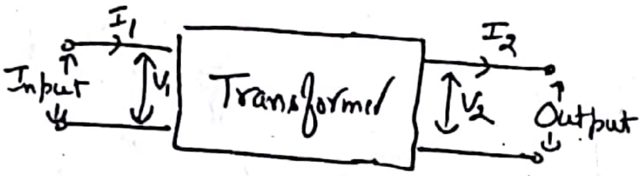
TRANSFORMER Unit-3

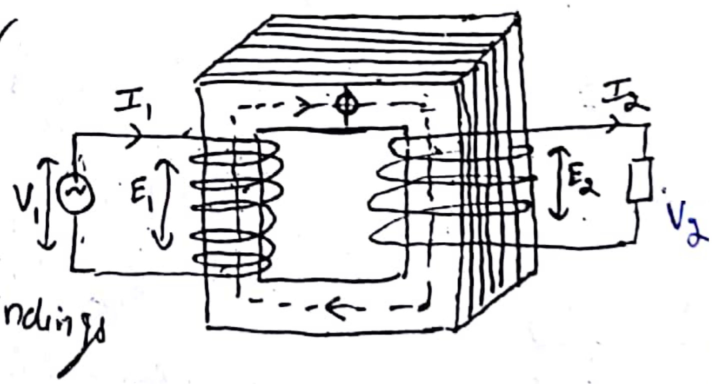
Transformer is a static device which transfers ac electrical power from one circuit to the other at the same frequency but the voltage level is changed



→ When the voltage is raised on the output side ($V_2 > V_1$), the transformer is called step up transformer, whereas the transformer in which the voltage is lowered on the output side ($V_2 < V_1$) is called a step down transformer.

Working Principle of Transformer

The Basic principle of transformer is electromagnetic induction.



It consists of two separate windings placed over the laminated silicon steel core.

The winding to which ac supply is connected is called primary winding and the winding to which load is connected is called secondary winding.

→ When ac supply of voltage V_1 is connected to primary winding, an alternating flux is set up in the core. This alternating flux when links with the secondary winding an emf is induced in it called <u>mutually induced emf</u>. The direction of this induced emf is opposite to the applied voltage V_1.

⇒ The same alternating flux also links with the primary winding and produces self induced emf E_1. This induced emf E_1 also acts in opposite direction to the applied voltage V_1.

⇒ Although, there is no electrical connection b/w primary and secondary winding, but electrial power is transferred from primary circuit to secondary circuit through mutual flux.

→ The induced emf in primary and secondary winding depends upon the rate of change of flux (i.e. $N\frac{d\phi}{dt}$). The rate of change of flux is same for both primary and secondary.

$$\therefore \; E_1 \propto N_1 \text{ and } E_2 \propto N_2$$

$$\frac{E_2}{E_1} = \frac{N_2}{N_1} = K \left(\underset{\text{Ratio}}{\text{Transformation}}\right)$$

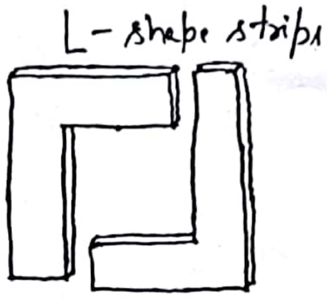
⇒ If $N_2 > N_1$ (Step up transfor
$N_2 < N_1$ (Step down transf

Transformer Construction

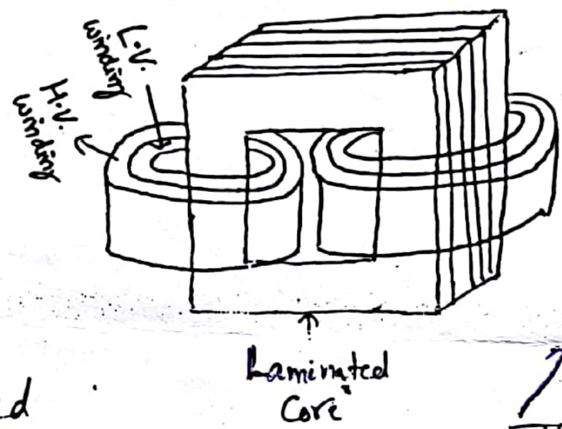
- The main elements of transformer are two coils and a laminated steel core. The two coils are insulated from each other as well as from steel core.
- The core of the transformer is constructed from laminations of sheet steel or silicon steel assembled to provide continuous magnetic path.
- The laminations reduce eddy current loss and silicon steel reduces hysteresis loss. The laminations are insulated from each other by a light coating of varnish or by an oxide layer. The thickness of lamination varies from 0.35mm to 0.5mm for a frequency of 50Hz.
- Acc. to core construction and manner in which the primary and secondary are placed around it, the transformer are named as (1) Core type transformers.
  (2) Shell type transformers.
- In core type transformers the windings surround a considerable part of the core, whereas in shell type, the core surrounds a considerable portion of winding.

Core Type Transformers

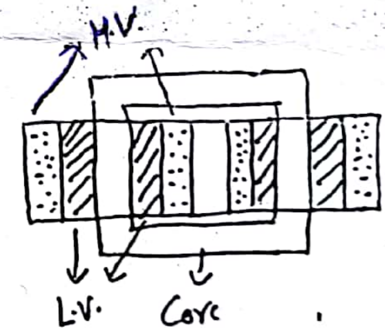
→ In a simple core type transformer, the magnetic core is built of laminations to form a rectangular frame. The laminations are cut in the form of L-shape.



→ The coils used are form wound and are of cylindrical type



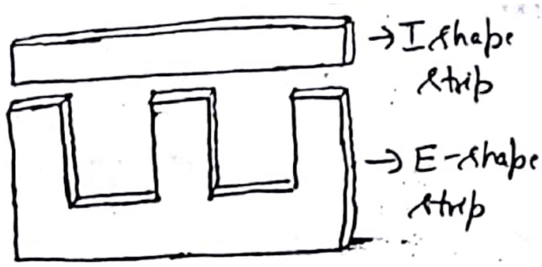
→ The low voltage winding is placed next to the core and high voltage winding is placed around the low voltage winding to reduce the insulating material required.



→ The two windings are arranged as concentric coils. Such a winding is therefore called concentric winding or cylindrical winding. While placing these windings an insulation layer is provided b/w core and lower winding and between the two windings.

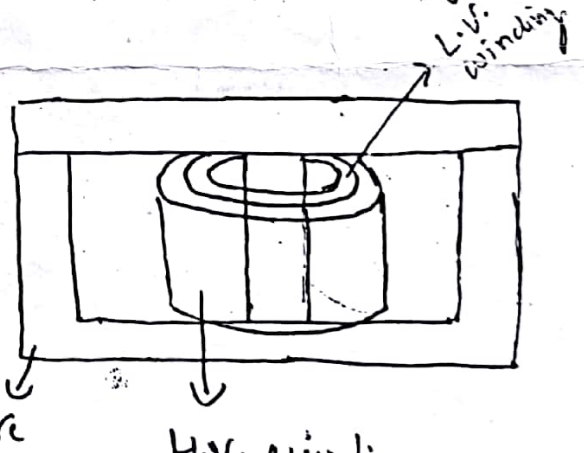
Shell Type Transformer

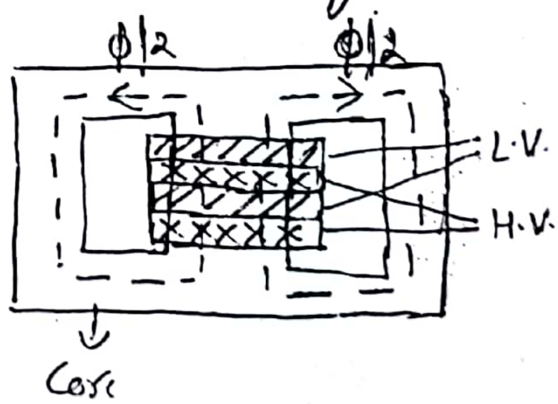
→ In case of shell type transformers, individual laminations are cut in the form of long strip of E's and I's



→ In the shell type transformer, both primary and secondary winding are wound on central limb and two outer limbs complete the low reluctance flux paths.

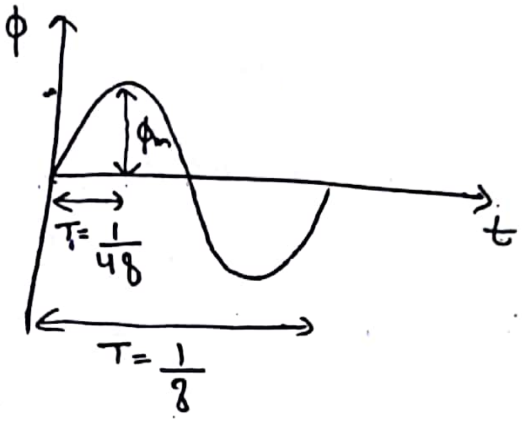
→ The core has three limbs. The central limb carries whole of the flux, whereas side limbs carry half of flux. Therefore, the width of central limb is about double to that of outer limbs.





Emf Equation of Transformer

- Let N_1 = No. of turns in primary
  N_2 = No. of turns in secondary
  ϕ_m = Max. value of flux (Wb)
  f = supply freq. in Hz



- Flux increases from its zero value to max. value in one quarter of cycle i.e. $\frac{1}{4f}$ sec

Average rate of change of flux $= \dfrac{\phi_m}{1/4f} = 4f\phi_m$ (Wb/s)

- Rate of change of flux per turn means induced emf in volts.

Average emf/turn $= 4f\phi_m$ (Volt)

- For a sinusoidal wave, $\dfrac{\text{Rms value}}{\text{Avg value}}$ = Form Factor = 1.11

Rms value of induced emf/turn = 1.11 × Average emf/turn
$= 1.11 \times 4f\phi_m = 4.44 f\phi_m$ (Volt)

- Rms value of induced emf in primary = Emf induced/turn × No. of primary turns

$E_1 = 4.44 f\phi_m \times N_1 = \underline{4.44 N_1 f\phi_m}$ (Volt)

Similarly, rms value of emf induced in secondary, $E_2 = \underline{4.44 N_2 f\phi_m}$ (Volts)

- $\dfrac{E_1}{N_1} = \dfrac{E_2}{N_2} = 4.44 f\phi_m$, Emf/turn is same in both windings.

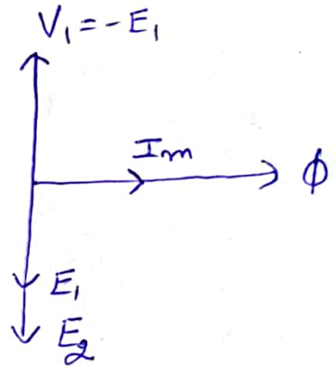
$\underline{E = 4.44 N f B_m A}$ [where B_m = Max Flux density $\dfrac{\phi_m}{A} = B_m$]

Ideal Transformer:

→ No winding resistance i.e the primary & secondary windings have zero resistance. It means that there is no ohmic power loss and no resistive voltage drop in an ideal transformer

→ No Magnetic leakage i.e. there is no leakage flux and all the flux set up is confined to the core and links both the windings.

→ No Iron Loss : Hysterisis and Eddy current losses in transformer core are zero.



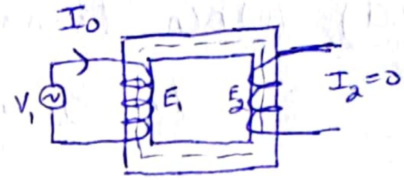
$$\text{Input } VA = \text{output } VA$$

$$V_1 I_1 = V_2 I_2$$

$$\frac{V_1}{V_2} = \frac{I_2}{I_1} = \frac{E_1}{E_2} = \frac{N_1}{N_2} = \frac{1}{K}$$

Ideal Transformer consists of two purely inductive coils wound on loss free core.

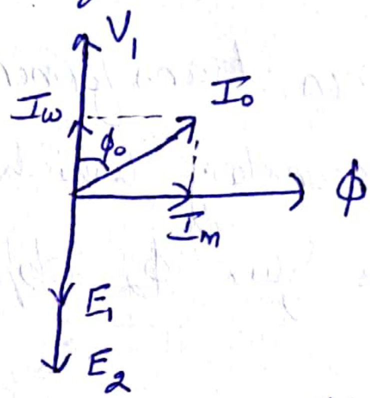
Transformer on No Load



→ Secondary Winding is open circuited and secondary Current I_2 is zero.

→ If transformer is on no load, a small current I_0 (2 to 10% of rated value) called exciting current is drawn by the primary.

→ Current I_0 lags behind the voltage V_1 by angle ϕ_0.



→ No Load Current, I_0 has two components

(a) I_w, in phase with applied voltage V_1, called Active or working component. It supplies the iron losses and small primary copper loss.

(b) I_m in quadrature with applied voltage V_1, called Reactive or Magnetizing component. It produces flux in the core & doesn't consume any power.

$$I_w = I_0 \cos\phi_0$$

$$I_m = I_0 \sin\phi_0$$

No Load current $I_0 = \sqrt{I_w^2 + I_m^2}$

P.F. at No Load, $\cos\phi_0 = \dfrac{I_w}{I_0}$

No Load Power Input $P_0 = V_1 I_0 \cos\phi_0$

13.8. TRANSFORMER ON LOAD

(Neglecting winding resistance and leakage flux)

When a certain load is connected across the secondary, a current I_2 flows through it as shown in fig. 13.12. The magnitude of current I_2 depends upon terminal voltage V_2 and impedance of the load. The phase angle of secondary current I_2 with respect to V_2 depends upon the nature of load *i.e.* whether the load is resistive, inductive or capacitive.

The operation of the transformer on load is explained below with the aid of diagram ;

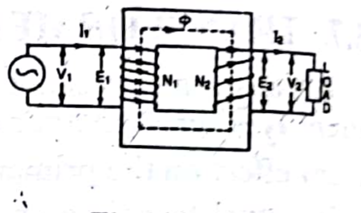


Fig. 13.12

(*i*) When the transformer is on no load as shown in fig. 13.13 (*a*) it draws no load current I_0 from the supply mains. The no load current I_0 produces an m.m.f. $N_1 I_0$ which sets up flux ϕ in the core.

(*ii*) When the transformer is loaded, current I_2 flows in the secondary winding. This secondary current I_2 produces an m.m.f. $N_2 I_2$ which sets up flux ϕ_2 in the core. This flux ϕ_2 opposes the flux ϕ which is set up by the current I_0, as shown in fig. 13.13 (*b*), according to Lenz's law.

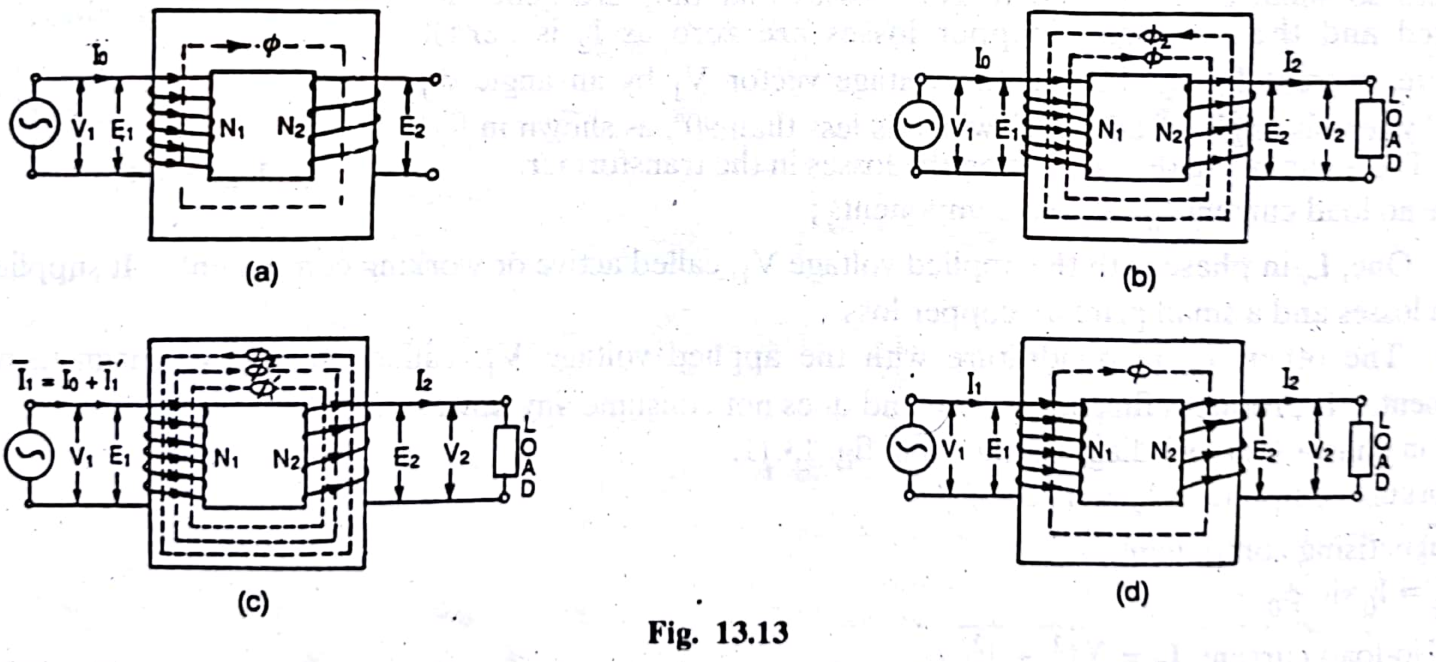


Fig. 13.13

(*iii*) Since ϕ_2 opposes the flux ϕ, therefore, the resultant flux tends to decrease and causes the reduction of self induced e.m.f. E_1 momentarily. Thus, V_1 predominates over E_1 causing additional primary current I_1' drawn from the supply mains. The amount of this additional current is such that the original conditions *i.e.,* flux in the core must be restored to original value ϕ, so that $V_1 = E_1$. The current I_1' is in phase opposition with I_2 and is called primary counter balancing current. This additional current I_1' produces an m.m.f. $N_1 I_1'$ which sets up flux ϕ_1' in the same direction as that of ϕ as shown in fig. 13.13 (c), and cancels the flux ϕ_2 set up by m.m.f. $N_2 I_2$.

Now $N_1 I_1' = N_2 I_2$ (ampere-turns balance) $\therefore\ I_1' = \frac{N_2}{N_1} I_2 = KI_2$

(*iv*) Thus, the flux is restored to its original value ϕ, as shown in fig. 13.13 (*d*). The total primary current I_1 is the vector ~~sum of~~ current I_0 and I_1' *i.e.* $\overline{I_1} = \overline{I_0} + \overline{I_1'}$.

13.9. PHASOR DIAGRAM OF A LOADED TRANSFORMER

(*Neglecting voltage drops in the windings, ampere-turns balance*)

Since the voltage drops in both the windings of the transformer are neglected, therefore,

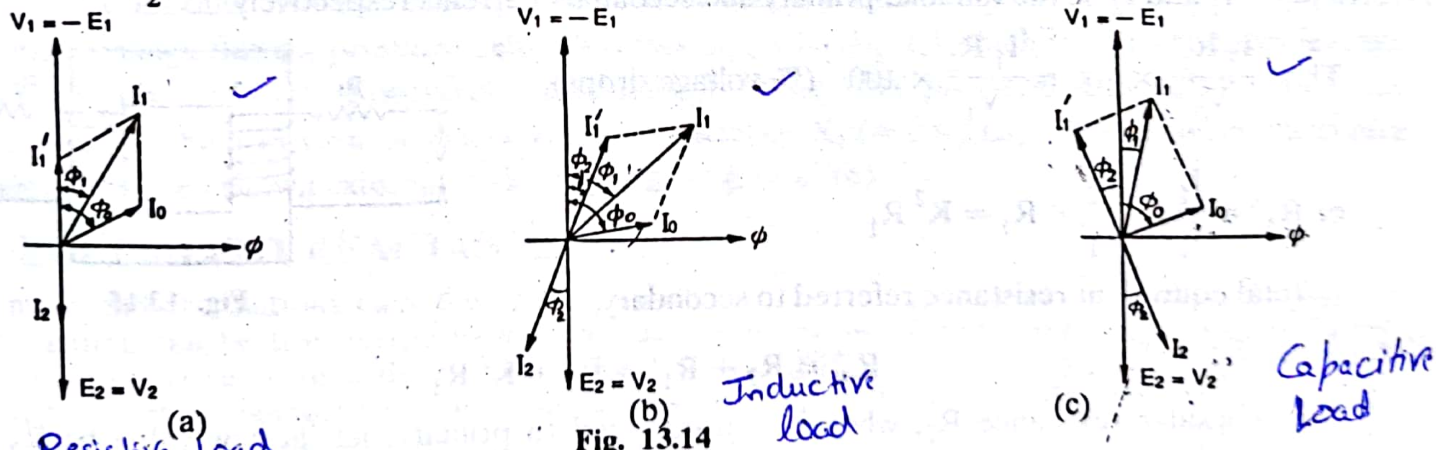
$$V_1 = E_1 \text{ and } E_2 = V_2$$

While drawing the phasor diagram the following important points are to be considered.

(*i*) For simplicity, let the transformation ratio K = 1 be considered, therefore, $E_2 = E_1$.

(*ii*) The secondary current I_2 is in phase, lags behind and leads the secondary terminal voltage V_2 by an angle ϕ_2 for resistive, inductive and capacitive load respectively.

(*iii*) The counter balancing current $I_1' = \frac{N_2}{N_1} I_2$ (*i.e.* $I_1' = K I_2$ here $K = 1 \therefore I_1' = I_2$) and is 180° out of phase with I_2.



(a) Resistive Load (b) Inductive load (c) Capacitive Load

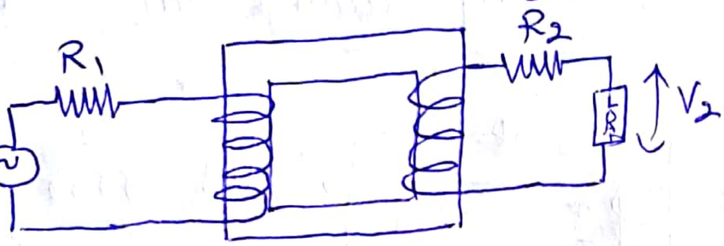
Fig. 13.14

(*iv*) The total primary current I_1 is the vector sum of no load primary current I_0 and counter balancing current I_1'.

i.e. $\overline{I_1} = \overline{I_0} + \overline{I_1'}$ or $I_1 = \sqrt{(I_0)^2 + (I_1')^2 + 2 I_0 I_1' \cos\theta}$

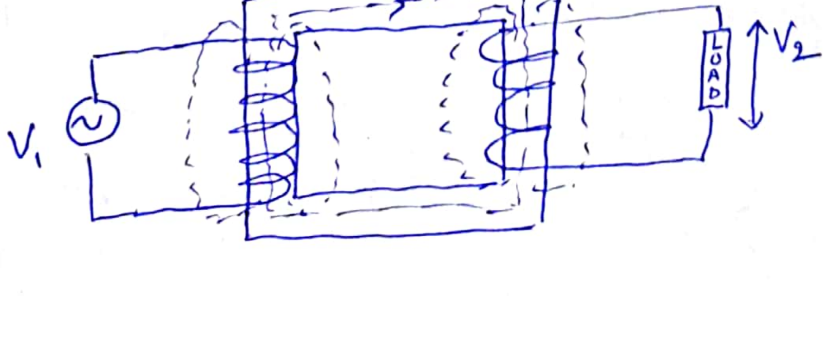
Transformer with winding resistance:

In an actual transformer, the primary and secondary windings have some resistance represented by R_1 and R_2 respectively.



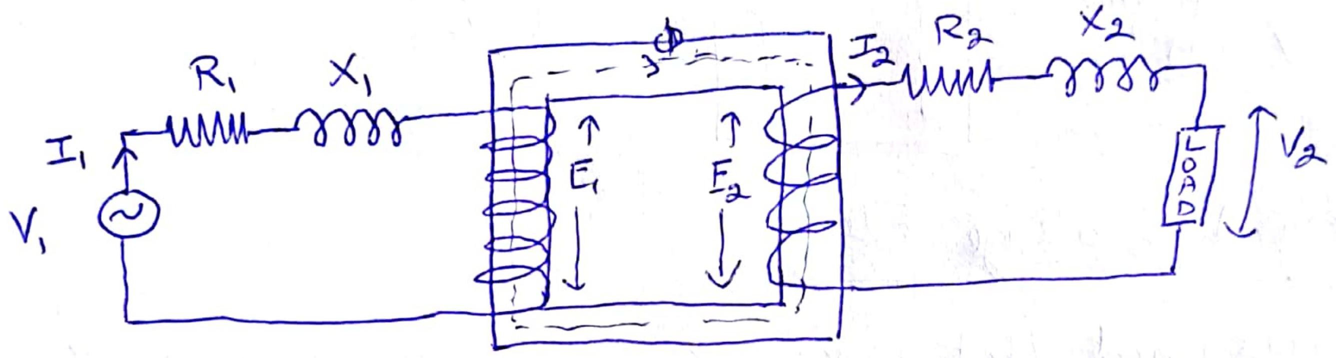
Mutual and Leakage Flux

It is assumed that when ac supply is given to the primary winding of a transformer, an alternating flux is set up in the core and whole of this flux links with both the primary and secondary windings. However, in an actual transformer, both the windings produce some flux that links only with the winding that produces it. The flux that links with both the windings of the transformer is called mutual flux and the flux which links only with one winding of the transformer is called leakage flux.



Actual Transformer:

An actual transformer has
(i) Primary and secondary resistances R_1 & R_2
(2) Primary and secondary leakage reactances X_1 & X_2



Primary Impedance, $Z_1 = R_1 + jX_1$

$$V_1 - I_1(R_1 + jX_1) = -E_1$$

$$V_1 = -E_1 + I_1(R_1 + jX_1)$$

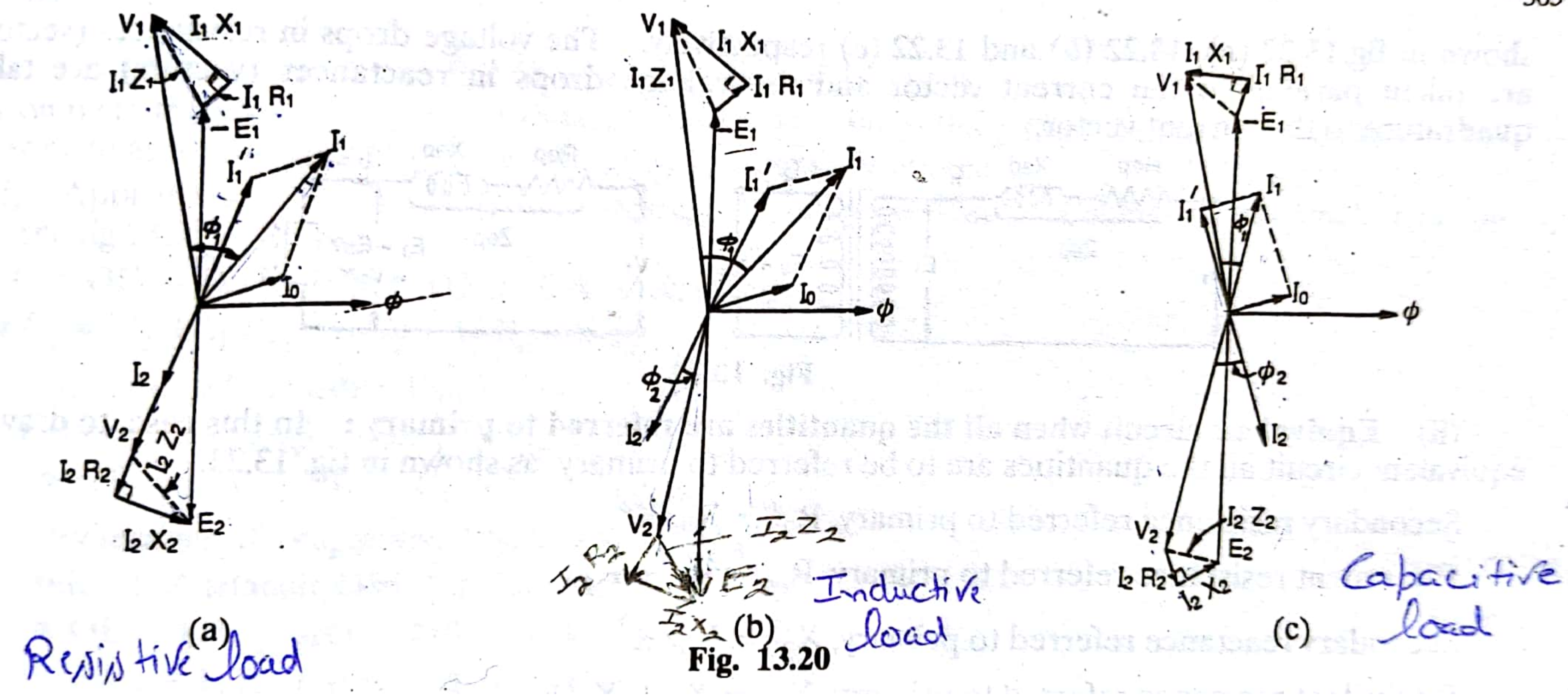
$$\boxed{V_1 = -E_1 + I_1 Z_1}$$

Secondary Impedance, $Z_2 = R_2 + jX_2$

$$E_2 - I_2(R_2 + jX_2) = V_2$$

$$E_2 = V_2 + I_2(R_2 + jX_2)$$

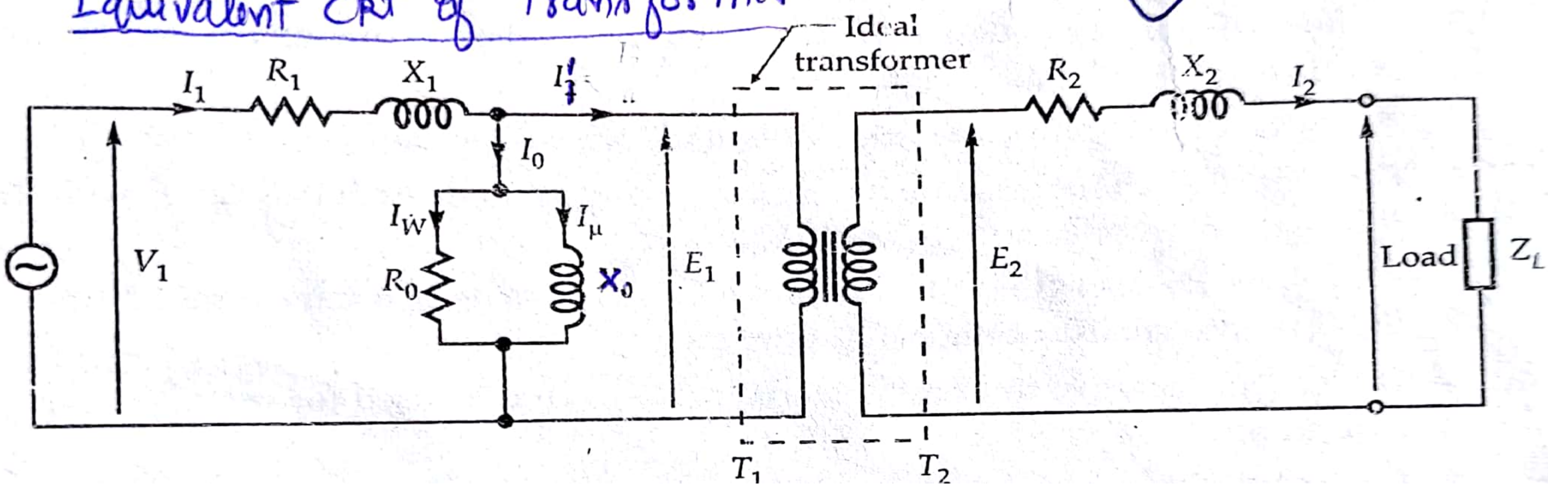
$$\boxed{E_2 = V_2 + I_2 Z_2}$$



V1
I1 X1
I1 Z1
I1 R1
-E1
I1'
I1
φ1
I0
φ
I2
V2
I2 Z2
I2 R2
E2
I2 X2
(a)
Resistive load
(b)
Inductive load
φ2
(c)
Capacitive load

Fig. 13.20

Equivalent ckt of Transformer



13.16. VOLTAGE REGULATION

When a transformer is loaded, with a constant supply voltage, the terminal voltage changes depending upon the load and its power factor. The agebric difference between the no-load and full-load terminal voltage is measured in terms of voltage regulation.

At a constant supply voltage, the change in secondary terminal voltage from no-load to full-load with respect to no-load voltage is called **voltage regulation** *of the transformer.*

Let, E_2 = Secondary terminal voltage at no-load.

V_2 = Secondary terminal voltage at full-load.

Then, voltage regulation $= \dfrac{E_2 - V_2}{E_2}$ (per unit)

In the form of percentage, $\% \text{ Reg} = \dfrac{E_2 - V_2}{E_2} \times 100$

2.1 SINGLE-PHASE AUTOTRANSFORMER

V_H = Input voltage on HV side
V_L = Output voltage on LV side

A *single-phase autotransformer* is a one-winding transformer in which a part of the winding is common to both high-voltage and low-voltage sides.

Consider a single winding *abc* of Fig. 2.1. The terminals *a* and *c* are the high-voltage terminals. The low-voltage terminals are *b* and *c* where *b* is a suitable tapping point. The portion *bc* of the full winding *abc* is common to both high-voltage and low-voltage sides. The winding *bc* is called the ***common winding*** and the smaller winding *ab* is called the ***series winding*** because it is connected in series with the common winding.

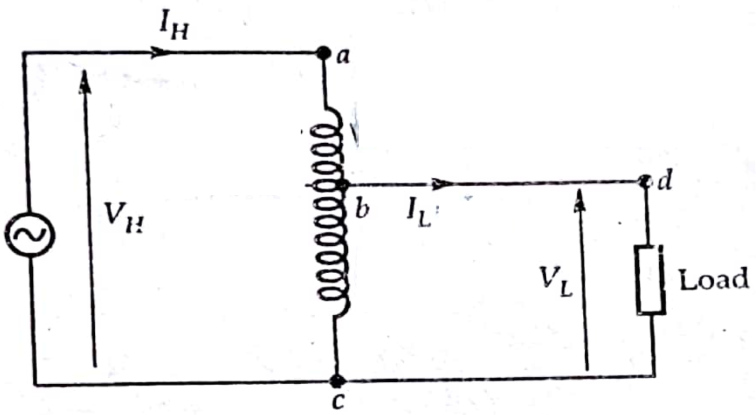


Fig. 2.1 Step-down autotransformer.

A *step-down autotransformer* is one in which the primary voltage is greater than the secondary voltage. The source voltage V_H is applied to the full winding *abc* and the load is connected across the secondary terminals *bc*. This arrangement is called the *step-down autotransformer* as shown in Fig. 2.1.

2.3 STEP-UP AUTOTRANSFORMER

Figure 2.2 shows a step-up autotransformer. Here the source is connected to the winding *bc* and the load is connected across the full windings *abc*. The step-up autotransformer may be analysed in a manner similar to that used for step-down autotransformer. The relationships between input, output and common winding currents

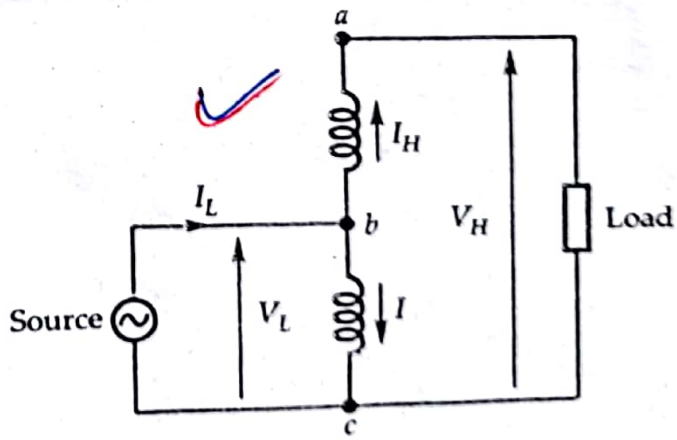


Fig. 2.2 Step-up autotransformer.

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Losses in Transformer

The losses which occur in actual transformer are:
(1) Core or Iron losses (2) Copper losses.

Core or Iron Loss:- The alternating flux is set up in the core, therefore hysterisis and eddy current losses occur in magnetic core.

(a) **Hysterisis Loss:** When the magnetic material is subjected to reversal of flux, power is required for the continuous reversal of molecular magnets. This power is dissipated in the form of heat and is known as hysterisis loss

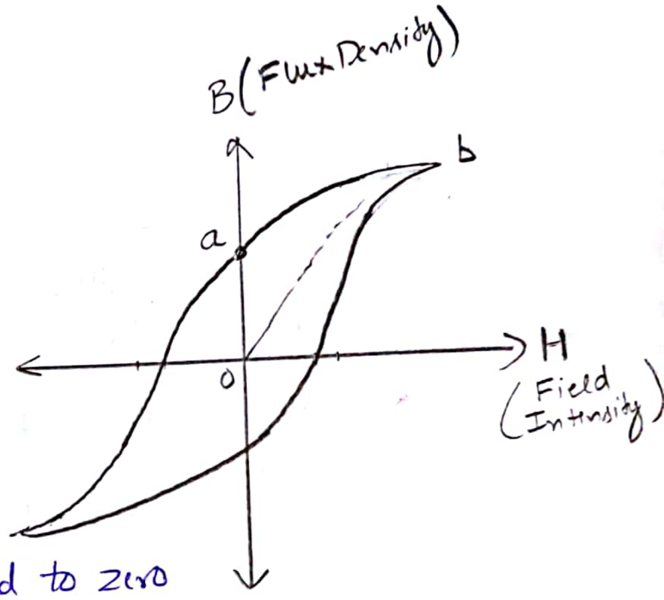
$$P_h = K_h V f B_m^{1.6}$$

Where V= Volume of core, f= supply frequency

B_m= Max. value of flux density; K_h = Hysterisis constant

This loss can be minimized by using silicon steel material for the construction of core.

Magnetic Hysterisis : The phenemenon of flux density lagging behind the magnetising force H in a magnetic material is called magnetic hysterisis.



When the fied intensity H is increased by increasing current in the solenoid, the flux density B also increases until saturation point b is reached and curve so obtained is ob.

If now the magnetising force is reduced to zero by decreasing current in the solenoid to zero. The flux density doesn't become zero and curve obtained is ba.

When magnetising force H is zero, flux density still has value oa.

oa is called residual magnetism.

b) <u>Eddy Current Loss</u> : Since the flux in transformer core is alternating, it links with the magnetic material of core. This induces emf in the core and circulates eddy currents. Power is required to maintain these eddy currents

Scanned by CamScanner

This power is dissipated in the form of heat and is known as eddy current loss.

$$P_e = K_e V f^2 t^2 B_m^2$$

This loss can be minimised by making the core of thin laminations.

Flux set up in the core of the transformer remains constant from no load to full load. Hence iron loss are independent of load and are constant losses.

2) <u>Copper Losses</u> · Copper losses occur in both primary and secondary windings due to their ohmic resistance.

If I_1, I_2 are primary and secondary currents and R_1, R_2 are primary and secondary resistance respectively.

$$\therefore \text{ Total copper losses} = I_1^2 R_1 + I_2^2 R_2$$

The current in the primary and secondary winding vary acc. to the load, therefore these losses vary acc. to the load and are known as variable losses.

Efficiency of a Transformer

Efficiency of transformer is defined as ratio of output power to the input power.

$$\eta = \frac{\text{Output power}}{\text{Input power}} = \frac{\text{Output Power}}{\text{Output Power + Losses}}$$

$$= \frac{\text{Output Power}}{\text{Output Power + Iron Losses + Copper Losses}}$$

$$= \frac{V_2 I_2 \cos\phi_2}{V_2 I_2 \cos\phi_2 + P_i + P_c}$$

where V_2 = Secondary terminal voltage ; I_2 = Full load secondary current

$\cos\phi_2$ = Power factor of load

P_i = Iron losses = Hysteresis Losses + Eddy current Losses

P_c = Copper Losses. $= I_2^2 R_{02}$, where R_{02} is equivalent resistance of transformer referred to secondary

If x is the fraction of full load, then efficiency is

$$\eta_x = \frac{x \times \text{output}}{x \times \text{output} + P_i + x^2 P_c} = \frac{x V_2 I_2 \cos\phi_2}{x V_2 I_2 \cos\phi_2 + P_i + x^2 I_2^2 R_{02}}$$

Condition for Maximum Efficiency

$$\eta = \frac{V_2 I_2 \cos\phi_2}{V_2 I_2 \cos\phi_2 + P_i + I_2^2 R_{02}} = \frac{V_2 \cos\phi_2}{V_2 \cos\phi_2 + \frac{P_i}{I_2} + I_2 R_{02}}$$

The terminal voltage V_2 is constant.

Therefore for a given p.f. efficiency depend upon load current I_2.

→ Numerator is constant and efficiency will be max. if denominator is minimum

→ Max. condition is obtained by differentiating the quantity in denominator wrt I_2

$$\frac{d}{dI_2}\left(V_2 \cos\phi_2 + \frac{P_i}{I_2} + I_2 R_{02}\right) = 0$$

$$0 - \frac{P_i}{I_2^2} + R_{02} = 0$$

$$I_2^2 R_{02} = P_i$$

Copper Losses = Iron Losses

Efficiency of a transformer will be max. when copper losses are equal to iron losses $\eta_{max} = \frac{V_2 I_2 \cos\phi_2}{V_2 I_2 \cos\phi_2 + 2P_i}$

$$I_2 = \sqrt{\frac{P_i}{R_{02}}}$$

Open Ckt Test (No Load Test)

The purpose of this test is to determine the core loss P_i and no load current I_o, which is helpful in finding no load parameters R_o and X_o of transformer.

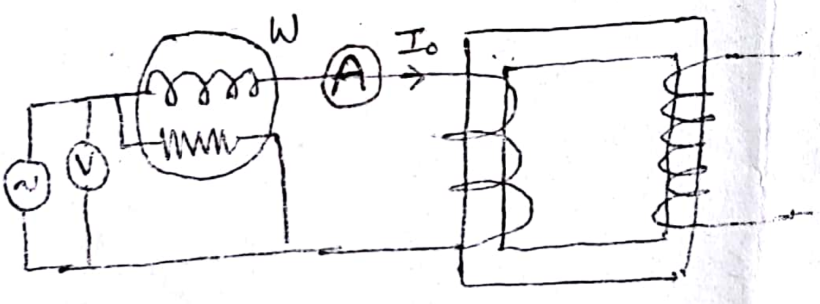
→ This test is carried out on low voltage side of the transformer. Primary winding is connected to normal voltage V_1

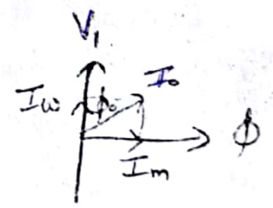
→ Secondary is kept open circuited

→ Since the secondary is open, the current drawn by the primary is no load current I_o (2 to 10% of full rated current)

→ Copper loss in primary are negligibly small and there is no copper loss in secondary as it is open

→ Therefore wattmeter reading represents core/iron loss





Let the Wattmeter reading $= W_o$

Voltmeter reading $= V_1$

Ammeter reading $= I_o$

Iron Loss, $P_i = W_o$

$V_1 I_o \cos\phi_o = W_o$

No Load power factor $\cos\phi = \dfrac{W_o}{V_1 I_o}$

$I_w = I_o \cos\phi_o$

Working Component, $I_w = \dfrac{W_o}{V_1}$

Magnetising Component,

$I_m = \sqrt{I_o^2 - I_w^2}$

$R_o = \dfrac{V_1}{I_w}$

$X_o = \dfrac{V_1}{I_m}$

Short Circuit Test

→ The purpose of this test is to determine full load copper loss and equivalent resistance and reactance referred to metering side

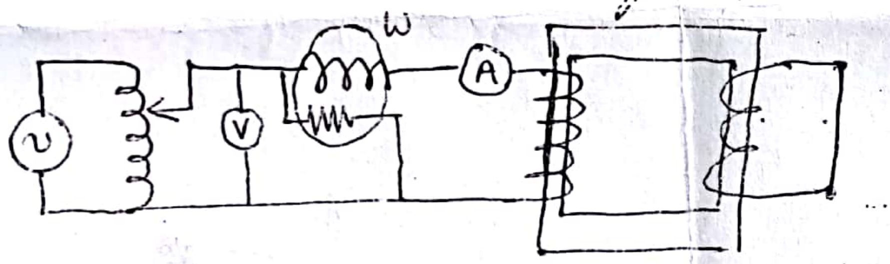
→ Test is usually carried out on high voltage side of the transformer.

→ Terminals of secondary winding (low voltage winding) are short circuited by thick wire

→ Since a low voltage (5 to 10% of normal rated voltage) is applied to the transformer winding.

∴ flux set up in the core is also small and therefore iron losses are also small that these can be neglected.

→ Hence Wattmeter reading represents copper loss.



Let the Wattmeter reading $= W_c$

Voltmeter reading $= V_s$

Ammeter reading $= I_s$

Full load Copper loss, $P_c = I_s^2 R_{es} = W_c$

Equivalent resistance, $R_{es} = \dfrac{W_c}{I_s^2}$

Equivalent Impedance, $Z_{es} = \dfrac{V_s}{I_s}$

Equivalent Reactance $X_{es} = \sqrt{Z_{es}^2 - R_{es}^2}$

Q Single phase transformer gave following test results:

Rating 100 KVA, 11KV/220V, 50Hz

OC Test: 220V, 45A, 2KW

SC Test: 500V, 9.09 A, 3KW

Determine equivalent circuit parameters referred to lv side.

Ans

OC Test

Working component, $I_w = \frac{W_o}{V_1} = \frac{2000}{220} = 9.091\,A$

Magnetising component, $I_m = \sqrt{I_o^2 - I_w^2} = \sqrt{45^2 - 9.091^2} = 44.07\,A$

$R_o = \frac{V_1}{I_w} = \frac{220}{9.091} = 24.2\,\Omega$

$X_o = \frac{V_1}{I_m} = \frac{220}{44.07} = 4.992\,\Omega$

SC Test

Equivalent resistance referred to hv side, $R_{es} = \frac{W_s}{I_s^2} = \frac{3000}{9.09^2} = 36.3\,\Omega$

Equivalent impedance referred to hv side, $Z_{es} = \frac{V_s}{I_s} = \frac{500}{9.09} = 55\,\Omega$

Equivalent reactance referred to hv side, $X_{es} = \sqrt{Z_{es}^2 - R_{es}^2}$

$= \sqrt{55^2 - 36.3^2}$

$= 41.32\,\Omega$

$\frac{R_{01}}{R_{02}} = \left(\frac{N_1}{N_2}\right)^2$

$\frac{X_{01}}{X_{02}} = \left(\frac{N_1}{N_2}\right)^2$

Equivalent resistance referred to lv side, $R_{01} = \left(\frac{N_1}{N_2}\right)^2 R_{02}$

$= \left(\frac{220}{11000}\right)^2 36.3 = 0.0145\,\Omega$

Equivalent reactance referred to lv side, $X_{01} = \left(\frac{N_1}{N_2}\right)^2 X_{02}$

$= \left(\frac{220}{11000}\right)^2 \times 41.32$

$= 0.0165\,\Omega$