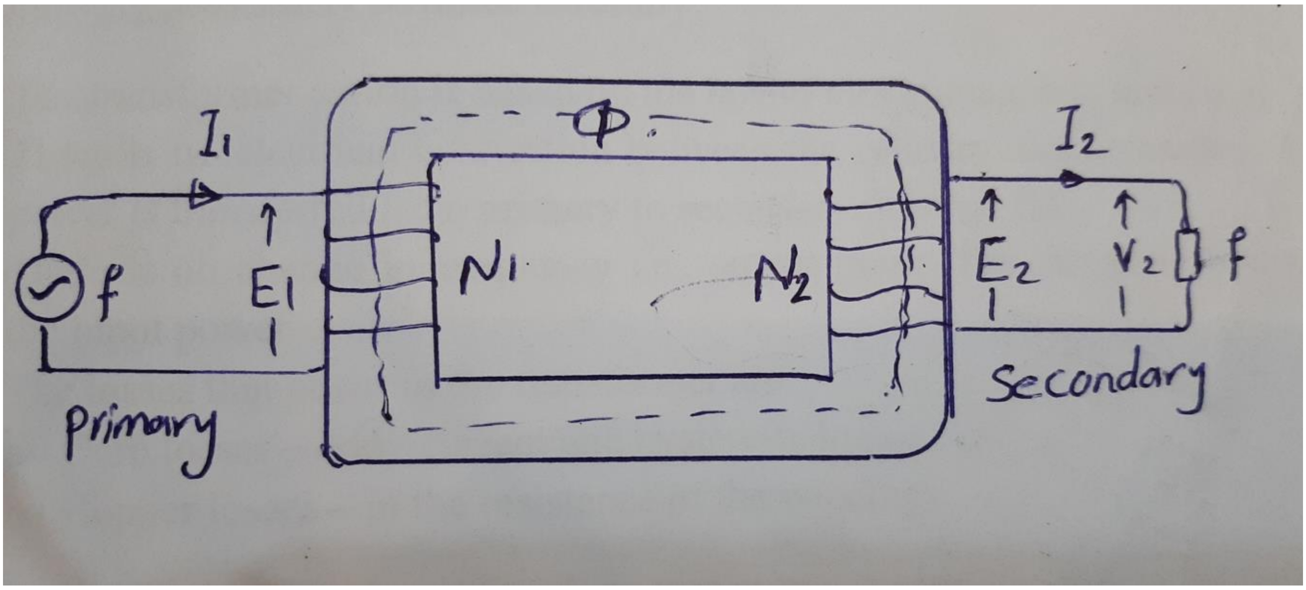
Transformers:

Introduction: The transformer is probably one of the most useful electrical devices ever invented. It can change the magnitude of alternating voltage or current from one value to another. This useful property of transformer is mainly responsible for the widespread use of alternating current rather than direct current i.e, electric power is generated, transmitted and distributed in the form of alternating current.

Transformers have no moving parts, rugged and durable in construction, thus requiring very little attention. They also have a very high efficiency as high as 99%.

Transformer: A transformer is a static piece of equipment used either for raising or lowering the voltage of an a.c. supply with a corresponding decrease or increase in current. It essentially consists of two windings, the primary and secondary, wound on a common laminated magnetic core as shown in figure below. The winding connected to the a.c. source is called primary winding (or primary) and the one connected to load is called secondary winding (or secondary). The alternating voltage V_1 whose magnitude is to be changed is applied to the primary. Depending upon the number of turns of the primary (N_1) and secondary (N_2), an alternating e.m.f. E_2 is induced in the secondary. This induced e.m.f. in the secondary cause a secondary current I_2. Consequently, terminal voltage V_2 will appear across the load. If $\mathbf{V_2 > V_1}$, it is called a step up transformer. on the other hand, if $\mathbf{V_2 < V_1}$, it is called a step down transformer.



Working: when an alternating voltage V_1 is applied to the primary an alternating flux Φ is set up in the core. This alternating flux links both the winding and induces e.m.f.s E_1 and E_2 in them according to Faraday's lows of electromagnetic induction. The e.m.f. E_1 is termed as primary e.m.f. and e.m.f. E_2 is termed as secondary e.m.f. Clearly,

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

$E_2 = - N_1 \frac{d\Phi}{dt}$

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

Note that the magnitude of E_2 and E_1 depend upon the number of turns on the secondary and primary respectively. If $N_2 > N_1$ then $E_2 > E_1$ (or $V_2 > V_1$) and we get a step-up transformer. On the other hand, if $N_2 < N_1$, then $E_2 < E_1$ (or $V_2 < V_1$) and we get a step-down transformer.

The following points may be noted carefully:

1- The transformer action is based on the law of electromagnetic induction.
2- There is no electrical connection between the primary and secondary. The a.c. power is transferred from primary to secondary through flux.
3- There is no change in frequency i.e., output power has the same frequency as the input power.
4- The losses that occur in the transformer are:
    a- Core losses – eddy current and hysteresis losses.
    b- Copper losses – in the resistance of the windings.

In practice, these losses are very small so that output power is nearly equal to the input power. In other wards, a transformer has very high efficiency.

Transformer Iron:

1/ Low silicon iron

1% silicon, 99% steel

Specific loss = 1.7 watt/kg at 1 Tesla & 50Hz.

2/ high silicon iron:

4-5% silicon, 95% - 96% steel

Specific loss = 1.2 Watt/kg at 1Tesla & 50Hz.

Transformer classification according to use:

1- Power transformers

   a/ large transformers:

   15 - 300 MVA
   10 - 500kV

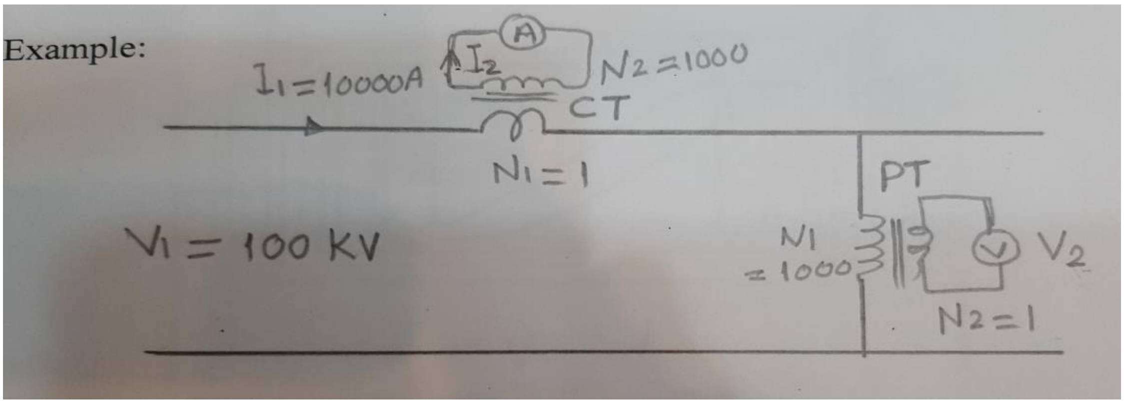
   Used in high voltage transmission lines

   b/ medium transformers:
   10 – 1000kVA
   3 – 30kV
   Used in distribution networks (distribution transformers)

   c/ small transformers.

2- Instrument transformers:

Used for measuring the current ("CT" current transformers) or for measuring the voltage ("PT" potential transformer)



CT

$I_2N_2 = I_1N_1 \longrightarrow I_2/I_1 = N_1/N_2 \longrightarrow I_2 = 1/1000 * 10000 = 10A$

PT

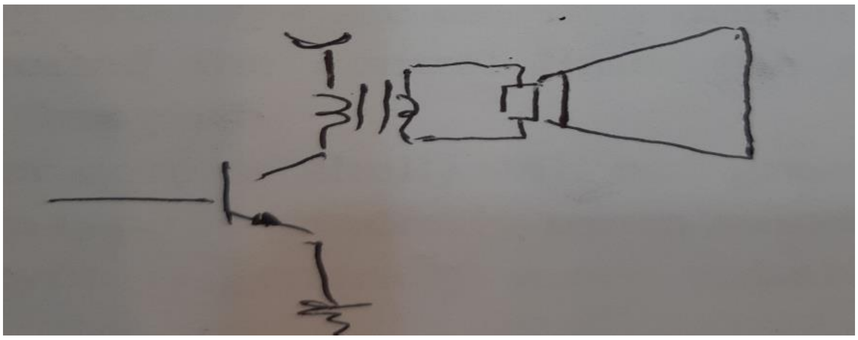
$V_2/V_1 = N_2/N_1 \longrightarrow V_2 = 1/1000 * 100 *10^3 = 100V$

3- High frequency transformers

Used in electronic circuits of high frequencies and low power. These transformers have air core to reduce the iron losses at high frequencies and for linearity.

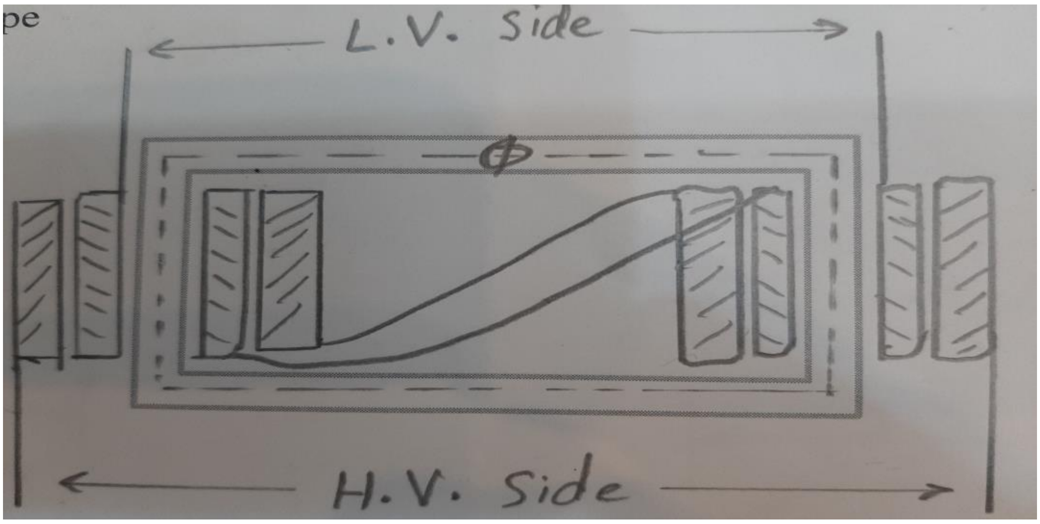
4- Impedance matching transformers:

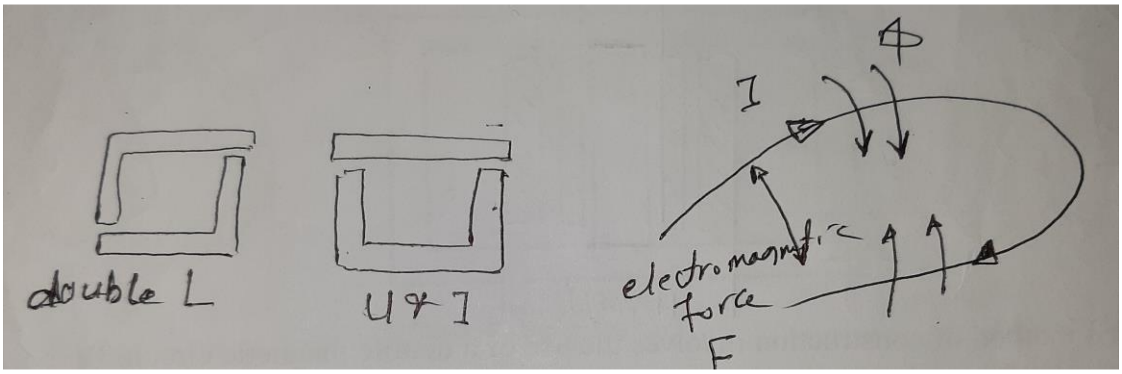
Used for impedance matching in communication circuits.



Iron core types:

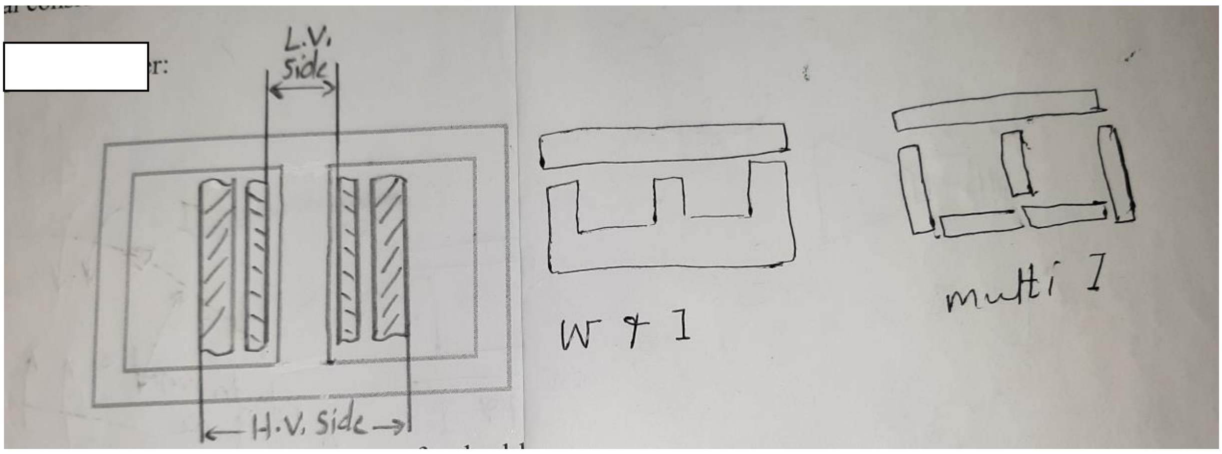
a/ Core type





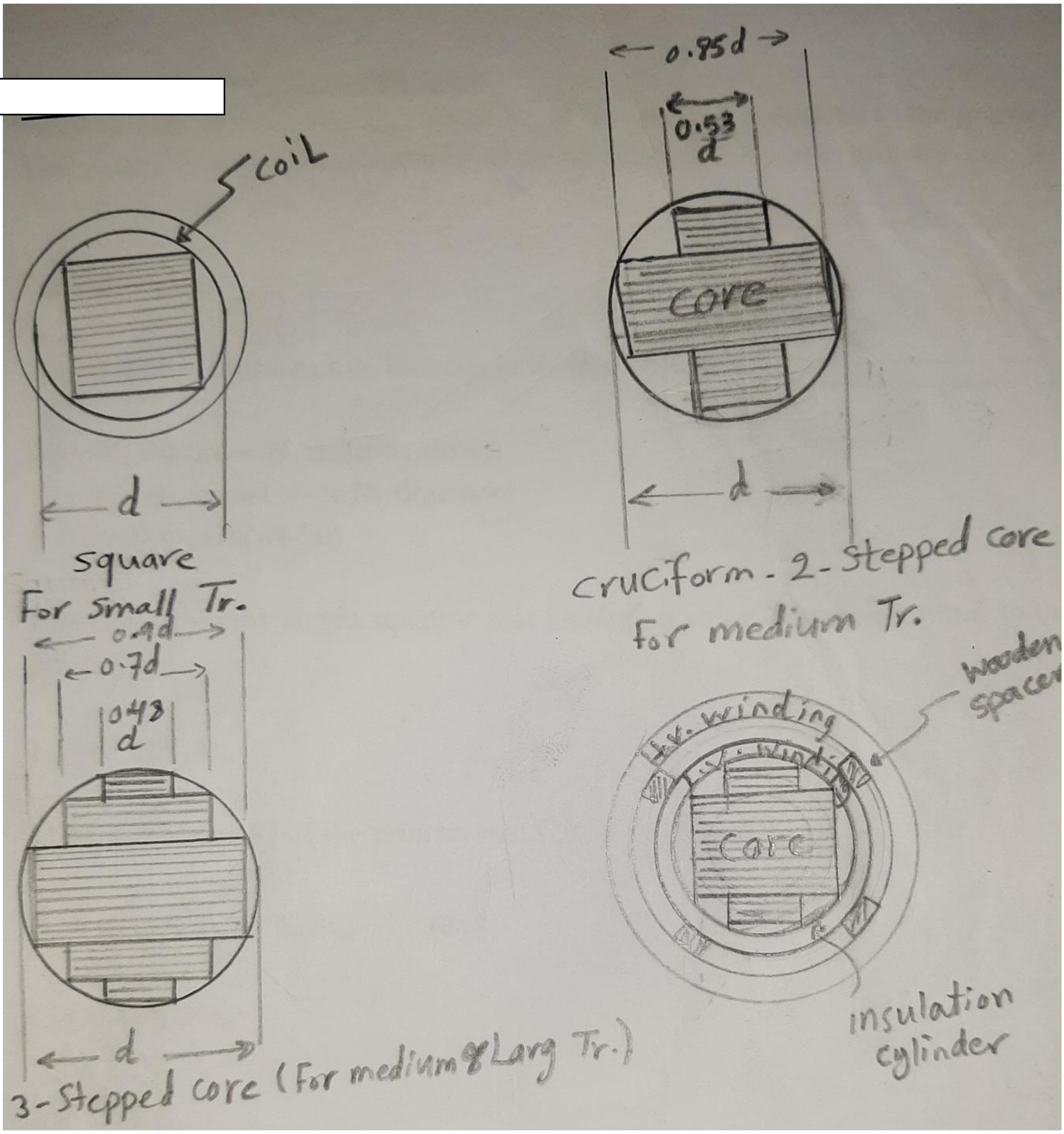
In core-type transformers, half of primary winding and half of the secondary winding are placed round each limb. This reduces the leakage flux. It is a useful practice to place the low-voltage winding below the high-voltage winding for mechanical considerations and to reduce the size of the insulator used.

b/ Shell-type transformer:

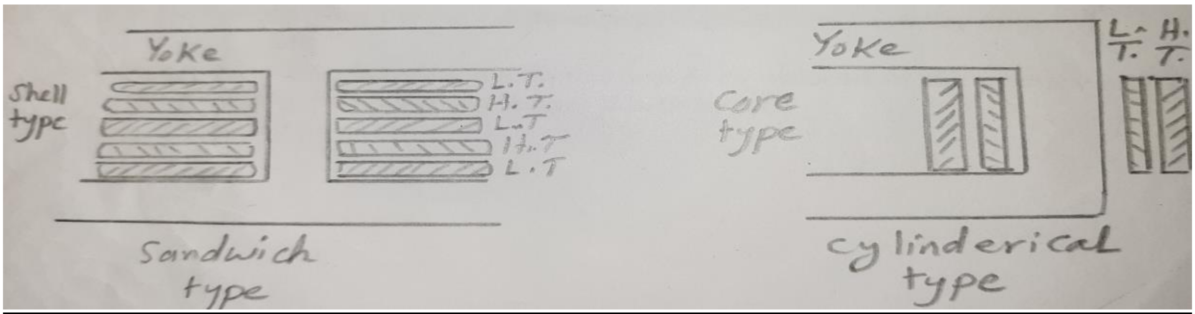


This method of construction involves the use of a double magnetic circuit. Both the windings are placed round the central limb, the other two limbs acting simply as a low-reluctance flux path.
The choice of type (whether core or shell) will not greatly effect the efficiency of the transformer. The core type is generally more suitable for high voltage and small current while shell-type is generally more suitable for low voltage and high current.

Core section:

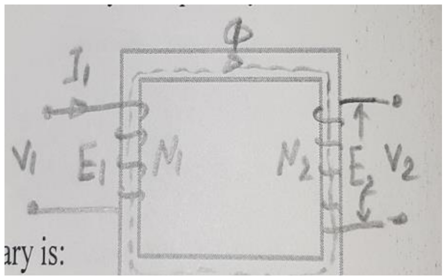


Winding:



E.M.F. equation of a transformer:

Consider that an alternating voltage $\mathbf{V_1}$ of frequency f is applied to the primary as shown below. The sinusoidal flux $\mathbf{\Phi}$ produced by the primary can be represented as:



$\mathbf{\Phi = \Phi_m \sin wt}$

The instantaneous e.m.f. $\mathbf{e_1}$ induced in the primary is:

$\mathbf{e_1 = -N_1\, d\Phi/dt = -N_1\, d/dt(\Phi_m \sin wt)}$
$\mathbf{= -wN_1\Phi_m \cos wt = -2\pi f N_1 \Phi_m \cos wt}$
$\mathbf{= 2\pi f N_1 \Phi_m \sin(wt-90)}$

It is clear from the above equation that maximum value of induced **e.m.f**. in the primary is

$\mathbf{E_{m1} = 2\pi f N_1 \Phi_m}$

The r.m.s. value $\mathbf{E_1}$ of the primary e.m.f. is

$\mathbf{E_1 = E_{m1}/\sqrt{2} = 2\pi f N_1 \Phi_m/\sqrt{2}}$ **,then**

$\mathbf{E_1 = 4.44 N_1 f \Phi_m}$

Similarly
$\mathbf{E_2 = 4.44 N_2 f \Phi_m}$ (as the e.m.f. $\mathbf{E_2}$ is produced by the same flux $\mathbf{\Phi = \Phi_m \sin wt}$ that cause $\mathbf{E_1}$. Thus the only difference of the two is the number of turns).

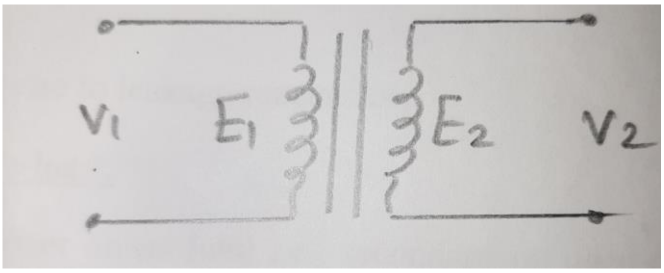
Note: it is clear from the above that e.m.f. $\mathbf{E_1}$ induced in the primary and $\mathbf{E_2}$ induced in the secondary lag behind flux $\mathbf{\Phi}$ by $\mathbf{90^o}$

Ideal transformers:

For ideal transformers

1/ $\mathbf{E_1 = V_1}$ **and** $\mathbf{E_2 = V_2}$ (As there is no voltage drop in the windings)

$\mathbf{E_2/E_1 = V_2/V_1 = N_2/N_1}$



2/ There are no losses, therefore, volt-amperes input to the primary are equal to the output volt-amperes i.e.,

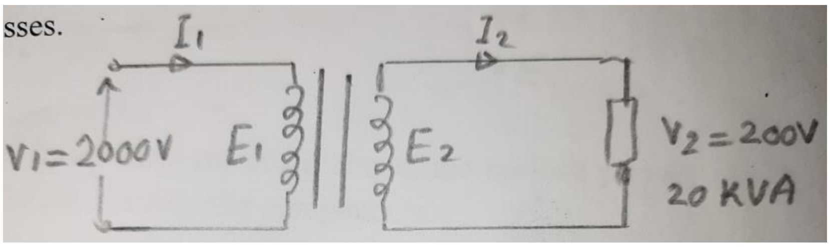
$\mathbf{V_1I_1 = V_2I_2}$

Or

$\mathbf{I_2/I_1 = V_1/V_2 = N_1/N_2}$

Hence currents are in the inverse ratio of the voltage transformation ratio. This simply means that if we rise the voltage, there is a corresponding decrease of current.

Example: A 2000/200V, 20kVA transformer has 66 turns in the secondary. Calculate 1/ primary turns 2/ primary and secondary full-load currents. Neglect the losses.



Solution:

1/ $V_1/V_2 = 2000/200 = N_1/N_2 \longrightarrow N_1 = N_2*2000/200 = 66*10 = 660$turns.

2/ $V_1I_1 = V_2I_2 = 20*10^3 \longrightarrow I_2 = 20*10^3/200 = 100A$

$I_1 = 20*10^3/2000 = 10A$

Practical transformers:

A practical transformer differs from the ideal transformer in many respects. The practical transformer has

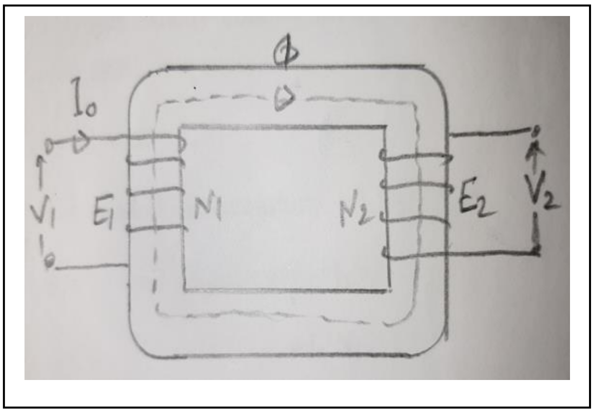
1- Iron loss
2- Winding resistance
3- Magnetic leakage, giving rise to leakage reactances.

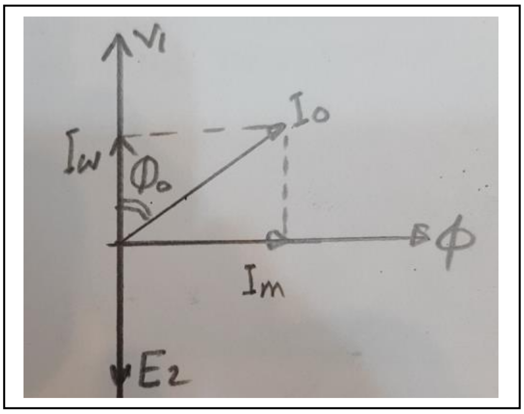
Practical transformer on no-load:

Consider a practical transformer on no-load i.e., secondary on open-circuit as shown in fig. below. The primary will draw a small current I_o to supply

(i) Iron losses and
(ii) A very small amount of copper loss in the primary. Hence the primary no load current I_o is not 90^o behind the applied voltage V_1 but lags it by an angle $\mathbf{\Phi_o < 90^o}$ as shown in the phasor diagram below.

No-load input power, $\mathbf{W_o = V_1 I_o \cos\Phi_o}$



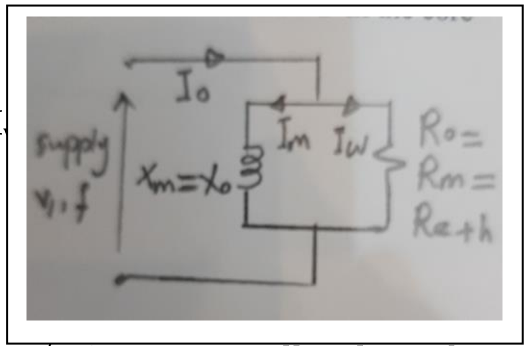


As seen from the phasor diagram in fig above, the no-load primary current $\mathbf{I_o}$ can be resolved into two rectangular components.

1/ the component $\mathbf{I_w}$ in phase with the applied voltage $\mathbf{V_1}$. This is known as active or working or iron loss component and supplies the iron loss and a very small primary copper loss.

$\mathbf{I_w = I_o \cos\Phi_o}$

2/ The component $\mathbf{I_m}$ lagging behind $\mathbf{V_1}$ by $\mathbf{90^o}$ and is known as magnetizing component. It is the component which produces the mutual flux $\mathbf{\Phi}$ in the core



$\mathbf{I_m = I_o \sin \Phi_o}$

Clearly, $\mathbf{I_o}$ is phasor sum of $\mathbf{I_m}$ and $\mathbf{I}$

$\mathbf{I_o} = \sqrt{\boldsymbol{Im^2 + Iw^2}}$

No load P.F., $\mathbf{\cos\Phi_o = I_w/I_o}$

The no-load primary copper loss (i.e. $I_o^2R_1$) is very small and may be neglected. Therefore, the no-load primary input power is practically equal to the iron loss in the transformer, i.e.

No load input power, W_o = Iron loss

Note: At no-load, there is no current in the secondary so that $V_2 = E_2$. On the primary side the drops due to I_o are very small because of the smallness of I_o.

Hence, we can say that at no-load, $V_1 = E_1$

Example: A 230/2300V transformer takes no-load current of 5A at 0.25 power factor lagging. Find 1/ the core loss and 2/ magnetizing current.

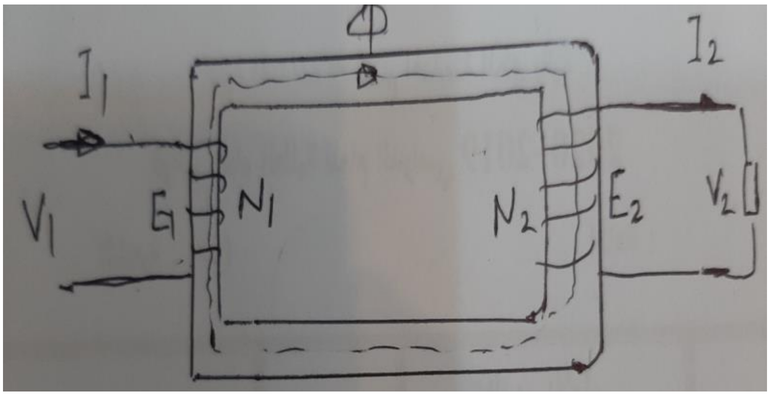
Solution:

1/ core loss, $W_o = V_1I_o\cos\Phi_o$ = 230*5*0.25 = 287.5W

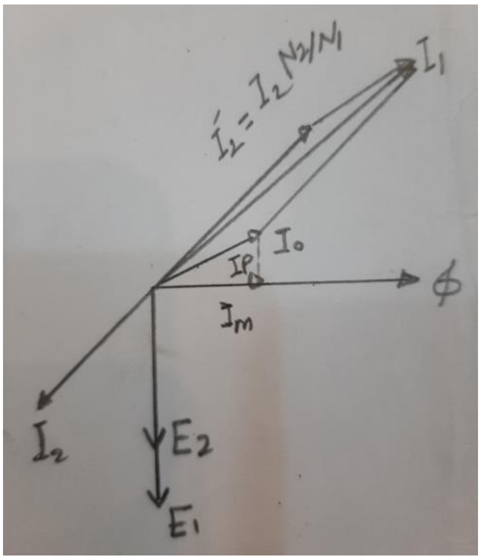
2/ Iron-loss current, $I_w = I_o \cos\Phi_o$ = 5*0.25 = 1.25A

Magnetizing current, $I_m = \sqrt{Io^2 - Iw^2} = \sqrt{5^2 - 1.25^2}$ = 4.84A

Transformer on load:



The secondary current I_2 sets up an m.m.f. $\mathbf{N_2I_2}$ which produces a flux in the opposite direction to the flux **Φ** originally set up in the primary by the magnetizing current. This will reduce the flux in the core from the magnetizing original value and hence reduce $\mathbf{E_1}$. Since applied voltage $\mathbf{V_1}$ is kept fixed, $\mathbf{E_1}$ must remain unchanged. This is possible only if the flux remain fixed. Hence, mutual flux **Φ** remains fixed whether a load is connected or not. In order to fulfill this condition, the primary must develop an m.m.f. which exactly counter balances the secondary m.m.f. $\mathbf{N_2I_2}$. Hence a primary current $\mathbf{I_1}$ must flow such that:



A.T. at no load = $\mathbf{I_0N_1}$

A.T. due to load on secondary = $\mathbf{I_2N_2}$

A.T. due to load on primary = $\mathbf{I_2N_2}$

$\mathbf{= I_2'N_1}$

$\longrightarrow \mathbf{I_2' = I_2N_2/N_1}$

Primary current $\mathbf{= I_1 = I_o + I_2'}$

- The power input, therefore, automatically Increase with the output.
- The flux in the core of the transformer is Constant, therefore the iron losses in the core are constant also.
- I_2' is 180^o out of phase with I_2