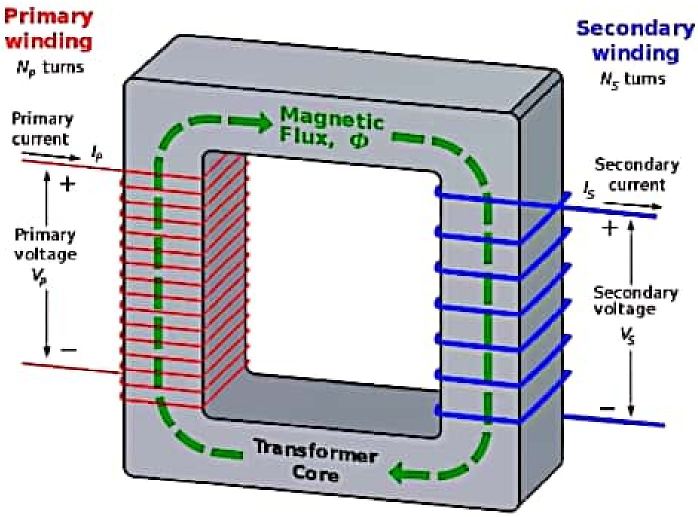
EMF EQUATION OF A TRANSFORMER



- In a transformer, an alternating electrical source is applied to the primary winding and due to this, magnetizing current flows through the primary winding which produces alternating flux in the core of the transformer.
- This flux links with both primary and secondary windings. As this flux is alternating in nature, there must be a rate of change of flux.
- According to Faraday's Law of EMI, if any coil or conductor links with any changing flux, there must be an induced emf in it.

EMF EQUATION OF A TRANSFORMER

- Let's say, T is number of turns in a winding, Φ_m is the maximum flux in the core in Wb.
- As per Faraday's Law of EMI,

$$emf,\ e = -T\frac{d\phi}{dt}$$

- Where φ is the instantaneous alternating flux and represented as,

$$\phi = \phi_m \sin 2\pi ft$$

$$Hence,\ e = -T\frac{d(\phi_m \sin 2\pi ft)}{dt}$$

$$\Rightarrow e = -T\phi_m \cos(2\pi ft) \times 2\pi f$$

$$\Rightarrow e = -T\phi_m \times 2\pi f \cos(2\pi ft)$$

EMF EQUATION OF A TRANSFORMER

- As the maximum value of cos2πft is 1, the maximum value of induced emf e is,

$$e_m = T\phi_m \times 2\pi f$$

- To obtain the rms value of induced counter emf, divide this maximum value of e by √2.

$$Then,\ E = \frac{2\pi}{\sqrt{2}} \times \phi_m f T$$

$$\boxed{E = 4.44\phi_m f T}\ Volts \quad (Since\ \frac{2\pi}{\sqrt{2}} = 4.44)$$

Gen

$$E = 4.44\phi_m f N$$

- This is the EMF equation of transformer.

EMF EQUATION OF A TRANSFORMER

- If E_1 & E_2 are primary and secondary emfs and T_1 & T_2 are primary and secondary turns then, **voltage ratio** or **turns ratio of transformer** is,

$$\frac{E_1}{E_2} = \frac{4.44\phi_m f T_1}{4.44\phi_m f T_2}$$

$$\Rightarrow \boxed{\frac{E_1}{E_2} = \frac{T_1}{T_2}} \text{ or } \boxed{\frac{V_1}{V_2} = \frac{N_1}{N_2}}$$

- This above stated ratio is also known as **voltage ratio of transformer** if it is expressed as ratio of the primary and secondary voltages of transformer.
- As the voltage in primary and secondary of transformer is directly proportional to the number of turns in the respective winding, the transformation ratio of transformer is sometime expressed in ratio of turns and referred as **turns ratio of transformer** .

EMF EQUATION OF A TRANSFORMER

- When a load is connected across the secondary winding, a current I_2 flows.
- Then, input power = output power, or $V_1 I_1 = V_2 I_2$, i.e., the **primary and secondary volt-amperes are equal.**
- Thus,

$$\boxed{\frac{V_1}{V_2} = \frac{I_2}{I_1}}$$

P. mmf = $N \times i_1$

- Combining the above equation with the previously derived voltage-turn ratio, we get

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

- The **rating** of a transformer is stated in terms of the volt-amperes that it can transform without overheating.
- The transformer rating is either $V_1 I_1$ or $V_2 I_2$, where, I_2 is the full load secondary current.

VOLTAGE & AMPERE-TURNS RATIO - NUMERICAL

3. An ideal transformer, connected to a 240V mains, supplies a 12V, 150W lamp. Calculate the transformer turns ratio and the current taken from the supply.

$V_1 = 240V$; $P = 150W$

$V_2 = 12V$ $\quad V_2 I_2 = 150$

$I_2 = \frac{150}{} = 12.5A$

$V_1 I_1 = V_2 I_2$

$I_1 = \frac{V_2 I_2}{V_1} = 0.625A/2$

$N_1 I_1 = N_2 I_2$

$\frac{N_1}{N_2} = \frac{I_2}{I_1}$

VOLTAGE & AMPERE-TURNS RATIO - NUMERICAL

4. A 5kVA single-phase transformer has a turns ratio of 10:1 and is fed from a 2.5 kV supply. Neglecting losses, determine (a) the full load secondary current, (b) the minimum load resistance which can be connected across the secondary winding to give full load kVA and (c) the primary current at full load kVA.

(a) $\frac{N_1}{N_2} = \frac{10}{1}$ and $V_1 = 2.5\,\text{kV} = 2500\,\text{V}$

Since $\frac{N_1}{N_2} = \frac{V_1}{V_2}$, secondary voltage

$$V_2 = V_1\left(\frac{N_2}{N_1}\right) = 2500\left(\frac{1}{10}\right) = 250\,\text{V}$$

The transformer rating in volt-amperes $= V_2 I_2$ (at full load), i.e. $5000 = 250 I_2$

Hence full load secondary current $I_2 = \frac{5000}{250}$

$= 20\,\text{A}$

(b) Minimum value of load resistance, $R_L = \frac{V_2}{I_2}$

$= \frac{250}{20}$

$= 12.5\,\Omega$

(c) $\frac{N_1}{N_2} = \frac{I_2}{I_1}$, from which primary current,

$$I_1 = I_2\left(\frac{N_2}{N_1}\right)$$

$$= 20\left(\frac{1}{10}\right)$$

$= 2\,\text{A}$

EMF EQUATION OF A TRANSFORMER - NUMERICAL

1. A 100kVA, 4000V/200V, 50Hz single-phase transformer has 100 secondary turns. Determine (a) the primary and secondary current, (b) the number of primary turns and (c) the maximum value of the flux.

$V_1 = 4000$ V, $V_2 = 200$ V, $f = 50$ Hz, $N_2 = 100$ turns

(a) Transformer rating $= V_1 I_1 = V_2 I_2 = 100\,000$ VA

Hence primary current, $I_1 = \dfrac{100\,000}{V_1} = \dfrac{100\,000}{4000}$

$= \mathbf{25\ A}$

and secondary current, $I_2 = \dfrac{100\,000}{V_2} = \dfrac{100\,000}{200}$

$= \mathbf{500\ A}$

(b) From equation (3), $\dfrac{V_1}{V_2} = \dfrac{N_1}{N_2}$

from which, primary turns, $N_1 = \left(\dfrac{V_1}{V_2}\right)(N_2)$

$= \left(\dfrac{4000}{200}\right)(100)$

i.e. $N_1 =$ **2000 turns**

(c) From equation (5), $E_2 = 4.44 f \Phi_m N_2$

from which, maximum flux Φ_m

$$= \frac{E_2}{4.44 f N_2} = \frac{200}{4.44(50)(100)}$$

(assuming $E_2 = V_2$)

$= \mathbf{9.01 \times 10^{-3}\ Wb\ or\ 9.01\ mWb}$

EMF EQUATION OF A TRANSFORMER - NUMERICAL

2. A single-phase, 50Hz transformer has 25 primary turns and 300 secondary turns. The cross-sectional area of the core is 300 sq. cm. When the primary winding is connected to a 250V supply, determine (a) the maximum value of the flux density in the core, and (b) the voltage induced in the secondary winding.

e.m.f. $E_1 = 4.44 f \Phi_m N_1$ volts i.e.

$$250 = 4.44(50)\Phi_m(25)$$

from which, maximum flux density,

$$\Phi_m = \frac{250}{(4.44)(50)(25)} \text{ Wb}$$

$$= 0.04505 \text{ Wb}$$

However, $\Phi_m = B_m \times A$, where B_m = maximum flux density in the core and A = cross-sectional area of the core.

Hence $B_m \times 300 \times 10^{-4} = 0.04505$

from which, maximum flux density,

$$B_m = \frac{0.04505}{300 \times 10^{-4}} = 1.50 \text{ T}$$

(b) $\frac{V_1}{V_2} = \frac{N_1}{N_2}$, from which, $V_2 = V_1\left(\frac{N_2}{N_1}\right)$

i.e. voltage induced in the secondary winding,

$$V_2 = (250)\left(\frac{300}{25}\right) = 3000 \text{ V or } 3 \text{ kV}$$

EMF EQUATION OF A TRANSFORMER - NUMERICAL

3. A single-phase 500V/100V, 50Hz, transformer has a maximum core flux density of 1.5T and an effective core cross-sectional area of 50 sq. cm. Determine the number of primary and secondary turns.

The e.m.f. equation for a transformer is $E = 4.44 f \Phi_m N$

and maximum flux, $\Phi_m = B \times A = (1.5)(50 \times 10^{-4})$

$$= 75 \times 10^{-4} \text{ Wb}$$

Since $E_1 = 4.44 f \Phi_m N_1$

then primary turns, $N_1 = \dfrac{E_1}{4.44 f \Phi_m}$

$$= \frac{500}{4.44(50)(75 \times 10^{-4})}$$

$$= \mathbf{300 \text{ turns}}$$

Since $E_2 = 4.44 f \Phi_m N_2$

then secondary turns, $N_2 = \dfrac{E_2}{4.44 f \Phi_m}$

$$= \frac{100}{4.44(50)(75 \times 10^{-4})}$$

$$= \mathbf{60 \text{ turns}}$$

EMF EQUATION OF A TRANSFORMER - NUMERICAL

4. A 4500V/225V, 50Hz single-phase transformer is to have an approximate e.m.f. per turn of 15V and operate with a maximum flux density of 1.4T. Calculate (a) the number of primary and secondary turns and (b) the cross-sectional area of the core.

(a) E.m.f. per turn $= \frac{E_1}{N_1} = \frac{E_2}{N_2} = 15$

Hence primary turns, $N_1 = \frac{E_1}{15} = \frac{4500}{15} = \mathbf{300}$

and secondary turns, $N_2 = \frac{E_2}{15} = \frac{225}{15} = \mathbf{15}$

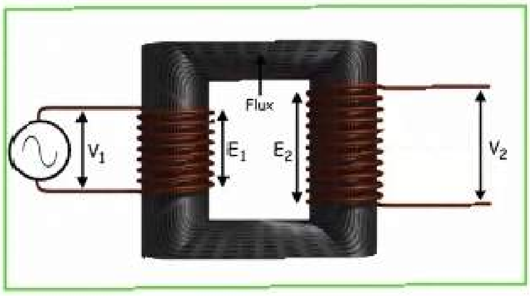
(b) E.m.f. $E_1 = 4.44 f \Phi_m N_1$

from which, $\Phi_m = \frac{E_1}{4.44 f N_1} = \frac{4500}{4.44(50)(300)}$
$= 0.0676$ Wb

Now flux $\Phi_m = B_m \times A$, where A is the cross-sectional area of the core, hence

area $A = \frac{\Phi_m}{B_m} = \frac{0.0676}{1.4} = \mathbf{0.0483\ m^2\ or\ 483\ cm^2}$

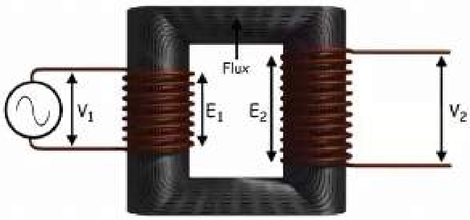
IDEAL TRANSFORMER



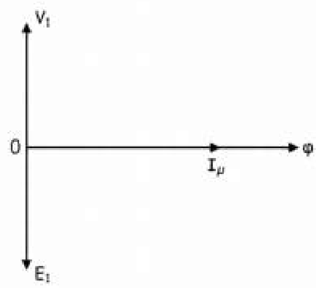
- An **ideal transformer** is a conceptual transformer which does not practically exist in reality. It has the following properties:

1. The power delivered by the transformer is equal to the power supplied to the transformer which means 100% efficiency.
2. There is no winding resistance & reactance, which eliminates the copper losses inside a transformer.
3. The core has infinite permeability which means there are no core losses i.e. there is no hysteresis loss or eddy current loss.
4. There is no leakage flux; the entire magnetic flux is linked through the core.

IDEAL TRANSFORMER

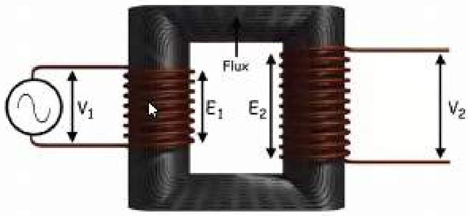


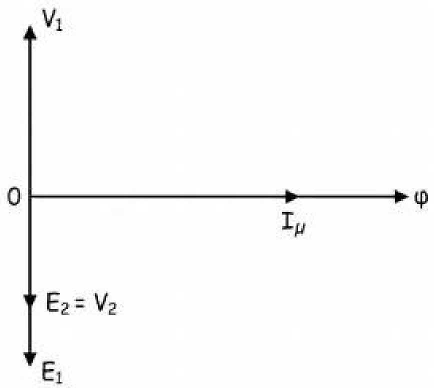
- For developing counter emf E_1 across the primary winding, it draws current from the source to produce required magnetizing flux.
- As the primary winding is purely inductive, that current lags 90° from the supply voltage. This current is called magnetizing current of transformer I_μ.



Abhishek Reddy Sheri's screen

IDEAL TRANSFORMER



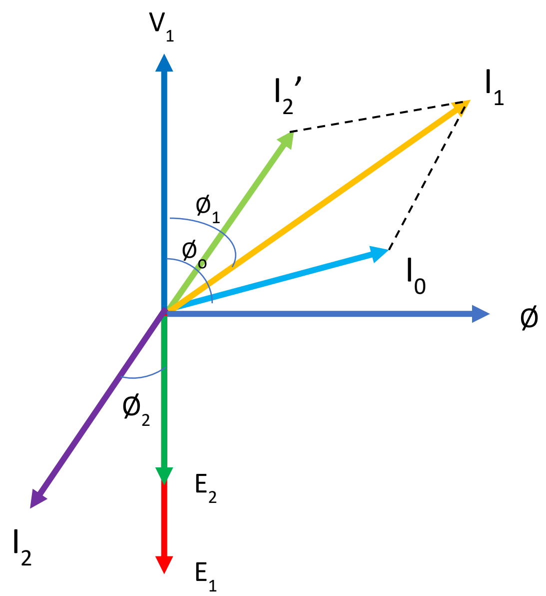


- This alternating magnetizing current I_μ produces an alternating magnetizing flux Φ.
- The flux is proportional to that current which producing it hence the flux would be in phase with the current.
- This flux also links the secondary winding through the core of the transformer.
- As a result, there would be another emf E_2 induced across the secondary winding, and this is mutually induced emf as shown in the figure.

k Reddy Sheri's screen

IDEAL TRANSFORMER ON LOAD

INDUCTIVE LOAD



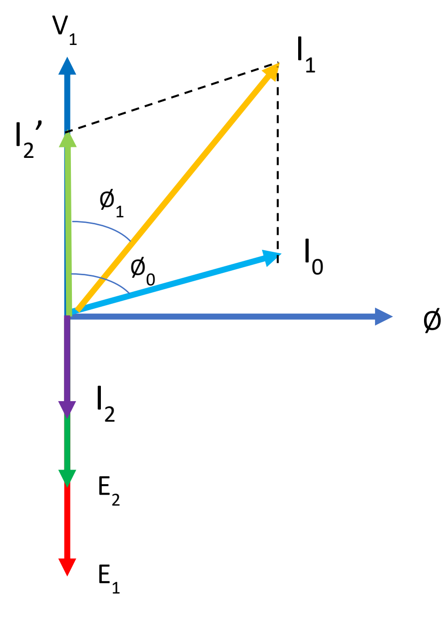
Phasor diagram of a transformer when load is inductive,

I_2= secondary current lags E_2 by φ_2.

I_2'= load component of primary current which is anti-phase with I_2 and equal to it in magnitude

I_1= Primary current which is vector sum of I_0 and I_2' and lags behind V_1 by angle φ_1.

RESISTIVE LOAD



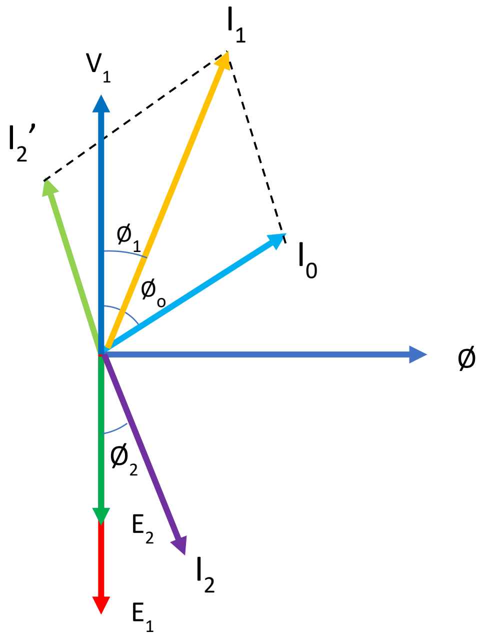
Phasor diagram of a transformer when load is resistive

I_2= secondary current in phase with E_2= V_2

I_2'= load component of primary current which is anti-phase with I_2 and equal to it in magnitude

I_1= Primary current which is vector sum of I_0 and I_2' and lags behind V_1 by angle φ_1.

CAPACITIVE LOAD



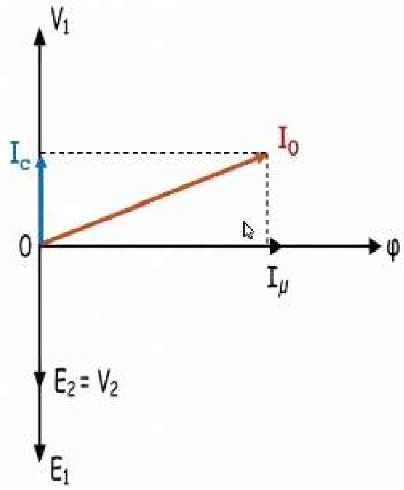
Phasor diagram of a transformer when load is capacitive,

I_2= secondary current leads E_2 by φ_2.

I_2'= load component of primary current which is anti-phase with I_2 and equal to it in magnitude

I_1= Primary current which is vector sum of I_0 and I_2' and lags behind V_1 by angle φ_1.

PRACTICAL TRANSFORMER ON LOAD

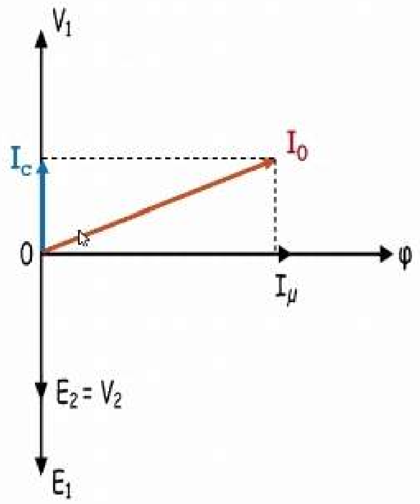


- In a practical transformer, there are hysteresis and eddy current losses in transformer core.
- Magnetizing current in a practical transformer is a little bit greater than actual magnetizing current.
- Total current supplied from the source has two components,

i. Magnetizing current component (I_μ) which is merely utilized for magnetizing the core, and

ii. Core loss component (I_c) of the source current is consumed for compensating the core losses in transformers.

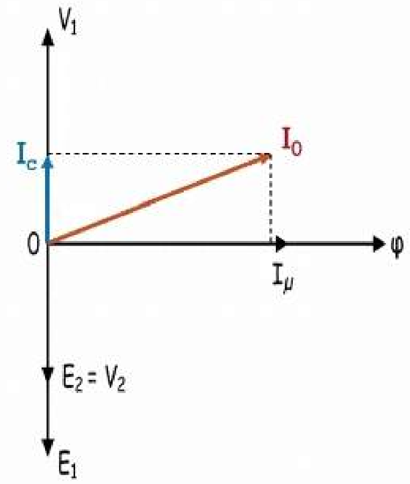
PRACTICAL TRANSFORMER ON LOAD



- Because of this core loss component, the source current in a transformer on no-load condition supplied from the source as source current is not exactly at 90° lags of the supply voltage, but it lags behind an angle θ is less than 90°.
- If total current supplied from source is I_o, it will have one component in phase with supply voltage V_1 and this component of the current I_c is core loss component.
- This component is taken in phase with the source voltage because it is associated with active or working losses in transformers.

Reddy Sheri's screen

PRACTICAL TRANSFORMER ON LOAD



- Another component of the source current is denoted as I_μ
- This component produces the alternating magnetic flux in the core, so it is watt-less; means it is a reactive part of the transformer source current.
- Hence I_μ will be in quadrature with V_1 and in phase with alternating flux Φ.
- Hence, total primary current in **a transformer on no-load** condition can be represented as:

$$\vec{I_o} = \vec{I_c} + \vec{I_\mu}$$

$$\text{where, } \vec{I_\mu} = I_o \cos \varnothing$$

$$\text{and } \quad \vec{I_c} = I_o \sin \varnothing$$

$$\boxed{I_0 = \sqrt{I_\mu^2 + I_c^2}}$$

k Reddy Sheri's screen

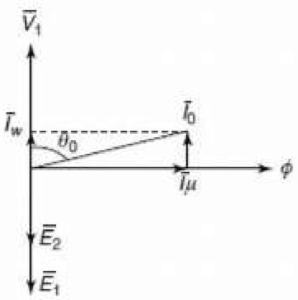
NUMERICAL ON IDEAL TRANSFORMER

1. The no-load current of a 4,400/440 V, sinlge-phase, 50 Hz transformer is0.04. It consumes power 80 W at no load when supply is given to LV side and HV side is kept open. Calculate the following:

i. Power factor of no-load current.

ii. Iron loss component of current.

iii. Magnetizing component of current.



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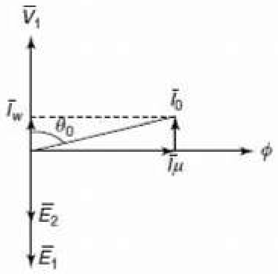

$I_0 = 0.04\ A$

$W_0 = 80\ W$

$V_0 = 4400\ V$

$W_0 = V_0 I_0 \cos\phi_0$

$\cos\phi_0 = \frac{W_0}{V_0 I_0}$

$= 0.45$

$\sin\phi_0 = 0.$

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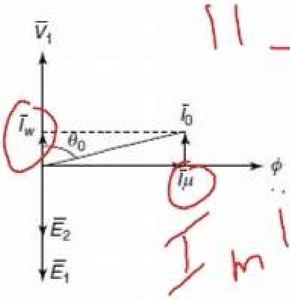

$I_0 = 0.04\ A$

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$V_0 = 4400\ V$

$W_0 = V_0 I_0 \cos\phi_0$

$\cos\phi_0 = \frac{W_0}{V_0 I_0}$

$= 0.45$

$\sin\phi_0 = 0$

ii $I_c = I_w = I_0 \sin\phi_0$

iii $I_m = I_\mu = I_0 \cos\phi_0$

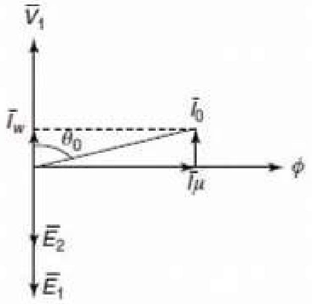
NUMERICAL ON IDEAL TRANSFORMER

1. The no-load current of a 4,400/440 V, sinlge-phase, 50 Hz transformer is0.04. It consumes power 80 W at no load when supply is given to LV side and HV side is kept open. Calculate the following:

i. Power factor of no-load current.

ii. Iron loss component of current.

iii. Magnetizing component of current.



$$W_0 = 80\text{ W}, I_0 = 0.04\text{ A}, V_1 = 4{,}400\text{ V}$$

$$W_0 = V_1 I_0 \cos\theta_0$$

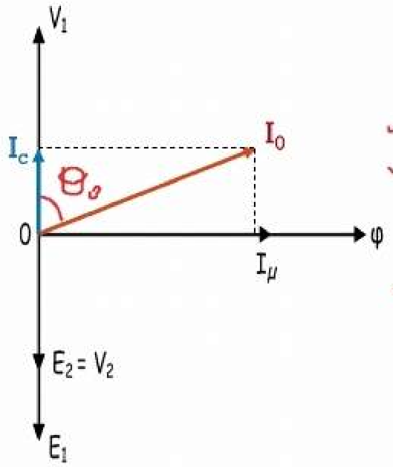
$$\cos\theta_0 = \frac{W_0}{V_1 I_0} = \frac{80}{4,400 \times 0.04} = 0.454 \qquad \sin\theta_0 = \sqrt{1-\cos^2\theta_0} = 0.891$$

The no-load power factor is 0.454 (lagging).

$$I_W = I_0 \cos\theta_0 = 0.04 \times 0.454 = 0.0187\text{ A}$$

$$\therefore I_\mu = I_0 \sin\theta_0 = 0.04 \times 0.891 = 0.0356$$

PRACTICAL TRANSFORMER ON LOAD



The following points are most important:

- The no-load primary current is 1–5 % of full-load current.
- Since I_0 is very small, the no-load copper loss is negligible. Hence, no-load input is practically equal to the iron loss in the transformer.
- Since core loss is solely responsible for shifting the current vector I_0, the angle θ_0 is known as *hysteresis angle of advance.*

NUMERICAL ON IDEAL TRANSFORMER

2. A transformer takes a current of 0.8A when its primary is connected to a 240 volt, 50Hz supply, the secondary being on open circuit. If the power absorbed is 72 watts, determine (a) the iron loss current, (b) the power factor on no-load and (c) the magnetizing current.

$I_0 = 0.8\,\text{A},\ V_1 = 240\,\text{V}$

(a) Power absorbed = total core loss = 72

$= V_1 I_0 \cos\phi_0$

Hence $72 = 240\, I_0 \cos\phi_0$

and iron loss current, $I_C = I_0 \cos\phi_0 = \dfrac{72}{240}$

$= \mathbf{0.30\,A}$

(b) Power factor at no load, $\cos\phi_0 = \dfrac{I_C}{I_0} = \dfrac{0.30}{0.80}$

$= \mathbf{0.375}$

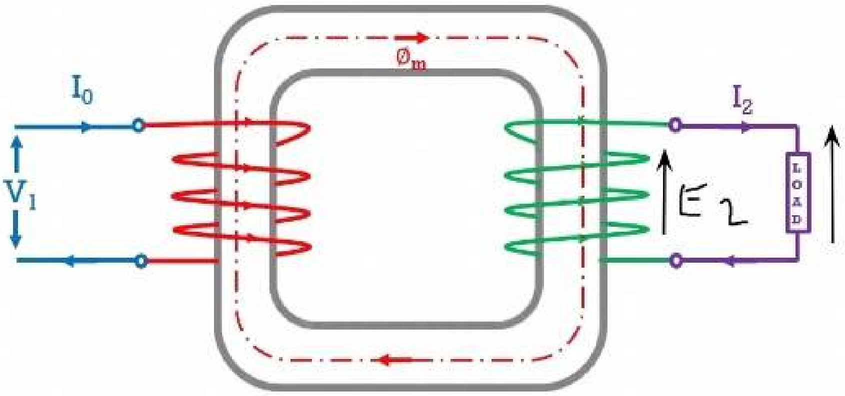
(c) $I_0^2 = I_C^2 + I_M^2$.

from which magnetizing current,

$I_M = \sqrt{(I_0^2 - I_C^2)} = \sqrt{(0.80^2 - 0.30^2)}$

$= \mathbf{0.74\,A}$

TRANSFORMER ON LOAD



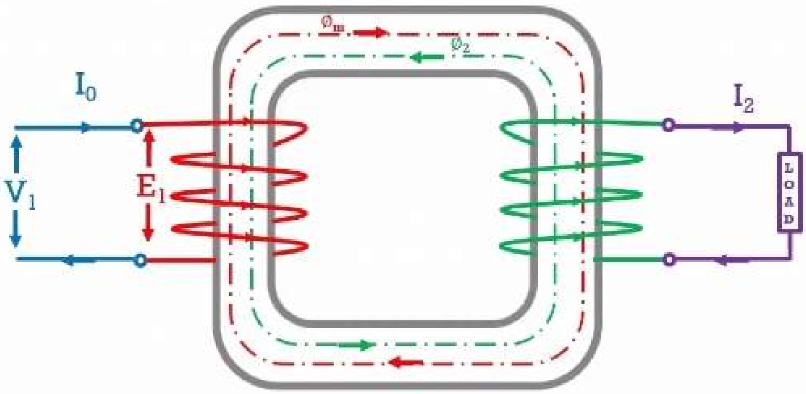
- When load is connected to the secondary winding of a transformer , I_2 (secondary current) is set up in the secondary winding.
- The magnitude and phase of I_2 with respect to V_2 (secondary voltage) depends upon the characteristics of the load.
- Secondary current I_2 *is*

i. in phase with V_2, if load is resistive,

ii. lags V_2 if load is inductive and

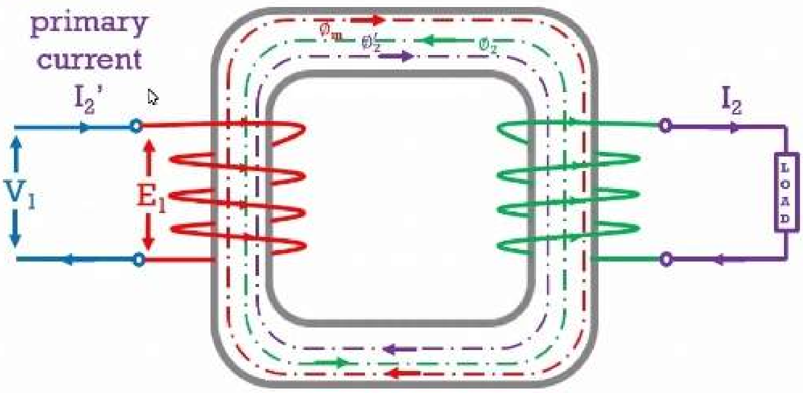
iii. it leads V_2 if load is capacitive

TRANSFORMER ON LOAD



- This secondary current sets up m.m.f ($=N_2I_2$) and hence it produces magnetic flux Φ_2 which is in opposition to the main primary flux Φ in accordance with Lenz's law.
- The secondary ampere-turns N_2I_2 are known as demagnetizing amp-turns.
- The opposing secondary flux Φ_2 weakens the primary flux Φ momentarily, hence the primary winding back e.m.f E_1 tends to be reduced.

TRANSFORMER ON LOAD



- For a moment $V_1 > E_1$ and hence more current to flow in the primary winding .
- Let the additional primary current be I_2' which is known as load component of primary current.
- This current (I_2') is anti-phase with I_2.
- This load component of primary current(I_2') sets up its own flux Φ_2' which is in opposition to secondary flux Φ_2, but is in the same direction as primary flux Φ.
- The flux Φ_2' is equal to Φ_2. Hence, the two flux cancel each other out.
- So, we can say that whatever the load conditions, the net flux passing through the core is approximately the same as at no-load.

Note: If a voltage or turns ratio is specified, it is always put in the order as, input : output which is primary : secondary. It is to be noted from eq. 12 that almost any desired voltage ratio can be obtained by adjusting the number of turns.

4.8 Step-Up And Step-Down Transformer

A transformer in which the output (secondary) voltage is greater than its input (primary) voltage is called a step-up transformer.

A transformer in which the output (secondary) voltage is lesser than its input (primary) voltage is called a step-down transformer.

A transformer may receive energy at one voltage and deliver it at the same voltage. Such a transformer is called a one-to-one (1:1) transformer. For a 1:1 T/F, $N_1 = N_2$ and $E_1 = E_2$. Such a transformer is used to isolate two circuits.

4.9 Ideal Transformer

An ideal transformer is just a conceptual device and does not practically exist in reality. It has the following properties:

(i) The primary and secondary resistances are negligible.

(ii) The core has infinite permiability (μ) so that negligible mmf is required to establish the flux in the core.

(iii) The leakage flux and leakage inductances are zero. The entire flux is confined to the core and windings linking them

(iv) There are no losses due to resistances, hysterisis and eddy currents. Thus the efficiency is 100%.

4.9.1 Ideal Transformer on No-load

Consider an ideal transformer on no-load as shown in fig. 4.7.

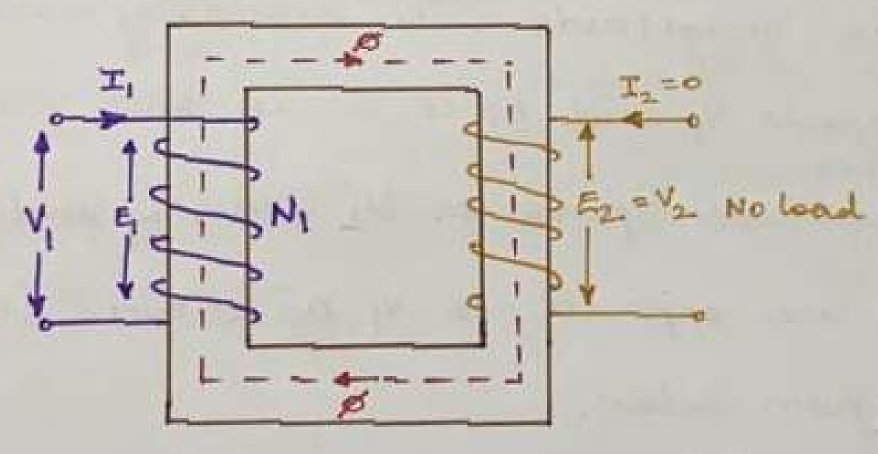


Fig. 4.7 Ideal Transformer on No-load

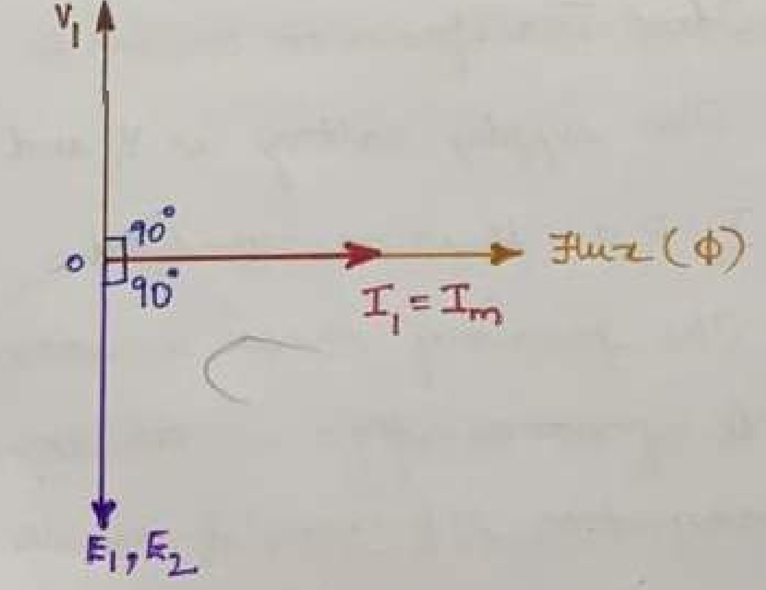
The supply voltage is V_1 and the secondary current is $I_2 = 0$ as it is on no-load.

The primary draws a current I_1 which is just necessary to produce flux in the core. As this current is used to magnetise the core, it is called magnetising current denoted by I_m.

As the transformer is ideal, the winding resistance is zero and is purely inductive in nature. The magnetising current I_m is very small and lags V_1 by 90°, as the winding is purely inductive. This I_m produces an alternating flux ϕ which is in phase with I_m.

The flux links with both the winding, producing induced emfs, E_1 and E_2, in the primary and secondary winding respectively.

According to Lenz's law, the induced emf opposes the very cause producing it which is the supply voltage V_1. Hence E_1 is in anti-phase with V_1 but it is equal in magnitude. The secondary induced emf E_2 also opposes V_1 and hence is in anti-phase with V_1 and its magnitude depends on N_2. Thus, E_1 and E_2 are in phase and are opposite to V_1 as shown in the phasor diagram below.



Phasor diagram of ideal T/F on No-load.

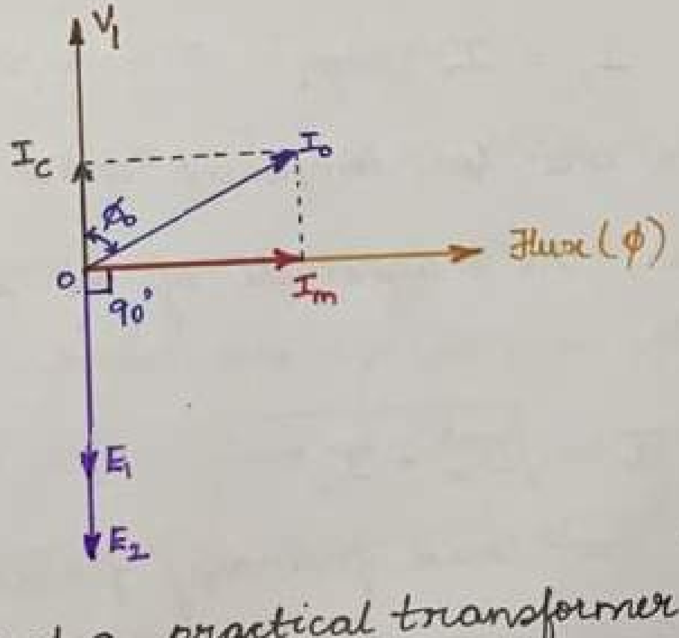
4.10 PRACTICAL TRANSFORMER ON NO-LOAD

Actually in practical transformer, iron core causes eddy-currents and hysterisis losses as it is subjected to alternating flux.

Apart from these losses in a practical transformer the primary winding has some resistance and hence, small primary copper loss is present.

Thus, the primary current under no-load has to supply the iron losses i.e., hysterisis and eddy current losses and also a small amount of copper loss. This current is denoted as I_0

In practical transformer, due to winding resistance, no-load current I_0 is no longer at 90° w.r.t V_1, but it lags V_1 by an angle ϕ_0 which is less than 90° as shown in the figure below.



Phasor diagram of a practical transformer on No-load.

From the phasor diagram it is clear that the no-load input current I_0 has two components:

(i) A purely reactive component I_m called the magnetising component of no-load current required to produce the flux. This is also called wattless component.

(ii) An active component I_c which supplies total losses under no-load condition called the power component of no-load current. This is also called core-loss component.

Therefore, the total current on no-load, I_0 is the vector sum of the above mentioned currents I_m, I_c

$$\therefore I_0 = I_m + I_c$$

From the phasor diagram,

$$I_m = I_0 \sin\phi_0$$

This is the magnetising component lagging V_1 by exactly 90°.

and,

$$I_c = I_0 \cos\phi_0$$

This is the core-loss component which is in phase with V_1.

Thus, the magnitude of no-load current is given by,

$$I_0 = \sqrt{I_m^2 + I_c^2}$$

while, $\phi_0 \rightarrow$ no-load primary power factor angle.

It may be noted that, the no-load current I_0 is very small, about 3% to 5% of the full-load current or rated current. Hence, primary copper loss is negligible and hence is called core loss or iron loss component.

Hence, power input W_0 on no-load always represents the iron losses, as Cu loss are negligibly small. The iron losses are denoted as P_i and are constant for all the load conditions.

$$W_0 = V_1 I_0 \cos\phi_0 = P_i = \text{iron losses}$$

4.11 TRANSFORMER ON LOAD

When the transformer is loaded, the current I_2 flows through the secondary winding. The magnitude and phase of I_2 is determined by the load.

- If the load is inductive, I_2 lags V_2
- If the load is capacitive, I_2 leads V_2
- If the load is resistive, I_2 is in phase with V_2.

There exists a secondary m.m.f $N_2 I_2$ due to which secondary current sets-up its own flux ϕ_2. This flux opposes the main flux ϕ which is produced in the core due to magnetising component of no-load current. Hence, mmf $N_2 I_2$ is called demagnetising ampere turns as shown in fig. 4.8.

The flux ϕ_2 momentarily reduces the main flux ϕ due to which the primary induced emf E_1 also reduces. Hence, the vector difference $(V_1 - E_1)$ increases due to which primary draws more current from the supply. This additional current drawn is due to the load and hence is called load component of primary current denoted as, I_2'

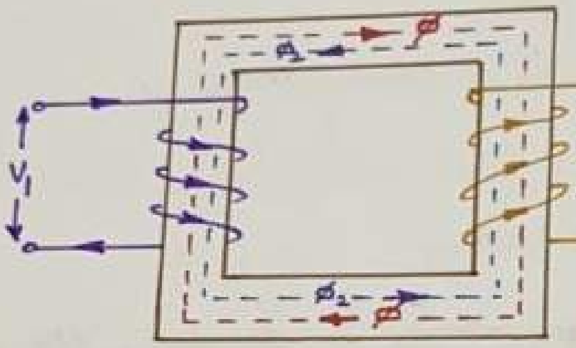


Fig. 4.8 ϕ_2 flux opposing ϕ

The current I_2' is in anti-phase with I_2 The current I_2' sets up its own flux which opposes the flux ϕ_2 The ϕ_2' flux neutralises the flux ϕ_2 produced by I_2 and helps the main flux ϕ.

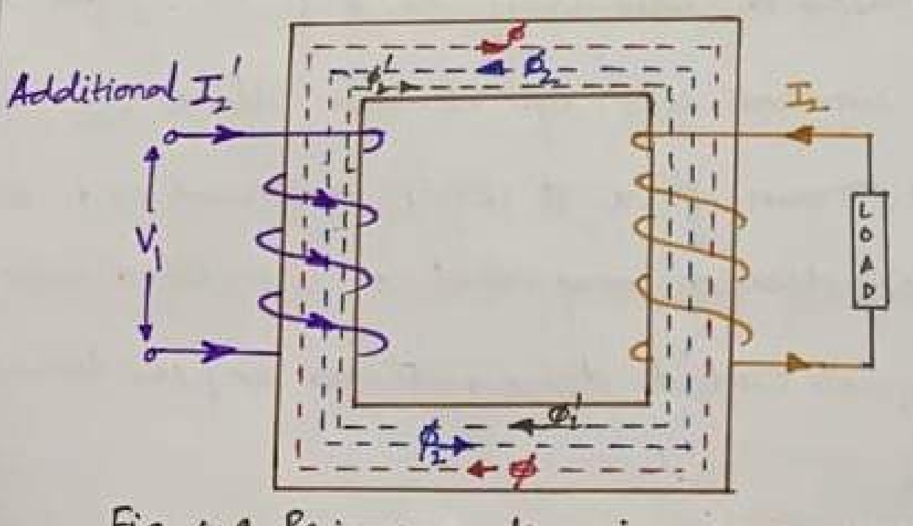


Fig. 4.9 Primary drawing more current I_2'

TRANSFORMER ON LOAD

- As the Ampere-turns are balanced,

$$\boxed{N_2 I_2 = N_1 I_2'}$$

$$I_2' = \frac{N_2}{N_1} I_2$$

$$I_2' = k . I_2 \text{, where } k = \frac{N_2}{N_1} = \text{turns ratio}$$

- Hence, when transformer is no load, the primary winding has two currents in it; one is I_0 and the other is I_2'
- The total primary current I_1 is the vector sum of I_0 and I_2'

$$\vec{I_1} = \vec{I_0} + \vec{I_2}'$$

where, $\vec{I_0}$ is the no-load current which lags V_1 by an angle Ø which has two components I_μ and I_c

and $\vec{I_2}'$ is the load component of primary current which is anti-phase with I_2. The phase of I_2 is decided by the nature of load

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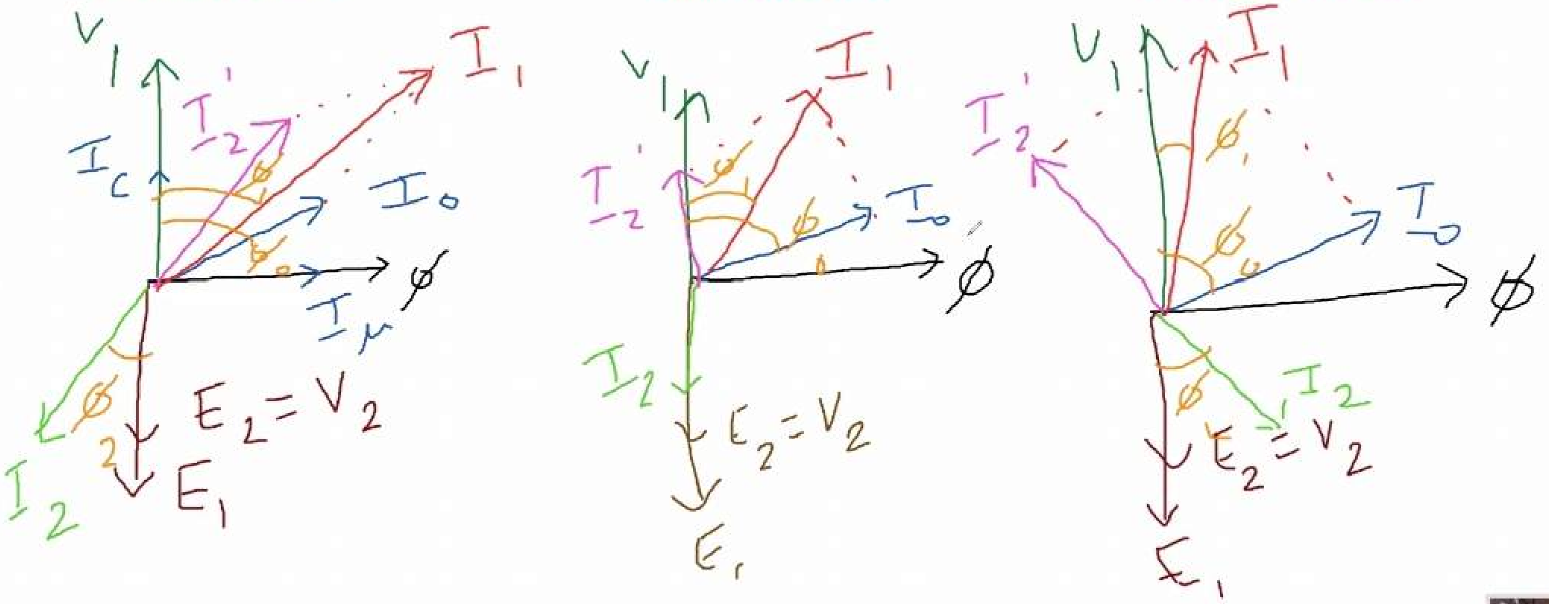
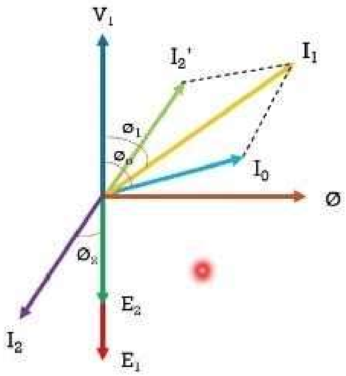
TRANSFORMER ON LOAD – PHASOR DIAGRAMS

INDUCTIVE LOAD RESISTIVE LOAD CAPACITIVE LOAD



TRANSFORMER ON LOAD – PHASOR DIAGRAMS

INDUCTIVE LOAD



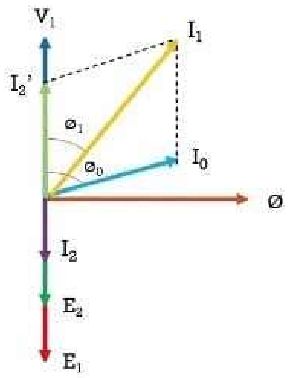
Phasor diagram of a transformer when load is inductive,

I_2= secondary current lags E_2 by φ_2.

I_2'= load component of primary current which is anti-phase with I_2 and also equal to it in magnitude(as K=1)

I_1= Primary current which is vector sum of I_0 and I_2' and lags behind V_1 by angle φ_1.

RESISTIVE LOAD



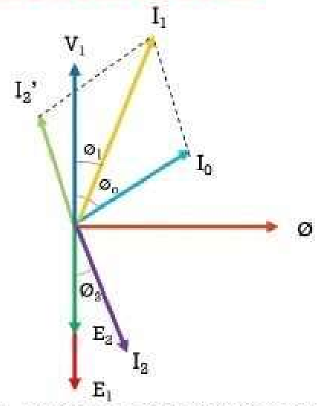
Phasor diagram of a transformer when load is resistive

I_2= secondary current in phase with E_2= V_2

I_2'= load component of primary current which is anti-phase with I_2 and also equal to it in magnitude

I_1= Primary current which is vector sum of I_0 and I_2' and lags behind V_1 by angle φ_1.

CAPACITIVE LOAD



Phasor diagram of a transformer when load is capacitive,

I_2= secondary current leads E_2 by φ_2.

I_2'= load component of primary current which is anti-phase with I_2 and also equal to it in magnitude(as K=1)

I_1= Primary current which is vector sum of I_0 and I_2' and lags behind V_1 by angle φ_1.

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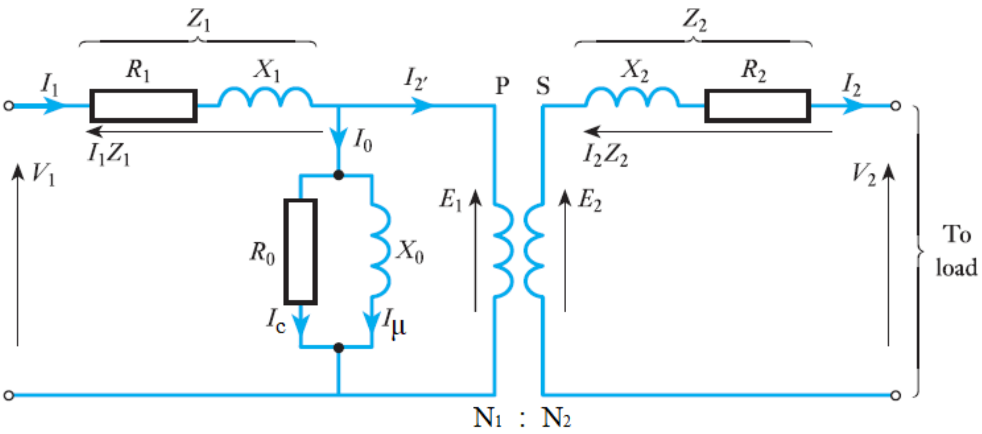
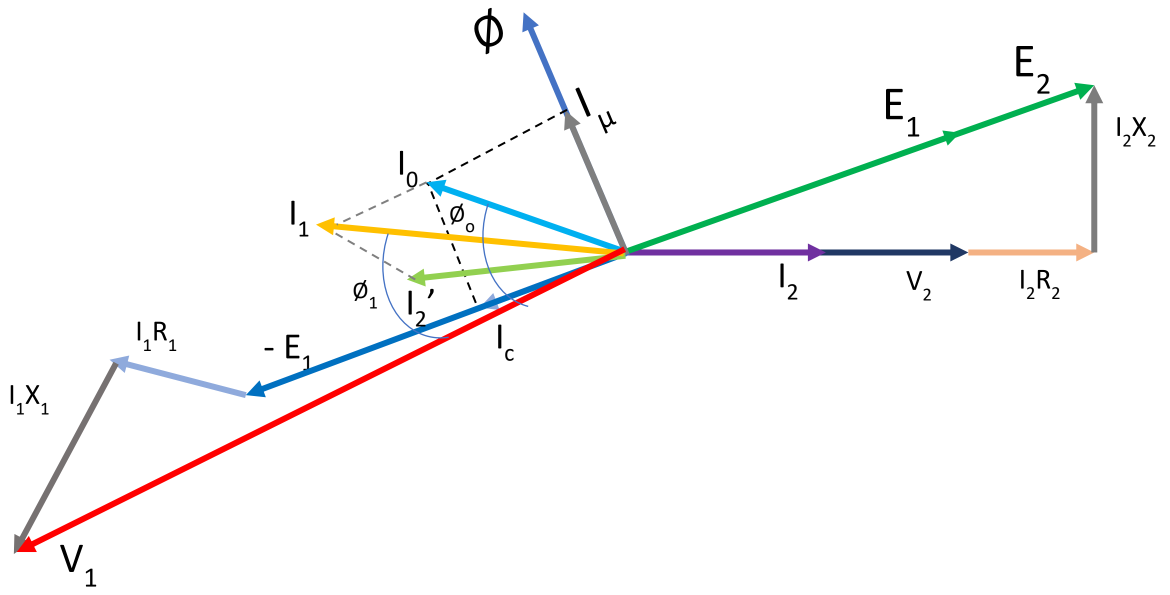
TRANSFORMER ON LOAD

Actual Transformer Equivalent circuit



- V_1 is the applied voltage to the transformer
- V_2 is the load voltage of the load connected to the transformer
- E_1 is the induced primary voltage in the transformer
- E_2 is the induced secondary voltage in the transformer
- R_1 and R_2 are resistances of the primary and secondary windings of the actual transformer
- X_1 and X_2 represent the reactance of the windings due to leakage flux in the actual transformer
- Z_1 and Z_2 are impedances of the primary and secondary windings of the actual transformer
- X_0 is inductive reactance such that it takes a reactive current equal to the magnetizing current I_μ of the actual transformer
- R_0 resistor for core losses due to hysteresis and eddy currents
- I_μ is magnetizing component of no-load current
- I_c is core loss component of no-load current
- I_0 is no-load current
- I_1 is primary current
- I_2' is load component of primary current
- I_2 is secondary current
- N_1 and N_2 are the primary and secondary turns
- I_1Z_1 is the series drop in the primary winding
- I_2Z_2 is the series drop in the secondary winding

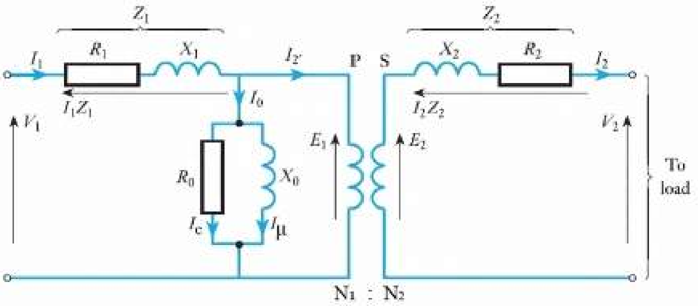
Phasor Diagram

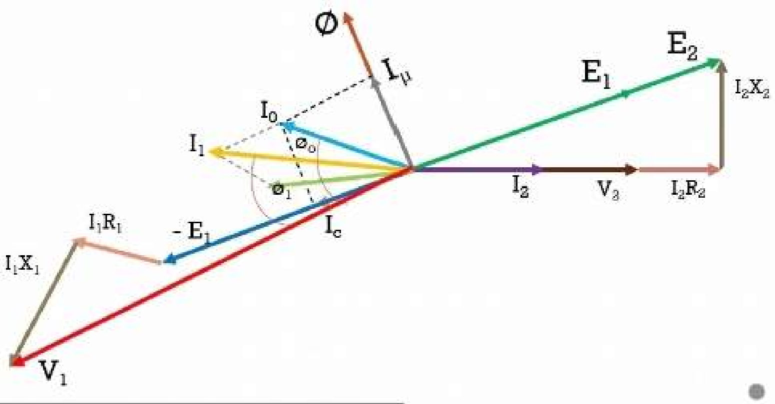


Construction Steps

1. Let's begin from load voltage V_2 and move towards the applied voltage V_1
2. I_2 will be in phase with V_2 because in a resistive load current is in phase with the voltage
3. The resistive drop I_2R_2 will be parallel to I_2 which means it is in phase with V_2 the reactive drop I_2X_2 will be in quadrature, i.e., in 90˚ with the resistive drop I_2R_2
4. Applying KVL in the secondary loop, we get the phasor $E_2 = V_2+I_2R_2+I_2X_2$ as shown
5. From the EMF equation, we know that flux Ø is responsible induced emfs E_1 and E_2 and flux Ø lead the emf by 90˚ so we draw the Ø phasor perpendicular to E_2
6. Same flux Ø is responsible for E_1, and if the no. of turns in the primary is less than secondary, the magnitude of E_1 would be less than E_2 shown by a phasor smaller in length compared to E_2
7. Flux Ø is produced due to the magnetising current I_μ so the current I_μ will be drawn in phase with flux Ø
8. The emf induced in the primary is in accordance with the Lenz's law which is - E_1 which is drawn equal and opposite to E_1, - E_1 is the voltage across resistance R_0 and the current flowing through R_0 is I_c so obviously I_c will be in phase with - E_1
9. From the figure, the no-load current I_0 is the phasor sum of I_μ and I_c which gives the I_0 phasor
10. Also, from the figure, the primary current I_1 is the phasor sum of I_0 and I_2' and the I_2' is in anti-phase with I_2. Hence, I_1 can be drawn as shown
11. Current I_1 flows through R_1 and X_1 which gives rise to two voltage drops, the resistive drop I_1R_1 and the reactance drop I_1X_1 where $I_1R_1$is in phase with I_1 and drop I_1X_1 is in quadrature with I_1R_1 drop. Since, both are voltage drops they should be added to the voltage phasor - E_1
12. Applying KVL in the primary loop, we get phasor $V_1 = - E_1 +I_1R_1+I_1X_1$ as shown
13. $Ø_o$ is the no load phase angle due no load current I_0 with respect to V_1
14. $Ø_1$ is the primary circuit phase angle due to primary current I_1 with respect to V_1.

ACTUAL TRANSFORMER ON RESISTIVE LOAD



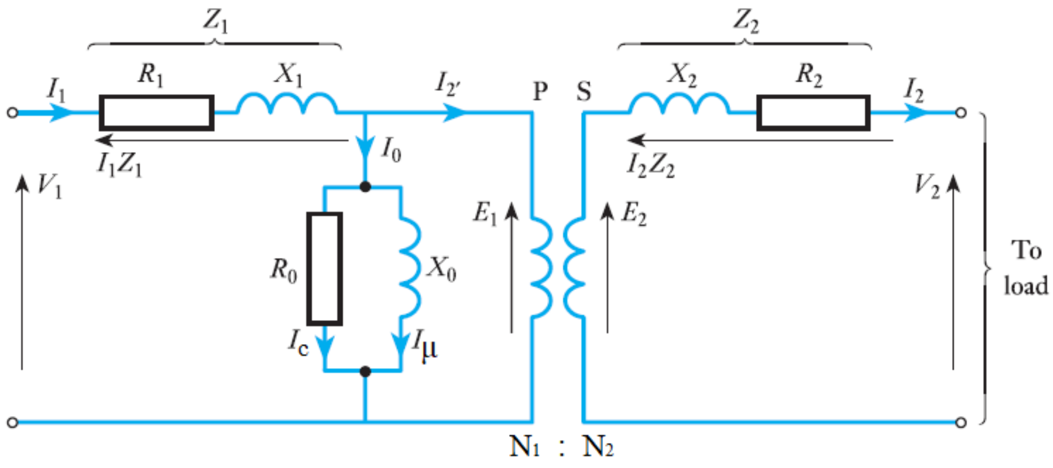


Construction Steps

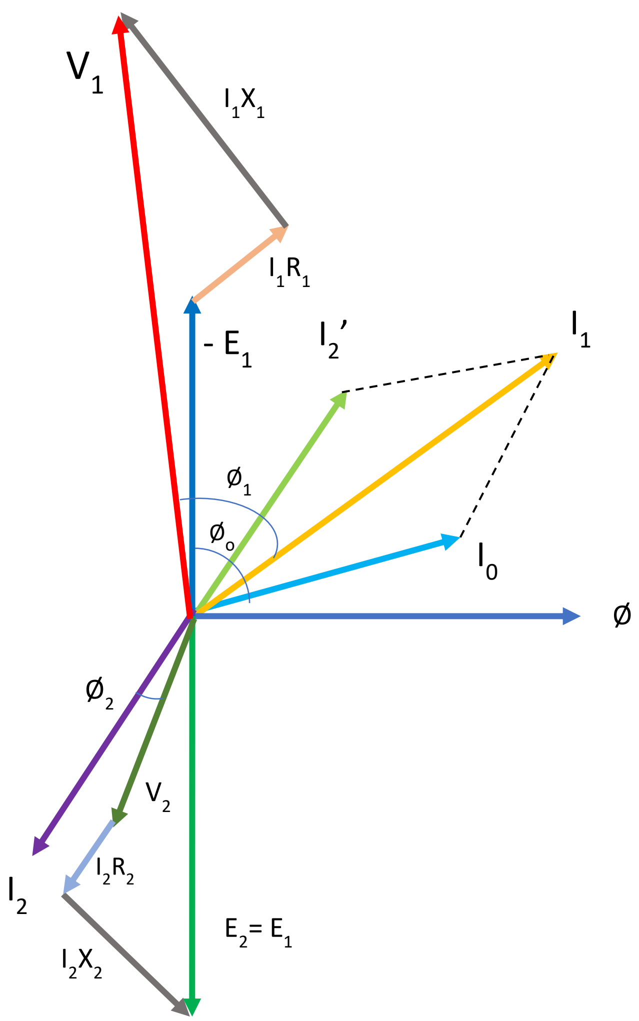
- Let's begin from load voltage V_2 and move towards the applied voltage V_1
- I_2 will be in phase with V_2 because in a resistive load current is in phase with the voltage
- The resistive drop I_2R_2 will be parallel to I_2 which means it is in phase with V_2 the reactive drop I_2X_2 will be in quadrature, i.e., in 90° with the resistive drop I_2R_2
- Applying KVL in the secondary loop, we get the phasor $E_2 = V_2+I_2R_2+I_2X_2$ as shown
- From the EMF equation, we know that flux Ø is responsible induced emfs E_1 and E_2 and flux Ø lead the emf by 90° so we draw the Ø phasor perpendicular to E_2

ACTUAL TRANSFORMER ON INDUCTIVE LOAD

Equivalent Circuit



Phasor Daigram



Construction Steps

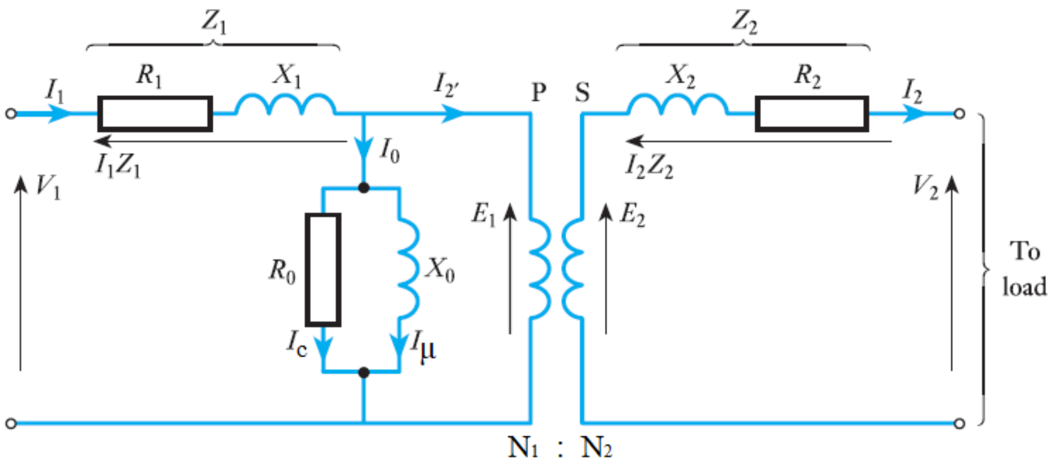
1. Take flux ϕ, a reference
2. Induces emf E_1 and E_2 lags the flux by 90 degrees.
3. The component of the applied voltage to the primary equal and opposite to induced emf in the primary winding, $-E_1$ (according to Lenz's Law)
4. Current I_0 lags the voltage c.
5. The power factor of the load is lagging. Therefore, current I_2 is drawn lagging V_2 by an angle ϕ_2.
6. The resistance and the leakage reactance of the windings result in a voltage drop, and hence secondary terminal voltage V_2 is the phase difference of E_2 and voltage drop.
7. $V_2 + I_2 R_2 + I_2X_2 = E_2$

   where, $I_2 R_2$ is in phase with I_2 and I_2X_2 is in quadrature with I_2.
8. The total current flowing in the primary winding is the phasor sum of I_1' and I_0.
9. Primary applied voltage V_1 is the phasor sum of $- E_1$ and the voltage drop in the primary winding.
10. Current I_1' is drawn equal and opposite to the current I_2
11. $V_1 = - E_1 + I_1 R_1 + I_1X_1$

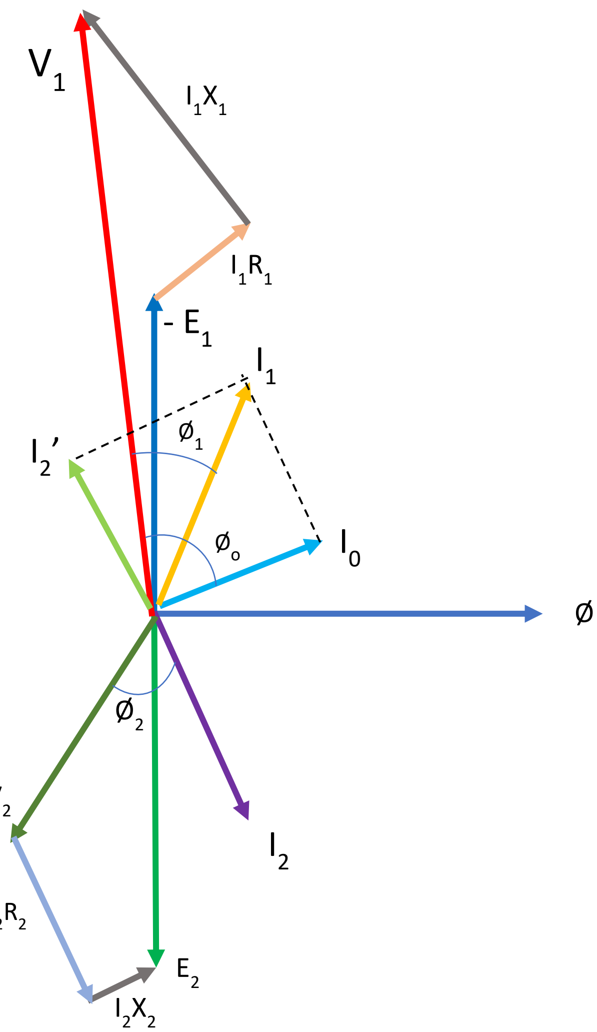
    where, I_1R_1 is in phase with I_1 and I_1X_I is in quadrature with I_1.
12. The phasor difference between V_1 and I_1 gives the power factor angle ϕ_1 of the primary side of the transformer.
13. The phasor difference between V_2 and I_2 gives the power factor angle ϕ_2 of the primary side of the transformer.
14. The phasor difference between V_1 and I_0 gives the no load power factor angle ϕ_0 of the primary side of the transformer.

ACTUAL TRANSFORMER ON CAPACITIVE LOAD

Equivalent Circuit



Phasor diagram



Construction Steps

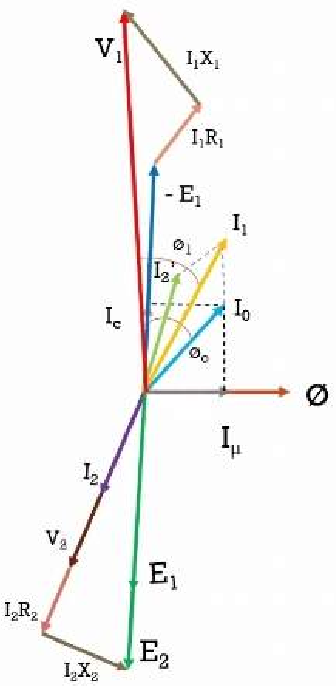
1. Take flux ϕ, a reference
2. Induces emf E_1 and E_2 lags the flux by 90 degrees.
3. The component of the applied voltage to the primary equal and opposite to induced emf in the primary winding, $-E_1$ (according to Lenz's Law)
4. Current I_0 lags the voltage $- E_1$.
5. The power factor of the load is leading. Therefore, current I_2 is drawn lagging V_2 by an angle ϕ_2.
6. The resistance and the leakage reactance of the windings result in a voltage drop, and hence secondary terminal voltage V_2 is the phase difference of E_2 and voltage drop.
7. $V_2 – (I_2 R_2 + I_2X_2) = E_2$

   where, $I_2 R_2$ is in phase with I_2 and I_2X_2 is in quadrature with I_2.
8. The total current flowing in the primary winding is the phasor sum of I_1' and I_0.
9. Primary applied voltage V_1 is the phasor sum of $- E_1$ and the voltage drop in the primary winding.
10. Current I_1' is drawn equal and opposite to the current I_2
11. $V_1 = - E_1 + I_1 R_1 + I_1X_1$

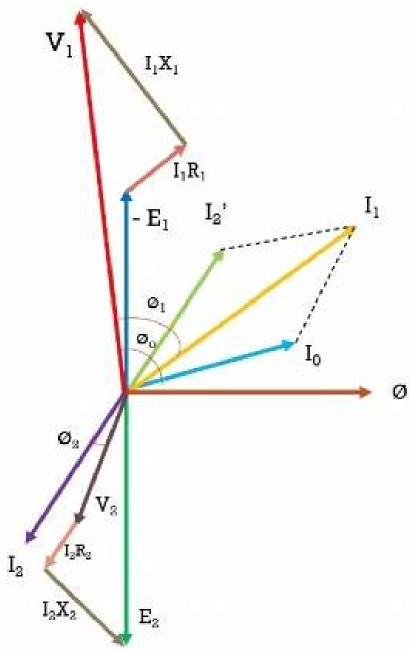
    where, I_1R_1 is in phase with I_1 and I_1X_I is in quadrature with I_1.
12. The phasor difference between V_1 and I_1 gives the power factor angle ϕ_1 of the primary side of the transformer.
13. The phasor difference between V_2 and I_2 gives the power factor angle ϕ_2 of the primary side of the transformer.
14. The phasor difference between V_1 and I_0 gives the no load power factor angle ϕ_0 of the primary side of the transformer.

ACTUAL TRANSFORMER ON VARIOUS LOADS

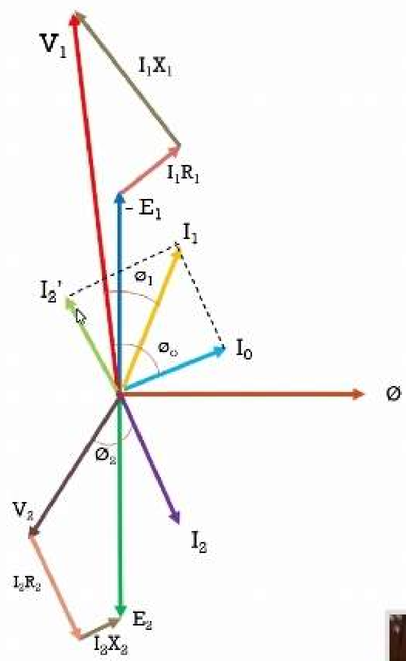
RESISTIVE LOAD



INDUCTIVE LOAD

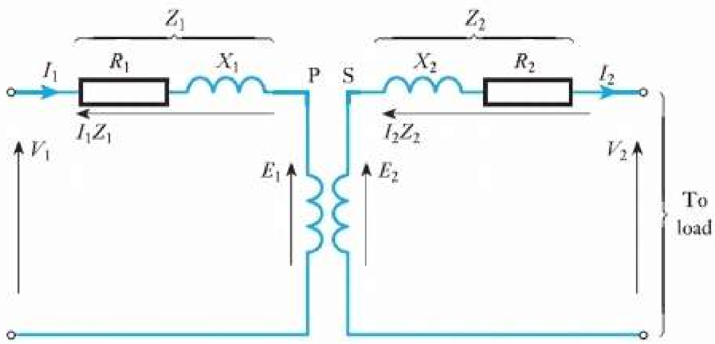


CAPACITIVE LOAD



APPROXIMATE EQUIVALENT CIRCUIT OF A TRANSFORMER

- Since the no-load current of a transformer is only about 1– 3 %of the full-load primary current, we can omit the parallel circuits R_0 and X_0 from the equivalent circuit without introducing an appreciable error when we are considering the behaviour of the transformer on full load.
- Thus we have the simpler equivalent circuit



REFERRING OF PARAMETERS

- It is theoretically possible to 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,

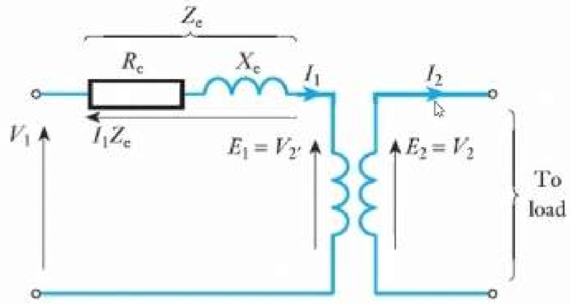
$$\boxed{R_e = R_1 + R_2' = R_1 + R_2\left(\frac{V_1}{V_2}\right)^2}$$

REFERRING OF PARAMETERS

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

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

- The simplified equivalent circuit of the transformer after referring the secondary parameters to primary can be drawn as,



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REFERRING OF PARAMETERS

- Similarly, since the inductance of a coil is proportional to the square of the number of turns, the primary leakage reactance X_1 can be replaced by an equivalent reactance X_2' in the secondary circuit, such that

$$X_1' = X_1\left(\frac{N_2}{N_1}\right)^2 \simeq X_1\left(\frac{V_2}{V_1}\right)^2$$

- If X_e is the single reactance in the secondary circuit equivalent to X_1 and X_2 of the actual transformer

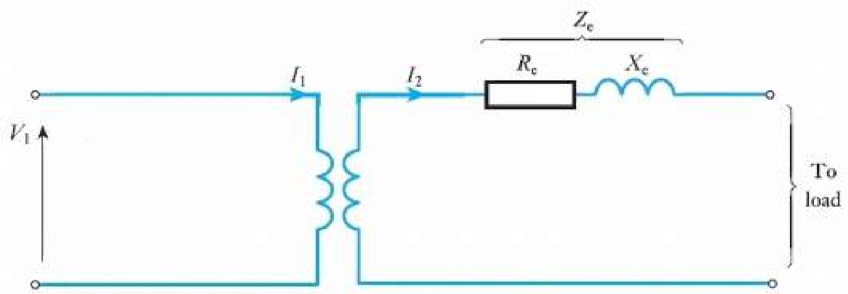
$$\boxed{X_e = X_2 + X_1' = X_2 + X_1\left(\frac{V_2}{V_1}\right)^2}$$

REFERRING OF PARAMETERS

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

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

- The simplified equivalent circuit of the transformer after referring the secondary parameters to primary can be drawn as,



LOSSES IN THE TRANSFORMER

Copper Losses (Variable Losses)

- **Copper losses** are variable and result in a heating of the conductors, since they possess resistance.
- If R_1 and R_2 are the primary and secondary winding resistances, then the total copper loss is $I_1^2R_1 + I_2^2R_2$

where,

$I_1^2R_1$ correspond to the primary copper losses and

$I_2^2R_2$ correspond to the secondary copper losses and

Iron Losses (Constant Losses)

- **Hysteresis loss** is the heating of the core as a result of the internal molecular structure reversals which occur as the magnetic flux alternates. The loss is proportional to the area of the hysteresis loop and thus low loss nickel iron alloys are used for the core since their hysteresis loops have small areas.
- **Eddy current loss** is the heating of the core due to e.m.f.s being induced not only in the transformer windings but also in the core. These induced e.m.f.s set up circulating currents, called eddy currents.

EFFICIENCY OF TRANSFORMER

$$\textbf{Efficiency}, \eta = \frac{\textbf{\textit{Output Power}}}{\textbf{Input Power}}$$

$$\textbf{Efficiency}, \eta = \frac{\textbf{\textit{Output Power}}}{\textbf{Output Power + losses}}$$

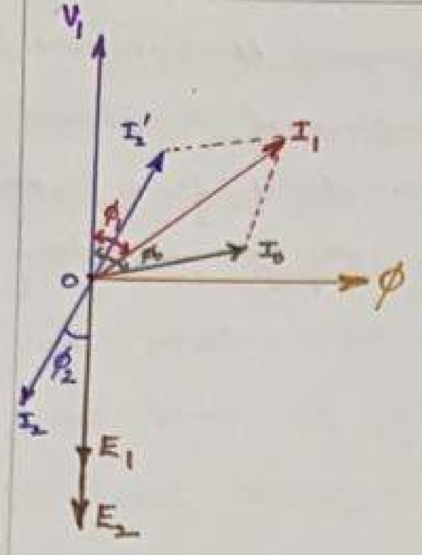
$$\textbf{Efficiency}, \eta = \frac{\textbf{\textit{Input Power} − \textit{losses}}}{\textbf{Input Power}}$$

- Efficiency is usually **expressed as a percentage.** It is not uncommon for power transformers to have efficiencies of between 95% and 98%.

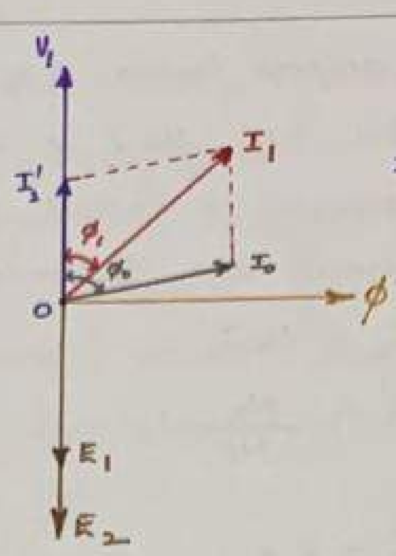
Output power=$V_2\, I_2 \cos\varphi_2$, where $\cos\varphi_2$ is the load power factor

total losses = copper loss + iron losses

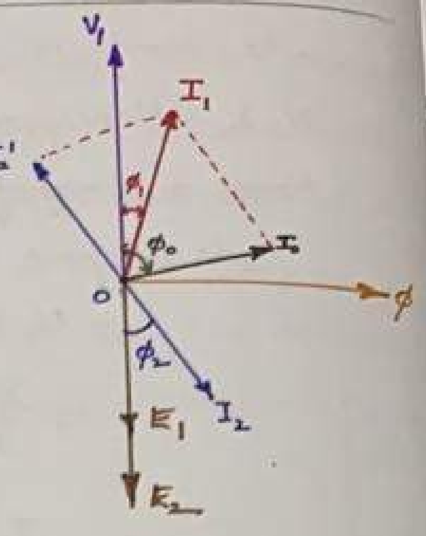
and input power = output power + losses



(a) Inductive load



(b) Resistive load

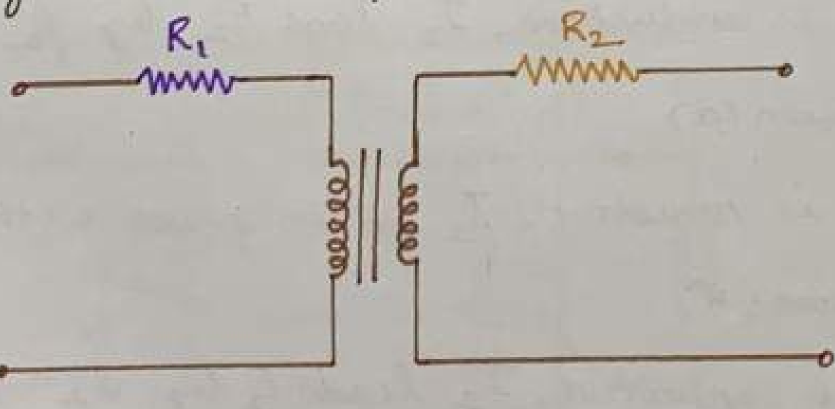


(c) Capacitive load.

4.12 REFERRED VALUES

In order to simplify calculations, it is theoritically possible to transfer voltage, current and impedance of one winding to the other and combine them into single values for each quantity. Thus, we have to work in one winding only which is more convenient.

Let us transfer the resistance of secondary winding R_2 to the primary side.



Suppose that R_2' is the resistance of the secondary winding referred or reflected to the primary winding. This reflected resistance R_2' should produce the same effect in primary as R_2 produces in the secondary.

Therefore, power consumed in R_2' when carrying the prima current is equal to the power consumed by R_2 due t the secondary current.

That is,

$$I_2'^2 R_2' = I_2^2 R_2$$

$$R_2' = \left[\frac{I_2}{I_2'}\right]^2 R_2$$

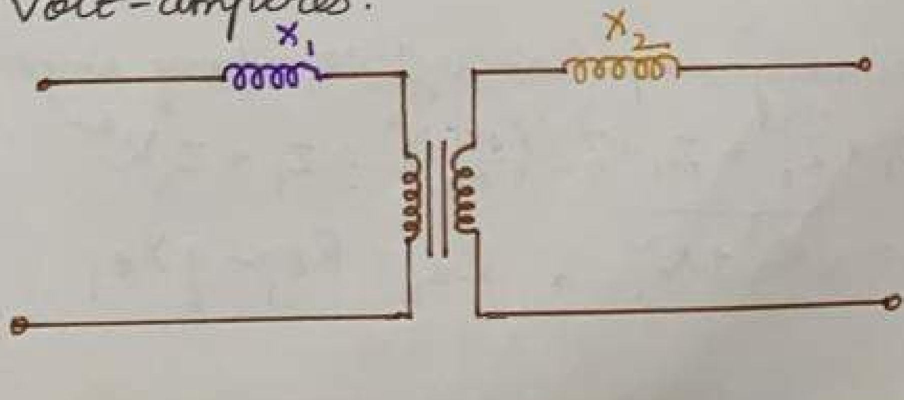
But,

$$I_2 N_2 = I_2' N_1$$

$$\frac{I_2}{I_2'} = \frac{N_1}{N_2} = K$$

and $$R_2' = \left(\frac{N_1}{N_2}\right)^2 R_2 = K^2 R_2$$

Let X_2' be the reactance of the secondary winding referred to the primary side. For X_2' to produce the same effect in the primary side a in the secondary side, each must absorb the sa reactive Volt-amperes.



$$VA_R = VI \sin\phi$$
$$= IZ \cdot I \cdot \frac{X}{Z}$$
$$= I^2 X$$

Equating the reactive voltaamperes consumed by X_2' and X_2 gives,

$$(I_2')^2 X_2' = I_2^2 X_2$$

$$X_2' = \left[\frac{I_2}{I_2'}\right]^2 X_2$$

$$X_2' = \left[\frac{N_1}{N_2}\right]^2 X_2$$

$$\therefore X_2' = K^2 X_2$$

Let Re_1, Xe_1 and Ze_1 represent the effective resistance, effective reactance and effective impedance respectively of the whole transformer referred to primary, then

Re_1 = primary resistance + secondary resistance referred to primary.

$$\therefore Re_1 = R_1 + R_2' = R_1 + R_2\left(\frac{N_1}{N_2}\right)^2 = R_1 + K^2 R_2$$

Similarly,

Xe_1 = Primary reactance + secondary reactance referred to primary

$$Xe_1 = X_1 + X_2' = X_1 + X_2\left(\frac{N_1}{N_2}\right)^2 = X_1 + K^2 X_2$$

Hence,

Ze_1 = Primary impedance + secondary impedance referred to primary.

$$Ze_1 = Z_1 + Z_2' = Z_1 + Z_2\left(\frac{N_1}{N_2}\right)^2 = Z_1 + Z_2 K^2$$

Also, $Ze_1 = \sqrt{Re_1^2 + Xe_1^2}$, $Ze_1 = Re_1 + j Xe_1$

Equivalent values referred to secondary

The equivalent values referred to secondary can also be found in the same manner. If R_{e_2}, X_{e_2} and Z_{e_2} denote the equivalent resistance, reactance and impedance respectively of the whole transformer referred to secondary, then

R_{e_2} = Secondary Resistance + Primary resistance ref. to secondary

$$\therefore R_{e_2} = R_2 + R_1' = R_2 + R_1\left(\frac{N_2}{N_1}\right)^2 = R_2 + \frac{R_1}{K^2}$$

Similary,

$$X_{e_2} = X_2 + X_1' = X_2 + X_1\left(\frac{N_2}{N_1}\right)^2 = X_2 + \frac{X_1}{K^2}$$

Hence,

$$Z_{e_2} = Z_2 + Z_1' = Z_2 + Z_1\left(\frac{N_2}{N_1}\right)^2 = Z_2 + \frac{Z_1}{K^2}$$

Also,

$$Z_{e_2} = R_{e_2} + jX_{e_2} \qquad Z_{e_2} = \sqrt{R_{e_2}^2 + X_{e_2}^2}$$

$$R_{e_1} = R_1 + R_2\left(\frac{N_1}{N_2}\right)^2$$

$$R_{e_1}\left(\frac{N_2}{N_1}\right)^2 = R_1\left(\frac{N_2}{N_1}\right)^2 + R_2 = R_{e_2}$$

$$\therefore R_{e_2} = R_{e_1}\left(\frac{N_2}{N_1}\right)^2 = \frac{R_{e_1}}{K^2}$$

Similarly,

$$X_{e_2} = X_{e_1}\left(\frac{N_2}{N_1}\right)^2 = \frac{X_{e_1}}{K^2}$$

and

$$Z_{e_2} = Z_{e_1}\left(\frac{N_2}{N_1}\right)^2 = \frac{Z_{e_1}}{K^2}$$

4.13 REGULATION

Majority of the loads connected to the transformer secondary are designed to operate at practically constant voltage. However, as the current is taken through the transformer, the load terminal voltage changes because of the voltage drop in the internal impedance of the transformer. The term voltage regulation is used to identify the characteristic of the voltage change in a transformer with loading.

The voltage regulation of a transformer is defined as the arithmatic difference between the no-load ($I_2 = 0$) and full-load ($I_2 = I_{2fl}$) at a given power factor with the same value of primary voltage for both rated and no-load.

It is expressed generally in percentage voltage regulation.

So,

$$\text{Voltage Regulation} = \frac{\text{Secondary No-load Voltage} - \text{Secondary load voltage}}{\text{Secondary no-load voltage}}$$

If E_2 = no load voltage

V_2 = load voltage

Then % Regulation $= \dfrac{E_2 - V_2}{E_2} \times 100\,\%$

4.14 LOSSES IN A TRANSFORMER

The losses which occur in a transformer are (a) Core losses or Iron losses, P_i
(b) Copper losses or I^2R losses, P_c

Iron or Core Losses (P_i)

Iron losses occur in the magnetic core of the transformer. This loss is the sum of hysterisis and eddy current losses, P_h and P_e respectively.

$$\therefore P_i = P_h + P_e$$

Hysterisis and Eddy current losses are given by,

$$P_h = k_h f B_m^x$$

$$P_e = K_e f B_m^2$$

where,

$k_h \rightarrow$ proportionality constant which depends on volume and quality of the core-material and the units used.

$K_e \rightarrow$ proportionality constant whose value depends on volume & resistivity of the core material, thickness of lamination and units used.

$B_m \rightarrow$ Maximum flux density in the core

$f \rightarrow$ Frequency of alternating current

$x \rightarrow$ Steinmetz constant. Value ranges from 1.5 to 2.5 depending on the core material used.

Copper loss or I^2R Losses

Copper loss is the I^2R losses which take place in the transformer primary and secondary windings because of their winding resistances.

Total copper loss in the transformer (P_c) = Primary winding Copper loss ($I_1^2R_1$) + Secondary winding copper loss ($I_2^2R_2$)

$$\therefore P_c = I_1^2R_1 + I_2^2R_2$$

Copper loss varies with the square of the load current.

As there are no moving parts in a transformer, there are no mechanical or rotational losses happening in the transformer.

4.15 EFFICIENCY OF A TRANSFORMER

Like all other machines, efficiency of the transformer is the ratio of output to the input.

$$\eta = \frac{\text{Output of the transformer}}{\text{Input of the transformer}}$$

where, input = output + losses

As discussed earlier, losses are iron and copper losses.

So efficiency is given as,

$$\eta = \frac{\text{Output}}{\text{Output} + \text{Iron loss} + \text{Cu losses}}$$

If.

V_2 is the voltage across the load

I_2 is the full load current

$\cos\phi_2$ is the load power factor and

P_i, P_c represents iron and Cu losses repectively

while R_2 is the total resistance referred to secondary side, then efficiency at full load

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

and $P_c = I_2^2 R_2$ Watts

Hence, percentage efficiency at full load is,

$$\eta = \frac{VA \times p.f}{VA \times p.f + P_i + P_c} \times 100\%$$

Efficiency at $x\%$ full-load can be found as,

$$\eta_x = \frac{x \times \text{full load output}}{x \times \text{full load o/p} + P_i + x^2 P_c}$$

Since,

(i) Iron losses are constant at all loading conditions

(ii) Copper losses vary according to the square of the loading condition.

VOLTAGE REGULATION OF A TRANSFORMER

- Voltage regulation is a measure of change in the voltage magnitude between the sending and receiving end of a component.
- It is commonly used in power engineering to describe the percentage voltage difference between no load and full load voltages
- 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.

$$\boxed{\textbf{\textit{Voltage Regulation}} = \frac{\textbf{\textit{No load voltage}} - \textbf{\textit{full load voltage}}}{\textbf{\textit{no load voltage}}}}$$

The equation for the **voltage regulation of transformer**, represented in percentage, is

$$\boxed{Voltage\ regulation(\%) = \frac{E_2 - V_2}{V_2} \times 100\%}$$

TESTING OF TRANSFORMERS

- The efficiency and regulation of a transformer on any load condition and at any power factor condition can be predetermined by indirect loading method.
- In this method, the actual load is not used on transformer. But the equivalent circuit parameters of a transformer are determined by conducting two tests on a transformer which are,

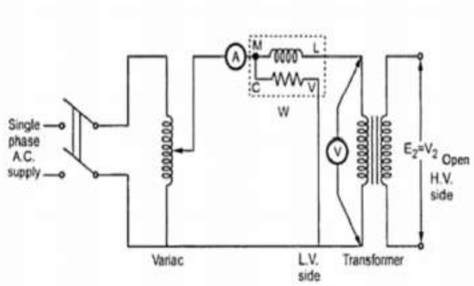
    1. Open circuit test (O.C Test)
    2. Short circuit test (S.C.Test)

- The parameters calculated from these test results are effective in determining the regulation and efficiency of a transformer at any load and power factor condition, without actually loading the transformer.
- The advantage of this method is that without much power loss the tests can be performed and results can be obtained.

TESTING OF TRANSFORMERS

- Suppose 400MVA, 20kV/400kV power transformer, to test this transformer directly by loading it, it will be really a monumental task. Firstly, finding a load for such high rating transformer is difficult.
- A load which will actually carry so much of current and it will dissipate so much of power, then to be able to cool it. This would waste so much money, time and energy.
- In open circuit test and short-circuit tests, we are essentially creating situations such that the transformer is put through such an operating condition which will emulate the normal loading condition, although not simultaneously.
- O.C. Test we apply rated voltage and low current
- S.C. Test we apply rated current and low voltage
- These two tests enable the efficiency and the voltage regulation to be calculated without actually loading the transformer and with an accuracy far higher than is possible by direct measurement of input and output powers and voltages.
- Also, the power required to carry out these tests is very small compared with the full-load output of the transformer.

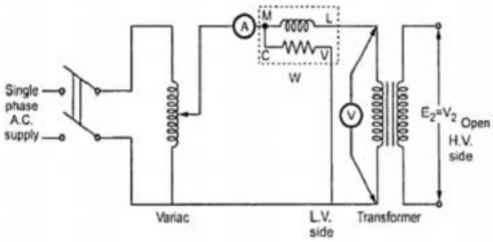
OPEN CIRCUIT (O.C.) TEST



- The circuit diagram for conducting the test is shown in figure.
- The **rated voltage** is applied to one winding and other winding is kept open *(usually LV winding is supplied, while HV is kept open for ease of testing and availability of supply)*.
- Since the **no-load current is a very small percentage of the full load current,** which can be in the range of 0.2 to 2%.
- The input power measured by a wattmeter consists of the core loss and primary winding ohmic loss.
- If the no-load current is 1% of full load current, ohmic loss in primary winding resistance is just 0.01% of the load loss at rated current; the value of winding loss is negligible as compared to the core losses.
- Hence, the **entire wattmeter reading can be taken as the total core loss.**

OPEN CIRCUIT (O.C.) TEST

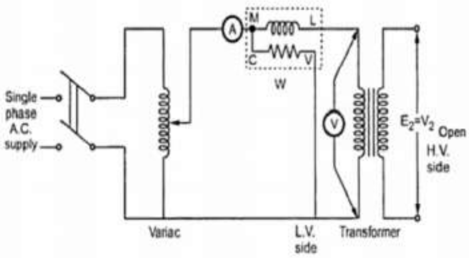
- Data obtained from O.C. Test



When the primary voltage is adjusted to its rated value with the help of variac, readings of ammeter and wattmeter are to be recorded.

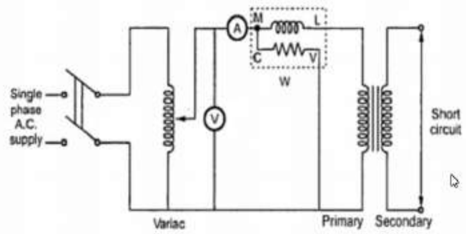
Voltage (V_0)	Current (I_0)	Power (W_0)
Rated Voltage of the Primary or LV winding	**Very small** percentage of the full load current	**Total Core loss**

OPEN CIRCUIT (O.C.) TEST



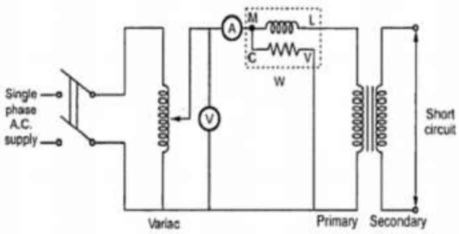
- The primary is excited by rated voltage, which is adjusted precisely with the help of a variac.
- The wattmeter measures input power.
- The ammeter measures input current.
- The voltemeter gives the value of rated primary voltage applied at rated frequency.

SHORT CIRCUIT (S.C.) TEST



- A short circuit test is done to measure the load loss of a transformer.
- The secondary is short circuited with the help of thick copper wire or solid link.
- As high voltage side always has low current side, it is convenient to connect high voltage side to supply and shorting the low voltage side.
- As **secondary is shorted**, its resistance is very very small and on rated voltage it may **draw very large current.**
- Such large current can cause overheating and burning of the transformer.
- To **limit this short circuit current, primary is supplied with low voltage** which is just enough to cause rated current to flow through primary which can be observed on an ammeter.

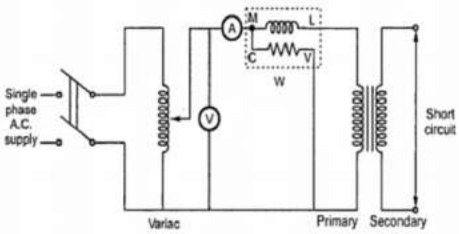
SHORT CIRCUIT (S.C.) TEST



- The low voltage can be adjusted with the help of variac. Hence this test is also called low voltage test or reduced voltage.
- Now the **current flowing through the windings are rated current** hence the total copper loss is full load copper loss.
- Now the **voltage supplied is low** which is a small fraction of the rated voltage.
- The **iron losses are function of applied voltage**. So **the iron losses** in reduced voltage test are very **small**.
- Hence, the **wattmeter reading** is the power loss which is **equal to full load copper losses** as iron losses are very low.

SHORT CIRCUIT (S.C.) TEST

- Data obtained from S.C. Test



The wattmeter reading as well as voltmeter, ammeter readings are recorded. The observation table is as follows,

Voltage (V_{SC})	Current (I_{SC})	Power (W_{SC})
Small fraction of the rated voltage	**Rated current**	**Total Copper loss**

CALCULATION OF EFFICIENCY FROM O.C. AND S.C. TESTS

- We know that,
  From O.C. test, W_o = Iron or Core losses = P_i
  From S.C. test, W_{sc} = Copper losses = P_{cu}
- Also, **Efficiency**, $\eta = \frac{\textit{Output Power}}{\textbf{Output Power+losses}}$

$$\therefore \boxed{\%\ \textbf{Efficiency},\ \eta = \frac{V_2 I_2 \cos\emptyset_2}{V_2 I_2 \cos\emptyset_2 + P_{cu} + P_i} \times 100}$$

Thus, for any p.f. cos Φ_2 the efficiency can be predetermined. Similarly at any load which is fraction of full load then also efficiency can be predetermined as,

$$\therefore \boxed{\%\ \textbf{Efficiency at any load } x,\ \ \eta_x = \frac{x V_2 I_2 \cos\emptyset_2}{x V_2 I_2 \cos\emptyset_2 + x^2 P_{cu} + P_i} \times 100}$$

where, x is the % of full load

O.C. & S.C. TEST - NUMERICAL

Recording

1. A 5 KVA, 500/250 V, 50 Hz, single phase transformer gave the following readings,
O.C. Test : 500 V, 1 A, 50 W (L.V. side open)
S.C. Test : 25 V, 10 A, 60 W (L.V. side shorted)
Determine : i) The efficiency on full load, 0.8 lagging p.f.

ii) The efficiency on 60% of full load, 0.8 leading p.f.

From O.C. test, W_o = Iron or Core losses = 50 W = P_i
From S.C. test, W_{sc} = Copper losses = 60 W = P_{cu}

i) The efficiency on full load, 0.8 lagging p.f.

$V_2 I_2 = 50\text{kVA} = 50 \times 10^3 \text{ VA}$

$cos\emptyset_2 = 0.8$, $\mathbf{P_i} = 50$ W , $\mathbf{P_{cu}} = 60$ W

$$\therefore \% \textbf{ Efficiency}, \eta = \frac{5\times10^3\times0.8}{5\times10^3\times0.8+60+50}\times 100 = \mathbf{97.32\ \%}$$

ii) The efficiency on full load, 60% of full load, 0.8 leading p.f.

$$\% \textbf{ Efficiency } \boldsymbol{at\ any\ load\ x},\ \eta_x = \frac{0.6\times5\times10^3\times0.8}{0.6\times5\times10^3\times0.8+(0.6^2\times60)+50}\times 100 = \mathbf{97.103\ \%}$$

Abhishek Reddy Sheri's screen

O.C. & S.C. TEST - NUMERICAL

2. The open circuit and short circuit tests on a 10 KVA, 125/250 V, 50 Hz, single phase transformer gave the following results :

O.C. test : 125 V, 0.6 A, 50 W (on L.V. side)
S.C. test : 15 V, 30 A, 100 W (on H.V. side)

Calculate : i) copper loss on full load
ii) full load efficiency at 0.8 leading p.f.
iii) half load efficiency at 0.8 leading p.f.

i) Copper loss on full load

(I_2) F.L. = VA rating/V_2 = $(10 \times 10^3)/250 = 40$ A

In short circuit test, $I_{sc} = 30$ A and not equal to full load value 40 A.

Hence W_{sc} does not give copper loss on full load

$\therefore$ $W_{sc} = P_{cu}$ at 30 A = 100 W

Now $P_{cu} \propto I^2$

$(P_{cu}$ at 30 A$)/(P_{cu}$ at 40 A$) = (30/40)^2$

$100/(P_{cu}$ at 40 A$) = 900/1600$

P_{cu} at 40 A = 177.78 W

$\therefore$ **(P_{cu}) F.L. = 177.78 W**

O.C. & S.C. TEST - NUMERICAL

- The open circuit and short circuit tests on a 10 KVA, 125/250 V, 50 Hz, single phase transformer gave the following results :

O.C. test : 125 V, 0.6 A, 50 W (on L.V. side)
S.C. test : 15 V, 30 A. 100 W (on H.V. side)

Calculate : i) copper loss on full load
ii) full load efficiency at 0.8 leading p.f.
iii) half load efficiency at 0.8 leading p.f.

ii) Full load η , $\cos \Phi_2 = 0.8$

$$\% \textbf{ Efficiency}, \eta = \frac{250\times40\times0.8}{250\times40\times0.8+50+177.78} \times 100 = 97.23 \%$$

iii) Half load η , $\cos \Phi_2 = 0.8$

$$\% \textbf{ Efficiency at any load x}, \ \eta_x = \frac{0.5\times10\times10^3\times0.8}{0.5\times10\times10^3\times0.8+(0.5^2\times177.78)+50} \times 100 = 97.103 \%$$

EQUIVALENT CIRCUIT PARAMETERS

Open Circuit Test

W_o = Iron losses

- The no load shunt parameters are calculated from the OC test as
- ✓The no load power factor, $\text{Cos } \Phi_o = W_o/V_oI_o$

Once the power factor is obtained, the no load component currents are determined as,

- ✓Magnetizing component of no load current, $I_m = I_o \sin \Phi_o$
- ✓Core loss component of no load current, $I_m = I_o \cos \Phi_o$
- ✓Then, the magnetizing branch reactance, $X_o = V_o / I_m$
- ✓Resistance representing core loss, $R_o = V_o / I_c$

Short Circuit Test

W_{sc} = Full load copper losses

- ✓Equivalent resistance referred to HV side, $R_{e1} = W_{sc} / I_{sc}^2$
- ✓Equivalent impedance referred to HV side, $Z_{01} = V_{sc} / I_{sc}$
- ✓Equivalent leakage reactance referred to HV side, $X_{01} = \sqrt{(Z^2_{01} - R^2_{01})}$
- ✓ And also short circuit power fact

$$\text{Cos } \Phi_{sc} = W_{sc}/V_{sc}I_{sc}$$

O.C. & S.C. TEST - NUMERICAL

- 3. The following results were obtained on a 50 kVA transformer. Opencircuit test – primary voltage, 3300 V; secondary voltage, 400 V; primary power, 430 W. Short-circuit test – primary voltage, 124 V; primary current, 15.3 A; primary power, 525 W; secondary current, full-load value. Calculate the efficiencies at full load and at half load for 0.7 power factor.

$$\text{Core loss} = 430 \text{ W}$$

$$I^2R \text{ loss on full load} = 525 \text{ W}$$

$$\therefore \quad \text{Total loss on full load} = 955 \text{ W} = 0.955 \text{ kW}$$

$$\text{and} \quad \text{Efficiency on full load} = \frac{50 \times 0.7}{(50 \times 0.7) + 0.955}$$

$$= \left(1 - \frac{0.955}{35.95}\right) = 0.973$$

$$= 97.3\ \%$$

$$I^2R \text{ loss on half load} = 525 \times (0.5)^2 = 131 \text{ W}$$

$$\therefore \quad \text{Total loss on half load} = 430 + 131 = 561 \text{ W} = 0.561 \text{ kW}$$

$$\text{and} \quad \text{Efficiency on half load} = \frac{25 \times 0.7}{(25 \times 0.7) + 0.561}$$

$$= \left(1 - \frac{0.561}{18.06}\right) = 0.969$$

$$= 96.9\%$$

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Numericals

- Determine the efficiency of the transformer in the previous problem at half full-load and 0.8 power factor.

$$\%\eta_x = \frac{x V_2 I_2 \cos\phi_2}{x V_2 I_2 \cos\phi_2 + P_i + x^2 P_{cu}}$$

$$= \frac{0.5 \times 40 \times 10^3 \times 0.8}{0.5 \times 40 \times 10^3 \times 0.8 + 500 + (0.5)^2 800} \times 100$$

$$\%\eta = 95.8\%$$

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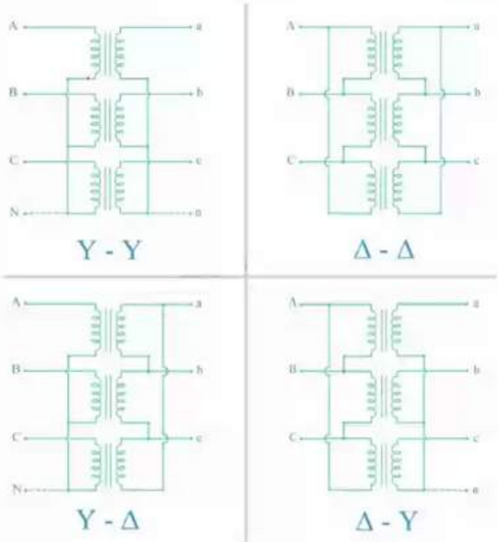
THREE PHASE TRANSFORMERS

- If we take three single-phase transformers and connect their primary windings to each other and their secondary windings to each other in a fixed configuration, we can use the transformers on a three-phase supply.
- Three-phase, also written as 3-phase or 3φ supplies are used for electrical power generation, transmission, and distribution, as well as for all industrial uses.
- Three-phase supplies have many electrical advantages over single-phase power and when considering three-phase transformers we have to deal with three alternating voltages and currents differing in phase-time by 120 degrees
- The three phase transformer consists three transformers either separate or combined with one core.
- The primary and secondary of the transformer can be independently connected either in star or delta.
- There are four possible connections for a 3-phase transformer bank.

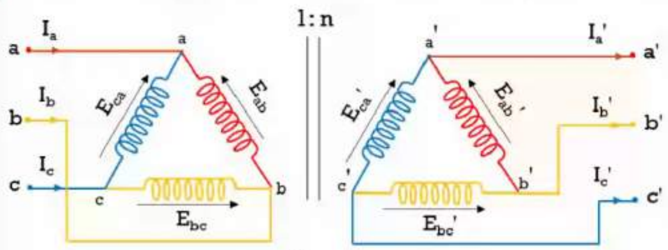
THREE PHASE TRANSFORMERS CONNECTIONS



i. Δ – Δ (Delta – Delta) Connection
ii. ϒ – ϒ (Star – Star) Connection
iii. Δ – ϒ (Delta – Star) Connection
iv. ϒ – Δ (Star – Delta) Connection

- The choice of connection of three phase transformer depends on the various factors likes the availability of a neutral connection for grounding protection or load connections, insulation to ground and voltage stress, availability of a path for the flow of third harmonics, etc.

Δ – Δ (DELTA – DELTA) CONNECTION



$n = \frac{N_2}{N_1}$ = turns ratio

Type equation here.

I_a, I_b, I_c are Primary Line Currents

E_{ab}, E_{bc}, E_{ca} are Primary Phase Voltages

I_a', I_b', I_c' are Secondary Line Currents

E_{ab}', E_{bc}', E_{ca}' are Secondary Phase Voltages

a, b, c are Primary terminals connected to source

a', b', c' Secondary terminals connected to load

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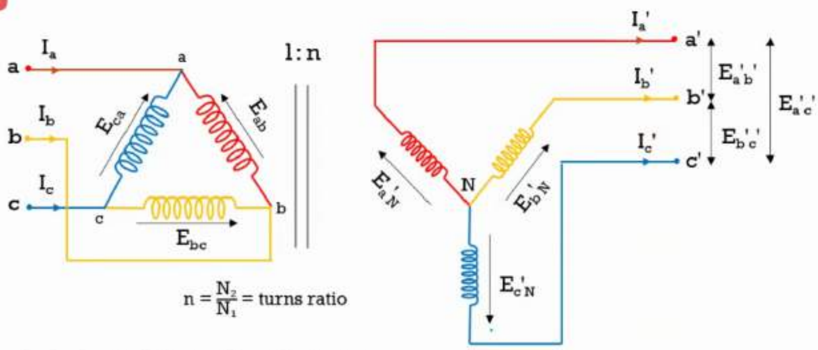


$n = \frac{N_2}{N_1}$ = turns ratio

I_a, I_b, I_c are Primary Line Currents

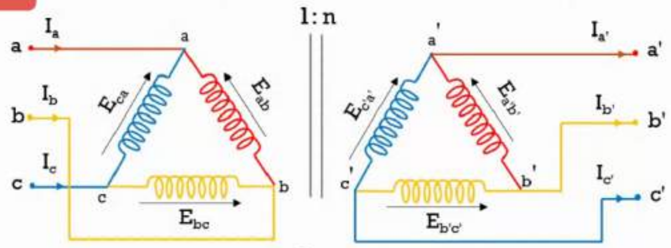
E_{ab}, E_{bc}, E_{ca} are Primary Phase Voltages

I_a', I_b', I_c' are Secondary Line Currents

$E_{a'N}$, $E_{b'N}$, $E_{c'N}$ are Secondary Phase Voltages

$E_{a'b'}$, $E_{b'c'}$, $E_{a'c'}$ are Secondary Line Voltages

$\Delta - \Delta$ (DELTA – DELTA) CONNECTION



$n = \frac{N_2}{N_1}$ = turns ratio

I_a, I_b, I_c are Primary Line Currents

E_{ab}, E_{bc}, E_{ca} are Primary Phase Voltages

$I_{a'}, I_{b'}, I_{c'}$ are Secondary Line Currents

$E_{a'b'}, E_{b'c'}, E_{c'a'}$ are Secondary Phase Voltages

a, b, c are Primary terminals connected to source

a ', b ', c ' Secondary terminals connected to load

Let the line current in the primary side of the Δ connection be I Amps

So, the phase current for a Δ connection will be $\frac{I}{\sqrt{3}}$ Amps

We know that ,

$$N_1 I_1 = N_2 I_2$$

Substituting $I_1 = \frac{I}{\sqrt{3}}$, we get ,

$$N_1 \times \frac{I}{\sqrt{3}} = N_2 I_2$$

$$I_2 = \frac{N_1}{N_2} \times \frac{I}{\sqrt{3}}$$

$$I_2 = \frac{I}{n\sqrt{3}}$$

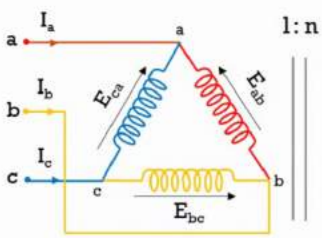
Also, $\frac{N_1}{V_1} = \frac{N_2}{V_2}$

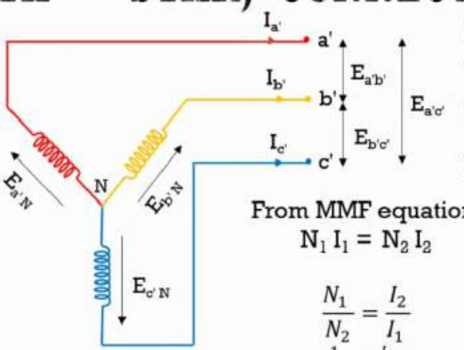
$$V_2 = \frac{N_2}{N_1} \times V_L$$

$$\Rightarrow V_2 = nV_L$$

REC

$\Delta - \Upsilon$ (DELTA – STAR) CONNECTION





$n = \frac{N_2}{N_1}$ = turns ratio

I_a, I_b, I_c are Primary Line Currents

E_{ab}, E_{bc}, E_{ca} are Primary Phase Voltages

$I_{a'}$, $I_{b'}$, $I_{c'}$ are Secondary Line Currents

$E_{a'N}$, $E_{b'N}$, $E_{c'N}$ are Secondary Phase Voltages

$E_{a'b'}$, $E_{b'c'}$, $E_{a'c'}$ are Secondary Line Voltages

For primary side ,

$V_L = V_{ph}$ for Δ connection

Let I_L = I Amps

$I_{ph} = \frac{I_L}{\sqrt{3}} = \frac{I}{\sqrt{3}}$ [Since $I_L = \sqrt{3}\, I_{ph}$]

From MMF equation,

$$N_1 I_1 = N_2 I_2$$

$$\frac{N_1}{N_2} = \frac{I_2}{I_1}$$

$$\frac{1}{n} = \frac{I_2}{I/\sqrt{3}} \times n$$

$$\frac{1}{n} = I_2 \times \frac{\sqrt{3}}{I}$$

$$\therefore I_p = \frac{I}{n\sqrt{3}}$$

We also know that,

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

$$\frac{1}{n} = \frac{V_L}{V_2}$$

$$\therefore V_2 = n\, V_L$$

So V_{ph} on the secondary side = $n\, V_L$

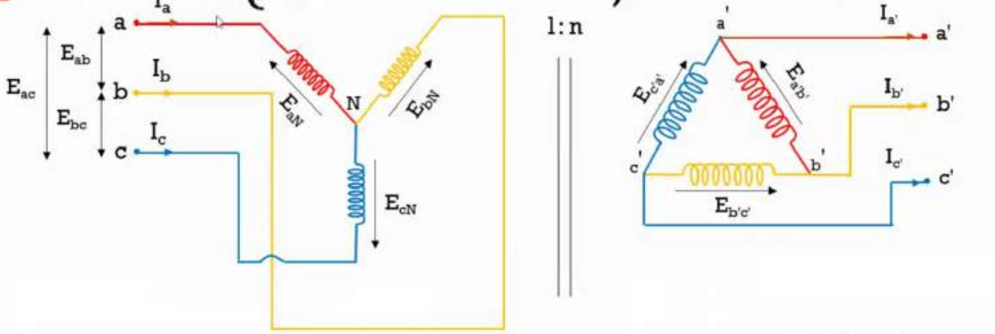
V_L on the secon

$\therefore V_L$

G

You

$\Upsilon - \Delta$ (STAR – DELTA) CONNECTION



On the primary side $I_L = I_{ph}$ and $V_L = \sqrt{3} \times V_{ph}$

$$\frac{N_1}{N_2} = \frac{I_2}{I_1} \Longrightarrow \frac{1}{n} = \frac{I_2}{I_L}$$

On the secondary side, $I_{ph} = \frac{I}{n}$; $I_L = \sqrt{3} \times I_{ph}$

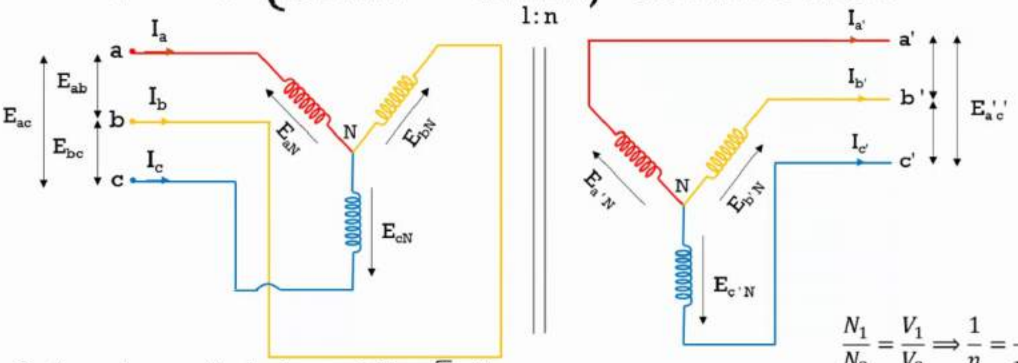
$$\therefore I_L = \frac{I\sqrt{3}}{n}$$

Also, $\frac{N_1}{N_2} = \frac{V_1}{V_2} \Longrightarrow \frac{1}{n} = \frac{V}{\sqrt{3}V_L}$

$$V_P = \frac{n \times V}{\sqrt{3}}$$

$$\therefore V_P = V_L = \frac{n \times V}{\sqrt{3}}$$

Y – Y (STAR – STAR) CONNECTION



On the primary side $I_L = I_{ph}$ and $V_L = \sqrt{3} \times V_{ph}$

$$\frac{N_1}{N_2} = \frac{I_2}{I_1} \Longrightarrow \frac{1}{n} = \frac{I_2}{I_L}$$

On the secondary side, $I_{ph} = \frac{I}{n}; I_L = I_{ph}$

$$\therefore I_L = \frac{I}{n}$$

$$\frac{N_1}{N_2} = \frac{V_1}{V_2} \Longrightarrow \frac{1}{n} = \frac{V}{\sqrt{3}\ V_2}$$

$$V_2 = \frac{n \times V}{\sqrt{3}} = V_P$$

For star connection, $V_L =$

$$\therefore V_L = \frac{n \times V\sqrt{3}}{\sqrt{3}} = n V$$

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COMPARISON OF CONNECTIONS

Connection Type	PRIMARY SIDE Line Voltage				SECONDARY SIDE Line Voltage			
Connection Type	Line Voltage	Phase Voltage	Line Current	Phase Current	Line Voltage	Phase Voltage	Line Current	Phase Current
$\Delta - \Delta$	V_L	$V_{ph} = V_L$	I_L	$I_{ph} = \frac{I_L}{\sqrt{3}}$	$V_L = nV_L$	$V_{ph} = nV_L$	$I_L = \frac{I}{n}$	$I_{ph} = \frac{I}{n\sqrt{3}}$
$\Delta - Y$	V_L	$V_{ph} = V_L$	I_L	$I_{ph} = \frac{I_L}{\sqrt{3}}$	$V_L = \sqrt{3}\,nV_L$	$V_{ph} = nV_L$	$I_L = \frac{I}{n\sqrt{3}}$	$I_{ph} = \frac{I}{n\sqrt{3}}$
$Y - \Delta$	V_L	$V_{ph} = \frac{V_L}{\sqrt{3}}$	I_L	$I_{ph} = I$	$V_L = \frac{nV_L}{\sqrt{3}}$	$V_{ph} = \frac{nV_L}{\sqrt{3}}$	$I_L = \frac{\sqrt{3}\,I}{n}$	$I_{ph} = \frac{I}{n}$
$Y - Y$	V_L	$V_{ph} = \frac{V_L}{\sqrt{3}}$	I_L	$I_{ph} = I$	$V_L = nV_L$	$V_{ph} = \frac{nV_L}{\sqrt{3}}$	$I_L = \frac{I}{n}$	$I_{ph} = \frac{I}{n}$

Transformers

$$\omega = 2\pi f$$

$$f = \frac{1}{2\pi}\left[\frac{-R}{2L} + \sqrt{\left(\frac{R}{2L}\right)^2 + \frac{1}{LC}}\right]$$

$$\omega_2 = \frac{R}{2L} + \sqrt{\left(\frac{R}{2L}\right)^2 + \frac{1}{LC}}$$

$$BW = \omega_2 - \omega_1$$

$$\boxed{BW = \frac{R}{2L} + \frac{R}{2L}} \Rightarrow \boxed{BW = \frac{R}{L}}$$

For. induced EMF in transformer

$$\phi = \phi_m \sin\omega t$$

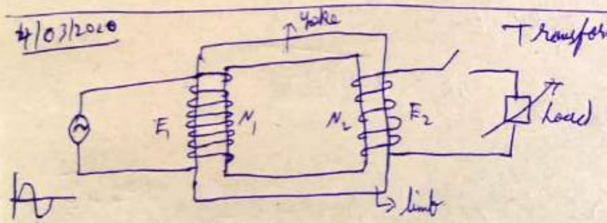
$$e = \frac{d\phi}{dt} = \phi_m \omega . \cos\omega t$$

$$\Rightarrow 2\pi f \phi_m \sin(\omega t - 90^\circ)$$

$$E_{max} \Rightarrow 2\pi f \phi_m$$

4/03/2020

Transformer.



$$\phi = \phi_m \sin\omega t.$$

$$e \propto \frac{d\phi}{dt}.$$

$$e_1 = N_1 \cdot \frac{d}{dt}(\phi_m \sin\omega t)$$

$$e_1 = N_1 \omega_1 \phi_m \cos\omega t.$$

$$e_1 = 2\pi f . \phi_m N_1 \sin(\omega t - 90^\circ)$$

$$(E_1)_{max} = 2\pi f \phi_m N_1$$

$$(E_1)_{rms} = \sqrt{2}\pi f \phi_m N_1$$

$$= 4.44 \phi_m f N_1$$

$$E_2 = N_2 \cdot \frac{d}{dt}(\phi_m \sin\omega t)$$

$$= \omega . \phi_m N_2 \sin(\omega t - 90)$$

$$(E_2)_{max} = 2\pi f \phi_m N_2$$

$$(E_2)_{rms} = \sqrt{2}\pi f \phi_m N_2$$

$$= 4.44 \phi_m f N_2$$

In an Ideal transformer power is conserved.

$$P_1 = P_2$$

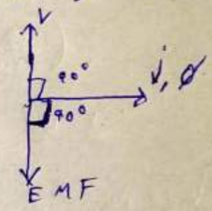
$$V_1 I_1 = V_2 I_2$$

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

$$K = \frac{E_1}{E_2} = \frac{N_1}{N_2} \Rightarrow \text{Transformation Ratio}$$

Transformer Principle: Electromagnetic Mutual Induction

phasor diagram:



∴ The V leads EMF by 180°

1) losses must be zero.

2) $\mu = \infty$

$N_2 > N_1$ → Step up voltage transformer
Step-down current transformer

$N_1 > N_2$ → Step down voltage transformer
Step-up current transformer

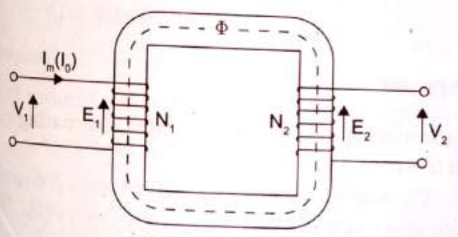
5.6 Ideal Transformer

An ideal transformer is one that has

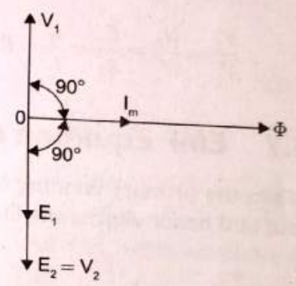
(i) no winding resistance.
(ii) no leakage flux i.e., the same flux links with both the windings.
(iii) no iron losses (i.e., eddy current and hysteresis losses) in the core.

Although ideal transformer cannot be physically realized, yet its study provides a very powerful tool in the analysis of a practical transformer. In fact, practical transformers have properties that come very close to an ideal transformer.

When the primary coil is connected to alternating voltage V_1 a current I_m (I_0) flows through it. Since the primary coil is purely inductive, the current I_m lags the applied voltage V_1 by 90°. Due to current I_m, flux is produced in the primary winding and some of the flux is also linked with the secondary winding and hence emf's E_1 and E_2 are induced in the primary and secondary windings respectively. According to Lenz's law the induced emf opposes the cause producing it which is supply voltage V_1. Hence E_1 is in antiphase with V_1 but equal in magnitude. The induced emf E_2 also opposes V_1 hence in antiphase with V_1 but its magnitude depends on N_2. Thus E_1 and E_2 are in phase. The phasor diagram of an ideal transformer is shown in the figure (5.6).



(a) Circuit diagram



(b) Phasor diagram

Figure (5.6): *Ideal transformer*

Here I_m = magnetizing current

Mathematically,

Let $\Phi = \Phi_m \sin\omega t = \Phi_m \angle 0°$ is taken as reference phasor

The induced emf in the primary

$$E_1 = -N_1\frac{d\Phi}{dt} = -N_1\frac{d}{dt}(\Phi_m \sin\omega t) = -N\Phi_m\omega\cos\omega t = N\Phi_m\omega\sin(\omega t - 90°) = E_{1m}\sin(\omega t - 90°)$$

$E_{1m} = N\Phi_m\omega = Max.\ value\ of\ induced\ e.m.f.$

i.e., E_1 lags the flux, Φ by an angle 90°

$$V_1 = -E_1 = N_1\frac{d\Phi}{dt} \quad or \quad V_1 = -E_1$$

i.e V_1 leads the flux, Φ by an angle $90°$

The induced emf in the secondary

$$E_2 = -N_2\frac{d\Phi}{dt} = -N_2\frac{d}{dt}(\Phi_m \sin\omega t) = -N_2\Phi_m\omega\cos\omega t = N_2\Phi_m\omega\sin(\omega t - 90°) = E_{2m}\sin(\omega t - 90°)$$

$$E_{2m} = N_2\Phi_m\omega = Max.\ value\ of\ induced\ emf$$

i.e., E_2 lags the flux, Φ by an angle $90°$, so E_1 and E_2 are phase.

In an ideal transformer there is no power loss

i.e., input VA = output VA

$$\Rightarrow E_1I_1 = E_2I_2$$

$$\Rightarrow V_1I_1 = V_2I_2\ (\because V_1 = E_1, V_2 = E_2)$$

$$\Rightarrow \frac{V_1}{V_2} = \frac{I_1}{I_2}$$

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

5.7 EMF Equation of a Transformer

When the primary winding is excited by an alternating voltage, it circulates alternating current and hence alternating flux is produced in the core

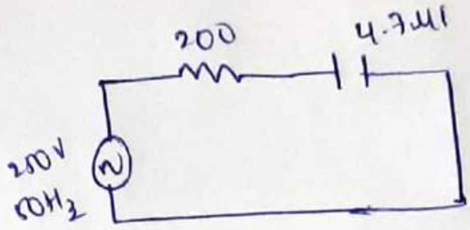
1) An RC circuit consisting of a 4.7µF capacitor in series with a 200 resistor is connected to a 250V, 50Hz supply. Determine, a) the current b) the power-factor and c) the values for true, apparant and reactive powers

$R = 200\Omega$

$C = 4.7\mu F$

$V = 250$

$f = 50Hz$



i) $I = \frac{V}{Z}$

$Z = \sqrt{R^2 + (X_C)^2}$

$= \sqrt{R^2 + \left(\frac{1}{WC}\right)^2}$

$Z = \sqrt{R^2 + \left(\frac{1}{2\pi \times f \times C}\right)^2}$

$Z = \sqrt{200^2 + \left(\frac{1}{2 \times 3.14 \times 50 \times 4.7 \times 10^{-6}}\right)^2}$

$Z = \cancel{706.21}\ 706.21$

$I = \frac{250}{706.21}$

$I = 0.354A$

ii) power factor

$\cos\phi = \frac{R}{Z}$

$\cos\phi = \frac{250}{706.21} \Rightarrow \cos\phi = 0.283$

$\phi = 73.56.$

Scanned with CamScanner

iii) True power = $VI\cos\phi$

$= 250 \times 0.354 \times \cos(73.56)$

$= 25.04$

Apparant power = $V \times I$

$= 250 \times 0.354$

$= 88.5$

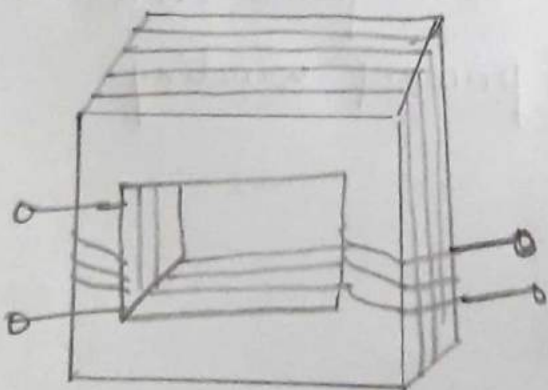
Reactive power = $VI\sin\phi$

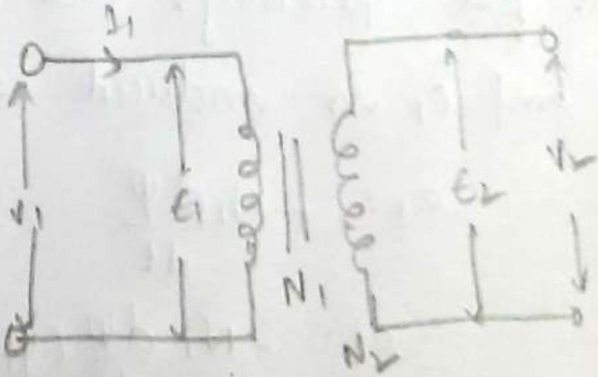
$= 250 \times 0.354 \times \sin(73.56)$

$= 84.88$

b) Explain the principle of operation of a single phase transformer. Derive the emf equation a single phase transformer.

When an alternating voltage V_1 is applied to a primary winding, an alternating current I_1 flows in it producing an alternating flux in the core. As per faradays law of electromagnetic induction, an emf e_1 is incuded in the primary winding





$$e_1 = -N_1 \frac{d\phi}{dt}$$

where N_1 is the number of turns in the primary winding. The induced emf in the primary winding is nearly equal and opposite to the applied voltage v_1. Assuming leakage flux to be negligible, almost the flux produced in primary winding links with the secondary winding

$$e_2 = -N_2 \frac{d\varphi}{dt}$$

where N_2 is the no. of turns in the secondary winding. If the secondary circuit is closed through the load, a current I_2 flows in secondary winding. The energy is transferred from the primary to secondary widing

EMF Equation

As the primary winding is excited by a sinusoidal alternating voltage, an alternating current flows in the winding producing sinusoidally varing flux ϕ in the core

$$\varphi = \varphi_m \sin \omega t$$

As per faraday's law of electromagnetic Induction in the primary winding an emf e_1 is induced

$$e_1 = -N_1 \frac{d\varphi}{dt}$$

$$e_1 = -N_1 \frac{d\varphi}{dt}(\varphi_m \sin \omega t)$$

$$e_1 = -N_1 \varphi_m \omega \cos \omega t$$

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

$= 2\pi f N_1 \varphi_m \omega \sin(\omega t - 90^\circ)$

Maximum value of induced emf $= 2\pi f \varphi_m N_1$

Hence rms value of induced emf in primary winding is

$$E_1 = \frac{E_{max}}{\sqrt{2}} = \frac{2\pi f N_1 \varphi_m}{\sqrt{2}}$$

$$E_1 = 4.44 f N_1 \varphi_m .$$

In secondary winding

$$E_2 = \frac{E_{max}}{\sqrt{2}} = \frac{2\pi f N_2 \varphi_m}{\sqrt{2}}$$

$$E_2 = 4.44 f N_2 \varphi_m$$

Emf per turn is same in primary and secondary winding and an equal emf is induced in each turn of primary and secondary winding.