LECTURE NOTES ON

ENERGY CONVERSION-I

SEMESTER- 4th

PREPARED BY

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SINGLE PHASE TRANSFORMER

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Transformer is a static piece of device by means of which (or electrostatic force) electric power (or energy) in one circuit is transformed into electric power of same frequency in another circuit (by mutual induction). It can raise or lower the voltage in circuit but with a corresponding decrease or increase in current.

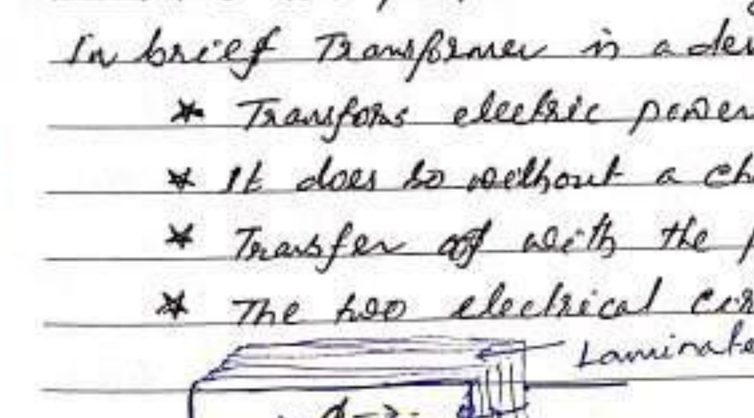
Working Principle:-

It works on the principle of mutual induction of two coils or Faraday law's of Electromagnetic Induction.

If one coil of transformer is connected to a source of an alternating voltage, an alternating flux is setup in the laminated core, most of which is linked with the other coil in which it produces mutually induced emf.

In brief Transformer is a device that

* Transfoms electric power from one circuit to another.
* It does so without a change of frequency.
* Transfer ~~of~~ with the principle of Electromagnetic Induction
* The two electrical circuit are linked by mutual induction.



$$E = -N\frac{d\phi}{dt}$$

Construction:-

The simple elements of a transformer consist of two coils having mutual inductance & laminated steel core. The two coils are insulated from each other and from steel core. Device also needs some suitable container for the assembled core and windings, a medium with which the core and windings can be insulated. Suitable bushings either porcelain, oil filled or Capacitor-type for insulating and bringing out the terminals of windings from the tank. The T/F core is made up of or constructed of transformer sheet steel laminations assembled to provide a continuous magnetic path with a minimum of air-gap included.

✓ The steel should have high permeability and low hysteresis loss. For this to happen, the steel should be made up of high silicon content and must also be heat treated. By effectively laminating the core, the eddy current losses can be reduced, the laminations being insulated from each other by a light coat of core-plate varnish or by an oxide layer on the surface.

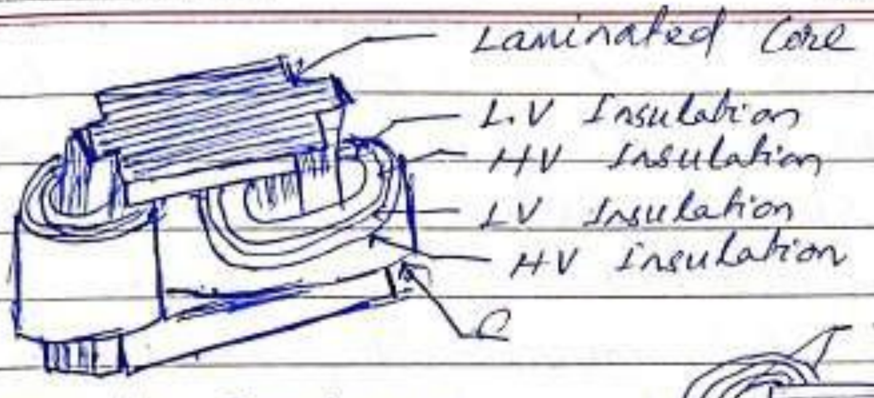
Type of Transformer :-

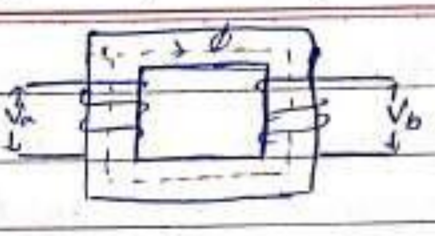
According to the design T/F can be classified into two :

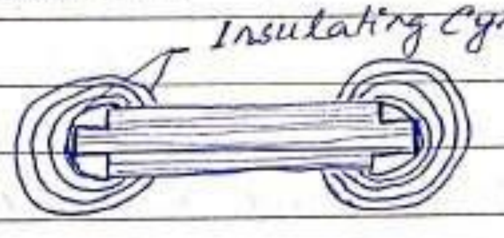
(a) Core type T/F :-

✓ The winding or coil used for this T/F surround a considerable part of core and form wound and are of cylindrical type. Such a type of T/F ~~can~~ can be applicable for small sized and large sized T/Fs.

In small sized type the core will be rectangular shape, and coil used are cylindrical, which are either circular or rectangular in form.







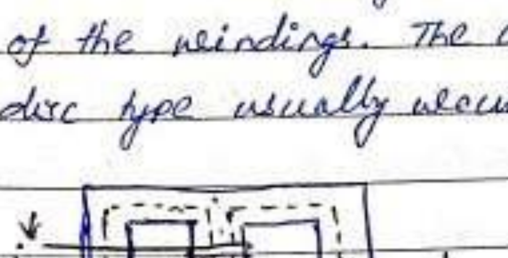
[Core type Transformer cruciform section]

→ The cylindrical coils will have different layers and each layer will be insulated from each other with the help of material like paper, cloth, micarta board and so on.

* These are popular in High Voltage application like Distribution T/F, Power T/F and Auto T/F

③ Shell-Type T/F :-

In shell-type T/F, the core surrounds a considerable portion of the windings. The coils are form-wound but are multilayer disc type usually wound in the form of pancakes.



(3 Limb shell type)

Paper is used to insulate the different layers of the multi-layer discs. The whole winding consist of discs stacked with insulation spaces between the coils. These form horizontal cooling & insulating ducts.

Both H.V & L.V coils are wound on the central limb surface the quantity of conductor required for woundings of shell type T/F in less than that of a similar core type T/F. The insulating material in more here as the winding are sandwitched on each other which would give rise to a risk of short-circuit faults.

Forced air and/or forced oil cooling is essential in shell type T/F as heat generated during working can't get dissipated easily from windings due to surrounding yoke and limbs.

Shell type T/F are mainly used for Low Voltage (LV) applications and are very often used in low voltage power circuits as well as in electronics circuits.

→ The sides of tank, The insulating oil used in the T/F ~~provide~~ needed to circulate through the device and cool the coils. It is also responsible for providing the additional insulation for the device when it is left in the air. When the smooth tank surface will not be able to provide the needed cooling are. In such cases the sides of the tank are assembled with radiators on the sides of the device.

→ Breather is used to absorb the moisture present in air before intering into the tank during expansion and contraction oil in the tank.

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Type according to the type of cooling employed :-

(A) Oil filled self cooled type :-

- It is used by small and medium sized distribution T/F. The assembled windings and core of such T/F are mounted in a welded, oil-tight steel tanks provided with a steel cover. The tank is filled with purified, high quality insulating oil as soon as the core is put back at its proper place. The oil helps in transforming the heat from core and the winding to the surroundings. For smaller size tanks are usually smooth surfaced but for large size T/F greater surface area is needed and is achieved by frequently corrugating the case.

(B) Oil filled Water cooled type :-

It is same as oil filled self cooled type, only difference is that a cooling coil is mounted near the surface of the oil, through which cold water keep circulating. This design is usually implimented on T/Fs that are used in high voltage transmission lines.

(C) Air Blast type :-

This type is used for T/Fs that use voltage below 25 KV. The transformer is housed in a thin sheet metal box open at both ends through which air is blown from the bottom to the top.

Sine of Angle = Cosine of its complement.

$\sin\theta = \cos(90-\theta)$

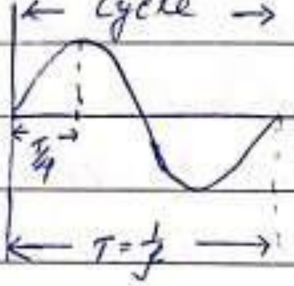
Mo Tu We Th Fr Sa Su $\cos\theta = \sin(90-\theta)$ or $\sin(90+\phi)$ Date / /

E.M.F. Equation of a Transformer :-

Let N_1 = No of turns in primary N_2 = No of turns in Secondary

ϕ_m = Max flux in core in Weber, $\phi_m = B_m \times A$

f = frequency of a.c input in Hz.



flux increases from zero to max value ϕ_m in one quarter of the cycle

$\therefore$ Average rate of change of flux $= \frac{\phi_m}{T/4}$

$= 4f\phi_m$ Wb/s or Volt

The rate of change of flux per turns means induced emf in volt. i.e

Average emf/turn $= 4f\phi_m$ Volt.

If ϕ varies sinusoidally, then rms value of induced emf is obtained by multiplying the average value by form factor

RMS Value = Form factor X Average Value

RMS Value of emf/turn $= 1.11 \times 4f\phi_m = 4.44f\phi_m$ Volt

RMS value of the induced emf in the whole of primary winding

= Induced emf/turn X No of primary turns

$E_1 = 4.44 f N_1 \phi_m = 4.44 f N_1 B_m A$ — ①

Similarly rms value of the emf induced in secondary is

$E_2 = 4.44 f N_2 B_m A$ — ②

From Eqn ① and ②

$$\boxed{\frac{E_1}{N_1} = \frac{E_2}{N_2} = 4.44 f B_m A}$$

OR $\phi = \phi_m \sin \omega t$ $\quad e = -N\frac{d\phi}{dt} = -N\frac{d}{dt}(\phi_m \sin\omega t) = -N\phi_m \cos\omega t \cdot \omega = -N_1\phi_m\omega \sin(90-\omega t)$

$\Rightarrow e_1 = N_1\phi_m\omega \sin(\omega t - 90)$

Rms value $E_1 = \frac{N_1\phi_m\omega}{\sqrt{2}} = \frac{N_1\phi_m(2\pi f)}{\sqrt{2}} = 4.44 N_1\phi_m f$

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* Voltage Transformation Ratio $(K) = \frac{E_2}{E_1} = \frac{N_2}{N_1}$

* Turn Ratio : $\frac{N_1}{N_2}$

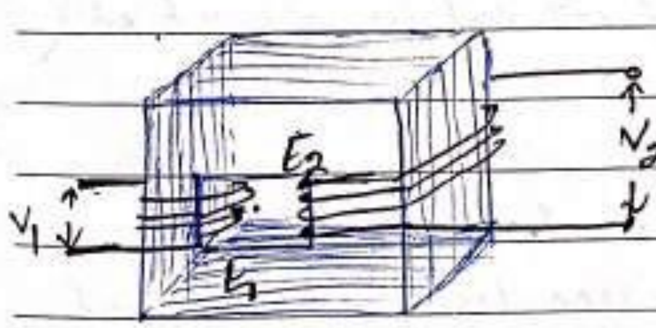
For ideal transformer input VA = output VA

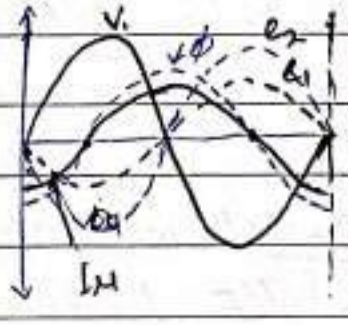
$V_1 I_1 = V_2 I_2$ or $\frac{I_2}{I_1} = \frac{V_1}{V_2} = \frac{1}{K}$ $\left\}\begin{array}{l}\text{Here } E_1 = V_1 \\ \text{\&} \quad E_2 = V_2\end{array}\right.$

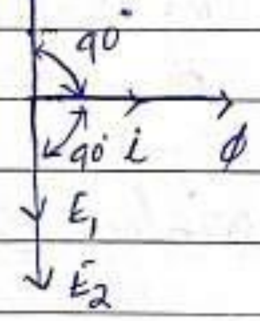
Ideal Transformer :-

An ideal T/F is one which has no losses i.e its winding have no ohmic resistance, there is no magnetic leakage and hence which has no I^2R and core losses. In other word, an ideal T/F consist of two purely inductive coils wound on a loss-free core.

Consider an ideal T/F whose secondary is open and primary is connected to sinusoidal alternating voltage V_1.







The potential difference causes an alternating current to flow in primary. Since primary coil is purely inductive and there is no output (secondary being open) the primary draws the magnetising current (I_M) only.

I_μ is small in size and lags V_1 by 90°. I_μ produces an alternating flux ϕ which is proportional to the current and is in phase with it. Because of change in flux linkage with primary and secondary windings, it produces self-induced emf (E_1) equal and opposite to V_1. Similarly in secondary side emf (E_2) is induced, known as mutually induced emf is antiphase with V_1

Care and Maintenance of Transformer :-

1) Oil level in the oil cap must be checked on a monthly basis.
2) Keep the breathing holes in the silica gel breather clean to ensure proper breathing action.
3) If T/F has oil filling bushing, make sure that the oil is filled to the correct level
4) Replace the silica gel if its colour changes to pink

Operation of Transformer at no-load.

In practical T/F there is iron loss in the core and copper loss in the winding and these are not entirely negligible When T/F in on no-load, the primary input current is not wholly reactive. Primary no load current (I_0) has to supply i) Iron losses in the core i.e hysteresis loss (W_h) and Eddy current losses (W_e) and ii) Very small

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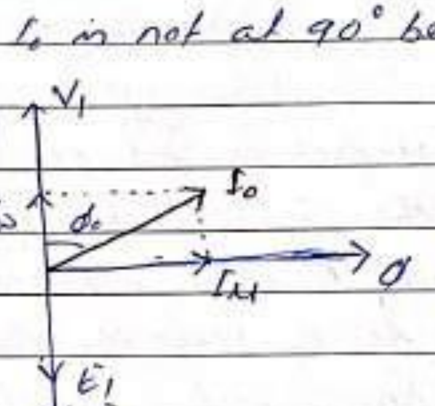
amount of copper loss in primary. So I_o is not at 90° behind V_1 but lags it by angle $\phi_o < 90°$

No Load Power Input $\boxed{(W_o) = V_1 I_o \cos\phi_o}$



I_o has two components i) one in phase with V_1 is known as active or working or Iron loss components I_w.

$\boxed{I_w = I_o \cos\phi_o}$

[Phasor diagram of No-Load T/F]

* I_w supplies the iron loss and small quantity of primary Cu. loss.

ii) Other component is quadrature with V_1 and is known as magnetising components I_μ, because its work is to sustain the alternating flux in core.

$\boxed{I_\mu = I_o \sin\phi_o}$

Here $\vec{I_o} = \vec{I_w} + \vec{I_\mu}$, hence $I_o = \sqrt{I_\mu^2 + I_w^2}$

* I_o is very small and is 1% of full Load current.
* As I_o is very small, so no-load primary Cu. Loss is negligible small hence No-Load Primary Input is practically equal to the Iron loss in T/F.
* Core loss or iron loss is responsible for shifting the current vector. hence ϕ_o is known as hysteresis angle of advance

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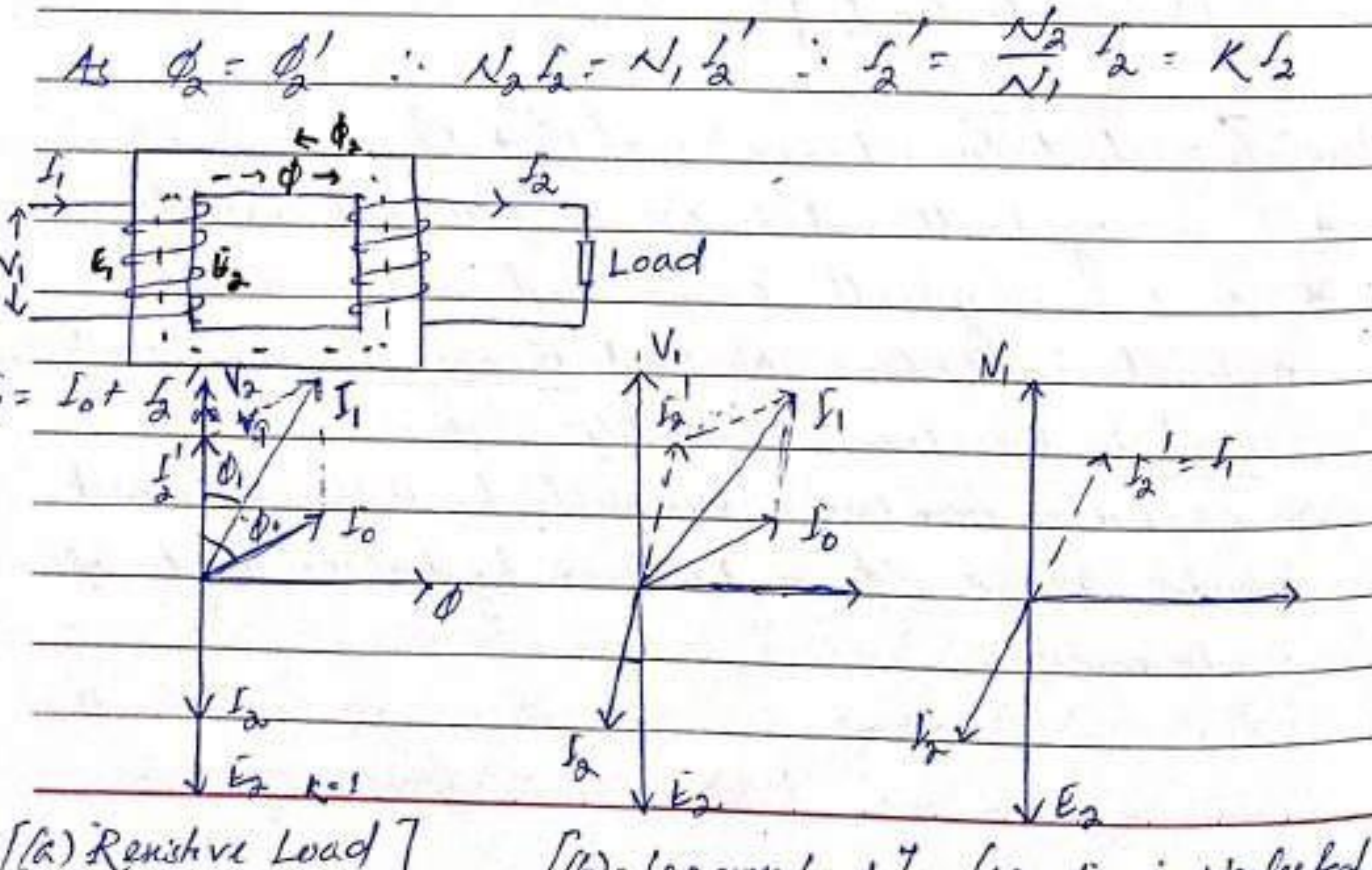
Transformer on Load :-

When the secondary in Loaded, the current I_2 in set up Magnitude And phase of I_2 with respect to V_2 is determined by the characteristics of Load. I_2 set up its own mmf($=N_2I_2$) and ϕ_2 and (A) it in opposite to the main flux.

As ϕ_2 reduces the main flux(ϕ) momentarily, hence primary back emf E_1 tends to be reduced. For a moment V_1 gain the upper hand and primary current increases and this additional current be I_2' and in antiphase with I_2 and setup its own flux ϕ_2', opposite to ϕ_2

*So net flux passing through the core in approximatly the same as at no-load. Hence core loss in also practically same under all load condition.

As $\phi_2 = \phi_2'$ $\therefore N_2I_2 = N_1I_2'$ $\therefore I_2' = \frac{N_2}{N_1} I_2 = KI_2$



[(a) Resistive Load] [(B)- Lagging Load] [(c) I_0 is Neglected]

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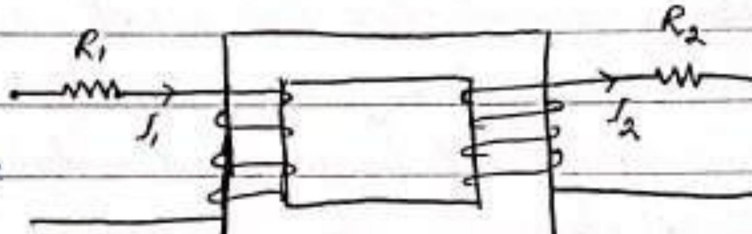
ϕ_1 is slightly greater than ϕ_2. If we neglect I_0 as compared to I_2' then $\phi_1 = \phi_2$

Hence $N_1 I_2' = N_2 I_2 = N_1 I_1 \quad \therefore \frac{I_2'}{I_2} = \frac{N_2}{N_1} = \frac{I_1}{I_2} = K$

(As $I_1 = I_2'$)

Equivalent Resistance, Reactance and Impedance :-



Primary & secondary winding, having resistance R_1, R_2 respectively is shown in figure.

The resistance of the two winding can be transferred to any one of the two winding. It makes calculations very simple and easy because one has to work one winding only.

where R_1' = The equivalent primary resistance as referred to secondary

& R_2' = " secondary " " Primary.

These can be calculated by considering the same losses (I^2R loss)

$$I_1^2 R_2' = I_2^2 R_2 \Rightarrow R_2' = \left(\frac{I_2}{I_1}\right)^2 R_2 \Rightarrow \boxed{R_2' = \frac{R_2}{K^2}}$$

Similarly $\boxed{R_1' = K^2 R_1}$

$\therefore$ Effective or Equivalent resistance of T/F as referred to primary $(R_{01}) = R_1 + R_2'$

$$= R_1 + R_2/K^2$$

& " " " to secondary $(R_{02}) = R_2 + R_1'$

$$= R_2 + K^2 R_1$$

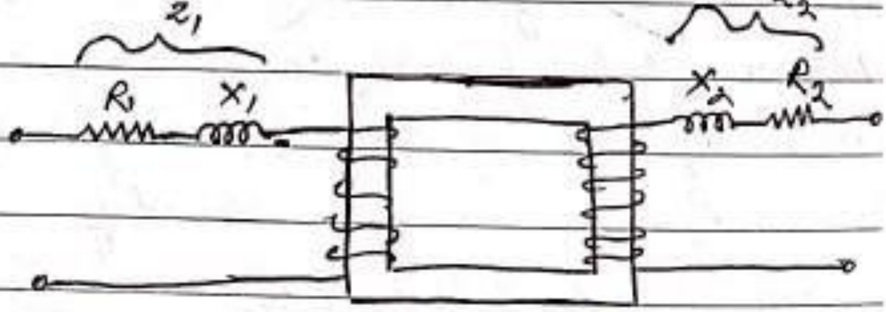
* A resistance of R_1 in Primary is equivalent to K^2R_1 in Secondary
* ,, R_2 in Secondary ,, R_2/K^2 in Primary

* But in practical all the flux linked with primary
* does not link the secondary, it is known as primary Leakage flux
* This leakage flux depends on primary and secondary current. leakage flux linking with each winding produces a self induced emf in that winding. Hence in effect it is equivalent to a small inductive coil in series with each winding.

→ The primary voltage V_1 will have to supply reactive drop I_1X_1 in addition to I_1R_1 and E_2 have to supply I_2R_2 and I_2X_2

$Z_1 = \sqrt{R_1^2 + X_1^2}$

$Z_2 = \sqrt{R_2^2 + X_2^2}$



$V_1 = E_1 + I_1(R_1 + jX_1)$ & $E_2 = V_2 + I_2(R_2 + jX_2)$

$\Rightarrow V_1 = E_1 + I_1 Z_1$ $\Rightarrow E_2 \Rightarrow V_2 + I_2 Z_2$

Leakage reactances can also be transferred from one winding to the other in the same way as resistance

$X_2' = X_2/K^2$ & $X_1' = K^2X_1$

And $X_{01} = X_1 + X_2' = X_1 + X_2/K^2$ and $X_{02} = X_2 + X_1' = X_2 + K^2X_1$

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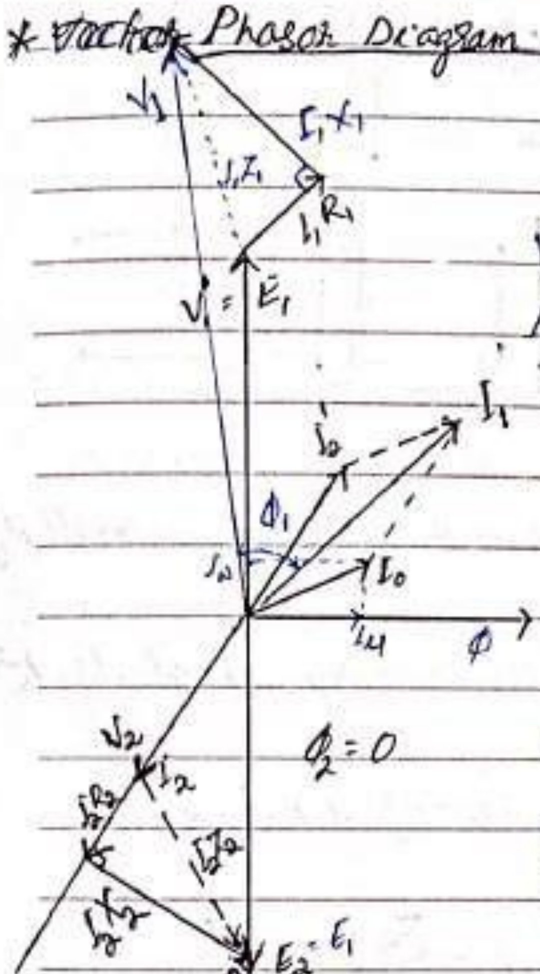
* ~~Vector~~ Phasor Diagram of T/F (With winding Resistance & Leakage Reactance) And With UPF, Lagging P.F & Leading PF)



V_1 = Voltage drop in the primary winding

I_1 = Primary current

I_0 = Primary No load current

I_2' = Load component of Primary current

E_1 = Induced emf (Primary)

I_μ = Magnetising component of No load current

I_w = Active or working " "

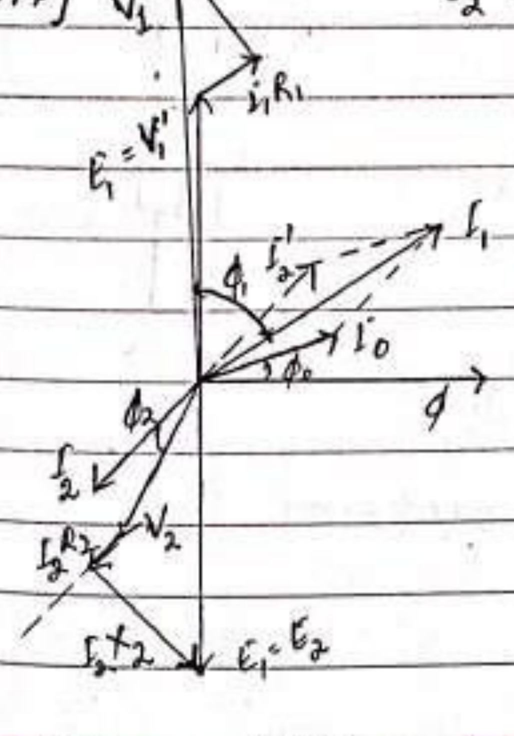
E_2 = Induced emf (secondary side)

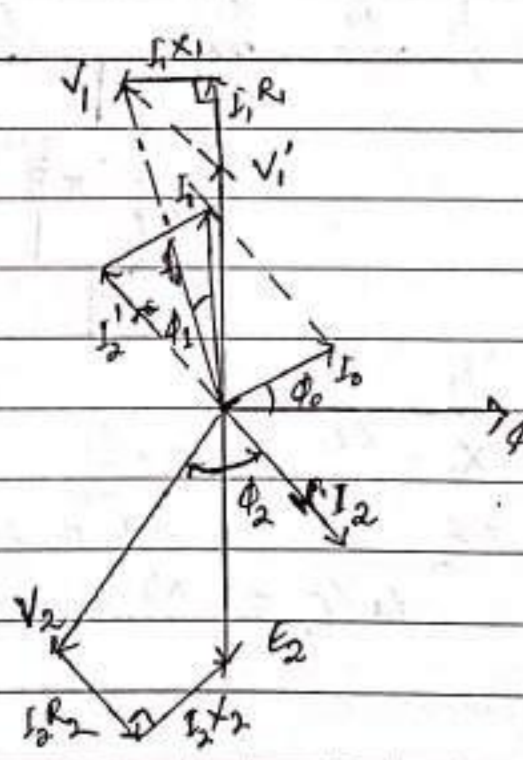
I_2 = secondary current

V_2 = secondary terminal voltage.

[UPF]

$I_2 = I_2'$





[Lagging P.F)

[Leading PF]

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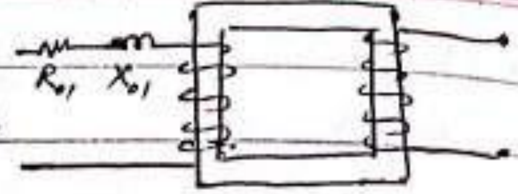
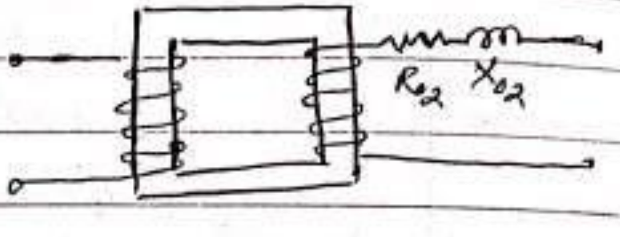
The total Impedance of transformer referred to Primary & Secondary is :-



$$Z_{01} = \sqrt{R_{01}^2 + X_{01}^2}$$

& $$Z_{02} = \sqrt{R_{02}^2 + X_{02}^2}$$

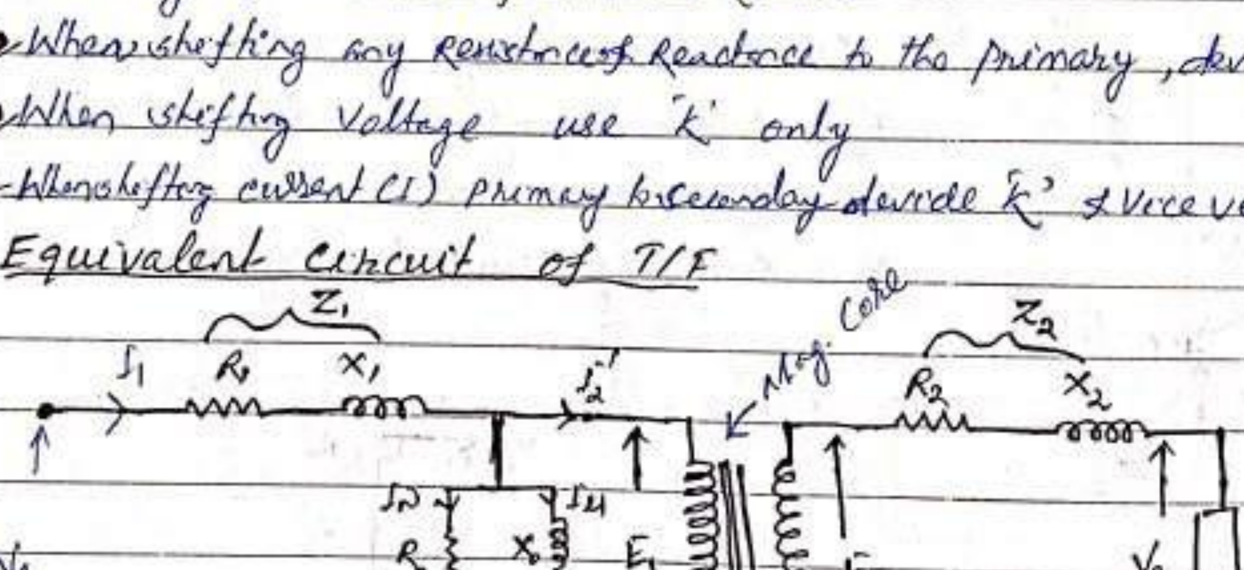


$R_{01} = R_1 + R_2'$ & $R_{02} = R_2 + R_1'$

$X_{01} = X_1 + X_2'$ & $X_{02} = X_2 + X_1'$

- When shifting any Resistance & Reactance to the secondary, multiply it by K^2 i.e (transformation Ratio)^2
- When shifting any Resistance & Reactance to the primary, divide it by K^2
- When shifting voltage use 'K' only
- When shifting current (I) primary to secondary divide 'K' & vice versa

Equivalent circuit of T/F



$X_0 = E_1 / I_0$, $R_0 = \frac{E_1}{I_w}$ again $X_0 = \frac{V_1}{I_\mu}$

E_1 & E_2 are related to each other by expression

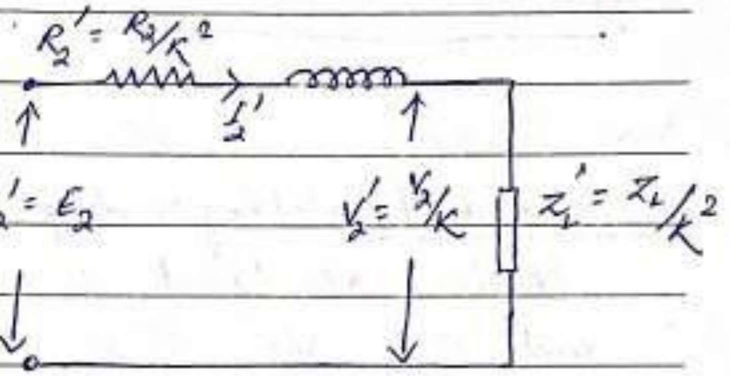
$$E_2/E_1 = N_2/N_1 = K$$

To make transformer calculation simpler, it is preferable to transfer voltage, current & impedance.

i.e. $E_2' = E_2/K = E_1$ (as $K=1$)

$V_2' = V_2/K$, $I_2' = KI_2$, $R_2' = R_2/K^2$, $X_2' = X_2/K^2$ & $Z_2' = Z_2/K^2$

So primary equivalent of secondary circuit can be drawn as →



Total Equivalent circuit of the T/F is obtained by primary equivalent of secondary to the primary.

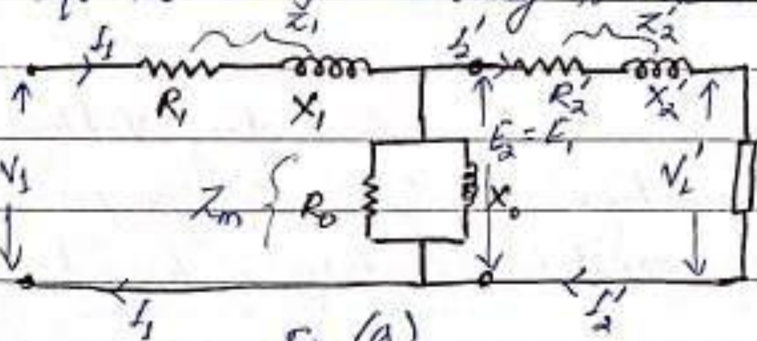
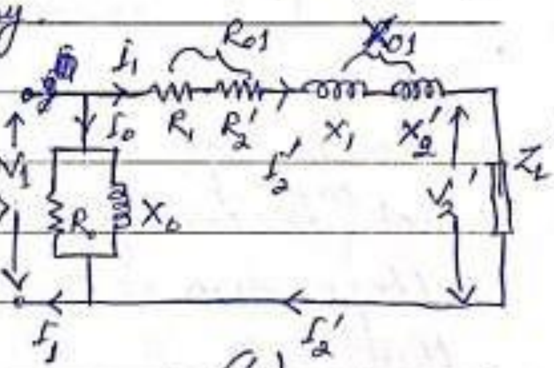
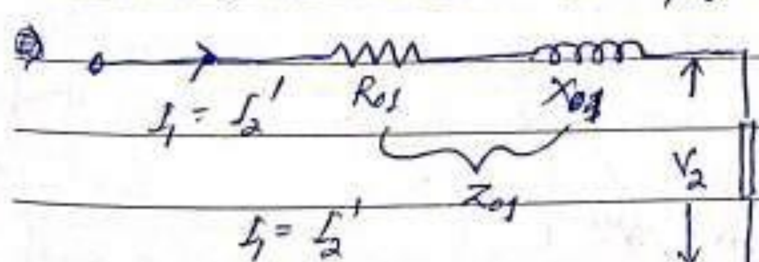


Fig (a)



(b)

At Last, the circuit is simplified by omitting I_0



(c)

From Fig (a) the equivalent Impedance between input is

$$Z = Z_1 + Z_m \| (Z_2' + Z_L')$$

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From

i.e $Z = Z_1 + \dfrac{Z_m (Z_2' + Z_L')}{Z_m + Z_2' + Z_L'}$ Z_m = Impedance of Exciting circuit

$$\therefore \boxed{V_1 = I_1 \left[Z_1 + \frac{Z_m (Z_2' + Z_L')}{Z_m + Z_2' + Z_L'} \right]}$$

Approximate voltage drop in a T/F

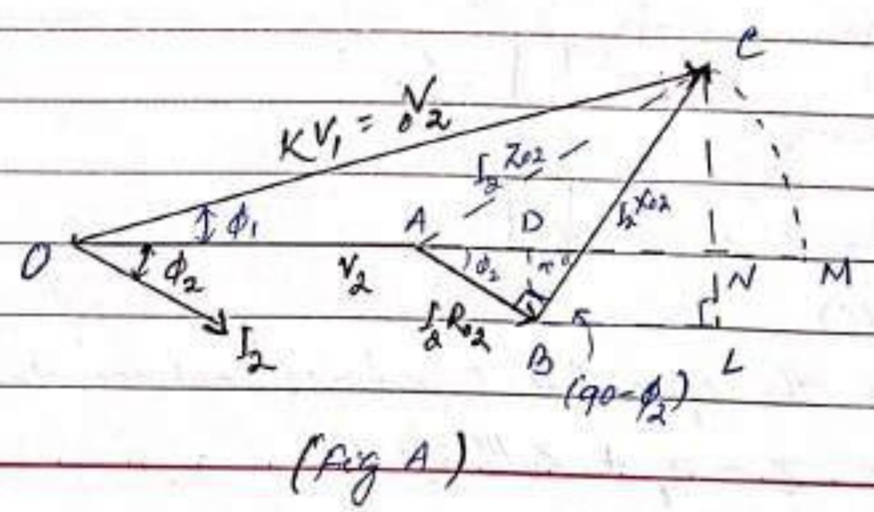
Under No Load $E_2 = KE_1 = KV_1$ (V_1 is approximately equal to E_1)

and $E_2 = {}_0V_2$ (${}_0V_2$ = No Load Secondary terminal Voltage)

$\therefore {}_0V_2 = KV_1$

V_2 = secondary Voltage on Load.

Hence ~~KV_1~~, difference between No load secondary Voltage and on Load secondary terminal voltage is $I_2 Z_{02}$. The approximate voltage drop of the T/F referred to secondary is found thus :-



(Fig A)

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From Fig 'A' total voltage drop $I_2 Z_{02}$ = AC = AM
which is approximately equal to AN
To calculate approximate voltage drop 'AN',
i) Perpendicular line of on AM is drawn from point 'B'
ii) ,, ,, on AM from C and is Extended downwards.
iii) Parallel line wrt AM from point B is drawn and it intersect extended CN to point 'L'
Now,
Approximate Voltage drop (AN) = AD + DN

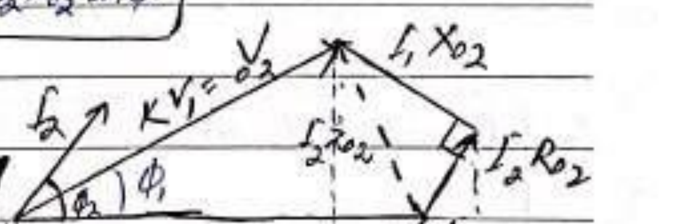
$= I_2 R_{02} \cos\phi_2 + I_2 X_{02} \sin\phi_2$

Again where $\phi_1 = \phi_2 = \phi$ (Approx)

So $\boxed{AN = I_2 R_{02} \cos\phi + I_2 X_{02} \sin\phi}$ for Lagging P.F

Similarly for Leading P.F

$\boxed{\text{Approximate Voltage drop} = I_2 R_{02} \cos\phi - I_2 X_{02} \sin\phi}$



$\boxed{\text{In general app. Volt drop} = I_2 R_{02} \cos\phi \pm I_2 X_{02} \sin\phi}$

+ve for Lagging & −ve for Leading

$\boxed{\text{Again Voltage drop referred to primary} = I_1 R_{01} \cos\phi \pm I_1 X_{01} \sin\phi}$

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Exact Voltage Drop

From fig 'A' exact voltage drop can be calculated by adding NM to AN.

Considering right angle Δ OCN

$NC^2 = OC^2 - ON^2 = (OC+ON)(OC-ON) = (OC+ON)(OM-ON)$

{as OC = OM (Radius)} and $OC \simeq ON$ so $OC+ON = 2OC$

$\Rightarrow NC^2 = 2OC \times NM$

$\Rightarrow NM = NC^2/2OC$ Now $NC = LC - LN = LC - BD$

$\therefore NC = I_2 X_{02} \cos\phi - I_2 R_{02} \sin\phi$

And $\boxed{NM = \frac{(I_2 X_{02} \cos\phi - I_2 R_{02} \sin\phi)^2}{2\,{}_0V_2}}$

$\therefore$ Exact Voltage drop for Lagging p.f is

$$= (I_2 R_{02} \cos\phi + I_2 X_{02} \sin\phi) + \frac{(I_2 X_{02} \cos\phi - I_2 R_{02} \sin\phi)^2}{2\,{}_0V_2}$$

$\therefore$ Exact Vol. drop for Leading p.f is

$$\boxed{= I_2 R_{02} \cos\phi - I_2 X_{02} \sin\phi + \frac{(I_2 X_{02} \cos\phi - I_2 R_{02} \sin\phi)^2}{2\,{}_0V_2}}$$

In general. Voltage drop is $= (I_2 R_{02} \cos\phi \pm I_2 X_{02} \sin\phi) + \frac{(I_2 X_{02} \cos\phi - I_2 R_{02} \sin\phi)^2}{2\,{}_0V_2}$

$$\boxed{\%\ \text{Drop} = \frac{I_2 R_{02} \cos\phi \pm I_2 X_2 \sin\phi}{{}_0V_2} \times 100 + \frac{(I_2 X_{02} \cos\phi - I_2 R_{02} \sin\phi)^2}{2\,{}_0V_2^2}}$$

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Regulation of T/F

When a T/F is Loaded with a constant primary Voltage, the secondary voltage decreases for Lagging PF and increases for leading PF because of its internal resistance and leakage reactance.

Let ${}_0V_2$ = No Load secondary Terminal Voltage
$= E_2 = EK_1 = KV_1$ because Impedance drops is negligible at no-load.

V_2 = secondary terminal voltage on full Load.

Regulation of T/F is the change in secondary terminal voltage from no-load to full load ie $({}_0V_2 - V_2)$

✓ % Voltage Regulation (down) $= \dfrac{{}_0V_2 - V_2}{{}_0V_2} \times 100$

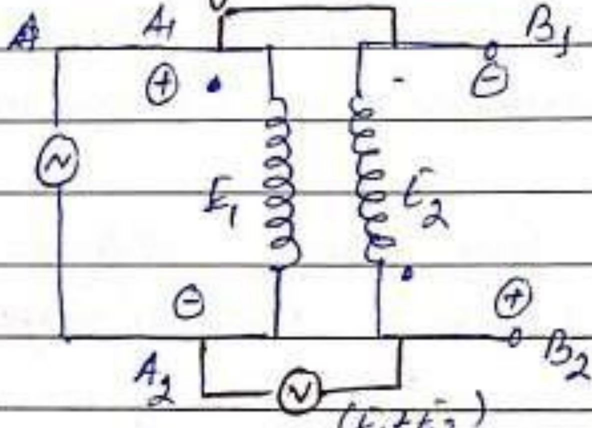
✓ " (UP) $= \dfrac{{}_0V_2 - V_2}{V_2} \times 100$

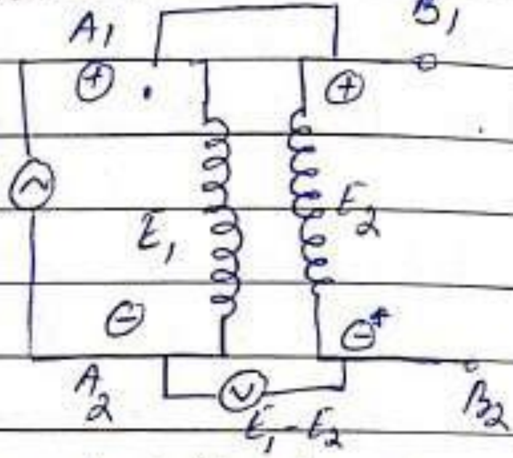
or Approximate % V.R $= \cancel{\dfrac{I_2R_{e2}\cos\phi \pm I_2X_{e2}\sin\phi}{V_1} \times 100 + \dfrac{1}{200}}$

$$= \frac{I_2R_{e2}\cos\phi \pm I_2X_{e2}\sin\phi}{V_1} \times 100 + \frac{1}{2V_1}(I_2X_{e2}\cos\phi - I_2R_{e2}\sin\phi)^2 \times 100$$

Testing of Transformer :-

(a) Polarity Test (A) DOT Notation





Terminal A_1 and B_1 are shorted and Voltmeter is connected across terminal A_2 and B_2 and observe the Voltmeter reading.

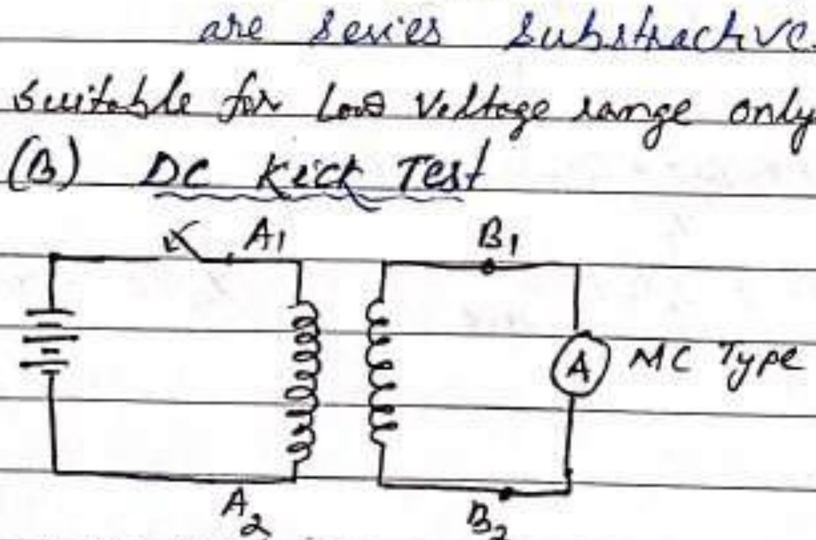
If Voltmeter Reading is

(i) $V = E_1 + E_2$ → Then series Additive polarity

ii) if $V = E_1 - E_2$ (i.e less than E_1 or E_2) then terminal are series Substractive.

* Suitable for Low Voltage range only. (dot Notation)

(B) DC Kick Test



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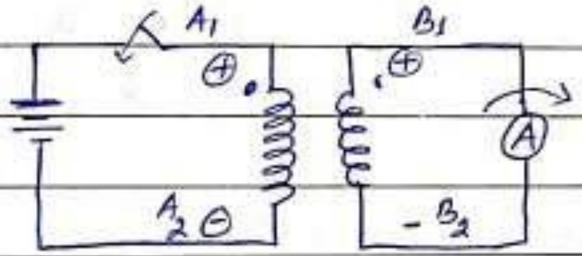
The High Voltage side winding is momentarily excitted with dc supply or dc source. H.V side in connected to dc source because there is a large value of resistance. And ammeter is is connected at low resistance side.

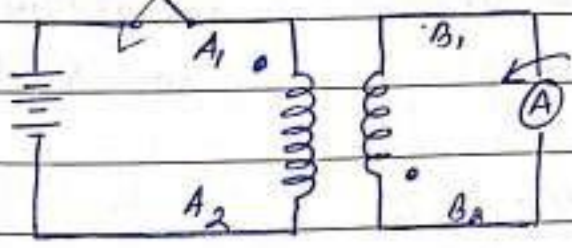
As switch is closed or during Excitation a small amount of current flows in the secondary. observe the ammeter deflection.

If Forward kick (A) then secondary terminals are indicated with same polarities.

*



* If Backward kick (A) then secondary terminals are indicated with opposite polarities.



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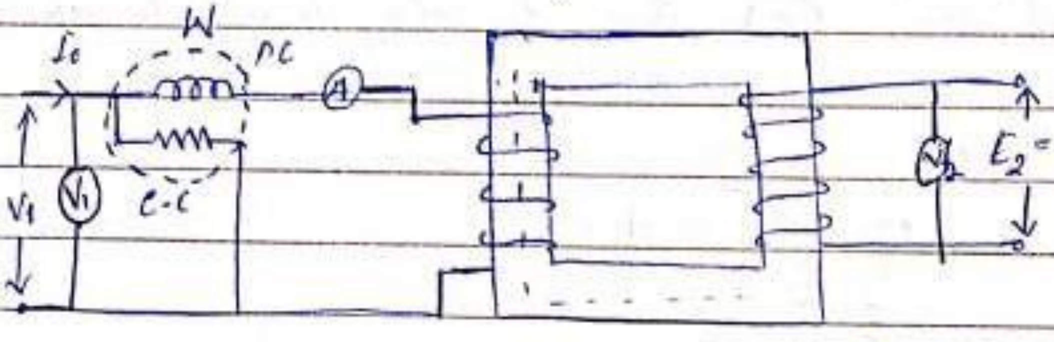
Open circuit test :-

The purpose of open ckt. test is to determine the no-load current (I_0) and losses of transformer and because of which their no load parameters R_0 and X_0 are determined.

→ This test is performed on Low Voltage side of Transformer.

* and high voltage winding is left open and other side is connected to nominal supply. (Voltage in high voltage side is too high and can't be measured & current is very high, which can't be measured)



L.V Side H.V Side

Wattmeter, ammeter and Voltmeter are connected to their L.V side as shown in figure above.

The value of I_0 is very small (i.e 2 to 10% of rated Load current) so Cu loss negligibly small in primary side and nil in secondary side. Hence the wattmeter reading represents practically the core loss under no-load.

(W) ⇒ Reads Core loss of T/F = W_0

→ As I_0 is very small, the pressure coil of wattmeter and voltmeter are connected such that the current doesn't pass through the current coil of wattmeter

→ High resistance voltmeter is connected across the secondary

(V_2) → Reads Induced emf in secondary side = E_2

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(A) → Reads No. load current 'I_0'

As. $W_0 = V_1 I_0 \cos\phi_0 \Rightarrow \cos\phi_0 = W_0 / V_1 I_0$

$\therefore I_\mu = I_0 \sin\phi_0$, $I_w = I_0 \cos\phi_0$

$$\boxed{X_0 = \frac{V_1}{I_\mu}} \text{ and } \boxed{R_0 = \frac{V_1}{I_w}}$$

As $I_0 \cong I_\mu$ (As current is all exciting current at no-load) and voltage drop is very small.

Exciting admittance $(Y_0) = \frac{I_0}{V_1}$

" conductance (G_0) is given by $W_0 = V_1^2 G_0 \Rightarrow \boxed{G_0 = \frac{W}{V_1^2}}$

Exciting susceptance $\boxed{B_0 = \sqrt{(Y_0^2 - G_0^2)}}$

Core loss depends on the frequency and maximum flux density when volume and the thickness of core laminations are given & const.

Core loss = Hysteresis Loss (W_h) + Eddy current Loss (W_e)

$\Rightarrow \quad = \eta B_{max}^x f V + K B_{max}^x f^2 t^2$

$\Rightarrow W_i = Af + Bf^2$

$$\Rightarrow \boxed{\frac{W_i}{f} = A + Bf}$$

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Short-Circuit or Impedance Test.

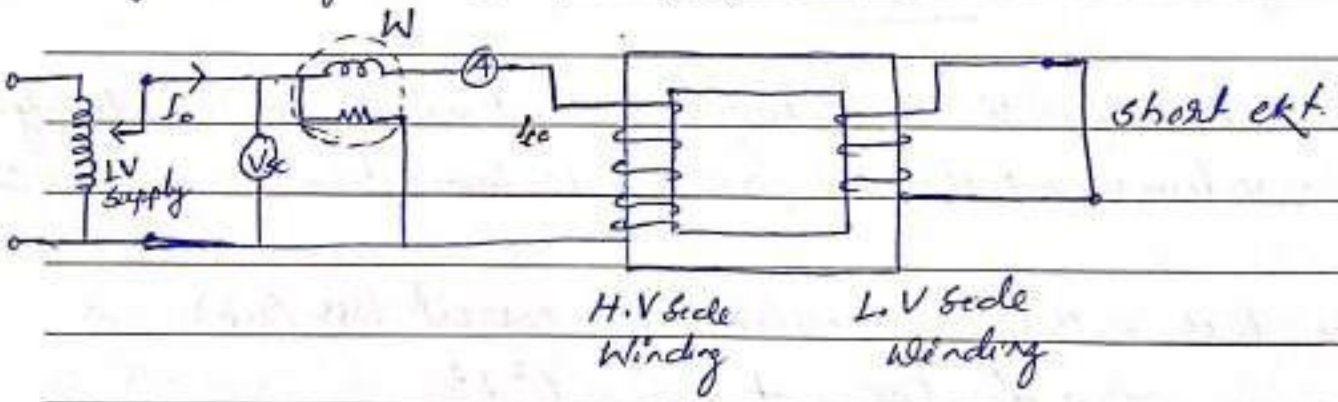
The economical method for determining

i) Equivalent impedance (Z_{01} or Z_{02}) Leakage reactance (X_{01} or X_{02}) and total resistance (R_{01} or R_{02})

ii) To find variable loss i.e Cu loss at full load and Efficiency

→ This test is performed on the secondary winding side i.e High Voltage side.

Wattmeter, Voltmeter and ammeter are connected to the high voltage side as shown below.



A low voltage (usually 5 to 10% of normal primary voltage) at correct frequency is applied and is continuously increased till full load current are flows in both primary & secondary side indicated by respective Ammeter.

As applied voltage is small percentage of normal voltage, the mutual flux ϕ is also small and hence core loss is very small. The result that the wattmeter

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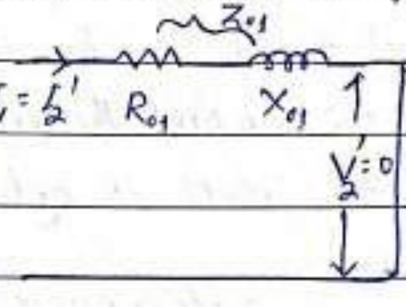
reading represent the full load cu. loss or I^2R loss. of whole T/F. Equivalent circuit under short ckt. can be drawn as fig.c



W_{sc} = Wattmeter Reading or I^2R loss

V_{sc} = Voltmeter Reading or voltage required to circulate rated load current

I_{sc} = Ammeter Reading or Rated full load current

As $W_{sc} = I_{sc}^2 R_{01}$ $\Rightarrow \boxed{R_{02} = \frac{W_{sc}}{I_{sc}^2}} = \frac{\text{Wattmeter Reading}}{(\text{Ammeter Reading})^2}$

$V_{sc} = I_{sc} \times Z_{01} \Rightarrow Z_{02} = \frac{V_{sc}}{I_{sc}}$

then

$X_{02} = \sqrt{(Z_{02}^2 - R_{02}^2)}$ $\qquad R_{01} = \left(\frac{N_1}{N_2}\right)^2 R_{02}$

Why Transformer Rating in KVA ?

* As cu loss of a T/F depends on current and iron loss on voltage i.e total loss depends on volt-ampere (VA) and not on phase angle between voltage and current. That is why rating of T/F is in KVA and not in KWatt.

*

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Efficiency of Transformer :-

The efficiency of a T/F at a particular load and power factor is defined as the output devided by the input. Thetwo being measured in the same units (either watt or kilowatt)

$$\text{Efficiency}(\eta) = \frac{\text{output (kW)}}{\text{Input (kW)}} = \frac{\text{output}}{\text{output + Losses}}$$

Though T/F being efficient piece of equipment, has very small loss. hence it is impractical to try to measure efficiency by measuring input & output.

* A better method is to determine the losses & then to calculate efficiency.

$$\eta = \frac{\text{output}}{\text{output + Losses}} = \frac{\text{output}}{\text{output + Cu. Loss + Iron Loss}}$$

$$= \frac{\text{Input - Losses}}{\text{Input.}} = 1 - \frac{\text{Losses}}{\text{Input}}$$

* Cu. loss can be calculated from short circuit test
* Iron loss or core loss from open circuit test.

$$\eta_{FL} = \frac{V_1 I_1 \cos\phi_1 - I_1^2 R_{01} - W_i}{V_1 I_1 \cos\phi_1}$$ Refered to Primary

$$\eta_{FL} = \frac{V_2 I_2 \cos\phi_2}{V_2 I_2 \cos\phi_2 + \underset{(I_2^2 R_{02})}{\text{FL Cu loss}} + \underset{(W_i)}{\text{Iron loss}}} \times 100$$

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$$\boxed{\eta_{x\ \text{of FL at given PF}} = \frac{x \times \text{Full load KVA} \times P.f}{(x \times \text{Full load KVA} \times PF) + x^2(I_2^2 R_{02}) + W_i} \times 100}$$

where x = Ratio of actual to full load KVA

Condition for Max. Efficiency :-

$$\eta = 1 - \frac{Losses}{Input} = 1 - \frac{I_1 R_{01}}{V_1 I_1 \cos\phi_1} - \frac{W_i}{V_1 I_1 \cos\phi_1}$$

for η to be maximum $\frac{d\eta}{dI_1} = 0$

$$\therefore \frac{d\eta}{dI_1} = 0 - \frac{R_{01}}{V_1 \cos\phi_1} - \frac{W_i}{V_1 I_1^2 \cos\phi_1} = 0$$

$$\Rightarrow \frac{R_{01}}{V_1 \cos\phi_1} = \frac{W_i}{V_1 I_1^2 \cos\phi_1} \Rightarrow W_i = I_1^2 R_{01} \text{ or } I_2^2 R_{02}$$

$\therefore$ $\boxed{\text{Cu. loss = Iron Loss}}$

To get maximum efficiency Cu. loss of a T/F must be equal to core loss (Iron loss) or constant loss.

All day Efficiency :-

All day efficiency means the power consumed by the transformer throughout the day.

$$\text{All day Efficiency } (\eta_{all\ day}) = \frac{\text{output in KWh}}{\text{output + losses}} \quad (\text{for 24 hours})$$

All day efficiency can track the performance of distribution T/F

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⇒ Load corresponding to Max Efficiency

Let 'x' be the ratio of actual to full load at which efficiency is maximum.

We know the condition for max efficiency is Cu. loss = Iron loss

Hence.

Cu. loss at x of F.L = Iron loss

$$\Rightarrow x^2 I_2^2 R_{02} = W_i$$

$$\Rightarrow x = \sqrt{\frac{W_i}{I_2^2 R_{02}}} \quad \text{i.e} \quad \boxed{x = \sqrt{\frac{\text{Iron Loss}}{\text{FL Cu Loss}}}}$$

$$\boxed{\text{Load KVA for } \eta_{max} = \text{F.L KVA} \times \sqrt{\frac{\text{Iron Loss}}{\text{F.L. Cu Loss}}}}$$

Variation of Efficiency with Power Factor :-

$$\eta = 1 - \frac{\text{Loss}}{\text{Input}} = 1 - \frac{\text{Losses}}{V_2 I_2 \cos\phi_2 + \text{Losses}}$$

Let $\text{Losses}/V_2 I_2 = y$ then

$$\eta = 1 - \frac{\text{Losses}/V_2 I_2}{\cos\phi_2 + \text{Losses}/V_2 I_2} = 1 - \frac{x}{\cos\phi_2 + x}$$

$$\Rightarrow \boxed{\eta = 1 - \frac{x/\cos\phi_2}{1 + x/\cos\phi_2}}$$

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Parallel operation of Transformer

* If two or more transformer are connected to a same supply on the primary side and to a same load on the secondary side, then it is called as parallel operation of transformer.

Necessity of parallel operation is (Need)

1) Increased Load :- Necessary to supply the increased load when Load exceeds the capacity of existing Transformer.
2) Non Availability of Large T/F :- When a large transformer is not available to meet the total requirement of load, then two or more small T/F are connected in parallel.
3) Increased reliability :- ~~(If)~~ Any ~~T/F~~ got fault T/F can can be taken for maintenance uninterrupting to serve the load.
4.) Transportation is easier for small T/F :- If installation site is located far away, then transportation is easier for and economical for smaller units.

Conditions for parallel operation of T/F :-

1) The line voltage ratio of two T/F must be equal.
2) The per unit impedance of each T/F ~~must~~ should be equal and they should have same ratio of equivalent leakage reactance to the resistance. (X/R)
3) The T/F should have same secondary winding polarity.
4) " " " " phase sequence.
5) The " " the zero relative phase displacement between secondary line voltage (3ϕ T/F)

Auto - Transformer

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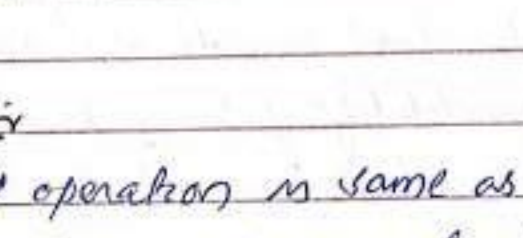
A transformer in which a part of the winding is common to both the primary and secondary circuit is called an Auto-transformer.

→ In auto-transformer the primary and secondary winding are not electrically isolated from each other as in case of two-winding Transformer.

Principle of operation :-

The principle of operation is same as that of common transformer. It works on the principle of Faraday's law of Electromagnetic - Induction.

AB is the primary winding having N_1 turns and BC is the secondary winding having N_2 turns



$N_1 : N_2$

[Fig(i)]

*Neglecting iron losses and No load current

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

As current in primary and secondary are practically in phase opposition and I_2 is greater than I_1. (Lenz's Law)

So Common Current (I_c) = $I_2 - I_1$

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* Saving of Cu. (Comparing Auto-transformer with two winding Transformer)

In case of stepdown T/F as shown in Fig-(a), $K < 1$

Volume and hence weight of Cu. is proportional to the length and area of the cross-section of conductor

Length of conductor $\propto$ Number of turn (N)

& Cross section $\propto$ current (I)

$\therefore$ Weight $\propto$ Product of Current and Number of turn (i.e NI)

Referring figure-(i)

Total weight of Cu. in Auto T/F (W_a) $\propto$ weight of Cu in section AC + weight of Cu in section BC

$$\Rightarrow W_a \propto (N_1 - N_2) I_1 + N_2 (I_2 - I_1) \quad \text{— eqn (1)}$$

Total weight of Cu. in two winding T/F (W_0) $\propto$ weight of Cu. in Primary side + Weight of Cu. in Secondary side

$$\Rightarrow W_0 = N_1 I_1 + N_2 I_2 \quad \text{— eqn (2)}$$

from Eqn (1) and Eqn (2)

$$\therefore \frac{\text{Wt. of Cu. in Auto. T/F}}{\text{Wt. of Cu. in Ordinary T/F}} = \frac{(N_1 - N_2) I_1 + N_2 (I_2 - I_1)}{N_1 I_1 + N_2 I_2}$$

$$= \frac{N_1 I_1 + N_2 I_2 - N_2 I_1 - N_2 I_1}{N_1 I_1 + N_2 I_2} = 1 - \frac{2 N_2 I_1}{N_1 I_1 + N_2 I_2}$$

$$= 1 - \frac{2 N_2 I_1 \times \frac{1}{N_1 I_1}}{(N_1 I_1 + N_2 I_2) \frac{1}{N_1 I_1}} = 1 - \frac{2 \frac{N_2}{N_1}}{1 + \frac{N_2}{N_1} \times \frac{I_2}{I_1}}$$

$$= 1 - K \quad \left[\text{as } \frac{N_2}{N_1} = \alpha \text{ and } \frac{I_2}{I_1} = K \right]$$

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i.e ie $\boxed{\frac{W_a}{W} = 1-k}$ or $\boxed{\frac{\text{Wt of Cu. in Auto T/F}}{\text{Wt. of Cu. in ordinary T/F}} = 1-k}$

$\therefore$ Weight of Cu. in Auto T/F = $(1-k)$ Weight of Cu. in Ordinary Transformer

Saving = $W_o - W_a$ = $W_o - (1-k)W_o$

$\boxed{\text{Saving} = kW_o}$

* Saving of Cu. will increases as 'k' approaches unity (1)

→ The power transformed inductively = $(1-k)$ Input

⇒ Rest Power = $k \times$ Input is conducted directly from the source to load i.e it is transferred conductively to the load.

Uses of Auto-transformer :-

1) It is used as a starter to give 50 to 60% of full voltage to starter of a squirrel cage Induction motor during starting
2) It is used to give a small boost to a distribution cable to correct the voltage drop.
3) It is used as a Voltage Regulator
4) Used as interconnecting T/F in 132 kV/330 kV power system ~~also in~~
5) Used in control equipment for 1ϕ and 3ϕ electrical locomotives

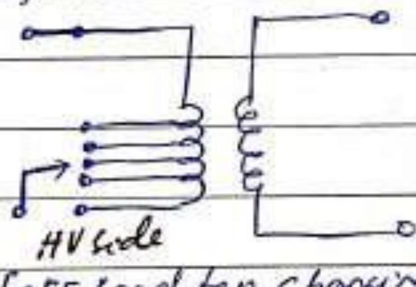
Tap changer with Transformer.

The change of voltage is affected by changing the number of the transformer provided with taps. For efficiently close control of voltage, tap are usually provided on the high voltage winding of the T/F.

Type of tap-changing T/F
a) Off-Load tap changing T/F
b) On-Load tap changing T/F

a) OFF-Load tap changing T/F :-

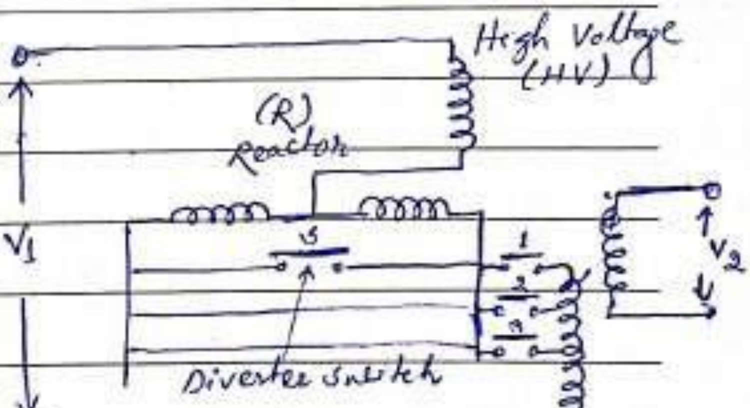
In this method, the transformer is disconnected from main supply when the tap setting is to be changed. The tap setting is done manually



[OFF-Load tap changing T/F]

b) ON-Load tap changing T/F

On load tap changing is used to supply uninterrupted power supply. While tapping, two essential conditions are to be filled



(i) The Load circuit should not be broken to avoid arcing and prevent the damage of contacts.
(ii) No part of the winding should be short-circuited while adjusting the tap.

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The transformer is in operation with switch 1 and 3' closed. To change to tap 2, switch 3' is opened and 2 is closed. Switch 1 is then opened, and 3' is closed to complete the tap change. It is to be noted that the diverter switch operates on load and no current flows through selector switch 3' during tap changing. During the tap change only half of the reactance which limits the current is connected in the circuit.

THREE PHASE TRANSFORMER

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Event though most of the equipments are connected by the single phase transformer, but these are not preferred for large power distribution in aspect of economy. The 3ϕ ~~T/F~~ power is used in almost all field of electrical power system such as power generation, transmission and distribution. Therefore 3ϕ T/F in used to step-up or step-down the voltage in 3ϕ system.

→ 3ϕ T/F is smaller and lighter in construction for the same power handling capacity and better operating characteristics

⇒ In order to reduce the power loss to the distribution end. the power in transmitted at higher voltage (132KV or 400KV) with 3ϕ T/F and again to step down at transmission and distribution end to level of 6600V, 400V, 230V, etc

* Due to single 3ϕ T/F amount of iron in the core and insulation materials are saved.

Construction :-

A 3ϕ T/F can be constructed by using common magnetic core for both primary & secondary winding. This can be of a bank of three ϕ core type T/F (3-core type single phase T/F are combined). Similarly a bank of 3ϕ shell type T/F (3 shell type single phase are combined)