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TECHNOLOGY, RESEARCH, SOCIAL INNOVATION & PARTNERSHIPS

Basics of Electrical and Electronics Engineering

ECE1022A

Unit IV - Single Phase Transformer

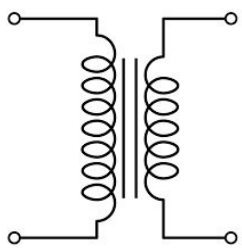
Topics:

- Working principle
- Construction
- Types
- Equivalent circuit
- Losses
- Efficiency
- Regulation

Single Phase Transformer

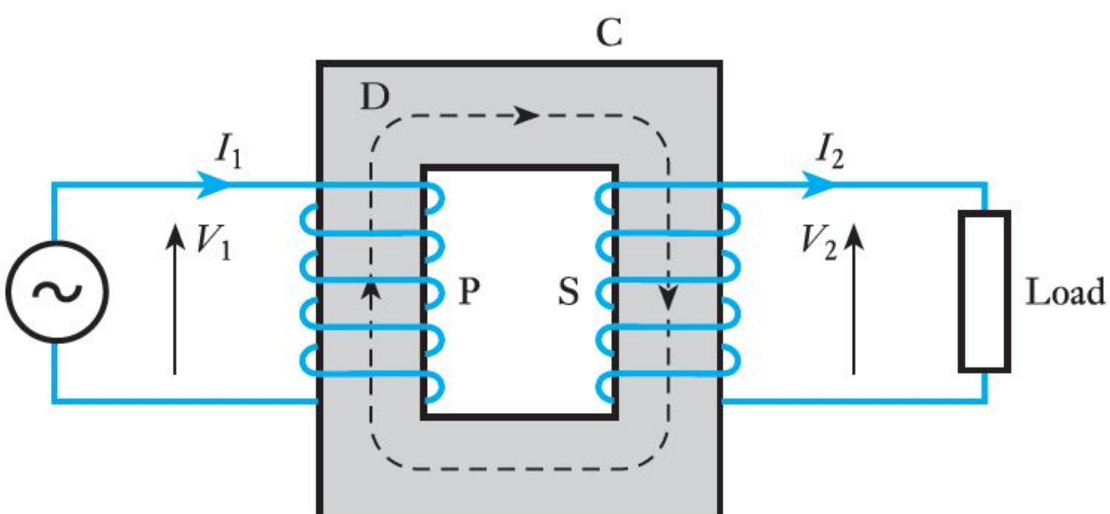
A static device which transfers electrical energy from one ac circuit to another with the desired change in voltage or current and without any change in frequency

- AC device
- Voltage/current can be amplified or reduced
- Step-up and step-down transformer
- Step-up: Step up to higher voltages for the transmission lines.
- Step-down: To step the voltage down to values suitable for motors, lamps, heaters, etc.
- Single phase transformer and three phase transformer
- Symbol of Transformer -



Working Principal of Single Phase Transformer

- A steel core C consists of laminated sheets, about 0.35–0.7 mm thick, insulated from one another.
- Coil P is connected to the supply and is therefore termed the *primary*; coil S is connected to the load and is termed the *secondary*.
- The magnetic flux forms the connecting link between the primary and secondary circuits



Working Principal of Single Phase Transformer

- An alternating voltage applied to P circulates an alternating current through P and this current produces an alternating flux in the steel core
- If the whole of the flux produced by P passes through S, the e.m.f. induced in each turn is the same for P and S.
- Hence, if N1 and N2 are the number of turns on P and S respectively,

$$\frac{\text{Total e.m.f. induced in S}}{\text{Total e.m.f. induced in P}} = \frac{N_2}{N_1}$$

$$\frac{V_2}{V_1} \simeq \frac{N_2}{N_1}$$

Primary and secondary power factors are nearly equal,

$$I_1 V_1 \simeq I_2 V_2$$

so that

Current ratio is given by:

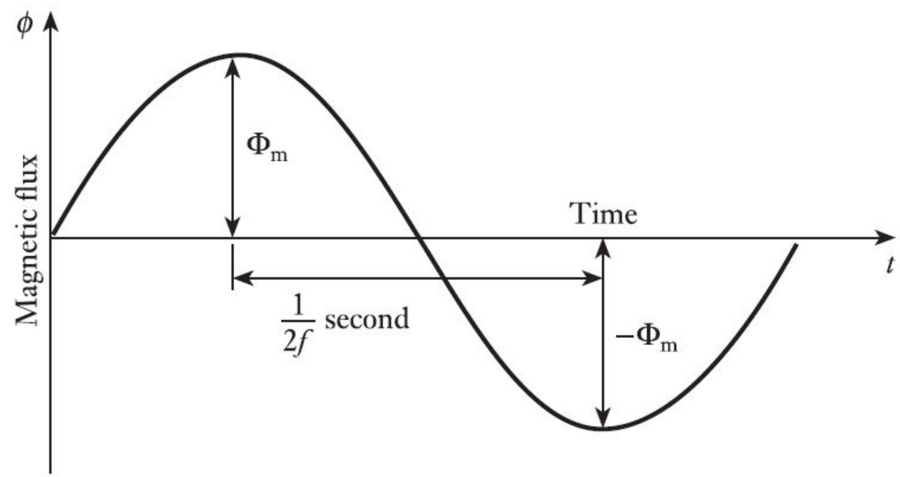
$$\frac{I_1}{I_2} \simeq \frac{V_2}{V_1}$$

$$\frac{I_1}{I_2} \simeq \frac{N_2}{N_1} \simeq \frac{V_2}{V_1}$$

EMF equation of a transformer

- The maximum value of the flux to be Φm webers and the frequency to be f hertz. From Fig. 34.3, the flux has to change from +Φm to −Φm in half a cycle, namely 1/2f in seconds.

Fig. 34.3 Waveform of flux variation



$$\therefore \qquad \text{Average rate of change of flux} = 2\Phi_m \div \frac{1}{2f}$$

$$= 4f\,\Phi_m \text{ webers per second}$$

and average e.m.f. induced per turn is

$$4f\,\Phi_m \text{ volts}$$

EMF equation of a transformer

But for a sinusoidal wave the r.m.s. or effective value is 1.11 times the average value,

$\therefore$ RMS value of e.m.f. induced per turn $= 1.11 \times 4 f \Phi_m$

Hence, r.m.s. value of e.m.f. induced in primary is

$$\boxed{E_1 = 4.44 N_1 f \Phi_m} \quad \text{volts} \qquad [34.4]$$

and r.m.s. value of e.m.f. induced in secondary is

$$\boxed{E_2 = 4.44 N_2 f \Phi_m} \quad \text{volts} \qquad [34.5]$$

Numerical Problems

1. A single phase transformer of 50 Hz, has a maximum flux in the core of 0.021 Wb, the number of primary being 460 and secondary 52. Calculate the emf induced in the primary and secondary windings of the transformer.

2. A single phase transformer of 50 Hz, has 300 primary turns and 750 secondary turns. The net cross sectional area of the core is 64 sq. cm. If the primary induced emf is 440 V find:
   a. maximum flux density in the core
   b. Calculate the emf induced in the secondary winding of the transformer.

3. A 250 kVA, 11 000 V/400 V, 50 Hz single-phase transformer has 80 turns on the secondary. Calculate:
   (a) the approximate values of the primary and secondary currents;
   (b) the approximate number of primary turns;
   (c) the maximum value of the flux.

Numerical 3

A 250 KVA, 11 000 V/400 V, 50 Hz single-phase transformer has 80 turns on the secondary. Calculate:

(a) the approximate values of the primary and secondary currents;

(b) the approximate number of primary turns;

(c) the maximum value of the flux.

(a) Full-load primary current

$$\simeq \frac{250 \times 1000}{11\,000} = \mathbf{22.7\ A}$$

and full-load secondary current

$$= \frac{250 \times 1000}{400} = \mathbf{625\ A}$$

(b) No. of primary turns

$$\simeq \frac{80 \times 11\,000}{400} = \mathbf{2200}$$

(c) From expression [35.5]

$$400 = 4.44 \times 80 \times 50 \times \Phi_m$$

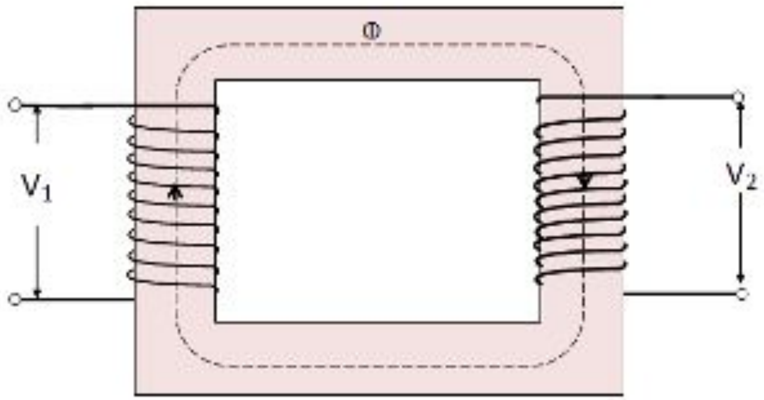
$$\Phi_m = \mathbf{22.5\ mWb}$$

Construction of Single Phase Transformer

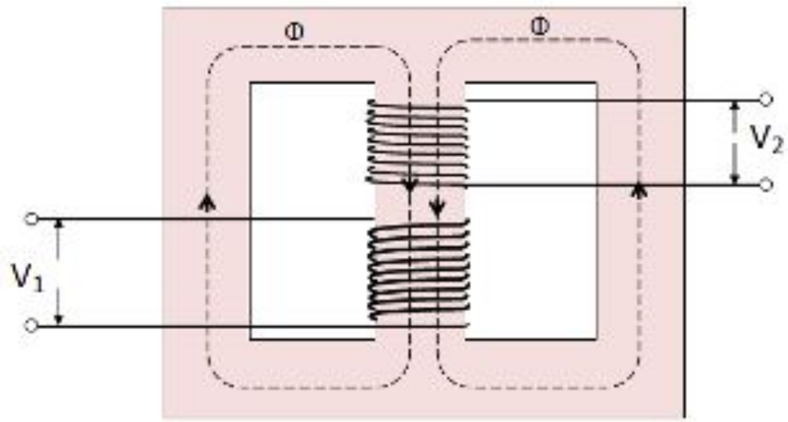
- A simple two-winding transformer construction consists of each winding being wound on a separate soft iron limb or core which provides the necessary magnetic circuit
- This magnetic circuit, known more commonly as the “transformer core” is designed to provide a path for the magnetic field to flow around, which is necessary for induction of the voltage between the two windings.
- The core is designed to reduce “eddy currents”, which cause heating and energy losses within the core decreasing the transformers efficiency.
- To reduce these unwanted power losses, transformer core is constructed from thin steel laminations.

Construction of Single Phase Transformer

- The two most common and basic designs of transformer construction are the Closed-core Transformer and the Shell-core Transformer.
- In the “closed-core” type (core form) transformer, the primary and secondary windings are wound outside and surround the core ring.
- In the “shell type” (shell form) transformer, the primary and secondary windings pass inside the steel magnetic circuit (core) which forms a shell around the windings as shown below.



Core Type Transformer

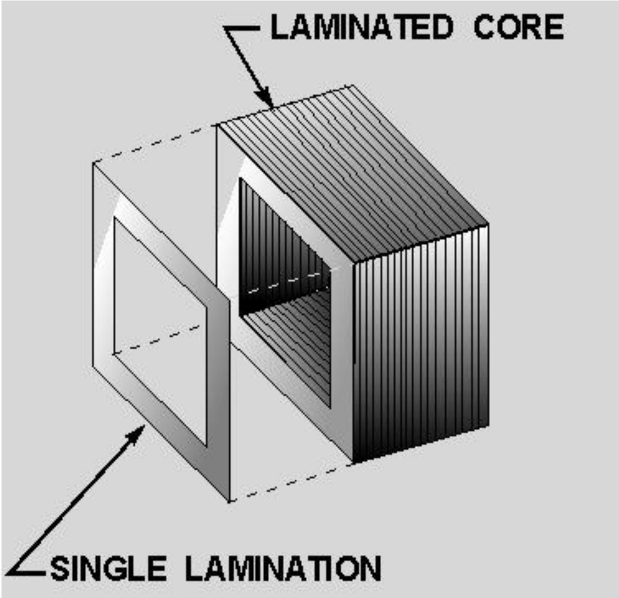


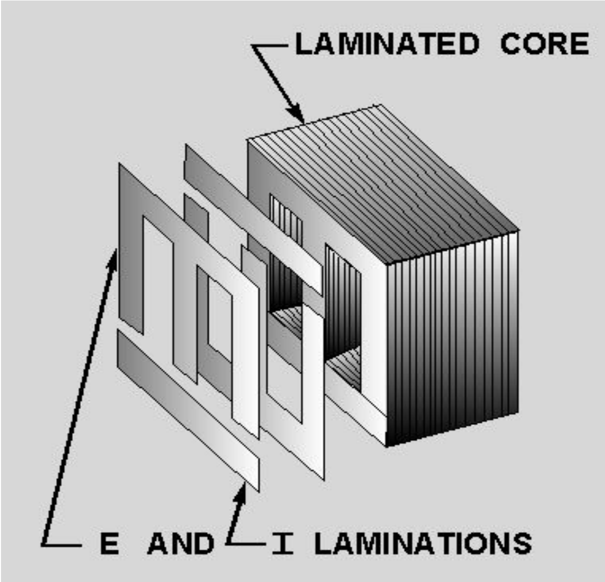
Shell Type Transformer

Construction of Single Phase Transformer

Core Construction:

- The central iron core is constructed from of a highly permeable material made from thin silicon steel laminations
- These thin laminations are assembled together to provide the required magnetic path with the minimum of magnetic losses
- Typically 0.35 to 0.7 mm thick

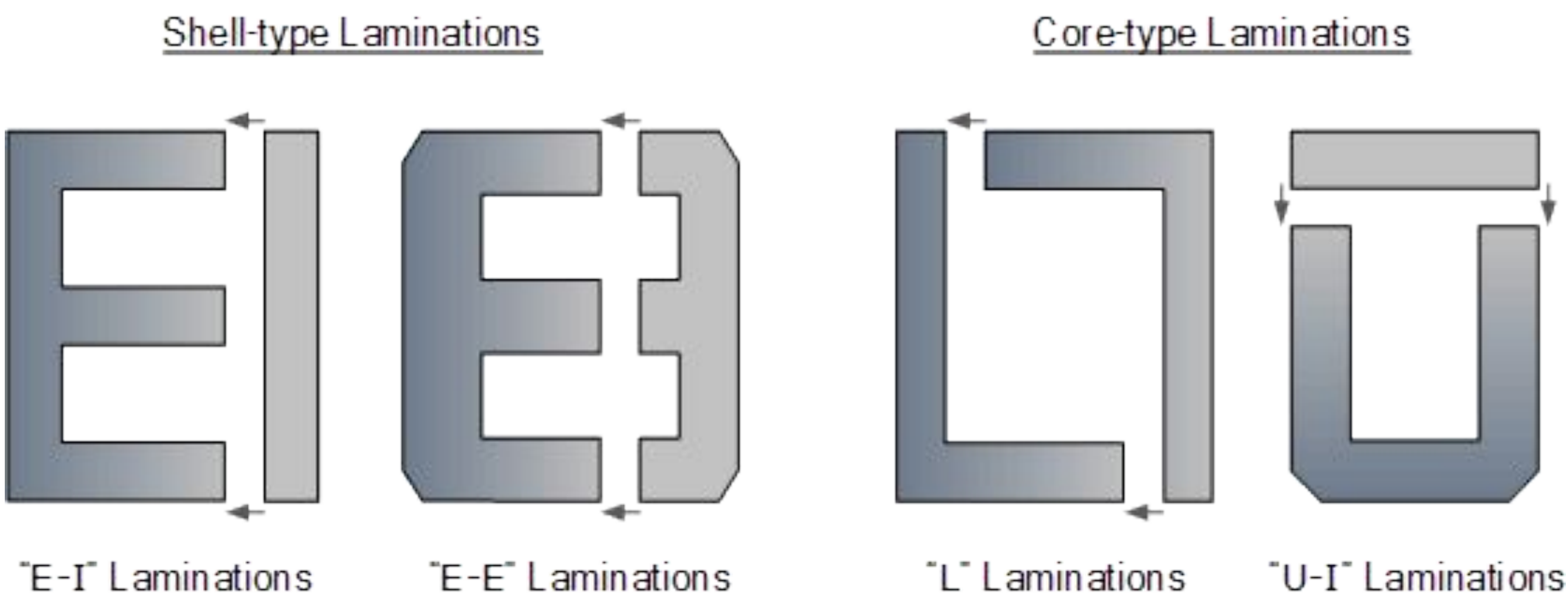




Construction of Single Phase Transformer

Laminations:

- The individual laminations are stamped out from larger steel sheets and formed into strips of thin steel resembling the letters "E"s, "L"s, "U"s and "I"s as shown below



Comparison

Core		Shell	
1.	Winding encircles the core	1.	Core encircles most of the windings
2.	Single magnetic circuit	2.	Double magnetic circuit
3.	Core has two limbs	3.	Core has three limbs
4.	Cylindrical coils are used	4.	Sandwich type coils are used
5.	Windings are distributed on two limbs hence natural cooling is effective	5.	Windings are surrounded by the core hence no natural cooling
6.	Coils can be easily removed for maintenance	6.	Coils cannot be removed easily
7.	For low voltage transformers	7.	For high voltage transformers

Types of Transformer

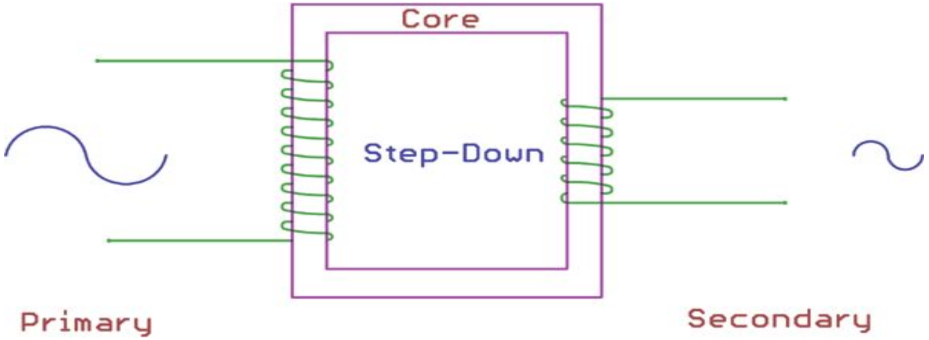
Transformer Types based on Voltage Level:

- Depending on the voltage level of the primary side and secondary side, the transformer has three categories.
  - ✔ Step Down
  - ✔ Step Up
  - ✔ Isolation Transformer.

Types of Transformer

1. Step-Down Transformer:

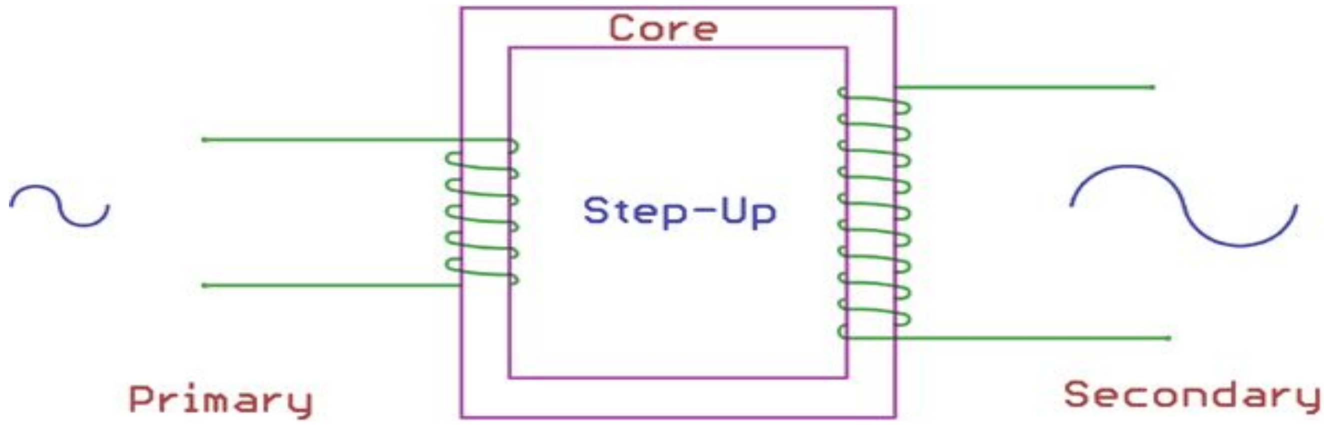
- A step-down transformer converts the primary voltage level to a lower voltage across the secondary output.
- This is achieved by the ratio of primary and secondary windings.
- For step-down transformers the number of windings is higher across the primary side than the secondary side. Therefore, the overall winding ratio of primary and secondary always remains more than 1.



Types of Transformer

2. Step-Up Transformer:

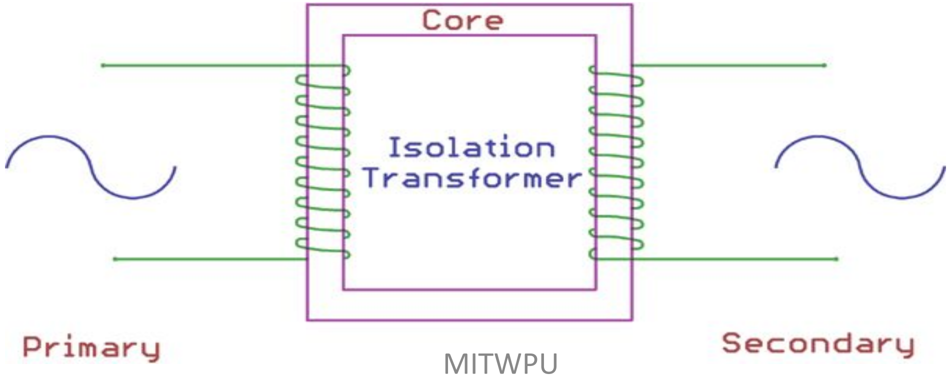
- Step Up transformer is exactly opposite of the step-down transformer.
- Step up transformer increase the low primary voltage to a high secondary voltage.
- It is achieved by the ratio of primary and secondary winding ratio.
- For the Step Up transformer, the ratio of the primary winding and the Secondary winding remains less than 1. That means the number turns in secondary winding is higher than the primary winding.



Types of Transformer

3. Isolation Transformer:

- Isolation transformer does not convert any voltage levels. The Primary voltage and the secondary voltage of an isolation transformer always remain the same.
- This is because the primary and the secondary winding ratio is always equal to the 1.
- That means the number of turns in primary and secondary winding is same in isolation transformer.
- The transformer does not have any electrical connections between primary and secondary, it is also used as an isolation barrier where the conduction happens only with the magnetic flux. **It is used for safety purpose and to cancel noise transfer from primary to secondary or vice-versa.**



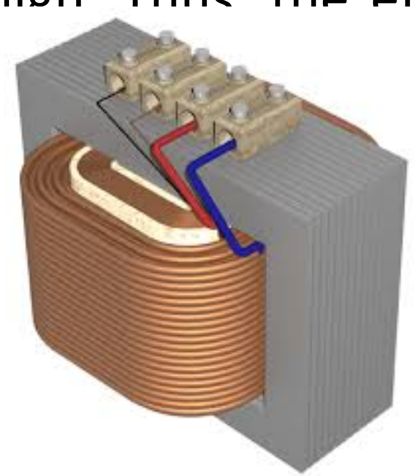
Types of Transformer

Transformer Types based on Core material:

- ✔ Iron Core Transformer
- ✔ Ferrite Core Transformer
- ✔ Air-core Transformer

1. Iron Core Transformer:

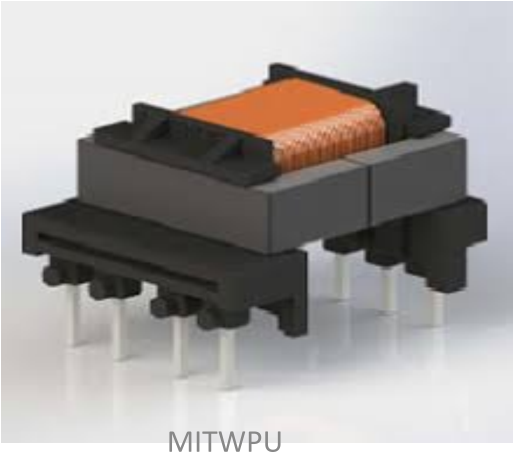
- Iron core transformer uses multiple soft iron plates as the core material.
- Due to the excellent magnetic properties of iron, the flux linkage of the iron core transformer is very high. Thus, the efficiency of the iron core transformer is also high.



Types of Transformer

2. Ferrite Core Transformer:

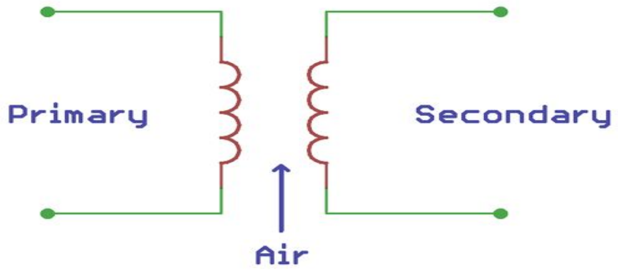
- A ferrite core transformer uses a ferrite core due to high magnetic permeability.
- This type of transformer offers very low losses in the high-frequency application.
- Due to this, ferrite core transformers are used in high-frequency application such as in switch mode power supply (SMPS), RF related applications, etc.



Types of Transformer

4. Air Core transformer:

- Air Core transformer does not use any physical magnetic core as the core material. The flux linkage of the air-core transformer is made entirely using the air.
- In air core transformer, the primary coil is supplied with alternating current which produces an electromagnetic field around it. When a secondary coil is placed inside the magnetic field, the secondary coil is induced with a magnetic field which further is used to power the load.
- However, air core transformer produces low mutual inductance compared to physical core material such as iron or ferrite core.



Types of Transformer

Transformer Types based on usage:

- ✔ Power transformers
- ✔ Measurement Transformers
- ✔ Distribution Transformers

1. Power transformers :

- The Power transformers are used in high power transfer applications for both step-up and step-down applications, where the operating voltages are more than 33KV.
- These are usually big in size depending upon the power handling capacity and its application.
- These transformers are available in three phase or single phase type.
- As these transformers are bulky, they are placed in large open area.

Types of Transformer

2. Measurement Transformers:

- The Measurement transformers are used for measuring high voltage and high currents.
- These are mostly helpful in isolating the circuits from them.
- These are mainly of two types, Current transformers and Voltage transformers.

Types of Transformer

3. Distribution Transformers:

- The Distribution transformers are used for distribution of electrical energy at end-user level.
- The operating voltages are around 33KV for industrial purposes and 440v-220v for domestic purposes.

Types of Transformer

Transformer Types based on supply used:

- ✔ Single phase transformer
- ✔ Three phase transformer

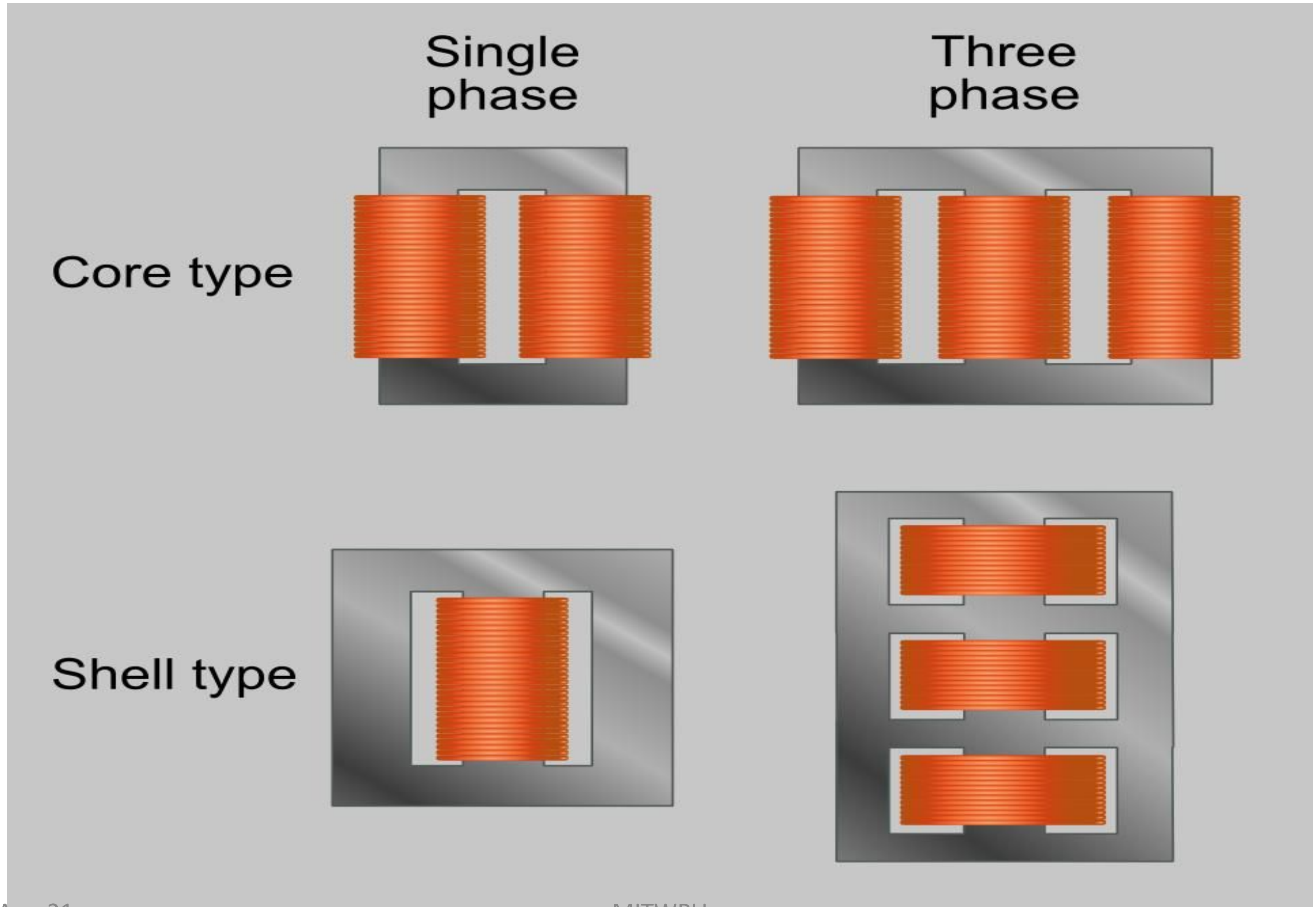
1. Single phase transformer

A normal transformer is a single phase transformer. It has a primary and a secondary winding and it is operated to either decrease or increase the secondary voltage.

2. Three phase transformer

For a three phase transformer, three primary windings are connected together and three secondary windings are connected together.

Types of Transformer



Equivalent circuit of a transformer

- The behaviour of a transformer may be conveniently considered by assuming it to be equivalent to an ideal transformer, i.e. a transformer having no losses and no magnetic leakage and a ferromagnetic core of infinite permeability requiring no magnetizing current, and

- Then allowing for the imperfections of the actual transformer by means of additional circuits or impedances inserted between the supply and the primary winding and between the secondary and the load.

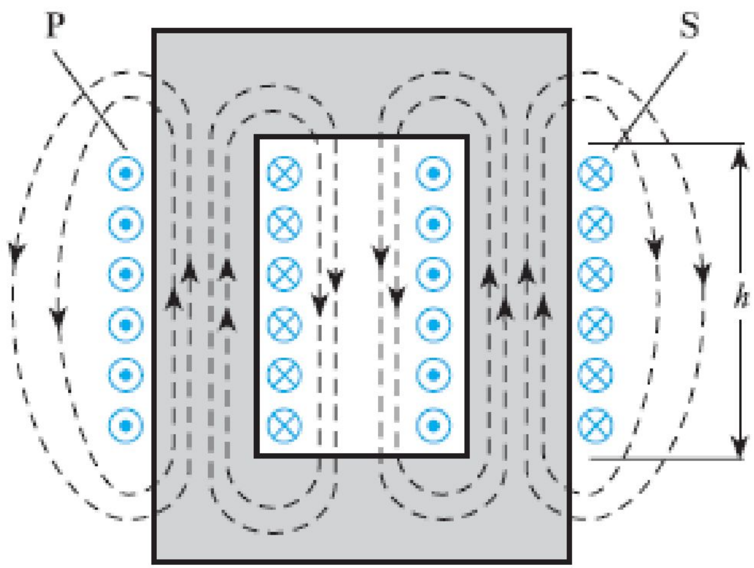


Fig. 34.11 Paths of leakage flux

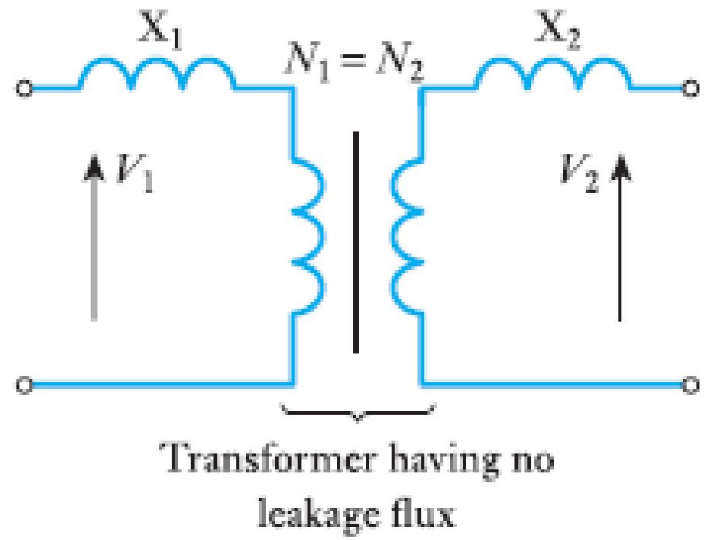


Fig. 34.13 Transformer with leakage reactances

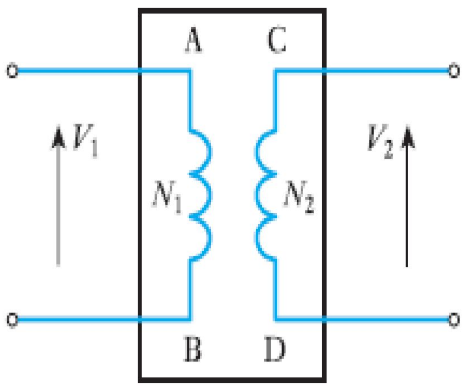


Fig. 34.12 Ideal transformer enclosed in a box

1. The useful flux, Φ_U, linked with both windings and remaining practically constant in value at all loads.
2. The leakage flux, Φ_L, half of which is linked with the primary winding and half with the secondary, and its value is proportional to the load.

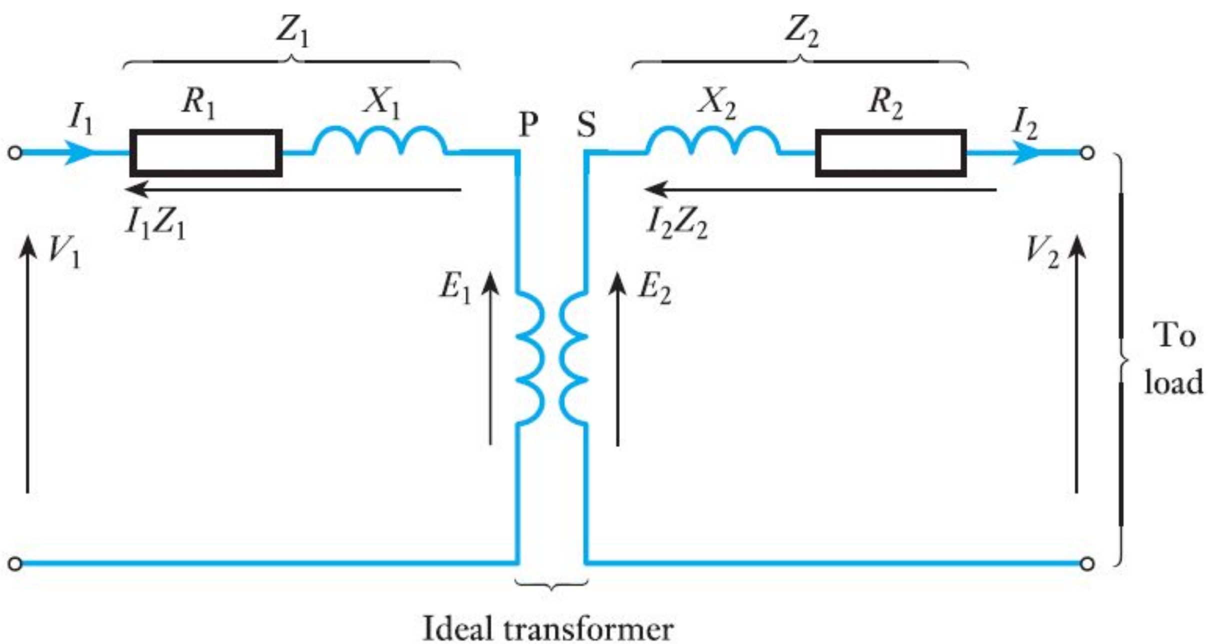
Effect of leakage flux in Equivalent Circuit

- The leakage flux is proportional to the primary and secondary currents and its effect is to induce e.m.f.s of self-induction in the windings.

- Consequently the effect of leakage flux can be considered as equivalent to inductive reactors X1 and X2 connected in series with a transformer having no leakage flux

Equivalent circuit of a transformer

- P and S represents the primary and secondary windings of the ideal transformer
- R1 and R2 are resistances equal to the resistances of the primary and secondary windings of the actual transformer
- Similarly, inductive reactance X1 and X2 represent the reactance of the windings due to leakage flux in the actual transformer



Approximate equivalent circuit of a transformer

Equivalent circuit of a transformer

I_2R_2 = voltage drop due to secondary resistance

I_2X_2 = voltage drop due to secondary leakage reactance

and I_2Z_2 = voltage drop due to secondary impedance

I_1R_1 = voltage drop due to primary resistance

I_1X_1 = voltage drop due to primary leakage reactance

I_1Z_1 = voltage drop due to primary impedance

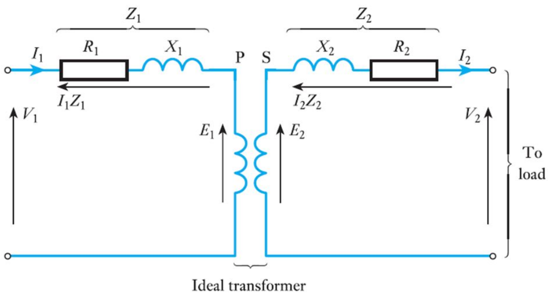
and $V_1 = E_1 + I_1Z_1$ = supply voltage

Simplified equivalent circuit of a transformer

Replace the resistance R_2 of the secondary by inserting additional resistance $R_{2'}$ in the primary circuit such that the power absorbed in $R_{2'}$ when carrying the primary current is equal to that in R_2 due to the secondary current, i.e

$$I_1^2 R_{2'} = I_2^2 R_2$$

$$R_{2'} = R_2 \left(\frac{I_2}{I_1} \right)^2 \simeq R_2 \left(\frac{V_1}{V_2} \right)^2$$



Hence if R_e is a single resistance in the primary circuit equivalent to the primary and secondary resistances of the actual transformer then

$$R_e = R_1 + R_{2'} = R_1 + R_2 \left(\frac{V_1}{V_2} \right)^2$$

Similarly, since the inductance of a coil is proportional to the square of the number of turns, the secondary leakage reactance X_2 can be replaced by an equivalent reactance $X_{2'}$ in the primary circuit, such that

$$X_{2'} = X_2 \left(\frac{N_1}{N_2} \right)^2 \simeq X_2 \left(\frac{V_1}{V_2} \right)^2$$

Simplified Equivalent circuit of a transformer

If Xe is the single reactance in the primary circuit equivalent to X1 and X2 of the actual transformer

$$X_e = X_1 + X_{2'} = X_1 + X_2\left(\frac{V_1}{V_2}\right)^2$$

If Ze is the equivalent impedance of the primary and secondary windings referred to the primary circuit

$$Z_e = \sqrt{(R_e^2 + X_e^2)}$$

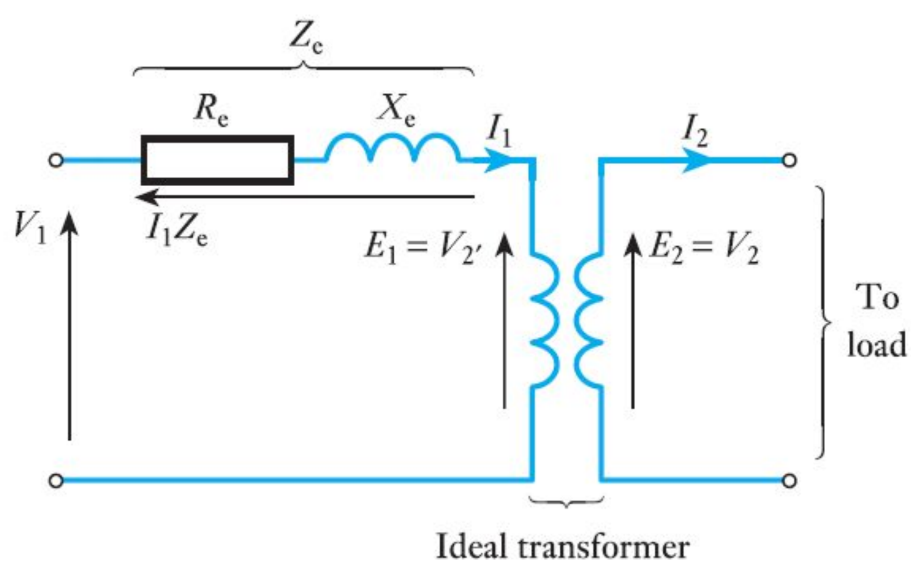
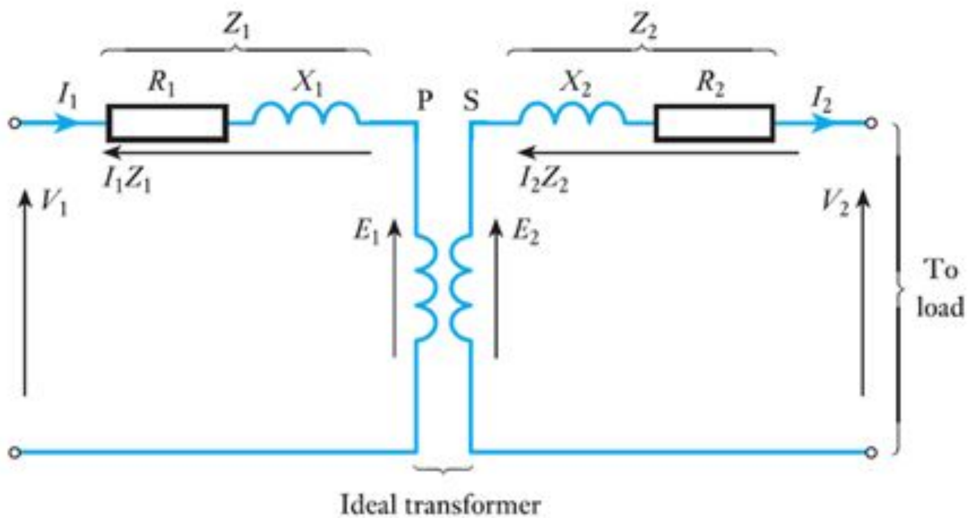
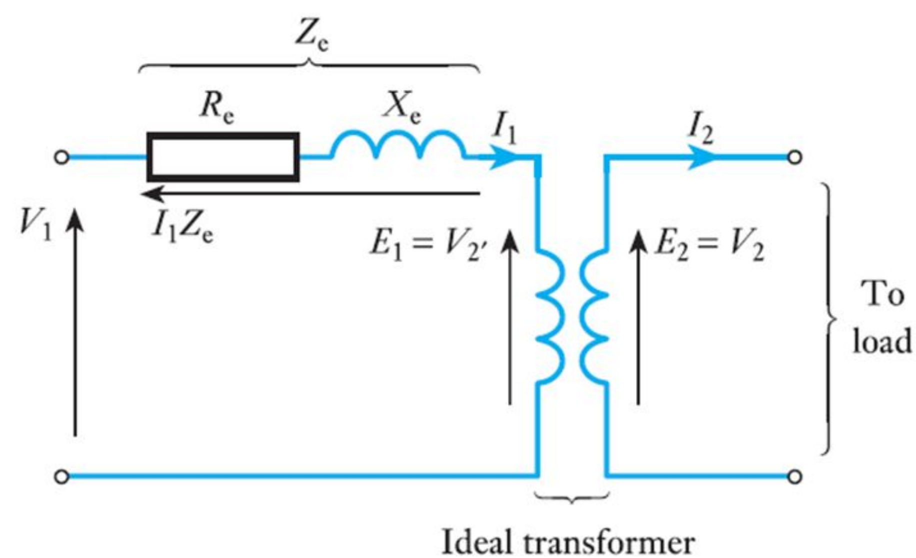


Fig: Simplified equivalent circuit of a transformer

Impedance Transformation





Voltage regulation of a transformer

- The voltage regulation of a transformer is defined as the variation of the secondary voltage between no load and full load, expressed as either a per-unit or a percentage of the no-load voltage, the primary voltage being assumed constant, i.e.

$$\text{Voltage regulation} = \frac{\text{no-load voltage} - \text{full-load voltage}}{\text{no-load voltage}}$$

If V_1 is primary applied voltage

Secondary voltage on no load = $V_1 \times \frac{N_2}{N_1}$

since the voltage drop in the primary winding due to the no-load current is negligible.

If V_2 is secondary terminal voltage on full load,

Voltage regulation of a transformer

$$\text{Voltage regulation} = \frac{V_1 \dfrac{N_2}{N_1} - V_2}{V_1 \dfrac{N_2}{N_1}}$$

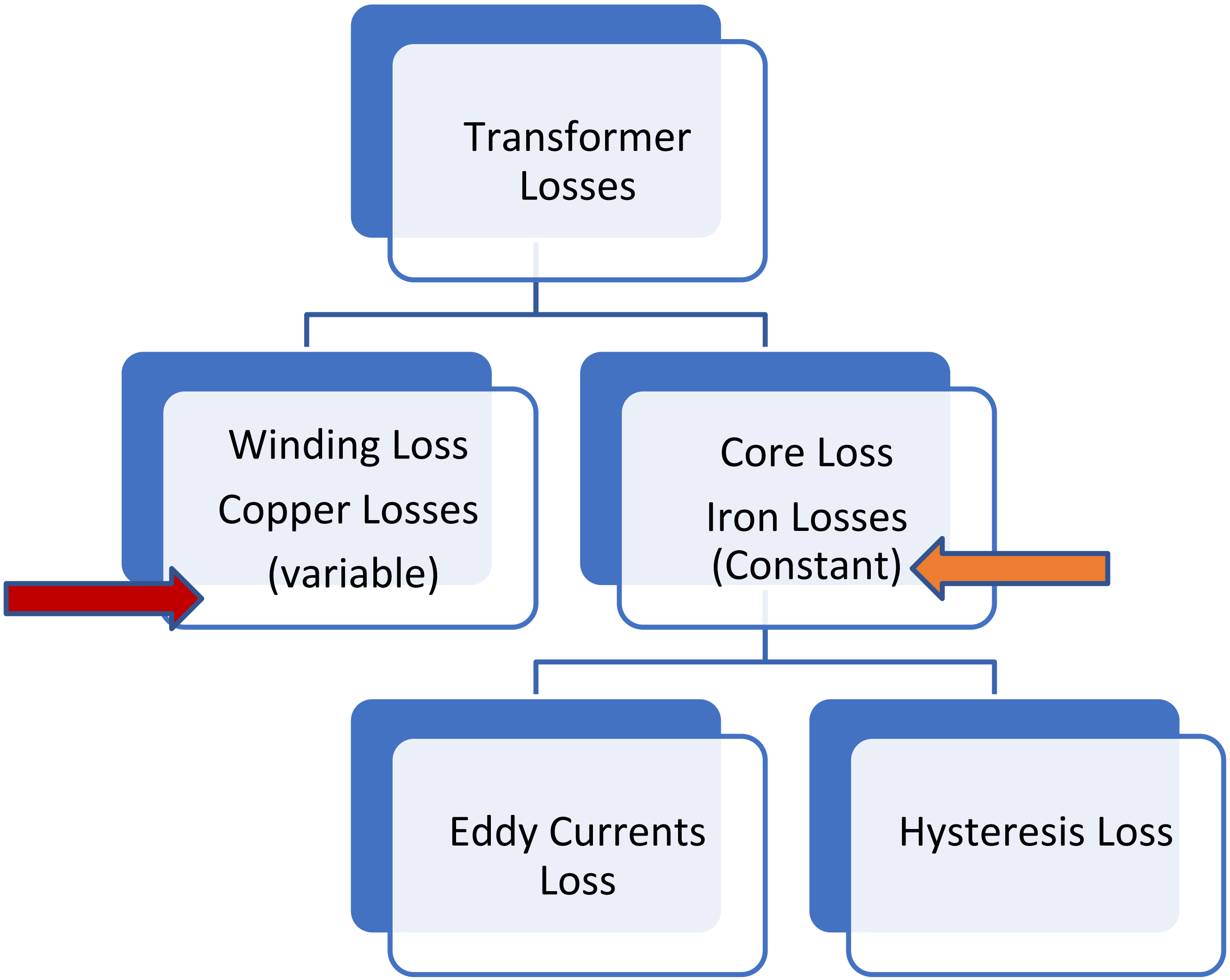
$$= \frac{V_1 - V_2 \dfrac{N_1}{N_2}}{V_1} \text{ per unit}$$

$$= \frac{V_1 - V_2 \dfrac{N_1}{N_2}}{V_1} \times 100 \text{ per cent}$$

$$\therefore \qquad \boxed{\text{Per-unit voltage regulation} = \frac{V_1 - V_{2'}}{V_1}}$$

Where, $V_{2'} = V_2 \, (N_1/N_2)$

Transformer losses



Transformer losses

Copper Losses:

- Due to resistance of the windings
- Power loss is proportional to the square of the currents and ultimately heat up the windings
- Total copper loss = ${I_1}^2 R_1 + {I_2}^2 R_2$

Where, $R_1 \& R_2$ are the primary and secondary resistances

- Material with good conductivity is used to reduce these losses, e.g. copper

Transformer losses

Eddy Currents Loss:

- The varying flux in the core induces e.m.f.s and hence currents in the core material. These losses are called eddy-current losses

$$P_e = K_e B_m^{\,2} f^2 t^2 v \quad watts$$

Where, t – thickness of laminations

Ke – constant

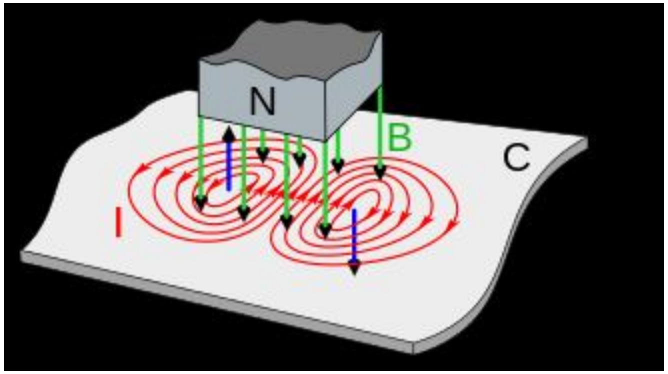
f - frequency in Hz

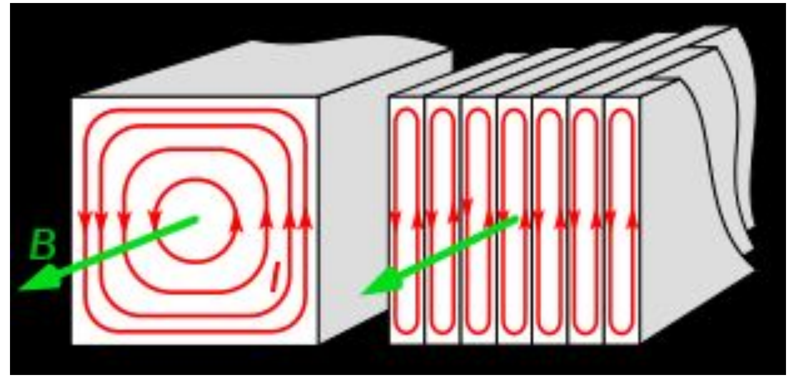
Bm – max flux density in tesla

v – volume of magnetic material in cubic meters

- **These losses are reduced by thin laminations of silicon steel**

Eddy Currents





Eddy currents are loops of electrical current induced within conductors by a changing magnetic field in the conductor according to Faraday's law of induction. Eddy currents flow in closed loops within conductors, in planes perpendicular to the magnetic field.

Eddy currents *(I, red)* within a solid iron transformer core. *(right)* Making the core out of thin laminations parallel to the field *(B, green)* with insulation between them reduces the eddy currents. Although the field and currents are shown in one direction, they actually reverse direction with the alternating current in the transformer winding.

When graphed, these circular currents within a piece of metal look vaguely like eddies or whirlpools in a liquid.

Transformer losses

Hysteresis Loss:

- The larger the loop the greater the energy required to create the magnetic field
- This requirement of supplying energy to magnetize the core is known as the hysteresis loss.

$$P_h = K_h B_m^{1.6} f v \quad watts$$

f - frequency in Hz

Bm – max flux density in tesla

v – volume of magnetic material in cubic meters

Kh- constant

- These losses are nearly constant, independent of current

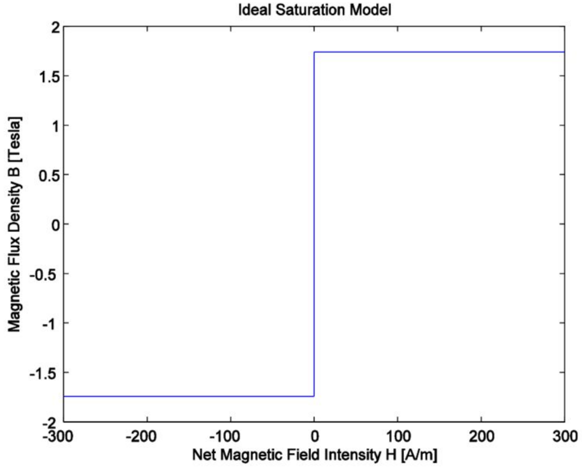


Fig. Ideal BH curve

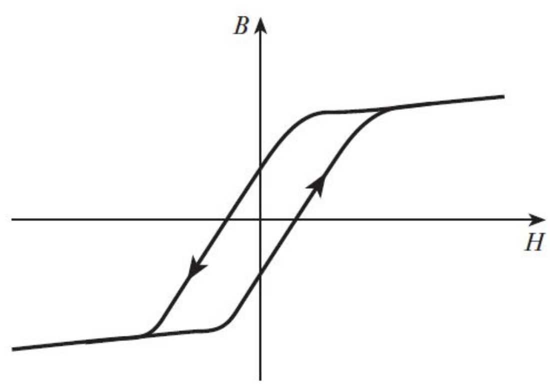
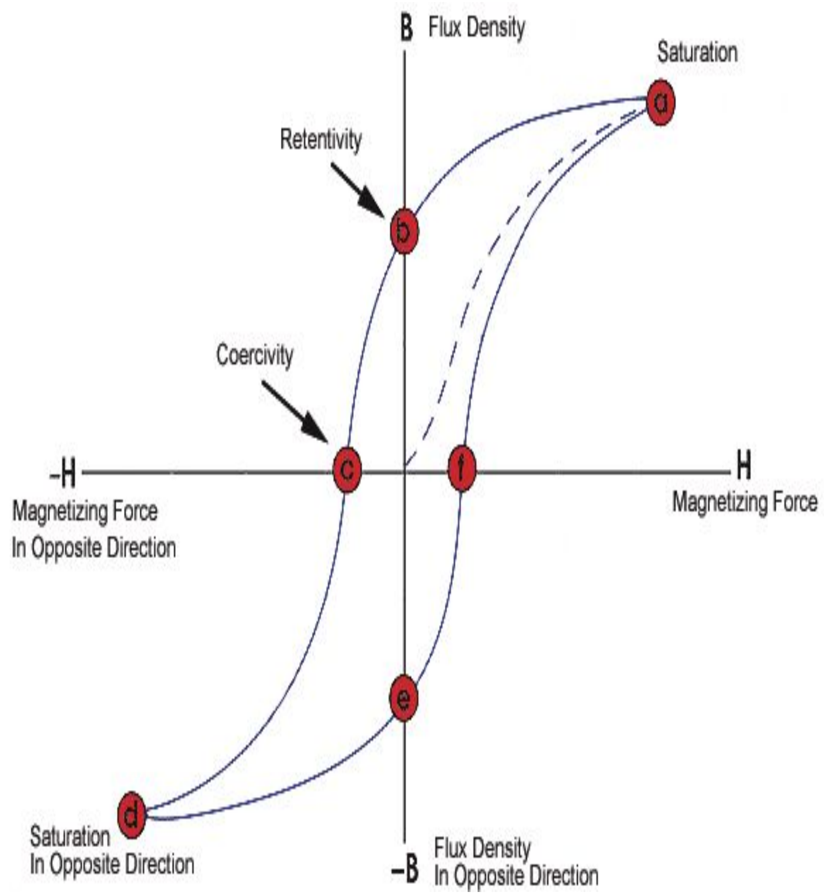
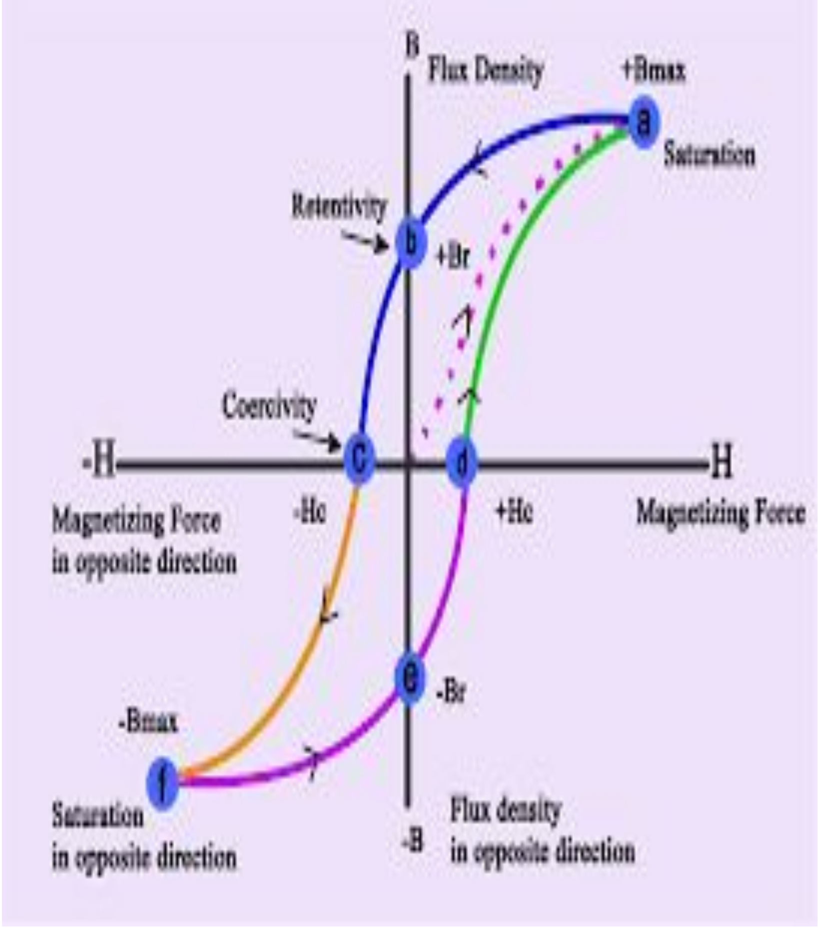


Fig. Hysteresis loop

Hysteresis Loop





Efficiency of a transformer

- The losses which occur in a transformer on load can be divided into two groups:
  1. I^2R losses in primary and secondary windings, namely $I_1^2\ R_1 + I_2^2\ R_2$
  2. Core losses due to hysteresis and eddy currents.

If,

P_C = total core loss,

Then,

Total losses in transformer = $P_C + I_1^2\ R_1 + I_2^2\ R_2$

Efficiency of a transformer is given by:

$$\text{Efficiency} = \frac{\text{output power}}{\text{input power}} = \frac{\text{input power} - \text{losses}}{\text{input power}}$$

$$\boxed{\eta = 1 - \frac{\text{losses}}{\text{input power}}}$$

Extra Learning resource:

- https://youtu.be/fbu1Xji27vc

- https://www.youtube.com/watch?v=UchitHGF4n8

- https://youtu.be/vh_aCAHThTQ