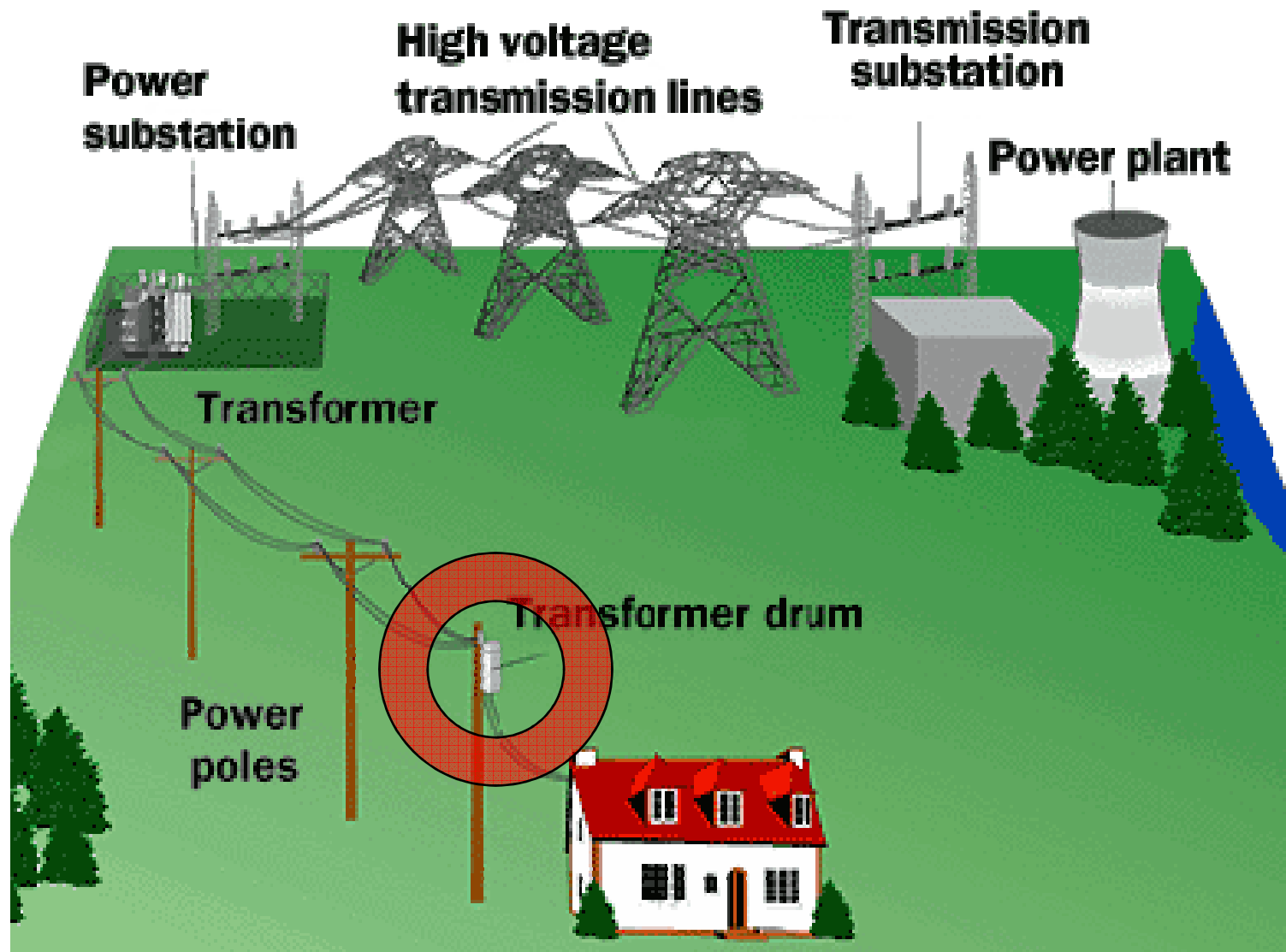
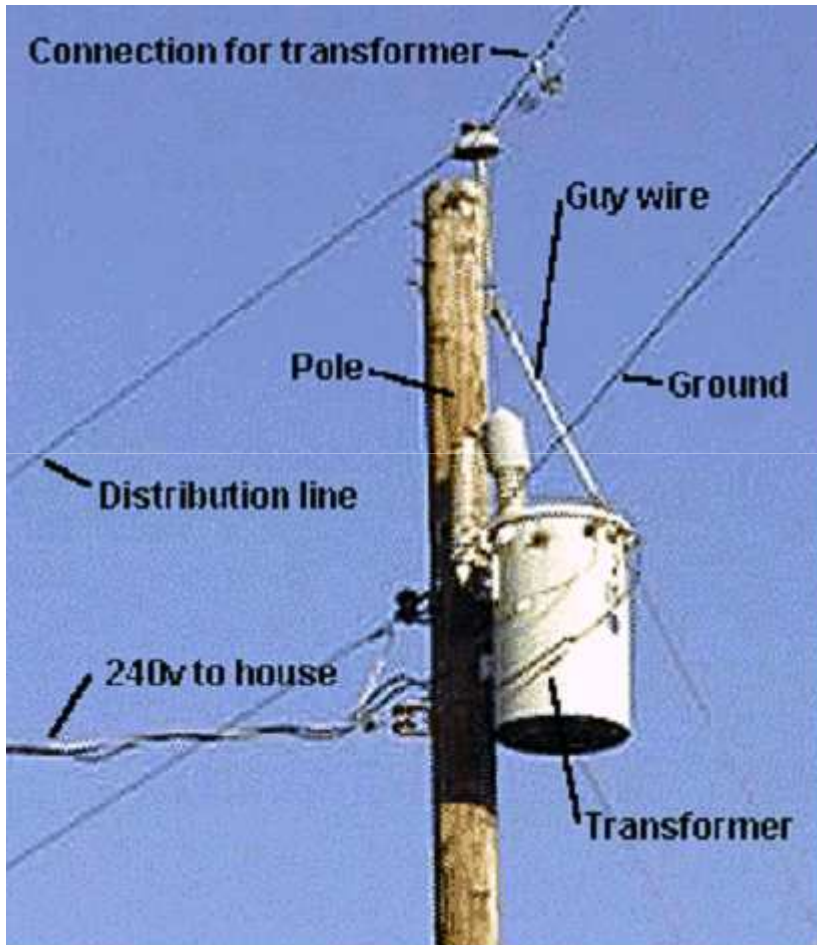


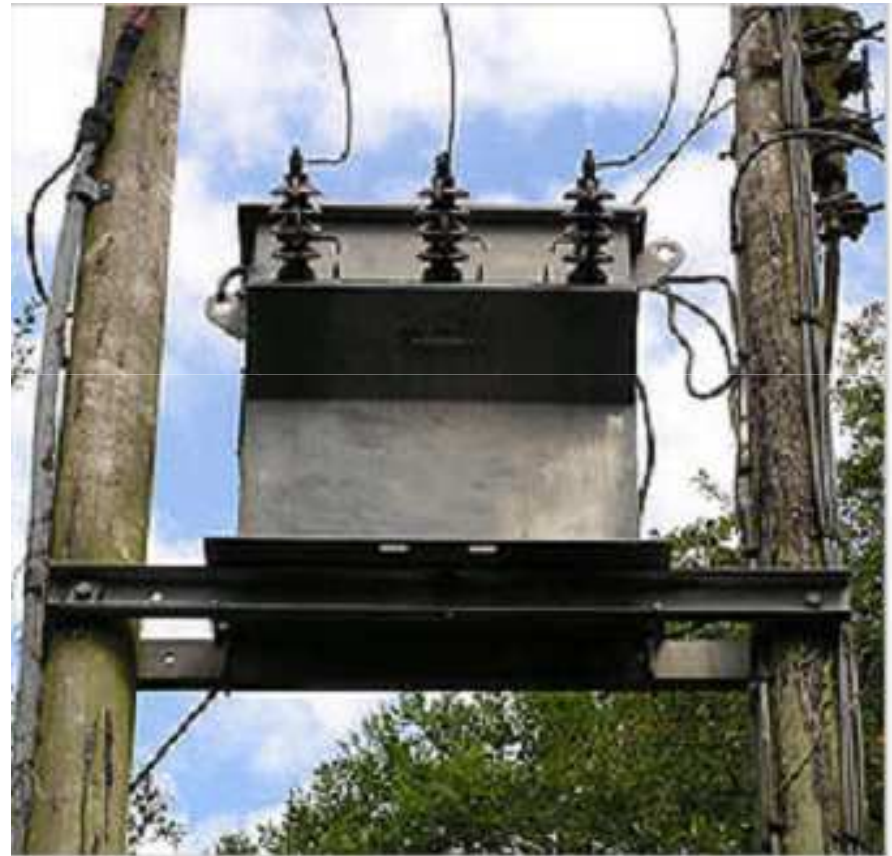
WELCOME TO THE LECTURE ON TRANSFORMER



Single Phase Transformer

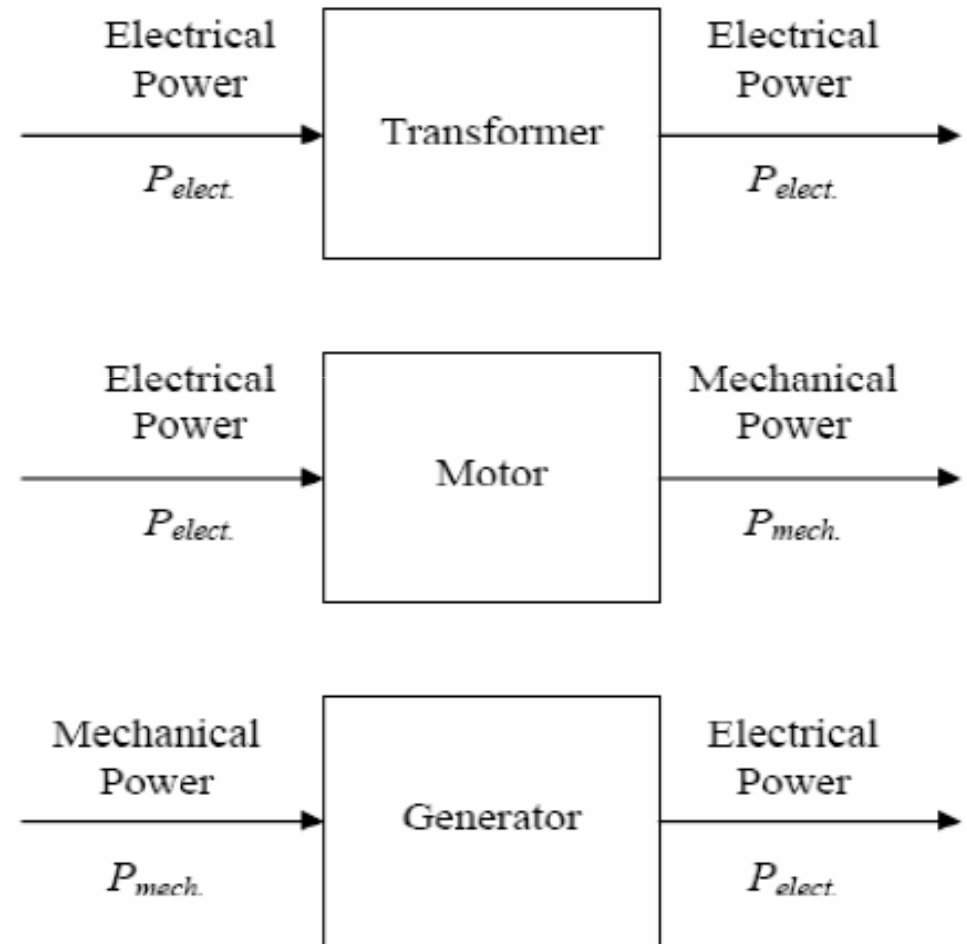


Three Phase Transformer



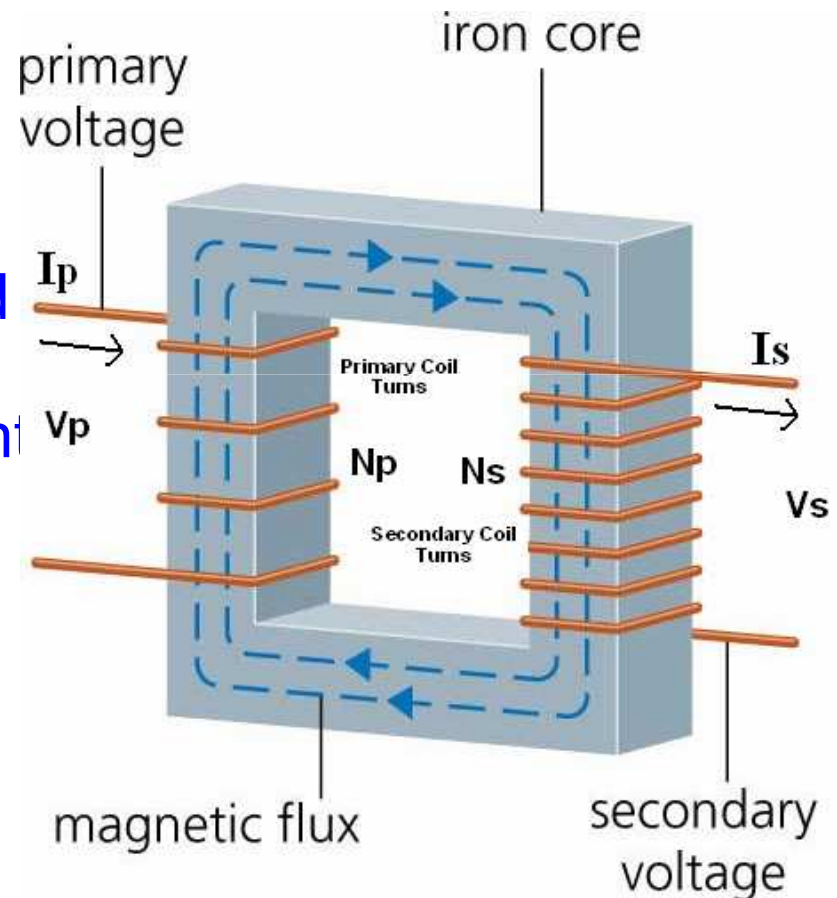
Transformer

- A transformer is a stationary electric machine which transfers electrical energy (power) from one voltage level to another voltage level.
- Unlike in rotating machines, there is no electrical to mechanical energy conversion.
- A transformer is a static device and all currents and voltages are AC.
- The transfer of energy takes place through the magnetic field.



Transformer Principles

- It has 2 electric circuits called *primary* and *secondary*.
- A magnetic circuit provides the link between primary and secondary.
- When an AC voltage is applied to the primary winding (V_p) of the transformer, an AC current will result (I_p). I_p sets up a time-varying magnetic flux ϕ in the core.
- A voltage is induced to the secondary circuit (V_s) according to the Faraday's law of Electromagnetic Induction. ($e = M di/dt$)



Transformer

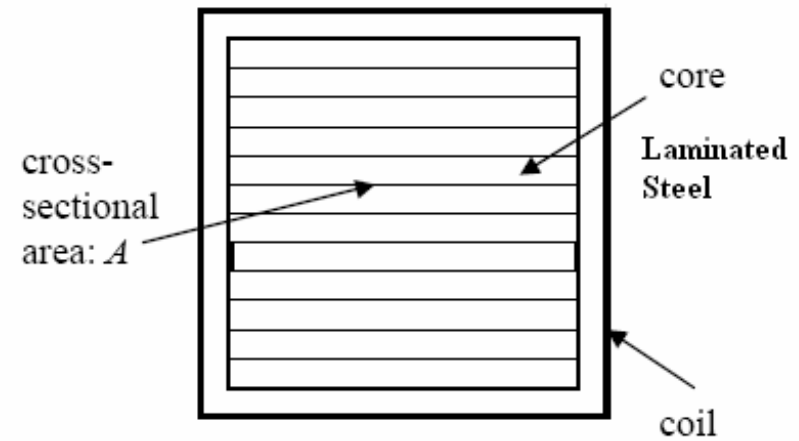
- Transformer is a device that:
 - Transfers electric power from one circuit to another.
 - It does so without a change of frequency
 - It accomplishes this by electromagnetic induction and
 - Where the two circuits are in mutual inductive influence of each other.

Transformer Core Types

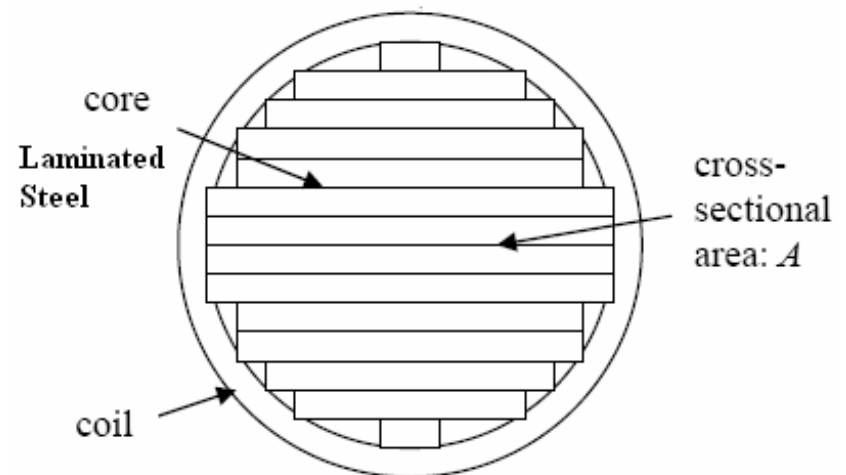
- The magnetic (iron) core is made of thin laminated steel.
- The reason of using laminated steel is to minimize the eddy current loss by reducing thickness

(t):
$$P_e = kh(B_{\max}tf)$$

- 2 common cross section of core is square or rectangular for small transformers and circular (stepped) for the large and 3 phase transformers.



(a) Square core

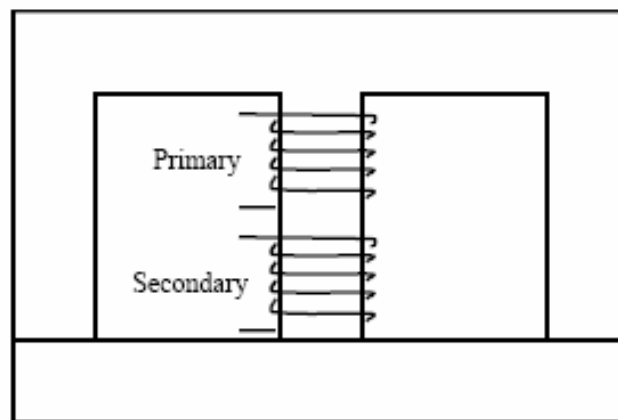
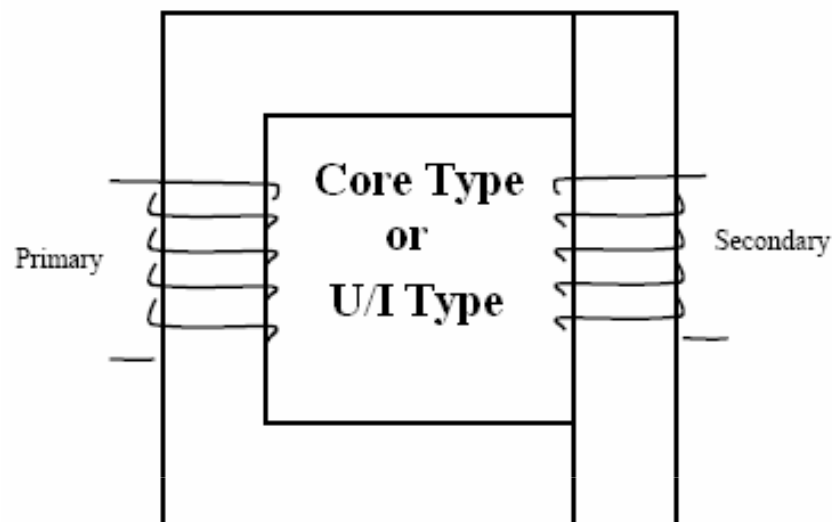


(b) Stepped core

Transformer Construction

- **2 Type of Transformers:**

- 1) **Core (U/I) Type:** is constructed from a stack of U- and I-shaped laminations. In a core-type transformer, the primary and secondary windings are wound on two different legs of the core.
- 2) **Shell (E/I) Type:** A shell-type transformer is constructed from a stack of E- and I-shaped laminations. In a shell-type transformer, the primary and secondary windings are wound on the same leg of the core, as concentric windings, one on top of the other.



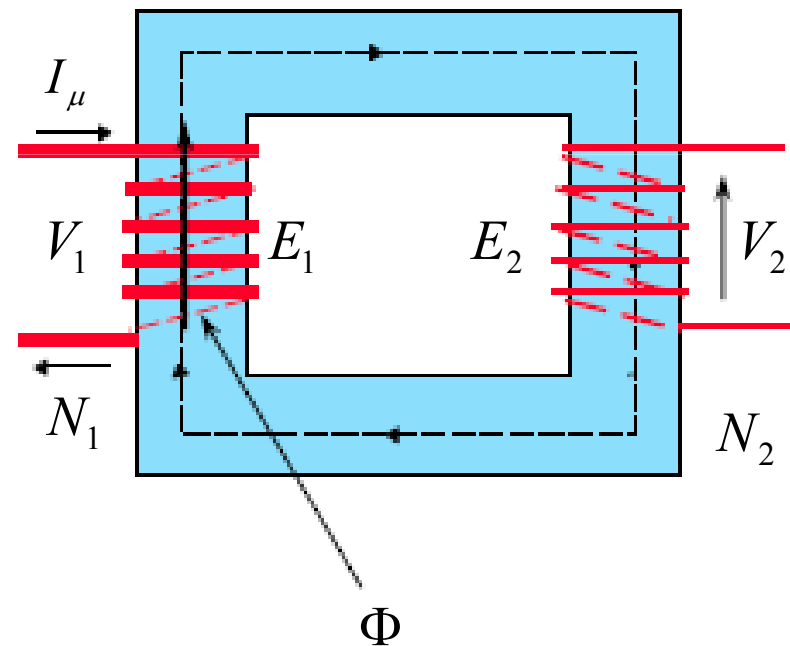
Shell Type or E/I type

Elementary Theory of an Ideal Transformer

- For a transformer to be an ideal one, the various assumptions are as follows:
 - 1) Winding resistances are negligible, i.e. no losses.
 - 2) There is no magnetic leakage and hence which has no I^2R and core losses.
 - 3) All the flux set up by the primary links the secondary windings, i.e. all the flux is confined to the magnetic core.
 - 4) The core has constant permeability, i.e. the magnetization curve for the core is linear.

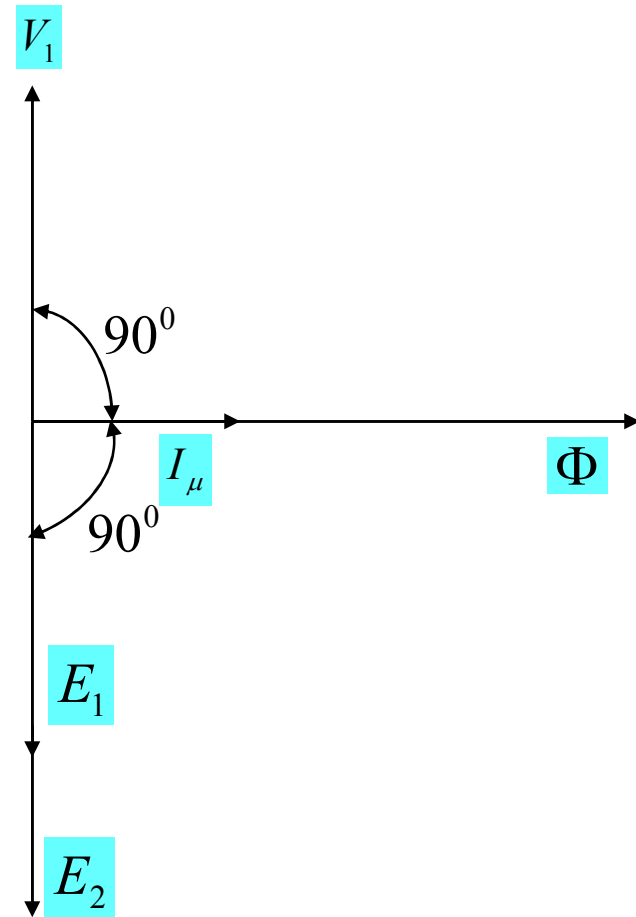
Elementary Theory of an Ideal Transformer (cont.)

- Secondary is open and primary is connected to sinusoidal alternation voltage, V_1
- Since secondary is open, the primary draws the magnetizing current I_μ only.
- I_μ is small in magnitude and lags V_1 by 90° .
- The alternating current produces an alternating flux Φ which is proportional to the current and is in phase with it.
- This flux produces *self-induced* e.m.f. in the primary.
- The *self-induced* e.m.f. E_1 equal to and in opposition to V_1
- E_1 is also known as *counter e.m.f.* or *back e.m.f.*



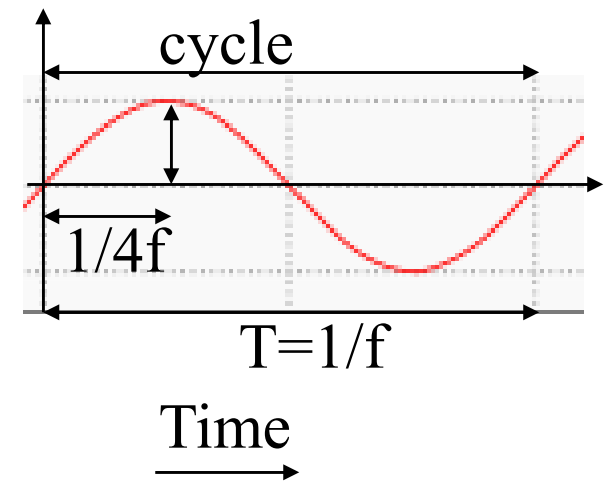
Elementary Theory of an Ideal Transformer (cont.)

- Similarly there is produced in the secondary an induced e.m.f. E_2 which is known as *mutually-induced* e.m.f.
- This e.m.f. is anti phase with V_1 and its magnitude is proportional to the rate of change of flux and the number of secondary turns.
- The vectorial representation of the effective values of the above quantities is shown in the right figure.



E.M.F. Equation of a Transformer

- N_1 =No. of turns in primary
- N_2 =No. of turns in secondary
- Φ_m =Maximum flux in core in webers
- f =frequency of a.c. input in Hz
- The figure shows flux increases from its zero value to maximum value Φ_m in one quarter of the cycle i.e. $\frac{1}{4}$ second.
- Average rate of change of flux = $\frac{\Phi_m}{1/4f}$
- Now, rate of change of flux per turn means induced e.m.f. in volts
- Average e.m.f./turn = $4f\Phi_m$ volt
- Form factor = $\frac{\text{r.m.s. value}}{\text{average value}} = 1.11$
- r.m.s. value of e.m.f./turn = $1.11 \times 4f\Phi_m = 4.44f\Phi_m$



E.M.F. Equation of a Transformer (cont.)

- r.m.s. value of the induced e.m.f. in the whole of primary winding=(induced e.m.f./turn) \times No.of primary turns

$$E_1 = 4.44 f\Phi_m N_1 = 4.44 fB_m AN_1 \dots \dots \dots (i)$$

- r.m.s. value of the induced e.m.f. in the whole of secondary winding=(induced e.m.f./turn) \times No.of secondary turns

$$E_2 = 4.44 f\Phi_m N_2 = 4.44 fB_m AN_2 \dots \dots \dots (ii)$$

- From (i) and (ii) we get, $\frac{E_1}{E_2} = \frac{N_1}{N_2} = 4.44 f\Phi_m$

- In Ideal transformer on no-load, $V_1 = E_1$ and $V_2 = E_2$

Voltage Transformation Ratio (K)

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

- This constant K is known as *voltage transformation ratio*.
- (i) If $N_2 > N_1$ i.e. $K > 1$, then transformer is called *step-up* transformer.
- (ii) If $N_2 < N_1$ i.e. $K < 1$, then transformer is called *step-down* transformer.

Transformer with Losses but no Magnetic Leakage

□ Two cases:

(i) Transformer on no-load:

➤ When the transformer is on no-load, the primary input current is not wholly reactive. The primary input current under no-load has to supply, (i) iron loss in the core and (ii) a very small amount of copper loss in primary (there being no Cu loss in secondary as it is open).

➤ Hence, the no-load primary input current I_0 is not at 90° behind V_1 but lags it by an angle $\phi_0 < 90^\circ$

➤ No-load input power

$$W_0 = V_1 I_0 \cos \phi_0$$

➤ Where $\cos \phi_0$ is primary power factor under no-load conditions.

Transformer with Losses but no Magnetic Leakage (cont.)

- No-load condition of an actual transformer is shown vectorially in the figure.
- The primary current has two components:

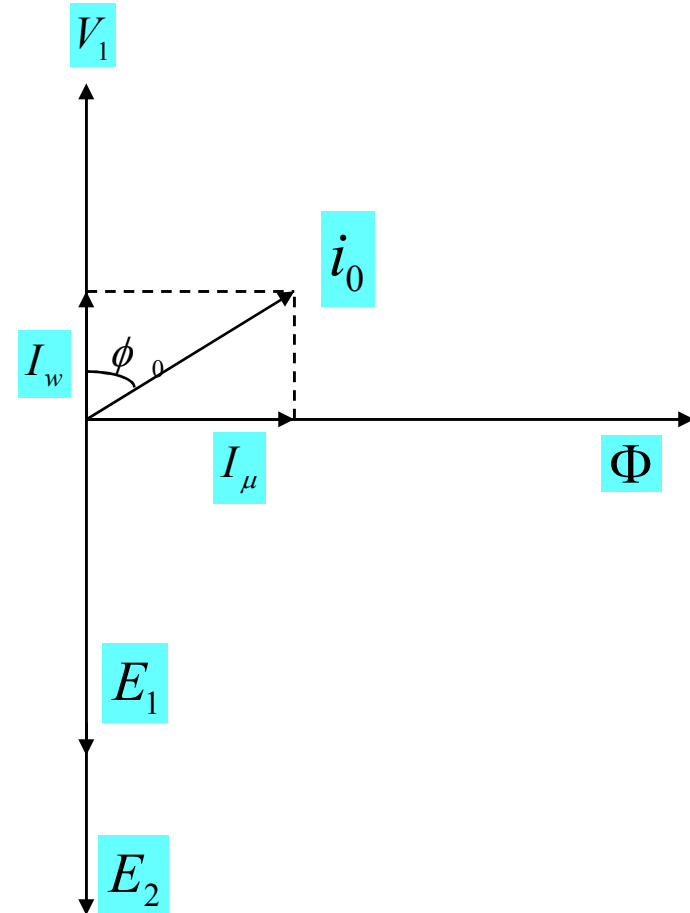
- i. One in phase with V_1 . This is known as active or working or iron loss component I_w . It mainly supplies the iron loss plus small quantity of primary Cu loss.

$$I_w = I_0 \sin \phi_0$$

- ii. The other component is in quadrature with V_1 and is known as magnetizing component I_μ . Its function is sustain the alternating flux in the core. It is wattless.

$$I_\mu = I_0 \cos \phi_0$$

$$I_0^2 = I_\mu^2 + I_w^2$$

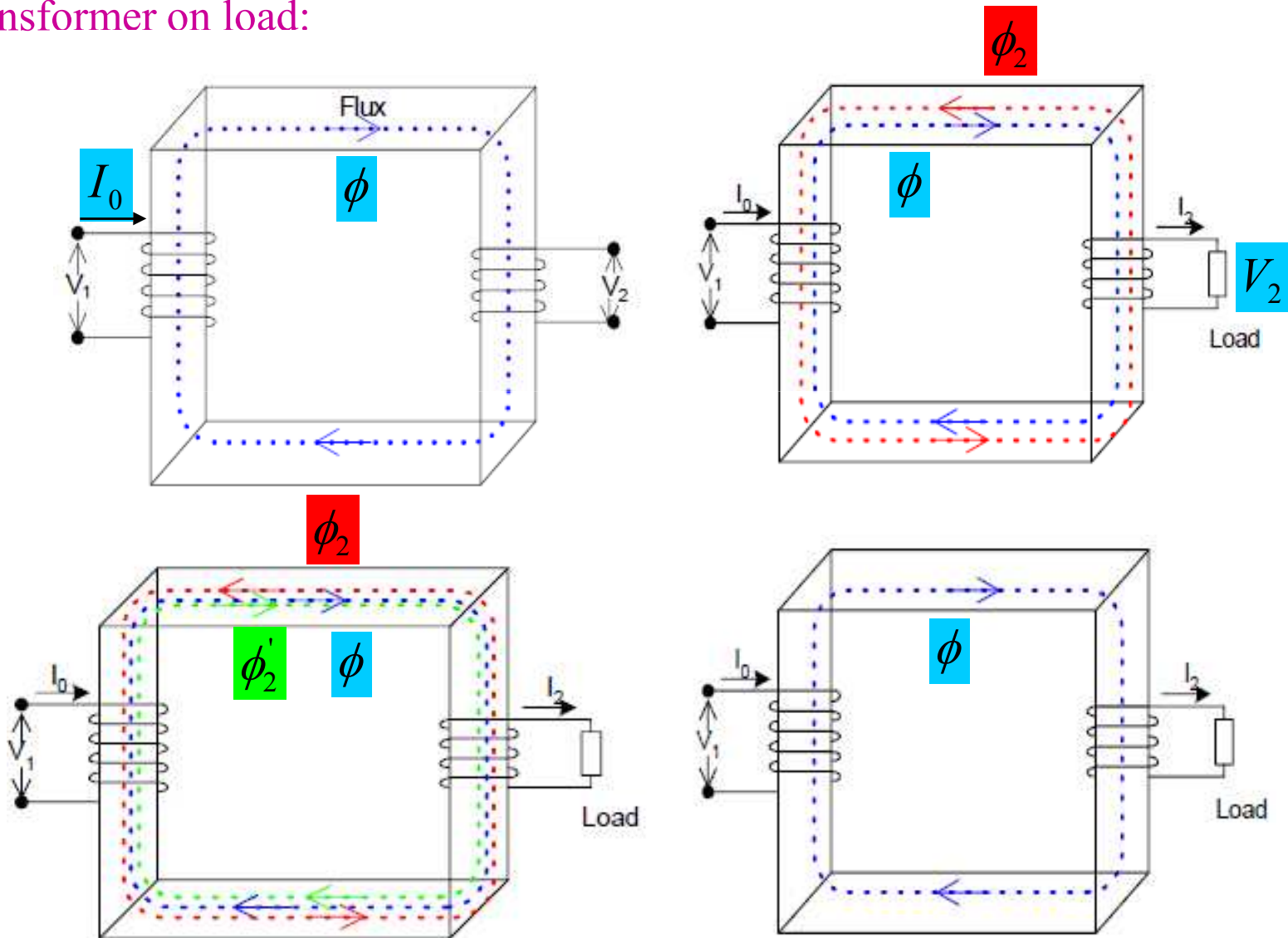


Transformer with Losses but no Magnetic Leakage (cont.)

- The following points should be carefully noted:
 - The no-load primary current I_0 is very small as compared to the full-load primary current. It is about 1 percent of the full-load current.
 - Owing to the fact that the permeability of the core varies with the instantaneous value of the exciting current, the wave of the exciting or magnetizing current is not truly sinusoidal. As such it should not be represented by a vector because only sinusoidally varying quantities are represented by rotating vectors. But, in practice, it makes no appreciable difference.
 - As I_0 is very small, the no-load primary Cu loss is negligibly small which means that no-load primary input is practically equal to the iron loss in the transformer.
 - As it is principally the core-loss which is responsible for shift in the current vector, angle ϕ_0 is known as *hysteresis angle of advance*.

Transformer with Losses but no Magnetic Leakage (cont.)

(ii) Transformer on load:



Transformer with Losses but no Magnetic Leakage (cont.)

- When the secondary is loaded, the secondary current I_2 is set up.
- The magnitude and phase of I_2 , with respect to V_2 is determined by the characteristics of the load.
- Current I_2 is in phase with V_2 if load is resistive, it lags if load is inductive and it leads if load is capacitive.
- The secondary current sets up its own m.m.f. and hence its own flux Φ_2 which is opposite to the main primary flux Φ .
- The secondary amp-turns $N_2 I_2$ are known as *demagnetizing amp-turns*.
- The opposing flux Φ_2 weakens Φ .
- V_1 gains the upper hand over E_1 and hence causes more current to flow in primary.
- The additional current I_2' is known as *load component of primary current*.
- The additional primary m.m.f. sets up its own flux Φ_2' which is opposition to Φ_2 and is equal to it in magnitude.
- Hence, the two cancel each other.
- Whatever the load conditions, the net flux passing through the core is approximately the same as at no-load.

Transformer with Losses but no Magnetic Leakage (cont.)

$$\Phi_2 = \Phi_2'$$

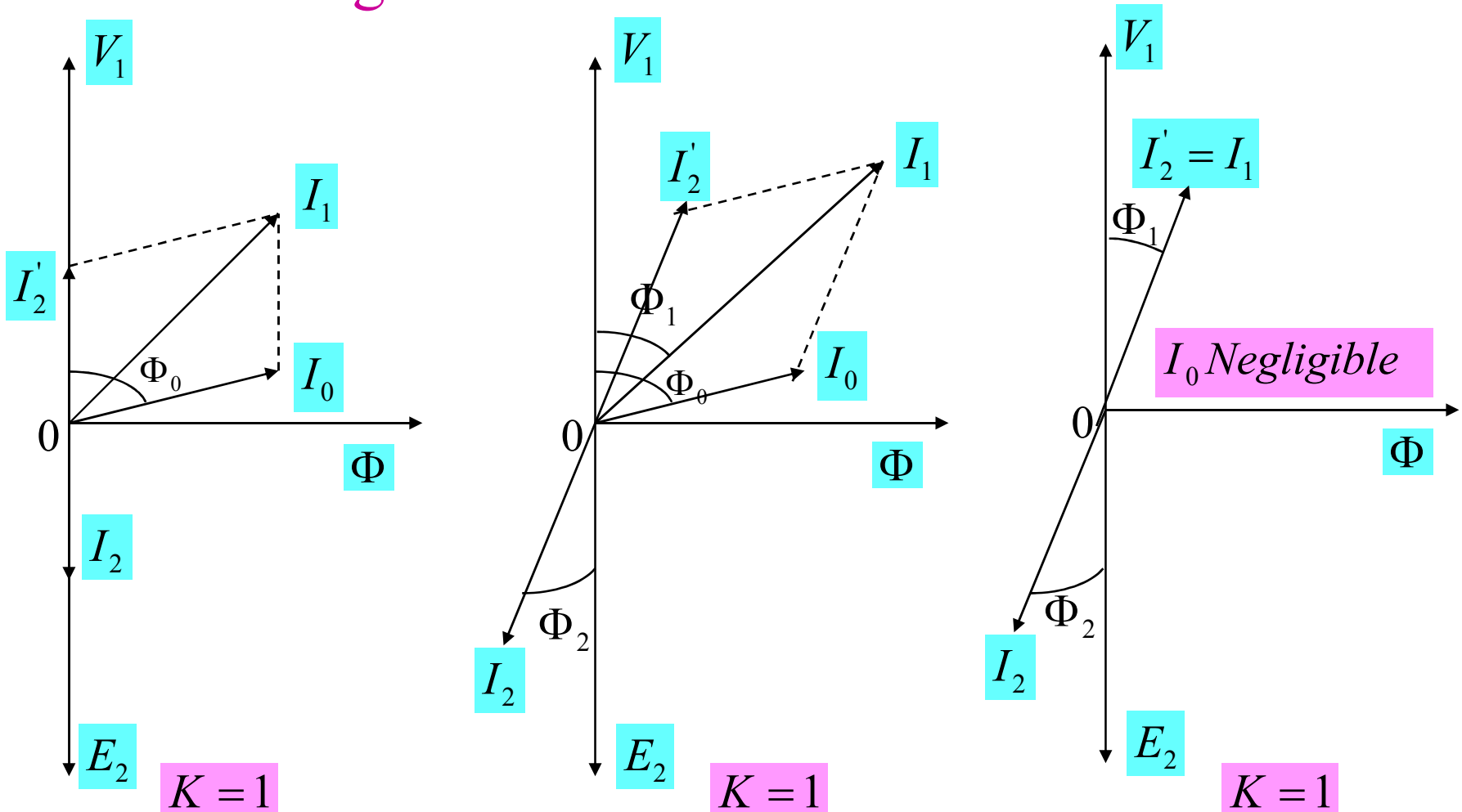
$$\therefore N_2 I_2 = N_1 I_2'$$

$$\therefore I_2' = \frac{N_2}{N_1} \times I_2 = KI_2$$

- Hence, when the transformer is on-load, the primary winding has two currents in it.
- The total primary current is the vector sum of I_0 and I_2'

Transformer with Losses but no Magnetic Leakage (cont.)

- Vector diagrams:



Transformer with Losses but no Magnetic Leakage (cont.)

- Under the assumption: I_0 is negligible, $\Phi_1 = \Phi_2$

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

Transformer with winding resistance but no Magnetic Leakage

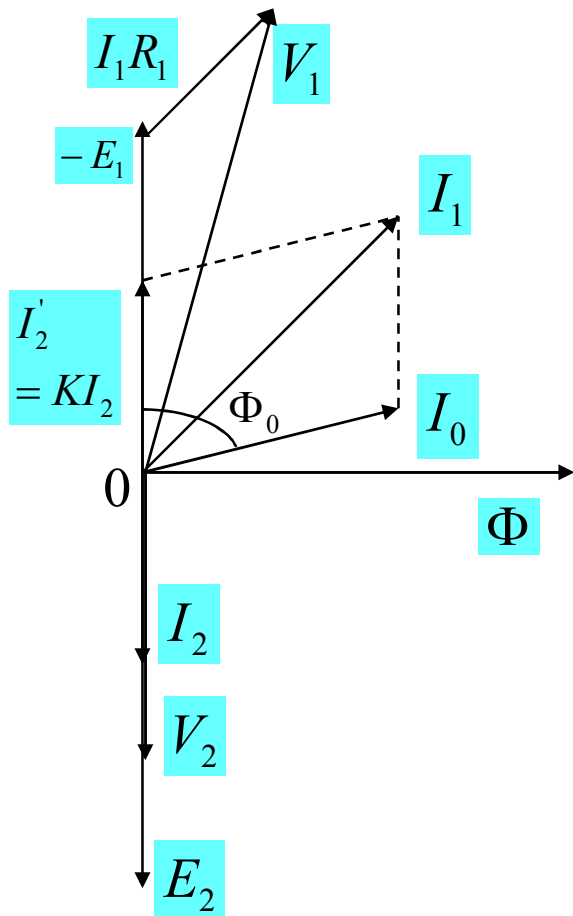
- An ideal transformer has no resistance, but an actual transformer has winding resistances.
- Due to this resistance, there is some voltage drop in the two windings. The result is that:
- The secondary terminal voltage V_2 is vectorially less than the secondary induced e.m.f. E_2 by an amount I_2R_2 where R_2 is the resistance of the secondary winding. Hence, V_2 is equal to the vector difference of E_2 and resistive voltage drop I_2R_2 .

$$V_2 = E_2 - I_2R_2$$

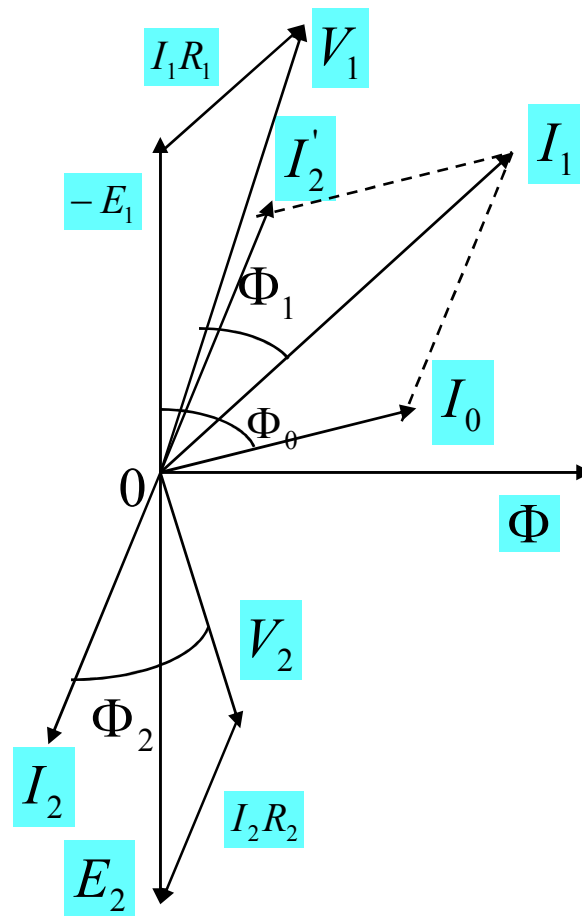
- Similarly, primary induced e.m.f. E_1 is equal to the vector difference of V_1 and I_1R_1 where R_1 is the resistance of the primary winding.

$$E_1 = V_1 - I_1R_1$$

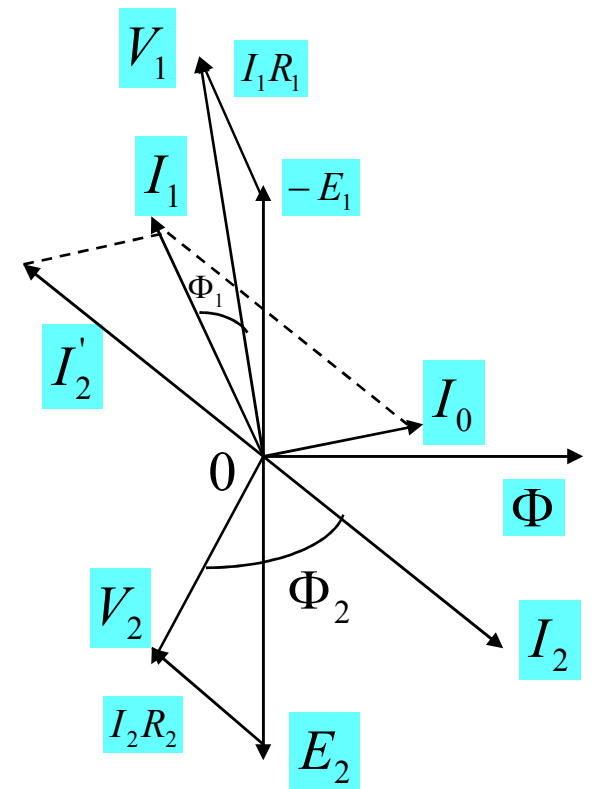
Transformer with winding resistance but no Magnetic Leakage (cont.)



Non-inductive



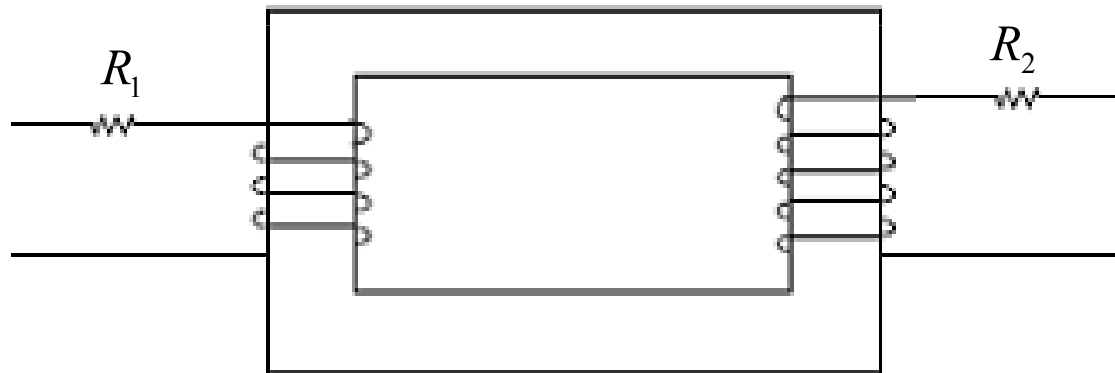
Inductive



Capacitive

Resistance of a Transformer

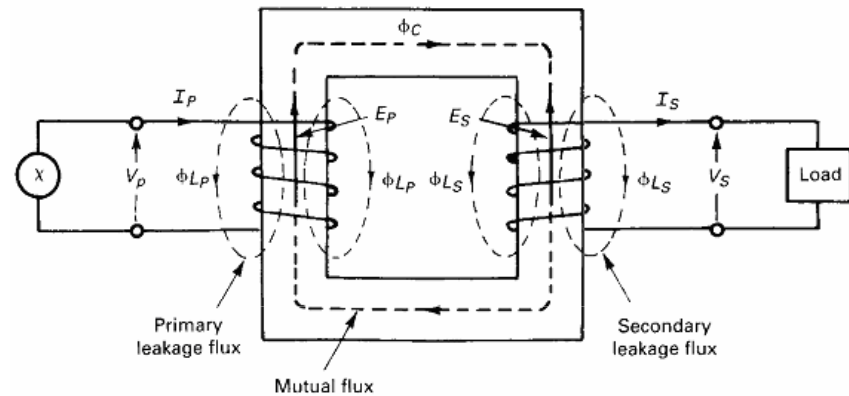
- A transformer whose primary and secondary windings have resistances of R_1 and R_2 respectively is shown in the figure.



Magnetic Leakage

- ❑ **Leakage Flux:** Not all of the flux produced by the primary current links the winding, but there is leakage of some flux into air surrounding the primary.
- ❑ Similarly, not all of the flux produced by the secondary current (load current) links the secondary, rather there is loss of flux due to leakage.
- ❑ These effects are modeled as leakage reactance in the equivalent circuit representation.
- ❑ A transformer with magnetic leakage is equivalent to an ideal transformer with inductive coils connected in both primary and secondary circuits as shown in the next slide.
- ❑ The internal e.m.f. in each inductive coil is equal to that due to the corresponding leakage flux in the actual transformer.

$$X_1 = \frac{e_{L1}}{I_1} \quad \text{and} \quad X_2 = \frac{e_{L2}}{I_2}$$



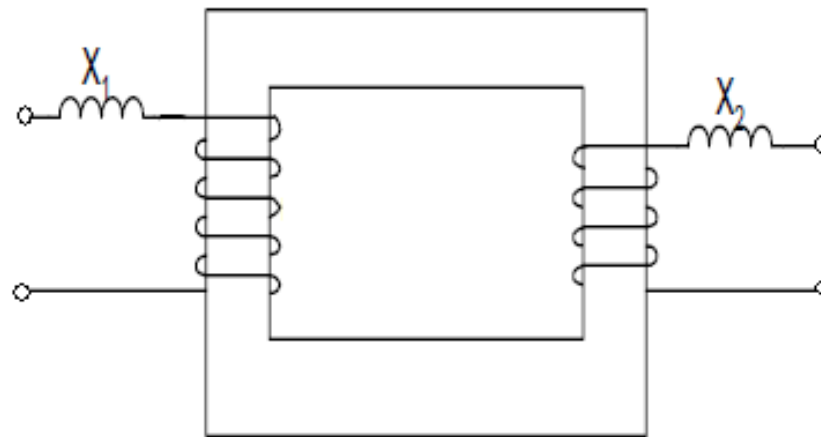
Transformer with Magnetic Leakage

- Important points:

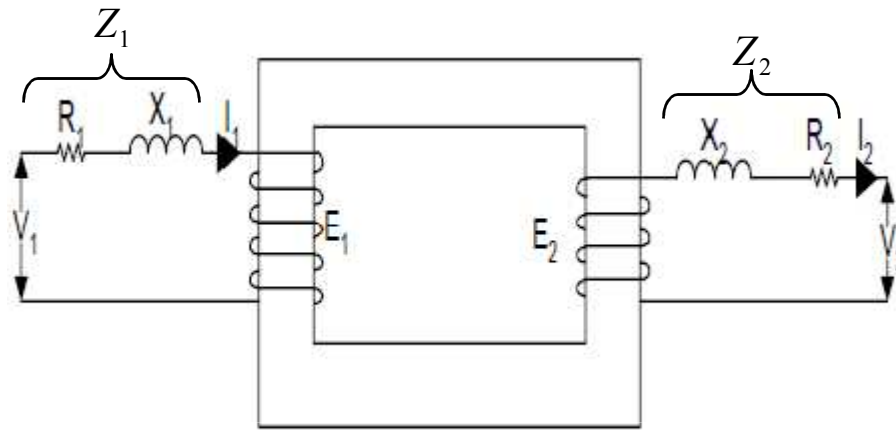
- The leakage flux links one or other winding but not both, hence it in no way contributes to the transfer of energy from the primary to the secondary winding.
- The primary voltage V_1 will have to supply reactive drop $I_1 X_1$ in addition to $I_1 R_1$.

Similarly, E_2 will have to supply $I_2 R_2$ and $I_2 X_2$.

- In an actual transformer, the primary and secondary windings are not placed on separate legs or limbs as shown below because due to their being widely separated, large primary and secondary leakage fluxes would result.



Transformer with Resistance and Leakage Reactance



□ The primary impedance: $Z_1 = \sqrt{(R_1^2 + X_1^2)}$

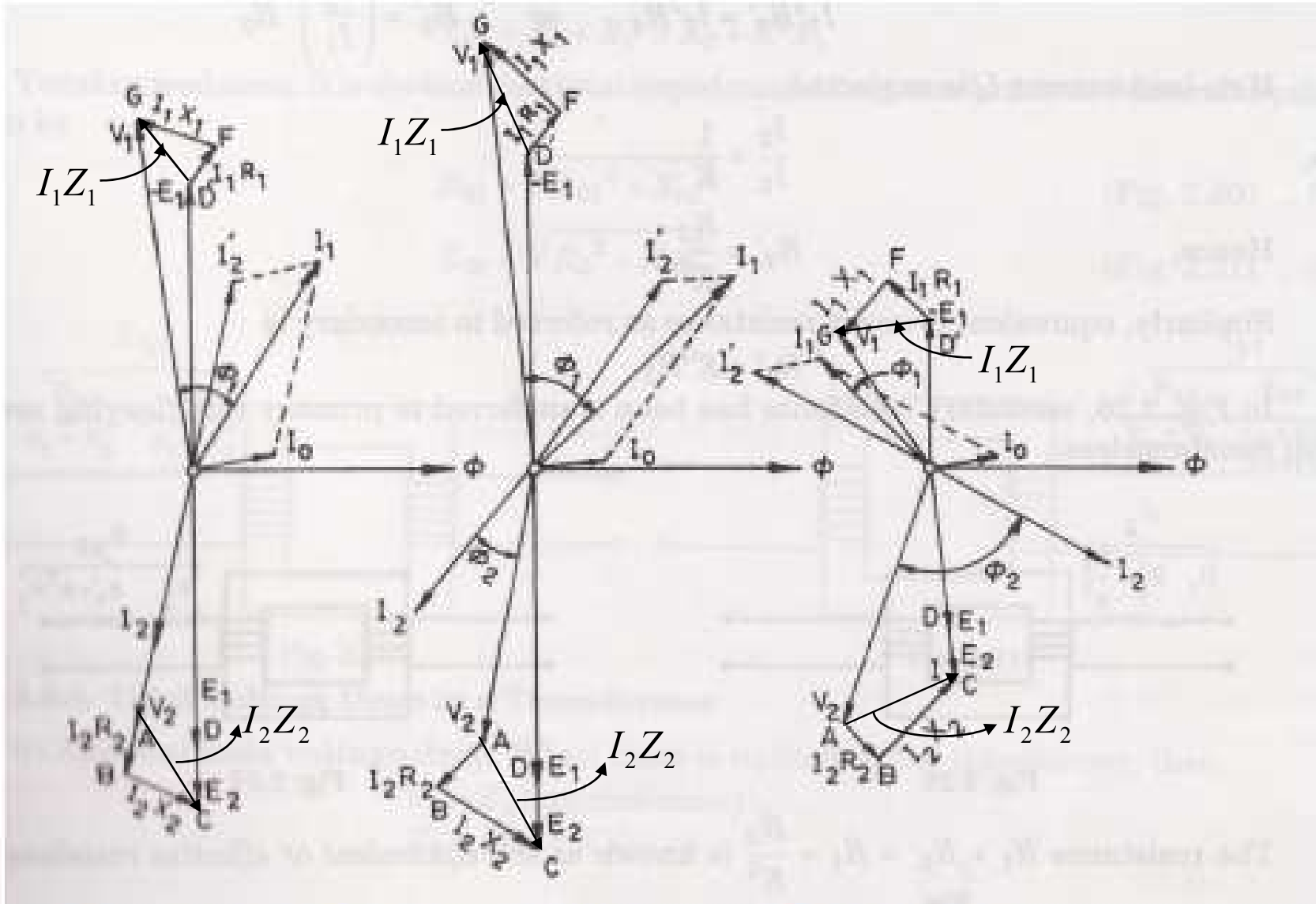
□ The secondary impedance: $Z_2 = \sqrt{(R_2^2 + X_2^2)}$

□ The Voltage drops:

$$V_1 = E_1 + I_1(R_1 + jX_1) = E_1 + I_1 Z_1$$

$$E_2 = V_2 + I_2(R_2 + jX_2) = V_2 + I_2 Z_2$$

Vector diagram of Actual Transformer



a) I_2 is resistive

b) I_2 is inductive

c) I_2 is capacitive

Transfer of resistances & reactances to any side

- The Cu loss by I_2 in secondary = $I_2^2 R_2$. If R_2' is the equivalent resistance in the primary which would have caused the same loss as R_2 in the secondary, then

$$I_2^2 R_2 = I_1^2 R_2'$$

or, $R_2' = \frac{R_2}{\left(\frac{I_1}{I_2}\right)^2} = \frac{R_2}{k^2}$

- Similarly, equivalent primary resistance as referred to secondary is

$$R_1' = k^2 R_1$$

Transfer of resistances & reactances to any side (cont.)

- Leakage reactances can also be transferred from one winding to other ;

$$X_2' = \frac{X_2}{k^2} \quad X_1' = k^2 X_1$$

Total resistance referred to primary is $R_{01} = R_1 + R_2'$

Total reactance referred to primary is $X_{01} = X_1 + X_2'$

- Total impedance of transformer referred to primary is

$$Z_{01} = \sqrt{R_{01}^2 + X_{01}^2}$$

Transfer of resistances & reactances to any side (cont.)

Similarly, total resistance referred to secondary is

$$R_{02} = R_2 + R_1'$$

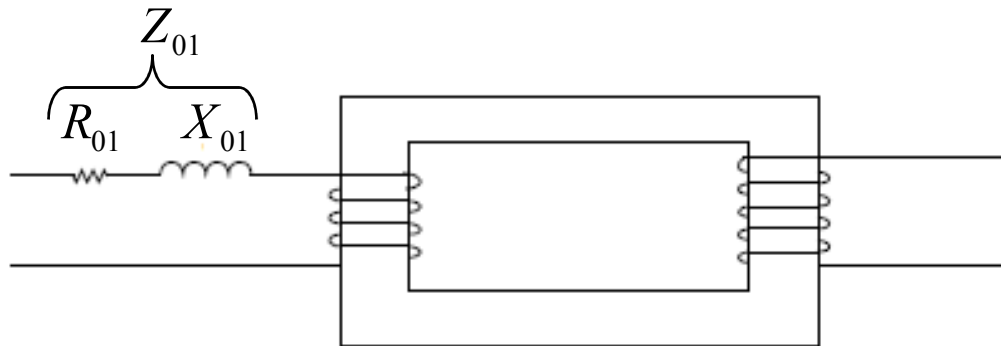
Similarly, total reactance referred to secondary is

$$X_{02} = X_2 + X_1'$$

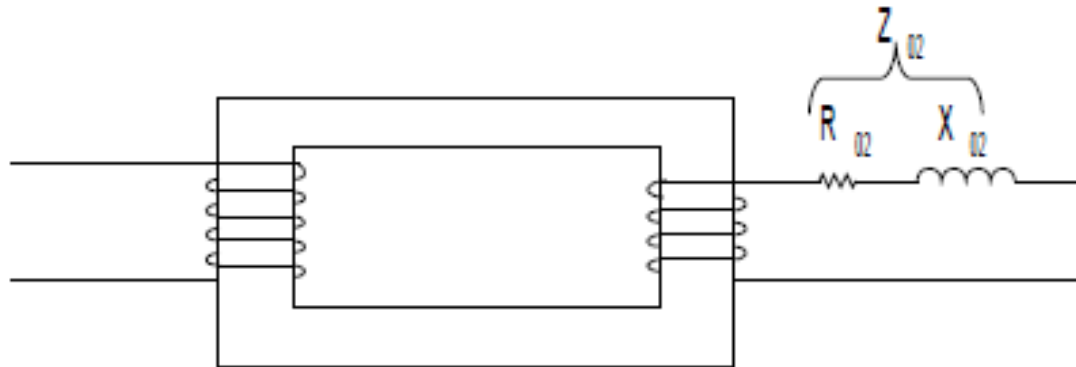
Similarly, total impedance of transformer referred to secondary is

$$Z_{02} = \sqrt{R_{02}^2 + X_{02}^2}$$

Transfer of resistances & reactances to any side (cont.)

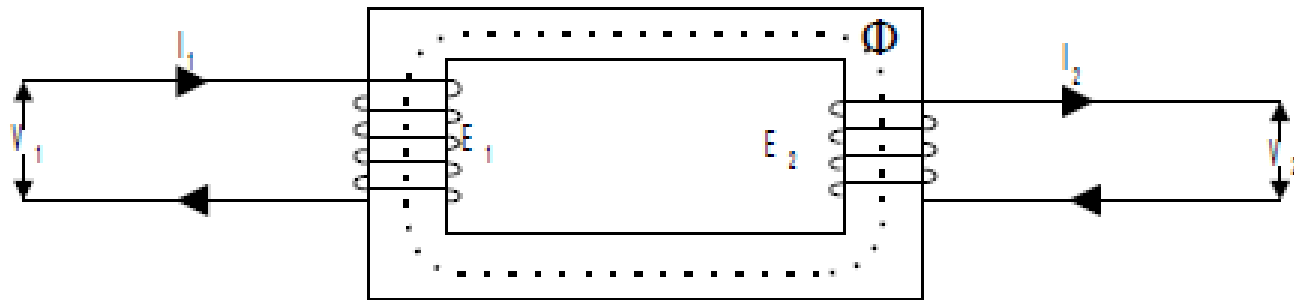


Impedance referred to primary

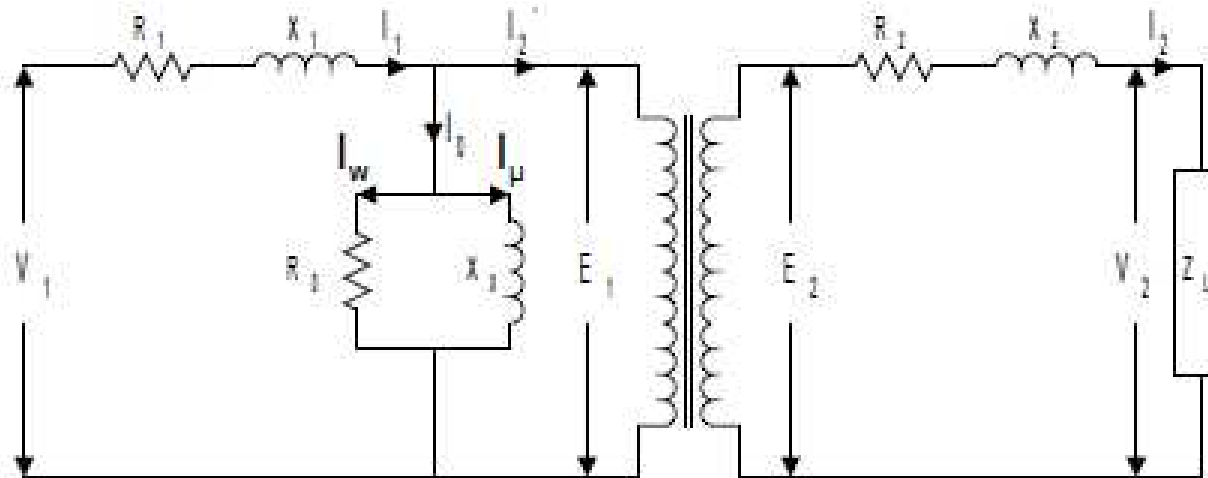


Impedance referred to secondary

Equivalent Circuit of a Transformer



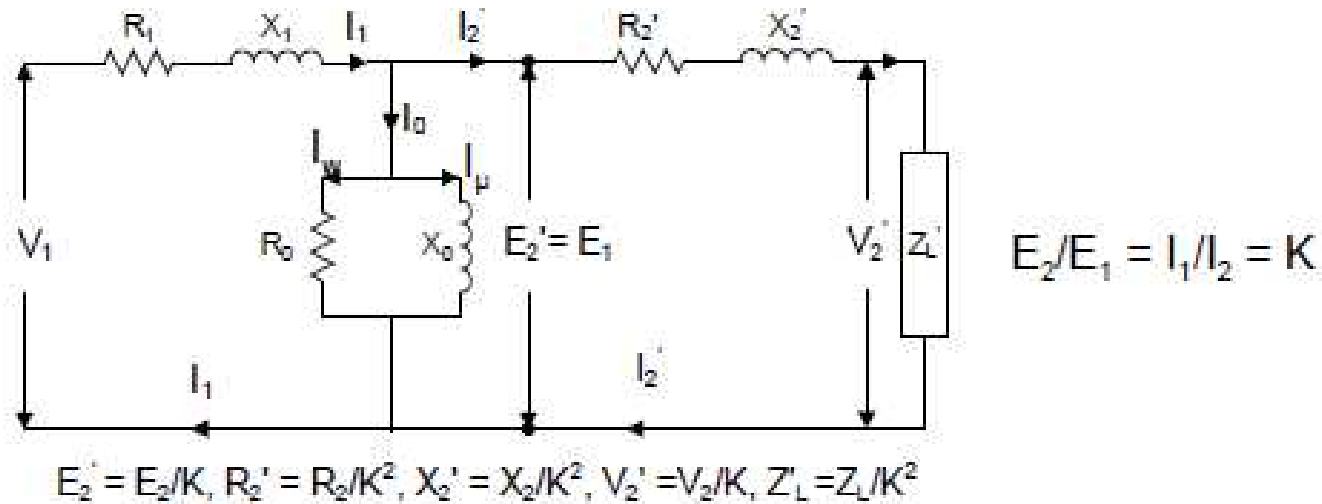
A) Circuit



B) Equivalent circuit of transformer

Equivalent circuit of a Transformer referred to primary/Exact

Equivalent circuit



C) Equivalent circuit with secondary impedances transferred to primary

$$R_2' = R_2/K^2, X_2' = X_2/K^2, Z_2' = Z_2/K^2 \quad E_2' = E_2/K = E_1, V_2' = V_2/K$$

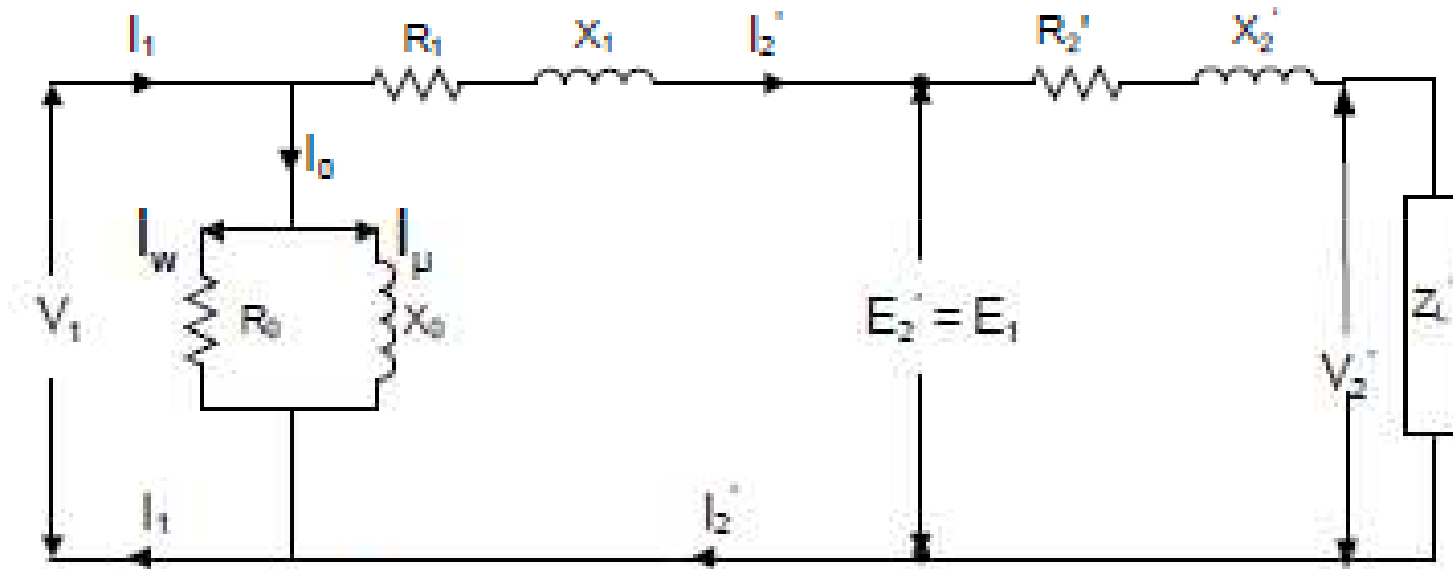
$$Z = Z_1 + Z_m \parallel (Z_2' + Z_L') = \left(Z_1 + \frac{Z_m (Z_2' + Z_L')}{Z_m + (Z_2' + Z_L')} \right)$$

- Where, $Z_2' = R_2' + jX_2'$ and Z_m = impedance of the exciting circuit

$$V_1 = I_1 \times \left(Z_1 + \frac{Z_m (Z_2' + Z_L')}{Z_m + (Z_2' + Z_L')} \right)$$

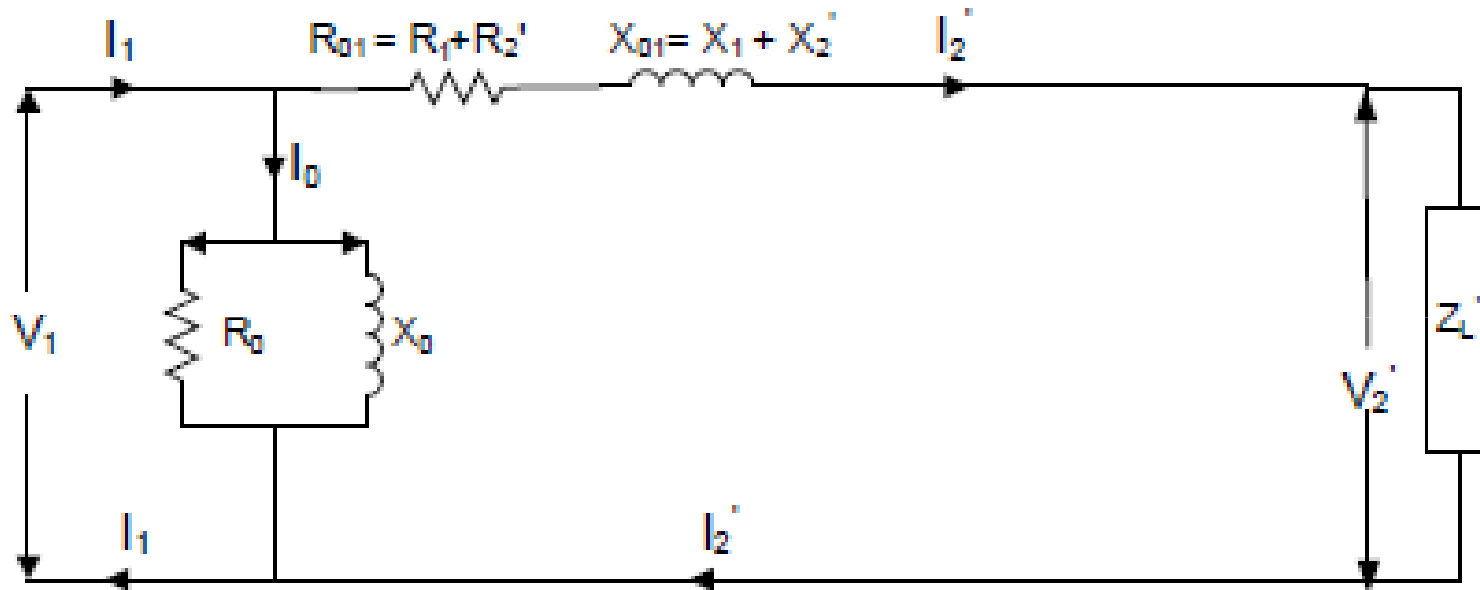
Approximate Equivalent Circuit

- Transfer exciting circuit as shown in figure:



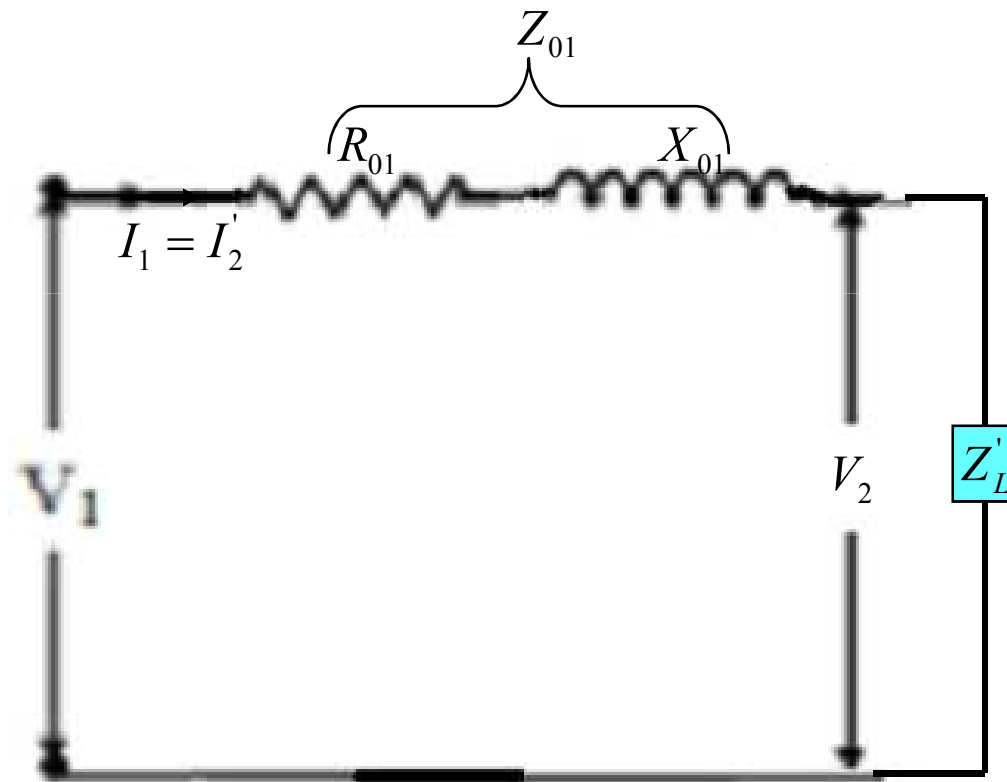
D) Approximate equivalent circuit

Approximate Equivalent circuit with secondary impedances transferred to primary



Equivalent Circuit (cont.)

- Neglecting the exciting circuit:



Why Transformer Rating in kVA?

- *Cu loss* of a transformer depends on *current*.
- *Iron loss* of a transformer depends on *voltage*.
- Hence, total transformer loss depends on *volt-ampere (VA)* and not on *phase angle* between voltage and current i.e. total transformer loss is independent of *load power factor*.
- That's why *transformer rating is in kVA and not in kW*.

Percentage Resistance, Reactance and Impedance

➤ Usually measured by the voltage drop at full-load current.

i. Percentage resistance at full-load:

$$\begin{aligned}\%R &= \frac{I_1 R_{01}}{V_1} \times 100 \\ \Rightarrow \%R &= \frac{I_1^2 R_{01}}{V_1 I_1} \times 100 \\ \Rightarrow \%R &= \frac{I_2^2 R_{02}}{V_2 I_2} \times 100\end{aligned}$$

$\%R = \%Cu \text{ Loss at full-load}$

$\%R = \%Cu \text{ Loss} = V_r$

Percentage Resistance, Reactance and Impedance (cont.)

ii. *Percentage reactance at full-load:*

$$\%X = \frac{I_1 X_{01}}{V_1} \times 100$$
$$\Rightarrow \%X = \frac{I_2 X_{02}}{V_2} \times 100 = v_x$$

iii. *Percentage impedance at full-load:*

$$\%Z = \frac{I_1 Z_{01}}{V_1} \times 100$$
$$\Rightarrow \%Z = \frac{I_2 Z_{02}}{V_2} \times 100$$

iv. *So,*

$$\%Z = \sqrt{(\%R^2 + \%X^2)}$$

Percentage Resistance, Reactance and Impedance (cont.)

- Now, $\%R = \frac{I_1 R_{01}}{V_1} \times 100$
 $\Rightarrow R_{01} = \frac{\%R \times V_1}{I_1 \times 100} = \frac{\%CuLoss \times V_1}{I_1 \times 100}$

Similarly, $\%R = \frac{I_2 R_{02}}{V_2} \times 100$
 $\Rightarrow R_{02} = \frac{\%R \times V_2}{I_2 \times 100} = \frac{\%CuLoss \times V_2}{I_2 \times 100}$

- Now, $\%X = \frac{I_1 X_{01}}{V_1} \times 100$
 $\Rightarrow X_{01} = \frac{\%X \times V_1}{I_1 \times 100} = \frac{v_x \times V_1}{I_1 \times 100}$

Similarly, $\%X = \frac{I_2 X_{02}}{V_2} \times 100$
 $\Rightarrow X_{02} = \frac{\%X \times V_2}{I_2 \times 100} = \frac{v_x \times V_2}{I_2 \times 100}$

➤ *Percentage resistance, reactance and impedance have the same value whether referred to primary or secondary.*

Losses in a Transformer

□ *Two types of losses*

i. Core or Iron Loss:

- It includes both hysteresis and eddy current loss. Because the core flux in a transformer remains practically constant for all loads. The core is practically same at all loads.

$$\text{Hysteresis Loss} = W_h = \eta B_{\max}^{1.6} fV \text{ watt};$$

$$\text{Eddy current Loss} = W_e = PB_{\max}^2 f^2 t^2 \text{ watt.}$$

- These losses are minimized by using steel of high silicon content for the core and by using very thin laminations.
- Iron or Core loss is found from the *Open Circuit test*.
- The input of the transformer when on no-load measures the core loss.

Losses in a Transformer (cont.)

ii. *Copper Loss:*

- This loss is due to the ohmic resistance of the transformer windings.
- Total Cu loss = $I_1^2 R_1 + I_2^2 R_2 = I_1^2 R_{01} = I_2^2 R_{02}$
- So, Cu loss is proportional to $(\text{current})^2$ or $(\text{kVA})^2$
- Cu loss is found from the *short-circuit test*.

Efficiency of a Transformer

$$\eta = \frac{\textit{Output}}{\textit{Output} + \textit{Losses}}$$

$$\Rightarrow \eta = \frac{\textit{Output}}{\textit{Output} + \textit{CuLoss} + \textit{IronLoss}}$$

$$\eta = \frac{\textit{Input} - \textit{Losses}}{\textit{Input}} = 1 - \frac{\textit{Losses}}{\textit{Input}}$$

- Efficiency is based on power output in watts and not in volt-amperes, although losses are proportional to VA.
- Thus, efficiency depends on power factor and maximum at a power factor of unity.

Condition for Maximum Efficiency

- Cu Loss = $I_1^2 R_{01}$
- Iron Loss = hysteresis loss + eddy current loss = W_i
- Primary Input = $V_1 I_1 \cos \phi_1$

$$\begin{aligned}\eta &= \frac{V_1 I_1 \cos \phi_1 - \text{Losses}}{V_1 I_1 \cos \phi_1} \\ \Rightarrow \eta &= \frac{V_1 I_1 \cos \phi_1 - I_1^2 R_{01} - W_i}{V_1 I_1 \cos \phi_1} \\ \Rightarrow \eta &= 1 - \frac{I_1^2 R_{01}}{V_1 I_1 \cos \phi_1} - \frac{W_i}{V_1 I_1 \cos \phi_1} \\ \Rightarrow \eta &= 1 - \frac{I_1 R_{01}}{V_1 \cos \phi_1} - \frac{W_i}{V_1 I_1 \cos \phi_1}\end{aligned}$$

Condition for Maximum Efficiency (cont.)

$$\frac{d\eta}{dI_1} = \frac{d}{dI_1} \left(1 - \frac{I_1 R_{01}}{V_1 \cos \phi_1} - \frac{W_i}{V_1 I_1 \cos \phi_1} \right)$$

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

$$\Rightarrow 0 = 0 - \frac{R_{01}}{V_1 \cos \phi_1} + \frac{W_i}{V_1 I_1^2 \cos \phi_1}$$

$$\Rightarrow \frac{R_{01}}{V_1 \cos \phi_1} = \frac{W_i}{V_1 I_1^2 \cos \phi_1}$$

$$\Rightarrow R_{01} = \frac{W_i}{I_1^2}$$

$$\Rightarrow R_{01} I_1^2 = W_i$$

or $R_{02} I_2^2 = W_i$

Therefore, **Cu loss = Iron Loss**

The output current corresponding to maximum efficiency is

$$I_2 = \sqrt{(W_i / R_{02})}$$

All-day Efficiency

- The distribution transformer have their primaries energized all the twenty-four hours, although their secondaries supply little or no-load much of the time during the day except during the house lighting period.
- The core loss occurs throughout the day, the Cu loss occurs only when the transformer is loaded.

$$\eta_{all-day} = \frac{\text{Output in kWh}}{\text{Input in kWh}} \quad (\text{for 24 hours})$$

Examples

- Ex-1: (a) A 2,200/200 V transformer draws a no-load primary current of 0.6 A and absorbs 400 watts. Find the magnetizing and iron loss currents.
- (b) A 2200/250 V transformer takes 0.5 A at p.f. of 0.3 on open circuit. Find magnetizing and working components of no-load primary current.

Examples

- Ex-2: A transformer has a primary winding of 800 turns and a secondary winding of 200 turns. When the load current on the secondary is 80A at 0.8 power factor lagging, the primary current is 25A at 0.707 power factor lagging. Determine the no-load current of the transformer and its phase.

Examples

- **Ex-3:** A 30 kVA, 2400/120-V, 50Hz transformer has a high voltage winding resistance of 0.1Ω and a leakage reactance of 0.22Ω . The low voltage winding resistance is 0.035Ω and the leakage reactance is 0.012Ω . Find the equivalent winding resistance, reactance and impedance referred to the (i) high voltage side and (ii) the low-voltage side.

Examples

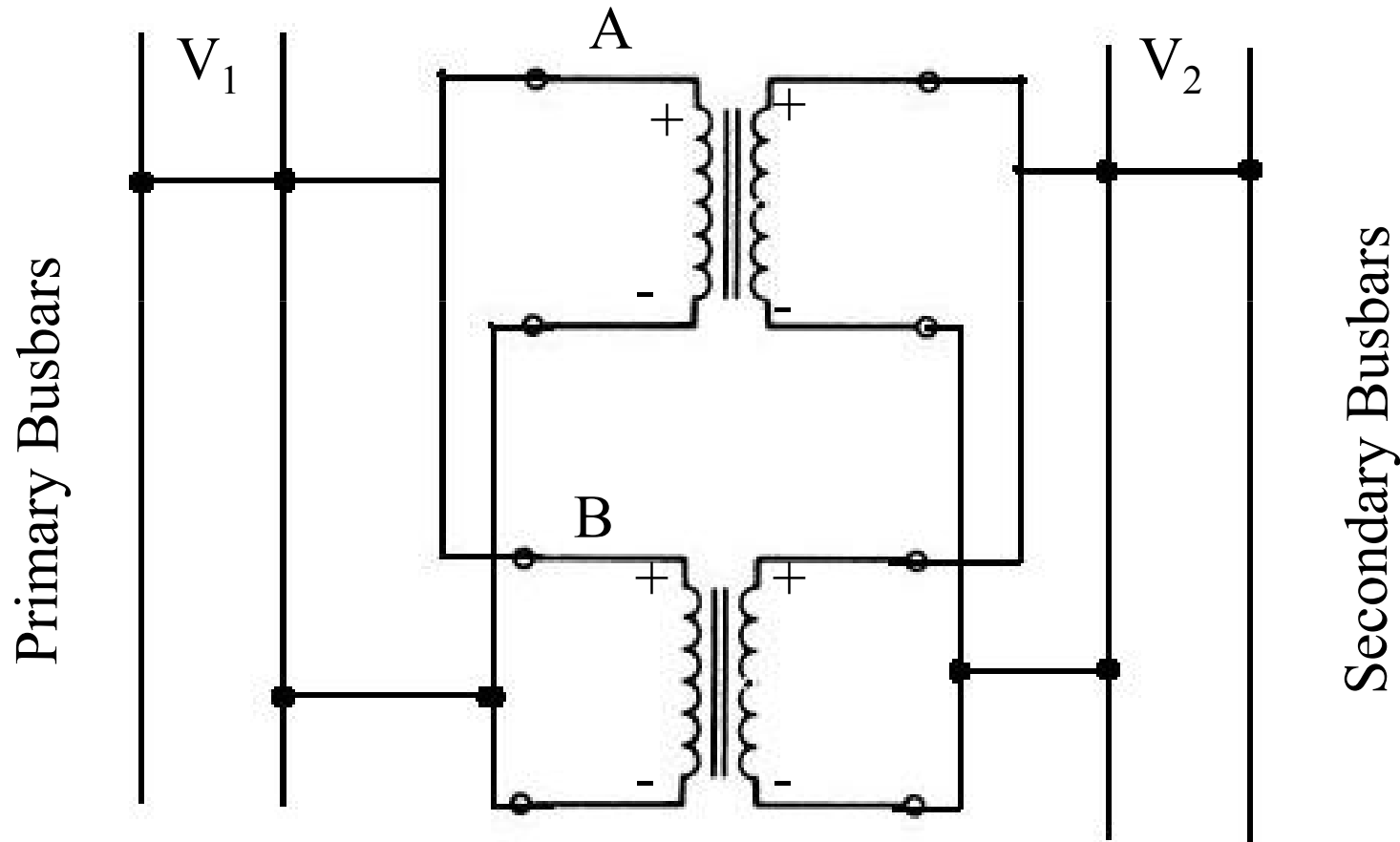
- **Ex-4:** In a 25 kVA, 2000/200-V, single phase transformer, the iron and full-load Cu losses are 350W and 400W, respectively. Calculate the efficiency at unity power factor on (i) full-load, (ii) half full-load.

Parallel Operation of a Single Phase Transformer

□ Conditions:

1. Primary winding of a transformer should be suitable for the supply system voltage and frequency.
2. The transformer should be properly connected with regard to polarity.
3. The voltage ratings of both primaries and secondaries should be identical. In other words, the transformers should have the same turn ratio i.e. transformation ratio.
4. The percentage impedance should be equal in magnitude and have the same X/R ratio in order to avoid the circulating currents and operation at different power factors.
5. With transformers having different kVA ratings, the equivalent impedances should be inversely proportional to the individual kVA rating if circulating currents are to be avoided.

Transformer Parallel Connection



Transformer Parallel Operation (cont.)

$$I = I_A + I_B;$$

$$V_2 = E - I_A Z_A = E - I_B Z_B = E - I Z_{AB};$$

$$\text{Also, } I_A Z_A = I_B Z_B$$

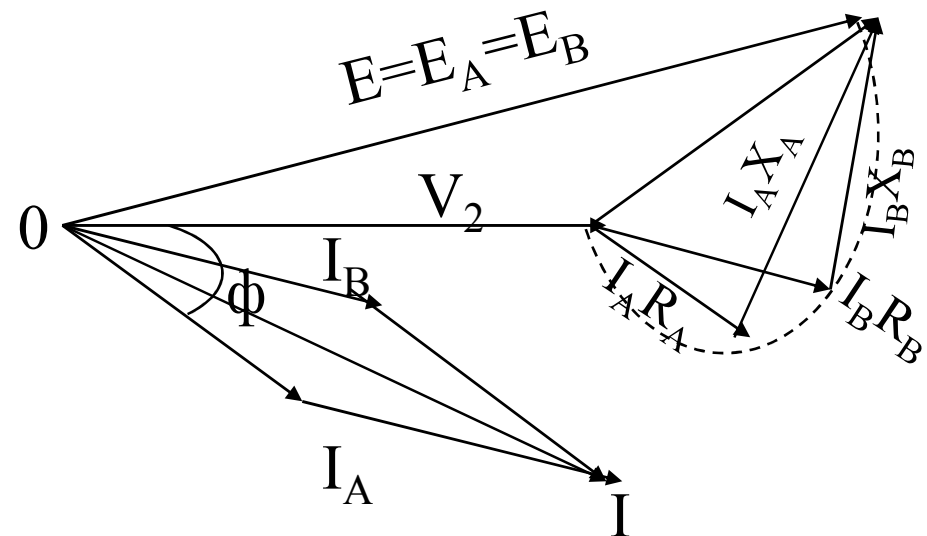
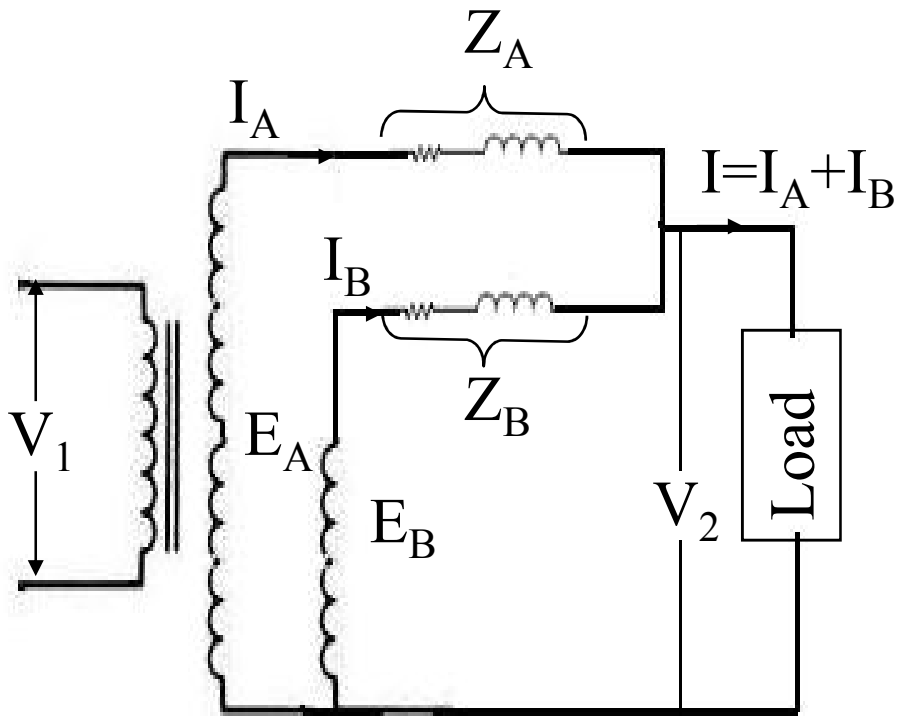
$$\Rightarrow I_A / I_B = Z_B / Z_A;$$

$$I_A = I Z_B / (Z_A + Z_B); I_B = I Z_A / (Z_A + Z_B)$$

Transformer Parallel Operation (cont.)

❖ Case 2: Equal Voltage Ratios

- Two transformers having the same voltage ratio.
- Impedance voltage triangles are different in size and shape.
- No-circulating current.



Transformer Parallel Operation (cont.)

$$I = I_A + I_B;$$

$$I_A Z_A = I_B Z_B$$

$$\Rightarrow I_A / I_B = Z_B / Z_A;$$

$$I_A = I Z_B / (Z_A + Z_B); I_B = I Z_A / (Z_A + Z_B)$$

- Multiplying both sides by V_2 ,

$$V_2 I_A = V_2 I \frac{Z_B}{Z_A + Z_B}$$

$$\Rightarrow S_A = S \frac{Z_B}{Z_A + Z_B}$$

$$V_2 I_B = V_2 I \frac{Z_A}{Z_A + Z_B}$$

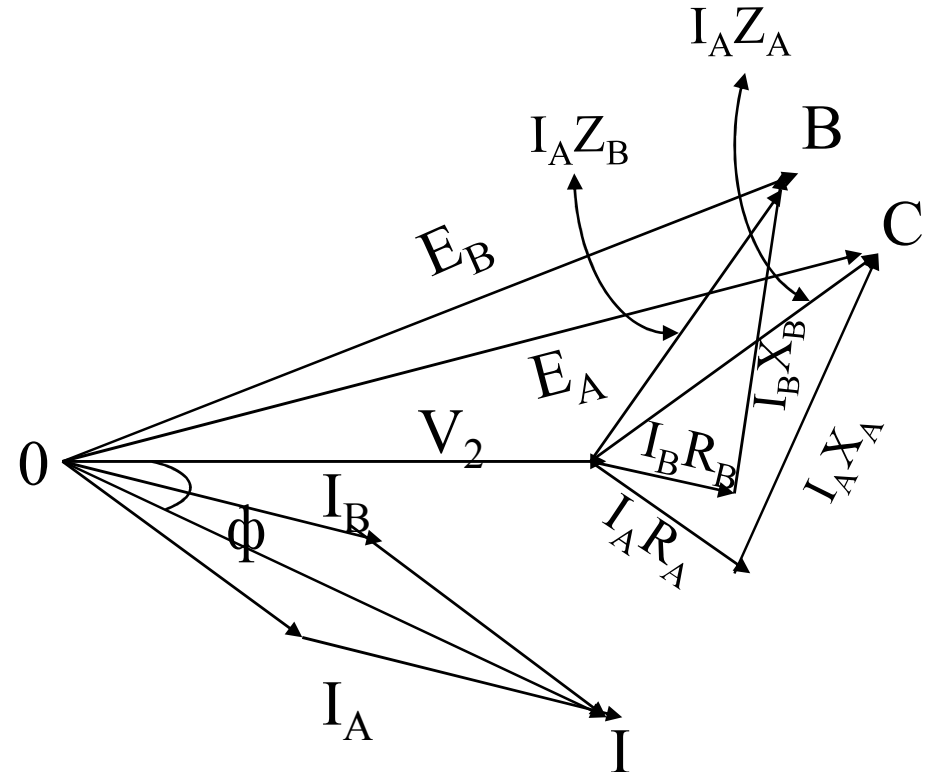
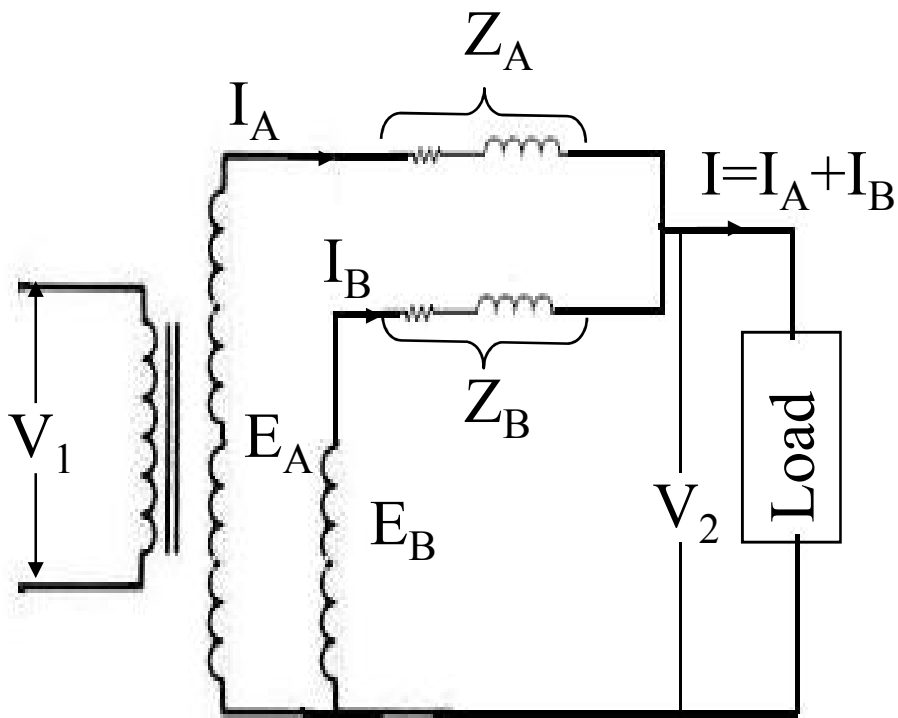
$$\Rightarrow S_B = S \frac{Z_A}{Z_A + Z_B}$$

- Where, $V_2 I \times 10^{-3} = S$ - the combined load kVA.

Transformer Parallel Operation (cont.)

❖ Case 3: Unequal Voltage Ratios

- Two transformers having different voltage ratio.
- Impedance voltage triangles are different in size and shape.
- Circulating current.



Transformer Parallel Operation (cont.)

$$E_A = I_A Z_A + V_2; E_B = I_B Z_B + V_2;$$

$$V_2 = I Z_L = (I_A + I_B) Z_L;$$

$$E_A = I_A Z_A + (I_A + I_B) Z_L;$$

$$E_B = I_B Z_B + (I_A + I_B) Z_L; \dots (iii)$$

$$E_A - E_B = I_A Z_A - I_B Z_B;$$

$$I_A = [(E_A - E_B) + I_B Z_B] / Z_A;$$

- Substituting this value in eqn (iii)

$$E_B = I_B Z_B + \left[\frac{\{(E_A - E_B) + I_B Z_B\}}{Z_A + I_B} \right] / Z_L;$$

$$I_B = [E_B Z_A - (E_A - E_B) Z_L] / [Z_A Z_B + Z_L (Z_A + Z_B)];$$

$$I_A = [E_A Z_B + (E_A - E_B) Z_L] / [Z_A Z_B + Z_L (Z_A + Z_B)];$$

$$I = I_A + I_B = \frac{E_A Z_B + E_B Z_A}{Z_A Z_B + Z_L (Z_A + Z_B)}$$

$$V_2 = I Z_L$$

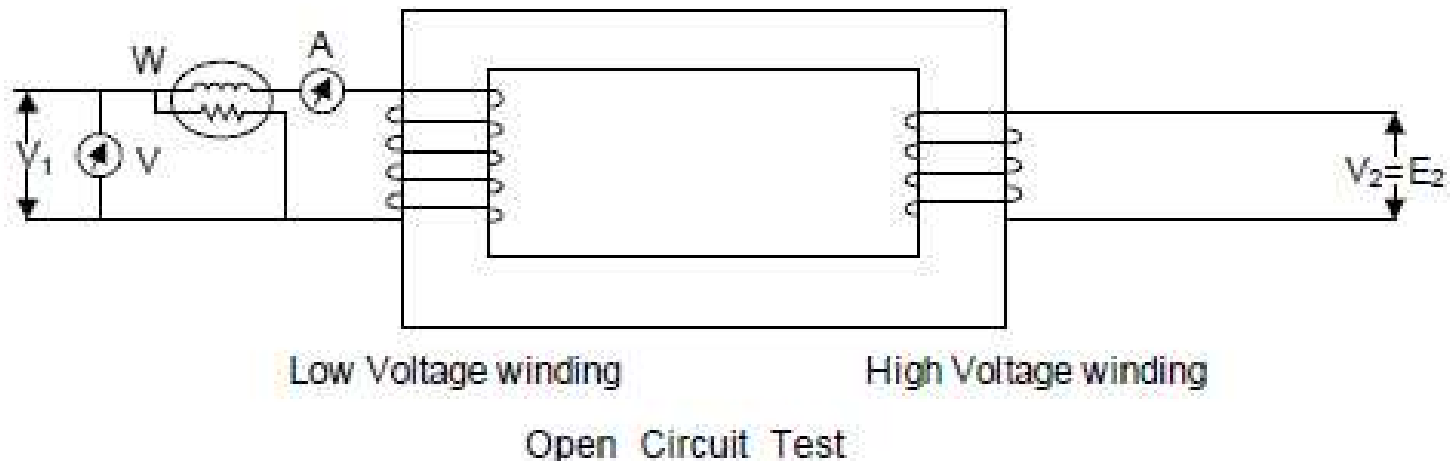
$$= \left[\frac{E_A Z_B + E_B Z_A}{Z_A Z_B + Z_L (Z_A + Z_B)} \right] Z_L$$

$$I_C = \frac{E_A - E_B}{Z_A + Z_B}$$

Transformer Test

- The performance of a transformer can be calculated on the basis of its equivalent circuit which contains the 4 main parameters:
 1. Equivalent resistance R_{01} (or R_{02})
 2. Equivalent leakage reactance X_{01} (or X_{02})
 3. Core loss resistance R_0
 4. Magnetizing reactance X_0
- These parameters are determined from the following tests:
 - a) Open circuit test
 - b) Short circuit test

Open Circuit Test



- As the primary no-load current I_0 is small, Copper loss is negligibly small in primary & nil in secondary. Hence, wattmeter reading represents the core loss under no load condition.

- Core loss = W = input power on no-load = $V_1 I_0 \cos \Phi_0$

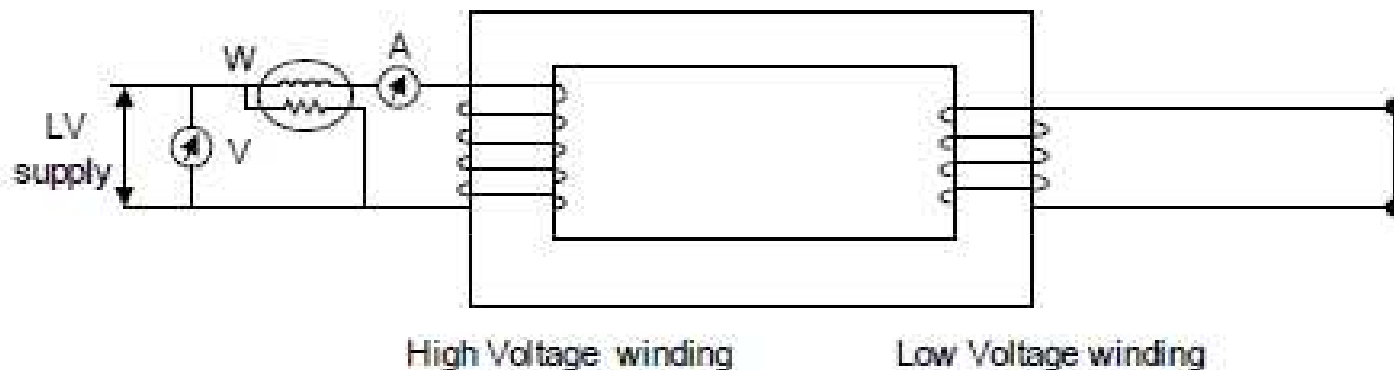
$$\Rightarrow \cos \Phi_0 = W / (V_1 I_0)$$

Hence, $I_w = I_0 \cos \Phi_0$ & $I_\mu = I_0 \sin \Phi_0$

Also, $X_0 = V_1 / I_\mu$ & $R_0 = V_1 / I_w$

Short Circuit Test

- This test is conducted to determine:
 1. Full-load copper loss
 2. Equivalent resistance & reactance referred to metering side.



- A low voltage (5 -10% of normal primary voltage) at correct frequency is applied to the primary winding & is continuously increased till full load currents flow both in primary & secondary. Since applied voltage is small, flux linking with core is very small & hence, iron loss can be neglected & reading of wattmeter gives total copper losses at full load.
- If V_{sc} is the voltage required to circulate rated load currents, then

$$Z_{01} = \frac{V_{sc}}{I_{sc}}; W = I_{sc}^2 R_{01} \implies X_{01} = \sqrt{Z_{01}^2 - R_{01}^2}$$

Transformer Regulation

- ❖ Loading changes the output voltage of a transformer.
Transformer regulation is the measure of such a deviation.

Definition of % Regulation

$$= \frac{|V_{\text{no-load}}| - |V_{\text{load}}|}{|V_{\text{load}}|} * 100$$

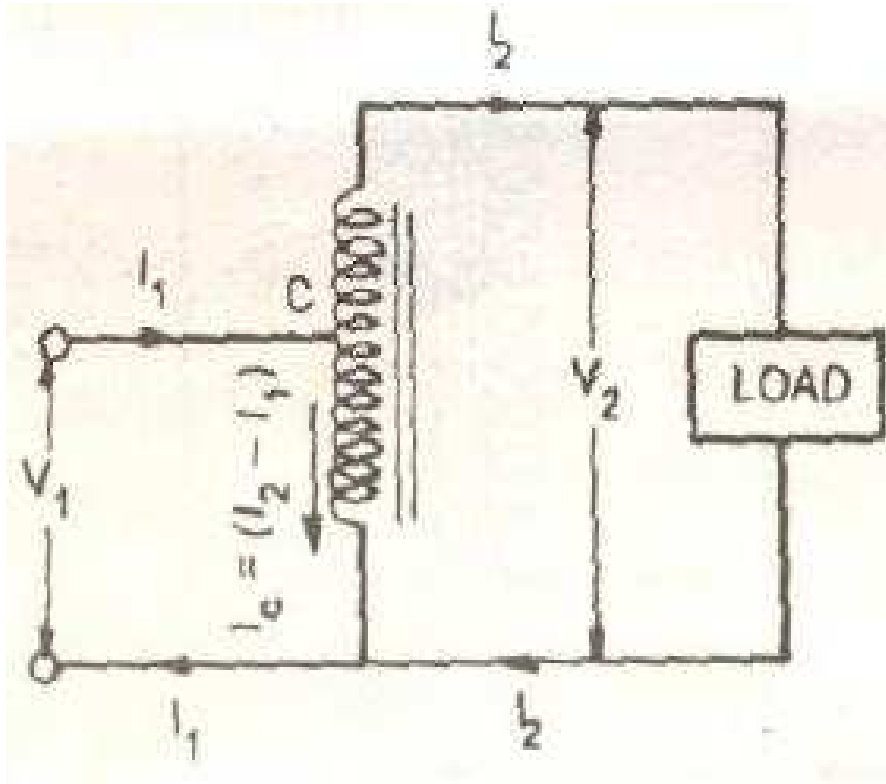
$V_{\text{no-load}}$ = RMS voltage across the load terminals without load

V_{load} = RMS voltage across the load terminals with a specified load

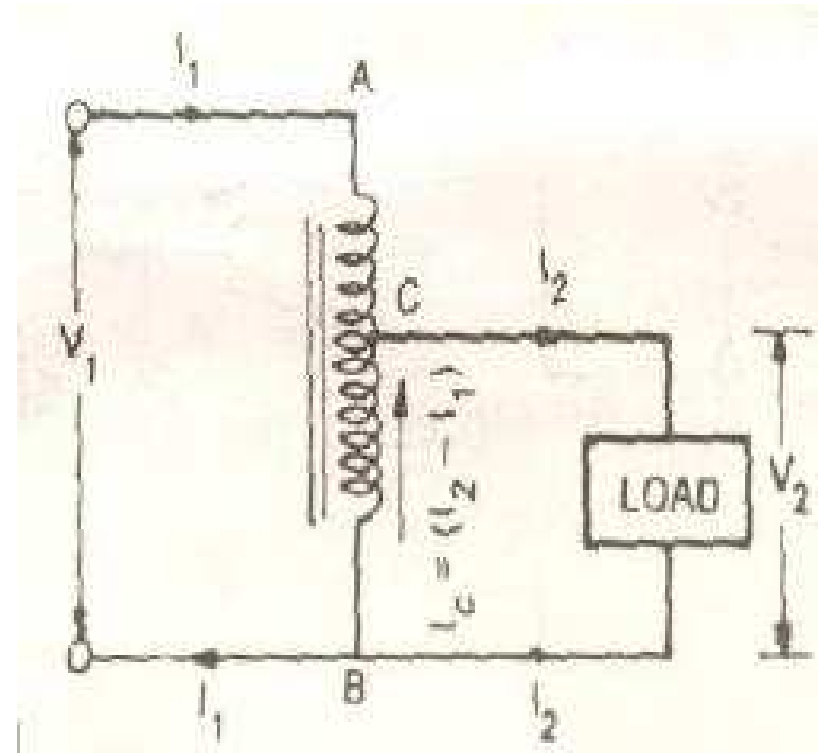
Auto Transformer

- ❖ It is a transformer with one winding only, part of it been common to both primary and secondary.
- ❖ Primary and Secondary winding are not electrically isolated from each other.
- ❖ Its theory and operation are similar to that of a two winding transformer.
- ❖ Because of one winding it is compact, efficient and cheaper.
- ❖ It is used where transformation ratio differs little from unity.
- ❖ It is also used as an adjustable transformer for both stepping up and stepping down the input voltage.

Auto Transformer (cont.)



Step up Auto transformer



Step down Auto transformer

Auto Transformer (cont.)

❖ Saving of Cu

- Volume and weight of Cu \propto length and area of the cross-section of the conductors.
- Length of conductor $\propto N$
- Cross-section $\propto I$
- Weight $\propto IN$
- Wt. of Cu in AC section $\propto (N_1 - N_2)I_1$;
- Wt. of Cu in BC section $\propto N_2 (I_2 - I_1)$;
- Total Wt. of Cu in Auto-transformer $\propto (N_1 - N_2)I_1 + N_2 (I_2 - I_1)$;
- If two-winding transformer perform the same duty, then
Wt. of Cu on its primary $\propto N_1 I_1$;
Wt. of Cu on its secondary $\propto N_2 I_2$;
Total Wt. of Cu $\propto N_1 I_1 + N_2 I_2$;

Auto Transformer (cont.)

$$\frac{\text{Wt. of Cu in Auto-transformer}}{\text{Wt. of Cu in ordinary transformer}} = \frac{(N_1 - N_2)I_1 + N_2(I_2 - I_1)}{N_1I_1 + N_2I_2}$$
$$= 1 - \frac{2 \frac{N_2}{N_1}}{1 + \frac{N_2}{N_1} \times \frac{I_2}{I_1}} = 1 - 2 \frac{K}{2} = 1 - K$$
$$\Rightarrow W_a = (1 - K)W_o$$

So, Saving of Cu = $W_o - W_a = W_o - (1 - K)W_o = KW_o$

Saving of Cu = KW_o

Examples

□ Ex-5: A 5 kVA, 2300/230-V, 50Hz transformer was tested for the iron losses with normal excitation and Cu losses at full-load and these were found to be 40W and 112W, respectively. Calculate the efficiency of the transformer at 0.8 power factor for 1.25kVA outputs.

Examples

- Ex-6: Find the all-day efficiency of 500kVA distribution transformer whose copper loss and iron loss at full load are 4.5kW and 3.5kW, respectively. During a day of 24 hours, it is loaded as under:

No. of hours	Loading in kW	Power factor
6	400	0.8
10	300	0.75
4	100	0.8
4	0	-

Examples

- **Ex-7:** A 600kVA, 1-ph transformer has an efficiency of 92% both at full-load and half-load at unity power factor. Determine its efficiency at 60% of full-load at 0.8 power factor lag.

Examples

- Ex-8: Ex: Two 1-ph transformers with equal turns have impedances of $(0.5+j3)$ ohm and $(0.6+j10)$ ohm with respect to the secondary. If they operate in parallel, determine how they will share a total load of 100 kW at p.f. 0.8 lagging?

Examples

- **Ex-9:** Ex: Two 2200/110-V, transformers are operated in parallel to share a load of 125kVA at 0.8 power factor lagging. Transformers are rated as below:
- A: 100 kVA; 0.9% resistance and 10% reactance.
B: 50 kVA; 1.0% resistance and 5.0% reactance.
- Find the load carried by each transformer.

Examples

- **Ex-10:** Ex: Two transformers A and B are operated in parallel to the same load. Determine the current delivered by each transformer having given: open-circuit e.m.f. 6600V for A and 6400V for B. Equivalent leakage impedance in terms of the secondary = $0.3+j3$ for A and $0.2+j1$ for B. The load impedance is $8+j6$.