

PART - A

UNIT - 1

BASIC CONCEPTS: Principle of operation of transformer, Constructional details of shell type and core type single-phase and three-phase transformers. EMF equation, operation of practical power transformer under no load and on load (with phasor diagrams). Concept of ideal transformers, current inrush in transformers. **6 Hours**

Transformers: The static electrical device which transfers the voltage from one level to another level by the principle of self and mutual induction without change in frequency.

Michael Faraday propounded the principle of electro-magnetic induction in 1831. It states that a voltage appears across the terminals of an electric coil when the flux linked with the same changes. The magnitude of the induced voltage is proportional to the rate of change of the flux linkages. This finding forms the basis for many magneto electric machines.

The earliest use of this phenomenon was in the development of induction coils. These coils were used to generate high voltage pulses to ignite the explosive charges in the mines. As the d.c. power system was in use at that time, very little of transformer principle was made use of. In the d.c. supply system the generating station and the load center have to be necessarily close to each other due to the requirement of economic transmission of power.

Transformers can link two or more electric circuits. In its simple form two electric circuits can be linked by a magnetic circuit, one of the electric coils is used for the creation of a time varying magnetic field. The second coil which is made to link this field has a induced voltage in the same. The magnitude of the induced emf is decided by the number of turns used in each coil. Thus the voltage level can be increased or decreased by changing

the number of turns. This excitation winding is called a primary and the output winding is called a secondary. As a magnetic medium forms the link between the primary and the secondary windings there is no conductive connection between the two electric circuits. The transformer thus provides an electric isolation between the two circuits. The frequency on the two sides will be the same. As there is no change in the nature of the power, the resulting machine is called a 'transformer' and not a 'converter'. The electric power at one Voltage/current level is only 'transformed' into electric power, at the same frequency, to another voltage/current level.

Even though most of the large-power transformers can be found in the power systems, the use of the transformers is not limited to the power systems. The use of the principle of transformers is universal. Transformers can be found operating in the frequency range starting from a few hertz going up to several mega hertz. Power ratings vary from a few miliwatts to several hundreds of megawatts. The use of the transformers is so wide spread that it is virtually impossible to think of a large power system without transformers. Demand on electric power generation doubles every decade in a developing country. For every MVA of generation the installed capacity of transformers grows by about 7MVA.

Classification of Transformer:

The transformers are classified according to:

1. The Type of Construction:
 - (a) Core Type Transformer
 - (b) Shell Type Transformer
2. The Number of Phases:
 - (a) Single Phase Transformer
 - (b) Three Phase Transformer
3. The Placements:
 - (a) Indoor Transformer
 - (b) Outdoor Transformer
4. The Load:
 - (a) Power Transformer
 - (b) Distribution Transformer

Ideal Transformer

To understand the working of a transformer it is always instructive, to begin with the concept of an *ideal* transformer with the following properties.

1. Primary and secondary windings have no resistance.
2. All the flux produced by the primary links the secondary winding i.e., there is no leakage flux.
3. Permeability μ_r of the core is infinitely large. In other words, to establish flux in the core vanishingly small (or zero) current is required.
4. Core loss comprising of *eddy current* and *hysteresis* losses are neglected.

Construction of a Transformer

There are two basic parts of a transformer:

1. Magnetic core
 2. Winding or coils
- **MAGNETIC CORE:** The core of a transformer is either square or rectangular in size. It is further divided in two parts. The vertical portion on which the coils are bound is called limb, while the top and bottom horizontal portion is called yoke of the core as shown in fig. 2.

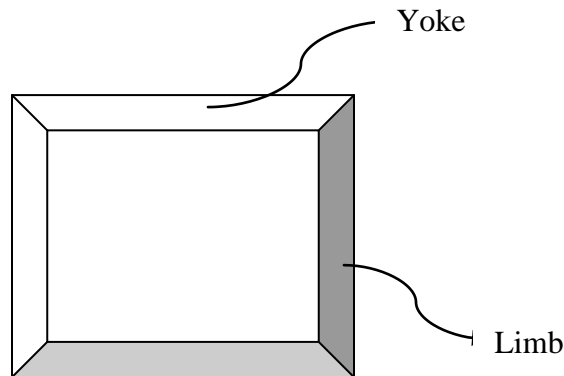


Fig. 2

Core is made up of laminations. Because of laminated type of construction, eddy current losses get minimized. Generally high grade silicon steel laminations (0.3 to 0.5 mm thick) are used. These laminations are insulated from each other by using insulation like varnish. All laminations are varnished. Laminations are overlapped so that to avoid the air

gap at the joints. For this generally 'L' shaped or 'I' shaped laminations are used which are shown in the fig. 3 below.

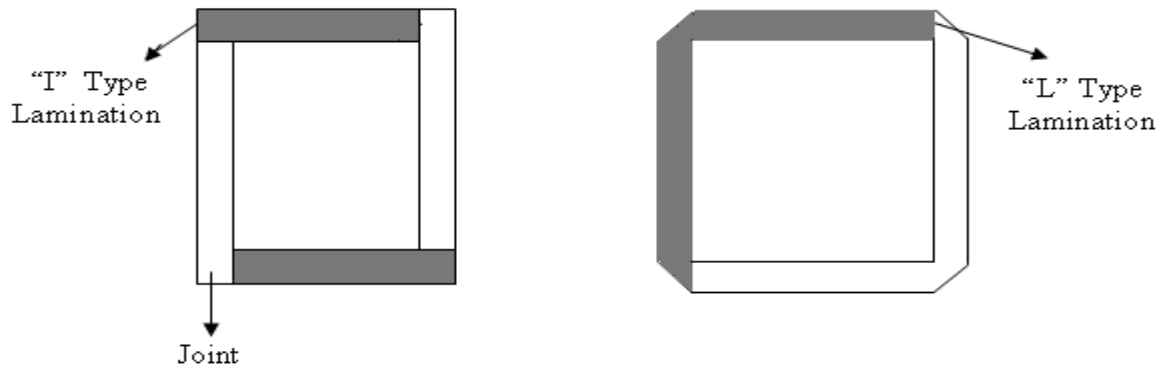


Fig. 3

WINDING: There are two windings, which are wound on the two limbs of the core, which are insulated from each other and from the limbs as shown in fig. 4. The windings are made up of copper, so that, they possess a very small resistance. The winding which is connected to the load is called secondary winding and the winding which is connected to the supply is called primary winding. The primary winding has N_1 number of turns and the secondary windings have N_2 number of turns.

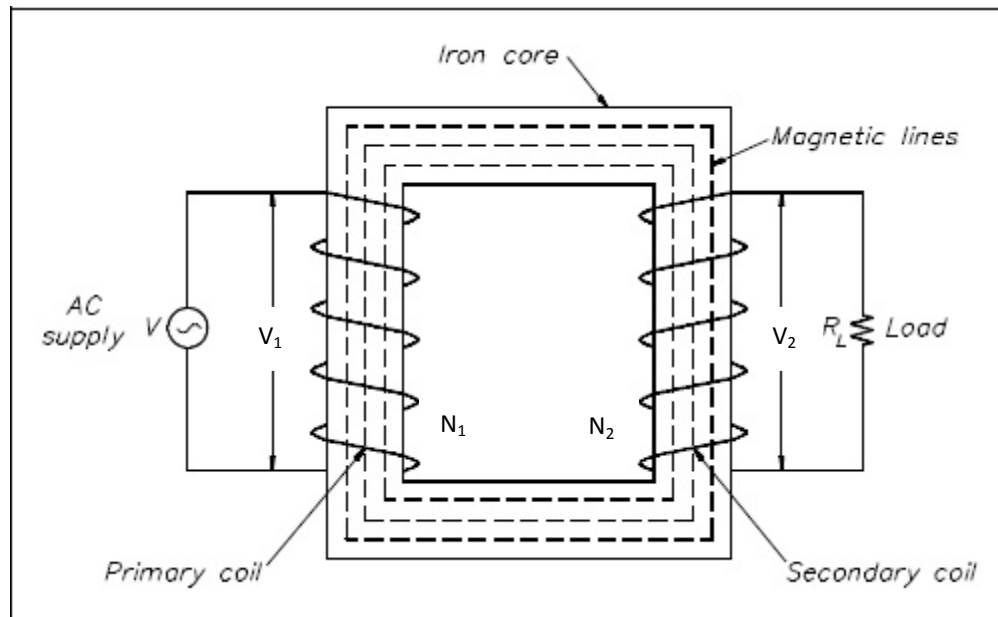


Fig. 4. Single Phase Transformer

TYPES OF TRANSFORMERS:

The classification of transformer is based on the relative arrangement or disposition of the core and the windings. There are two main types of transformers.

1. Core type
2. Shell type

CORE TYPE:

Fig 5(a)& (b) shows the simplified representation of a core type transformer, where the primary and secondary winding have been shown wound on the opposite sides. However, in actual practise, half the primary and half the secondary windings are situated side by side on each limb, so as to reduce leakage flux as shown in fig 6. This type of core construction is adopted for small rating transformers.

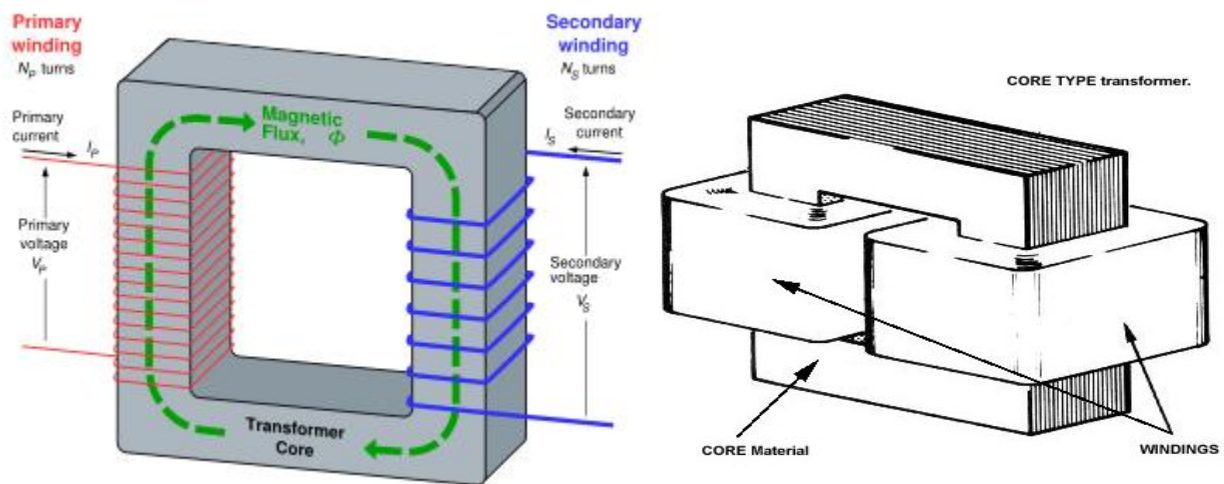
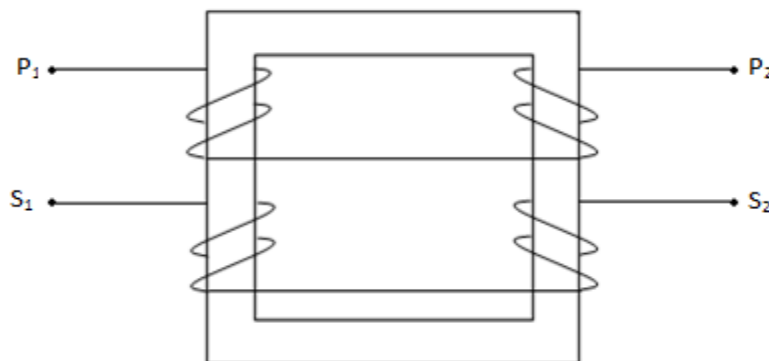


Fig. 5(a) & (b) Single Phase Core Type Transformer



SHELL TYPE:

In this type, the windings occupy a smaller portion of the core as shown in fig 5. The entire flux passes through the central part of the core, but outside of this a central core, it divides half, going in each direction. The coils are form wound, multilayer disc-type, each of the multilayer discs is insulated from the other by using paper. This type of construction is generally preferred for high voltage transformers.

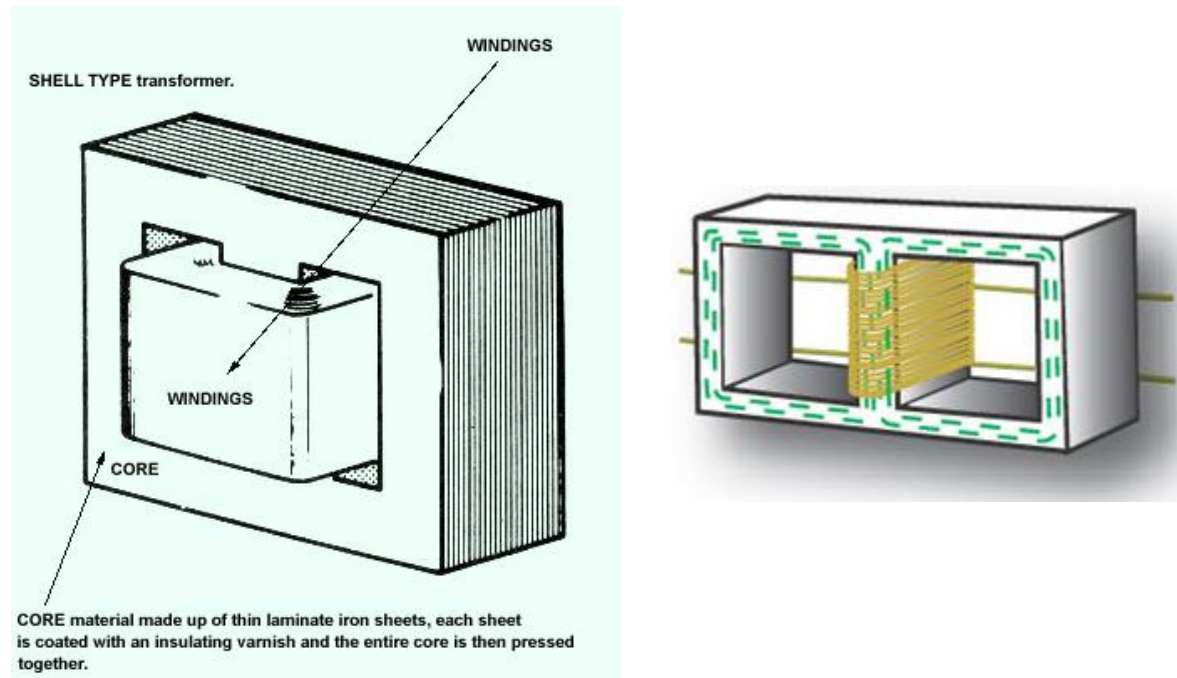
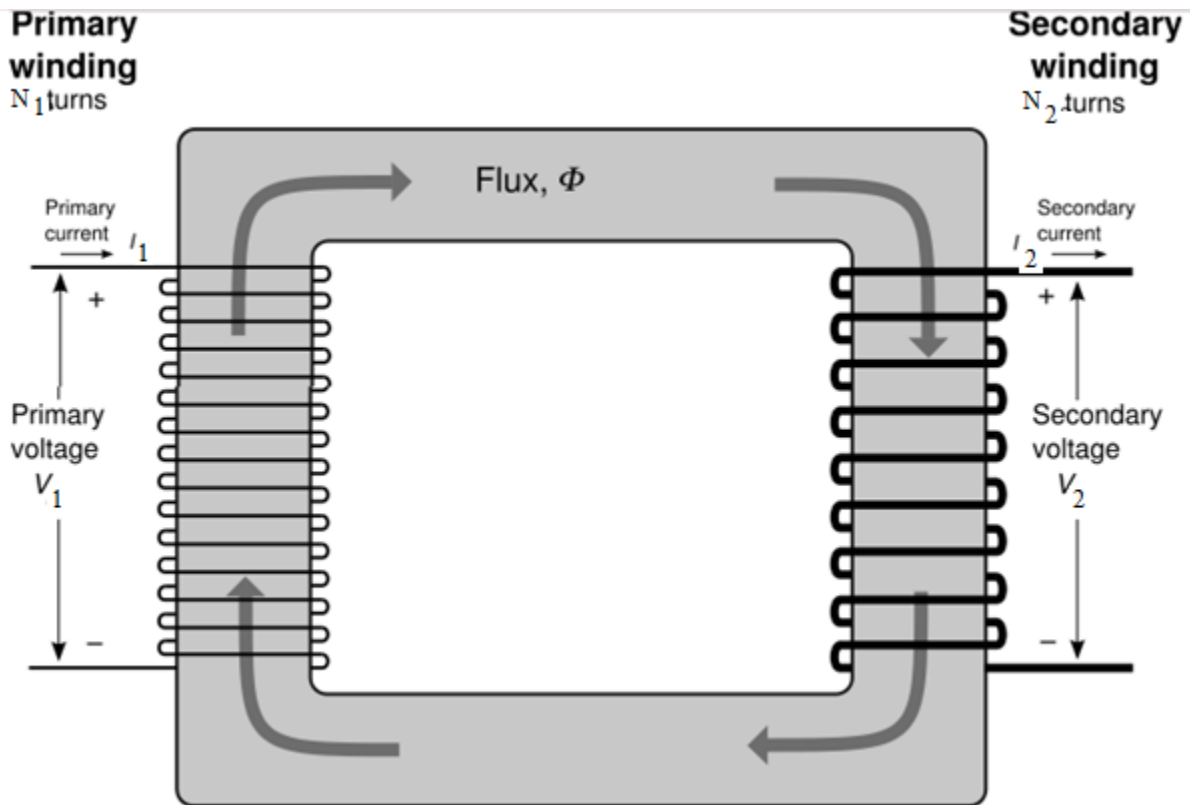


Fig. 7 (a) & (b) Single Phase Shell Type Transforme

Principle of Operation of a Single Phase Transformer



A single phase transformer works on the principle of mutual induction between two magnetically coupled coils. When the primary winding is connected to an alternating voltage of r.m.s value, V_1 volts, an alternating current flows through the primary winding and setup an alternating flux ϕ in the material of the core. This alternating flux ϕ , links not only the primary windings but also the secondary windings. Therefore, an e.m.f e_1 is induced in the primary winding and an e.m.f e_2 is induced in the secondary winding, e_1 and e_2 are given $e_1 = -N_1 \frac{d\phi}{dt}$ ----- (a)

$$e_2 = -N_2 \frac{d\phi}{dt} \text{ -----(b)}$$

If the induced e.m.f is e_1 and e_2 are represented by their rms values E_1 and E_2 respectively, then

$$E_1 = -N_1 \frac{d\phi}{dt} \text{ ----- (1)}$$

$$E_2 = -N_2 \frac{d\phi}{dt} \text{ ----- (2)}$$

Therefore, $\frac{E_2}{E_1} = \frac{N_2}{N_1} = k$ ----- (3)

K is known as the transformation ratio of the transformer. When a load is connected to the secondary winding, a current I_2 flows through the load, V_2 is the terminal voltage across the load. As the power transferred from the primary winding to the secondary winding is same,

Power input to the primary winding = Power output from the secondary winding.

$$E_1 I_1 = E_2 I_2$$

(Assuming that the power factor of the primary is equal to the secondary).

Or, $\frac{E_2}{E_1} = \frac{I_1}{I_2} = k$ ----- (4)

From eqn (3) and (4), we have

$$\frac{E_2}{E_1} = \frac{N_2}{N_1} = \frac{I_1}{I_2} = k$$
 ----- (5)

The directions of emf's E_1 and E_2 induced in the primary and secondary windings are such that, they always oppose the primary applied voltage V_1 .

EMF Equation of a transformer:

Consider a transformer having,

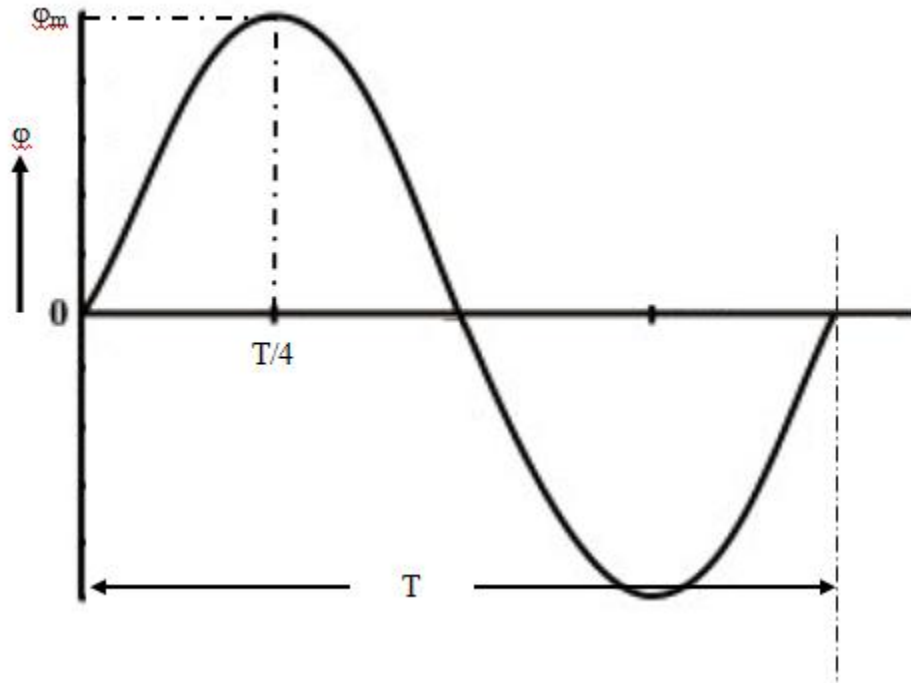
N_1 = Primary turns

N_2 = Secondary turns

Φ_m = Maximum flux in the core

$\Phi_m = B_m \times A$ webers

f = frequency of ac input in hertz (Hz)



The flux in the core will vary sinusoidally as shown in figure, so that it increases from zero to maximum “ ϕ_m ” in one quarter of the cycle i.e, $\frac{1}{4f}$ second

$$\begin{aligned}\text{Therefore, average rate of change of flux} &= \frac{\phi_m}{1/4f} \\ &= 4f\phi_m\end{aligned}$$

We know that, the rate of change of flux per turn means that the induced emf in volts.

Therefore, average emf induced per turn = $4f\phi_m$ volts.

Since the flux is varying sinusoidally, the rms value of induced emf is obtained by multiplying the average value by the form factor .

$$\begin{aligned}\text{Therefore, rms value of emf induced per turns} &= 1.11 \times 4f \times \phi_m \\ &= 4.44f\phi_m \text{ volts}\end{aligned}$$

The rms value of induced emf in the entire primary winding = (induced emf per turn) \times number of primary turns

$$\text{i.e, } E_1 = 4.44 f \phi_m \times N_1 = 4.44 f B_m \times A \times N_1$$

Similarly;

$$E_2 = 4.44 f \phi_m \times N_2 = 4.44 f B_m \times A \times N_2$$

Transformation Ratio:

- (1) Voltage Transformation Ratio
- (2) Current Transformation Ratio

Voltage Transformation Ratio:

Voltage transformation ratio can be defined as the ratio of the secondary voltage to the primary voltage denoted by K

$$\text{Mathematically given as } K = \frac{\text{Secondary Voltage}}{\text{Primary Voltage}} = \frac{V_2}{V_1}$$

$$K = \frac{E_2}{E_1} = \frac{4.44 f \phi_m N_2}{4.44 f \phi_m N_1} = \frac{N_2}{N_1}$$

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

Current Transformation Ratio:

Consider an ideal transformer and we have the input voltampere is equal to output voltampere.

Mathematically, *Input Voltampere = Output Voltampere*

$$V_1 I_1 = V_2 I_2$$

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

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

Coupled circuits

- When two coils separated by each other, a change in current in one coil will effect the voltage in another coil by mutual induction
- Self Inductance: A coil capable of inducing an emf in itself by changing current flowing through it, this property of coil is known as self inductance.
- The self induced emf is directly proportional to the rate of change of current.

$$e \propto di/dt; e = L di/dt$$

- Where L =coefficient of self inductance.

Mutual Inductance

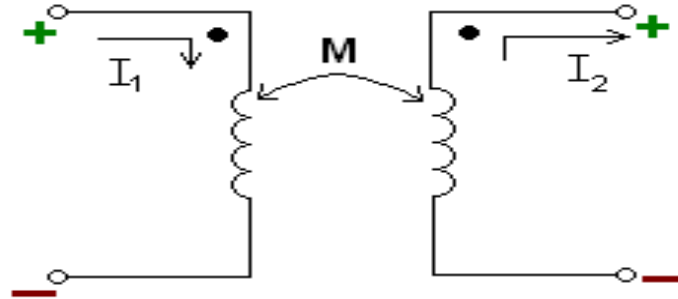
- Current in one coil changes, there occurs a change in flux linking with other as result an emf is induced in the adjacent coils.
- The mutually induced emf e_2 in the second coil is dependent on the rate of change of current in the first coil.
- $e_2 \propto di_1/dt; e_2 = M di_1/dt$

COEFFICIENT OF COUPLING

- $K = M/(L_1 L_2)$
- The two coils are said to be tightly or perfectly coupled only when $K=1$ and therefore $M=L_1 L_2$ it's said to be maximum mutual inductance
- When the distance between the two coils is greater than the coils are said to be loosely packed
- Coefficient of coupling will help in deciding whether the coils are closely packed or loosely packed.

Derivation for Co-efficient of coupling

Dot Convention

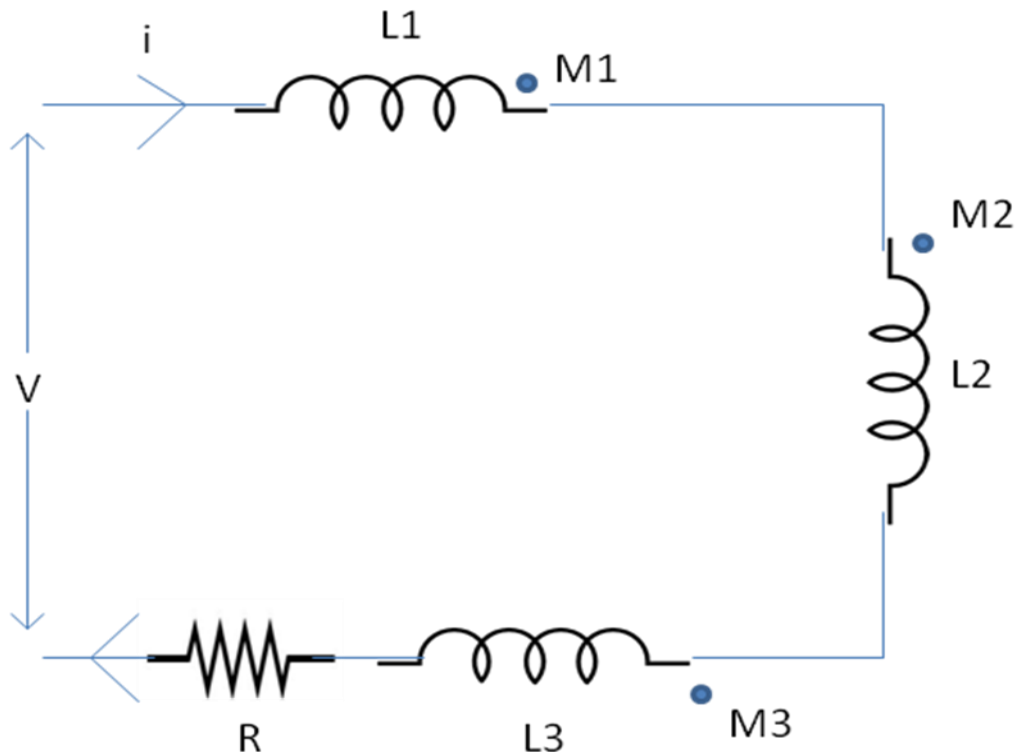


- A current entering the dotted terminal of one coil produces an open-circuit voltage which is positively sensed at the dotted terminal of the second coil
- A current entering the undotted terminal of one coil produces an open-circuit voltage which is positively sensed at the undotted terminal of the second coil.
- The advantage of dot convention is to find out the direction of the winding and direction of flux linking the coil
- The direction of the flux due to rate of change of flux can be analyzed by right hand thumb rule.

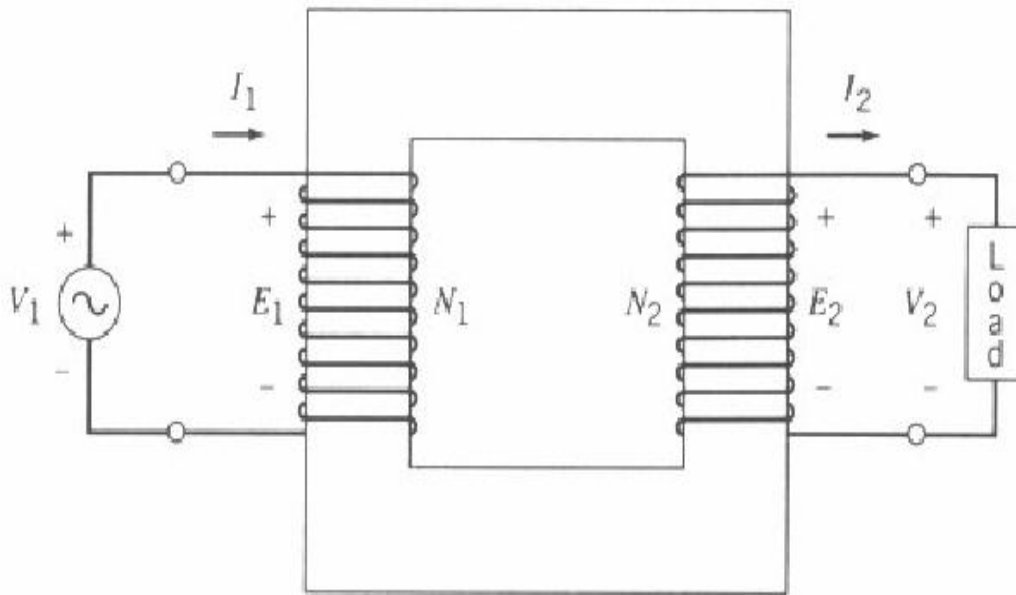
Different connections of coupled circuits

- Series Aiding:
- Series Opposing:
- Parallel Aiding:
- Parallel Opposing
- **Refer Circuit diagram and derivation for the class notes.**

Equilibrium Equations



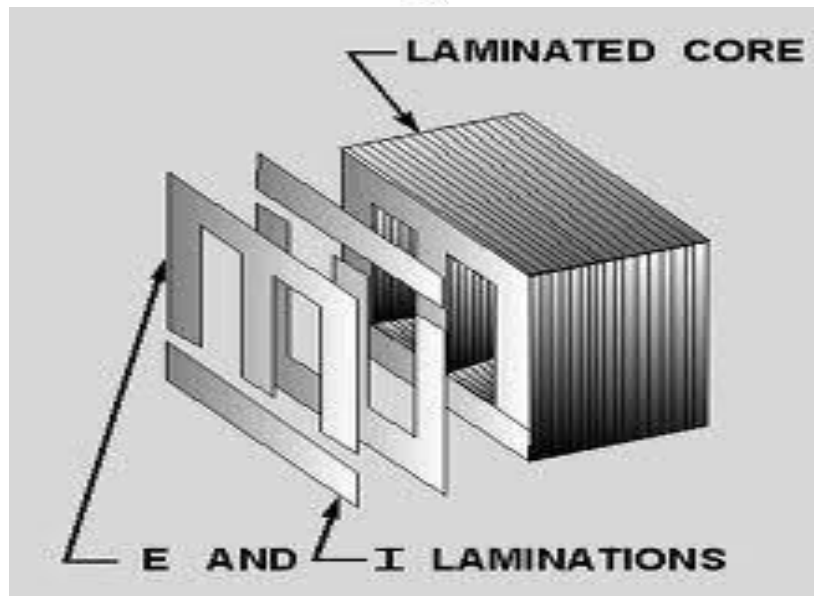
- The coil where electrical energy is fed is considered as Primary
- The coil where load is connected to draw the current from mutual induction is Secondary
- There are Two main part in Transformer 1) Core 2) Windings
- Core: The top and bottom part of the core is Yoke, The side limbs are considered as Legs. The core is made up of Silicon steel to avoid the Eddy current and Hysteresis Loss.
- Windings: Basically it is made up of Copper and depends on the current value based on this it is of two types Low Voltage and High Voltage Winding.



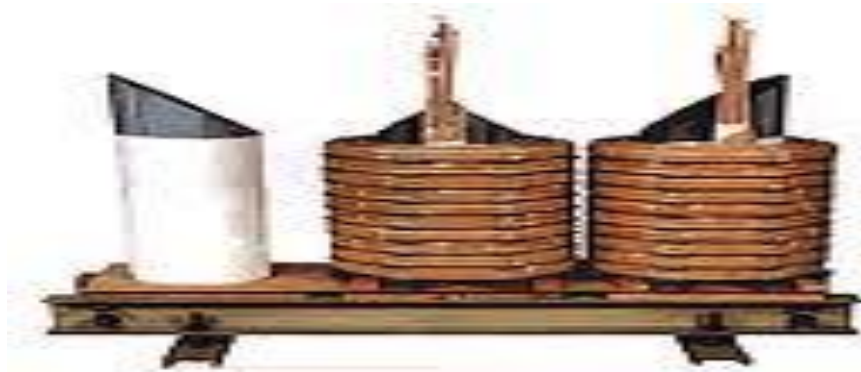
❖ There are Two main part in Transformer

1) Core 2) Windings

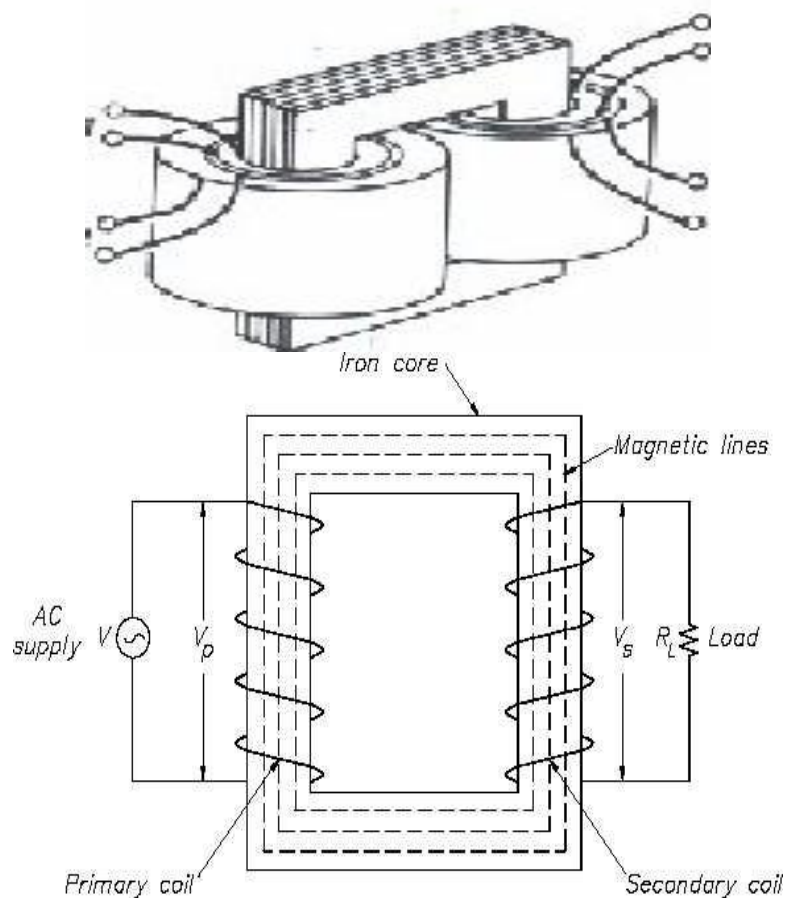
- Core: The top and bottom part of the core is Yoke, the Vertical portions are considered as of Limbs Legs.
- The core is made up of Silicon steel laminations of thickness 0.33m (CRGO) to avoid the Eddy current and Hysteresis Loss.
- Each laminations are varnished one another and bolted to form a L or T or I shaped structures.



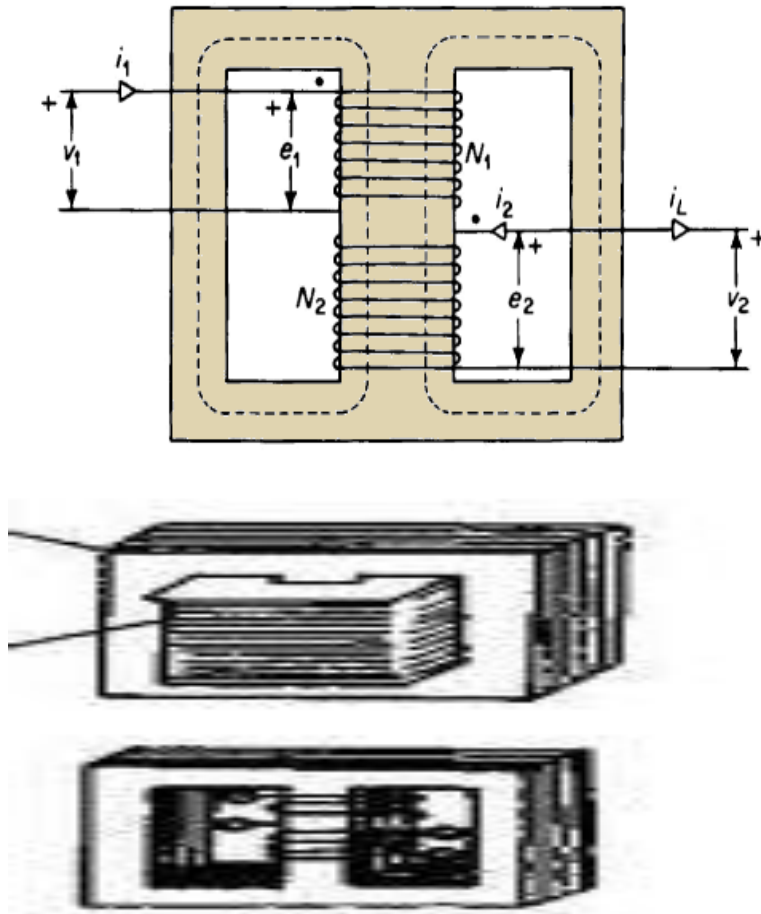
- Windings: Basically it is made up of Copper and depends on the current value based on this it is of two types Low Voltage and High Voltage Winding.
- The LV and HV coils should be placed close to each other as to increase the mutual induction.
- The two coils are separated by insulated materials such as paper, cloth or mica
- Coils maybe placed Helically(Cylindrical) or Sandwiched in the window of transformer



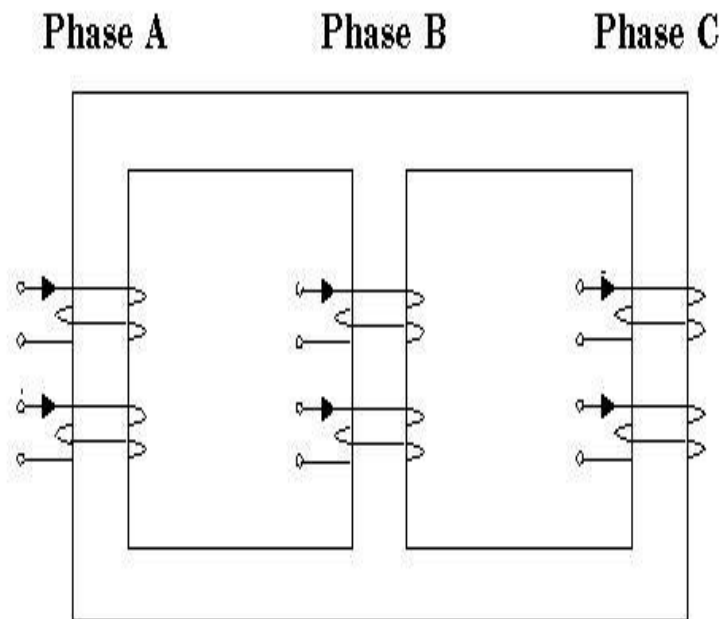
- Rectangular core, two limbs.
- Winding encircles core and Low voltage coil is placed near the limb and insulation by paper and High voltage on it.
- Windings are distributive type and natural cooling is effective and top laminations can be removed for maintenance work.



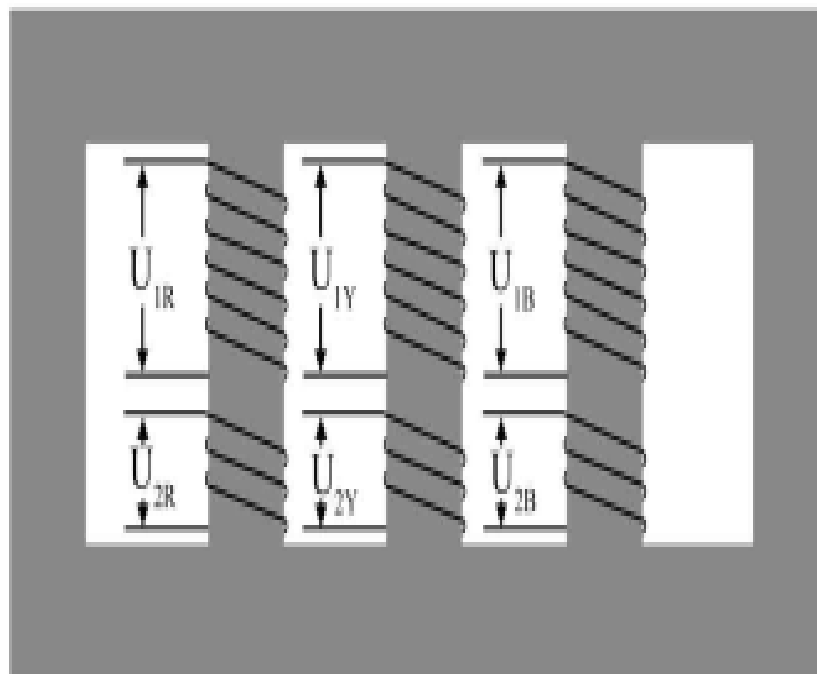
- Core Encircles most of windings
- Natural cooling is not possible
- Maintenance work is difficult
- For HV Transformers
- 1- ϕ requires three limbs
- Double magnetic circuit



- Core consists of three limbs, top and bottom yokes.
- Each limb consists of primary and secondary winding(LV and HV winding)
- Three phase transformer can also designed by arranging three single phase transformer in series.



- Shell type(five limb)is used for large transformer because they can be made with a reduced height.
- The cost of three phase shell type transformer is more.
- For cooling of transformer fans are fixed at the radiators.



Core type

- Winding encircles core
- Cylindrical coils
- Natural cooling is effective
- Maintenance work is easy
- Single magnetic circuit
- Low Voltage and distribution type
- Two limbs for 1-phase and three for 3-phase

Shell type

- Core encircles windings
- Disc type
- Natural cooling is not effective
- Maintenance work is difficult

- Double magnetic circuit
- High Voltage transformer
- Three limbs for 1-phase and 6-limbs for three phase

Types of Transformer

- Power Transformer
- Distribution Transformer
- Constant Voltage Transformer
- Constant Current Transformer
- Variable Frequency Transformer
- Auto Transformer

Power transformer of rating 500 mVA 11kv/230v

- Transformer having rating more than 200kva is power transformers
- Usually this transformers are placed near the generating and substations to either step up or step down voltage levels
- The transformers which are used to transform the transmission voltage to the voltage level of primary feeders are called substation transformers



Fig: Power Transformer

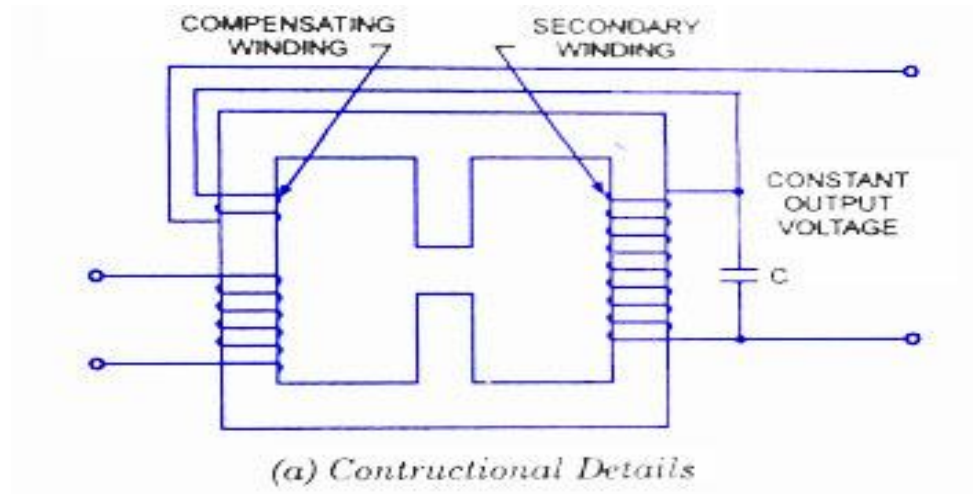
Pad mounted & pole mounted distribution transformer

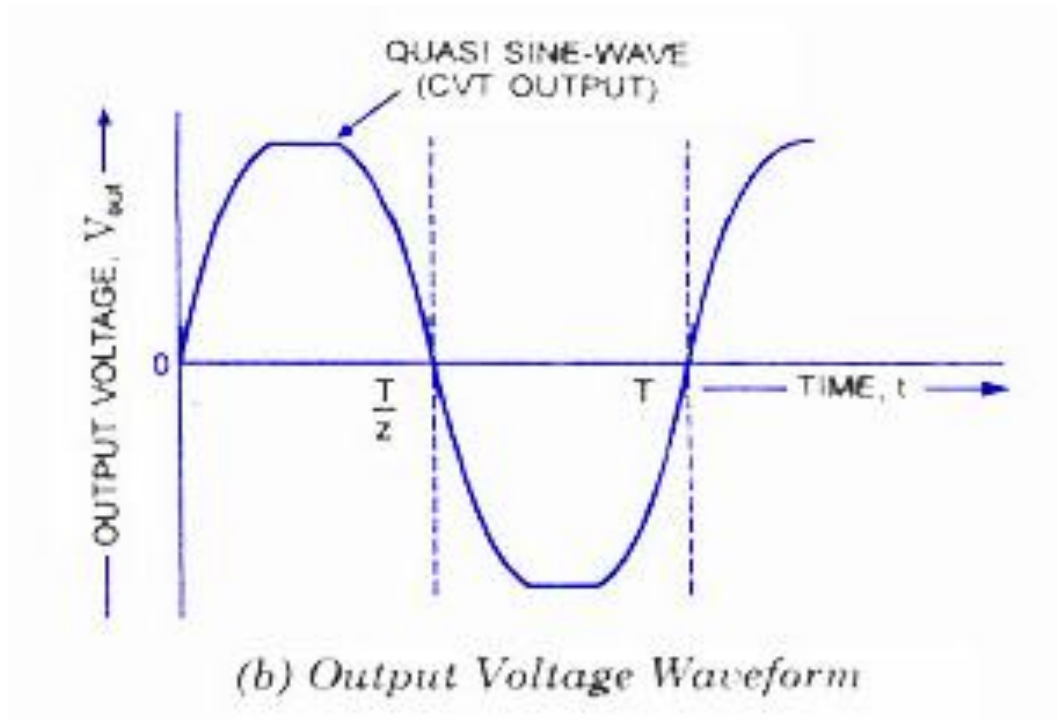
- It changes feeder voltage to the utilization voltage for customer requirements.
- These transformers operate throughout the day therefore iron loss will be throughout the day and copper loss occur only when it is loaded.
- These are low load high efficiency machines.
- It is designed in such way to maintain the small leakage reactance to get good voltage regulation as it wants to operate throughout the day.
- Depending on the installation it is of pole mounted or pad mounted as shown in the diagram.



Constant voltage transformer and its output

- It uses the leakage inductance of its secondary windings in combination with external capacitors to create one or more resonant circuits.
- It consists of linear inductor which is unsaturated and this will be primary.
- The non linear inductor(saturated) forms the secondary of the transformer.
- The capacitor connected in parallel saturates by drawing the secondary current due to saturation a constant output voltage is produced.
- Since the output is a quasi sine wave because of the constant in output voltage and this is improved by the compensating winding.





Constant Current transformer

- It consists of Primary and secondary winding but one is movable and mounted on the same core
- A counter weight is used to balance the moving winding.
- The principle is production of two oppositely directed magnetic field
- If load impedance decreases load current increases due to this large opposition between two magnetic fields produced by primary and secondary
- Due to repulsion movable winding moves up and further gets separated from stationary and large leakage flux reduces and in turn mutual flux reduces thus secondary voltage reduces

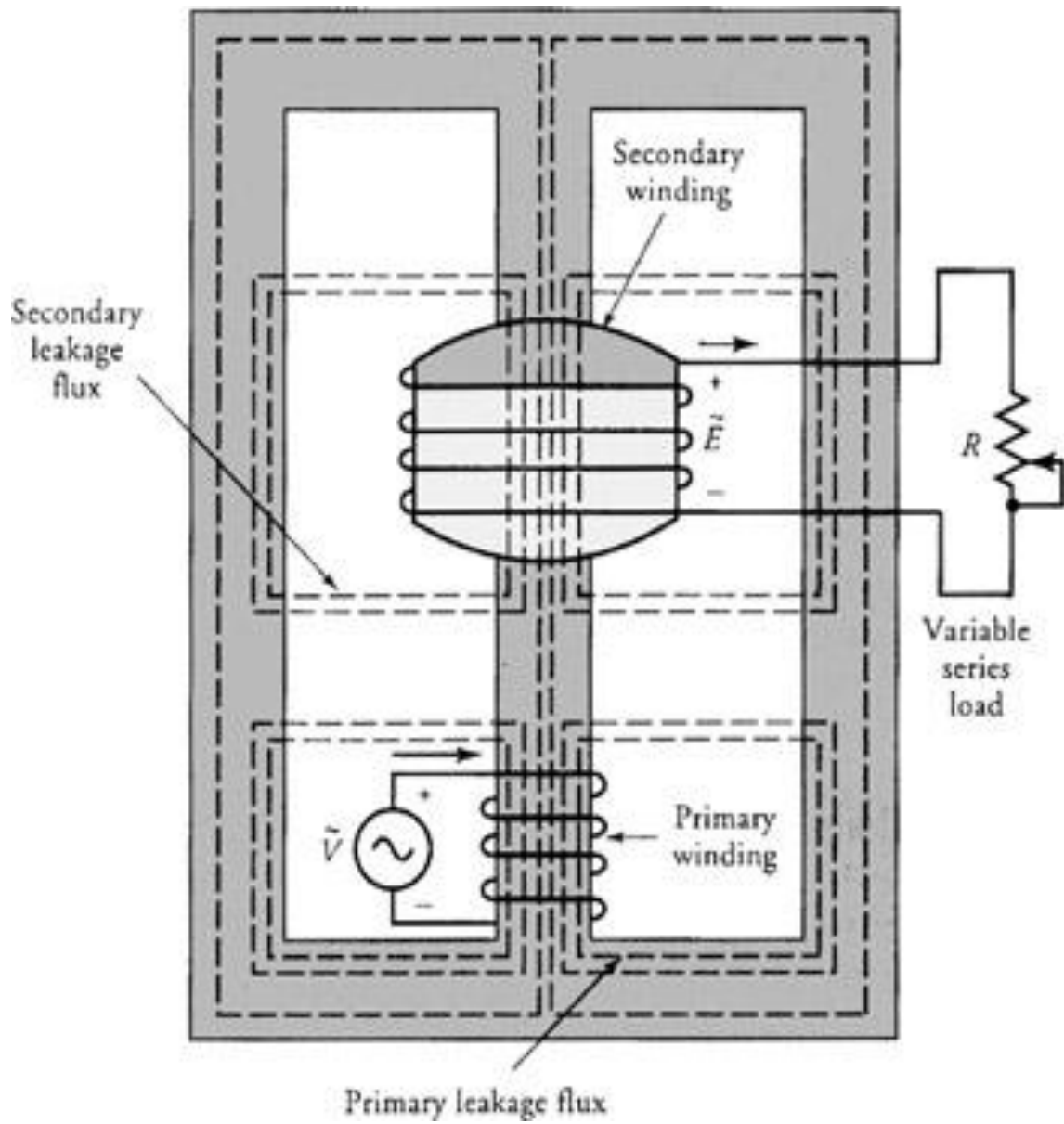


Fig: Constant Current Transformer

Variable frequency transformer

- The variable frequency transformer (VFT) is essentially a continuously variable phase shifting transformer that can operate at an adjustable phase angle
- A **variable frequency transformer** is used to transmit electricity between two asynchronous alternating current domains.
- A variable frequency transformer is a doubly-fed electric machine resembling a vertical shaft hydroelectric generator with a three-phase wound rotor, connected by slip rings to one external power circuit. A direct-current torque motor is mounted on the same shaft
- The phase shift between input and output voltage should also be small over the range of frequencies.
- The applications of VFT are Electronic circuits, Communication, Control and measurement which uses wide band of frequencies.

Auto transformer

- Transformer having only one winding such that part of winding common to both primary and secondary
- In the fig 1 the auto transformer is step down because $N_1 > N_2$ and here N_1 is common to both sides
- In the fig2 the autotransformer is step down because $N_1 < N_2$ and here N_2 is common to both
- It works on the principle of both induction and conduction
- Power transfer also takes by both induction and conduction.
- Weight of copper in autotransformer can be reduced

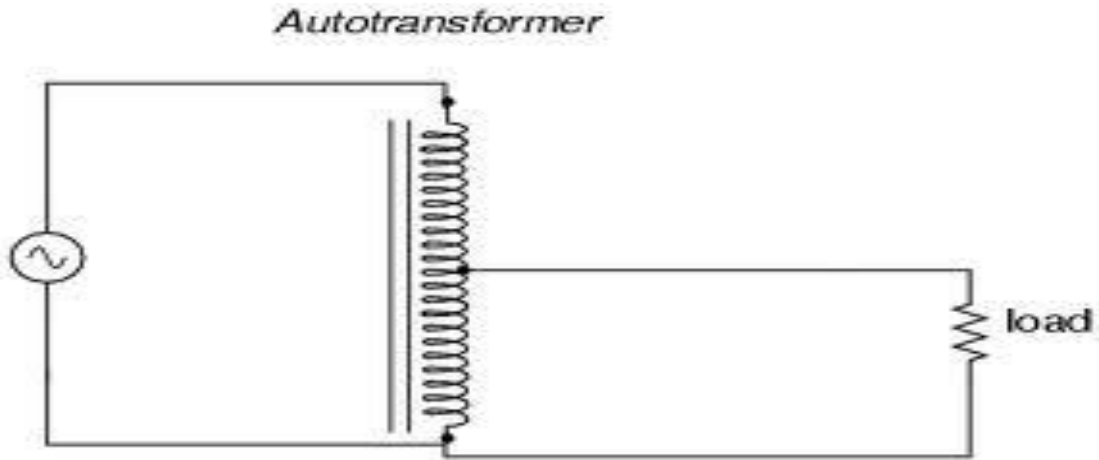
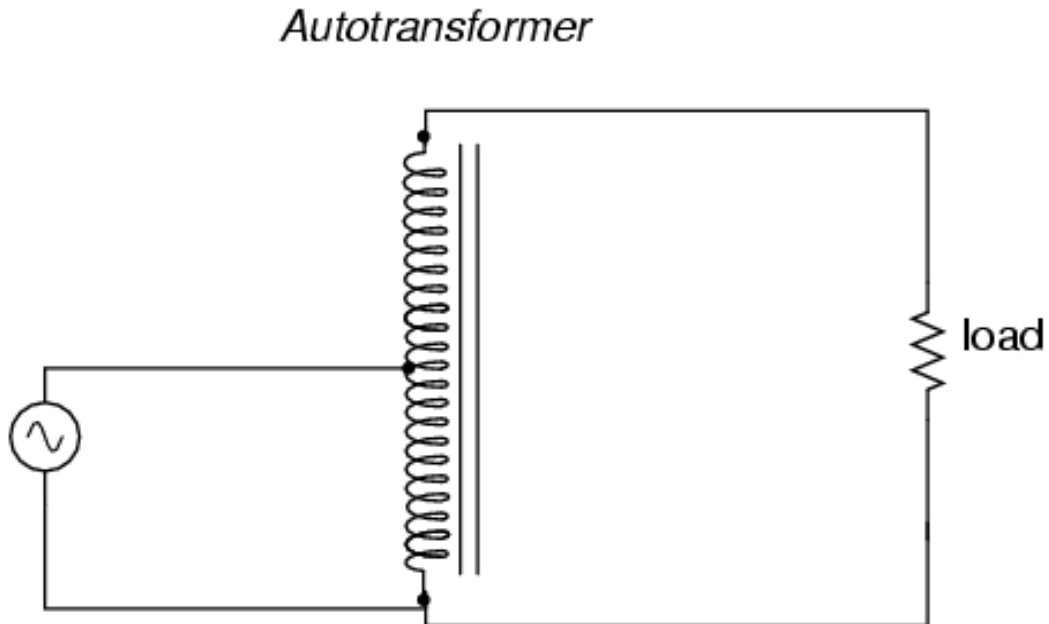


Fig 1



- Transformer having only one winding such that part of winding common to both primary and secondary
- In the fig 1 the auto transformer is step down because $N_1 > N_2$ and here N_1 is common to both sides
- In the fig2 the autotransformer is step up because $N_1 < N_2$ and here N_2 is common to both
- It works on the principle of both induction and conduction

- Power transfer also takes by both induction and conduction.
- Weight of copper in autotransformer can be reduced

Advantages of Autotransformer

- Copper required is very less and hence copper loss is reduced.
- Efficiency is higher compared to two winding transformer
- The power rating is more compared to two winding transformer
- The size and cost is less compared to two winding transformer

Applications of Autotransformer

- It is used as variac for starting of machines like Induction machines, Synchronous machines.
- The voltage drop is compensated and acts as booster.
- It used as furnace transformer at the required supply.
- It can be connected between two systems operating at same voltage level.