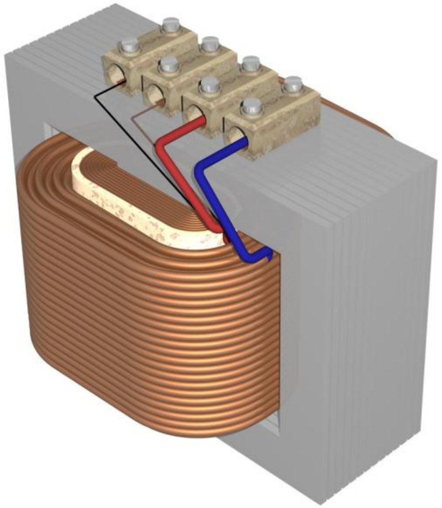
Electrical Circuits for Engineers (EC1000)

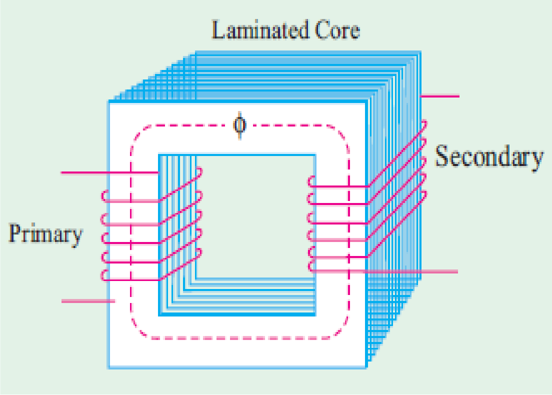
Lecture-11
Transformers



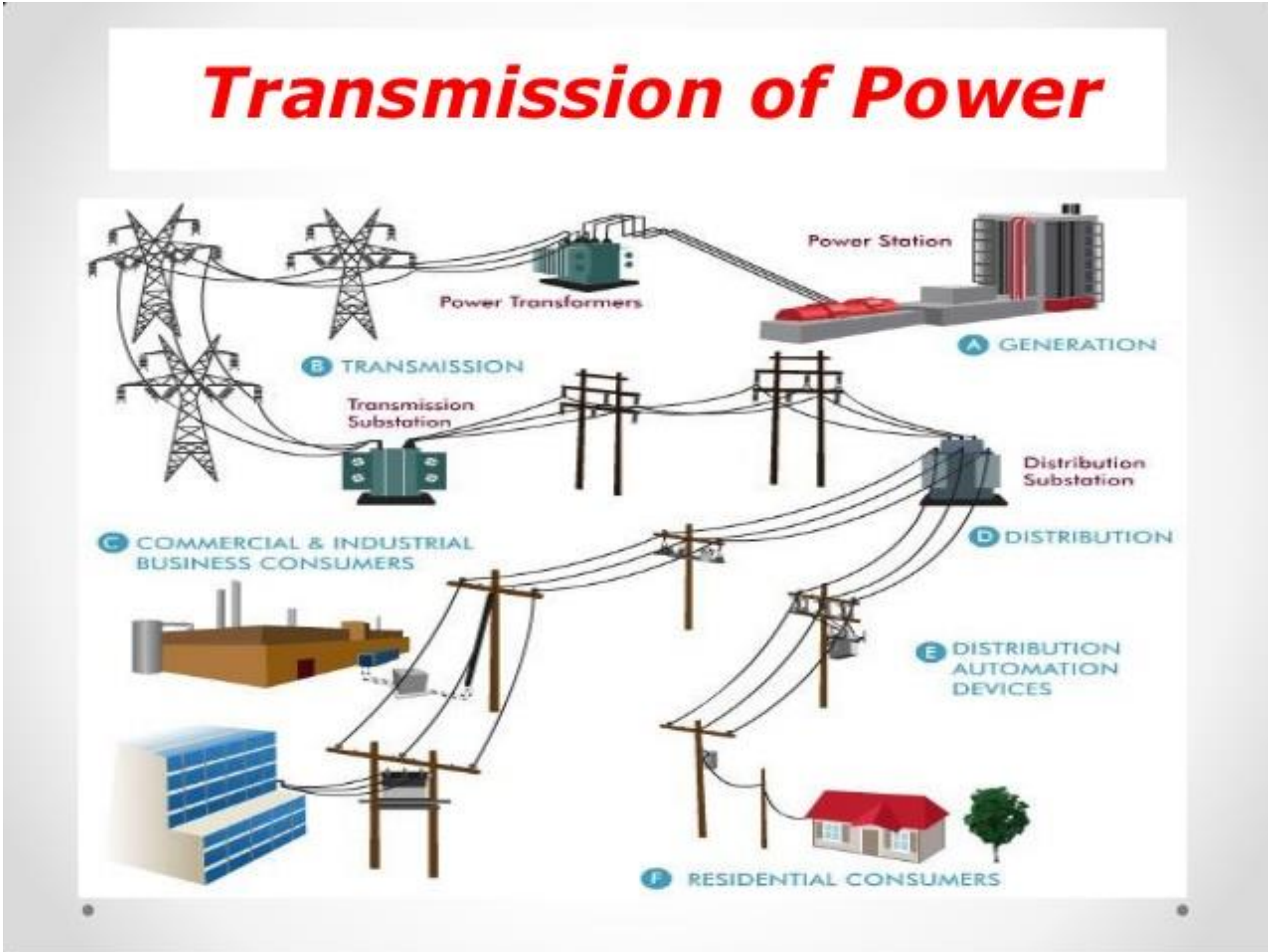
Introduction

William Stanley invented the transformer during 1885

Transformer is a Static device, used to transfer electrical energy from one circuit to another circuit without change in frequency
Use to change the AC voltage level from one to another.
Works under Faraday's law of Electro Magnetic Induction
It contains
1) Winding (Primary & Secondary)- Electrical Circuit
(Copper/Aluminium conductor)
2) Magnetic Core (Iron Core)– Magnetic circuit



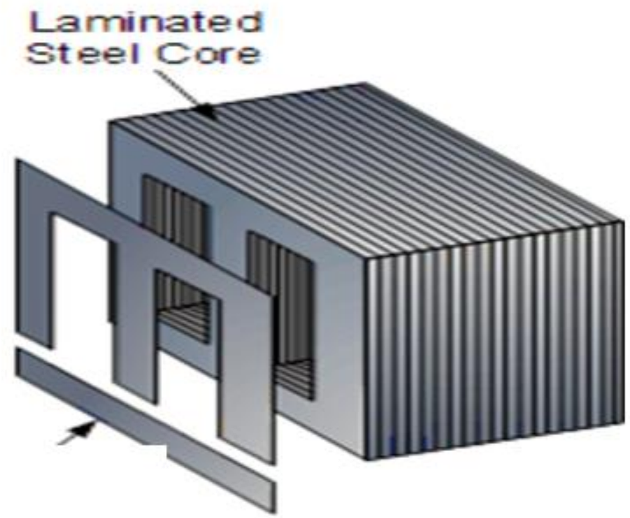
Both windings are magnetically coupled and Electrically Isolated


Transmission of Power
Power Station
Power Transformers
A GENERATION
B TRANSMISSION
Transmission Substation
Distribution Substation
C COMMERCIAL & INDUSTRIAL BUSINESS CONSUMERS
D DISTRIBUTION
E DISTRIBUTION AUTOMATION DEVICES
F RESIDENTIAL CONSUMERS

Transformer

The essential components of the transformer are:

1. Magnetic core
2. Two windings, namely primary and secondary windings
3. A time varying magnetic flux

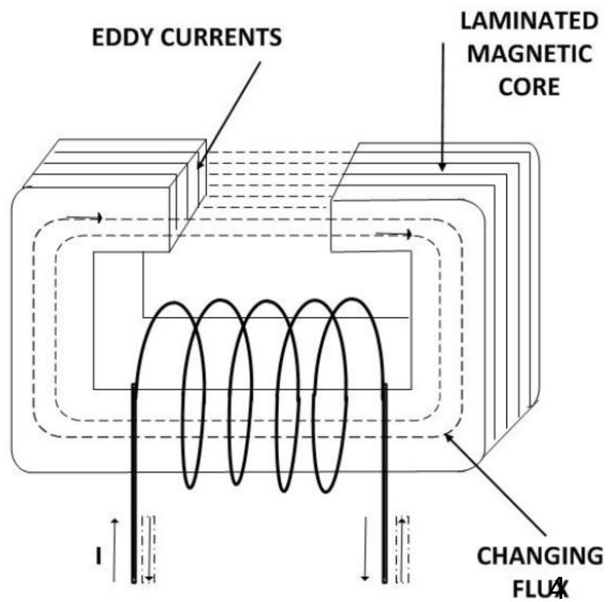


Magnetic circuit

The core of the transformer is made of high-grade silicon steel or sheet steel lamination, which has low hysteresis loss and provides a continuous magnetic path.

The main functions of the magnetic circuit are:

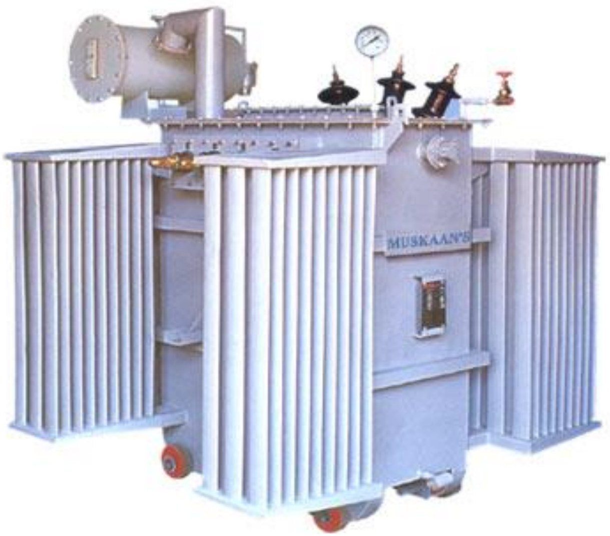
- Provides low reluctance path for carrying the flux.
- Carries the windings required for electric power transfer.



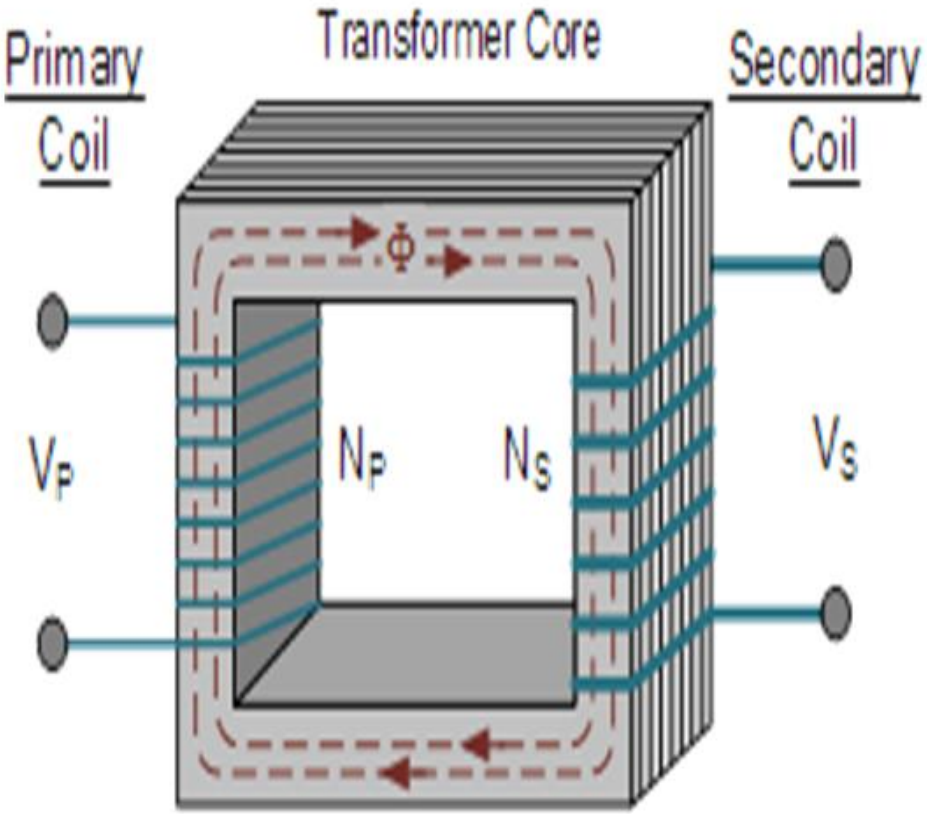
Transformer

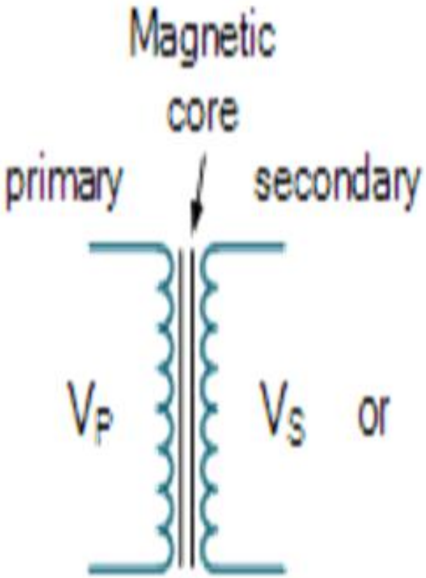
Electric circuit

- In the transformer, there are two windings, namely primary and secondary windings.
- The winding connected to the input side is called the *primary winding*,
- The winding connected to the output side is called the *secondary winding*.
- These windings are made of copper



Transformer





Transformer Symbol

Types of Transformer

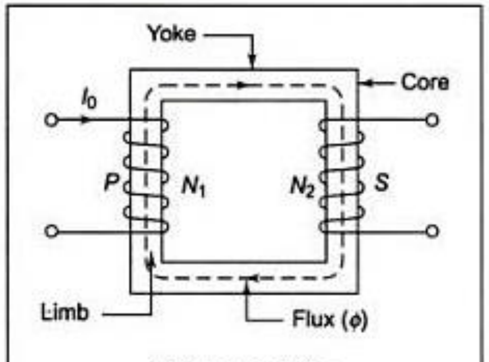
According to the core construction and the manner in which the windings are wound, transformers are classified as

- **core-type**
- **shell-type**

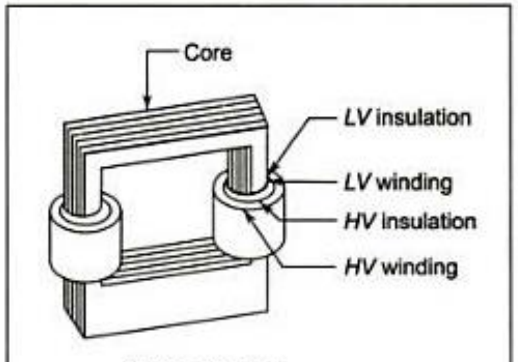
In the core-type transformer, the windings surround the core.

In the shell-type transformer, the core surrounds the windings.

core-type

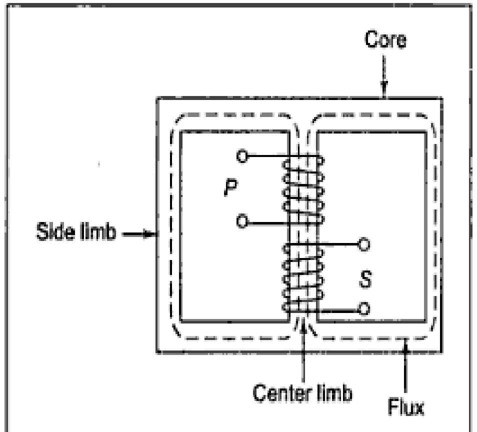


(a) Representation

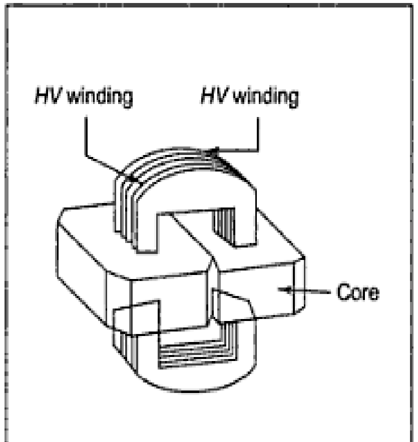


(b) Construction

shell-type

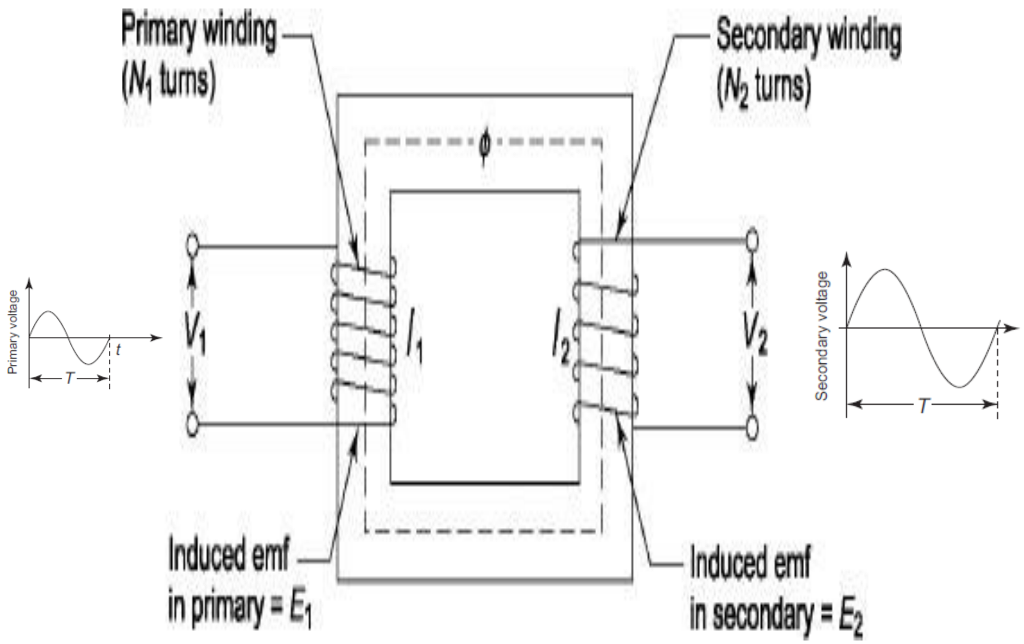


(a) Representation



(b) Construction

EMF Equation of a transformer



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

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

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

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

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

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

•Where:

- f - is the flux frequency in Hertz, $= \omega/2\pi$
- N - is the number of coil windings.
- Φ - is the amount of flux in webers

Transformation Ratio

$E_1 = 4.44\, f\, \Phi_m N_1$ $\quad E_2 = 4.44\, f\, \Phi_m N_2$

$$K = \frac{E_2}{E_1}$$

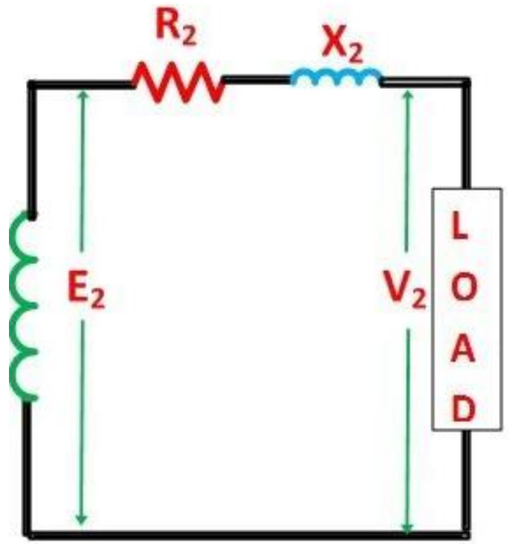
$$K = \frac{4.44\, f\, \Phi_m N_2}{4.44\, f\, \Phi_m N_1} \Rightarrow K = \frac{N_2}{N_1}$$

- Primary side power is same as secondary power

$$E_1 \cdot I_1 = E_2 \cdot I_2 \Rightarrow \frac{E_2}{E_1} = \frac{I_1}{I_2} \Rightarrow K = \frac{I_1}{I_2}$$

$$K = \frac{E_2}{E_1} = \frac{N_2}{N_1} = \frac{I_1}{I_2}$$

Transformer Regulation



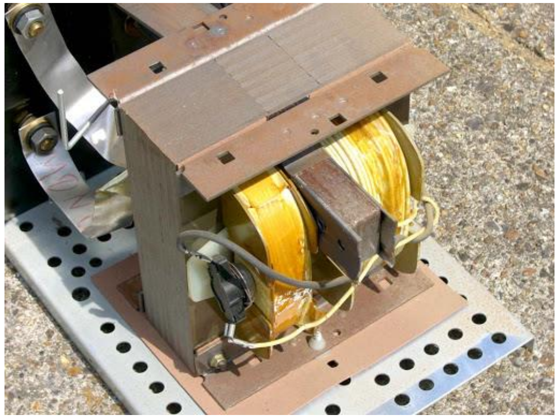
The measure of how well a power transformer maintains constant secondary voltage over a range of load currents is called the transformer's voltage regulation

$$\text{Regulation Percentage} = \frac{E_{\text{no-load}} - E_{\text{full-load}}}{E_{\text{full-load}}}(100\%)$$

If $E_2 > E_1$, Then The Transformer is called as Step up Transformer.

If $E_2 < E_1$, Then The Transformer is called as Step down Transformer.

$E_2 = E_1$, Isolation Transformer



Example Problems

1. The maximum flux density in the core of a 250/3000-volts, 50-Hz single-phase transformer is 1.2 Wb/m^2. If the e.m.f. per turn is 8 volt, determine (i) primary and secondary turns (ii) area of the core.

Solution. (*i*) $E_1 = N_1 \times \text{e.m.f. induced/turn}$

$N_1 = 250/8 = \mathbf{32}$; $N_2 = 3000/8 = \mathbf{375}$

(*ii*) We may use $E_2 = -4.44\, f\, N_2\, B_m\, A$

$\therefore \quad 3000 = 4.44 \times 50 \times 375 \times 1.2 \times A$; $\mathbf{A = 0.03 m^2}$.

Example Problems

2. A single-phase transformer has 400 primary and 1000 secondary turns. The net cross-sectional area of the core is 60 cm^2. If the primary winding be connected to a 50-Hz supply at 520 V, calculate (i) the peak value of flux density in the core (ii) the voltage induced in the secondary winding.

Solution. $K = N_2/N_1 = 1000/400 = 2.5$

(i) $E_2/E_1 = K \quad \therefore \quad E_2 = KE_1 = 2.5 \times 520 =$ **1300 V**

(ii) $E_1 = 4.44\, f N_1 B_m A$

or $520 = 4.44 \times 50 \times 400 \times B_m \times (60 \times 10^{-4}) \;\therefore\; B_m =$ **0.976 Wb/m^2**

Example Problems

3. A 25-kVA transformer has 500 turns on the primary and 50 turns on the secondary winding. The primary is connected to 3000-V, 50-Hz supply. Find the full-load primary and secondary currents, the secondary e.m.f. and the maximum flux in the core. Neglect leakage drops and no-load primary current.

Solution. $K = N_2/N_1 = 50/500 = 1/10$

Now, full-load $I_1 = 25{,}000/3000 = \mathbf{8.33\ A}$. F.L. $I_2 = I_1/K = 10 \times 8.33 = \mathbf{83.3\ A}$

e.m.f. per turn on primary side $= 3000/500 = 6\ \text{V}$

$\therefore$ secondary e.m.f. $= 6 \times 50 = \mathbf{300\ V}$ (or $E_2 = KE_1 = 3000 \times 1/10 = 300\ V$)

Also, $E_1 = 4.44\, f\, N_1 \Phi_m$; $3000 = 4.44 \times 50 \times 500 \times \Phi_m$ $\therefore$ $\Phi_m = \mathbf{27\ mWb}$

Practice Problem

1. The required no-load ratio in a 1 -phase 50 Hz core type transformer is 6000/250 V. Find the no. of turns in each winding if the flux is to be about 0.06 wb. (Ans: 480, 20 turns).

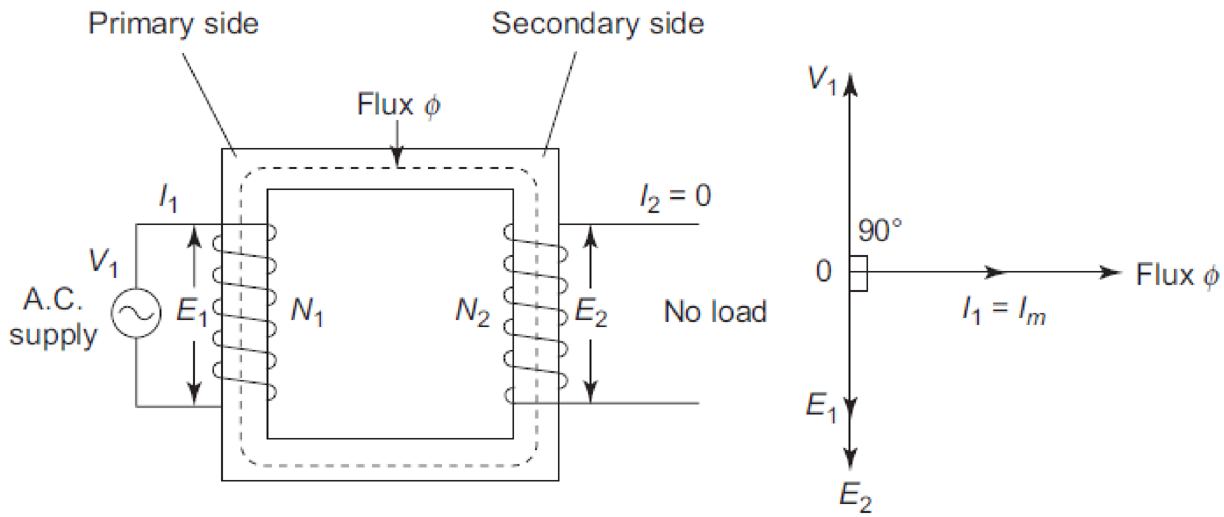
2. A 25 kVA, single-phase transformer has 250 turns on the primary and 40 turns on the secondary winding. The primary is connected to 1500-volt, 50 Hz mains. Calculate (i) Primary and Secondary currents on full-load, (ii) Secondary e.m.f., (iii) maximum flux in the core.
(Ans: 25 mWb, .240V, 16.67 A, 104.2 A)

Ideal Transformer

Ideal transformer

An ideal transformer has the following properties:

- Absence of winding resistance
- Infinite permeability of the core
- No leakage flux
- 100% efficiency



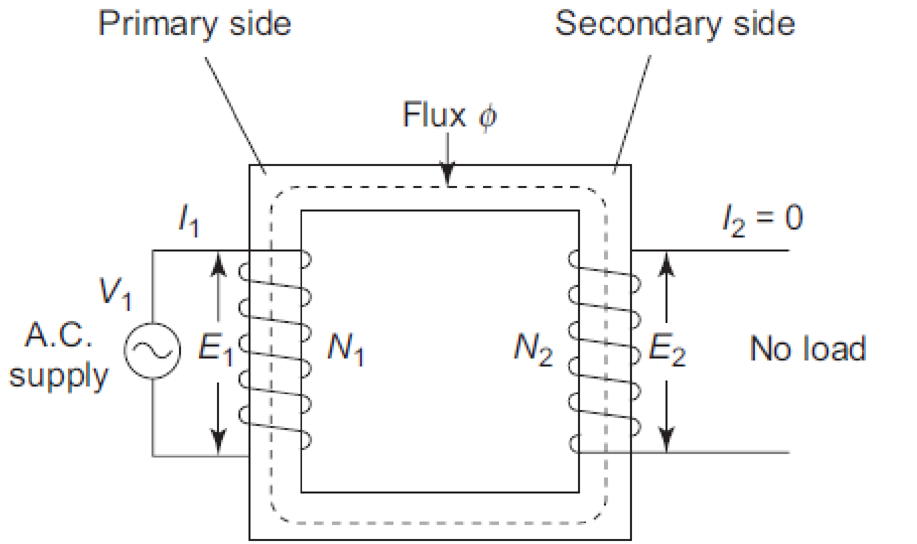
Ideal Transformer on No-load

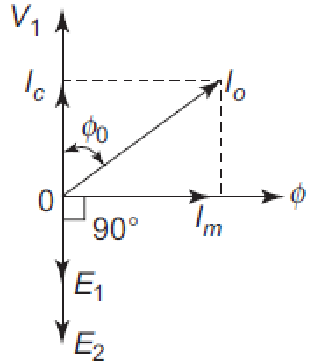
- The current drawn from the source is used to produce the magnetic flux.
- Hence, the current drawn from the primary winding is called magnetizing current.
- As the winding is purely inductive, the magnetizing current I_m lags the supply voltage by 90°.
- The alternating flux Φ is in phase with I_m.
- This alternating flux induces an emf in the primary winding, E_1, which opposes the supply voltage i.e., the phase angle between E_1 and V_1 is 180°.
- Since an alternating flux links the secondary winding, an emf, E_2, is induced in the secondary winding.
- Induced emf in secondary winding, E_2, depends on the number of turns, N_2, in the secondary winding.
- Since the secondary circuit is not closed, the secondary current, $I_2 = 0$

Practical Transformer

On No-load

- The primary current drawn from the source has two components
  - Magnetising component: The magnetizing current, I_m, which is a purely reactive component of I_o that lags V_1 by 90°, is required to magnetise the core and to produce the magnetic flux.
  - Loss component: The core loss component Ic, supplies the total losses of the transformer under no load condition.
- Hence, the total no-load current of a transformer, I_o is the vector addition of I_m and I_c.
- Since I_c is very small, approximately 0.04 times the full-load rated current, it contributes more to core loss or iron loss when compared to primary copper loss.
- Hence, the no load input power, W_o, supplies the iron loss of the transformer, which is constant for different load conditions.
- Since the secondary circuit is not closed, the secondary current, $I_2 = 0$.



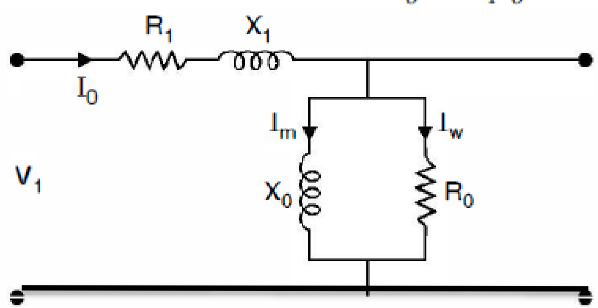


I_o = No load current
I_m = Magnetizing current
I_c = Core loss component
E_1 = Induced emf in primary side winding
E_2 = Induced emf in secondary side winding
V_1 = Source voltage

$$\bar{I}_o = \bar{I}_m + \bar{I}_c$$

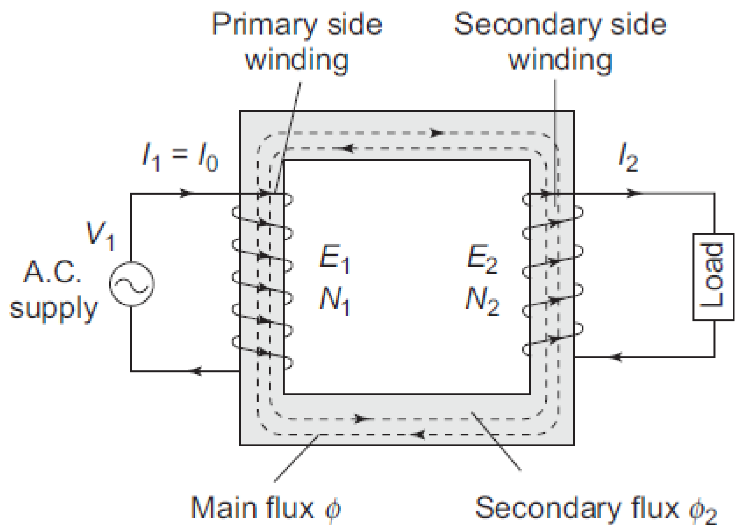
$$I_c = I_o \cos \phi_0 \text{ and } I_m = I_o \sin \phi_0$$

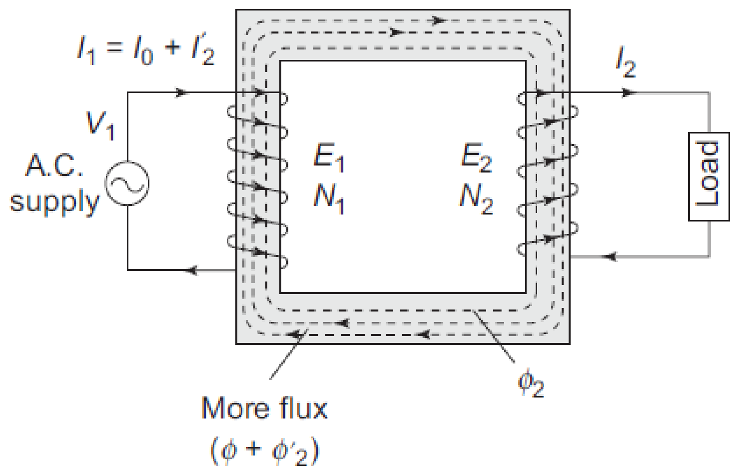
$$W_o = V_1 I_o \cos \phi_o$$



Transformer on Load

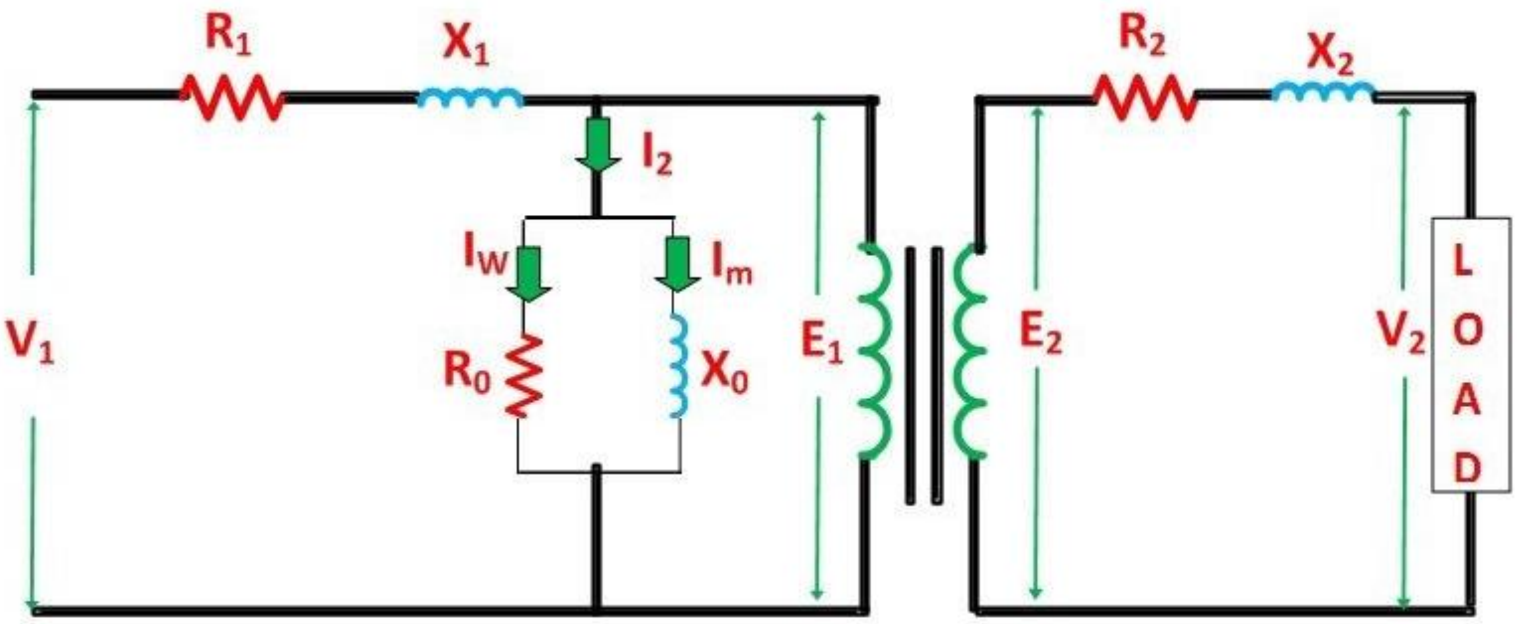
- Since the load is connected to the secondary winding, the current I_2 flows through the winding and an output voltage V_2 is obtained across the load.
- The phase difference between the output voltage V_2 and I_2 depends on the load
  - If load is inductive, I_2 lags V_2,
  - If load is capacitive, I_2 leads V_2
  - If load is resistive, I_2 is in phase with V_2.
- The current I_2 flowing through secondary winding produces its own magnetic flux Φ_2, which opposes the magnetic flux Φ. Since Φ_2 opposes Φ , there is a momentary reduction in the magnetic flux Φ, which further decreases the induced emf E_1.
- This decrease in E_1 increases the difference between V_1 and E_1 that causes the primary winding to draw extra current I_2' , thereby producing an additional flux Φ_2' opposite to Φ_2.
- Since this current I_2' neutralizes Φ_2, the flux is maintained constant in the transformer and hence, it is also known as constant flux machine.





Transformer on Load

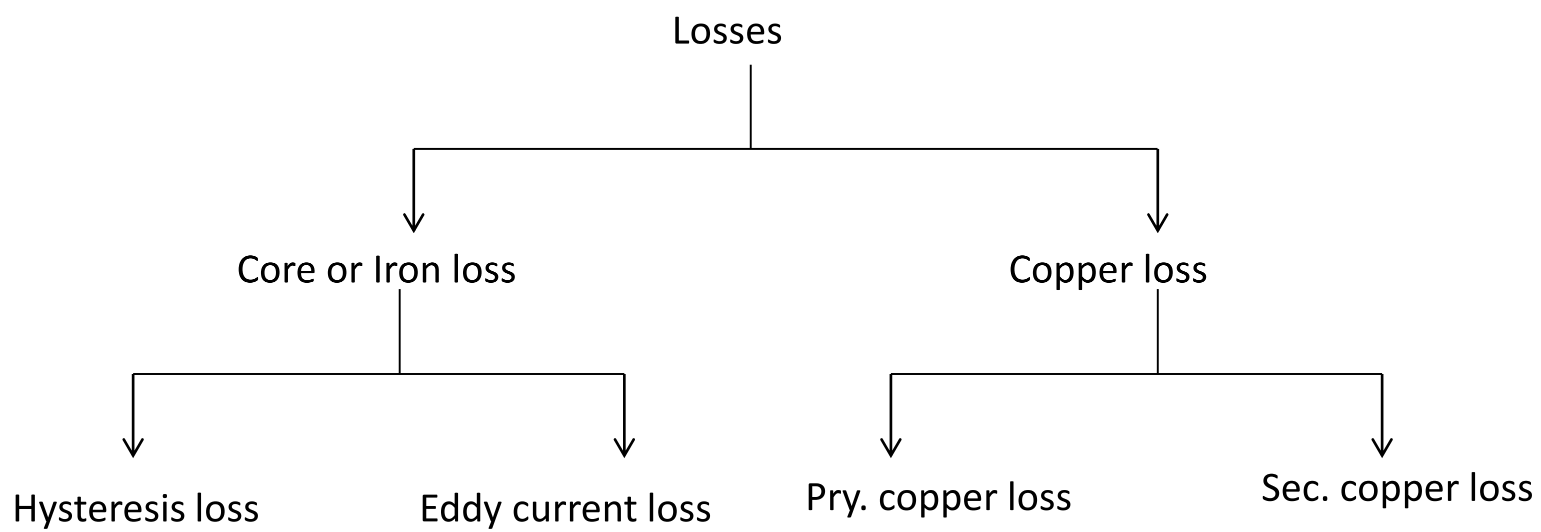
Equivalent Circuit



Losses in transformer

Two types of losses occur in a transformer:

1. Core loss or iron loss occurs in a transformer because it is subjected to an alternating flux.
2. The windings carry current due to loading and hence copper losses occur.



Efficiency of transformer

the efficiency of the transformer is defined as the ratio of the power output to power input

$$\eta = \frac{\text{Power output}}{\text{Power intput}}$$

$$\text{Power input} = \text{Power output} + \text{Total losses}$$

$$\eta = \frac{\text{Power output}}{\text{Power output} + \text{total losses}} = \frac{\text{Power output}}{\text{Power output} + P_i + P_c}$$

The **transformer efficiency is maximum** when the copper loss is equal to the core loss

Applications of transformer

Transformers are used in the following applications:

(i) Power transformers located in Power Plants are used to step-up the generated voltage to a high transmission voltage.

(ii) Transformers are used in distribution circuit to step-down voltages to the desired level.

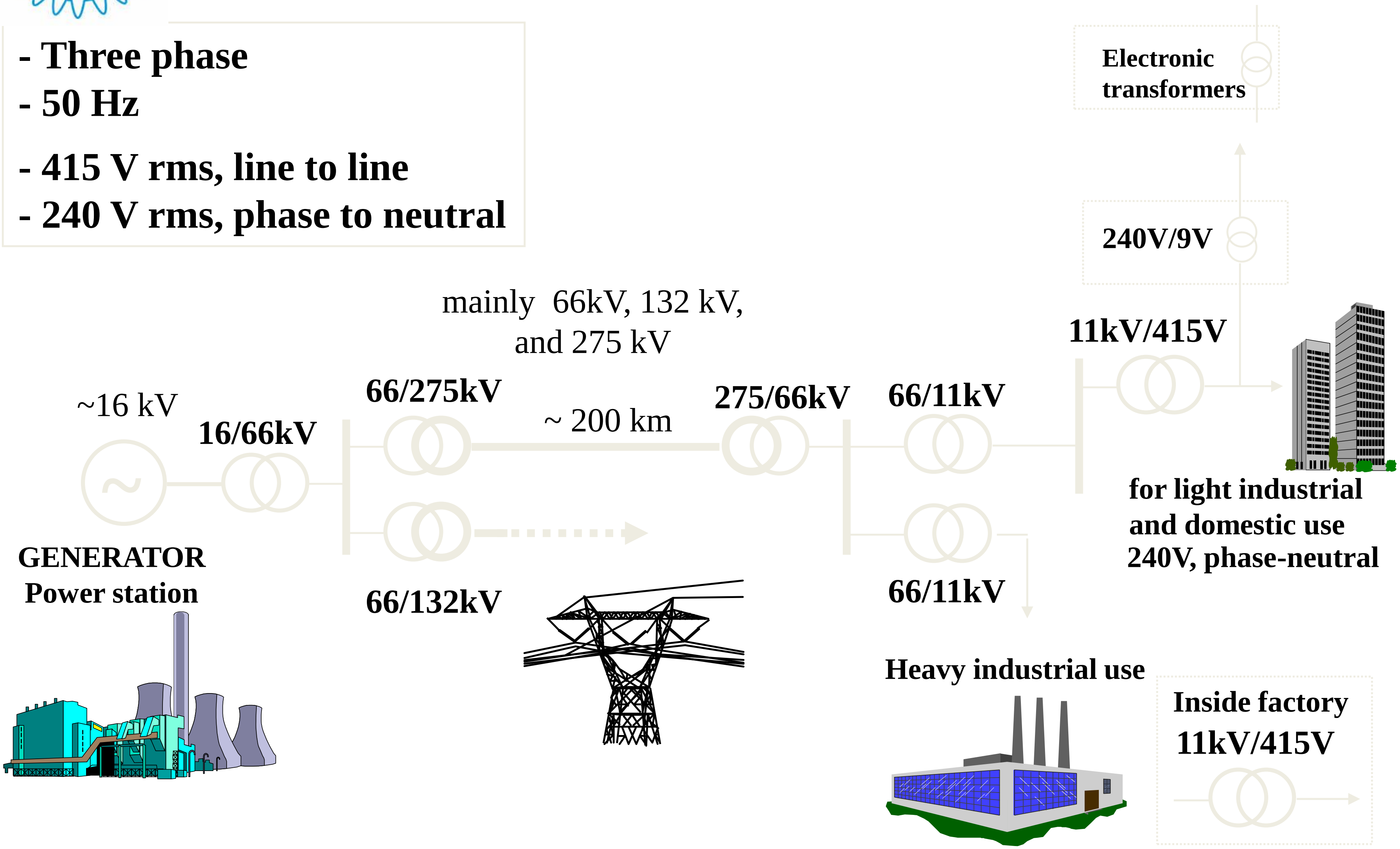
(iii) Almost all electronic circuits use transformers.

(iv) Potential transformers are used to measure high voltages and current transformers are used to measure high currents.

(v) Furnace transformers and welding transformers are some special applications of transformers.

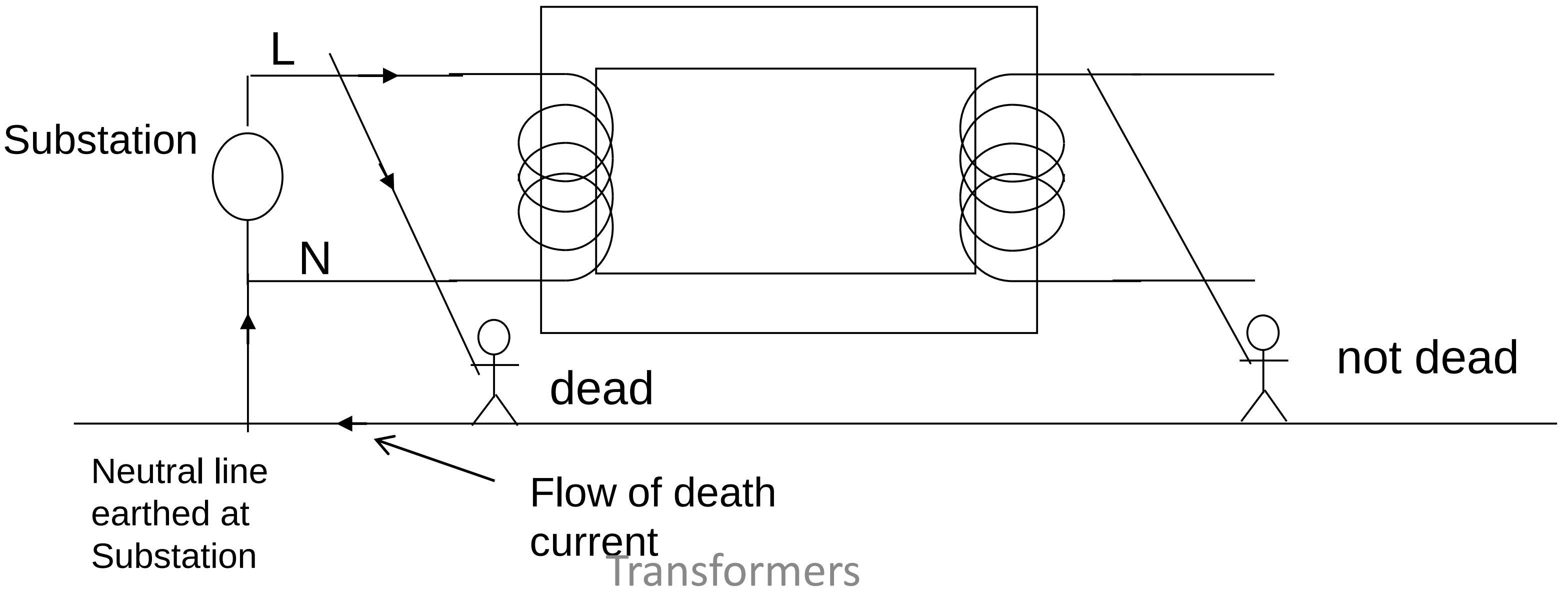
POWER DISTRIBUTION

- Three phase
- 50 Hz
- 415 V rms, line to line
- 240 V rms, phase to neutral



Isolation and Safety

- There is no electrical connection between the primary circuit and the secondary circuit
- The secondary circuit is "electrically isolated" from the primary
- Study the following in which someone makes contact with the conductors:



Ratings

Rating: Maximum power delivered by the transformer without exceeding permissible Temperature Rise.

In a name plate, or on a website, a Transformer is typical described as: 240/15V, 150 VA, 20%, 50 Hz. This means:

240 V: Rated input voltage

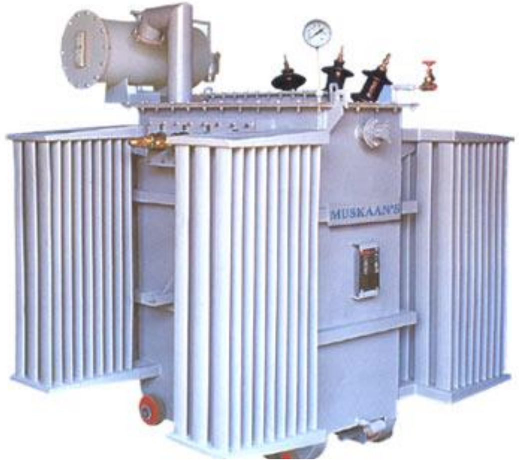
15 V: Full load output voltage V_2

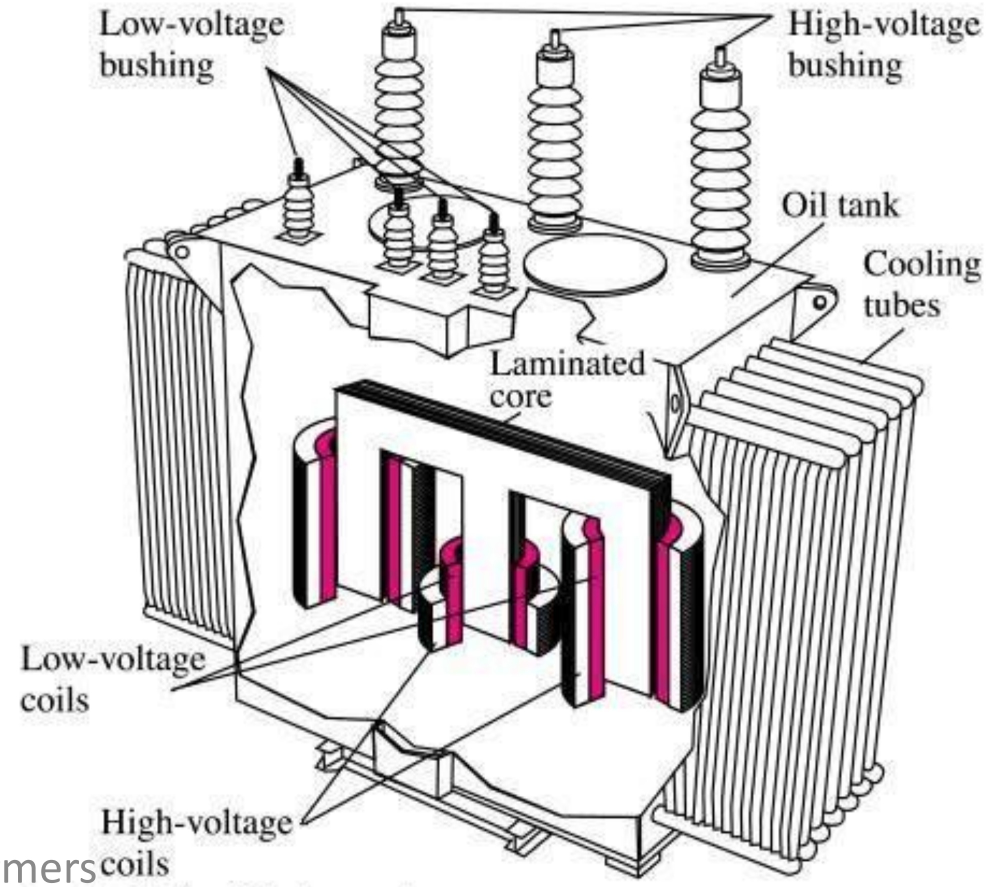
50 Hz: The frequency that the TF is designed for

150 VA: Volt-Amp rating = $V_2 I_2$ (values rms)

Note: Power is $|\tilde{V}_2||\tilde{I}_2| cos\,\theta_2$ and if TF supplying inductive load then $\theta = 90°$ and $P = 0$, even though $|\tilde{I}_2|$ could be at rated value of 10A rms

Name Plate Details





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A good transformer should have:

- ✓ **high permeability**:
  the core is made of iron, and therefore small magnetising current
- ✓ **low iron losses**:
  core is laminated (high resistivity silicon steel or soft ferrite)
- ✓ **small leakage reactance**:
  the primary and secondary coils on top of each other
- ✓ **low winding resistances**:
  reduced $I^2 R$ loss (heat), and → higher efficiency
- ✓ **conductors**:
  aluminium, copper, and heavier insulation