Republic of Iraq Ministry of Higher
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Electrical technology

Transformer

تكنلوجيا الكهرباء

المحاضرة الاولى

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Transformer

What is a Transformer?

A Transformer is a static electrical machine which transfers AC electrical power from one circuit to the other circuit at the constant frequency, but the voltage level can be altered that means voltage can be increased or decreased according to the requirement.

Necessity of a Transformer

In Iraq, usually, electrical power is generated at 11Kv. For economic reasons AC power is transmitted at very high voltages say 132 kV or 400 kV over long distances. Therefore a step up transformer is applied at the generating stations. Now for safety reasons the voltage is stepped down to different levels by step down transformer at various substations to feed the power to the different locations and thus the utilization of power is done at



If (V2 > V1) the voltage is raised on the output side and is known as Step-up transformer

If (V2 < V1) the voltage level is lowered on the output side and is known as Step down transformer

It works on the principle of Faraday's Law of Electromagnetic Induction which states that "the magnitude of voltage is directly proportional to the rate of change of flux".

Construction of a Transformer

It mainly consists of:

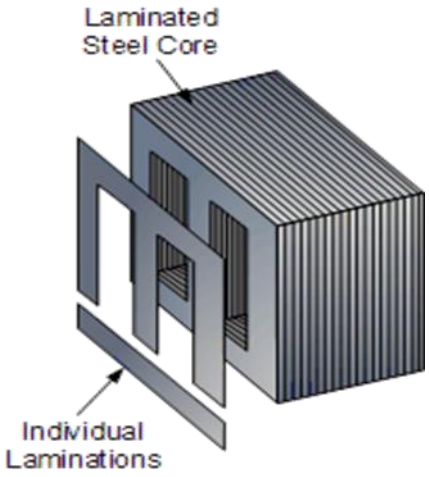
1-Magnetic circuit (consisting of core, limbs, yoke and damping structure

2-Electrical circuit (consists of primary and secondary windings(

. 3-Dielectric circuit (consisting of insulations in different forms and used at the different places(

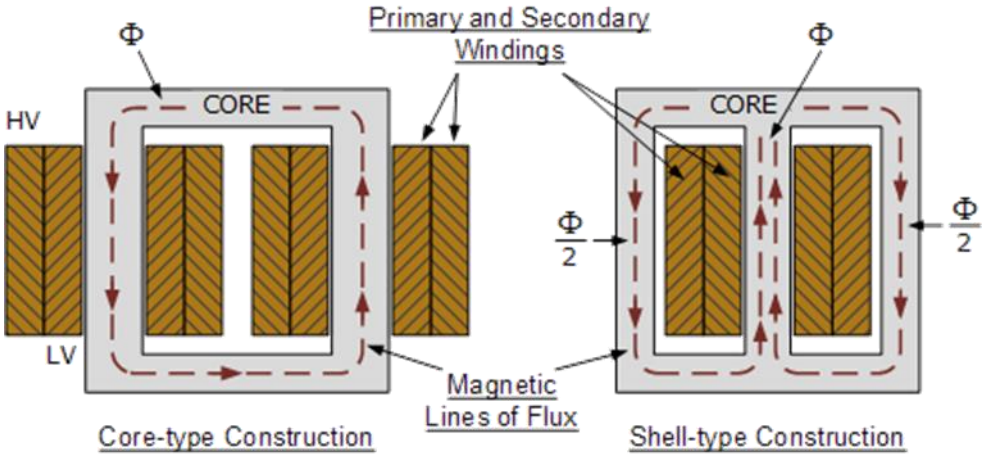
.4 4-Tanks and accessories (conservator, breather, bushings, cooling tubes, etc(.

The construction of a simple two-winding transformer consists of each winding being wound on a separate limb or core of the soft iron form which provides the necessary magnetic circuit. This magnetic circuit, know more commonly as the "transformer core" is designed to provide a path for the magnetic field to flow around, which is necessary for induction of the voltage between the two windings .



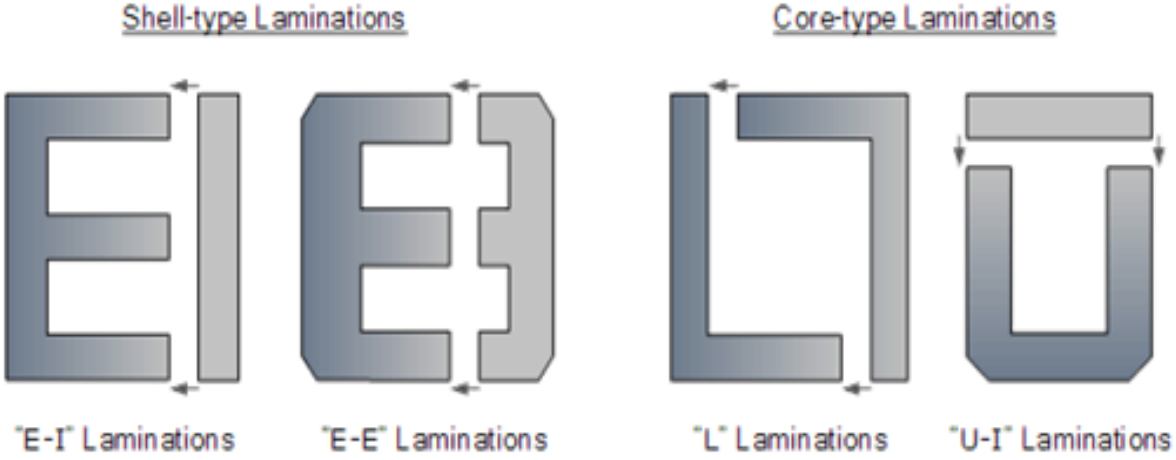
In all types of transformer construction, the central iron core is constructed from of a highly permeable material made from thin silicon steel laminations assembled together to provide the required magnetic path with the minimum of losses. The resistivity of the steel sheet itself is high reducing the eddy current losses by making the laminations very thin These steel transformer laminations vary in thickness's from between 0.25mm to 0.5mm and as steel is a conductor, the laminations are electrically insulated from each other by a very thin coating of insulating varnish or by the use of an oxide layer on the surface.

The two most common and basic designs of transformer construction are the Closed-core transformer and the Shell-core Transformer.



Transformer Laminations

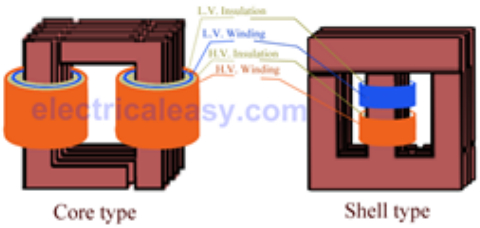
The individual laminations are stamped or punched out from larger steel sheets and formed into strips of thin steel resembling the letters "E's", "L's", "U's" and "I's" as shown below.

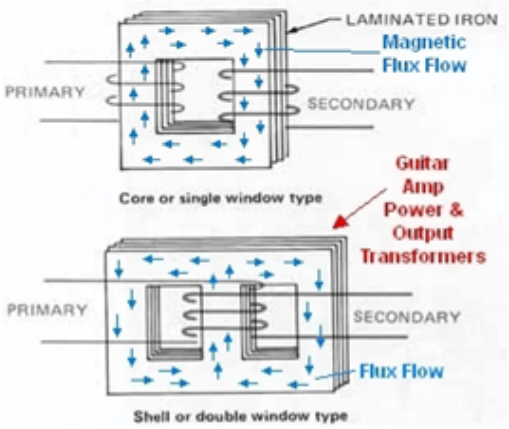


Types of Transformer

1. Position of the windings with respect to the core(On the basis of construction)

- Core type
- Shell type





2. According to the transformation ratio or number of turns in the windings (On the basis of their purpose).

-Step up transformer

-Step down transformer

3. on basis of voltage

- **Step down voltage**
- **Sep up voltage**

4. On the basis of the supply

- Single phase
- Three phase

5. On the basis of cooling

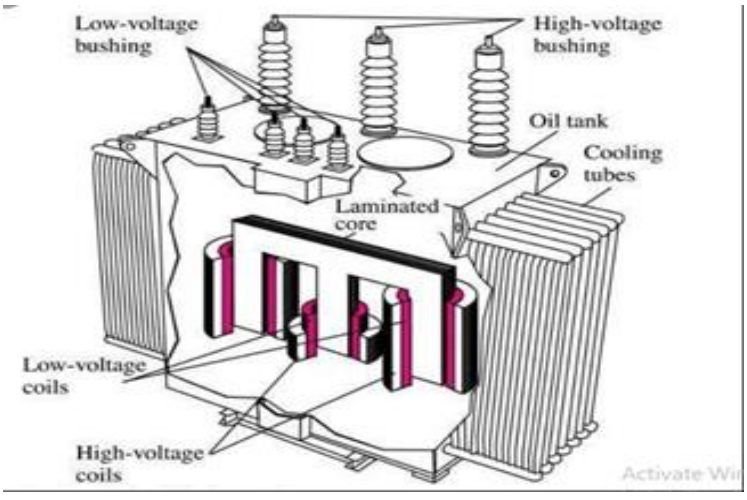
For dry air nature and for oil immersed air natural

6. According to the transformation ratio or number of turns in the windings (On the basis of their purpose)

- Step up transformer
- Step down transformer

7 . Types of services

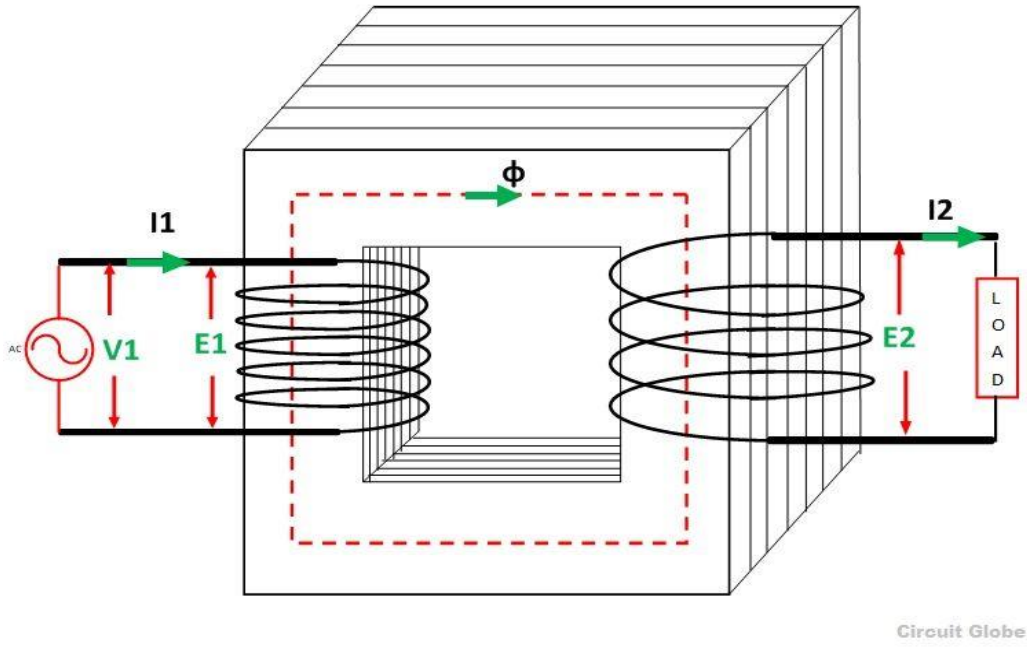
- Power transformer
- Distribution transformer
- Instrument transformer
  - Current transformer
  - Potential transformer
  - Auto transformer



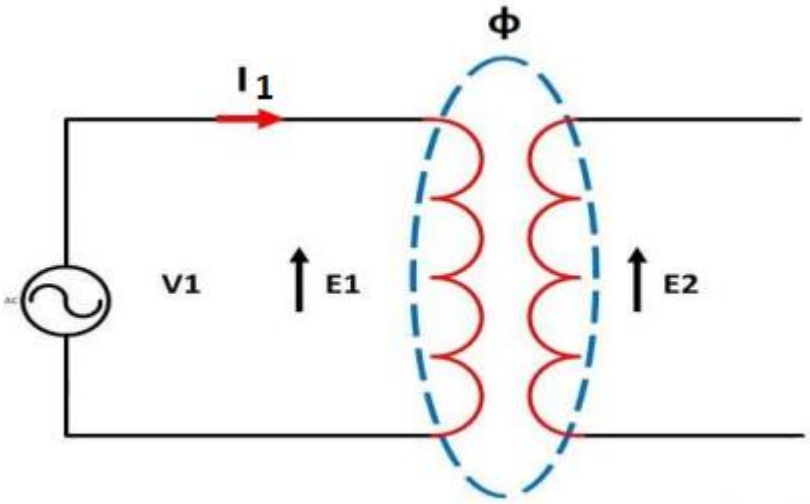
Working Principle of a Transformer

The basic principle on which the transformer works is **Faraday's Law of Electromagnetic Induction** or mutual induction between the two coils. The working of the transformer is explained below.The transformer consists of two separate windings placed over the laminated silicon steel core. The winding to which AC supply is connected is called primary winding and to which load is connected is called secondary winding as shown in the figure below. It works on the alternating current only because an alternating flux is required for mutual induction between the two windings.

When the AC supply is given to the primary winding with a voltage of



V1, an alternating flux ϕ sets up in the core of the transformer, which links with the secondary winding and as a result of it, an emf is induced in it called Mutually Induced emf. The direction of this induced emf is opposite to the applied voltage V1; this is because of the Lenz's law shown in the figure below



The induced emf in the primary and secondary windings depends upon the rate of change of flux linkage that is

)N dϕ/dt.(

ϕd/dt is the change of flux and is same for both the primary and secondary windings. The induced emf E1 in the primary winding is proportional to the number of turns N1 of the primary windings (E1 ∞ N1). Similarly induced emf in the secondary winding is proportional to the number of turns on the secondary side. (E2 ∞ N2) .

Turn Ratio

It is defined as the ratio of primary to secondary turns.

$$\text{Turn ratio} = \frac{N_1}{N_2}$$

If $N_2 > N_1$ the transformer is called Step up transformer

If $N_2 < N_1$ the transformer is called Step down transformer

Transformation Ratio

The transformation ratio is defined as the ratio of the secondary voltage to the primary voltage. It is denoted by K.

$$K = \frac{E_2}{E_1} = \frac{N_2}{N_1}$$

Ideal Transformer

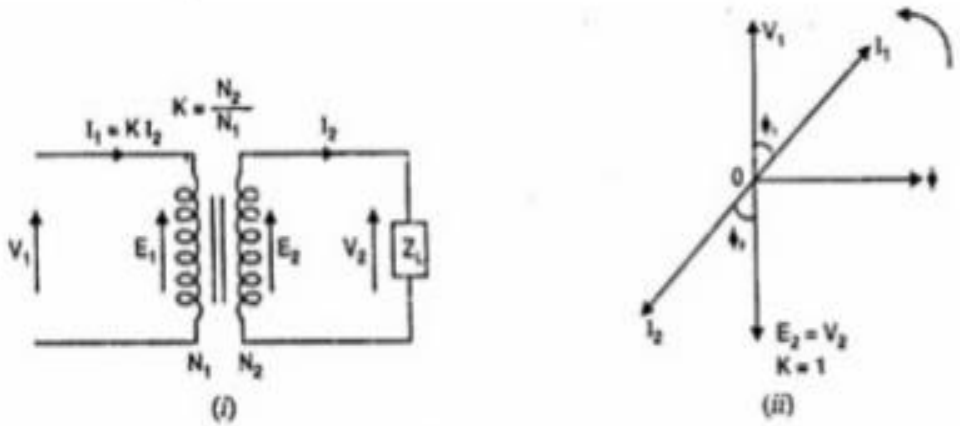
An ideal transformer is one which has no ohmic resistance and no magnetic leakage flux that means 100% flux passes through the core and links with the primary as well as with the secondary winding. It has no iron and copper losses. There are two purely inductive coils in the Ideal Transformer, which are wound on a core. As in Ideal transformer, there are no losses. Hence, the core of the transformer is free from the losses.

K= $\frac{V_2}{V_1}$

The resistance of the winding is zero, and there is no leakage reactance.

$$N_1 I_1 = N_2 I_2$$

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



The core of the transformer is infinitely permeable. It is an imaginary transformer and practically it is not possible for a transformer to behave as an ideal transformer. In an ideal transformer, there is no power loss. Therefore, the output power is equal to the input power.

$$E_2 I_2 \cos\varphi = E_1 I_1 \cos\varphi \quad \text{or} \quad E_2 I_2 = E_1 I_1$$

OR

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

Since $E_2 \propto N_2$ and $E_1 \propto N_1$, also E_1 is similar to V_1 and E_2 is similar to V_2

Therefore, transformation ratio will be given by the equation shown below

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

EMF Equation of the transformer is shown below

Let:

1.ϕm is the maximum value of flux in Weber.

2. f be the supply frequency in Hz.

3 .N1 is the number of turns in the primary winding

4. N2 is the number of turns in the secondary winding .

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

$$E_2 = 4.44 f N_2 \varphi_m \ .$$

$$\frac{E_2}{E_1} = \frac{4.44 f N_2 \varphi_m}{4.44 f N_1 \varphi_m}$$

Or

$$\frac{E_2}{E_1} = \frac{N_2}{N_1} = K$$

$\phi_m = B_m \times A_i$

Where

Ai is the iron area and

B_m is the maximum value of flux density

$$E_1 = 4.44 N_1 f B_m A_i \text{ Volts} \quad \text{and} \quad E_2 = 4.44 N_2 f B_m A_i \text{ Volts}$$

Example.1: A single-phase transformer has 400 primary and 1000 secondary turns. The net cross-sectional area of the core is 60 cm^2

If the primary winding be connected to a 50-Hz supply at 520 V, calculate (i) the voltage induced in the secondary winding. (ii) the peak value of flux density in the core

Solution:

(i) $K = N_2/N_1$

$= 1000/400 = 2.5$

$E_2/E_1 = K$

$E_2 = KE_1$

$= 2.5 \times 520 = 1300$ V

(ii)

$E_1 = 4.44\, f\, N_1\, B_m A$

$520 = 4.44 \times 50 \times 400 \times Bm \times (60 \times 10^{-4})$

Bm = 0.976 Wb/m2

Example .2: A 25-kVA ideal transformer has 500 turns on the primary and 50 turns on the secondary winding. The primary is connected to 3000-V, 50-Hz supply. Find the full-load primary and secondary currents, the secondary e.m.f. and the maximum flux in the core..

Solutions:

K= N_2/N_1 = 50/500 = 1/10

Now, full-load I_1 = 25,000/3000 = 8.33 A

$$V_1 I_1 = V_2 I_2$$

F.L. $I_2 = I_1/K = 10 \times 8.33 = 83.3$ A

$E_2 = K E_1 = 3000 \times 1/10 = 300$ V

Also, $E_1 = 4.44 f N_1 \Phi_m$

$3000 = 4.44 \times 50 \times 500 \times \Phi m$

$\therefore \quad \Phi m = 27$ mWb

EXAMPLE **3** *A 25 kVA transformer has a voltage ratio of 3300 / 400 V. Calculate the primary and secondary currents.*

SOLUTION. $$\text{kVA} = \frac{V_1 I_1}{1000}$$

$$I_1 = \frac{1000 \times \text{kVA}}{V_1} = \frac{1000 \times 25}{3300} = 7.58 \text{ A}$$

Also, $$\text{kVA} = \frac{V_2 I_2}{1000}$$

$$I_2 = \frac{1000 \times \text{kVA}}{V_2} = \frac{1000 \times 25}{400} = 62.5 \text{ A}$$

Example 4 : *A single-phase, 50 Hz transformer has 80 turns on the primary winding and 400 turns on the secondary winding. The net cross-sectional area of the core is 200 cm^2. If the primary winding is connected to a 240 V, 50 Hz supply, determine :*

i) The e.m.f. induced in the secondary winding.

ii) The maximum value of the flux density in the core.

Solution : $N_1 = 80$, $f = 50$ Hz, $N_2 = 400$, $a = 200\ cm^2 = 200 \times 10^{-4}\ m^2$

$$E_1 = 240\ V$$

$$K = \frac{N_2}{N_1} = \frac{400}{80} = \frac{5}{1}$$

$$\therefore \quad K = \frac{E_2}{E_1} = \frac{E_2}{240} = \frac{5}{1}$$

$$\therefore \quad E_2 = 5 \times 240 = 1200\ V$$

Now $$E_1 = 4.44\ f\ \phi_m\ N_1$$

$$240 = 4.44 \times 50 \times \phi_m \times 80$$

$$\phi_m = \frac{240}{4.44 \times 50 \times 80} = 0.01351\ Wb$$

$$B_m = \frac{\phi_m}{a} = \frac{0.01351}{200 \times 10^{-4}} = 0.6756\ Wb/m^2$$

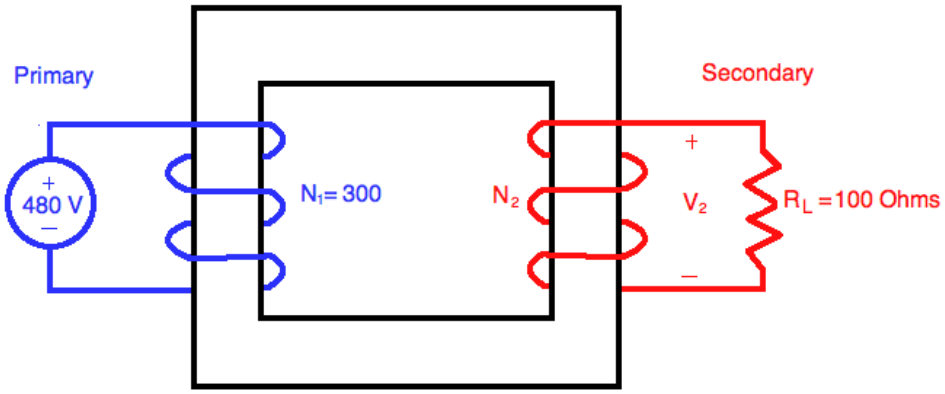
EX 5: An ideal transformer with a 300 turn primary connected to a 480 V, 50 Hz supply line needs to output 220 V from the secondary. If a 100 Ω resistor is connected across the secondary, determine:

A) How many turns the secondary must have to output the desired voltage.

B) The current through the resistor,

C) The current drawn through the primary.

D) The maximum flux in the core of the transformer



Solution:

Part A:

The ratio of primary voltage to secondary voltage is directly proportional to the ratio of number of turns on the primary to number of turns on the secondary:

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

Where V_1 =Voltage across primary, V_2 =Voltage across secondary, N_1 = Number of turns in primary, N_2 = Number of turns in secondary

$$\frac{480\ volts}{120\ volts} = \frac{300\ turns}{N_2}$$

$$N_2 = \frac{300 \cdot 120}{480} \Rightarrow N_2 = 75\ turns$$

Part B:

The voltage across the secondary is given in the problem statement as 120 volts. Using ohms law $V = i \cdot R$, we can solve for the current in the loop (i_2).

$$i_2 = \frac{V_2}{R_L}$$

Where i_2 = Current through secondary, V_2 =Voltage across secondary, R_L = Load Resistor (R_L = 100 Ω)

$$i_2 = \frac{120\ volts}{100\ \Omega} \Rightarrow i_2 = 1.2\ A$$

Part C:

The ratio of primary current to secondary current is inversely proportional to the ratio of number of turns on the primary to number of turns on the secondary:

$$\frac{i_1}{i_2} = \frac{N_2}{N_1}$$

Where i_1 =Current in primary, i_2 =Current in secondary, N_1 = Number of turns in primary, N_2 = Number of turns in secondary

$$\frac{i_1}{1.2\ A} = \frac{75\ turns}{300\ turns}$$

Rearranging to solve for i_1:

$$i_1 = i_2 \cdot \frac{N_2}{N_1} \Rightarrow 1.2A \cdot \frac{75\ turns}{300\ turns} \Rightarrow i_1 = .3\ A$$

Part D:

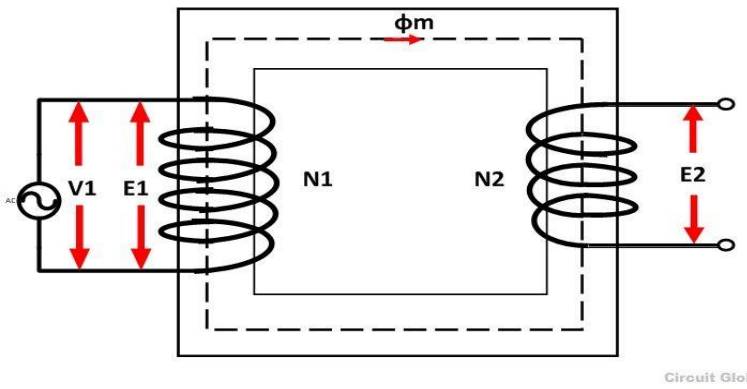
The induced emf of the secondary can be calculated by: for Φ_m, we can calculate the maximum flux in the core: $V_2 = 4.44 \cdot f \cdot N_2 \cdot \Phi_m$

$$\Phi_m = \frac{V_2}{4.44 \cdot f \cdot N_2}$$

$$\Phi_m = \frac{120}{4.44 \cdot 60\ Hz \cdot 75} \Rightarrow \Phi_m = 6.006\ mWb$$

Phasor Diagram of Ideal Transformer

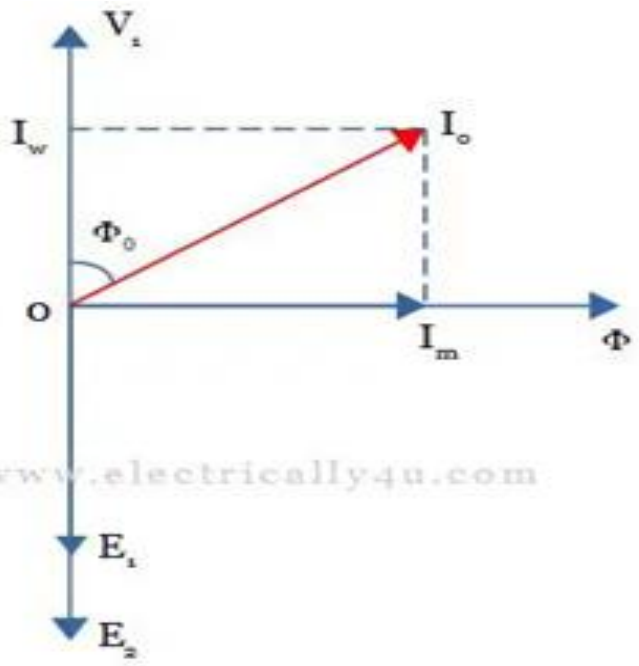
Consider an ideal transformer whose secondary side is open circuited that



means the load is not connected in the secondary side of the transformer

When the primary side is connected to the sinusoidal alternating voltage V_1, a current I_m known as magnetizing current flows through it. These current sets up the alternating flux ϕ or mutual flux ϕ_m in the core and

magnetize it. Hence, it is called Magnetizing current. The flux ϕ_m is proportional to the current Im and is in phase with it. As the primary coil is purely inductive the magnetizing current (I_m) lags behind the applied voltage V_1 by 90



.Both E_1 and E_2 lags behind the flux ϕ by 90

Then we can define an ideal transformer as having

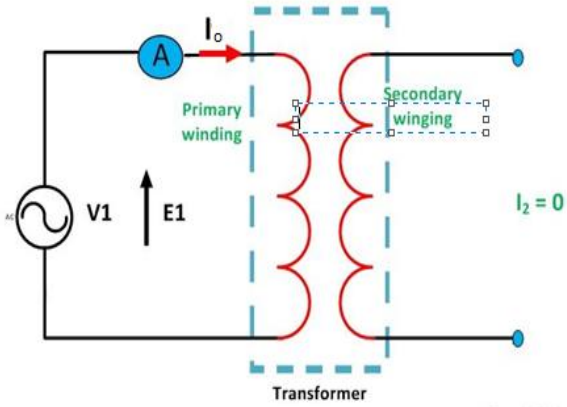
1. No Hysteresis loops or Hysteresis losses → 0

2. Infinite Resistivity of core material giving zero Eddy current losses → 0

3. Zero winding resistance giving zero I2R copper losses → 0.

Transformer on No Load Condition

When the transformer is operating at no load, the secondary winding is open circuited, which means there is no load on the secondary side of the transformer and, therefore, current in the secondary will be zero, while primary winding carries a small current I0 called no load current which is 2 to 10% of the rated current. This current is responsible for supplying the iron losses (hysteresis and eddy current losses) in the core and a very small amount of copper losses in the primary winding. The angle of lag



depends upon the losses in the transformer. The power factor is very low and varies from 0.1 to 0.15.

The no load current consists of two components

1. Reactive or magnetizing component I_m

2. Active or power component I_w, also known as working component

)It is in phase with the applied voltage V_1. It supplies

The following steps are given below to draw the phasor diagram.

1. The function of the magnetizing component is to produce the magnetizing flux, and thus, it will be in phase with the flux

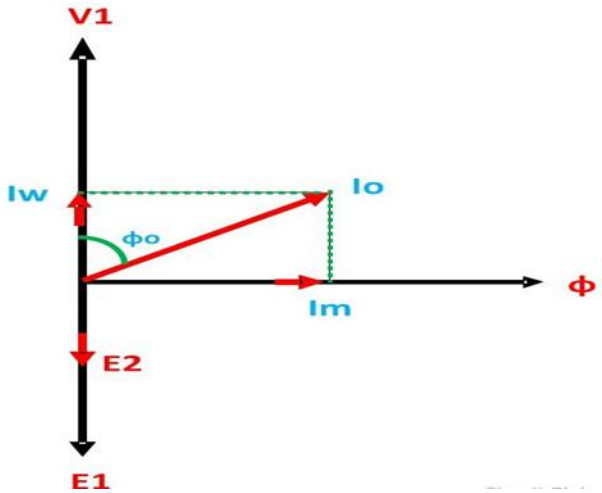
2. Induced emf in the primary and the secondary winding lags the flux ϕ by 90 degrees

3. The primary copper loss is neglected, and secondary current losses are zero as $I_2 = 0$. Therefore, the current I_0 lags behind the voltage vector V_1 by an angle ϕ_0 called no-load power factor angle shown in the phasor diagram above.

4. The applied voltage V_1 is drawn equal and opposite to the induced emf E1 because the difference between the two, at no load, is negligible

5. Active component I_w is drawn in phase with the applied voltage V_1.

The phasor sum of magnetizing current Im and the working current I_w gives the no load current I_0



Working component $I_w = I_o \cos\varphi_o$

No load current $I_o = \sqrt{I_w^2 + I_m^2}$

Magnetizing component $I_m = I_o \sin\varphi_o$

Power factor $\cos\varphi_o = \frac{I_w}{I_o}$

No load power input $P_o = V_1 I_o \cos\varphi_o$

No-load input power is given by

$$W_0 = V_1 I_0 cos\phi_0$$

where cos φ_o is the power factor under no-load conditions.

EXAMPLE 1 *A 125 kVA transformer having primary voltage of 2000 V at 50 Hz has 182 primary and 40 secondary turns. Neglecting losses, calculate (a) the full-load primary and secondary currents, (b) the no-load secondary induced e.m.f. and (c) the maximum flux in the core.*

SOLUTION. (*a*) $\text{kVA} = \frac{V_1 I_1}{1000} = \frac{V_2 I_2}{1000}$

$$I_1 = \frac{1000 \times \text{kVA}}{V_1} = \frac{1000 \times 125}{2000} = 62.5 \text{ A}$$

$$I_2 = \frac{I_1 N1}{N2} = \frac{62.5 \times 182}{40} = 284.4 \text{ A}$$

$\therefore$ $\mathbf{E_2 = 5 \times 240 = 1200 \text{ V}}$

Now $\mathbf{E_1 = 4.44 \, f \, \phi_m \, N_1}$

$\mathbf{240 = 4.44 \times 50 \times \phi_m \times 80}$

(*b*) $\frac{E_2}{\mathbf{E1}} = \frac{\mathbf{N2}}{\mathbf{N1}}$

$$E_2 = \frac{E_1 \mathbf{N2}}{\mathbf{N1}} = \frac{2000 \times 40}{182} = 439.6 \text{ V}$$

(*c*) $E_1 = 4.44 \, \Phi_m f \, \mathbf{N1}$

$$\Phi_m = \frac{E_1}{4.44 \, f \mathbf{N1}} = \frac{2000}{4.44 \times 50 \times 182} = 0.0495 \text{ Wb}$$

EXAMPLE 2 *Find the active and reactive components of no-load current, and the no-load current of a 440/220 V single-phase transformer if the power input to the hv winding is 80 W. The low-voltage winding is kept open. The power factor of the no-load current is 0.3 lagging.*

SOLUTION. $P_o = V_1 I_o \cos\phi_o$

Active component of no-load current

$$I_W = I_o \cos\phi_o = \frac{P_o}{V_1} = \frac{80}{440} = 0.182 \text{ A}$$

No-load current $$I_o = \frac{P_o}{V_1 \cos\phi_o} = \frac{80}{440 \times 0.3} = 0.606 \text{ A}$$

Reactive component of no-load current

$$I_m = \sqrt{I_o^2 - I_W^2} = \sqrt{(0.606)^2 - (0.182)^2} = 0.578 \text{ A}$$

Alternatively

$$I_m = I_o \sin\phi_o = I_o \sin(\cos^{-1}\phi_o) = 0.606 \sin(72.54°) = 0.578 \text{ A}$$

EXAMPLE 4: *A 230/110 V single-phase transformer takes an input of 350 VA at the load and rated voltage. The core loss is 110 W. Find (i) the iron-loss component of no-load current, (ii) the magnetizing component of no-load current and (iii) no-load power factor.*

SOLUTION. $V_1 I_o = 350$ VA

$$I_o = \frac{350}{V_1} = \frac{350}{230} = 1.52 \text{ A}$$

(*i*) No-load p.f. $\cos \phi_o$

Core loss $= V_1 I_o \cos \phi_o$

$$110 = 350 \cos \phi_o, \quad \cos \phi_o = \frac{110}{350} = 0.314$$

(*ii*) Core-loss component of no-load current

$$I_W = I_o \cos \phi_o = \frac{\text{core loss}}{V_1} = \frac{110}{230} = 0.478 \text{ A}$$

(*iii*) Magnetizing component of no-load current

$$I_m = \sqrt{I_o^2 - I_W^2} = \sqrt{(1.52)^2 - (0.478)^2} = 1.44 \text{ A}$$

Example 5 : *The no load current of a transformer is 10 A at a power factor of 0.25 lagging, when connected to 400 V, 50 Hz supply. Calculate,*

a) Magnetising component of no load current

b) Iron loss and c) Maximum value of flux in the core.

Assume primary winding turns as 500.

Solution : The given values are, $I_o = 10$ A, $\cos \phi_b = 0.25$, $V_1 = 400$ V and $f = 50$ Hz

a) $I_m = I_o \sin \phi_b$ = magnetising component

$\phi_b = \cos^{-1}(0.25) = 75.522°$

$\therefore \quad I_m = 10 \times \sin(75.522°) = \mathbf{9.6824\ A}$

b) P_i = iron loss = power input on no load

$= W_o = V_1 I_o \cos \phi_b = 400 \times 10 \times 0.25$

$= \mathbf{1000\ W}$

c) On no load, $E_1 = V_1 = 400$ V and $N_1 = 500$

Now $E_1 = 4.44\, f\, \phi_m\, N_1$

$\therefore \quad 400 = 4.44 \times 50 \times \phi_m \times 500$

$\therefore \quad \phi_m = \mathbf{3.6036\ mWb}$

Example. 6: A 230 VI 115 V single-phase transformer takes a no-load current of 2 A at a power factor of 0.2 lagging with low voltage winding kept open. If the low voltage winding is now loaded to take a current of 15 A at 0.8 power factor lagging find the current taken by high voltage winding

Solutlon.

Primary, $E_1 = V_1 = 230$ V

Secondary, $E_2 = V_2 = 115$ V

No-load current 10 = 2 A

No-load power factor, $\cos \phi_0 = 0.2$ or $\phi_0 = 78.46°$ or $78° 29'$

Load power factor, $\cos \phi_2 = 0.8$ or $\phi 2 = 36.9°$ or $36° 54'$

Current taken by h.v, winding, I_1

Now, transformation ratio

$$K = \frac{V_2}{V_1} = \frac{E_2}{E_1} = \frac{115}{230} = \frac{1}{2}$$

∴ Secondary current referred to primary,

$$I_2' = KI_2 = \frac{1}{2} \times 15 = 7.5 \text{ A}$$

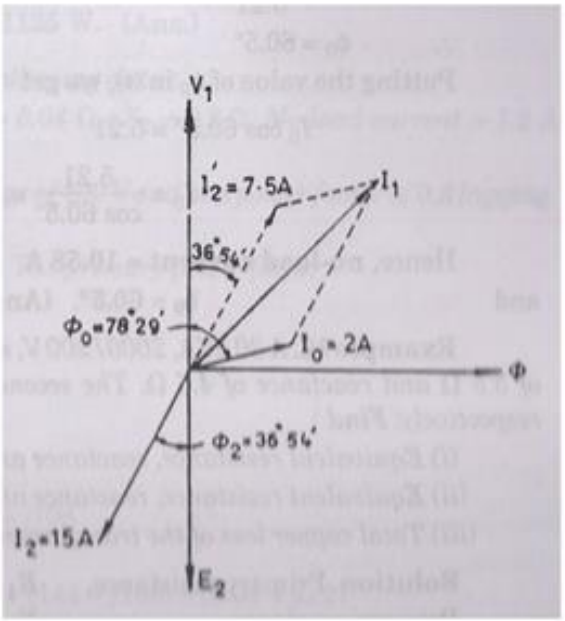
Phase angle, between I_0 and I_2'

$= 78.1.6° - 36.9° = 41.56°$ or $41° 34'$

Using parallelogram law of forces (Fig. 12), we get

$$I_1 = \sqrt{2^2 + 7.5^2 + 2 \times 2 \times 7.5 \times \cos 41.56°}$$

$I_1 = 9.09$ A.



Home work:

A230/110V single phase transformer takes an input of 350VAat no load and rated voltage .the core losses 110w.Find (i) the iron losses component of no load current,(ii)the magnetizing component of no load current and (iii)no load power factor

Ans: (i=1.52A,ii= 0.478A ,iii=1.44A)

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