CHAPTER : 5
ELECTRIC MACHINES

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REVIEW OF MAGNETIC CIRCUITS

- Terminologies
- Magnetic circuit
- Magnetic losses
- Eddy current loss
- Hysteresis loss
- Hysteresis loop

- A **magnetic circuit** is made up of one or more closed loop paths containing a magnetic flux. The flux is usually generated by permanent magnets or electromagnets and confined to the path by magnetic cores consisting of ferromagnetic materials like iron, although there may be air gaps or other materials in the path. Magnetic circuits are employed to efficiently channel magnetic fields in many devices such as electric motors, generators, transformers, relays,etc.

Terminologies

- **Magnetic flux (*Φ*):**
  - No. of magnetic lines of force created in a magnetic circuit
  - Unit is Weber (**Wb**)

- **Flux Density: (B)**
  - No. of magnetic lines of force created in a magnetic circuit per unit area normal to the direction of flux lines
  - B = ***Φ/A***
  - Unit is Weber/sq.m (Tesla)

Terminologies

- **Magneto motive force: (F)**
  - Force which drives or tends to drive the magnetic flux through a magnetic circuit
  - **MMF = No. of turns*Current = N I**
  - Unit is **AT** (ampere - Turns)

- **Magnetic field strength: (H)**
  - The magneto motive force per meter length of the magnetic circuit
  - **H = (N I) / L**
  - **Unit is AT / meter**

Terminologies

- **Permeability [μ]**
  - A property of a magnetic material which indicates the ability of magnetic circuit to carry electromagnetic flux.
  - Ratio of flux density to the magnetizing force, ***μ = B / H***
  - Unit: ***henry / meter***
- Permeability of free space or air or non magnetic material

$$\mu_0 = 4\pi \times 10^{-7}\, H/m$$

- **Relative permeability [μ_r] :**

Ratio of the flux density produced by a given mmf in a magnetic material to the flux density produced in a non magnetic material.

$$\mu_r = \frac{B}{B_0} = \frac{\mu H}{\mu_0 H}; \quad \mu = \mu_0 \mu_r$$

Terminologies

- **Reluctance [S]**
  - It is the opposition of a magnetic circuit to setting up of a **magnetic flux** in it.

$$Flux = \phi = BA\ ;\ F = mmf = Hl\ ;\ B = \mu H$$

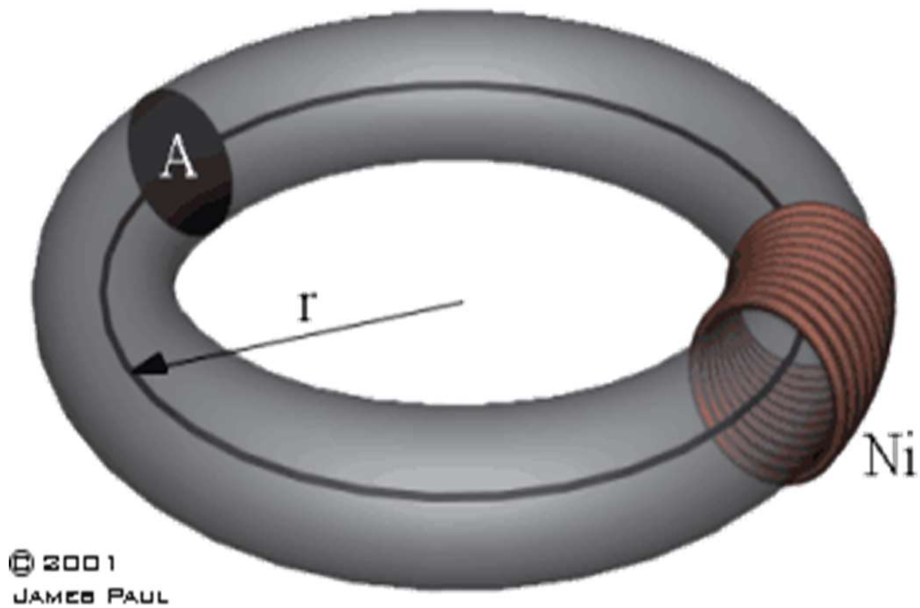
$$\frac{\phi}{F} = \frac{BA}{Hl} = \frac{\mu_0 \mu_r A}{l}\ ;\ Hence \quad \phi = \left(\frac{\mu_0 \mu_r A}{l}\right) F$$

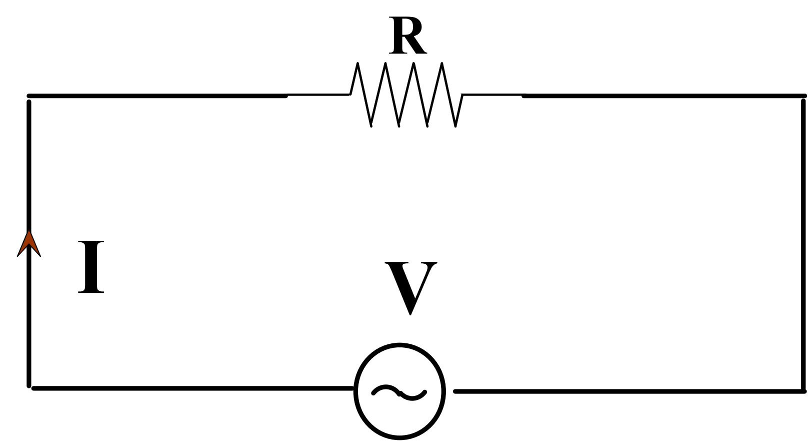
$$\phi = \frac{F}{\left(\dfrac{l}{\mu_0 \mu_r A}\right)} = \frac{F}{S}\ ;\ \textbf{where} \quad S = \left(\frac{l}{\mu_0 \mu_r A}\right)$$

  - ‘S’ is called the reluctance of the magnetic circuit
  - Reluctance = mmf / Magnetic flux
  - Unit: ***AT / Wb***

Magnetic circuit

- The complete closed path followed by any group of magnetic lines of flux is referred to **a magnetic circuit**



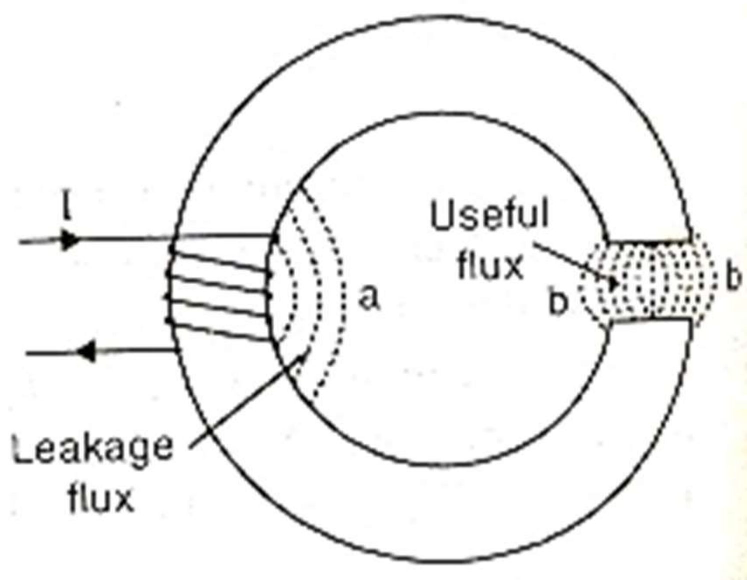


Equivalent electrical circuit

Analogy with Electric circuits

Electric circuit	Magnetic circuit
Similarities:	
Emf, volt	mmf, ampere Turn
Current, ampere	flux, weber
Resistance, ohm	Reluctance, A / Wb
Current density, A / m^2	flux density, T or Wb / m^2
Conductivity	Permeability
Difference:	
Current actually flows	flux is created, but does not flow
Circuit may be open or closed	Circuit is always closed

Leakage flux



- Leakage Flux : The flux that does not follow the intended path in the magnetic circuit

Magnetic circuits losses

Two types of losses:

- Hysteresis losses
- Eddy current losses

Eddy current losses are caused due to conduction of core and is reduced by laminating the core, and insulating to an extent, one leaf of the core from another. E and I are interleaved to form the final core.
I2R losses are due to finite resistances of the wires used in primary and secondary.
Hysteresis loss is due to residual magnetization and depends on core. In general this loss increases as frequency is increased.
The losses are minimized using copper wires for the coils, to reduce copper loss, laminating the core to reduce eddy current losses, and selecting appropriate cores for reduction of hysteresis loss

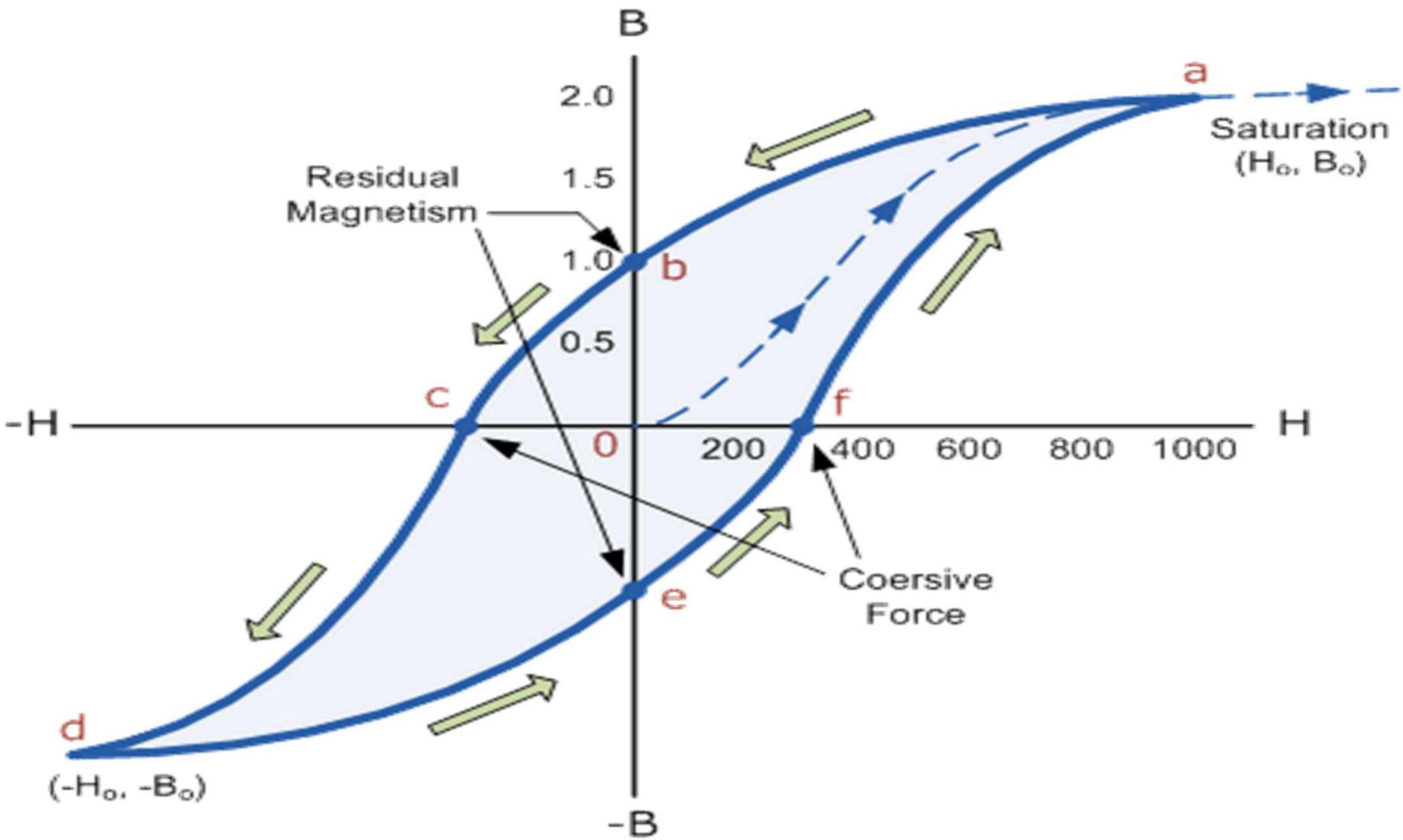
Magnetic Hysteresis

The lag or delay of a magnetic material known commonly as **Magnetic Hysteresis**, relates to the magnetisation properties of a material by which it firstly becomes magnetised and then de-magnetised. We know that the 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 more commonly called "Flux Density". Given the symbol B with the unit of flux density being the Tesla, T.

$$B = \frac{\Phi}{A} \quad \text{and} \quad \frac{B}{H} = \mu_o$$

- So for ferromagnetic materials the ratio of flux density to field strength (B/H) is not constant but varies with flux density. However, for air cored coils or any non-magnetic medium core such as woods or plastics, this ratio can be considered as a constant and this constant is known as μ_o, the permeability of free space, ($\mu_o = 4.\pi.10^{-7}$ H/m). By plotting values of flux density, (B) against the field strength, (H) we can produce a set of curves called **Magnetisation Curves**, **Magnetic Hysteresis Curves** or more commonly **B-H Curves** for each type of core material used as shown below.

Hysteresis Loop



- The **Magnetic Hysteresis** loop above, shows the behavior 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 around the core reduces to zero but the magnetic flux does 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 the reverse current causes the core to be magnetised in the opposite direction and increasing this magnetisation current will cause the core to reach saturation but in the opposite direction, point d on the cure which 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**.

TRANSFORMER

- ❖ Working principle
- ❖ EMF equation
- ❖ Equivalent circuit of transformer
- ❖ Referred to primary and secondary
- ❖ Open circuit (O.C) test
- ❖ Short circuit (S.C) test

TRANSFORMERS

Voltage Transformer Basics

One of the main reasons that we use alternating AC voltages and currents in our homes and workplace's is that it can be easily generated at a convenient voltage, transformed into a much higher voltage and then distributed around the country using a national grid of cables over very long distances. The reason for transforming the voltage is that higher distribution voltages implies lower currents and therefore lower losses along the grid. These high AC voltages and currents are then reduced to a much lower and safer voltage supply were it is needed in our homes and workplaces, and all this is possible due to the basic **Voltage Transformer**.

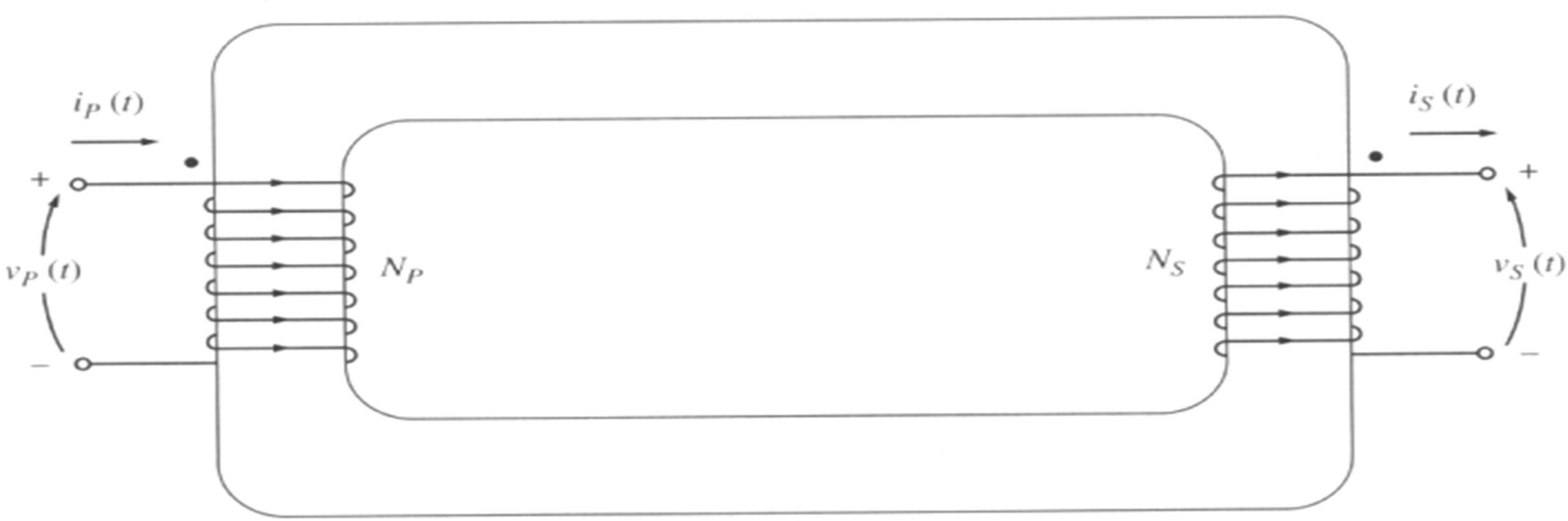
The transformer is very simple static (or stationary) electro-magnetic passive electrical device that works on the principle of Faraday's law of induction. It does this by linking together two or more electrical circuits using a common oscillating magnetic circuit which is produced by the transformer itself. A transformer operates on the principals of "electromagnetic induction", in the form of *Mutual Induction*.

A transformer is a device that converts one AC voltage to another AC voltage at the same frequency. It consists of one or more coil(s) of wire wrapped around a common ferromagnetic core. These coils are usually not connected electrically together. However, they are connected through the common magnetic flux confined to the core.

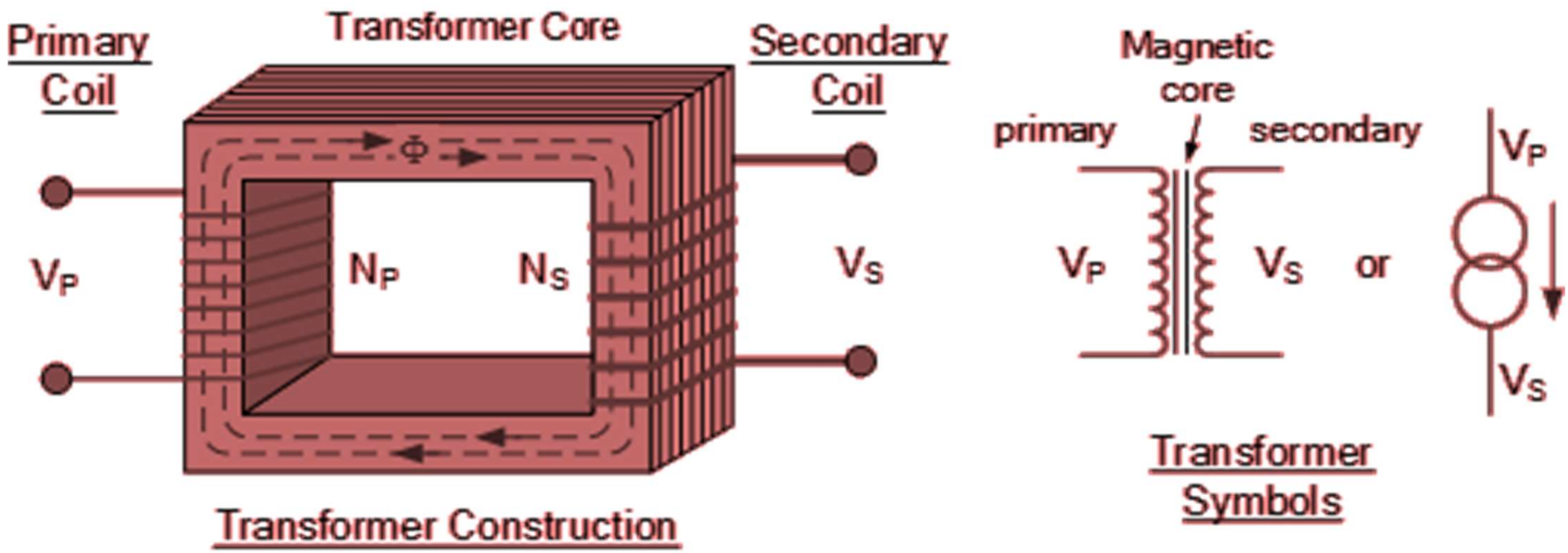
Assuming that the transformer has at least two windings, one of them (primary) is connected to a source of AC power; the other (secondary) is connected to the loads.

WORKING PRINCIPLE

A single phase voltage transformer basically consists of two electrical coils of wire, one called the "Primary Winding" and another called the "Secondary Winding" . These two windings are electrically isolated from each other but are magnetically linked through the common core allowing electrical power to be transferred from one coil to the other.



In other words, for a transformer there is no direct electrical connection between the two coil windings. Generally, the primary winding of a transformer is connected to the input voltage supply and converts or transforms the electrical power into a magnetic field. While the secondary winding converts this magnetic field into electrical power producing the required output voltage as shown.



Where:

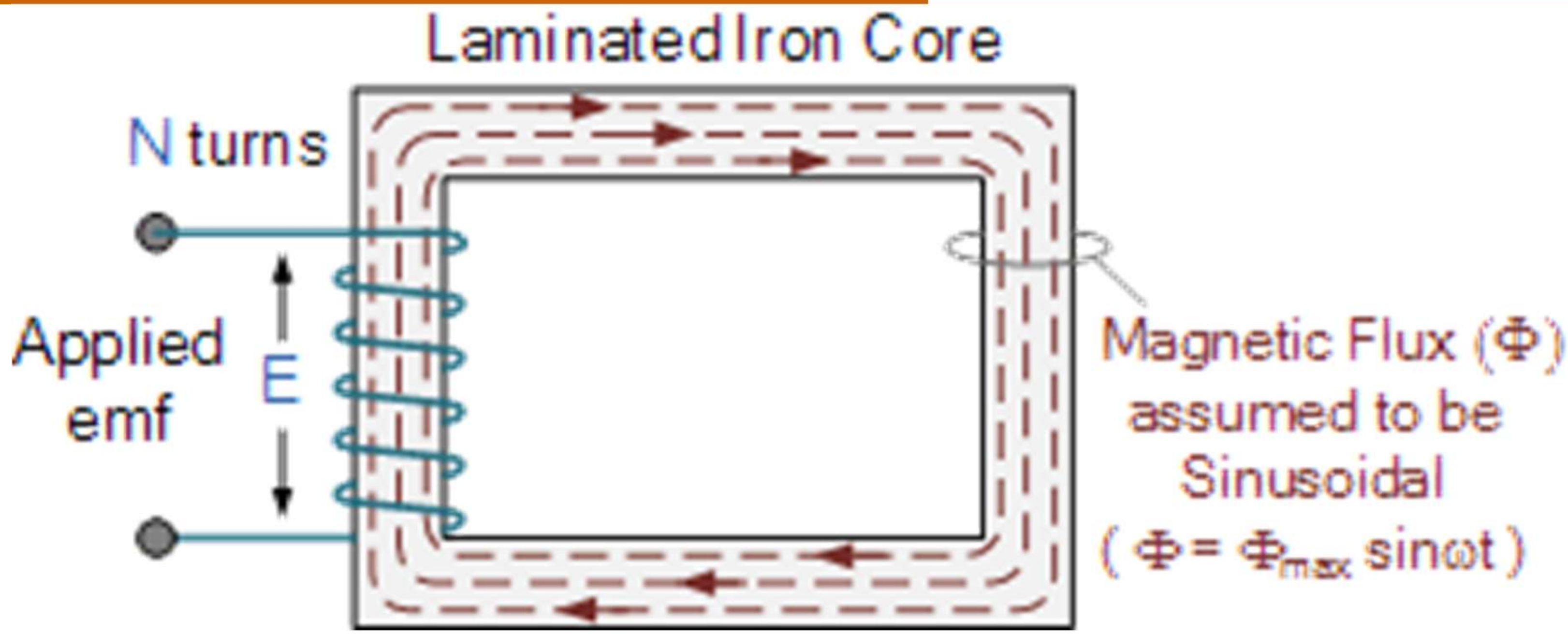
- V_P - is the Primary Voltage
- V_S - is the Secondary Voltage
- N_P - is the Number of Primary Windings
- N_S - is the Number of Secondary Windings
- Φ (phi) - is the Flux Linkage

A transformer is all about "ratios", and the turns ratio of a given transformer will be the same as its voltage ratio. In other words for a transformer: "turns ratio = voltage ratio". The actual number of turns of wire on any winding is generally not important, just the turns ratio and this relationship is given as:

$$k = N_2 / N_1 = E_2 / E_1$$

Note that the two coil windings are not electrically connected but are only linked magnetically. A single-phase transformer can operate to either increase or decrease the voltage applied to the primary winding. When a transformer is used to "increase" the voltage on its secondary winding with respect to the primary, it is called a **Step-up transformer**. When it is used to "decrease" the voltage on the secondary winding with respect to the primary it is called a **Step-down transformer**.

EMF equation of transformer



When the magnetic lines of flux flow around the core, they pass through the turns of the secondary winding, causing a voltage to be induced into the secondary coil. The amount of voltage induced will be determined by:

$E=N.d\Phi/dt$ (Faraday's Law),

where,N is the number of turns in a coil.

Also this induced voltage has the same frequency as the primary winding voltage.

As the magnetic flux varies sinusoidally,

$$\Phi=\Phi_{max}\sin\omega t,$$

then the basic relationship between induced emf, (E) in a coil winding of N turns is given by:

emf=turns*x*rateofchange

$$E = N\frac{d\Phi}{dt}$$

$$E = N \times \omega \times \Phi_{max} \times \cos(\omega t)$$

$$E_{max} = N\omega\Phi_{max}$$

$$E_{rms} = \frac{N\omega}{\sqrt{2}} \times \Phi_{max} = \frac{2\pi}{\sqrt{2}} \times f \times N \times \Phi_{max}$$

$$\therefore E_{rms} = 4.44 f N \Phi_{max}$$

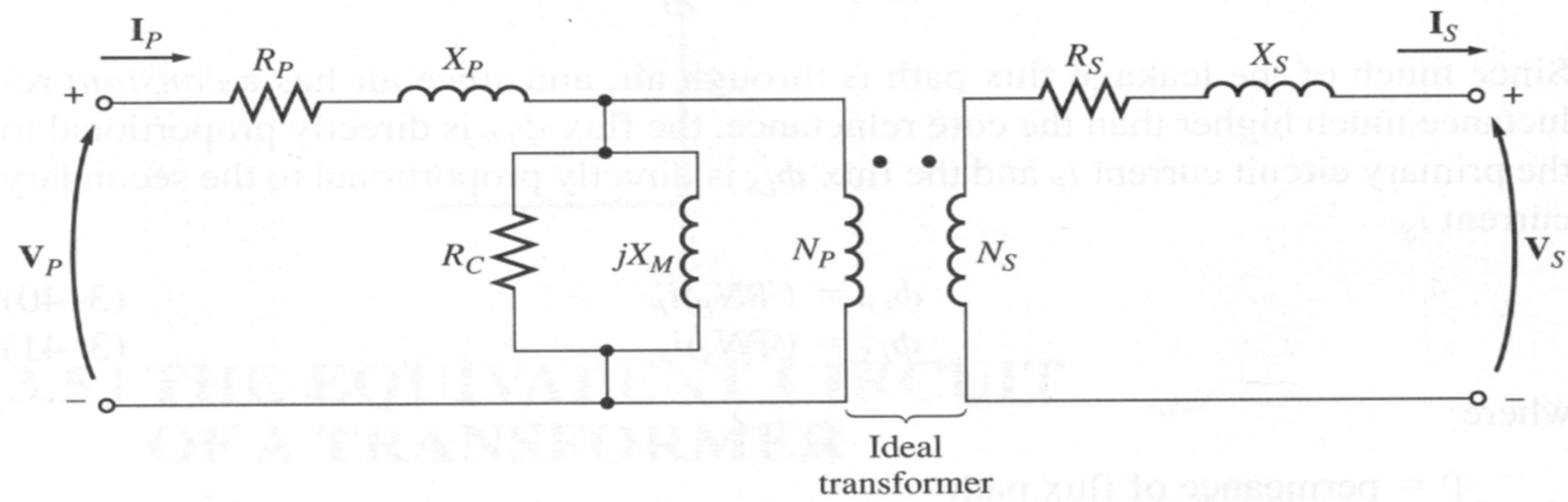
Where: f - is the flux frequency in Hertz,
N - is the number of coil windings.
Φ - is the flux density in webers

This is known as the Transformer EMF Equation. For the primary winding emf, N will be the number of primary turns, (N_P) and for the secondary winding emf, N will be the number of secondary turns, (N_S).

Transformers require an alternating magnetic flux to operate correctly, transformers cannot therefore be used to transform DC voltages or currents, since the magnetic field must be changing to induce a voltage in the secondary winding. In other words, **Transformers DO NOT Operate on DC Voltages**.

Equivalent Circuit of Transformer

- Equivalent **impedance of Transformer** is essential for estimating different parameters of electrical power system , so it may be required to calculate total internal impedance of the transformer viewing from primary side or secondary side as per requirement. This calculation requires **equivalent circuit of transformer referred to primary** or **equivalent circuit of transformer referred to secondary** sides respectively.



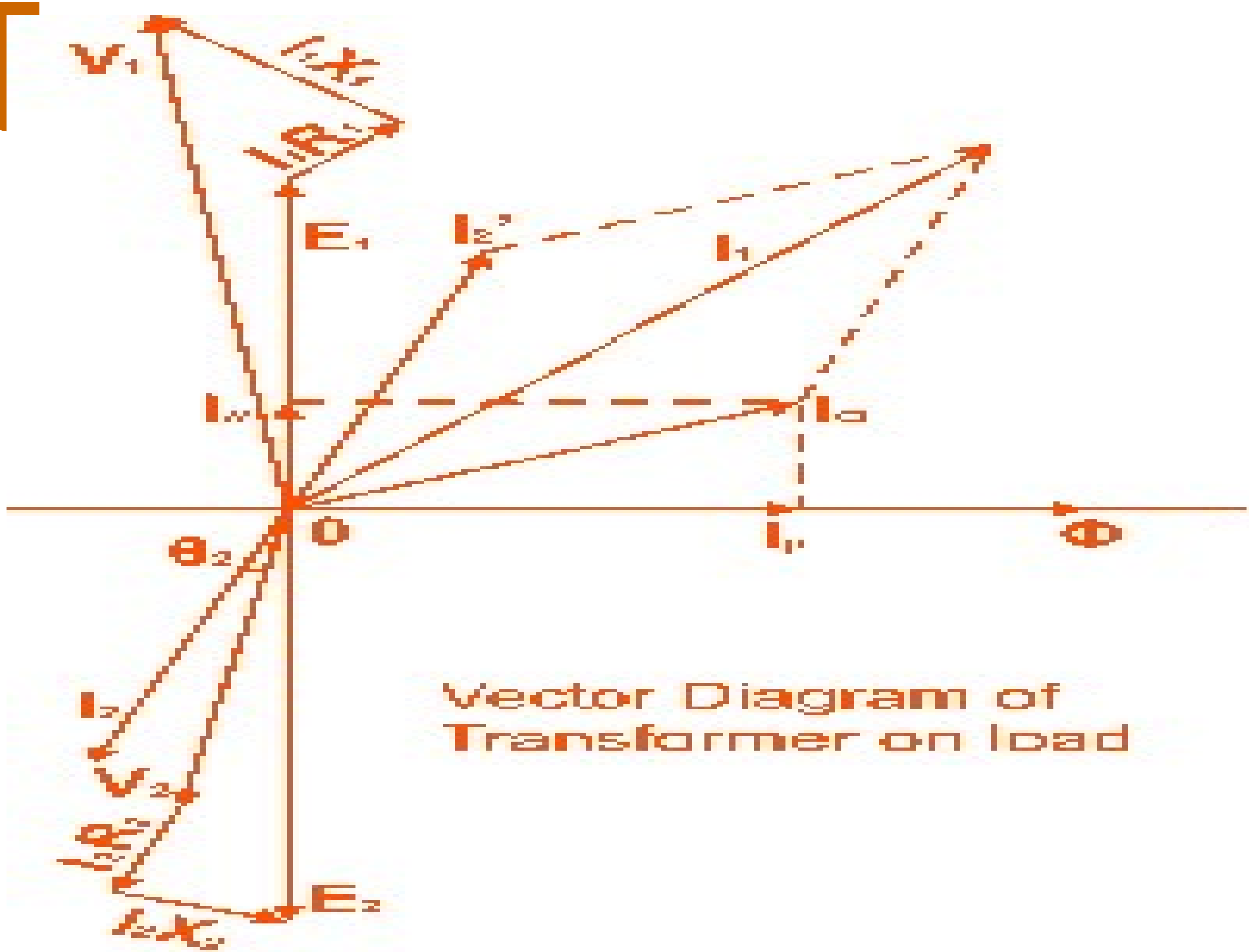
Equivalent Circuit of Transformer referred to Primary

Let us consider the transformation ratio be,

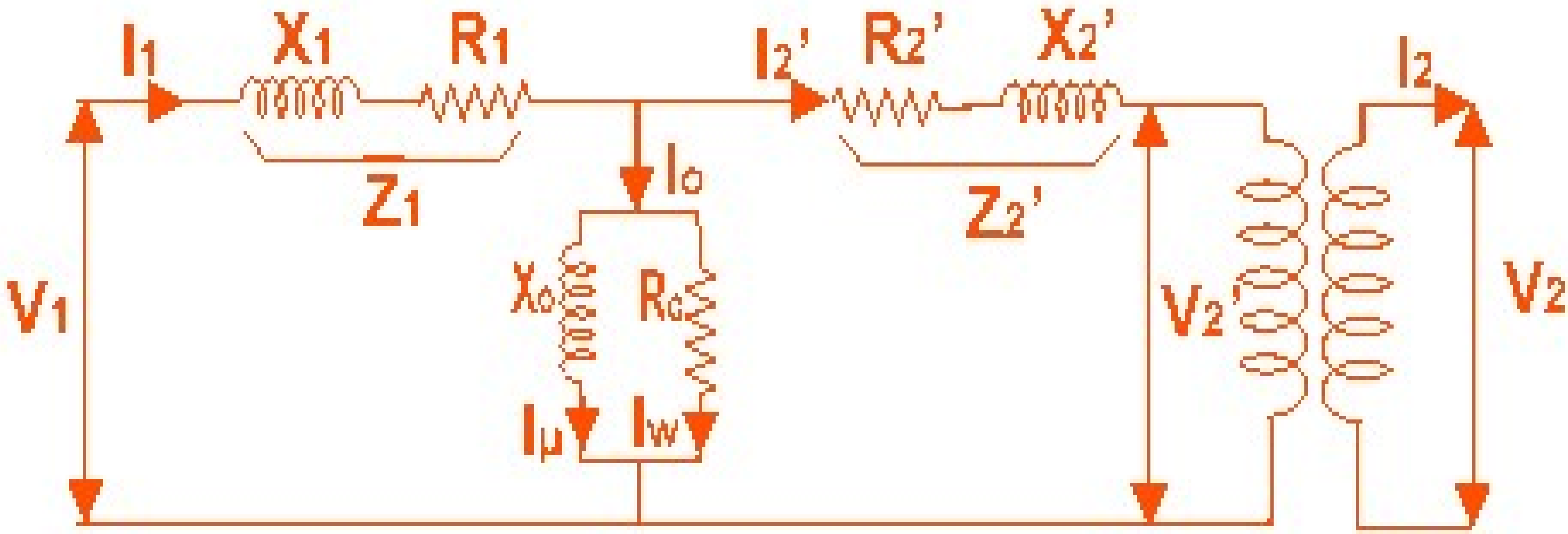
$K = N_2 / N_1 = E_2/E_1$

the applied voltage to the primary is V_1 and voltage across the the primary winding is E_1. Total electric current supplied to primary is I_1. So the voltage V_1 applied to the primary, is partly dropped by I_1Z_1 or $I_1R_1 + j.I_1X_1$ before it appears across primary winding. So voltage equation of this portion of the transformer can **be written as**

$$V_1 - (I_1R_1 + j.I_1X_1) = E_1$$



Vector Diagram of Transformer on load



Equivalent Circuit of Transformer referred to Primary

- Now it is found that total primary current I_1 has two components one is no – load component I_o and other is load component I_2'. As this primary current has two components or branches so there must be a parallel path with primary winding of transformer. This parallel path of electric current is known as excitation branch of equivalent circuit of transformer. The resistive and reactive branches of the excitation circuit can be represented as
$R_o = E_1 / I_w$ and $X_o = E_1 / I_\mu$.

- Now if we see the voltage drop in secondary from primary side then it would be '1/K' times greater and would be written as $Z_2.I_2./K$

  Again $I_2'.N_1 = I_2.N_2$

  $\Rightarrow I_2 = I_2'.N_1 / N_2$

  $\Rightarrow I_2 = I_2'/K$

- Therefore, $Z_2.I_2 /K = = Z_2.I_2'/K^2$

  From above equation,

  Secondary impedance of transformer referred to primary is, $Z_2' = Z_2 /K^2$

  Hence, $R_2' = R_2 /K^2$

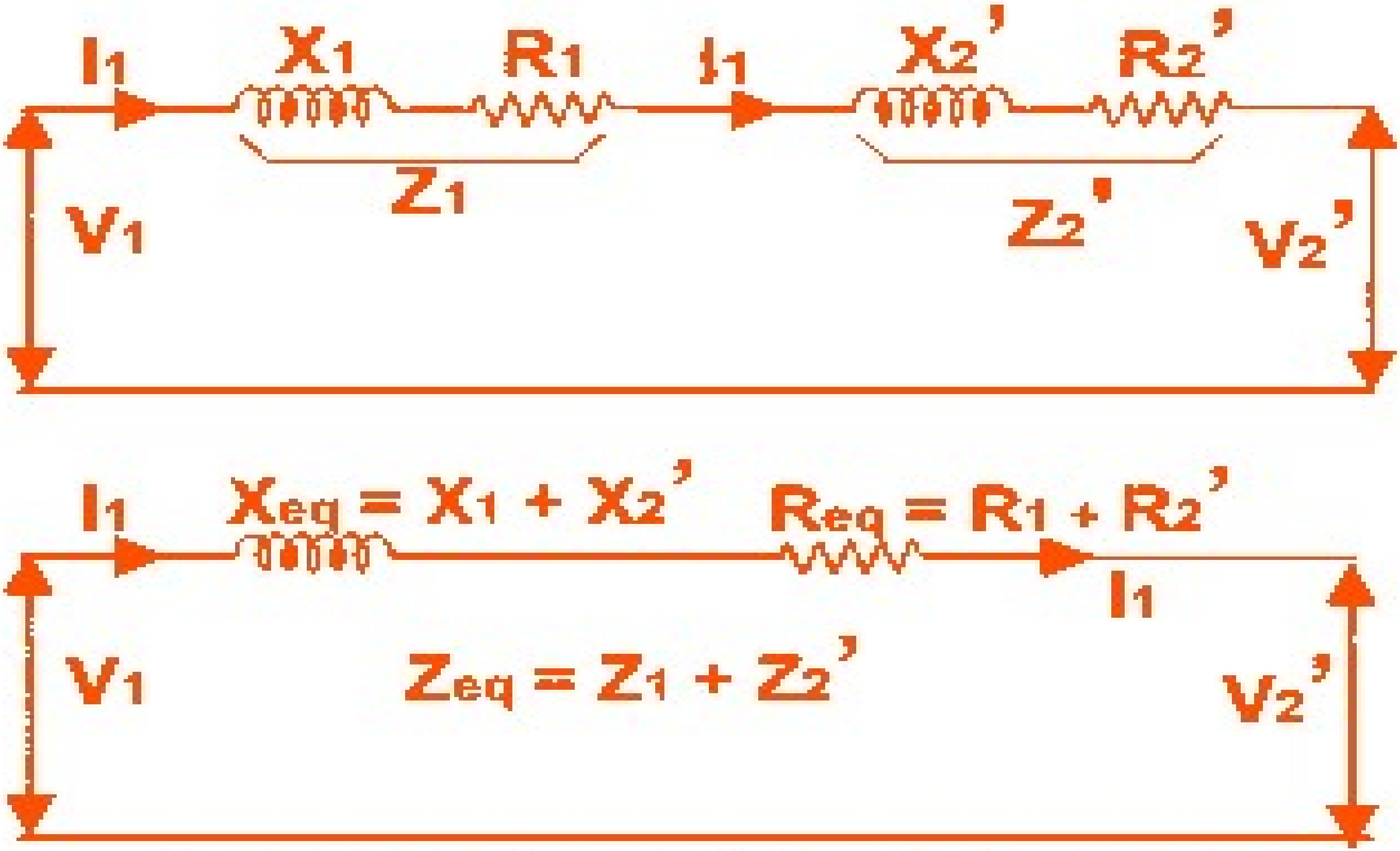
  and $X_2' = X_2 /K^2$

  So The complete equivalent circuit of transformer referred to primary is shown in the figure below,

Approximate Equivalent Circuit of Transformer

- Since I_o is very small compared to I_1, it is less than 5% of full load primary current, I_o changes the voltage drop insignificantly. Hence, it is good approximation to ignore the excitation circuit in approximate equivalent circuit of transformer. The winding resistance and reactance being in series can now be combined into equivalent resistance and reactance of transformer referred to any particular side. In this case it is side 1 or primary side.

Here $V_2' = V_2 / K$



Approximate equivalent circuit of transformer referred to primary

Equivalent Circuit of Transformer referred to Secondary

- In similar way approximate equivalent circuit of transformer referred to secondary can be drawn.

  Where, equivalent impedance of transformer referred to secondary, can be derived as

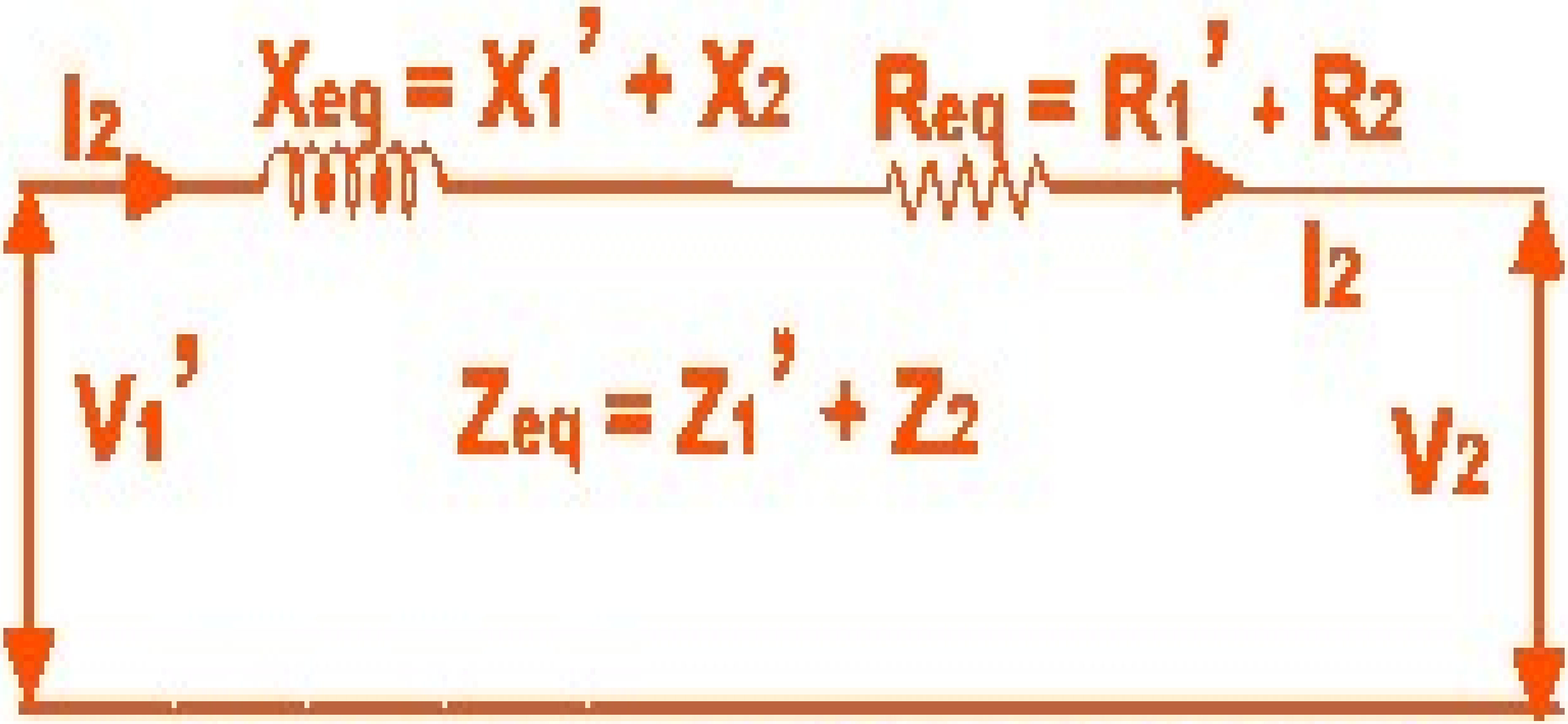
  $Z_1' = Z_1 \cdot K^2$

  Therefore,

  $R_1' = R_1 \cdot K^2$ and

  $X_1' = X_1 \cdot K^2$

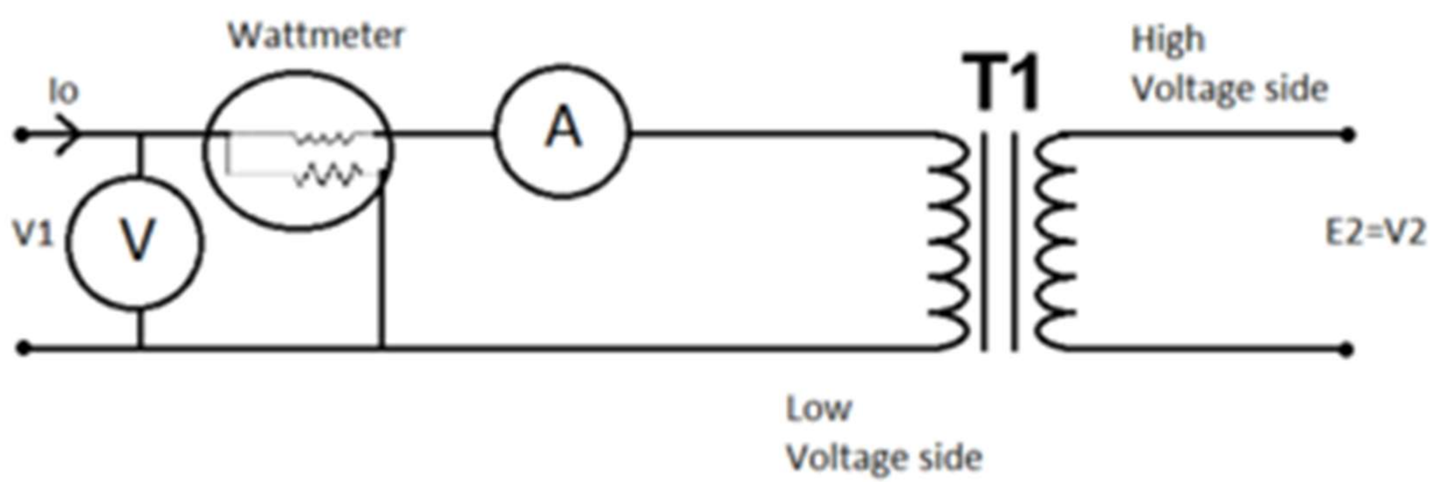
  Here, $V_1' = V_1 \cdot K$



Approximate equivalent circuit of transformer referred to secondary

Open circuit test

- The **open circuit test**, or "no-load test", is one of the methods used in electrical engineering to determine the no-load impedance in the excitation branch of a transformer.



- The secondary of the transformer is left open-circuited. A wattmeter is connected to the primary. An ammeter is connected in series with the primary winding. A voltmeter is optional since the applied voltage is the same as the voltmeter reading. Rated voltage is applied at primary.
- Since the secondary of the transformer is open, the primary draws only no-load current, which will have some copper loss. This no-load current is very small and because the copper loss in the primary is proportional to the square of this current, it is negligible. There is no copper loss in the secondary because there is no secondary current.

- Now the components of o.c tests are

$$W = VI\cos\phi$$

$$I_m = I_0 \cos\phi$$

$$I_w = I_0 \sin\phi$$

$$R_0 = V_1 / I_w$$

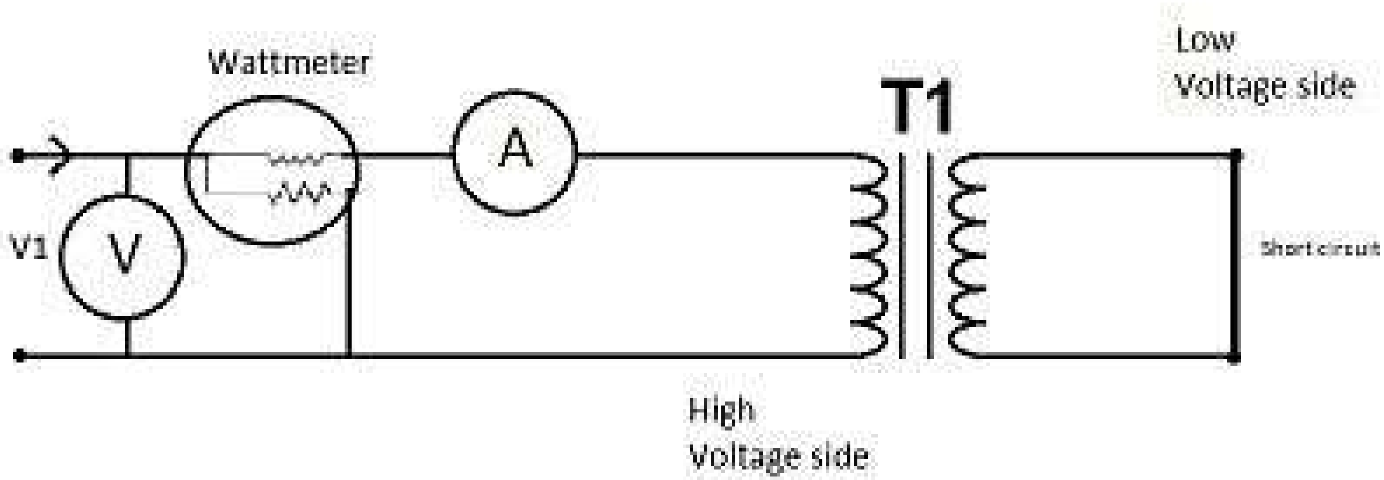
$$X_0 = V_1 / I_m$$

Where,

W	is the wattmeter reading
V_1	is the applied rated voltage
I_0	is the no-load current
I_m	is the magnetizing component of no load current.
I_w	is the core loss component of no load current

Short circuit test

- The purpose of a **short circuit test** is to determine the series branch parameters of the equivalent circuit of a Real transformer.



- The test is conducted on the high voltage (HV) side of the transformer where the low voltage (LV) side or the secondary is short circuited. The supply voltage required to circulate rated current through the transformer is usually very small and is of the order of a few percent of the nominal voltage and this voltage is applied across primary. Thus the wattmeter reading measures only the full load copper loss

- W is the Full load copper loss
- V_1 is the applied voltage
- I_1 is the rated current
- R_{01} is the resistance as viewed from the primary
- Z_{01} is the total impedance as viewed from the primary
- X_{01} is the reactance as viewed from the primary

$$W = I_1^2 R_{01}$$

$$X_{01} = \sqrt{Z_{01}^2 - R_{01}^2}$$

$$Z_{01} = \frac{V_1}{I_1}$$

$$R_{01} = \frac{W}{I_1^2}$$

DC MACHINE

- Construction of motor
- Types of DC generator
- Separately excited
- Self excited
- Three phase induction motor
- Synchronous motor
- Uses of synchronous motor

- A dc machine is a device which converts mechanical energy in to electrical energy and vice-versa.
- When the device converts mechanical energy in to electrical then it is called generator and if it converts electrical energy in to mechanical energy then it is known as motor. Thus electrical machine can be made to work either a generator or motor.
- Generators and motors are very similar to each other in essential parts and construction.

- An **electric motor** is an electric machine that converts electrical energy into mechanical energy.
- In normal motoring mode, most electric motors operate through the interaction between an electric motor's magnetic field and winding currents to generate force within the motor
- **Motor construction**

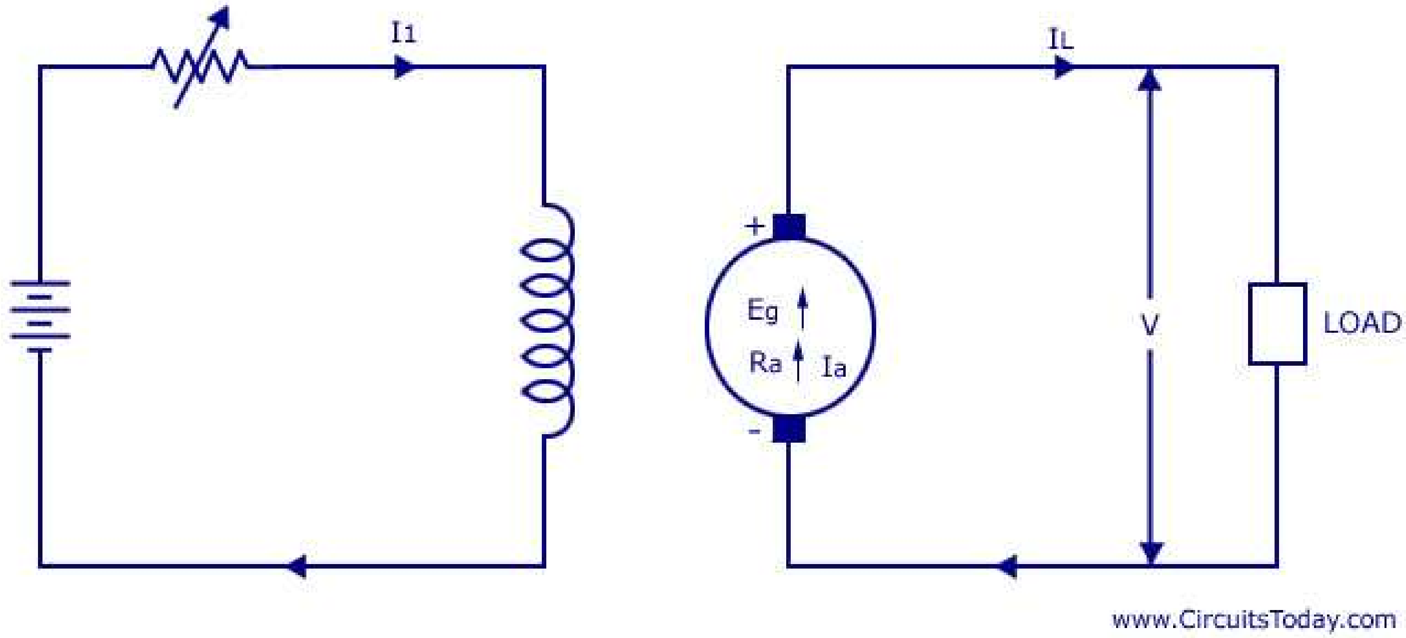
- Rotor; In an electric motor the moving part is the **rotor** which turns the shaft to deliver the mechanical power. The rotor usually has conductors laid into it which carry currents that interact with the magnetic field of the stator to generate the forces that turn the shaft. However, some rotors carry permanent magnets, and the stator holds the conductors.
- Stator; The stationary part is the **stator**, usually has either windings or permanent magnets.
- **Air gap;** In between the rotor and stator is the air gap. The air gap has important effects, and is generally as small as possible, as a large gap has a strong negative effect on the performance of an electric motor.

- **Winding**
- Windings are wires that are laid in coils, usually wrapped around a laminated soft iron magnetic core so as to form magnetic poles when energized with current.
- Some motors have conductors which consist of thicker metal, such as bars or sheets of metal, usually copper, although sometimes aluminum is used. These are usually powered by electromagnetic induction.
- **Commutator**
- A **commutator** is a mechanism used to switch the input of certain AC and DC machines consisting of slip ring segments insulated from each other and from the electric motor's shaft.

- **Types of DC Generators**
- ***"Energy can be converted from one form to other form"*** – A generator does the same – it converts mechanical energy to electrical energy. Mechanical energy can be created by using water turbines, steam turbines, internal combustion engines etc. And a generator converts this mechanical energy to electrical energy. Generators can be broadly classified as AC generators and DC generators.
- DC generators are classified based on their method of excitation. So on this basis there are two types of DC generators:-

- **1. Separately excited DC generator**
- **2. Self excited DC generator**

- **1. Separately excited DC generator**
- As we can guess from the name itself , this dc generator has a field magnet winding which is excited using a separate voltage source (like battery. The output voltage depends on the speed of rotation of armature and field current. The higher the speed of rotation and current – the higher the output e.m.f
- **Note:** Separately excited DC generators are rarely used in practice



Armature current, $I_a = I_L$

Terminal voltage, $V = E_g - I_a R_a$

Electric power developed $= E_g I_a$

Power delivered to load $= E_g I_a - I_a^2 R_a = I_a\left(E_g - I_a R_a\right) = V I_a$

- **2. Self Excited DC Generator**
- These are generators in which the field winding is excited by the output of the generator itself. Self excited DC generator can again be classified as
- **1) Series**
- **2) Shunt and**
- **3) Compound.**

- **A series DC generator** is shown below in fig (a) – in which the armature winding is connected in series with the field winding so that the field current flows through the load as well as the field winding. Field winding is a low resistance, thick wire of few turns. Series generators are also rarely used.

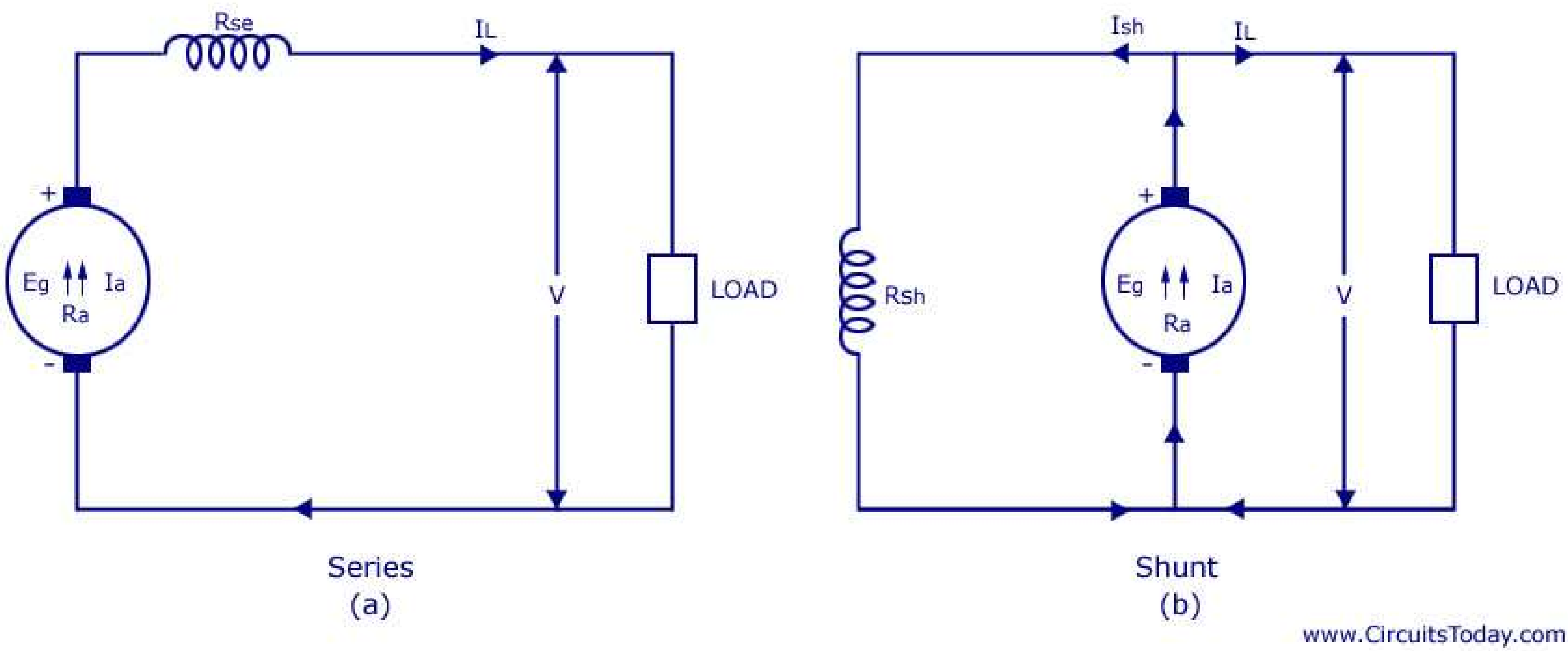
Armature current, $I_a = I_{se} = I_L = I(say)$

Terminal voltage, $V = E_G - I(R_a + R_{se})$

Power developed in armature $= E_g I_a$

Power delivered to load

$$= E_g I_a - I_a^2(R_a + R_{se}) = I_a\left[E_g - I_a(R_a - R_{se})\right] = VI_a \text{ or } VI_L$$


Rse
IL
Eg
Ia
Ra
V
LOAD
Series
(a)
Ish
IL
Rsh
Eg
Ia
Ra
V
LOAD
Shunt
(b)
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- **A shunt DC generator** is shown in figure (b), in which the field winding is parallel to armature winding so that the voltage across both are same. The field winding has high resistance and more number of turns so that only a part of armature current passes through field winding and the rest passes through load.

Shunt field current, $I_{sh} = V/R_{sh}$

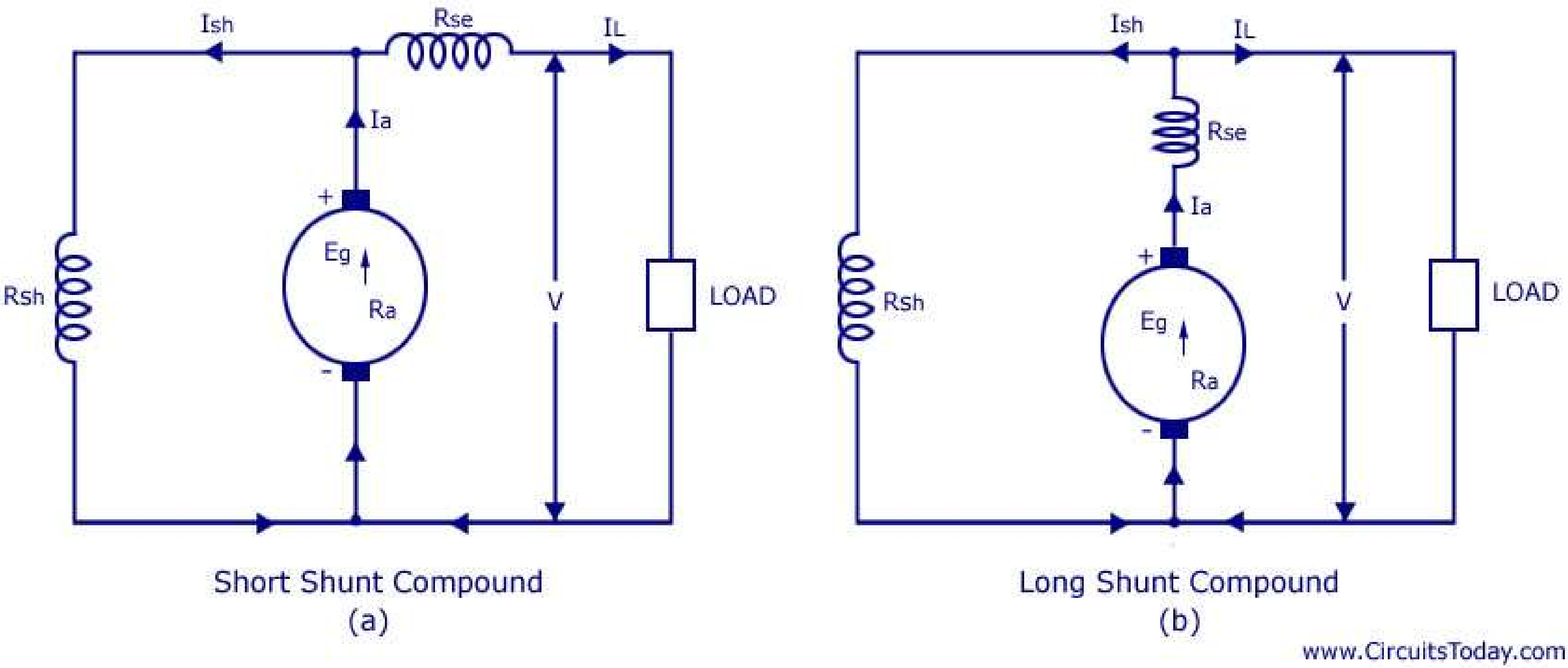
Armature current, $I_a = I_L + I_{sh}$

Terminal voltage, $V = E_g - I_aR_a$

Power developed in armature $= E_gI_a$

Power delivered to load $= VI_L$

A compound generator is shown in figure below. It has two field findings namely Rsh and Rse. They are basically shunt winding (Rsh) and series winding (Rse).
Compound generator is of two types –
Short shunt and Long shunt



Short Shunt Compound
(a)

Long Shunt Compound
(b)

Short shunt

Series field current, $I_{se} = I_L$

Shunt field current, $I_{sh} = \dfrac{V + I_{se}R_{se}}{R_{sh}}$

Terminal voltage, $V = E_g - I_aR_a - I_{se}R_{se}$

Power developed in armature $= E_gI_a$

Power delivered to load $= VI_L$

Here the shunt field winding is wired parallel to armature and series field winding is connected in series to the load. It is shown in fig (1)

Long shunt

Series field current, $I_{se} = I_a = I_L + I_{sh}$

Shunt field current, $I_{sh} = V/R_{sh}$

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

Power developed in armature $= E_g I_a$

Power delivered to load $= VI_L$

Here the shunt field winding is parallel to both armature and series field winding (Rse is wired in series to the armature). It is shown in figure (2)

- Now we can say that these generators are used only for special industrial purposes where there is huge demand for DC production. Otherwise electrical energy is produced by AC generators and is transmitted from one place to other as AC itself. When a DC power is required, we usually convert AC to DC using rectifiers.

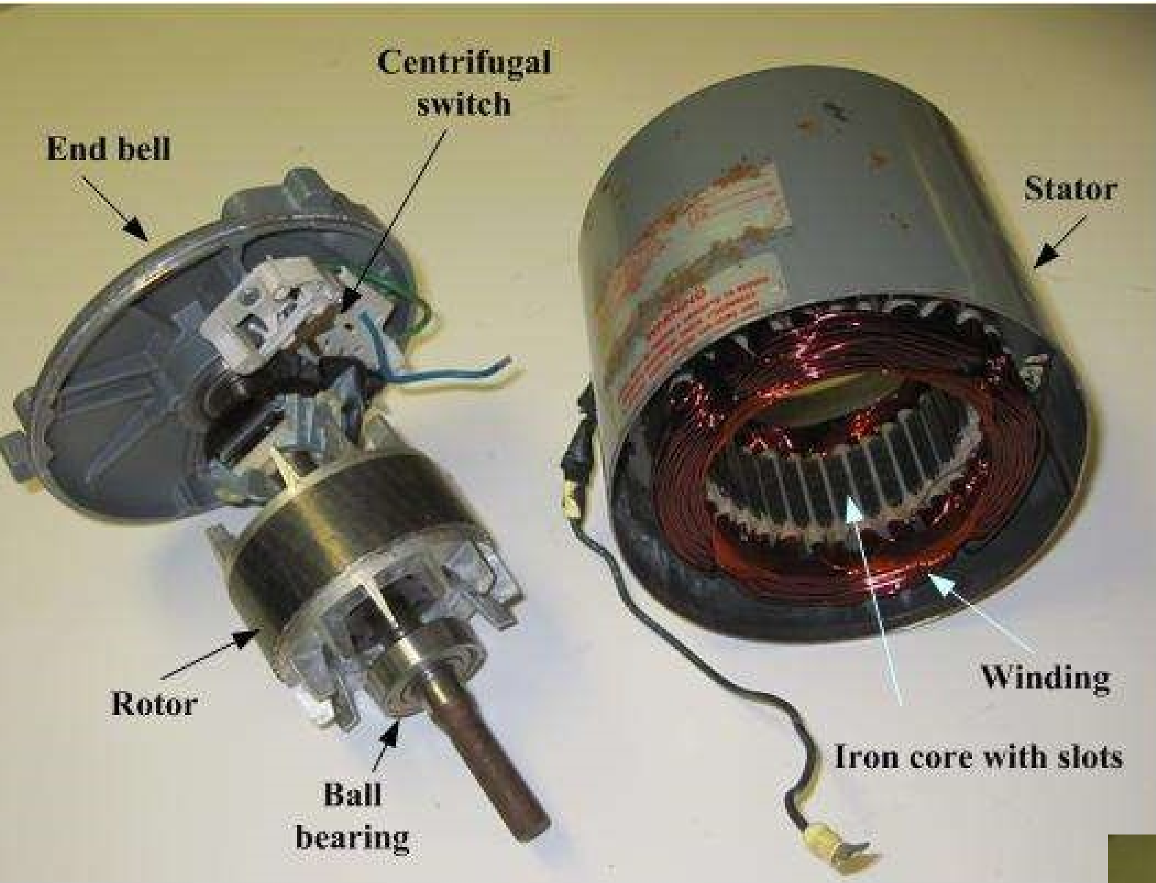
THREE PHASE INDUCTION MOTOR

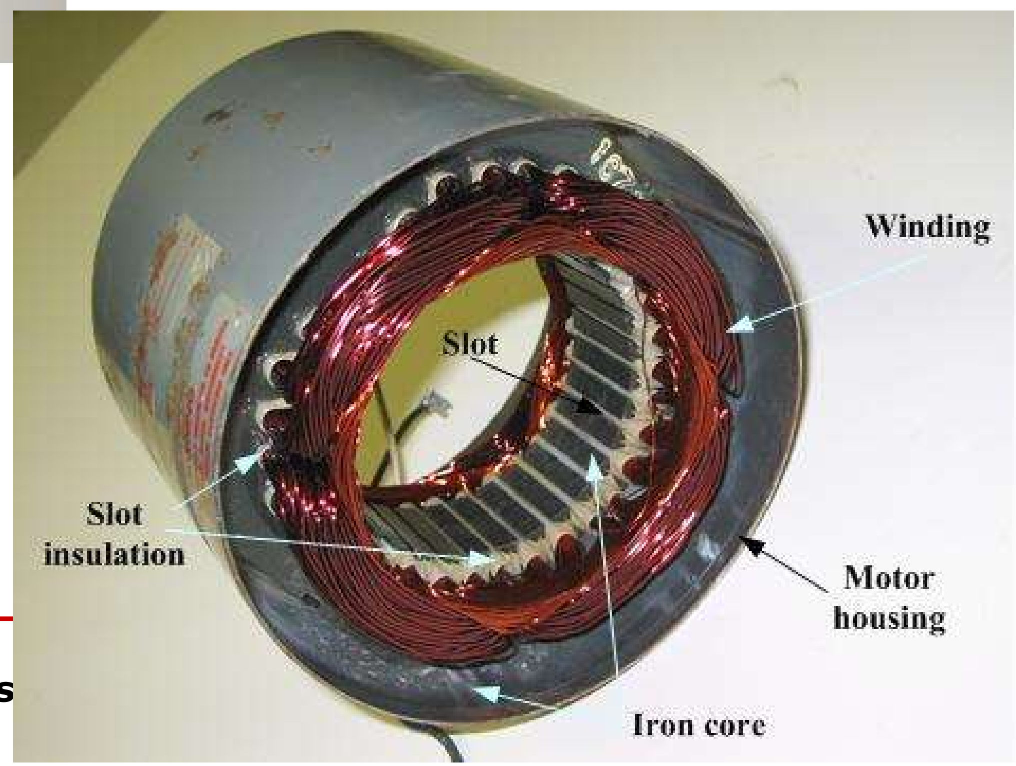
- An electrical motor is such an electromechanical device which converts electrical energy into a mechanical energy. In case of three phase AC operation, most widely used motor is Three phase induction motor as this type of motor does not require any starting device or we can say they are self starting induction motor.
- The basic constructional feature of this motor consists of two major parts:
- Stator: **Stator of three phase induction motor** is made up of numbers of slots to construct a 3 phase winding circuit which is connected to 3 phase AC source. The three phase windings are arranged in such a manner in the slots that they produce a rotating magnetic field after AC is given to them.

- The stator of the motor consists of overlapping windings offset by an electrical angle of 120°. When the primary winding or the stator is connected to a 3 phase AC source, it establishes a rotating magnetic field which rotates at the synchronous speed.
- Rotor: **Rotor of three phase induction motor** consists of cylindrical laminated core with parallel slots that can carry conductors. Conductors are heavy copper or aluminum bars which fits in each slots & they are short circuited by the end rings.

- The number of magneic poless of the revolving field will be same as the number of poles for which each phase of primary or stator winding is wound or wrapped. The speed at which the field produced by the primary current will revolve is called synchronous speed of motor and is given by
- $N_S = 120 \times f / p$
- *Where N_s is the synchronous speed*
- *F is the frequency*
- *P is the no. of poles on stator.*

- The difference between the stator (synchronous speed) and rotor speeds is called the slip. The rotation of the magnetic field in an induction motor has the advantage that no electrical connections need to be made to the rotor.
- Thus the Three Phase Induction Motor is:
  - Self-starting.
  - Robust in construction.
  - Economical.
  - Easier to maintain.


Centrifugal switch
End bell
Stator
Rotor
Winding
Iron core with slots
Ball bearing


Winding
Slot
Slot insulation
Motor housing
Iron core

Synchronous motor

- A synchronous motor operates on synchronous (constant) speed, hence the motor develop a constant torque in the direction of rotation.
- It is electrically identical with an alternator or AC generator.
  - It runs either at synchronous speed or not at all i.e while running it maintains constant speed
  - It is capable off being operated under a wide range of power factors both lagging and leading
  - It can be used for power correction purpose in addition to supplying torque to drive loads.

USE OF1-ϕ SYNCHRONOUS MOTOR

- They are small ,constant speed motors.
- Built for the wide range of output and speed.
- Is power is on the range of 0.001 KW and are used in clocks, control apparatus timing devices etc.