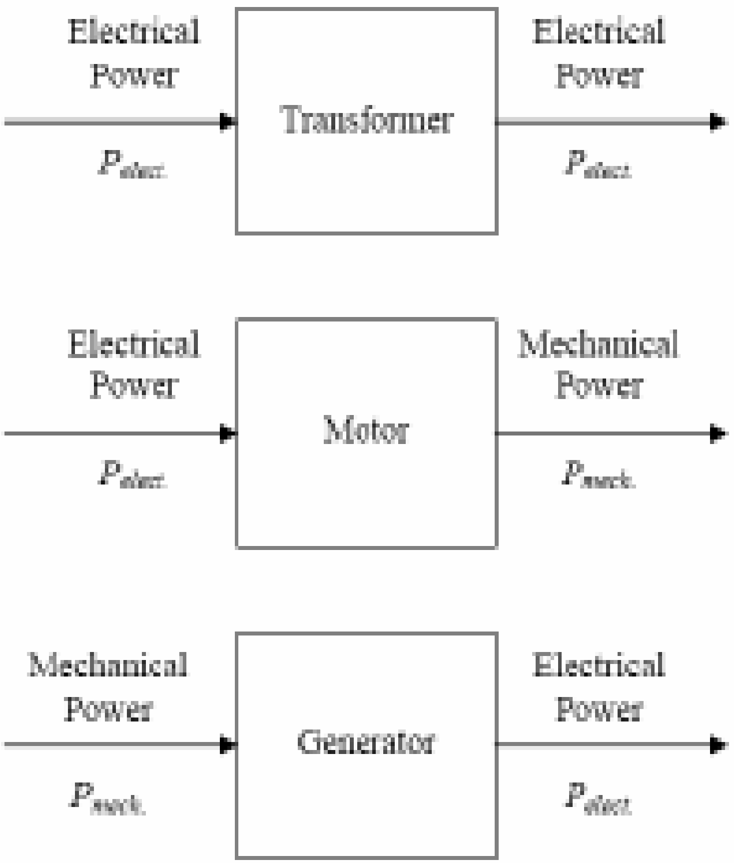
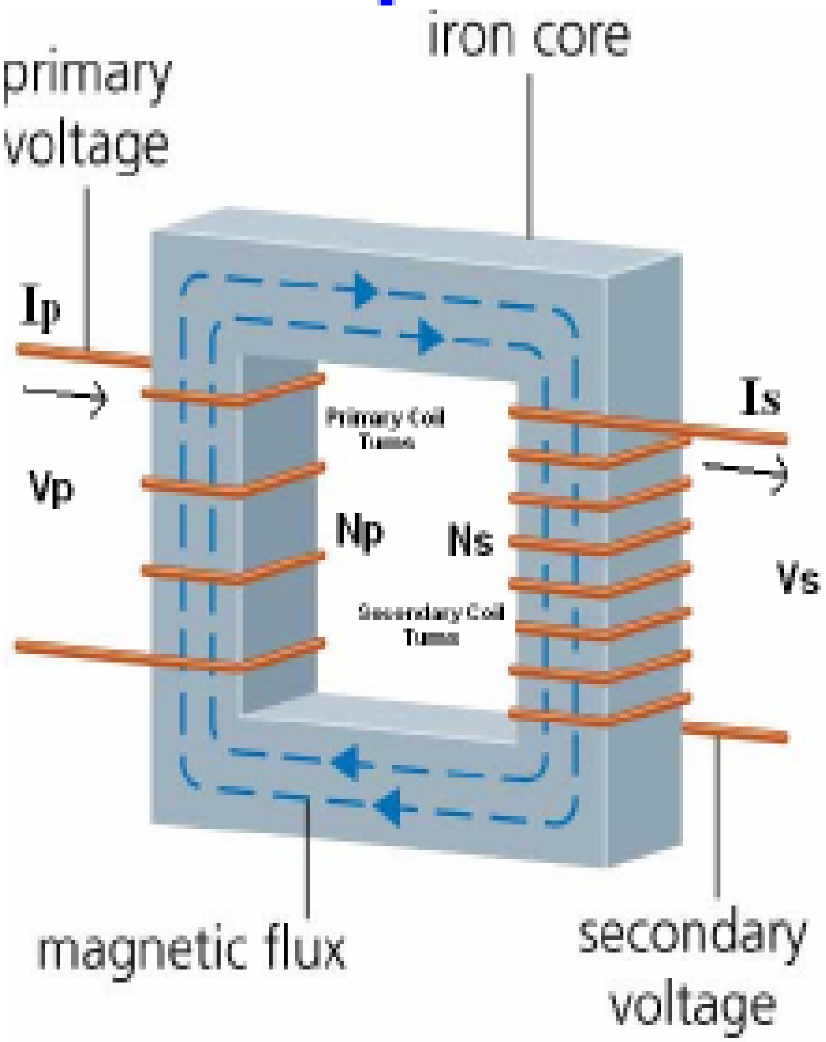
Transformer

- A transformer is a stationary electric machine which transfers electrical energy (power) from one voltage level to another voltage level.
- Unlike in rotating machines, there is no electrical to mechanical energy conversion .
- A transformer is a static device and all currents and voltages are AC.
- The transfer of energy takes place through the magnetic field.



Transformer Principles

- It has 2 electric circuits called *primary* and *secondary*.
- A magnetic circuit provides the link between primary and secondary.
- When an AC voltage is applied to the primary winding (Vp)of the transformer, an AC current will result (Ip). Ip sets up a time-varying magnetic flux φ in the core.
- A voltage is induced to the secondary circuit (Vs) according to the Farday's law.

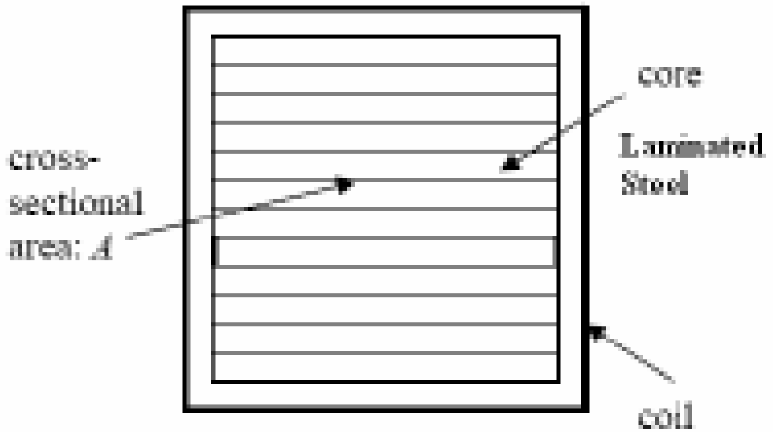


Transformer Core Types

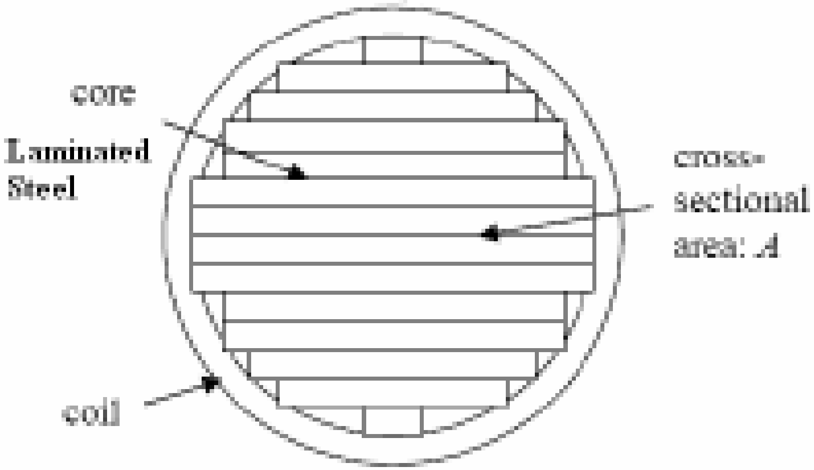
- The magnetic (iron) core is made of thin laminated steel.
- The reason of using laminated steel is to minimizing the eddy current loss by reducing thickness (t):

$$Pe = k_h (B_{max}\, t\, f)^2$$

- 2 common cross section of core is square or rectangular) for small transformers and circular (stepped) for the large and 3 phase transformers.

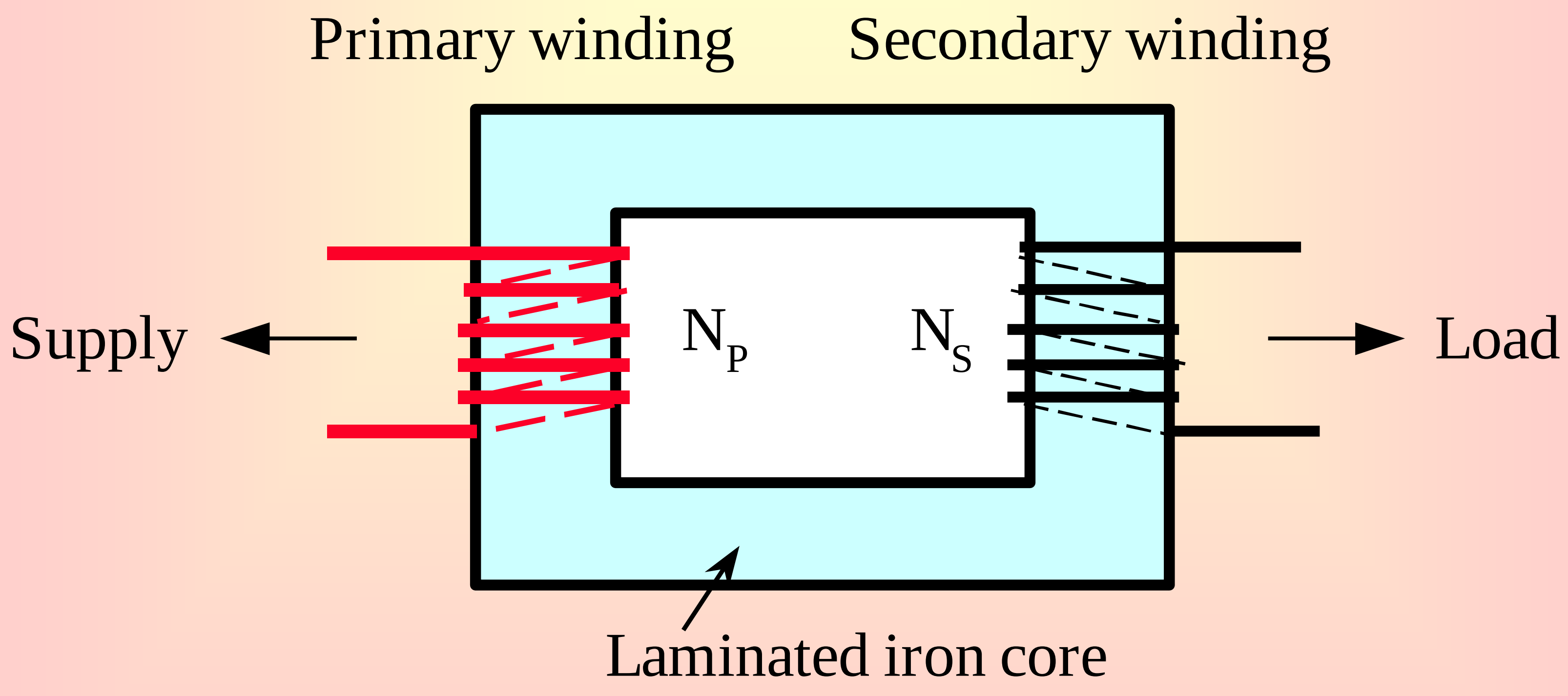


(a) Square core



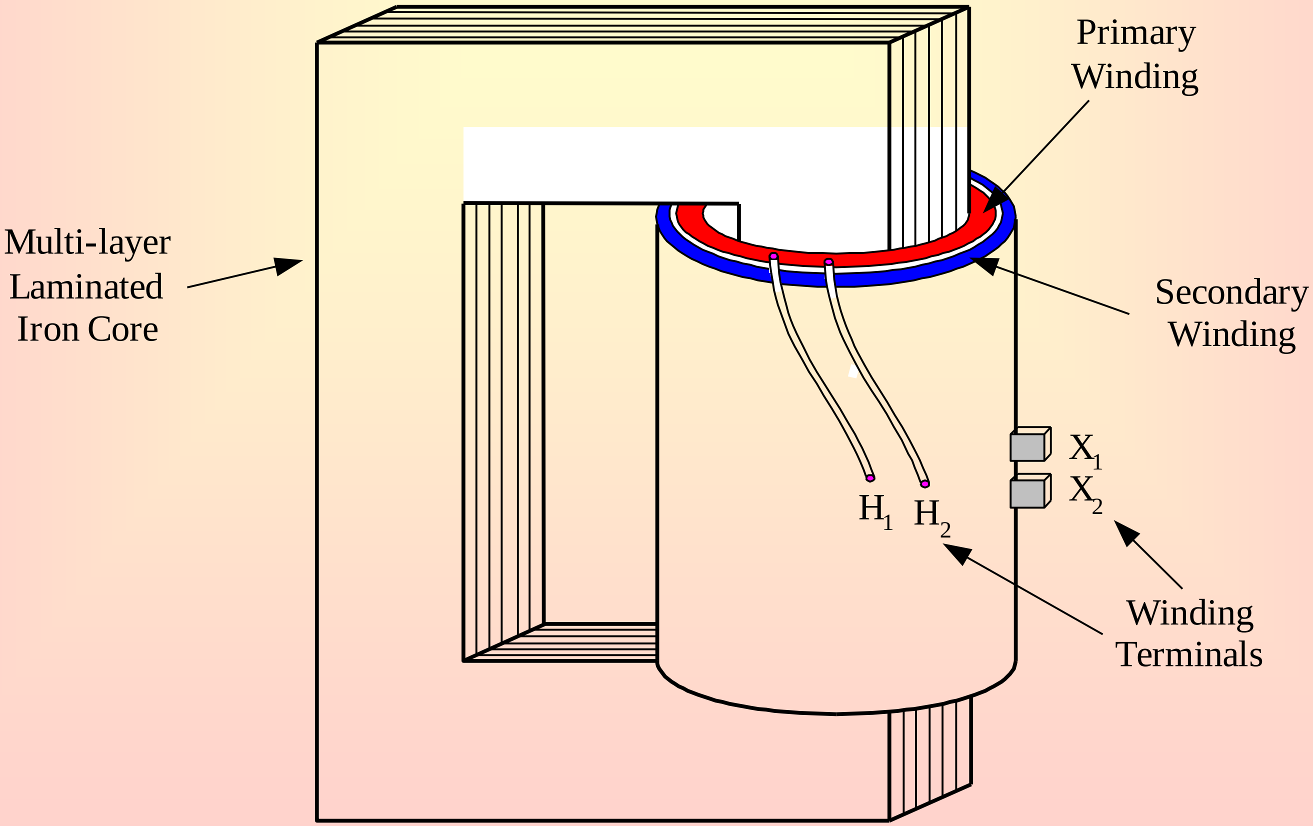
(b) Stepped core

Transformer Construction



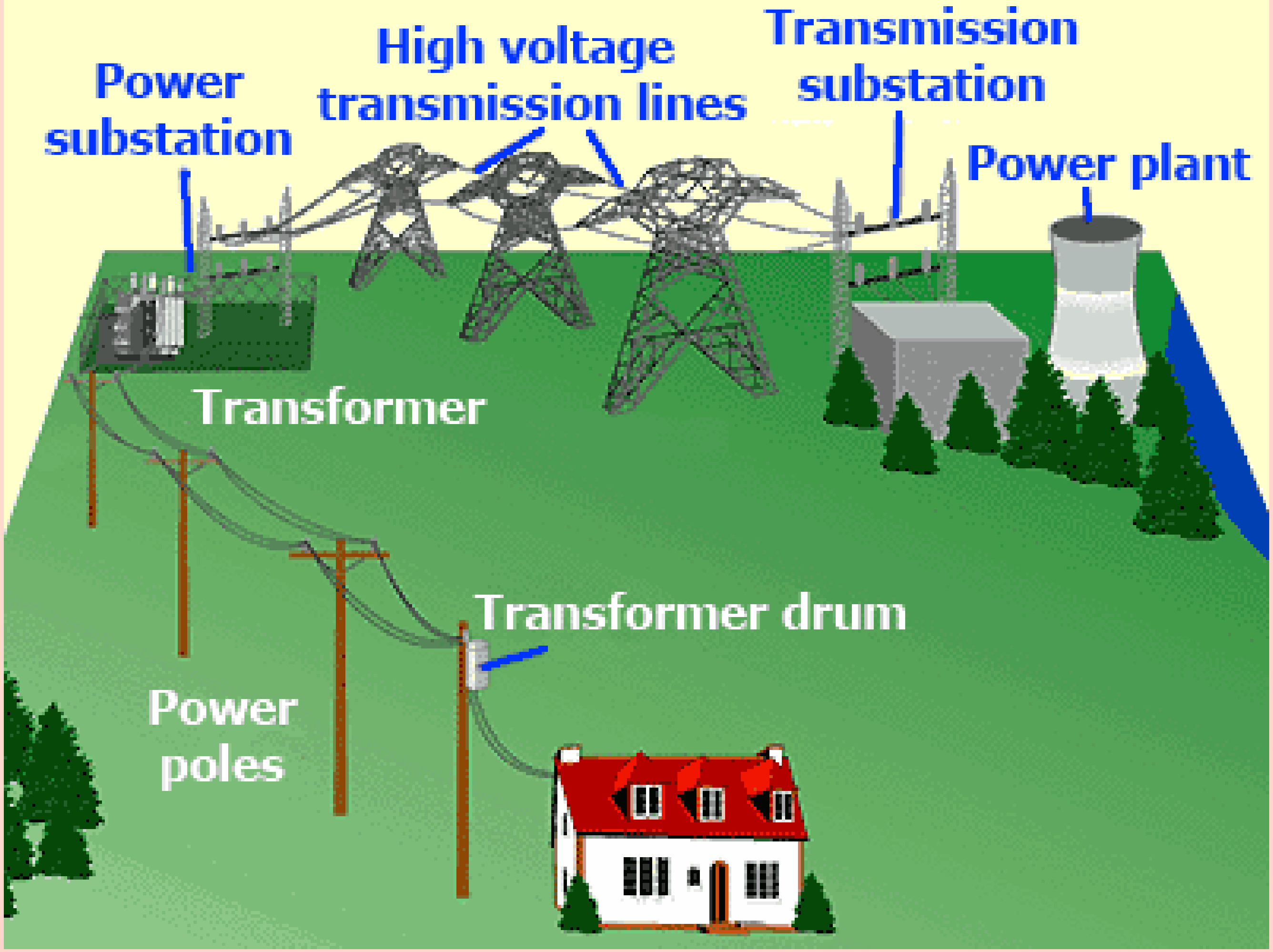
Basic Component of single phase transformer

Transformer

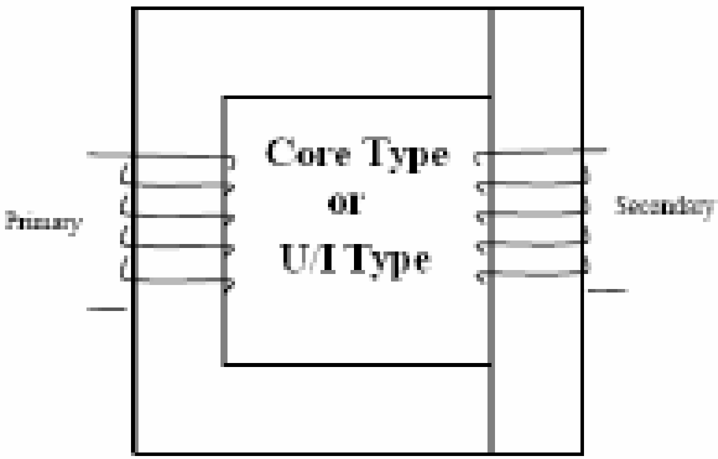


Configuration of single phase transformer

Application of Transformer



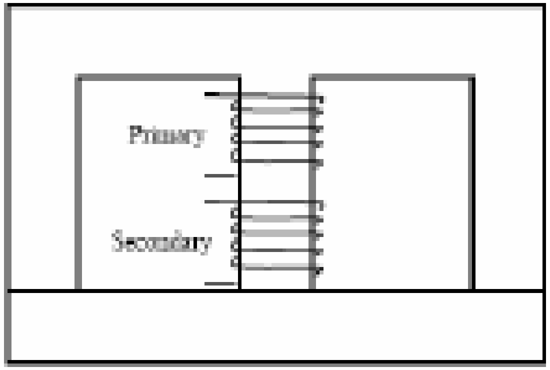
Transformer Construction



2 Type of Transformers:

- 1- Core (U/I) Type: is constructed from a stack of U- and I-shaped laminations. In a core-type transformer, the primary and secondary windings are wound on two different legs of the core.

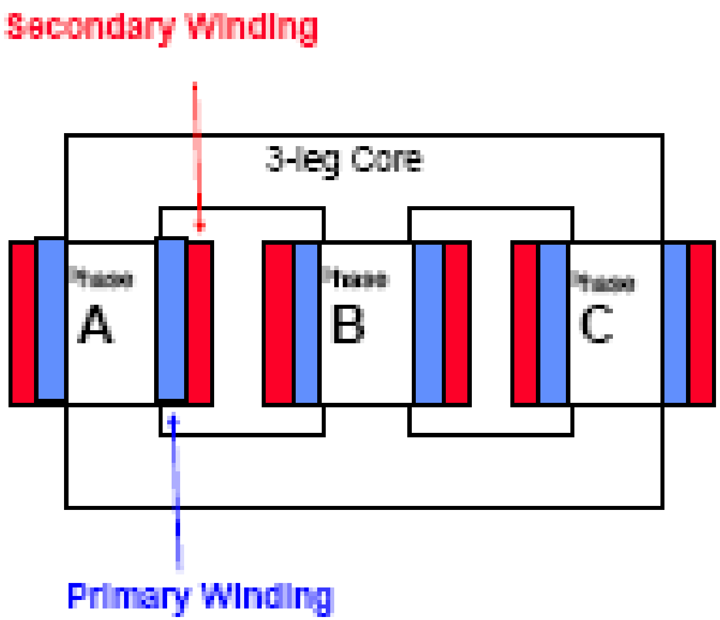
- 2- Shell Type: A shell-type transformer is constructed from a stack of E- and I-shaped laminations. In a shell-type transformer, the primary and secondary windings are wound on the same leg of the core, as concentric windings, one on top of the other one.



Shell Type or E/I type

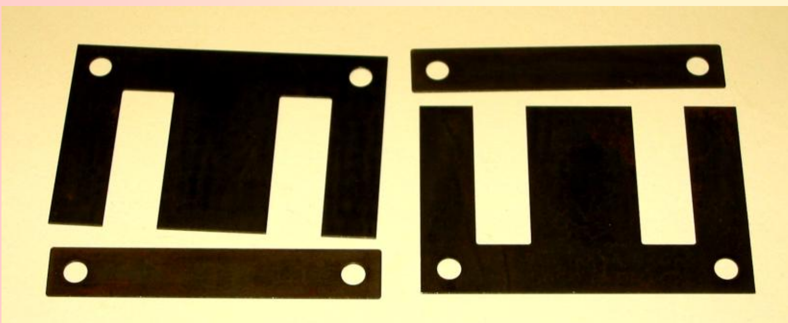
3 Phase Transformer

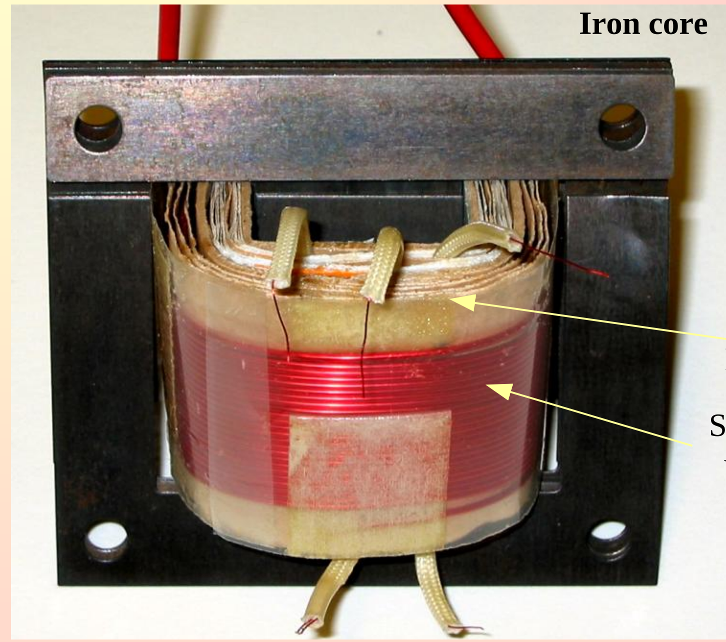
- The three phase transformer iron core has three legs.
- A phase winding is placed in each leg.
- So, each leg has 2 sets of winding : Primary and Secondary. They are placed on top of each other and insulated by layers or tubes.



- **All the 3 legs have the same primary coil turns (NpA=NpB=NpC). The 3 secondary winding have aslo the same coil turns(NsA=NsB=NsC). Otherwise the induced voltage is unbalanced.**

Transformer



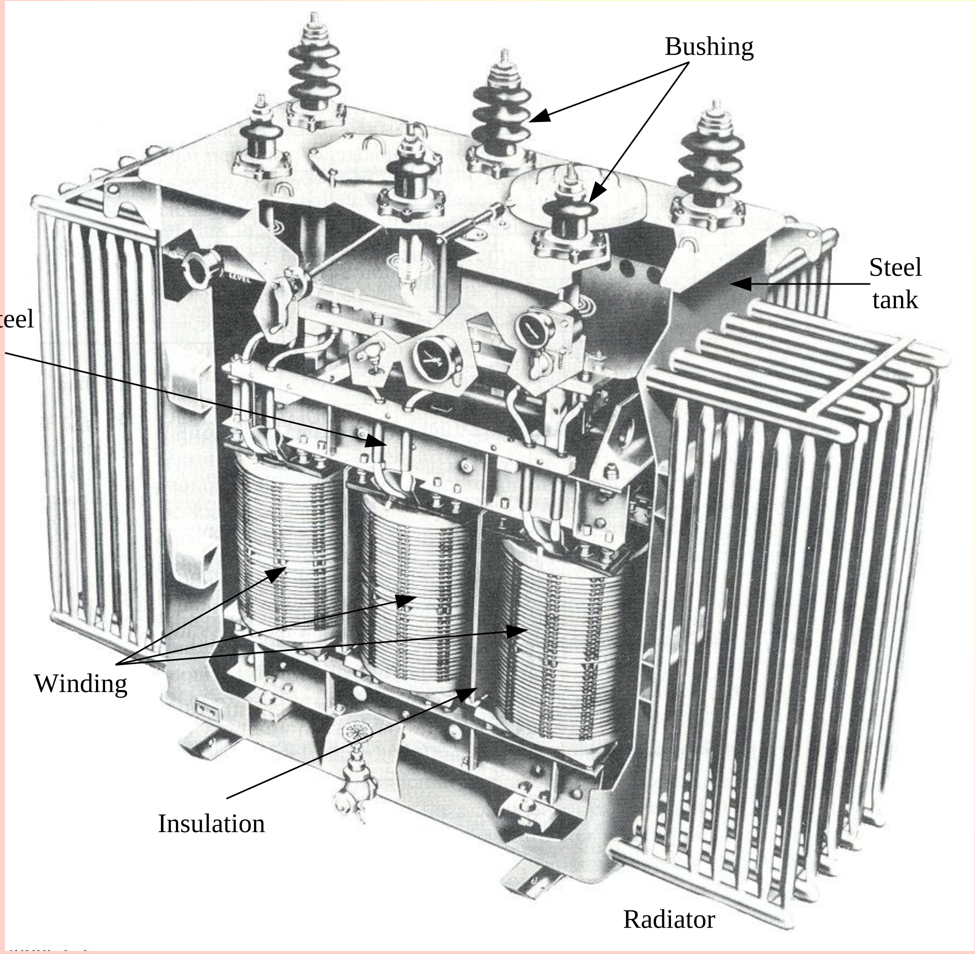


Construction of a small transformer a) *Lamination* b) Iron core and winding

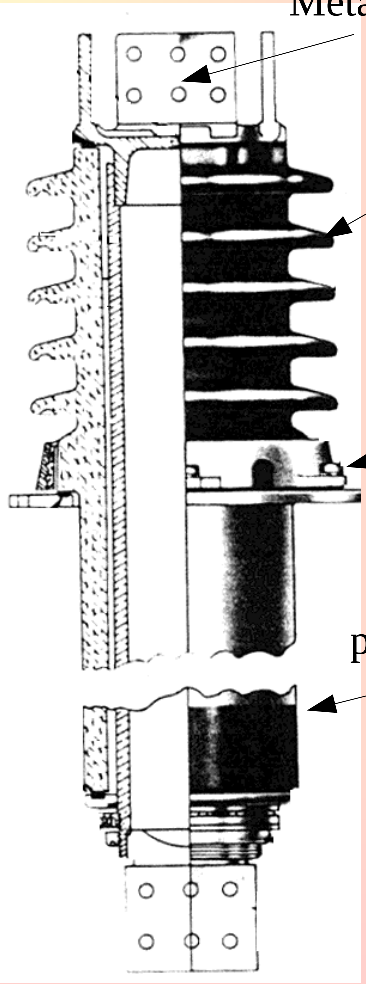
Transformer

Dry-type 3 phase transformer

Transformer

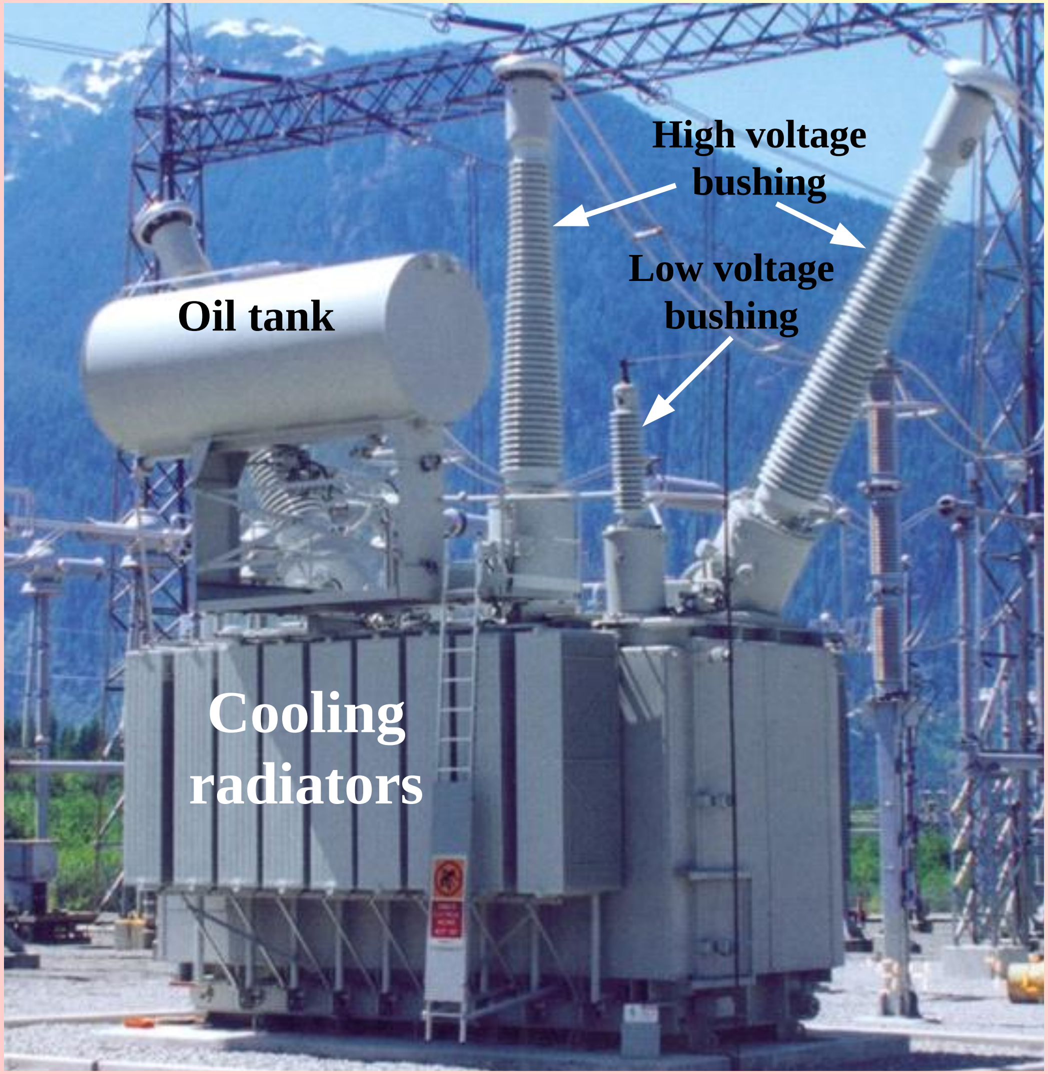


Oil insulated type transformer with cooling system



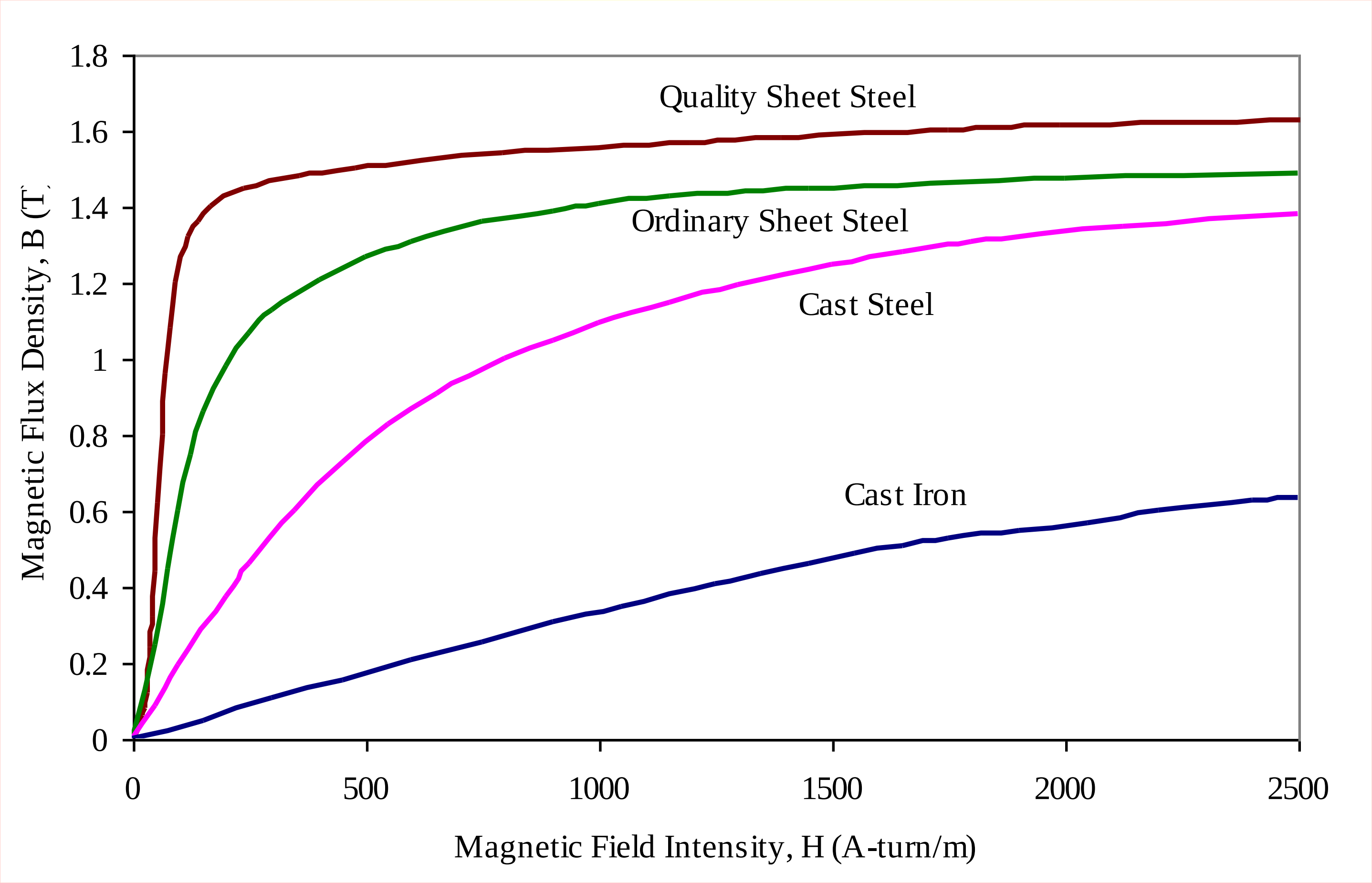
Porcelain transformer bushing

Transformer



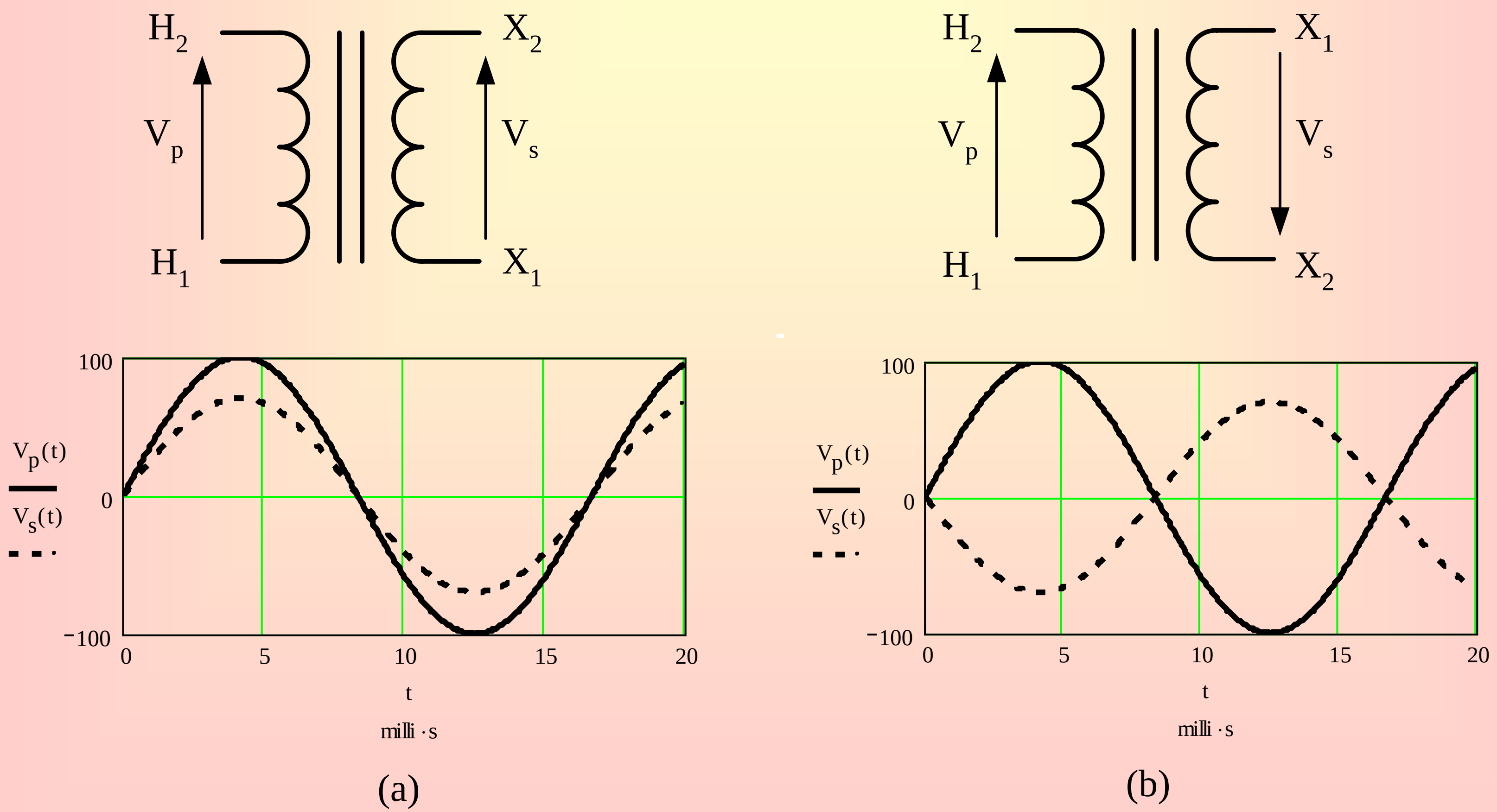
High Voltage Transformer with Cooling System

Transformer Core Material



B(H) Magnetising Curve

Transformer Magnetic Circuit



Transformer Polarity

Transformer Magnetic Circuit

- **Ampere's Law**

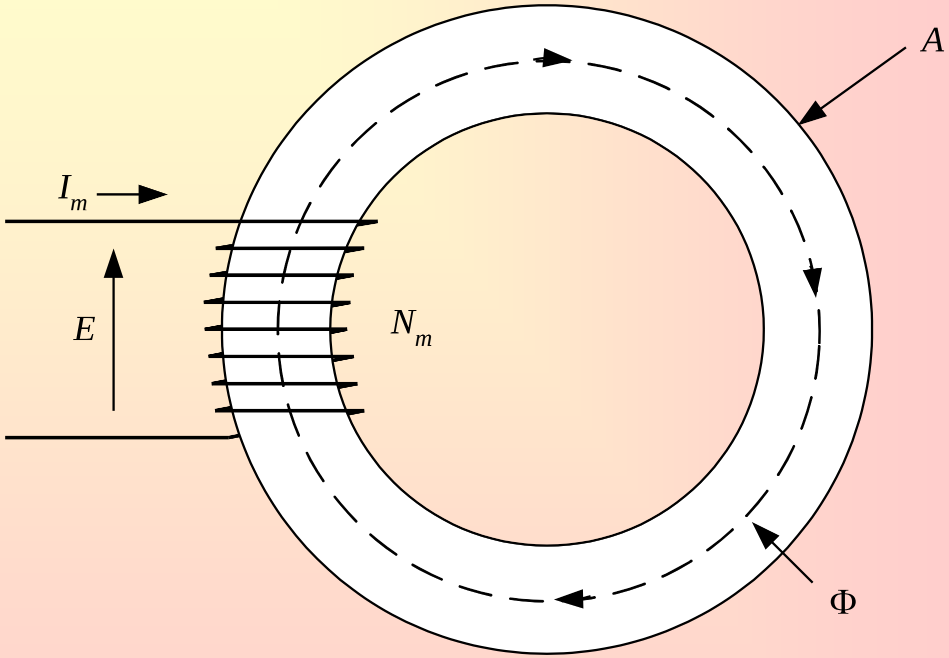
$$I_m \; N_m = H \; \ell$$

- Flux Density

$$B = \mu \; H$$

- Flux

$$\Phi = B \; A$$



Magnetic Circuit

Voltage Induced in a Transformer

- **Voltage Induced**

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

- Modifying the above equation:

$$E = N_m \frac{d(B\,A)}{dt} = A\,N_m \frac{d(\mu\,H)}{dt} = \mu\,A\,N_m \frac{d}{dt}\left(\frac{I_m\;N_m}{\ell}\right) = \frac{\mu\,A\,N_m^2}{\ell}\,\frac{dI_m}{dt}$$

- Voltage Induced

$$E = L\,\frac{dI_m}{dt}$$

Transformer Inductance and Magnetic Energy

- **Inductance**

$$L = \frac{\mu \ A \ N_m^2}{\ell}$$

- Magnetic Energy

$$Energy = \frac{L \ I_m^2}{2}$$

Transformer Magnetic Circuit Analysis

- **Core measurement**

w = 3in, h = w, a = 1in, b = 1.5in

Im = 2A, Nm = 20, f = 60Hz,

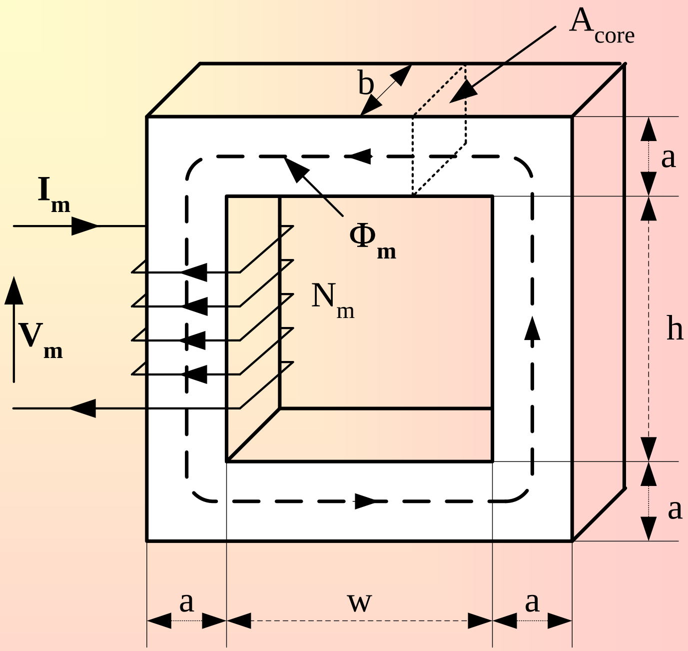
- **Magnetic path length and area**

Lm = 2 (w + a) + 2 (h + a)

Acore = a b

- **Magnetic field intensity**

$$H_m := \frac{I_m \cdot N_m}{L_m} \qquad H_m = 98.425\ \frac{A}{m}$$



Rajah 13: Litar Magnetik

Transformer Magnetic Circuit Analysis

- **Magnetic flux density**

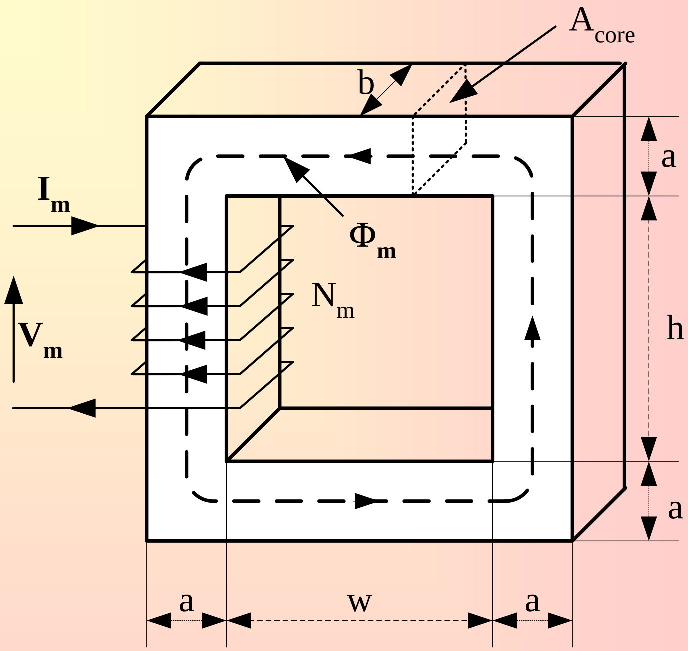
$$B_m := \mu_o \cdot \mu_r \cdot H_m$$

- ***free space or air permeability***

$$\mu_o := 4 \cdot \pi \cdot 10^{-7} \cdot \frac{H}{m}$$

- **Magnetic flux intensity (H)**

$$H_m = 98.425 \frac{A}{m}$$



Magnetic Circuit

Transformer Magnetic Circuit Analysis

- **Magnetic flux**

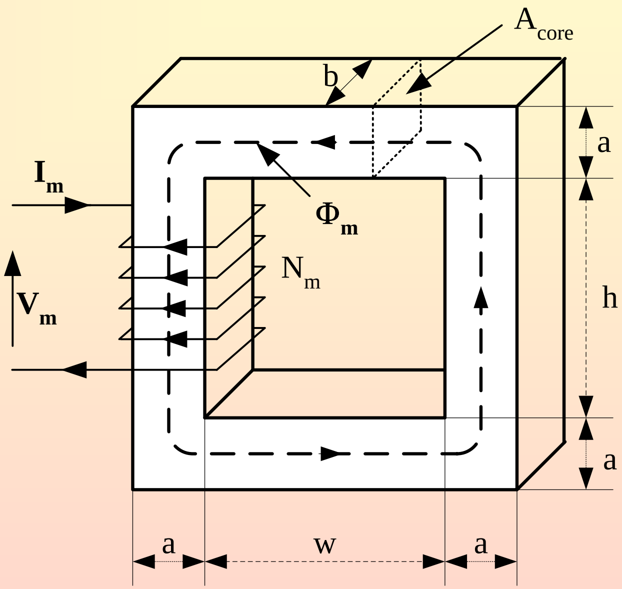
$$\Phi_m := B_m \cdot A_{core}$$

- **Or**

$$\Phi_m := \mu_o \cdot \mu_r \cdot \frac{A_{core} \cdot N_m}{L_m} \cdot I_m$$

- **Magnetising sinusoidal current**

$$I_{mag}(t) := \sqrt{2} \cdot I_m \cdot \cos(\omega \cdot t)$$



Transformer Magnetic Circuit Analysis

- **Magnetic Flux a function of time**

$$\Phi_{mag}(t) := \mu_o \cdot \mu_r \cdot \frac{A_{core} \cdot N_m}{L_m} \cdot \left(\sqrt{2} \cdot I_m \cdot \cos(\omega \cdot t)\right)$$

- **Maximum Flux :**

$$\Phi_{max} := \sqrt{2} \cdot \left(\mu_o \cdot \mu_r \cdot \frac{A_{core} \cdot N_m}{L_m}\right) \cdot I_m$$

- **Flux a function of time :**

$$\Phi_{mag}(t) := \Phi_{max} \cdot \cos(\omega \cdot t)$$

Voltage Induced in a Transformer

$$E_{ind}(t) := N_m \cdot \frac{d}{dt} \Phi_{mag}(t)$$

$$E_{ind}(t) := N_m \cdot \frac{d}{dt} \left(\Phi_{max} \cdot \cos(\omega \cdot t) \right)$$

$$E_{ind}(t) := -N_m \cdot \Phi_{max} \cdot \omega \cdot \sin(\omega \cdot t)$$

- **RMS Voltage**

$$E_{rms} := \frac{N_m \cdot \Phi_{max} \cdot \omega}{\sqrt{2}}$$

Voltage Induced in a Transformer

- **Voltage Induced**

$$E_{rms} := 4.443 \cdot f \cdot N_m \cdot \Phi_{max}$$

- **Voltage Induced :**

$$E_{ind}(t) = L_{ind} \cdot \frac{d}{dt} I_{mag}(t)$$

$$N_m \cdot \frac{d}{dt} \Phi_{mag}(t) = L_{ind} \cdot \frac{d}{dt} I_{mag}(t)$$

Transformer Inductance

$$L_{ind} = \frac{N_m \cdot \Phi_{mag}(t)}{I_{mag}(t)}$$

$$L_{ind} = \frac{N_m \cdot \left(\Phi_{max} \cdot \cos(\omega \cdot t)\right)}{\sqrt{2} \cdot I_m \cdot \cos(\omega \cdot t)}$$

$$L_{ind} = \frac{N_m \cdot \Phi_{rms}}{I_m}$$

$$L_{ind} := \frac{N_m \cdot \left[\sqrt{2} \cdot \left(\mu_o \cdot \mu_r \cdot \frac{A_{core} \cdot N_m}{L_m}\right) \cdot I_m\right]}{\sqrt{2} \cdot I_m}$$

$$L_{ind} := \mu_o \cdot \mu_r \cdot \frac{A_{core} \cdot N_m{}^2}{L_m}$$

Ideal Transformer

- **Induced Voltages:**

  The induced emf in primary winding is:

  $$E_p = 4.44\ N_p\ \Phi_m\ f,$$

  where N_p is the number of winding turns in primary winding, Φ_m, the maximum (peak) flux, and f the frequency of the supply voltage.

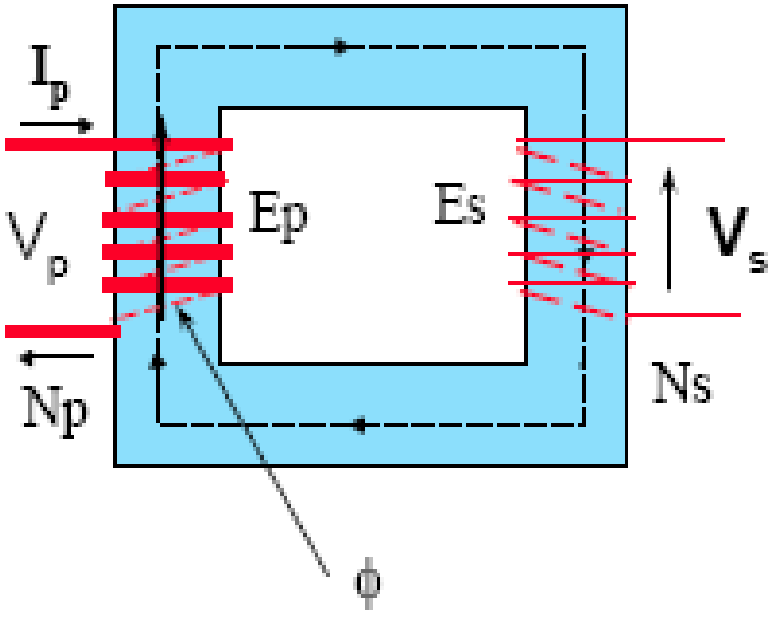
- Similarly, the induced emf in secondary winding:

  $$E_s = 4.44\ N_s\ \Phi_m\ f,$$

- where N_s is the number of winding turns in secondary winding.

- **Turns Ratio, a = $E_p/E_s = N_p/N_s$**

Voltage generation



Ideal Transformer

- If the transformer is ideal,

  Pin=Pout

  (Input power = Output power).

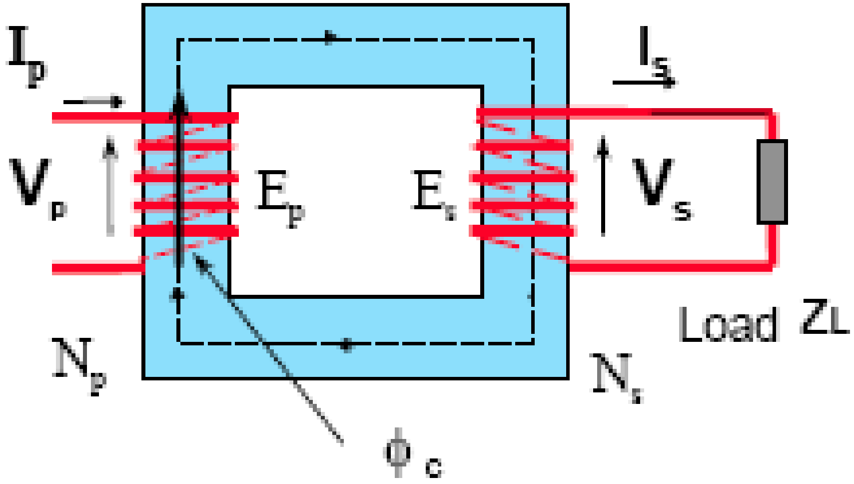
- Assuming the power factor to be same on both sides,

$$V_p I_p = V_s I_s$$

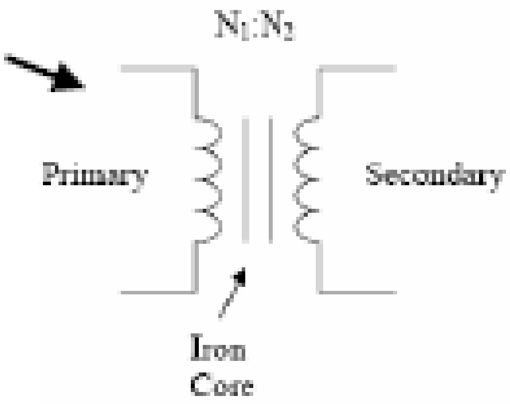
Hence, $N_p/N_s = V_p/V_s = I_s/I_p = a$

Note that in transformers, subscripts "1" and "p" are used interchangeably for the primary-side quantities. Also, subscripts "2" and "s" are used interchangeably for the secondary-side quantities.

Transformer loaded



Symbol Circuit
Of a transformer



Ideal Transformer

- Relation between current that flows in the primary winding, $i_p(t)$ and current that flows in the secondary winding, $i_s(t)$:

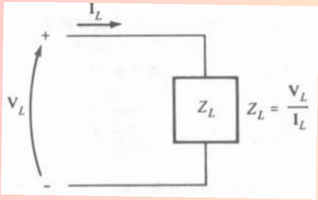
$$N_P i_P(t) = N_S i_S(t) \qquad (2)$$

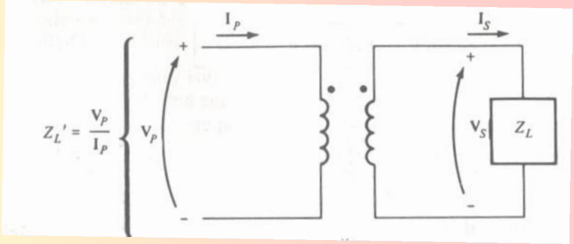
$$\frac{i_P(t)}{i_S(t)} = \frac{1}{a} \qquad (3)$$

$$\frac{V_P}{V_S} = a \qquad (4)$$

$$\frac{I_P}{I_S} = \frac{1}{a} \qquad (5)$$

Transformer Impedance





- Primary Impedance:

$$Z_L' = \frac{V_P}{I_P} \qquad \textbf{(15)}$$

- Primary Voltage:

$$V_P = aV_S \qquad \textbf{(16)}$$

- Primary Current:

$$I_P = \frac{I_S}{a} \qquad \textbf{(17)}$$

- Primary impedance in terms of secondary impedance

$$Z_L' = \frac{V_P}{I_P} = \frac{aV_S}{I_S / a} = a^2 \frac{V_S}{I_S}$$

$$Z_L' = a^2 Z_L \qquad \textbf{(18)}$$

Example 1

A transformer coil possesses 4000 turns and links an ac flux having a peak value of 2 mWb. If the frequency is 60 Hz, calculate the effective value of the induced voltage E.

Ans: 2131V

Example 2

A coil having 90 turns is connected to a 120V, 60 Hz source. If the effective value of the magnetizing current is 4 A, calculate the following:

a. The peak value of flux
b. The peak value of the mmf
c. The inductive reactance of the coil
d. The inductance of the coil.