

Unit - IV
Single phase Transformer

Classification of Transformers

There are many ways in which transformers can be classified the transformers can be classified as follows:

1. Based on number of phases :-

- (a) single phase transformer.
- (b) three phase transformer.

2. Based on construction or design :-

- (a) core type transformer.
- (b) shell type transformer.
- (c) Belly type transformer

3. Based on function :-

- (a) power transformer.
- (b) step-up transformer
- (c) step-down transformer

(b) Distribution transformer

- (i) pole-mounted transformer
- (ii) plinth-mounted transformer

4. Instrument transformer :-

- (i) current transformer (C.T)
- (ii) potential transformer (P.T)

5. Based on cooling :-

- (a) oil-filled self-cooled transformer.
- (b) oil-filled water-cooled transformer.
- (c) air-blast type transformer.

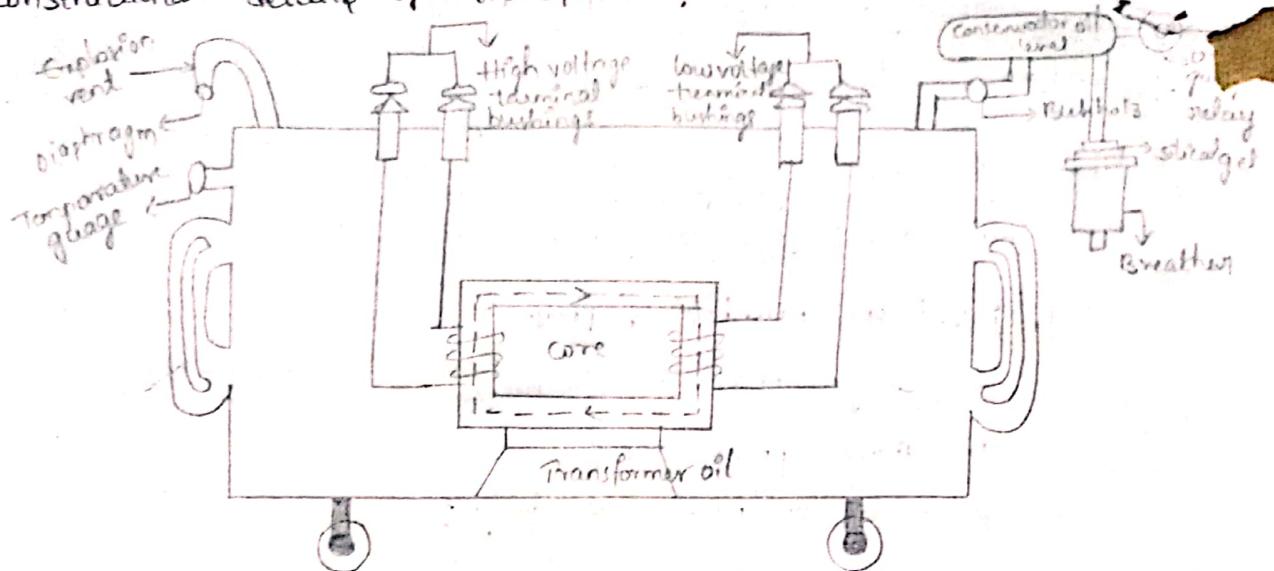
6. Based on type core material :-

- (a) Iron-core transformer
- (b) Air-core transformer

7. Special purpose transformer :-

- (a) Auto transformer
- (b) welding transformer
- (c) Audio frequency transformer
- (d) pulse transformer
- (e) trigger transformer

constructional details of transformer



the transformer is simple in construction, since there are no rotating parts. the transformer has following parts

- 1) core
- 2) windings
- 3) Tank
- 4) Transformer oil
- 5) conservator
- 6) Breather
- 7) Terminals and bushings
- 8) Exhaust pipe, oil guage
- 9) cooling system.

Core :-

The purpose of core is to provide a path of low reluctance for the magnetic flux. It is made with silicon steel laminations. The purpose of laminating the core is to reduce eddy current loss. These laminations are made with silicon steel to reduce hysteresis loss, because silicon steel has low hysteresis co-efficient. The thickness of lamination varies from 0.35mm for 50Hz frequency to 0.5mm for 25Hz frequency. The core is divided into two parts namely yoke and limb (or) leg. The vertical position of the core on which winding is wound known as limb.

The top and bottom horizontal positions are called yoke of the core. Yoke and limb together provides a closed path for magnetic flux. The laminations are cut in the form of long strips of different shapes like L, E, I, U, C etc.

Depending upon the type of construction of core, the transformer are classified as,

- i) core type
- ii) shell type and
- iii) Berry type

i) core type transformer:

In core type transformer core is so surrounded by it has two limbs. In this type the magnetic flux has only one path. There may be some leakage flux that may not be linked with one winding and not with the other. It is necessary to reduce the leakage of flux to improve the performance of the transformer. In this type of transformer L.V. is placed over the core and H.V. winding is wound over L.V. winding in order to minimize amount of insulation required. Core type construction is used for high voltage, high power transformer.

ii) Shell -type transformer:

In shell-type transformer the winding is surrounded by a shell. It has three limbs, two side limbs and one central limb. In this type, the magnetic flux has two magnetic paths. The total flux is passing through the central limb and half the flux is passing through each side limb. The L.V. and H.V. windings are placed on the side limbs, hence the winding is surrounded by the core shell. This type of construction is used for low voltage, low power transformer. This type of construction is commonly used for small transformer.

iii) Berry type transformer:

In this case the distributed path of the magnetic field is such that one limb of all the cores passes through the centre of the coil. The width of the core inside the coils is less than the width of the limb outside the winding. These are used for the variable voltage.

- | | |
|--|--------------------------------------|
| ② Cylindrical type winding is used | 2) Sandwiched |
| ③ The core has two limbs. | 3) The core has |
| ④ The magnetic flux has only the magnetic path. | 4) Magnetic flu paths. |
| ⑤ Used for high voltage. | 5) Used for dc |
| ⑥ The shape of core laminations are rectangular 'I' type | 6) The shape of core 'E' type |
| ⑦ Gross-section area of core is less, hence more turns required. | 7) cross section more, so less turns |
| ⑧ Easy to insulate and repair. | 8) Difficult to |
| ⑨ L.V and H.V windings are wound on both limbs. | 9) The L.V and H.V are wound |

② Windings:-

The windings are made with copper conductors arranged on the cores. The winding which is connected to supply primary and the winding which is connected to load secondary winding. The winding which is connected to high voltage (H.V) is known as L.V winding and the winding which is connected to low voltage (L.V) is known as H.V winding.

According to the construction and arrangement are mainly classified into:-

- i) cylindrical type winding and
- ii) sandwich type winding.

cylindrical type winding:-

This winding is layered type and is made up of turns close to each other. This type

③ Tanks

Transformers are generally housed in a tightly-fitted sheet metal tanks filled with special insulating oil. The core and windings are completely immersed in the oil inside the tank. In case of small transformers, the tanks are made with iron sheets whereas in case of large transformers, the tanks are made with cast-aluminium plates. Those sheets are water proof brackets when the transformer is working, heat is produced in the tank, hence needs cooling.

For cooling purpose, cooling tubes are welded around the tank. An eye-bolt is welded to the tank at the top for lifting purpose and wheels are provided at the bottom for moving the T/F into position. A tank must be able to withstand all the stresses developed inside and has provision for connecting to the load and supply.

④ Transformer oil

The insulating oil which is used in the tank of a T/F is called T/F oil. It has three functions.

- 1) It acts as insulating medium between windings and tank.
- 2) It provides better cooling by circulating through the cooling tubes.
- 3) It carries away the heat generated in the core and windings and quench the arc, if any.

The T/F oil is obtained by fractional distillation of crude petroleum. The mineral oil is most commonly used as T/F oil.

⑤ Conservator tank (or) Expansion tank

It is a small tank mounted above the transformer and connected to the main tank by pipe. The oil level changes with change in temperature of oil which in turn depends upon the load on the T/F. The oil expands with the increase in load and contracts with decrease in load. The conservator is not completely filled with oil to facilitate the expansion. As it receives the oil during expansion, it is also called as expansion tank.

⑥ Breathers

The transformer oil expands when it is heated and contracts when cooled. When the oil expands, the air air is expelled out and air is drawn inside under contraction of oil. This process is known as breathing since the oil is in contact with air. The air entering the tank through an apparatus called breather.

A breather consists of a silica gel crystals and is connected to the conservator through vent pipe. Silica gel absorbs the moisture. Silica gel is blue in colour when dry and becomes whitish pink when it absorbs moisture.

⑦ Terminals and Bushings:-

The connections to the windings are copper rods. The windings are connected to H.V and L.V lines through insulator bushings, mounted over the T/F. The bushings consist of a current carrying element of a pole clad in cylinder.

⑧ Exhaust pipe, oil gauge, Temperature gauge:-

Many transformers are provided with exhaust pipe made of steel. It protects the tank from large expansion of the accident gas formation.

Every T/F is provided with oil gauge and temperature gauge. Oil indicates the level of oil in the tank. It provides an alarm which gives an alarm when the oil level has dropped. Temperature gauge indicates the temperature of the oil.

⑨ Cooling system:-

Whenever current is flowing through the windings, heat is produced which should be dissipated, if it is not dissipated the windings may get damaged. Hence cooling is necessary for a T/F which can be provided by different methods such as natural air cooling, oil immersed forced air, water and oil cooling and air-blast cooling.

Minimization of hysteresis and eddy current losses:-

Iron and core losses (w_i) are caused by the alternating flux in the core and consists of hysteresis and eddy current losses.

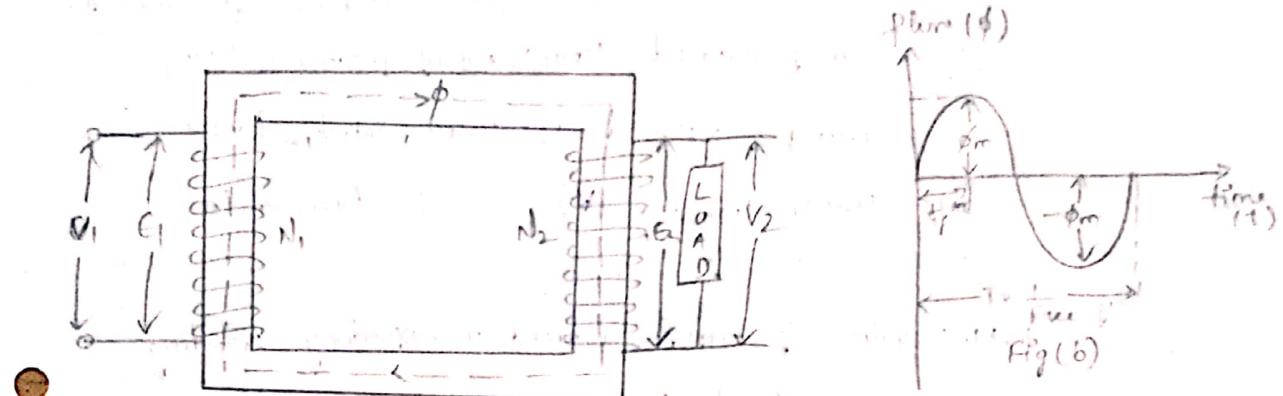
$$\Rightarrow \text{hysteresis loss, } w_h = k_h B_{\max}^1 F v \text{ (watts)}$$

$$\Rightarrow \text{eddy current loss, } w_e = k_e B_{\max}^2 t^2 v \text{ (watts)}$$

where k_h & k_e are proportional constants which depend on volume and material of core. 'F' is frequency 'V' is the volume of the core. B_{\max} is the maximum value of flux density in the core. 't' is the thickness of core laminations.

→ the hysteresis loss can be minimised by using steel of high silicon content, whereas the eddy current loss can be minimised by making the core with thin laminations. Hence, iron losses can be minimised by making core with silicon steel laminations [lamination ranges b/w 0.3 to 0.5 mm].

Cmf equation of a 1-Φ transformer



⇒ Consider a 1-Φ transformer as shown in fig (b)

Let, V_1 = primary A.C supply voltage in volts (v)

I_1 = primary current in ampere (A)

E_1 = Induced emf in primary in volts (v)

N_1 = no. of turns in primary winding

N_2 = no. of turns in secondary winding

E_2 = induced emf in secondary in volts (v)

I_2 = secondary current in ampere (A)

V_2 = secondary voltage in volts (v)

ϕ_m = maximum flux in core in weber (wb)

$$\phi_m = B_m \times A$$

F = Frequency of a.c supply (Hz)

→ When a.c voltage is applied to the primary winding, an alternating flux is produced in the core.

→ The magnetic flux is increasing from zero to maximum value

ϕ_m in 1/4 of cycle.

∴ Average rate of change of flux, $\frac{d\phi}{dt} = \frac{\phi_m}{1/4 F} = 4F\phi_m(v)$

→ Now, rate of change of flux is equal to the average e.m.f induced per turn.

$\therefore \text{Average e.m.f / turn} = 4F\phi_m$

we know

$$\text{Form factor} = \frac{\text{R.M.S value}}{\text{Average value}} = 1.11$$

R.M.S value of e.m.f / turn = $1.11 \times \text{Average e.m.f / turn}$

$$= 1.11 \times 4F\phi_m(V) = 4.44F\phi_m(V)$$

Now, R.M.S value of e.m.f induced in primary winding,

$$E_1 = \text{e.m.f induced / turn} \times \text{no. of primary turns}$$
$$= 4.44F\phi_m \times N_1 \text{ volts} = 4.44FN_1\phi_m(V) \quad \text{--- (1)}$$

$$E_1 = 4.44FN_1B_{mA} \quad (\because B_m = \phi_m/A) \quad \boxed{(1)}$$

Now, R.M.S value of e.m.f induced in secondary winding

$$E_2 = \text{e.m.f induced / turn} \times \text{No. of secondary turns}$$
$$= 4.44F\phi_m \times N_2 = 4.44FN_2\phi_m(V) \quad \text{--- (2)}$$

$$E_2 = 4.44FN_2B_{mA} \quad (V) \quad \boxed{(2)}$$

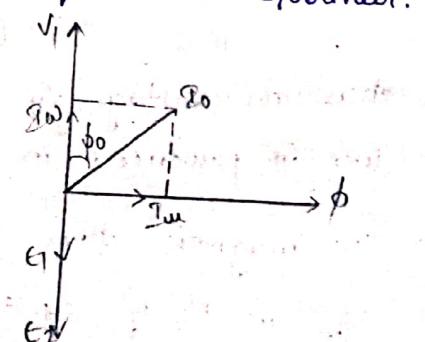
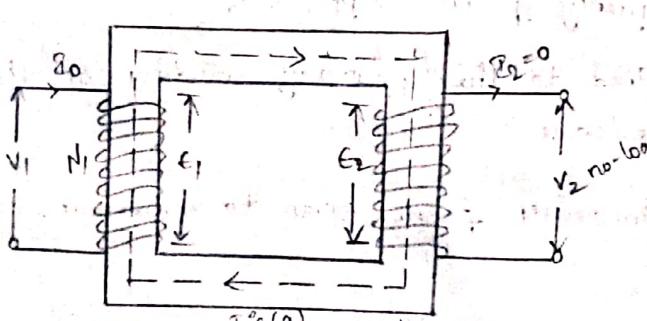
Eqn(1) is known as e.m.f Eqn of primary winding of T/F

Eqn(2) is known as e.m.f. Eqn of secondary winding of T/F.

Operation of Transformer on no-load and, on load :-

No-load :-

An ideal transformer is one that has no core losses and copper losses. whenever load is not connected on the secondary winding and primary winding is connected to a.c supply, the condition is said to no-load condition of the transformer.



→ Consider a practical T/F whose secondary is open-circuited ($V_2 = 0$) and primary winding is connected a.c supply as shown above. The primary will draw a small no-load

current ' I_0 ' which lags the applied voltage ' V_1 ' by an angle $\phi_0 < 90^\circ$ as shown in fig(b).

∴ primary no-load current I_0 has to supply

i) Iron losses for the core and

ii) Very small amount of cu losses in primary long

no-load f/p power, $w_0 = V_1 I_0 \cos\phi_0$

where ϕ_0 , power factor under no load condition.

No-load current (I_0) can be resolved into two components.

They are :-

i) Active (or) wattful (or) working component (I_w) :-

$$I_w = I_0 \cos\phi_0$$

$$\cos\phi_0 = I_w / I_0$$

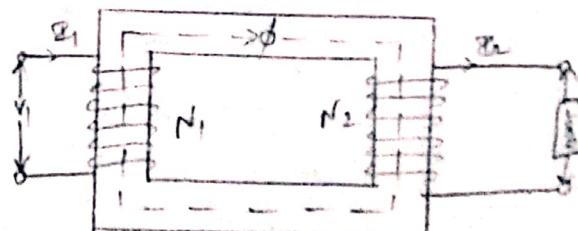
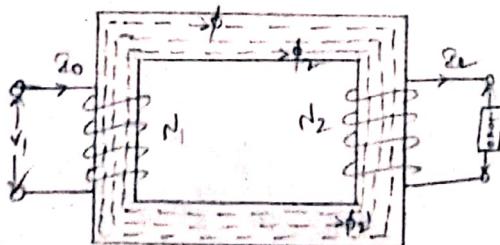
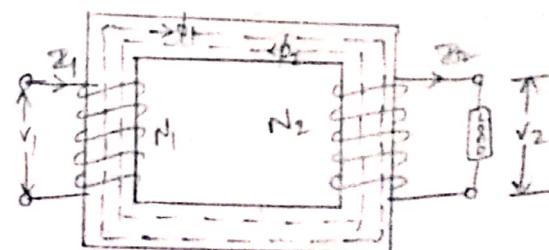
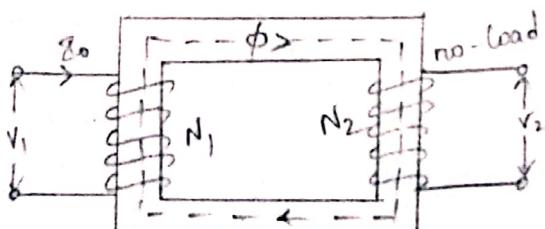
No load power factor,

ii) Reactive (or) magnetizing component :-

$$I_m = I_0 \sin\phi_0$$

$$\sin\phi_0 = I_m / I_0$$

on load :-



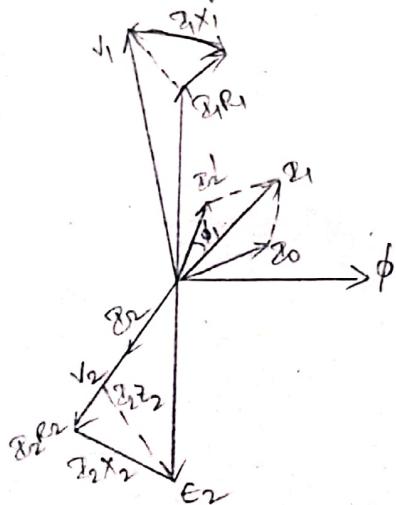
when the secondary winding of a transformer is connected to a load, the transformer is said to be on load. When T/F is loaded a current I₂ will flow through the secondary winding. The current I₂ will be in phase with V₂ if the load is resistive, it lags behind V₂ if the load is inductive and leads V₂ if the load is capacitive.

- when the T/F is on no-load as shown in fig(a), it draws no-load current I_0 from the supply. The current I_0 sets up an m.m.f ($N_1 I_0$) which produces flux ' ϕ ' in the core.
- when load is connected as shown in fig(b) a current ' I_2' flows through the secondary long. This I_2 current set up its own m.m.f ($N_2 I_2$) and hence produces flux ϕ_2 . This flux ' ϕ_2 ' produces the flux ' ϕ ' and also ϕ_2 flux weakness the flux ϕ and tends to reduce the primary back e.m.f E_1 . Hence, more current flows in primary.

Let, the additional primary current be I_2' as shown in fig(c) it is known as load component of primary current. This current is antiphase with I_2 . Then the I_2' sets up an additional m.m.f $N_1 I_2'$ which sets up its own flux ' ϕ_2' $\Rightarrow \phi_2 = \phi_2'$, $N_2 I_2 = N_1 I_2'$.

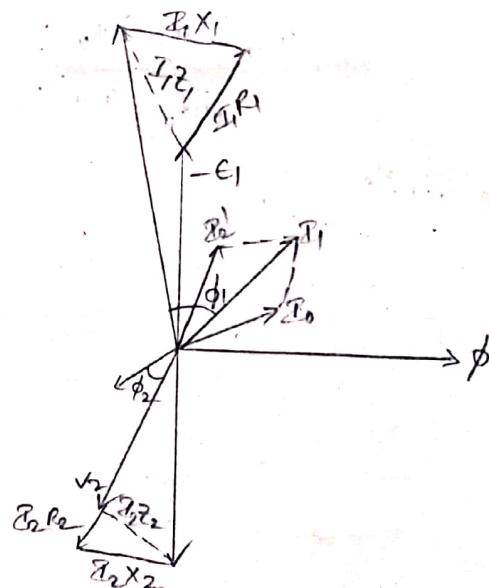
- Hence, when the transformer is on load, the primary winding has two components currents I_0 and I_2' . I_0 is usually small and can be neglected.

Phasor diagrams:-



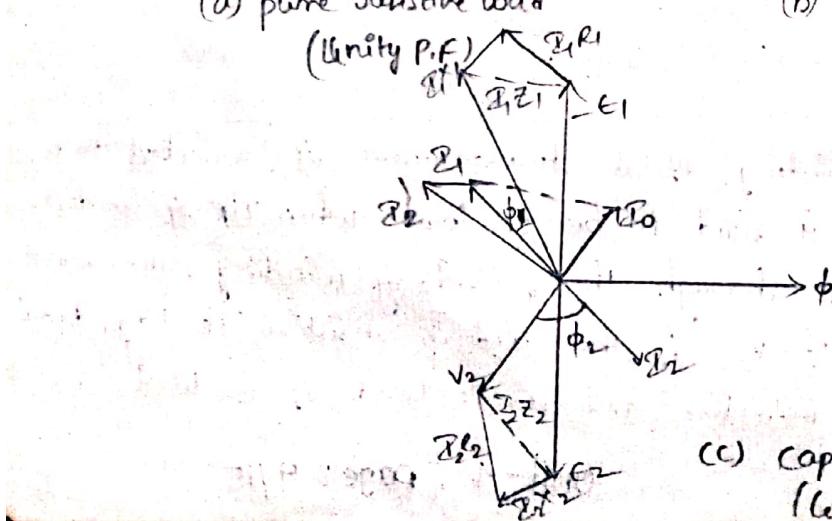
(a) pure resistive load

(Unity P.F.)



(b) Inductive load

(Lagging P.F.)



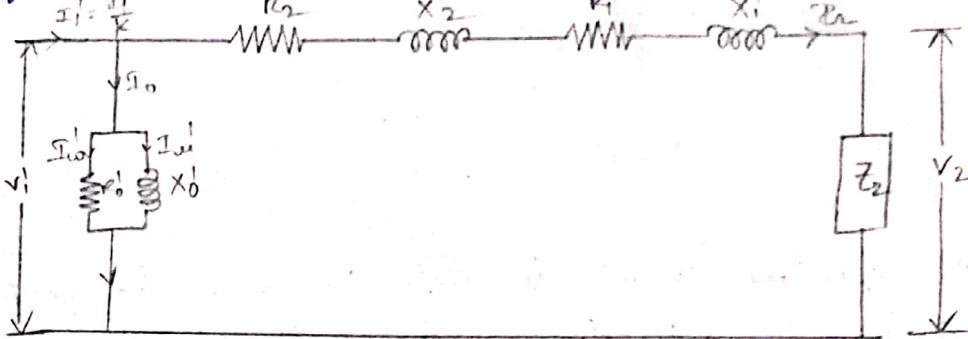
(c) Capacitive load

(Leading P.F.)

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referred to secondary :-

If all the primary quantities are transferred to secondary side, we get equivalent circuit of a T/F referred to secondary.

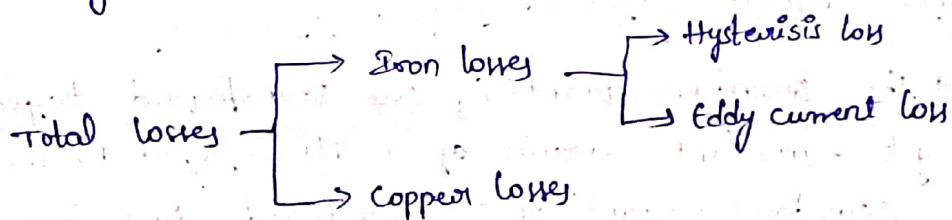


$$R_1' = K^2 R_1; \quad X_1' = K^2 X_1; \quad Z_1' = K^2 Z_1; \quad V_1' = KV_1$$

$$I_1' = \frac{V_1}{K}; \quad R_{02} = R_2 + R_1'; \quad X_{02} = X_2 + X_1'; \quad Z_{02} = R_{02} + jX_{02}$$

Losses in a transformer :-

Transformer is a static device, therefore there are no friction and windage losses. The various losses occur in a transformer are:-



Iron losses (w_i) :-

These losses are caused by the alternating flux in the core and consists of hysteresis and eddy current losses.

$$\text{hysteresis losses } w_h = K_h B_{\text{max}} F V \text{ (volts)}$$

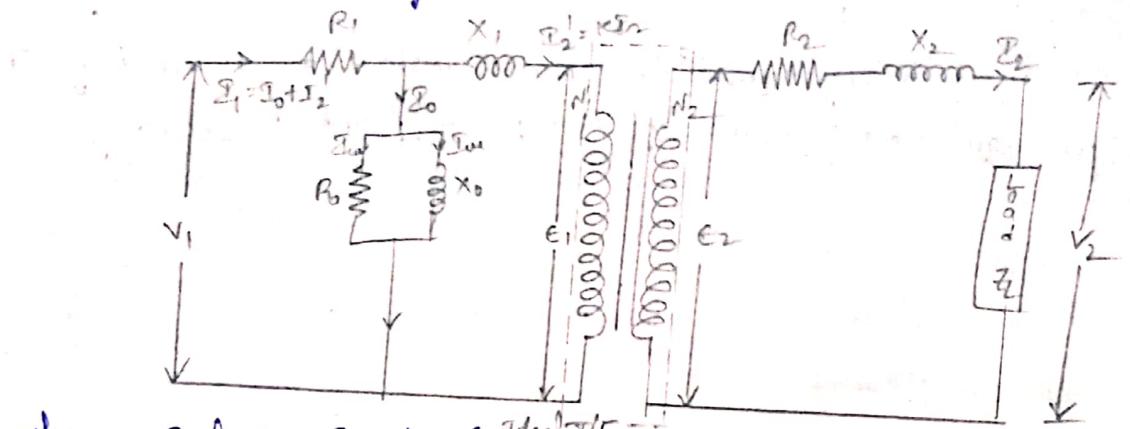
$$\text{Eddy current losses } w_e = K_e B_{\text{max}}^2 F^2 t^2 V \text{ (volts)}$$

$$\text{Iron losses } (w_i) = w_h + w_e = \text{constant losses.}$$

Copper losses (w_{cu}) :-

These losses occur in both the primary and secondary wind due to their ohmic resistance.

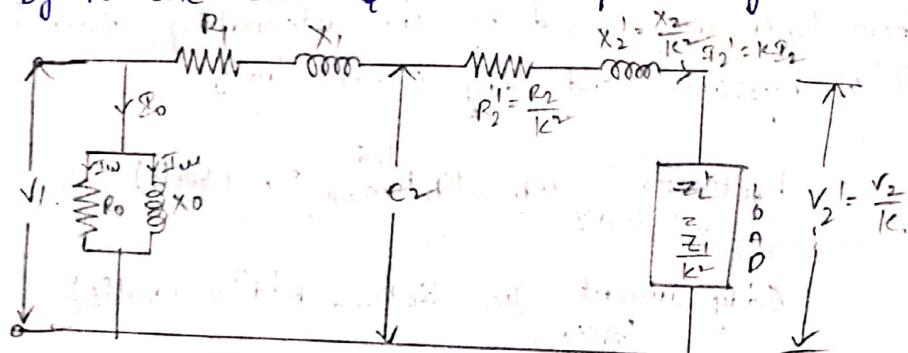
Equivalent circuit of a transformer.



The equivalent circuit is useful to know the performance and behaviour of a transformer. The resistance R_0 represents the effect of core loss. The current I_{0w} passing through R_0 and supplying the core losses. The reactance X_0 is a loss-free coil through which magnetizing current I_{0u} . The vector sum of I_{0u} and I_{0w} is the no-load primary current I_0 .

Equivalent circuit referred to primary :-

If all the secondary quantities are transferred to primary side, we get equivalent circuit of a T/F referred to the primary when the secondary quantities are referred to primary, resistance | reactance | impedance are divided by k^2 , voltages are divided by k and currents are multiplied by k .



$$R_2' = \frac{R_2}{k^2} \quad X_2' = \frac{X_2}{k^2} \quad Z_2' = \frac{Z_2}{k^2}$$

$$V_2' = \frac{V_2}{k} \quad Z_2' = kZ_2 \quad R_0' = kR_0$$

$$X_{01}' = X_1 + X_{02}' \quad Z_{01}' = R_0 + jX_{01}'$$

$$\text{Total cu losses } w_{cu} = I_1'^2 R_1 + I_2'^2 R_2 = I_1'^2 R_0' = I_2'^2 R_2 (w)$$

→ If cu losses at full-load are w_{cu} , then the cu losses at one-half of full-load will be $\left(\frac{1}{2}\right)^2 w_{cu}$.

→ The cu losses are the major losses and can may be 90% of the total losses.

$$\text{Total losses} = \text{Iron losses}(\text{W}_i) + \text{copper losses}(\text{W}_{cu}) \\ = \text{constant losses} + \text{variable losses.}$$

Efficiency of a transformer :-

The efficiency of a transformer is defined as the ratio of output power to the input power. It is expressed in percentage and is denoted by the letter ' η '.

$$\text{Efficiency, } \eta = \frac{\text{output power}}{\text{Input power}} = \frac{\text{o/p}}{\text{o/p} + \text{total loss}}$$

$$= \frac{\text{I/p} - \text{total loss}}{\text{I/p}}$$

$$\% \eta = \frac{\text{output power}}{\text{Input power}} \times 100.$$

A good transformer has a very high efficiency in the range of 95 to 99%. The o/p and i/p powers may be in watts (or) kilo-watts.

Voltage regulation of a transformer :-

The voltage regulation is defined as the change in secondary terminal voltage from no-load to full-load, expressed as a percentage of no-load secondary voltage.

$$\therefore \text{Voltage regulation} = \frac{\text{no-load voltage} - \text{full load voltage}}{\text{no-load voltage}} \times 100$$

$$= \frac{E_2 - V_2}{E_2} \times 100$$

i.e., E_2 = no-load voltage

V_2 = full-load voltage.

i) Regulation for lagging P.F :-

The secondary voltage drop for lagging P.F is δ_2 .

$$(R_{02} \cos \phi_2 + X_{02} \sin \phi_2)$$

$$\% \text{ regulation} = \frac{\text{voltage drop}}{\text{no-load voltage}} \times 100$$

$$= \frac{Z_2 [R_{02} \cos \phi_2 + X_{02} \sin \phi_2]}{E_2} \times 100$$

(iii) Regulation for leading P.F :-

The secondary voltage drop for leading P.F is $Z_2 (R_{02} \cos \phi_2 - X_{02} \sin \phi_2)$

$$\% \text{ regulation} = \frac{\text{voltage drop}}{\text{no-load voltage}} \times 100$$

$$= \frac{Z_2 [R_{02} \cos \phi_2 - X_{02} \sin \phi_2]}{E_2} \times 100$$

(iv) Regulation for unity P.F :-

The secondary voltage drop for unity P.F is $Z_2 R_{02}$, because $\phi_2 = 0, \sin \phi_2 = 0$ and $\cos \phi_2 = 1$

$$\% \text{ regulation} = \frac{Z_2 R_{02}}{E_2} \times 100$$

Condition for maximum Efficiency

$$\text{full-load o/p power} = V_2 Z_2 \cos \phi_2$$

$$\text{Iron losses} = w_i$$

$$\text{full-load core losses} = w_{cu} = Z_2^2 R_{02} (\text{or}) Z_2^2 R_{01}$$

$$\text{T/F efficiency} (\eta) = \frac{\text{o/p}}{\text{o/p} + \text{Total losses}}$$

$$\eta = \frac{\text{o/p}}{\text{o/p} + w_i + w_c} = \frac{V_2 Z_2 \cos \phi_2}{V_2 Z_2 \cos \phi_2 + w_i + Z_2^2 R_{02}} \quad \text{--- (1)}$$

Dividing the eqn (1) both numerator and denominator with Z_2 , we get,

$$\eta = \frac{V_2 \cos \phi_2}{V_2 \cos \phi_2 + \frac{w_i}{Z_2^2} + R_{02}}$$

For a T/F V_2 is approximately constant, hence efficiency is maximum when the denominator is minimum. Hence to get maximum efficiency, differentiate the denominator w.r.t. Z_2 and equate to zero.

$$\begin{aligned}
 &= \frac{d}{dI_2} \left[V_2 \cos \phi_2 + \frac{w_i^2}{I_2^2} + I_2 R_{02} \right] = 0 \\
 &= 0 - \frac{w_i^2}{I_2^2} + R_{02} = 0 \\
 &\Rightarrow I_2^2 R_{02} = w_i^2 \rightarrow (2)
 \end{aligned}$$

Copper losses = Iron losses

Hence, efficiency of a T/F will be maximum when copper losses are equal to iron losses.

From eqn(2), the load current I_2 corresponding to maximum efficiency is given by

$$I_2 = \sqrt{\frac{w_i^2}{R_{02}}}$$

All day efficiency (or) Energy distribution :-

The all-day efficiency of a transformer is defined as the ratio of output in kWh to the input in kWh over a 24 hours period.

$$\therefore \text{All-day Efficiency, } \eta_{\text{all-day}} = \frac{\text{kWh output in 24 hours}}{\text{kWh input in 24 hours}}$$

Since, the distribution transformer does not supply the rated load for the whole day hence the all-day efficiency of such T/F will be less than ordinary efficiency. The all-day efficiency can be calculated for any length of load cycle, knowing its load variation. As the efficiency is calculated for a day of 24 hours, hence it is called all-day efficiency.