INTRODUCTION

- Applications, Types, and Construction of Transformers
- Applications: Transfers Electric Energy, changing the voltage level (or current level), through a magnetic field (In our study)
- Other applications: e.g., voltage & current sampling and measurement, impedance transformation
- It has two or more coils wrapped around a common electromagnetic core
- Generally, flux in the core is common among the coils

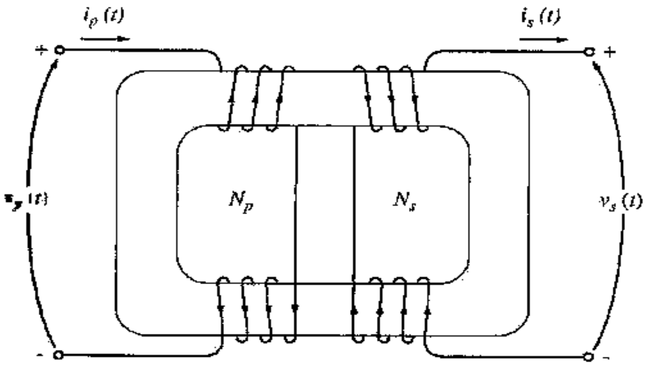
INTRODUCTION

- One winding is connected to source of ac power, the 2nd (& 3rd) supplies power to loads
- Winding connected to source named “*Primary*”
- Winding connected to load named “*Secondary*”
- If there is another one is called “*Tertiary*”
- **Importance of Transformers:**
- **Main**: to transfer electrical energy over long distances (from power plants to load centers)
- In modern power system electric energy is generated at voltages between 12 to 25 kV, Transformers step up voltage between 110 kV to 1200 kV for transmission over long distances with very small losses
- in Iran 230 and 420 kV for transmission and 63 kV and 132 kV for sub-transmission (and frequency of 50 Hz)
- Then Transformers step down to 33 kV or 24 kV for local distribution & finally supply safely homes, offices & factories at voltages as low as 230 V, as 1 phase and 400 V as 3 phase

INTRODUCTION

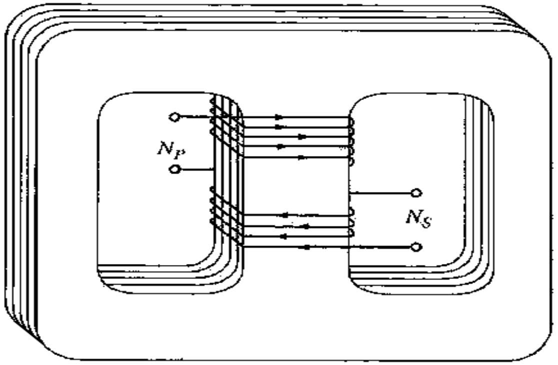
- Transformers are classified, based on types of core structure, into: (both use thin laminations)

1- Core form, transformer windings wrapped on two legs as shown



2- Shell form, transformer windings Wrapped only on center leg as shown:

(leakage flux is minimized)



INTRODUCTION

- The primary and secondary windings are wrapped one on top of the other to:

  Reduce the leakage flux

- And the low-voltage winding innermost to :

  Simplify insulating of the high-voltage winding

  from the core

Types of transformers :

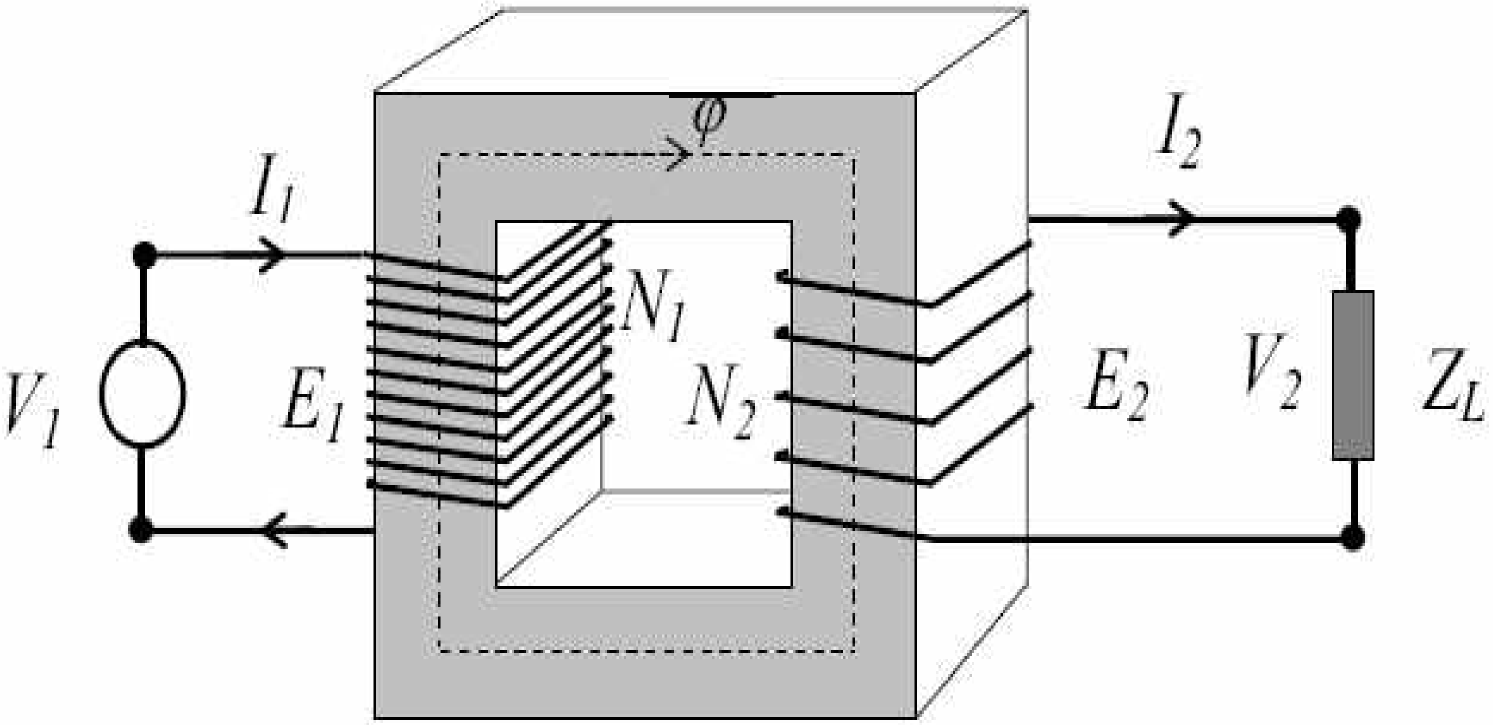
- Step up/Unit transformers – located at output of a generator to step up the voltage level to transmit the power
- Step down/Substation transformers – Located at main distribution or secondary level transmission substations to lower the voltage levels for distribution 1st level purposes
- Distribution Transformers – located at small distribution substation. It lowers the voltage levels for 2nd level distribution purposes.
- Special Purpose Transformers - E.g. Potential Transformer (PT) , Current Transformer (CT)

Oil immersed Distribution Transformers

Dry Type Distribution Transformers

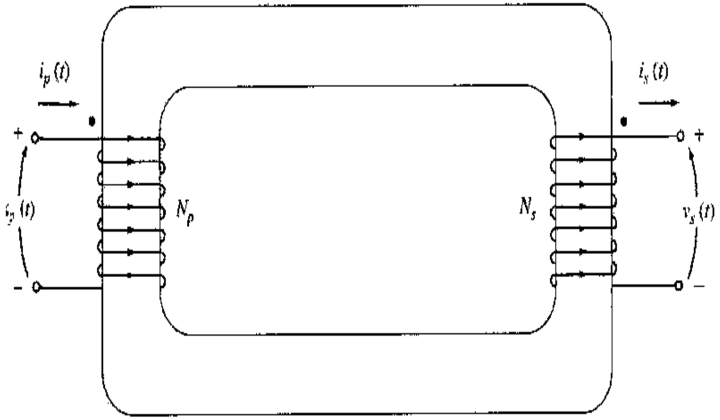
TWO WINDING TRANSFORMER CONNECTION

- SINGLE PHASE

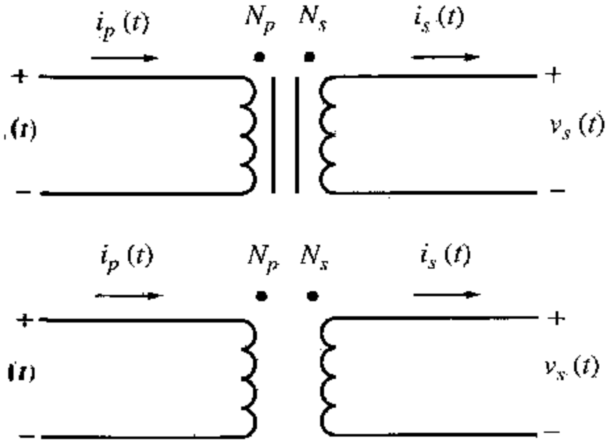


IDEAL TRANSFORMER (SINGLE PHASE)

- a lossless transformer with an input winding and an output winding in which magnetic core has an infinite permeability
- Figure below shows: ideal transformer and schematic symbols of a transformer



(a)



(b)

IDEAL TRANSFORMER

- Np : turns of wire on its primary side
- Ns : turns of wire on its secondary sides
- The relationship between the primary and secondary voltage is as follows: (*a:* is the turns ratio)

$$\frac{v_p(t)}{v_s(t)} = \frac{N_p}{N_s} = a$$

- The relationship between primary and secondary current is $N_p\, i_p(t) = N_s\, i_s(t)$
-

$$\frac{i_p(t)}{i_s(t)} = \frac{1}{a}$$

IDEAL TRANSFORMER

- In terms of Phasor quantities:
- $V_p/V_s=a$, $I_p / I_s=1/a$
- while:

  1- phase angles of V_p and V_s are the same

  2- phase angles of I_p and I_s are the same
- ideal transformer turn ratio affects the magnitude of voltages & currents not their angles
- Now: given primary circuit voltage is positive at specific end of coil, what would be the polarity of secondary circuit's voltage?

IDEAL TRANSFORMER

- It is possible to specify the secondary’s polarity only if transformers were opened & it windings examined
- To avoid requirement of this examination, transformers employ *a dot convention:*
- If the primary **voltage** is +ve at the dotted end of the winding wrt the undotted end, then the secondary voltage will be positive at the dotted end also. Voltage polarities are the same wrt the dots on each side of the core.
- If the primary **current** of the transformer flows **into** the dotted end of the primary winding, the secondary current will flow **out** of the dotted end of the secondary winding

IDEAL TRANSFORMER

- Power in Ideal Transformer

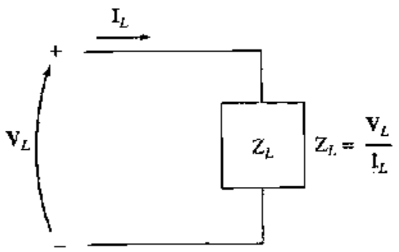
-Power supplied to Transformer: $P_{in}= V_p I_p \cos\theta_p$

-Power supplied to loads : $P_{out}=V_s I_s \cos\theta_s$

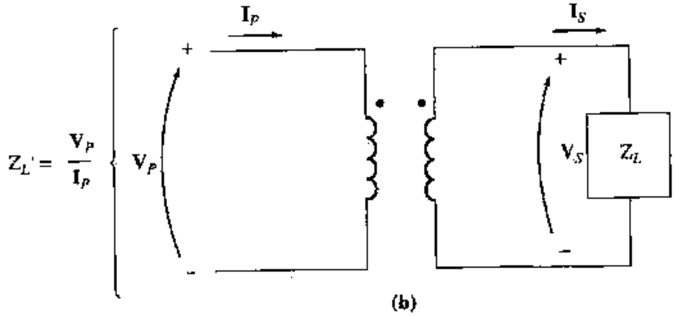
- Since V & I angles unaffected by ideal transformer $\theta_p = \theta_s=\theta$
- Using the turn ratio; $V_p/V_s=a$, $I_p / I_s=1/a$
- $P_{out} = V_p / a \, (a I_p) \cos\theta = P_{in}$
- similiar relation for reactive power Q & S
- $Q_{in}= V_p I_p \sin\theta_p= V_s I_s \sin\theta_s = Q_{out}$
- $S_{in}= V_p I_p = V_s I_s = S_{out}$

IDEAL TRANSFORMER
Impedance Transformation

- Load impedance $Z_L = V_s/I_s$ and apparent impedance of primary circuit: $Z'_L=V_p/I_p$
- $V_p = aV_s$
- $I_s = a\ I_p$
- $Z'_L=V_p/I_p= aV_s / I_s /a= a^2 Z_L$
- With a transformer, it is possible to match magnitude of a load impedance with source impedance by picking proper turn ratio



(a)



(b)

IDEAL TRANSFORMER

- Analysis of CCT.s containing Ideal Transformer

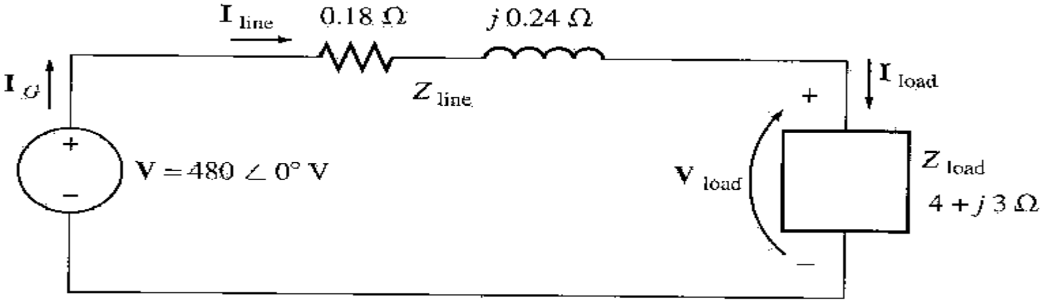
  In equivalent cct.

  a) Voltages & impedances replaced by scaled values,

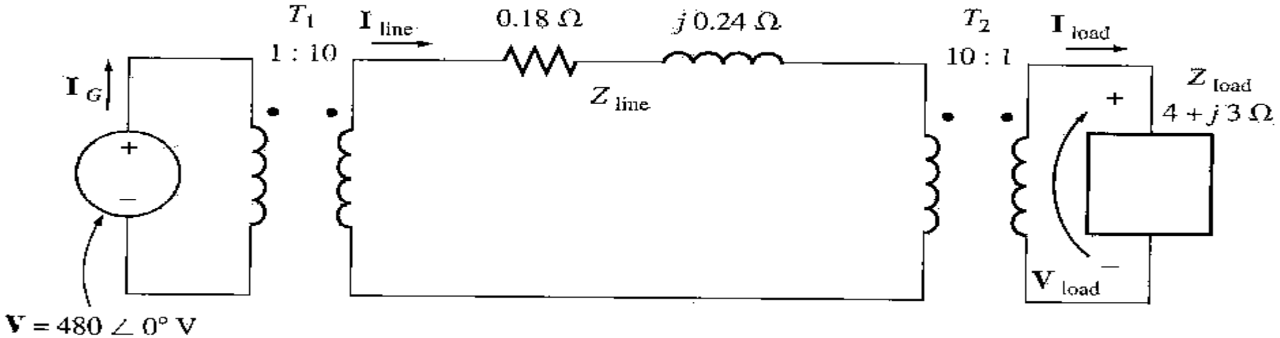
  b) polarities reversed if the dots on one side of transformer windings are reversed compared to dots on the other side of transformer windings
- Example: A single phase power system consists of a 480 V, 50 Hz generator supplying a load $Z_{load}=4+j3\ \Omega$ through a transmission line of impedance: $Z_{line}=0.18+j0.24\ \Omega$
- a) what is the voltage at load? What is the transmission losses?

IDEAL TRANSFORMER

- b) a 1:10 step-up transformer placed at the generator end of transmission line & a step down transformer placed at load end of line. What is load voltage ? What is transmission losses?



(a)



IDEAL TRANSFORMER

- a) $I_G = I_{line} = I_{load}$
- $I_{line} = V / (Z_{line} + Z_{load}) = 480 \angle 0^\circ$ / [(0.18b+ j 0.24)+(4+j3)] = $480 \angle 0^\circ$ / (4.18 + j 3.24) = $480 \angle 0^\circ$/ $5.29 \angle 37.8^\circ$ = $90.8 \angle -37.8^\circ$ A
- Load voltage : $V_{load} = I_{line} Z_{load} = (90.8 \angle -37.8^\circ)(4+j3) =$ $454 \angle -0.9\circ$ V
- And the losses are :
- $P_{line} = (I_{line})^2 R_{line} = (90.8)^2(0.18) = 1484$ W

IDEAL TRANSFORMER

b) need to convert the system to a common voltage

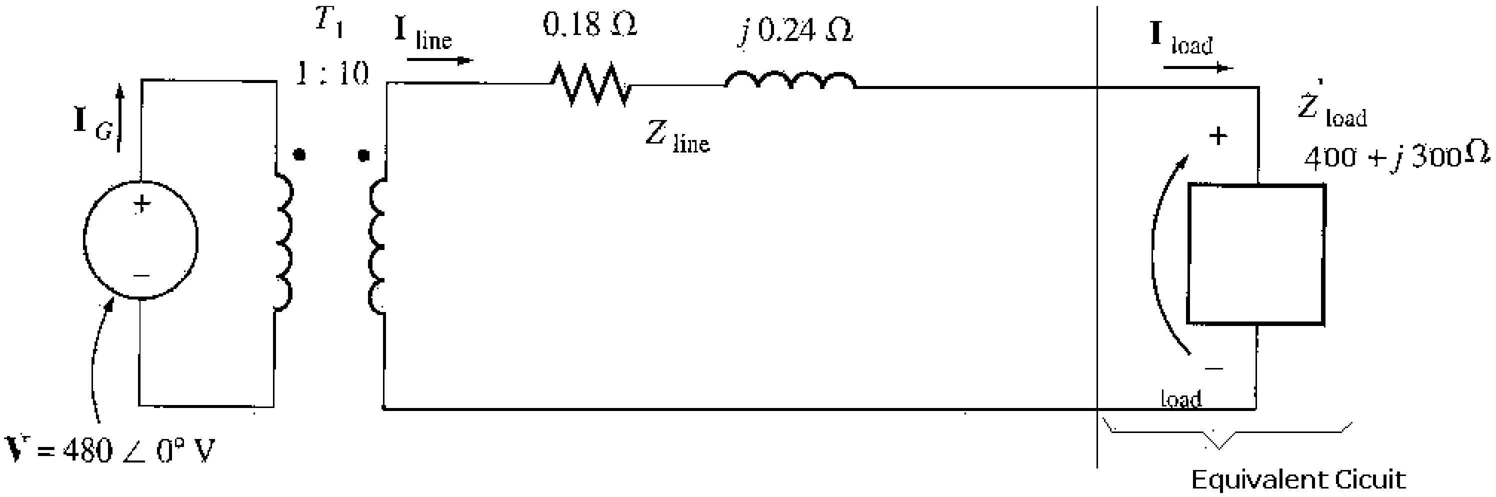
- Need two steps to be followed:

1- eliminate T2 referring to load to Transmission line's voltage

2-eliminate T1 by referring transmission line's elements & equivalent load to source side

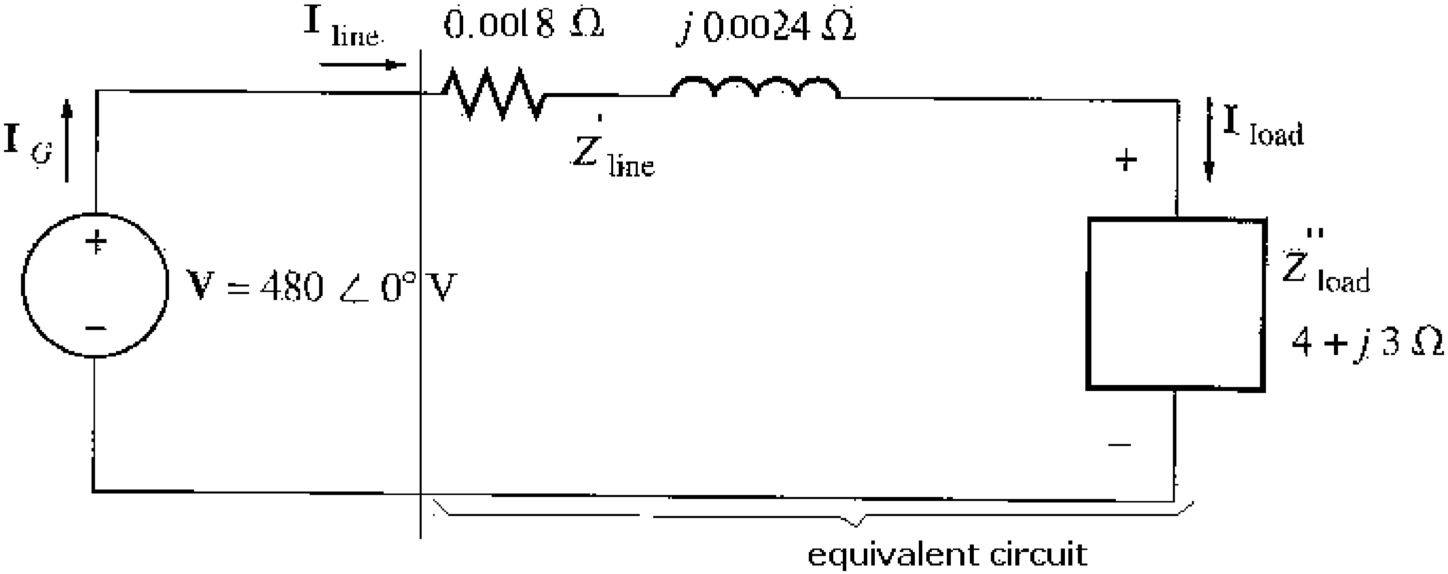
step 1: $Z'_{load} = a^2 Z_{load} = (10/1)^2 (4+j3) = 400+j300\Omega$

$Z_{eq} = Z_{line} + Z'_{load} = 400.18+j300.24\Omega = 500.3 \angle 36.88^\circ \ \Omega$



IDEAL TRANSFORMER

- Step 2: total impedance reflected cross T1 to source side
- $Z'_{eq}=a^2\ Z_{eq}=a^2\ (Z_{line}+Z'_{load})$
- $=(1/10)^2(0.18+j0.24+400+j300)=$
- $= 0.0018+j0.0024+4+j3=5.003\angle 36.88^\circ\ \Omega$



IDEAL TRANSFORMER

- The generator’ current is :
- $I_G=480/\ [5.003\ \angle 36.88^\circ\ ]\ =95.94\ \angle -36.88^\circ$
- Now it can be worked back to find I_{line} & I_{load} through T_1
- $N_{p1}I_G=N_{S1}I_{line} \rightarrow I_{line} = N_{p1}/N_{s1}\ I_G\ =(1/10)(9.594\angle -36.88^\circ)$
- Working back through T2:
- $N_{p2}I_G=N_{S2}I_{line}$
- $I_{load} = N_{p2}/N_{s2}\ I_{line}\ =(10/1)(95.94\ \angle -36.88^\circ)=95.94\angle -36.88^\circ$
- The load voltage:
- $V_{load} =I_{load}\ Z_{load}=(95.94\angle -36.88^\circ)(5\ \ \angle 36.87^\circ\ )=479.7\angle -0.01^\circ$ Volts

IDEAL TRANSFORMER

- The line losses are given:

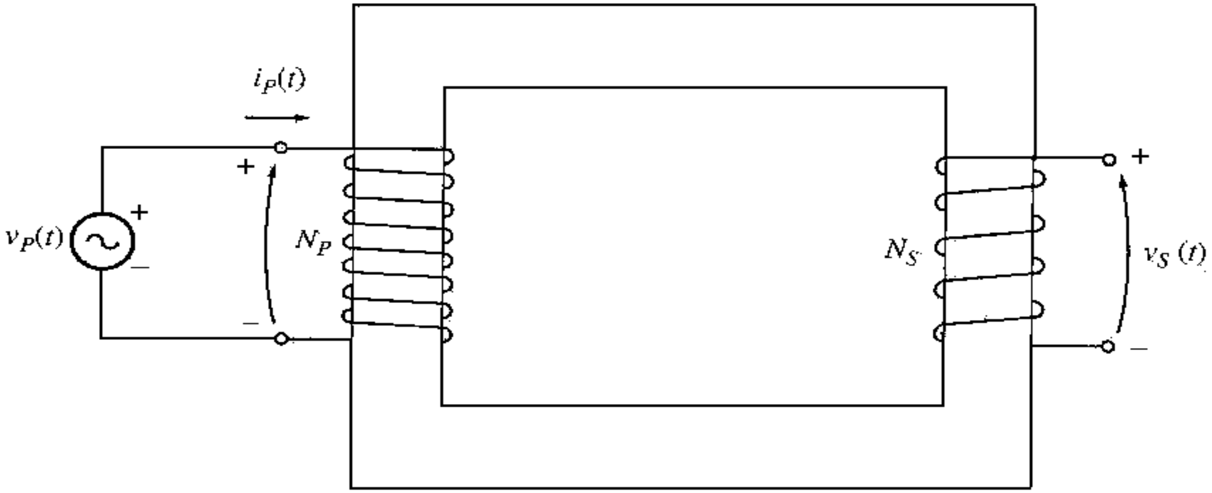
  $P_{loss} = I_{line}^2 R_{line} = 9.594^2\ 0.18 = 16.7\ W$

- Note: rising transmission voltage of power system reduced transmission losses by a factor of 90

  Also voltage at load dropped much less

REAL SINGLE PHASE TRANSFORMER

- Operation of a real Transformer

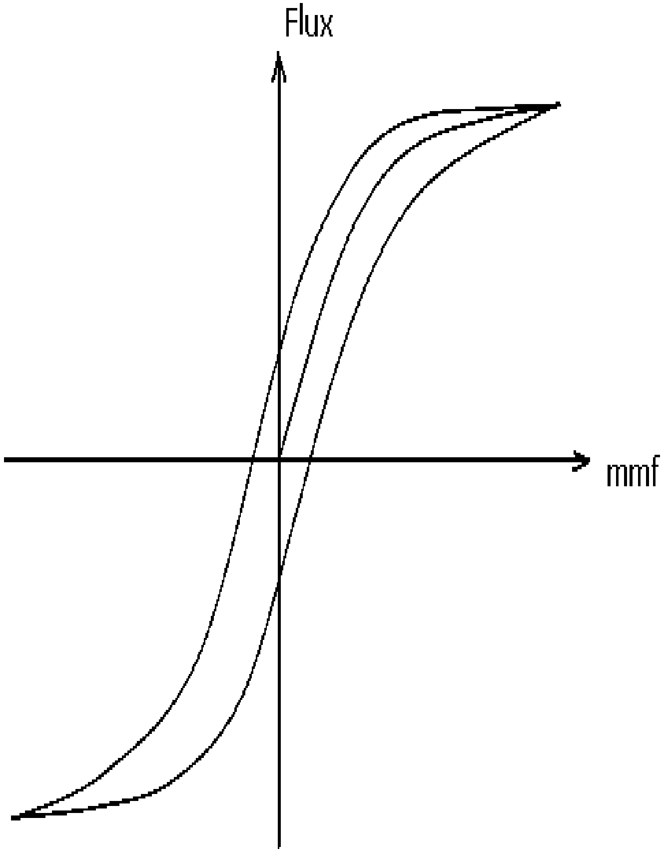


- primary connected to ac source, secondary open circuited

REAL SINGLE PHASE TRANSFORMER

- The transformer's hysteresis curve is shown
- Based on Faraday's law:
- $e_{ind} = d\lambda / dt$

  Where $\lambda = \sum \varphi_i$ (on N turn)
- $\Phi_{av.} = \lambda / N$
- And $e_{ind} = N \, d\Phi_{av}/dt$



REAL SINGLE PHASE TRANSFORMER

- Voltage Ratio of realizing the leakage flux in a real Transformer
- $\varphi_p = \varphi_m + \varphi_{Lp}$
- $\varphi_S = \varphi_m + \varphi_{LS}$
- Since $\varphi_m >> \varphi_{LS}$, $\varphi_m >> \varphi_{Lp}$
- φ_m can be employed to determine the induced voltage in the windings and approximately : $V_p(t)/V_s(t) = N_p/N_S = a$
- As smaller the leakage fluxes, the better ideal transformer turn ratio approximate the real transformer turn ratio

REAL SINGLE PHASE TRANSFORMER

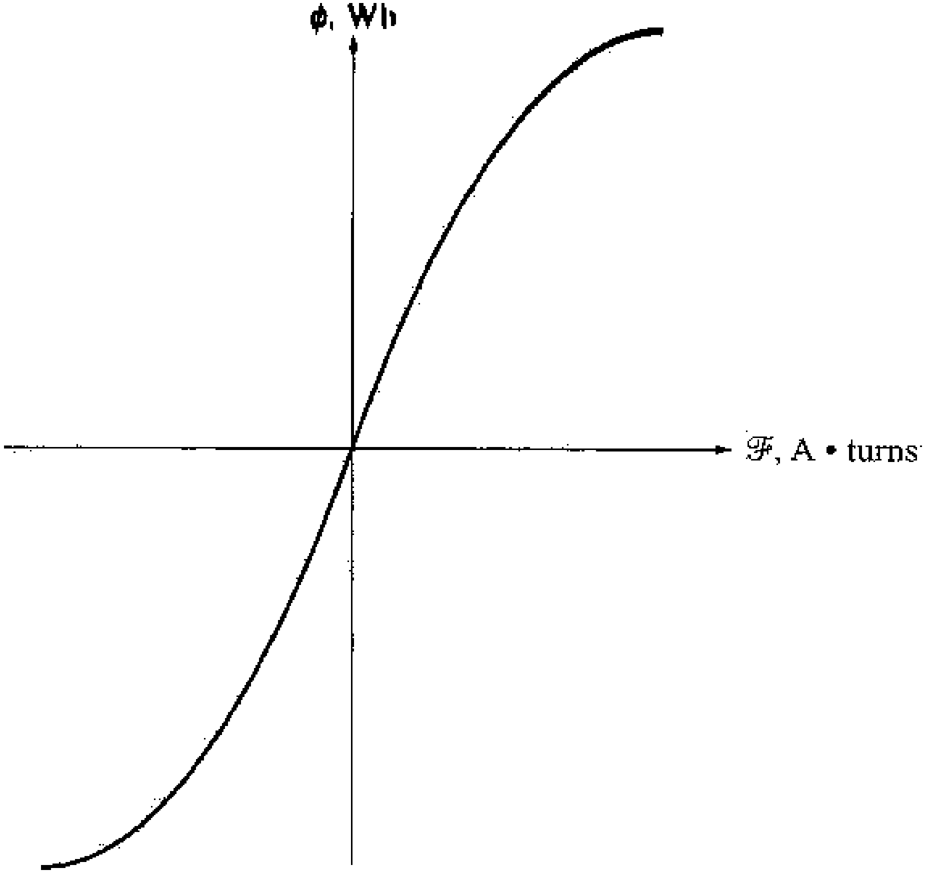
- Magnetization Current in a Real Transformer
- ac source even when the secondary is open circuited supply a current to produce flux in real ferromagnetic core (as seen in chapter One)
- There are two components in the current:

(a) magnetization current i_M, required to produce flux

(b) core-loss current i_{h+e} supplies hysteresis & eddy current losses of core

REAL SINGLE PHASE TRANSFORMER

- Magnetization curve of a typical transformer core can be considered as a saturation curve



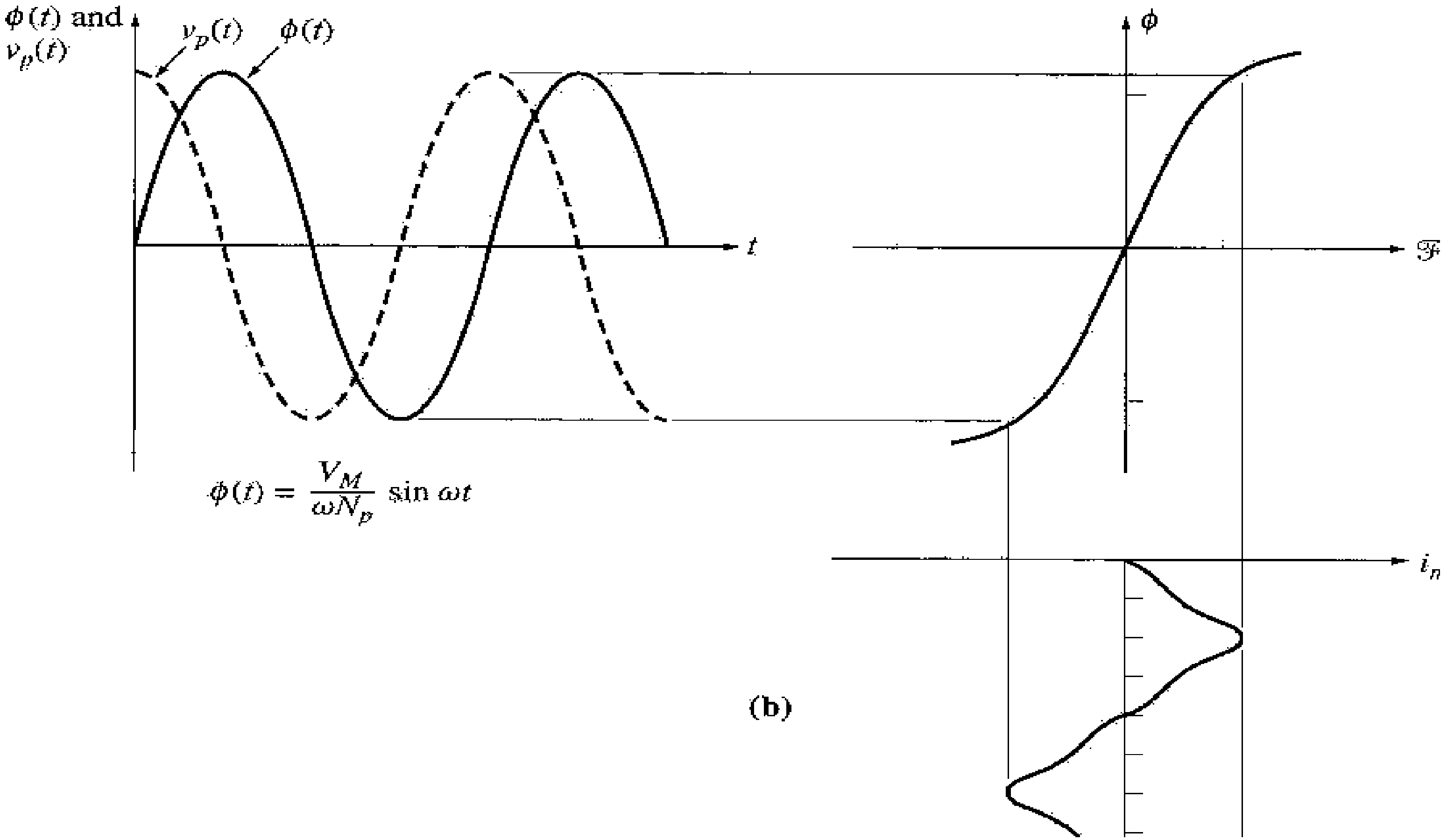
REAL SINGLE PHASE TRANSFORMER

- Knowing the flux in the core magnitude of magnetization current can be found from curve
- Ignoring the leakage flux in the core:
- $\varphi_{av} = 1/N_p \int v_p(t)\, dt$
- If $v_p(t) = V_m \cos \omega t \rightarrow \varphi_{av} = 1/N_p \int V_m \cos \omega t\, dt =$

  $= V_m/(\omega N_p) \sin \omega t$
- If current required to produce a given flux determined at different times from the magnetization curve (above), the magnetization current can be found

REAL SINGLE PHASE TRANSFORMER

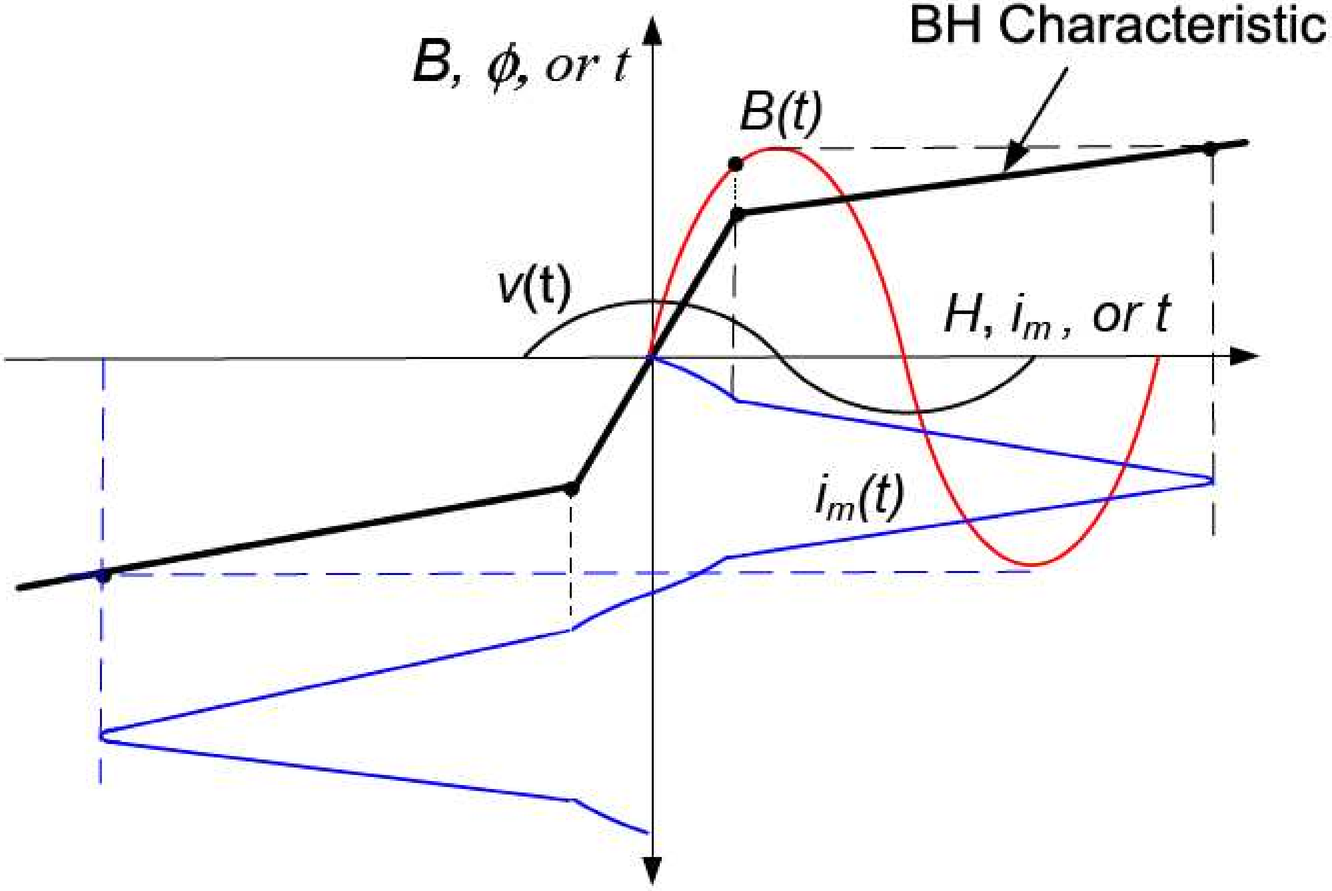
- Finding magnetization current



(b)

REAL SINGLE PHASE TRANSFORMER

- Magnetizing current (another example)



REAL SINGLE PHASE TRANSFORMER

- Note (Magnetization Current):

1 – magnetization current is nonsinusoidal

2 - once peak flux reaches the saturation point, a small increase in peak flux results in a very large increase in magnetization current

3 - fundamental component of magnetization current lags the voltage applied by 90°

4 - higher harmonics (odd one) are present in the magnetization current and may have relatively large amount compared to the fundamental &

as core driven further into saturation, larger the harmonic components become

REAL SINGLE PHASE TRANSFORMER

- **Other components of no-load current of transformer**
- is required to supply the hysteresis and eddy current losses in the core
- assuming sinusoidal flux in the core , eddy current loss in core proportional to dφ/dt and is largest when flux pass 0
- Eddy and hysteresis loss shown in Fig 1 and the total current required to produce flux in the core shown in Fig 2

REAL SINGLE PHASE TRANSFORMER

- Exciting Current (components: e+h & m)

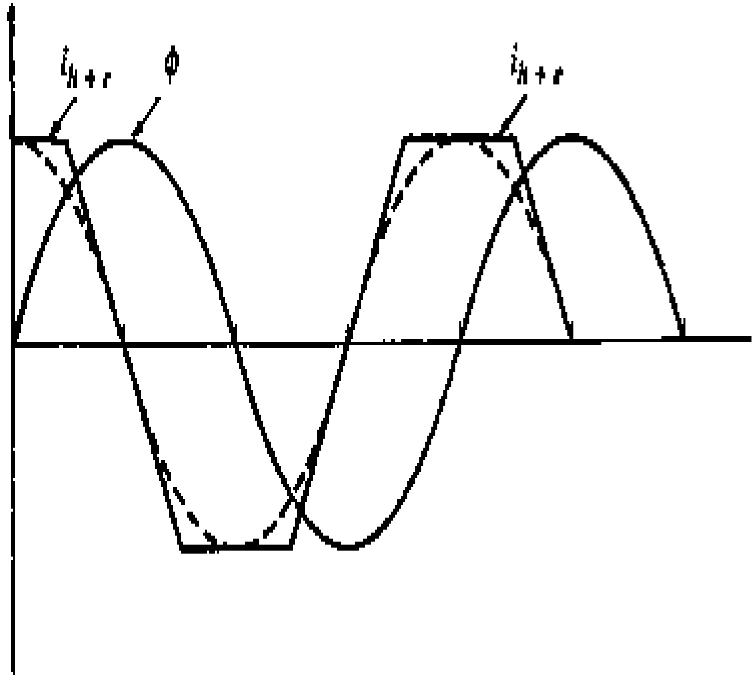


Fig 1

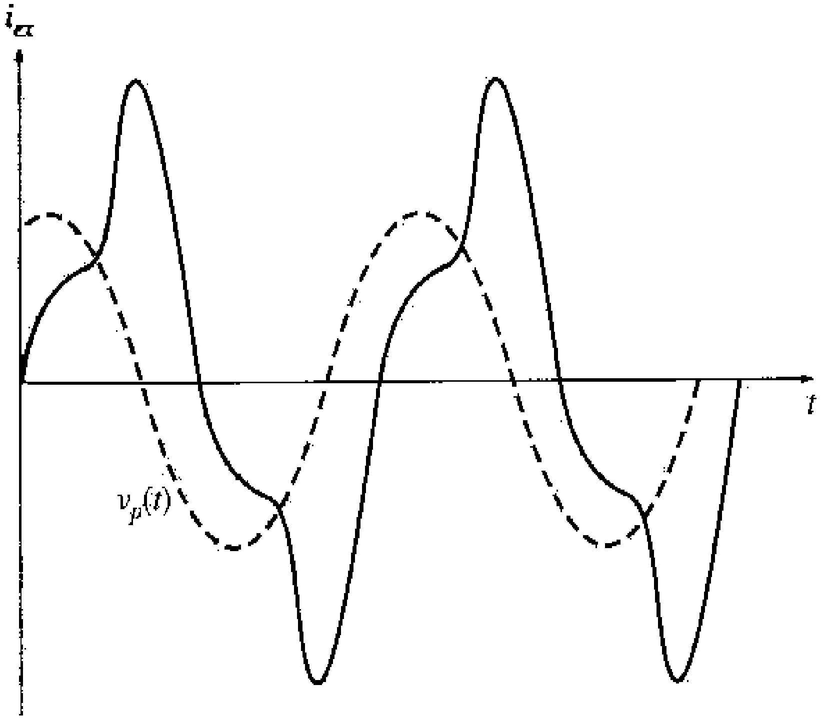
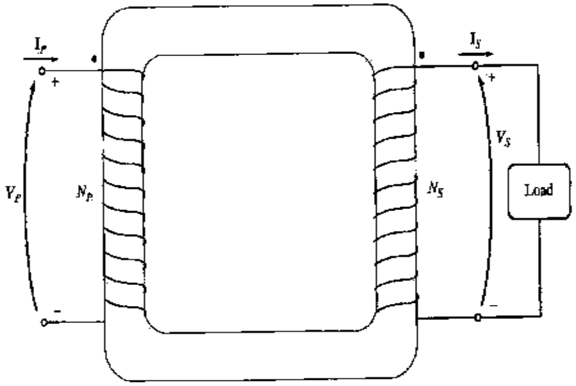


Fig 2

REAL SINGLE PHASE TRANSFORMER

- **Current Ratio & Dot Convention**
- A current flowing into dotted end of winding produces a pos. mmf, while current flowing to undotted end of winding proguces neg. mmf



- Two current flowing into dotted ends of their respective windings produce mmfs that add
- If one current flows into a dotted end of a winding and one flows out of dotted end, then mmfs will subtract each other

REAL SINGLE PHASE TRANSFORMER

- In this situation as shown in last figure
- $\zeta_P = N_P I_P$, $\zeta_S = -N_S I_S$
- $\zeta_{net} = N_P I_P - N_S I_S$
- The net mmf produce net flux in core
- $\zeta_{net} = N_P I_P - N_S I_S = \varphi R$
- Where R; reluctance of transformer core
- Since R of well designed is very small until core saturate $\zeta_{net} = N_P I_P - N_S I_S \approx 0$
- Therefore until core unsaturated $N_P I_P \approx N_S I_S$
- $I_P / I_S \approx N_P / N_S = 1/a$

REAL SINGLE PHASE TRANSFORMER

- To convert a real transformer to an ideal transformer following assumptions are required:

1- core must have no hysteresis or eddy current

2- magnetization curve must have shape shown (infinite permeabilty before satuartion)$\zeta_{net}=0$ and

$N_P I_P = N_S I_S$

3- leakage flux in core must be zero, implying all flux in core couples both windings

4- resistance of transformer windings must be zero

Transformers

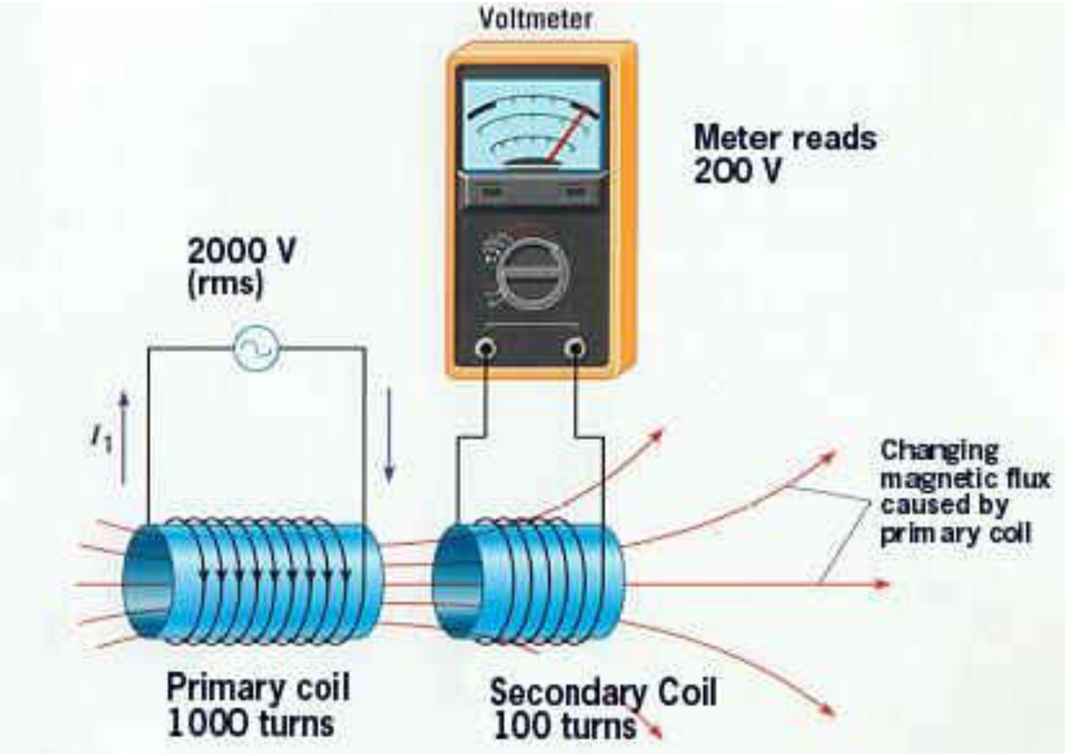
Transformer

An A.C. device used to change high voltage low current A.C. into low voltage high current A.C. and vice-versa without changing the frequency

In brief,

1. Transfers electric power from one circuit to another
2. It does so without a change of frequency
3. It accomplishes this by electromagnetic induction
4. Where the two electric circuits are in mutual

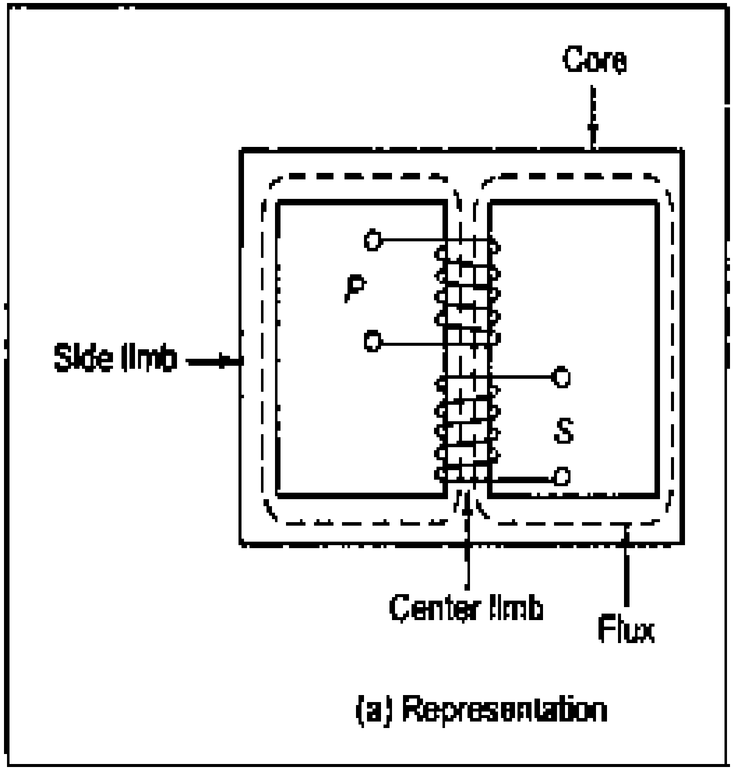
Principle of operation



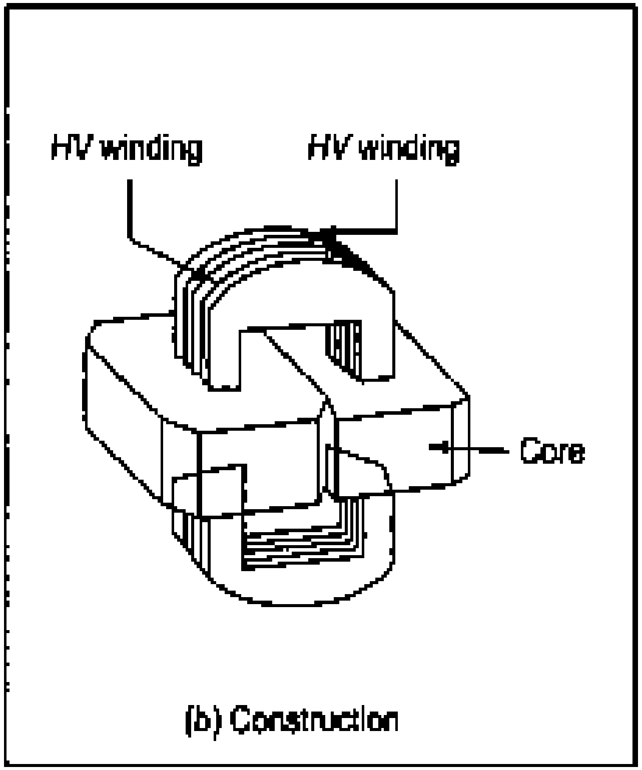
It is based on principle of MUTUAL INDUCTION.

According to which an e.m.f. is induced in a coil when current in the neighbouring coil changes.

Constructional detail : Shell type



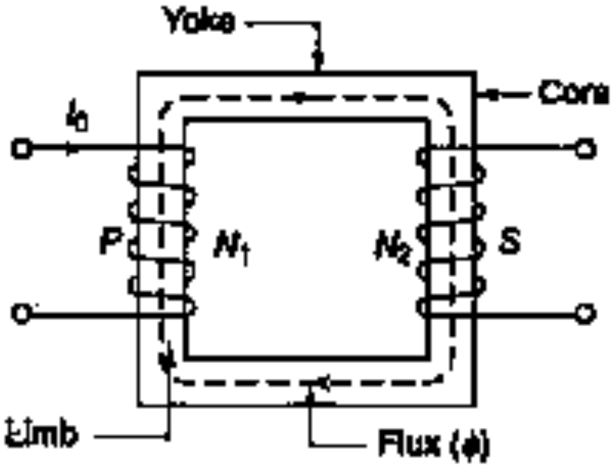
(a) Representation



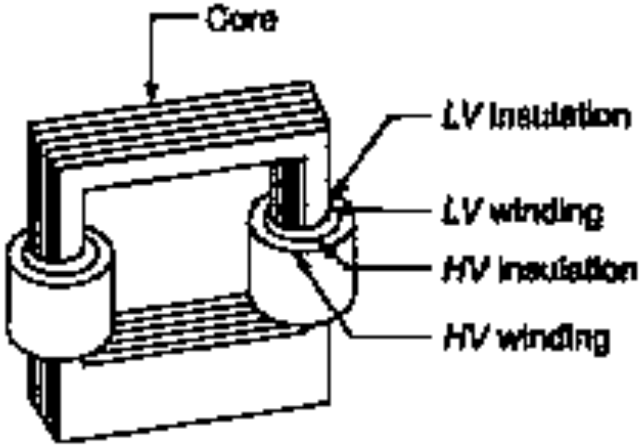
(b) Construction

- Windings are wrapped around the center leg of a laminated core.

Core type



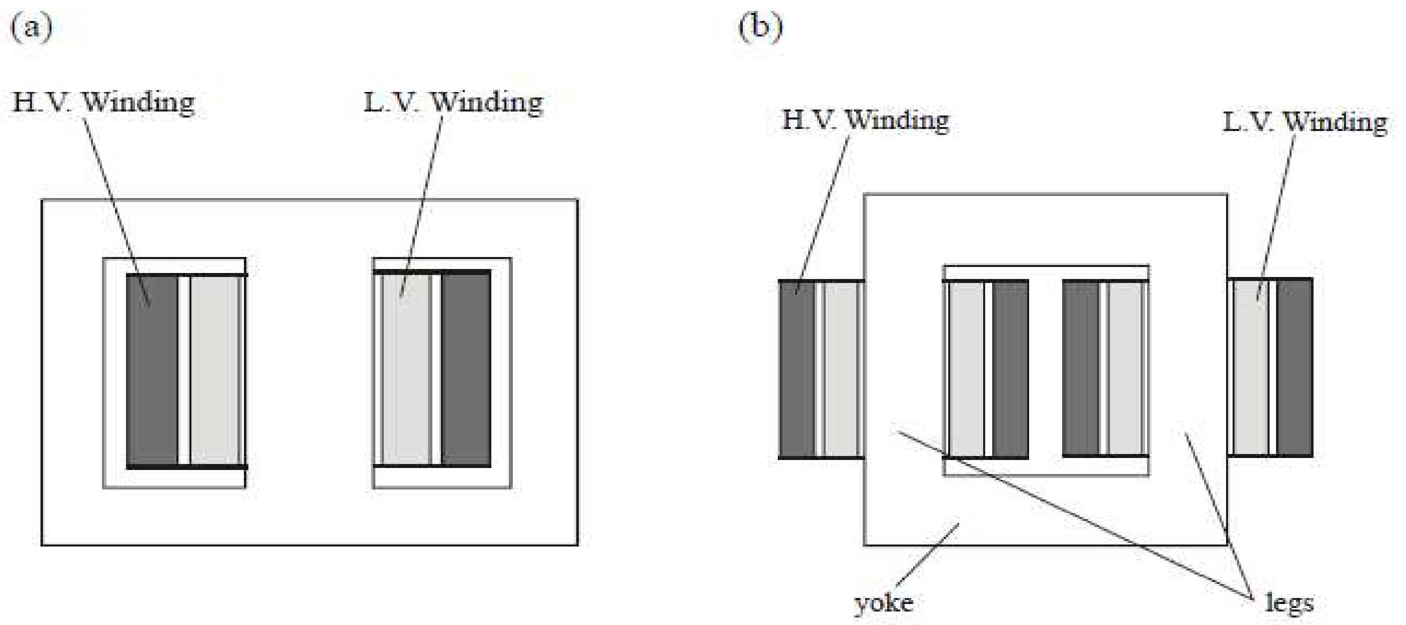
(a) Representation



(b) Construction

- Windings are wrapped around two sides of a laminated square core.

Sectional view of transformers

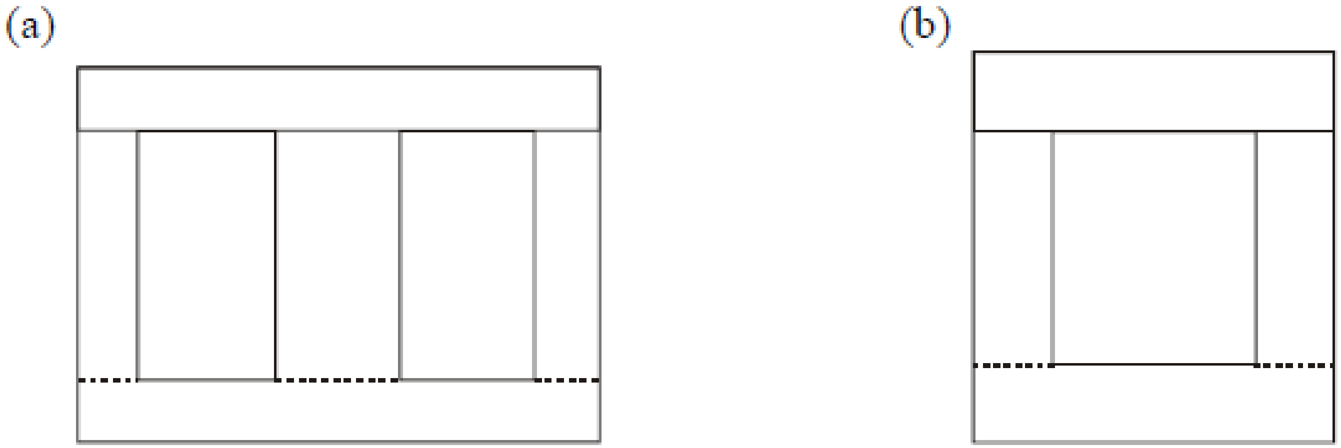


(a) Shell-type transformer, (b) core-type transformer

Note:

High voltage conductors are smaller cross section conductors than the low voltage coils

Construction of transformer from stampings



(a) Shell-type transformer, (b) core-type transformer

Core type

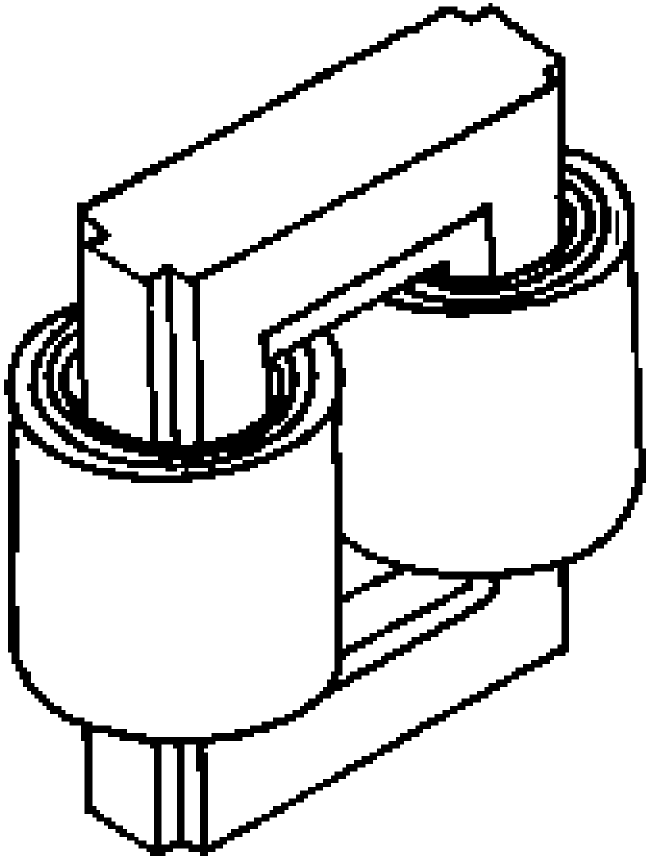


Fig1: Coil and laminations of core type transformer

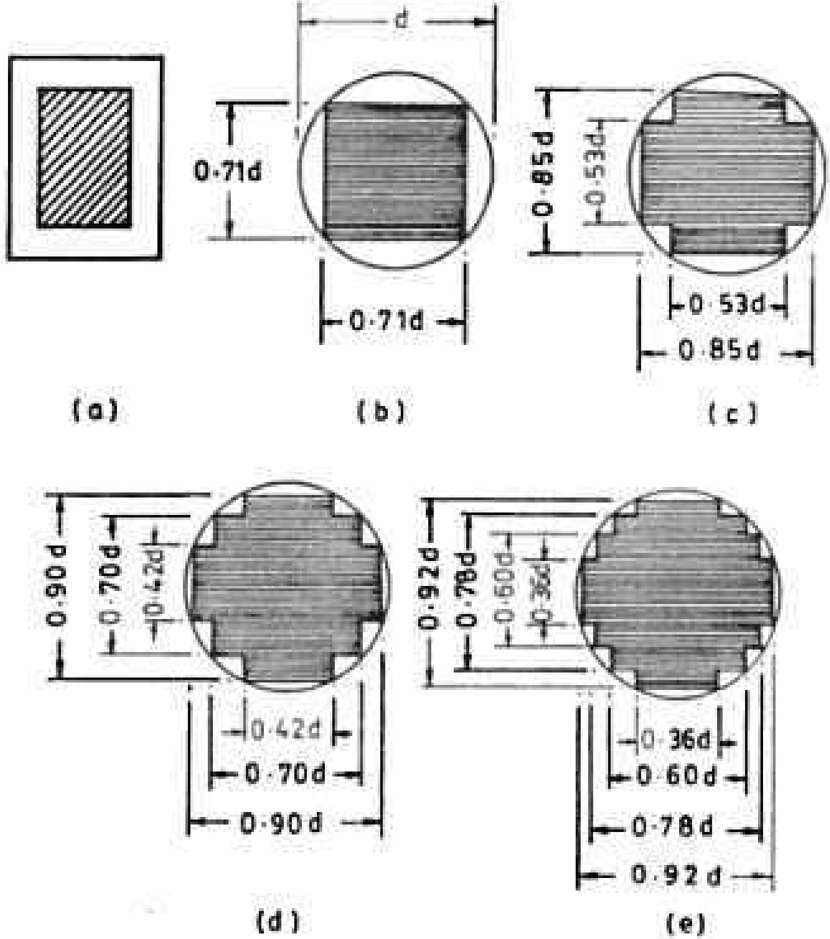


Fig2: Various types of cores

Shell type

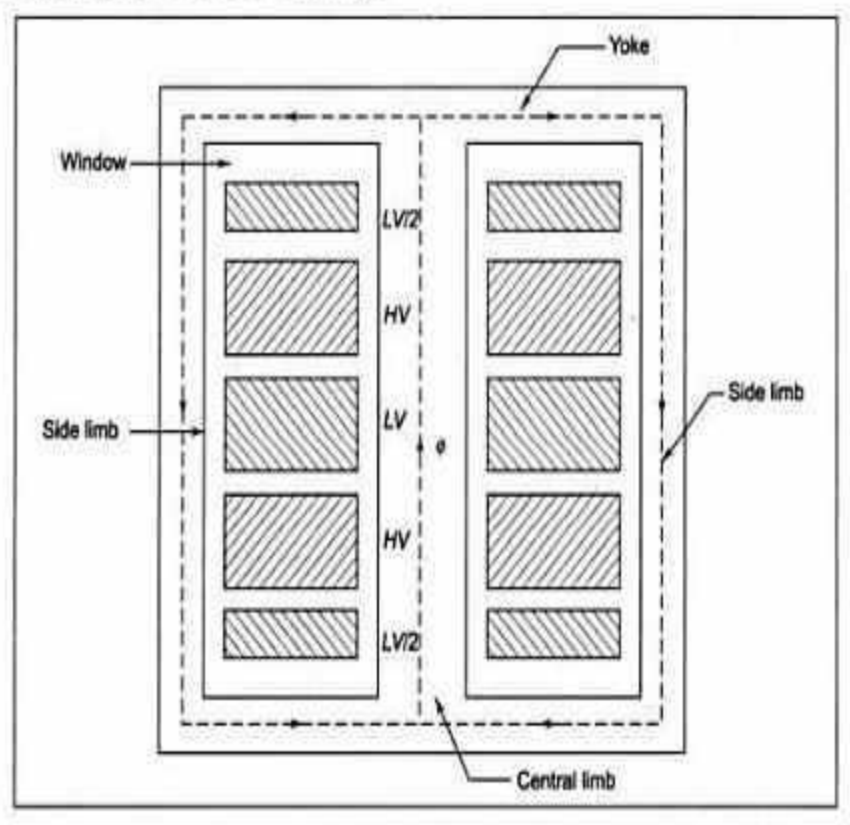
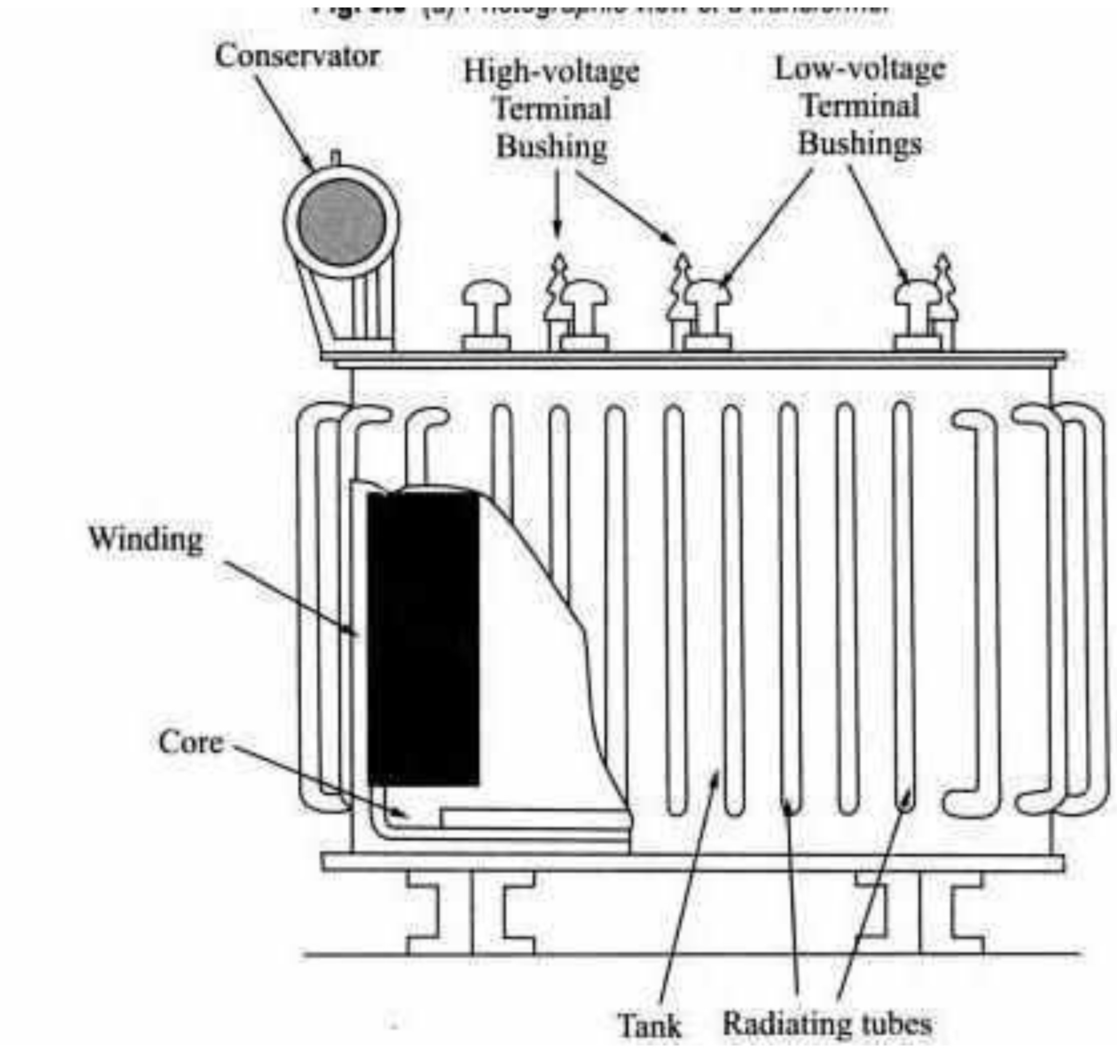


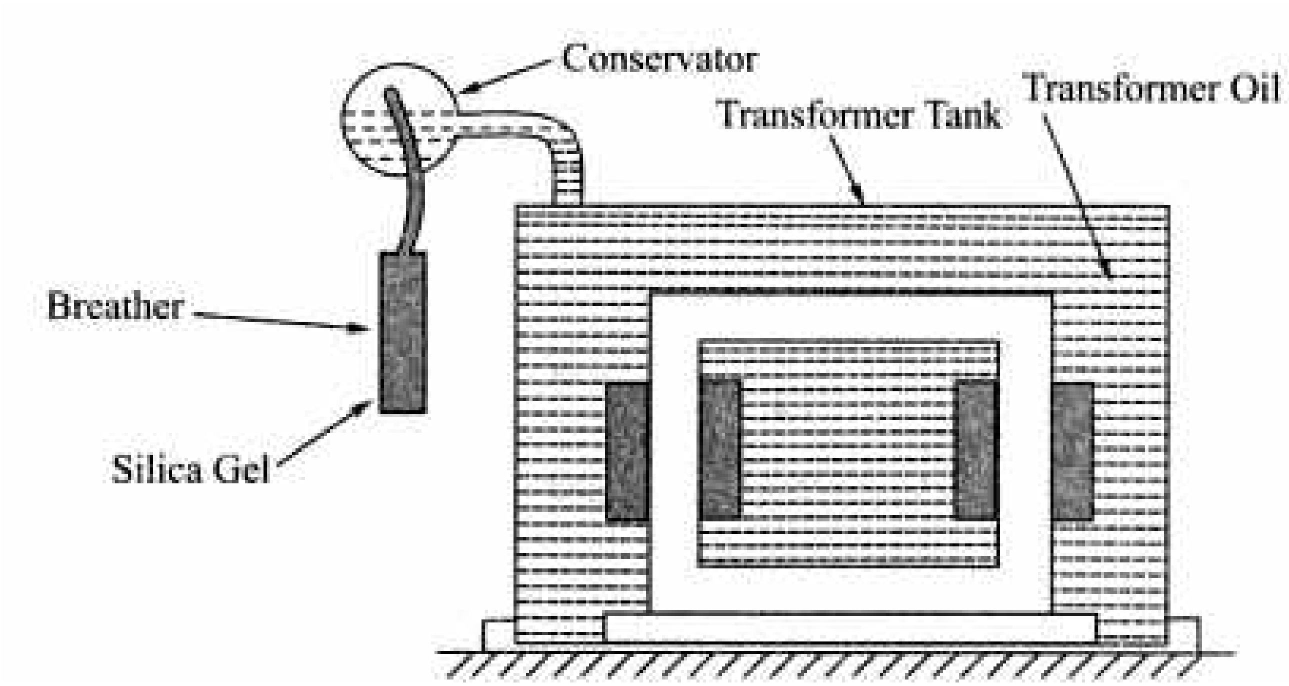
Fig: Sandwich windings

- The HV and LV windings are split into no. of sections
- Where HV winding lies between two LV windings
- In sandwich coils leakage can be controlled

Cut view of transformer

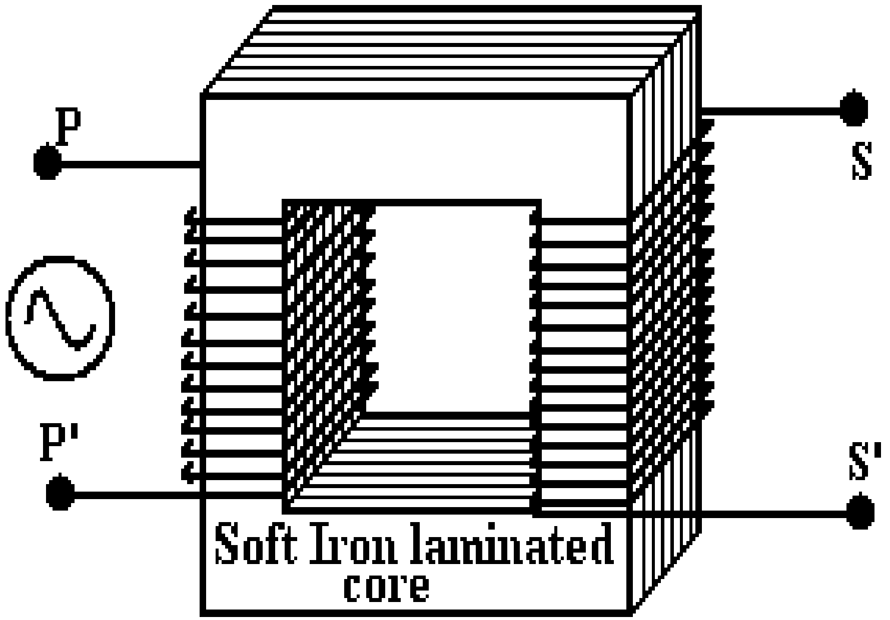


Transformer with conservator and breather



Working of a transformer

1. When current in the primary coil changes being alternating in nature, a changing magnetic field is produced
2. This changing magnetic field gets associated with the secondary through the soft iron core
3. Hence magnetic flux linked with the secondary coil changes.
4. Which induces e.m.f. in the secondary.



Single Phase Transformer

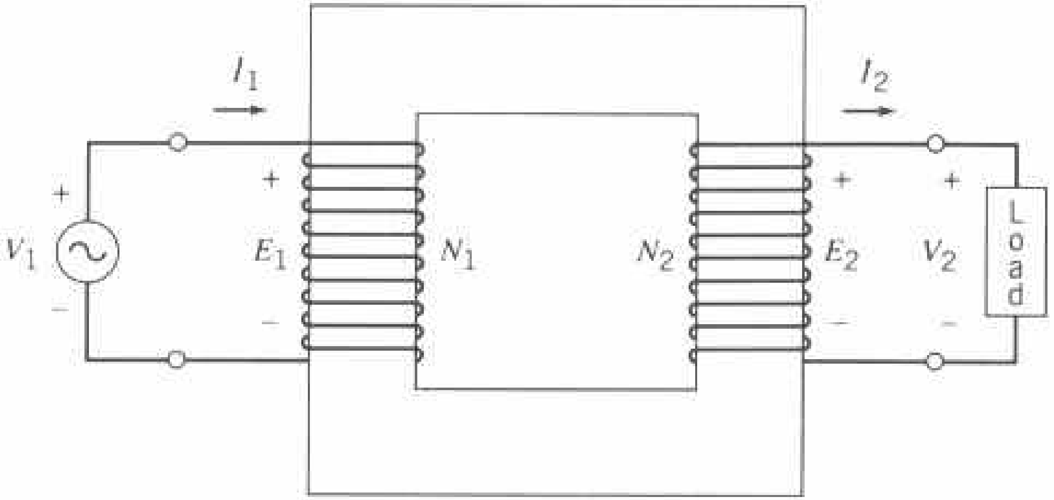


FIGURE 4.8 A transformer circuit.

- A single phase transformer
  - Two or more winding, coupled by a common magnetic core

Ideal Transformers

- **Zero leakage flux:**

  -Fluxes produced by the primary and secondary currents are confined within the core

- **The windings have no resistance:**

  - Induced voltages equal applied voltages

- **The core has infinite permeability**

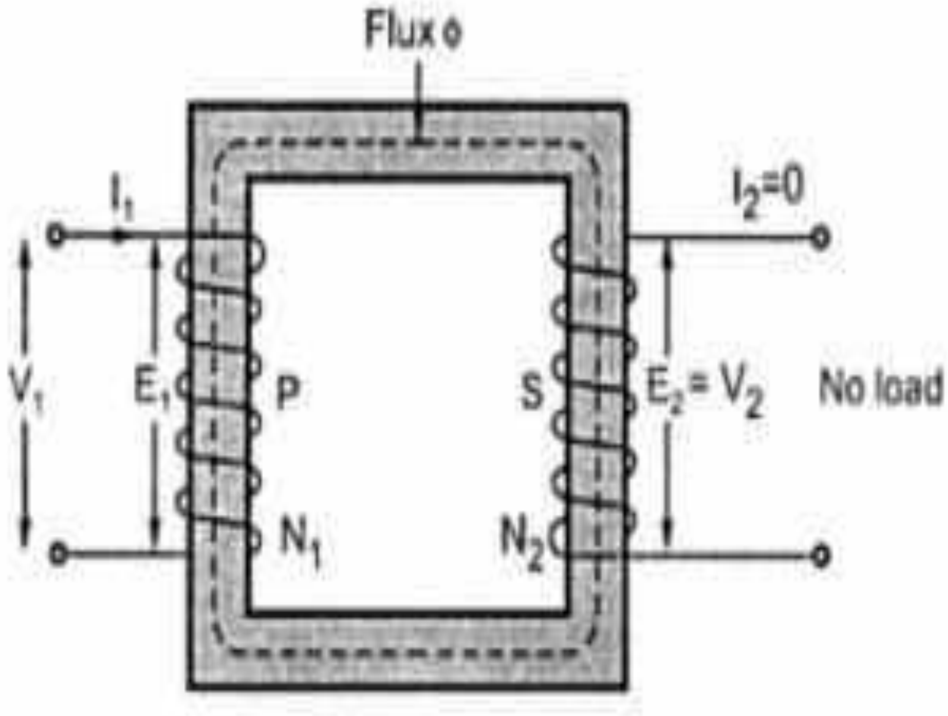
  - Reluctance of the core is zero

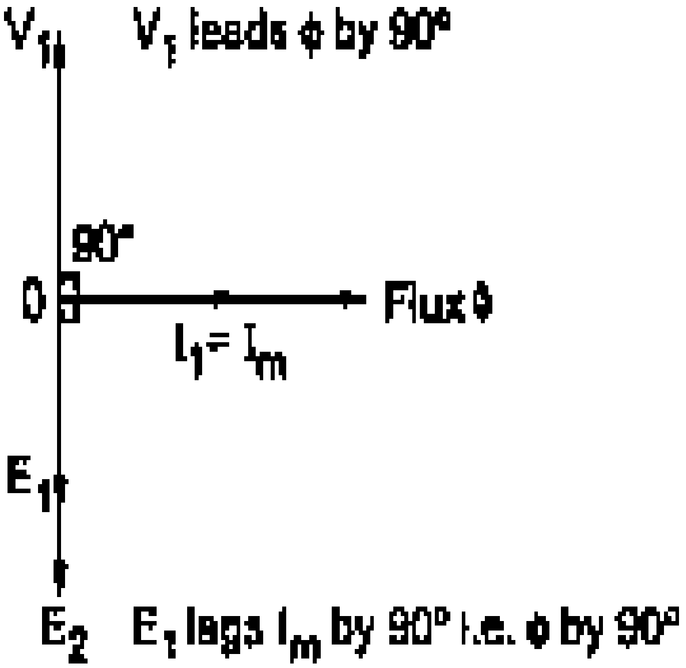
  - Negligible current is required to establish magnetic flux

- **Loss-less magnetic core**

  - No hysteresis or eddy currents

Ideal transformer





V_1 – supply voltage ;

V_{2}- output voltgae;

I_m- magnetising current;

E_1-self induced emf ;

I_1- noload input current ;

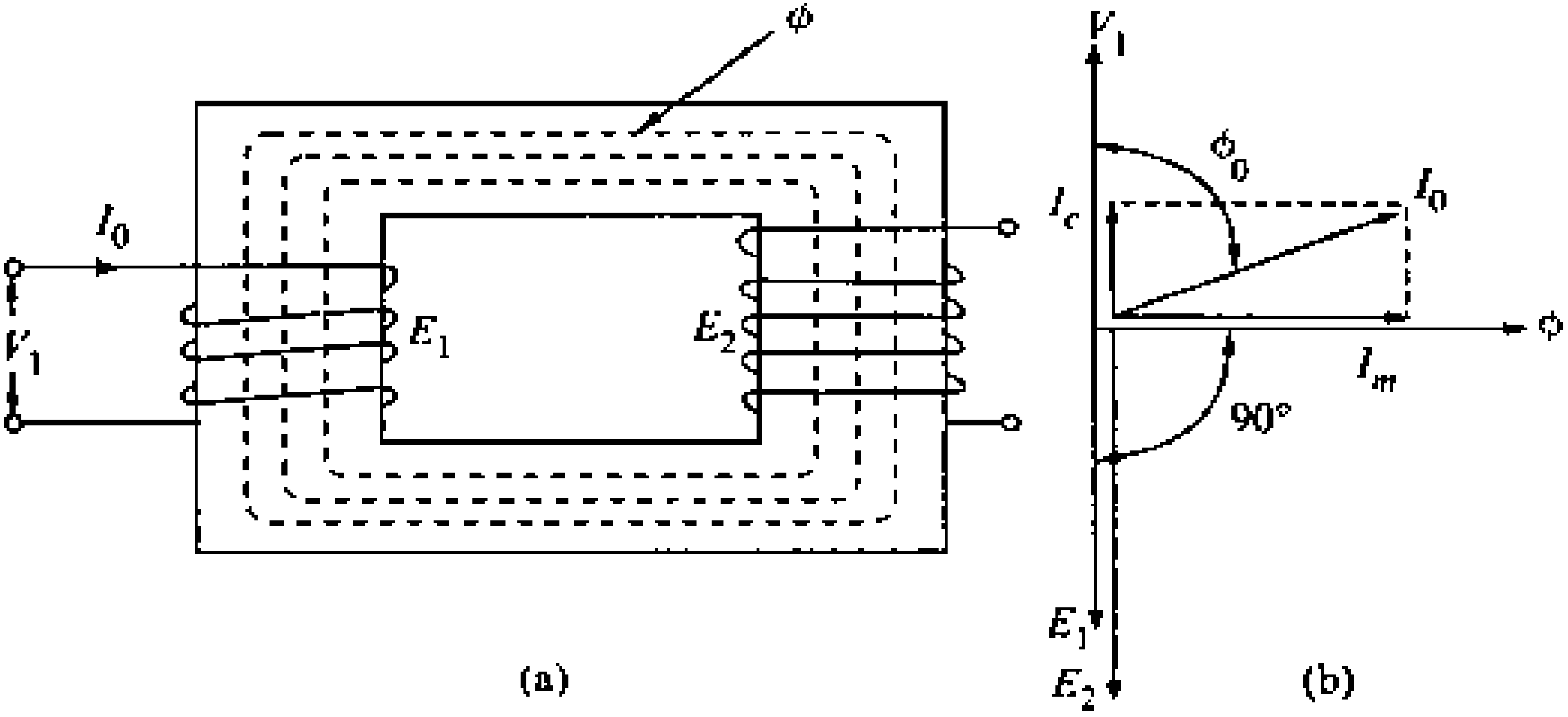
I_2- output current

E_2- mutually induced emf

EMF equation of a transformer

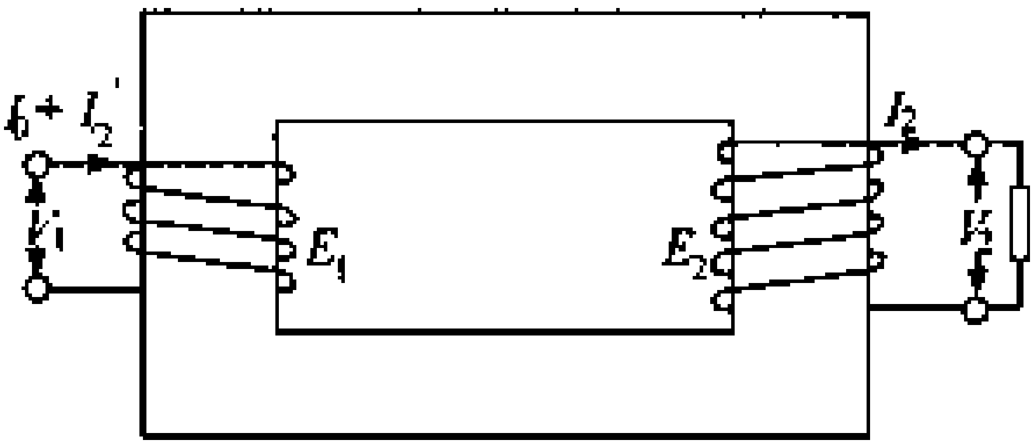
- Worked out on board /
- Refer pdf file: emf-equation-of-tranformer

Phasor diagram: Transformer on No-load



(a) Transformer on no-load (b) Phasor diagram of a transformer on no-load

Transformer on load assuming no voltage drop in the winding



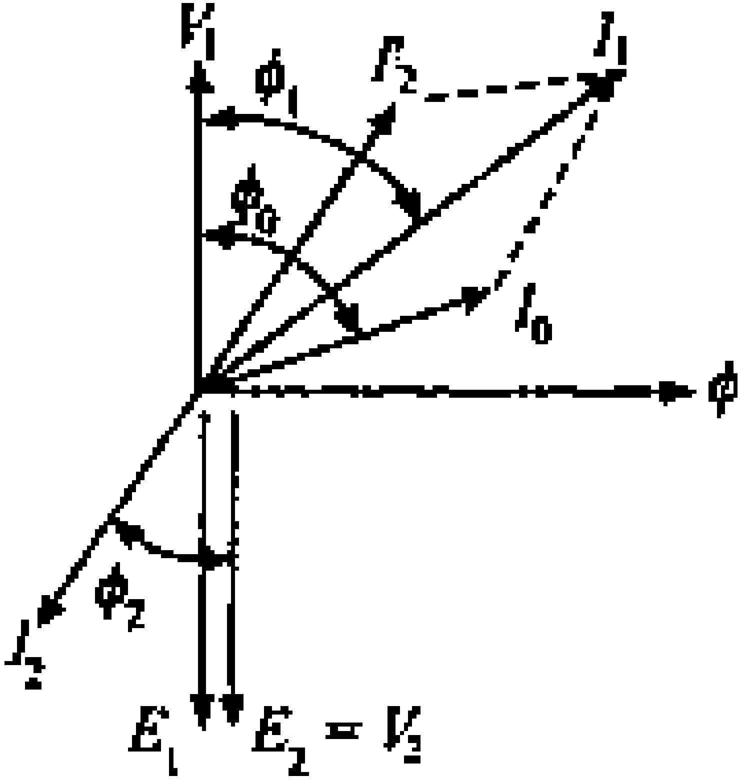


Fig shows the Phasor diagram of a transformer on load by assuming

1. No voltage drop in the winding
2. Equal no. of primary and secondary turns

Transformer on load

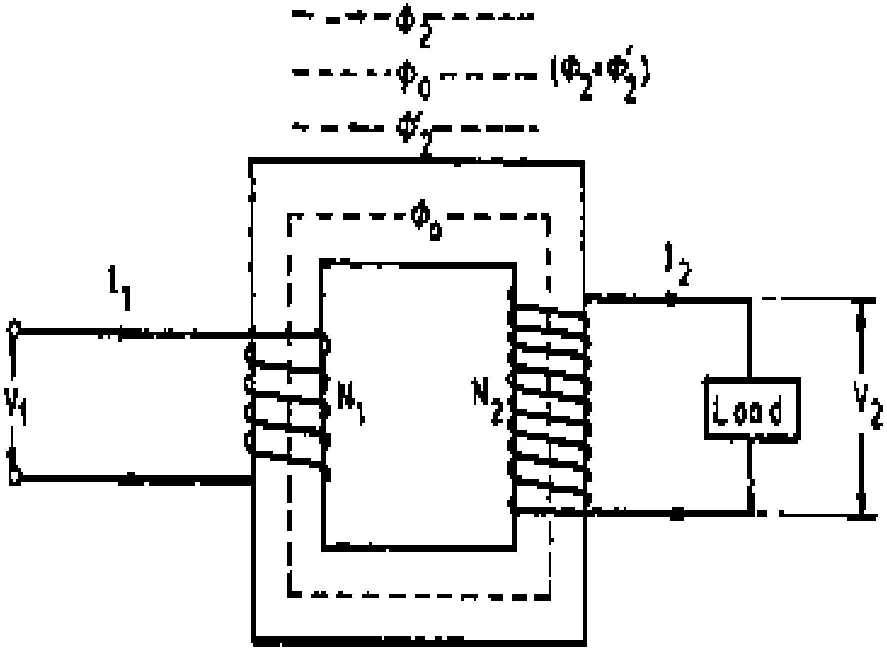


Fig. a: Ideal transformer on load

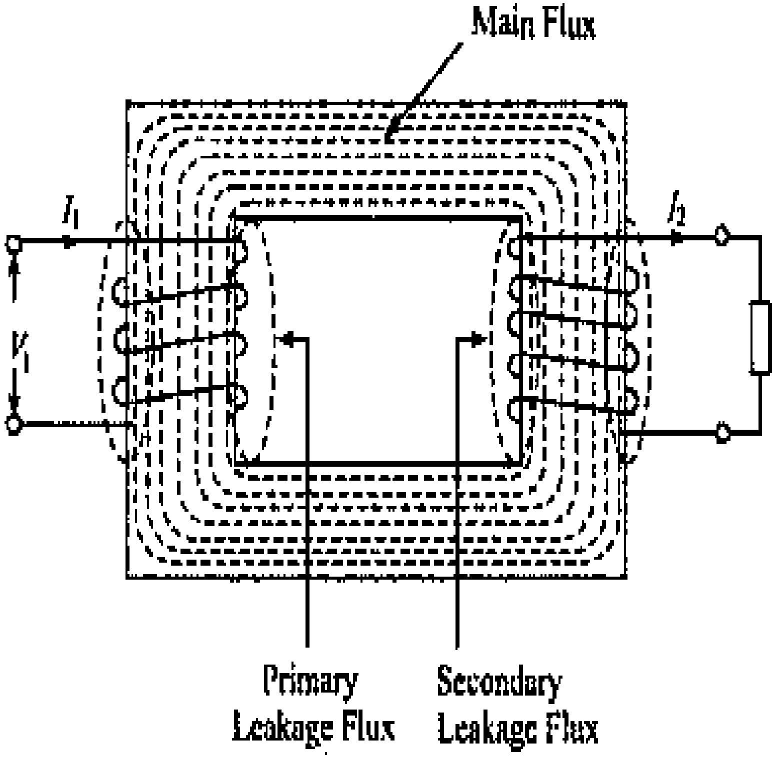
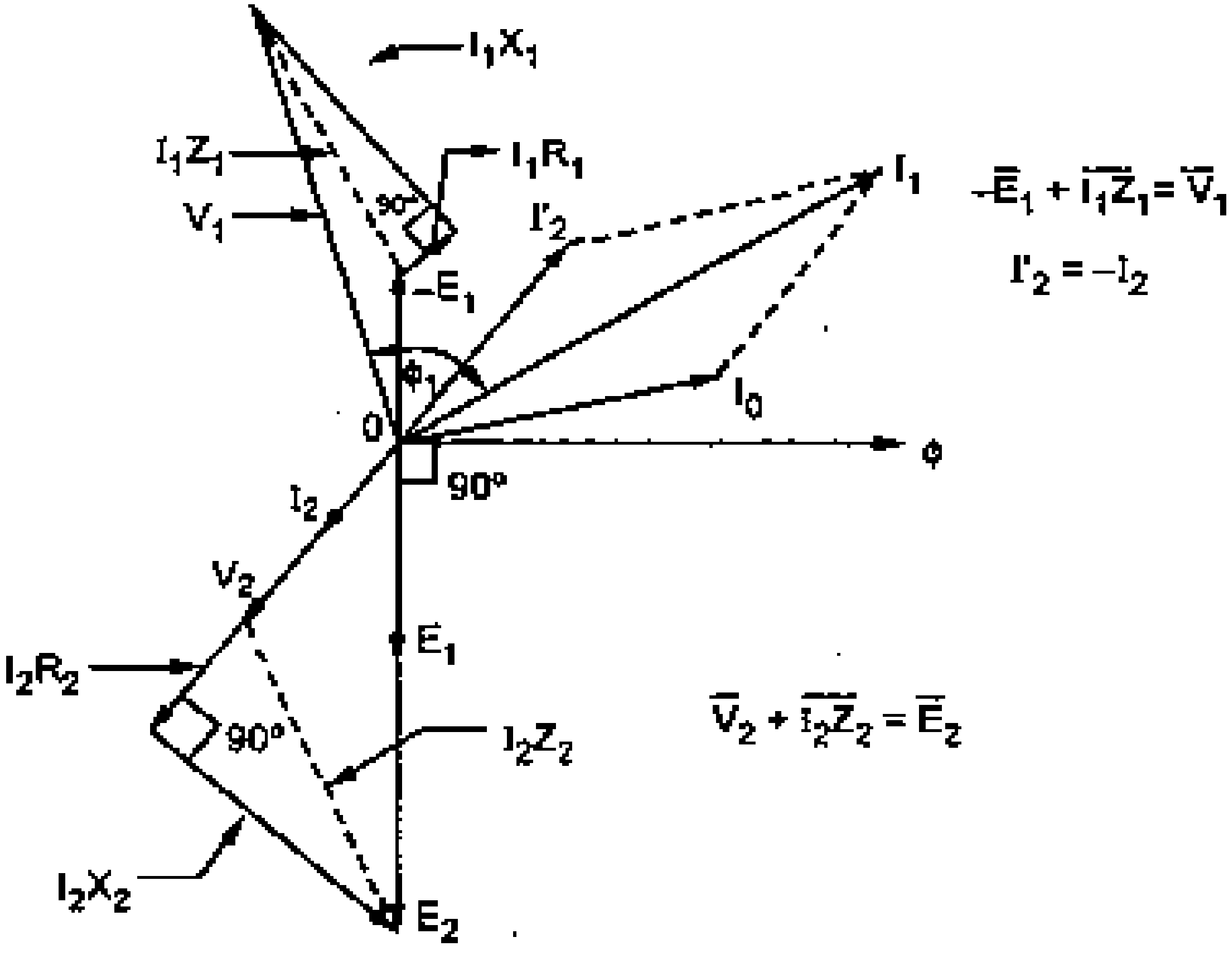
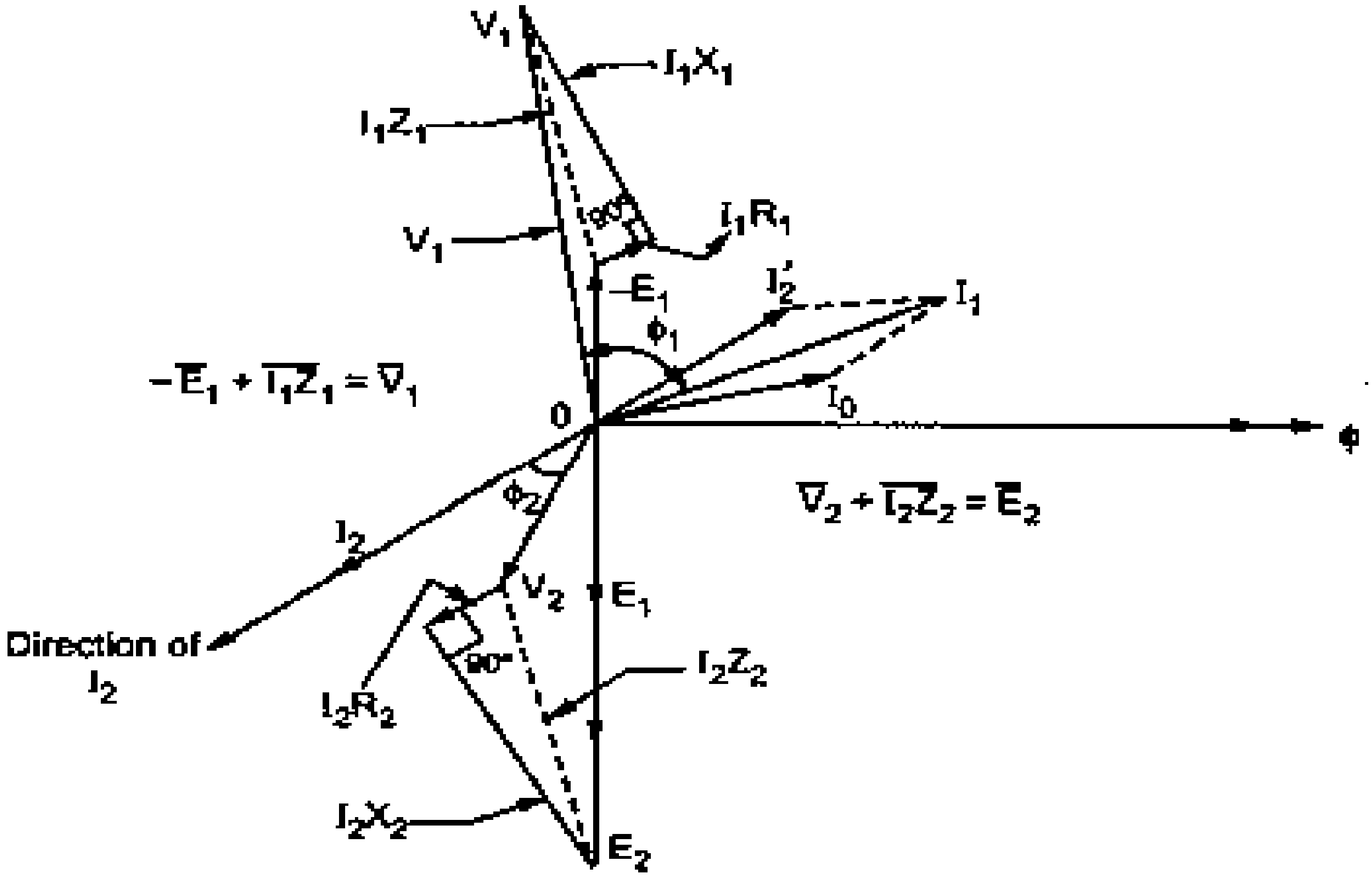


Fig. b: Main flux and leakage flux in a transformer

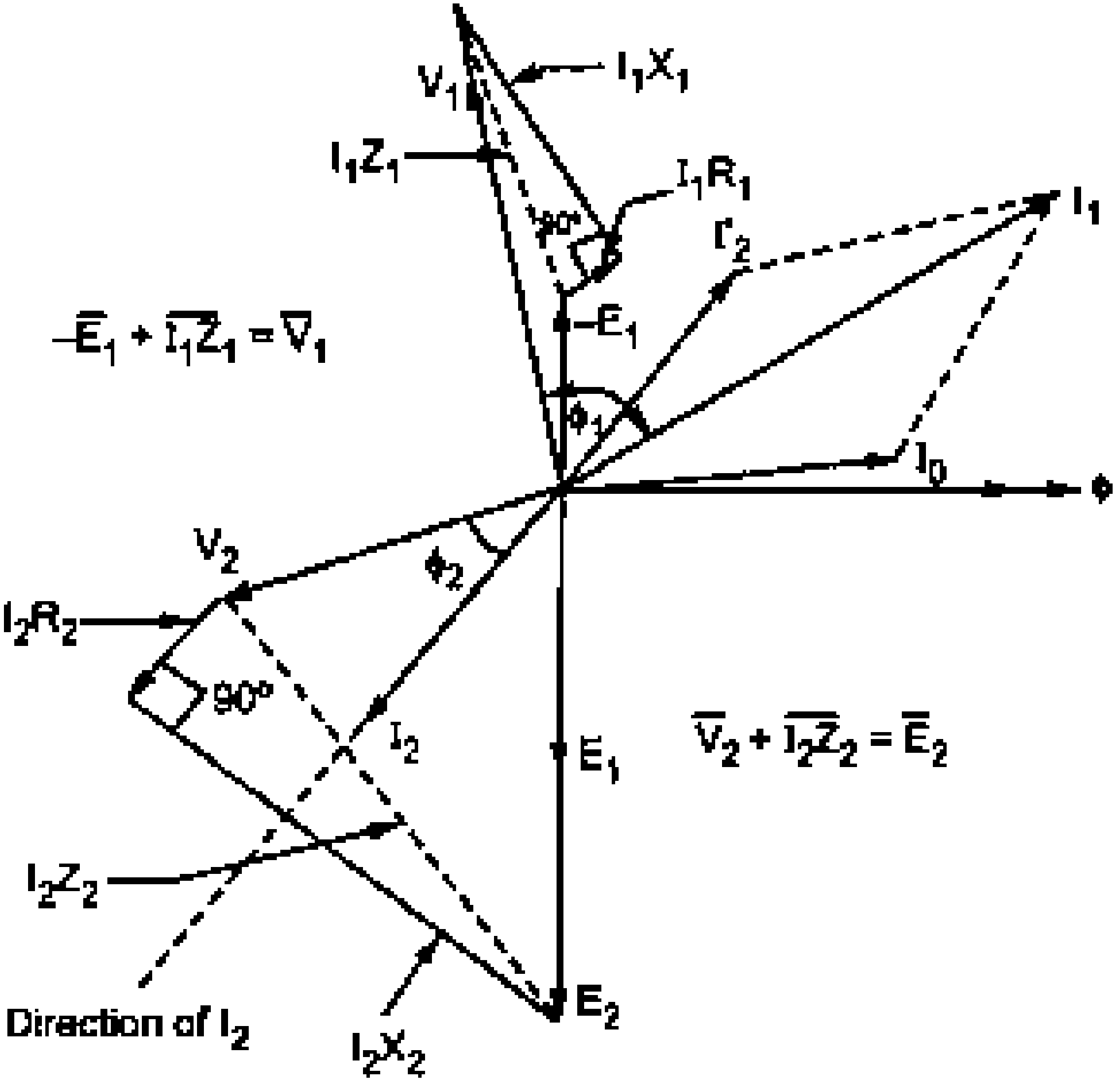
Phasor diagram of transformer with UPF load



Phasor diagram of transformer with lagging p.f load

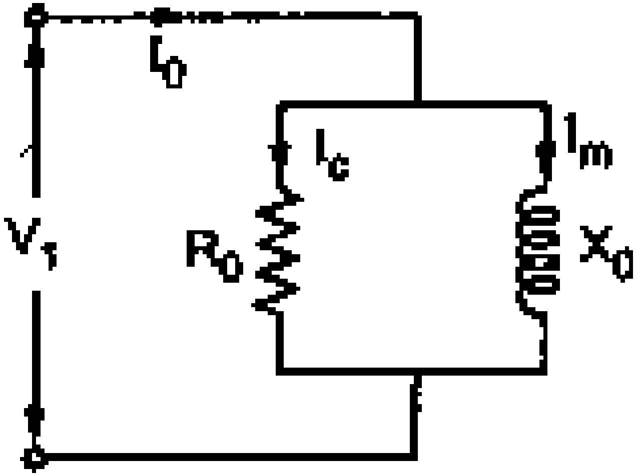


Phasor diagram of transformer with leading p.f load



Equivalent circuit of a transformer

No load equivalent circuit:



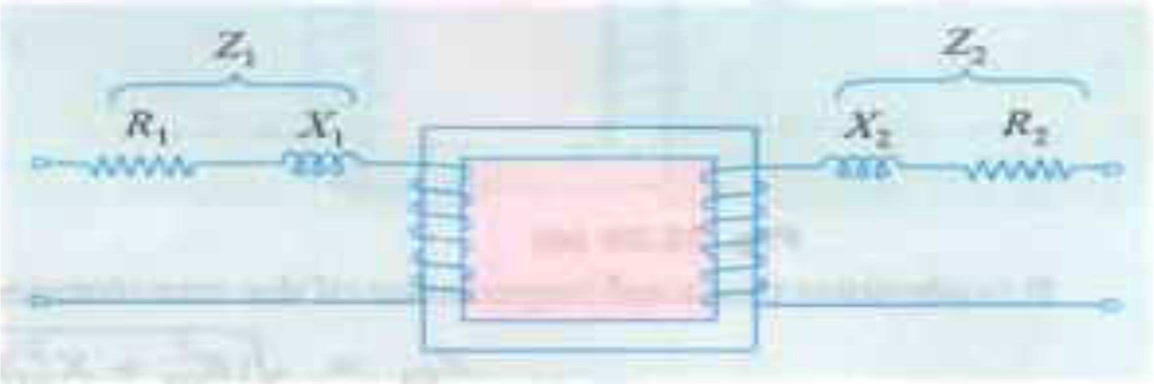
$$R_0 = \frac{V_1}{I_c}$$

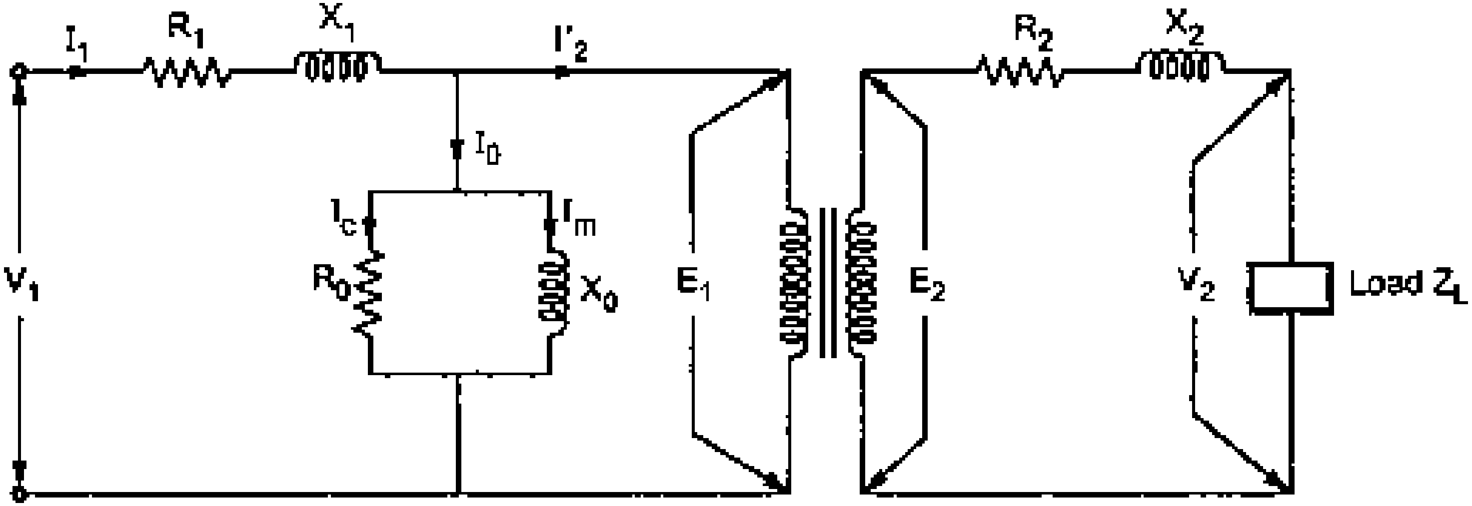
$$X_0 = \frac{V_1}{I_m}$$

$I_m = I_0 \sin\phi_0$ = Magnetising component

$I_c = I_0 \cos\phi_0$ = Active component

Equivalent circuit parameters referred to primary and secondary sides respectively





Contd.,

- The effect of circuit parameters shouldn't be changed while transferring the parameters from one side to another side
- It can be proved that a resistance of R_2 in sec. is equivalent to R_2/k^2 will be denoted as R_2'(ie. Equivalent sec. resistance w.r.t primary) which would have caused the same loss as R_2 in secondary,

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

$$\mathrm{R}_2' = \left(\frac{I_2}{I_1}\right)^2 R_2$$

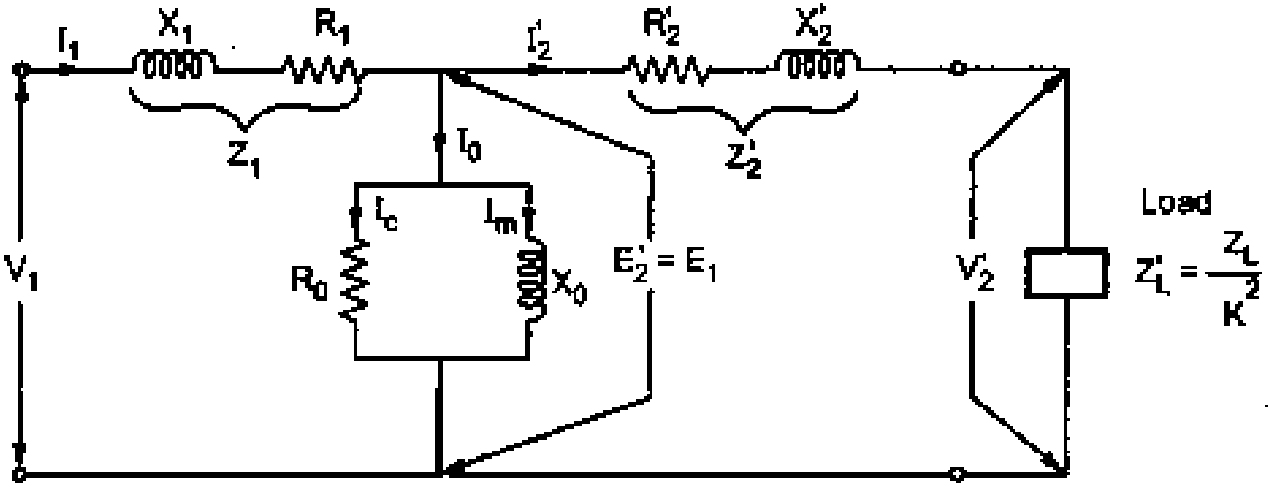
$$= \frac{\mathrm{R}_2}{\mathrm{k}^2}$$

Transferring secondary parameters to primary side

$$R'_2 = \frac{R_2}{K^2}, \qquad X'_2 = \frac{X_2}{K^2}, \qquad Z'_2 = \frac{Z_2}{K^2}$$

While $$E'_2 = \frac{E_2}{K}, \qquad I'_2 = KI_2$$

where $$K = \frac{N_2}{N_1}$$



Exact equivalent circuit referred to primary

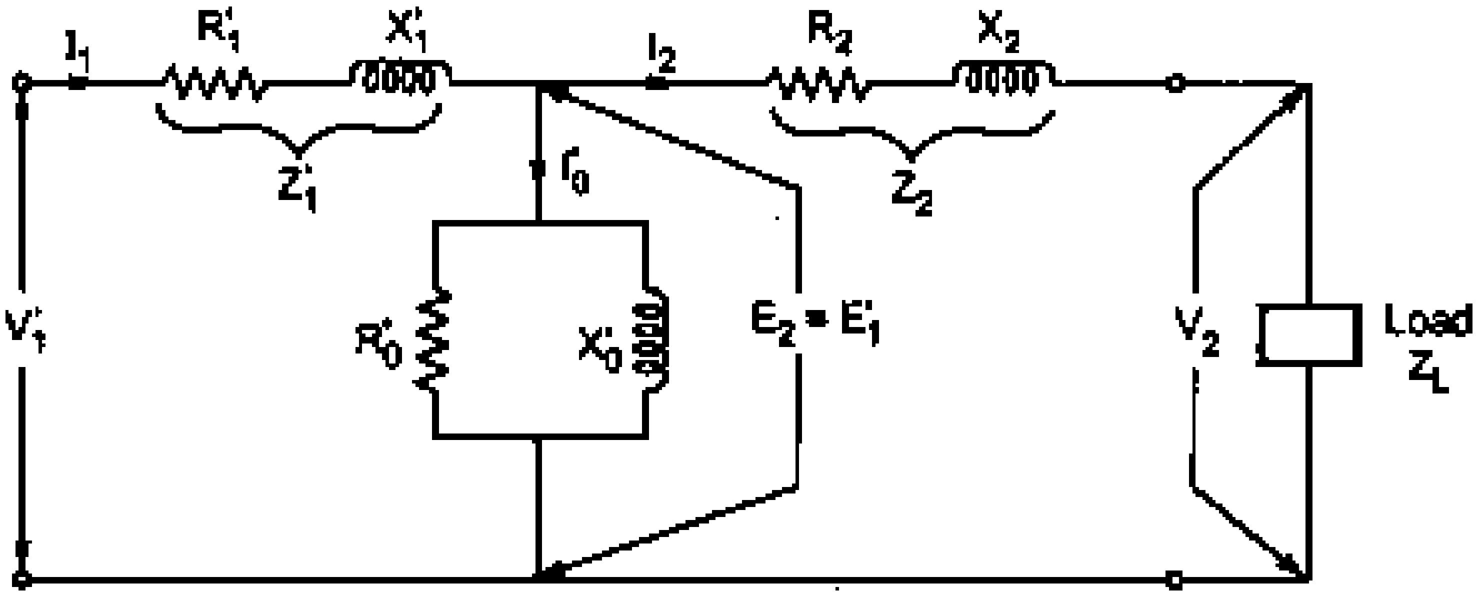
Equivalent circuit referred to secondary side

- Transferring primary side parameters to secondary side

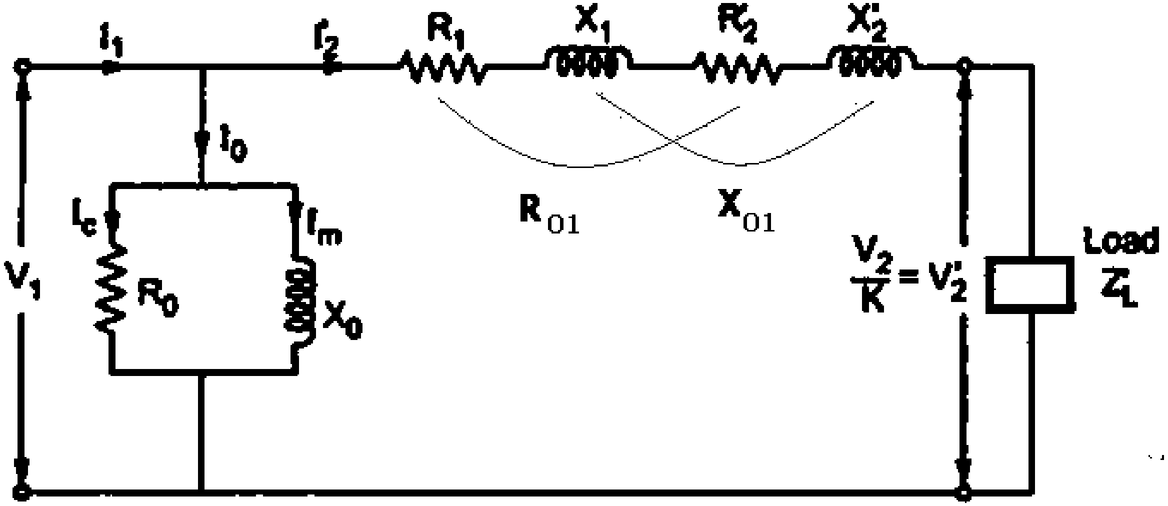
$$R_1' = K^2 R_1, \quad X_1' = K^2 X_1, \quad Z_1' = K^2 Z_1$$

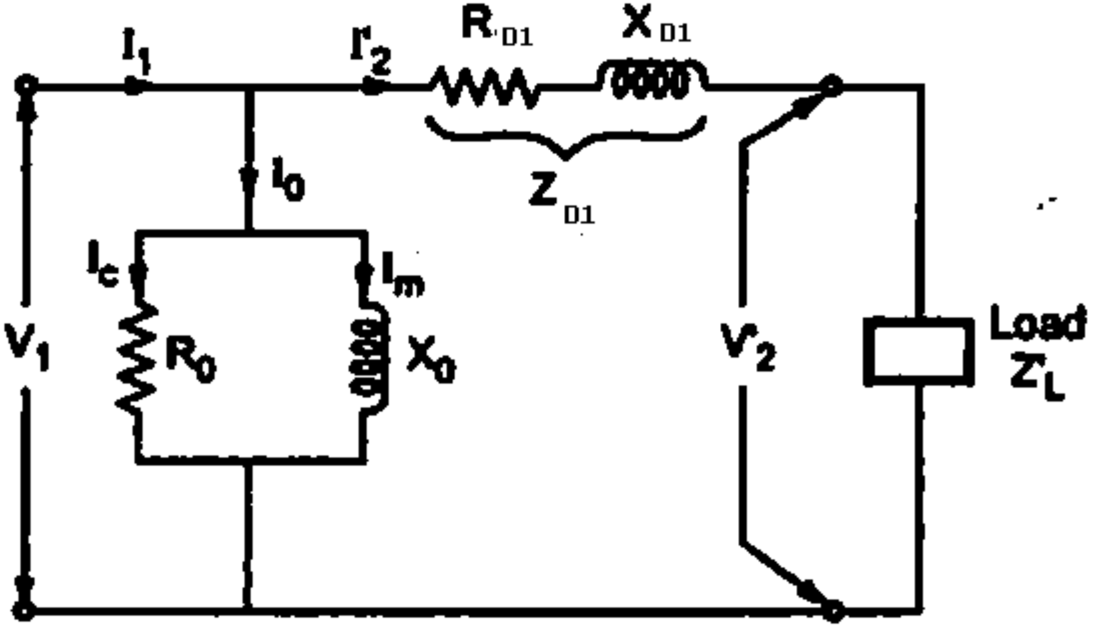
$$E_1' = K E_1, \quad I_1' = \frac{I_1}{K}, \quad I_0' = \frac{I_0}{K}$$

Similarly exciting circuit parameters are also transferred to secondary as R_o' and X_o'



equivalent circuit w.r.t primary





where

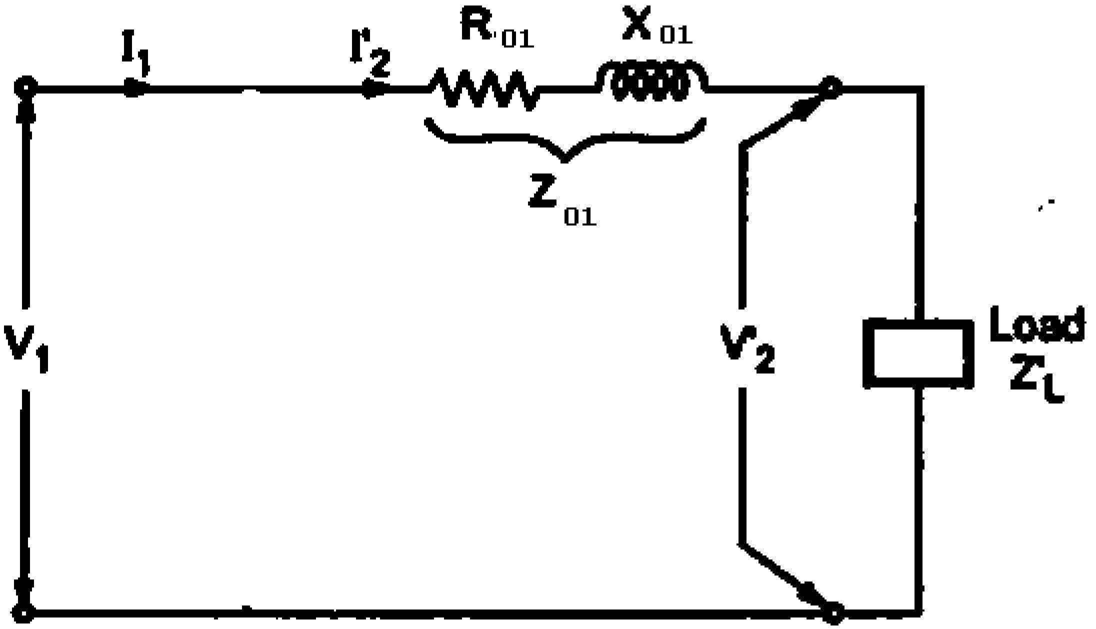
$$R_{01} = R_1 + R_2' = R_1 + \frac{R_2}{K^2}$$

$$X_{01} = X_1 + X_2' = X_1 + \frac{X_2}{K^2}$$

$$Z_{01} = R_{01} + j\,X_{01}$$

Approximate equivalent circuit

- Since the noload current is 1% of the full load current, the nolad circuit can be neglected

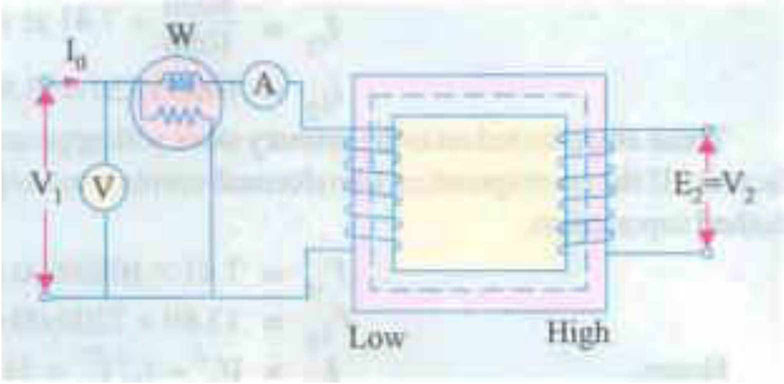


Transformer Tests

- The performance of a transformer can be calculated on the basis of equivalent circuit
- The four main parameters of equivalent circuit are:
  - R_{01} as referred to primary (or secondary R_{02})
  - the equivalent leakage reactance X_{01} as referred to primary (or secondary X_{02})
  - Magnetising susceptance B_0 (or reactance X_0)
  - core loss conductance G_0 (or resistance R_0)
- The above constants can be easily determined by two tests
  - Oper circuit test (O.C test / No load test)
  - Short circuit test (S.C test/Impedance test)
- These tests are economical and convenient
  - these tests furnish the result without actually loading the transformer

Open-circuit Test

In Open Circuit Test the transformer's ***secondary winding is open-circuited***, and its ***primary winding is connected to a full-rated line voltage***.



$$\text{Core loss} = W_{oc} = V_0 I_0 \cos\phi_0$$

$$\cos\phi_0 = \frac{W_{oc}}{V_0 I_0}$$

$$\mathrm{I_c} \, or \, \mathrm{I_w} = I_0 \cos\phi_0$$

$$\mathrm{I_m} \, or \, \mathrm{I}_\mu = I_0 \sin\phi_0 = \sqrt{I_0^2 \text{-} I_w^2}$$

$$\mathrm{I_0 = V_0 Y_0}; \quad \therefore \mathrm{Y_o} = \frac{I_0}{V_0}$$

$$R_0 = \frac{V_0}{I_w}$$

$$X_0 = \frac{V_0}{I\mu}$$

$$G_0 = \frac{I_w}{V_0}$$

$$B_0 = \frac{I\mu}{V_0}$$

$$\mathrm{W_{oc} = V_0^2 G_0}; \quad \therefore \text{Exciting conductance } \mathrm{G_0} = \frac{\mathrm{W_{oc}}}{\mathrm{V_0^2}}$$

$$\& \quad \text{Exciting susceptance } \mathrm{B_0} = \sqrt{Y_0^2 - G_0^2}$$

- Usually conducted on H.V side
- To find

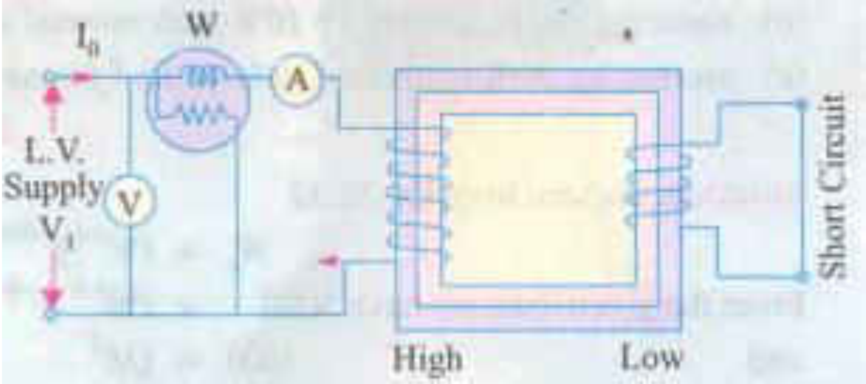
  (i) No load loss or core loss

  (ii) No load current I_o which is helpful in finding G_o(or R_o) and B_o (or X_o)

Short-circuit Test

In Short Circuit Test the ***secondary terminals are short circuited***, and the ***primary terminals are connected to a fairly low-voltage source***

The input voltage is adjusted until the current in the short circuited windings is equal to its rated value. The input voltage, current and power is measured.

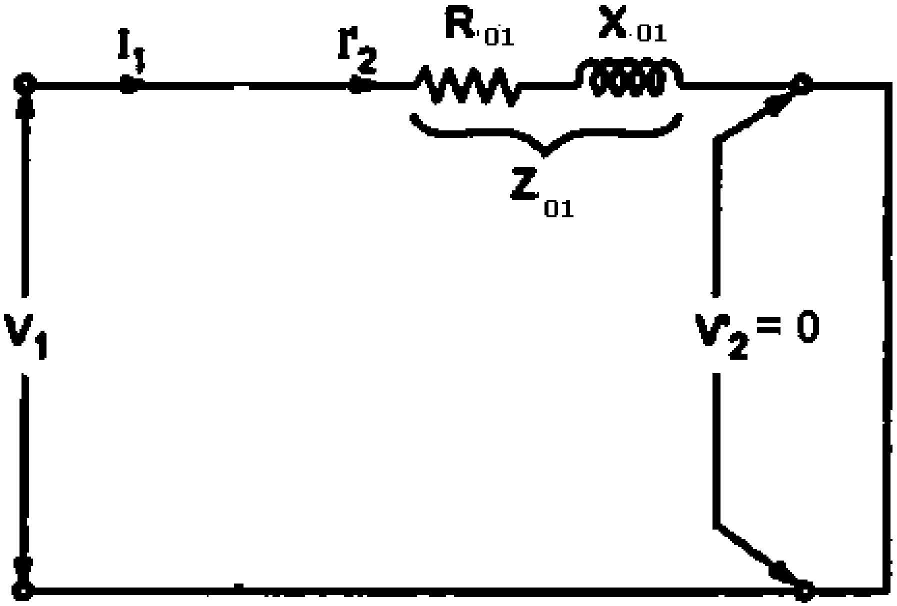


- Usually conducted on L.V side
- To find

  (i) Full load copper loss – to pre determine the efficiency

  (ii) Z_{01} or Z_{02}; X_{01} or X_{02}; R_{01} or R_{02} - to predetermine the voltage regulation

Contd…



$$\text{Full load cu loss} = \mathrm{W_{sc}} = I_{sc}^2 R_{01}$$

$$\mathrm{R_{01}} = \frac{\mathrm{W_{sc}}}{I_{sc}^2}$$

$$Z_{01} = \frac{V_{sc}}{I_{sc}}$$

$$\therefore \mathrm{X_{01}} = \sqrt{Z_{01}^2 - R_{01}^2}$$

Transformer Voltage Regulation and Efficiency

The output voltage of a transformer varies with the load even if the input voltage remains constant. This is because a real transformer has series impedance within it. Full load Voltage Regulation is a quantity that compares the output voltage at no load with the output voltage at full load, defined by this equation:

$$\text{At noload } k = \frac{V_s}{V_p}$$

$$\text{Regulation up} = \frac{V_{S,nl} - V_{S,fl}}{V_{S,fl}} \times 100\%$$

$$\text{Regulation down} = \frac{V_{S,nl} - V_{S,fl}}{V_{S,nl}} \times 100\%$$

$$\text{Regulation up} = \frac{(V_P / k) - V_{S,fl}}{V_{S,fl}} \, x \, 100\%$$

$$\text{Regulation down} = \frac{(V_P / k) - V_{S,fl}}{V_{S,nl}} \, x \, 100\%$$

Ideal transformer, VR = 0%.

Voltage regulation of a transformer

$$\text{Voltage regulation} = \frac{\text{no-load voltage} - \text{full-load voltage}}{\text{no-load voltage}}$$

recall $\frac{\mathrm{V_s}}{\mathrm{V_p}} = \frac{\mathrm{N_s}}{\mathrm{N_p}}$

Secondary voltage on no-load $V_2 = V_1\left(\frac{N_2}{N_1}\right)$

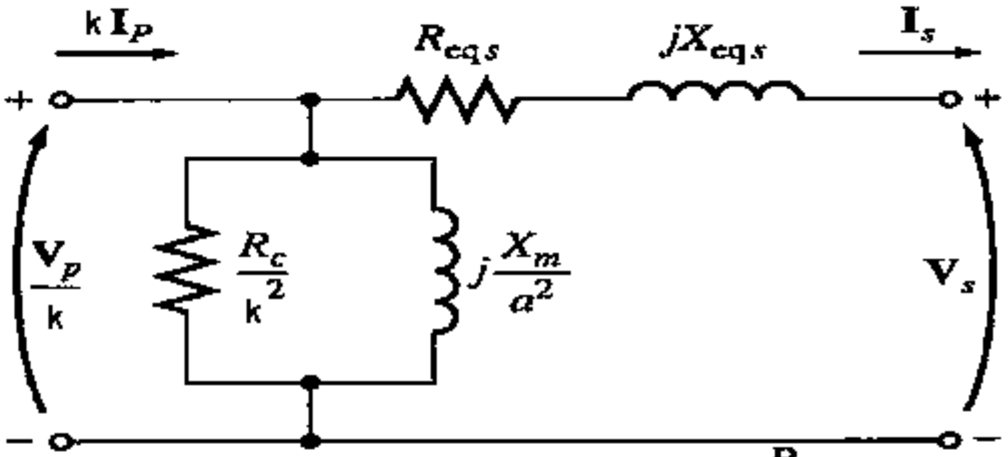
$\mathrm{V_2}$ is a secondary terminal voltage on full load

Substitute we have

$$\text{Voltage regulation} = \frac{V_1\left(\frac{N_2}{N_1}\right) - V_2}{V_1\left(\frac{N_2}{N_1}\right)}$$

Transformer Phasor Diagram

To determine the voltage regulation of a transformer, it is necessary understand the voltage drops within it.



$$R_{eq\,s} = \frac{R_p}{k^2} + R_s$$

$$X_{eq\,s} = \frac{X_p}{k^2} + X_s$$

Transformer Phasor Diagram

Ignoring the excitation of the branch (since the current flow through the branch is considered to be small), more consideration is given to the series impedances (R_{eq} +jX_{eq}).

Voltage Regulation depends on magnitude of the series impedance and the phase angle of the current flowing through the transformer.

Phasor diagrams will determine the effects of these factors on the voltage regulation. A phasor diagram consist of current and voltage vectors.

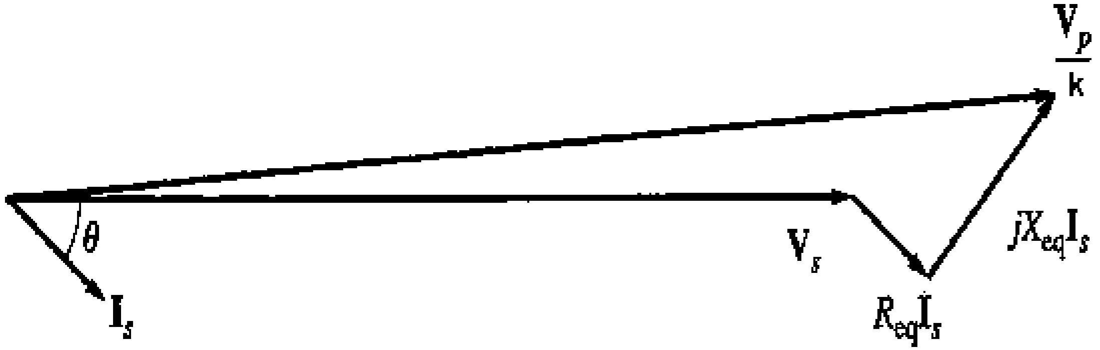
Assume that the reference phasor is the secondary voltage, V_S. Therefore the reference phasor will have 0 degrees in terms of angle.

Based upon the equivalent circuit, apply Kirchoff Voltage Law,

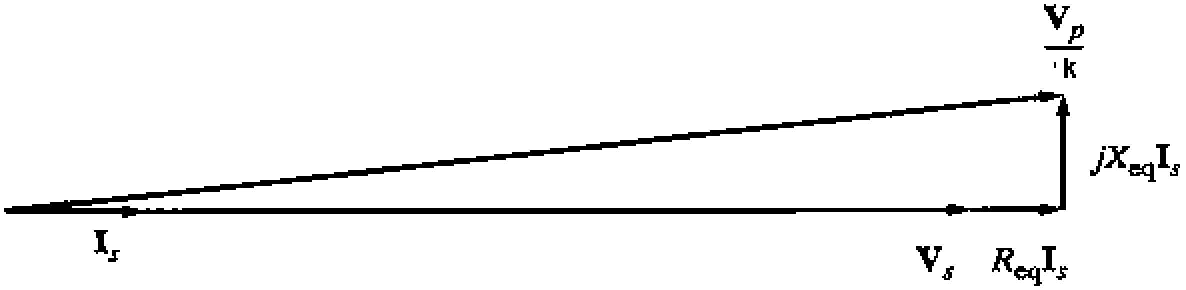
$$\frac{V_P}{k} = V_S + R_{eq} I_S + jX_{eq} I_S$$

Transformer Phasor Diagram

For lagging loads, $V_P / a > V_S$ so the voltage regulation with lagging loads is > 0.



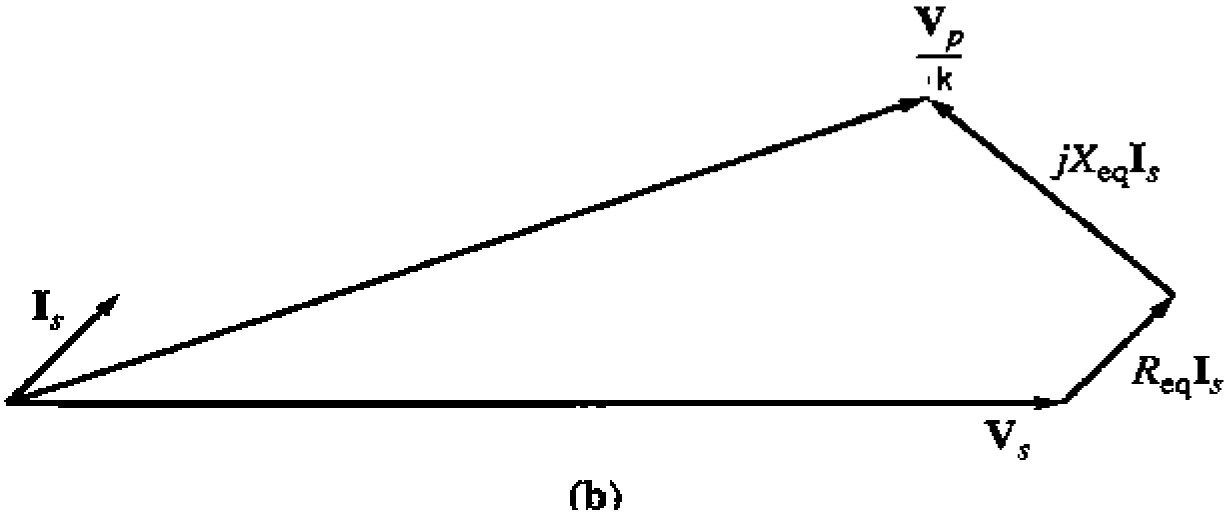
When the power factor is unity, V_S is lower than V_P so VR > 0.



(a)

Transformer Phasor Diagram

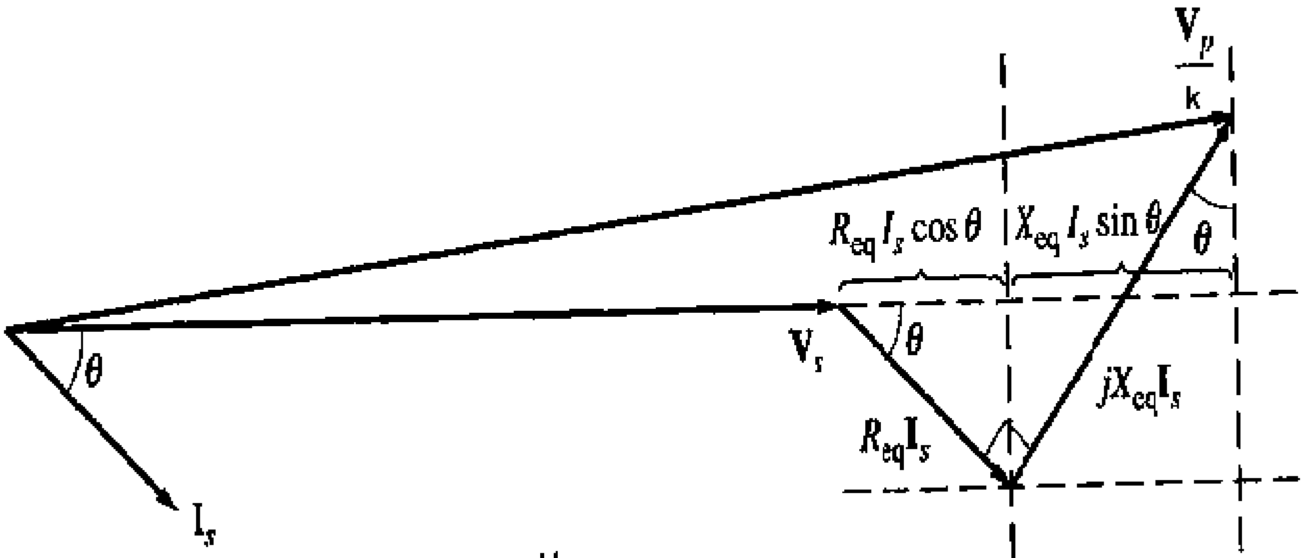
With a leading power factor, V_S is higher than the referred V_P so VR < 0



(b)

Transformer Phasor Diagram

For lagging loads, the vertical components of R_{eq} and X_{eq} will partially cancel each other. Due to that, the angle of V_P/a will be very small, hence we can assume that V_P/k is horizontal. Therefore the approximation will be as follows:



$$\frac{V_p}{k} \approx V_s + R_{eq} I_s \cos\theta + X_{eq} I_s \sin\theta$$

Formula: voltage regulation

In terms of secondary values

$$\%\ \text{regulation} = \frac{{}_{0}\mathrm{V}_{2} - V_{2}}{{}_{0}\mathrm{V}_{2}} = \frac{I_{2}R_{02}\cos\phi_{2} \pm I_{2}X_{02}\sin\phi_{2}}{{}_{0}\mathrm{V}_{2}}$$

where '+' for lagging and '-' for leading

In terms of primary values

$$\%\ \text{regulation} = \frac{\mathrm{V}_{1} - V_{2}^{'}}{\mathrm{V}_{1}} = \frac{I_{1}R_{01}\cos\phi_{1} \pm I_{1}X_{01}\sin\phi_{1}}{\mathrm{V}_{1}}$$

where '+' for lagging and '-' for leading

Transformer Efficiency

Transformer efficiency is defined as (applies to motors, generators and transformers):

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

$$\eta = \frac{P_{out}}{P_{out} + P_{loss}} \times 100\%$$

Types of losses incurred in a transformer:

- Copper I^2R losses
- Hysteresis losses
- Eddy current losses

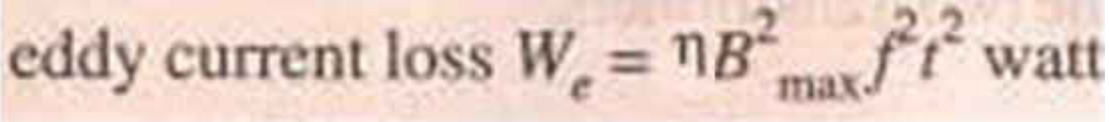
Therefore, for a transformer, efficiency may be calculated using the following:

$$\eta = \frac{V_S I_S \cos\theta}{P_{Cu} + P_{core} + V_S I_S \cos\theta} x100\%$$

Losses in a transformer

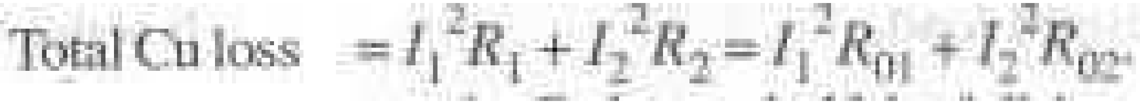
Core or Iron loss:

Hysteresis loss $W_h = \eta B^{1.6}_{\max} f V$ watt;



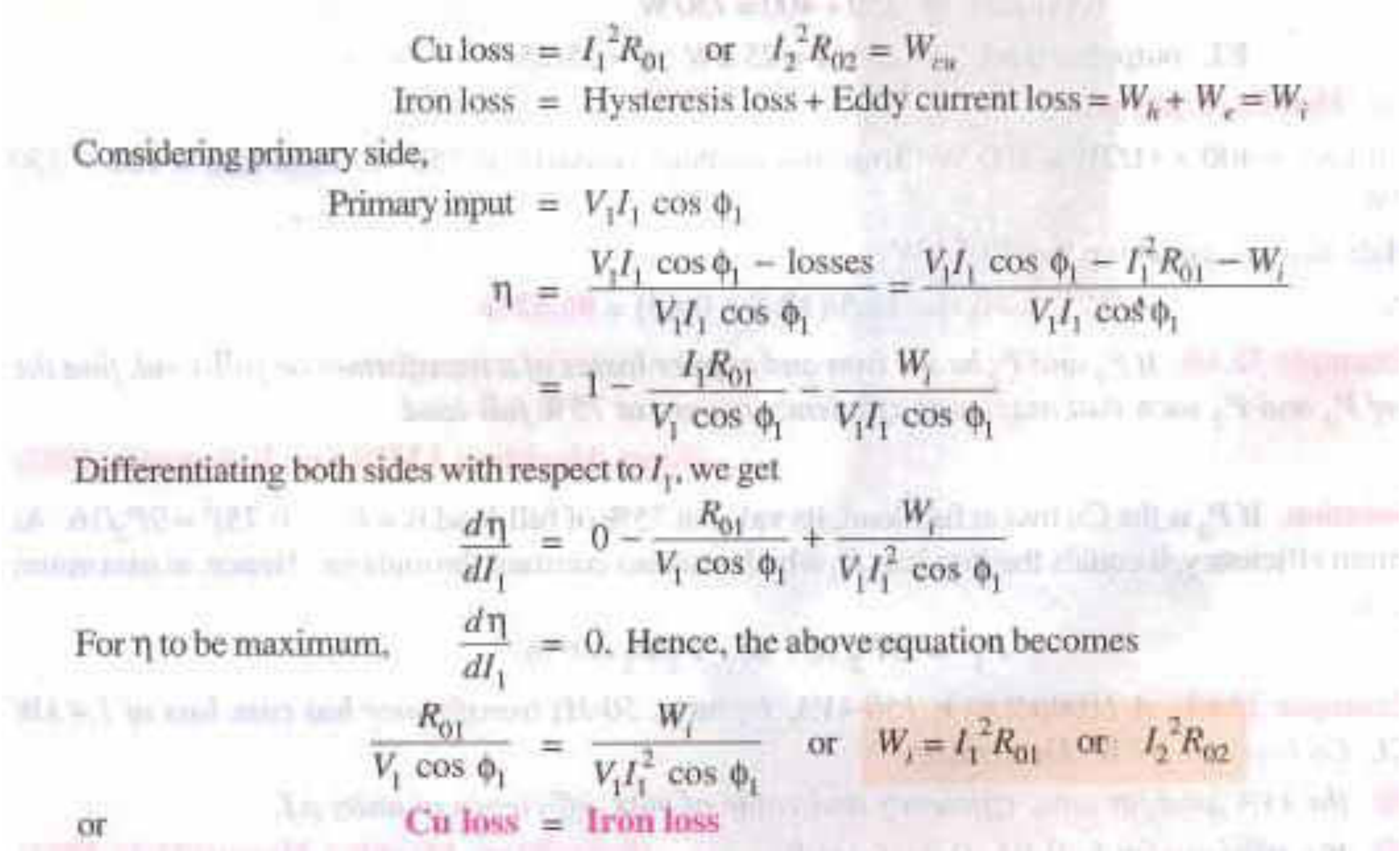
eddy current loss $W_e = \eta B^2_{\max} f^2 t^2$ watt

Copper loss:



Total Cu loss $= I_1^2 R_1 + I_2^2 R_2 = I_1^2 R_{01} + I_2^2 R_{02}$.

Condition for maximum efficiency



$$\text{Cu loss} = I_1^2 R_{01} \quad \text{or} \quad I_2^2 R_{02} = W_{cu}$$

$$\text{Iron loss} = \text{Hysteresis loss} + \text{Eddy current loss} = W_h + W_e = W_i$$

Considering primary side,

$$\text{Primary input} = V_1 I_1 \cos\phi_1$$

$$\eta = \frac{V_1 I_1 \cos\phi_1 - \text{losses}}{V_1 I_1 \cos\phi_1} = \frac{V_1 I_1 \cos\phi_1 - I_1^2 R_{01} - W_i}{V_1 I_1 \cos\phi_1}$$

$$= 1 - \frac{I_1 R_{01}}{V_1 \cos\phi_1} - \frac{W_i}{V_1 I_1 \cos\phi_1}$$

Differentiating both sides with respect to I_1, we get

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

For η to be maximum, $\frac{d\eta}{dI_1} = 0$. Hence, the above equation becomes

$$\frac{R_{01}}{V_1 \cos\phi_1} = \frac{W_i}{V_1 I_1^2 \cos\phi_1} \quad \text{or} \quad W_i = I_1^2 R_{01} \quad \text{or} \quad I_2^2 R_{02}$$

or **Cu loss = Iron loss**

Contd.,

The output current corresponding to maximum efficiency is $I_2 = \sqrt{(W_i/R_{02})}$.

The load at which the two losses are equal $= \text{Full load} \times \sqrt{\left(\frac{\text{Iron loss}}{\text{F.L. Cu loss}}\right)}$

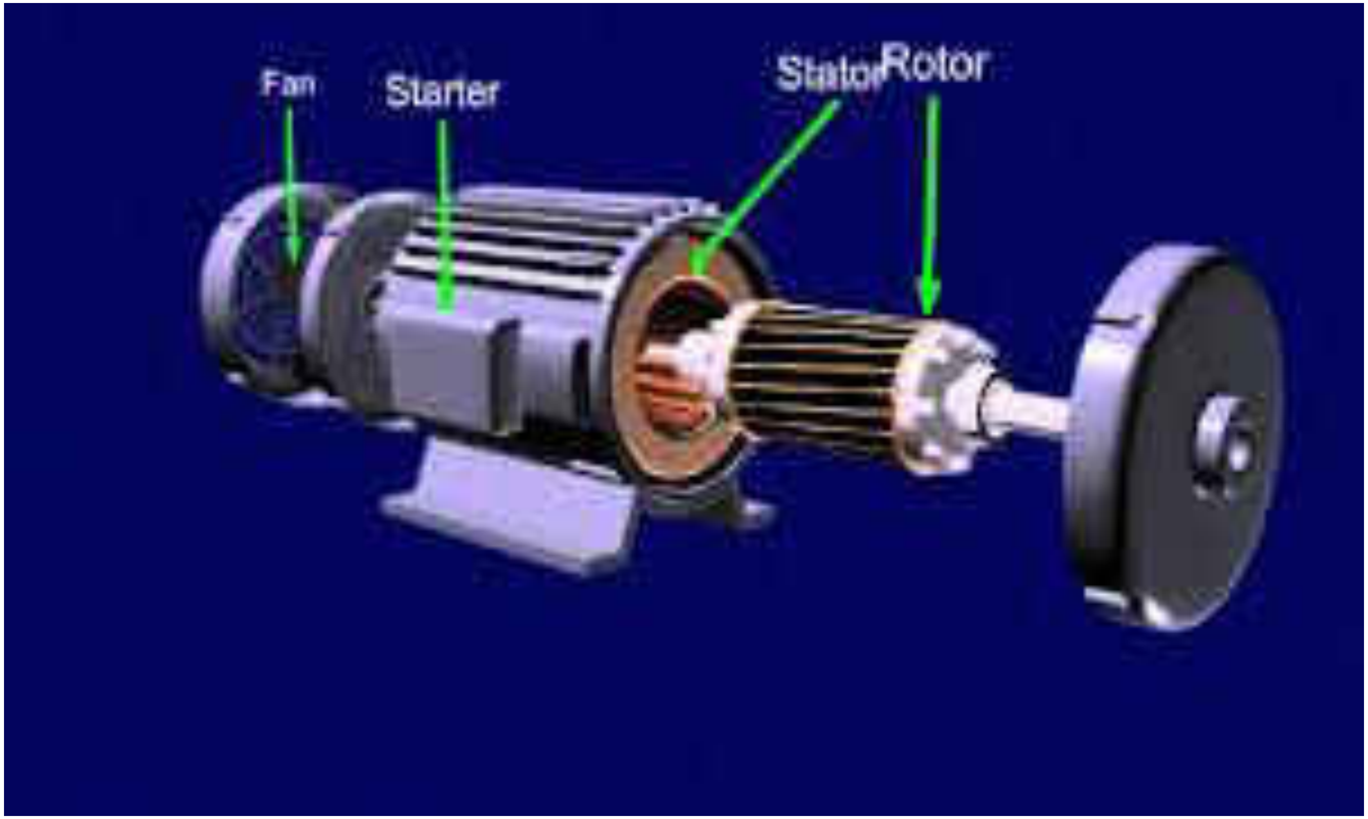
All day efficiency

$$\text{ordinary commercial efficiency} = \frac{\text{out put in watts}}{\text{input in watts}}$$

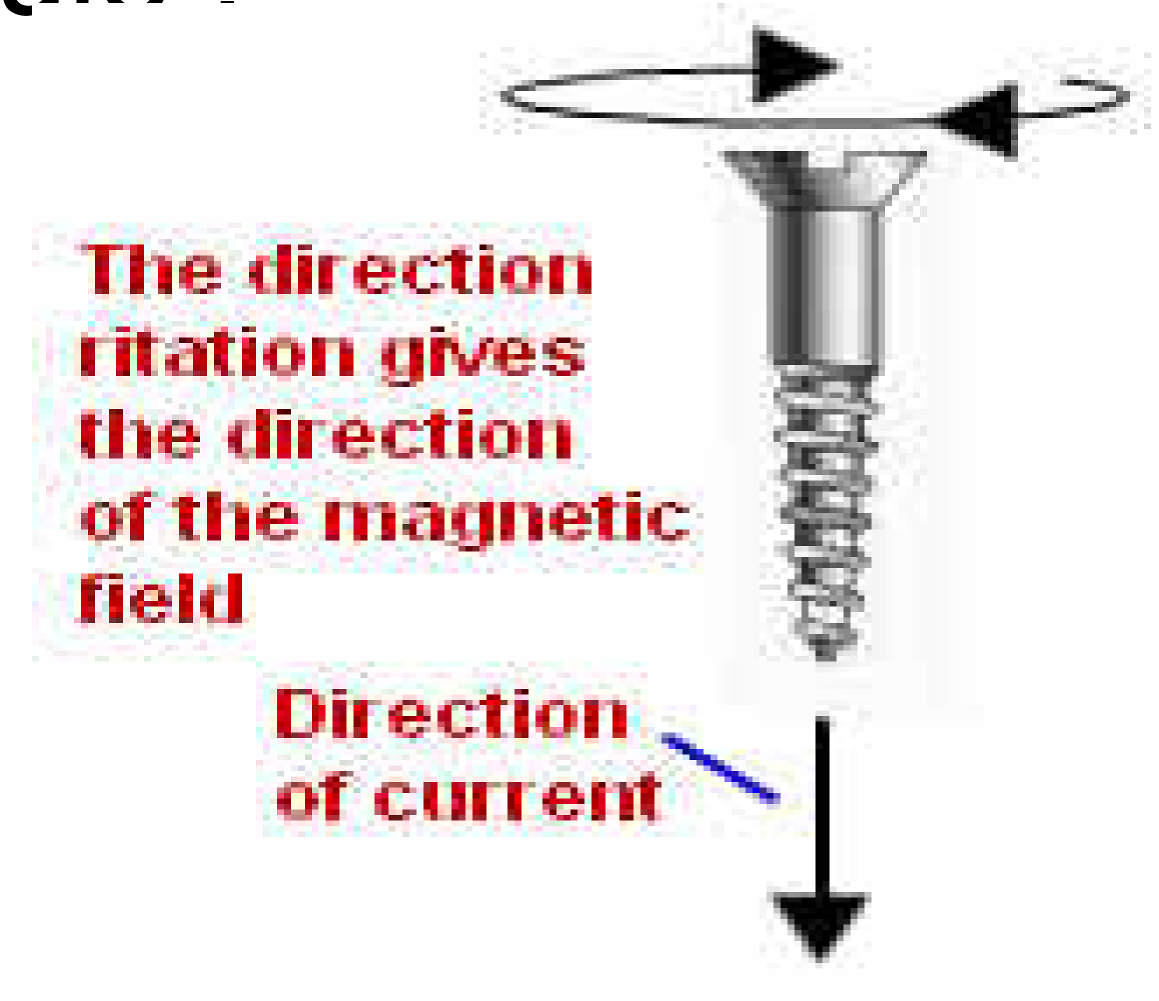
$$\eta_{all\,\text{day}} = \frac{\text{output in kWh}}{\text{Input in kWh}}(\mathit{for}\ 24\ \text{hours})$$

- All day efficiency is always less than the commercial efficiency

DC MACHINES



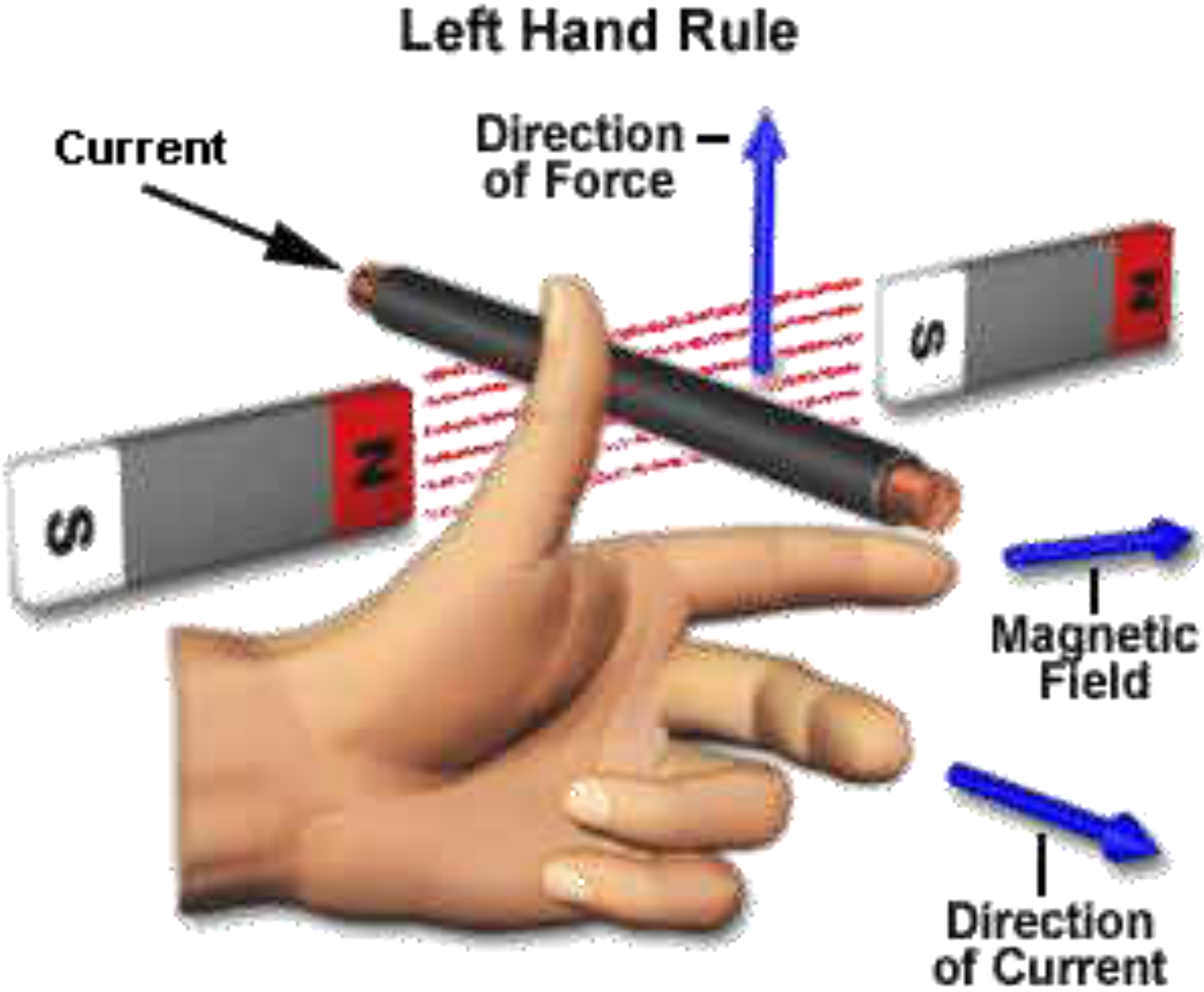
Maxwell’s Cork screw Rule :



Maxwell’s Cork screw Rule :

Hold the cork screw in yr right hand and rotate it in clockwise in such a way that it advances in the direction of current. Then the <u>direction in which the hand rotates will be the direction of magnetic lines of force .</u>

Fleming's left hand rule



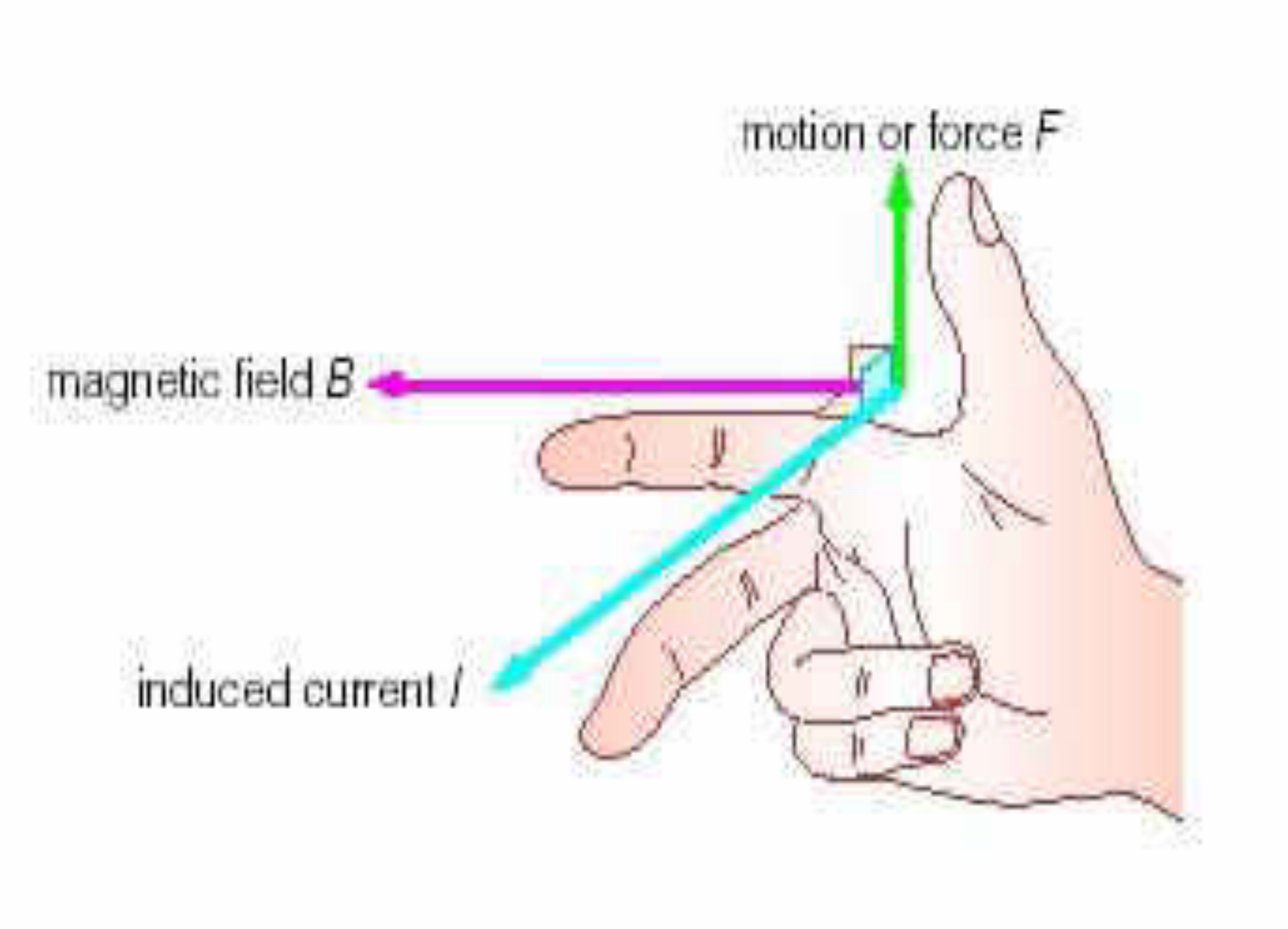
Fleming´s left hand rule

- Used to determine the direction of force acting on a current carrying conductor placed in a magnetic field .
- The middle finger , the fore finger and thumb of the left hand are kept at right angles to one another .

- The middle finger represent the direction of current
- The fore finger represent the direction of magnetic field
- The thumb will indicate the direction of force acting on the conductor .

This rule is used in motors.

Fleming’s Right hand rule



Fleming's Right hand rule

- Used to determine the direction of emf induced in a conductor
- The middle finger , the fore finger and thumb of the left hand are kept at right angles to one another.
  - The fore finger represent the direction of magnetic field
  - The thumb represent the direction of motion of the conductor
  - The middle finger will indicate the direction of the inducted emf .

This rule is used in DC Generators

Len’s Law

The direction of induced emf is given by Lenz’s law .

According to this law, the induced emf will be acting in such a way so as to oppose the very cause of production of it .

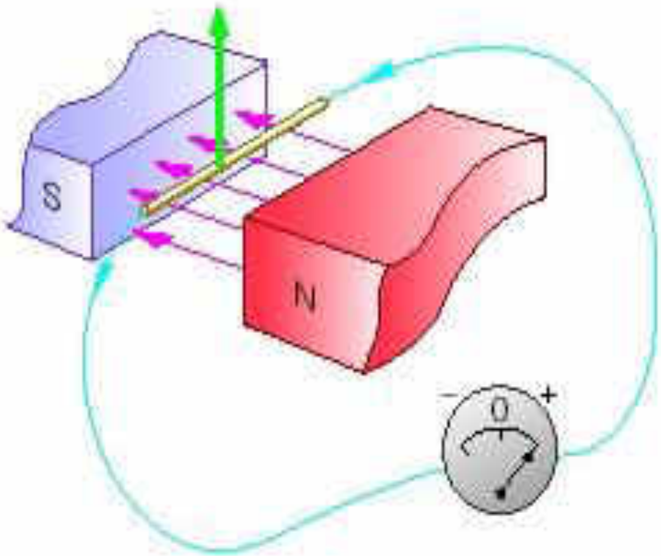
- $e = -N\,(d\varnothing/dt)$ volts

DC Generator

Mechanical energy is converted to electric energy

Three requirements are essential

1. Conductors
2. Magnetic field
3. Mechanical energy



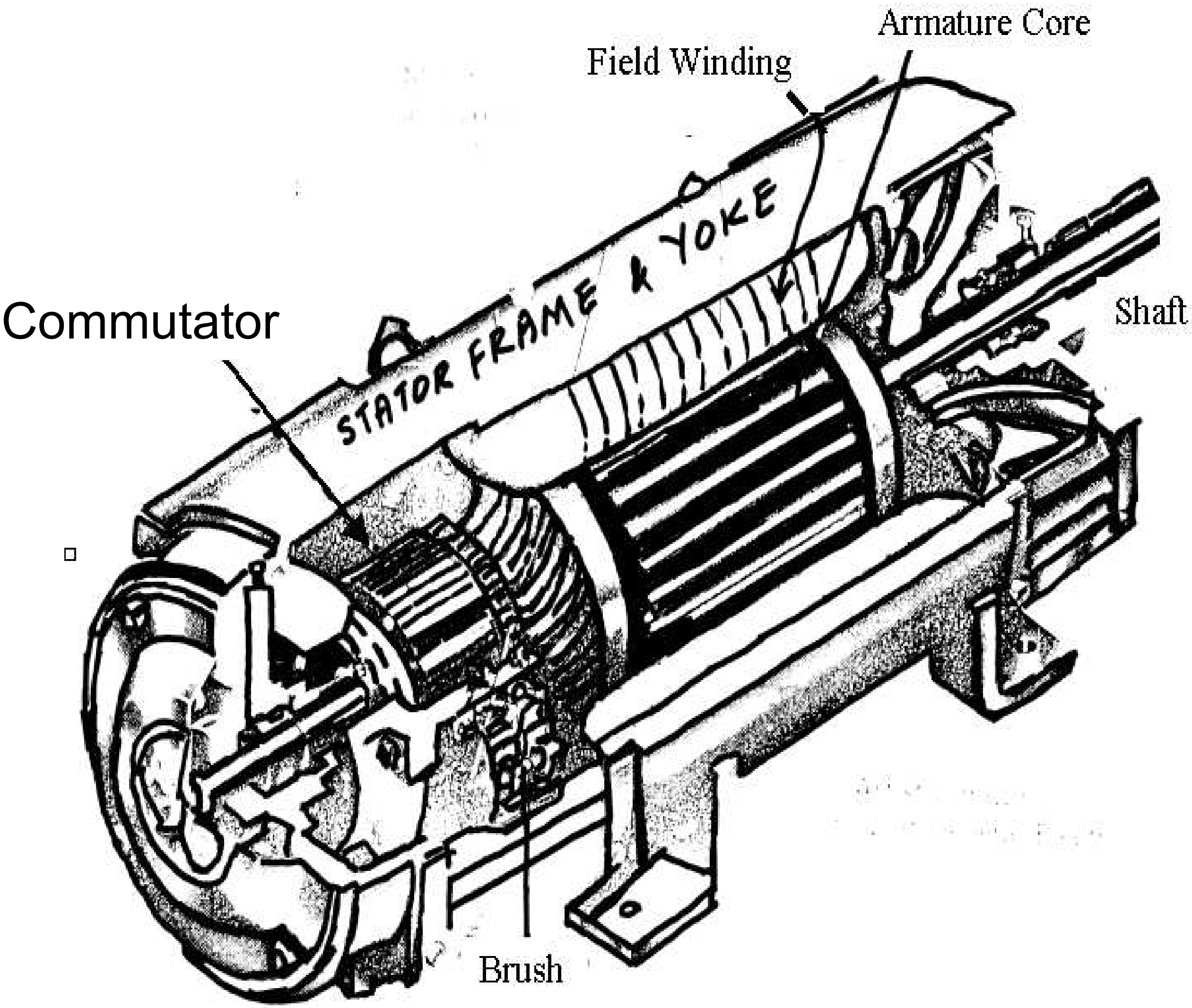
Working principle

- A generator works on the principles of Faraday's law of electromagnetic induction

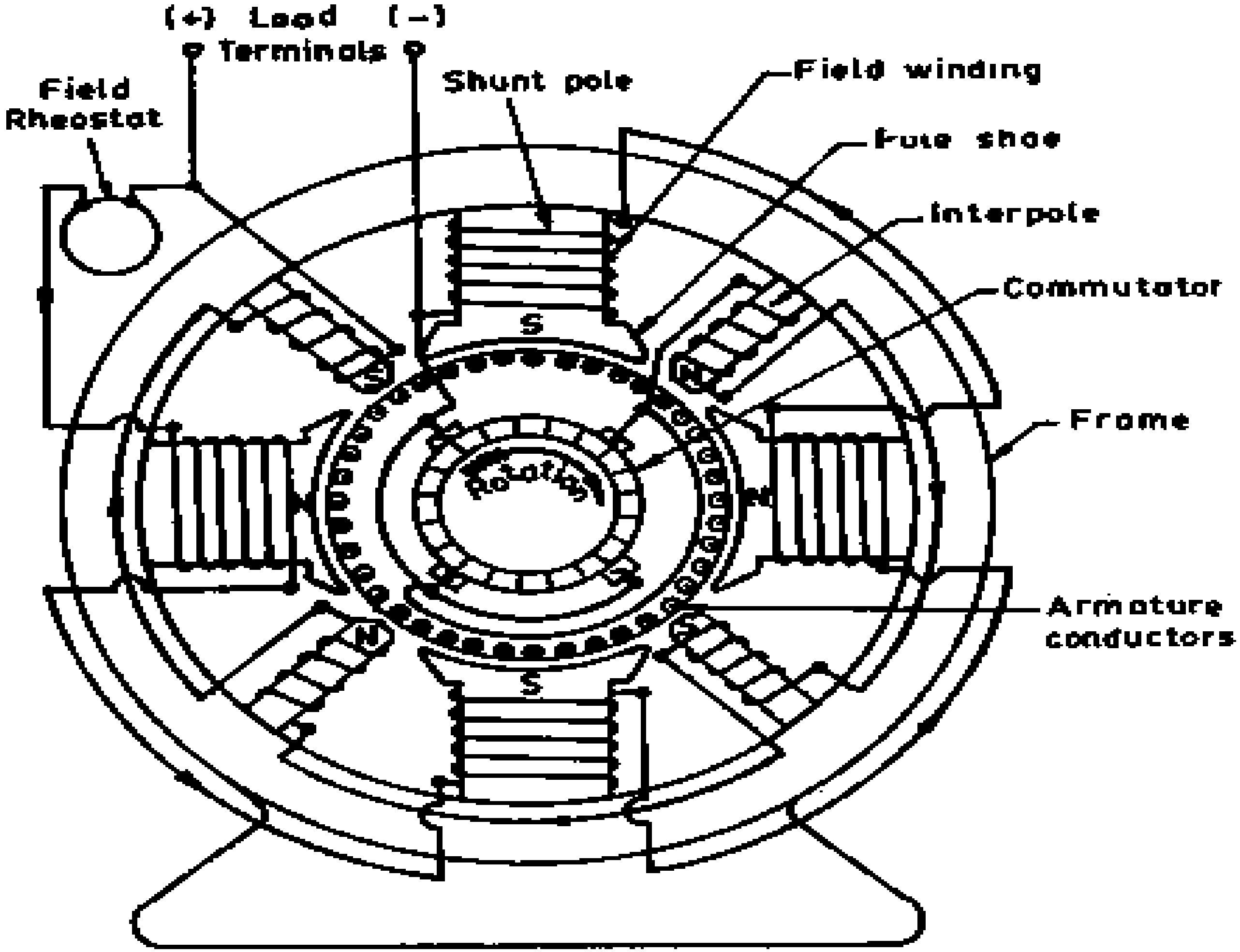
- Whenever a conductor is moved in the magnetic field , an emf is induced and the magnitude of the induced emf is directly proportional to the rate of change of flux linkage.

- This emf causes a current flow if the conductor circuit is closed .

DC Machine

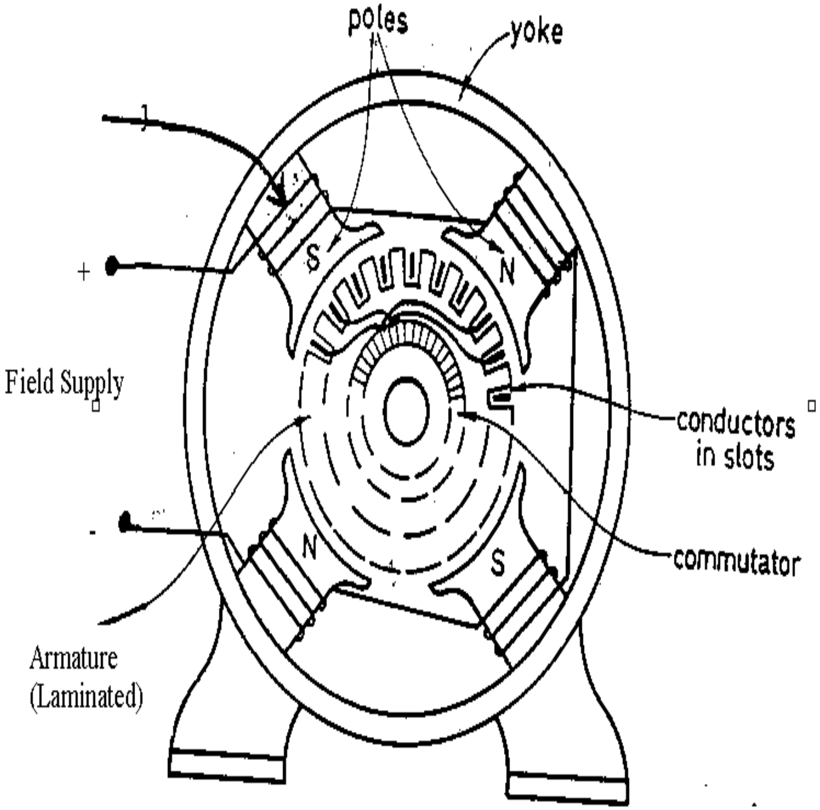

Armature Core
Field Winding
STATOR FRAME & YOKE
Commutator
Shaft
Brush

Sectional view of a DC machine



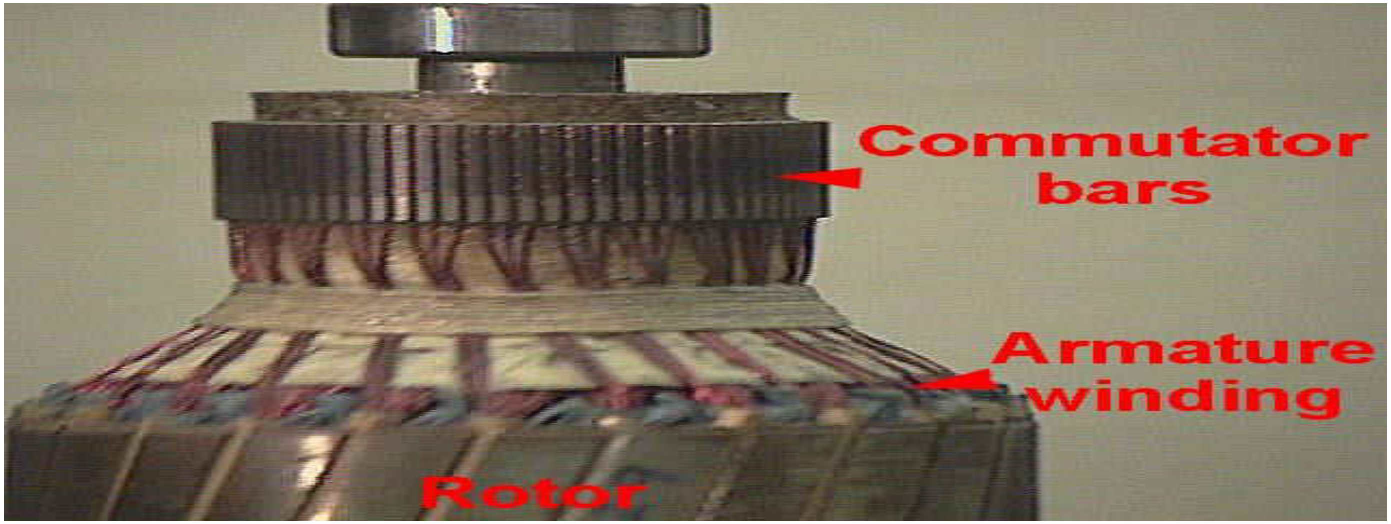
Construction of DC Generator

- Field system
- Armature core
- Armature winding
- Commutator
- Brushes

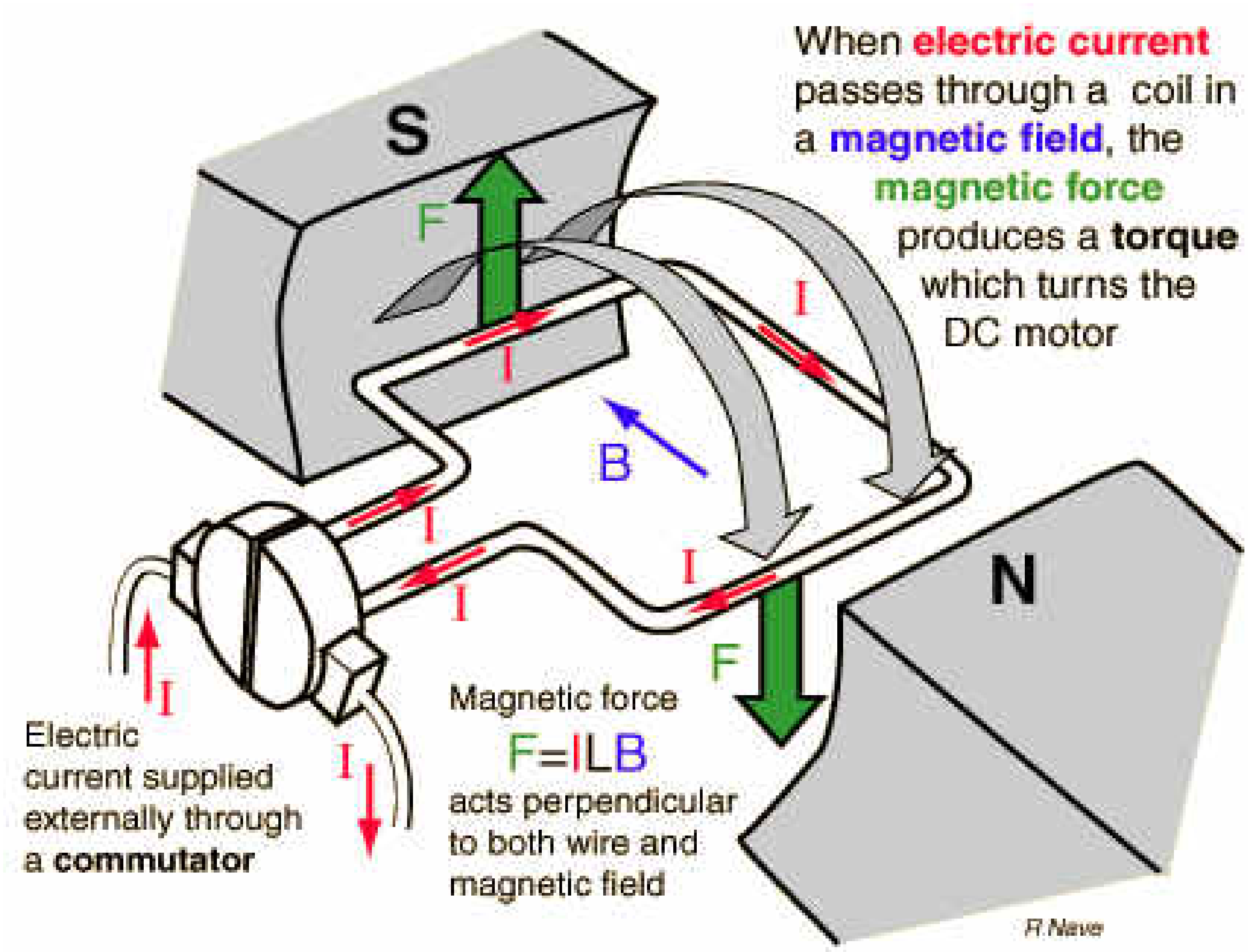


Field winding

Rotor and rotor winding



Working principle of DC motor

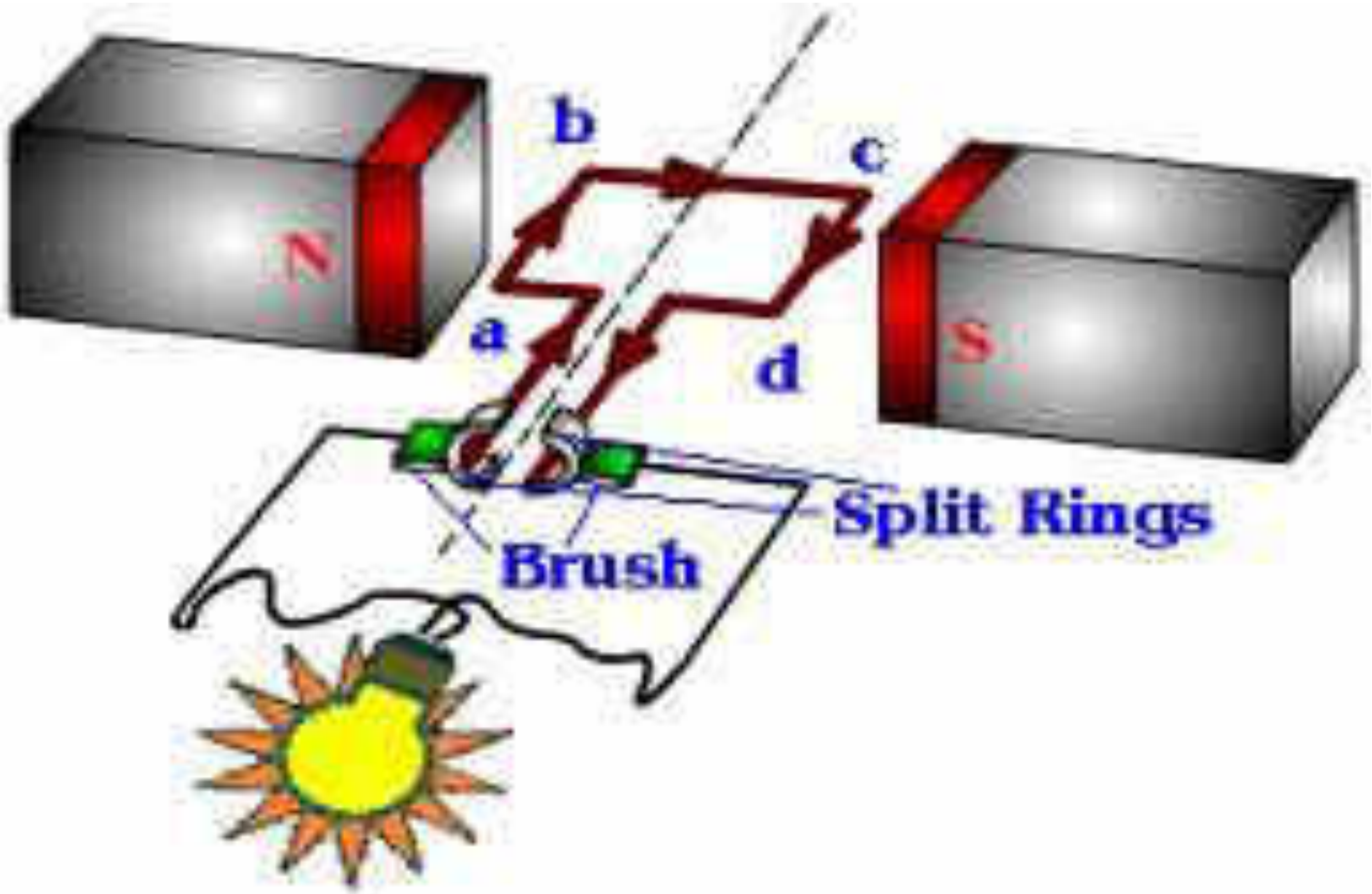


When **electric current** passes through a coil in a **magnetic field**, the **magnetic force** produces a **torque** which turns the DC motor

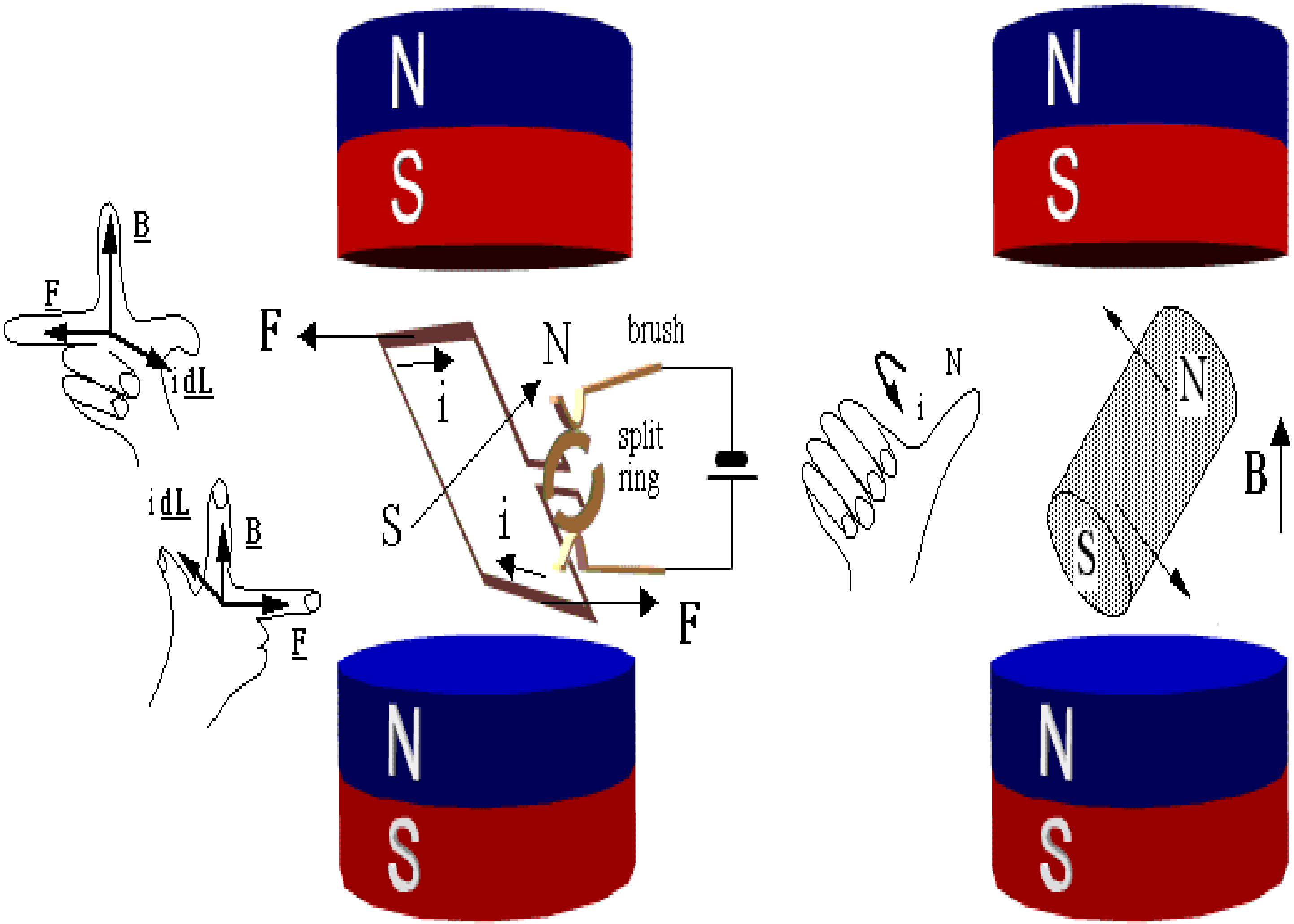
Electric current supplied externally through a **commutator**

Magnetic force F=ILB acts perpendicular to both wire and magnetic field

Working principle of DC motor



Force in DC motor



Armature winding

There are 2 types of winding

Lap and Wave winding

Lap winding	**Wave winding**
A = P	**A = 2**
The armature windings are divided into no. of sections equal to the no of poles	It is used in low current output and high voltage.
	2 brushes

Field system

- It is for uniform magnetic field within which the armature rotates.
- Electromagnets are preferred in comparison with permanent magnets
- They are cheap , smaller in size , produce greater magnetic effect and
- Field strength can be varied

Field system consists of the following parts

- Yoke
- Pole cores
- Pole shoes
- Field coils

Armature core

- The armature core is cylindrical
- High permeability silicon steel stampings
- Impregnated
- Lamination is to reduce the eddy current loss

Commutator

- Connect with external circuit
- Converts ac into unidirectional current
- Cylindrical in shape
- Made of wedge shaped copper segments
- Segments are insulated from each other
- Each commutator segment is connected to armature conductors by means of a cu strip called riser.
- No of segments equal to no of coils

Carbon brush

- Carbon brushes are used in DC machines because they are soft materials
- It does not generate spikes when they contact commutator
- To deliver the current thro armature
- Carbon is used for brushes because it has negative temperature coefficient of resistance
- Self lubricating , takes its shape , improving area of contact

Brush rock and holder

Carbon brush

- Brush leads (pig tails)
- Brush rocker (brush gear)
- Front end cover
- Rear end cover
- Cooling fan
- Bearing
- Terminal box

EMF equation

Let,

- Ø= flux per pole in weber
- Z = Total number of conductor
- P = Number of poles
- A = Number of parallel paths
- N =armature speed in rpm
- Eg = emf generated in any on of the parallel path

EMF equation

Flux cut by 1 conductor in 1 revolution $= P * \varphi$

Flux cut by 1 conductor in 60 sec $= P \varphi N / 60$

Avg emf generated in 1 conductor $= P\varphi N/60$

Number of conductors in each parallel path $= Z / A$

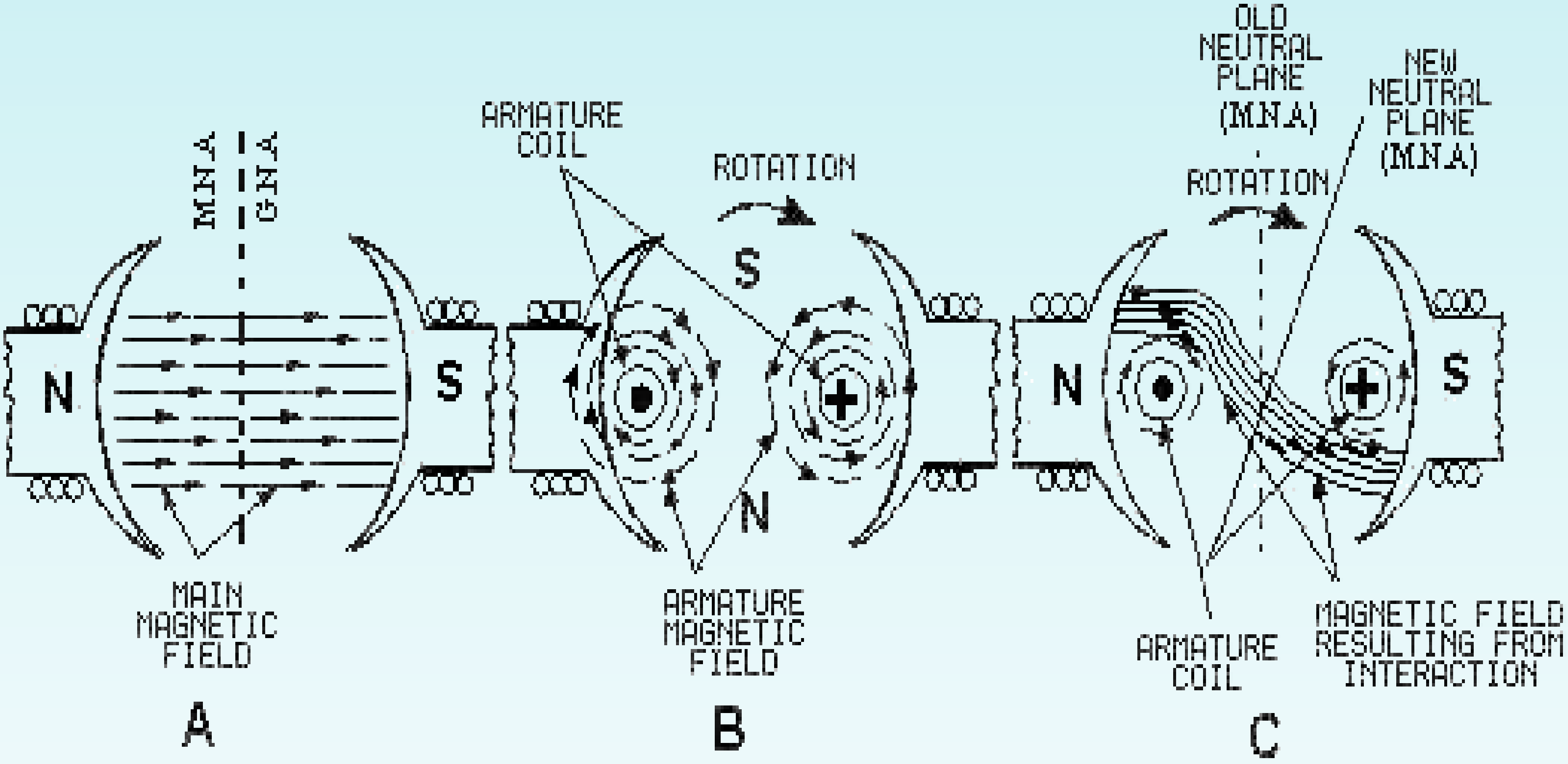
$E_g = P\varphi NZ/60A$

Critical field resistance

For appreciable generation of emf, the field resistance must be always less certain resistance, that resistance is called as the critical resistance of the machine .

Armature Reaction

Interaction of Main field flux with Armature field flux



Effects of Armature Reaction

- It decreases the efficiency of the machine
- It produces sparking at the brushes
- It produces a demagnetising effect on the main poles
- It reduces the emf induced
- Self excited generators some times fail to build up emf

Armature reaction remedies

1. Brushes must be shifted to the new position of the MNA
2. Extra turns in the field winding
3. Slots are made on the tips to increase the reluctance
4. The laminated cores of the shoe are staggered
5. In big machines the compensating winding at pole shoes produces a flux which just opposes the armature mmf flux automatically

Losses in DC Generators

1. Copper losses or variable losses
2. Stray losses or constant losses

Stray losses : consist of (a) iron losses or core losses and (b) windage and friction losses .

Iron losses : occurs in the core of the machine due to change of magnetic flux in the core . Consist of hysteresis loss and eddy current loss.

Hysteresis loss depends upon the

Losses

Hysteresis loss depends upon the frequency , Flux density , volume and type of the core .

Eddy current losses : directly proportional to the flux density , frequency , thickness of the lamination .

Windage and friction losses are constant due to the opposition of wind and friction .

Back emf

The induced emf in the rotating armature conductors always acts in the opposite direction of the supply voltage .

According to the Lenz’s law, the direction of the induced emf is always so as to oppose the cause producing it .

In a DC motor , the supply voltage is the cause and hence this induced emf opposes the supply voltage.

Classification of DC motors

DC motors are mainly classified into three types as listed below:

- Shunt motor
- Series motor
- Compound motor
  - Differential compound
  - Cumulative compound

Torque

The turning or twisting force about an axis is called torque .

- $P = T * 2 \pi N / 60$
- $Eb\ Ia = Ta * 2 \pi N / 60$
- $T \infty \phi\ I\ a$
- $Ta \infty I2a$

Characteristic of DC motors

- T/ Ia characteristic

- N/ I a characteristic

- N/T characteristic

Armature voltage control method

- The speed is directly proportional to the voltage applied across the armature .

- Voltage across armature can be controlled by adding a variable resistance in series with the armature

Potential divider control :

If the speed control from zero to the rated speed is required , by rheostatic method then the voltage across the armature can be varied by connecting rheostat in a potential divider arrangement .

Starters for DC motors

Needed to limit the starting current .

1. Two point starter
2. Three point starter
3. Four point starter

References

- Slideshare.com