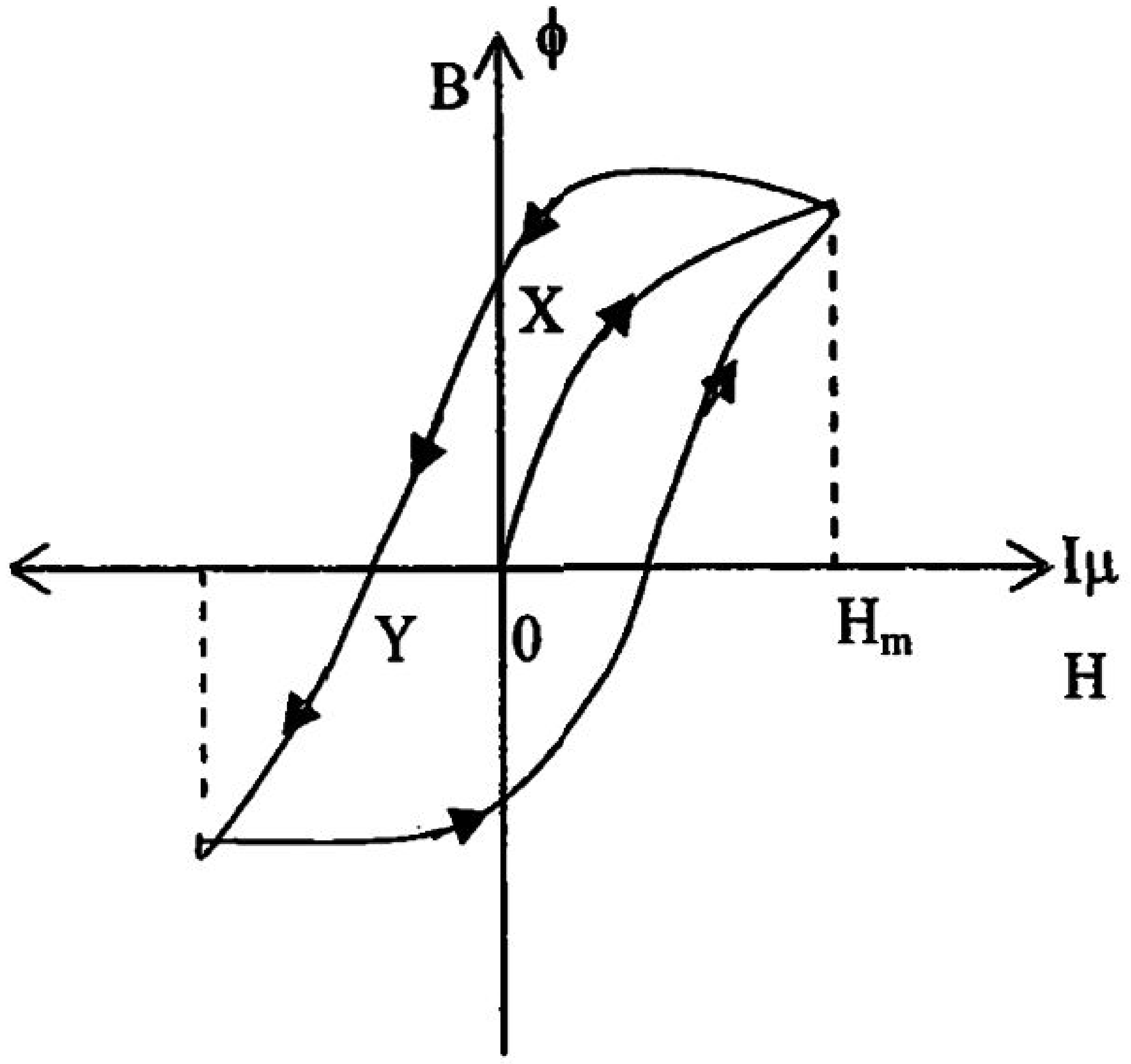
Magnetisation Curve: The magnetic reversal of transformer core is plotted by means of curve called Magnetisation curve.



Where, 0X = Residual flux due to Retentivity.

0Y = Coersive force due to coessivity.

Retentivity: The property of a magnetic material to retain some flux i.e even though the magnetizing force is zero.

Corsivity: The magnetizing force ($-H_c$ or H_c) is required to bring (make) the residual flux to zero is known as coersive force. This property of the magnetic material is known as corsivity.

Hysteresis loss per once cycle = Area enclosed with in one hysteresis loop.

Hysteresis loss for given supply frequency

= Area enclosed within one hysteresis loop ×f

Hysteresis loss: It is due to reversal of magnetization of transformer core whenever it is subjected to alternatig nature of magnetizing force.

Whenever a magnetic material is subjected to alternating magnetic to force, the domain present in the magnetic material will change their orientation after every half cycle.

The power consumed by the magnetic domains to change their orientation after every half cycle whenever core is subjected to alternating nature of magnetizing force is called as Hysteresis loss.

Steinmetz's formula:

Hysteresis loss can be determined by using stenmetz formulae given by

$W_h = \eta B_{max}^{x} fV$

Where η = stenmetz coefficient.

f = frequency of magnetization

= supply frequency.

V = volume of core.

x = stenmetz exponent

= Hysteresis coefficient

(range 1.5 to 2.5)

x = 1.6 for silicon steel

In hysteresis loop,

1. Height is determined by B_{max} of transformer core.
2. Width is determined by volume of transformer core.
3. No. of hysteresis loops are determined by supply frequencies.

During operation of transformer: (η and volume of core are constant)

$$B_{max} \propto \frac{V_1}{f}$$

Case 1: $\frac{V_1}{f} = \text{constant} \Rightarrow B_m = \text{constant}$

Area enclosed with in one hysteresis loop = constant.

$W_h \propto f$

$W_h = Af$

Case 2: $\frac{V_1}{f} \neq \text{constant}$

$\Rightarrow B_{mas} \neq \text{constant}$

Area enclosed within one hysteresis loop $\neq$ constant

$$w_h \propto \eta\left(\frac{V_1}{f}\right)^x .fV \qquad \left[\because B_{max} \alpha \frac{V_1}{f}\right]$$

$$w_h \propto V_1^x . f^{1-x}$$

$$w_h \propto V_1^{1.6} f^{-0.6} \qquad \text{(If } x = 1.6\text{)}$$

$$w_h = A\,V_1^{1.6} f^{-0.6}$$

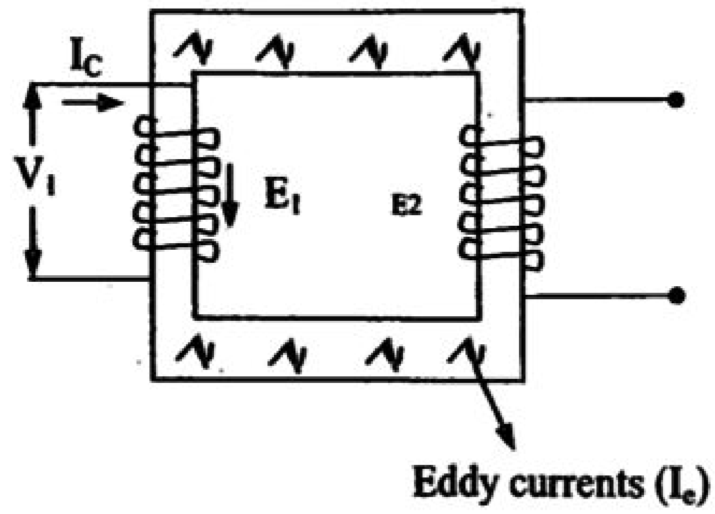
Case 3: V_1 = Constant, frequency is decreased

$$\uparrow B_m \propto \frac{V}{f\downarrow}$$

$$W_h \propto f^{-0.6}$$

- By keeping applied voltage constant, if the frequency of operation is reduced in a transformer, then there hysterisis loss increases.
- By keeping frequency constant if applied voltage is decreases then hysteresis loss decreases as per case (2).

Eddy current loss:



Eddy current loss is basically I^2R loss present in the core due to production of eddy currents in the core, because of its conductivity.

$R_{Ce} \rightarrow$ Resistance offered by core to flow of eddy current.

$I_e \propto \sigma \Rightarrow$ Eddy currents are directly proportional to conductivity of core.

$R_{ce} \propto \frac{1}{\sigma} \Rightarrow$ Resistance offered by core is inversely proportional to conductivity of core and $w_e \propto \sigma^2 \times \frac{1}{\sigma} \Rightarrow w_e\, \alpha\, \sigma$

$\Rightarrow$ Eddy current losses are directly proportion to the conductivity of core.

Eddycurrent reducing methods:

The eddy current loss can be reduced by reducing conductivity of core. The conductivity of core can be reduced without affecting its magnetic properties by using following methods.

a). By adding silica content upto an extent of 4 to 5 % to steel.

b) By using laminated core instead of solid core

- Eddy current loss $w_e = KB_m^2 f^2 t^2$

  Where, $K = \frac{\pi^2}{6\rho}$;

  B_{max} = Maximum flux density.

  f = frequency of eddy current (supply frequency).

  t = Thickness of lamination

Observations:

$w_e \propto t^2$

The eddy current loss can be effectively reduced by reducing thickness of laminations.

More the design frequency of transformer, thinner will be the thickness of lamination required.

For a 50Hz transformer $\Rightarrow t = 0.5mm$

60Hz transformer $\Rightarrow t = 0.35mm$

High frequency transformers are designed with thin laminations.

$\therefore$ Its stacking factor is low.

Low frequency transformers are designed with thick lamination

$\therefore$ its stacking factor is high.

During operation of transformer:

$B_{max} \propto \frac{V_1}{f}$ and $W_e = K.B_{max}{}^2.f^2.t^2$

Case 1: $\frac{V_1}{f} = \text{constant}$

$\Rightarrow B_{max} = \text{constant.}$

Therefore $W_e \; \alpha \; f^2$

$W_e = Bf^2$

Total Iron loss $W_i = W_h + W_e$

$W_i = Af + Bf^2$

Case 2: $\frac{V_1}{f} \neq \text{constant} \Rightarrow B_m \neq \text{constant}$

$$B_m \propto \frac{V_1}{f}$$

$$\Rightarrow W_e \propto k.\left(\frac{V_1}{f}\right)^2 f^2 t^2 \quad \left(\because B_m \propto \frac{V_1}{f}\right)$$

$$W_e \propto V_1^2$$

Total Iron loss $W_i = W_h + W_e$

$W_i = AV_1{}^{1.6} f^{-0.6} + BV_1{}^2$

Single -Phase Transformers

Features:

- Transformer is a static device which transfers power from one circuit to another circuit without change in frequency.
- As Transfomer does not change the frequency of the system, it can be treated as **constant frequency** device.
- As Transfomer transfers almost same amount of power from one circuit to another circuit, it can be treated as **constant power** device.
- Transformer is an electromagnetic energy conversion device (If internal conversion process is considred). However, the complete Transformer is not an energy conversion device, as the input and output are of electrical nature.

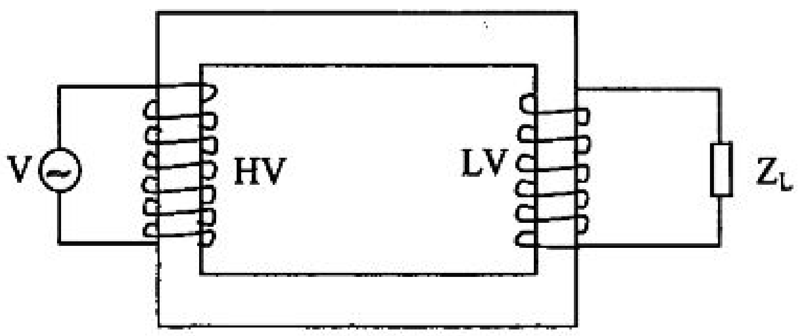
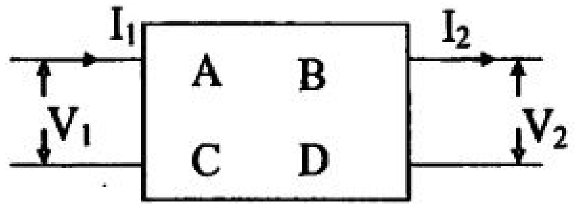


Fig: Transformer with winding

- In transformer, two windings are electrically isolated but magnetically coupled. Hence, transformer is a coupled circuit.
- Transformer can be treated as a **Phase-Shifting Device**, since it offers a displacement of approx 180^0 between two circuits.
- Transformer is a singly exited device, since it requires only one external voltage source to energise any no. of windings placed on its core.
- As the amount of flux in transformer core is constant irrespective of power transfer, it can be treated as **"Constant-flux device".**
- Transformer is a **negative feedback** circuit because it satisfies 'Lenz's law'.
- Transformer is a four terminal 2-port network as shown below.



Working Principle:
The transformer works based on **"Faraday's law of electromagnetic Induction"**
According to Faraday's law, whenever there is a relative space (or) time variation between magnetic field and set of conductors an emf will be induced in the conductors".

Basic requirements to generate e.m.f are:
According to Faraday's law,

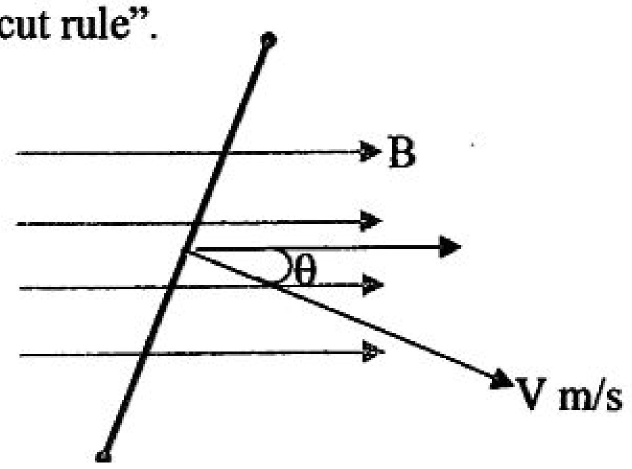
1. Magnetic field
2. Set of conductors
3. Relative variation in space or time between magnetic field and set of conductors.

There are two possibilities to generate e.m.f. by using Faraday's law:
(a) Relative space variation
(b) Relative time variation.

The emf induced in set of conductors due to relative space variation w.r.t steady magnetic field is called **dynamically induced** emf.
Ex: DC Generator

The emf induced in set of stationary conductors due to relative time variation w.r.t magnetic field is called **statically induced** emf.
Ex: Transformer

Dynamically Induced emf:
Magnitude of dynamically induced emf is found by "flux-cut rule".



- According to flux-cut rule, the magnitude of dynamically induced emf is $E_d = B\ell_e V \sin\theta$

  Where θ = Angle between $\bar{B}$ and $\bar{V}$.

  B = Flux density in Tesla of steady magnetic field.

  V = Linear velocity with which conductor is being moved

  ℓ_e = Effective length of conductor.

  The length of conductor which cuts the flux is called active length or effective length of conductor (ℓ_e).

- The direction of dynamically induced emf can be found by "Fleming right hand rule".

  Fore finger → Direction of flux.

  Thumb → Dirction of motion of conductor.

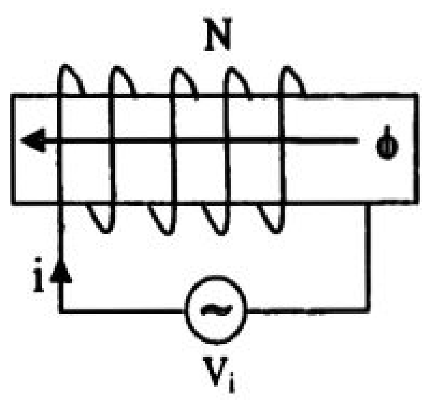
  Middle finger → Direction of induced emf.

  According to Fleming right hand rule the induced emf is always in the direction outward perpendicular to the plane containing velocity and flux density vectors.

  $E_d = (\bar{V} \times \bar{B})\ell_e$

Statically Induced emf:

- The magnitude of statically induced emf can be found by faraday's second law.
- According to Faraday's second law magnitude of statically induced emf is equal to rate of change of flux linkages.
- Flux linkages are required to generate statically induced emf.
- Flux cuttings are required to generate dynamically induced emf.



Let N = No.of turns in a coil and $i = I_m \sin(\omega t)$

MMF = Ni

$= NI_m \sin\omega t$

$$\text{Flux} = \frac{\text{MMF}}{\text{Reluctance}}$$ [Ohm's law for magnetic circuit]

$$\text{Flux} = \frac{NI_m \sin\omega t}{R}$$

$\text{Flux}\ (\phi) = \phi_{max} \sin\omega t$

$N\phi$ = flux linkages

$$E_s = \frac{d}{dt}(N\phi)$$

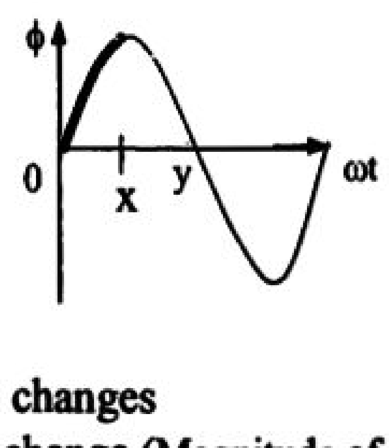
$$\boxed{E_s = -N\frac{d\phi}{dt}}$$

'–' represents direction of statically induced emf and it can be found by Lenz's law.

$E_s = -N\frac{d\phi}{dt}$ is the summarization of faraday law and lenz's law.

Lenz's Law:

The direction of statically induced emf is such that the current due to this emf will flow through a closed circuit in such a direction that it which in turn produce some flux according to Electro Magnetic Theory and this flux must opposes the changes in main field flux which is the cause for production of emf as well as current.



Flux has two changes

1. 0 to x one change (Magnitude of flux increases)
2. x to y another change (Magnitude of flux decreases)