SINGLE PHASE TRANSFORMER

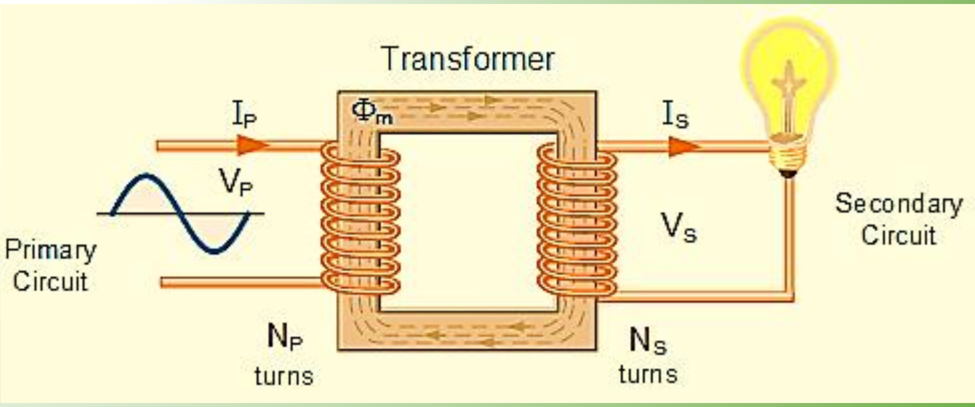
- **Electrical transformer** is a static electrical machine which transforms electrical power from one circuit to another circuit, without changing the frequency.
- Transformer can increase or decrease the voltage with corresponding decrease or increase in current.
- The reason for transforming the voltage to a much higher level is that higher distribution voltages implies lower currents for the same power (and therefore lower I^2 R losses along the networked grid of cables.

- P ↑ = V x I ↑ ; For High value of power P, if voltage is kept constant at some low value then current increases to high values.

This results in high I^2 R losses in the transmission conductor. Thus reducing the efficiency .

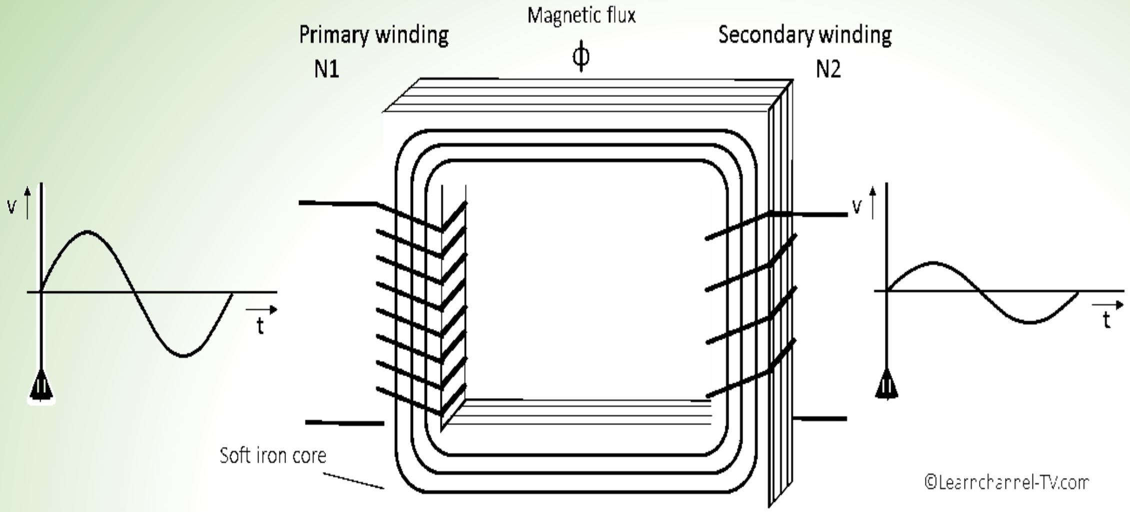
- If at high power voltage is increased then the current required is less.

i.e. P ↑ = V ↑ x I ; thus if high power is transmitted at high voltage then current in the system will be less. This results in less I^2 R losses in the transmission conductor.



Description:

A transformer is a device which converts magnetic energy into electrical energy.



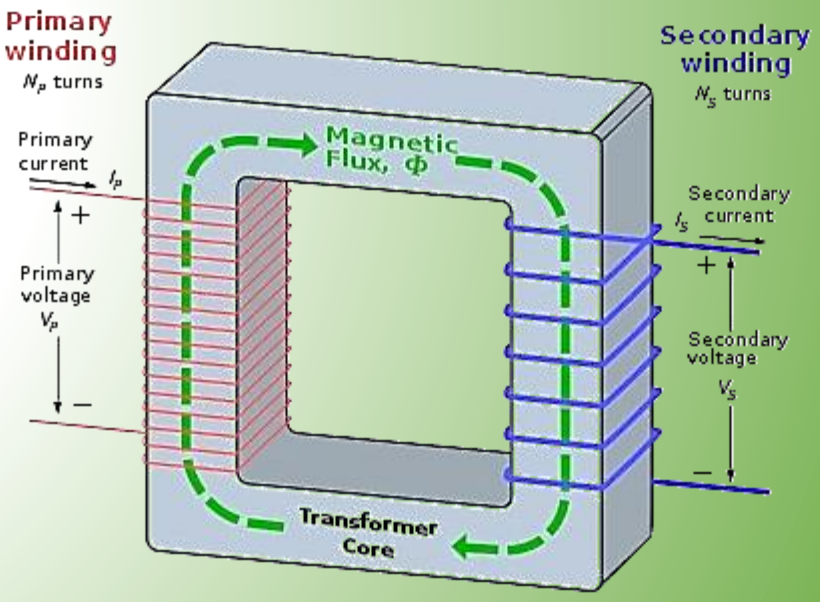
- It consists of two electrical coils called as a primary winding and secondary winding.
- The primary winding of a transformer receives power, while the secondary winding delivers power.
- A magnetic iron circuit called “core” is commonly used to wrap around these coils.
- Though these two coils are electrically isolated, they are magnetically linked.

Principle of Single Phase Transformer

- The single-phase transformer works on the principle of Faraday’s Law of Electromagnetic Induction.
- Typically, mutual induction between primary and secondary windings is responsible for the transformer operation in an electrical transformer.

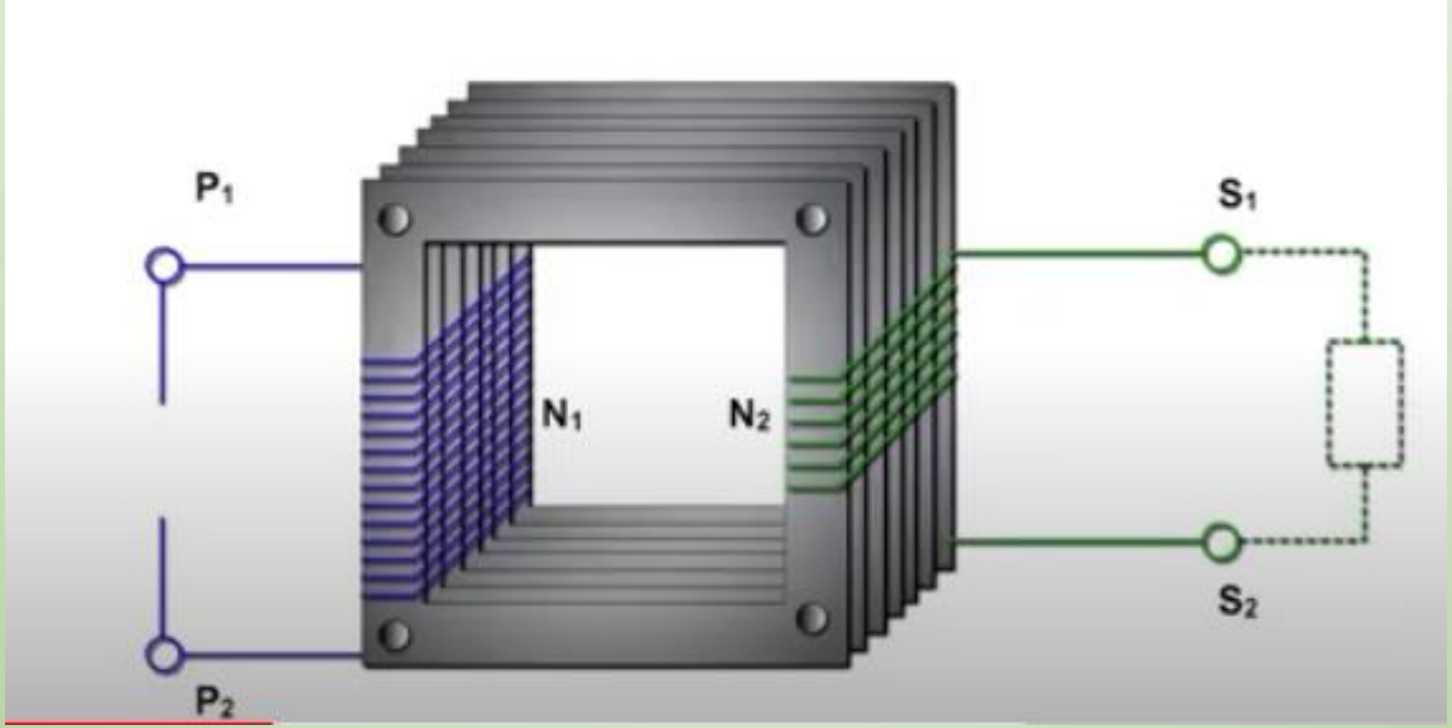
Working of Single Phase Transformer

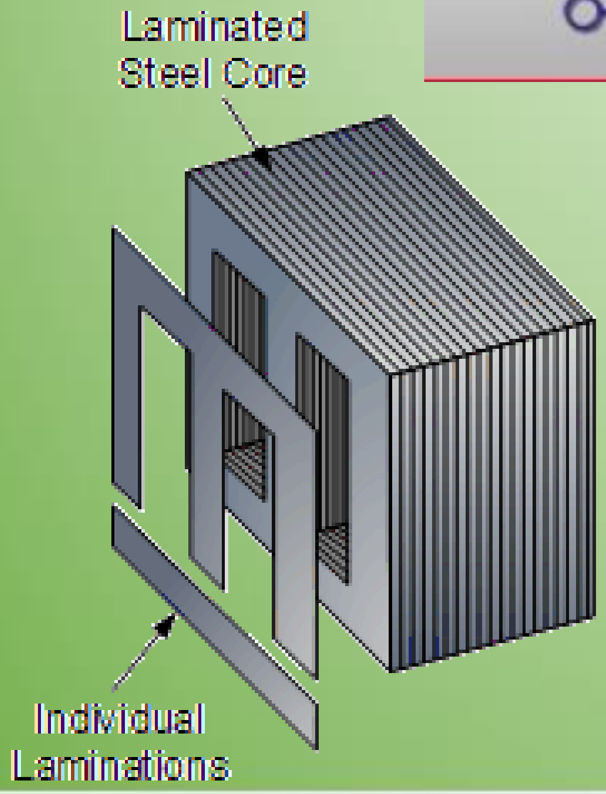
- A transformer is a static device that transfers electric power in one circuit to another circuit of the same frequency.
- It consists of primary and secondary windings. It operates on the principle of mutual inductance.
- When the primary of a transformer is connected to an AC supply, current flows in the coil and a magnetic field build-up.
- This electromagnet forms the magnetic lines of force and expands outward from the coil forming a path of magnetic flux.
- As the current increases from zero to its maximum value, the magnetic field strengthens and is given by $d\phi/dt$.
- The turns of both windings get linked by this magnetic flux.
- As the magnetic lines of flux flow around the core, it passes through the secondary winding, inducing voltage across it.
- The Faraday's Law is used to determine the voltage induced across the secondary coil and it is given by: **$N. d\phi/dt$**
- If a load is connected across the secondary winding it forms a closed path and current starts flowing in the secondary circuit.
- The magnetic flux and current are directly proportional to each other.

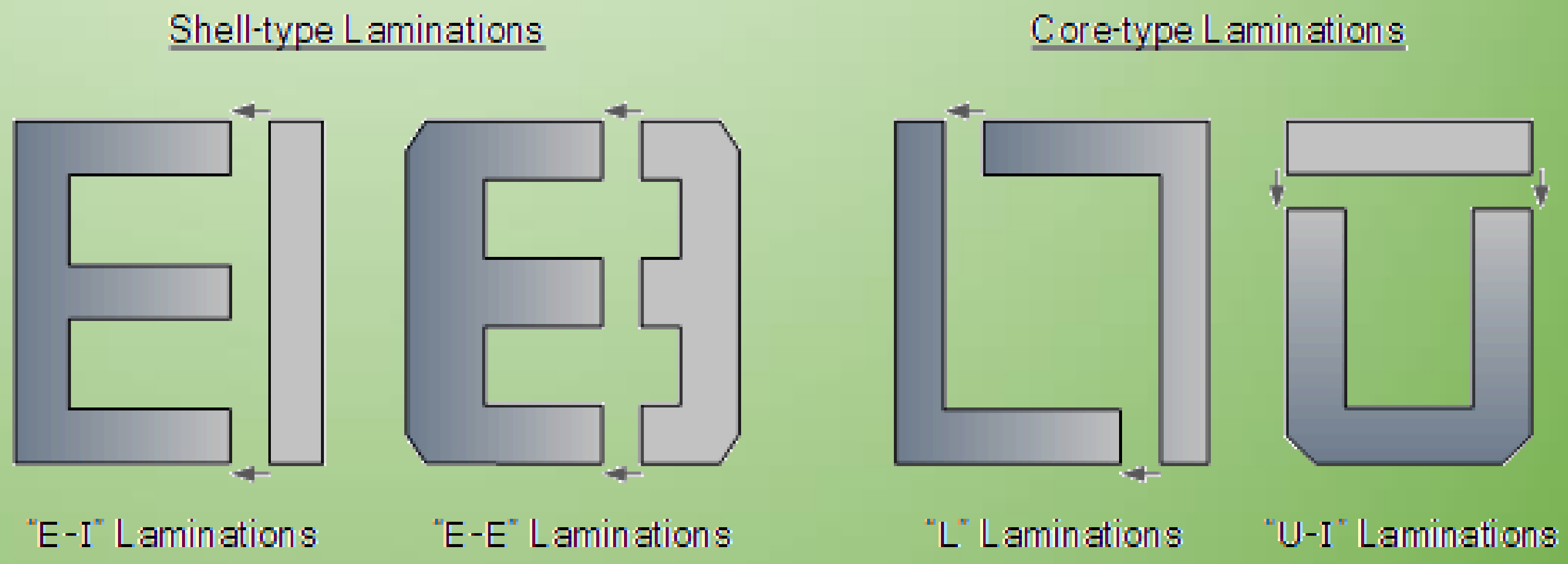


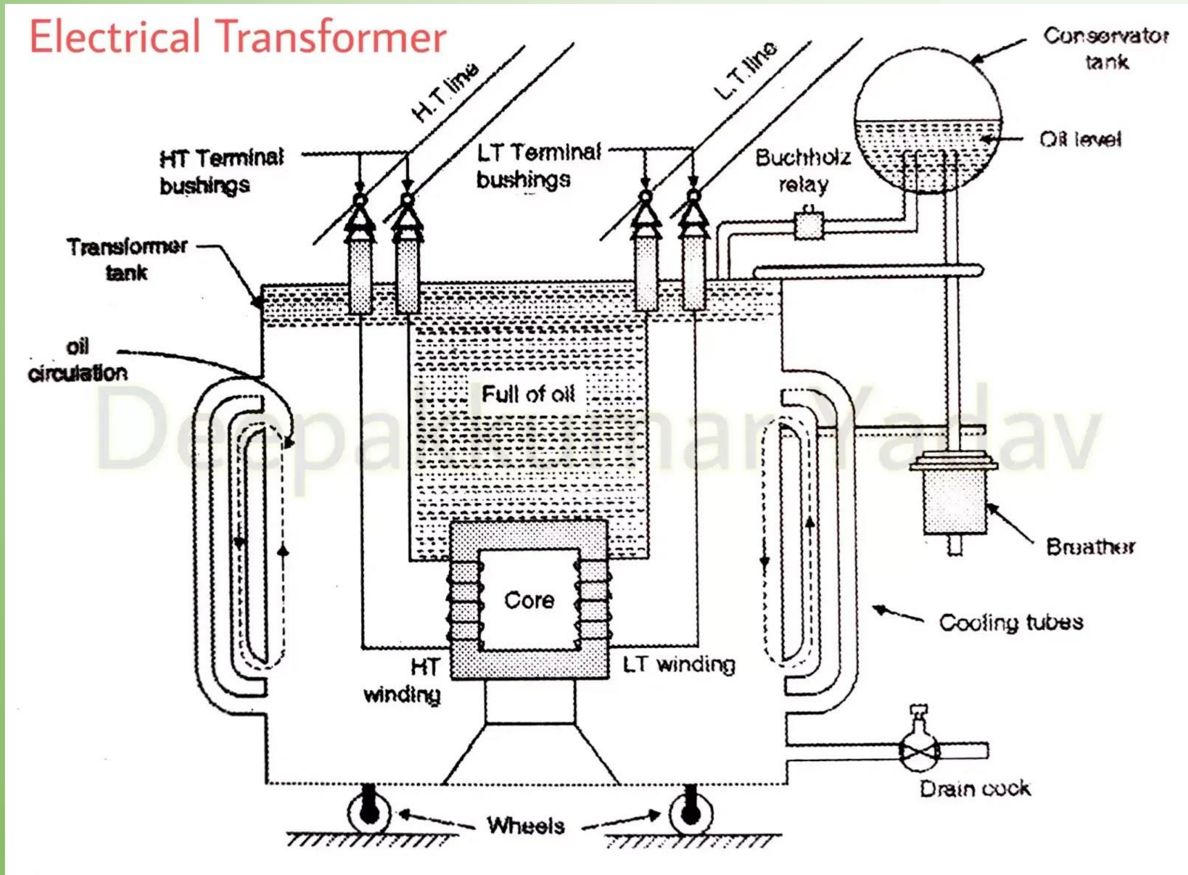
Construction of Single Phase Transformer

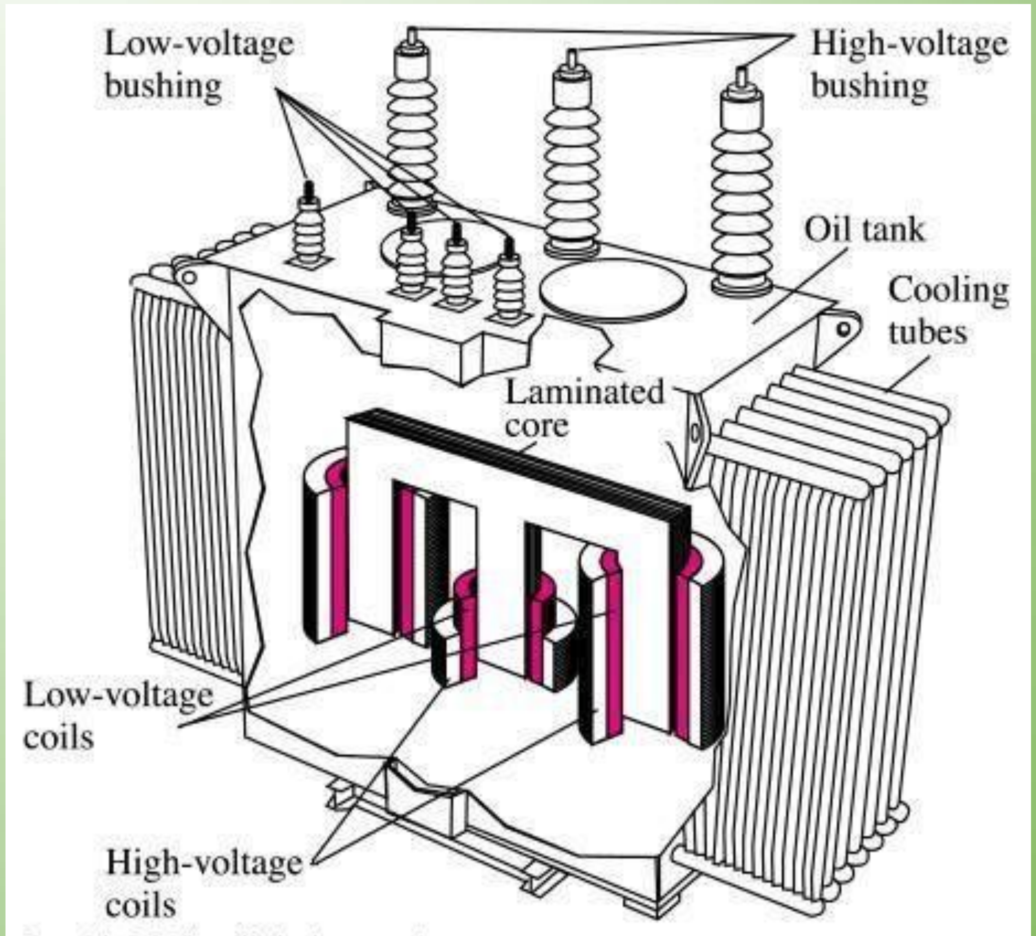
- A simple single-phase transformer has each winding being wound cylindrically on a soft iron limb separately to provide a necessary magnetic circuit, which is commonly referred to as “transformer core”.
- It offers a path for the flow of the magnetic field to induce voltage between two windings.
- In all types of transformers, core is constructed by assembling (stacking) laminated sheets of steel, with minimum air-gap between them (to achieve continuous magnetic path).
- Laminated sheets of steel are used to reduce eddy current loss.
- The steel used is having high silicon content and sometimes heat treated, to provide high permeability and low hysteresis loss.
- To avoid high reluctance at joints, laminations are stacked by alternating the sides of joint.
- The sheets are cut in the shape as E,I and L.
- The oil conservator to provide oil in the transformer tank for cooling purposes etc.
- It consist of suitable bushings to take out the terminals.
- Based on how the windings are wound around the central steel laminated core, the transformer construction is divided into two types: 1. Core Type 2. Shell Type


P1
P2
N1
N2
S1
S2

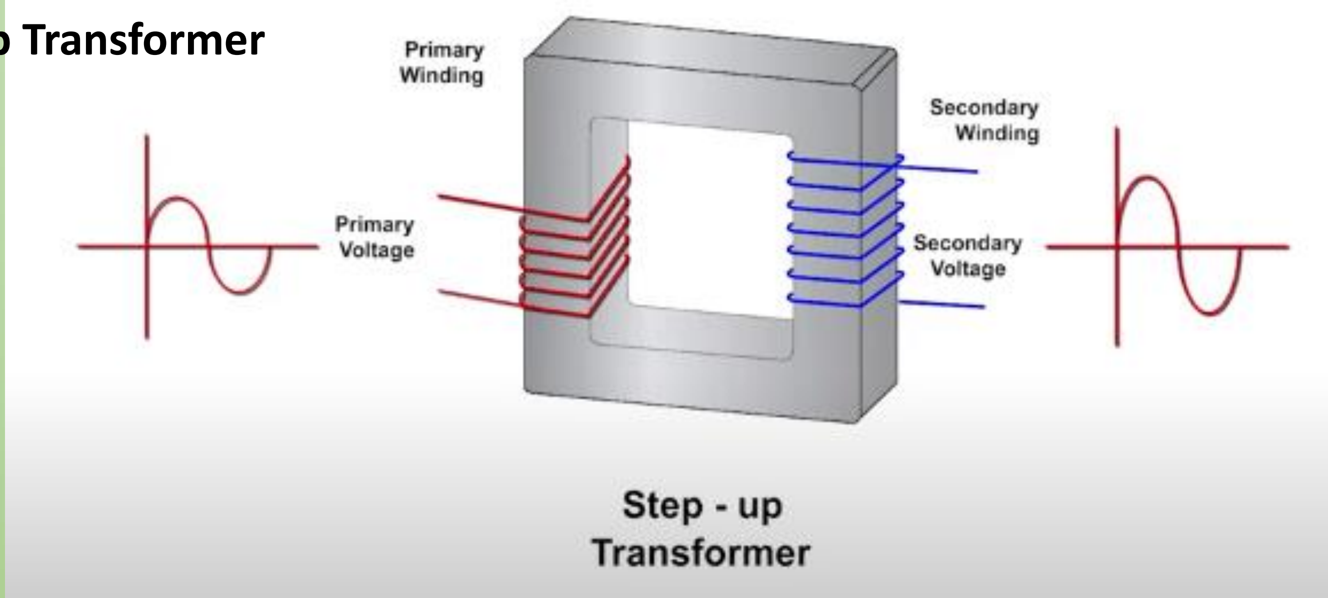

Laminated Steel Core
Individual Laminations


Shell-type Laminations
Core-type Laminations
"E-I" Laminations
"E-E" Laminations
"L" Laminations
"U-I" Laminations

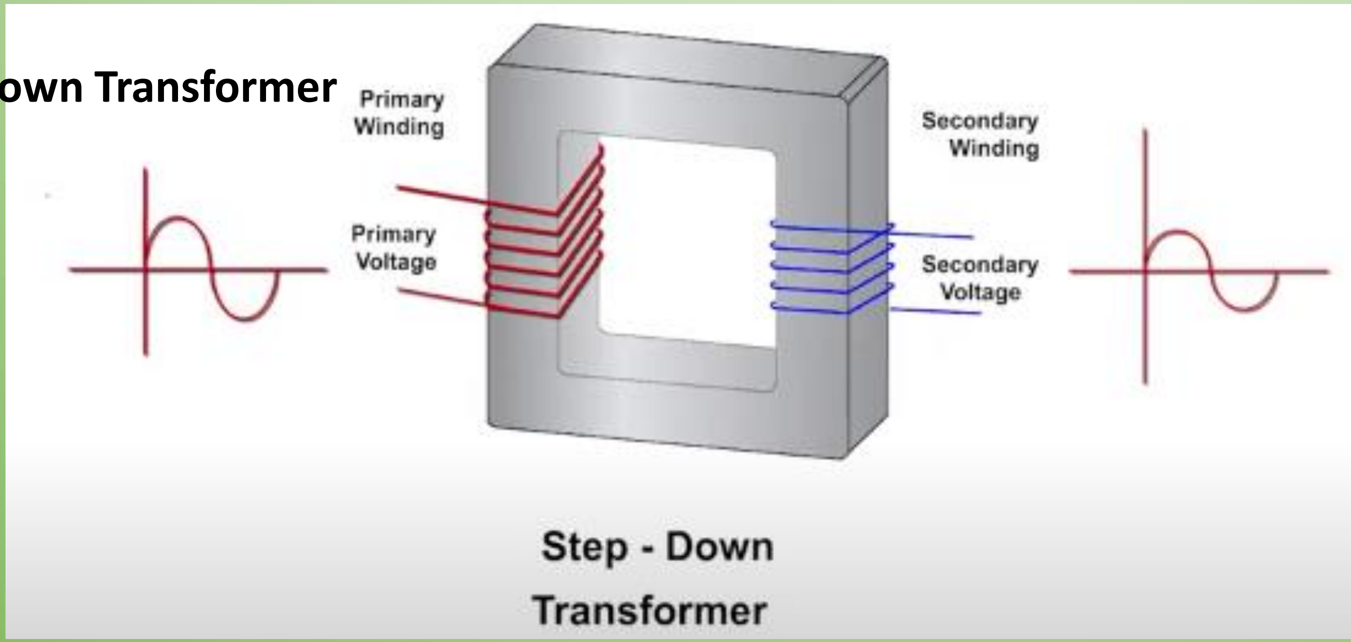

Electrical Transformer
H.T line
L.T line
Conservator tank
Oil level
HT Terminal bushings
LT Terminal bushings
Buchholz relay
Transformer tank
oil circulation
Full of oil
Breather
Core
Cooling tubes
HT winding
LT winding
Drain cock
Wheels


Low-voltage bushing
High-voltage bushing
Oil tank
Cooling tubes
Laminated core
Low-voltage coils
High-voltage coils

Step – up Transformer

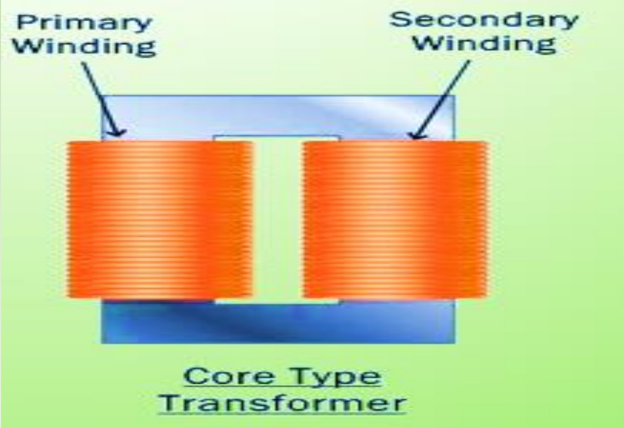


Step – down Transformer



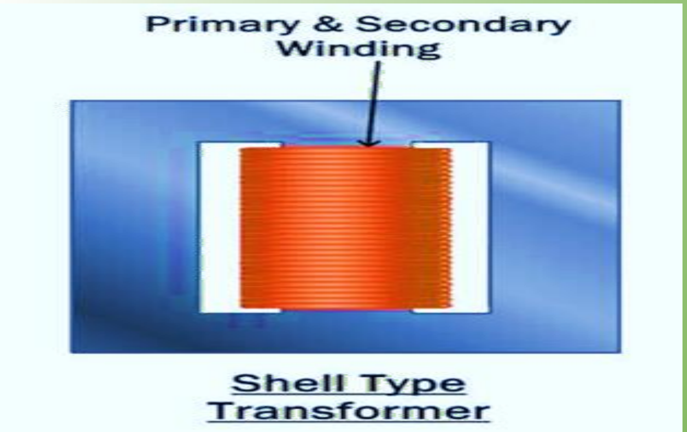
Construction of Single Phase Transformer

Core-type Transformer

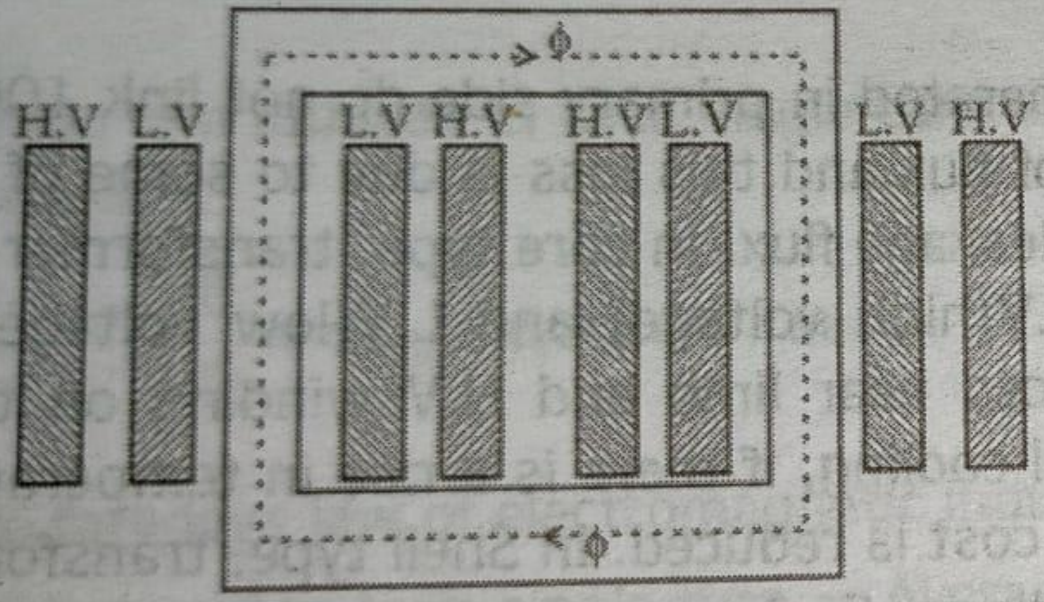


- The main disadvantage of the core-type transformer is the leakage flux that occurs due to the flow of a small proportion of magnetic lines of force outside the core.
- In this type of construction, only half of the windings are wound cylindrically around each leg of a transformer to enhance magnetic coupling.
- This type of construction ensures that magnetic lines of force flow across both the windings simultaneously.

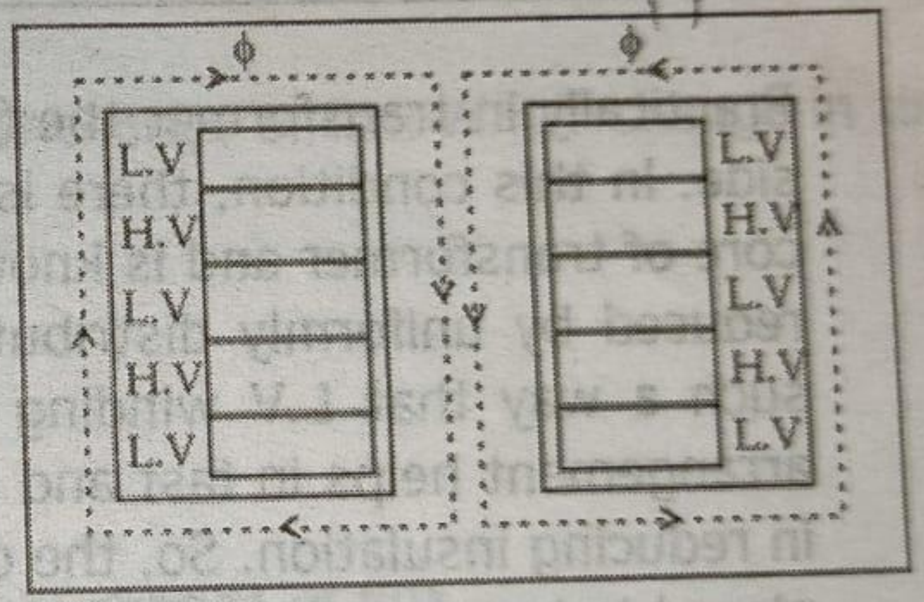
Shell-type Transformer



- In this type of transformer construction, the primary and secondary windings are positioned cylindrically on the center limb resulting in twice the cross-sectional area than the outer limbs.
- There are two closed magnetic paths in this type of construction and the outer limb has the magnetic flux $\phi/2$ flowing.
- Shell type transformer overcomes leakage flux, reduces core losses and increases efficiency.



a. Core Type Transformer



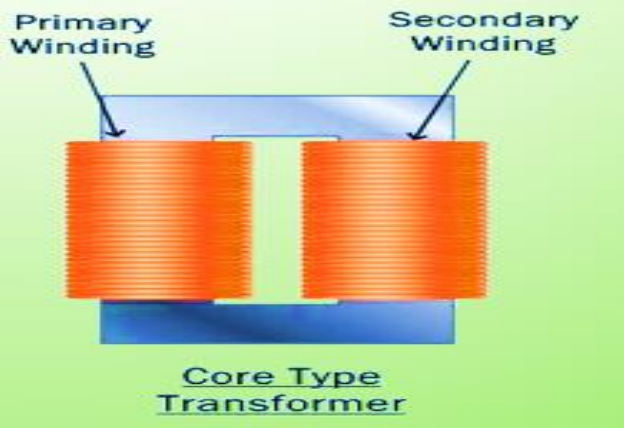
b. Shell Type Transformer

Core Type Transformer

1. They are popular in **High voltage applications** like Distribution transformers, Power transformers, and auto transformers.

2. High voltage corresponds to high flux. So, for keeping the iron loss low thicker core should be used. So core type is better choice.

3. At high voltage, heavy insulation is required. In core type winding it is easier to insert insulation.



Shell Type Transformer

1. They are popular in **Low voltage applications** like transformers used in electronic circuits and power electronic converters etc.

2. At low voltage, volume for the copper wires required is more than that of iron core. So the windows cut on the laminated sheets have to be of bigger proportion with respect to the whole size of the transformer. So, shell type is a better choice.

3. Here you don't care about the insulation much and insulation is thin and light.

EMF EQUATION OF A SINGLE PHASE TRANSFORMER:

When a sinusoidal voltage is applied to the primary winding of a transformer, alternating flux ϕ_m sets up in the iron core of the transformer. This sinusoidal flux links with both primary & secondary winding and is a sine wave:

$\Phi = \Phi_m \, \mathrm{Sin}(\omega t)$ Φ_m = Maximum flux in the core (in Wb) = $(B_m \times A)$

Let,

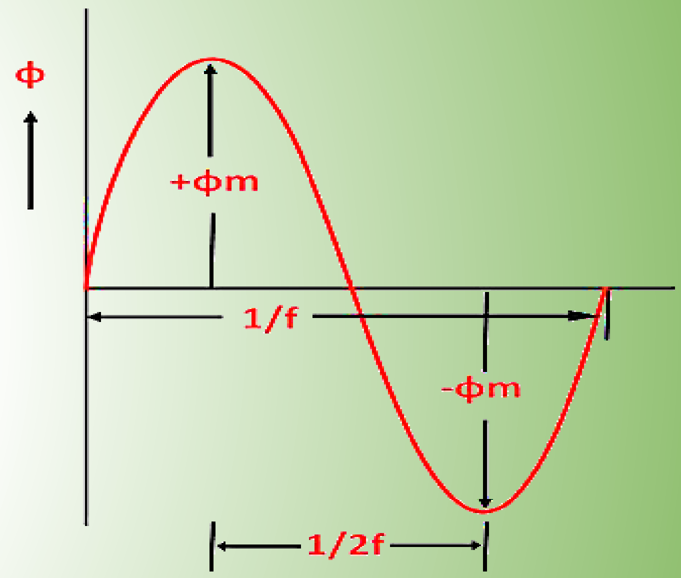
N_1 = Number of turns in primary winding

N_2 = Number of turns in secondary winding

ω = angular frequency of the AC supply (in radians/ sec)

By Faraday's Law of electromagnetic induction the emf induced in the primary winding having N_1- turns is given as

$$E_1 = \frac{-N_1 d\Phi}{dt} = \frac{-N_1 d[\Phi_m \, \mathrm{Sin}(\omega t)]}{dt} = -N_1 \omega \Phi_m \, \mathrm{Cos}(\omega t) = +N_1 \omega \Phi_m \, \mathrm{Sin}(\omega t - 90^\circ)$$



So the induced emf lags behind the magnetic flux by 90˚.

Maximum value of EMF , $E_m = N_1 \omega \Phi_m$ (when $\omega t = 0^\circ$).

i.e. , $E_m = N_1 (2\pi f) \Phi_m$

And the RMS value of emf induced in primary winding, $E_1 = \frac{E_m}{\sqrt{2}} = \sqrt{2}\pi f N_1 \Phi_m = 4.44 f \, N_1 \Phi_m$

$\boxed{E_1 = 4.44 f \, N_1 \, \Phi_m}$ **............................ eq (1)**

Similarly, RMS induced emf in secondary winding (E_2) can be given as

$E_2 = 4.44f\, N_2\, \Phi_m$. .... (eq 2)

$$\boxed{E_1 = 4.44f\, N_1\, \Phi_m} \qquad \text{.............................. eq (1)}$$

This is called the **emf equation of transformer**

Divide eq(2) by eq(1)

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

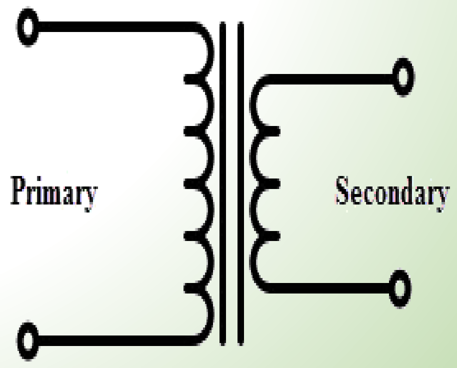
Thus we can write $\dfrac{E_2}{E_1} = \dfrac{N_2}{N_1} = K = \dfrac{V_2}{V_1}$

where K is a constant, It is called **Voltage transformation ratio** or **turns ratio** or **voltage ratio**

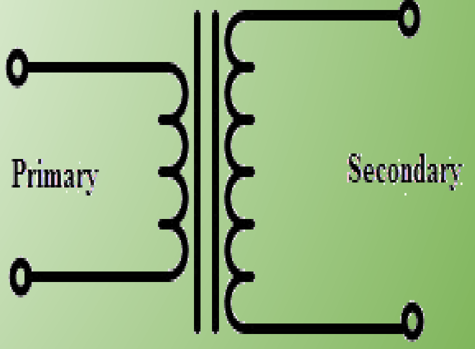
And $\dfrac{E_1}{N_1} = \dfrac{E_2}{N_2} = 4.44\, f\, \Phi_m$

The above expression shows that emf per turn $\left[\dfrac{E}{N}\right]$ is same for both primary and secondary winding.

- **If $N_1 > N_2$, i.e. $K > 1$ → Primary Voltage > Secondary Voltage. This transformer is called Step- down Transformer.**
- **If $N_1 < N_2$, i.e. $K < 1$ → Primary Voltage < Secondary Voltage. This transformer is called Step- Up Transformer.**
- **If $N_1 = N_2$, i.e. $K = 1$ → Primary Voltage = Secondary Voltage. This transformer is called Isolation Transformer.**



Step-down Transformer

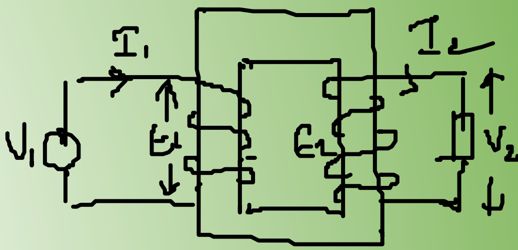


Step-up Transformer

IDEAL TRANSFORMER

Definition: The transformer which is free from all types of losses is known as an ideal transformer.
It is an imaginary transformer that has no core loss, infinite permeability of core, no ohmic resistance, and no leakage flux.

In an ideal transformer, there is no power loss. Therefore, the output power is equal to the input power.



Input Power , Pin = $V_1 \times I_1$ & Output Power , Pout = $V_2 \times I_2$

As we know $E_1 = V_1$ & $E_2 = V_2$

Input Power , Pin = $P_1 = E_1 \times I_1$ & the Output Power , Pout = $P_2 = E_2 \times I_2$

Input Power , Pin = $P_1 = V_1 \times I_1$ & the Output Power , Pout = $P_2 = V_2 \times I_2$

For an Ideal Transformer, $P_1 = P_2$

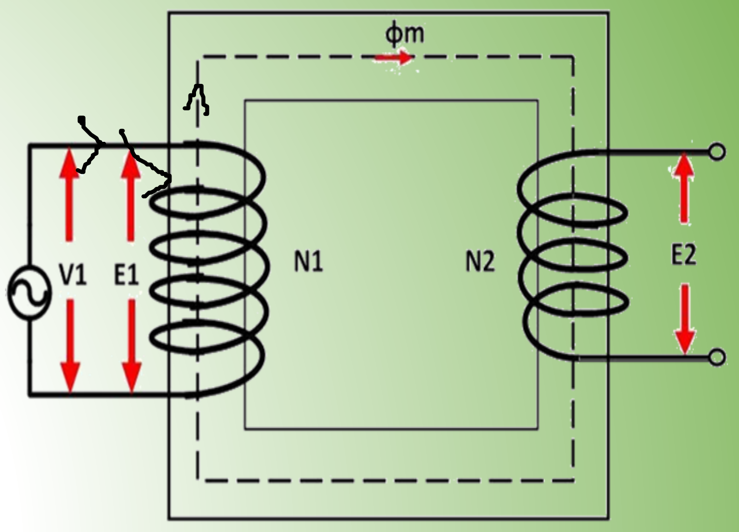
i.e. $E_1 \times I_1 = E_2 \times I_2$

Or $V_1 \times I_1 = V_2 \times I_2$

Thus, $\frac{V_2}{V_1} = \frac{I_1}{I_2} = K$ Or $\frac{V_2}{V_1} = \frac{N_2}{N_1} = \frac{E_2}{E_1} = \frac{I_1}{I_2} = K$ …… **Transformation Ratio**

IDEAL TRANSFORMER (on No- Load)

- The voltage source V_1 is applied across the primary winding of the transformer.
- The secondary winding is kept open.
- The N_1 and N_2 are the numbers of turns of their primary and secondary winding.
- The primary winding of the transformer carries current I_m which is called as the magnetizing current.
- The magnetizing current produces the flux φ_m in the core of the transformer.
- As the permeability of the core is infinite for an ideal transformer the flux of the core link with both the primary and secondary winding of the transformer.
- The flux link with the primary winding induces the emf E_1 because of self-induction
- The flux link with the secondary winding induces the emf E_2 because of mutual-induction
- The direction of the induced emf, E_1 & E_2 , is opposite to that of the applied voltage V_1.



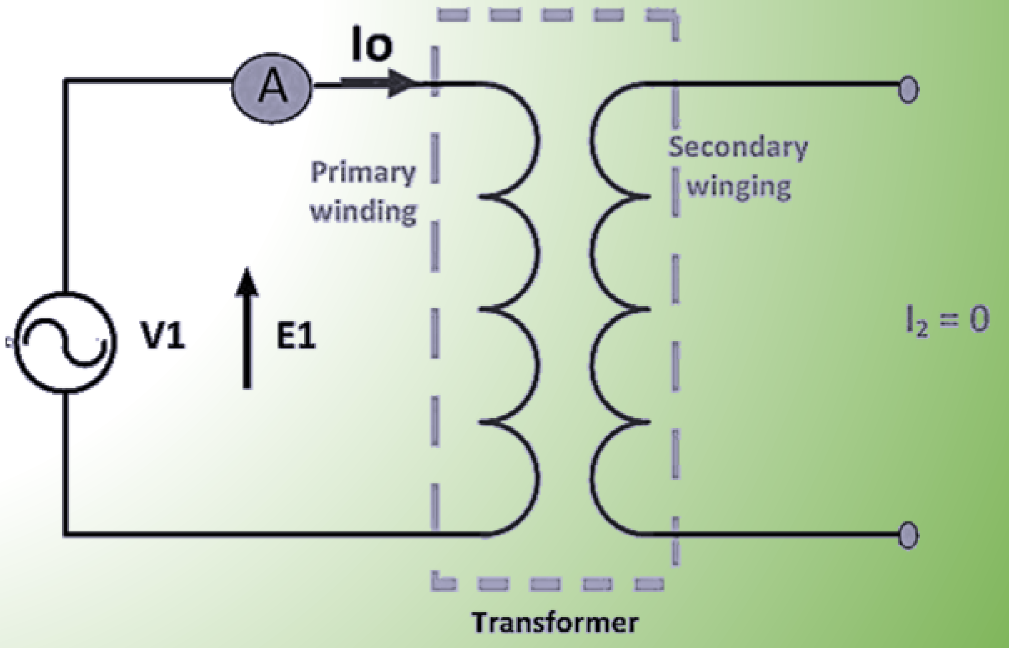
Practical Transformer on No Load

- **The practical transformer** has core loss, winding resistance and leakage flux and core permeability is not infinite.
- 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 I_0 called no-load current which is **2 to 10% of the rated current**.
- The no-load current consists of two components:

a. Reactive or magnetizing component I_m : It produces flux in the core and does not consume any power. It is in quadrature with the applied voltage V_1

b. Active or working component I_w: It supplies the iron losses and a small amount of primary copper loss. It is in phase with the applied voltage V_1.

- **i.e. $\bar{I}_o = \bar{I}_m + \bar{I}_w$ or $I_o = I_m + j\, I_w$**



Working component $I_w = I_0 \cos\varphi_0$

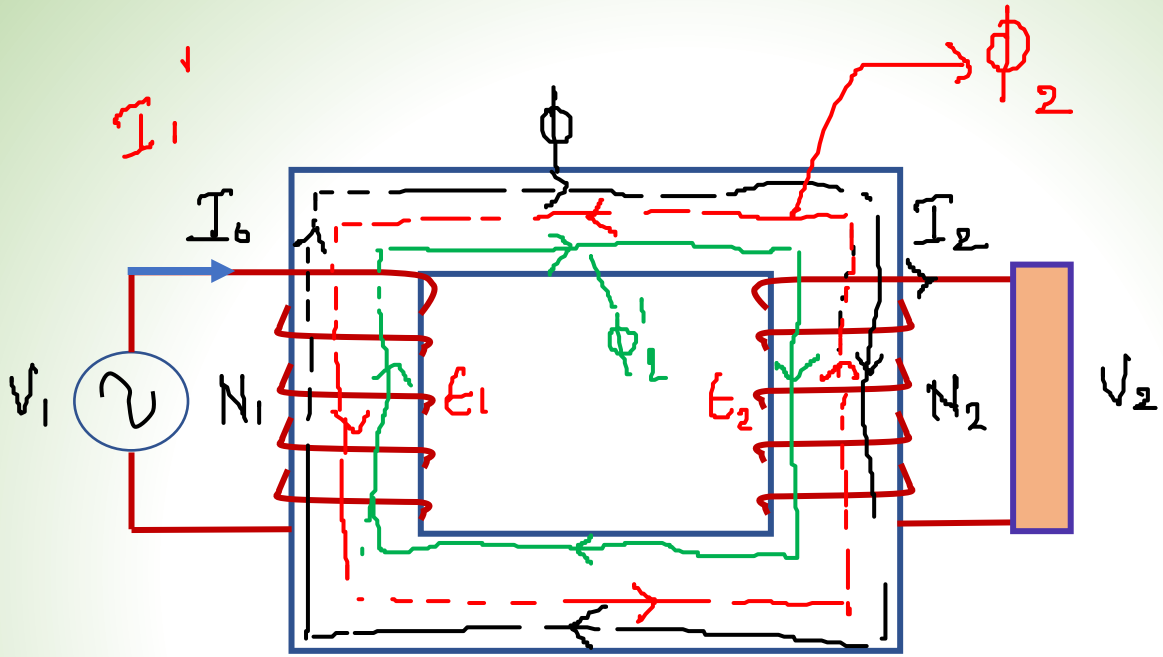
Magnetizing component $I_m = I_0 \sin\varphi_0$

No load current $I_0 = \sqrt{I_w^2 + I_m^2}$

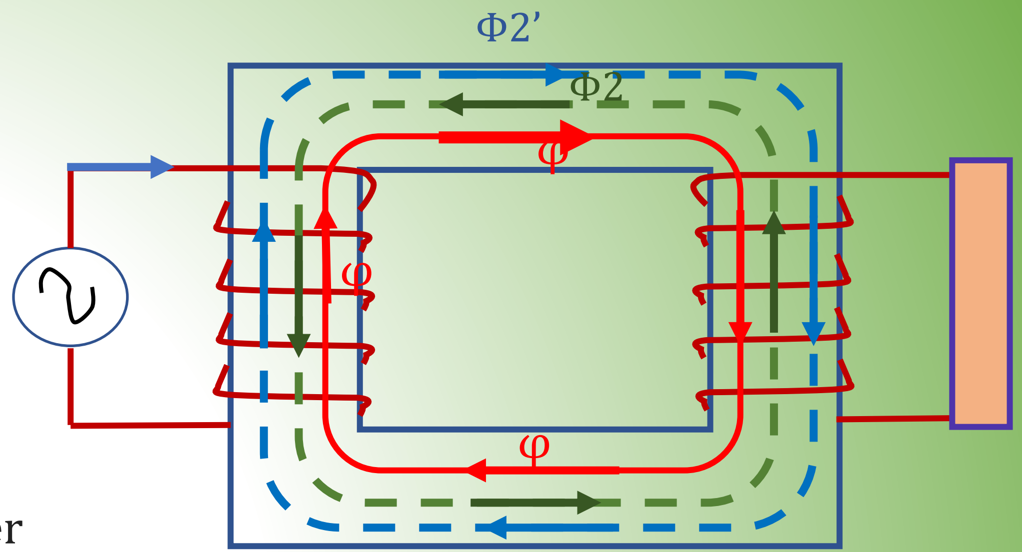
Power factor $\cos\varphi_0 = \dfrac{I_w}{I_0}$

No load power input $P_0 = V_1 I_0 \cos\varphi_0$

Practical Transformer On Load



Practical Transformer On Load



- When the load is connected to the secondary of the transformer, I_2 current flows through their secondary winding.
- The secondary current induces the magnetomotive force N_2I_2 on the secondary winding of the transformer.
- This force set up the flux φ_2 in the transformer core.
- The flux φ_2 opposes the flux φ, according to **Lenz's law**.
- As the flux φ_2 opposes the flux φ, the resultant flux of the transformer decreases and this reduces the induced EMF E_1.
- Thus, the difference (V_1 - E_1) increases and primary winding draws an additional current I'_1 drawn from the supply.
- The additional current is used for restoring the original value of the flux in the core of the transformer so that $V_1 = E_1$.
- This additional current I'_1 opposes the secondary current I_2. Thus, it is called the **primary counter-balancing current**.
- This current induces the magnetomotive force $N_1I'_1$ and sets up its own flux $\varphi'_2 = \varphi_2$.
- The direction of the flux is the same as that of the φ and it cancels the flux φ_2

Now, $N_1I_1' = N_2I_2$ Thus $I_1' = \left(\frac{N_2}{N_1}\right)I_2 = KI_2$

Now the total current flowing in the primary winding $\overline{I_1} = \overline{I_0} + \overline{I_1'}$

Losses in Transformer:

1. Iron Loss/ core loss

Iron Loss: This is the power loss that occurs in the iron part. This loss is due to the alternating frequency of the emf. Iron loss is called as the Constant loss as the supply voltage and frequency are constants. Iron loss in further classified into two other losses.

a) Eddy current loss b) Hysteresis loss

a) EDDY CURRENT LOSS:

--due to the alternating flux linking the core, which will induced an emf in the core called the eddy emf, due to which a current called the eddy current is being circulated in the core. As there is some resistance in the core with this eddy current circulation converts into heat called the eddy current power loss.

Eddy current loss is proportional to the square of the supply frequency.

b) HYSTERISIS LOSS:

--due to the magnetic reversal of the flux in the core, which produces heat in the core. This loss is directly proportional to the supply frequency.

2. Copper Loss (winding)

This is the power loss that occurs in the primary and secondary coils when the transformer is on load.

This power is wasted in the form of heat due to the resistance of the coils.

This loss is proportional to the sequence of the load hence it is called the Variable loss

EFFICIENCY OF SINGLE PHASE TRANSFORMER

- **Efficiency is the ratio of the output power to the input power of a transformer.**

$$\text{Efficiency} = \frac{\text{Output Power}}{\text{Input Power}} = \frac{\text{Pout}}{\text{Pin}}$$

$$\eta = \frac{\text{Pout}}{\text{Pin}} = \frac{\text{Pout}}{\text{Pout+Losses}} = \frac{\text{Pout}}{\text{Pout+Iron Loss+Copper Loss}}$$

- For the efficiency to be maximum for any device the losses must be minimum.
- The iron loss is the fixed loss and the copper loss is the variable loss.
- When these two losses are equal and also minimum the efficiency will be maximum.

i.e. The Condition for maximum efficiency in a transformer is when Copper Loss = Iron Loss

VOLTAGE REGULATION OF SINGLE PHASE TRANSFORMER

- The transformer windings have impedance so there will be a voltage drop across them that changes with current.
- The secondary voltage will vary as the load changes.
- Voltage regulation is a measure of the change in secondary voltage from no-load to full-load at a specified power factor and is usually expressed as a percentage of the full-load voltage.
- Voltage regulation is the measure of how well a power transformer can maintain constant secondary voltage given a constant primary voltage and wide variance in load current. The lower the percentage (closer to zero), the more stable the secondary voltage and the better the regulation it will provide.

$$\therefore \text{Regulation}\,\% = \frac{V_{(\text{no-load})} - V_{(\text{full-load})}}{V_{(\text{no-load})}} \times 100$$

- The voltage regulation of a transformer is defined as the change in the secondary terminal voltage between no load and full load expressed as a percentage of the no load terminal voltage.
- If there is no load on the transformer, the current would be zero and the referred secondary voltage would be equal to the primary voltage.
- The no-load voltage (referred to the primary) of the transformer is the primary voltage.
- As the load increases to full load, current flows in the windings of the transformer and there is a voltage drop across the transformer, and the referred value of the secondary voltage is no longer equal to the primary voltage.

Q.2. The maximum flux density in the core of a 250/3000-volts, 50-Hz single-phase transformer is 1.2 Wb/m^2. If the e.m.f. per turn is 8 volt, determine

(i) primary and secondary turns

(ii) area of the core.

$E_1 = 250V$

$E_2 = 3000V$

$f = 50Hz$

$B = 1.2 \ Wb/m^2$

$emf/turn = 8V$

$E_1 = N_1 \times emf/turn$

$N_1 = \frac{E_1}{emf/turn} = \frac{250}{8} = 31.25 \approx 31$

$E_2 = N_2 \times emf/turn \quad N_2 = 375.$

$E_2 = 4.44 f N_2 B A$

$A = \frac{E_2}{4.44 f N_2 B} = 0.03 \ m^2.$

Q.1. A 25 kVA, single-phase transformer has 250 turns on the primary and 40 turns on the secondary winding. The primary is connected to 1500-volt, 50 Hz mains. Calculate

(i) Primary and Secondary currents on full-load,

(ii) Secondary e.m.f

(iii) maximum flux in the core

$P = 25000$ VA

$N_1 = 250$

$N_2 = 40$

$V_1 = 1500$V

$f = 50$H

I_1

I_2

E_2

ϕ

$P = VI$

$I_1 = P/V = \frac{25000}{1500} = 16.66$A.

$\frac{N_2}{N_1} = K = \cancel{\frac{250}{40}} = 0.16 = \frac{40}{250} =$

$\frac{I_1}{I_2} = K.$ $I_2 = I_1/K = 16.66/0.16 = 104.125$ A.

emf/turn $= 1500/250 = 6$V

$E_2 =$ emf/turn $\times N_2 = 6 \times 40 = 240$V

$E_2/E_1 = k.$

$E_2 = K \times E_1 = 240$V

$E_1 = 4.44 f N_1 \phi_m$ $\phi_m = E_1/4.44 f N_1 = 0.027$ Wb

$= 27$ mWb.

Q. A 2200/200 V transformer draws a no-load primary current of 0.6A and absorbs 400 watts. Find the magnetizing and iron loss currents

$V_1 = 2200\,V$

$V_2 = 200\,V$

$I_1 = 0.6A$

$P = 400\,W$

I_w

I_m

$P = VI\cos\phi$

$\cos\phi = \frac{P}{VI} = \frac{400}{2200 \times 0.6} = 0.30$

$\phi = 72.36^\circ$

$I_w = I_0\cos\phi = 0.18A$

$I_m = I_0\sin\phi = 0.57A$

$I_0 = \sqrt{I_w^2 + I_m^2}$

Q.3 A 6600/600V, 50Hz single phase transformer has a maximum flux density of 1.35T in its core. If the net cross sectional area of iron core is $200 cm^2$. Calculate the no. of turns in the primary and secondary windings of the transformer.

Q.4. A 2200/ 220V, 50 hz transformer has no load current 5A at power factor 0.2 .Find the working and magnetizing current. If the e.m.f. per turn is 4 volt, determine primary and secondary turns

Q.5 A 80 kVA, 3200/400V transformer has 111 turns on secondary. Calculate (i) no. of turns in primary winding, (ii) Secondary current, (iii) cross sectional area of the core, if the max. flux density is 1.2T.

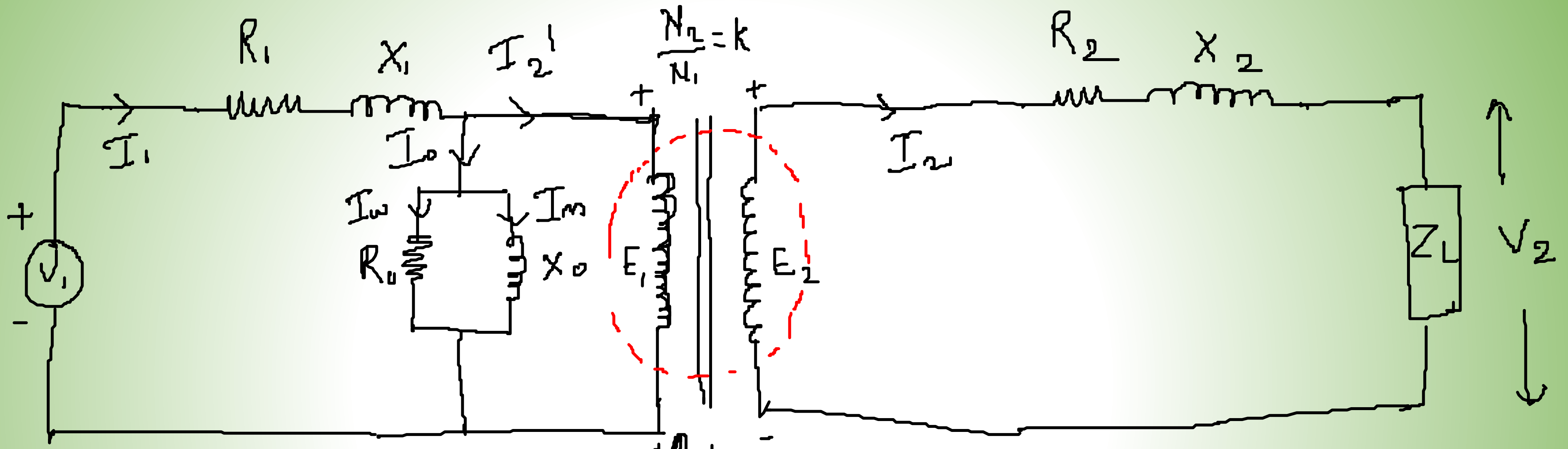
Equivalent Circuit of a Transformer

ASSUMPTIONS

- The transformer under consideration has losses in terms of Core loss, Copper Loss , Losses due to winding resistance and leakage reactance.
- The secondary of the transformer is loaded with an inductive load
- The secondary has more number of turns than primary

IDEAL TRANSFORMER + LOSSES = PRACTICAL TRANSFORMER

Equivalent Circuit of a Transformer



ϕ

$V_1 > E_1$ $E_2 > V_2$

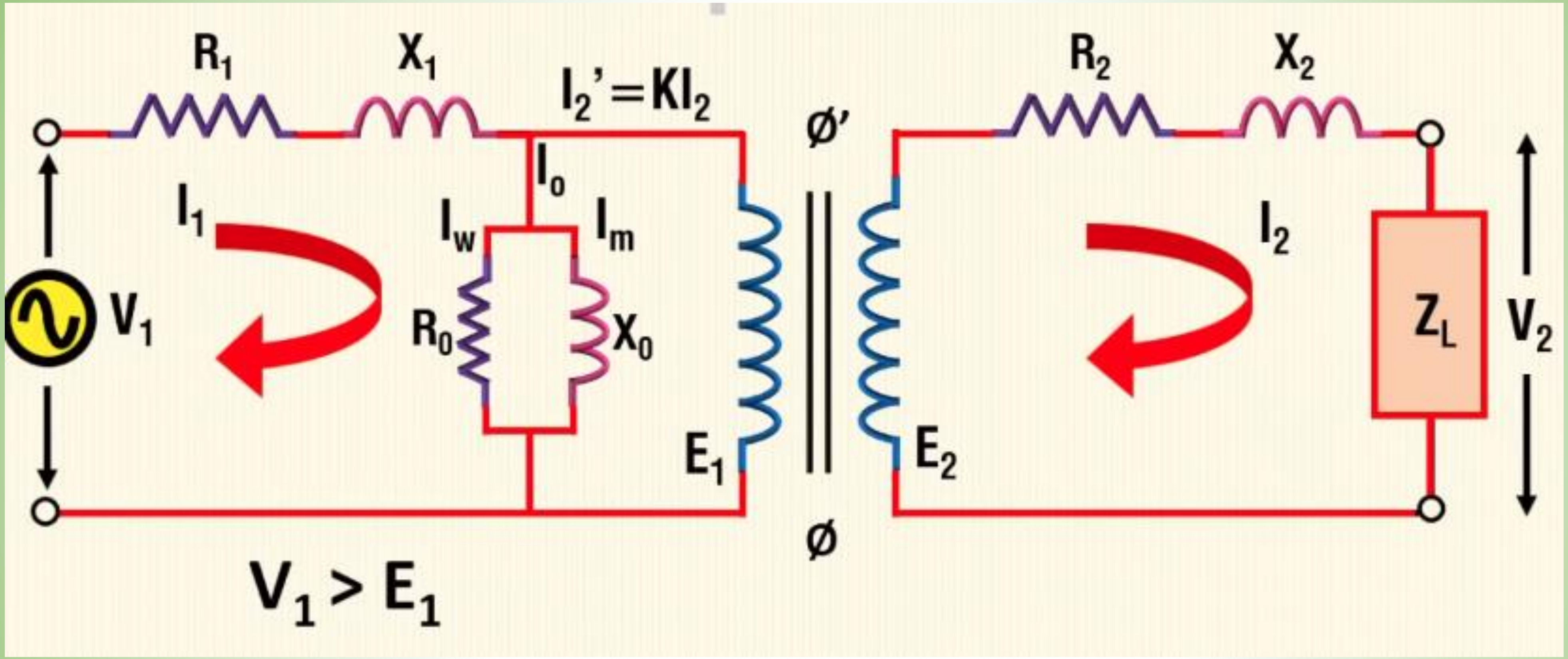
ϕ'

$(V_1 - E_1)\uparrow$

$E_1 \downarrow$

$I_m + I_2'$ I_2

Equivalent Circuit of a Transformer



$V_1 = E_1 + I_1(R + jX_1)$

$I_1 = I_2' + I_0$

$I_0 = I_m + I_w$

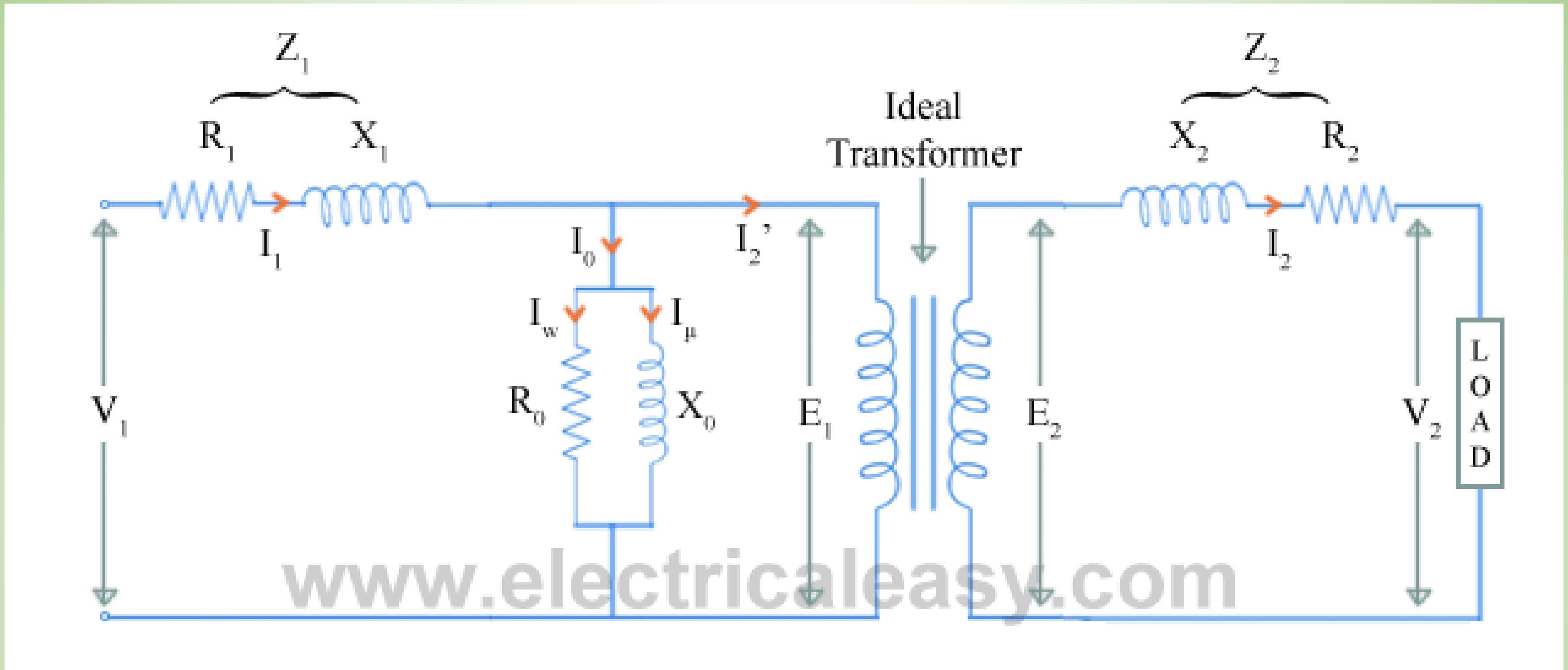
(I_μ)

$E_2 = V_2 + I_2(R_2 + jX_2)$

$V_2 = E_2 - I_2(R_2 + jX_2)$

I_2

Equivalent Circuit of a Transformer



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

$$\frac{E_2}{K} = E_1 = E_2'$$

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

$$I_2' = K I_2$$

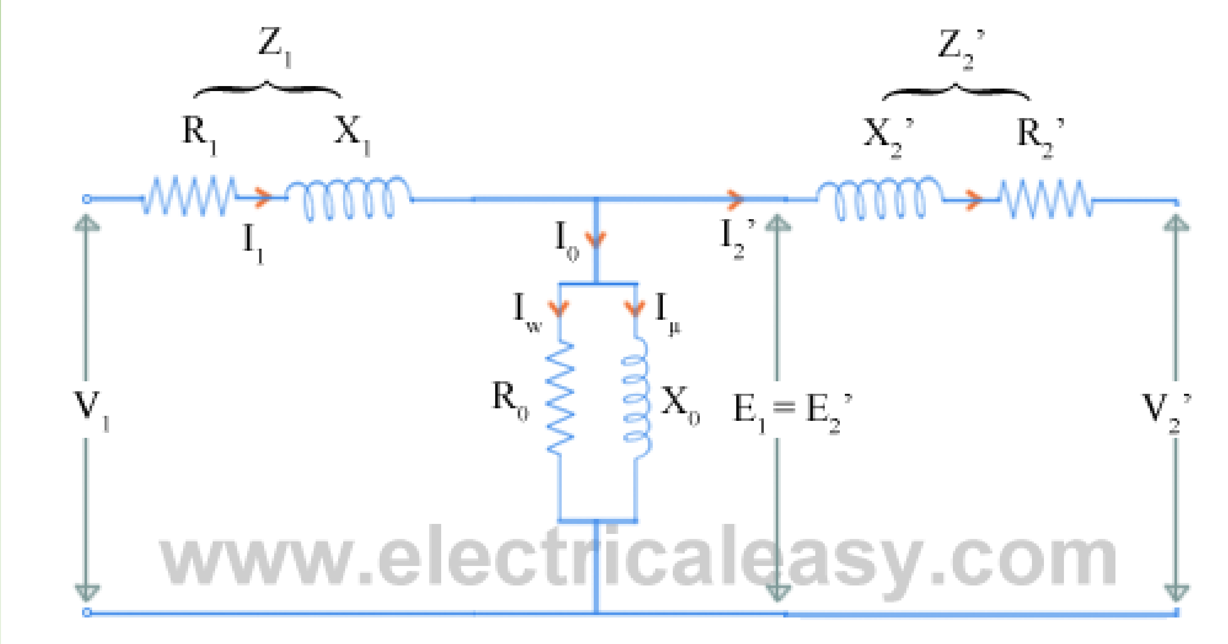
$$R_2' = R_2/K^2$$

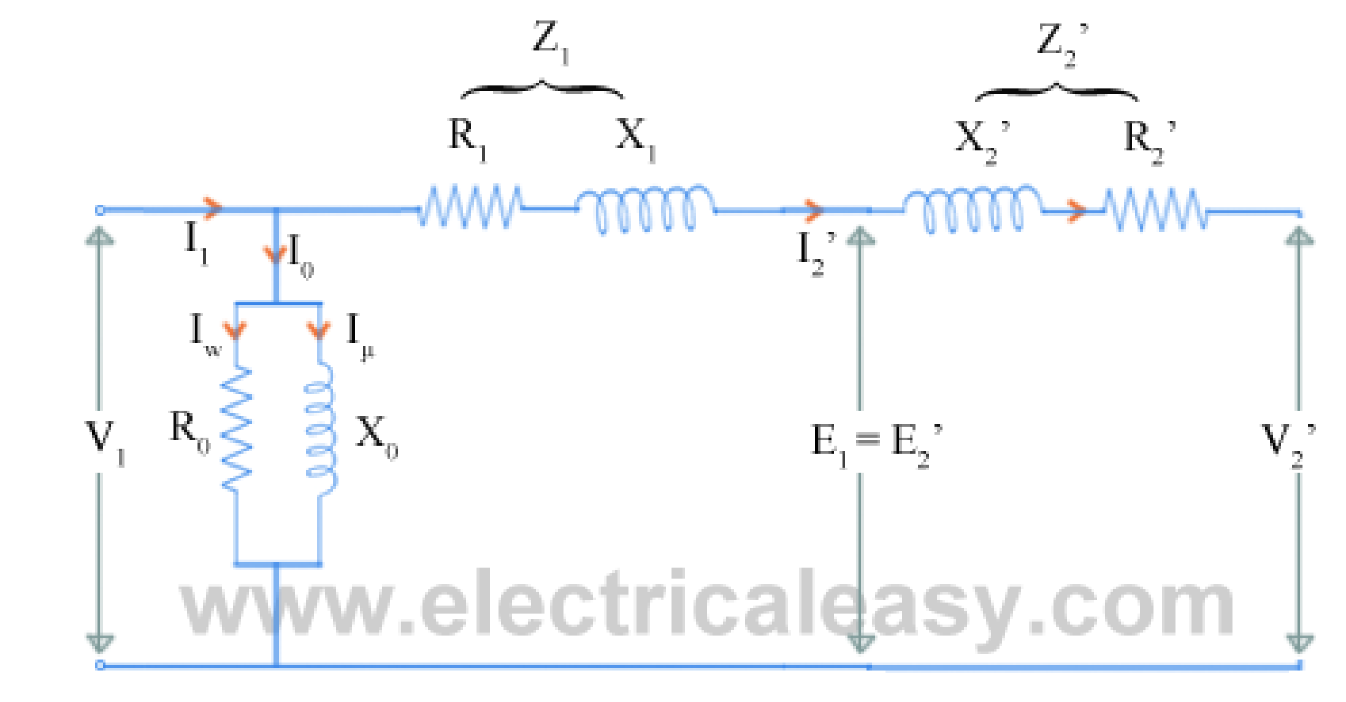
$$X_2' = X_2/K^2$$

$$Z_2' = Z_2/K^2$$

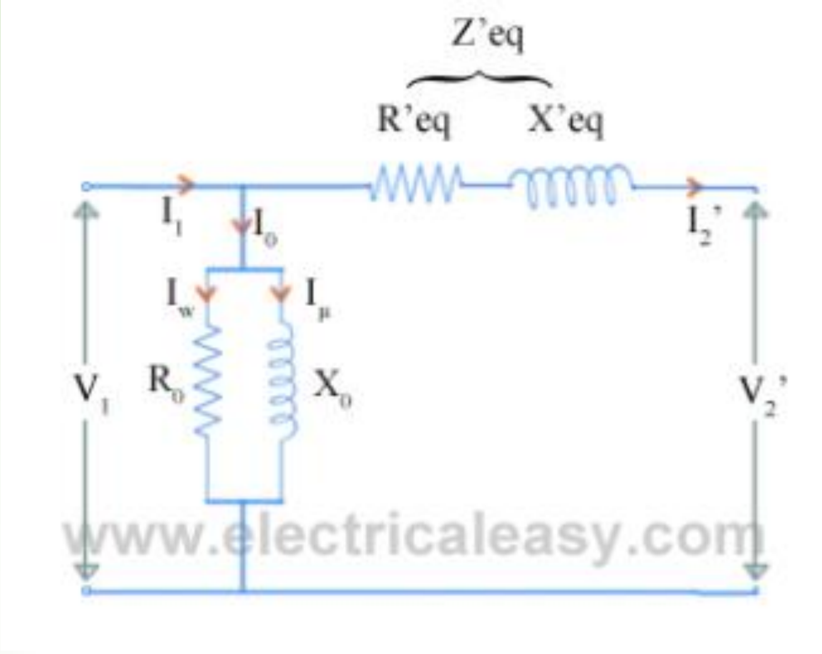
$V = IR.$

$$R_2' = \frac{V_2'}{I_2'} = \frac{V_2/K}{K I_2} = V_2/I_2 \times 1/K^2$$





Vtg drop across Z_1 is negligible.



$R'_{eq} = R_1 + R_2'$

$X'_{eq} = X_1 + X_2'$

Approximate Equivalent Circuit Of Transformer

Voltage Regulation -