ELECTRICAL MACHINES(EE 554)

Chapter-2 (Transformer)

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2.1 Introduction:

- Transformer is a static machine which transfers electrical power from one circuit to another circuit.

- The two circuits **are electrically isolated** from each other, but they are linked by **common magnetic flux.**

- While transferring the electrical power from one circuit to another circuit, the voltage level of the second circuit may be different from that of the first circuit, but the **frequency of both circuits remains same**.

- Fig.2.1 represents the block diagram of a transformer.

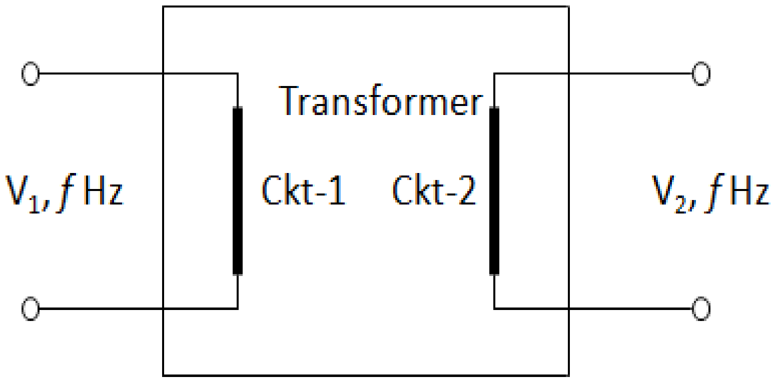


Fig.2.1 Block diagram representation of transformer

2.2 Basic construction and operating principle:

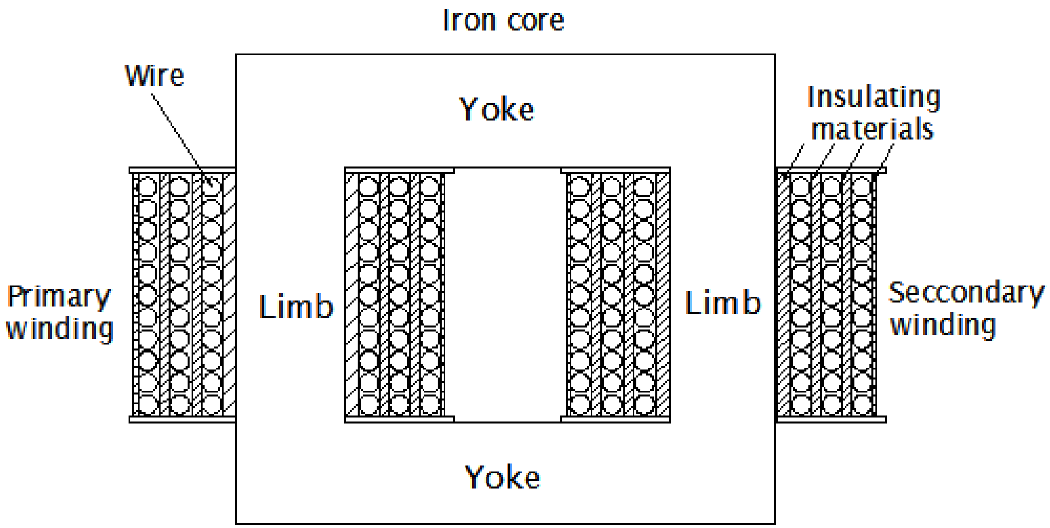


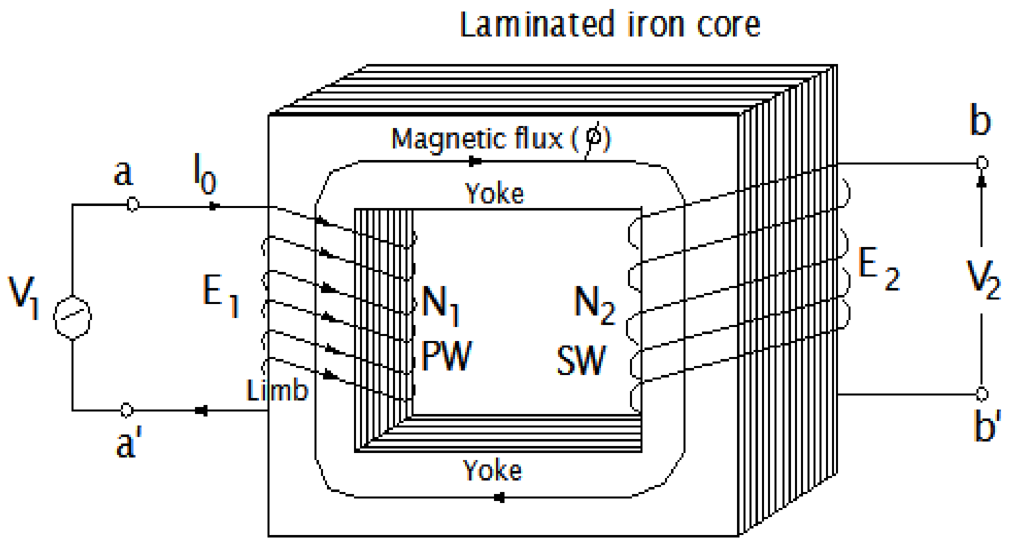
Fig.2.2 Basic construction of transformer

-Basically, a transformer consists of a rectangular window shaped iron core as shown in Fig.2.2. The horizontal part of the core is known as ‘**yoke**’ and the vertical part of the core is known as **‘limb**’.

-The core is made of **laminated silicon steel**. Two separate coils (windings) are wound on the two separate limbs of the core. The coils are made of **enamel insulated copper wire**.

Operating principle:

When one of the winding (say a-a') is excited by ac voltage source 'V_1', then the winding will draw some current (say I_0). If the winding is assumed to be purely inductive with zero resistance, the current I_0 lags the supply V_1 by 90^0 as shown in Fig.2.4.



.2.3 Circuit representation of transformer

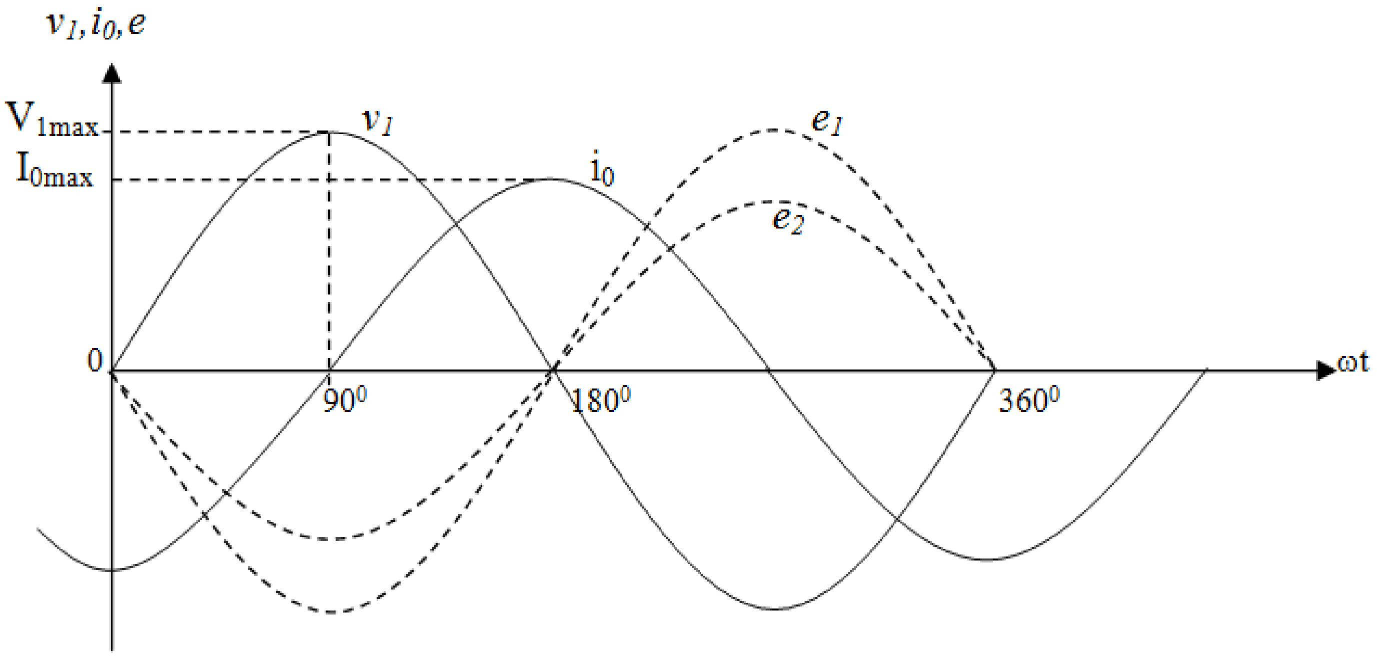
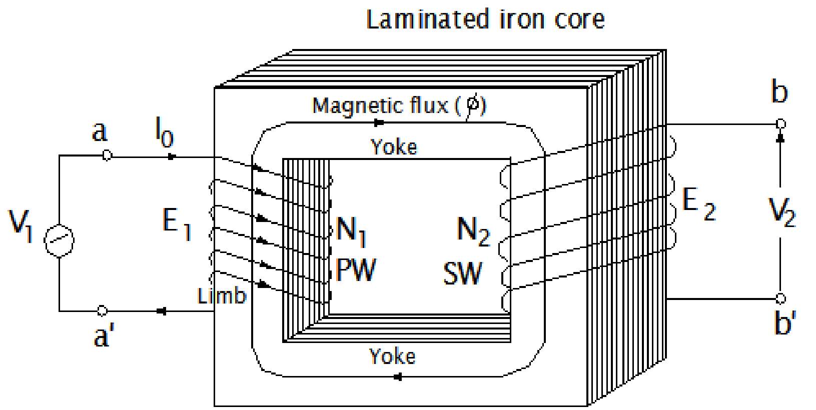


Fig.2.4.Waveforms of input voltage, no-load current and emf induced

Operating principle:

The iron core gets magnetized and magnetic flux will circulate through the iron core. The magnitude of magnetic flux is given by:

$$\phi = \frac{N_1.i_0}{\text{Re}\,l} \qquad (2.1)$$



Where, N_1 = Number of turns in the coil a-a’
i_0 = Instantaneous value of current through the coil a-a’
Rel = Reluctance of the core.

Since the applied voltage v_1 is alternating in nature, the current i_0 also will be alternating in nature. Hence, the **magnetic flux (ϕ)** also will be alternating in nature and **in phase with i_0** as shown in Fig.2.5.

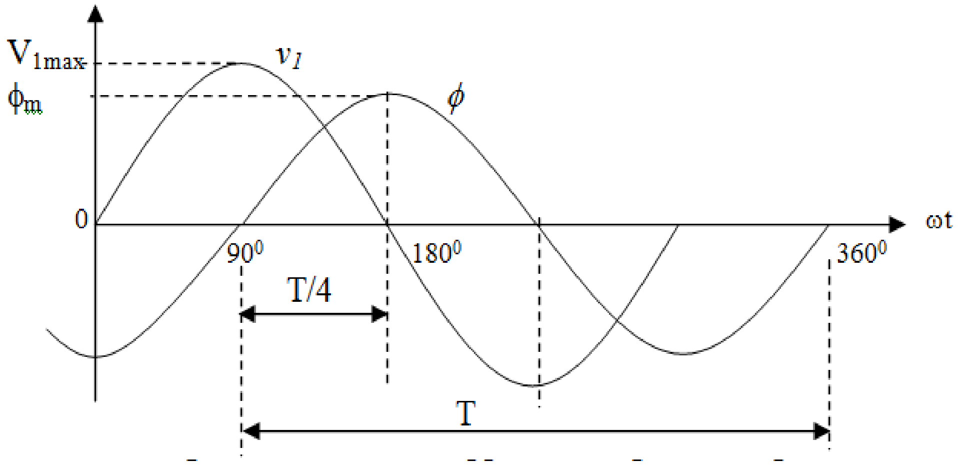


Fig.2.5 Waveforms of input voltage and magnetic flux

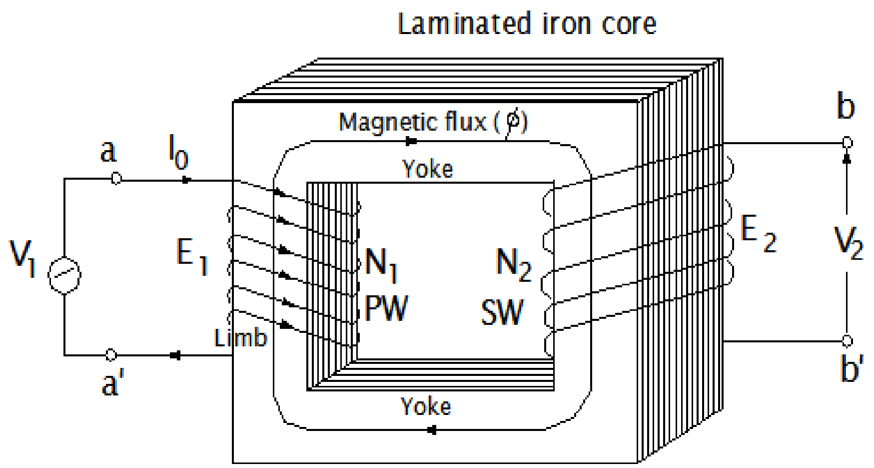
Operating principle:

- The magnitude of magnetic flux in the core is changing with respect to time and it is linking with the second coil on the another limb.

- Hence, according to **Faraday's law of electromagnetic induction, emf (e_2)** will induce in the second coil b-b'.

- If the load is connected across the second coil, electric current will circulate through the load thus by transferring the electrical power from coil a-a' to coil b-b'.

- This is the operating principle of transformer

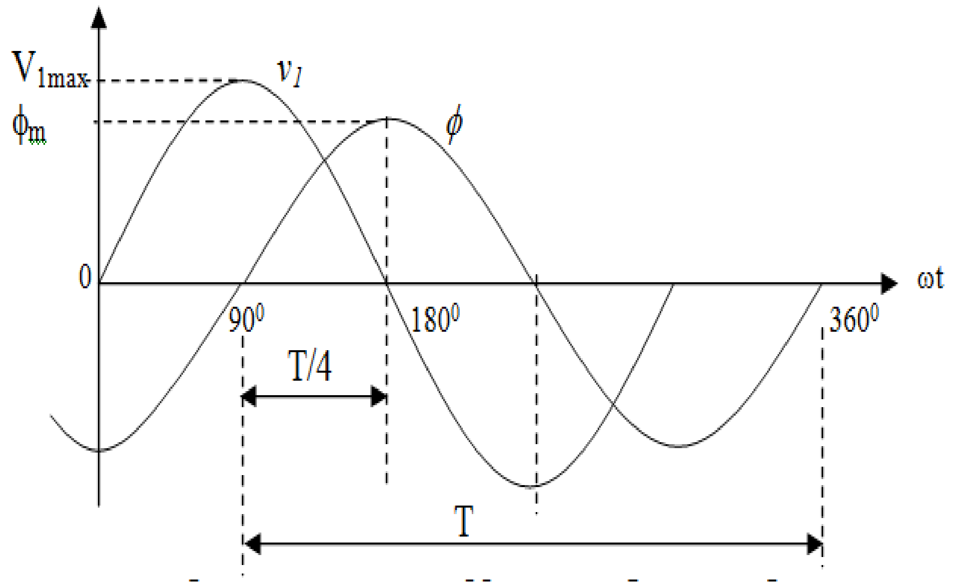


  - The coil, on which the supply voltage is applied, is known as **primary winding (PW)**
  - The second coil, on which the **emf (e_2) is induced**, is known as **secondary winding (SW).**

Calculation of induced emf:

According to 2nd law of Faraday's law of electromagnetic induction, the average value of emf induced (e_2) is given by:

$$E_{2(avg)} = N_2 \frac{d\phi}{dt} \qquad (2.2)$$



Where, N_2 = Number of turns in secondary winding

$\frac{d\phi}{dt}$ = Average rate of change of magetic flux

Magnetic flux changes from 0 to ϕ_m in T/4 sec.

$$\text{Hence, } \frac{d\phi}{dt} = \frac{\phi_m - 0}{T/4} = \frac{4.\phi m}{T} = 4\, f\, \phi m \quad (\text{Because, } f = \frac{1}{T})$$

$$\therefore\ E_{2(avg)} = N_2 \frac{d\phi}{dt} = 4\, N_2\, f\, \phi m$$

$$\text{For sine-wave, form factor} = \frac{\text{RMS Value}}{\text{Average Value}} = 1.11$$

$\therefore$ RMS value of emf induced in the secondary winding is given by:

$$E_2 = 4.44\, N_2\, f\, \phi_m \ \text{Volt} \qquad (2.3)$$

- According to the **Lenz's law** the direction of **e_2 at every instant opposes the direction of v_1** at every instant.

- As the magnetic flux also links with the primary winding, emf (e_1) will also induced in the primary winding.

-The direction of e_1 at every **instant opposes the direction of v_1** at every instant.

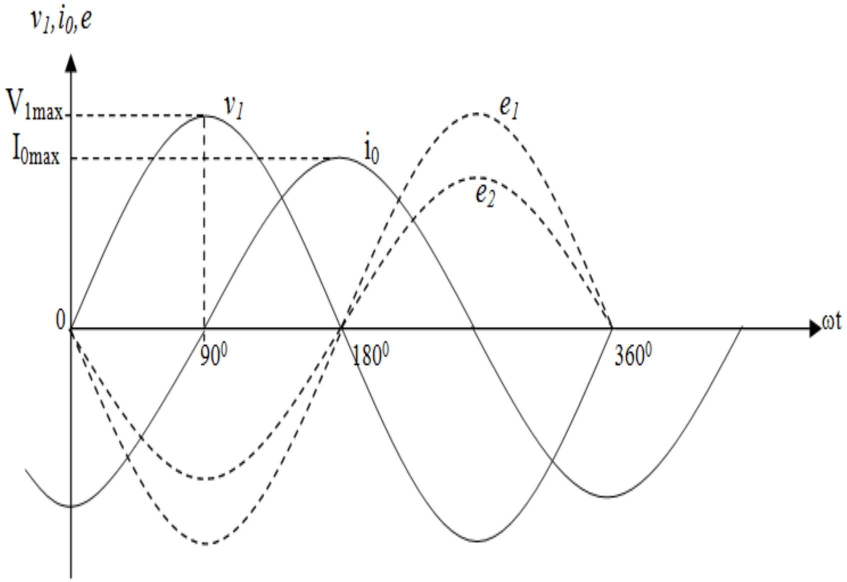
-The magnitude of emf induced in the primary winding is given by:

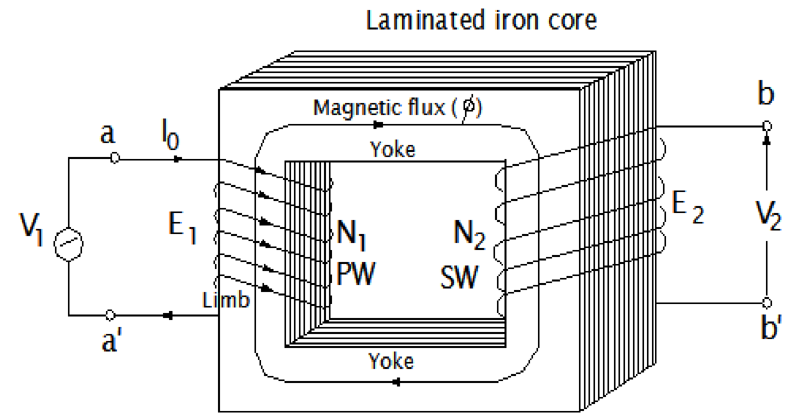
$$E_1 = 4.44\, N_1\, f\, \phi_m \qquad (2.4)$$

Now the primary winding is under the pressure of two voltages V_1 and E_1. The magnitude E_1 will be little less than the magnitude of V_1. Therefore, the current I_0 is given by:

$$\tilde{I}_0 = \frac{\tilde{V}_1 - \tilde{E}_1}{Z_1} \qquad (2.5)$$

$$\text{OR} \quad \tilde{V}_1 - \tilde{I}_0 Z_1 = \tilde{E}_1 \qquad (2.6)$$

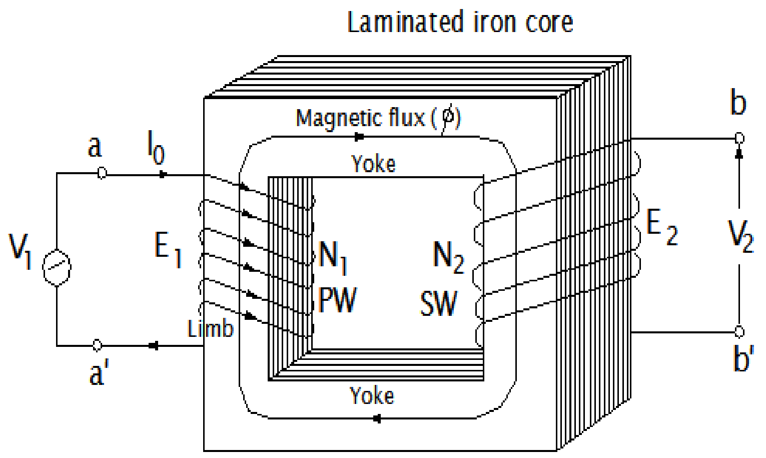




-Where, **Z_1** is the **impedance of the primary winding**.
- Since **E_1 opposes the flow of current I_0**, it is also known as **back emf**.

At no-load condition (i.e. secondary winding open),

- no current flows through the secondary winding and no voltage drop take place in the secondary winding internal impedance.



$\therefore$ **$V_2 = E_2$, Where V_2 is the load terminal voltage at secondary side.**

As the primary current (I_0) at no-load condition is **very small**, the voltage drop in the internal impedance of primary winding **($I_0 Z_1$) is very small.**

$\therefore$ $V_1 \approx E_1$ (Nearly equal)

Dividing eqn (2.3) by eqn (2.4) gives: $\dfrac{E_2}{E_1} = \dfrac{4.44\,N_2\, f\, \phi_m}{4.44 N_1\, f\, \phi_m} = \dfrac{N_2}{N_1} = \dfrac{V_2}{V_1}$

$$V_2 = \frac{N_2}{N_1} V_1 = K.V_1 \qquad (2.7)$$

Where, $K = \dfrac{N_2}{N_1}$ = Transformation Ratio

The magnitude of emf induced in the secondary winding depends upon the transformation ratio. The following three cases may exist:

Case-I : If **$N_2 > N_1$**, i.e. $K > 1$, then **$V_2 > V_1$**
Such a transformer is known as **step up transformer**

Case-II : If **$N_2 < N_1$**, i.e. $K < 1$, then **$V_2 < V_1$**
Such a transformer is known as **step down transformer**

Case-III : If **$N_2 = N_1$**, i.e. $K = 1$, then **$V_2 = V_1$**
Such a transformer is known as **isolation transformer**

2.3 Ideal Transformer :

- An ideal transformer is that which has **purely inductive winding** without any resistance, **without any magnetic leakage flux** and which is **100% efficient** without any power loss within the transformer.

- This is just the mathematical realization and such transformer can not be constructed in real practice.
- The operating principle of the transformer so far explained was based on the assumption of ideal transformer.
- Now, operation of **real transformer** shall be described in the following sections.

<u>Illustrative example2.1</u>:

The primary winding of a 50Hz transformer is supplied by 6600V and it has 520 turns. The secondary winding has 260 turns**. Calculate**: Peak value of magnetic flux in the core and Secondary voltage.

<u>Solution</u>:

The emf induced in the primary winding is given by:

$E_1 = 4.44\ N_1\ f\ \phi_m$ It is nearly equal to the applied voltage to primary winding(V_1).

$$\therefore V_1 = 4.44\ N_1\ f\ \phi_m$$

Or, Peak value of flux in the core = $\phi_m = \dfrac{V_1}{4.44 \times N_1 \times f} = \dfrac{6600}{4.44 \times 520 \times 50} = 0.0572\ \mathrm{Wb}$

$$\text{Secondary Voltage } V_2 = V_1 \times \frac{N_2}{N_1} = 6600 \times \frac{260}{520} = 3300V$$

2.4 No-Load and Loaded Operation of Real Transformer :

- When the primary winding is supplied by AC voltage source of rated voltage and frequency, keeping secondary winding open without load as shown in Fig.2.6, such a operation is known as no-load operation. The current drawn by the primary winding (I_0) is known as no-load primary current.

- **At no-load**, output power from secondary winding is zero.
- Therefore no power is transferred from primary winding to secondary winding.
- Only emf is induced in the secondary winding.

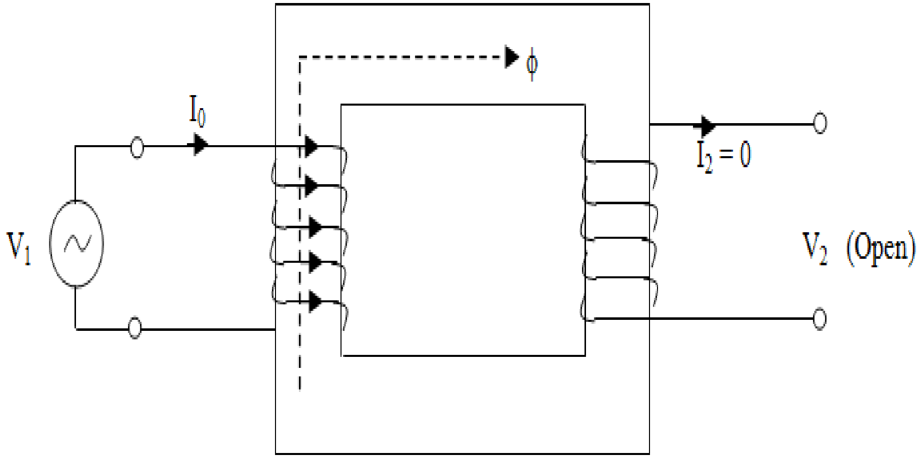


Fig.2.6 No-load operation of transformer

- The power (VA) consumed by the primary winding is utilized to supply:
    - No-load power loss (Active Power loss due to heating of iron core)
    - Reactive Power loss to establish the magnetic flux in the core.
    - Note: Active power loss **α** Current in phase with V_1
    - Reactive power loss **α** Current lagging by 90^0 with V_1

Therefore no-load current I_0 has two components as shown in the Fig.2.7.

That means the **no-load current (I_0)** of a real transformer does not lag by 90^0 with V_1 as explained in the operating principal of ideal transformer. It lags by an angle ϕ_0 which is less than 90^0.

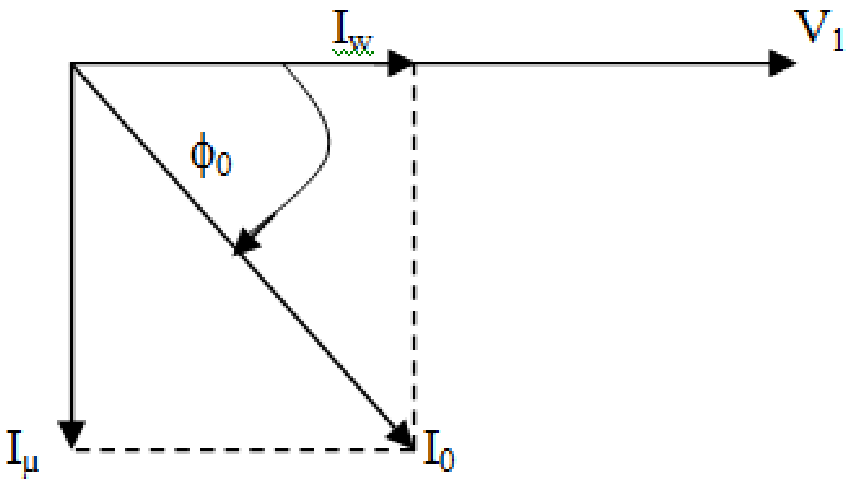


Fig.2.7 Phasor diagram for no-load operation

- I_w = Component of I_0 in phase with V_1,
  $I_w = I_0 \cos\phi_0$ = Loss component of I_0

- I_μ = Component of I_0 which lags V_1, by 90^0,
  $I_\mu = I_0 \sin\phi_0$ = Magnetizing component of I_0

The active power consumed by transformer at no-load is given by:

$W_0 = V_1 I_0 \cos\phi_0 = V_1 I_w$ Watts (2.8)

- This power will be lost within the transformer in **heating the iron core**. Hence, $\mathbf{W_0}$ is known as no-load power loss or iron loss of the transformer.
- Therefore, the component $\mathbf{I_w}$ is responsible for producing heat loss in the iron core.
- $\mathbf{Cos\phi_0}$ is known as **no-load power factor** of the transformer.

The reactive power consumed by transformer at no-load is given by:

$$\mathbf{W_0 = V_1 I_0 \sin\phi_0 = V_1 I_\mu} \quad \textbf{Vars} \qquad (2.9)$$

This reactive power is utilized to maintain magnetic flux in the core. Therefore, the component I_μ is responsible for maintaining magnetic flux in the iron core. Here it shall be noted that only reactive power can establish magnetic flux in magnetic circuit excited by AC voltage.

From the phasor diagram , it can be written as:

$$I_0 = \sqrt{I_w^2 + I_\mu^2} \qquad (2.10)$$

<u>When the transformer is loaded</u> as shown in Fig.2.8, Current (I_2) will flow through the secondary winding. Now the secondary mmf N_2I_2 will set up its own magnetic flux $\boldsymbol{\phi_2}$, whose direction will be opposite to main flux $\boldsymbol{\phi}$. **(as per Lenz's law)**

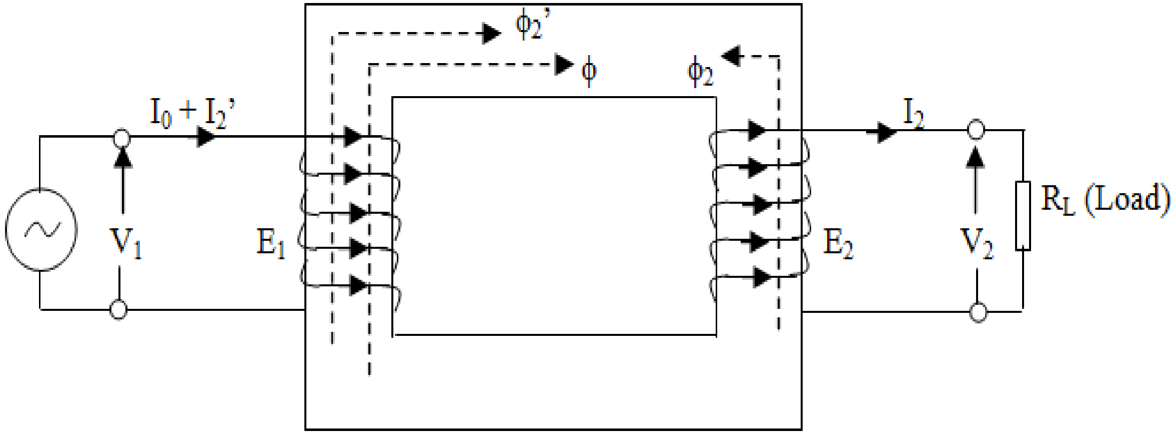


Fig.2.8 Loaded operation of transformer

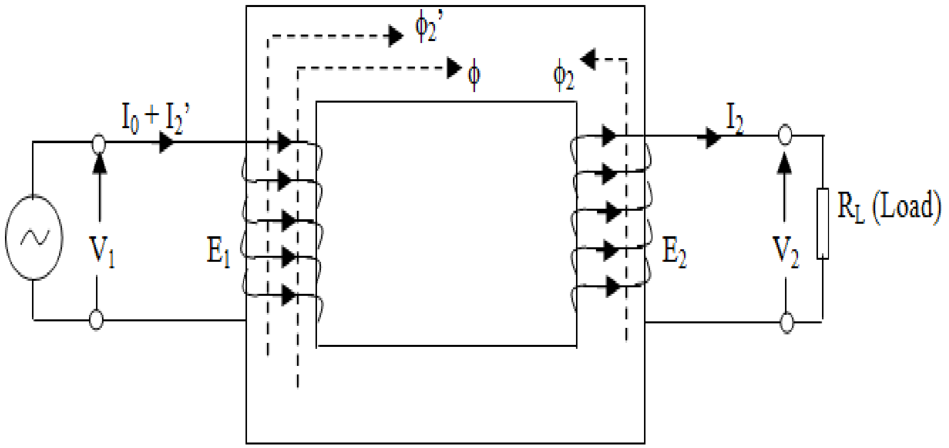
-At no-load, the output volt-amp (V_2I_2) is equal to zero, but input volt-amp is V_1I_0. This input volt-amp is lost within the transformer.

-When the transformer is loaded, the output volt-amp of the transformer is V_2I_2.

-Now in order to make power balance between primary winding and secondary winding, some additional current I_2' will flow in the primary winding to increase the power in primary winding.

-This additional current in the primary winding will set up additional magnetic **flux ϕ_2'**, whose magnitude is equal to ϕ_2 and direction is opposite to ϕ_2. Therefore**,** ϕ_2' cancels ϕ_2. and net magnetic flux in the core remains constant and equal to main flux ϕ irrespective of load.

-That means magnetic flux in the core remains constant at any load conditions.



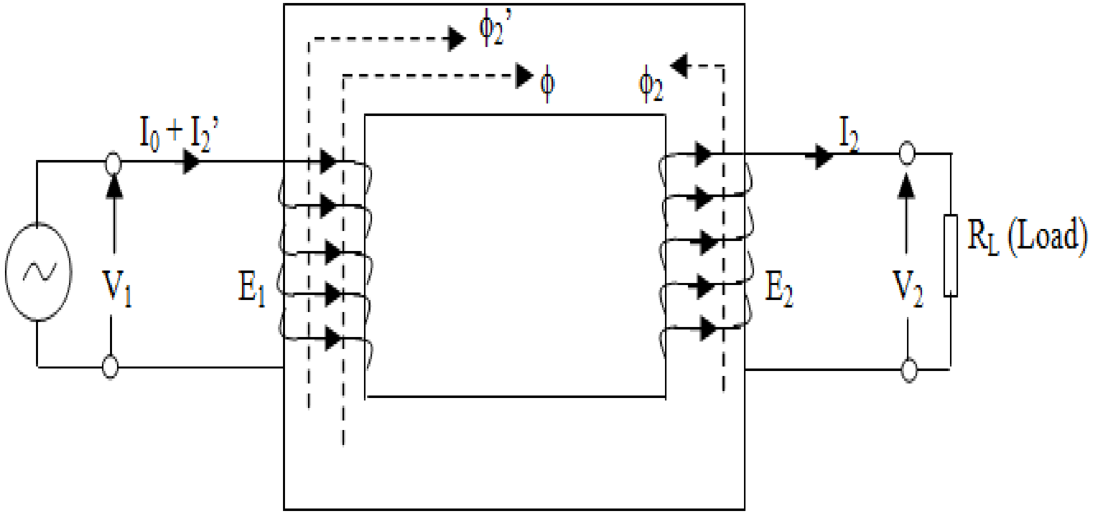
The additional power in the primary winding should be equal to the power in the secondary winding.

$$\therefore\ \mathbf{V_1.I_2' = V_2.I_2} \quad \text{OR} \quad \frac{I_2'}{I_2} = \frac{V_2}{V_1} = \frac{N_2}{N_1} \quad \textbf{Or} \quad \mathbf{N_1.I_2' = N_2.I_2}\ \textbf{(Amp-turn balance)}$$

According to magnetic circuit theory:

$$\phi_2 = \frac{N_2.I_2}{RELUCTANCE} \qquad \text{And} \qquad \varphi_2' = \frac{N_1.I_2'}{RELUCTANCE}$$

The reluctance for both the cases are equal. Therefore, $\boldsymbol{\phi_2 = \phi_2'}$ and **they cancel each other**.



2.5 Equivalent Circuit of Real Transformer:

- It is seen that the net magnetic flux remains constant, it does not depend on the load current I_2 and it only depends on no-load current.
- In order to satisfy these physical conditions of the transformer, the equivalent circuits of the transformer without load and with load are developed as shown in Fig.2.9 and Fig.2.10 respectively.

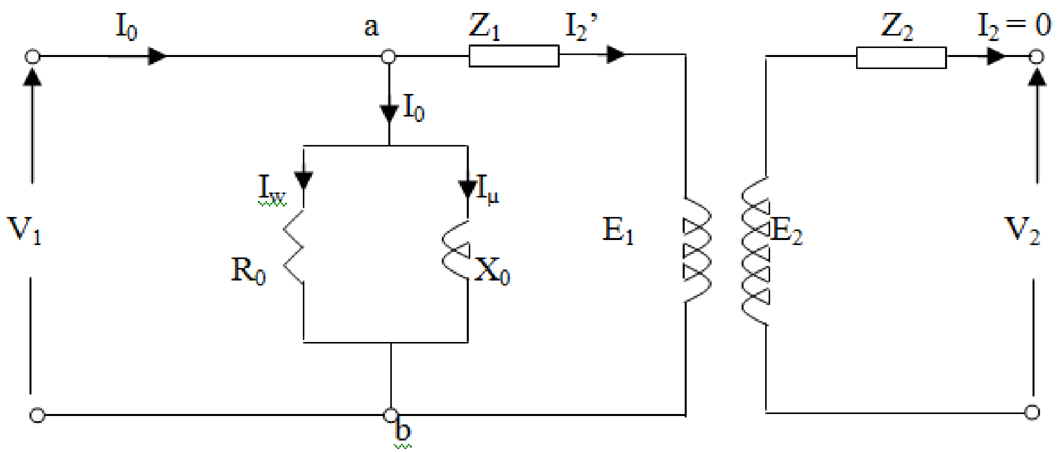


Fig.2.9 Equivalent circuit of transformer at no-load

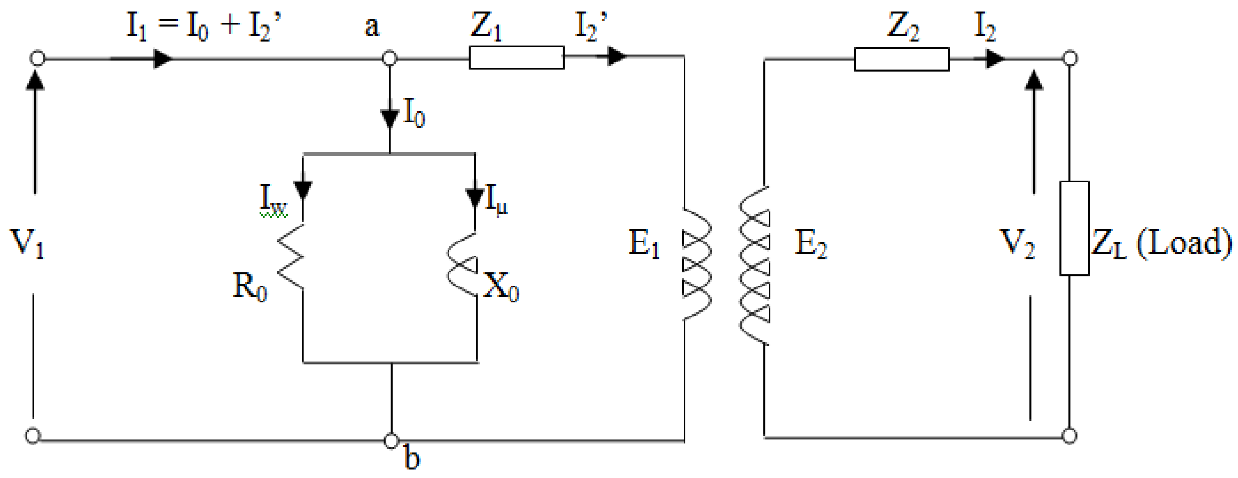


Fig.2.10 Equivalent circuit of transformer with load

V_1 = Input voltage
E_1 = Emf induced across the P.W.
E_2 = Emf induced across the S.W.
V_2 = Load terminal voltage (< E_2)
I_0 = No-load primary current (remains constant)
I_2 = Load current = S.W. current (Varies with load)
I_2' = Additional current in primary P.W. due to load on secondary side.
R_1 = Resistance of P.W.
X_1 = Leakage reactance of P.W.
R_2 = Resistance of S.W.
X_2 = Leakage reactance of S.W.
R_0 = Shunt branch core loss resistance
X_0 = Shunt branch magnetizing reactance
$I_w = V_1/R_0$ = In phase component of I_0
$I_\mu = V_1/X_0$ = 90^0 lagging component of I_0
$I_w^2 R_0$ = Iron loss (core loss)
$I_\mu^2 X_0$ =Reactive power consumes by transformer to produce magnetic flux in the core

$$Z_1 = (R_1 + jX_1) = \text{Series Impedance of primary winding}$$

$$Z_2 = (R_2 + jX_2) = \text{Series Impedance of secondary winding}$$

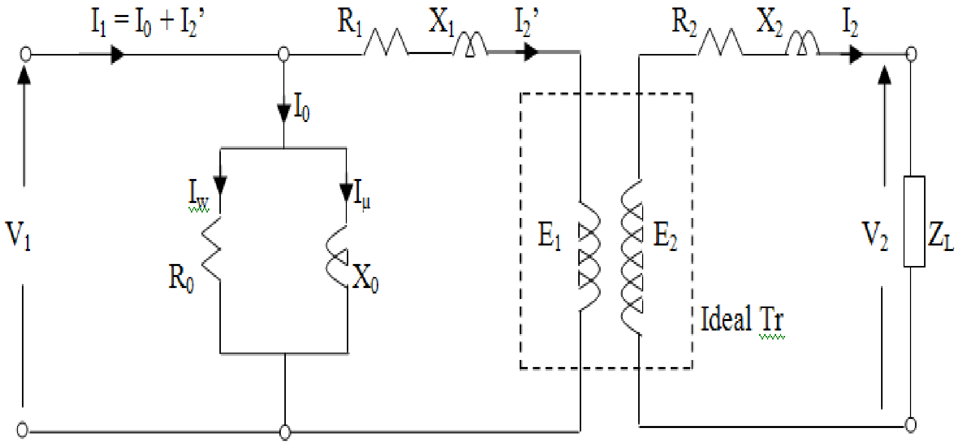


Fig.2.10 Detail Equivalent circuit of transformer

$$\tilde{V}_1 - \tilde{I}_2'.(R_1 + jX_1) = \tilde{E}_1$$ Since $\mathbf{I_0}$ **is <<** $\mathbf{I_2'}$ **,** $\mathbf{I_1 \approx I_2'}$

$$\textit{Therefore}\ \tilde{V}_1 - \tilde{I}_1.(R_1 + jX_1) = \tilde{E}_1 \text{ (approximately)} \qquad (2.11)$$

$$\text{And}\quad \tilde{V}_2 = \tilde{E}_2 - \tilde{I}_2.(R_2 + jX_2) \qquad (2.12)$$

The physical significance of leakage reactance can be explained with the help of Fig.2.12.

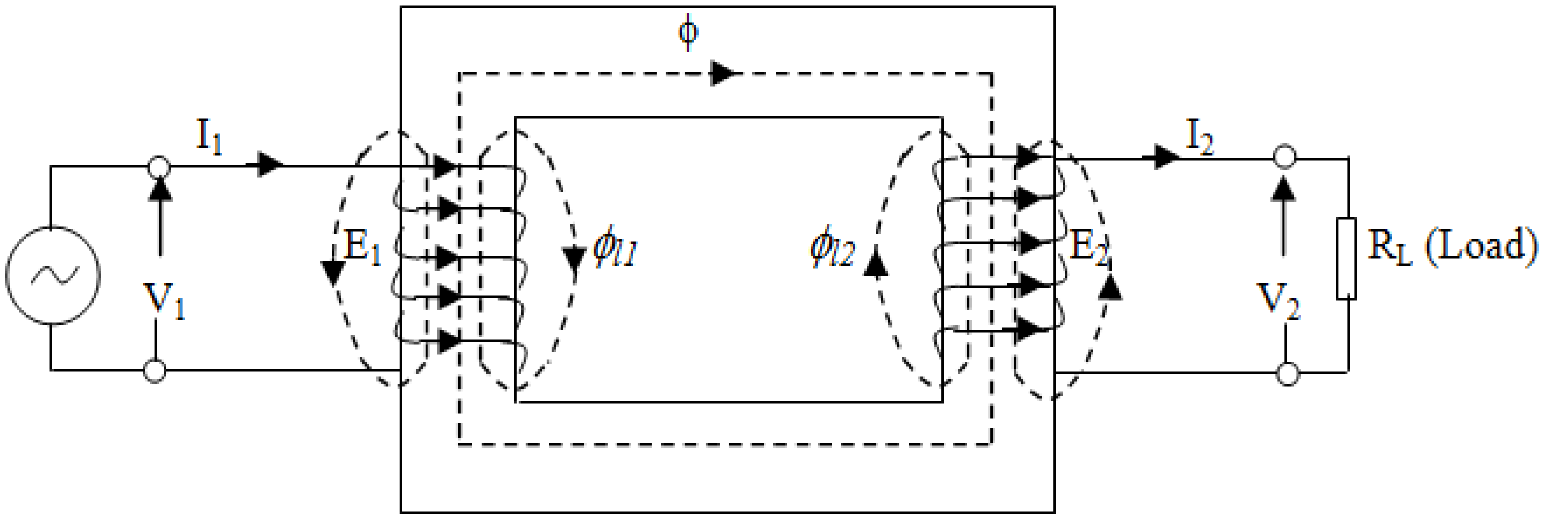


Fig.2.12 Magnetic flux leakage in transformer

- The primary winding current produces magnetic flux in the core.
- Out of the total flux produced by the primary current, major part of the flux (ϕ) passes through the iron core and links with the secondary winding.
- However, a small amount of flux leaks through the air path locally and links with only the primary winding.
- This flux is known as primary leakage flux and denoted by 'ϕ_{l1}'.

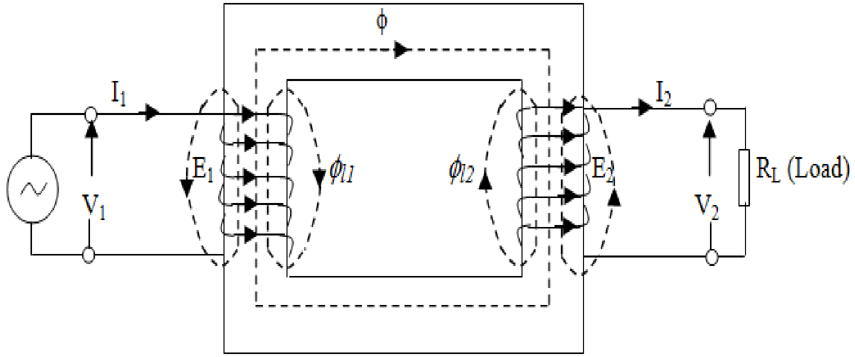
- Similarly, ϕ_{l2} is the secondary leakage flux.

- The emf E_1 induced in the primary winding opposes the supply voltage V_1 and it is proportional to the main flux ϕ and does not depend on load currents. i.e E_1 remains constant.

- The primary leakage flux (ϕ_{l1}) will also causes a self induced emf e_{l1} in the primary winding. This self induced emf opposes the supply voltage V_1 causing some voltage drop (because, there is no opposing flux to cancel ϕ_{l1} , increases with I_1)

- The magnitude of primary leakage flux depends upon the primary current I_1. Therefore, the self induced emf e_{l1} also depends upon the primary current I_1.

- The self induced emf e_{l1} which varies with I_1 can be treated as the **reactive voltage drop (I_1 X_1),**
- where $\mathbf{X_1 = 2\pi f\ (\mathit{l}_{1l})}$ is the leakage reactance of primary winding and $\boldsymbol{l_{1l}}$ is the leakage inductance of primary winding and can be defined as follow.



$$\boldsymbol{l_{1l} = \frac{N_1 . \varphi_{l1}}{I_1}} \qquad (\mathbf{2.11})$$

- Similarly, $I_2.X_2$ is the reactive voltage drop in the secondary winding due to secondary leakage flux, where $X_2 = 2\pi f\ (l_{2l})$ is the leakage reactance of secondary winding and l_{2l} is the leakage inductance of secondary winding and can be defined as follow:

$$\boldsymbol{l_{2l} = \frac{N_2 . \varphi_{l2}}{I_2}} \qquad (\mathbf{2.12})$$

2.5 Transformation of Impedance :

The equivalent circuit shown in Fig.2.10 further can be simplified by transferring the resistance and leakage reactance of the secondary winding to the primary side as as shown in Fig.2.13

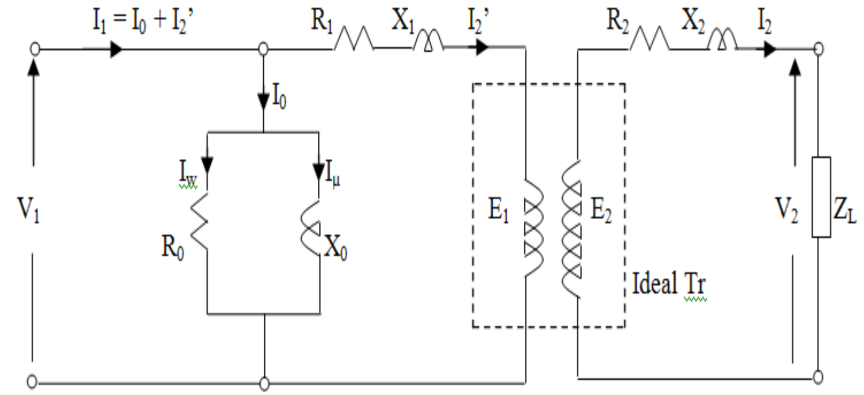


Fig.2.10 Detail Equivalent circuit of transformer

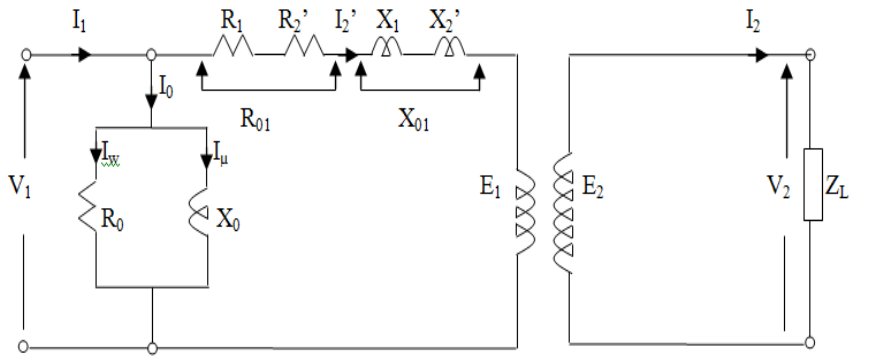


Fig.2.13 Equivalent circuit of transformer referred to primary side

R_2 is transferred to primary side with a new value R_2' in such a way that **R_2' produces same amount of power loss in primary side as it produces in the secondary side**. R_2' is known as equivalent of R_2 referred to primary side.

Equating power loss in primary and secondary side, it gives:

$$(I_2')^2 R_2' = (I_2)^2 R_2 \text{(Assuming } I_1 \approx I_2')$$

$$(I_1)^2 R_2' = (I_2)^2 R_2 \qquad \text{OR} \quad R_2' = \left(\frac{I_2}{I_1}\right)^2 .R_2$$

$$\text{But} \quad \frac{I_2}{I_1} = \frac{N_1}{N_2} = \frac{1}{K} \qquad \therefore \; R_2' = \frac{1}{K^2}.R_2 \qquad (2.16) \qquad \text{Similarly} \quad X_2' = \frac{1}{K^2}.X_2 \qquad (2.17)$$

Now final equivalent circuit of the transformer referred to primary side can be written as shown in Fig.2.14. Here, Load impedance and load voltage also has been transferred to primary side.

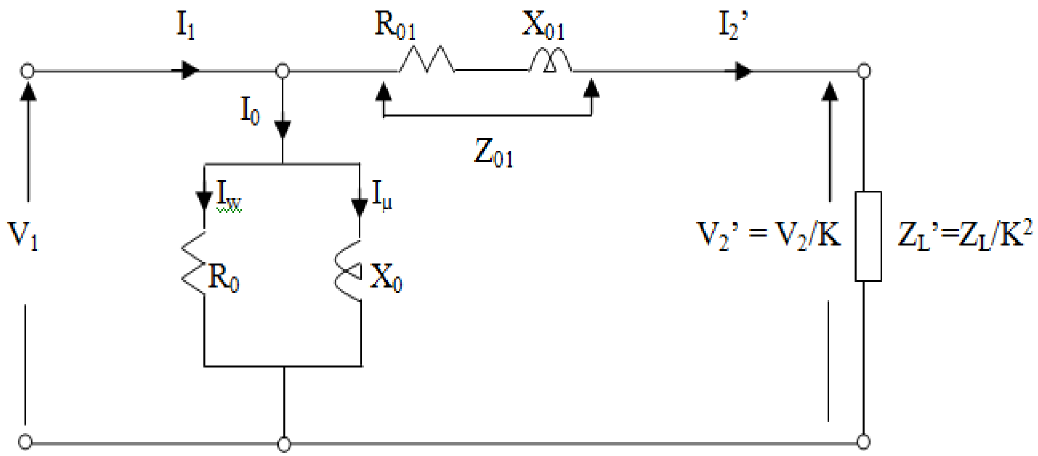


Fig.2.14 Final equivalent circuit of the transformer referred to primary side

$R_{01} = R_1 + R_2'$ = Total series resistance of the transformer referred to primary side

$X_{01} = X_1 + X_2'$ = Total series reactance of the transformer referred to primary side

$Z_{01} = \sqrt{R_{01}^2 + X_{01}^2}$ = Total series Impedance of the transformer referred to primary side

$Z_L' = \dfrac{Z_L}{K^2}$ = Equivalent of load impedance refer to primary side

$V_2' = \dfrac{V_2}{K}$ = Equivalent of load voltage refer to primary side

The equivalent circuit also can be developed by transferring the resistance and leakage reactance of the primary winding to the secondary side as shown in Fig.2.15.

R_1 is transferred to secondary side with a new value R_1' in such a way that R_1' produces same amount of power loss in secondary side as it produces in the primary side.

R_1' is known as equivalent of R_1 referred to secondary side.

Equating power loss in secondary and primary side, it gives:

$(I_2)^2 R_1' = (I_2')^2 R_1$ OR $R_1' = \left(\frac{I_2'}{I_2}\right)^2 . R_1 = \left(\frac{I_1}{I_2}\right)^2 R_1$ (assuming $I_2' \approx I_1$)

But $\frac{I_1}{I_2} = \frac{N_2}{N_1} = K$ $\therefore\ R_1' = R_1 . K^2$

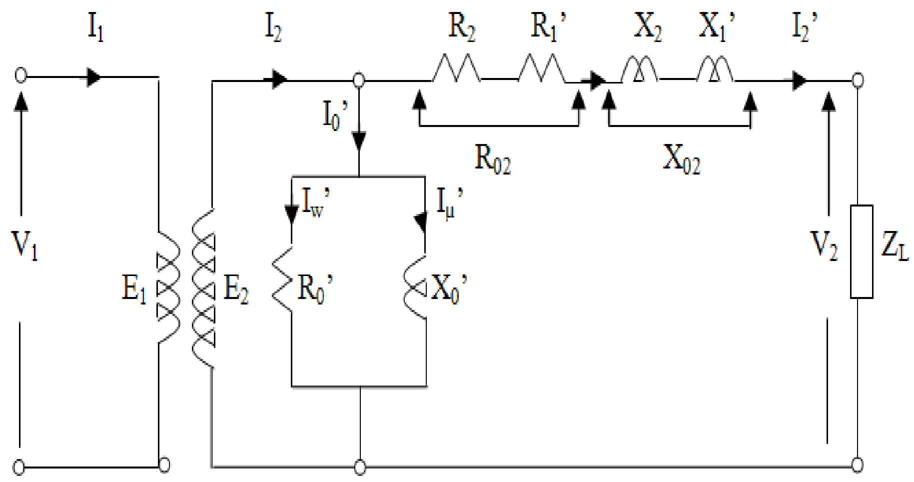


Fig.2.15 Equivalent circuit of transformer referred to secondary side

Similarly, $X_1' = X_1 . K^2$, $R_0' = R_0 . K^2$ And $X_0' = X_0 . K^2$

Now final equivalent circuit of the transformer referred to secondary side can be written as shown in Fig.2.16. Here, input voltage V_1, I_0 and I_μ also has been transferred to secondary side.

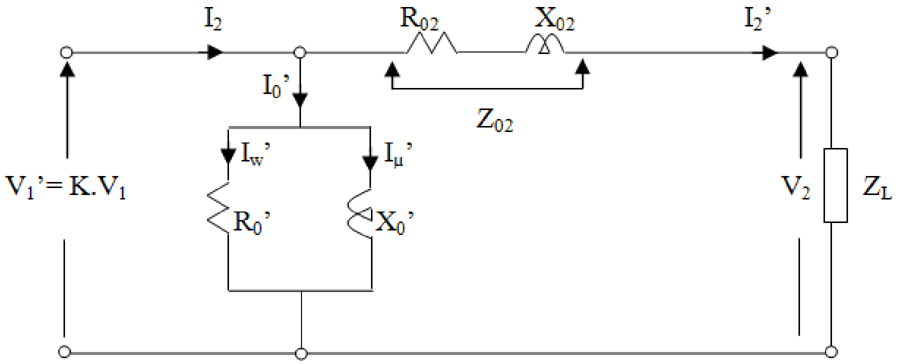


Fig.2.16 Complete equivalent circuit of transformer referred to secondary side

$R_{02} = R_2 + R_1'$ = Total series resistance of the transformer referred to secondary side

$X_{02} = X_2 + X_1'$ = Total series reactance of the transformer referred to secondary side

$Z_{02} = \sqrt{R_{02}^2 + X_{02}^2}$ = Total series Impedance of the transformer referred to seconary side

$V_1' = K.V_1$ = Equivalent of V_1 refer to seconary side

$I_0' = \frac{I_0}{K}$ = Equivalent of I_0 refer to secondary side

$I_w' = \frac{I_w}{K}$ = Equivalent of I_w refer to secondary side

$I_\mu' = \frac{I_\mu}{K}$ = Equivalent of I_μ refer to secondary side

Illustrative example2.2:

A 2200V/250V, 50Hz, single phase transformer draws a current of 0.5 amp at no-load. The no-load current lags the applied voltage by an angle of 70^0. Calculate:

a) Iron loss of transformer

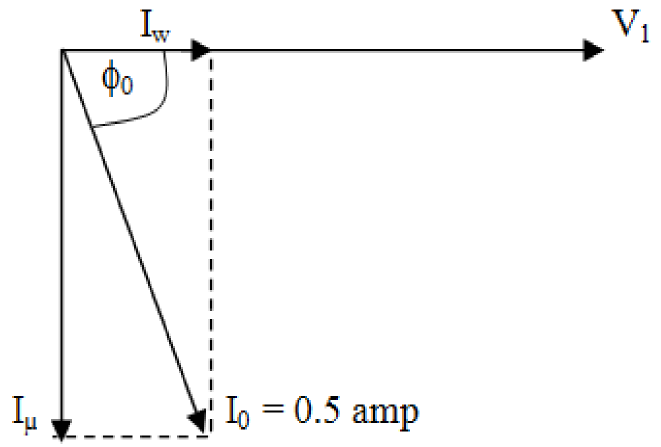
b) R_0 and X_0 parameters

Solution:

The phasor diagram at no-load is shown below:

Iron loss of transformer = power consumed at no-load = $V_1 . I_0 \, Cos\phi_0$

Or Iron loss of transformer = $2200 \times 0.5 \times Cos70^0 = 376$ watts



$$I_W = I_0 \, Cos\phi_0 = 0.5 \times Cos70^0 = 0.171 \text{ amp}$$

$$I_\mu = I_0 \, Sin\phi_0 = 0.5 \times Sin70^0 = 0.469 \text{ amp}$$

$$R_0 = \frac{V_1}{I_w} = \frac{2200}{0.171} = 12865 \text{ Ohms}$$

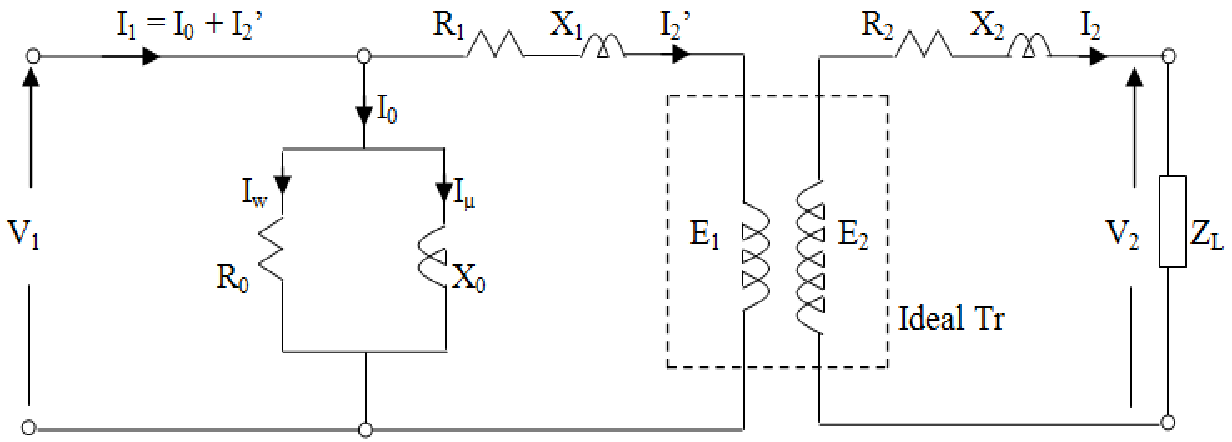
$$X_0 = \frac{V_1}{I_\mu} = \frac{2200}{0.469} = 4691 \text{ Ohms}$$

Illustrative example2.3:

A step-up single phase transformer supplies a current of 5 amp to the load at 200V at 0.8 lagging power factor. R_1 = 0.5 ohm, X_1 = 1 ohm, R_2 = 2 ohm, X_2 = 4 ohm, R_0= 400 ohms, X_0 = 240 ohms, turn ratio N_2/N_1 = 2. Find V_1, I_1 and input power factor.

Solution:

The equivalent circuit of the transformer is shown below:

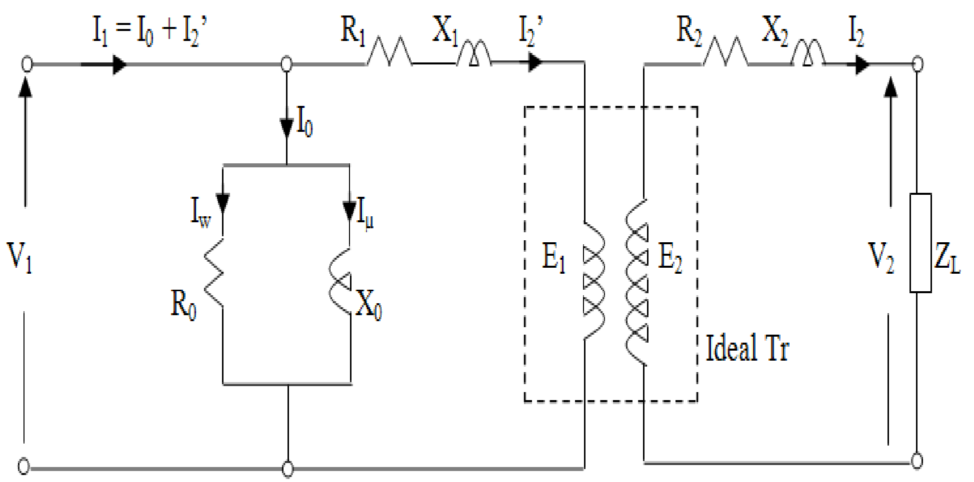


Let $\tilde{V}_2$ be the reference phasor, i.e. $\tilde{V}_2 = 200\angle 0^0$

I_2 lags V_2 by ϕ_2, where $\phi_2 = \cos^{-1}(0.8) = 36.87^0$ $\therefore\ \tilde{I}_2 = 5\angle -36.87^0$

$\tilde{E}_2 = \tilde{V}_2 + \tilde{I}_2.(R_2 + jX_2)$ = $200\angle 0^0 + (5\angle -36.87^0).(2+j4)$

OR $\tilde{E}_2 = 200\angle 0^0 + (5\angle -36.87^0)(4.472\angle 63.43^0) = 220.2\angle 2.6^0$



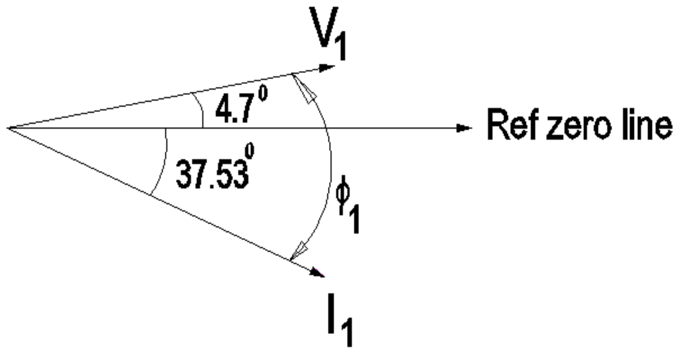
$$\tilde{I}'_2 = \tilde{I}_2 \times \frac{N_2}{N_1} = 10\angle -36.87^0$$

$$\tilde{E}_1 = \tilde{E}_2 \times \frac{N_1}{N_2} = 110.1\angle 2.6^0$$

And $\tilde{V}_1 = \tilde{E}_1 + \tilde{I}'_2.(R_1 + jX_1) = 110\angle 2.6^0 + (10\angle -36.87^0).(0.5 + j1)$

$$\tilde{V}_1 = 120.29\angle 4.7^0$$

$$\tilde{I}_\mu = \frac{\tilde{V}_1}{X_0} = \frac{120.29\angle 4.7^0}{240\angle 90^0} = 0.501\angle -85.3^0 \qquad \tilde{I}_W = \frac{V_1}{R_0} = \frac{120.29\angle 4.7^0}{400} = 0.3\angle 4.7^0$$



$$\tilde{I}_0 = \tilde{I}_W + \tilde{I}_\mu = (0.3\angle 4.7^0) + (0.501\angle -85.3^0) = 0.5825\angle -54.53^0$$

$$\tilde{I}_1 = \tilde{I}_0 + \tilde{I}'_2 = (10\angle -36.87^0) + (0.5825\angle -54.53^0) = 10.548\angle -37.53^0$$

Phase Angle between $\tilde{V}_1$ and $\tilde{I}_1 = \phi_1 = 4.7^0 - (-37.53^0) = 42.23^0$ $\qquad$ $\tilde{I}_1$ Lags $\tilde{V}_1$ by 42.23^0

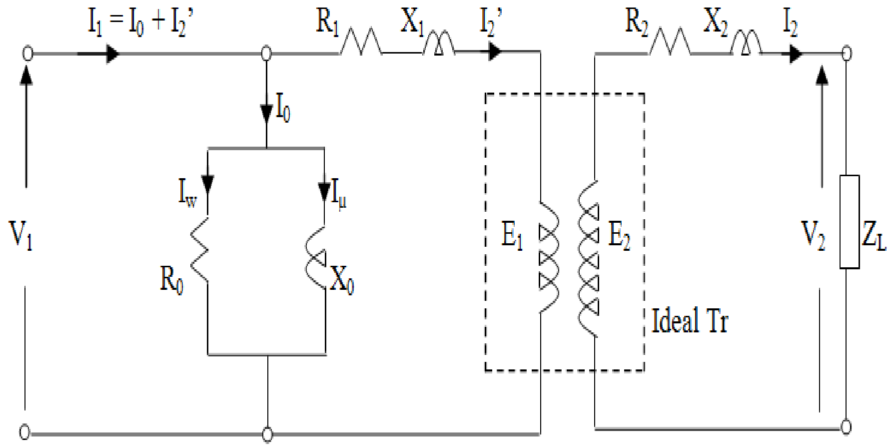
Hence, input power factor = $\text{Cos}(42.23^0)$ = 0.74 lagging

Power Losses and Efficiency of Transformer:

- The input power of the transformer is equal to $V_1I_1Cos\phi_1$

- The output power is equal to $V_2I_2Cos\phi_2$.

- The output power of a transformer is always less than the input power, because there are some power losses within the transformer.



-There are mainly two types of power losses in the transformer:

i) Iron loss and ii) Copper loss.

i) Iron loss: This is the power loss due to heating of iron core of the transformer. This power loss is equal to the no-load power loss and remains constant at any load. Therefore, iron loss is also known as constant power loss. The power loss in the iron core take place due to **eddy current loss and hysteresis loss**.

Eddy current loss:

When the time varying magnetic flux circulates through the iron core, according to Faraday's law of electromagnetic induction, emf will also induce in the iron core. Because of this emf induced in the iron core, current will circulate within the iron core and it is known as eddy current. The eddy current produces heat in the iron core, which **is proportional to the square of the induced eddy current**. The power loss due to heat produced in the iron core due to eddy current is known as eddy current loss. In order to reduce eddy current loss, the transformer core is made of laminated core rather than solid iron core.

<u>Hysteresis loss</u>:

Since the exciting current is alternating in nature, in every cycle of exciting current, the magnetic core undergoes through the process of magnetic reversal thus by causing hysteresis power loss in every cycle.

In order to reduce the hysteresis loss, silicon steel is used to make the core of the transformer. About **0.3% to 4.5 % of silicon is mixed with the steel by weight**, which helps to **reduce residual flux** density and accordingly hysteresis loss will reduce.

Above **5% of silicon content, the resulting alloy will be very brittle and can not be punched**. The addition of silicon with steel increases the resistivity of steel. Hence, the use of silicon steel also helps to reduce eddy current loss

ii) <u>Copper loss</u>: When the transformer is loaded, current flows through primary winding as well as secondary winding. The internal resistance of the primary winding and the secondary winding produces heat due to current flowing through them. The power loss due to the heat so produced is known as copper loss. The magnitude of copper loss depends upon the square of current and can be calculate as follow:

$$\text{Total copper loss} = \text{Copper in PW} + \text{Copper in SW} = I_1^2 R_1 + I_2^2 R_2 \qquad (2.21)$$

$$\text{OR Total copper loss} = = I_1^2 R_{01} = I_2^2 R_{02} \text{ (watts)}$$

It is clear from the eqn (2.21) that the copper loss of the transformer varies with the load current. Hence, it is also known as variable loss.

Input power is given by: $P_{in} = V_1 I_1 \cos\phi_1$

Output power: $P_{out} = P_{in}$ – Iron loss – Copper loss = $V_1 I_1 \cos\phi_1 - W_i - I_1^2 R_{01}$

Efficiency of transformer $\eta = \dfrac{P_{out}}{P_{in}}$ pu. Or $\eta = \dfrac{P_{out}}{P_{in}} \times 100\,\%$

$$\text{OR} \quad \eta = \frac{V_1.I_1 \cos\phi_1 - W_i - I_1^2 R_{01}}{V_1.I_1 \cos\phi_1} \qquad (2.22)$$

From the eqn (2.22), it is clear that the efficiency of transformer varies with the load current. At no-load, output power is zero and input power is $V_1 I_0 \cos\phi_0 = W_i$. Hence, the efficiency is zero at no-load. When the load goes on increasing, the output power goes on increasing and efficiency also increases accordingly.

However, there is a limit on increasing the efficiency. At a particular value of load current, the efficiency becomes maximum. Further increased in load beyond this value will cause decrease in efficiency.

Load current for maximum efficiency

$$\eta = \frac{V_1.I_1\ \cos\phi_1 - W_i - I_1^2 R_{01}}{V_1.I_1\ \cos\phi_1} \qquad (2.22)$$

Equation (2.22) can be re-write as :

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

Differentiating with respect to **I_1**, gives:

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

Efficiency will be maximum, when $\frac{d\eta}{dI_1} = 0$

OR When $\frac{W_i}{V_1.I_1^2\ \cos\phi_1} - \frac{R_{01}}{V_1.\cos\phi_1} = 0$

OR When $\frac{W_i}{V_1.I_1^2\ \cos\phi_1} = \frac{R_{01}}{V_1.\cos\phi_1}$

OR $W_i = I_1^2 R_{01}$

OR when $I_1 = \sqrt{\frac{W_i}{R_{01}}}$ (2.23)

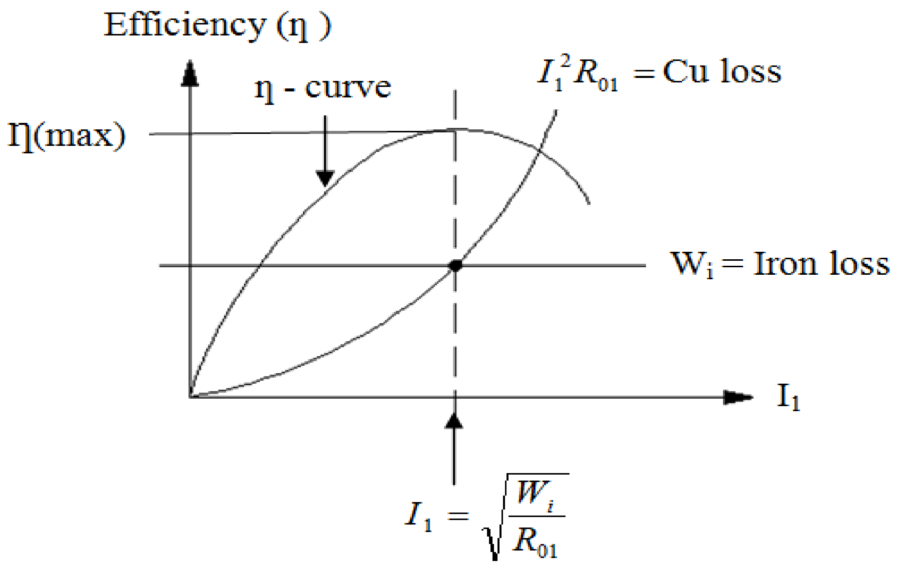


Fig.2.17 Variation of efficiency with load

Hence, efficiency will be maximum at $I_1 = \sqrt{\frac{W_i}{R_{01}}}$ OR when

Iron loss = Copper loss

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