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ENGINEERING COLLEGE
TRIBHUVAN UNIVERSITY AFFILIATE

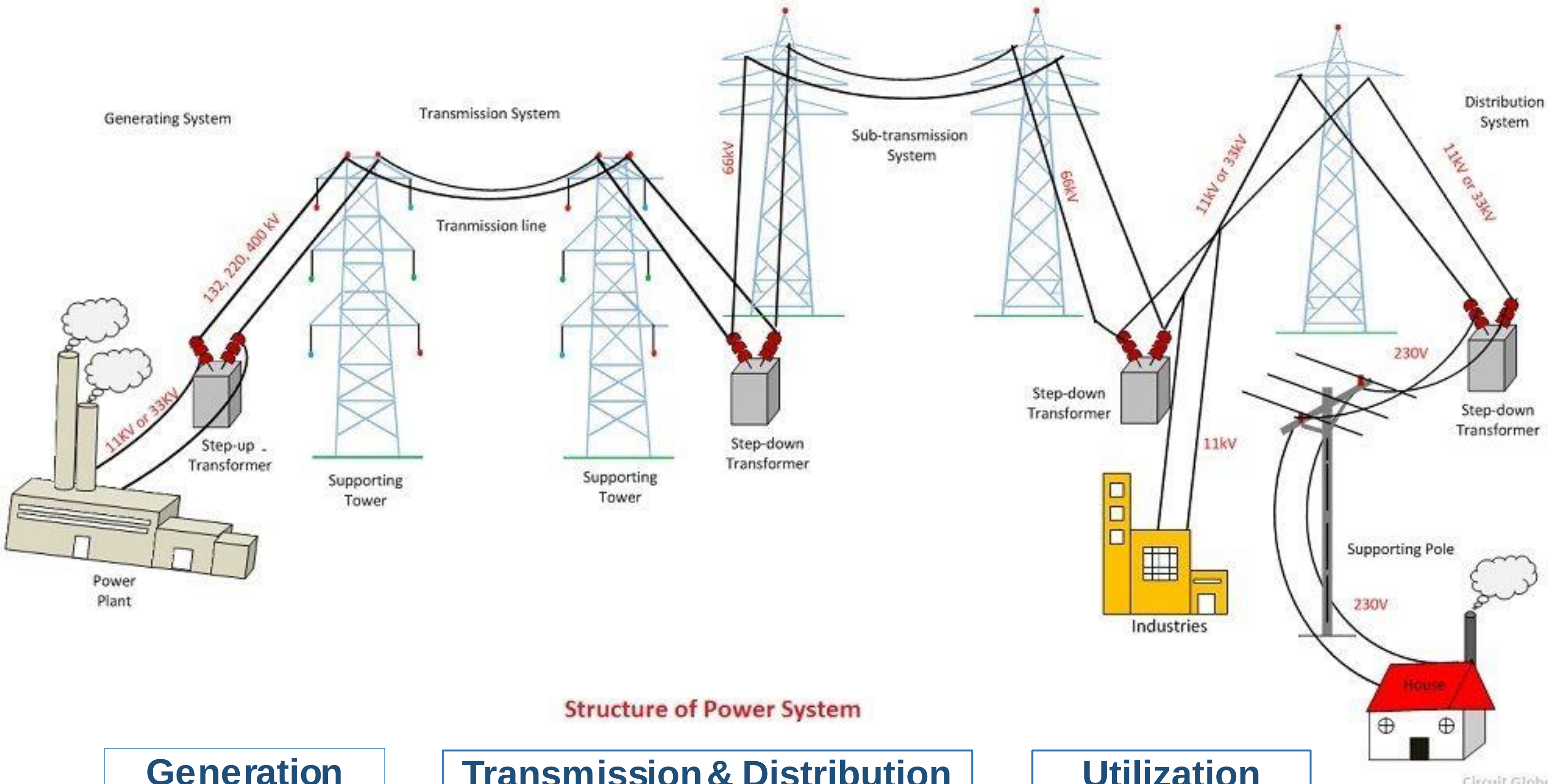
Electrical Machines

BCT – II/II

Department of Electronics & Computer Engineering

Ramesh Shrestha
Associate Professor/Principal

Components of Power Supply System



Structure of Power System

Generation	→	Transmission & Distribution	→	Utilization
Generator		Transformer		Motor

Courses/Chapters

1. Magnetic Circuits and Induction
2. Transformers
3. DC Generators
4. DC Motors
5. Three Phase Induction Machines
6. Three Phase Synchronous Machines
7. Fractional Kilowatt Motor

Reference Books

1. A Text Book of Electrical Technology - Vol II
   By A. K. Theraja and B. L. Theraja
2. Principles of Electrical Machines
   By V. K. Mehta
3. Electrical Machines
   By S. K. Bhattacharya
4. Electric Machines
   By I. J. Nagrath and D. P. Kothari
5. Electric Machinery
   By A. E. Fitzgerald, Charles Kingsley and Stephen D. Umans

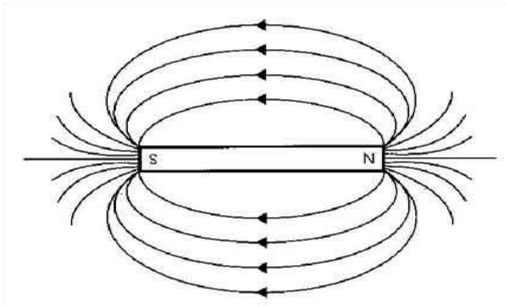
Evaluation/Internal Assessment

Particulars	Marks	Remarks
Attendance	2	
End Class Quiz/Test	6	
End Chapter Assignments	6	
Final Online Test/Viva	6	
Total	**20**	

Background

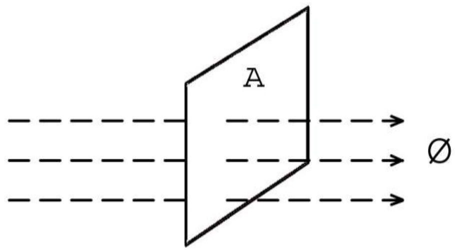
Magnetic Flux

- Magnetic field is represented by magnetic lines of force
- Quantitative representation of magnetic field is “**Magnetic Flux”**
- 10^8 lines of force = 1 weber



Magnetic Flux Density

- Flux per unit area
- $B = \frac{\emptyset}{A} \, (\frac{wb}{m2} = Tesla)$



“Area A normal to Ø”

Background

Magnetic Flux due to an electric current

Right hand rule for a straight wire

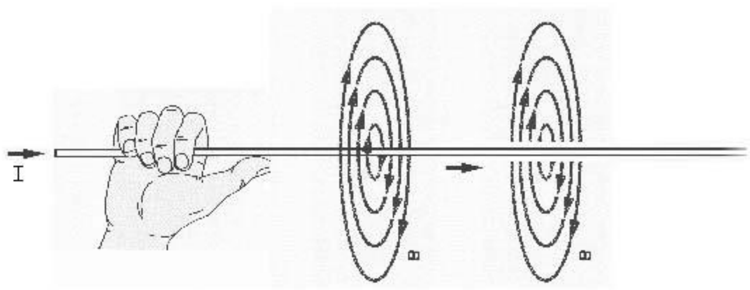


fig 1

Right hand rule for a coil

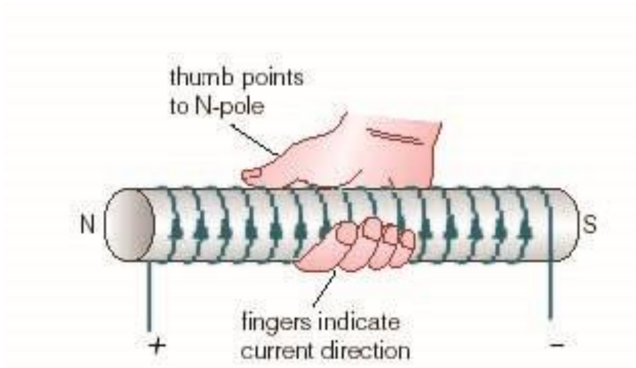


fig 2

1.1 Magnetic Circuits

- A closed path followed by magnetic flux, like a closed path followed by current in an Electric Circuit
- ABCDA is a magnetic circuit
- $MMF = Number\ of\ Turns * Current$
- $\mathrm{F} = N * I$

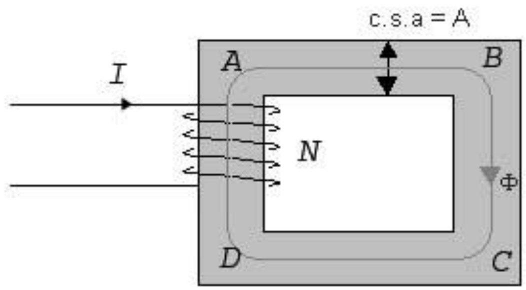


fig 4

1. Magnetic Circuits and Induction

1.2 Ohm's Law for Magnetic Circuits

Let, $l = mean\ length\ of\ magnetic\ circuit,$ ABCDA (m)

$A = Cross - sectional\ Area\ of\ the\ core$ (m^2)

$I = Current\ through\ the\ coil$ (Amp)

$\emptyset = Flux\ set\ up\ in\ the\ material\ (wb)$

$B = Flux\ Density$ (wb/m^2)

$\mu_{r.} = Relative\ Permeability$

We have,

$$B = \mu_0\mu_r H = \mu_0\mu_r \frac{N*I}{l}\ (Hl = NI, as\ per\ Work\ Law)$$

$$\frac{\emptyset}{A} = \mu_0\mu_r \frac{N*I}{l}\ (\text{where}\ \mu_0 = Permeability\ of\ free\ spac$$

$$\emptyset * \frac{l}{\mu_0\mu_r A} = N*I$$

$$\emptyset * R = F\ (\text{where}\ R = Reluctance = \frac{l}{\mu_0\mu_r A})$$

$\emptyset = \frac{F}{R}$ which is Ohm's Law for Magnetic Circuits

(Which is equivalent to $I = \frac{E}{R}$, where, $R = \rho\frac{l}{A}$)

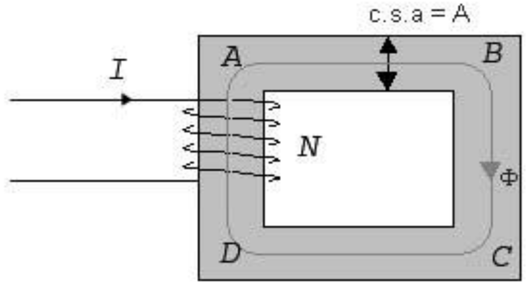
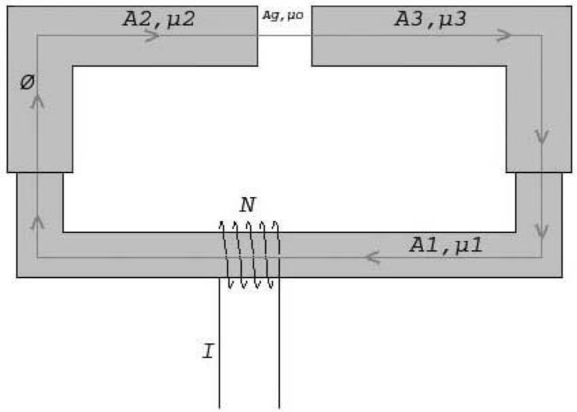


fig 4

1. Magnetic Circuits and Induction

1.3.1 Series Magnetic Circuits

- Same magnetic flux passes through all the section of the magnetic circuit
- Total Reluctance = Sum of Reluctance of individual Section
- $R = \sum \frac{l}{\mu A} = \frac{l_1}{\mu_1 A_1} + \frac{l_2}{\mu_2 A_2} + \frac{l_g}{\mu_0 A_g} + \frac{l_3}{\mu_3 A_3}$
- Total MMF= Flux $*$ Total Reluctance
- $F = \emptyset \sum \frac{l}{\mu A}$



1.3.2 Parallel Magnetic Circuits

- A magnetic circuit with more than one path for flux
- The flux Ø, set up by the coil divides at B into two paths.
- Total MMF = MMF across path EFAB + MMF across path BE (or Path BCDE)
- $F = Ø_1 R_1 + Ø_2 R_2 = Ø_1 \frac{l_1}{\mu_1 A_1} + Ø_2 \frac{l_2}{\mu_2 A_2}$

or

- $F = Ø_1 R_1 + Ø_3 R_3 = Ø_1 \frac{l_1}{\mu_1 A_1} + Ø_3 \frac{l_3}{\mu_3 A_3}$

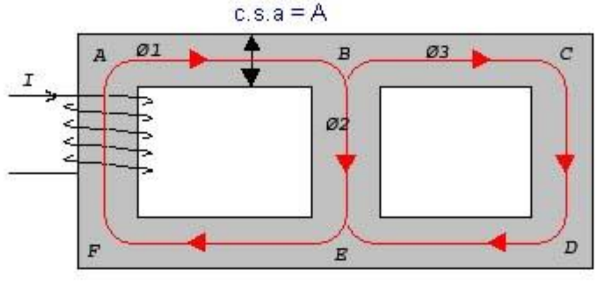


fig 1 parallel magnetic circuit

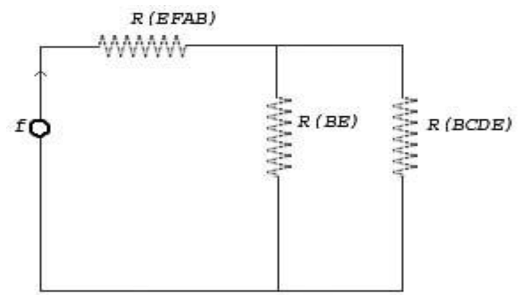


fig 2 Equivalent circuit

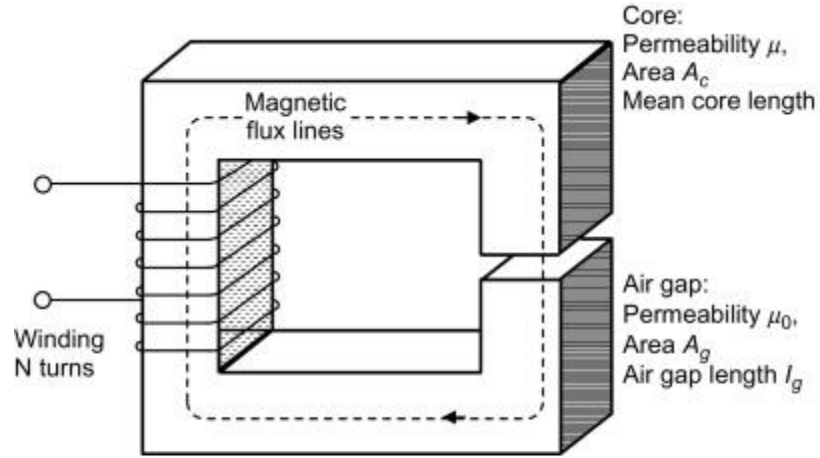
1. Magnetic Circuits and Induction

1.4 Core with air gap

- Air gap has high reluctance

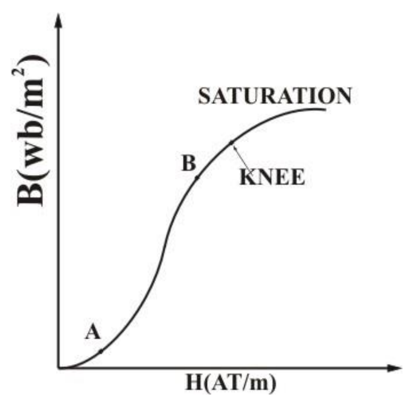
  $(R = Reluctance = \frac{l}{\mu_0 \mu_r A})$

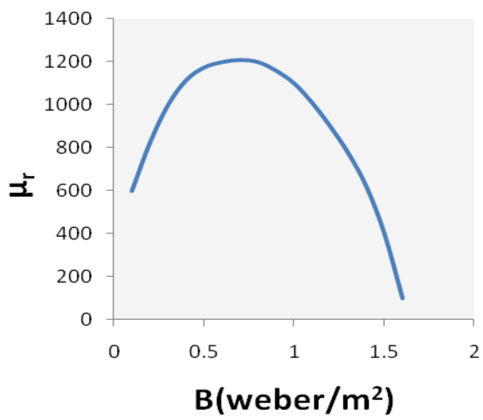
- Reduces magnetic flux
- Similar to addition of very high resistance in series with low resistance, in case of series electric circuit



1.5 B-H Curve/Magnetization Curve

- Relationship between flux density (B) and magnetizing force (H)
- Non-linearity of the curve indicates that μ_r (= B / μ_o H) is not constant but depends very largely upon the flux density





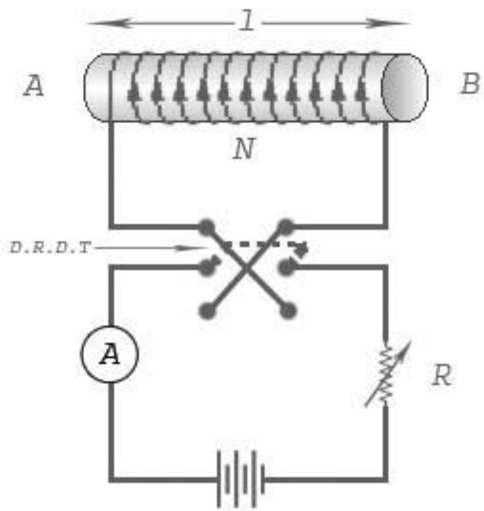
1.6.1 Hysteresis with DC excitation

***Hysteresis**:*

Phenomenon of lagging of flux density (B) behind the magnetizing force (H), subjected to cycles of magnetization

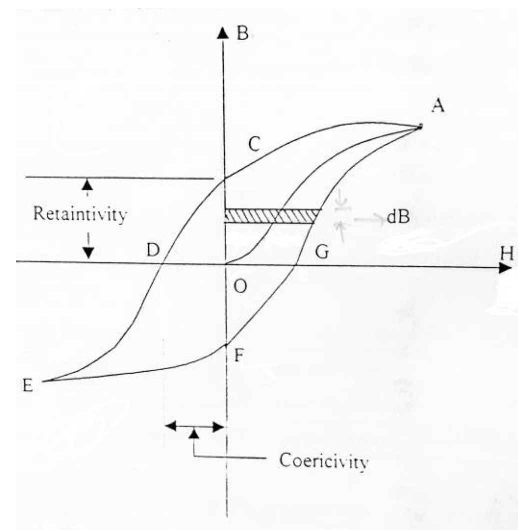
Hysteresis Loop:

A closed curve showing the variation of B with H when magnetic field is changed through a complete cycle of magnetization



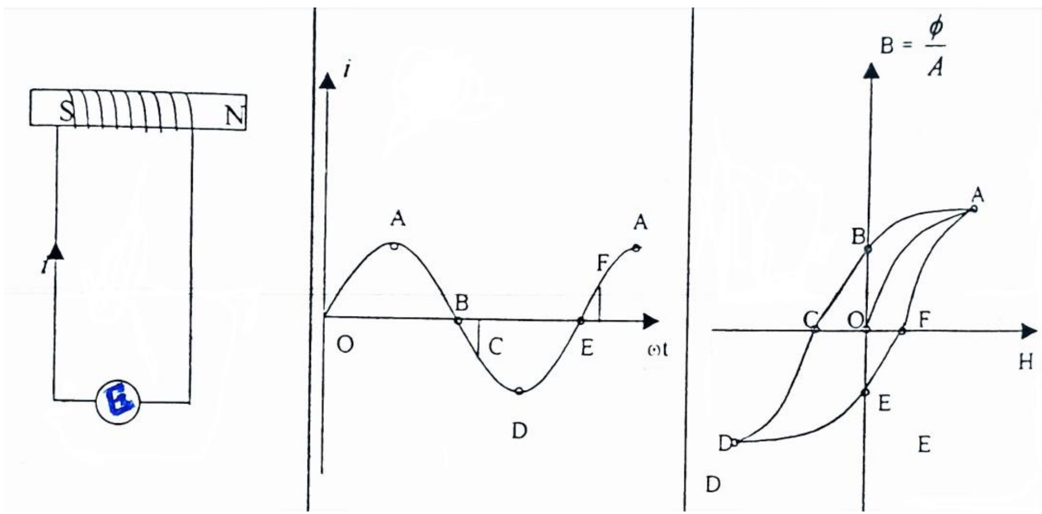
$$B = \frac{\emptyset}{A}$$

$$H = \frac{N * I}{l}$$



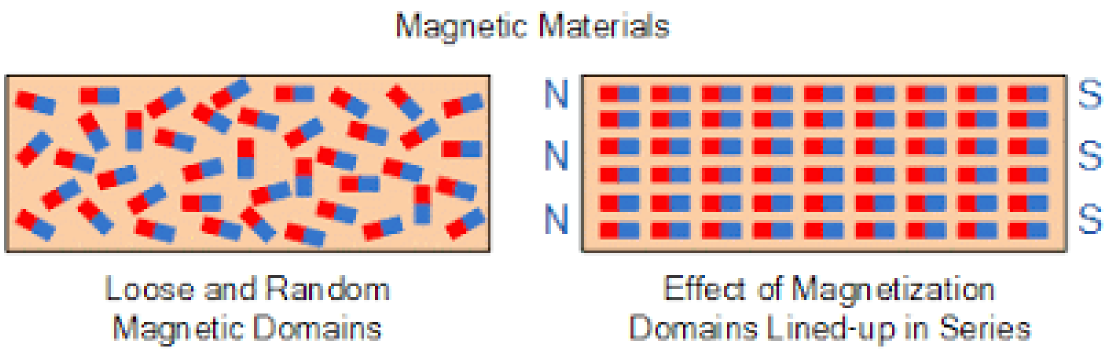
1.6.2 Hysteresis with AC excitation

- Magnetic reversal twice in one cycle of AC excitation
- Energy proportional to the triangular shaded area is lost in every cycle to demagnetize the residual magnetic flux
- Area of hysteresis loop is equal to energy loss due to hysteresis



1.7.1 Hysteresis Loss

- Weber's molecular theory of magnetism:
  Molecular magnets gets aligned in a straight line after magnetization
- Energy loss due to molecular friction
- Energy expended/loss as a heat in overcoming the opposition



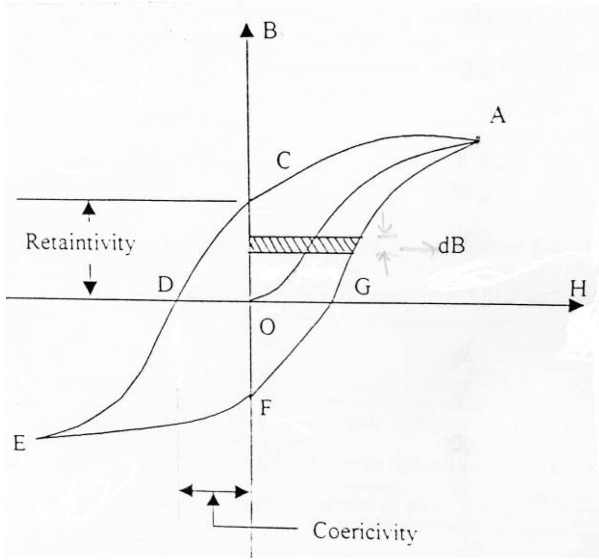
1.7.1 Hysteresis Loss Calculation

Let, $l = Length\ of\ an\ iron\ core$ (m)

$A = Cross-sectional\ Area\ of\ the\ core$ (m²)

$N = Number\ of\ turns$ of the coil

$B = Flux\ Density$ (wb/m²)



Emf induced due to time varying flux is:

$e = N\frac{d\phi}{dt} = N\frac{d}{dt}(B.A) = NA\frac{d}{dt}(B)$

When current 'I' is supplied, H is given by

$H = \frac{N*I}{l}$ or, $I = \frac{H*l}{N}$

Power (rate of expenditure of Energy)

$p = e.I = NA\frac{d}{dt}(B) . \frac{H*l}{N} = A.l.H .\frac{d}{dt}(B)$

Energy spent in time dt is given by

$dw = pdt = A.l.H.dB$ Joule

Hence, total energy spent in a cycle of magnetization, $W = A.l.\oint H.dB$

$\therefore$ Energy spent per cycle per unit volume $= \oint H.dB =$ Area of the hysteresis loop

$\therefore W_h = \oint H.dB$

1. Magnetic Circuits and Induction

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1.7.1 Hysteresis Loss

Experimentally,

Hysteresis Loss is given by

$$W_e = \eta B_m^{1.6} f \, V watts$$

where,

B_m = maximum value of flux density

f = frequency of the exciting current

V = volume of iron core

η = Steinmetz constant

= 502 Joules/m^3 for sheet steel

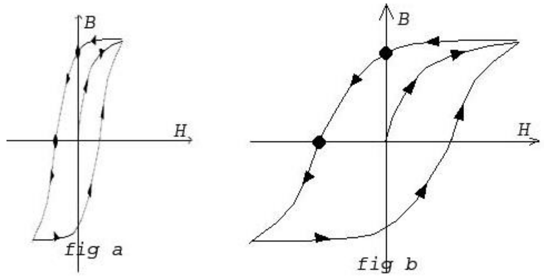
= 191 Joules/m^3 for silicon steel

Soft Magnetic Material

- High retaintivity and Low coercivity
- Hysteresis loop area is smaller (Fig: a)
- Hysteresis loss is less
- Suitable for making transformer core and rotating machines

Hard Magnetic Material

- High retaintivity and High coercivity
- Larger Hysteresis loop area (Fig: b)
- Greater Hysteresis loss
- Suitable for making Permanent Magnet



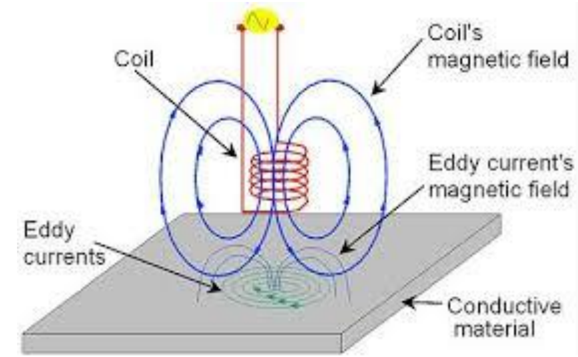
1.7.2 Eddy Current Loss

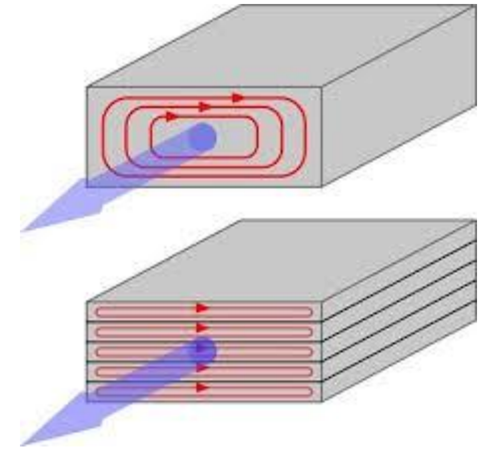
- Eddy Current:
  Circulating current due to emf induced in a core
- Power loss due to heat produced by the circulating current is eddy current loss
- Experimentally, Eddy Current Loss is given by

$$W_e = KBm^2 f^2 t^2 \, V \; watts$$

where,

B_m = maximum value of magnetic flux density
f = frequency of the exciting current
V = volume of iron core
t = thickness of each lamination
k = constant depending upon the nature of core.





1.8.1 Faraday's Law of Electromagnetic Induction

1st Law:

Whenever the magnitude of magnetic flux linking with a coil/conductor changes with respect to time, an emf induces across the coil/conductor.

2nd Law:

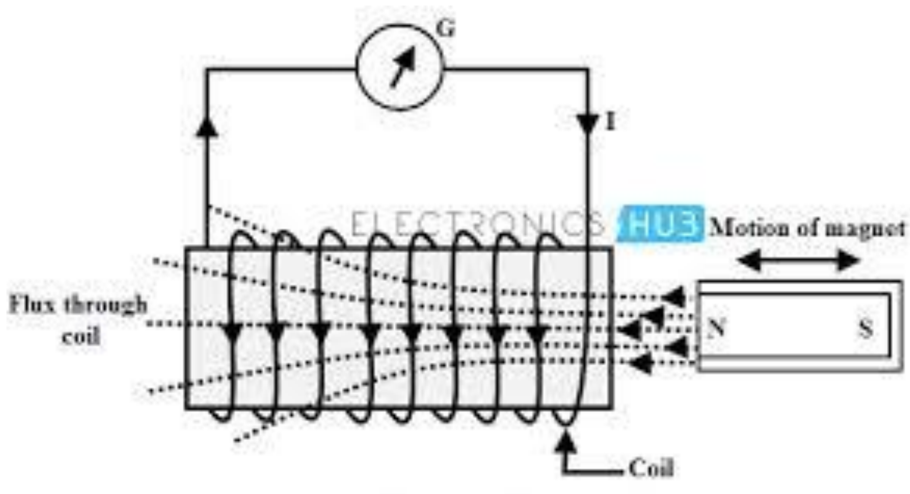
The magnitude of induced emf is equal to the rate of change of flux linkage, i.e.,

$e = -\frac{d(N\emptyset)}{dt} = -N\frac{d\emptyset}{dt}$, where NØ is called flux linkage

https://youtu.be/yU--8Zk57-Y

1.8.2 Statically Induced emf

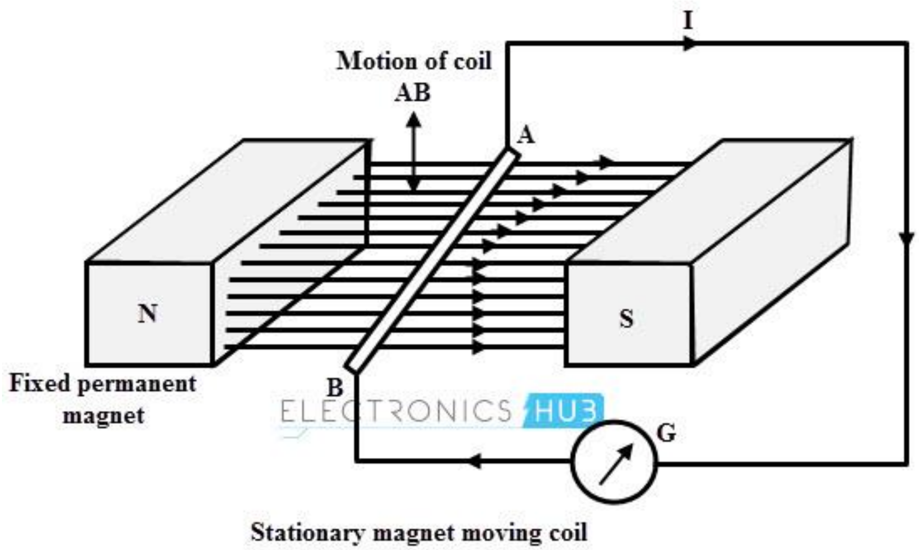
- Coil remains stationary with respect to the flux
- Magnitude of flux through the coil changes with respect to time



Stationary Coil Moving Magnet

1.8.3 Dynamically Induced emf

- Magnetic flux remains constant and stationary
- Coil moves relative to the magnetic flux



1.9 Force on a current carrying conductor

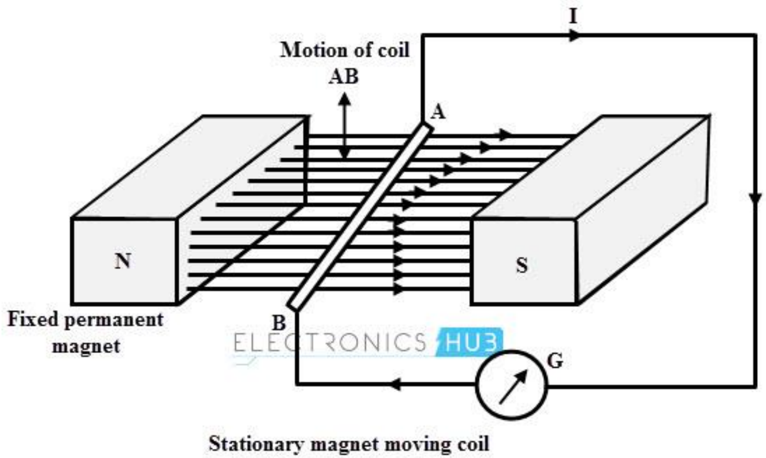
- Current carrying conductor in a magnetic field experiences a force
- The magnitude of the force is: F= $B.I.L$ (Newton)

Where,

B = Magnetic Field Density (wb/m^2)

I = Current through the conductor (Amp)

L = Length of the conductor (m)



Questions!

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Chapter 2: Transformers

Electrical Machines

BCT – II/II

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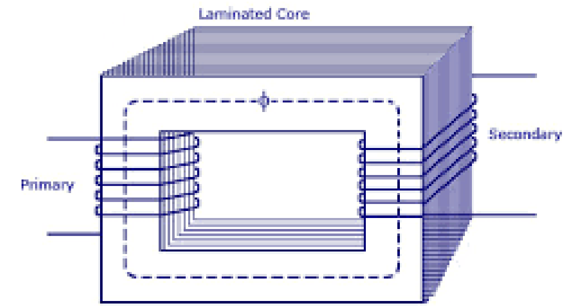
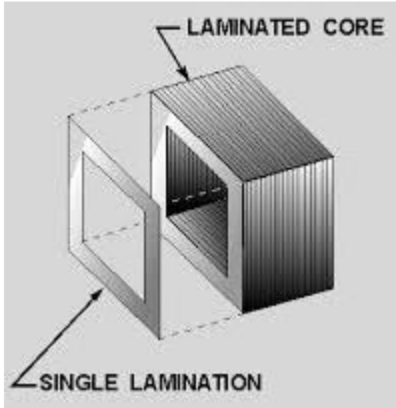
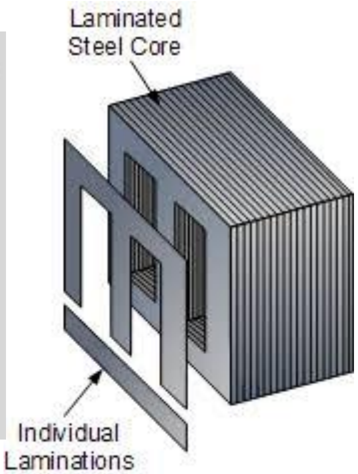
2. Transformers

2.1 Definition and Construction

- Transfers electrical power from one circuit to the other.
- The two circuits are electrically isolated but magnetically linked.
- Voltage level in both the circuits may be different but the frequency remains the same.
- Transformers are made up of laminated steel core.
- The core is constructed by assembling laminated sheets of steel.
- The silicon steel is used to provide high permeability and low hysteresis loss.
- Laminated sheets are used to reduce eddy current loss



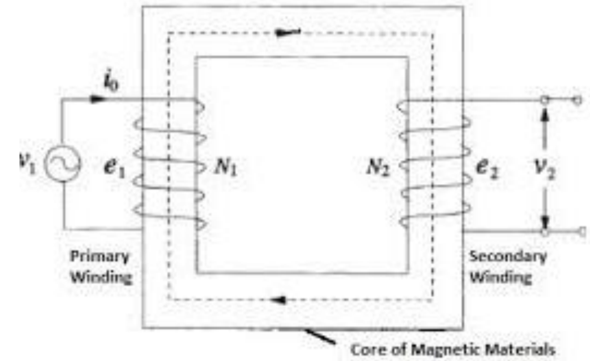




2. Transformers

2.2.1 Working Principle

- Primary circuit/coil when supplied by ac voltage draws current I_0
- I_0 set up alternating magnetic flux (Ø) in the iron core,
- The alternating flux Ø induces EMFs E_1 and E_2 according to Faraday's laws of electromagnetic induction



2.2.2 EMF Equation

- When alternating voltage V_1 of frequency f is applied to primary, sinusoidal flux Ø produced in the core is given by

$$\emptyset = \emptyset_m Sin\omega t$$

EMF induced in the primary winding is

$$e_1 = -N_1\frac{d\emptyset}{dt} = -N_1\frac{d}{dt}(\emptyset_m Sin\omega t) = -\omega N_1\emptyset_m Cos\omega t$$

$$= -2\pi f N_1\emptyset_m Cos\omega t = 2\pi f N_1\emptyset_m Sin(\omega t - 90) \text{ .... (1)}$$

$\therefore E_{m1} = 2\pi f N_1\emptyset_m$ *and* rms value of E_{m1} is given by

$$E_1 = \frac{Em1}{\sqrt{2}} = \frac{2\pi f N_1\emptyset_m}{\sqrt{2}} = 4.44 f N_1\emptyset_m \text{ ....(2)}$$

Similarly, $E_2 = 4.44 f N_2\emptyset_m$ ....(3)

From equation (2) and (3)

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

Where,

$\frac{N_2}{N_1}$ = K = Transformation Ratio

$E_2 I_2 = E_1 I_1$

$$\frac{E_2}{E_1} = \frac{I_1}{I_2} = \frac{N_2}{N_1}$$

(i) If $N_2 > N_1 (K > 1)$,

Step up Transformer

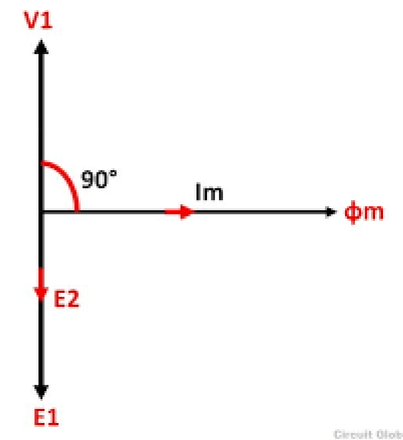
(ii) If $N_2 < N_1 (K < 1)$,

Step down Transformer

2. Transformers

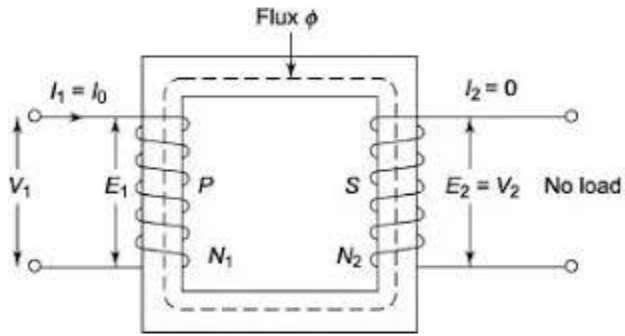
2.3 Ideal Transformer

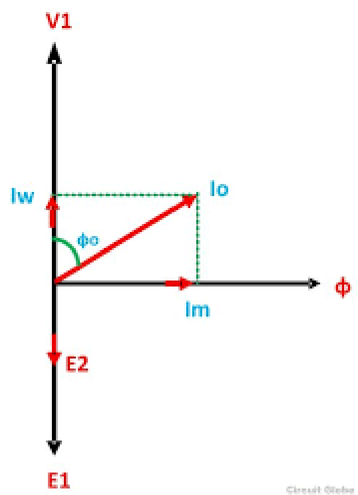
- With purely inductive windings without any resistance
- No magnetic leakage flux
- 100% efficient without any power loss
- Just a mathematical abstraction, cannot be realized in practice



2. Transformers

2.4. No-load operation



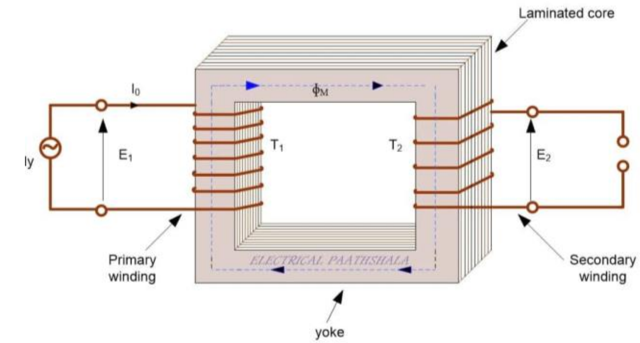


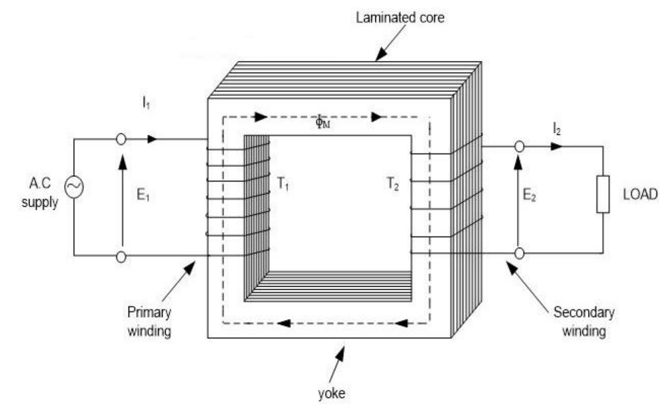
- $I_w = I_0\, Cos\, \emptyset_0 = Working\ Compponent\ of\ I_0$
- $I_m = I_0\, Sin\, \emptyset_0 = Magnetising\ Compponent\ of\ I_0$
- $Cos\, \emptyset_0 = \frac{I_w}{I_0} = No\ load\ power\ factor\ of\ T/F$
- $I_0 = \sqrt{{I_w}^2 + Im^2} = No\ load\ current$
- $W_0 = V_1 I_0\, Cos\, \emptyset_0 = No\ load\ power\ loss$
- I_w is responsible for producing heat loss in the core
- I_m is responsible for producing magnetic flux in the core
- W_0 is power consumed by the transformer at no-load

2. Transformers

2.5 Full load operation (T/F with Load)

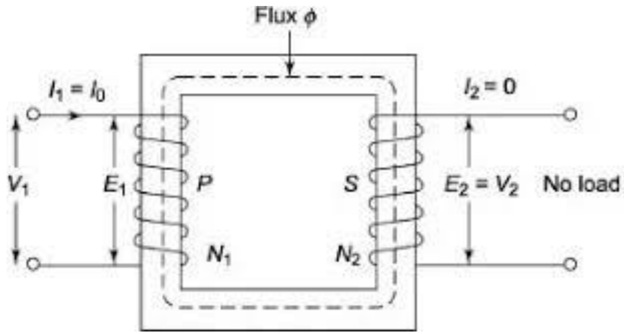
- At no load,
  Output = $V_2 I_2$ = 0 and Input = $V_1 I_0$ = Power Loss at no load
- When Loaded, I_2 starts flowing through the secondary circuit. MMF $N_2 I_2$ sets up its own flux $\emptyset_2$, in a direction opposite to the main flux $\emptyset$.
  Output = $V_2 I_2 \neq 0$
- Additional current I_2' will flow in the primary circuit to maintain the power in the secondary circuit.
- The I_2' will set up its own flux $\emptyset_2'$ with equal in magnitude but in opposite to the direction of $\emptyset_2$. And hence the flux in the core remains constant. Mathematically,
- $V_1 I_2' = V_2 I_2$ or, $\frac{V_2}{V_1} = \frac{I_2'}{I_2} = \frac{N_2}{N_1}$ or, $N_1 I_2' = N_2 I_2$
- $\emptyset_2 = \frac{N_2 I_2}{Reluctance}$ and $\emptyset_2' = \frac{N_1 I_2'}{Reluctance}$
- Since Reluctance for both the case is the same, $\emptyset_2 = \emptyset_2'$

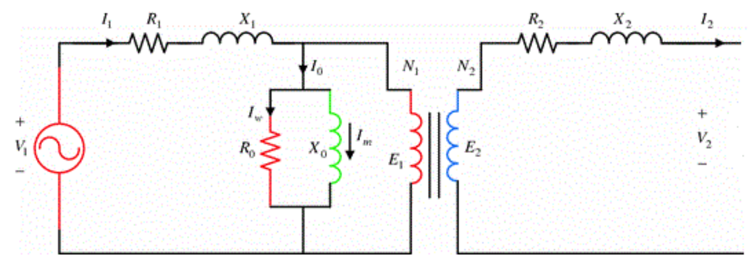




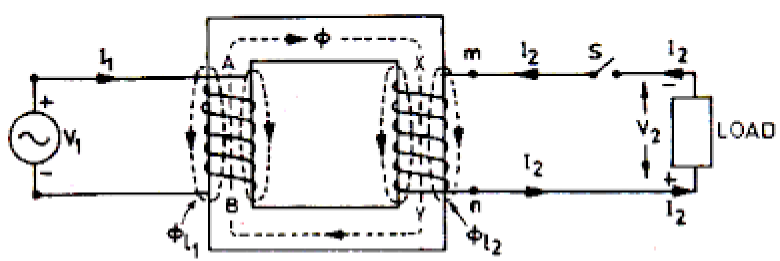
2.6.1 Equivalent Circuits

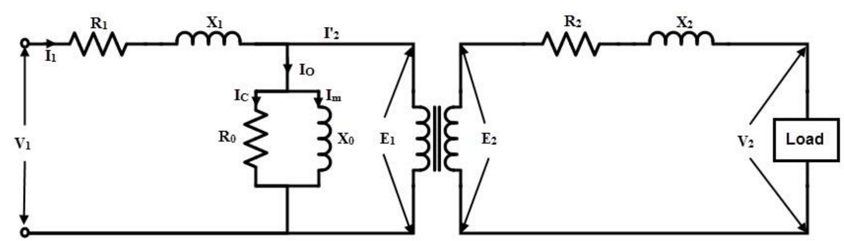
At no load:





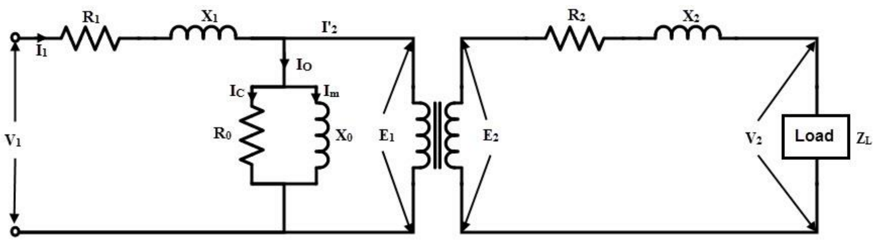
At full load:

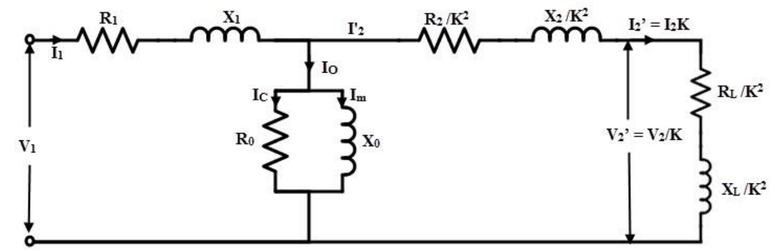


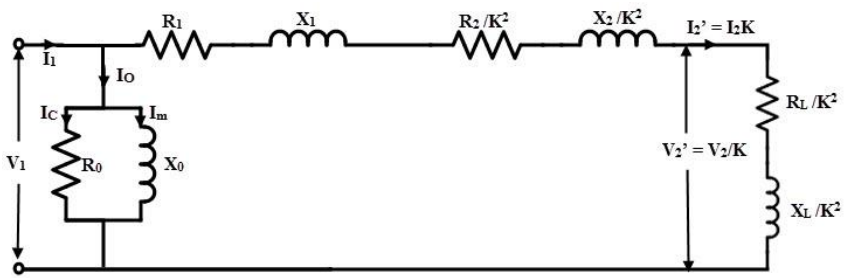


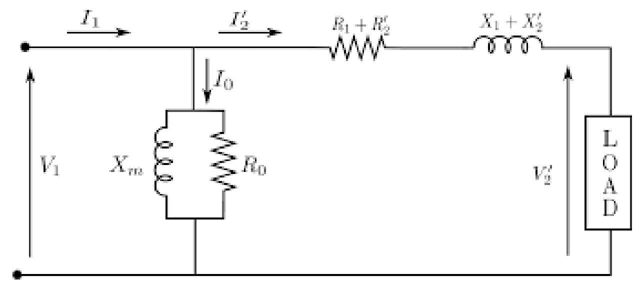
2. Transformers

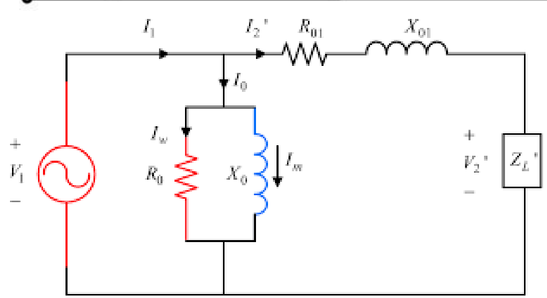
2.6.2 Equivalent Circuits as referred to primary side









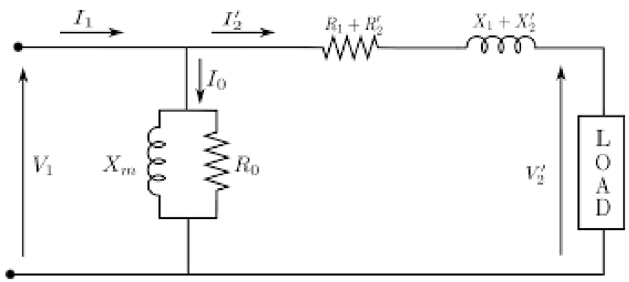


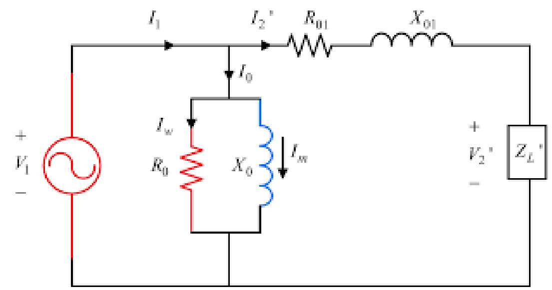
R_2' is the equivalent of R_2 referred to primary side

Effect of R_2' in primary sided is equivalent to the effect of R_2 in secondary side

$I_2'^2 R_2' = I_2^2 R_2$ or $R_2' = \left(\frac{I_2}{I_2'}\right)^2 R_2 = \left(\frac{N_1}{N_2}\right)^2 R_2$ or $R_2' = \left(\frac{1}{K^2}\right) R_2$

2.6.2 Equivalent Circuits as referred to primary side



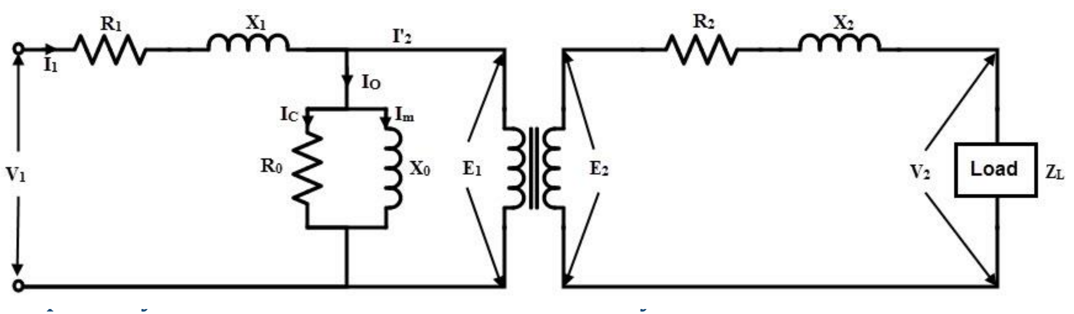


$$R_{01} = R_1 + R_2{}' = R_1 + \left(\frac{N_1}{N_2}\right)^2 R_2 = R_1 + \left(\frac{1}{K^2}\right) R_2 = Total\ Eq. Resistance\ of\ a\ TF\ referred\ to\ Primary\ Side$$

$$X_{01} = X_1 + X_2{}' = X_1 + \left(\frac{N_1}{N_2}\right)^2 X_2 = X_1 + \left(\frac{1}{K^2}\right) X_2 = Total\ Eq. Reactance\ of\ a\ TF\ referred\ to\ Primary\ Side$$

$$Z_{01} = \sqrt{R_{01}{}^2 + X_{01}{}^2} = Total\ Eq. Impedance\ \ of\ a\ TF\ referred\ to\ Primary\ Side$$

2.6.3 Phasor Diagram



$$V_1 - I_1R_1 - jI_1X_1 = E_1$$

$$V_1 = E_1 + I_1R_1 + jI_1X_1$$

$$E_2 - I_2R_2 - jI_2X_2 = V_2$$

$$V_2 = E_2 - I_2R_2 - jI_2X_2$$

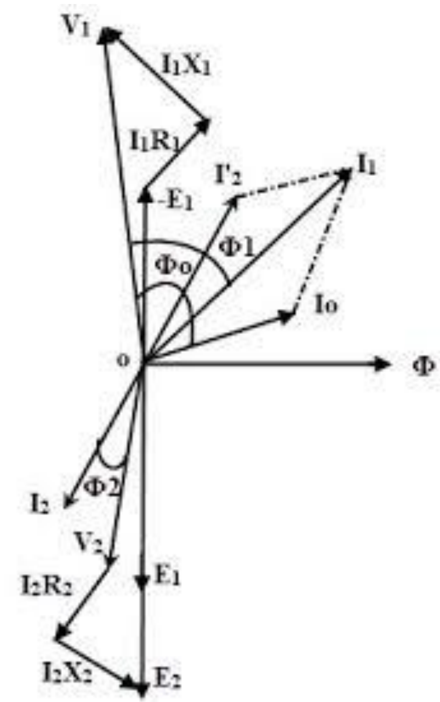
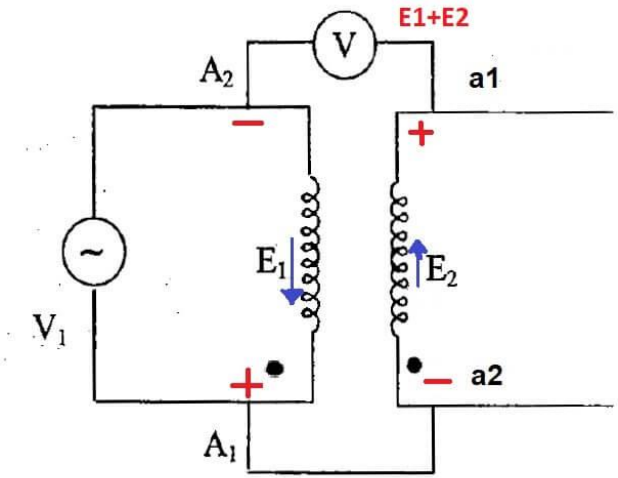


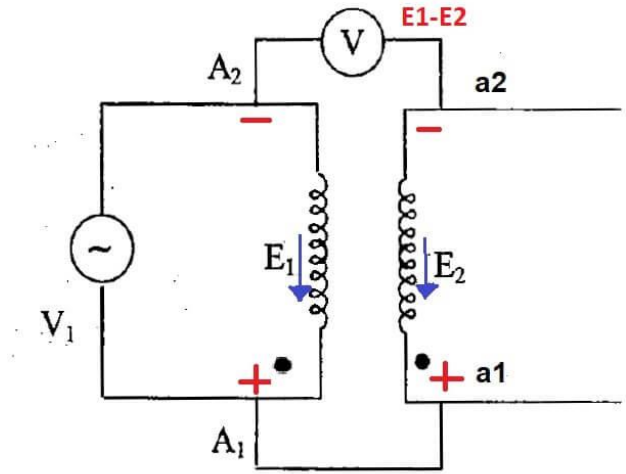
Fig: Phasor diagram of a T/F with Inductive Load

2.7 Transformer Tests

2.7.1 Polarity Test



Additive polarity

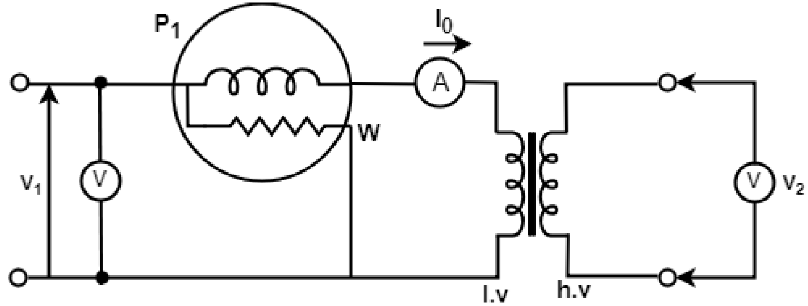


Subtractive polarity

2.7 Transformer Tests

2.7.2 Open Circuit Test (OC TEST)

- Objectives: To find R_0 and X_0 or R_0' and X_0'
- Open HV side, perform test on lv side
- Wattmeter reading is considered to be equal to iron loss, as the copper loss is negligibly small in case of OC Test



V_0 = Voltmeter Reading
I_0 = Ammeter Reading
W_0 = Wattmeter Reading

$$W_i = W_0 = V_1 I_0 \, Cos\emptyset_0$$

$$Cos\,\emptyset_0 = \frac{W_0}{V_1 I_0} = no\ load\ pf$$

$\therefore I_w = I_0 Cos\emptyset_0$ and

$$I_m = I_0\,Sin\,\emptyset_0$$

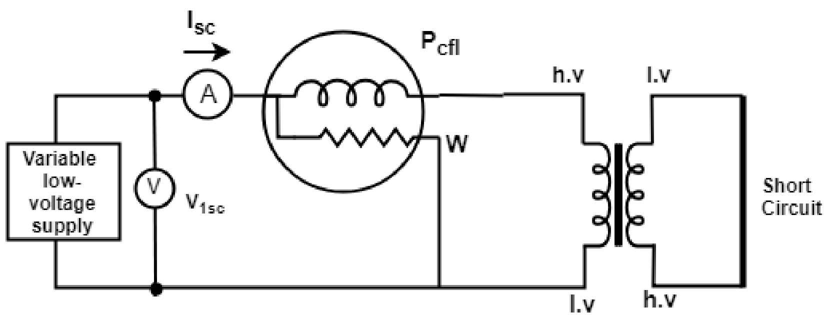
$$R_0 = \frac{V_1}{I_w}$$

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

2.7 Transformer Tests

2.7.3 Short Circuit Test (SC Test)

- Objectives: To find R_{01} and X_{01} or R_{02} and X_{02}
- Short circuit LV side, perform test on HV side
- Wattmeter reading is considered to be equal to copper loss, as the iron loss is negligibly small in case of SC Test



V_{sc} = Voltmeter Reading
I_{sc} = Ammeter Reading
W_{sc} = Wattmeter Reading

Wattmeter reading is considered to be equal to copper loss, i.e.

$$W_{Cu} = W_{sc} = I_{sc}^2 R_{02}$$

$$R_{02} = \frac{W_{sc}}{I_{sc}^2}$$

$$Z_{02} = \frac{V_{sc}}{I_{sc}}$$

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

2. Transformers

2.8 Voltage Regulation

A measure of change in the magnitude of secondary voltage of a transformer when load is changed from no load to full load keeping the primary voltage constant.

$$Voltage\ Regulation = \frac{V_{nl} - V_{fl}}{V_{nl}} = \frac{E_2 - V_2}{E_2}$$

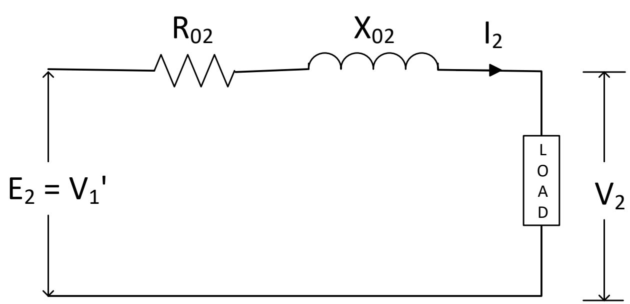
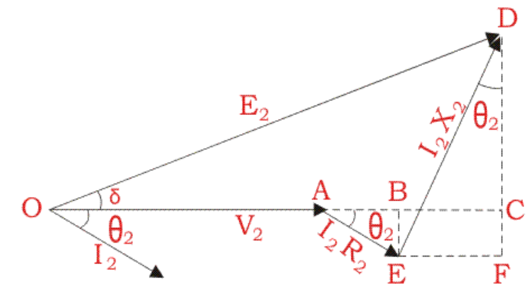


Fig: Eq. Ckt diagram of a Transformer

From the eq. circuit, a voltage equation is

$$E_2 - I_2R_{02} - jI_2X_{02} = V_2$$
$$E_2 = V_2 + I_2R_{02} + jI_2X_{02}$$

Voltage Regulation of a T/F for Inductive Load



From the above phasor diagram

$$OC = OA + AB + BC$$
$$= OA + AB + EF$$
$$OC = V_2 + I_2R_{02}Cos\ \theta_2 + I_2X_{02}Sin\ \theta_2$$
$$OD = V_2 + I_2R_{02}Cos\ \theta_2 + I_2X_{02}Sin\ \theta_2$$ [For small arc, OC=OD]
$$E_2 = V_2 + I_2R_{02}Cos\ \theta_2 + I_2X_{02}Sin\ \theta_2$$
$$E_2 - V_2 = I_2R_{02}Cos\ \theta_2 + I_2X_{02}Sin\ \theta_2$$
$$= I_2(R_{02}Cos\ \theta_2 + X_{02}Sin\ \theta_2)$$

$$\therefore Voltage\ Regulation\ (\%) = \frac{E_2 - V_2}{E_2}\ X\ 100\%$$
$$= \frac{I_2(R_{02}Cos\ \theta_2 + X_{02}Sin\ \theta_2)}{E_2}\ X\ 100\%$$

2. Transformers

2.9.1 Losses and Efficiency

- Loss is the difference between input power and output power.
- Transformer has Iron Loss (Core Loss) and Copper Loss.
- Iron Loss (W_i) is the sum of hysteresis loss and eddy current loss.
- Hysteresis loss and Eddy current loss is due to alternating flux in a transformer core. Since flux remains always constant in a transformer core, **iron loss is always constant**. Hence, it is known as constant loss.
- Copper loss (W_{cu}) is due to ohmic resistance of the transformer windings.

  $W_{Cu} = I_1^2R_1 + I_2^2R_2 = I_1^2R_{01} = I_2^2R_{02}$

  Where,

  I_1 and I_2 are primary and secondary winding current

  R_1 and R_2 are resistances of primary winding and secondary winding

  R_{01} is total eq. resistance of a transformer referred to primary side

  R_{02} is total eq. resistance of a transformer referred to secondary side

- Cu loss is proportional to the square of current, and current depends on the load. Hence **copper loss in transformer varies with the load**

2. Transformers

2.10.1 Efficiency

Efficiency of a transformer is given by

$$\eta = \frac{Output}{Input} = \frac{Input - Losses}{Input} = \frac{V_1 I_1 Cos\emptyset_1 - Losses}{V_1 I_1 Cos\emptyset_1}$$

$$\eta = \frac{Output}{Input} = \frac{Output}{Output + Losses} = \frac{V_2 I_2 Cos\emptyset_2}{V_2 I_2 Cos\emptyset_2 + Losses} = \frac{V_2 I_2 Cos\emptyset_2}{V_2 I_2 Cos\emptyset_2 + W_{cu} + Wi}$$

∴ Efficiency, $\eta = \frac{VA * pf}{VA * pf + W_{cu} + Wi}$

Efficiency at Full Load, $\eta_{fl} = \frac{Full\ Load\ VA * pf}{Full\ Load\ VA * pf + W_{cu} + Wi}$

Efficiency at any Load, $\eta = \frac{x * Full\ Load\ VA * pf}{x * Full\ Load\ VA * pf + x^2 * Wcu + Wi}$

Where x is loading factor (e.g. for 60% load, $x = {}^{60}/_{100}$ = 0.6, for half load, x = ½ = 0.5)

2. Transformers

2.10.2 Condition for Maximum Efficiency

Efficiency of a transformer is given by

$$\eta = \frac{V_1 I_1 Cos\emptyset_1 - Losses}{V_1 I_1 Cos\emptyset_1} = \frac{V_1 I_1 Cos\emptyset_1 - (W_{cu} + Wi)}{V_1 I_1 Cos\emptyset_1}$$

$$\eta = 1 - \frac{I_1{}^2 R_{01}}{V_1 I_1 Cos\emptyset_1} - \frac{W_i}{V_1 I_1 Cos\emptyset_1} = 1 - \frac{I_1 R_{01}}{V_1 Cos\emptyset_1} - \frac{W_i}{V_1 I_1 Cos\emptyset_1}$$

For Maximum Efficiency,

$$\frac{d\eta}{dI_1} = 0$$

$$\frac{d}{dI_1}[1 - \frac{I_1 R_{01}}{V_1 Cos\emptyset_1} - \frac{W_i}{V_1 I_1 Cos\emptyset_1}] = 0$$

$$0 - \frac{R_{01}}{V_1 Cos\emptyset_1} + \frac{W_i}{V_1 I_1{}^2 Cos\emptyset_1} = 0$$

$$\frac{R_{01}}{V_1 Cos\emptyset_1} = \frac{W_i}{V_1 I_1{}^2 Cos\emptyset_1}$$

$$I_1{}^2 \mathrm{R}_{01} = W_i \qquad or, \qquad I_2{}^2 \mathrm{R}_{02} = Wi \quad i.e.,$$

$$Copper\ Loss = Iron\ Loss$$

Efficiency of a transformer will be maximum when
Copper Loss and Iron Loss are equal

From above equation, the load current corresponding to maximum efficiency is

$$I_2 = \sqrt{\frac{W_i}{R_{02}}}$$

For maximum efficiency,

$$x^2 * Wcu = Wi$$

$$x = \sqrt{\frac{W_i}{W_{cu}}}$$

Output KVA corresponding to maximum efficiency

$$= x * full\ load\ KVA$$

$$= full\ load\ KVA * \sqrt{\frac{W_i}{W_{cu}}}$$

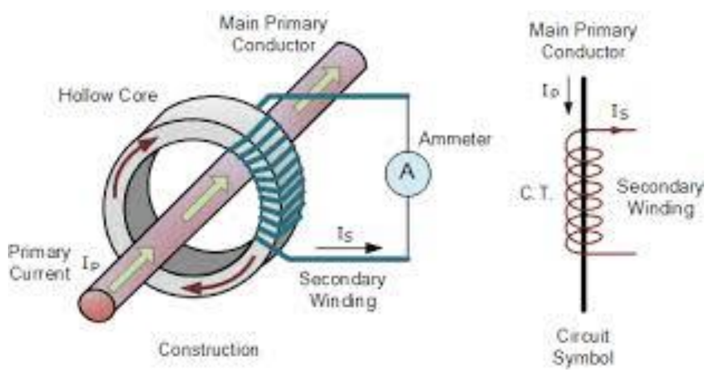
2.10.3 All Day Efficiency

- Iron or core loss takes place in the core of a transformer. It occurs for the whole day, even when there is no load. It is also known as constant loss.
- Copper loss takes place in the winding of a transformer. It occurs only when the transformer is on loaded condition. It is also known as variable loss.
- The performance of a transformer, therefore cannot be judged by the commercial or ordinary efficiency, but the efficiency is calculated or judged by All Day Efficiency also known as operational efficiency or energy efficiency which is computed by the energy consumed for 24 hours.
- All Day Efficiency is defined as the ratio of output power to input power in kWh of a transformer over 24 hours of time.

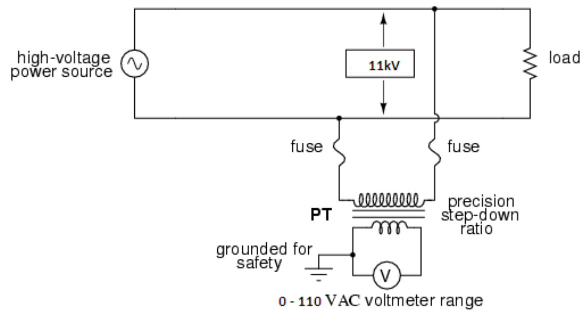
$$\eta_{\text{all day}} = \frac{Output\ in\ kWh}{Input\ in\ kWh}\ (for\ 24\ hours)$$

2.11 Instrument Transformers

- Specially constructed transformers for the measurement of high voltage and high current in ac circuits
- The primary winding of the transformer is connected to the high voltage or high current circuit, and the meter or relay is connected to the secondary circuit.
- Types of Instrument Transformers:
  1. Potential Transformer (PT)
  2. Current Transformers (CT)



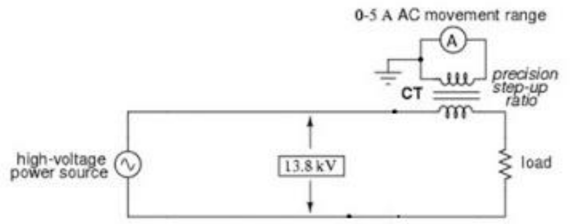
2.11.1 Potential/Voltage Transformer (PT)



- PT is used to measure voltage of very high magnitude. It is a step down transformer which steps down the voltage of high magnitude to a lower voltage which can be measured with normal range voltmeter. For example, a 11kV:110V PT would mean the voltage across secondary is 110 volts when primary voltage is 11kV volts.
- The primary winding of PT is connected in parallel with the line across which voltage is to be measured and the secondary is connected to the voltmeter.

2.11.2 Current Transformer (CT)

- CT is used to measure currents of high magnitude. It steps down the current to be measured, so that it can be measured with a normal range ammeter.
- It has only one or very few number of primary turns. The secondary winding has large number turns. Thus the current transformer steps up (increases) the voltage while stepping down (lowering) the current. A 5:100 CT would mean the secondary current of 5 amperes when primary current is 100 amperes.
- The primary winding of CT is connected in series with the line in which current is to be measured and the secondary is connected to the ammeter.

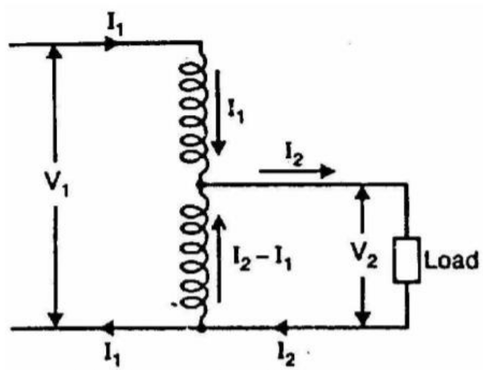


2. Transformers

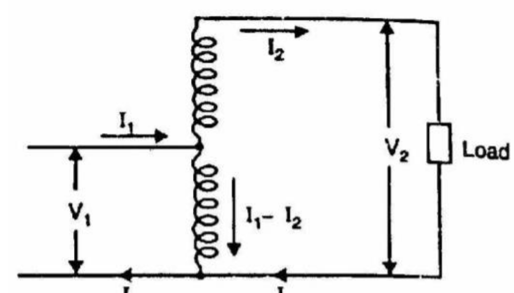
2.12 Auto Transformer

2.12.1 Construction and Working Principle

- A single winding transformer
- A part of the winding is common to both primary and secondary circuits
- Primary and secondary windings are connected electrically as well as magnetically.
- Therefore, power from the primary is transferred to the secondary conductively as well as inductively (transformer action).



Step-down autotransformer

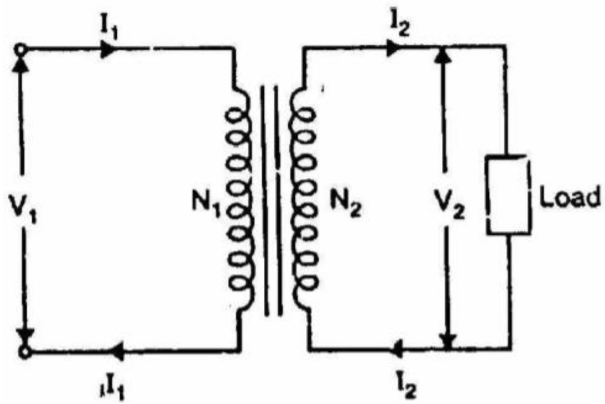


Step-up autotransformer

2.12.2 Cu Saving in an Auto Transformer

- For the same output and voltage transformation ratio K(N2/N1), an autotransformer requires less copper than an ordinary 2-winding transformer.

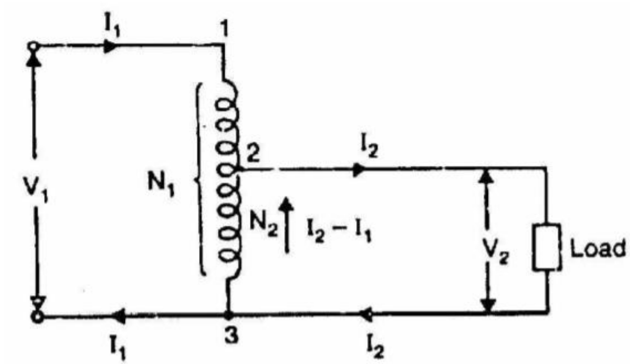
- $Weight \propto Volume \propto (Length * Area\ of\ Cross\ Section)$
$$\propto Number\ of\ Turns * Current\ Rating$$
$$\propto N * I$$



Now,

<u>In a two winding ordinary transformer,</u>

$Total\ Wt.of\ Cu\ required, W_O \propto (N_1I_1 + N_2I_2)$



<u>In an auto transformer,</u>

$Wt.of\ Cu\ required\ in\ section\ 1 - 2 \propto (N_1 - N_2)I_1$

$Wt.of\ Cu\ required\ in\ section\ 2 - 3 \propto N_2(I_2 - I_1)$

$Total\ Wt.of\ Cu\ required, Wa \propto [(N_1 - N_2)I_1 + N_2(I_2 - I_1)]$

$$\frac{\text{Weight of Cu in autotransformer}}{\text{Weight of Cu in ordinary transformer}} = \frac{I_1(N_1 - N_2) + (I_2 - I_1)N_2}{I_1N_1 + I_2N_2}$$

$$= \frac{N_1I_1 - N_2I_1 + N_2I_2 - N_2I_1}{N_1I_1 + N_2I_2}$$

$$= \frac{N_1I_1 + N_2I_2 - 2N_2I_1}{N_1I_1 + N_2I_2}$$

$$= 1 - \frac{2N_2I_1}{N_1I_1 + N_2I_2}$$

$$= 1 - \frac{2N_2I_1}{2N_1I_1} \qquad (\because\ N_2I_2 = N_1I_1)$$

$$= 1 - \frac{N_2}{N_1} = 1 - K$$

$\therefore$ Wt. of Cu in autotransformer (W_a)

$= (1 - K) \times$ Wt. in ordinary transformer (W_o)

or $\quad W_a = (1 - K) \times W_o$

$\therefore \quad$ Saving in Cu $= W_o - W_a = W_a - (1 - K)W_o = K\ W_o$

or $\quad$ Saving in Cu $= K \times$ Wt. ofCu in ordinary transformer

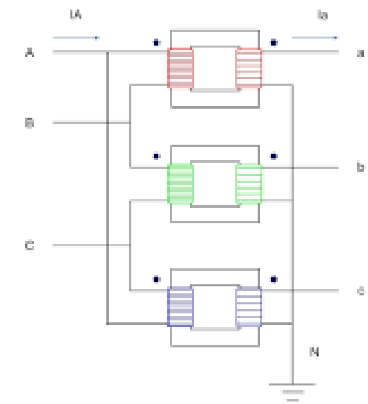
Thus if $K = 0.1$, the saving of Cu is only 10% but if $K = 0.9$, saving of Cu is 90%. Therefore, the nearer the value of K of autotransformer is to 1, the greater is the saving of Cu.

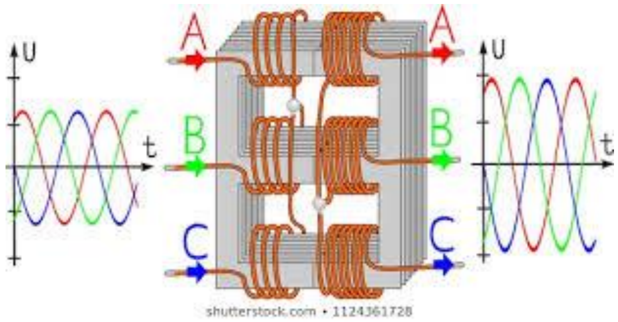
2. Transformers

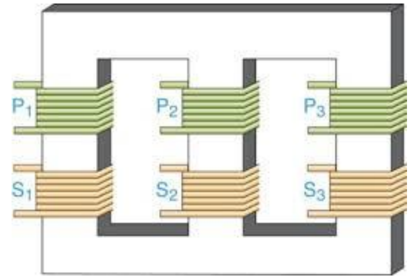
2.13 Three Phase Transformer

- Constructed either by connecting together three single-phase transformers, or by using one pre-assembled and balanced three phase transformer which consists of three pairs of single phase windings mounted onto one single laminated core.

- For the same kVA rating, a single three phase transformer will be smaller, cheaper and lighter than three individual single phase transformers connected together because less copper and iron core are used more effectively.

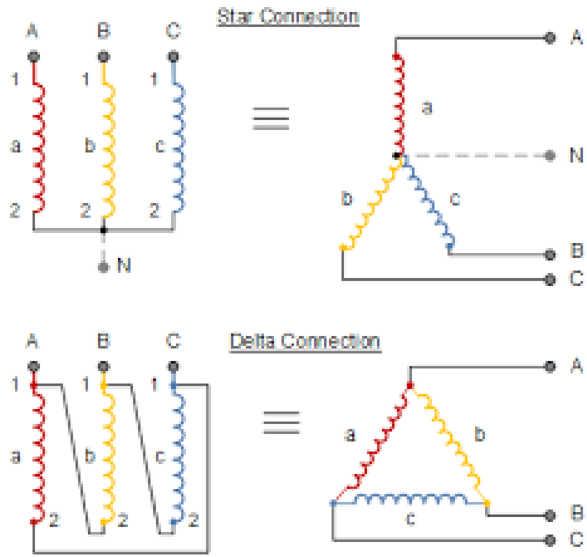






2. Transformers

2.13 Three Phase Transformer Connection



2.13 Advantages and Disadvantages of Three Phase Transformer

Advantages

- Needs less space to install and it is easier to install
- Less weight and reduced size
- Higher efficiency
- Low cost
- Transportation cost is low

Disadvantages

- The entire unit shuts down in case of fault or loss occurs in any one unit of a transformer as a common core is shared by all three units.
- Repair costs are higher
- Cost of spare units are high

Questions!

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ENGINEERING COLLEGE
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Chapter 3: DC Generators

Electrical Machines

BCT – II/II

Ramesh Shrestha
Associate Professor/Principal

3. DC Generator

3.1.1 Introduction:

- Rotating electrical machines, an electromechanical energy conversion device

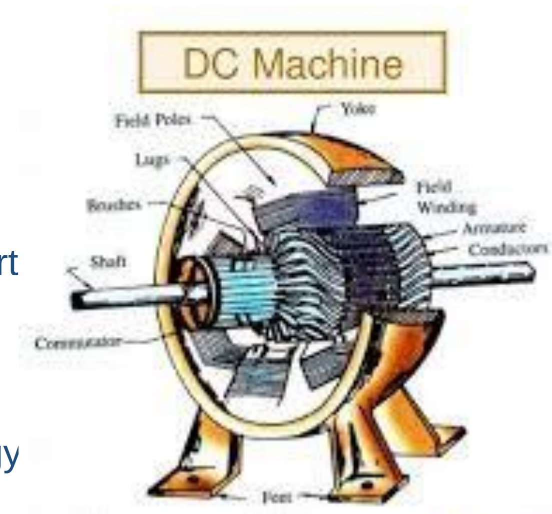
- Working principle based on Faraday's Law of electromagnetic Induction

- Field acts as a stationery part and armature acts as a rotating part

- Types of DC Machines:

  DC Generator: Converts Mechanical Energy into Electrical Energy

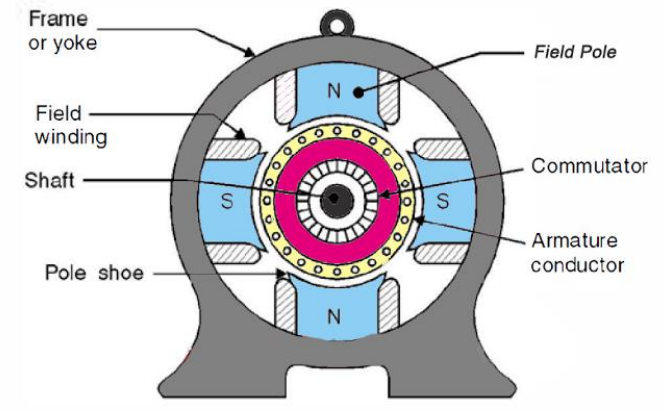
  DC Motor: Converts Electrical Energy into Mechanical Energy

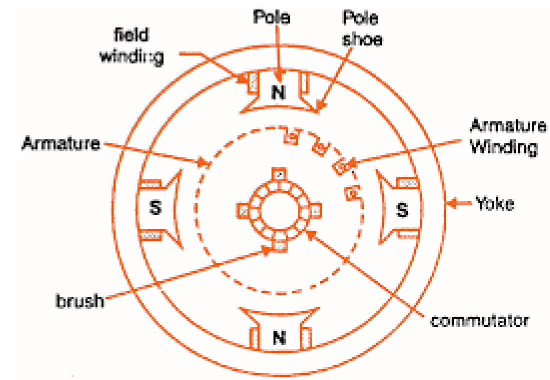


3. DC Generator

3.1.2 Constructional Features

- **Yoke:** A frame to provide protection and mechanical support to the field poles
- **Field Pole:** To produce magnetic field when field winding is excited. A part where field winding is wound over.
- **Field Conductor/Winding:** Current is passed through the field winding to magnetize (or excite) the pole
- **Armature Core and Armature Conductors:** Armature conductors are placed in the armature core.
- **Commutator:** Converts alternating emf induced in the armature conductor to dc voltage
- **Carbon Brush:** To transmit current from static to rotating part or from rotating to static part of dc machines

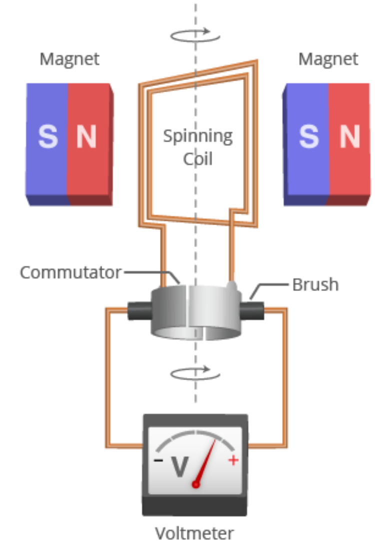


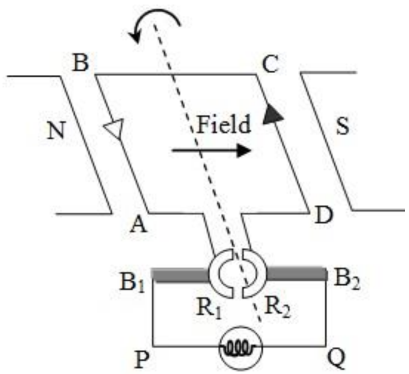


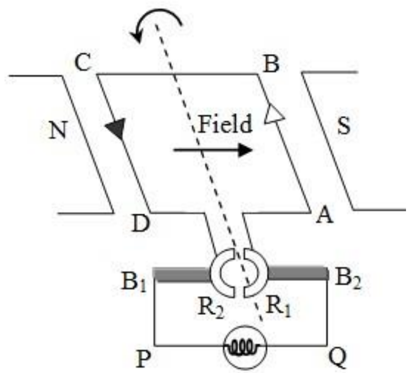
3. DC Generator

3.2.1 Working Principle

- When armature is rotated to cut the magnetic flux, alternating emf is induced in the armature winding according to Faraday's law of electromagnetic induction
- The alternating emf is converted to DC voltage with the help of commutator segments.
- The DC voltage is collected as an output with the help of carbon brush.
- The armature is rotated with the help of some external device known as prime mover. The commonly used prime movers are diesel engines, steam engines, steam turbines, water turbines etc.







3. DC Generator

8.2.2 EMF Equation

Let $\emptyset$ = flux/pole in Wb

Z = total number of armature conductors

P = number of poles

A = number of parallel paths (2 for wave winding & P for lap winding)

N = speed of armature in rpm (revolution per minute)

Now,

E_g = EMF of the generator = EMF/parallel path

Flux cut by one conductor in one revolution of the armature,

$$d\emptyset = P\emptyset \text{ weber}$$

Time taken to complete one revolution,

$$dt = 60/N$$

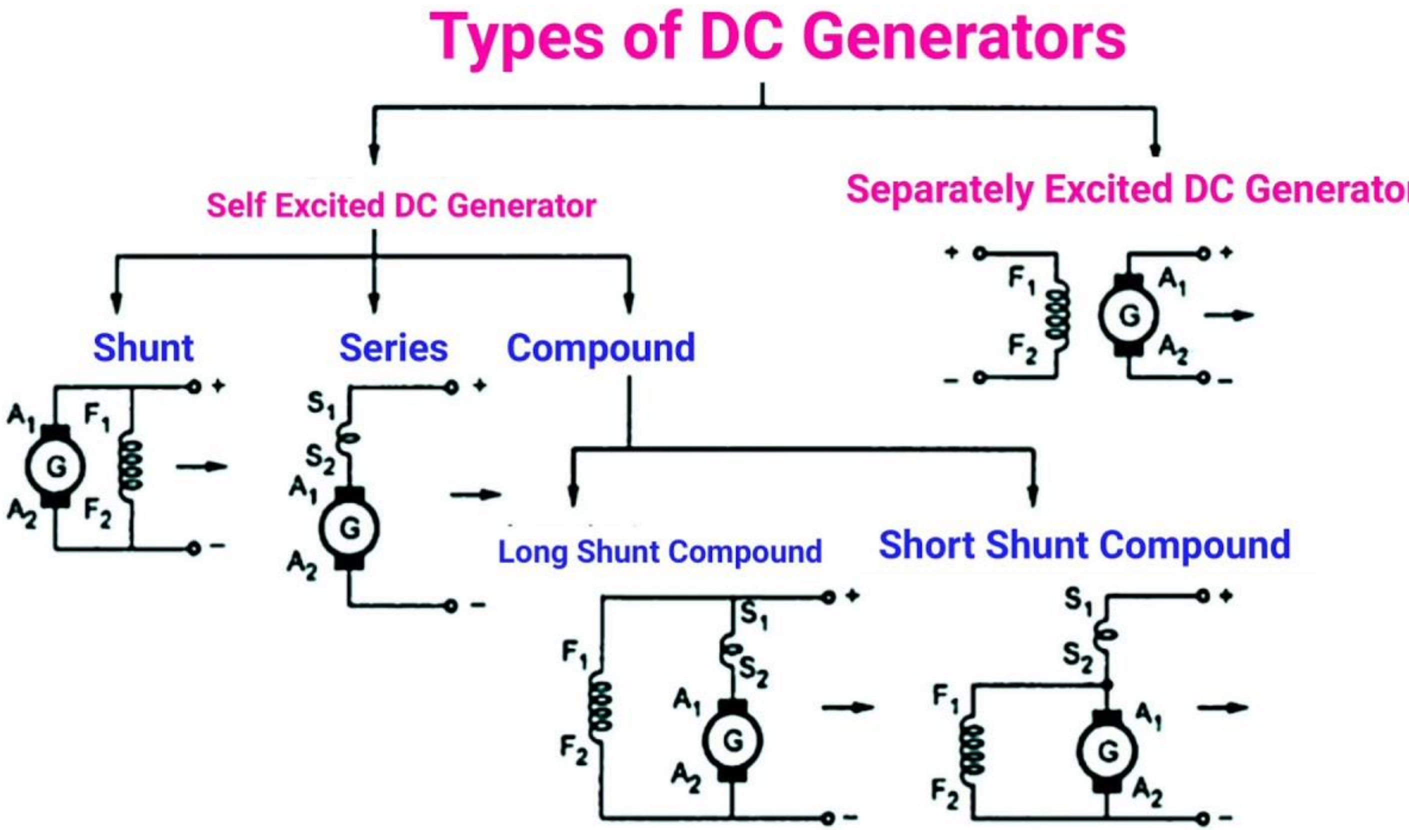
$$\therefore \text{EMF generated/conductor} = \frac{d\emptyset}{dt} = \frac{P\emptyset}{60/N} = \frac{P\emptyset N}{60} \text{ volts}$$

$\therefore$ EMF of generator, E_g = EMF per parallel path

= (EMF/conductor) X No. of conductors in series per parallel path

$$E_g = \frac{P\emptyset N}{60} \text{ X } \frac{Z}{A} = \frac{ZN\emptyset}{60} \text{ X } \frac{P}{A} \text{ volts}$$

3.4 Classification



3.5 Performance Characteristics

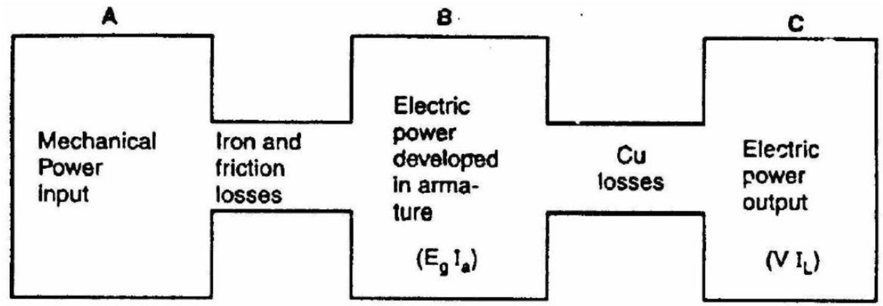
3.6.1 Losses

- Losses appear as heat and raise the temperature of the machine, which ultimately lower the efficiency of the machine.
- **Types of losses**
  (i) Copper Losses, (ii) Iron/Core Losses, (ii) Mechanical Losses
- **Copper Losses:** due to current through windings
  (i) Armature copper loss = $I_a^2 R_a$
  (ii) Shunt field copper loss = $I_{sh}^2 R_{sh}$
  (iii) Series field copper loss = $I_{se}^2 R_{se}$
- **Iron or Core Losses:** sum of hysteresis loss and eddy current loss
  (i) Hysteresis loss, $W_h = \eta B_m^{1.6} f V$ watts
  (ii) Eddy Current loss, $W_e = K B_m^2 f^2 t^2 V$ watts
- **Mechanical Losses:** due to friction and windage, depends on the speed of the machine. But for a given speed, they are practically constant.
  (i) friction loss e.g., bearing friction, brush friction etc.
  (ii) windage loss i.e., air friction of rotating armature.
- Iron losses and mechanical losses together are called stray losses.

3.6.2 Constant and Variable Losses

- **Losses broadly sub-divided into:**
  (i) Constant Losses and
  (ii) Variable Losses
- **Constant Losses: remains constant in all loads**
  (i) Iron or Core Losses
  (ii) Mechanical Losses
  (iii) Shunt field copper loss = $I_{sh}^2 R_{sh}$
- **Variable Losses: vary with load**
  (i) Copper loss in armature winding = $I_a^2 R_a$
  (ii) Copper loss in series field winding= $I_{se}^2 R_{se}$
- **Total Loss=Constant Losses + Variable Losses**

3.7.1 Powe Stages and Efficiency



(*i*) **Mechanical efficiency**

$$\eta_m = \frac{B}{A} = \frac{E_g I_a}{\text{Mechanical power input}}$$

(*ii*) **Electrical efficiency**

$$\eta_e = \frac{C}{B} = \frac{V I_L}{E_g I_a}$$

(*iii*) **Commercial** or **overall efficiency**

$$\eta_c = \frac{C}{A} = \frac{V I_L}{\text{Mechanical power input}}$$

Clearly, $\eta_c = \eta_m \times \eta_e$

Unless otherwise stated, commercial efficiency is always understood.

Now, commercial efficiency, $\eta_c = \frac{C}{A} = \frac{\text{output}}{\text{input}} = \frac{\text{input} - \text{losses}}{\text{input}}$

3.7.2 Voltage Regulation

3.7.3 Condition for maximum efficiency

Efficiency of a dc generator varies with load.

If a shunt generator has load current a I_L and a terminal volage V_t, then
Generator Output = VtIL
Generator Input = Output + Losses = V_tI_L+Variable Losses + Constant Losses
= $V_tI_L + Ia^2 R_a + WC = V_tI_L + (IL+Ish)^2 R_a + WC$
I_{sh} is generally negligibly small as compare to IL and therefore, it can be neglected.
Generator Input =$V_tI_L + IL^2 Ra + WC$
Now, efficiency is given by,

$$\eta = \frac{\text{Output}}{\text{Input}} = \frac{V_tI_L}{V_tI_L + IL^2 Ra + WC} = \frac{1}{1 + \frac{I_LR_a}{V_t} + \frac{W_C}{V_tI_L}}$$

The efficiency will be maximum when the denominator of the above equation is minimum, i.e.

$$\frac{d}{dI_L}\left(1 + \frac{I_LR_a}{V_t} + \frac{W_C}{V_tI_L}\right) = 0, \quad \text{or} \quad \frac{R_a}{V_t} - \frac{W_C}{V_tI_L^2} = 0, \quad \text{or} \quad I_L^2 R_a = WC$$

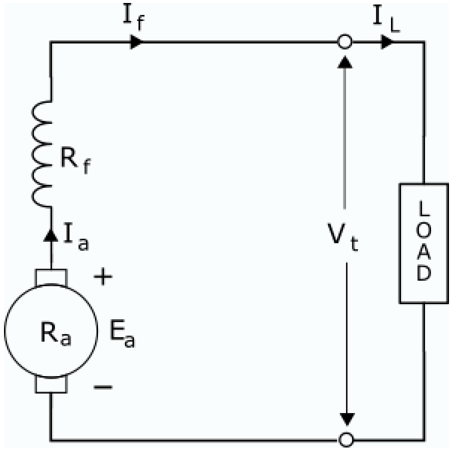
i.e. **Variable Loss = Constant Loss**

The load current corresponding to maximum efficiency is given by,

$$I_L = \sqrt{\frac{W_C}{R_a}}$$

3 DC Generator

8.1.4 DC Series and Shunt Generator



$$E_a - I_aR_a - I_aR_{Se} - V_t = 0$$

$$E_a = V_t + IaR_a + I_aR_f$$

Where,

$$I_a = I_L = I_f$$

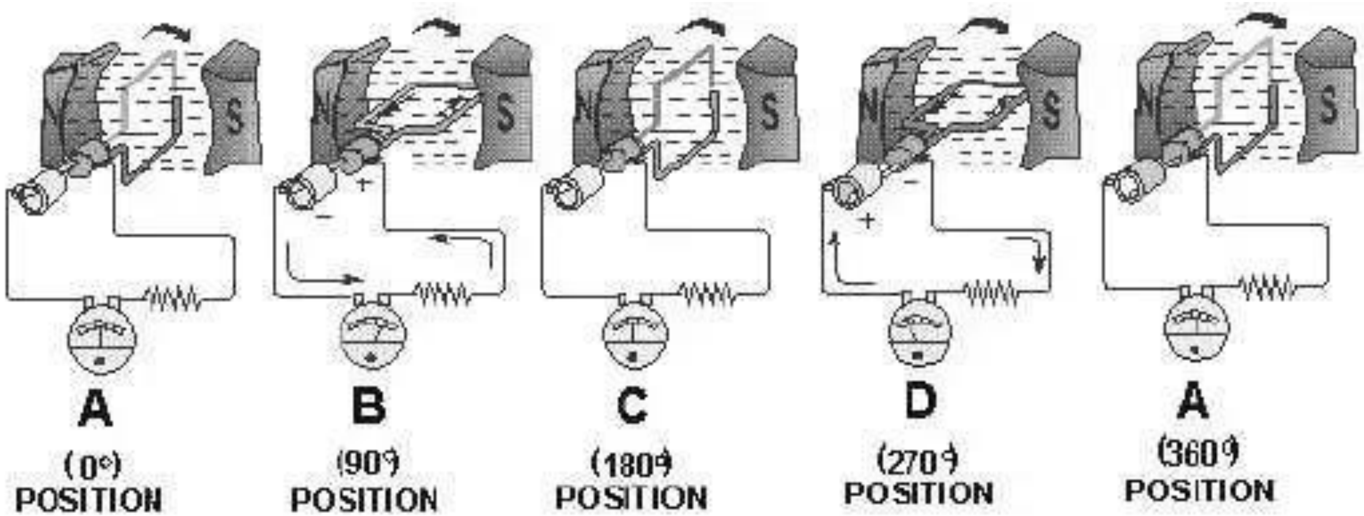
$$E_a - IaR_a - V_t = 0$$

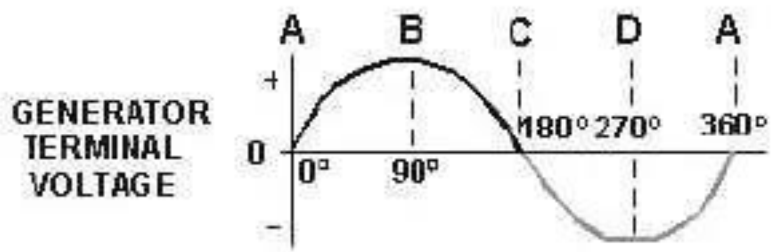
$$E_a = Vt + IaR_a$$

Where,

$$I_a = I_L + I_f = I_L + \frac{V_L}{R_f}$$

Alternating emf generation





Questions!

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Chapter 4: DC Motor

Electrical Machines

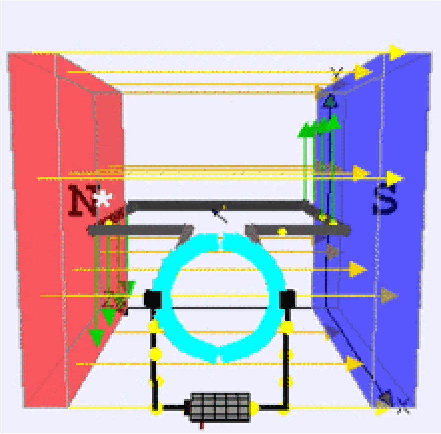
BCT – II/II

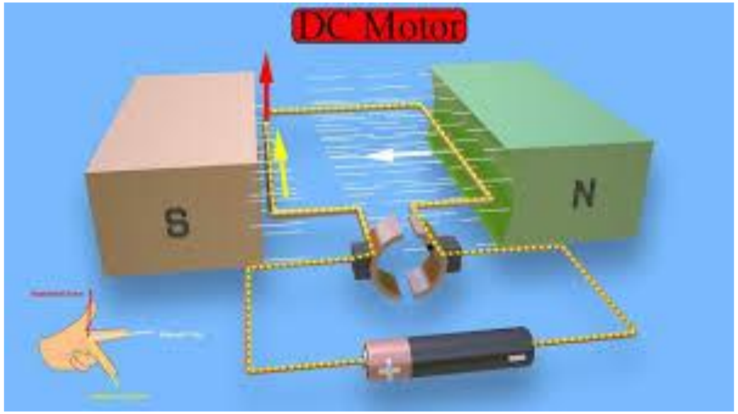
Ramesh Shrestha
Associate Professor/Principal

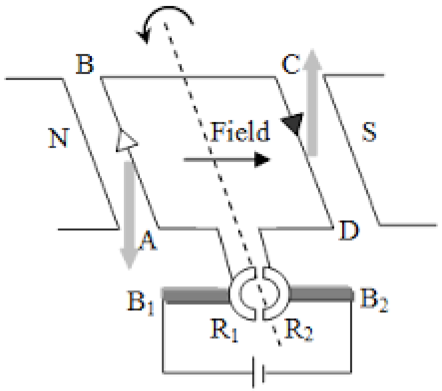
4. DC Motor

4.1.1 Working Principle

- When a DC voltage is supplied to armature winding, current starts to flow through the armature conductors.
- The current carrying armature conductors within an external magnetic field experience a force which ultimately creates rotation (mechanical force/torque) in the armature.
- DC motor converts electrical energy into mechanical energy (kinetic energy) through the interaction of two magnetic fields.







4. DC Motor

8.3.2 Torque Equation of a DC Motor

Let ϕ = flux/pole in Wb

Z = total number of armature conductors

P = number of poles

A = number of parallel paths (2 for wave winding & P for lap winding)

N = speed of armature in rpm (revolution per minute)

R = radius of the armature

Now,

Armature Torque, $T_a = F * R$ (N-m)

Work done by this force in one revolution = Force X distance travelled by the armature in one rev.

$$= F \times 2\pi R$$

$$\text{Power developed by the armature} = \frac{\text{Work done in one revolution}}{\text{Time taken by the armature in one revolution}}$$

$$E_b \times I_a = \frac{F \times 2\pi R}{60/N} = \frac{F \times R \times 2\pi N}{60}$$

$$\frac{ZN\phi}{60} \times \frac{P}{A} \times I_a = \frac{F \times 2\pi R}{60/N} = \frac{T_a \times 2\pi N}{60}$$

$$T_a = \frac{ZP}{2\pi A} \times \phi I_a \qquad T_a \,\alpha\, \phi I_a$$

4. DC Motor

4.2.1 Back EMF

When the armature of a dc motor rotates in presence of magnetic field, emf is induced in the armature windings/conductors according to the "Faraday's Laws of Electromagnetic Induction" emf is induced in the conductors. Thus induced emf always acts in opposite to the applied voltage as per the "Fleming's Right Hand Rule“ and is know as back emf (E_b) of dc motor. An expression of back emf is given by

$$E_b = \frac{ZN\emptyset}{60} * \frac{P}{A} \qquad \text{i.e.} \qquad E_b \; \alpha \; N\emptyset$$

4.2.2 Roles of Back EMF of a dc Motor

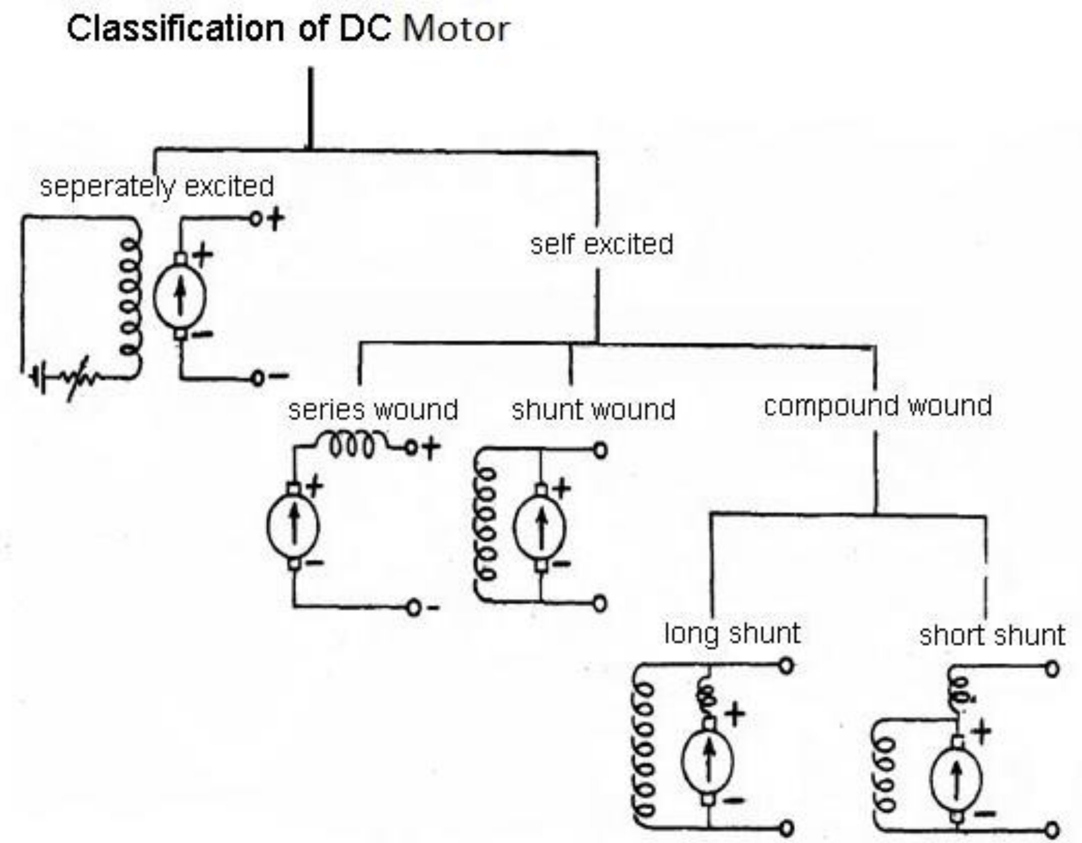
1. It protects the armature windings from short circuit during running condition. If there is no back emf during running condition, the armature will draw very high current
2. It helps a dc motor to produce required amount of torque according to increased or decreased external load torque.

   $E_b \; \alpha \; N\emptyset$, $\qquad I_a = \frac{V_s - E_b}{R_a}$ $\qquad T_a \; \alpha \; \emptyset Ia$

   Load ↑ ⟶ N ↓ ⟶ E_b ↓ ⟶ I_a ↑ ⟶ T_a ↑

   Load ↓ ⟶ N ↑ ⟶ E_b ↑ ⟶ I_a ↓ ⟶ T_a ↓
3. It acts as an opposing agent necessary in every energy converting system.

4.3 Classification of DC Motor



4.4. Performance Characteristics of dc Motor

- Characteristics curve for a dc Motor are:
  1. Armature Torque vs. Armature Current (T_a vs. I_a)
  2. Speed vs. Armature Current (N vs. I_a)
  3. Speed vs. Armature Torque (N vs. T_a)
- Characteristics are determined by the following two equations:

$E_b = \frac{ZN\emptyset}{60} * \frac{P}{A}$ i.e. $E_b \; \alpha \; N\emptyset$

$T_a = \frac{ZP}{2\pi A} * \emptyset I_a$ i.e. $T_a \; \alpha \; \emptyset I_a$

4. DC Motor

4.4.1 Characteristics of dc Series Motor

$N \,\alpha\, \frac{E_b}{\emptyset}$, $V_s - IaRf - IaRa = Eb$, $I_a = \frac{V_s - Eb}{R_a + Rf}$ $\emptyset \,\alpha\, I_f$, $I_f = Ia$, $T_a \,\alpha\, \emptyset I_a$

1. Armature Torque vs. Armature Current (T_a - I_a)

Before saturation of field poles,

- $\emptyset \;\alpha\; I_a$, $\therefore$ $T_a \;\alpha\; Ia^2$,
- Therefore, T_a - I_a curve is parabolic before magnetic saturation.

After saturation of field poles,

- $\emptyset$ is independent of I_a and is constant
- $T_a \;\alpha\; Ia$,
- Therefore, T_a - I_a curve becomes straight lines after magnetic saturation

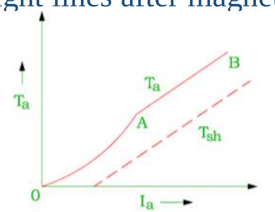


FIG A : TORQUE - ARMATURE CURRENT CHARACTERISTIC

- As T_a increases as the square of I_a prior to magnetic saturation, these motors are used where high starting torque is required.

2. Speed vs. Armature Current (N - I_a)

- For a small armature current at light load, change in back emf is very small due to small voltage drop in armature and series field resistance.
- Therefore, speed is inversely proportional (to flux) for a small armature current.
- At heavy load, I_a is large which results in increase of magnetic field and reduction in speed. (As a result, back emf decreases and more armature current allow to flow)

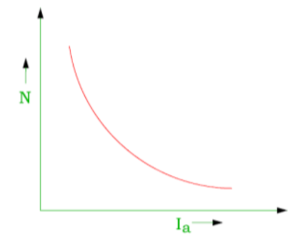


FIG B : SPEED - ARMATURE CURRENT CHARACTERISTIC

3. Speed vs. Armature Torque (N - Ta)

- Small load torque requires low value of armature current which is equal to field current
- Low field current results in weak magnetic field and hence speed goes high
- High load torque requires large value of armature current which is equal to field current
- Large field current results in high value of magnetic field and hence speed goes down

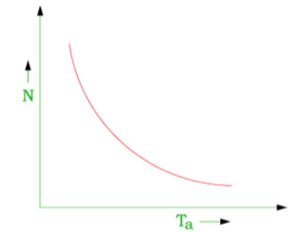


FIG C : SPEED - TORQUE CHARACTERISCTIC

4. DC Motor

4.4.2 Characteristics of dc Series Motor

Why dc Series Motor should never be started at no load?

$N \; \alpha \; \frac{E_b}{\emptyset}$, $V_s - IaRf - IaRa = Eb$, $I_a = \frac{V_s - Eb}{R_a + Rf}$

$\emptyset \; \alpha \; I_f$, $I_f = Ia$, $T_a \; \alpha \; \emptyset I_a$

- At no load/light load, the armature current is very small. which results in high value of E_b and low value of ∅. Therefore the speed becomes dangerously high. The increase in back emf weakens the armature current and hence the field flux also. This will again increase in speed and therefore increase of back emf again…….
- Therefore the speed continues to increase until the armature gets damaged due to heavy centrifugal forces. That's why the DC Series motor is never started at no load.

4. DC Motor

4.4.3 Characteristics of dc Shunt Motor

$E_b = V_s - IaRa,$ $I_a = \frac{V_s - Eb}{R_a},$ $N \; \alpha \; \frac{E_b}{\emptyset},$ $T_a \; \alpha \; \emptyset I_a$

1. Armature Torque vs. Armature Current (T_a - I_a)

- Since $\emptyset$ is constant in dc shunt motor, $T_a \; \alpha \; I_a$
- T_a - I_a characteristic is a straight line passing through the origin.
- The shaft torque, T_{sh} is less than T_a and is shown by a dotted line.
- Since a very large current is required to start a heavy load, a dc shunt motor should not be started on heavy load.

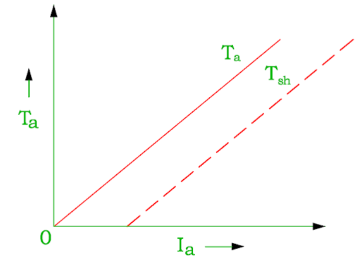


FIG D : TORQUE - ARMATURE CURRENT CHARACTERISTIC

2. Speed vs. Armature Current (N - I_a)

- When I_a is increased due to increase in load, a small decrease E_b is observed due to voltage drop in armature resistance R_a.
- Due to small decrease in Eb, there is slight change in the speed from no-load to full-load. Hence, it is essentially a constant-speed motor and suitable for lathes, machine tools, milling machine, conveyors etc.

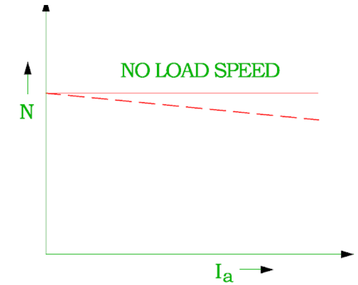


FIG E : SPEED - ARMATURE CURRENT CHARACTERISTIC

3. Speed vs. Armature Torque (N - Ta)

- Since $\emptyset$ is constant for dc shunt motor,
  $N \; \alpha \; E_b$
- Since $\emptyset$ is constant for dc shunt motor,
  $T_a \; \alpha \; I_a$
- As the speed N of the motor decreases, the back emf E_b will also decrease, which will eventually increase armature current I_a and hence the armature torque Ta will increase as shown in figure.

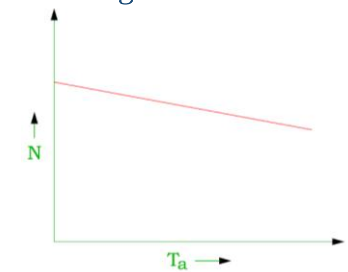
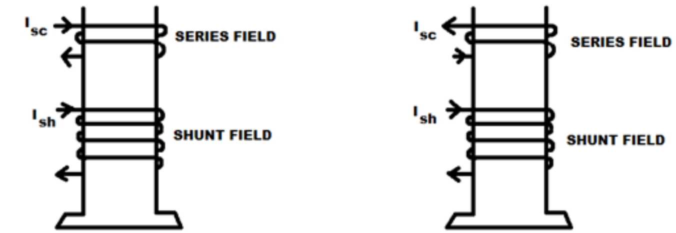


FIG F : SPEED - TORQUE CHARACTERISCTIC

4. DC Motor

4.4.4 Characteristics of dc Compound Motor

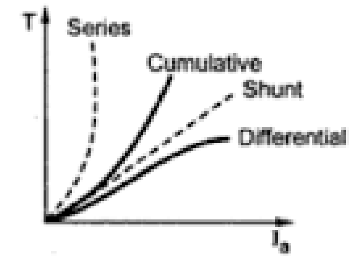
- DC Compound Motors have both series and shunt field windings.
- **Cumulative compound motor**: series and shunt field windings are connected in such a way that the fields produced by both the windings are in the same direction.
- **Differential compound motor:** The windings are connected in such a way that the fields produced by both the windings are in opposite direction.



CUMULATIVE COMPOUNDING DIFFERENTIAL COMPOUNDING

Characteristics of cumulative compound motor:

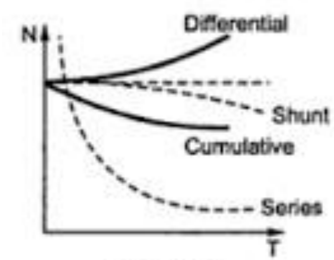
- the series field supports the shunt field so that Ø increases with Ia. Therefore the T_a - I_a characteristics will be as shown in figure.
- At a particular value of torque, due to cumulative effect of series field the Ø will be more with compare to plain shunt motor. Therefore, the T_a - N characteristics lies below that of shunt motor as shown in figure,



(a) T Vs I_a

Characteristics of differential compound motor:

- the series field opposes the shunt field so that Ø decreases with I_a. Therefore the T_a - I_a characteristics lies below that of shunt motor as shown in figure.
- At a particular value of torque, due to differential effect of series field the Ø will be less with compare to plain shunt motor. Therefore, the T_a - N characteristics lies above that of shunt motor as shown in figure,



(c) N Vs T

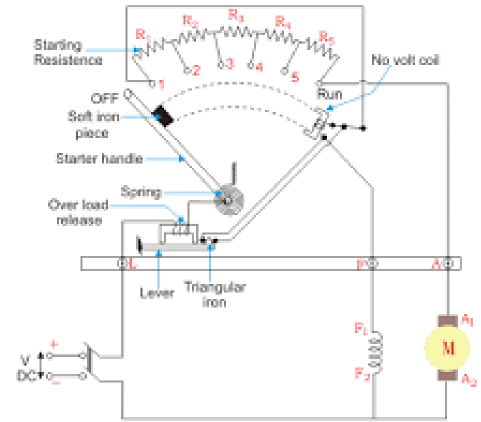
4. DC Motor

4.5 DC Motor Starters

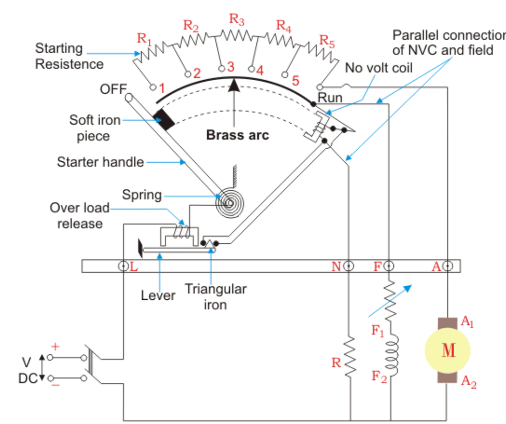
- Current drawn by the armature circuit of a dc motor is,

$$I_a = \frac{V_s - E_b}{R_a}$$

- As there is no back emf at the instant of starting, the armature will draw a very high current, which may be 20-30 times greater than its rated full load current.
- This high starting current may blowout the fuses and the armature winding and/or commutator-brush arrangement may get damaged.
- The basic concept behind any **dc motor starter** is adding variable resistance in series with armature winding.
- Types of Starter:
    - 3-Point starter
    - 4-Point starter



Three Point Starter



Four Point Starter

4. DC Motor

4.6 Speed Control of DC Motor

$E_b = \frac{ZN\emptyset}{60} \text{ x } \frac{P}{A}$ or $N = \frac{E_b \text{ x } 60 \text{ x } A}{Z \text{ x } \emptyset \text{ x } P}$ or $N \, \alpha \, \frac{E_b}{\emptyset}$ or $N \, \alpha \, \frac{V_s - I_a R_a}{\emptyset}$

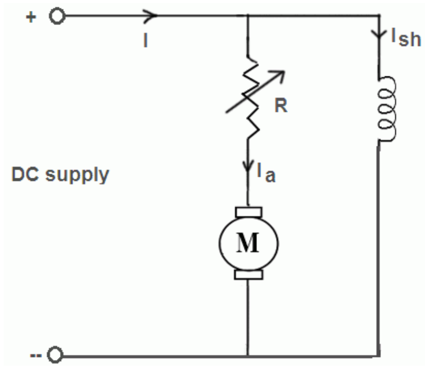
- The speed depends upon the supply voltage V_s, the armature circuit resistance R_a, and the field flux Φ.
- Thus, there are three general methods of speed control of dc motors:

1. **Armature Control Method:** by varying armature resistance R_a
2. **Field Control Method:** by varying field flux Φ
3. Armature Voltage Control Method: by varying the supply voltage V_s
    - Multiple voltage control Method
    - Ward-Leanard System/ Method

4. DC Motor

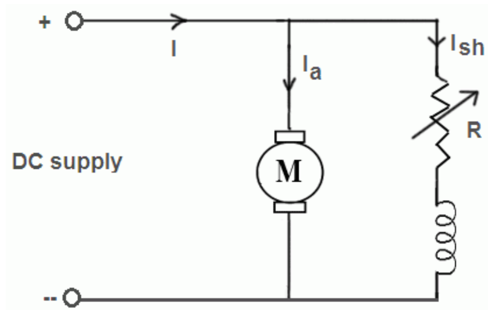
4.6.1 Speed Control of DC Shunt Motor

a) Armature Control Method



- Voltage across armature is varied by inserting a variable resistance R in series with armature circuit
- If the variable resistance R is increased, I_a will remain constant to maintain load torque constant ($T_a \alpha \emptyset I_a$), as Ø is constant in a dc shunt motor. But, the potential difference across the armature will decrease. And hence, the speed of the armature/motor will decrease.
- This method is used to control the speed below the rated speed

a) Field Control Method

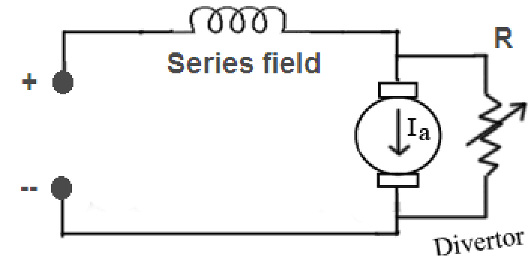


- A variable resistance R is inserted in series with field winding to regulate field current, thereby regulating flux per pole.
- When variable resistance R is added to the field circuit, field current will reduce to $I_f = V_s/(R_f + R)$ from $I_f = V_s/R_f$, thereby reducing the flux per pole, which ultimately increases the speed of the motor.
- Therefore, this method is suitable only for regulating the speed above the rated speed.

4.6.2 Speed Control of DC Series Motor

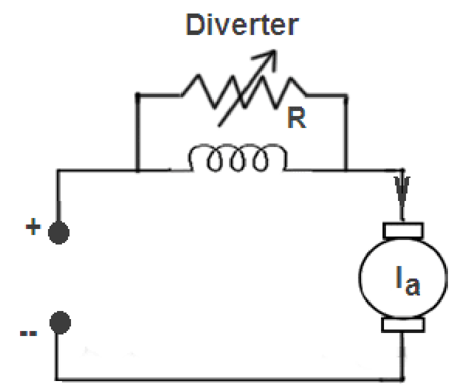
a) Armature Diverter Method

- A variable resistance R is connected across the armature winding
- Some of the armature current I_a gets diverted and pass through R
- Since I_a is reduced due to diverter R, Ø must increase to maintain constant torque, ($T_a \; \alpha \; \emptyset I_a$), This results in an increase in supply current and an increase in the speed of motor ($N \; \alpha \; \frac{E_b}{\emptyset}$).
- This method is suitable only for controlling the speed below the rated speed



b) Field Diverter Method

- A variable resistance R is connected across the field winding
- Some of the field current I_a gets diverted and pass through R
- Desired amount of current can be passed through the field winding by adjusting the value of R. Hence flux can be decreased and the speed of the motor can be increased
- This method is suitable only for controlling the speed above the rated speed.



4. DC Motor

4.7.1 Losses

- Losses appear as heat and raise the temperature of the machine, which ultimately lower the efficiency of the machine.
- **Types of losses**
  (i) Copper Losses, (ii) Iron/Core Losses, (ii) Mechanical Losses
- **Copper Losses:** due to current through windings
  (i) Armature copper loss = $I_a^2 R_a$
  (ii) Shunt field copper loss = $I_{sh}^2 R_{sh}$
  (iii) Series field copper loss = $I_{se}^2 R_{se}$
- **Iron or Core Losses:** sum of hysteresis loss and eddy current loss
  (i) Hysteresis loss, $W_h = \eta B_m^{1.6} f V$ watts
  (ii) Eddy Current loss, $W_e = K B_m^2 f^2 t^2 V$ watts
- **Mechanical Losses:** due to friction and windage, depends on the speed of the machine. But for a given speed, they are practically constant.
  (i) friction loss e.g., bearing friction, brush friction etc.
  (ii) windage loss i.e., air friction of rotating armature.
- Iron losses and mechanical losses together are called stray losses.

4.7.2 Constant and Variable Losses

- **Losses broadly sub-divided into:**

  (i) Constant Losses and

  (ii) Variable Losses

- **Constant Losses: remains constant in all loads**

  (i) Iron or Core Losses

  (ii) Mechanical Losses

  (iii) Shunt field copper loss = $I_{sh}^2 R_{sh}$

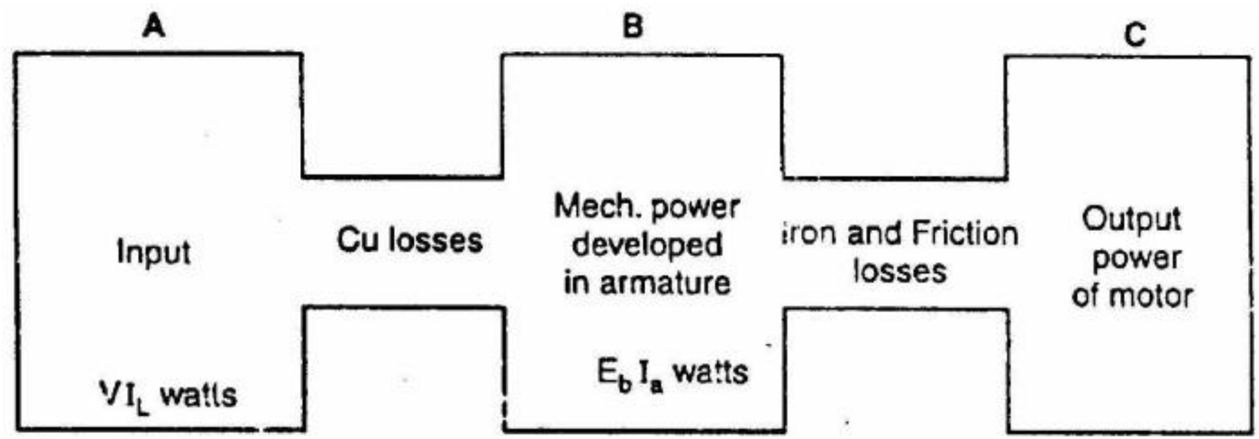
- **Variable Losses: vary with load**

  (i) Copper loss in armature winding = $I_a^2 R_a$

  (ii) Copper loss in series field winding= $I_{se}^2 R_{se}$

- **Total Loss=Constant Losses + Variable Losses**

4.7.3 Powe Stages and Efficiency



$$\text{Overall Efficiency}, \eta = \frac{C}{A}$$

$$\text{Electrical Efficiency}, \eta = \frac{B}{A}$$

$$\text{Mechanical Efficiency}, \eta = \frac{C}{B}$$

4. DC Motor

4.7.4 Condition for maximum efficiency

If a shunt generator has supply current a I_S and a supply volage V_S, then

Motor Input = $V_S I_S$

Motor Output = Input - Losses = $V_S I_S$ - Variable Losses - Constant Losses

$= V_S I_S - I_a^2 R_a - W_C = V_S I_S - (I_S - I_{sh})^2 R_a - W_C$

I_{sh} is generally negligibly small as compare to I_S and therefore, it can be neglected.

Motor Output $= V_S I_S - I_S^2 R_a - W_C$

Now, efficiency is given by,

$$\eta = \frac{\text{Output}}{\text{Input}} = \frac{V_S I_S - I_S^2 Ra - WC}{V_S I_S} = 1 - \frac{I_S R_a}{V_S} - \frac{W_C}{V_S I_S}$$

The efficiency will be maximum when.

$$\frac{d}{dI_s}\left(1 - \frac{I_S R_a}{V_S} - \frac{W_C}{V_S I_S}\right) = 0, \quad \text{or} \quad -\frac{R_a}{V_S} + \frac{W_C}{V_S I_S^2} = 0, \quad \text{or} \quad I_S^2 R_a = W_C$$

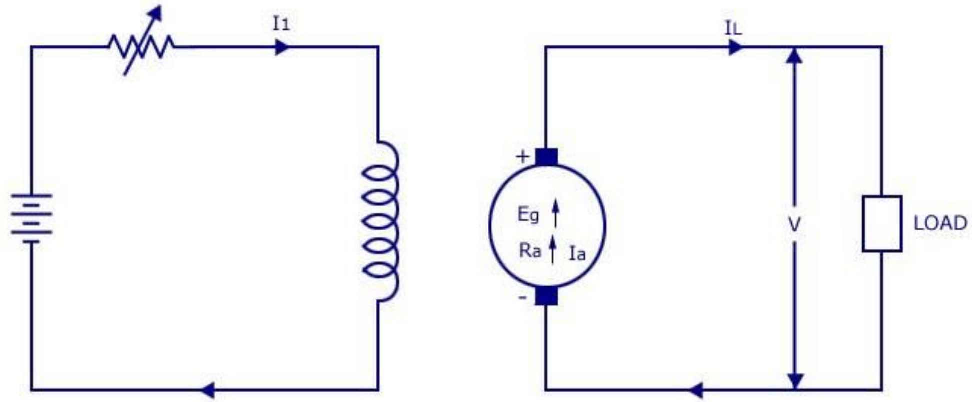
i.e. **Variable Loss = Constant Loss**

The supply current corresponding to maximum efficiency is given by,

$$I_S = \sqrt{\frac{W_C}{R_a}}$$

8.1 DC Machines

8.1.4 Separately Excited



$$E_a - I_aR_a - V_t = 0$$

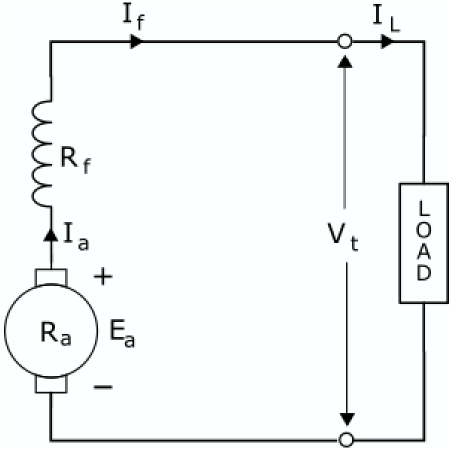
$$E_a = I_aR_a + V_t$$

And,

$$I_f = \frac{V_f}{R_f}$$

8.1 DC Machines

8.1.4 DC Series and Shunt Motor



$$E_a - I_aR_a - I_aR_{Se} - V_t = 0$$

$$E_a = V_t + IaR_a + I_aR_f$$

Where,

$$I_a = I_L = I_f$$

$$E_a - IaR_a - V_t = 0$$

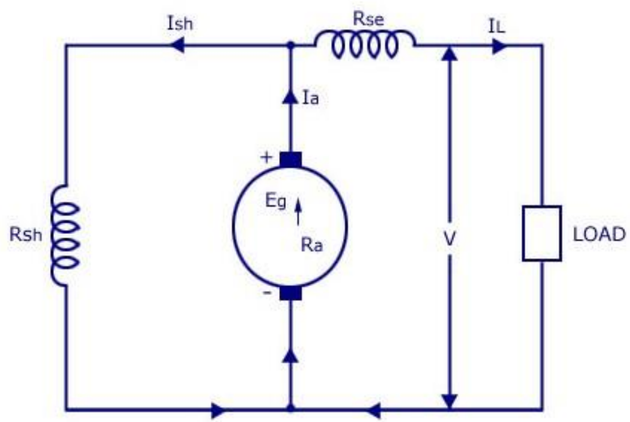
$$E_a = Vt + IaR_a$$

Where,

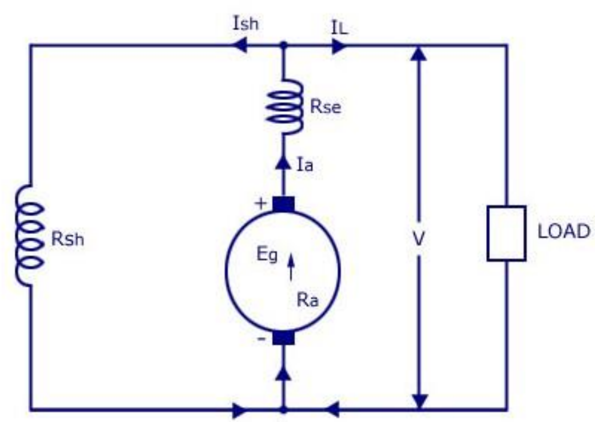
$$I_a = I_L + I_f = I_L + \frac{V_L}{R_f}$$

8.1 DC Machines

8.1.4 DC Long Shunt and Short Shunt Motor



Short Shunt Compound



Long Shunt Compound

$$E_a - I_a R_a - I_L R_{Se} - V_t = 0$$

$$E_a = V_t + I_a R_a + I_L R_{Se}$$

Where,

$$I_a = I_L + I_{sh} = I_L + \frac{V_t}{R_{sh}}$$

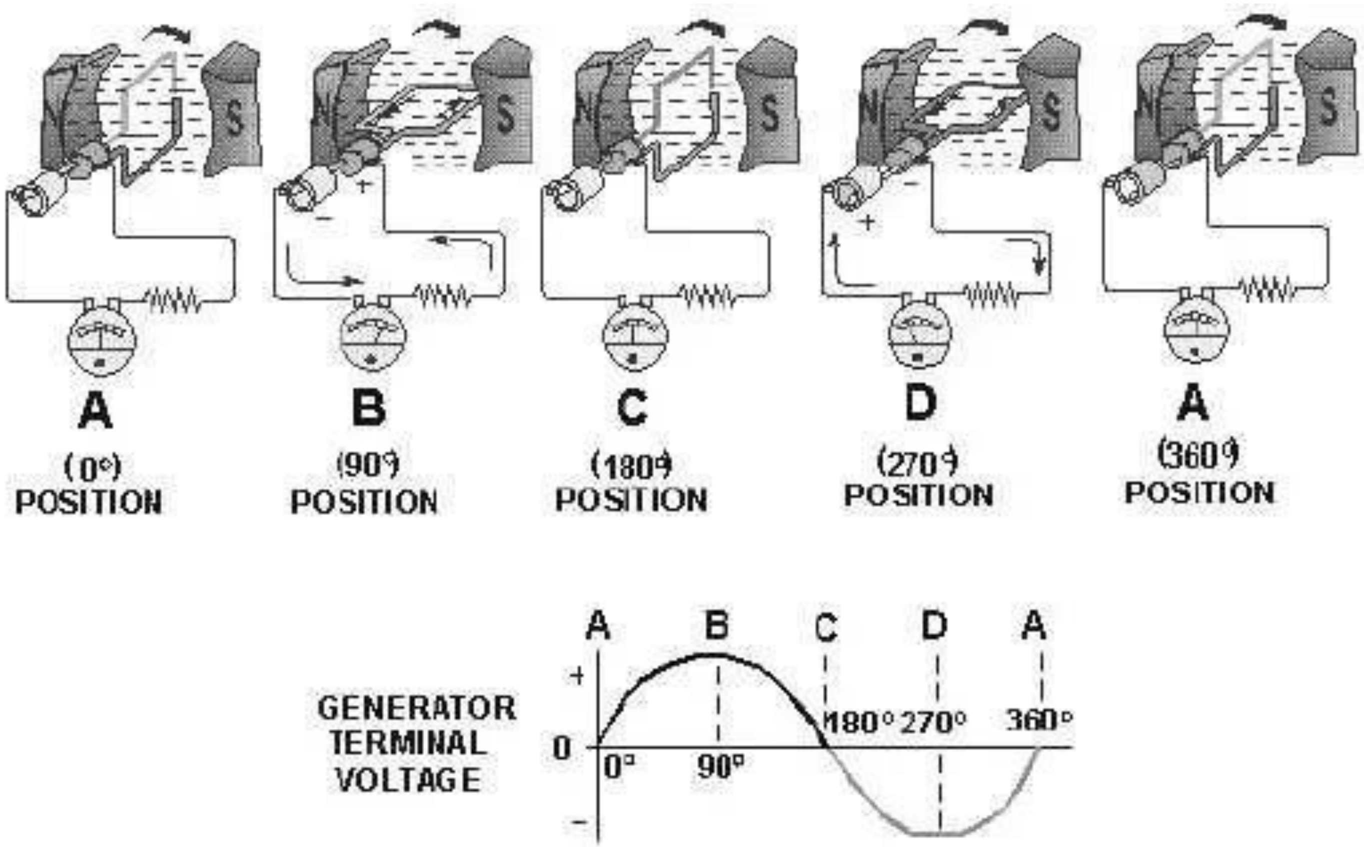
$$E_a - I_a R_a - I_a R_{Se} - V_t = 0$$

$$E_a = V_t + I_a R_a + I_a R_{Se}$$

Where,

$$I_a = IL + I_{sh} = IL + \frac{V_t}{R_{sh}}$$

Alternating emf generation



Torque according to increased or decreased external load torque

For a dc shunt motor,

$$V_s - IaRa = Eb$$

$$I_a = \frac{V_s - E_b}{R_a} = \frac{V_s - 0}{R_a} = \frac{V_s}{R_a},$$

which is just like a short circuiting the applied voltage V_s by a low resistance l

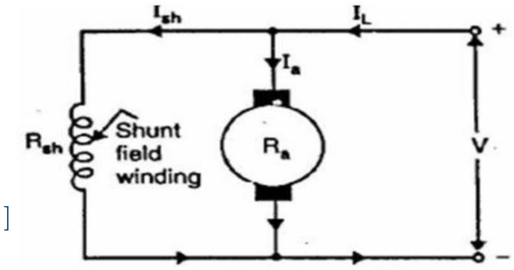


Fig.(1):DC shunt motor schematic diagram

- Example:
  For an armature winding with Ra = 0.8Ω designed for 200V, 10kW,
  Full load armature current, $I_a = \frac{10*1000}{200} = 50A$.
- For emf E_b=190V at certain load, $Ia = \frac{V_s - E_b}{Ra} = \frac{200-190}{0.8} = 12.5A$,
  which is less than full load current.
- If there is no back emf, then $Ia = \frac{V_s - E_b}{R_a} = \frac{V_s - 0}{Ra} = \frac{200-0}{0.8} = 250A$,
  Which is five times greater than the rated full load current

Questions!

Chapter 5: Three Phase Induction Machines

Electrical Machines

BCT – II/II

Ramesh Shrestha
Associate Professor

5.1 Three phase Induction Motors

Introduction:

- Most commonly used ac motors in industry.
- Runs essentially at constant speed from no-load to full-load.
- Simple and rugged construction, low cost, high efficiency, reasonably good power factor, self-starting and low maintenance cost
- Speed depends on the frequency of the supply voltage
- Starting torque is inferior to dc shunt motor
- https://youtu.be/AQqyGNOP_3o
- https://youtu.be/JPn5Ou-N0b0

5.1 Three phase Induction Motors

Construction:

1) Stator 2) Rotor

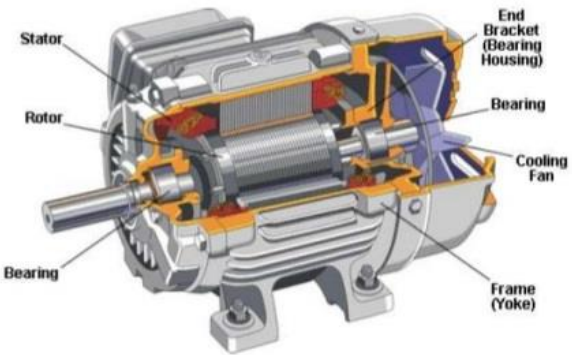
Stator:

Stationary part, made up of thin laminations of silicon steel to minimize eddy current and hysteresis losses; has three main parts (i) Outer Frame, (ii) Stator Core and (iii) Stator Winding.

- *Outer Frame: outer body/frame of the motor, provides protection and mechanical strength to stator core and all the inner parts of the machine. Known as Yoke.*
- *Stator Core: Slots are punched on the inner periphery of the stator core to accommodate stator winding, carries the rotating magnetic field*
- *Stator Winding: The slots in the stator core carries a 3-phase winding, supplied from a 3-phase AC supply system. Terminals of the winding are connected in the terminal box of the machine.*

Rotor:

- Rotating part, mounted on a shaft, is a hollow laminated core having slots on its outer periphery.
- The slots carries rotor conductor/winding
- Connected to the mechanical load through the shaft.
- Types: Squirrel-cage Rotor and Wound (Slip Ring) Rotor
- Shaft is connected to rotor to transmit mechanical power



Parts of a Motor

5.1 Three phase Induction Motors

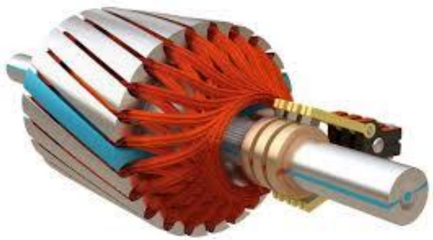
Types of 3 phase Induction Motor:

1. Squirrel-cage Induction Motor: A motor with Squirrel-cage Rotor

2. Slip-Ring (wound) Induction Motor: A motor with Slip-Ring Rotor

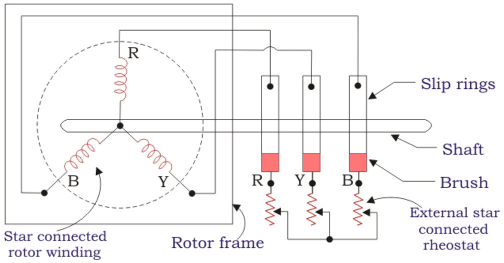
Squirrel-cage Rotor:

- *Laminated cylindrical core of high quality magnetic material.*
- *Semi-closed circular slots are punched at the outer periphery.*
- *Aluminium/copper bar as rotor conductors are inserted in the slots and short circuited at each end by aluminium/copper rings, called short circuiting rings. Thus, the rotor winding is permanently short circuited.*



Slip-Ring (Wound) Rotor:

- *Carries a 3- phase winding, similar to the one in the stator*
- *The open ends of the rotor winding are brought out and joined to three insulated slip rings mounted on the rotor shaft with one brush resting on each slip ring.*
- *The three brushes are connected to a 3-phase star-connected rheostat as shown in Figure.*
- *At starting, the external resistances are included in the rotor circuit to increase starting torque. These resistances are gradually reduced to zero as the motor gains its normal speed. The external resistances are used during starting period only.*

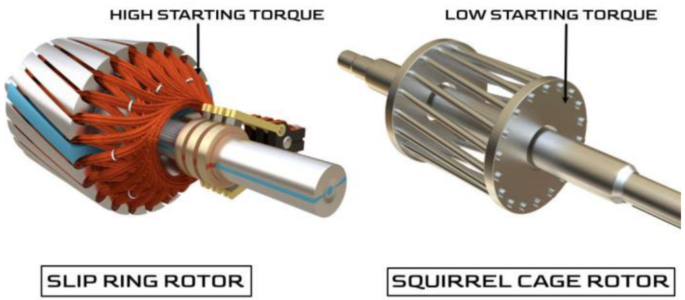


Slip Ring Three Phase Induction Motor

Rotor conductors/windings are skewed, why?

The rotor slots are usually not parallel to the shaft but are skewed because:

- *Reduces humming thus ensuring quiet running of a motor,*
- *Results in a smoother torque curves for different positions of the rotor,*
- *Reduces the magnetic locking of the stator and rotor,*
- *Increases the rotor resistance due to the increased length of the rotor bar conductors.*



5.1 Three phase Induction Motors

Principle of Operation/Working Principle:

- *When 3-phase stator winding is energized from a 3-phase supply, a rotating magnetic field is set up which rotates round the stator at synchronous speed N_s (= 120 f/P).*
- *The rotating field passes through the air gap and cuts the rotor conductors, which are stationary. Due to the relative speed between the rotating flux and the stationary rotor, emf is induced in the rotor conductors according to Faraday's Law of Electromagnetic Induction. Since the rotor circuit is short-circuited, currents start flowing in the rotor conductors.*
- *The current-carrying rotor conductors in presence of rotating magnetic field produced by the stator develops mechanical force on the rotor conductors. The sum of the mechanical forces on all the rotor conductors produces a torque which tends to move the rotor in the same direction as the rotating field according to Lenz's Law.*
- *According to Lenz's law, the direction of rotor currents will be such that they tend to oppose the cause producing them. Now, the cause producing the rotor currents is the relative speed between the rotating field and the stationary rotor conductors. Hence to reduce this relative speed, the rotor starts running in the same direction as that of stator field and tries to catch it.*

At what speed will the motor run? Can it run at the synchronous speed?

If rotor runs at the synchronous speed equal to the same speed of the rotating magnetic field, there wll be no relative speed between the magnetic field and the rotor winding/conductors and the rotor will appear stationary to the rotating magnetic field and hence no emf will be induced and no current will flow in the rotor conductor. As a result, no rotor magnetic flux will be produced to develop torque and the rotor speed will fall below the synchronous speed. Once the speed falls, the rotating magnetic field will cut the rotor windings and a torque will be produced.

So, the Induction Motor always runs at a speed lower than the synchronous speed.

5.1 Three phase Induction Motors

Rotating magnetic Field:

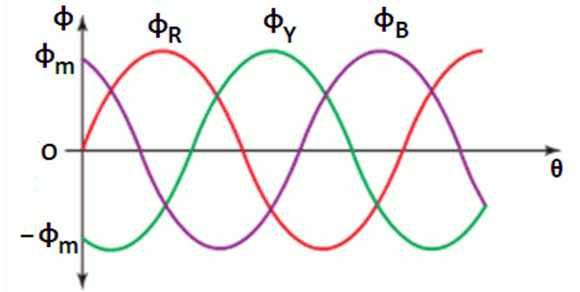
- *When a 3-phase winding is energized from a 3-phase supply, a rotating magnetic field is produced. It means that its poles do not remain in a fixed position on the stator but go on shifting their positions around the stator.*
- *The magnitude of this rotating field is constant and is equal to 1.5Φm where Φm is the maximum flux.*
- *The three phases R, Y and B are energized from a 3-phase source and currents in these phases are indicated as IR, IY and IB*
- *The fluxes produced by these currents are given by:*

$\Phi_R = \Phi_m \text{Sin } \omega t$

$\Phi_Y = \Phi_m \text{Sin } (\omega t\text{-}120^0)$

$\Phi_B = \Phi_m \text{Sin } (\omega t\text{-}240^0)= \Phi_m \text{Sin } (\omega t+120^0)$

Fig. (8.5) shows the phasor diagram of the three fluxes. We shall now prove that this 3-phase supply produces a rotating field of constant magnitude equal to 1.5 fm.



Fluxes produced by line currents

5.1 Three phase Induction Motors

Slip:

- *The difference between the synchronous speed N_S of the rotating stator magnetic field and the actual rotor speed N is called slip ad is expressed as a percentage of synchronous speed*

$$\%Slip\ (S) = \frac{N_S - N}{N_s}\ X\ 100\%$$

- *In practice, the rotor can never reach the speed of stator flux. The rotor speed (N) is always less than the suitor field speed (Ns). This difference in speed depends upon load on the motor.*
  - *The quantity Ns - N is sometimes called slip speed.*
  - *When the rotor is stationary (i.e., N = 0), slip, s = 1 or 100 %.*
  - *In an induction motor, the change in slip from no-load to full-load is between 0.1% and 3% .*

Rotor Current Frequency:

The frequency of emf/voltage or current induced due to the relative speed between a rotor conductor and a magnetic field is given by

$$f = \frac{N_S P}{120}$$

Where, N = Relative speed between magnetic field and the winding and P = Number of poles

For a rotor speed N, the relative speed between the rotating flux and the rotor is Ns - N. Consequently, the rotor current frequency f' is given by;

$$f' = \frac{(N_S - N)P}{120} = \frac{(SN_S)P}{120} = S\frac{N_S P}{120} = Sf$$

Therefore, Rotor current frequency = S x Supply frequency

- *When the rotor is at standstill or stationary, S = 1 and hence the frequency of rotor current is the same as that of supply frequency*
- *As the rotor picks up speed, the relative speed between the rotating field and the rotor decreases. Consequently, the slip S and hence rotor current frequency decreases.*
- *Thus at any slip s,*
  - *Rotor emf/phase = sE2*
  - *Rotor reactance/phase = sX2*
  - *Rotor frequency = sf*
  - *where E2,X2 and f are the corresponding values at standstill*

Questions!

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Chapter 6
Three Phase Synchronous Machines

Electrical Machines

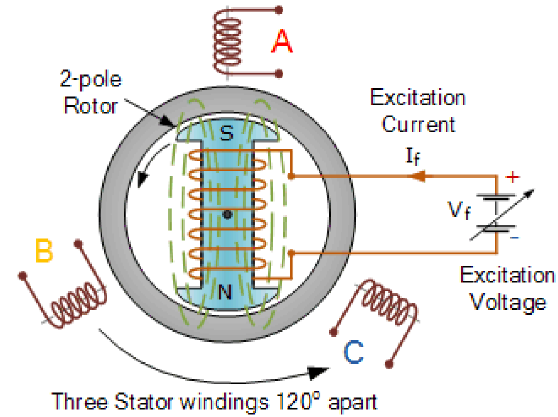
BCT – II/II

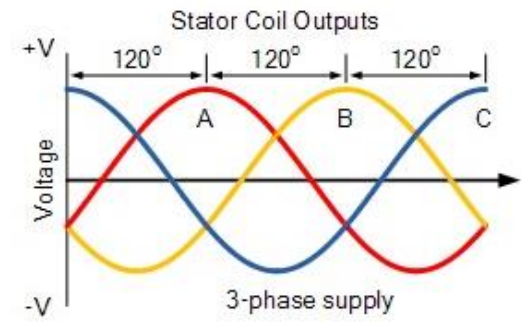
Ramesh Shrestha
Associate Professor/Principal

6.1 Three Phase Synch. Generator

6.1.0 Introduction

- Always runs at a constant speed known as synchronous speed, ($N_S = 120\ f/P$)
- Armature winding is on a stationary element called stator and field windings on a rotating element called rotor
- Also known as ALTERNATOR
- Advantages of Stationary Armature:
  - Easier to insulate stationary armature winding for high voltages
  - 3-phase output voltage can be directly connected to load in case of generator and 3-phase supply can be directly fed into the stationary armature winding in case motor, without going through large, unreliable slip rings and brushes.
  - Only two slip rings are required for dc supply to the field winding on the rotor. Since the exciting current is small, the slip rings and brush gear required are of light construction.

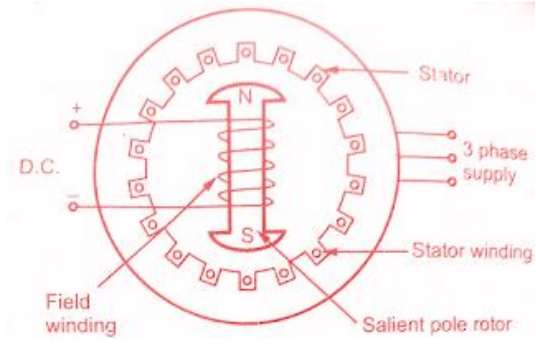




6.1 Three Phase Synch. Generator

6.1.1 Construction

Major Parts: (i) Stator (ii) Rotor (iii) Exciter

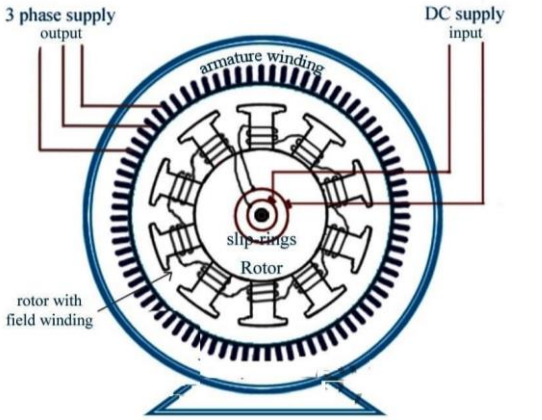


Stator:

- Stationary part of the machine, built up of sheet-steel laminations having slots on its inner periphery.
- 3-phase winding is placed in these slots and serves as the armature winding of the alternator.
- Armature winding is always connected in star and the neutral is connected to ground

Rotor:

- Rotating part, carries a field winding supplied with dc source through two slip rings
- The dc source (called exciter) is a small dc shunt or compound generator mounted on the shaft of the alternator.
- Rotor types:
  - (i) Salient (or projecting) pole type
  - (ii) Non-salient (or cylindrical) pole type

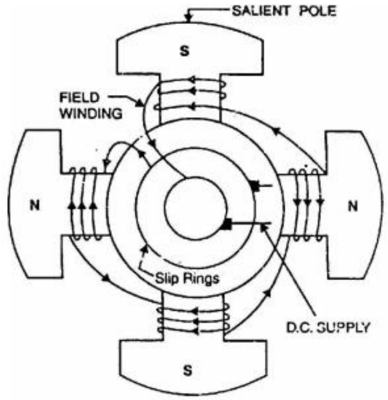


6.1 Three Phase Synch. Generator

6.1.1 Construction

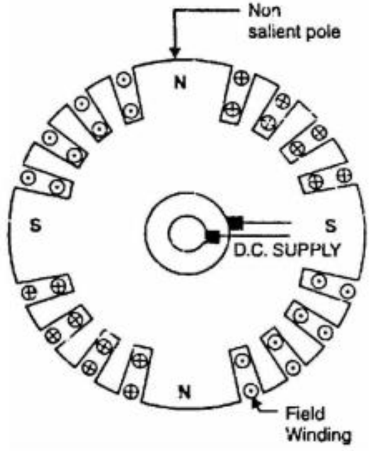
(i) Salient (or projecting) Pole Rotor:

- Used for low and medium-speed alternators (120-400 rpm) such as those driven by diesel engines or water turbines because
- Excessive windage loss if driven at high speed and would tend to produce noise.
- Cannot be made strong enough to withstand the mechanical stresses that is produced at higher speeds.



(ii) Non-salient (or cylindrical) Pole Rotor:

- Used for high-speed alternators (1500 or 3000 rpm) such as those driven by steam turbines
- Mechanically robust and gives noiseless operation at high speeds.
- Flux distribution around the periphery is nearly a sine wave and hence a better emf waveform is obtained than in the case of salient-pole type.



Exciter:

- A dc generator to supply dc voltage to rotor winding, to produce magnetic field

6.1 Three Phase Synch. Generator

6.1.2 Working Principle

- N and S poles are developed on the rotor by energizing rotor winding.
- When the rotor is rotated by a prime mover, the stator or armature conductors are cut by the magnetic flux of rotor poles. Consequently, emf is induced in the armature conductors due to electromagnetic induction.
- The induced emf is alternating since N and S poles of rotor alternately pass the armature conductors.
- The direction of induced emf can be found by Fleming's right hand rule
- Frequency of the induced emf is given by $f = \frac{NP}{120}$

  where, N = Speed of Rotor in rpm

  P = No. of Rotor Poles

6.1 Three Phase Synch. Generator

6.1.3 EMF Equation

Let Z = No. of conductors or coil sides in series per phase

f = Flux per pole in weber

P = Number of rotor poles

N = Rotor speed in rpm

Flux cut by each stator conductor in one revolution, $d\emptyset = P\emptyset$

Time taken to complete one revolution, $dt = \frac{60}{N}$

$\therefore$ Average emf induced in one stator conductor $= \frac{d\emptyset}{dt} = \frac{P\emptyset}{60/N} = \frac{P\emptyset N}{60}$ volts

Since there are z conductors in series per phase,

Average emf/phase $= \frac{P\emptyset N}{60}\ x\ Z = \frac{P\emptyset Z}{60}\ x\ 120\frac{f}{p} = 2f\emptyset Z\ volts$

RMS value of emf/phase = Average emf/phase x form factor $=2f\emptyset Z x\ 1.11 = 2.22f\emptyset Z$

E_{rms}/Phase $= 2.22f\emptyset Z = 2.22f\emptyset\ x\ 2T = 4.44\emptyset fT$ [Since No. of conductors = 2 x No. of Turns]

If K_p and K_d are the pitch factor and distribution factor of the armature winding, then,

E_{rms}/Phase $= 2.22K_pK_d\emptyset fZ = 4.44KpKd\emptyset fT$ volts

6.1.3 Pitch Factor, K_P

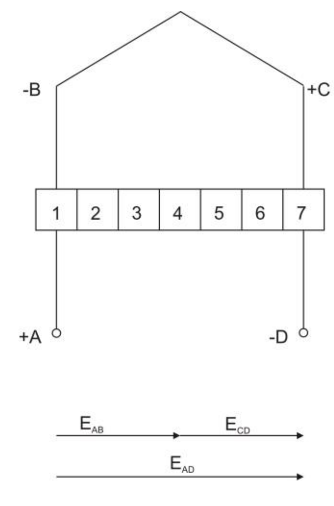
- A coil whose sides are separated by one pole pitch (i.e., coil span is 180° electrical) is called a full-pitch coil.
- In a full-pitch coil, the EMFs induced in the two coil sides is in phase with each other and the resultant EMF is the arithmetic sum of individual EMFs.
- Waveform of the resultant EMF can be improved by making the coil pitch less than a pole pitch. Such a coil is called short-pitch coil.

$$Pitch\ Factor, KP = \frac{EMF\ in\ short\ pitch\ Coil}{EMF\ in\ full\ pitch\ Coil}$$

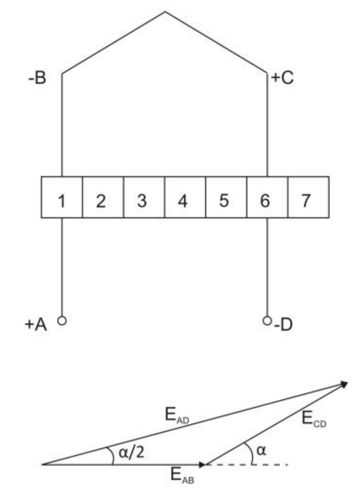
$$Pitch\ Factor, KP = \frac{E_{AB}Cos\alpha/2\ +\ E_{CD}Cos\alpha/2}{E_{AB} + ECD}$$

$$Pitch\ Factor, KP = \frac{2EAB_{Cos}\alpha/2}{2E_{AB}}\ [Since\ EAB = ECD]$$

$$\therefore\ KP = Cos\alpha/2$$



Full Pitched winding

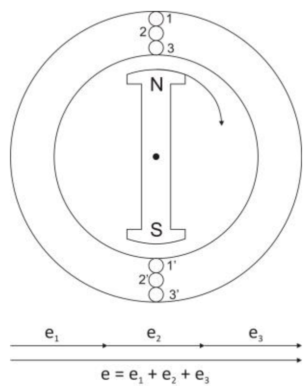


Short Pitched winding

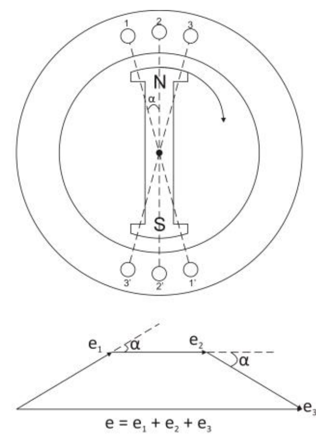
6.1 Three Phase Synch. Generator

6.1.3 Distribution Factor, K_d

- Winding with only one slot per pole per phase is called a concentrated winding.
- EMF generated/phase is equal to the arithmetic sum of the individual coil EMFs.
- If the coils/phase are distributed over several slots in space (distributed winding), the EMFs in the coils are not in phase but are displaced from each by the slot angle α. The EMF/phase will be the phasor sum of coil EMFs.
- Slot angle is angular displacement in electrical degrees between the adjacent slots



Induced emf in a concentrated winding



Induced emf in a distributed winding winding sagarmatha ENGINEERING COLLEGE TRIBHUVAN UNIVERSITY AFFILIATE

6.1.3 Distribution Factor, K_d

$$Distribution\ Factor, Kd = \frac{EMF\ with\ distributed\ winding}{EMF\ with\ concentrated\ winding}$$

$$Let, \quad \alpha = slot\ angle = \frac{180^0\ electrical^*}{No.of\ slots/pole}$$

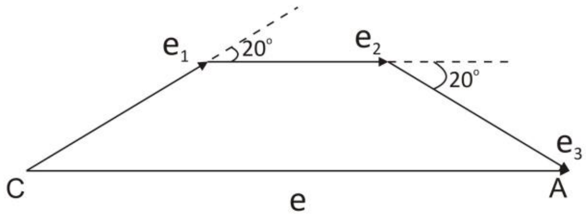
$$n = slots/pole/phase$$

K_d can be determined by constructing a phasor diagram for the coil EMFs. Let, n =3

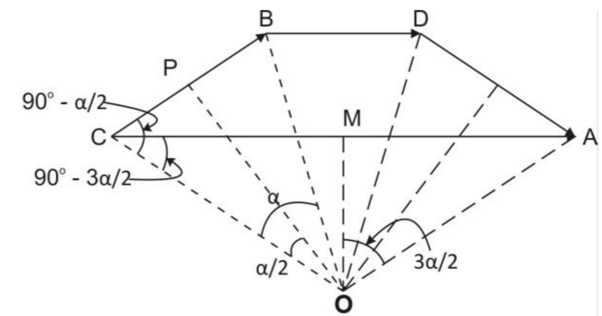
$$K_d = \frac{CA}{n\ x\ CB} = \frac{2\ x\ CM}{n\ x\ (2CP)} = \frac{CM}{n\ x\ CP} = \frac{OC\ x\ Sin(\frac{n\alpha}{2})}{n\ xOC\ x\ Sin(\frac{\alpha}{2})}$$

$$K_d = \frac{Sin(\frac{n\alpha}{2})}{n\ Sin(\frac{\alpha}{2})}$$

$$[^*Electrical\ Degree = Mechanical\ Degree\ X\ \frac{P}{2}]$$



Emf induced in the coils has a time phase difference due to their placementin different slots

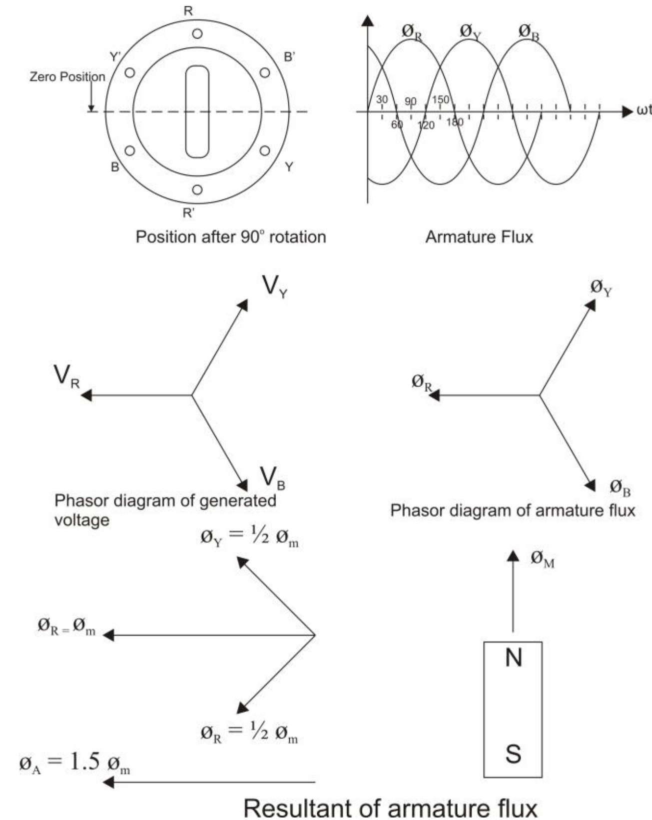


Calculation of resultant voltage in terms of emf induced in the individual coils

6.1 Three Phase Synch. Generator

6.1.4 Armature Reaction and its effects

- At no-load, there is no current flowing through the armature winding and hence the flux produced will be only due to the rotor ampere-turns.
- When the alternator is loaded, the three-phase currents flowing through the armature winding will also produce a rotating magnetic field in the air-gap. Consequently, the air-gap flux will be changed due to the field produced by/at the armature windings.
- The effect of armature field to the main field produced by the rotor ampere-turns is called armature reaction.
- The effect of the to armature field to the main field depends on the magnitude of stator current and on the power factor of the load.
- The load power factor determines whether the armature flux distorts, opposes or helps the field produced by rotor ampere-turns.



6.1 Three Phase Synch. Generator

sagarmatha ENGINEERING COLLEGE TRIBHUVAN UNIVERSITY AFFILIATE

6.1.4 Effects of Armature Reaction

$\emptyset_R = \emptyset_m Sin\omega t$
$\emptyset_Y = \emptyset_m Sin(\omega t - 120^0)$
$\emptyset_B = \emptyset_m Sin(\omega t - 2400) = \emptyset_m Sin(\omega t + 120^0)$

(i) For Resistive Load (i.e when load pf is unity)

At $\omega t = 90^0$,

$\emptyset_R = \emptyset_m Sin\ 90^0 = \emptyset_m$
$\emptyset_Y = \emptyset_m Sin(90^0 - 120^0) = \emptyset_m Sin(-30^0) = -1/2\emptyset_m$
$\emptyset_B = \emptyset_m Sin(90^0 - 240^0) = \emptyset_m Sin(-150^0)) = -1/2\emptyset_m$

Now,

$$\emptyset_H = \emptyset_m + \frac{1}{2}\emptyset_m Cos600 + \frac{1}{2}\emptyset_m Cos600 = \emptyset_m + \frac{1}{4}\emptyset_m + \frac{1}{4}\emptyset_m$$

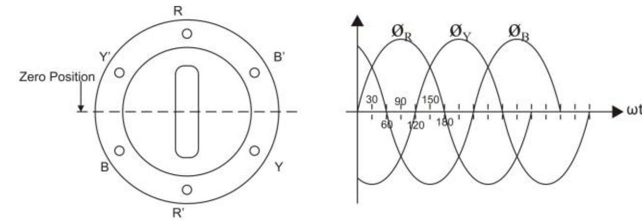
$$\therefore \emptyset_H = \frac{6}{4}\emptyset_m = \frac{3}{2}\emptyset_m = 1.5\emptyset_m$$

$$\emptyset_V = \frac{1}{2}\emptyset_m Sin60^0 - \frac{1}{2}\emptyset_m Sin60^0 = 0$$

$$\therefore \emptyset_A = \emptyset_T = \sqrt{\emptyset_H{}^2 + \emptyset_V{}^2} = 1.5\emptyset_m$$

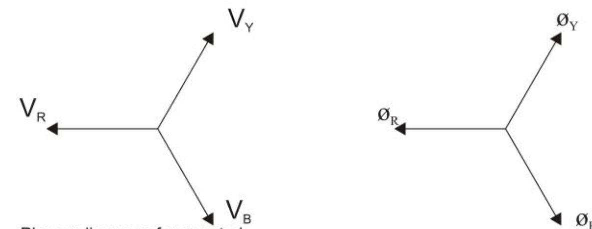
$$\theta = Tan^{-1}\frac{\emptyset_V}{\emptyset_H} = Tan^{-1}0 = 0^0$$

∴The effect is cross magnetizing



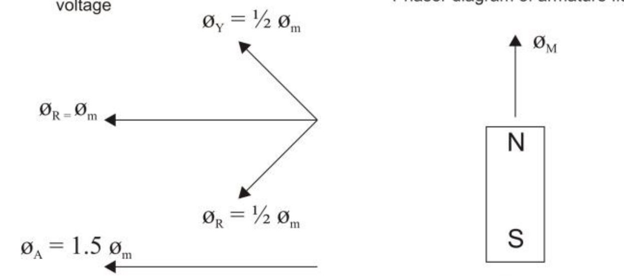
Position after 90° rotation

Armature Flux



Phasor diagram of generated voltage

Phasor diagram of armature flux



Resultant of armature flux

6.1 Three Phase Synch. Generator

6.1.4 Effects of Armature Reaction

(ii) For Inductive Load (i.e when load pf is lagging)

∴The effect is de-magnetizing

(ii) For Capacitive Load (i.e when load pf is leading)

The effect is magnetizing

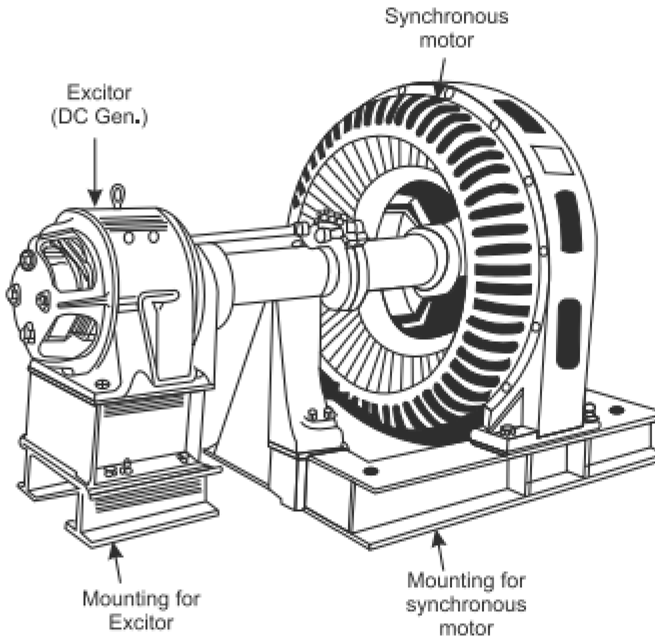
6.1 Three Phase Synch. Generator

6.1.5 Alternator with load and its phasor diagram

6.2 Three Phase Synch. Motor

6.2.0 Introduction

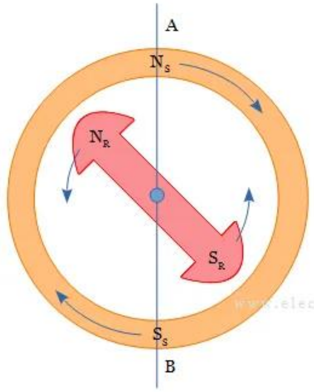
- The same synchronous machine can be operated as a generator (called alternator/synchronous generator) when driven mechanically or as a motor (called synchronous motor) when driven electrically
- Runs either at synchronous speed or not at all i.e. it maintains a constant speed. The only way to change its speed is to vary the supply frequency (because Ns = 120 f / P).
- Not inherently self-starting. Has to be run up to synchronous or near to synchronous) speed by some means, before connected to 3 phase supply.
- Capable of being operated under a wide range of power factors, both lagging and leading. Hence, it can be used for power factor correction purposes, in addition to supplying torque to drive loads



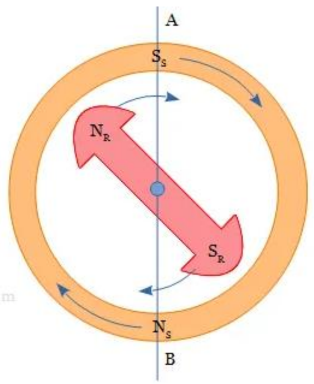
6.2 Three Phase Synch. Motor

6.2.1 Operating Principle

- 3 phase stator winding when supplied by a 3 phase AC source produces rotating magnetic field in stator. The rotor winding is fed with DC supply to produce rotor field.
- As the stator poles are revolving with synchronous speed (lets say clockwise), N pole of the rotor when comes near to the N pole of the stator (as shown in figure a), then the poles of the stator and rotor will repel each other, and the torque produced will be anticlockwise.
- As the stator poles are continuously rotating with synchronous speed, after some time N pole of the rotor will come near to S pole of stator as shown in figure band the rotor can not rotate in the same direction (due to inertia), In this case, poles of the stator will attract the poles of rotor, and the torque produced will be clockwise. Hence, the rotor will undergo to a rapidly reversing torque, and the motor will not start.
- But, if the rotor is rotated upto the synchronous speed by means of an external force (in the direction of revolving field of the stator), and then the rotor winding is supplied by a DC source to produce rotor field, the stator pole will keep attracting the opposite pole of the rotor. Now, the rotor will undergo unidirectional torque. The opposite poles of the stator and rotor will get locked with each other, and the rotor will rotate at the synchronous speed.



(a)



(b)

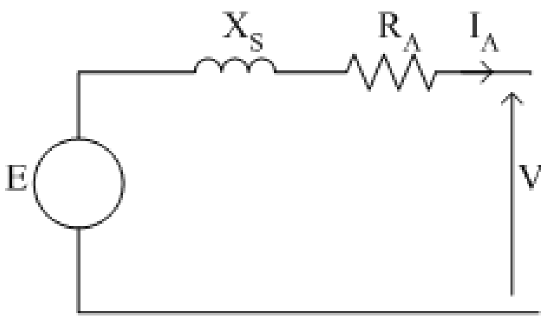
6.2 Three Phase Synch. Motor

6.2.2 Starting Methods

- A dc motor coupled to the shaft of synchronous motor
- Using field exciter of synchronous motor as dc motor
- Using damper winding as a squirrel case induction motor

6.2 Three Phase Synch. Motor

6.2.3 No load and full load operation



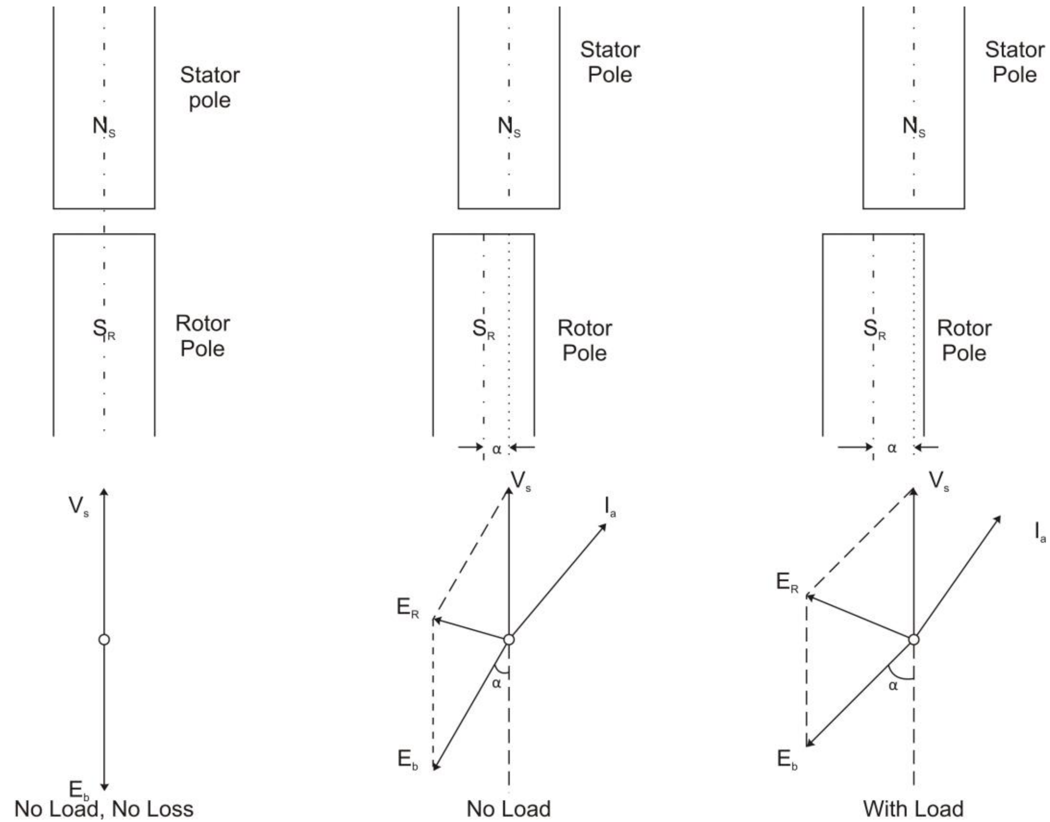
per-phase armature circuit

$$V_s - IaR_a - jIaX_s - Eb = 0$$

$$V_s - Ia(R_a + jX_s) = E_b$$

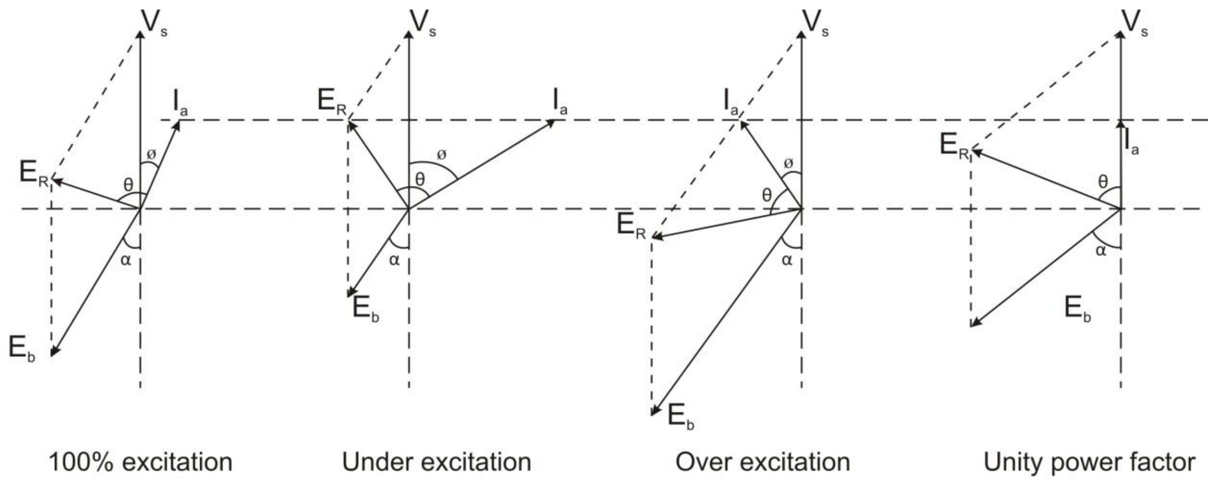
$$V_s - Eb = I_aZ_s$$

$$I_a = \frac{V_s - Eb}{Z_s} = \frac{E_R}{Z_s}$$



6.2 Three Phase Synch. Motor

6.2.4 Effect of excitation and pf control



Effect of excitation on armature current and power factor

$$V_s - IaR_a - jIaX_s - Eb = 0$$

$$V_s - Eb = I_a(R_a + jXs)$$

$$E_R = Ia(R_a + jXs)$$

$$\theta = Tan^{-1}\frac{X_s}{R_a}$$

Where θ is phase angle between I_a and E_R

Since XS and Ra are constant, θ also remains constant

Questions!

Chapter 7: Single Phase Induction Motors

Electrical Machines

BCT – II/II

Ramesh Shrestha
Associate Professor

7. Single phase Induction Motors

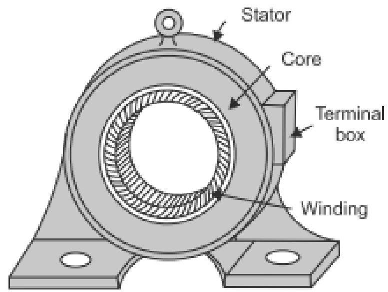
Introduction:

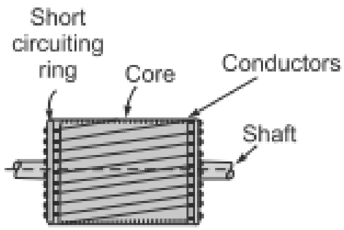
- Extensively used in home appliances: fans, refrigerators, air-conditioners, vacuum cleaners, washing machines, hair driers, mixer grinders, centrifugal pumps, tools, small farming appliances, blowers etc.…
- Used for low power but constant speed devices such as agricultural tools and machinery
- Simple in construction and economical for small power rating
- Usually have output less than one horse-power or one kilowatt, hence are called fractional horse-power or fractional kilowatt motors.
- Not self starting

7. Single phase Induction Motors

Construction:

- Similar to 3-phase Squirrel Cage Induction Motor in construction
- Consists of 2 main parts: Stator and Rotor
- Stator: A stationary part of the motor, has three main parts, namely. (i) Outer Frame, (ii) Stator Core and (iii) Stator Winding.
    - *Outer Frame: outer body of the motor, to support the stator core and to protect the inner parts of the machine. Usually, it is made of cost iron.*
    - *Stator Core: Carries the alternating magnetic field, Slots are punched on the inner periphery of the core to accommodate stator winding.*
    - *Stator Winding: Stator core carries a single phase winding, supplied from a single phase AC supply system. Terminals of the winding are connected in the terminal box of the machine.*
- Rotor: A rotating part of the motor.
    - *A squirrel cage rotor is used.*
    - *Consists of a laminated cylindrical core of high quality magnetic material.*
    - *Semi-closed circular slots are punched at the outer periphery.*
    - *Aluminium/copper bar conductors are placed in these slots and short circuited at each end by aluminium/copper rings, called short circuiting rings. Thus, the rotor winding is permanently short circuited.*





7. Single phase Induction Motors

Why rotor slots are skewed?

The rotor slots are usually not parallel to the shaft but are skewed.

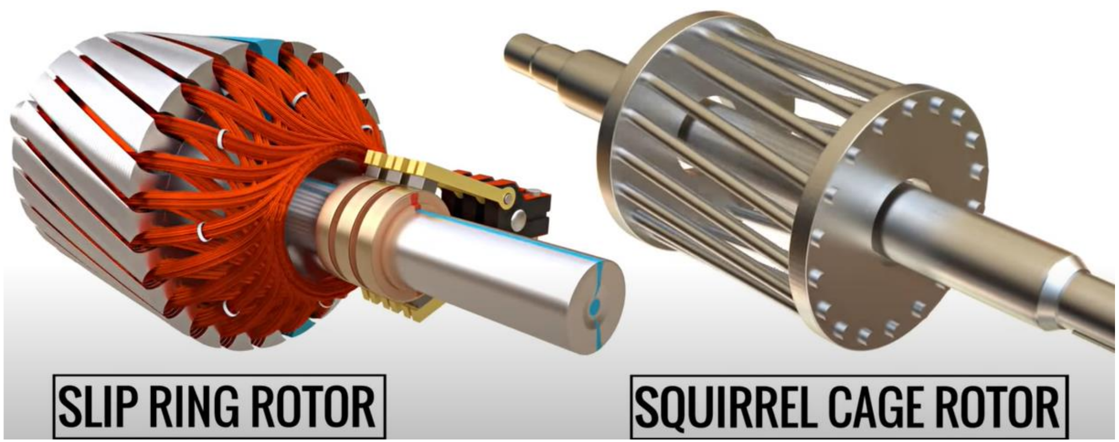
Skewing of rotor has the following advantages:

(a) Reduces humming thus ensuring quiet running of a motor,

(b) Results in a smoother torque curves for different positions of the rotor,

(c) Reduces the magnetic locking of the stator and rotor,

(d) Increases the rotor resistance due to the increased length of the rotor bar conductors.



7. Single phase Induction Motors

Working Principle:

- Stator winding when supplied by a 1-phase source, a pulsating magnetic field is produced
- In the pulsating field, the rotor does not rotate due to inertia. Therefore, it's not self-starting and requires particular starting means.
- when rotor is given an initial start by external force in either direction, motor accelerates to its final speed and keeps running with its rated speed. This is not a practical method of starting a motor.
- The behavior of 1-phase Induction Motor can be explained with the help of Double Field Revolving Theory

https://youtu.be/awrUxv7B-a8

7. Single phase Induction Motors

Double Field Revolving Theory:

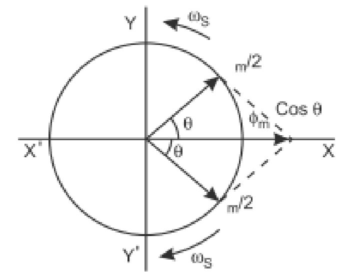
- A pulsating field can be resolved into two components of equal magnitude. And each of these components rotates in opposite direction with the same speed.
- The magnitude of these two fields is equal to the half the maximum value of the pulsating field.
- Let $\emptyset_m$ be the pulsating field which has two components each of magnitude $\emptyset_m/2$. Both are rotating at the same speed ω_s rad/sec but in opposite direction as shown in Fig (a.) The resultant of the two fields is $\emptyset_m \cos\theta$, which is shown in Fig (b).
- Consider the phasor diagram shown in Fig. (a), where two magnetic fluxes each of magnitude $\emptyset_m/2$ are revolving in opposite direction. At any instant t, the two fluxes have been rotated through angle θ $(\theta = \omega t)$.

  Mathematically,

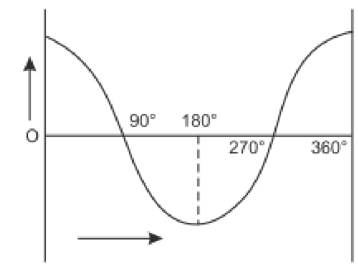
  Total value of flux along x-axis $= \frac{\emptyset_m}{2} cos\omega t + \frac{\emptyset_m}{2} cos\omega t = \emptyset_m cos\omega t$

  Total value of flux along y-axis $= \frac{\emptyset_m}{2} sin\omega t - \frac{\emptyset_m}{2} sin\omega t = 0$

  ∴ Resultant flux, $\emptyset = \sqrt{(\emptyset_m cos\omega t)^2 + 0^2} = \emptyset_m cos\omega t$
- As the two components are rotating in opposite direction, they cancel each other and hence the net torque experienced by the rotor at the starting condition is zero.



(a) Phasor diagram



(b) Wave diagram

7. Single Phase Induction Motors

Classification:

Single-phase ac motors are generally built in the fractional-horsepower range and are classified into the following four basic types:

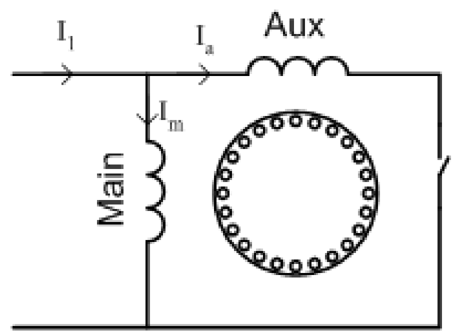
1. **Single-phase induction motors**
   i. Split Phase Type
   ii. Capacitor Type
      - Capacitor-Start Motor
      - Capacitor-Start Capacitor-Run Motor
   iii. Shaded Pole Type

2. A.C. series motor or universal motor

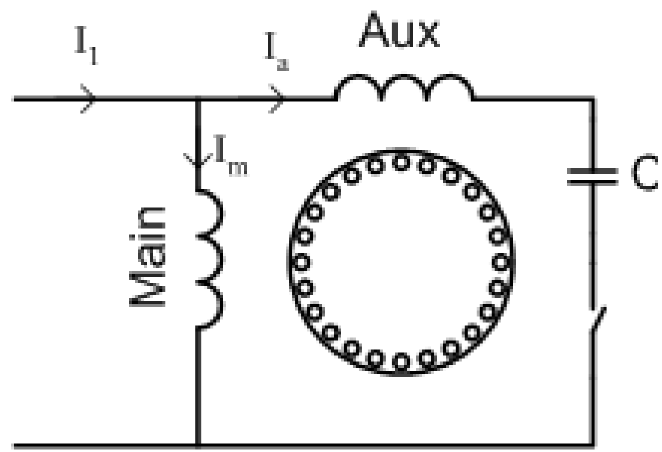
3**. Repulsion motors**
   i. Repulsion-start induction-run motor
   ii. Repulsion-induction motor

4. Synchronous motors
   i. Reluctance motor
   ii. Hysteresis motor

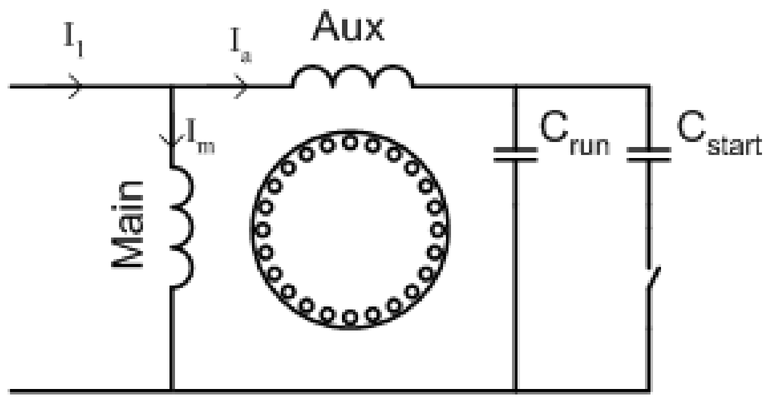
Split Phase Induction Motor



Capacitor Start Induction Motor

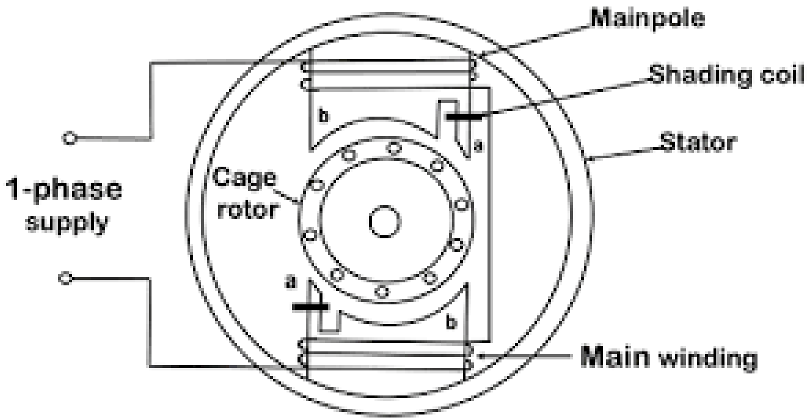


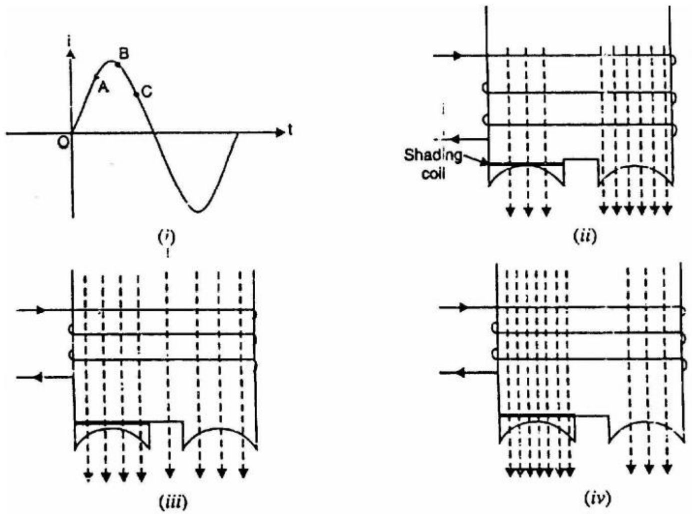
Capacitor-Start Capacitor-Run Induction Motor



7. Single phase Induction Motors

Shaded Pole Induction Motor

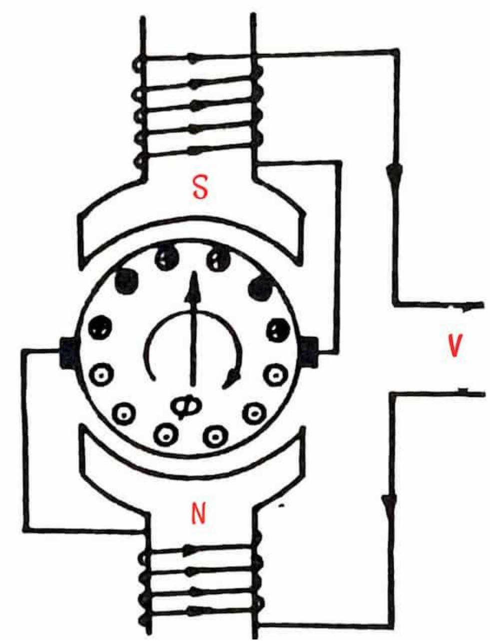




7. AC Series or Universal Motor

Introduction:

- A dc series motor when operated by 1-phase ac supply is know as ac series motor.
- Also known as a Universal Motor as it can operated either on ac or dc supply
- Construction of an ac series motor is very similar to a dc series motor
- Some modifications must be made in the dc series motor to operate satisfactorily on ac supply.
- The magnetic circuit must be laminated.
- Field circuit must be designed for much lower reactance than dc motor in order to reduce the reactance voltage drop and improve power factor.
- Distributed compensation winding is required to minimize the reactance of armature winding.



7. AC Series or Universal Motor

Working Principle:

- The working principle is the same as that of dc series motor.
- When an ac series motor connected to the ac supply the alternating current start flowing through the field and armature winding.
- The field winding produces an alternating flux Φ that reacts with current flowing in armature winding to produce a torque.
- Since both armature and field current reverse simultaneously, the torque always produced in the same direction.
- Mathematically,

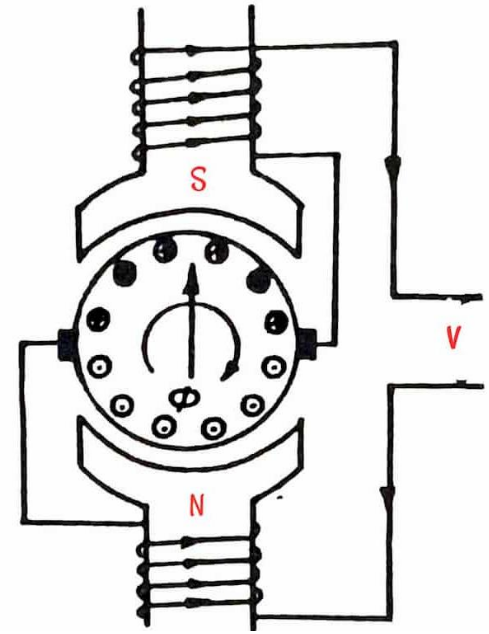
  Torque in DC series motors, $T \propto \emptyset I_a$.

  When AC supply is given to series motor,

  For positive half cycle, $T \propto \emptyset Ia$

  For negative half cycle, $T \propto (-\emptyset)(-Ia) \propto \emptyset Ia$

  Thus same torque is produced during positive and negative half cycle.



7. AC Motors

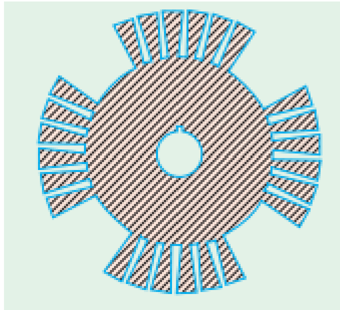
Reluctance Motor:

Introduction:

- A single-phase synchronous motor which does not require dc excitation to the rotor.
- Operation based on the following principle:
  Whenever a piece of ferromagnetic material is located in a magnetic field; a force is exerted on the material, tending to align the material so that reluctance of the magnetic path that passes through the material is minimum.

Construction:

- Stator: Carries a single-phase winding along with an auxiliary winding to produce a synchronous-revolving magnetic field.
- Squirrel-cage rotor: has unsymmetrical magnetic construction. This is achieved by symmetrically removing some of the teeth from the squirrel cage rotor to produce salient poles on the rotor.
- https://youtu.be/qDon7Nrj1Tk



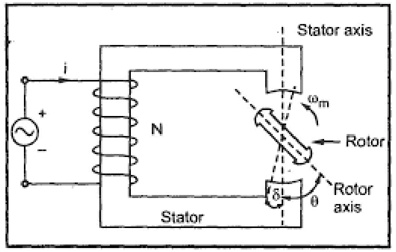
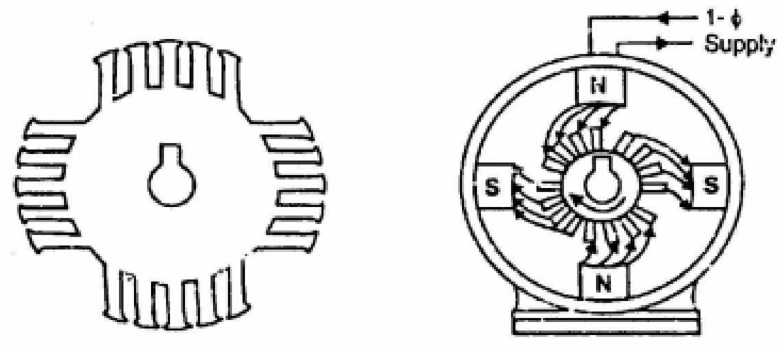


Fig. 7.2 Elementary reluctance motor

Reluctance Motor:

Operation:

- When single-phase stator having an auxiliary winding is energized, a synchronously-revolving field is produced. The motor starts as a standard squirrel-cage induction motor and will accelerate to near its synchronous speed.
- As the rotor approaches synchronous speed, the rotating stator flux will exert reluctance torque on the rotor poles tending to align the salient-pole axis with the axis of the rotating field. The rotor assumes a position where its salient poles lock with the poles of the revolving field. Consequently, the motor will continue to run at the speed of revolving flux i.e., at the synchronous speed.
- Reference: https://youtu.be/qDon7Nrj1Tk

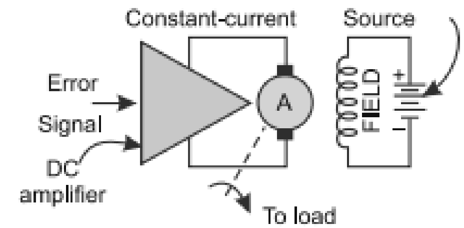


(i) (ii)

7. AC Motors

Servo Motor:

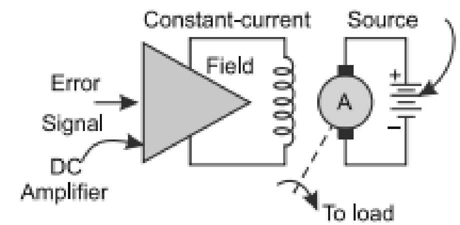
- Responds to the error signal abruptly and accelerate the load quickly.
- Servomotors are usually employed with control system
- Characteristics of servomotor (DC or AC) :
  - The output torque should be proportional to its applied control voltage (developed by the amplifier in response to an error signal).
  - The direction of the toque is determined by the polarity of the control voltage.



DC Servo Motor

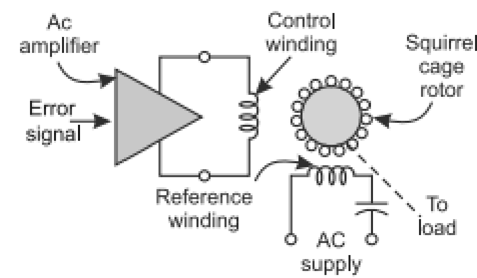
DC motors employed in the control system are called DC servomotors

- Field-controlled DC Servomotors
- Armature-controlled DC Servomotors



AC Servo Motor:

AC motors employed in the control system are called AC servomotors



Application:
Used in many applications like toy car, RC helicopters and planes, Robotics, etc.

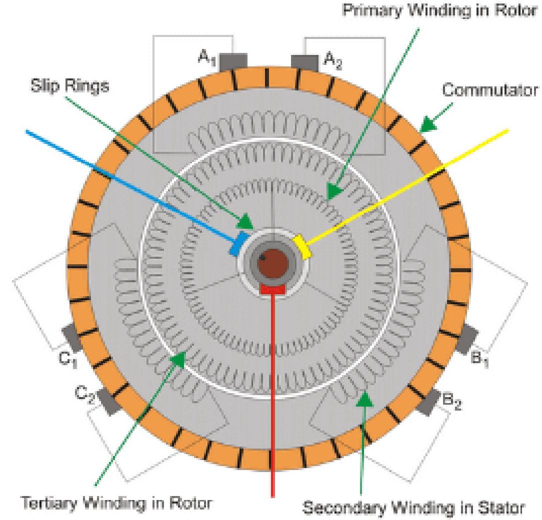
References:

https://circuitdigest.com/article/servo-motor-working-and-basics
https://youtu.be/ditS0a28Sko

7. AC Motors

Scharge Motor:

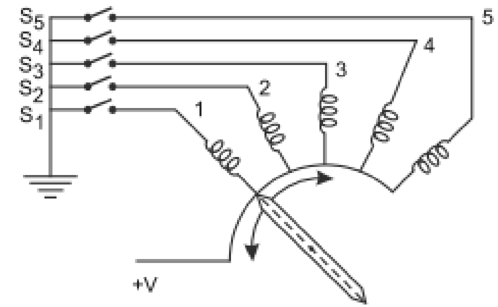
- A motor that contains both power factor correction arrangement and speed control
- An inverted poly phase induction motor. Unlike induction motor the primary winding of Schrage motor is on the rotor. Three phase supply is given to the primary with the help of 3 slip rings. The secondary winding is on the stator.
- A third type of winding called as tertiary winding is connected to the commutator. The primary and tertiary are housed in the same rotor slots.
- The secondary winding terminals are connected to the commutator via three sets of movable brushes A1A2, B1B2 and C1C2.
- The brush position can be changed by a wheel provided at the back of motor.
- The angular displacement between the brushes determines the injected emf into the secondary winding which is required for speed and power factor control.
- Applications
  Used in drives requiring variable speed such as cranes, fan, centrifugal pumps, conveyors etc.
- **Reference:**
  https://www.electrical4u.com/schrage-motor-operation-principle-and-characteristics-of-schrage-motor/

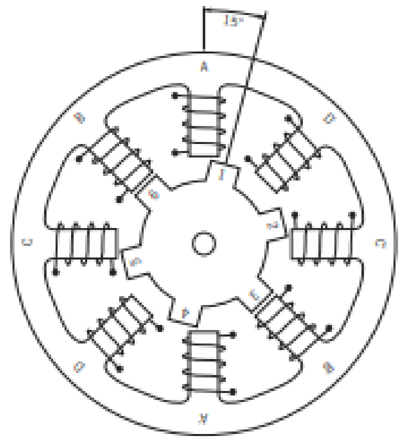


7. AC Motors

Stepper Motor:

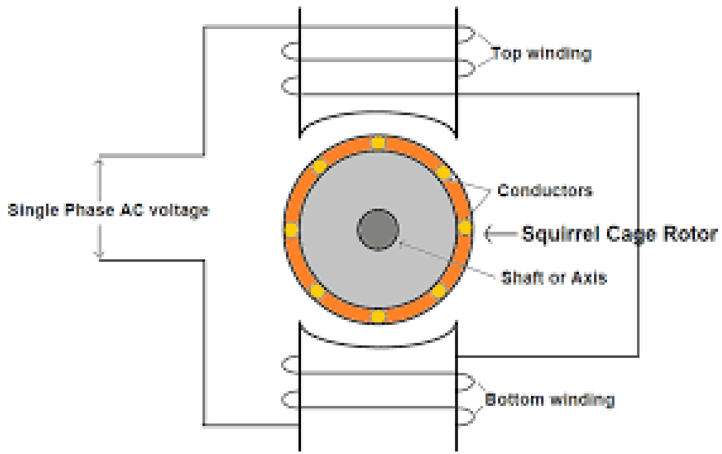
- Motor where its rotor turns in discrete movements is called a stepper motor.
- Turns in discrete movements called steps.
- After the rotor makes a step, it stops turning until it receives the next command (or signal)
- Motor rotates through a fixed angular step in response to each input current pulse received by its controller.
- The rotation angle of the motor is proportional to the input pulse.
- Excellent response to starting/ stopping/reversing
- A wide range of rotational speeds can be realized as the speed is proportional to the frequency of the input pulses

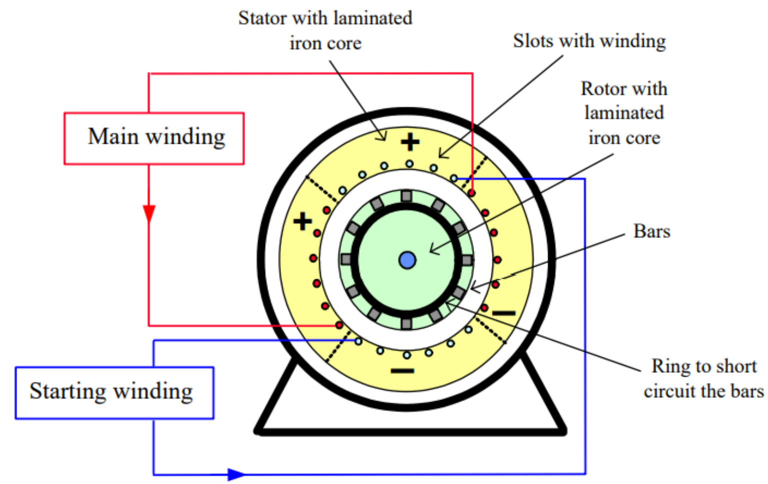




- **References:**

https://youtu.be/VfqYN1eG9Zk
http://users.ece.utexas.edu/~valvano/Datasheets/StepperBasic.pdf


Top winding
Single Phase AC voltage
Conductors
Squirrel Cage Rotor
Shaft or Axis
Bottom winding


Stator with laminated iron core
Slots with winding
Rotor with laminated iron core
Main winding
Bars
Starting winding
Ring to short circuit the bars

Questions!