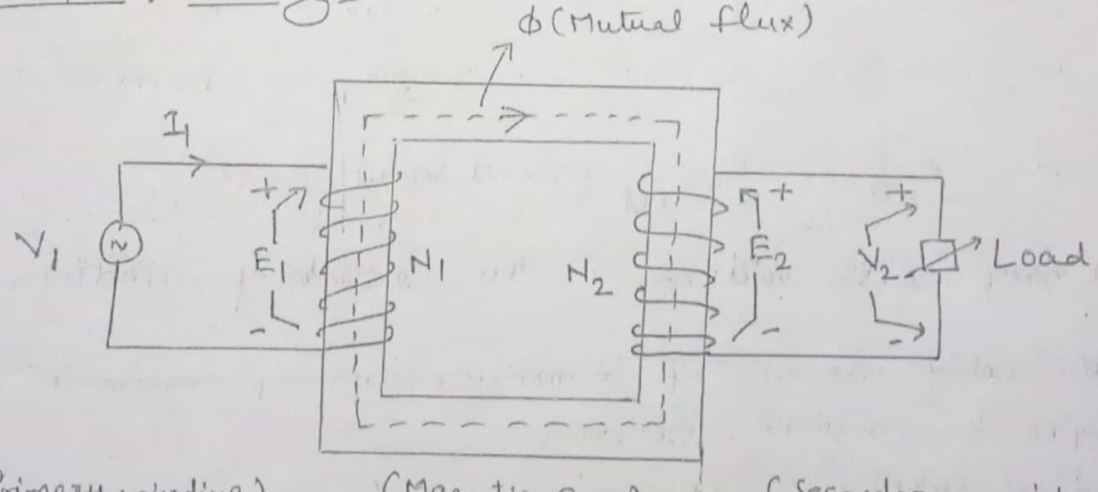
Que What is a Single Phase Transformer. also explain its Principle of operation.

Ans. Transformer is a Static, Electromagnetic Device, which transfer electrical energy from one electrical Circuit to other electrical Circuit Via a magnetic Path with out change in frequency

- it is Static because it has no rotating Parts.
- it is electromagnetic because it convert electrical energy in to magnetic energy
- it Transfer electrical energy & do not Convert electrical energy to other form of energy.
- it uses a magnetic Path for energy Transfer & frequency of input & out put Voltage remain Same.

Principle / working :-



(Primary winding) (Magnetic Core) (Secondary winding)

it is based on Principle of Electromagnetic Induction.

- when Single phase AC. Voltage (V_1) is applied to Primary winding of Transformer then a current I_1 flows in Primary winding and an MMF ($N_1 I_1$) is produced.

This MMF. will Set up a magnetic flux in Core

$$\phi = \frac{MMF.}{Reluctance}$$

- This alternating flux when link with Secondary winding then according to faraday's law of electromagnetic Induction, an EMF. will induce in the Secondary wdg. ($E = d\phi/dt$)
- if load is Connected to Secondary winding, a Secondary current will flow in the load (I_2).

Que Can transformer work on d.c. supply?

Ans. NO, Transformer Cannot work on DC. supply because

(i) if dc Voltage is applied to transformer input then it will produce Constant magnetic flux So By faraday's law of Electro magnetic Induction

$$E_2 = -N_2\frac{d\phi}{dt} = -N_2 \frac{d}{dt}[\text{Constt Value}] = 0$$

No Emf. will induce in the Secondary winding.

(ii) Practically the winding Resistance is very Small as Compare to Inductive Reactance and at Supply dc, $f=0$

$Z = R + jX_L$

$Z = R + j(2\pi f L) = R$

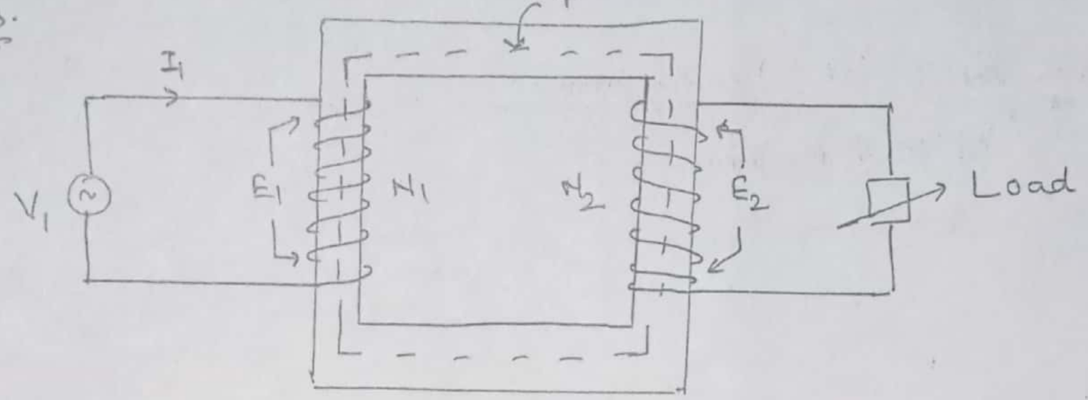
$Z = R \rightarrow$ very low Value

$\uparrow\uparrow \text{Current} = \frac{V}{Z\downarrow\downarrow}$ $\boxed{I^2Rt \uparrow \text{loss}}$ heating

Because of very low Impedance, Primary winding will draw a very high current. This high current may Produce extra heat and it may damage the circuit.

Que ~~Proof~~ Prove the EMF. Equation of Transformer

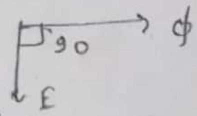
Ans.



When Primary winding is connected to an alternating Voltage V_1, an alternating flux(ϕ_m) will Set up in the core

Let the alternating flux is given by

Transfer produced the emf. lags the flux by 90°



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

This flux will induce Emf. in the two windings By faraday law of Electro Magnetic Induction

$$e = -N\, d\phi/dt$$

$$e = -N \cdot \frac{d}{dt}\left[\phi_m \sin \omega t\right]$$

$$e = -N\phi_m \cos\omega t \cdot \omega \rightarrow = -N\phi_m \omega \cdot \sin(90 - \omega t).$$

$$e = N\phi_m \cdot \omega \;\sin(\omega t - \pi/2)$$

$$e = E_m \sin[\omega t - \pi/2] \quad \text{———} \quad (1)$$

$$E_m = N\phi_m \cdot \omega = N\phi_m 2\pi f$$

$$E_{rms} = \frac{E_m}{\sqrt{2}} = \frac{N \cdot \phi_m \cdot \omega}{\sqrt{2}} = \frac{N \cdot \phi_m \cdot 2\pi f}{\sqrt{2}} = \sqrt{2}\,\pi f N \cdot \phi_m$$

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$$\boxed{E_{rms} = \sqrt{2}\,\pi f N \phi_m}$$

Primary Emf.

$$E_1 = \sqrt{2}\,\pi f \cdot N_1 \cdot \phi_m$$

Secondary Emf:

$$E_2 = \sqrt{2}\,\pi f N_2 \phi_m$$

- **Voltage Ratio of Transformer**

$$\frac{E_1}{E_2} = \frac{\sqrt{2}\,\pi f \cdot N_1 \phi_m}{\sqrt{2}\,\pi f N_2 \phi_m}$$

$$\boxed{\frac{E_1}{E_2} = \frac{N_1}{N_2}}$$ *

[Per turn voltage in primary & secondary winding is same.]

- **Current Ratio of Transformer**

Input Power = output Power

$$V_1 I_1 = V_2 I_2$$

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

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

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

$\cancel{E} \cancel{\approx} \cancel{\sqrt{2}\pi f}$

$\rightarrow E = E_m \sin(\omega t - 90^\circ)$

$\rightarrow E_1 = \sqrt{2}\pi f N_1 \phi_m = 4.44 f N_1 \phi_m$ —— (i)

$E_2 = \sqrt{2}\pi f N_2 \phi_m = 4.44 f N_2 \phi_m$ —— (ii)

$$\frac{E_1}{E_2} = \frac{N_1}{N_2} \quad \text{—— (iii)}$$

→ As we know, Power loss in Transformer is very less

$P_1 = P_2$

$V_1 I_1 = V_2 I_2 \Rightarrow E_1 I_1 = E_2 I_2 \Rightarrow \frac{E_1}{E_2} = \frac{I_2}{I_1}$

By Eqn. (iii)

$$\frac{E_1}{E_2} = \frac{I_2}{I_1} = \frac{N_1}{N_2}$$

→ ~~Beq~~ By Eqn (i) & (ii) :-

$$\left.\begin{aligned} \frac{E_1}{N_1} &= 4.44 f \phi_m \\ \frac{E_2}{N_2} &= 4.44 f \phi_m \end{aligned}\right\} \text{Primary Voltage Per Turn} = \text{Secondary Voltage Per Turn}$$

→ **Step up Transformer :-**

Secondary voltage (output voltage) > Primary voltage (input voltage)

$N_2 > N_1$

Step down transformer :-

Secondary (o/p) voltage < Primary (input) voltage

$N_2 < N_1$

One to One (1:1) transformer :-

Secondary (o/p) Voltage = Primary (input) voltage

$N_2 = N_1$

Q A 3300/250 V, 50 Hz. Single phase Transformer is build on a Core having an effective Cross Sectional area of 125 cm^2 & 70 turns on low Voltage winding. Calculate (a) Max. flux density (b) turns on H.V. side

Ans $E_1 = 3300$ V, $E_2 = 250$ V, $f = 50$ Hz., $A_x = 125 \times 10^{-4} m^2$.

$N_2 = 70$

* $E_2 = 4.44 f N_2 \phi_m \Rightarrow 250 = 4.44 \times 50 \times 70 \times \phi_m$

$\phi_m =$

$$B_m = \frac{\phi_m}{A_x} = \frac{250}{4.44 \times 50 \times 70 \times 125 \times 10^{-4}}$$

$B_m = 1.289$ T Ans

* $\frac{E_1}{E_2} = \frac{N_1}{N_2} \Rightarrow \frac{3300}{250} = \frac{N_1}{70} \Rightarrow N_1 = 924$

Q A transformer with 800 primary turns & 200 secondary turns is supplied from a 100V ac supply. Calculate the Secondary Voltage & the Volts per turn.

Ans $N_1 = 800$, $N_2 = 200$, $E_1 = 100$, E_2 ?? & $\frac{E_1}{N_1}$?

(Ans: $V_2 = E_2 = 25V$, $\frac{E_1}{N_1} = \frac{V_1}{N_1} = \frac{V_2}{N_2} = 0.125$)

Q A transformer with an output Voltage of 4200 V. is supplied at 230V. if the Secondary has 2000 turns, Calculate the No. of Primary turns

Ans 109.52 turns

Que A 200 kVA, 3300/240 Volt, 50 Hz., 1ϕ transformer has 80 turns on secondary winding, calculate
(i) Primary & secondary currents on full load
(ii) Maximum value of flux.
(iii) Number of primary winding turns.

Soln.

Volt Amp Rating = VA Rating = 200×10^3 VA.

$V_1 = 3300$ Volt

$V_2 = 240$ Volt

$N_2 = 80$

(3)

(i) * Primary Power = Secondary Power = VA Rating

$= 200 \times 10^3$ VA.

when

~~Primary Power = 200×10^3~~

$V_1 I_1 = 200 \times 10^3$

$3300 \times I_1 = 200 \times 10^3$

$I_1 = \dfrac{200 \times 10^3}{3300} = 60.6$ Amp

when

Secondary Power $= 200 \times 10^3$

$V_2 I_2 = 200 \times 10^3$

$240 \times I_2 = 200 \times 10^3$

$I_2 = \dfrac{200 \times 10^3}{240} = 833.3$ Amp

(ii) $E_1 = \sqrt{2}\pi f N_1 \phi_m$ or $E_2 = \sqrt{2}\pi f N_2 \phi_m$

because N_2 is given so we will use equation of E_2

$E_2 = \sqrt{2}\pi f N_2 \phi_m$

$\phi_m = \dfrac{E_2}{\sqrt{2}\pi f N_2} = \dfrac{240}{\sqrt{2} \times \pi \times 50 \times 80} = 13.51$ m wb

(iii) $\dfrac{N_1}{N_2} = \dfrac{E_1}{E_2}$

$N_1 = \dfrac{E_1}{E_2} \times N_2 = \dfrac{3300}{240} \times 80 = 1100$ Ans

12.5 CONSTRUCTION OF SINGLE-PHASE TRANSFORMERS

A single-phase transformer consists of primary and secondary windings put on a magnetic core. Magnetic core is used to confine flux to a definite path. Transformer cores are made from thin sheets (called *laminations*) of high-grade silicon steel. The laminations reduce eddy-current loss and the silicon steel reduces hysteresis loss. The laminations are insulated from one another by heat resistant enamel insulation coating. L-type and E-type laminations are used. The laminations are built up into stack and the joints in the laminations are staggered to minimize airgaps (which require large exciting currents). The laminations are tightly clamped.

There are two basic types of transformer constructions, the core type and the shell type.

12.5.1 Core-type Construction

In the core-type transformer, the magnetic circuit consists of two vertical *legs* or *limbs* with two horizontal sections, called *yokes*. To keep the leakage flux to a minimum, half of each winding is placed on each leg of the core as shown in Fig. 12.3. The low-voltage winding is placed next to the core and the high-voltage winding is placed around the low-voltage winding to reduce the insulating material required. Thus, the two windings are arranged as *concentric coils*. Such a winding is, therefore, called *concentric winding* or *cylindrical winding*.

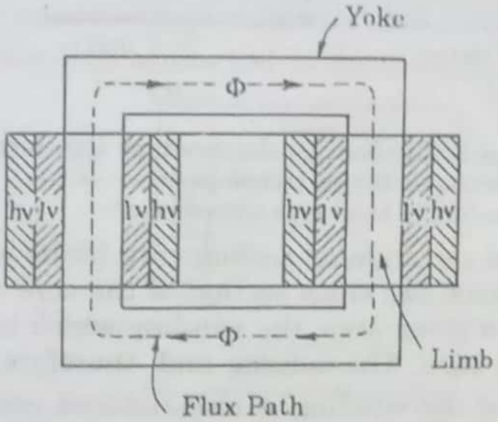


Fig. 12.3. Core-type transformer

12.5.2 Shell-type Transformer

In the shell-type transformer (Fig. 12.4), both primary and secondary windings are wound on the central limb, and the two outer limbs complete the low-reluctance flux paths. Each winding is subdivided into sections. Low-voltage (lv) and high-voltage (hv) subsections are alternately put in the form of a sandwich. Such a winding is, therefore, called *sandwich* or *disc winding*.

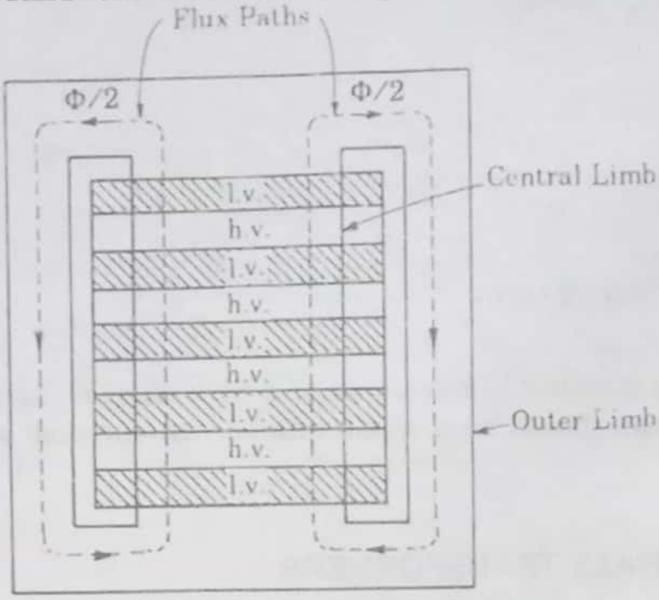


Fig. 12.4. Shell-type transformer.

A core must be made up of at least two types of laminations. The laminations for the core-type transformers are of U and I shape as shown in Fig. 12.5*a*. The U-shaped laminations are first stacked together for the required length. Half of the prewound low voltage (*lv*) coil is placed around the limbs. The *lv* coil is further provided with insulation. Then half of the prewound high-voltage (*hv*) coil is placed around the *lv* coil. The core is then closed by the I-shaped laminations at the top.

The core for the shell-type transformer is made up of either U and T shape (Fig. 12.5*b*) or E and I shape (Fig. 12.5*c*). In this type T or E shaped laminations are stacked together. The entire prewound low-voltage coil is placed around the central limb and the full prewound high-voltage coil is placed around the low-voltage coil. The core is then closed by U or I type laminations.

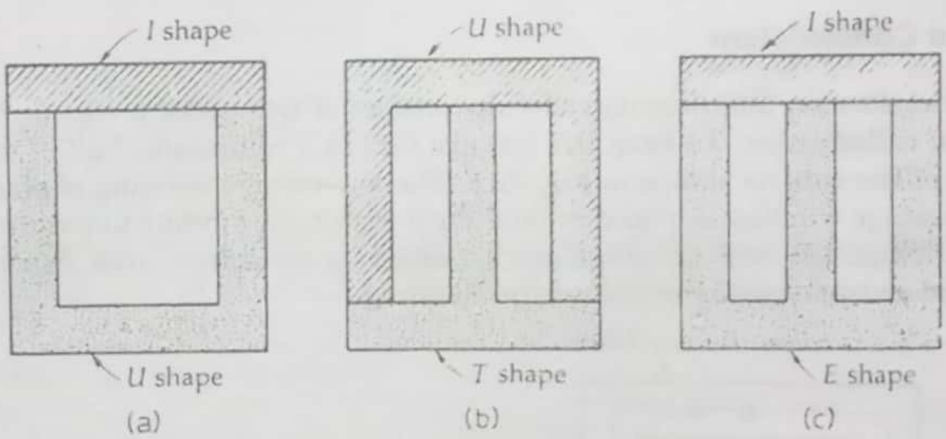


Fig. 12.5. Core laminations (*a*) U and I type laminations for the core-type transformer
(*b*) U and T laminations for the shell-type transformer
(*c*) E and I shaped laminations for the shell-type transformer

Ideal Transformer :-

Ideal transformer must have following properties :-

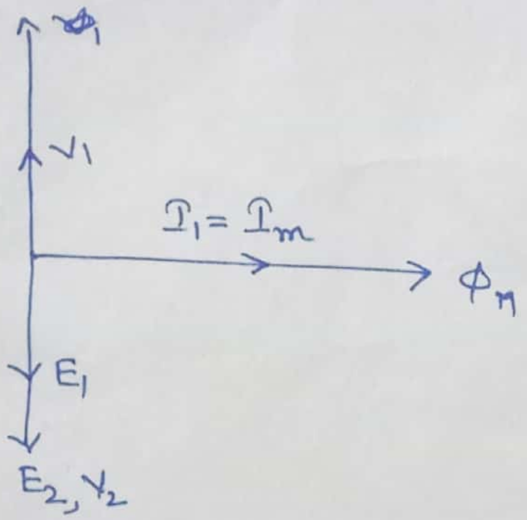
(i) ~~Neo~~ Zero Primary & Secondary winding Resistance

(ii) Infinite Permeability of core (To Produce max. flux)

(iii) Zero leakage flux & leakage inductance

(iv) Zero losses due to resistance, hysteresis & eddy currents i.e. 100% efficiency.

Phasor diagram of ideal transformer on No load



- Primary current (I_1) is required to magnetize the transformer core hence $I_1 = I_m$ & I_m will be in same phase with flux.
- if $\phi = \phi_m \sin \omega t$ then $E = E_m \sin(\omega t - 90^\circ)$

  hence Emfs lag the flux by 90°
- By Lenz's law, E_1 is equal and opposite to V_1
- Since E_2 & E_1 are produced by same mutual flux hence they will be in same direction
- For Ideal transformer $E_1 I_1 = E_2 I_2$ & $V_1 I_1 = V_2 I_2$

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Equivalent Circuit of Transformer :-

Equivalent circuit means the electrical equivalent of Transformer. So that electrical analysis can be done in this circuit to find useful results.

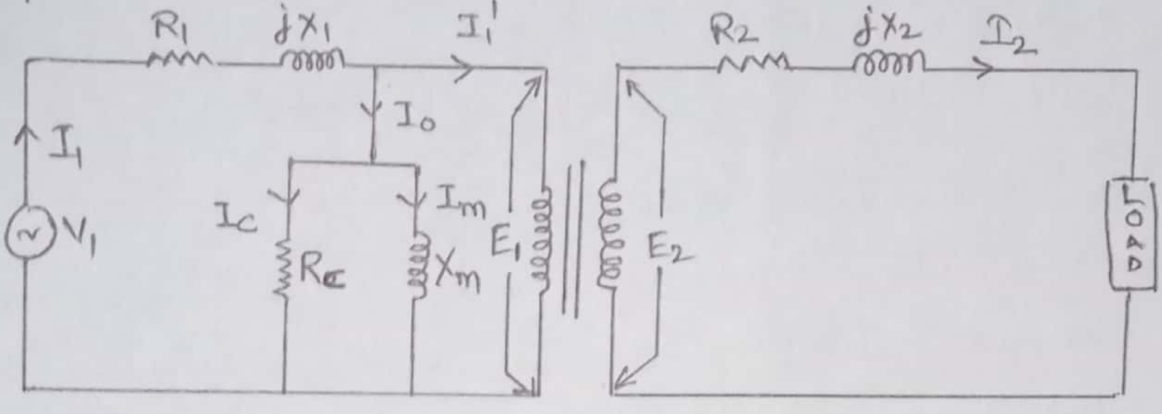


fig (i)

→ Fig (i) shows the Electrical equivalent circuit of single phase transformer. it is devided into two parts – (i) Primary circuit (ii) Secondary circuit.

→ The Primary & Secondary equivalent circuits are saparated by transformer core (which is shown by two lines in Parallel, in fig)

→ Primary Circuit :-

V_1 - supply voltage (single phase AC, Volt)
I_1 - Primary current (Amp)
R_1 - Primary winding Resistance (Ω)
X_1 - Primary winding leakage Reactance (Ω)
I_0 - No load Current (Amp)
I_1' - load Component of current. (Amp.)
I_c - Active Component of current (Amp.)
Watt ful Component of No load current
I_m - Magnetising Component of Current. (Amp.)
Reactive / watt less Component of No-load Current.
E_1 = Emf. Induced in primary winding (Volt)

→ Secondary Circuit :-

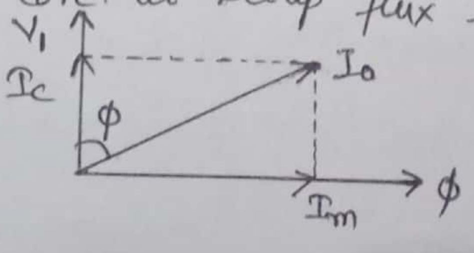
I_2 - Secondary Current (Amp.)
R_2 - Secondary winding Resistance (Ω)
X_2 - Secondary winding leakage Reactance (Ω)
V_2 - Voltage across load. (Volt)
E_2 - Emf induced in Secondary winding (Volt)

→ Winding Resistance :- (R_1 & R_2) :-
in ideal transformer, winding resistance must be zero. but real transformer always have some winding resistances.
These Resistances are connected in series with each winding.

→ Leakage Reactance :- (X_1 & X_2) :-
in ideal transformer, all the flux produced by Primary winding must link with Secondary winding i.e. there is no leakage of flux. but In actual transformer, a portion of this flux link with air. This is known as Primary leakage flux & Secondary leakage flux.
These leakage flux are shown by Reactances (X_1 & X_2).
These are connected in series with each winding.

→ Active Current Component (I_c) :-
This current component is responsible for core losses in transformer. $I_c^2 \cdot R_c$ = Hysteresis loss + Eddy current loss

→ Magnetising Current Component (I_m) :-
This current component is responsible for magnetising of the transformer core. it setup flux in transformer core.

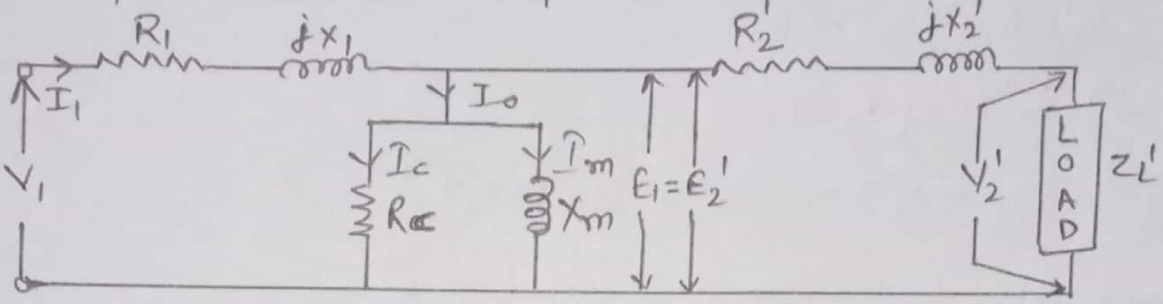


→ Exact Equivalent circuit of 1ϕ Transformer :-

(a) Exact equivalent circuit refer to primary side :-

if the secondary side electrical quantities (like secondary voltage, secondary current, R_2, X_2 etc.) are refered to the primary side.

then primary circuit can be ~~directly~~ electrically connected to secondary side for its circuit analysis.



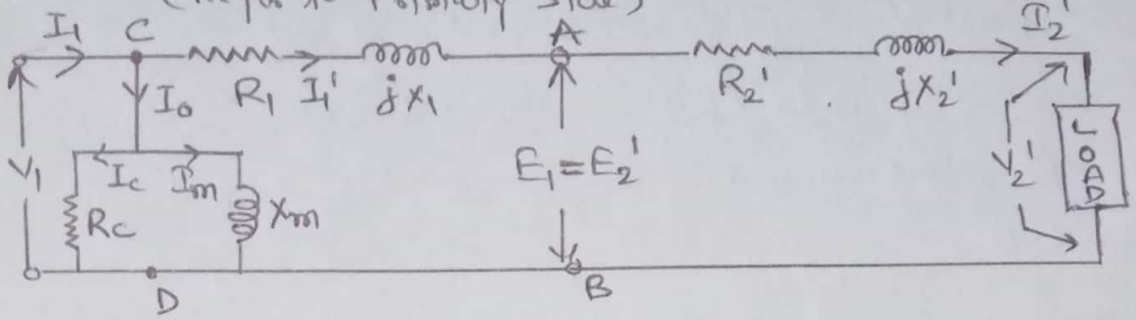
$R_2' = R_2 \left[\frac{N_1}{N_2}\right]^2$ $\quad X_2' = X_2 \left[\frac{N_1}{N_2}\right]^2$ $\quad Z_L' = Z_L \left[\frac{N_1}{N_2}\right]^2$

$E_2' = E_2 \left[\frac{N_1}{N_2}\right]$ $\quad I_2' = I_2 \left[\frac{N_2}{N_1}\right]$ $\quad V_2' = V_2 \left[\frac{N_1}{N_2}\right]$

(b) Exact equivalent circuit refer to secondary side :-

→ Approximate equivalent circuit of Transformer :-

(Refer to Primary side)



when Shunt branch is connected across AB:-

$V_1 - I_1(R_1 + jX_1) - E_1 = 0$

$V_1 - (I_1' + I_0)[R_1 + jX_1] = E_1$

$V_1 = E_1 + I_1'(R_1 + jX_1) + I_0(R_1 + jX_1)$ —— (i)

when Shunt branch is connected across CD:-

$V_1 - I_1'(R_1 + jX_1) - E_1 = 0$

$V_1 = I_1'(R_1 + jX_1) + E_1$ ———— (ii)

- To make eqn. (i) & eqn. (ii) equal, the component $I_0(R_1 + jX_1)$ must be zero.

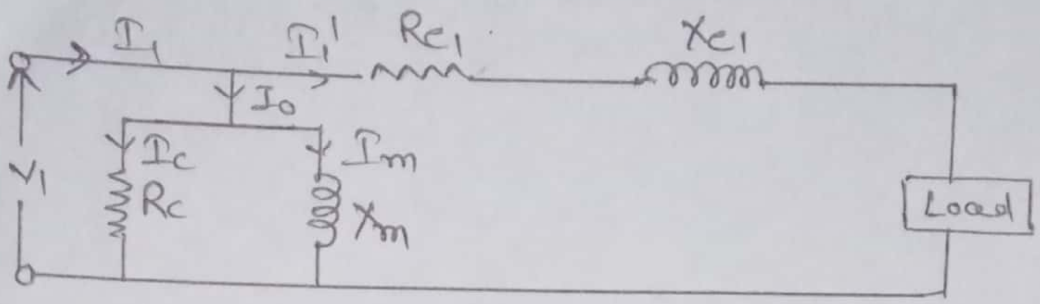
  ie the shunt branch can be shifted toward supply side if $I_0(R_1 + jX_1) \simeq 0$

- As we know, the No load (I_0) is very less. It is only (3-5)% of full load primary current (I_1).

  $I_0 = (3-5)\%$ of I_1

  So $I_0 << I_1$, I_0 can be neglected.

  So the voltage drop produced by I_0 with $(R_1 + jX_1)$ ie. $I_0(R_1 + jX_1)$ is very less so the shunt branch can be connected before $(R_1 + jX_1)$



effective Resistance refer to primary side (R_{e1}):-

$$R_{e1} = R_1 + R_2' = R_1 + R_2 \left[\frac{N_1}{N_2}\right]^2$$

effective Reactance refer to Primary side (X_{e1}):-

$$X_{e1} = X_1 + X_2' = X_1 + X_2 \left[\frac{N_1}{N_2}\right]^2$$

Que A 30 KVA, 2000/200 V, 1 ϕ, 50 Hz. Transformer has a primary resistance of 3.5 Ω & reactance of 4.5 Ω. The secondary resistance & reactance are 0.015 Ω & 0.02 Ω respectively. find-

(i) Equivalent Resistance, Reactance & Impedance refer to Primary side

(ii) Total Copper losses of Transformer.

Ans

$R_{e1} = R_1 + R_2'$ [5 Ω]

$X_{e1} = X_1 + X_2'$ [6.5 Ω]

$Z_{e1} = \sqrt{R_{e1}^2 + X_{e1}^2}$ [8.2 Ω]

$P_{cu}(total) = I_1^2 R_{e1}$ [1125 W]

$I_1 = \frac{VA}{V_1}$

Referred Values (Equivalent Circuit refer to Primary):

- $E_1 = E_2'$ $\qquad \left(\frac{E_1}{E_2} = \frac{N_1}{N_2} \Rightarrow E_1 = \frac{N_1}{N_2} \cdot E_2 \right)$

$$\frac{N_1}{N_2} E_2 = E_2'$$

$$\boxed{E_2' = E_2 \cdot \left(\frac{N_1}{N_2}\right)} \rightarrow \text{Voltage Transformation (Refer to Primary)}$$

- $I_1' = I_2'$ $\qquad \left(N_1 I_1' = N_2 I_2 \quad I_1' = \frac{N_2}{N_1} \cdot I_2 \right)$

$$\cancel{I_1'} = \frac{N_2}{N_1} I_2 \cdot I_2'$$

$$\boxed{I_2' = I_2 \cdot \frac{N_2}{N_1}} \rightarrow \text{Current Transformation (Refer to Primary)}$$

- Power Consumed by R_2' = Power Consumed by R_2

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

$$R_2' = \left(\frac{I_2}{I_2'}\right)^2 \cdot R_2$$

$$\boxed{R_2' = \left(\frac{N_1}{N_2}\right)^2 \cdot R_2} \rightarrow \text{Resistance Transformation (Refer to Primary)}$$

- Reactance (X) absorb the reactive Volt amperes (VAr)

$$VAr = VI \sin\phi = (IZ) \cdot (I) \left(\frac{X}{Z}\right) = I^2 X$$

Reactive VAr Consumed by X_2' = Reactive VAr Consumed by X_2

$$I_2'^2 X_2' = I_2^2 X_2$$

$$X_2' = \left(\frac{I_2}{I_2'}\right)^2 \cdot X_2$$

$$\boxed{X_2' = \left(\frac{N_1}{N_2}\right)^2 \cdot X_2} \rightarrow \text{Reactance Transformation (Refer to Primary)}$$

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

$$Z_2' = \sqrt{R_2^2 \cdot \left(\frac{N_1}{N_2}\right)^4 + X_2^2 \left(\frac{N_1}{N_2}\right)^4}$$

$$Z_2' = \left(\frac{N_1}{N_2}\right)^2 \cdot \sqrt{R_2^2 + X_2^2}$$

$$\boxed{Z_2' = \left(\frac{N_1}{N_2}\right)^2 \cdot Z_2} \rightarrow \text{Impedance Transformation (Refer to Primary)}$$

Que A 200 KVA 1φ Transformer with a voltage ratio of 6350/660 V has the following winding resistances & Reactances:

$R_1 = 1.56\,\Omega$, $R_2 = 0.016\,\Omega$, $X_1 = 4.67\,\Omega$, $X_2 = 0.048\,\Omega$

Calculate the resistance & reactance of the transformer referred to the high voltage winding

Soln.

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

$$R_{e_1} = 1.56 + 0.016 \left(\frac{6350}{660}\right)^2 = 3.04\,\Omega$$

$$\boxed{X_{e_1} = X_1 + X_2 \left(\frac{N_1}{N_2}\right)^2}$$

$$X_{e_1} = 4.67 + 0.048 \left(\frac{6350}{660}\right)^2 = 9.12\,\Omega$$

Que A 1ϕ Transformer has 180 & 90 turns respectively in its Secondary and Primary windings. The respective resistances are 0.233Ω and 0.067Ω. Calculate the equivalent resistance of (a) Primary in terms of Secondary winding (b) Secondary in terms of the primary winding and (c) the total resistance of the Transformer in terms of the primary

Soln (a) $R_1' = R_1 \left(\frac{N_2}{N_1}\right)^2 = (0.067)\left(\frac{180}{90}\right)^2 = 0.268\Omega$

(b) $R_2' = R_2 \left(\frac{N_1}{N_2}\right)^2 = (0.233)\left(\frac{90}{180}\right)^2 = 0.058\Omega$

(c) $R_{e_1} = R_1' + R_2' = R_1 + R_2 \left(\frac{N_1}{N_2}\right)^2 = 0.125\Omega$

Que Enlist Transformer losses & explain them.

Ans Transformer Losses → Copper losses (P_{cu})
→ Iron losses (P_i)
→ Hysteresis losses (P_h)
→ Eddy Current losses (P_e)

(i) Transformer Copper losses – (Variable losses)

These losses occur due to winding Resistance & given by formula, I^2R watt.

if Primary winding Resistance is R_1 Ω & Primary winding current is I_1 amp.

then Primary winding copper losses $= I_1^2 R_1$ watt.

if Secondary winding Resistance is R_2 Ω & Secondary wdg. Current is I_2 amp

then Secondary winding Copper losses $= I_2^2 R_2$ watt.

Total Copper losses of transformer, $P_{cu} = I_1^2 R_1 + I_2^2 R_2$

* These are Variable losses because, they depend on current & Current depend on load because the load is Variable so these losses are also variable.

Transformer Hysteresis losses (P_h) (fixed losses/Constant Losses)

When the magnetic material is magnetised, its domains are aligned in the direction of applied magnetic field if the magnetic material is magnetised in the reverse direction then domains align themselves in the opposite direction.

In this process there is losses of power due to movement of domains. This is called hysteresis losses.

Because the transformer core is magnetic material & supply provided to transformer is single phase alternating so during positive half cycle of input voltage, domains are aligned in one direction and during negative half cycle of input voltage, domains are aligned in other direction

Hence power loss in magnetic core of transformer due to domains movement is called Hysteresis loss.

$$\boxed{P_h = K_h \cdot f \cdot B_m^n} \quad \text{or} \quad \boxed{P_h \propto f}$$

K_h - Constant, f - frequency of supply voltage

B_m - Maximum flux density

B_m^n = where $n = 1.6$

Eddy Current loss (P_e) – (fixed losses/Constant losses)

if the flux is time varying (alternating) and it link with a conducting material (Magnetic core of transformer) then voltage induces in the core, this induced voltage causes a current to flow in the core. This current is called eddy current

P.T.O

Heat is generated in transformer core due to the flow of eddy current, and the power loss due to eddy currents is called Eddy current losses.

* Eddy current losses are reduced by Laminating the transformer core.

$$\boxed{P_e = K_e \cdot f^2 \cdot B_m^2} \quad \text{or} \quad \boxed{P_e \propto f^2}$$

K_e - Constant, f - Supply frequency

B_m - Max. flux density.

(8)

→ Transformer Efficiency :- Imp

The Ratio of the output power to the input power in a transformer is known as Transformer Efficiency.

$$\eta = \frac{\text{output Power}}{\text{Input Power}}$$

$$\eta = \frac{\text{output Power}}{\text{output Power + Copper loss + Iron loss}}$$

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

we know $P_{cu} = (I_1^2 R_1 + I_2^2 R_2) = I_1^2 R_{e_1} = I_2^2 R_{e_2}$

$$\boxed{\eta = \frac{V_2 I_2 \cos\phi_2}{V_2 I_2 \cos\phi_2 + I_2^2 R_{e_2} + P_i}}$$

Condition for max. Efficiency :-

$$\frac{d\eta}{dI_2} = 0$$

$$\frac{d}{dI_2}\left[\frac{V_2 I_2 \cos\phi_2}{V_2 I_2 \cos\phi_2 + I_2^2 R_{e_2} + P_i}\right] = 0$$

$$P_i = I_2^2 R_{e_2}$$

$$\boxed{P_i = P_{cu}}$$

Current at max. Efficiency :-

$$P_i = P_{cu} \Rightarrow P_i = I_{2M}^2 R_{e_2}$$

I_{2M} = Secondary Max Current

$$P_i = I_{2M}^2 R_{e_2}$$

$$I_{2M}^2 = \frac{P_i}{R_{e_2}}$$

$$I_{2M}^2 = \frac{I_{2(fl)}^2 P_i}{I_{2(fl)}^2 R_{e_2}}$$

$$I_{2M} = \sqrt{\frac{I_{2(fl)}^2 P_i}{I_{2(fl)}^2 R_{e_2}}}$$

$$\boxed{I_{2M} = I_{2(fl)}\left(\sqrt{P_i/P_{cu(fl)}}\right)}$$

Current at Max. η = (full load i) $\times \sqrt{\frac{\text{Constant Iron loss}}{\text{Full load Cu loss}}}$

<u>KVA Rating at max. η</u> :-

$$I_{2M} = I_{2(fl)} \sqrt{\frac{P_i}{P_{cu(fl)}}}.$$

multiply both side by V_2

$$V_2 I_{2M} = V_2 I_{2(fl)} \sqrt{P_i/P_{cu(fl)}}$$

$$\boxed{S_M = S_{(fl)}\left(\sqrt{\frac{P_i}{P_{cu(fl)}}}\right)}$$

<u>Example</u> :- A 40 KVA Transformer has a Core loss of 400W. and full load copper loss of 800 W. if the P.F of the load is 0.9 lag. find (a) η_{fl} (b) load at which η_{max} occur.

<u>Sol</u>

$$\boxed{\%\eta = \frac{m \times (KVA) \times P.F}{m \times (KVA) \times PF + P_i + m^2 P_{cu}} \times 100}$$

m = fraction of load.

96.77%

$$\boxed{\text{load for } \eta_{max} = \sqrt{\frac{P_i}{P_{cu(fl)}}}}$$

5) A 40 KVA Transformer has a Core loss of 400 watt and full load Copper loss of 800 watt if the Power factor of load is 0.9 lag. Calculate :

(a) The full load efficiency 96.77 %

(b) Percentage of the full load at which max. η occurs.? 70.71 % (UPTU - 2007-08)

(c) η_{max} ~~97.82~~% 96.95 %.

6) A 10 KVA, 1ϕ Transformer with 2000/400 V at no load, has resistance & leakage reactance of primary wdg. of 5.5 Ω & 12 Ω resp, the corresponding values of Secondary winding being 0.2 Ω & 0.45 Ω. Determine the value of Secondary Voltage at full load, 0.8 PF lagging, when the primary applied voltage is 2000V (UPTU - 2006-07)

[V_2 = 377.65 V]

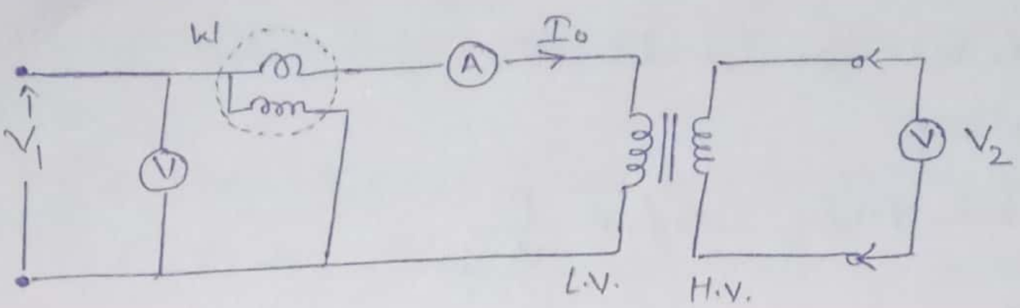
7) A 250 KVA, 1ϕ Transformer has iron loss of 1.8 KW. The full load Copper loss is 2000 W. Calculate Efficiency at full load 0.8 lag. P.f. [98.13 %]

8) In a 25 KVA, 2000/200V Transformer, the Constant and Variable losses are 350 W & 400 W resp. Cal the efficiency on unity P.f at
(a) full load (b) half load [97.08 %, 96.53 %

<u>Allday Efficiency</u> / <u>Full day Efficiency</u> :-
All day efficiency is defined for <u>Distribution Transformers</u>, where the load varies continuously

$$\text{All day Efficiency} = \frac{\text{Total Energy output for 24 hours}}{\text{Total Energy input for 24 hours}}$$

OPEN-CIRCUIT TEST :-



(Connection Diagram)

- This test is performed on L.V. side
- This test is performed at rated voltage & freq. hence voltmeter will read primary voltage V_1
- Since secondary is open-circuited, a very small current (No load current) I_0 will flow through primary hence Ammeter will read No load current (I_0).
- at no load, secondary winding current is zero; so the copper losses at secondary side ($I_2^2 R_2$) will be zero

at primary side, very small primary current flow (3-5% of full load current) so primary copper losses will also be negligible.

hence wattmeter will measure constant core losses

Ammeter Reading = No load current I_0

Voltmeter Reading = Primary Rated Voltage V_1

Wattmeter Reading = Iron / Core loss P_i

From these measured Values, the Components of the no load equivalent Circuit can be determined -

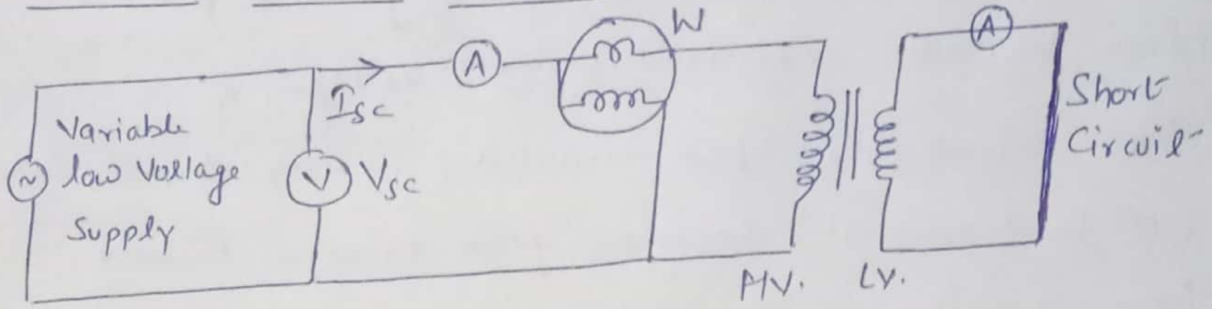
$P_i = V_1 I_0 \cos\phi_0$

No load Power Factor, $\cos\phi_0 = \frac{P_i}{V_1 I_0}$

$I_c = I_0 \cos\phi_0$, $I_m = I_0 \sin\phi_0$

$R_0 = \frac{V_1}{I_c}$, $X_0 = \frac{V_1}{I_m}$

SHORT-CIRCUIT TEST :-



- In s.c test; low voltage side is short circuited & an ammeter is connected to measure the short circuit current.
- A Variable low Voltage AC Supply is provided on H.V. side and a Voltmeter, a ammeter & a wattmeter is connected to measure ~~Current~~ ~~to~~ supply voltage, short circuit current & full load copper losses respectively.
- The high Voltage winding is supplied at reduced Voltage from Variable Voltage supply
- The supply Voltage is gradually increased until full load Primary Current flows.

in this Situation rated full load Current will also flow in Secondary side by transformer action

- Since the applied voltage is low (about 5-10% of the normal rated supply voltage), the flux ϕ produced is low.

  Also, since the core loss is nearly proportional to the square of the flux, the core loss is so small that it can be neglected.

- The windings are carrying normal full load current & therefore the input power will be supplied to full load copper losses.

  Thus the wattmeter gives the full load copper losses.

Ammeter Reading = Full load Primary Current (I_{1sc})

Voltmeter Reading = Short Circuit Voltage (V_{1sc})

Wattmeter Reading = Full load Copper losses. (P_{cFL})

Equivalent resistance referred to primary -

$$R_{e_1} = \frac{P_{cFL}}{I_{1sc}^2}$$

Equivalent Impedance referred to Primary -

$$Z_{e_1} = \frac{V_{1sc}}{I_{1sc}}$$

Equivalent Reactance referred to primary -

$$X_{e_1} = \sqrt{Z_{e_1}^2 - R_{e_1}^2}$$

$$\cos\phi_{sc} = \frac{R_{e1}}{Z_{e_1}}$$

Q. Why the short circuit test is performed on low voltage side & measurements are taken on H.V. side ??

Ans. (a) The Rated current on H.V. side is lower than that on L.V. side. This current can be safely measured with available lab ammeters.

(b) ~~Since~~ Since the applied voltage is less than 5% of rated voltage of winding, greater accuracy in the voltmeter reading is possible when the HV. side is used as primary.

12.17 FULL-LOAD PHASOR DIAGRAM

Figure 12.21 shows the phasor diagram for the exact circuit model of transformer of Fig. 12.15. It is assumed that the load is inductive, which is generally the case. Let cos ϕ_2 be the power factor of the load (lagging). The phasor $\mathbf{V}_2$ is taken as reference. Since the load power factor is lagging, the secondary current $\mathbf{I}_2$ lags behind $\mathbf{V}_2$ by the power factor angle ϕ_2. The secondary current $\mathbf{I}_2$ flows through R_2 and X_2 and produces voltage drops across them equal to I_2R_2 and I_2X_2. The resistive voltage drop I_2R_2 is in phase with $\mathbf{I}_2$ and the inductive voltage drop I_2X_2 leads the current $\mathbf{I}_2$ by 90°. The secondary induced voltage $\mathbf{E}_2$ is the phasor sum of V_2, I_2R_2 and I_2X_2.

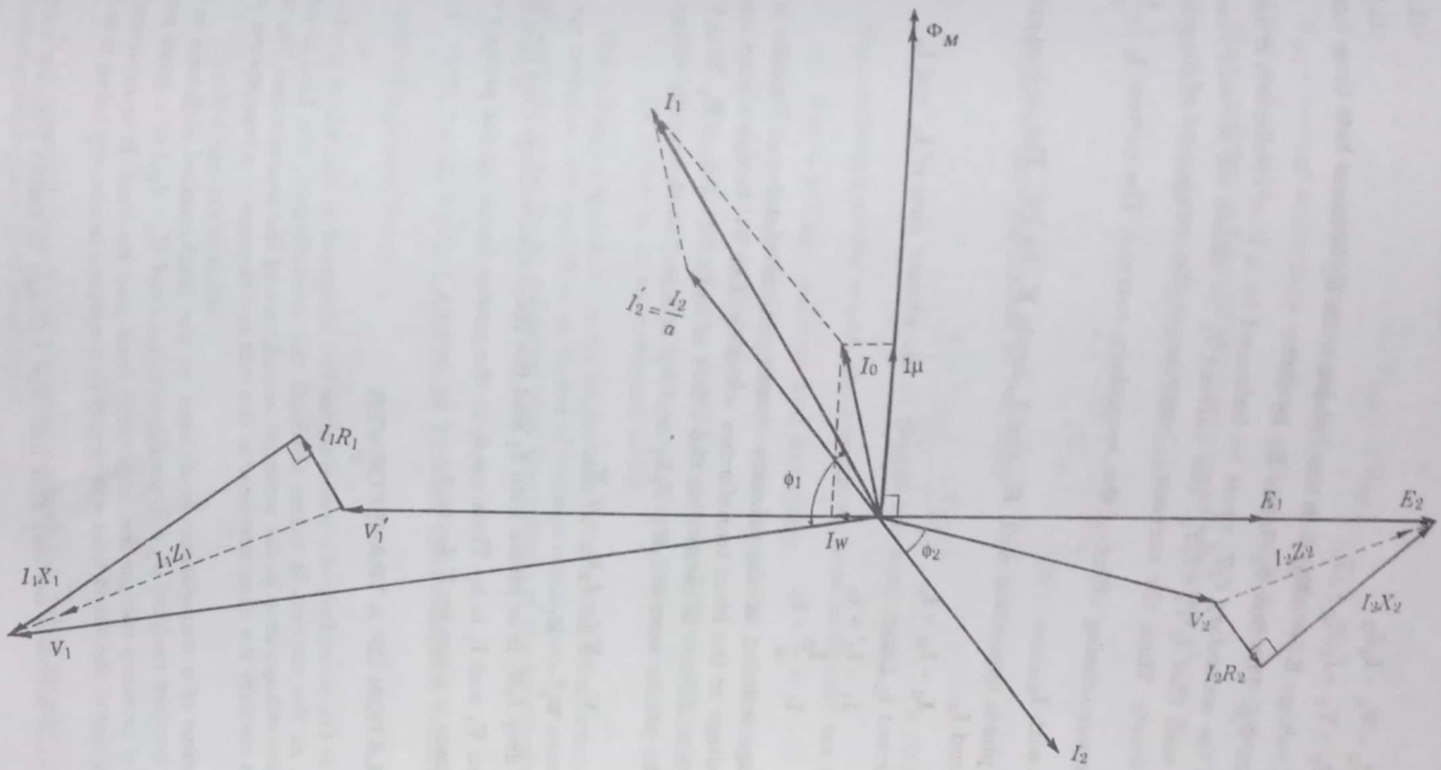


Fig. 12.21. Phasor diagram for the exact equivalent circuit of real transformer of Fig. 12.15

That is,

$$\mathbf{E}_2 = \mathbf{V}_2 + \mathbf{I}_2\mathbf{Z}_2 \tag{12.17.1}$$

$$\mathbf{E}_2 = \mathbf{V}_2 + I_2(R_2 + jX_2) \tag{12.17.2}$$

The primary induced voltage $\mathbf{E}_1$ ($= a\mathbf{E}_2$) is in time phase with $\mathbf{E}_2$ because both these voltages are induced by the same flux Φ_M. The flux Φ_M leads $\mathbf{E}_1$ by 90°.

The ampere turns of the secondary I_2T_2 must be balanced by a load component of current I_2 in the primary winding such that $I_2'T_1 = I_2T_2$. The current I_2' is called the *secondary current referred (reflected) to the primary*. Thus, the current I_2' represents the component of the primary current to neutralize the demagnetizing effect of the secondary current. The current $\mathbf{I}_2'\left(=\frac{\mathbf{I}_2}{a}\right)$ is therefore 180° out of phase with $\mathbf{I}_2$.

The current $\mathbf{I}_W$ is in phase opposition with $\mathbf{E}_1$ and $\mathbf{I}_\mu$ leads $\mathbf{E}_1$ by 90°. The no-load current $\mathbf{I}_0$ is the phasor sum of $\mathbf{I}_W$ and $\mathbf{I}_\mu$.

$$\mathbf{I}_0 = \mathbf{I}_W + \mathbf{I}_\mu$$

The total primary current $\mathbf{I}_1$ taken from the supply is the phasor sum of $\mathbf{I}_2'$ and $\mathbf{I}_0$.

$$\mathbf{I}_1 = \mathbf{I}_2' + \mathbf{I}_0$$

$$\mathbf{I}_1 = \frac{\mathbf{I}_2}{a} + \mathbf{I}_0$$

Since $\mathbf{E}_1$ is the voltage induced in the primary winding, it is equal and opposite to the component of the applied voltage at the ideal transformer winding. Let $\mathbf{V}_1'$ be the voltage applied to the primary of the ideal transformer to neutralize the effect of induced voltage $\mathbf{E}_1$. Thus $\mathbf{V}_1'$ is equal and opposite to $\mathbf{E}_1$. The phasor sum of I_1R_1, I_1X_1 and $\mathbf{V}_1'$ is equal to the supply voltage $\mathbf{V}_1$. That is,

$$\mathbf{V}_1 = \mathbf{V}_1' + I_1R_1 + jI_1X_1$$

$$\mathbf{V}_1' = -\mathbf{E}_1$$

The resistive voltage drop I_1R_1 is in phase with $\mathbf{I}_1$ and the inductive voltage drop I_1X_1 leads $\mathbf{I}_1$ by 90°. The angle between $\mathbf{V}_1$ and $\mathbf{I}_1$ is ϕ_1. Thus $\cos\phi_1$ is the power factor on the primary side. Power input to the transformer is given by $V_1I_1\cos\phi_1$.

12.18 VOLTAGE REGULATION OF A TRANSFORMER

Majority of loads connected to the secondary of a transformer 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 arithmetical difference in the secondary terminal voltage between no-load ($I_2 = 0$) and full-rated load ($I_2 = I_{2fl}$) at a given power factor with the same value of primary voltage for both rated load and no-load.* It is expressed as either a per unit or a percentage of the rated load voltage. Rated voltage is usually taken to be the nameplate value.

The numerical difference between no-load and full-load voltage is called *inherent voltage regulation*.

Inherent voltage regulation

$$\overset{\Delta}{=} |\mathbf{V}_{2nl}| - |\mathbf{V}_{2fl}| \tag{12.18.1}$$

where V_{2fl} = rated secondary terminal voltage at rated load

V_{2nl} = no-load secondary terminal voltage with the same value of primary voltage for both rated load and no load

The quantities in Eq. (12.18.1) are *magnitudes, not phasors.*

Per-unit voltage regulation at full load

$$\overset{\Delta}{=} \left. \left| \frac{|\mathbf{V}_{2nl}| - |\mathbf{V}_{2fl}|}{|\mathbf{V}_{2fl}|} \right| \right|_{|V_1| = \text{constant}} \tag{12.18.2}$$

Percent voltage regulation at full load

$$\overset{\Delta}{=} \left. \left| \frac{|\mathbf{V}_{2nl}| - |\mathbf{V}_{2fl}|}{|\mathbf{V}_{2fl}|} \right| \right|_{|V_1| = \text{constant}} \times 100 \tag{12.18.3}$$

The conditions under which the regulation is to be figured are as follows :

(1) Rated voltage, current and frequency.

(2) When regulation is stated without specific reference to the load conditions, rated load is to be understood.

(3) Waveform of voltage should be assumed sinusoidal unless stated otherwise.

(4) Power factor of the load should be mentioned. If the power factor is not specified, its value is to be assumed unity.

The voltage regulation is an important measure of transformer performance. The limits of voltage variation are specified in terms of voltage regulation. For example, transformers in public supply systems must be so adjusted that the voltage at the terminals of the consumers must not exceed ± 5%.