# Transformer

A Transformer consists of two windings that are electrically isolated from each other. When a time varying voltage is applied to one winding, it sets up an alternating flux in the magnetic core. Due to the high permeability of the core, most of the flux links the other winding and induces an alternating emf in that winding. The frequency of the induced emf in the winding is same as that of the voltage in the first winding. If the other winding is connected to load, the induced emf in the winding circulates a current in it. Thus the power is transferred from one winding to the other through the magnetic flux in the core.

The winding to which the alternating voltage is applied is called the primary winding. The winding that delivers power to the load is called the secondary winding. Either winding may be connected to the source or to the load.

# Introduction to Transformers:-

Construction:-

As compared to rotating machines, the static transformer is much simpler, because of less complex interrelations between the magnetic and electric circuits. The transformer, either single or 3-phase, mainly consists of the followings.

i) Magnetic circuit consisting of limbs (core), yokes and clamping structure (providing the flux path)

ii) Electric circuit consisting of primary and secondary windings.

iii) Dielectric circuit consisting of insulation in different forms and used at different places in the transformer (i.e core to primary winding, primary winding to secondary winding etc).

(iv) Tank and accessories.

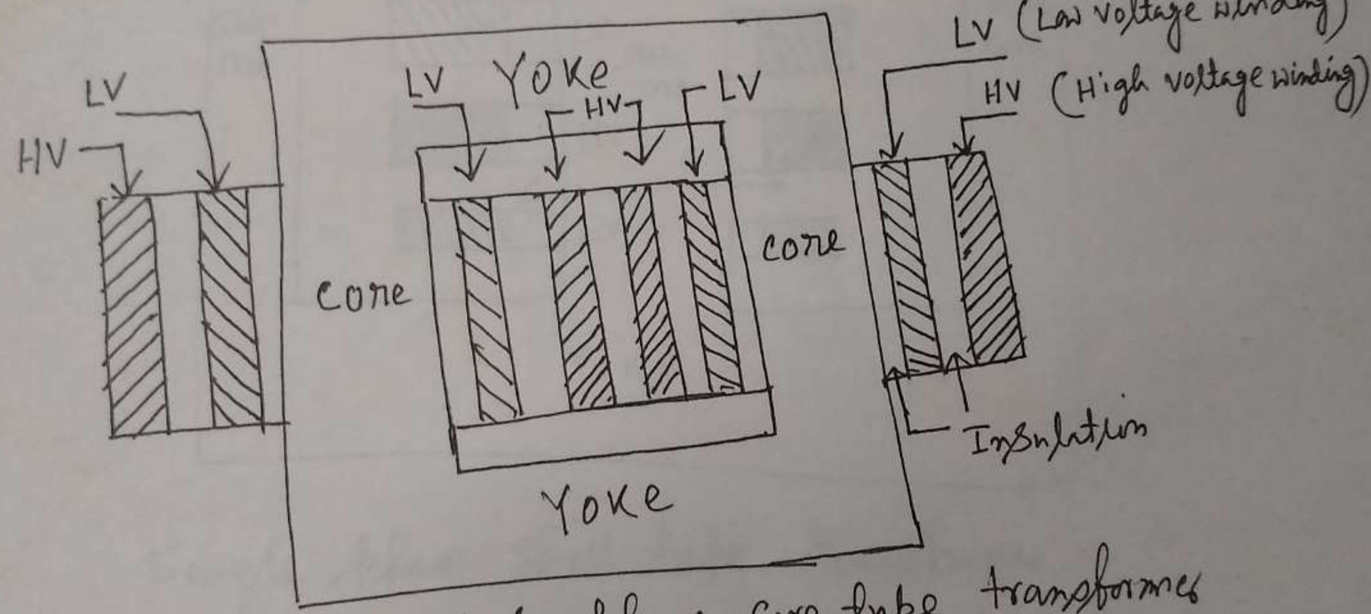
Magnetic circuit:- Magnetic circuit of the transformer consists of cores and yokes. The circuit provides the path to the flow of magnetic flux.

The flux flowing in the magnetic frame is alternating in nature and as a result hysteresis and eddy current losses will occur in the core and yoke of the transformer. Eddy current losses are directly proportional to the square of the thickness of the core. As such, core and yokes of the transformer are laminated to reduce the eddy current losses of the transformer. They are built up of thin sheets of special silicon steel of 0.3 to 0.35 mm thickness. Silicon content in the steel increases resistivity to the eddy currents, thereby reduces eddy current loss.

# Core type Transformer

A Single Phase Core type transformer Consists of a magnetic frame with two cores, upper yoke and bottom yoke. The primary and secondary coils are split into two parts. ~~Half~~ Half the turns of the primary and half the secondary turns are placed on each core (limb).

Generally circular coils (winding) are used in the core type transformers which indicate theoretically that a circular core should be used. It is very complicated to manufacture a circular core and as a result stepped core is generally used. However, for a small transformers, a rectangular or square core can be used. A schematic diagram showing the magnetic frame and the windings on the cores for single phase core type transformer is shown below:-

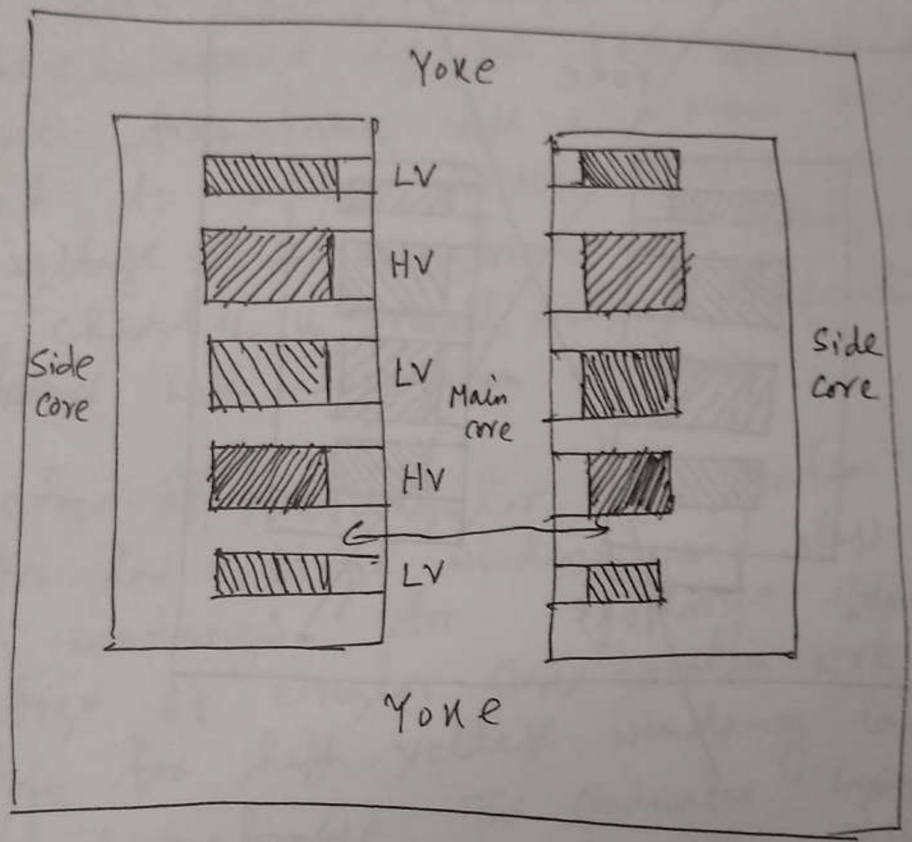



single phase core type transformer

Shell type Transformer:-

A single phase shell type transformer consists of a magnetic frame with a central core (limb) and two side cores, completing the path of magnetic flux. Primary and secondary coils (winding) are placed on the central core in the particular configuration as shown in the figure below:-

Such an arrangement forms a shell of iron around the copper. The central leg flux $\phi$ is divided at the yoke section, half, that is $\phi/2$ towards each side leg. As the flux in the section of yoke and side cores is only half, the cross section of the yokes and the side cores is approximately half the section of the central limb.



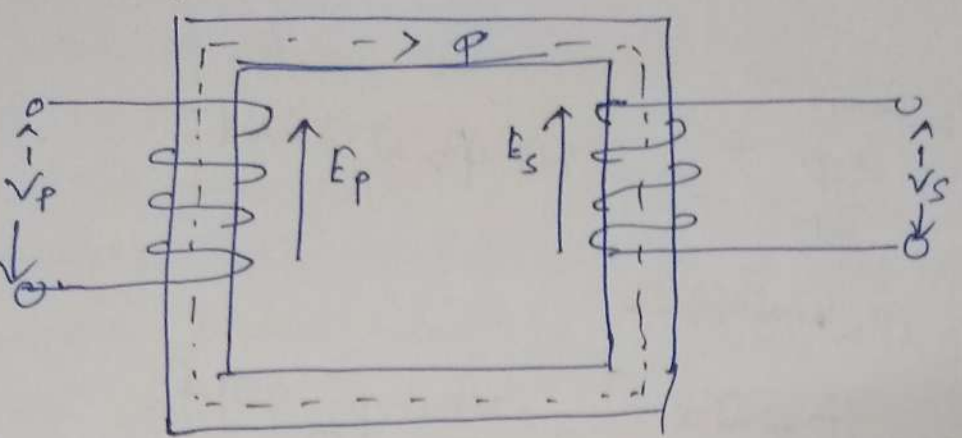

Single phase shell type transformer.

A core type transformer is more easily repaired on site. The shell type of transformers are ~~most~~ more robust mechanically.

## Electric circuit:-

The electric circuit of the transformer mainly consists of primary and secondary windings usually of copper. Recently, some manufacturers have started using aluminium instead of copper, due to deficiency of copper. Though aluminium is cheaper than copper, the advantage is counterbalanced by the high cost of extras. A small transformer with aluminium winding is cheaper compared to copper, however with increase in rating and voltage, the transformer with copper winding is much cheaper in overall costs as compared to the transformer with aluminium winding.

Conductors of rectangular cross-section are generally used for low voltage winding and also for high voltage windings for large transformers. Conductors of circular cross section are used mainly for high voltage winding in comparatively small transformers. The conductor insulation may be double cotton or single cotton with an underlayer of enamel or synthetic enamel.




The primary and secondary coils are insulated from each other. When an alternating voltage $V_p$ applied across the primary coil, a current $I_p$ flows in it producing magnetic flux $\phi$ in the transformer core. As the current in the primary winding is alternating, the magnetic flux set up in the core is also alternating.

As Faraday's law of electromagnetic induction, the emf induced, $E_p = -N_p \frac{d\phi}{dt}$.

Also $E_s = -N_s \frac{d\phi}{dt}$.

The apparent power drawn from the primary is equal to the apparent power transferred to the secondary.

i.e. $V_p I_p = V_s I_s$ & $\frac{V_p}{V_s} = \frac{I_s}{I_p} = \frac{N_p}{V_p}$

$N_p I_p + N_s I_s = 0$

$N_p I_p = - N_s I_s$

$\left| \frac{I_p}{I_s} \right| = \frac{N_s}{N_p}$

Emf equation.

$$\phi = \phi_m \cos\omega t$$

$$e_p = -N_p \frac{d\phi}{dt} = -N_p \phi_m \omega \sin\omega t$$

$$E_{p\,max} = N_p \phi_m \omega \cancel{\sin\omega t}$$

$$E_p = \frac{N_p \phi_m \omega}{\sqrt{2}} = \frac{N_p}{\sqrt{2}} \phi_m 2\pi f$$

$$= 4.44 N_p \phi_m f \text{ volt}$$

P. The required no load voltage ratio in a 1 $\phi$ transfer 50 H core type transformer is 66w/5w. find the number of turns in each winding, if the flux is ~~to~~ to be 0.06 wb

i) $5w = 4.44 N_p \times 0.06 \times 50$

$= 37.5$

$= 38$

$$N_S = N_p \times \frac{V_S}{V_P} = 501.6 \text{ (not possible)}$$

A single phase transformer has 350 primary and 1050 secondary turns. The net cross-sectional area of the core is 55 $cm^2$. If the primary winding be connected to a 400 volt, 50 Hz single phase supply, calculate i) the maximum value of flux density in the core and ii) the voltage induced in the secondary winding.

Soln:

i) voltage applied to the primary = 400 v

Induced emf in the primary $E_p \simeq$ voltage applied to the primary

$= 400$ volt.

No. of turns in primary, $N_p = 350$

Net cross. sectional area $A_i = 55 \ cm^2$

$= 55 \times 10^{-4} \ m^2$

Induced emf in the primary, $E_p = 4.44 f B_m A_i N_p$

Thus,
$$400 = 4.44 \times 50 \times B_m \times 55 \times 10^{-4} \times 550$$

$$\therefore B_m = \frac{400}{4.44 \times 50 \times 55 \times 10^{-4} \times 350} = 0.93 \text{ tesla } (Wb/m^2)$$

ii) No. of turns in secondary winding, $N_s = 1050$

for the transformer, $\frac{E_s}{E_p} = \frac{N_s}{N_p}$

$\therefore$ voltage induced in 2ndry wdg. $E_s = E_p \times \frac{N_s}{N_p}$

$= 400 \times \frac{1050}{350}$

$= 1200$ volt.

P1 A Single Phase 4 KVA transformer has 400 primary turns and 1000 secondary turns. The net cross-sectional area of the core is 60 $cm^2$. When the primary winding is connected to 500V, 50Hz supply. Calculate

i) the maximum value of flux density in the core

ii) the voltage induced in the secondary winding, and

iii) the secondary full load current.

Sol, i) $E_1 = 500V = 4.44\, B_m A f N_1$

$B_m = 0.9384\, Wb/m^2$

ii) $E_2 = \frac{N_2}{N_1} E_1 = 1250\,V$

iii) secondary current, $I_2 = \frac{VA}{E_2} = 3.2\,A.$

P2 A 1000/200 V transformer takes 0.3A at p.f of 0.2 on open circuit. Find the magnetizing and iron loss component of no-load primary current.

P3 A 80 kVA, 3200/400 volts transformer has 111 turns on secondary. Calculate i) number of turns on primary winding ii) secondary current iii) the cross sectional area of the core, if the maximum flux density is 1.2 Tesla.

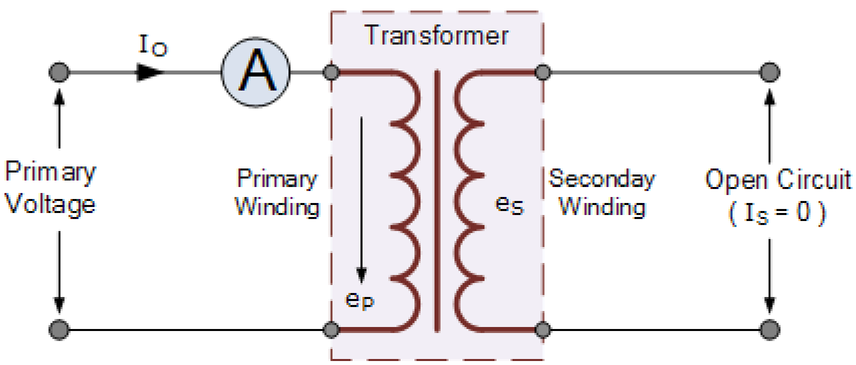
In the previous transformer tutorials, we have assumed that the transformer is ideal, that is one in which there are no core losses or copper losses in the transformers windings. However, in real world transformers there will always be losses associated with the transformers loading as the transformer is put “on-load”. But what do we mean by: **Transformer Loading**.

Well first let’s look at what happens to a transformer when it is in this “no-load” condition, that is with no electrical load connected to its secondary winding and therefore no secondary current flowing.

A transformer is said to be on “no-load” when its secondary side winding is open circuited, in other words, nothing is attached and the transformer loading is zero. When an AC sinusoidal supply is connected to the primary winding of a transformer, a small current, $I_{OPEN}$ will flow through the primary coil winding due to the presence of the primary supply voltage.

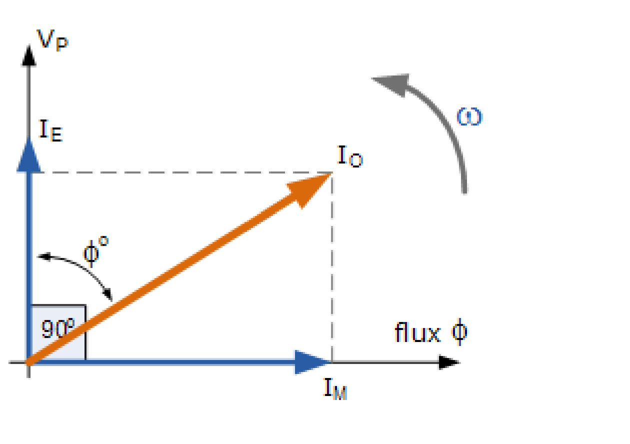
With the secondary circuit open, nothing connected, a back EMF along with the primary winding resistance acts to limit the flow of this primary current. Obviously, this no-load primary current ( Io ) must be sufficient to maintain enough magnetic field to produce the required back emf. Consider the circuit below.

**Transformer “No-load” Condition**




The ammeter above will indicate a small current flowing through the primary winding even though the secondary circuit is open circuited. This no-load primary current is made up of the following two components:

- An in-phase current, $I_E$ which supplies the core losses (eddy current and hysteresis).
- A small current, $I_M$ at 90° to the voltage which sets up the magnetic flux.




$$I_E = I_O \cos\phi$$

$$I_M = I_O \sin\phi$$

$$I_O = \sqrt{I_M^2 + I_E^2}$$

Note that this no-load primary current, Io is very small compared to the transformers normal full-load current. Also due to the iron losses present in the core as well as a small amount of copper losses in the primary winding, Io does not lag behind the supply voltage, Vp by exactly 90º, ( cosϕ = 0 ), there will be some small phase angle difference.

**Transformer Loading Example No1**

A single phase transformer has an energy component, $I_E$ of 2 Amps and a magnetising component, $I_M$ of 5 Amps. Calculate the no-load current, Io and resulting power factor.

$$I_O = \sqrt{I_M^2 + I_E^2}$$

$$I_O = \sqrt{5^2 + 2^2}$$

$$I_O = 5.4\text{Amps}$$

$$I_M = I_O \sin\phi$$

$$\sin\phi = \frac{I_M}{I_O} = \frac{5}{5.4} = 0.9259$$

$$\therefore \sin^{-1}\phi = 67.8^\circ$$

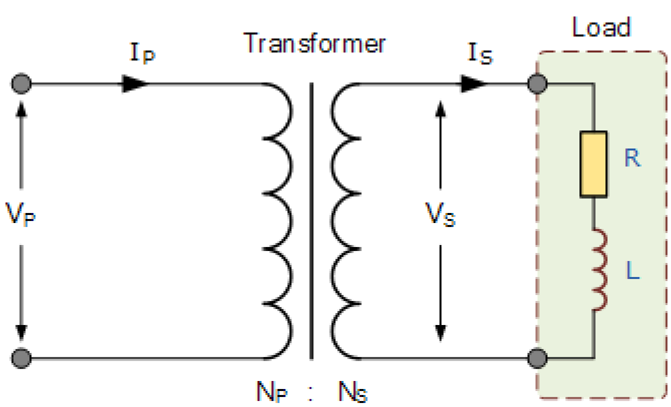
**Transformer "On-load"**

When an electrical load is connected to the secondary winding of a transformer and the transformer loading is therefore greater than zero, a current flows in the secondary winding and out to the load. This secondary current is due to the induced secondary voltage, set up by the magnetic flux created in the core from the primary current.

The secondary current, $I_S$ which is determined by the characteristics of the load, creates a self-induced secondary magnetic field, $\Phi_S$ in the transformer core which flows in the exact opposite direction to the main primary field, $\Phi_P$. These two magnetic fields oppose each other resulting in a combined magnetic field of less magnetic strength than the single field produced by the primary winding alone when the secondary circuit was open circuited.

This combined magnetic field reduces the back EMF of the primary winding causing the primary current, $I_P$ to increase slightly. The primary current continues to increase until the cores magnetic field is back at its original strength, and for a transformer to operate correctly, a balanced condition must always exist between the primary and secondary magnetic fields. This results in the power to be balanced and the same on both the primary and secondary sides. Consider the circuit below.

**Transformer "On-load"**




We know that the turns ratio of a transformer states that the total induced voltage in each winding is proportional to the number of turns in that winding and also that the power output and power input of a transformer is equal to the volts times amperes, ( V x I ). Therefore:

$$Power_{Prim} = Power_{Sec}$$

$$V_P \times I_P = V_S \times I_S$$

$$\text{then } \frac{V_P \times I_P}{V_S} = I_S$$

$$\therefore \frac{V_P}{V_S} = \frac{I_S}{I_P}$$

But we also know previously that the voltage ratio of a transformer is equal to the turns ratio of a transformer as: "voltage ratio = turns ratio". Then the relationship between the voltage, current and number of turns in a transformer can be linked together and is therefore given as:

**Transformer Ratio**

$$n = \frac{N_P}{N_S} = \frac{V_P}{V_S} = \frac{I_S}{I_P}$$

- Where:
- $N_P/N_S = V_P/V_S$ – represents the voltage ratio
- $N_P/N_S = I_S/I_P$ – represents the current ratio

Note that the current is inversely proportional to both the voltage and the number of turns. This means that with a transformer loading on the secondary winding, in order to maintain a balanced power level across the transformers windings, if the voltage is stepped up, the current must be stepped down and vice versa. In other words, "higher voltage — lower current" or "lower voltage — higher current".

As a transformers ratio is the relationships between the number of turns in the primary and secondary, the voltage across each winding, and the current through the windings, we can rearrange the above transformer ratio equation to find the value of any unknown voltage, ( V ) current, ( I ) or number of turns, ( N ) as shown.

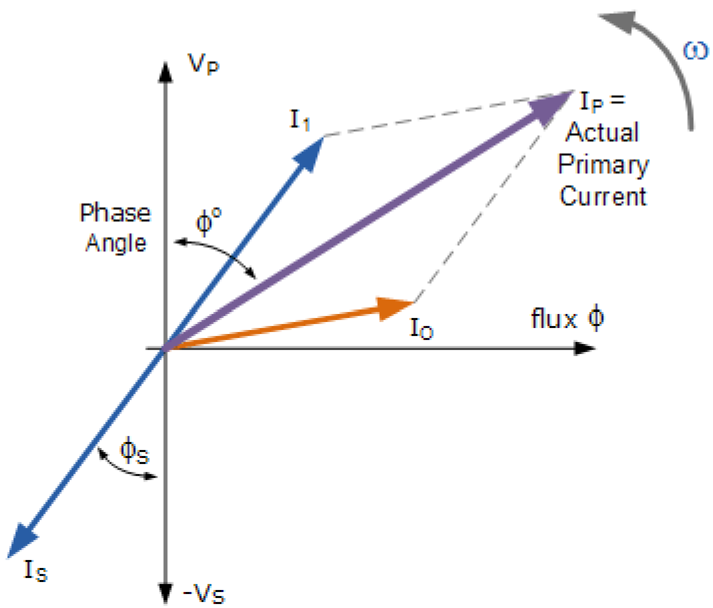
$$V_P = \frac{V_S N_P}{N_S} = \frac{V_S I_S}{I_P}, \qquad V_S = \frac{V_P N_S}{N_P} = \frac{V_P I_P}{I_S}$$

$$N_P = \frac{V_P N_S}{N_P} = \frac{N_S I_S}{I_P}, \qquad N_S = \frac{V_S N_P}{V_P} = \frac{N_P I_P}{I_S}$$

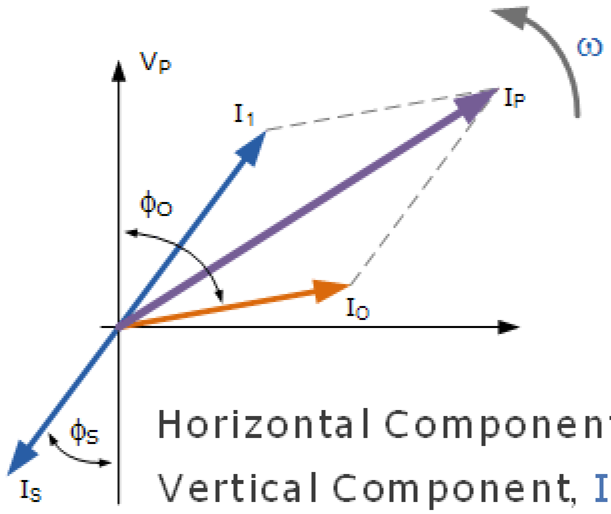
$$I_P = \frac{V_S I_S}{V_P} = \frac{N_S I_S}{N_P}, \qquad I_S = \frac{V_P I_P}{V_S} = \frac{N_P I_P}{N_S}$$

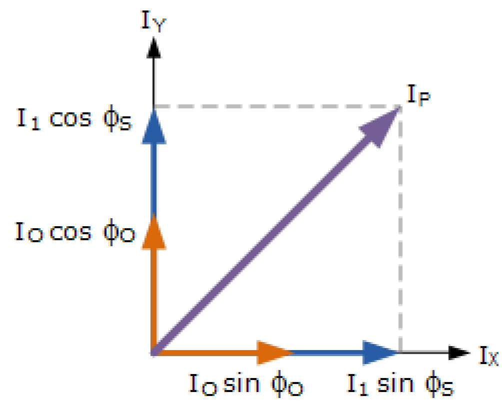
The total current drawn from the supply by the primary winding is the vector sum of the no-load current, Io and the additional supply current, $I_1$ as a result of the secondary transformer loading and which lags behind the supply voltage by an angle of Φ. We can show this relationship as a phasor diagram.

**Transformer Loading Current**




If we are given currents, $I_S$ and Io, we can calculate the primary current, $I_P$ by the following methods.




$$\text{Horizontal Component, } I_X = I_O \sin\phi_O + I_1 \sin\phi_S$$

$$\text{Vertical Component, } I_Y = I_O \cos\phi_O + I_1 \cos\phi_S$$

$$\therefore\ I_P = \sqrt{I_X^2 + I_Y^2} \quad \text{and} \quad \text{p.f.} = \cos\phi = \frac{I_Y}{I_P}$$

**Transformer Loading Example No2**

A single phase transformer has 1000 turns on its primary winding and 200 turns on its secondary winding. The transformers "no-load" current taken from the supply is 3 Amps at a power factor of 0.2 lagging. Calculate the primary winding current, $I_P$ and its corresponding power factor, ϕ when the secondary current supplying a transformer loading is 280 Amperes at 0.8 lagging.

$$\frac{N_P}{N_S} = \frac{I_S}{I_P} \quad \therefore\ I_1 = \frac{N_S \times I_S}{N_P} = \frac{200 \times 280}{1000} = 56\text{Amps}$$

$$\phi_O = \cos^{-1} 0.2 = 78.5^o$$

$$\phi_S = \cos^{-1} 0.8 = 36.8^o$$

$$I_X = I_O \sin\phi_O + I_1 \sin\phi_S$$
$$I_X = 3\times\sin 78.5 + 56\times\sin 36.8$$
$$I_X = 36.48A$$

$$I_Y = I_O \cos\phi_O + I_1 \cos\phi_S$$
$$I_Y = 3\times\cos 78.5 + 56\times\cos 36.8$$
$$I_Y = 45.44A$$

$$I_P = \sqrt{I_X^2 + I_Y^2}$$
$$I_P = \sqrt{36.48^2 + 45.44^2}$$
$$I_P = 58.3 \text{ Amperes}$$

$$\text{p.f.} = \cos\phi = \frac{I_Y}{I_P} = \frac{45.44}{58.3} = 0.78 = 38.8^{\circ}$$