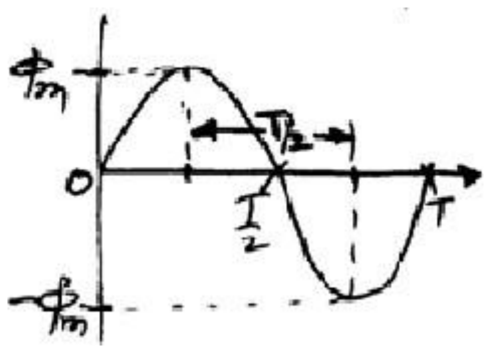


Figure showing the sinusoidal varying flux of peak value $\mathbf{\Phi_m}$.

Whenever a coil of N no- of tunes are linked by a time varying flux ϕ , the average emf induced in this coil is

$$e = \frac{Nd\phi}{dt}$$

As the flux is sinusoidal the change in flux from $+\phi_m$ **to** $-\phi_m$ is $d\phi = 2\phi_m$, and this change takes place in a duration dt = T/2 seconds.

The average induced emf in these N numbers of turns is

$\mathbf{E_{avg} = N.d\phi /dt = N.2\phi_m / (T/2) = 4\phi_m N/T = 4f\phi_m N}$ **volts (as f =1/T)**

We know that the Form factor of a pure sine wave **F.F.** $\mathbf{= E_{rms}/E_{avg} = 1.11}$

Therefore, $\mathbf{E_{rms} = 1.11\ E_{avg}}$.

$\mathbf{= (1.11)(4f\phi_m N) = 4.44\ f\phi_m N}$ **volts.**

In the primary coil, $\mathbf{N = N_1}$, $\mathbf{E1 = 4.44f\phi_m N_1}$ **volts**

In the secondary coil, N = $\mathbf{N_2}$, $\mathbf{E_2 = 4.44f\phi_m N_2}$ **volts**

LOSSES AND EFFICIENCY:

There are two types of power losses occur in a transformer

1) Iron loss 2) Copper loss

1) Iron Loss (P_i): This is the power loss that occurs in the iron part. This loss is due to the alternating frequency of the emf. Iron loss in further classified into two other losses.

a) Eddy current loss b) Hysteresis loss

The Iron losses are called as the constant losses.

a) Eddy current loss (We) :

- This power loss is due to the alternating flux linking the core, which will induced an emf , due to which a current called the eddy current is being circulated in the core.
- As there is some resistance in the core with this eddy current circulation converts into heat called the eddy current power loss.
- Eddy current loss is proportional to the square of the supply frequency.
- Eddy current loss can be minimized by using the core made of thin sheets of silicon steel material, and each lamination is coated with varnish insulation to suppress the path of the eddy currents.

b) Hysteresis loss (W_h): This is the loss in the iron core, due to the magnetic reversal of the flux in the core, which results in the form of heat in the core. This loss is directly proportional to the supply frequency.

- Hysteresis loss can be minimized by using the core material having high permeability.

Total Iron loss $P_i = W_e + W_h$

2) Copper loss or I^2R losses (Pcu) :
    - This is the power loss that occurs in the primary and secondary coils when the transformer is on load.
    - This power is wasted in the form of heat due to the resistance of the coils.
    - This loss is proportional to the sequence of the load hence it is called the Variable loss where as the Iron loss is called as the Constant loss as the supply voltage and frequency are constants

    Total losses of the transformer = $P_i + P_{cu}$

Efficiency: It is the ratio of the output power to the input power of a transformer

$$\eta = \frac{Output\ \ power}{Input\ \ power}$$

Input = Output + Total losses

= Output + Iron loss + Copper loss

Efficiency =

$$\eta = \frac{outputpower}{outputpower + Ironloss + copperloss}$$

$$= \frac{V_2 I_2 \cos\phi}{V_2 I_2 \cos\phi + Pi + Pcu}$$

Where, V_2 is the secondary (output) voltage, I_2 is the secondary (output) current and $\cos\Phi$ is the power factor of the load.

The transformers are normally specified with their ratings as KVA

Therefore,

$$\text{Efficiency} = \frac{(KVA)(10^3)\cos\Phi}{(KVA)(10^3)\cos\Phi + P_i + Pcu}$$

Since the copper loss varies as the square of the load the efficiency of the transformer at any desired load n is given by

$$\text{Efficiency} = \frac{n\,(KVA)(10^3)\cos\Phi}{n\,(KVA)(10^3)\cos\Phi + P_i + (n)^2\,P_{cu}}$$

where Pcu is the copper loss at full load

$P_{cu} = I^2R$ watts

CONDITION FOR MAXIMUM EFFICIENCY:

- In general for the efficiency to be maximum for any device the losses must be minimum.
- Between the iron and copper losses the iron loss is the fixed loss and the copper loss is the variable loss.
- When these two losses are equal and also minimum the efficiency will be maximum.

- The load current at which the efficiency attains maximum value is denoted as I_{2m} and maximum efficiency is denoted as η_{max}.
- The efficiency is a function of load i.e. load current I_2 assuming $\cos\phi_2$ constant. The secondary terminal voltage V_2 is also assumed constant.
- So for maximum efficiency,

$$\frac{d\eta}{dI_2} = 0 \quad \text{while} \quad \eta = \frac{V_2\, I_2 \cos\phi_2}{V_2\, I_2 \cos\phi_2 + P_i + I_2^2\, R_{2e}}$$

$$\therefore \quad \frac{d\eta}{dI_2} = \frac{d}{dI_2}\left[\frac{V_2\, I_2 \cos\phi_2}{V_2\, I_2 \cos\phi_2 + P_i + I_2^2\, R_{2e}}\right] = 0$$

$$\therefore (V_2\, I_2 \cos\phi_2 + P_i + I_2^2\, R_{2e})(V_2 \cos\phi_2) - (V_2\, I_2 \cos\phi_2)(V_2 \cos\phi_2 + 2I_2\, R_{2e}) = 0$$

- Cancelling $(V_2 \cos\phi_2)$ from both the terms we get,

$$V_2\, I_2 \cos\phi_2 + P_i + I_2^2\, R_{2e} - V_2\, I_2 \cos\phi_2 - 2\, I_2^2\, R_{2e} = 0 \quad \text{i.e.} \quad P_i - I_2^2\, R_{2e} = 0$$

$$\therefore \quad \boxed{P_i = I_2^2\, R_{2e} = P_{Cu}}$$

So condition to achieve maximum efficiency is that,

$$\boxed{\text{Copper losses} = \text{Iron losses} \quad \text{i.e.} \quad P_i = P_{Cu}}$$

Therefore the condition for maximum efficiency in a transformer is

Iron loss = Copper loss (whichever is minimum)

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Problems

1. Find the number of turns on the primary & secondary side of a 440/230 V, 50 Hz single phase transformer, if the net area of cross section of the core is 30 cm^2& the maximum flux density is 1 Wb/m^2
2. A single phase transformer working at 0.8 p.f. has an efficiency 945 at both three fourth full load & full load of 600kW. Determine the eefficiency at half full-load, unity power factor.
3. A 600 kVA, 1 phase transformer has an efficiency of 92% both at full load & half load upf. Determine its efficiency at 75% full load 0.9 p.f.
4. A 50 kVA, 400/200 V, single phase transformer has an efficiency of 98% at full load & 0.8 p.f., while its efficiency is 96.9% at 25% of full load & unity power factor. Determine the iron & full load copper losses & voltage regulation, if the terminal voltage on full load is 195 V.
5. A transformer is rated at 100 kVA. At full load its copper loss is 1200W & its iron loss is 960W. calculate (i) the efficiency at full, upf (ii) the efficiency at half load, 0.9 p.f (iii) the load kVA at which maximum efficiency will occur.
6. The maximum efficiency at full load & upf of a single phase, 25 kVA, 500/1000 V, 50 Hz, transformer is 98%. Determine its efficiency at (i) 75% load, 0.9 p.f. (ii) 50% load, 0.8 p.f. (iii) 25% load, 0.6 p.f.
7. A single phase has 1000 turns on its primary & 400 turns on the secondary. An A.C voltage of 1250 V, 50 Hz is applied to its primary side with the secondary open circuited. Calculate the secondary emf, maximum value of flux density, given that the effective cross sectional area of core is 60 cm^2
8. A 250 kVA, 1 phase transformer has 98.135% efficiency at full load & 0.8 lagging p.f. The efficiency at half load & 0.8 lagging p.f. is 97.751%. calculate the iron loss & full load copper loss.
9. The primary winding of a transformer is connected to a 240 V, 50 Hz supply. The secondary winding has 1500 turns. If the maximum value of the core flux is 0.00207 Wb, determine the secondary emf, number of turns on primary, cross sectional area of the core if the flux density has a maximum value of 0.465 Tesla.
10. A 40 kVA single phase transformer has core loss of 450 W & full load copper loss of 850 W. if the p.f. of the load is 0.8, calculate , (i) full load efficiency (ii) load corresponding to maximum efficiency (iii) maximum efficiency at upf.

Unit 5 (b):

Induction Motors:-

- The asynchronous motors or the induction motors are most widely used ac motors in industry.
- They convert electrical energy in AC form into mechanical energy.
- They work on the principle of electromagnetic induction.
- They are simple and rugged in construction, quite economical with good operating characteristics and efficiency, requiring minimum maintenance, but have a low starting torque.
- They run at practically constant speed from no load to full load condition.
- The 3 - phase induction motors are self starting while the single phase motors are not self starting as they produce equal and opposite torques (zero resultant torque) making the rotor stationary.
- The speed of the squirrel cage induction motor cannot be varied easily.

CLASSIFICATION:

They are basically classified into two types based on the rotor construction

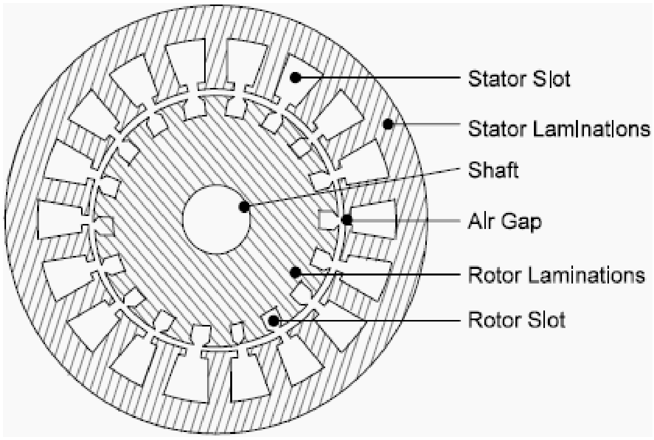
1. Squirrel cage motor
2. Slip ring motor or phase wound motor

CONSTRUCTION

- Induction motor consists of two parts (1) stator (2) rotor

1. Stator

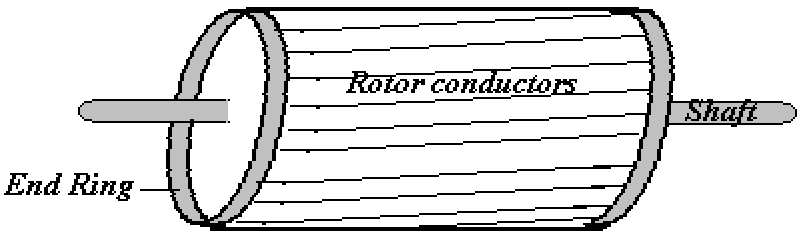
- It is the stationary part of the motor supporting the entire motor assembly.
- This outer frame is made up of a single piece of cast iron in case of small machines.
- In case of larger machines they are fabricated in sections of steel and bolted together.
- The core is made of thin laminations of silicon steel and flash enameled to reduce eddy current and hysteresis losses.
- Slots are evenly spaced on the inner periphery of the laminations.
- Conductors insulated from each other are placed in these slots and are connected to form a balanced 3 - phase star or delta connected stator circuit.
- Depending on the desired speed the stator winding is wound for the required number of poles. Greater the speed lesser is the number of poles.



2. Rotor

1. **Squirrel cage motor :**

- Squirrel cage rotors are widely used because of their ruggedness.
- The rotor consists of hollow laminated core with parallel slots provided on the outer periphery.
- The rotor conductors are solid bars of copper, aluminum or their alloys.
- The bars are inserted from the ends into the semi-enclosed slots and are brazed to the thick short circuited end rings.
- This sort of construction resembles a squirrel cage hence the name "squirrel cage induction motor".
- The rotor conductors being permanently short circuited prevent the addition of any external resistance to the rotor circuit to improve the inherent low starting torque.
- The rotor bars are not placed parallel to each other but are slightly skewed which reduces the magnetic hum and prevents cogging of the rotor and the stator teeth.

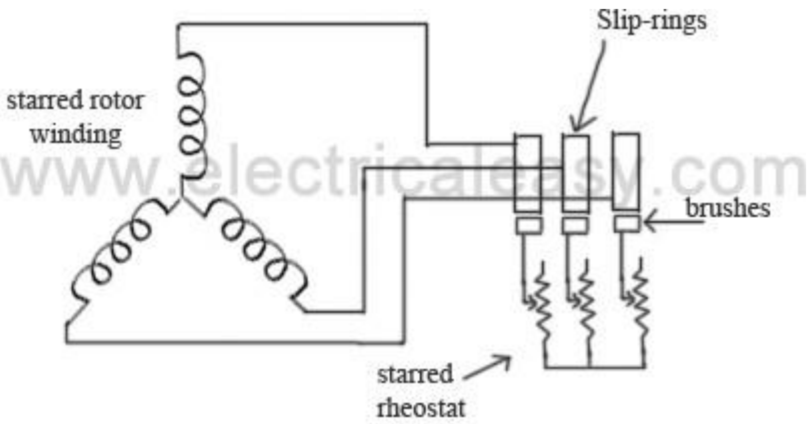


Squirrel cage induction rotor

2. **Slip ring motor or phase wound motor**

- The rotor in case of a phase wound/ slip ring motor has a 3-phase double layer distributed winding made up of coils, similar to that of an alternator.
- The rotor winding is usually star connected and is wound to the number of stator poles.

- The terminals are brought out and connected to three slip rings mounted on the rotor shaft with the brushes resting on the slip rings.
- The brushes are externally connected to the star connected rheostat in case a higher starting torque and modification in the speed torque characteristics are required.
- Under normal running conditions all the slip rings are automatically short circuited by a metal collar provided on the shaft and the condition is similar to that of a cage rotor.
- Provision is made to lift the brushes to reduce the frictional losses. The slip ring and the enclosures are made of phosphor bronze.



Phase wound rotor connections

- In both the type of motors the shaft and bearings (ball and roller) are designed for trouble free operation.
- Fans are provided on the shaft for effective circulation of air.
- The insulated (mica and varnish) stator and rotor windings are rigidly braced to withstand the short circuit forces and heavy centrifugal forces respectively. .
- Care is taken to maintain a uniform air gap between the stator and the rotor.

Comparison of the squirrel cage and slip ring rotors

The cage rotor has the following advantages:

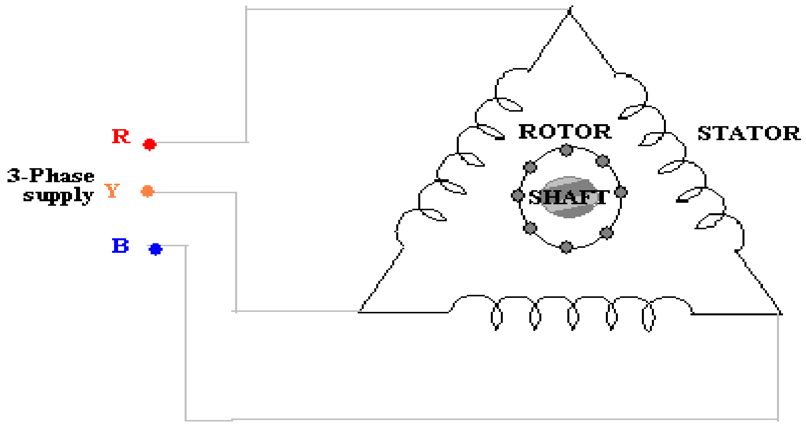
1. Rugged in construction and economical.
2. Has a slightly higher efficiency and better power factor than slip ring motor.
3. The absence of slip rings and brushes eliminate the risk of sparking which helps in a totally enclosed fan cooled (TEFC) construction.

The advantages of the slip ring rotor are:

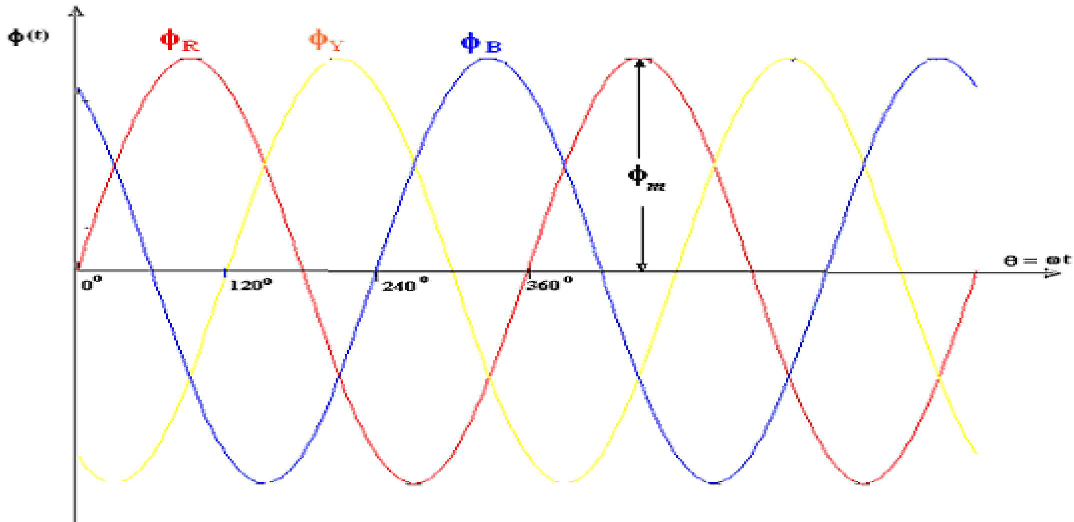
1. The starting torque is much higher and the starting current much lower when compared to a cage motor with the inclusion of external resistance.
2. The speed can be varied by means of solid state switching

ROTATING MAGNETIC FIELD

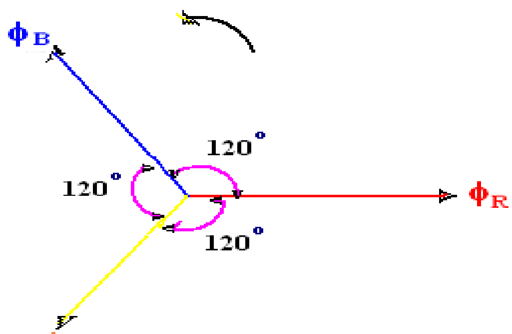
Consider a 3- phase induction motor whose stator windings mutually displaced from each other by 120° are connected in delta and energized by a 3- phase supply.



. The currents flowing in each phase will set up a flux in the respective phases as shown.



Waveforms of the flux in three phases



Phase Sequence RYB - Positive

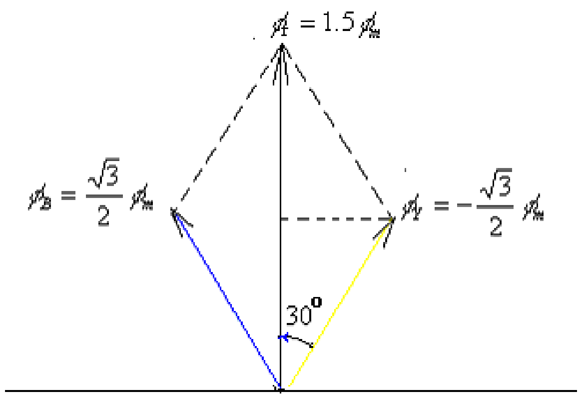
The corresponding phase fluxes can be represented by the following equations

$$\Phi_R = \Phi_m \sin \omega t = \Phi_m \sin\theta$$
$$\Phi_Y = \Phi_m \sin(\omega t - 120°)$$
$$\Phi_Y = \Phi_m \sin(\theta - 120°)$$

$$\Phi_B = \Phi_m \sin(\omega t - 240°)$$
$$\Phi_B = \Phi_m \sin(\theta - 240°)$$

The resultant flux at any instant is given by the vector sum of the flux in each of the phases.

(i) When $\theta = 0°$, from the flux waveform diagram ,we have



Resultant flux at $\theta = 0^0$

$$\phi_R = 0$$

$$\phi_Y = \phi_{km} \sin(-120°) = -\frac{\sqrt{3}}{2}\phi_m$$

$$\phi_B = \phi_m \sin(-240°) = \frac{\sqrt{3}}{2}\phi_m$$

The resultant flux ϕ_r is given by,

$$\phi_r = 2 * \frac{\sqrt{3}}{2}\phi_m \cos(30°) = 1..5\phi_m$$

$$\phi_B = \frac{\sqrt{3}}{2}\phi_m$$

$$\phi_Y = -\frac{\sqrt{3}}{2}\phi_m$$

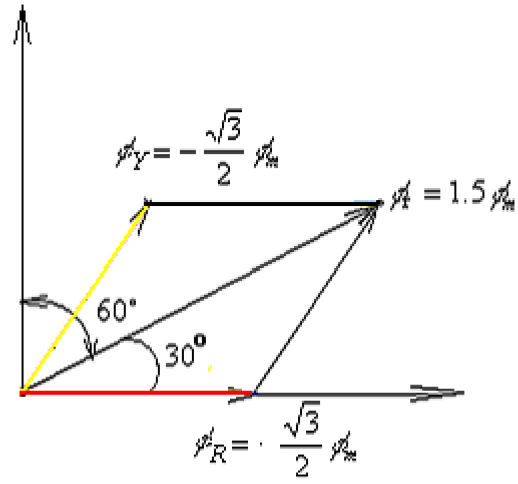
$$\phi_r = 1.5\phi_m$$

(ii) *When* $\theta = 60^\circ$

$$\phi_R = \frac{\sqrt{3}}{2}\phi_m$$

$$\phi_Y = -\frac{\sqrt{3}}{2}\phi_m$$

$$\phi_B = 0$$



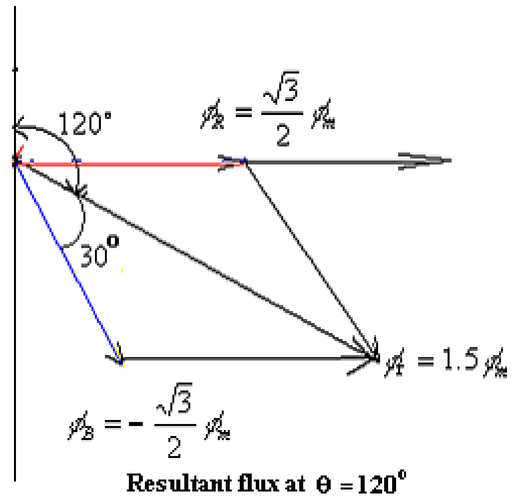
Resultant flux at θ = 60°

(iii) *When* $\theta = 120^\circ$

$$\phi_R = \frac{\sqrt{3}}{2}\phi_m$$

$$\phi_Y = 0$$

$$\phi_B = -\frac{\sqrt{3}}{2}\phi_m$$



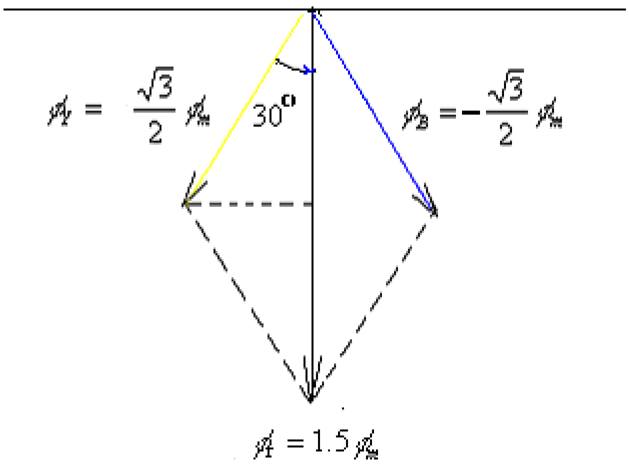
Resultant flux at θ = 120°

(iv) *When* $\theta = 180^\circ$

$$\phi_R = 0;$$

$$\phi_Y = \frac{\sqrt{3}}{2}\phi_m$$

$$\phi_B = -\frac{\sqrt{3}}{2}\phi$$



Resultant flux at θ = 180°

From the above discussion it is very clear that when the stator of a 3-phase induction motor is energized, a magnetic field of constant magnitude (1.5 φ_m) rotating at synchronous speed

(**N_s**) with respect to stator winding is produced.

WORKING PRINCIPLE:

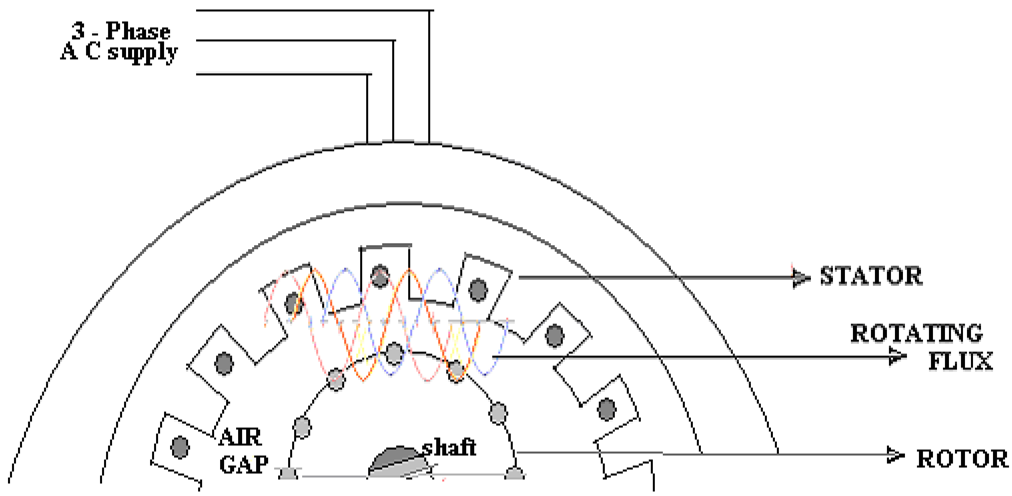
- When a 3-Φ supply is given to the stator winding a magnetic field of constant magnitude 1.5Φ_m and rotating with the synchronous speed Ns is produced.
- This rotating speed sweeps across the conductors and hence an emf is induced in rotor conductors.
- According to lenz's law, the direction of the induced emf is such as to oppose the very cause producing it. The cause is the relative speed between the rotating magnetic field and static stator
- Since rotor conductors are short circuited by themselves, the induced emf sets up the current in rotor conductors in such a direction to produce torque, which rotates the rotor in same direction as the magnetic field.
- But as the speed of the rotor is in the same direction of rotating magnetic field , the relative speed decreases.
- The speed of the rotor gradually increases and tries to catch up the speed of rotating magnetic field . But if it catches up the speed , then the relative speed becomes zero and hence , no emf will be induced in the rotor conductors hence the torque becomes zero hence motor stops . thus rotor will not be able to catch the speed of the magnetic field ,but rotates at a speed slightly lesser than the synchronous speed.

Consider a 3- phase stator winding energized from a 3 phase supply. As explained earlier a rotating magnetic field is produced running at a synchronous speed N_S

$$N_S = \frac{120 f}{P}$$

Where f = supply frequency

P = Number of stator poles



CONCEPT OF SLIP (*S*):

- According to Lenz's law, the direction of rotor current will be such that they tend to oppose the cause producing it.
- The cause producing the rotor current is the relative speed between the rotating field and the stationary rotor.
- Hence, to reduce this relative speed, the rotor starts running in the same direction as that of stator field and tries to catch it.
- In practice the rotor can never reach the speed of the rotating magnetic field produced by the stator.
- This is because if rotor speed equals the synchronous speed, then there is no relative speed between the rotating magnetic field and the rotor.
- This makes the rotor current zero and hence no torque is produced and the rotor will tend to remain stationary.
- In practice, windage and friction losses cause the rotor to slow down. Hence, the rotor speed (N) is always less than the stator field speed (N_S).
- Thus the induction motor cannot run with ZERO SLIP. The frequency of the rotor current $f_r = sf$.
- The difference between the synchronous speed (N_S) of the rotating stator field and the actual rotor speed (N) is called the **slip speed.**
- Slip speed = $N_S - N$ depends upon the load on the motor

$$\% \text{ Slip } (s) = \frac{N_S - N}{N_S} * 100$$

Note: In an induction motor the slip value ranges from 2% to 4%

APPLICATIONS OF INDUCTION MOTORS:

Squirrel cage induction motor

- Squirrel cage induction motors are simple and rugged in construction, are relatively cheap and require little maintenance.
- Hence, squirrel cage induction motors are preferred in most of the industrial applications such as in

    i) Lathes
    ii) Drilling machines
    iii) Agricultural and industrial pumps
    iv) Industrial drives.

Slip ring induction motors

- Slip ring induction motors when compared to squirrel cage motors have high starting torque, smooth acceleration under heavy loads, adjustable speed and good running characteristics.

They are used in

i) Lifts
ii) Cranes
iii) Conveyors , etc.,

Necessity of starters for 3 phase induction motor

- When a 3- phase motor of higher rating is switched on directly from the mains it draws a starting current of about 4 -7 times the full load (depending upon on the design) current.
- This will cause a drop in the voltage affecting the performance of other loads connected to the mains.
- Hence starters are used to limit the initial current drawn by the 3 phase induction motors.
- The starting current is limited by applying reduced voltage in case of squirrel cage type induction motor and by increasing the impedance of the motor circuit in case of slip ring type induction motor.
- This can be achieved by the following methods.

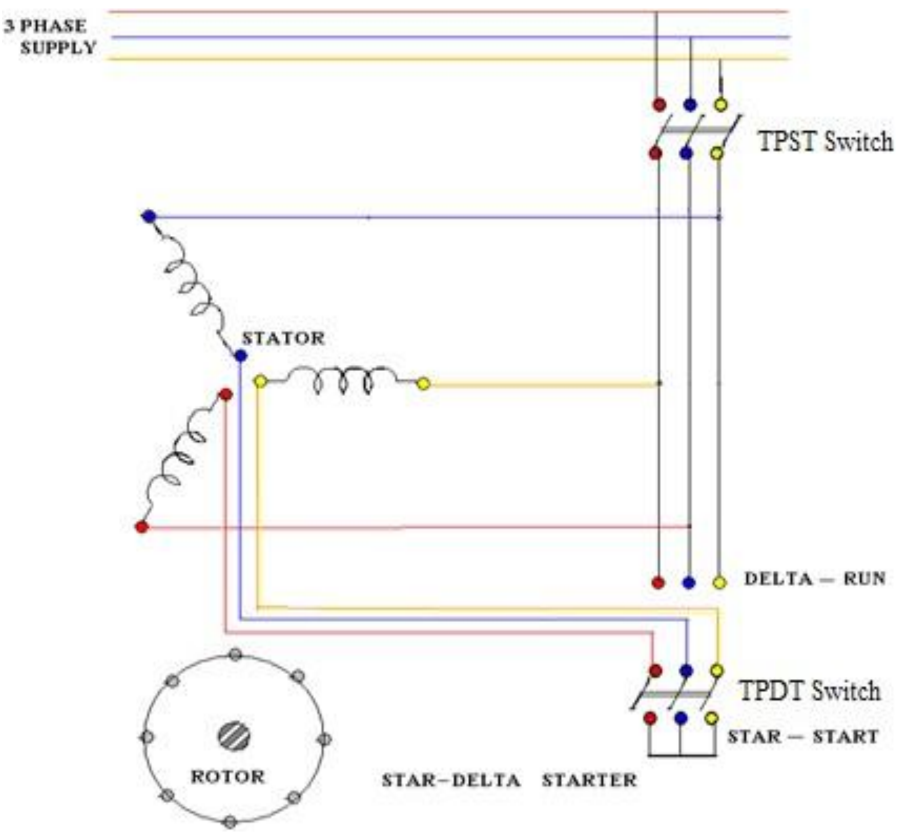
1. Star –delta starter

2. Auto transformer starter

3. Soft starter

<u>Star delta starter</u>

- This is the cheapest starter of all.
- It uses TPDT [Triple pole double through switch] which connects the stator winding in star and in delta during normal running conditions.
- Hence this starter is suitable only for those motors designed to run with the delta connected stator winding.
- The two ends of each phase of the stator winding are drawn out and connected to the starter terminals as shown in the following figure.



Initially when the TPDT Switch is in start position, the stator winding gets connected in star, hence phase voltage gets reduced by a factor of $1/\sqrt{3}$. Due to this starting current also gets reduced by a factor of $1/\sqrt{3}$.

When motor attains 50% to 60% of normal speed, the TPDT switch is thrown in the run position. Hence, the stator winding now gets connected in delta and each phase of the winding gets the rated voltage.

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Problems

1. The frequency of the emf in the stator of a 4 pole induction motor is 50 Hz, & that in the rotor is 1.5 Hz. What is its slip, & at what speed is the motor running?
2. A 4 pole, 3 phase, 50 Hz induction motor runs at a speed of 1470 rpm. Find the frequency of the induced emf in the rotor under this condition
3. A 10 pole induction motor is supplied by a 6 pole alternator which is driven at 1200 rpm. If the motor runs with a slip of 3% , what is its speed?
4. A 3-phase, 6 pole, 50 Hz induction motor has a slip of 1% at no load, & 3% at full load. Determine synchronous speed, no-load speed, full-load speed, frequency of rotor current at stand still & frequency of rotor current at full load.
5. An 8 pole alternator runs at 750 rpm & supplies power to a 6 pole, 3 phase induction motor which runs at 970 rpm. What is the slip of induction motor?
6. If the electromotive force in the stator of an 8 pole induction motor has a frequency of 50 Hz & that in the rotor 1.5 Hz, at what speed is the motor running & what is the slip?
7. A 6 pole, 3 phase, star connected alternator has an armature with 90 slots & 10 conductors/slot. It revolves at 1000 rpm. The flux/pole is 0.05 Wb. Calculate the emf generated/phase, if the winding factor is 0.97 & all conductors in each phase are in series.
8. A 6 pole induction motor supplies from a 3 phase, 50 Hz supply has a rotor frequency of 2.3 Hz. Calculate the %slip & the speed of the motor.