UNIVERSITY OF ZAMBIA

EE321 LECTURE PART II

SICHILALU SAM

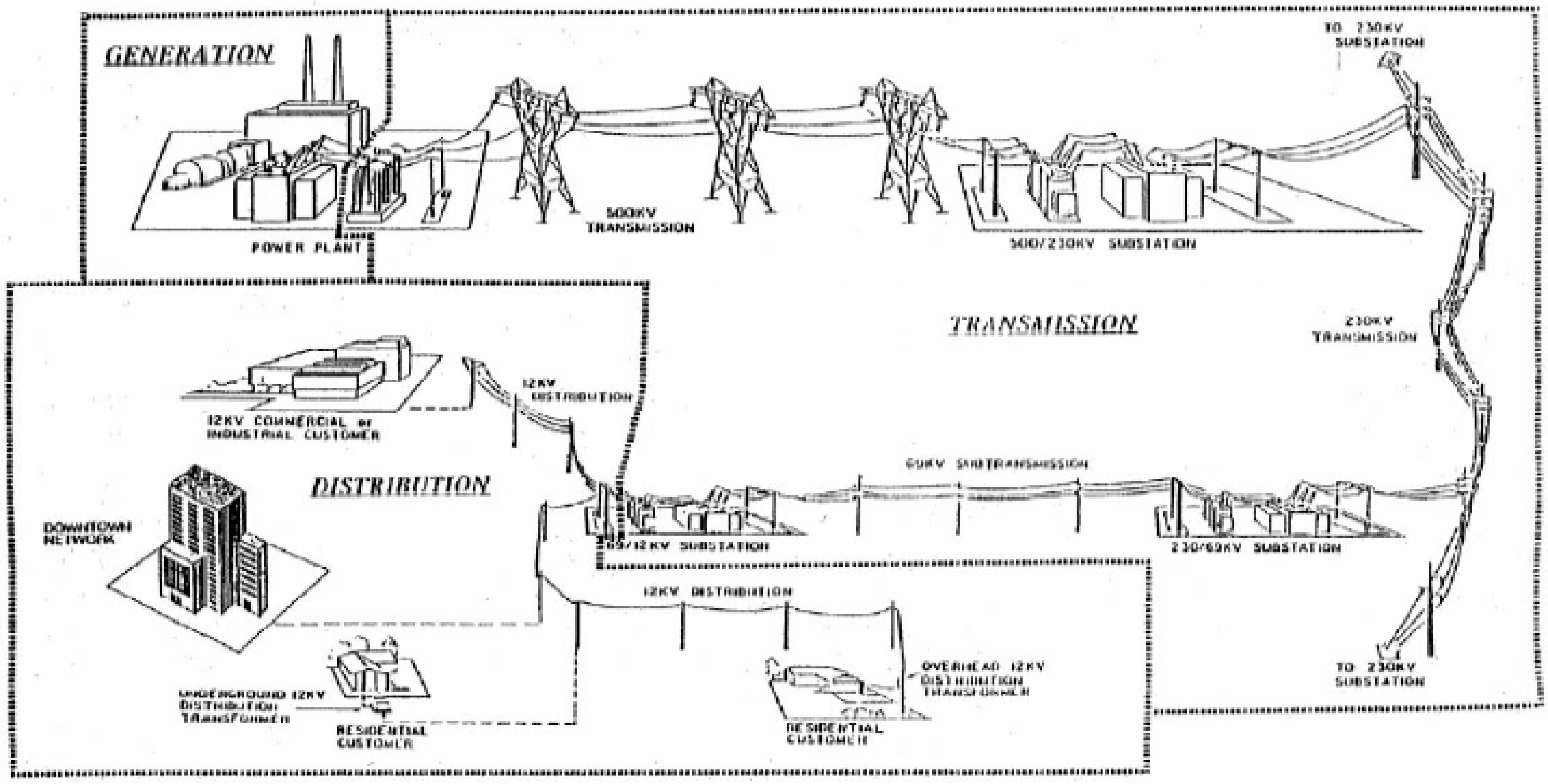
2010

POWER SYSTEMS

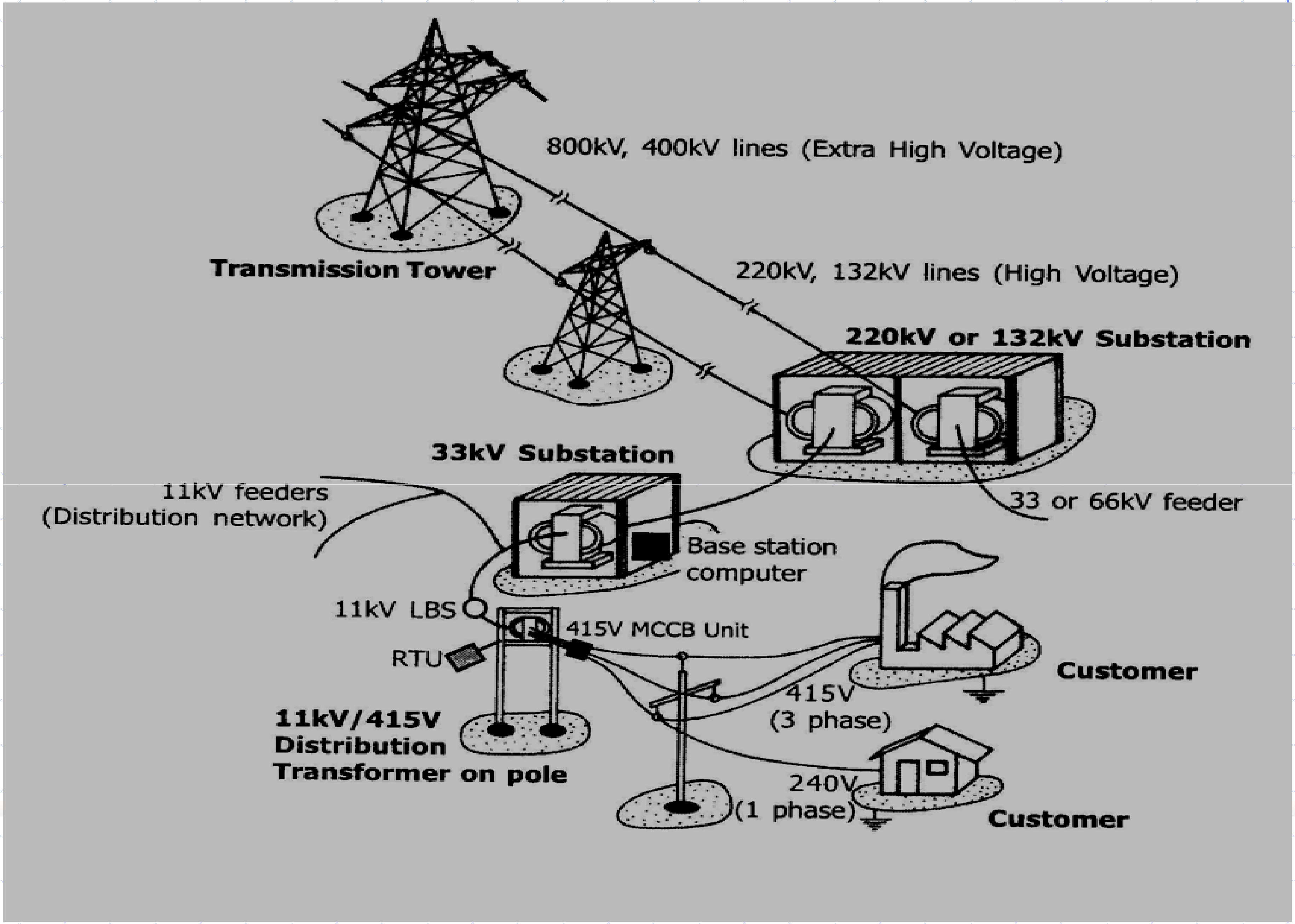
ELECTRIC POWER SYSTEMS

1.Alternator **2. Power transformer** **3.Transmission lines**

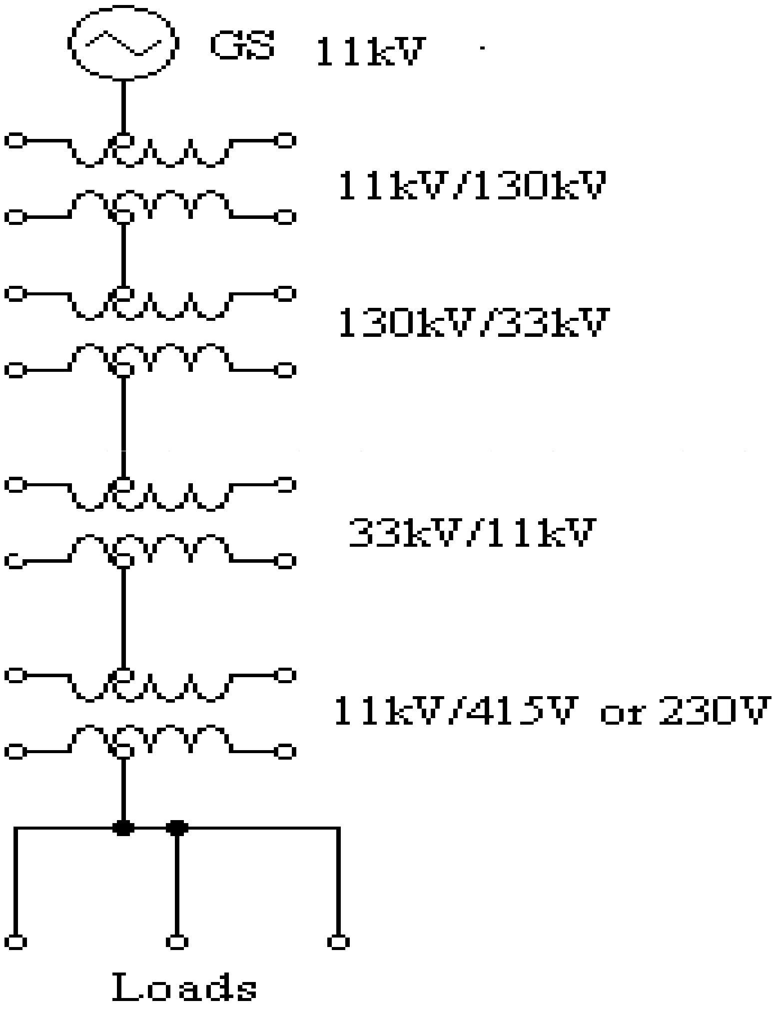
4. Substation transformer **5.Distribution transformer** **6.Loads**



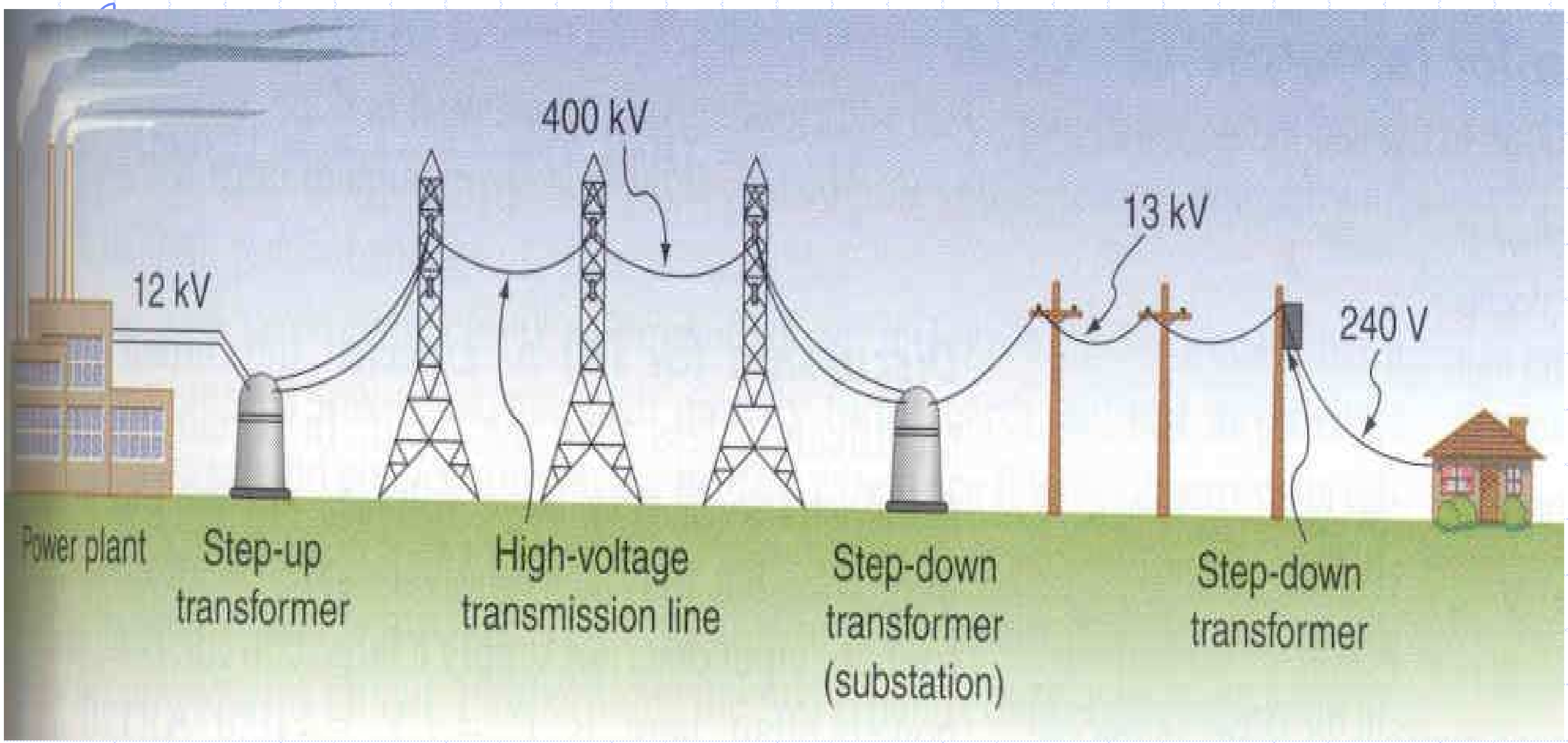
Concept of electric energy transmission.


800kV, 400kV lines (Extra High Voltage)
Transmission Tower
220kV, 132kV lines (High Voltage)
220kV or 132kV Substation
33kV Substation
11kV feeders
(Distribution network)
33 or 66kV feeder
Base station
computer
11kV LBS
415V MCCB Unit
RTU
Customer
415V
(3 phase)
11kV/415V
Distribution
Transformer on pole
240V
(1 phase)
Customer

Power systems and network



Electrical power transmission



- AC of 50 Hz produced by generator
- Resistance losses are smallest at high voltages and low currents

Electrical Generation

FEATURES OF GENEARATION- SOURCES OF ENERGY, NEEDS AND ELECTRICAL

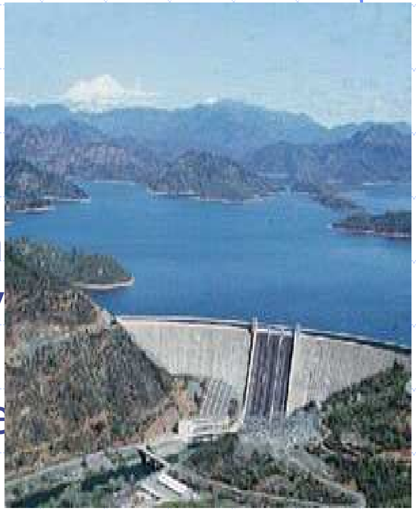
- **Sources :** Wood, charcoal, solar, hydropower, nuclear etc…
- Here in zambia, electrical power system is mainly based on hydroelectric power (i.e., from water)
  - The power associated is:

    where ρ: water density= $10^3 kg/m^3$;

    g = $9.81 m/s^2$;

    Q: water flow rate [m^3/s], and

    H: height [m] ·
- **Needs/Utilisation:** Heating, mechanical power, communication
- **Electrical network components:** Electricity supply systems hav power to many types of load.
  - The greater the power supplied, for a given voltage, the current.



GENERATION OF THREE PHASE E.M.F

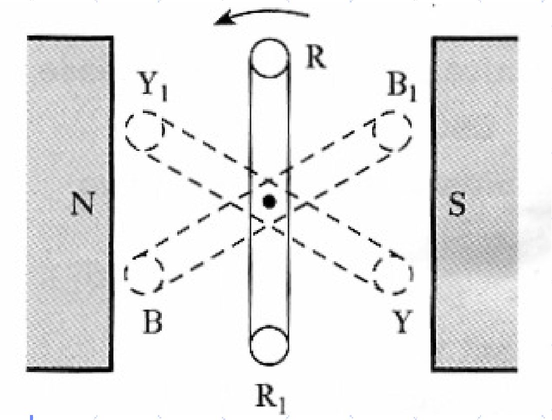


Fig.1: Generation of three-phase e.m.f.s

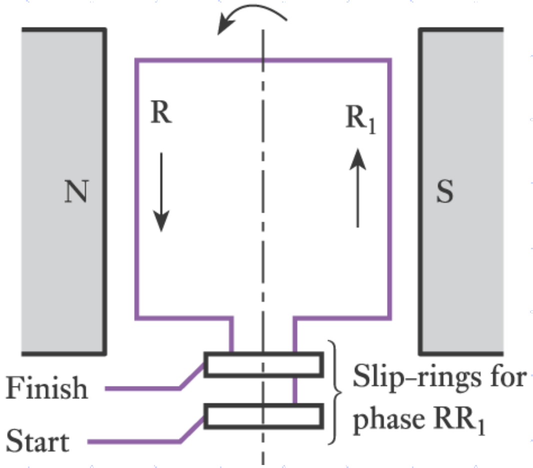
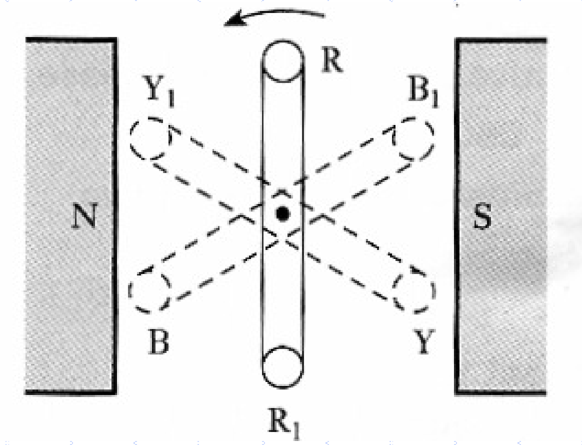
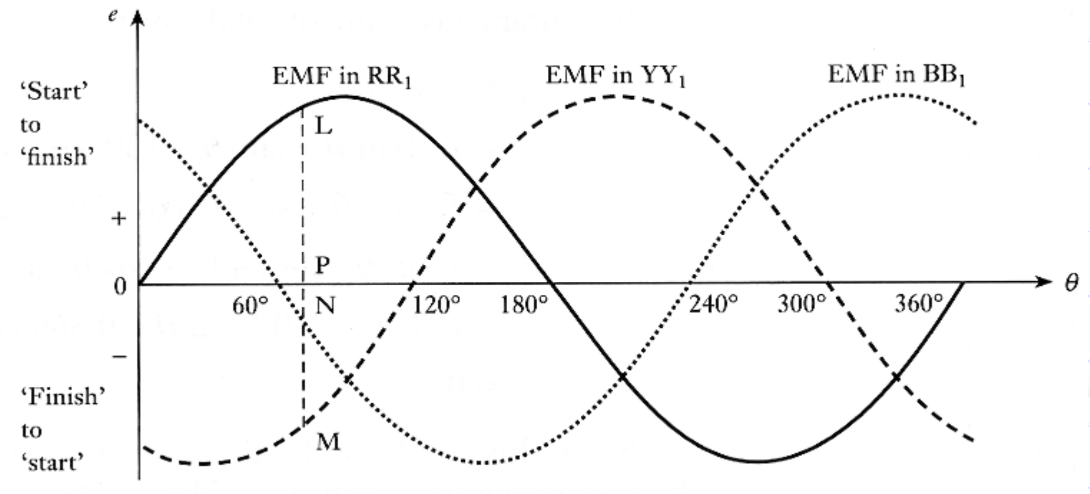


Fig.2: Loop RR_1 at instant of maximum e.m.f.

- In Fig. 4-3.1, RR_1, YY_1 and BB_1 represent three similar loops fixed to one another at angles of 120^0, each loop terminating in a pair of slip-rings carried on the shaft in Fig.4-3.2.
- We shall refer to the slip-rings connected to sides R, Y and B as the 'finishes' of the respective phases and those connected to R_1, Y_1 and B_1 as the 'starts'.

- The letters R, Y and B are abbreviations of 'red', 'yellow' and 'blue', namely the colors used to identify the three phases.
- Also, 'red-yellow-blue' is the sequence that is universally adopted to denote that the e.m.f. in the yellow phase lags that in the red phase by a third of a cycle (120^0), and the e.m.f. in the blue phase lags that in the yellow phase by another third of a cycle.





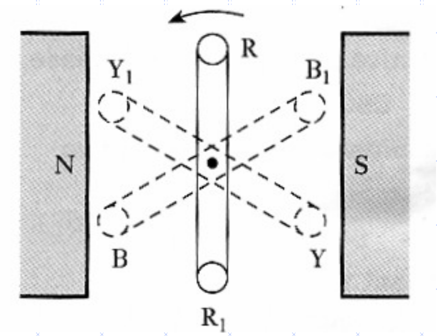


Fig1: Generation of three-phase e.m.f.s

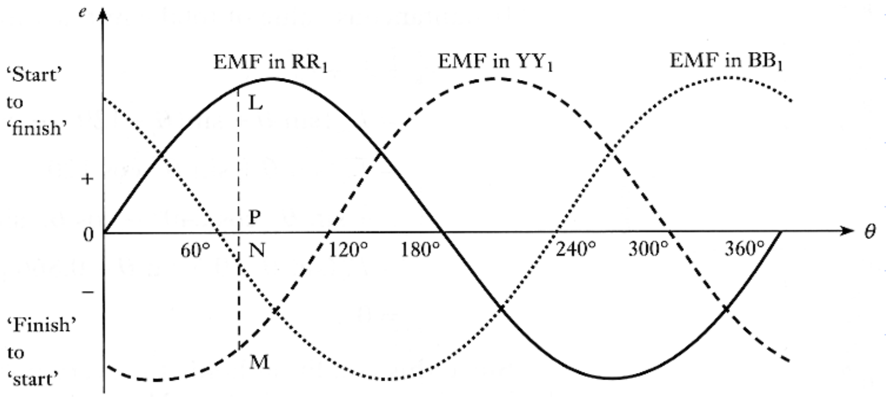


Fig.3: Waveforms of three phase e.m.f.s

- Hence the e.m.f.s generated in loops RR_1, YY_1 and BB_1 are represented by the three equally spaced curves of Fig. 3, the e.m.f.s being assumed positive when their directions round the loops are from 'start' to 'finish' of their respective loops.
- If the instantaneous value of the e.m.f. generated in phase RR_1 is represented by

then instantaneous e.m.f. in YY_1 is

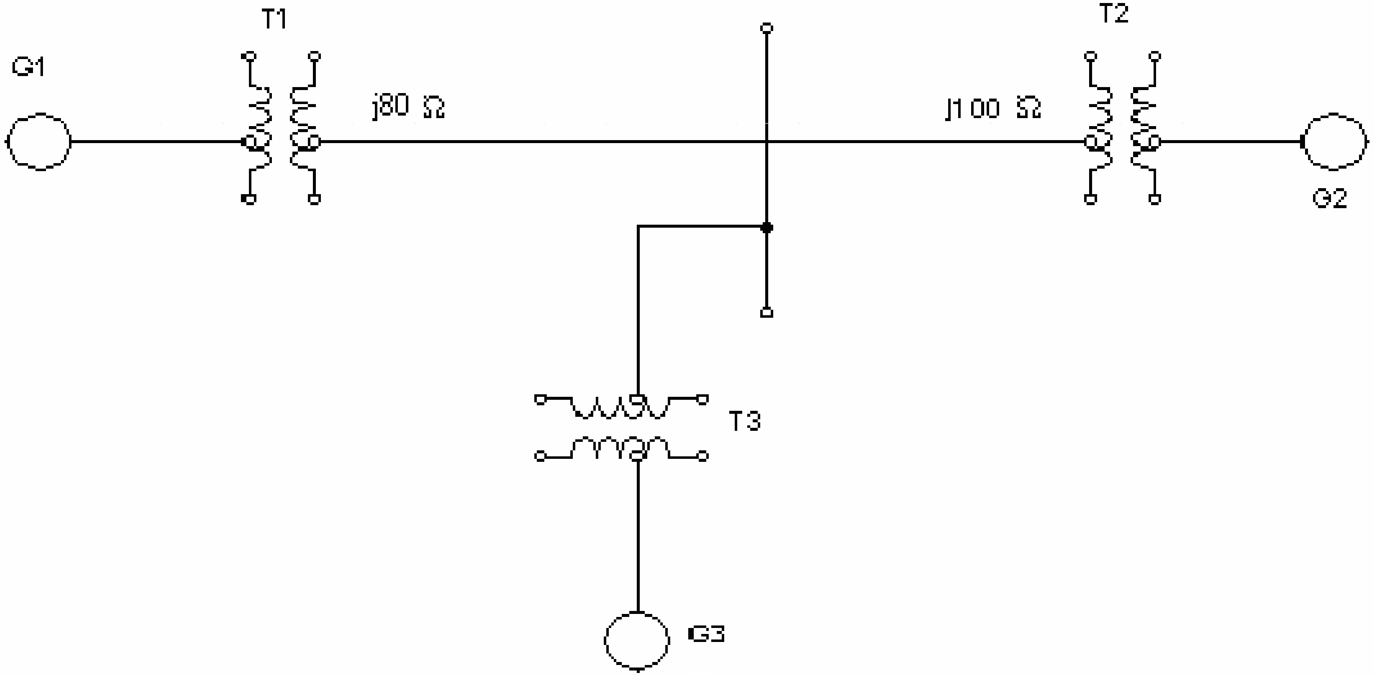
$$e_Y = E_m \sin$$

and instantaneous e.m.f. in BB_1 is

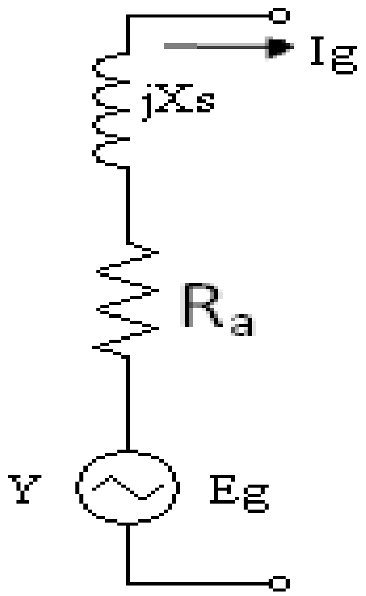
$$e_B = E_m \sin$$

SINGLE LINE DIAGRAM

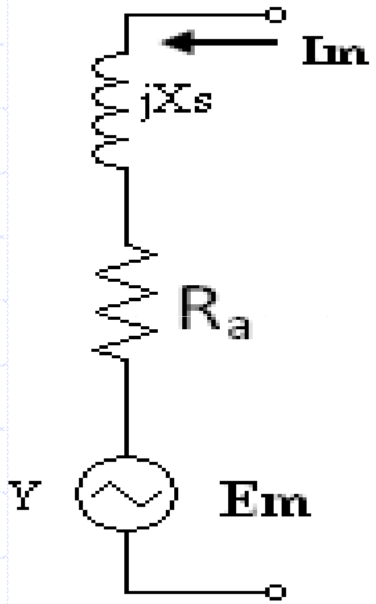
It is a diagrammatic representation of a power system in which the components are represented by their symbols.



MODELLING OF GENERATOR AND SYNCHRONOUS MOTOR

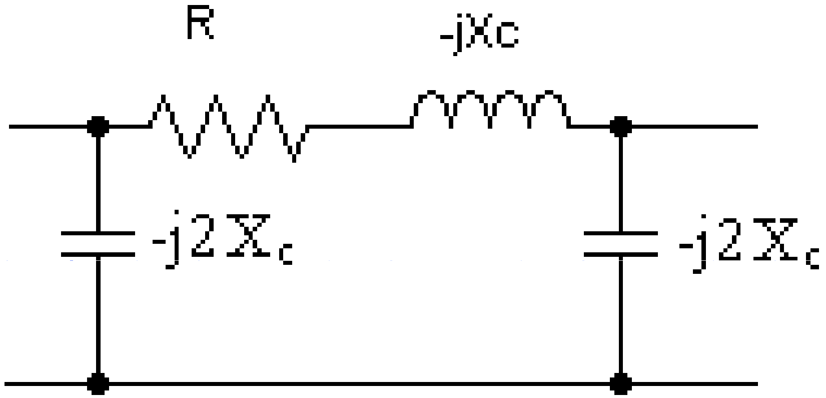


1Φ equivalent circuit of generator

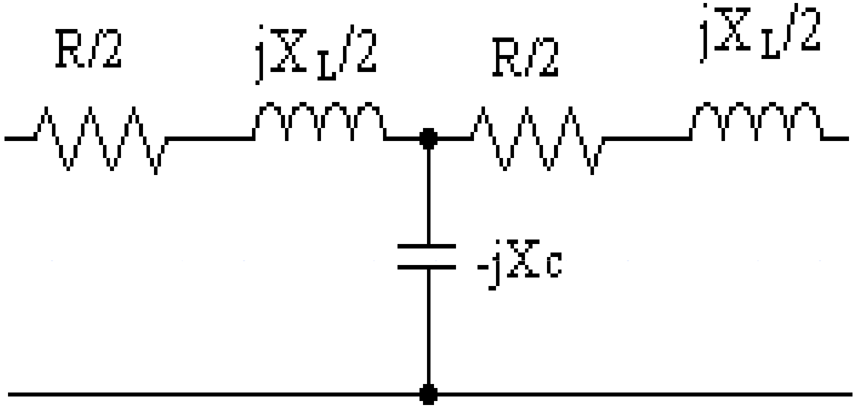


1Φ equivalent circuit of synchronous motor

MODELLING OF TRANSMISSION LINE

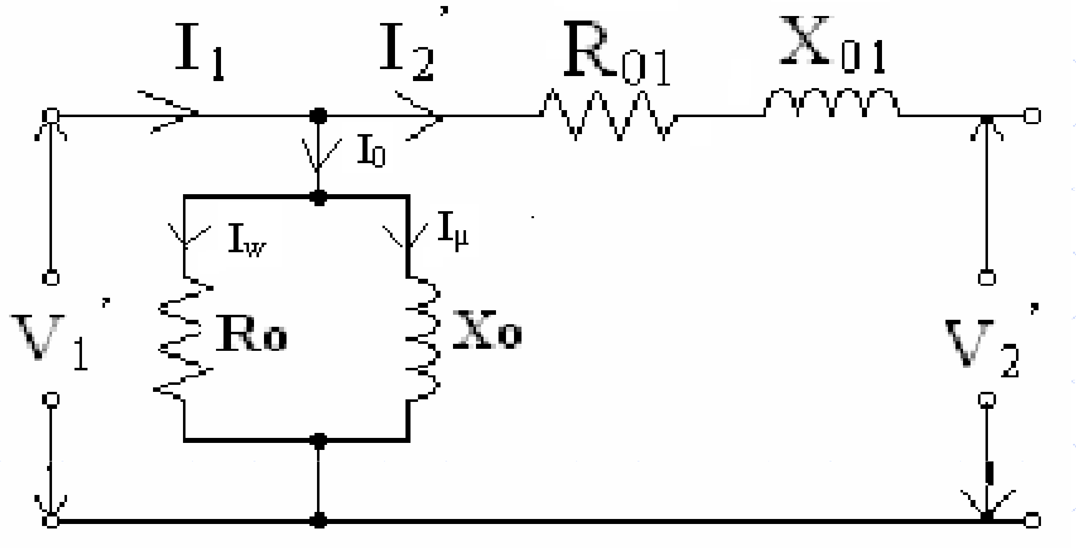


Π type



T type

MODELLING OF TRANSFORMER

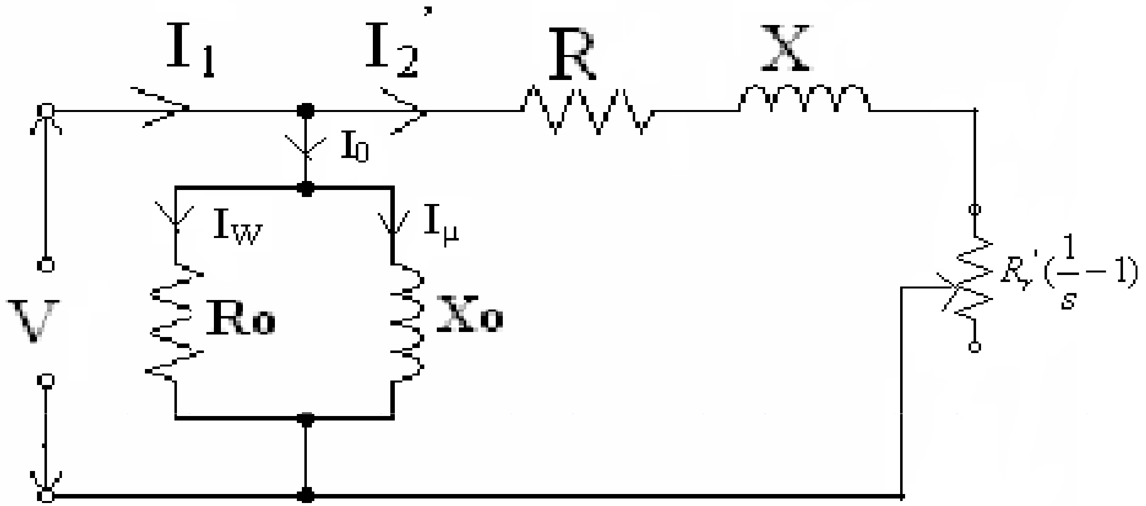


$$K = \frac{E_2}{E_1} = \frac{N_2}{N_1} = \frac{I_1}{I_2}$$

$$R_{01} = R_1 + R_2^{'} = R_1 + \frac{R_2}{K^2}$$ =Equivalent resistance referred to 1ᵒ

$$X_{01} = X_1 + X_2^{'} = X_1 + \frac{X_2}{K^2}$$ =Equivalent reactance referred to 1ᵒ

MODELLING OF INDUCTION MOTOR



$R_r'(\frac{1}{s}-1)$ =Resistance representing load

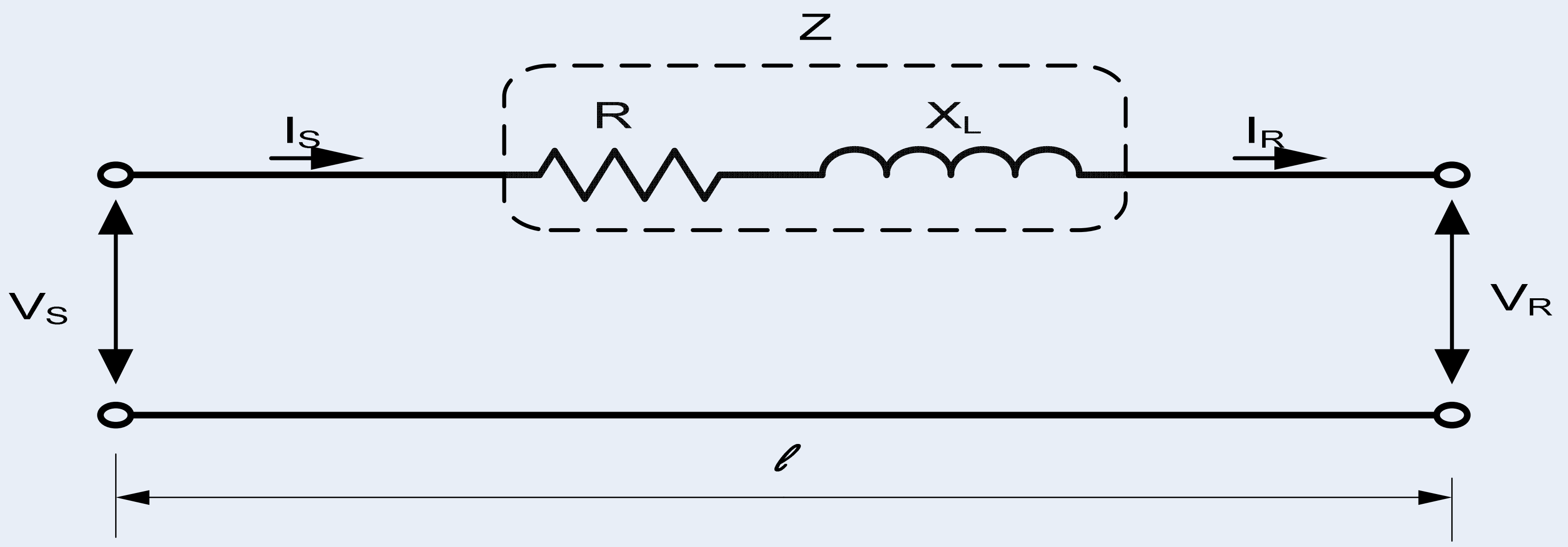
$R = R_s + R_r'$ =Equivalent resistance referred to stator

$X = X_s + X_r'$ =Equivalent reactance referred to stator

Transmission Line Representation

- Short Line Model
  - < 80 km in length
  - Shunt effects are neglected.
- Medium Line Model
  - Range from 80–240 km in length
  - Shunt capacitances are lumped at a few predetermined points along the line.
- Long Line Model
  - >240 km in length.
  - Uniformly distributed parameters.
  - Shunt branch consists of both capacitance and conductance.

Short Line



$$Z = z\ell = (r + j\omega L)\ell$$
$$= R + jX_L$$

where:

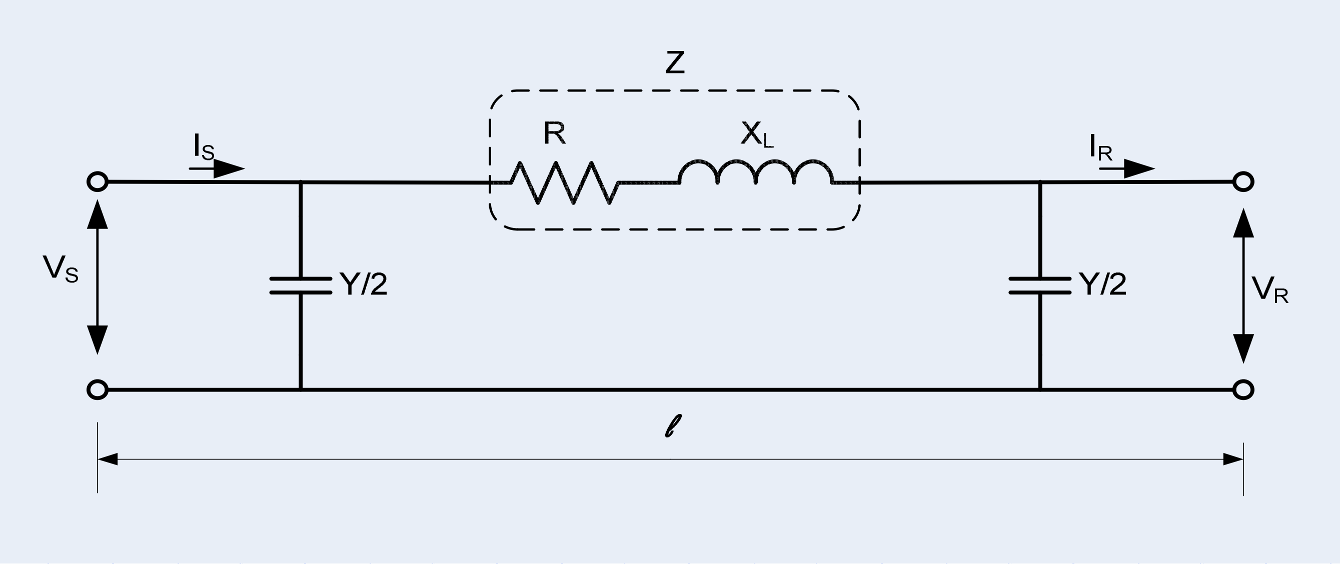
r = per-phase resistance

L = per-phase inductance

ℓ = line length

$$V_s = I_R Z + V_R$$

Medium Line – Nominal π Circuit



- Shunt capacitor is considered.
- ½ of shunt capacitor considered to be lumped at each end of the line – π circuit

Total shunt admittance, Y

$$Y = (g + j\omega C)\ell$$

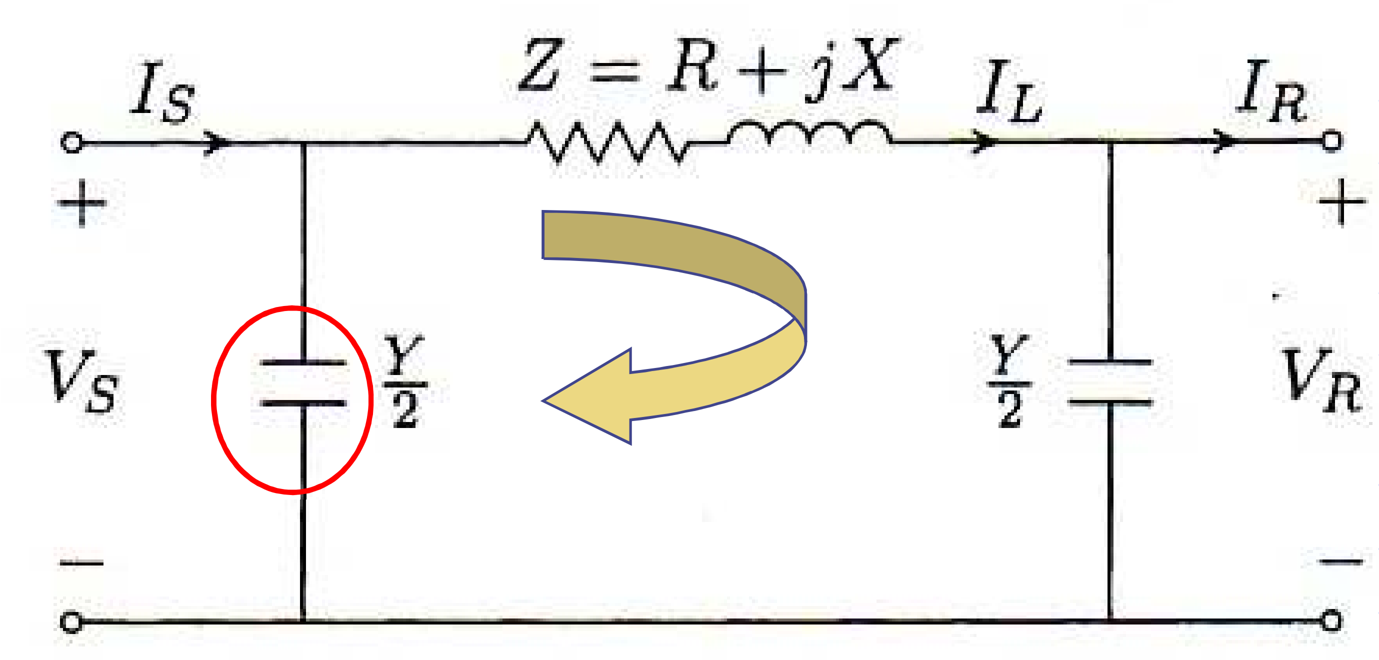
where :

C = line to neutral capacitance per km

g = line conductance per km

ℓ = line length

Medium Line Model



- Using KCL and KVL, the sending–end voltage is:

$$V_S = V_R + ZI_L \qquad ..[1]$$

$$I_L = I_R + \frac{Y}{2}V_R \qquad ..[2]$$

From [1] and [2]

$$V_S = V_R + Z\left(I_R + \frac{Y}{2}V_R\right)$$

$$= \left(1 + \frac{ZY}{2}\right)V_R + ZI_R \qquad ..[3]$$

- Using KCL to obtain equation for sending–end current:

$$I_S = I_L + \frac{Y}{2} V_S \qquad ..[4]$$

Substitute $[2]$ and $[3]$ into $[4]$

$$I_S = I_R + \frac{V_R Y}{2} + \left[\left(1 + \frac{YZ}{2} \right) V_R + Z I_R \right] \frac{Y}{2}$$

$$= Y \left(1 + \frac{YZ}{4} \right) V_R + \left(1 + \frac{YZ}{2} \right) I_R \qquad ..[5]$$

Complex Power

Remember!

$$|V_{line}| = \sqrt{3}|V_{phase}|$$

- Sending end power

$$S_{S(3\phi)} = 3V_{S(phase)}I^*_{S(phase)}$$

$$or$$

$$S_{S(3\phi)} = \sqrt{3}V_{S(line)}I^*_{S(line)}$$

- Receiving end power

$$S_{R(3\phi)} = 3V_{R(phase)}I^*_{R(phase)}$$

$$or$$

$$S_{R(3\phi)} = \sqrt{3}V_{R(line)}I^*_{R(line)}$$

Transmission Line Efficiency

- Total Full–Load Line Losses

$$S_{L(3\phi)} = S_{S(3\phi)} - S_{R(3\phi)}$$

- Transmission Line Efficiency

$$\eta = \frac{P_{R(3\phi)}}{P_{S(3\phi)}} \qquad \%\eta = \frac{P_{R(3\phi)}}{P_{S(3\phi)}} \times 100$$

- Note that only Real Power are taken into account!

Example

- A 220-kV, three-phase transmission line is 40 km long. The resistance per phase is 0.15 Ω/km and the inductance per phase is 1.5915 mH/km. The shunt capacitance is negligible.

Use the line model to find the voltage and power at the sending end and efficiency when the line is supplying a three-phase load of

a) 381 MVA at 0.8 pf lagging at 220 kV

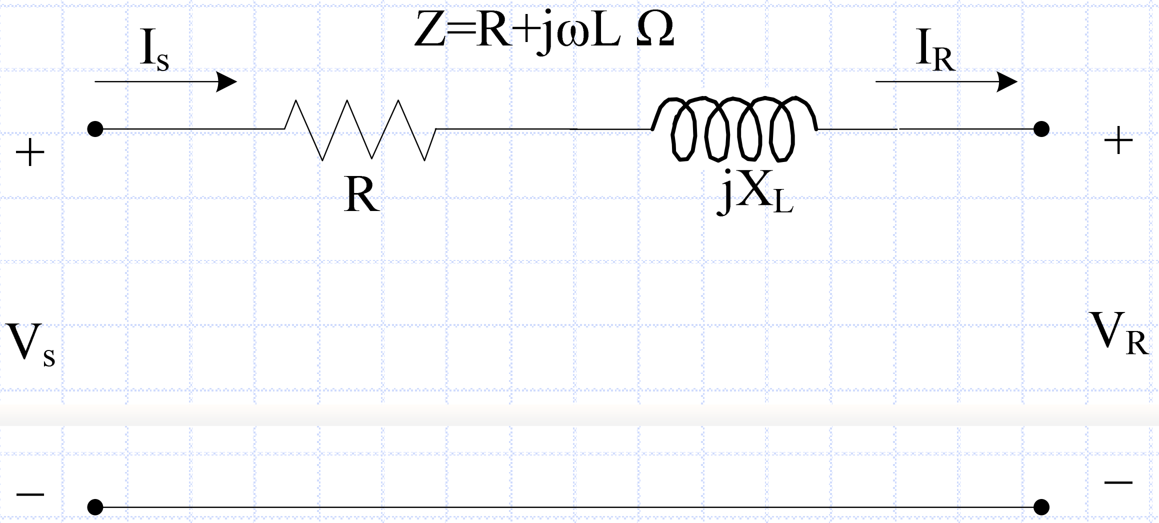
Solution

- Given

  R = 0.15 Ω/km , L = 1.5915 mH/km

  S =381 MVA with pf 0.8 lag

  $V_{R(line)}$=220 kV



Find sending end voltage, $V_S = V_R + ZI_R$

Therefore, find $\boxed{V_R , Z, \text{ and } I_R}$

$$V_{R(phase)} = \frac{V_{R(Line)}}{\sqrt{3}}$$

$$= \frac{220 \angle 0^o kV}{\sqrt{3}}$$

$$\boxed{= 127 \angle 0^o kV}$$

The series impedance per phase;

$$Z_{40\text{km}} = (r + j\omega L)l$$

$$= (0.15 + j(2\pi)(50)(1.5915m))40$$

$$\boxed{= 6 + j20\Omega}$$

$$\mathrm{S} = 381 \ \mathrm{MVA}, \quad \theta = \cos^{-1} 0.8 = 36.87^{o}$$

Thus ,

$$S_R = 381 \angle 36.87^{o} MVA = 304.8 MW + j228.6M \ \mathrm{var}$$

$$\mathrm{S}_{\mathrm{R}} = 3\mathrm{V}_{\mathrm{R(Phase)}} \ \mathrm{I}_{\mathrm{R}}^{*}$$

$$\mathrm{I}_{\mathrm{R}}^{*} = \frac{\mathrm{S}_{\mathrm{R}}}{3\mathrm{V}_{\mathrm{R(Phase)}}}$$

$$\mathrm{I}_{\mathrm{R}} = \frac{\mathrm{S}_{\mathrm{R}}^{*}}{3\mathrm{V}_{\mathrm{R(Phase)}}^{*}} = \frac{381 \angle -36.87^{o} MVA}{3\left(127 \angle 0^{o} kV\right)}$$

$$\boxed{= 1000 \angle -36.87^{o} A}$$

Therefore,

$$\mathrm{V}_{\mathrm{S(Phase)}} = \mathrm{V}_{\mathrm{R}(\mathrm{Phase})} + ZI_R$$

$$= 127\angle 0^o\, kV + (6 + j20\Omega)(1000\angle -36.87^o$$

$$\boxed{= 144.3\angle 4.93^o\, kV}$$

$$\left|V_{S(Line)}\right| = \sqrt{3}\left|V_{S(Phase)}\right|$$

$$= \sqrt{3}\left|144.3\right|$$

$$\boxed{= 250\mathrm{V}}$$

Find Sending - end Power, $S_S = 3V_{S(Line)} I_S$

$$I_S = I_R = 1000 \angle -36.87^o A$$

$$S_S = 3V_{R(Phase)} I_R^*$$

$$= 3(144.33 \angle 4.93^o V)(1000 \angle 36.87^o A)$$

$$= 322.8 MW + j288.6 M \text{ var}$$

$$\boxed{= 433 \angle 41.8^o MVA}$$

Effiency,η

$$\% \eta = \frac{P_R}{P_S} \times 100$$

$$= \frac{304.8}{322.8} \times 100$$

$$\boxed{= 94.4\%}$$

DELTA CONNECTION OF THREE-PHASE WINDINGS.

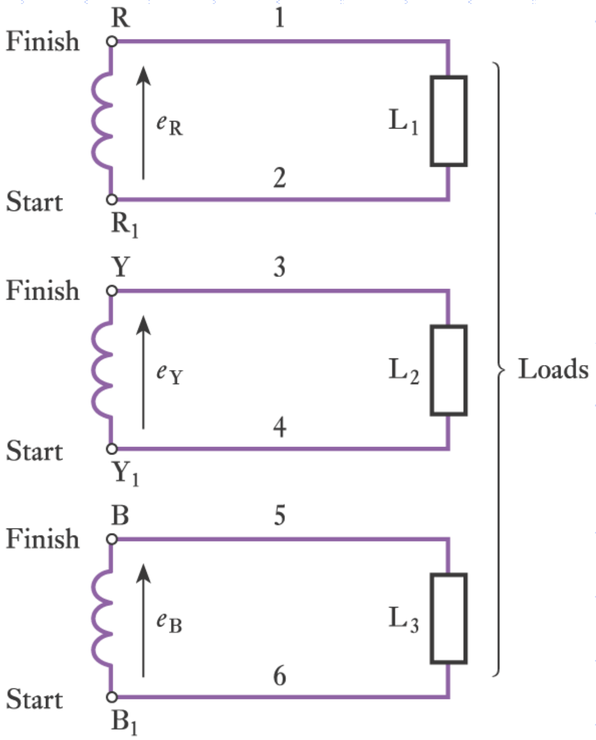


Fig.4-4.1: Three-phase windings with six lines conductors

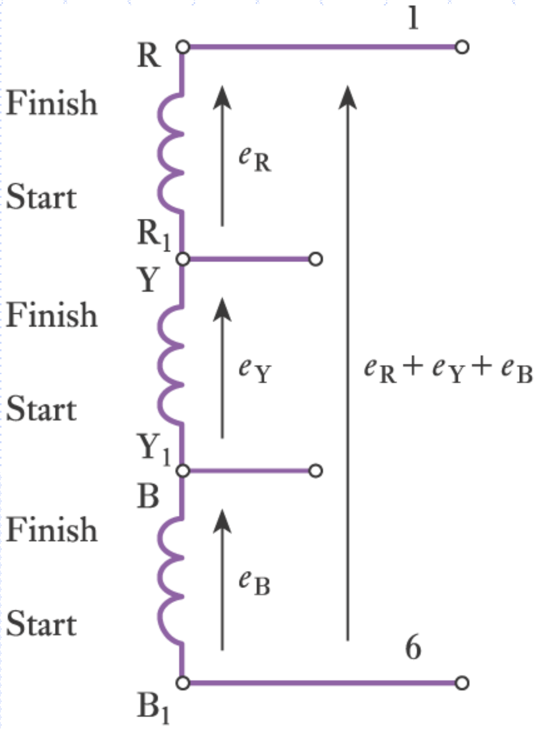
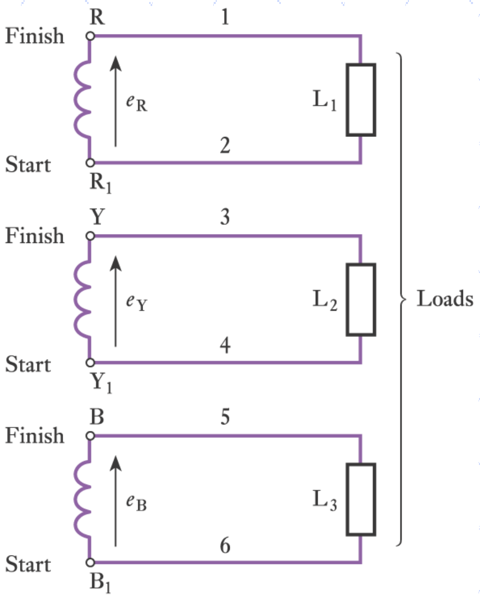


Fig.4-4.2: Resultant e.m.f. in a delta-connected winding

- The three phases can, for convenience, be represented as in Fig. 4-4.4 where the phases are shown isolated from one another; L_1, L_2, and L_3 represent loads connected across the respective phases.

Fig.4-4.3



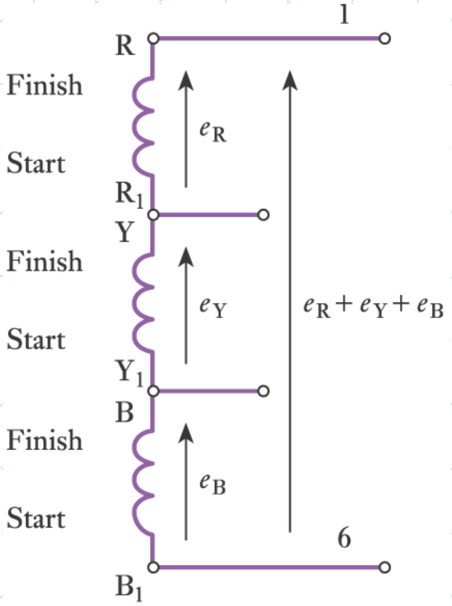
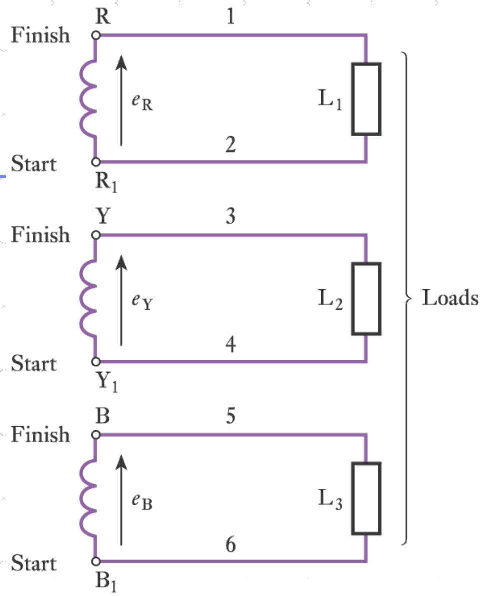


Fig.4-4.4

- **Since the e.m.f.s are assumed acting from 'start' to 'finish', they can be represented by the arrows e_R, e_Y and e_B in Fig. 4-4.3.**
- **This arrangement being cumbersome and expensive, let us consider how it may be simplified.**
  - **For instance, let us join R_1 and Y together as in Fig. 4-4.4, thereby enabling conductors 2 and 3 of Fig. 4-4.4 to be replaced by a single conductor.**
  - **Similarly, let us join Y_1 and B together so that conductors 4 and 5 may be replaced by another single conductor.**

Fig.4-4.3



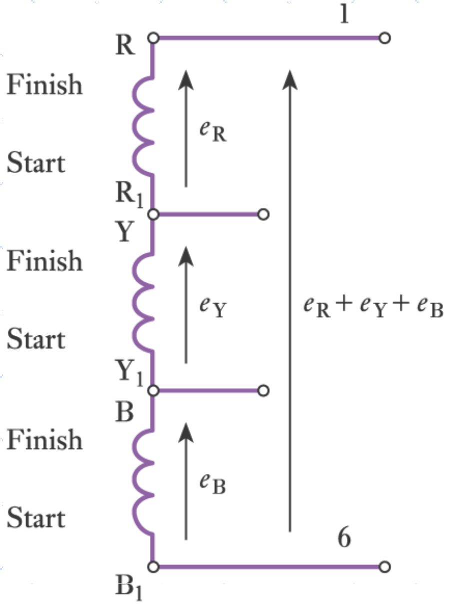


Fig.4-4.4

- If we join ‘start’ B$_1$ to ‘finish’ R, there will be three e.m.f.s chasing each other around the loop and these would produce a circulating current in that loop.

- However, we can next show that the resultant e.m.f. between these two points is zero and that there is therefore no circulating current when these points are connected together.

- Instantaneous value of total e.m.f. acting from B$_1$ to R is:

$$
\begin{aligned}
e_R + e_Y + e_B \\
&= E_m\{\sin\theta + \sin(\theta - 120°) + \sin(\theta - 240°)\} \\
&= E_m(\sin\theta + \sin\theta \cdot \cos 120° - \cos\theta \cdot \sin 120° \\
&\quad + \sin\theta \cdot \cos 240° - \cos\theta \cdot \sin 240°) \\
&= E_m(\sin\theta - 0.5\sin\theta - 0.866\cos\theta - 0.5\sin\theta + 0.866\cos\theta) \\
&= 0
\end{aligned}
$$

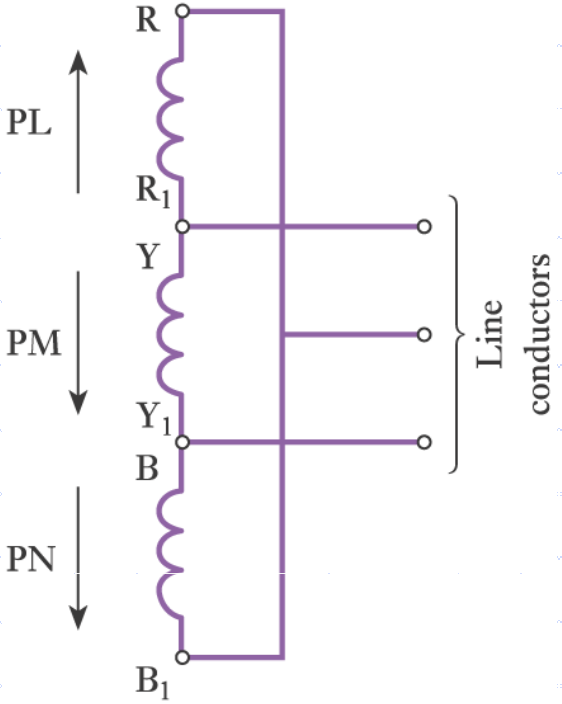


Fig.4-4.5

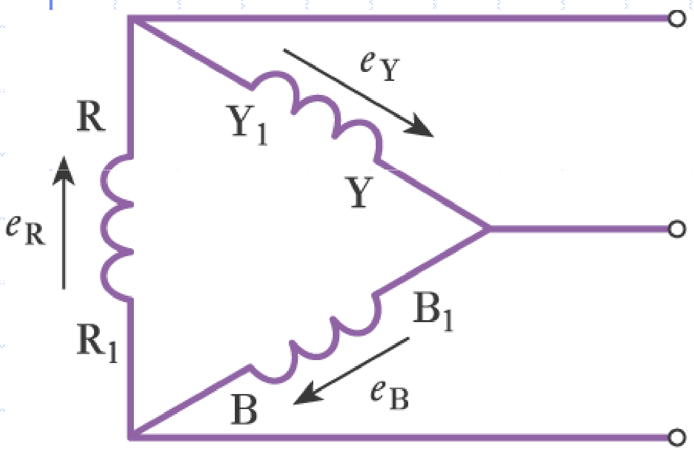


Fig.4-4.6: **Conventional representation of a delta or mesh-connected winding.**

- ➢ **Since this condition holds for every instant, it follows that R and B_1 can be joined together, as in Fig.4-4.5, without any circulating current being set up around the circuit.**

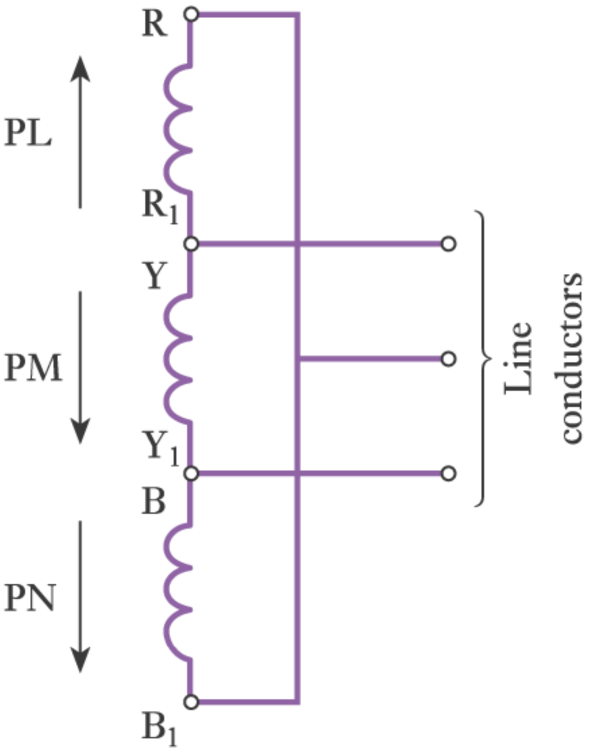


Fig.4-4.5

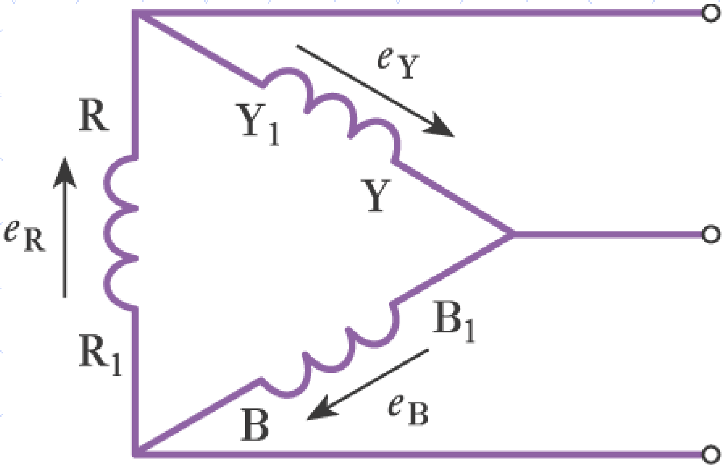


Fig.4-4.6

- By visual inspection, the algebraic sum of the e.m.f.s round the closed circuit formed by the three windings is zero at any instant.

- It should be noted that the directions of the arrows in Fig. 4-4.6 represent the directions of the e.m.f. at a *particular instant,* whereas arrows placed alongside symbole*,* as in Fig.4-4.5, represent the *positive* directions of the e.m.f.s.

STAR CONNECTION OF THREE-PHASE WINDINGS.

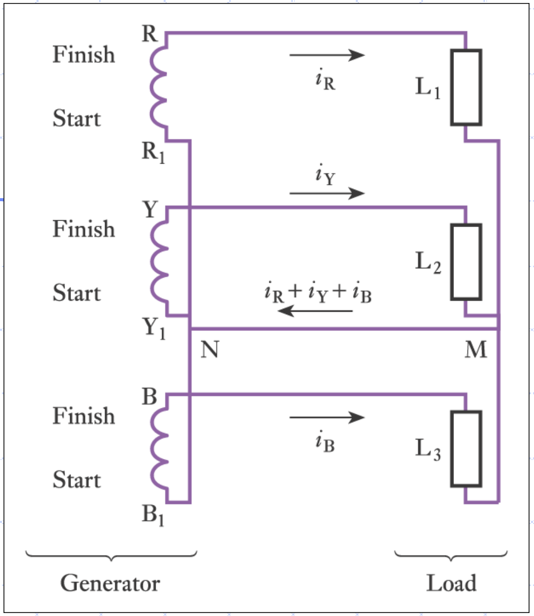


Fig.4-5.1: Star connection of three-phase winding

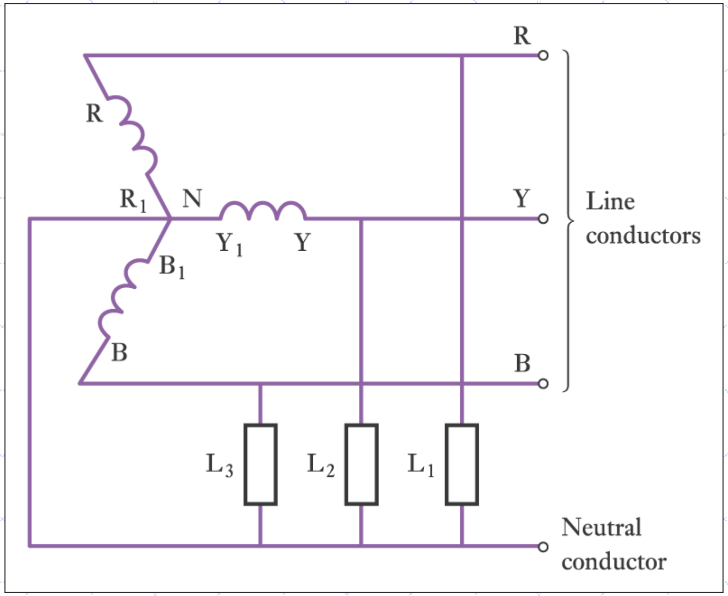


Fig.4-5.2: Four-wire star-connected system

- Let us go back to Fig. 4-3.4 and join together the three 'starts', R_1, Y_1 and B_1 at N, as in Fig. 4-5.1, so that the three conductors 2, 4 and 6 of Fig.4-4.3 can be replaced by the single conductor NM of Fig.4-5.1.

- Since the generated e.m.f. has been assumed positive when acting from 'start' to 'finish', the current in each phase must also be regarded as positive when flowing in that direction, as represented by the arrows in Fig. 4-5.1.

Fig.4-5.1

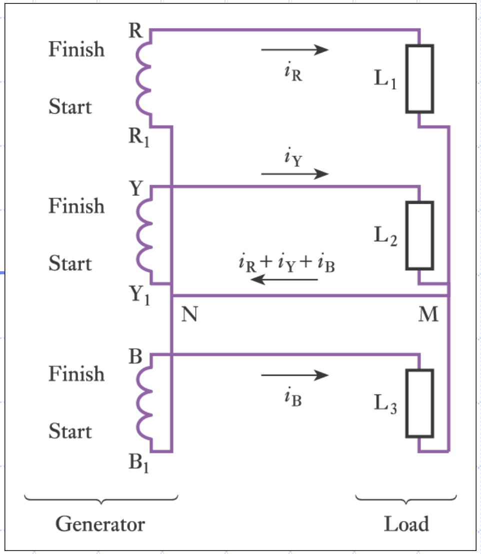
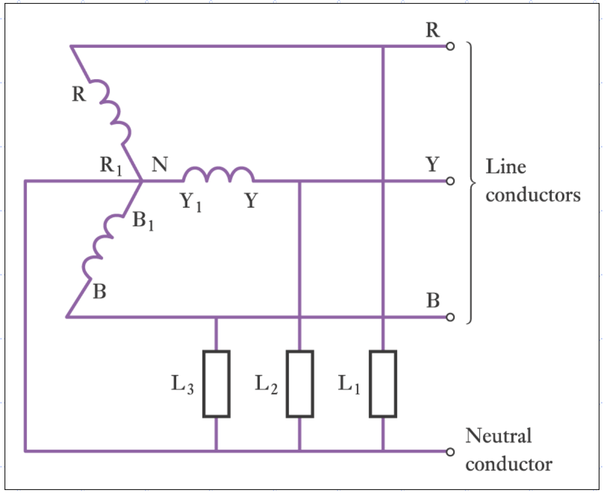


Fig.4-5.2

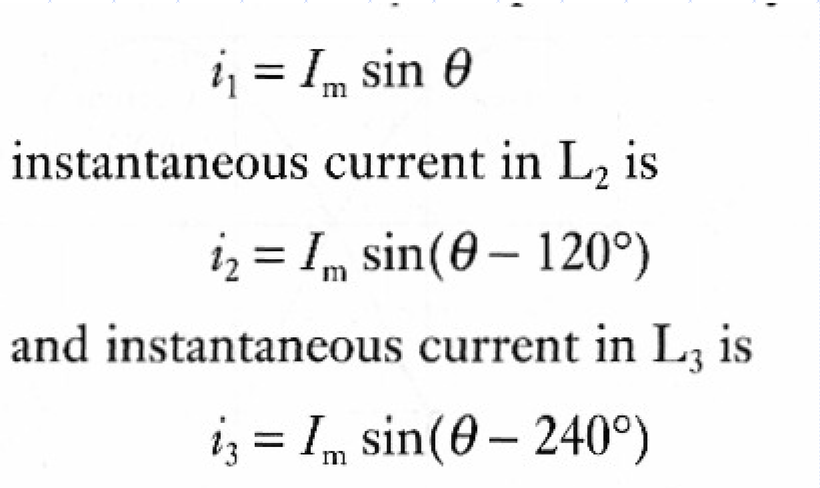


- If i_R, i_Y and i_B are the instantaneous values of the currents in the three phases, the instantaneous value of the current in the common wire MN is ($i_R + i_Y + i_B$), having its positive direction from M to N.

- This arrangement is referred to as a *four-wire star-connected* system and is more conveniently represented as in Fig.4-5.2, and junction N is referred to as the *star* or *neutral point.*

- Three-phase motors arc connected to the line conductors R, Y and B, whereas lamps, heaters, etc. are usually connected between the line and neutral conductors, as indicated by L_1, L_2 and L_3, total load being distributed as equally as possible between the three lines.

- If these three loads are exactly alike, **the phase currents have the same peak value, ‘m and differ in phase by 120^0.**
- Hence if the instantaneous value of the current in **load L_1** is represented by:



$$i_1 = I_m \sin \theta$$

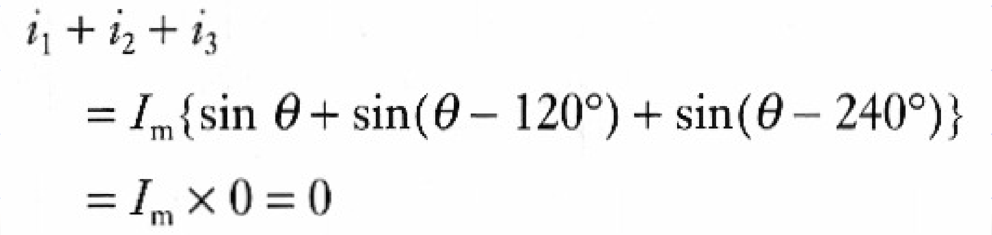
instantaneous current in L_2 is

$$i_2 = I_m \sin(\theta - 120°)$$

and instantaneous current in L_3 is

$$i_3 = I_m \sin(\theta - 240°)$$

- Hence instantaneous value of **the resultant current in neutral conductor MN** is:



$$\begin{aligned} & i_1 + i_2 + i_3 \\ & \quad = I_m\{\sin \theta + \sin(\theta - 120°) + \sin(\theta - 240°)\} \\ & \quad = I_m \times 0 = 0 \end{aligned}$$

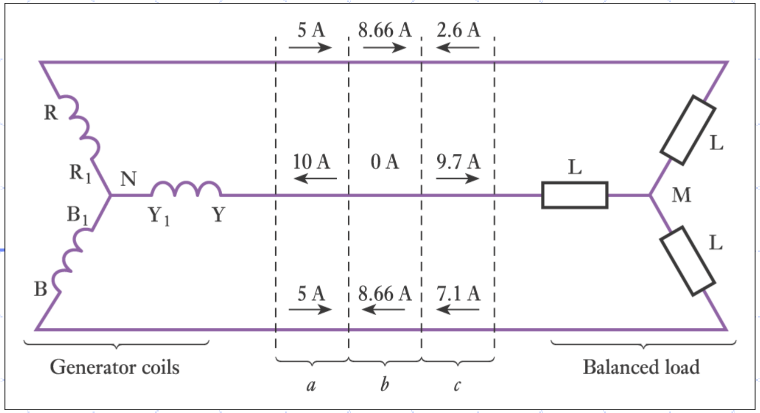


Fig.4-5.3: Three-wire star- connected system with balanced load

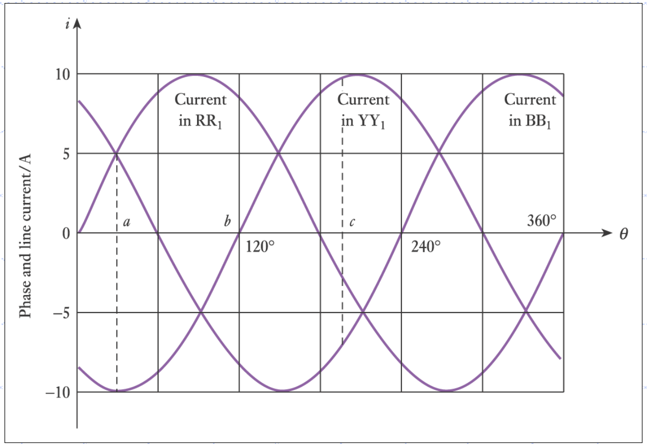


Fig.4-5.4: Waveforms of current in a balanced 3-φ system

i.e. with a balanced load the resultant current in the neutral conductor is zero at *every* instant; hence this conductor can be dispensed with, thereby giving us the *three-wire star-connected* system shown in Fig.4-5.3

- **When we are considering the distribution of current in a three-wire, three-phase system it is helpful to bear in mind:**
  - **That arrows such as those of Fig.4-5.1, placed alongside *symbols,* indicate the direction of the current when it is assumed to be *positive* and not the direction at a particular instant.**
  - **That the current flowing outwards in one or two conductors is equal to that flowing back in the remaining conductor or conductors (see Fig.4-5.4)**

VOLATGES AND CURRENTS IN STAR CONNECTED SYSTEM.

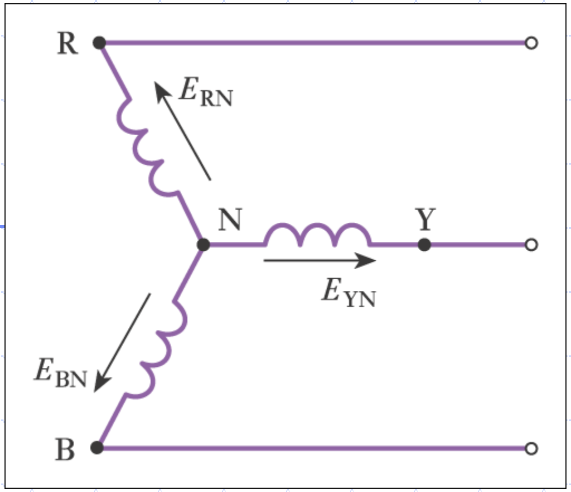


Fig.4-6.1: Star-connected generator

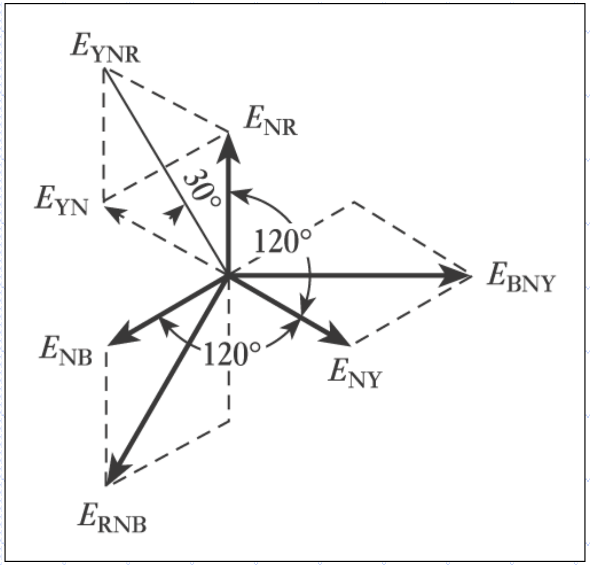


Fig.4-6.2: Phasor diagram

- Let us again assume the e.m.f. in each phase to be positive when acting from the neutral point outwards, so that the r.m.s. values of the e.m.f.s generated in the three phases can be represented by E_{NR}, E_{NY} and E_{NB} in Figs.4-6.1 and 4-6.2.

- When the relationships between line and phase quantities are being derived for either the star- or the delta—connected system, it is essential to relate the phasor diagram to a circuit diagram and to indicate on each phase the direction in which the voltage or current is assumed to be positive. A phasor diagram by itself is meaningless.

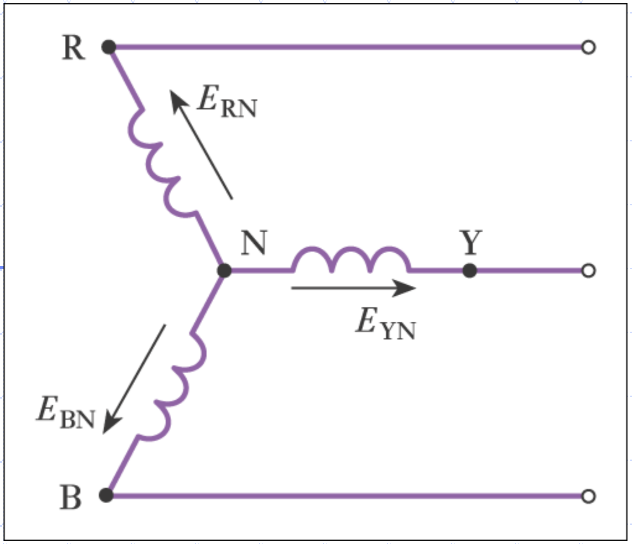


Fig.4-6.1.

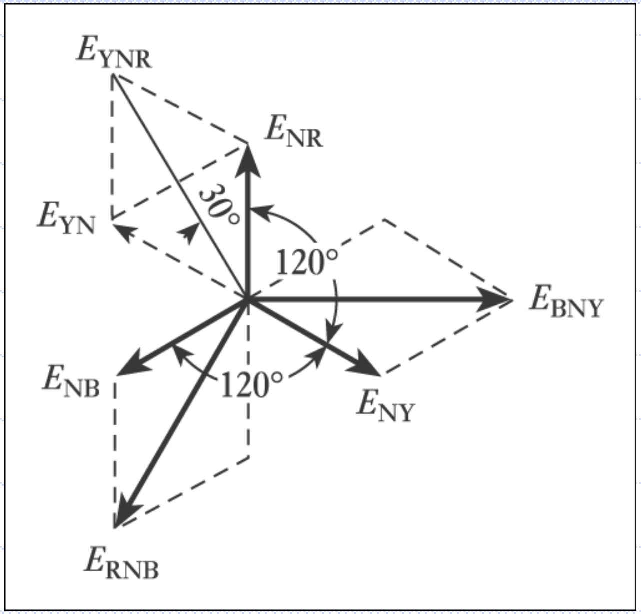


Fig.4-6.2

- Here E_{RNB} is obtained by subtracting E_{NR} from E_{NB}, and E_{BNY} is obtained by subtracting E_{NB} from E_{NY}, as shown in Fig.4-6.2.

- From the symmetry of this diagram it is evident that the line voltages are equal and are spaced 120^0 apart.

- Further, since the sides of all the parallelograms are of equal length, the diagonals bisect one another at right angles. Also, they bisect the angles of their respective parallelograms; and, since the angle between E_{NR} and E_{YN} is 60°

$$\therefore \quad E_{YNR} = 2E_{NR} \cos 30° = \sqrt{3}E_{NR}$$

i.e. Line voltage = 1.73 × star (or phase) voltage

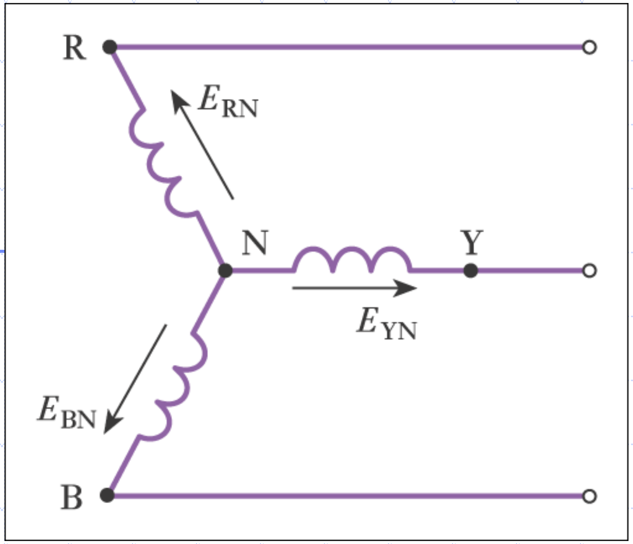


Fig.4-6.1.

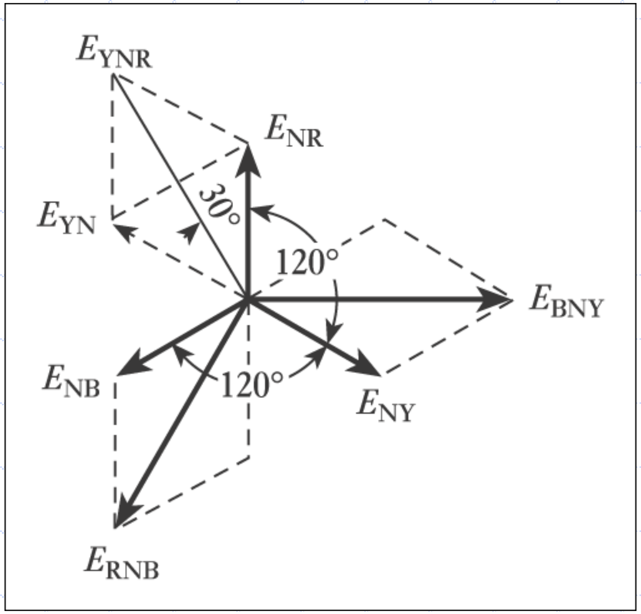
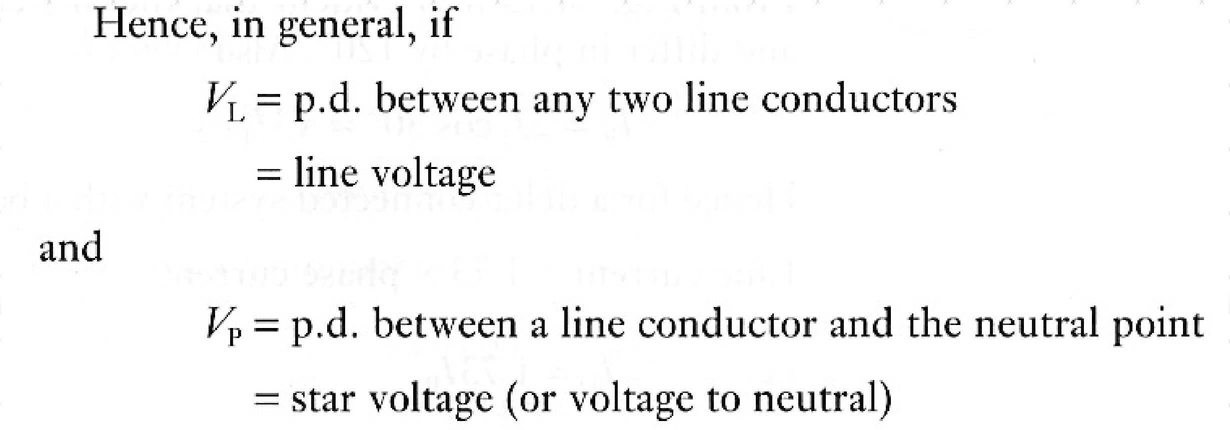


Fig.4-6.2

- **From Fig.4-6.1 it is obvious that in a star-connected system the current in a line conductor is the same as that in the phase to which that line conductor is connected.**



Hence, in general, if

V_L = p.d. between any two line conductors

= line voltage

and

V_P = p.d. between a line conductor and the neutral point

= star voltage (or voltage to neutral)

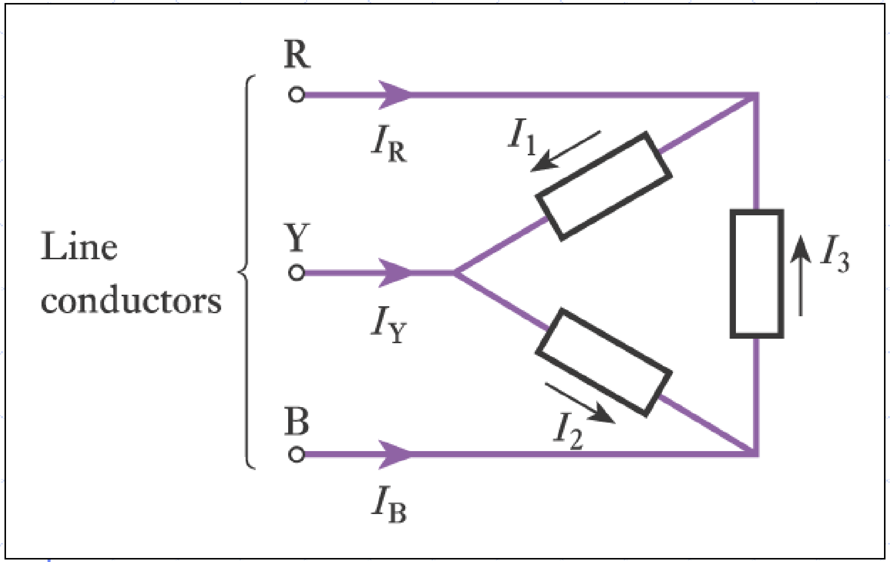
and if I_L and I_p are **line and phase currents** respectively, **then for a star-connected system**

- In practice, it is the **voltage between two line conductors or between a line conductor and the neutral point** that is measured.

- Owing to the internal impedance drop in the windings, **this p.d. is different from the corresponding e.m.f. generated in the winding**, except when **the generator is on open circuit**; hence, **in general, it is preferable to work with the potential difference, *V*, rather than with the e.m.f., *E*.**

- The **voltage given for a three-phase system** is **always the line voltage** unless it is stated otherwise.

VOLATGES AND CURRENTS IN DELTA COONECTED SYSTEM.



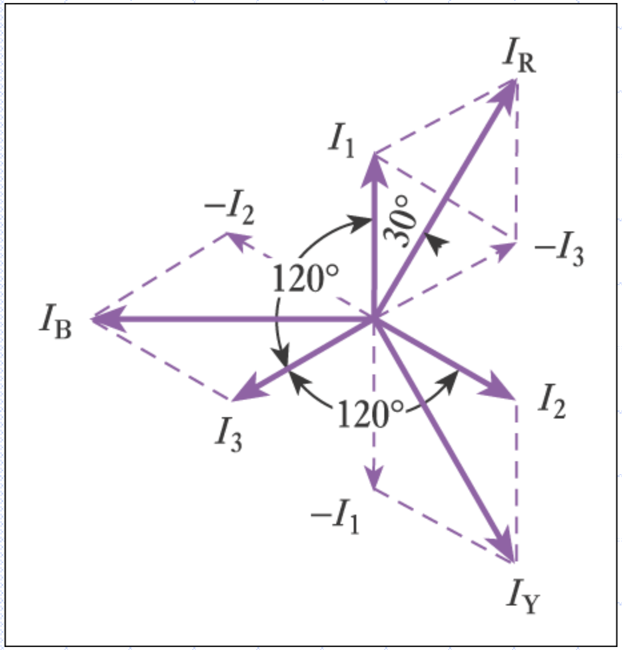
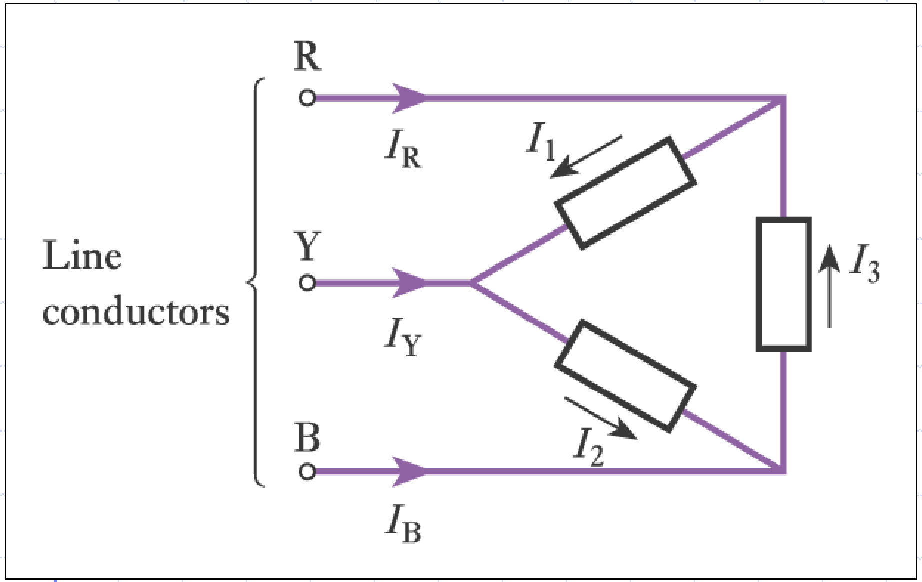
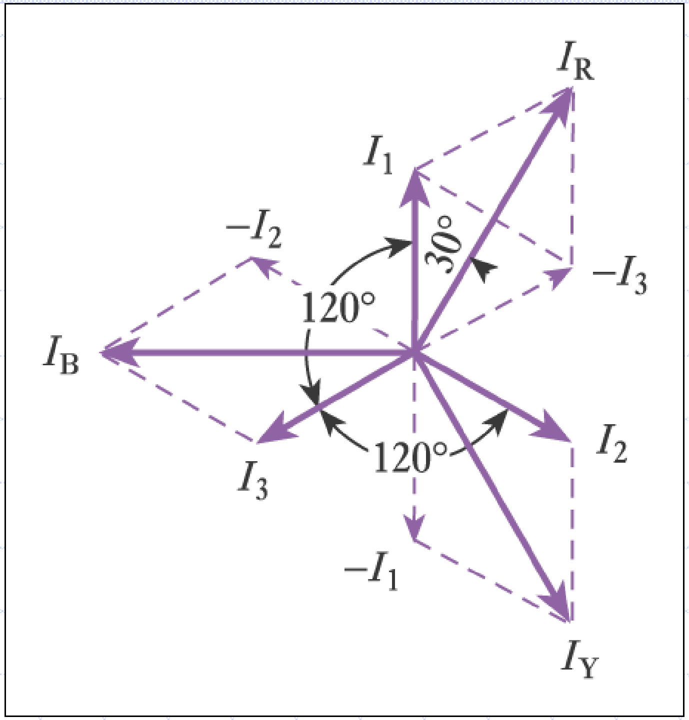


Fig.4-7.1: Delta-connected system with balanced load

- **In Fig. 4-7.1, the load is assumed to be balanced, hence these currents are equal in magnitude and differ in phase by 120°, as shown in Fig.4-7.2.**

- **From Fig.4-7.1 it will he seen that I_1, when positive, flows away from line conductor R, whereas I_3, when positive, flows towards it.**





- Consequently, I_R is obtained by subtracting I_3 from I_1, as in Fig.4-15.
- Similarly, I_Y is the phasor difference of I_2 and I_1, and I_B is the phasor difference of I_3 and I_2.
- From Fig.4-15, it is evident that the line currents are equal in magnitude and differ in phase by 120°.

- **Also**

$$I_R = 2I_1 \cos 30° = \sqrt{3}I_1$$

Hence for a delta-connected system with a balanced load

Line current = 1.73 × phase current

i.e. [illegible]

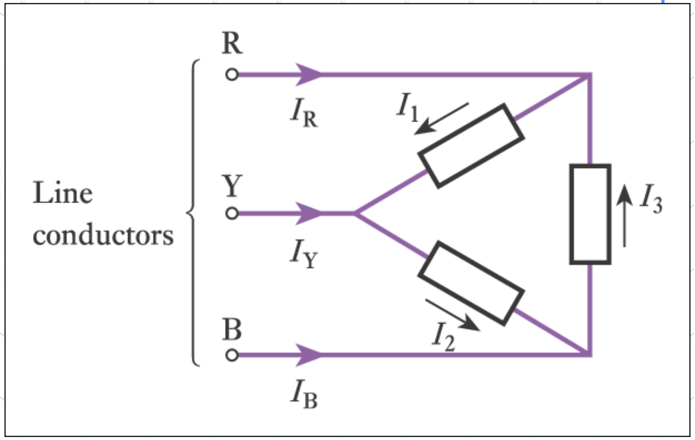


Fig.4-7.1

- **From Fig.4.1.4 it can be seen that in a delta-connected system, the line and the phase voltages are the same, i.e.**

[illegible]

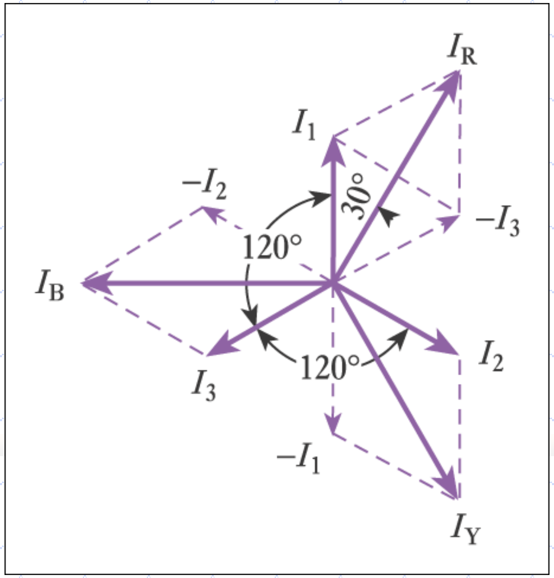


Fig.4-7.2

POWER IN A THREE-PHASE SYSTEM WITH A BALANCED LOAD.

- **If I_p is the r.m.s. value of the current in each phase and V the r.m.s. value of the p.d. across each phase,**

$$\text{Active power per phase} = I_P V_P \times \text{power factor}$$

and $$\text{Total active power} = 3 I_P V_P \times \text{power factor}$$

p P

If I_L and V_L are the r.m.s. values of the line current and voltage respectively, then for a *star-connected system*,

$$V_P = \frac{V_L}{1.73} \quad \text{and} \quad I_P = I_L$$

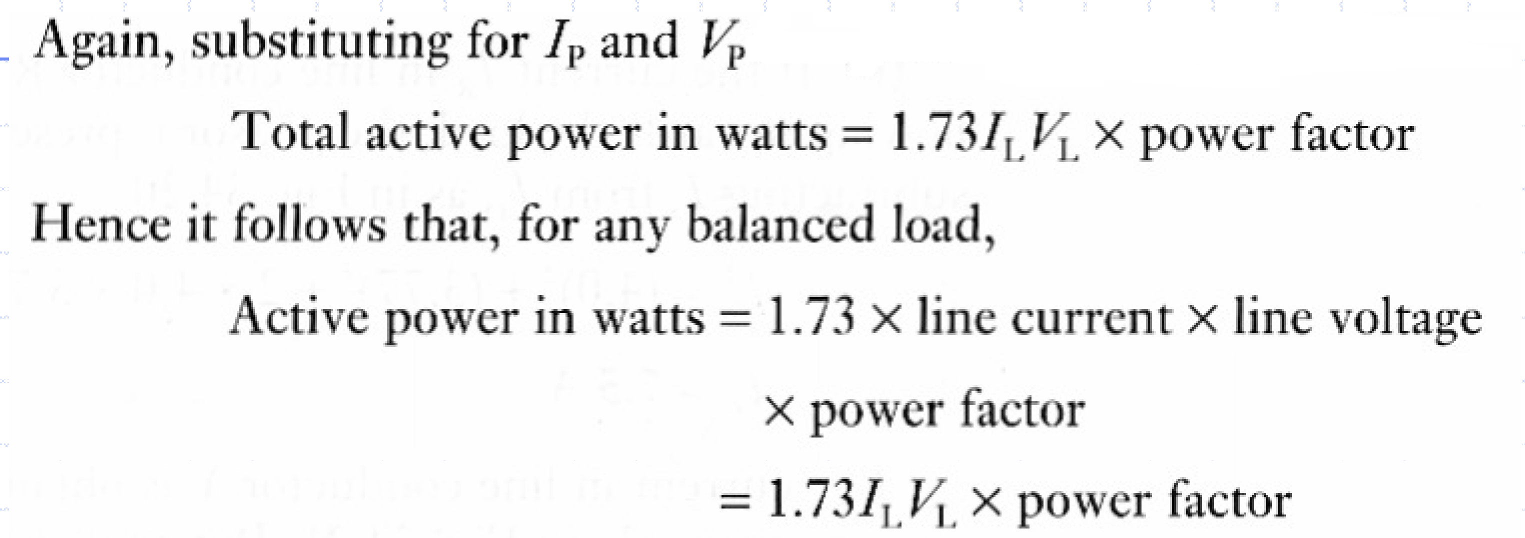
- **Substituting for I_p and V_p, we get**

$$\text{Total active power in watts} = 1.73 I_L V_L \times \text{power factor}$$

For a *delta-connected system*

$$V_P = V_L \quad \text{and} \quad I_P = \frac{I_L}{1.73}$$

POWER IN A 3-ϕ SYSTEM WITH A BALANCED LOAD-Cntd.



Again, substituting for I_P and V_P

$$\text{Total active power in watts} = 1.73 I_L V_L \times \text{power factor}$$

Hence it follows that, for any balanced load,

$$\begin{aligned}\text{Active power in watts} &= 1.73 \times \text{line current} \times \text{line voltage} \\ &\quad \times \text{power factor} \\ &= 1.73 I_L V_L \times \text{power factor}\end{aligned}$$

$$P = \sqrt{3}\, I_L V_L \cos$$

MEASUREMENT OF ACTIVE POWER IN A THREE-PHASE THREE WIRES SYSTEM.

STAR-CONNECTED BALANCED LOAD,WITH NEUTRAL POINT ACCESSIBLE

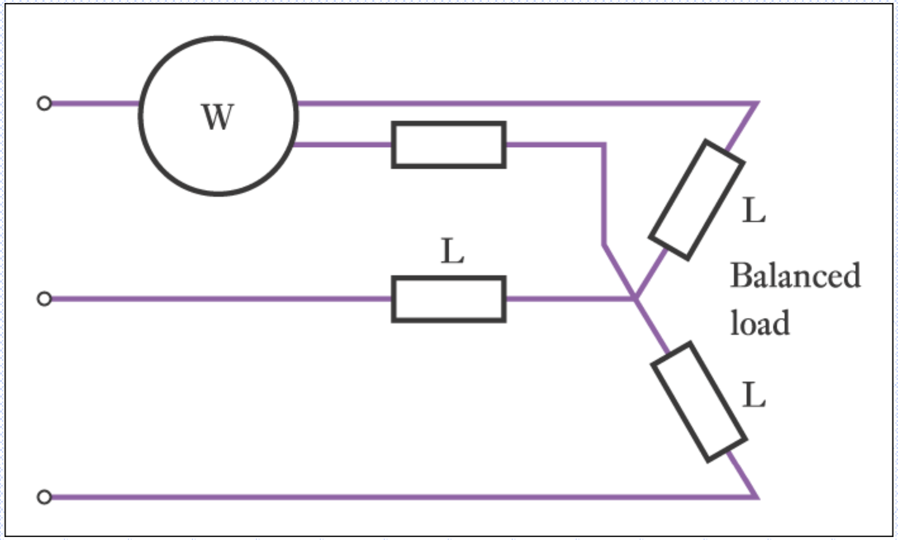


Fig.4-9.1: Measurement of active power in a star-connected balanced load

- If a wattmeter **W** is connectcd with its current coil in one line and the voltage circuit between that line and the neutral point, as shown in Fig.4-9.1, the reading on the wattmeter gives the power per phase:

$$\boxed{\therefore \qquad \text{Total active power} = 3 \times \text{wattmeter reading}}$$

4.9.2 BALANCED OR UNBALANCED LOAD, STAR-OR DELTA-CONNECTED, THE TWO-WATTMETER METHOD.

- Suppose the three loads L_1, L_2 and L_3 are connected in star, as in Fig.4-9.2.
- The current coils of the two wattmeters are connected in any two lines, say the 'red' and 'blue' lines, and the voltage circuits are connected between these lines and the third line.
- Suppose v_{RN}, v_{YN} and v_{BN} are the instantancous values of the p.d.s across the loads, these p.d.s being assumed positive when the respective line conductors are positive in relation to the neutral point.

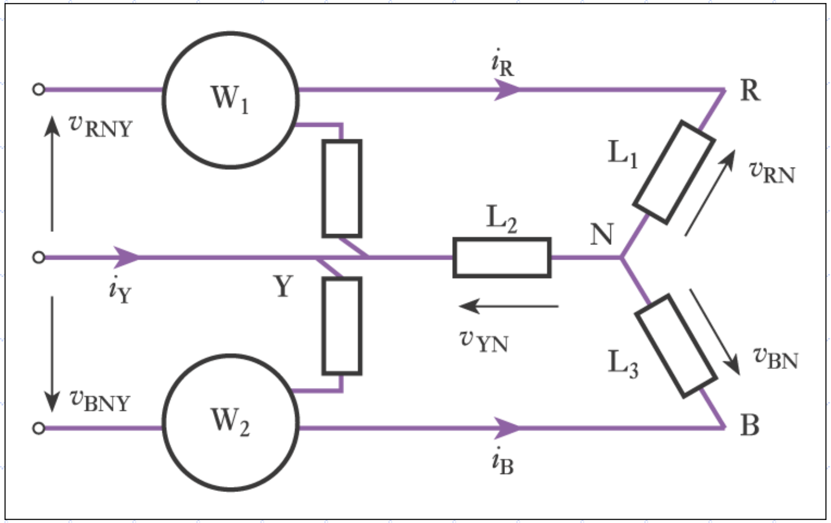


Fig.4-9.2: Measurement of power by two wattmeters

- Also, suppose, I_R, I_Y and I_B are the corresponding instantaneous values of the line (and phase) currents.
- Therefore instantancous power in load L1 = $i_R v_{RN}$, instantaneous power in load in $L_2 = i_Y v_{YN}$, and instantancous power in load $L_3 = i_B v_{BN}$.

- Therefore, total instantaneous power is

$$\text{power} = i_R v_{RN} + i_Y v_{YN} + i_B v_{BN}$$

- From Fig.4-9.2 it is seen that instantaneous current through current coil of W_1 is i_R and instantaneous p.d. across voltage circuit of W_1 is: $v_{RN} - v_{YN}$. Therefore, instantaneous power measured by W_1 is:

$$W_1 = i_R(v_{RN} - v_{YN})$$

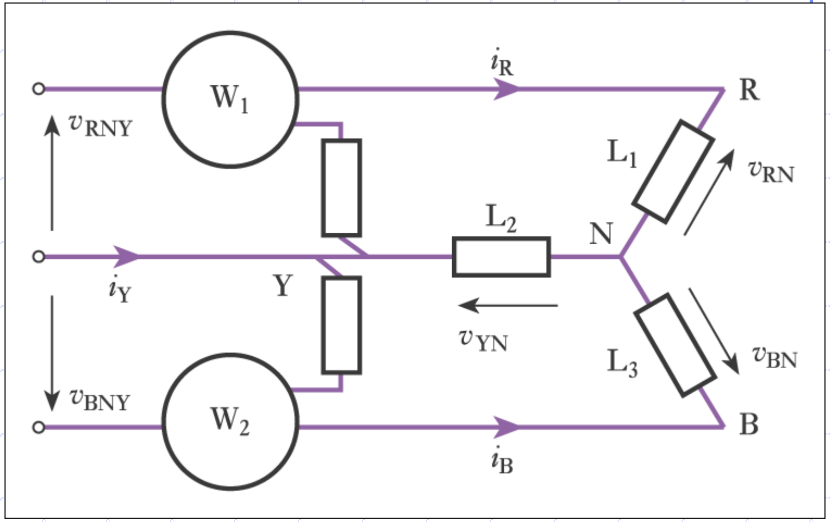


Fig.4-9.2

- Similarly, instantaneous current through current coil of W_2 is i_B and instantaneous p.d. across voltage circuit of W_2 is: v_{BN}-v_{YN}.

- Note that this **pd. is not** v_{YN} - v_{BN}. This is **due** to the fact that a wattmeter reads positively when the currents in the current and voltage coils are *both* flowing from the junction of these coils or *both* towards that junction; and since the positive direction of the current in the current coil of W_2 has already been taken as that of the arrowhead alongside i_B in Fig. 4-9.2 it follows that the current in the voltage circuit of W_2 is positive when flowing from the 'blue' to the 'yellow' line.

- The instantaneous measured by

$W_2 = i_B(v_{BN} - v_{YN})$

- Hence the sum of the instantaneous powers of W_1 and W_2 is

$$i_R(v_{RN} - v_{YN}) + i_B(v_{BN} - v_{YN})$$
$$= i_R v_{RN} + i_B v_{BN} - (i_R + i_B) v_{YN}$$

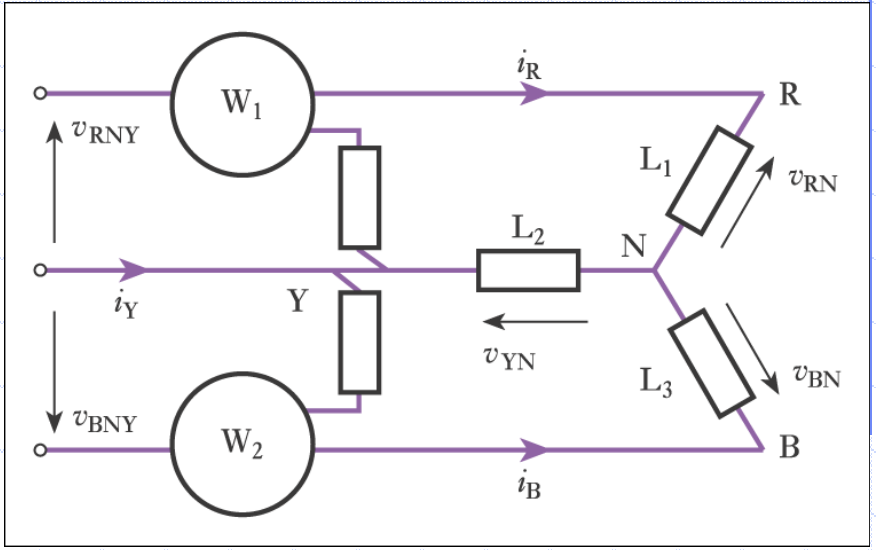


Fig.4-9.2

- From KCL's law, the algebraic sum of the instantancous currents at N is zero, i.e.

$$i_R + i_Y + i_B = 0$$
$$\therefore \quad i_R + i_B = -i_Y$$

so that sum of instantancous powers measured bv W_1 and W_2 is

$$\boxed{\begin{aligned} & i_R v_{RN} + i_B v_{BN} + i_Y v_{YN} \\ & \quad = \text{total instantaneous power} \end{aligned}}$$

POWER FACTOR MEASUREMENT BY MEANS OF THE TWO-WATTMETERS

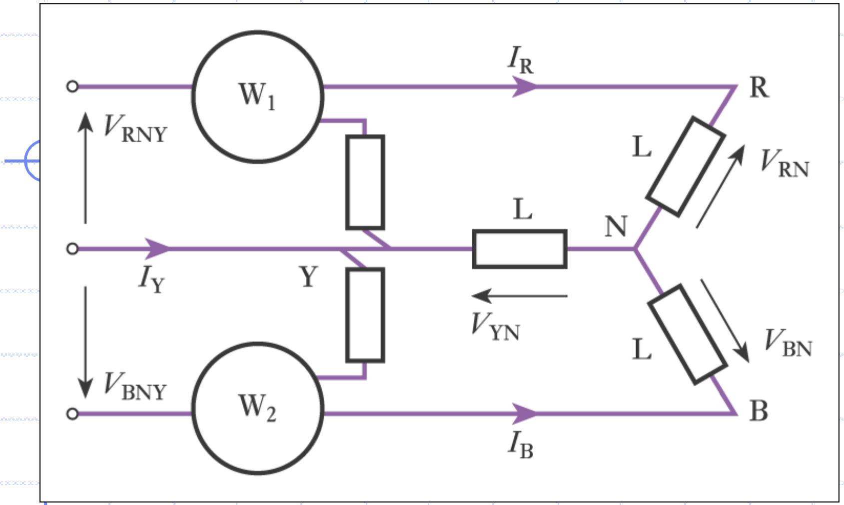


Fig.4-9.3: Measurement of active power and power factor by two wattmeters

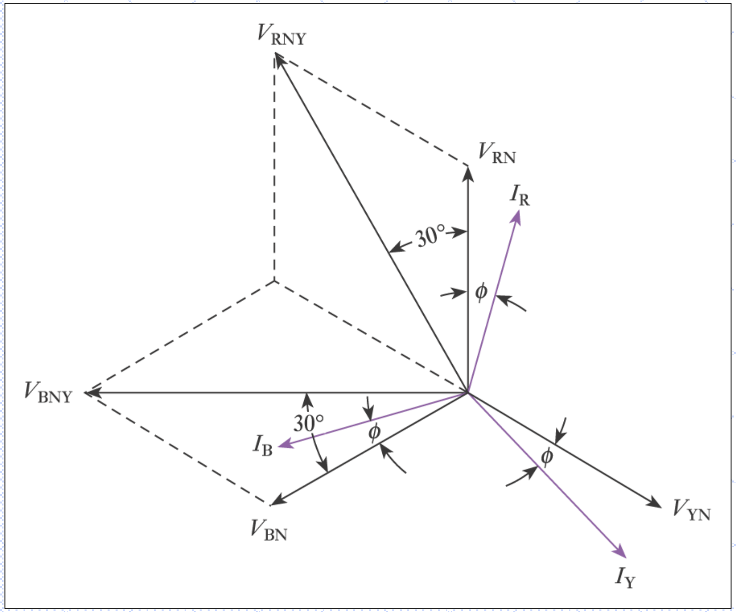
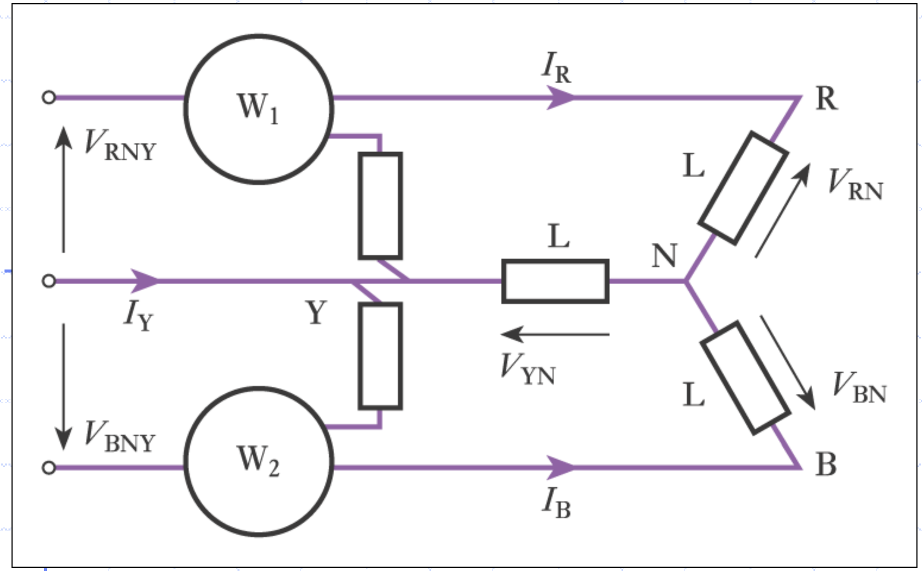


Fig.4-9.4: Phasor diagram

- Suppose L in Fig.4-9.3 to represent three similar loads connected in star, and suppose V_{RN} and V_{BN} to be the r.m.s. values of the phase voltages and I_R, I_Y and I_B be the r.m.s. values of the currents.

- Since these voltages and currents are assumed sinusoidal, they can be represented by phasors, as in Fig. 4-9.3, the currents being assumed to lag the corresponding phase voltages by an angle Φ.



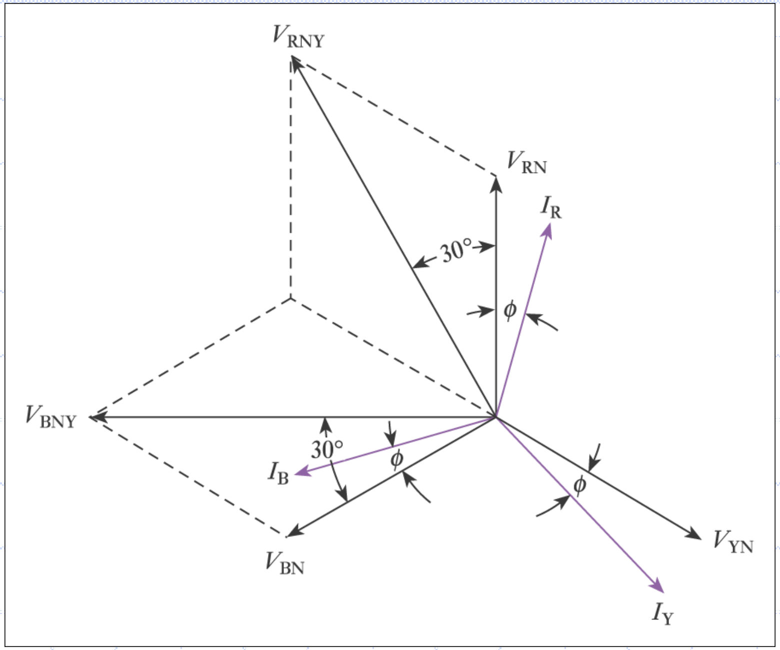


Fig.4-9.2

Fig.4-9.3

- **Current through current coil of W_1 is I_R. Potential difference across voltage circuit of W_1 is**

Phasor difference of V_{RN} and $V_{YN} = V_{RNY}$

Phase difference between I_R and $V_{RNY} = 30° + \phi$. Therefore reading on W_1 is

$$P_1 = I_R V_{RNY} \cos(30° + \phi)$$

- Current through current coil of $W_2 = I_B$. Potential difference across voltage circuit of W_2 is

$$\text{Phasor difference of } V_{BN} \text{ and } V_{YN} = V_{BNY}$$

Phase difference between I_B and $V_{BNY} = 30° - \phi$. Therefore reading on W_2 is

$$P_2 = I_B V_{BNY} \cos(30° - \phi)$$

Since the load is balanced,

$$I_R = I_Y = I_B = \text{(say) } I_L, \text{ numerically}$$

and

$$V_{RNY} = V_{BNY} = \text{(say) } V_L, \text{ numerically}$$

Hence

$$\boxed{P_1 = I_L V_L \cos(30° + \phi)}$$

and

$$\boxed{P_2 = I_L V_L \cos(30° - \phi)}$$

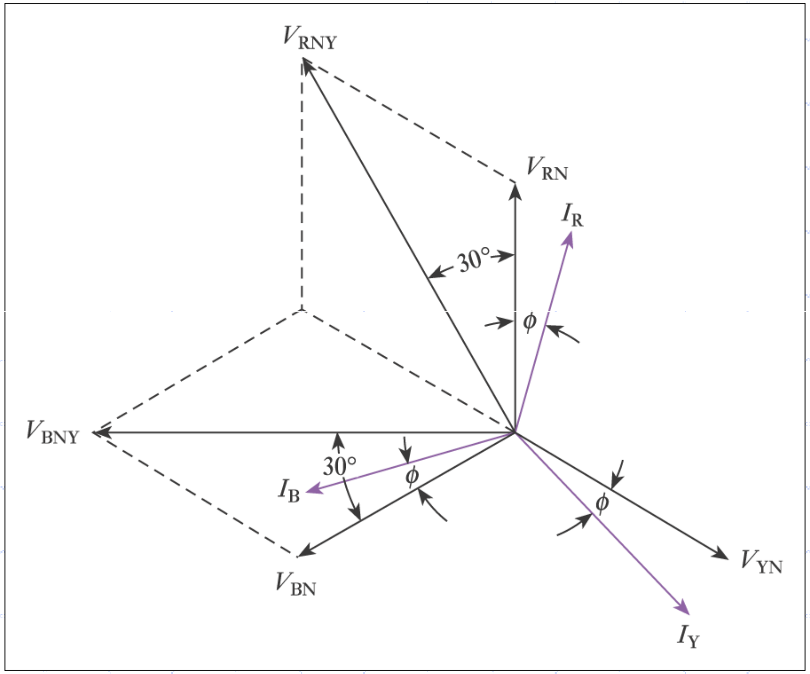


Fig.4-9.3.

$$P_1 + P_2 = I_L V_L\{\cos(30° + \phi) + \cos(30° - \phi)\}$$

$$P_1 + P_2 = I_L V_L(\cos 30° \cdot \cos \phi - \sin 30° \cdot \sin \phi$$
$$+ \cos 30° \cdot \cos \phi + \sin 30° \cdot \sin \phi)$$

$$\boxed{P_1 + P_2 = 1.73 I_L V_L \cos \phi}$$

- This is an **alternative method of proving that the sum of the two wattmeter readings gives the total active power**, but it should be noted that **this proof assurred a balanced load** and **sinusoidal voltages and currents.**
- By division of P_1/P_2, gives:

$$\frac{P_1}{P_2} = \frac{\cos(30° + \phi)}{\cos(30° - \phi)} = (\text{say})\, y$$

$$y = \frac{(\sqrt{3}/2)\cos \phi - (1/2)\sin \phi}{(\sqrt{3}/2)\cos \phi + (1/2)\sin \phi}$$

so that

$$\sqrt{3}y \cos \phi + y \sin \phi = \sqrt{3} \cos \phi - \sin \phi$$

from which

$$\sqrt{3}(1 - y)\cos \phi = (1 + y)\sin \phi$$

$$\therefore \qquad 3\left(\frac{1-y}{1+y}\right)^2 \cos^2\phi = \sin^2\phi = 1 - \cos^2\phi$$

$$\left\{1 + 3\left(\frac{1-y}{1+y}\right)^2\right\}\cos^2\phi = 1$$

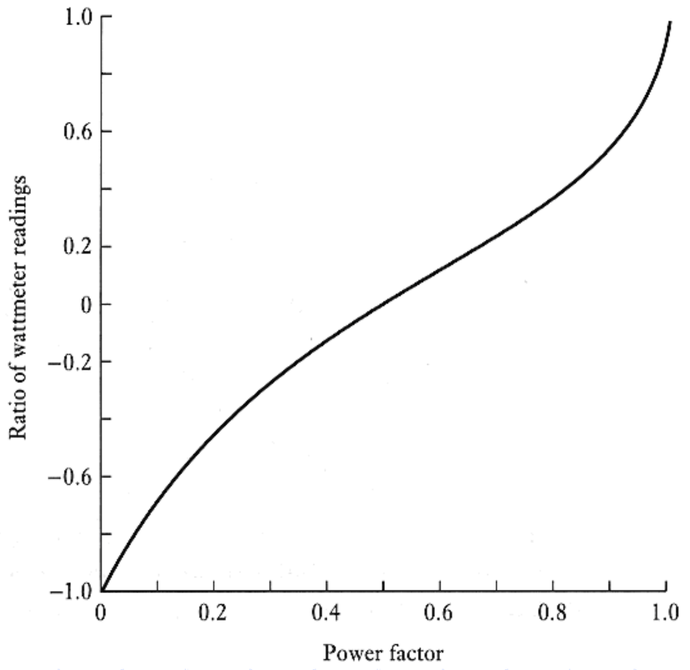


Fig.4-9.4: Reationship between power factor and ratio of wattmeter readings

- A more convenient method is to draw a graph of the power factor for various ratios of P_1/P_2 and in order that these ratios may lie between +1 and -1, it is always the practice to take P_1 as the smaller of the two readings.
- By adopting this practice, it is possible to derive reasonably accurate values of the power factor from the graph.

- When the power factor of the load **is 0.5 lagging**, **Φ is 60**; and the reading on **$W_1 = I_L V_L \cos 90° = 0$.**

- When the power factor is **less than 0.5 lagging**, **Φ is greater than 60°** and **$(30^0 + \Phi)$ is therefore greater than 90°.** Hence the reading on **W_1 is negative.**

- To measure **this active power it is necessary to reverse the connections to either the currcnt or the voltage coil, but the reading thus obtaincd must be taken as negative when the total active power** and **the ratio of the wattmeter readings are being calculated.**

- An alternative **method of deriving the power factor is as follows:**

$$P_2 - P_1 = I_L V_L \sin \phi$$

and

$$\boxed{\tan \phi = \frac{\sin \phi}{\cos \phi} = 1.73 \left(\frac{P_2 - P_1}{P_2 + P_1} \right)}$$

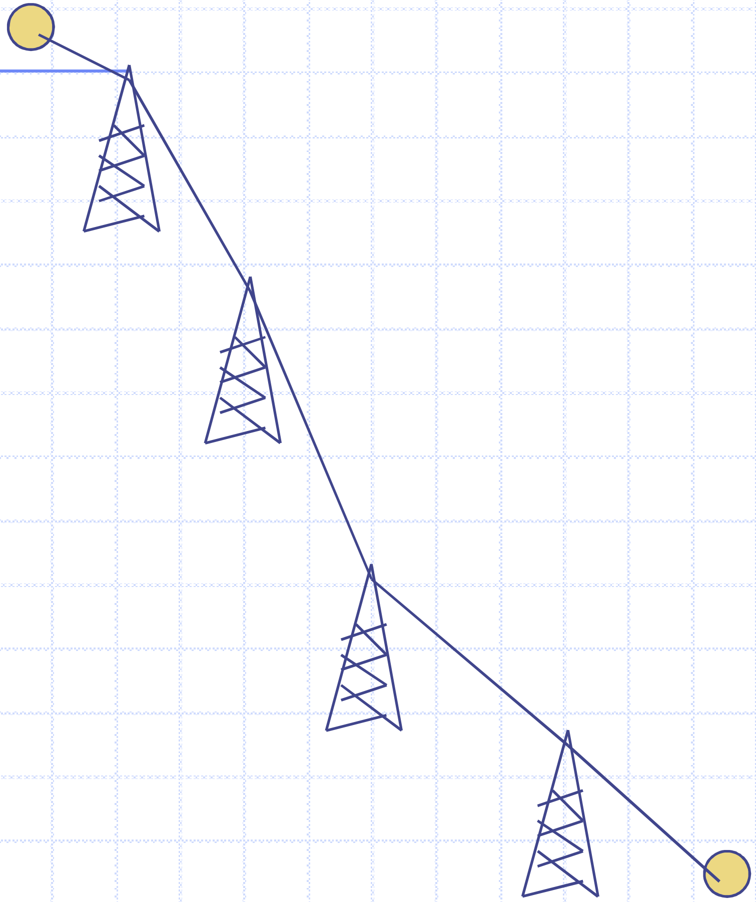
ASSIGNMENT ON POWER MEASUREMENT

Explain in details the three wattmeter power measurement method, Its advantage and disadivantages.

ELECTROMECHANICAL ENERGY CONVERSION

Electrical energy is the most popular form of energy, because:

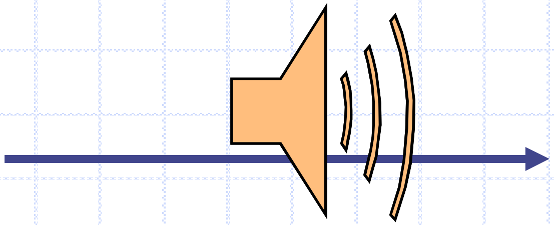
1. it can be transmitted easily for long distance, at high efficiency and reasonable cost.
2. It can be converted easily to other forms of energy such as sound, light, heat or mechanical energy.



Hidro power station, kariba

Power consumers,
lusaka

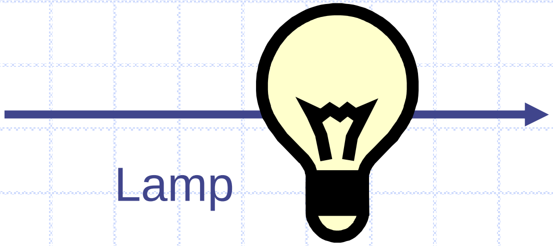
Electrical energy



Loud speaker

Sound energy

Electrical energy



Lamp

Light energy

Electrical energy

Kettle

Heat energy

Electromechanical energy conversion device:

converts electrical energy into mechanical energy or converts mechanical energy into electrical energy.

There are various electromechanical conversion devices may categorized as under:

a. Small motion

- telephone receivers, loud speakers, microphones

b. Limited mechanical motion

- electromagnets, relays, moving-iron instruments, moving-coil instruments, actuators

c. Continuous energy conversion

- motors, generators

Principle of Energy Conversion

According to the *principle of conservation of energy*, energy can neither be created nor destroyed, it can merely be converted from one form into another.

The total energy in a system is therefore constant.

Energy conversion in electromechanical system

In an energy conversion device, out of the total input energy, some energy is converted into the required form, some energy is stored and the rest is dissipated.

It is possible to write an equation describing energy conversion in electromechanical system:

Electrical energy from source = Mechanical energy to load + Increase of field energy + Energy converted to heat (losses) —— 3.1

Electrical energy from source = Mechanical energy to load + Increase of field energy + Energy converted to heat (losses) —— 3.1

The last term on the right-hand side of Eq. 3.1 (the losses) may be divided into three parts:

Energy converted to heat (losses) = Resistance losses + Friction and windage losses + Field losses —— 3.2

Then substitution from Eq. 3.2 in Eq. 3.1 yields

Electrical energy from source minus resistance losses = Mechanical energy to load plus friction and windage losses + Increase of magnetic coupling field energy plus core losses

Now consider an electromechanical system (actuator) illustrated in Fig. 3.1.

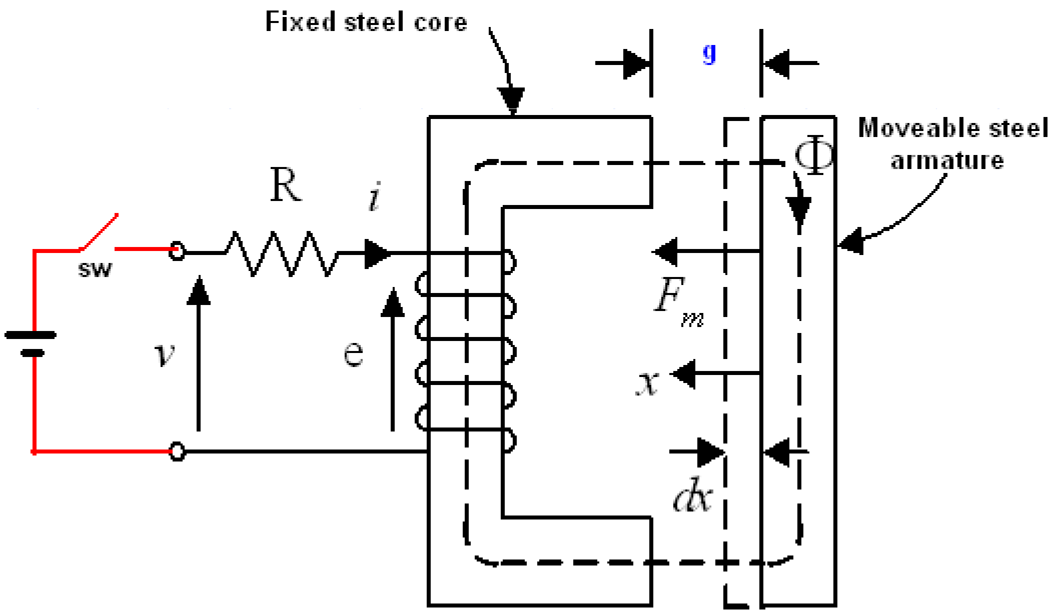


fig 3.1

At any instant, the emf e induced in the coil by the change in the flux linkage λ is

$$e = \frac{d\lambda}{dt} \quad \text{volt} \qquad ③.④$$

Consider now a differential time interval dt, during which the current in the coil is changing and the armature is moving.

Therefore, the differential energy transferred in time *dt* from the electric source to the coupling field is given by the energy output of the source minus the resistance loss:

$$dW_e = vidt - Ri^2dt$$

$$= (v - Ri)idt$$

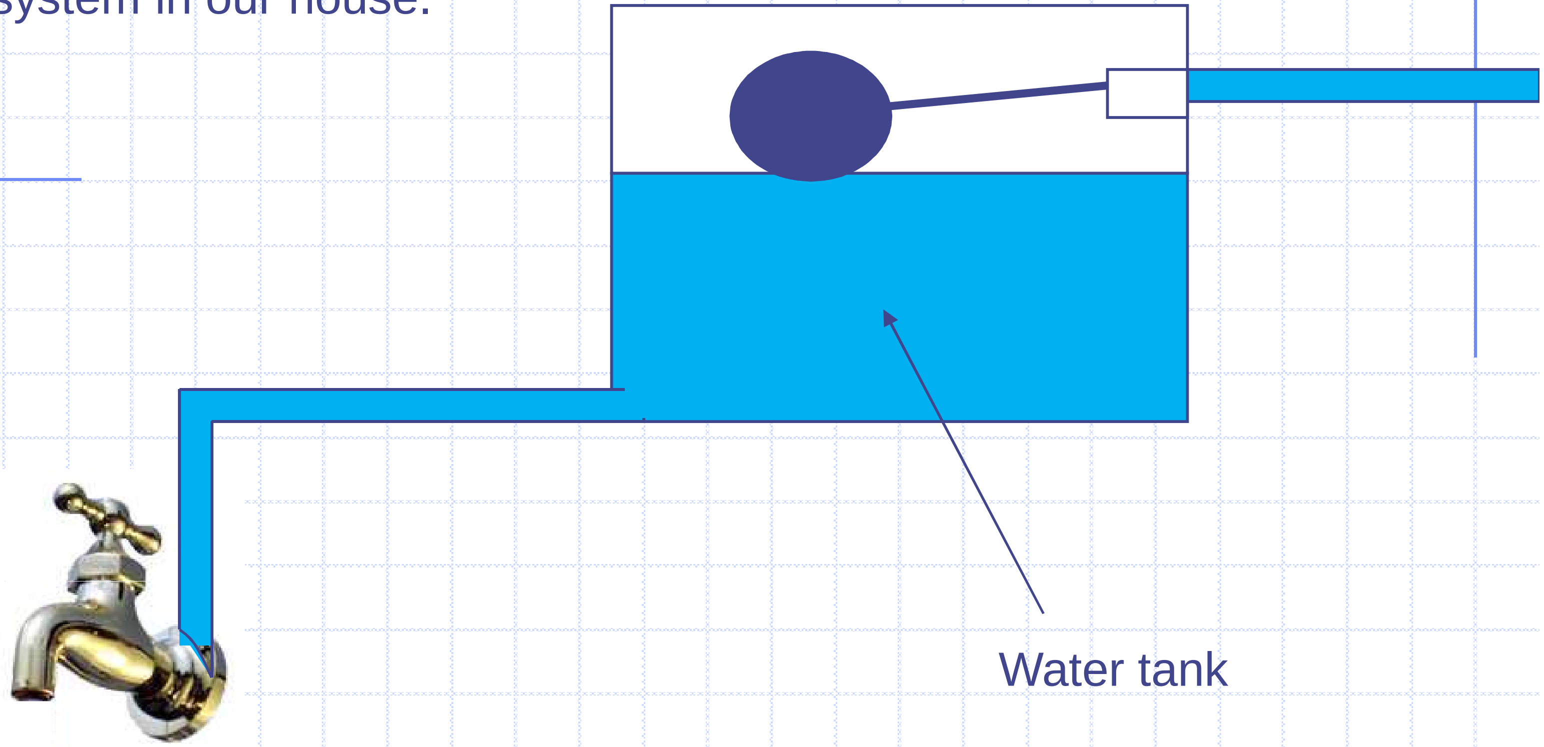
$$= eidt$$

$$\Rightarrow \quad dW_e = eidt \quad \text{Joule} \quad \text{———} ③.⑤$$

The coupling field forms an energy storage to which energy supplied by the electric system. At the same time, energy is released from the coupling field to the mechanical system.

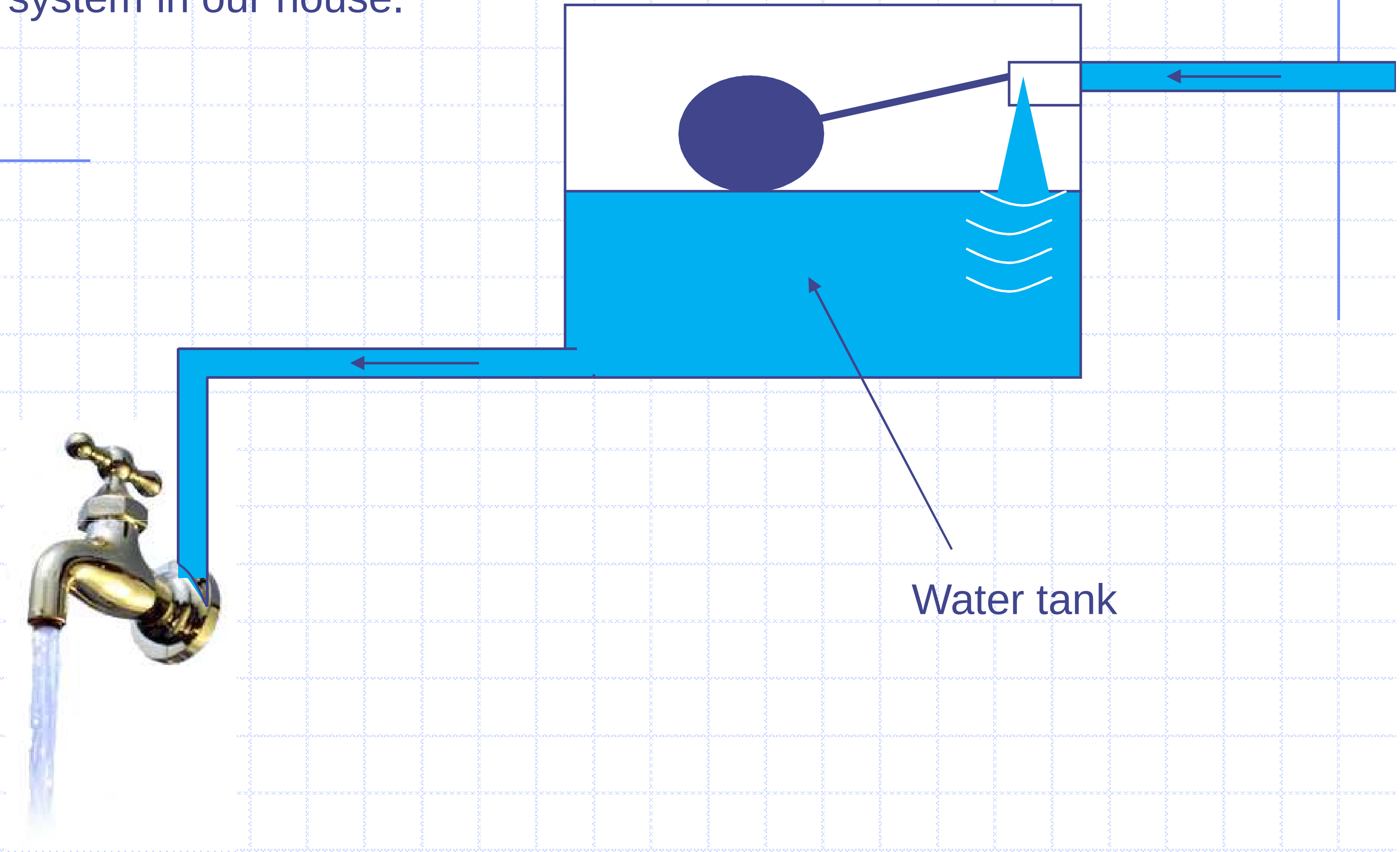
The rate of release energy is not necessarily equal at any instant to the rate of supply of energy to the field, so that the amount of energy stored in the coupling field may vary.

It’s like a pipe system in our house.



The water out from the tap will make water flow into the storage tank from the supply.

It’s like a pipe system in our house.



The water out from the tap will make water flow into the storage tank from the supply.

In time dt, let dW_f be the energy supplied to the field and either stored or dissipated. Let dW_m be the energy converted to mechanical form, useful or as loss, in the same time, dt.

Then, by the *principle of conservation of energy*, the following equation may be written for the field:

$$dW_e = dW_m + dW_f \qquad (3.6)$$

Field Energy

To obtain an expression for for dW_f of Eq. 3.6 in terms of the system variables, it is first necessary to find an expression for the energy stored in the magnetic field for any position of the armature. The armature will therefore be clamped at some value of air-gap length g so that no mechanical output can be produced.

$$dW_m = 0 \qquad \boxed{3.6}$$

Field Energy (continue…..)

If switch SW in Fig. 3.1 is now closed, the current will rise to a value *V/R*, and the flux will be established in the magnetic system. Let the relationship between coil flux linkage λ and the current *i* for the chosen air-gap length be that shown in Fig. 3.2

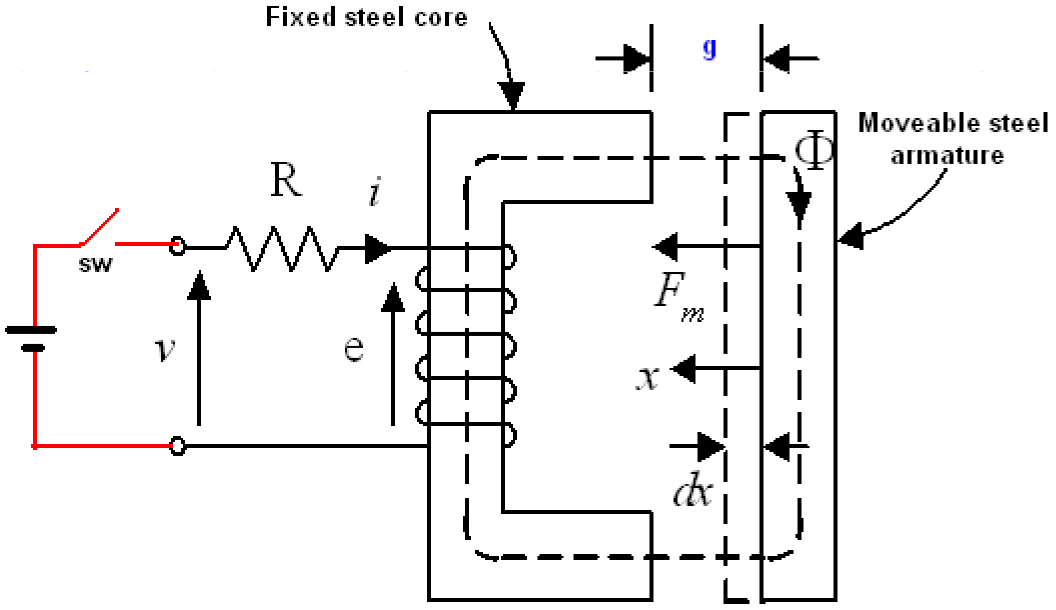


fig 3.1

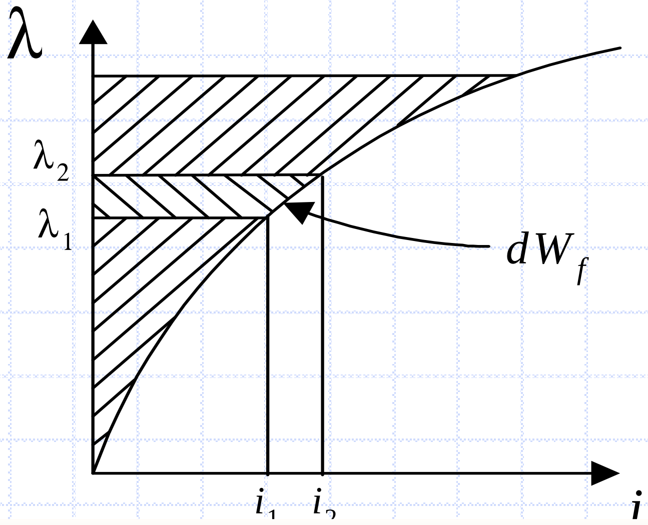
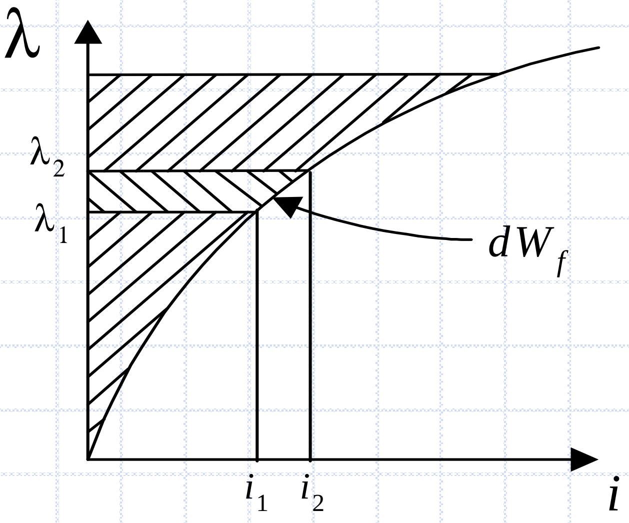


Fig. 3.2

Field Energy (continue…..)

Since core loss is being neglected, this will be a single-valued curve passing through the origin. In the absence of any mechanical output energy, all of the electric input energy must be stored in the magnetic field:



$$dW_e = dW_f \qquad 3.8$$

Substitution from Eqs. 3.4 and 3.8 in Eq. 3.5 yields

$$dW_f = dW_e = i.edt = id\lambda \quad \text{J} \qquad 3.9$$

Field Energy (continue…..)

If now v is changed, resulting in a change in current from i_1 to i_2, there will be a corresponding change in flux linkage from λ_1 to λ_2 .

The increase in energy stored during the transition between these two states is

$$dW_f = \int_{\lambda_1}^{\lambda_2} i d\lambda \quad \text{J}$$

3.10

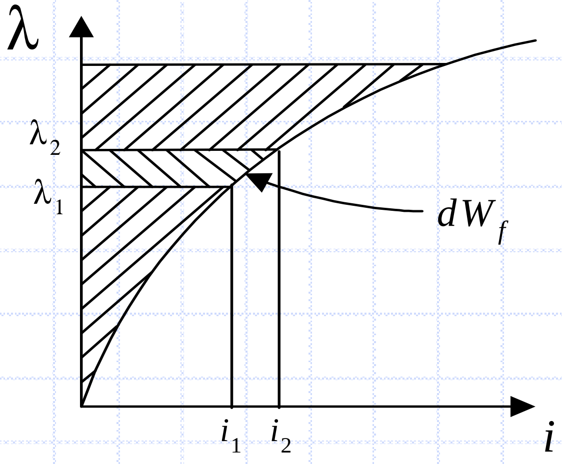


Fig 3.2.

The area is shown in Fig 3.2. When the flux linkage is increased from zero to λ, the total energy stored in the field is

$$W_f = \int_0^{\lambda} i d\lambda \quad \text{J}$$

3.11

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Field Energy (continue…..)

This integral represents the area between the λ–i characteristic and the λ–axis, the entire shaded area of Fig. 3.2.

If it is assumed that there is no leakage flux, so that all flux Φ in the magnetic system links all N turns of the coil, then

$$\lambda = N\Phi \quad \text{Wb} \longrightarrow 3.12$$

From Eqs. 3.9 and 3.12,

$$dW_f = id\lambda = Nid\Phi = \mathscr{F}d\Phi \quad \text{J} \qquad 3.13$$

where $\mathscr{F} = Ni$ A 3.14

$\mathscr{F}$ is mmf (magneto-motive force)

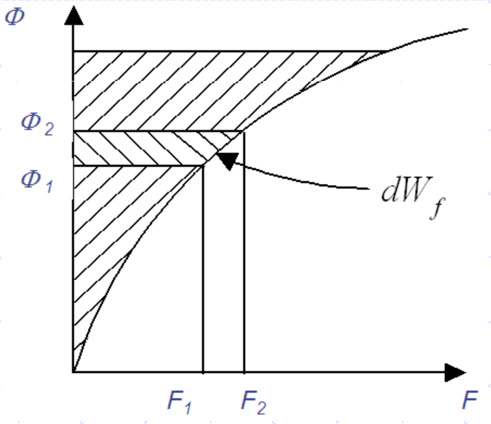


Fig. 3.3

The characteristic of Fig. 3.3 can also represent the relationship between Φ and $\mathscr{F}$.

Field Energy (continue…..)

If the reluctance of the air gap forms a large part of the total reluctance of the magnetic system, then that of the steel may be neglected and the λ–i characteristic becomes the straight line through the origin shown in Fig. 3.3. For this system,

$$\lambda = Li \quad \text{Wb} \qquad (3.15)$$

Where L is the inductance of the coil. Substitution in Eq. 3.11 gives the energy W_f in several useful forms:

$$W_f = \int_0^{\lambda} \frac{\lambda}{L} d\lambda = \frac{\lambda^2}{2L} = \frac{Li^2}{2} = \frac{i\lambda}{2} \quad \text{J} \qquad (3.16)$$

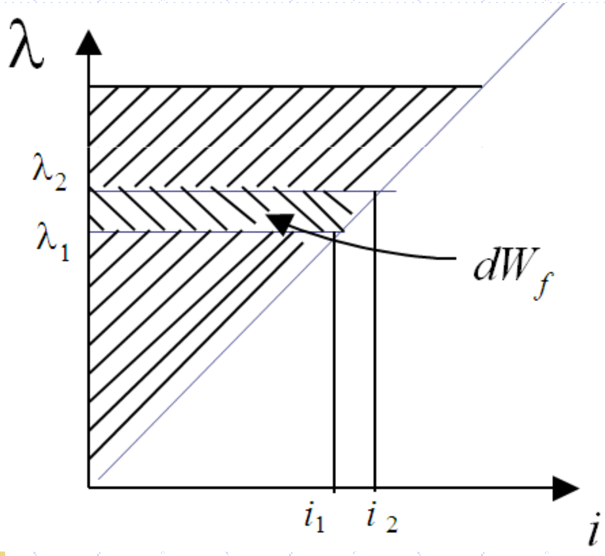


Fig. 3.3

Field Energy (continue…..)

If the reluctance of the magnetic system (that is, of the air gap) as seen from the coil is S, then $\mathscr{F} = S\,\Phi$, and from Eq. 3.13,

$$W_f = \int_0^{\phi} \mathscr{F}\, d\lambda = \frac{S\phi^2}{2} = \frac{\mathscr{F}^2}{2S} \quad \text{J} \qquad 3.17$$

If A is the cross-section area of the core and $l = 2g$ is the total length of air gap in a flux path, then from Eq. 3.16,

$$W_f = \frac{i\lambda}{2} = \frac{F\phi}{2} = \frac{1}{2}HBlA \quad \text{J} \qquad 3.18$$

Field Energy (continue…..)

Where B is the flux density in the air gaps. Since $B/H=\mu_0$ and lA is the total gap volume, it follows from Eq. 3.18 that the energy density in the air gaps is

$$w_f = \frac{W_f}{lA} = \frac{1}{2}BH = \frac{1}{2}\mu_0 H^2 = \frac{1}{2}\frac{B^2}{\mu_0} \quad \text{J/m}^3 \qquad (3.19)$$

Equations 3.16, 3.17 and 3.19 represent three different ways of expressing the field energy.

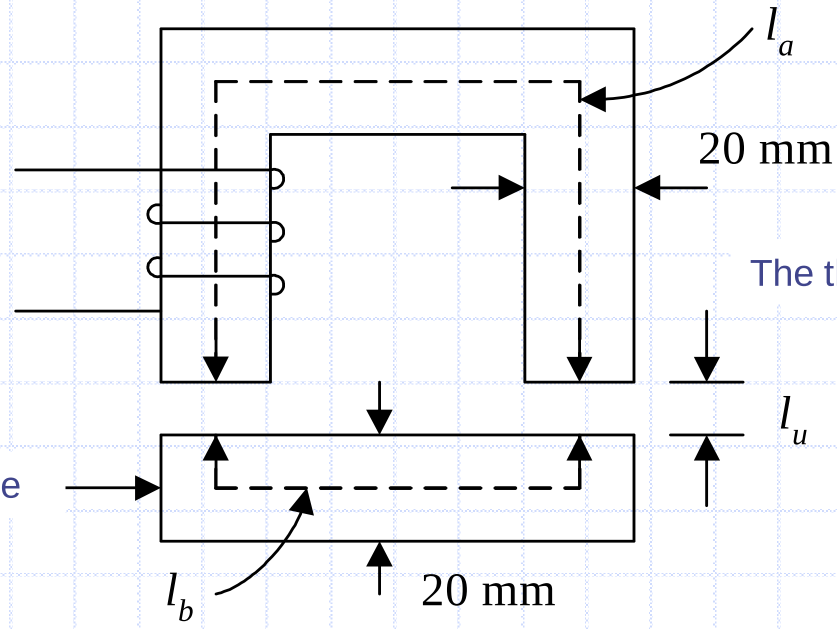
Example 3.1 The core and armature dimensions of the actuator of Fig. 3.1 are shown in Fig. 3.4. Both parts are made of mild steel, whose magnetization curve is given in Fig. 3.5. Given l_a = 160 mm, l_b = 80 mm. The coil has 2000 turns. Leakage flux and fringing may be neglected. The armature is fixed, so that the length of the air gas, l_u= 9 mm, and a direct current is passed through the coil, producing a flux density of 0.8 T in the air gap.

a) Determine the required coil current.

b) Determine the energy stored in the air gap.

c) Determine the energy stored in the steel.

d) Determine the total field energy.



The thickness = 20 mm

Fig. 3.4

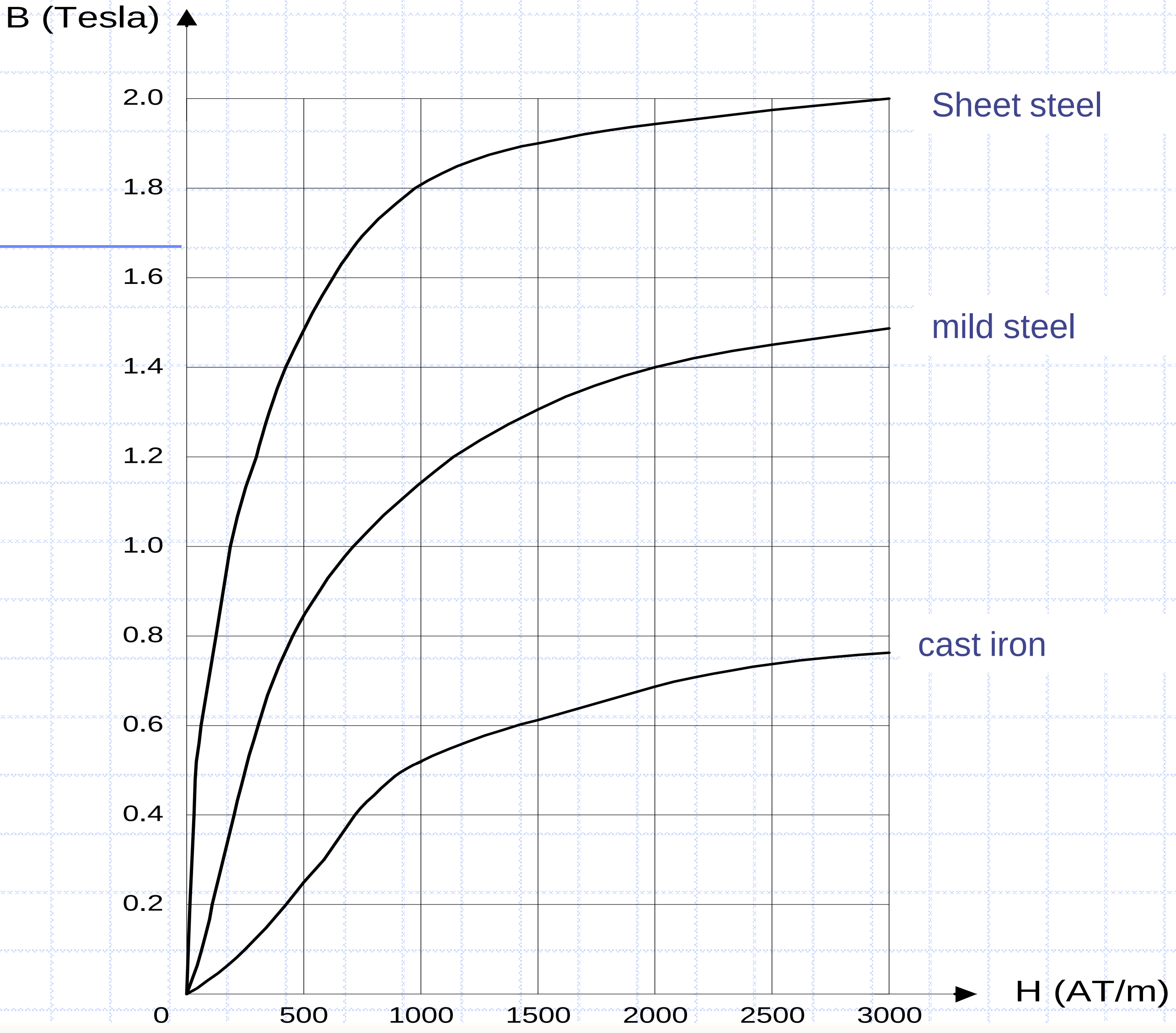

B (Tesla)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
500
1000
1500
2000
2500
3000
H (AT/m)
Sheet steel
mild steel
cast iron

Fig. 3.5

Solution

(a) Area, $A = (20 \times 10^{-3})(20 \times 10^{-3}) = 4 \times 10^{-4}\ \text{m}^2$.

$$Ni = H_t l_t + H_u l_u$$

$l_t = 160 + 80 = 240\ \text{mm} = 240 \times 10^{-3}\ \text{m}$

$l_u = 2 \times 9\ \text{mm} = 18\ \text{mm} = 18 \times 10^{-3}\ \text{m}$

Given $B_u = 0.8\ \text{T}$

$B_u = B_t = 0.8\ \text{T}$

From Fig. 3.6, magnetic field intensity in the steel is,

$H_t = 450\ \text{A/m}$

For the air gaps

$$H_u = \frac{B_u}{\mu_o} = \frac{0.8}{4\pi \times 10^{-7}} = 636.62 \times 10^3$$ A/m

$$i = \frac{(450)(240 \times 10^{-3}) + (636.62 \times 10^3)(18 \times 10^{-3})}{2000}$$

$$= \frac{11567.16}{2000} = 5.78$$ A

(b) Energy density in the air gaps is

$$w_{fu} = \frac{B^2}{2(4\pi \times 10^{-7})} = 254.65 \times 10^3$$ J/m³

Volume of air gaps = length of air gaps × area of air gaps

$$= 0.018 \times 0.02 \times 0.02$$

$$= 7.2 \times 10^{-6}\ \text{m}^3$$

Energy stored in the air gaps,

$$W_{fu} = \text{the volume of air gaps} \times w_{fu}$$

$$= (7.2 \times 10^{-6}) \times 254.65 \times 10^3$$

$$= 1.834\ \text{Joule.}$$

(c) Energy density in the steel,

$$w_{ft} = \int_0^{0.8} H dB$$

Energy density in the steel is given by the area enclosed between the characteristic and the *B* axis in Fig. 3.6 up to value of 0.8 T.

$w_{ft} \cong ½ \times 0.8 \times 450 = 180$ J/m^3 (straight-line approximation)

Volume of steel= length of steel × area of steel

$= (240 \times 10^{-3}) \times (0.02 \times 0.02)$

$= 9.6 \times 10^{-5}$ m^3

∴ Energy stored in the steel,

$$W_{ft} = 9.6 \times 10^{-5} \times 180 = 0.01728 \text{ Joule}$$

(d) Total field energy,

$$\begin{aligned} W_f &= W_{ft} + W_{fu} \\ &= 0.01728 + 1.834 \\ &= 1.851 \text{ Joule.} \end{aligned}$$

The proportion of field energy stored in the steel is, therefore, seen to be negligibly.

Coenergy

Coenergy, W_f' is the area enclosed between the λ-i characteristic and the i axis of Fig.3.2.

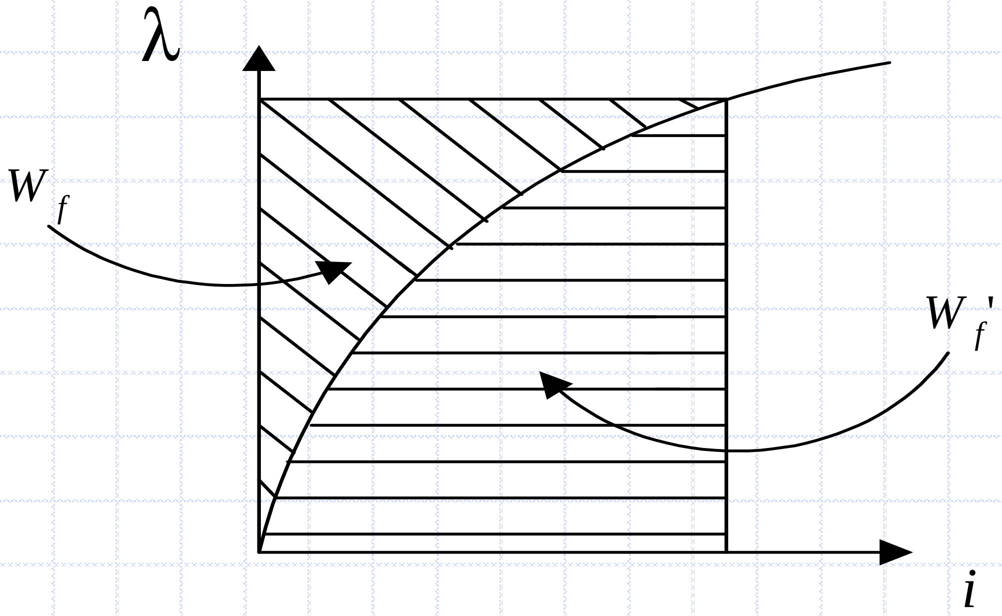


Fig. 3.6 Field energy and coenergy

For linear λ-i characteristic, $W_f' = W_f$.
For nonlinear λ-i characteristic, $W_f' > W_f$.

Mechanical Energy in a Linear System

It will be assumed that the armature of the actuator in Fig. 3.1 may move from position x_1 to position x_2, as a result, the length of air gaps is reduced. The λ–i characteristics for the two extreme positions of the armature may be assumed to be the two straight lines (linear).

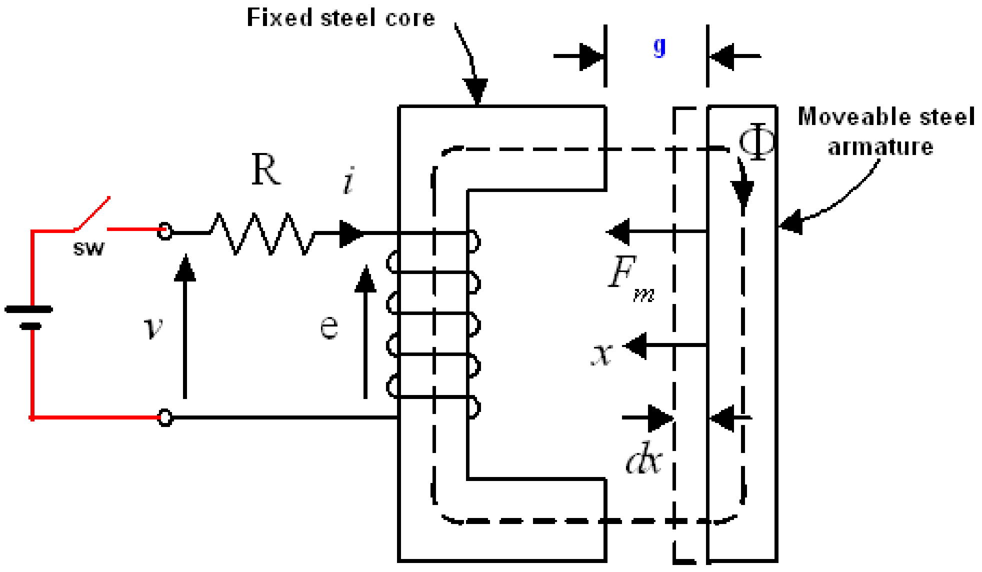
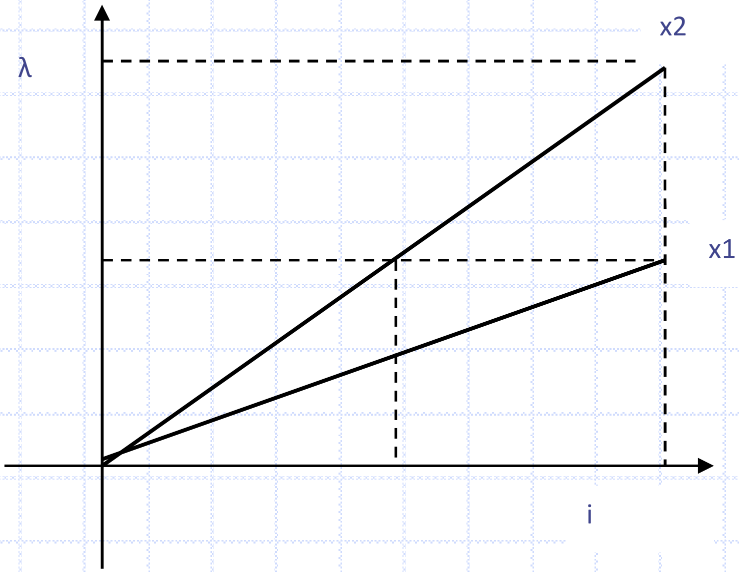


fig 3.1



Mechanical Energy in a Linear System

Consider a very slow armature displacement. It may assumed that it takes place at essentially constant current as illustrated in Fig. 3.7 (as $d\lambda/dt$ is negligible). The operational point has changed from ***a*** to ***b***.

At the moment of armature movement,

$$\Delta W_e = \int eidt = \int_{\lambda_1}^{\lambda_2} id\lambda = i_o(\lambda_2 - \lambda_1) \qquad \text{(3.20)}$$

The change of field energy,

$$\Delta W_f = \tfrac{1}{2} i_o \lambda_2 - \tfrac{1}{2} i_o \lambda_1$$

$$= \tfrac{1}{2} i_o(\lambda_2 - \lambda_1) \qquad \text{(3.21)}$$

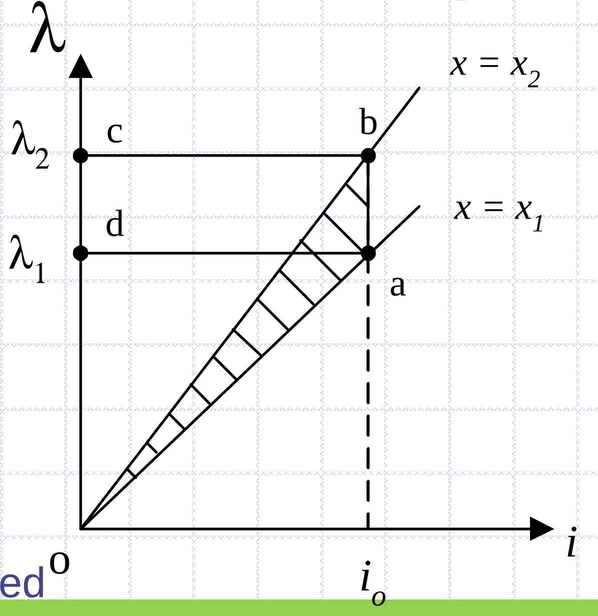


Fig. 3.7 Current is fixed

Mechanical Energy in a Linear System

From Eq. (3.6),

$$\Delta W_e = \Delta W_m + \Delta W_f$$

$$\Delta W_m = \Delta W_e - \Delta W_f$$

$$\therefore \quad = i_o(\lambda_2 - \lambda_1) - \tfrac{1}{2} i_o(\lambda_2 - \lambda_1)$$

$$= \tfrac{1}{2} i_o(\lambda_2 - \lambda_1)$$

$= \Delta W_f$

$= \Delta W_f'$ = the change of coenergy

Mechanical Energy in a Linear System

For small change of x or dx,

$$\because \qquad dW_m = dW_f'$$

$$\Rightarrow \qquad F_m dx = dW_f' \qquad \text{—— } ③.21$$

where

$$dW_m = F_m dx$$

F_m = mechanical force on moving part (armature)

Eq. 3.21 can be written as,

$$\boxed{F_m = \frac{\partial W_f'}{\partial x}(i,x)\Big|_{i = \text{constant}}} \quad \text{N} \text{ —— } (3.22)$$

Eq. 3.22 is partial differential since W_f is function of more than one variable.

Mechanical Energy in a Linear System

Consider now a very rapid differential armature displacement dx. It may be assumed that it takes place at essentially constant flux linkage λ_o, as illustrated in Fig. 3.8. At the instant, the current is changed from i_1 to i_2 , where $i_1 > i_2$.

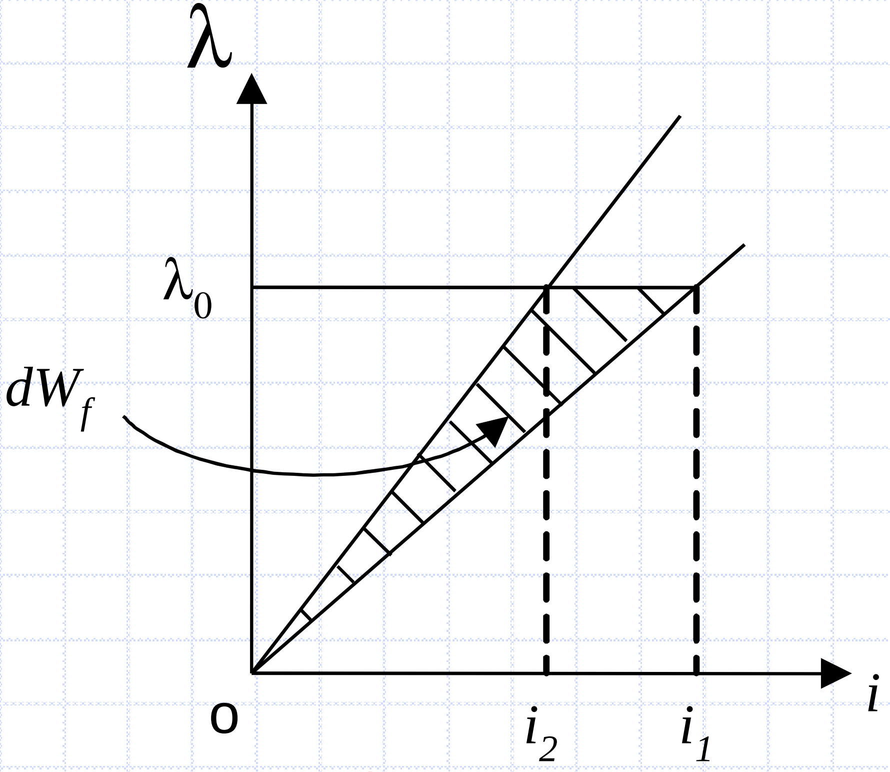


Fig. 3.8

Mechanical Energy in a Linear System

$$dW_e = dW_m + dW_f$$

$$\therefore -F_m dx = dW_f \qquad (3.25)$$

$$\Rightarrow \quad -F_m dx = \tfrac{1}{2}\lambda_o (i_2 - i_1) \qquad (3.26)$$

= the change of field energy

Eq. 3.26 can be written as,

$$\boxed{F_m = -\frac{\partial W_f}{\partial x}(\lambda, x)\Big|_{\lambda = \text{constant}}} \qquad (3.27)$$

Since the electrical input energy is zero, the mechanical output energy has been supplied entirely by the coupling field.

For a linear electromagnetic system,

$$\lambda = L(x)\, i \qquad (3.28)$$

where

$L(x)$ = the inductance of the coil which dependent on length of the air gaps.

From Eqs. 3.11 and 3.28,

$$W_f = \int_0^{\lambda} i\,d\lambda = \int_0^{\lambda} \frac{\lambda}{L(x)}\,d\lambda = \frac{\lambda^2}{2L(x)} \qquad (3.29)$$

$$= \frac{L(x)^2 i^2}{2L(x)} = \tfrac{1}{2} L(x) i^2 \qquad (3.30)$$

$$W_f = W_f' = \tfrac{1}{2} L(x) i^2 \qquad (3.31)$$

From Eqs. 3.22 and 3.31,

$$F_m = \frac{\partial W_f'}{\partial x}(i, x) \Bigg|_{i = \text{constant}}$$

$$= \frac{\partial}{\partial x}\left(\tfrac{1}{2} L(x) i^2\right) \Bigg|_{i = \text{constant}}$$

$$= \frac{1}{2} i^2 \frac{dL(x)}{dx} \qquad \text{3.32}$$

$$\Rightarrow \qquad F_m = \frac{1}{2} i^2 \frac{dL(x)}{dx} \qquad \text{3.33}$$

Mechanical Energy in a Linear System

From Fig. 3.1 (for linear system),

$$Ni = H_u 2g$$

$$= \frac{B_u}{\mu_o} 2g \qquad ③④ \text{ 3.34}$$

From Eq. 3.18

W_f = volume of air gaps $\times \frac{B_u{}^2}{2\mu_o}$

$$= A_u 2g \times \frac{B_u{}^2}{2\mu_o} \qquad \text{3.35}$$

where A_u = cross section area of air gap

From Fig. 3.1, it is seen that a positive displacement dx will correspond to a reduction dg in the air gap length. Thus,

$$dx = -dg \text{ m} \qquad ③.36$$

From Eqs. 3.27, 3.35 and 3.36 yield,

$$F_m = \frac{\partial}{\partial g}\left(A_u 2g \times \frac{B_u^{\ 2}}{2\mu_o} \right)$$

$$\Rightarrow \qquad F_m = 2A_u \frac{B_u^{\ 2}}{2\mu_o} \qquad 3.37$$

where

$2A_u$ = The total cross-section area of air gaps

Mechanical Energy in a Linear System

∴ The force per unit area of air gaps, f_m is

$$f_m = \frac{B_u^{\ 2}}{2\mu_o} \quad \text{N/m}^2 \qquad (3.38)$$

Example 3.2

An electromagnet system is shown in Fig. 3.9.

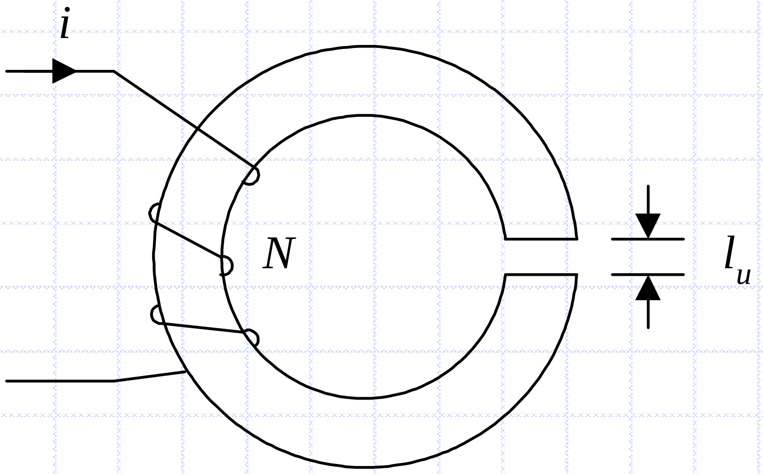


Fig. 3.9: linear system

Given that $N = 600$, $i = 3$ A, cross section area of air gap is 5 cm^2 and air gap length is 1.5 mm. By neglecting core reluctance, leakage flux and fringing effects, find:

(a) Force between the electromagnetic surfaces.

(b) Energy stored in the air gap.

Solution

(a) The total cross-section area of air gap = A_u, Eq. 3.37 becomes,

$$F_m = A_u \frac{B_u{}^2}{2\mu_o}$$

3.39

For linear system,

$$Ni = H_u l_u = \frac{B_u l_u}{\mu_o}$$

$$\Rightarrow \quad B_u = \frac{\mu_o Ni}{l_u}$$

3.40

Substitution from Eq. 3.40 in Eq. 3.39 yields

$$\therefore \quad F_m = \frac{A_u \mu_o N^2 i^2}{2 l_u{}^2}$$

$$= \frac{(5\times10^{-4})(4\pi\times10^{-7})(600)^2(3)^2}{2(1.5\times10^{-3})^2}$$

= <u>452.39 N</u>

(b) Since the system is linear, the entire field energy is stored in the air gap,

$$W_f = \text{volume of air gap} \times \frac{B_u{}^2}{2\mu_o}$$

$$= l_u \times A_u \times \frac{B_u{}^2}{2\mu_o}$$

$= \; l_u \times F_m$

$= \; (1.5 \times 10\text{-}3) \times 452.39$ Nm

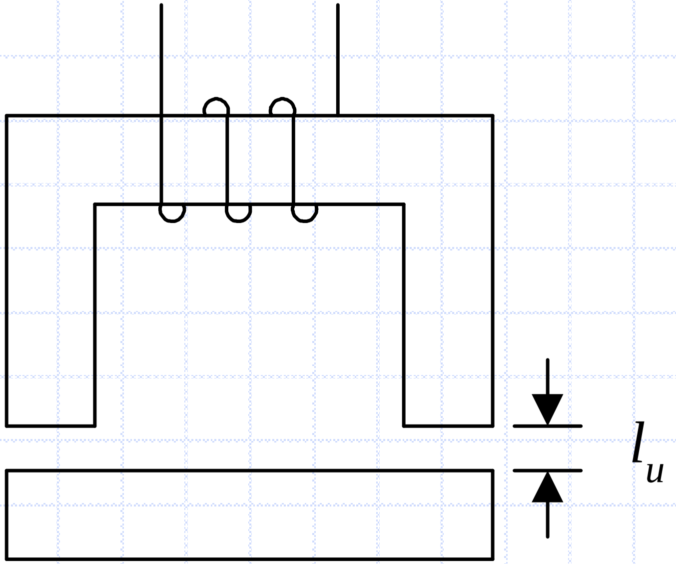
$= \; 0.6789$ Nm

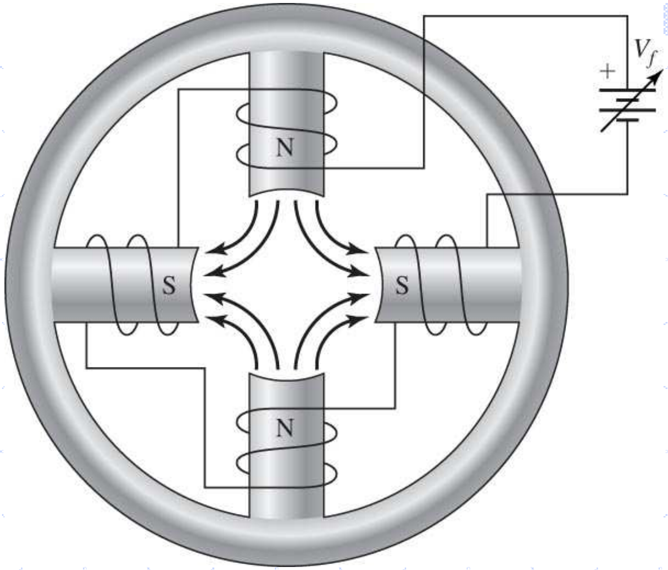
= <u>0.6789 Joule</u>

ASSIGNMENT ON ELECTRO-MECH ENERGY CONVERSION

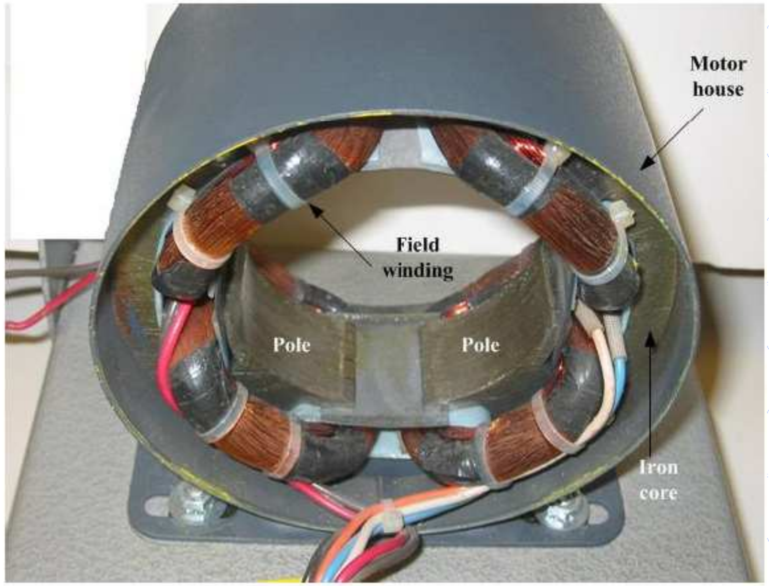
Electromagnet system in Fig. 3.10 has cross-section area 25 cm^2. The coil has 350 turns and 5 ohm resistance. Magnetic core reluctance, fringing effects and leakage flux can be neglected. If the length of air gap is 4 mm and a 110 V DC supply is connected to the coil, find

(a) Stored field energy
(b) Lifting force





Direct-Current Machine

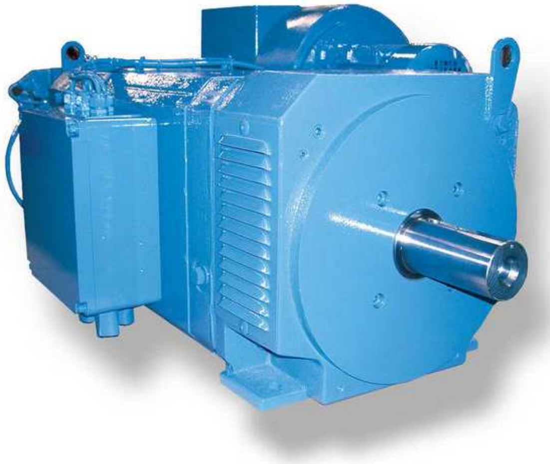


Electric Machine

- Electric machines can be used as motors and generators
- Electric motor and generators are rotating energy-transfer electromechanical motion devices
- Electric motors convert electrical energy to mechanical energy
- Generators convert mechanical energy to electrical energy

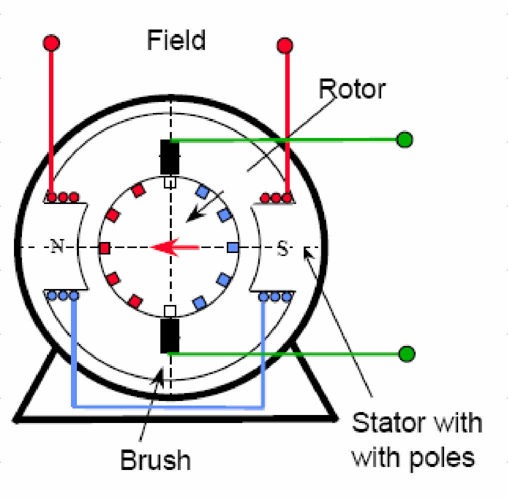
Electric Machine

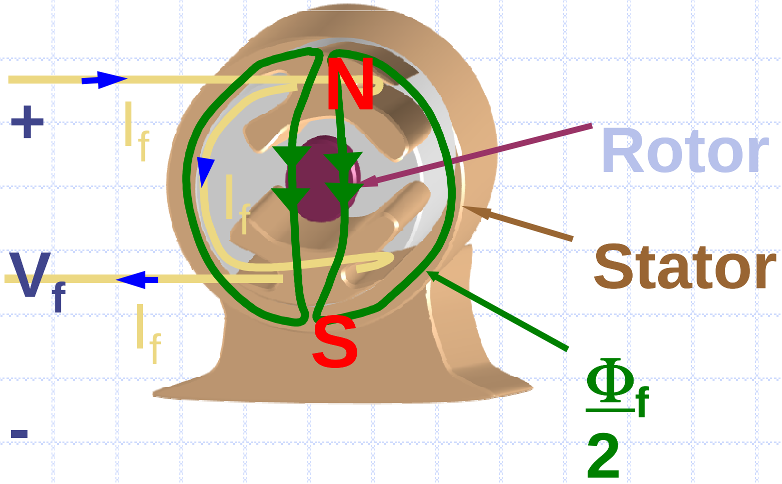
- Electric machines can be divided into 2 types:
  - AC machines
  - DC machines
- Several types DC machines
  - Separately excited
  - Shunt connected
  - Series connected
  - Compound connected
  - Permanent magnet



Electric Machine

- All Electric machines have:
  - Stationary members (stator)
  - rotating members (rotor)
  - Air gap which is separating stator and rotor

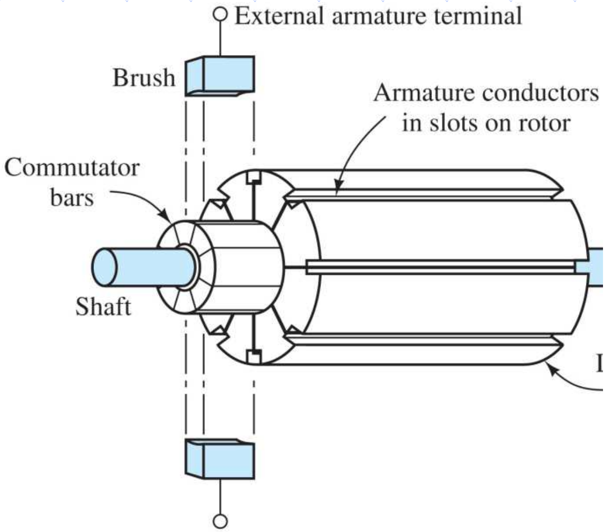


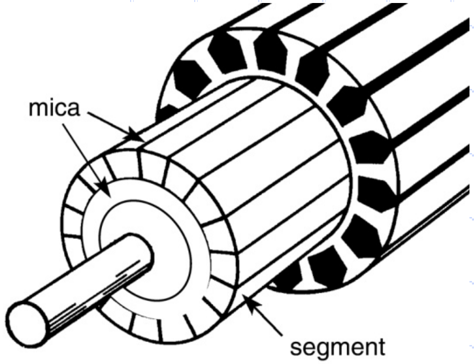


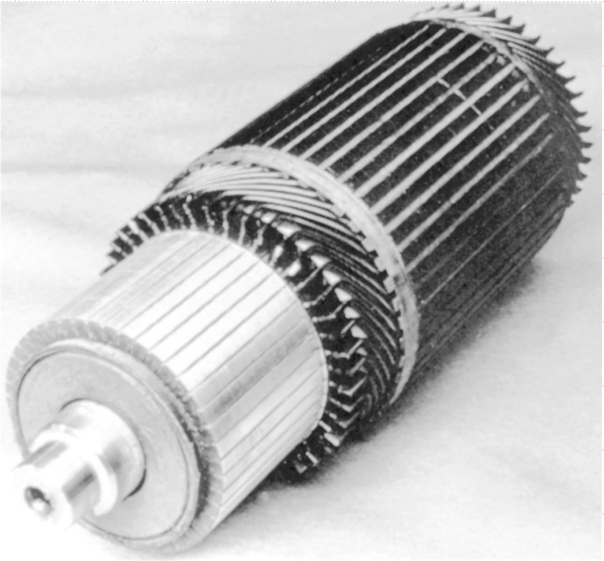
- The rotor and stator are coupled magnetically

Electric Machine

- The armature winding is placed in the rotor slot and connected to rotating commutator which rectifies the induced voltage
- The brushes which are connected to the armature winding, ride on commutator

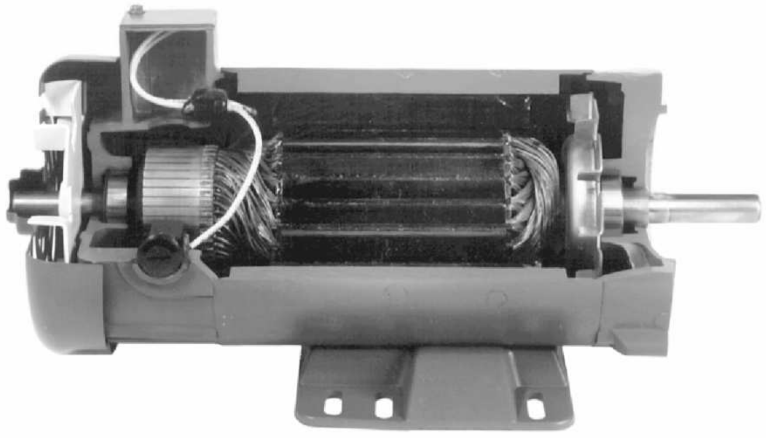


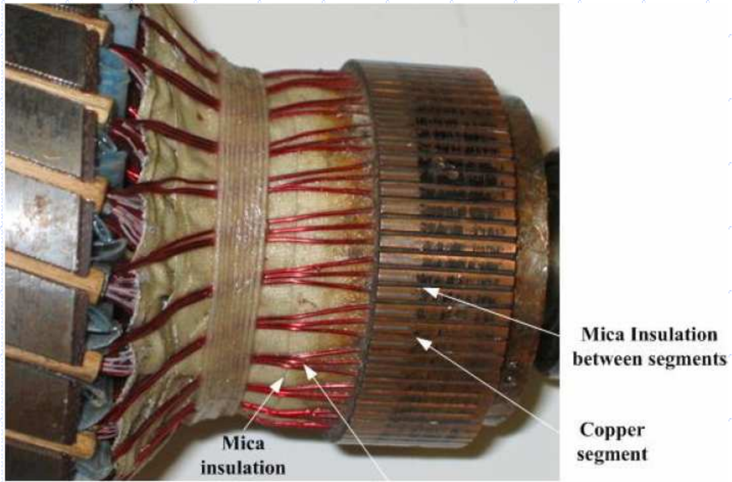




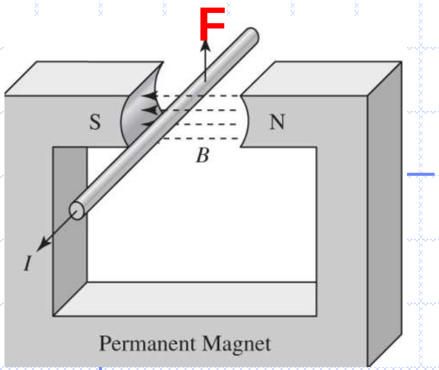
Electric Machine

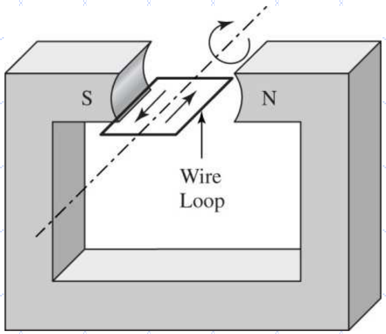
- The armature winding consists of identical coils carried in slots that are uniformly distributed around the periphery of the rotor
- Conventional DC machines are excited by direct current, in particular if a voltage-fed converter is used a dc voltage is supplied to the stationary field winding
- Hence the excitation magnetic field is produced by the field coils
- Due to the commutator, armature and field windings produce stationary magnetomotive forces that are displaced by 90 electrical degrees

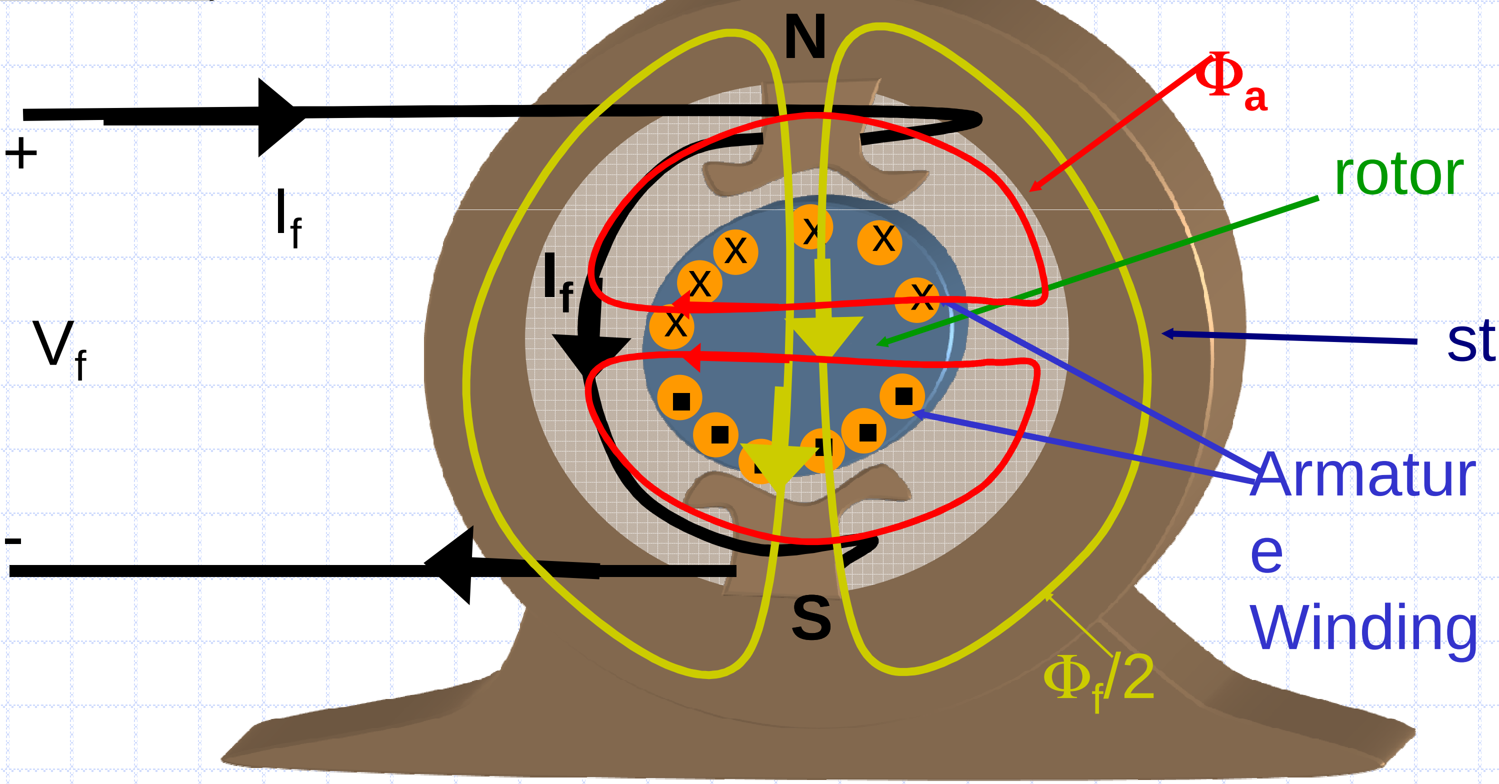




Magnetic Flux in DC machines

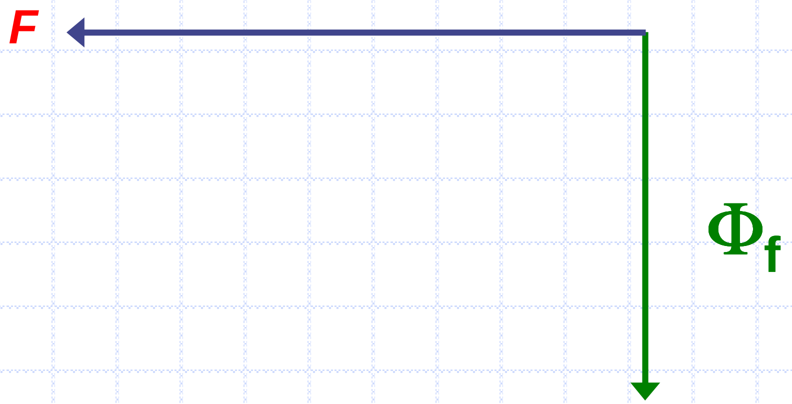






DC Machines

- The current is induced in the **Rotor Winding** (**i.e.** the **Armature Winding**) since it is placed in the field (***Flux Lines***) of the Field Winding.



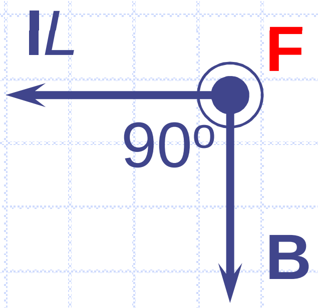
Orthogonality of Magnetic Fields in DC Machines

- mmf produced by the armature and mmf produced by the field winding are orthogonal.

$$\mathbf{F} = \mathbf{I}L \times \mathbf{B} = ILB\sin\left(90^{o}\right)$$

Magnetic field due to field winding

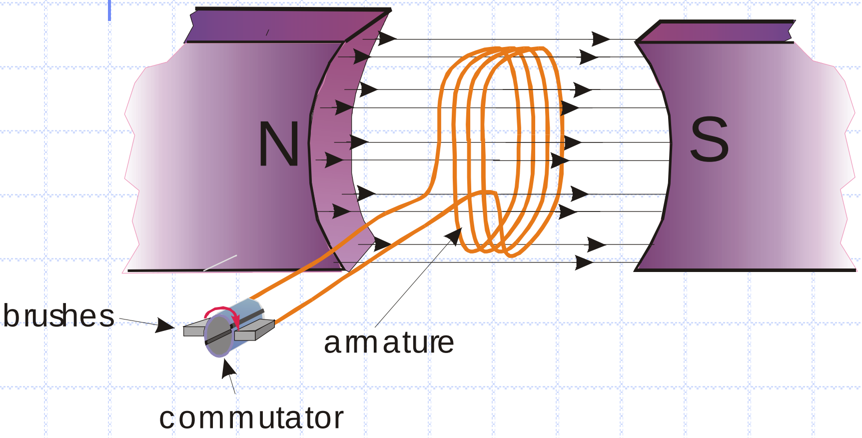
Magnetic field due to armature winding

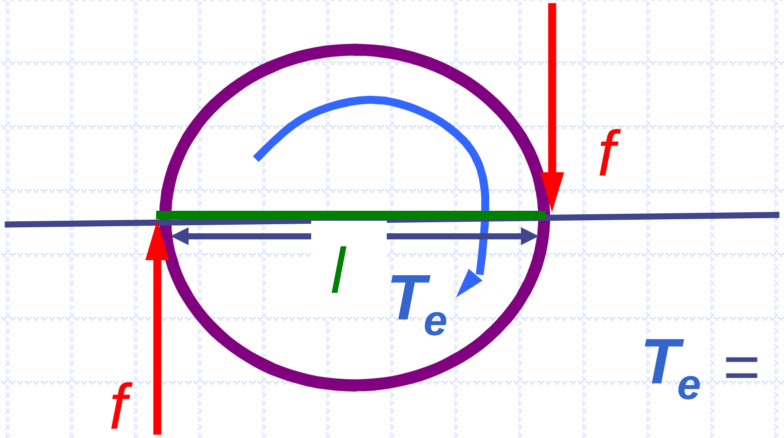


DC Machines

- The force acting on the rotor, is expressed as

$$f = \underbrace{I\,L}_{\text{Due to the Armature}} \times \underbrace{B}_{\text{Due to the Field}}$$

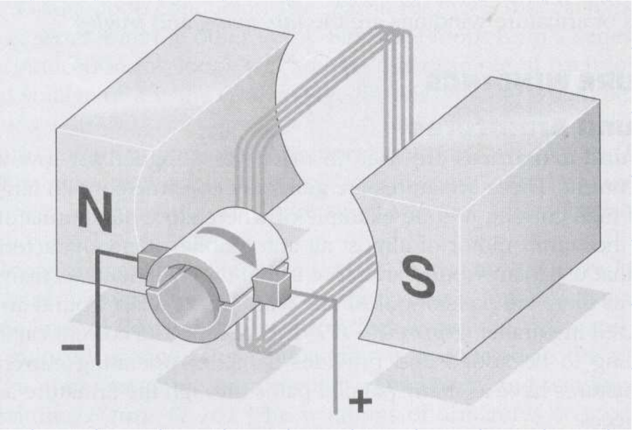


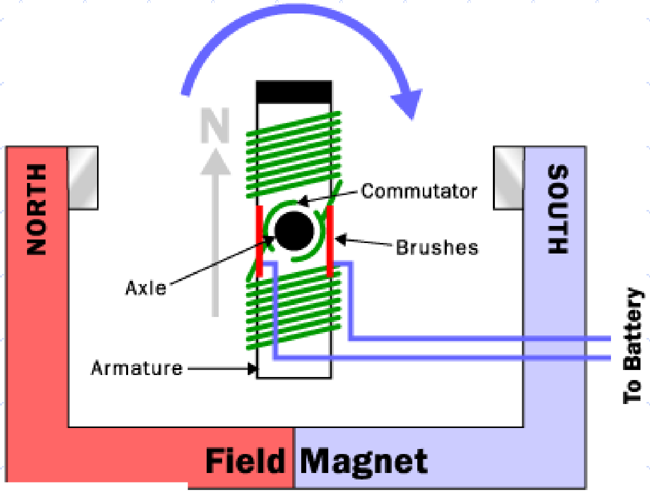


$T_e = f \times l$

DC Machines

- The Field winding is placed on the stator and the current (voltage) is induced in the rotor winding which is referred also as the armature winding.
- In DC Machines, the ***mmf*** produced by the field winding and the ***mmf*** produced by the armature winding are at right-angle with respect to each other.
- The torque is produced from the interaction of these two fields.

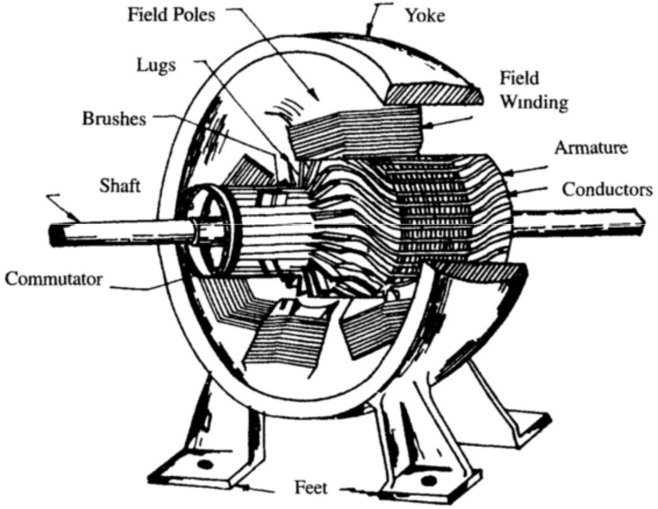




Difference DC Motor/Generators

- Electric machine can be either a motor or a generator depending on whether it drives a load or it is driven by a prime mover
- The direction of the armature current is reversed when an electric machine changes from motor to generator operation
- However line voltage polarity, direction of rotation and field current are the same

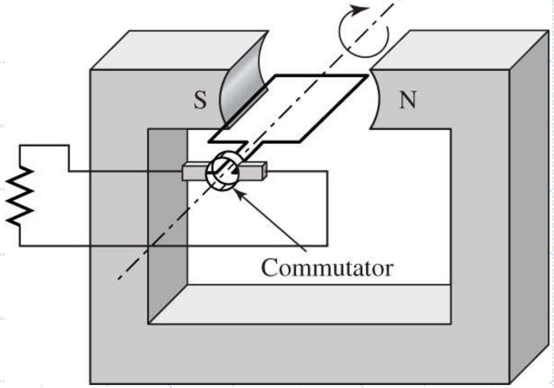
$$i_a = \frac{u_a - E_a}{r_a}$$



- (MOTOR) If u_a is greater than E_a , the armature current is positive i_a
- (GENERATOR) If E_a is greater than u_a , the armature current is negative

The elementary dc generator produces a pulsating dc voltage.

generator with commutator and brushes



⇒

DC generator output waveform.

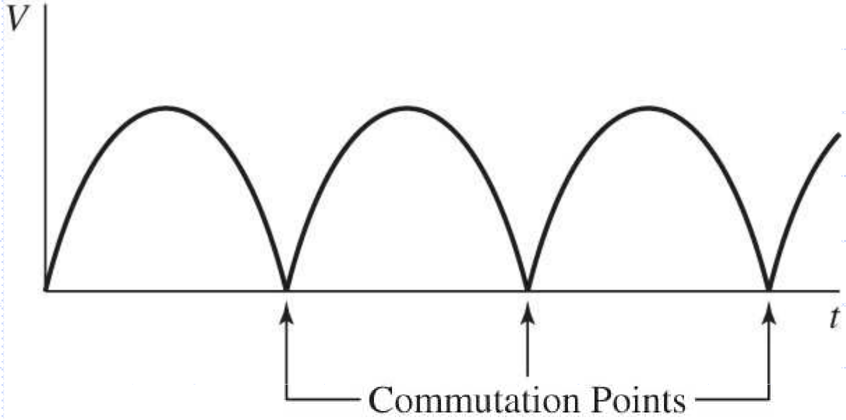
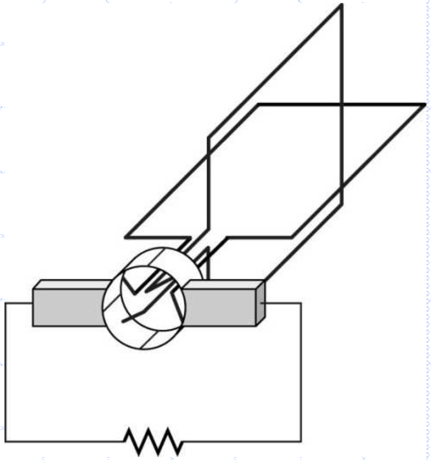


Fig.5-7a: for 2 poles with one coil conductor



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Coil and output waveforms for a two-winding rotor.

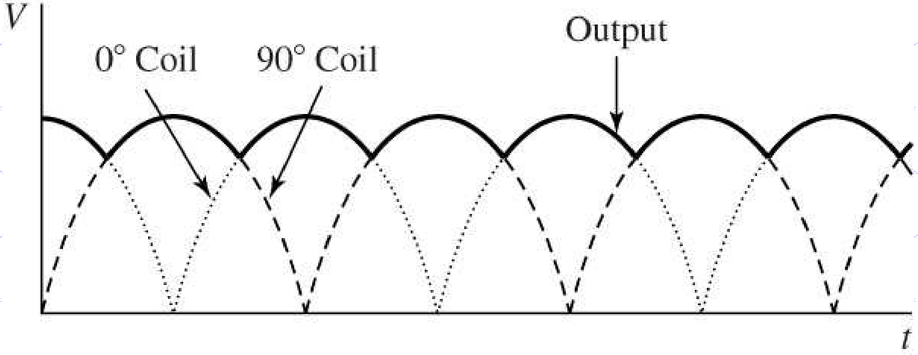
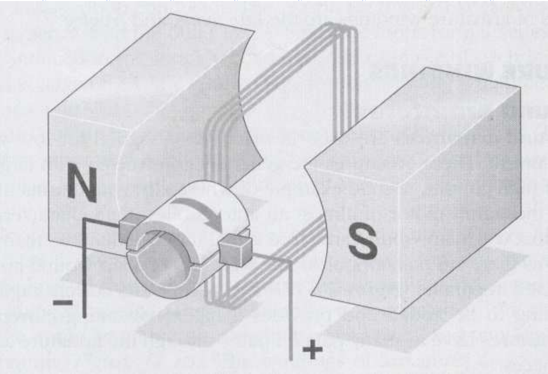
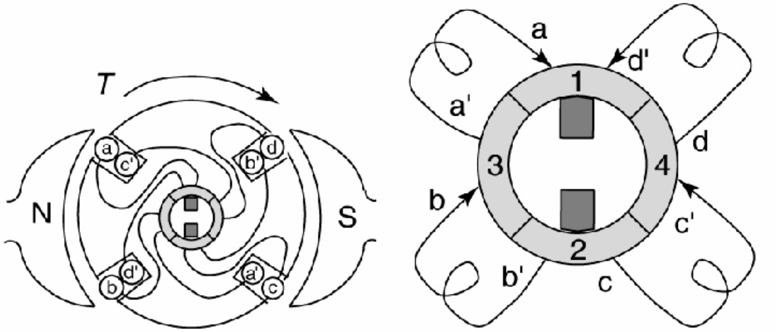


Fig.5-7b: 2 poles DC generator rotor with two coils for in series.

- The elementary dc generator produces a pulsating dc voltage.

Effect of additional coil





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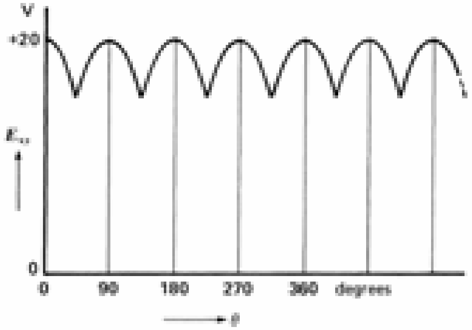
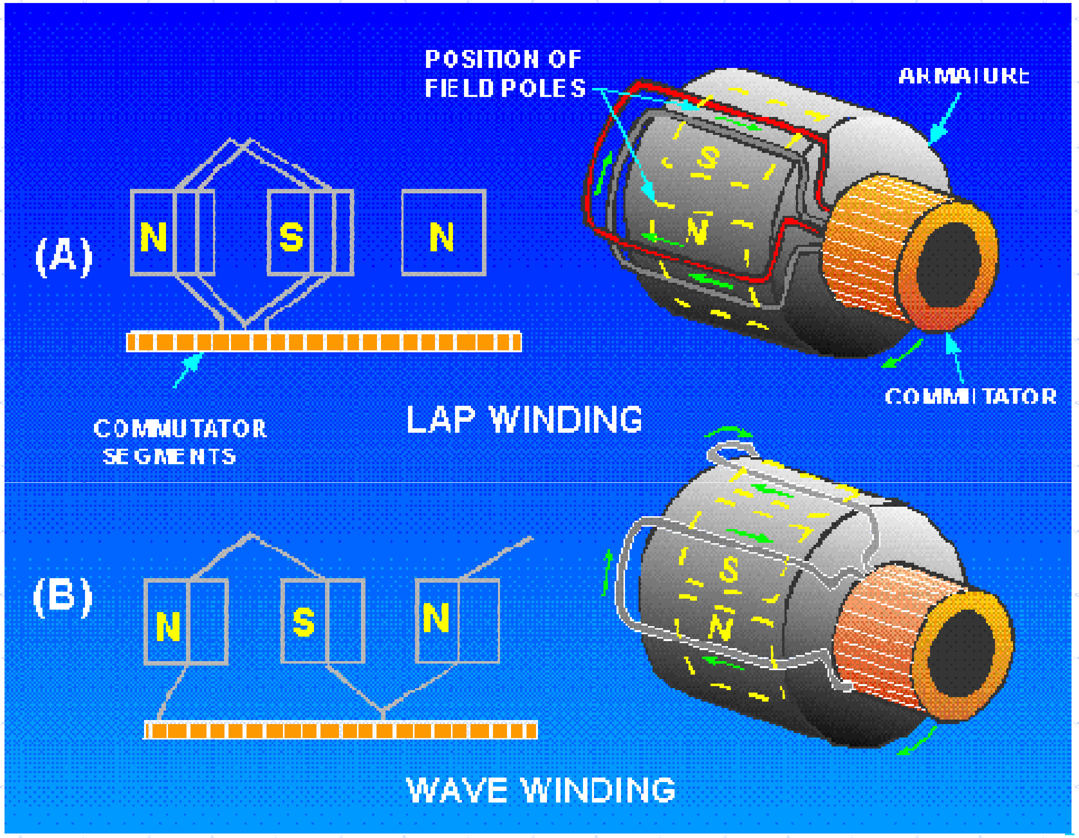
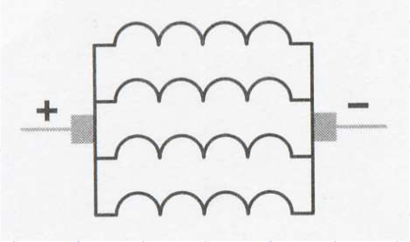


- If Z_a is the **number of conductors arranged in c parallel paths between brushes (+,-),** then $Z_s = Z_a/c$ **per path.**

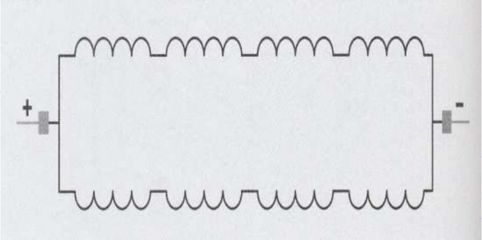
for 2 poles with Z_s conductors in series.

ARMATURE WINDINGS





Lap wound armatures

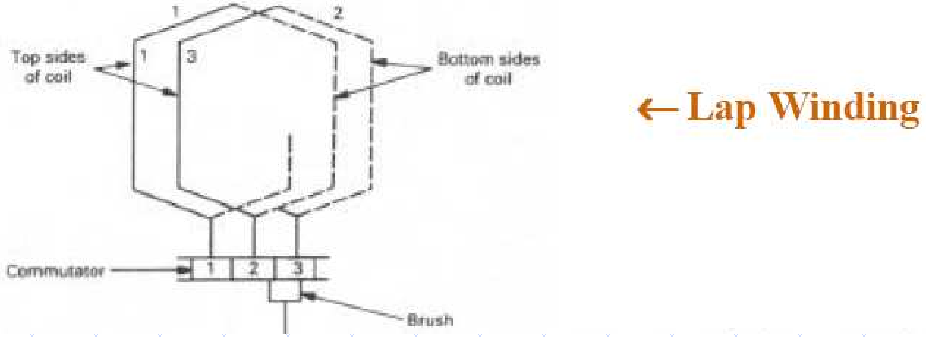


Wave wound armatures

for 2 poles with Z_s conductors in series.

Lap Wound Armatures:

are used in machines designed for low voltage and high current.

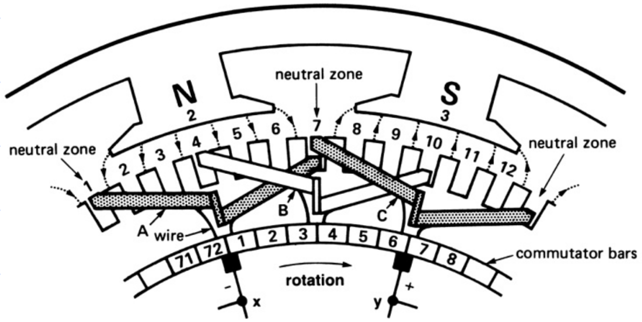


← Lap Winding

Fig.5-7a :**2 ends of a coil** are connected to adjacent segmants

- The armatures are constructed with large wire because of high current
  - Eg: are used is in the starter motor of almost all automobiles.
  - The windings of a lap wound armature are connected in parallel. This permits the current capacity of each winding to be added and provides a higher operating current.
  - No of current path, **c=2p** ; p=no of poles.

← Lap winding (single bar)

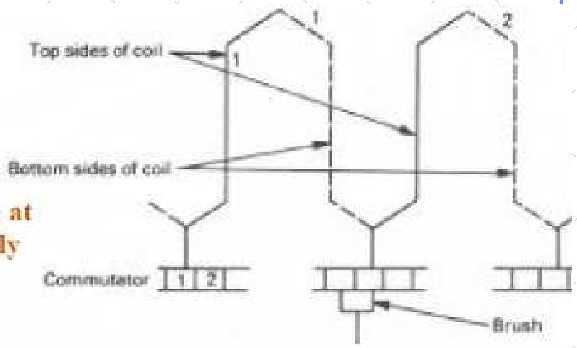


Close-up view of the armature coils between adjacent brushes.

Wave Wound Armatures:

are used in machines designed for high voltage and low current

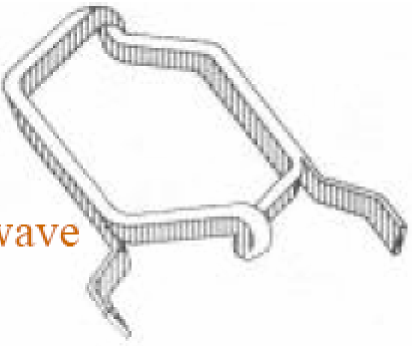
- Their windings are connected in series.
- When the windings are connected in series, the voltage of each winding adds, but the current capacity remains the same.
- They are used is in the small generator in hand-cranked megohmmeters.
- No of current path, **c=2**



Wave Winding →

Odd- and even-numbered conductors are at the top and bottom of the slots respectively

Fig.5-7b :**2 ends of a coil** are connected to adjacent segmants



Multi-turn wave winding →

- **Frogleg Wound Armatures :** are the most used in practical nowadays.
  - Are designed for use with moderate current and moderate armatures voltage
  - The windings are connected in series parallel.
  - Most large DC machines use frogleg wound armatures.

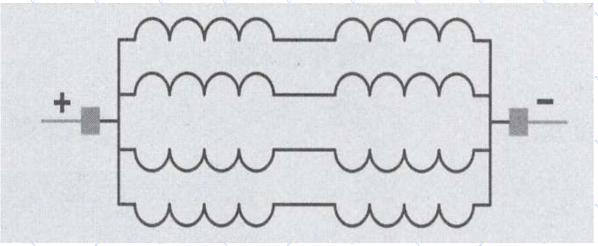


Fig.5-7C : Frogleg wound armatures

Equation of the Voltage and Torque produced:

- **E.m.f. induced i.e. armature voltage E_a** is given by**:**

$$\boxed{E_a = \frac{2pZ}{c_a} n \phi_p \triangleq k_g \phi_p \omega_m}$$: is called generated voltage equation

where k_g : is called generator constant for a dc machine and is solely a function of the design of the machine – specifically, the number of poles and the type of winging.

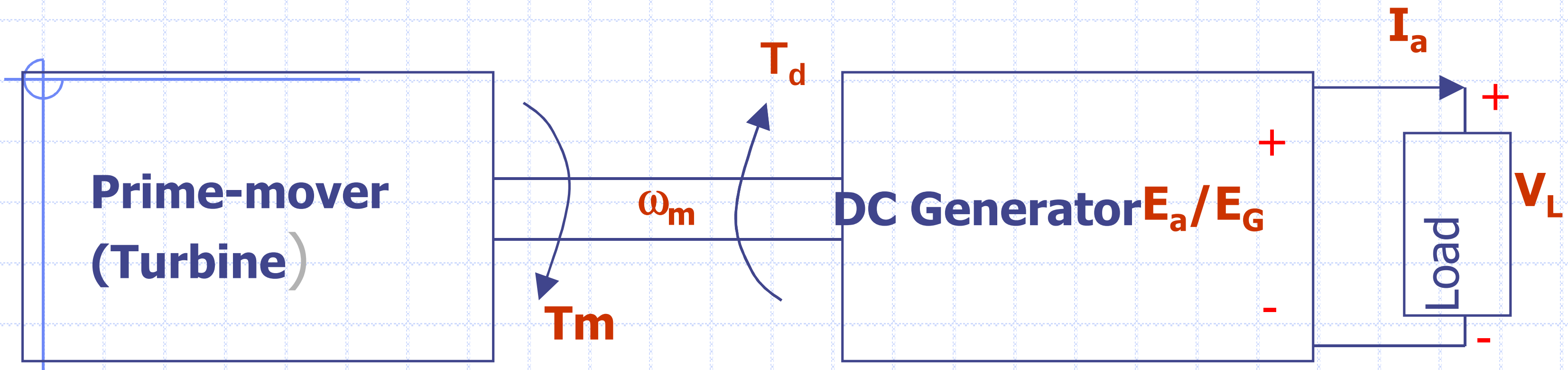
- **Developed electromagnetic torque/armature torque T_d** is given by**:**

$$T_d = \frac{2_a\, n_a}{\pi} = \frac{2\,'_a\, nc}{\pi} .n\, \phi_p .I_a ;$$

$$\Rightarrow \boxed{T_d = \frac{pZ}{\pi c_a} . \phi . I_a \triangleq k_g \phi_p .}$$

CONFIGURATIONS AND EQUIVALENT CIRCUIT D.C. MACHINES.

Interaction of Prime-mover DC Generator and Load

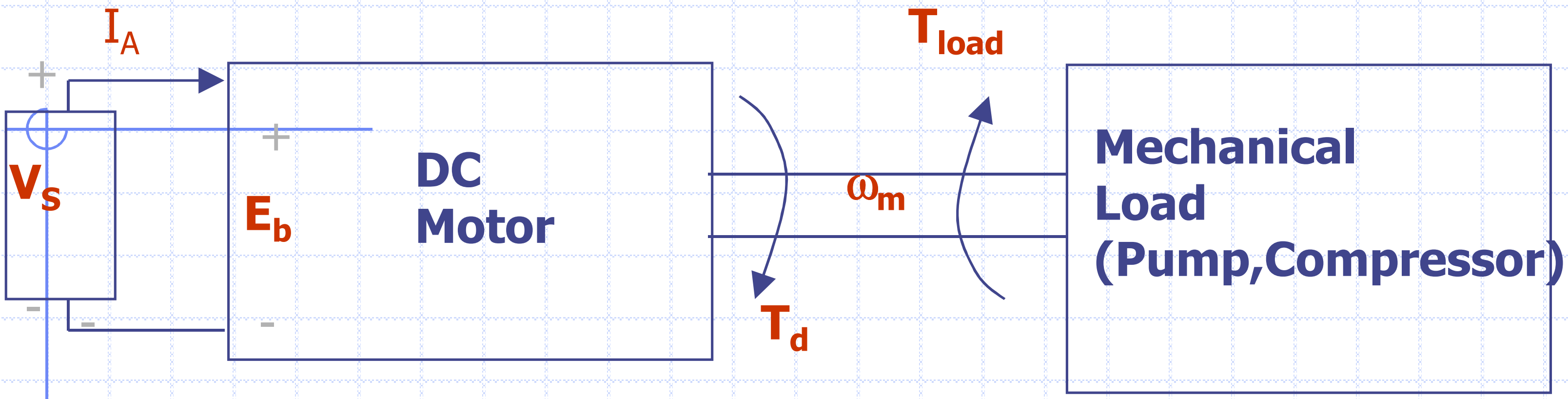


- E_a/E_G is Generated voltage;
- V_L/V_t is Load voltage/terminal voltage ;
- T_m is the Torque generated by Prime Mover;
- T_d is the opposing generator torque.

$$E_a = \frac{2pZ}{a\,c}\, n\, \phi_p = \underbrace{2p\,\phi_p}_{\text{total magnetic flux}} \cdot \frac{Z}{a\,c}\, n;$$ E.m.f/armature voltage.

configutation of a **dc generator**.

Interaction of the DC Motor and Mechanical Load



- E_b is Back EMF;
- V_S/V_t is Applied voltage/supply voltage;
- T_d is the Torque developed by DC Motor;
- T_{load} is the opposing load torque

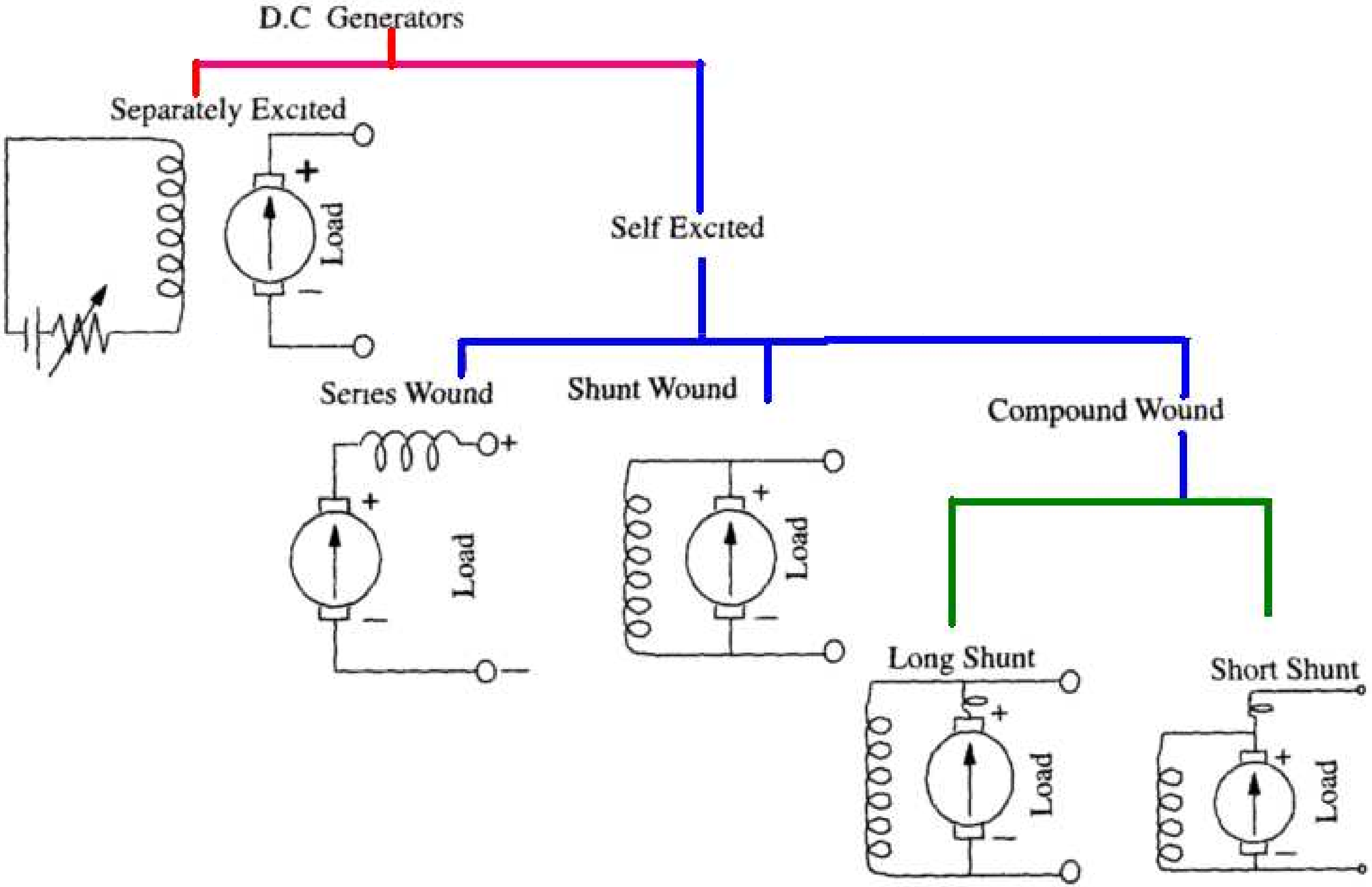
$$E_{ind} = E_b = \frac{2pZ}{c}{}_a \, n \, \phi^p = 2p \, \phi^p \, . \, \frac{Z}{c}{}_a \, n;$$ back E…..

total ~~magnetic~~ flux

configuration of a **d.c. motor**.

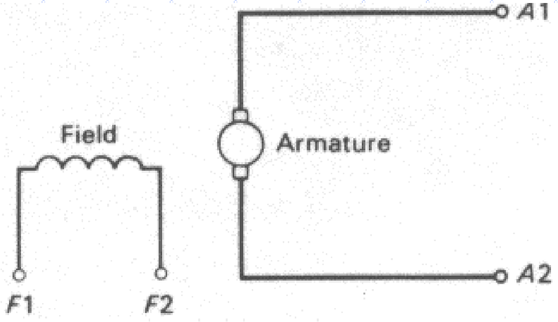
Types DC Generators

Generators are usually classified according to the way in which their fields are excited. Generators may be divided into (*a*) separately-excited generators and (*b*) self-excited generators.



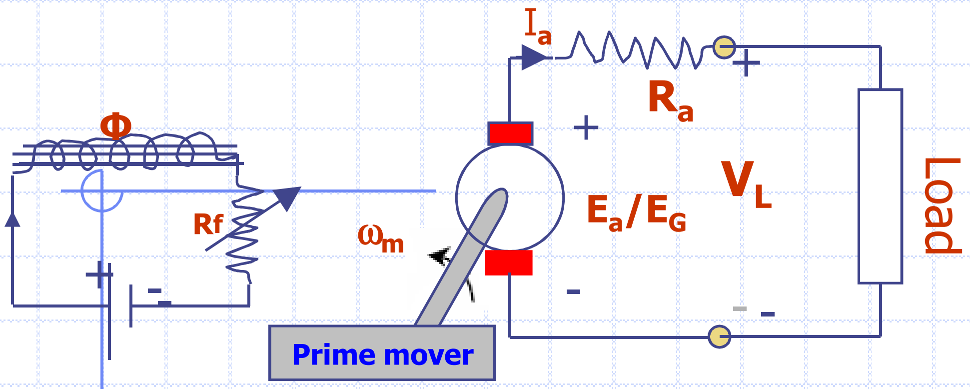
Conventional separately excited DC Generator

- Stator and rotor windings excited by dc current
- The rotor has the commutator
- Dc voltage to the armature windings is supplied through the brushes which establish electric contact with the commutator
- The brushes are fixed with respect to the stator and they are placed in the specified angular displacement
- To maximize the electromagnetic torque, the stator and rotor magnetic axes are displaced by 90 electrical degrees using a commutator

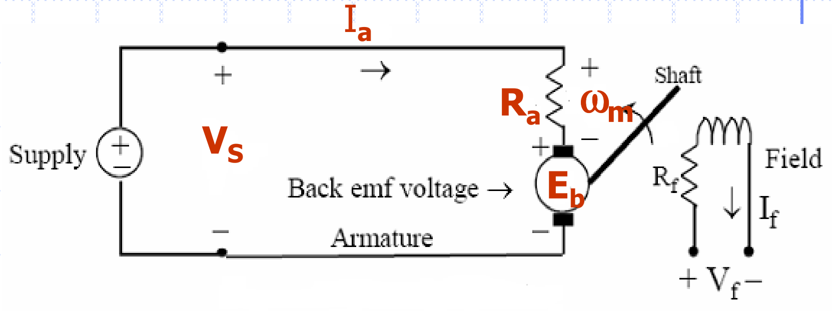


Separately excited (armature & field *separated*)

Equivalent Circuits: E_{indA} vs **Terminal voltage/Supply** voltage



(a) dc generator



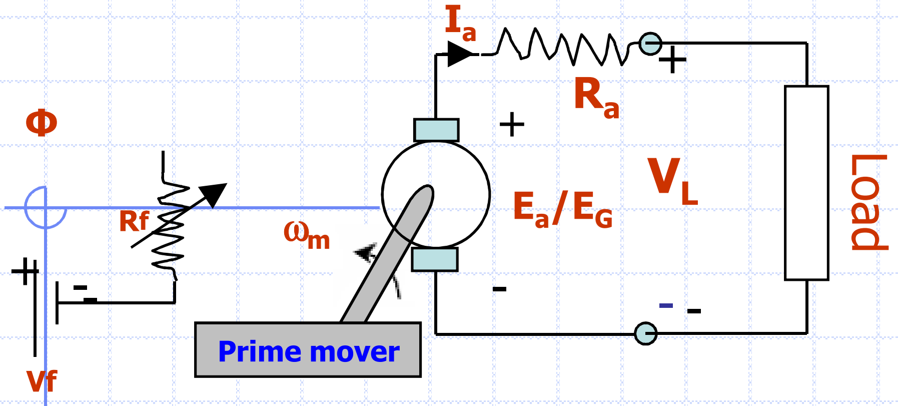
(b) dc mMotor

- By **K.V.L, the relations are asfollows:**
  - **Generator**: **$V_L=E_a-I_aR_a$; (a)**
  - **Motor: $V_S=E_a+I_aR_a$; (b)**

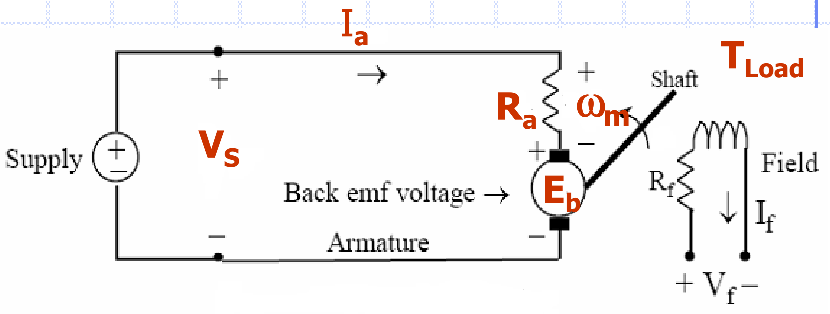
where

I_a : armature current flowing from generator or into the motor;
R_a: armature resistance ;
R_f: variable field resistor;
V_f: applied field voltage=> **$V_f=I_fR_f$**, or **$I_f=V_f/R_f$**

Equivalent Circuits:



(a) dc generator



(b) dc mMotor

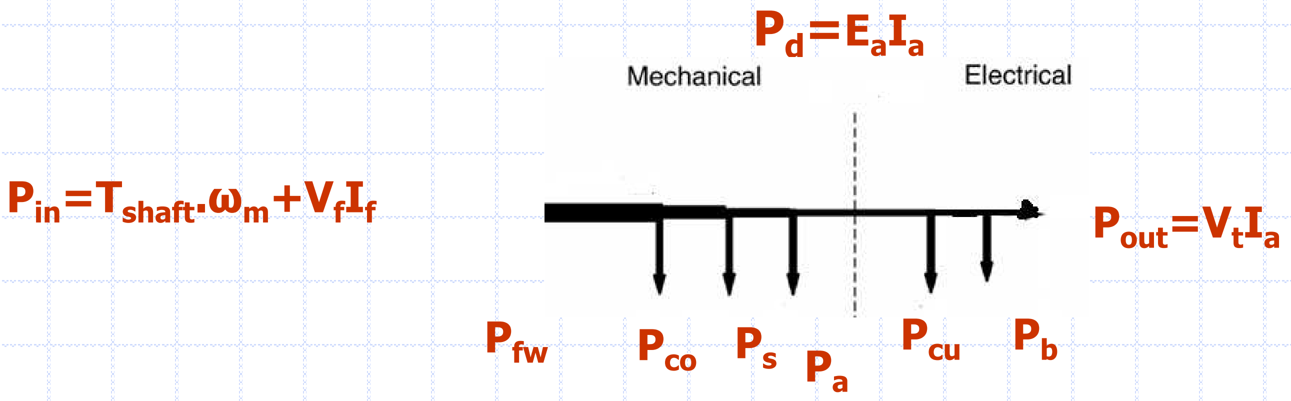
- If the equation(a) and (b)are multiplied by I_a, simple power conversions equations result:
  - **Generator**: $V_L I_a = E_a I_a - I^2_a R_a$;
  - **Motor:** $V_S I_a = E_b I_A + I^2_a R_a$;

  For the **generator/motor,** the **first term** is the **output/input electrical power**, the **second term** is equal to the **input/output mechanical power** ($T_{pm}\omega_m$), and the **third term** reprents **ohmic losses** in the armature winding.

Machine Losses: All forms of dc machines may be regarded as energy convertors. Certain losses are inherent in the machine are common tomboth motors and generators. These are:

- **Rotor losses/Magnetic circuit iron losses** (**P_{co}**) due to hysteresis and eddy currents. These are vary with the field the flux and the speed of the rotor;
- **Rotor coper losses** in the armature (**$P_a=R_aI^2_a$**) and field coper losses (**$P_f=R_fI^2f=V_fI_f$**) due to the coil/wire resistance;
- **Friction and windage losses** (**P_{fw}**) due to the bearings and the setting up of air currents in the machine. These are also called **mechanical /rotational losses.** In most generators, cooling fans are attached to the rotor to circulate air through the generator, thus promoting cooling and allowing the generator to be operated at higher output currents.These cooling fins increase the windage loss.
- **Brush losses** (**P_b**); : There is power loss in the brush-commutator interface. This loss is proportional to the rotor current and brush drop and is V_bI_a. contact resistance losses at the commutator
- **Stray losses** (**P_s**): by convention, stray-load losses are considered to be 1% of the rated output for dc machines.

Power flow diagrams Generator



separatetely excited generator.

- **Generator:**

( )

=mechanical power $\underbrace{T_d\omega_m}$ =electrical power E_aI_a

~~mechanical losses:~~ windage, friction

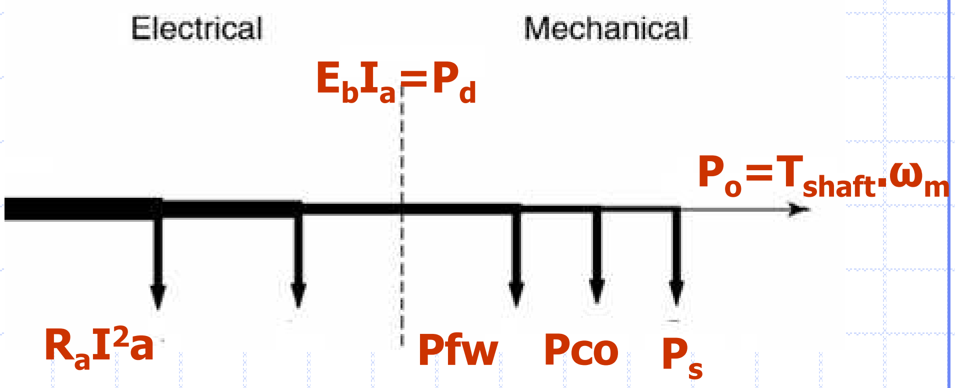
where the input mechanical power to the dc generator:

$$P_d = T_d\omega_m = k_m\phi_pI_a\omega_m = E_aI_a \equiv \underbrace{P_{out}}_{\text{electric power to the load}=V_TI_a\text{(or }V_LI_L)} + \underbrace{P_{cu}}_{\text{electrical losses: }I_a^2R_a+I_f^2R_f} + \underbrace{P_{co}}_{\text{magne... } P_h+P_e};$$

$$\Rightarrow \boxed{\text{Efficiency} = \frac{\text{Electrical } P_{output} \text{ delivered to the load}}{\text{Mechanical } P_{input} \text{ applied to the shaft}}}$$

Power flow diagrams in Motor

$P_{in}=V_tI_a+V_fI_f$



separately excited motor.

- **Motor:**

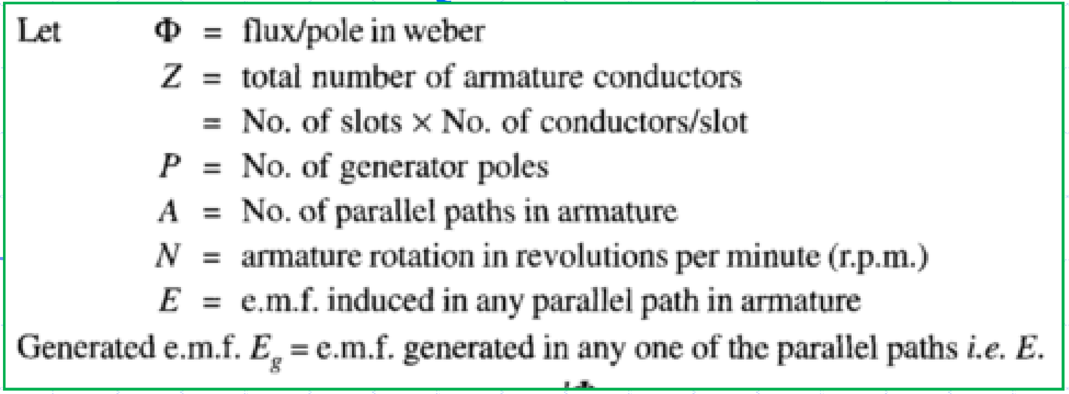
$$\boxed{P_{in\,(electric)} = V_s I_a \ (\text{or } I_{line}) + V_f I_f = E_b I_a + R_a I_a^2 + V_f I_f \equiv P_d + P_{cu} + P_{co}}$$

where

$$P_d = E_b I_a = T_d \omega_m \equiv \underbrace{P_{out}}_{\substack{\text{mechanical load}\\ = T_L \omega_m}} + \underbrace{P_{rotional}}_{\substack{\text{mechanical losses due to :}\\ \text{windages, bearing friction}}}$$: is called the developed power of the machine; it represents the portion of input that isconverted to mechanical power.

$$\Rightarrow \boxed{\text{Efficiency : } \eta = \frac{\text{Mechanical } P_{output}}{\text{Electrical } P_{input}} \equiv \frac{\text{Input - Losses}}{\text{Input}} = \frac{\text{output}}{\text{Output + Losses}}}$$

GENERALISED EMF EQUATION OF ALL DC GENERATOR



Let Φ = flux/pole in weber

Z = total number of armature conductors

= No. of slots × No. of conductors/slot

P = No. of generator poles

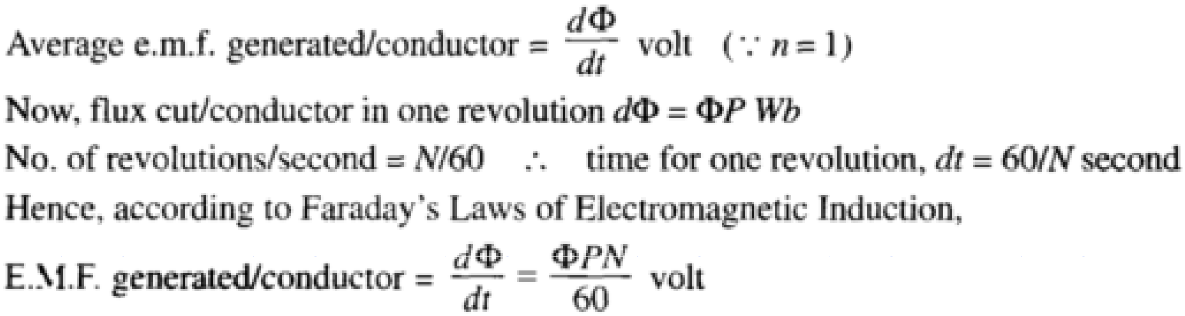
A = No. of parallel paths in armature

N = armature rotation in revolutions per minute (r.p.m.)

E = e.m.f. induced in any parallel path in armature

Generated e.m.f. E_g = e.m.f. generated in any one of the parallel paths *i.e.* E.

Therefore



Average e.m.f. generated/conductor $= \dfrac{d\Phi}{dt}$ volt $(\because n = 1)$

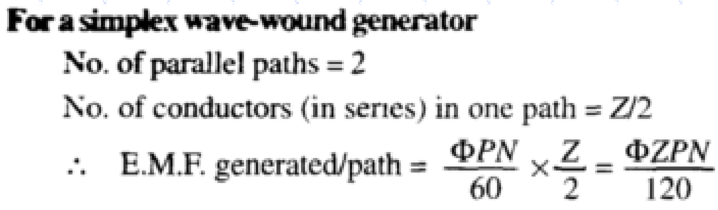
Now, flux cut/conductor in one revolution $d\Phi = \Phi P\ Wb$

No. of revolutions/second = $N/60$ $\quad\therefore\quad$ time for one revolution, $dt = 60/N$ second

Hence, according to Faraday's Laws of Electromagnetic Induction,

E.M.F. generated/conductor $= \dfrac{d\Phi}{dt} = \dfrac{\Phi PN}{60}$ volt

1.



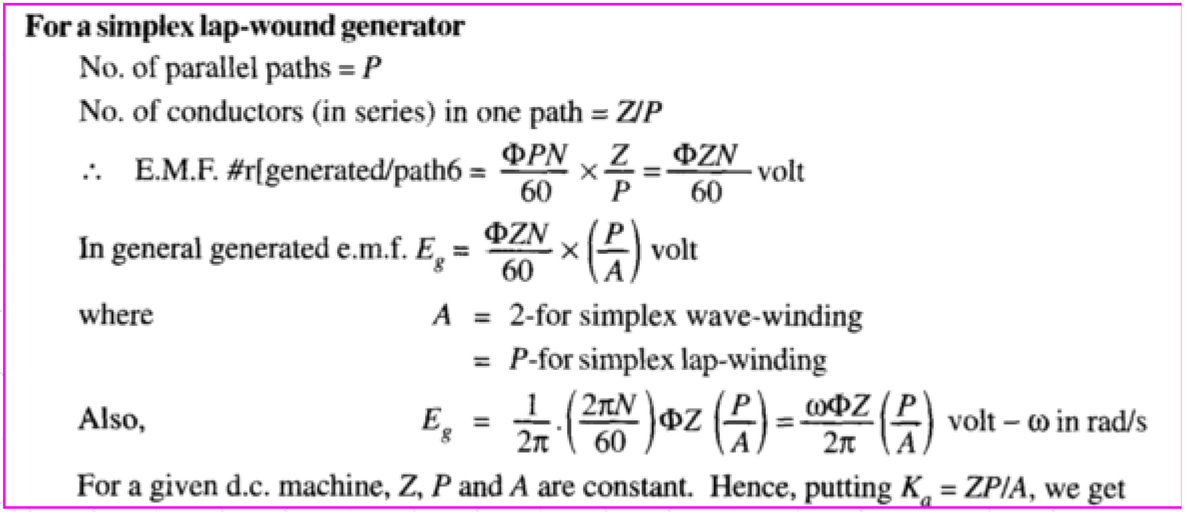
For a simplex wave-wound generator

No. of parallel paths = 2

No. of conductors (in series) in one path = $Z/2$

$\therefore$ E.M.F. generated/path $= \dfrac{\Phi PN}{60} \times \dfrac{Z}{2} = \dfrac{\Phi ZPN}{120}$

2.



For a simplex lap-wound generator

No. of parallel paths = P

No. of conductors (in series) in one path = Z/P

$\therefore$ E.M.F. #r[generated/path6 $= \dfrac{\Phi PN}{60} \times \dfrac{Z}{P} = \dfrac{\Phi ZN}{60}$ volt

In general generated e.m.f. $E_g = \dfrac{\Phi ZN}{60} \times \left(\dfrac{P}{A}\right)$ volt

where A = 2-for simplex wave-winding

= P-for simplex lap-winding

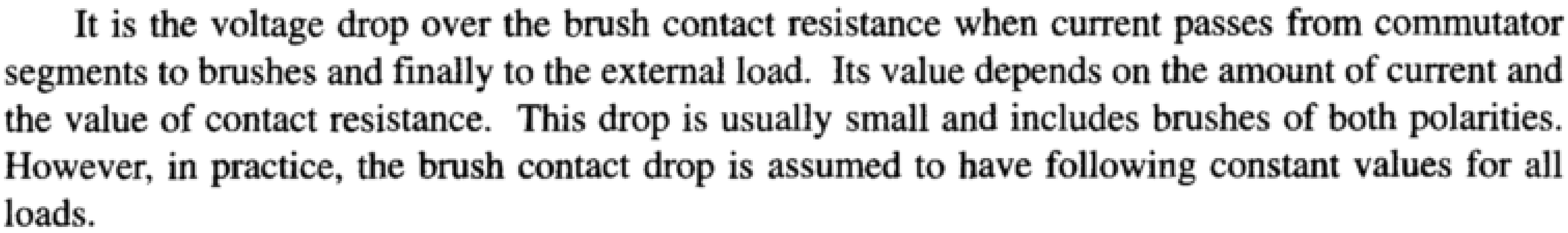
Also, $E_g = \dfrac{1}{2\pi} \cdot \left(\dfrac{2\pi N}{60}\right) \Phi Z \left(\dfrac{P}{A}\right) = \dfrac{\omega \Phi Z}{2\pi}\left(\dfrac{P}{A}\right)$ volt – ω in rad/s

For a given d.c. machine, Z, P and A are constant. Hence, putting $K_a = ZP/A$, we get

Final EMF in r.p.s

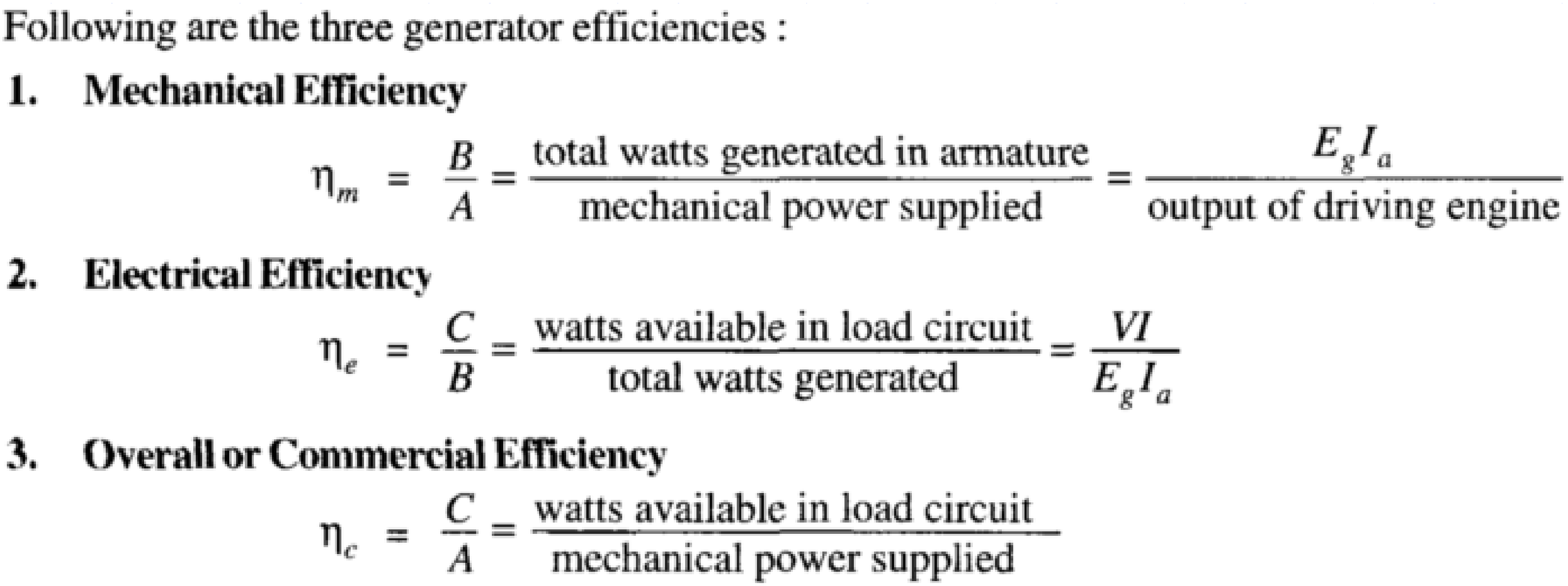
$E_g = K_a \Phi N$ volts—where N is in r.p.s.

Brush contact Voltage drop



It is the voltage drop over the brush contact resistance when current passes from commutator segments to brushes and finally to the external load. Its value depends on the amount of current and the value of contact resistance. This drop is usually small and includes brushes of both polarities. However, in practice, the brush contact drop is assumed to have following constant values for all loads.

0.5 V for metal-graphite brushes.
2.0 V for carbon brushes.



Following are the three generator efficiencies :

1. Mechanical Efficiency

$$\eta_m = \frac{B}{A} = \frac{\text{total watts generated in armature}}{\text{mechanical power supplied}} = \frac{E_g I_a}{\text{output of driving engine}}$$

2. Electrical Efficiency

$$\eta_e = \frac{C}{B} = \frac{\text{watts available in load circuit}}{\text{total watts generated}} = \frac{VI}{E_g I_a}$$

3. Overall or Commercial Efficiency

$$\eta_c = \frac{C}{A} = \frac{\text{watts available in load circuit}}{\text{mechanical power supplied}}$$

Examples 1. of self excited generator

A separately excited generator running at 1000 r.p.m supplied 200A at 125V. What will be the load current when the speed drops to 800 r.p.m if *If* is unchanged? Given that the armature resistance = 0.04 ohm and brush drop=2 V

Given: N_1=1000rpm

N_2=800rpm

I=100A

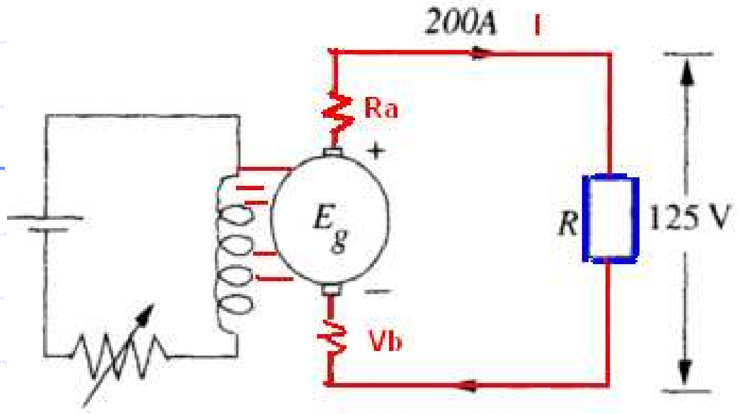
V=125V

Vb=2V

Ra=0.04ohm

SOLUTION

Examples 1. of self excited generator contd….



The load resistance R= 125/200 = 0.625 ohm

$E_{g1} = V + IRa + Vb$

$E_{g1} = 125 + 200x\ 0.04 + 2 = 135V$ at N1=1000rpm

therefore

At 800rpm $E_{g2} = 135 \times 800/1000 = 108V$

If *I* is the new load current, then terminal voltage V is given by;

$$V = 108 - 0.04\,I - 2 = 106 - 0.04\,I$$

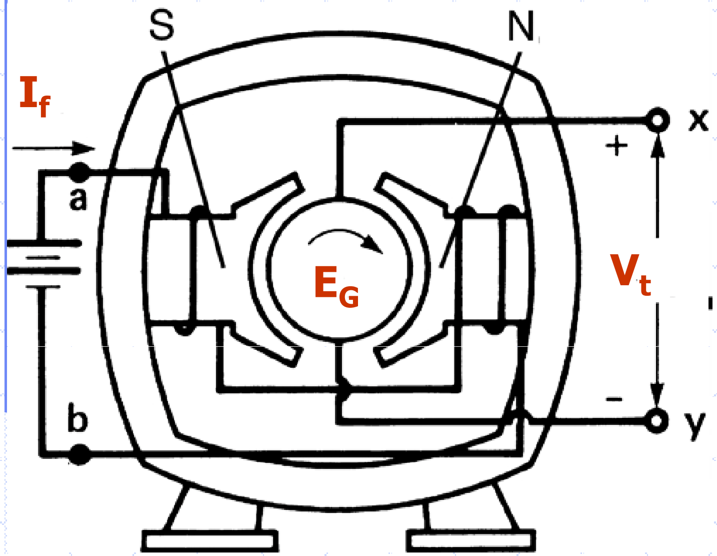
$V = 108 - 0.04I - 2 = (106 - 0.04I)V$

therefore $I = V/R = (106 - 0.04I)/0.625$

$I = (0.625-106)/ -0.04 = 159.4A$

SEPARATELY EXCITED GENARATOR CHARATERISTICS

- These are generators whose field magnets are energized from an independent external source of direct current(**Fig.4-18**). The excitation voltage $V_f \rightarrow I_f \rightarrow \Phi \Rightarrow E_{ind}/E_G$;



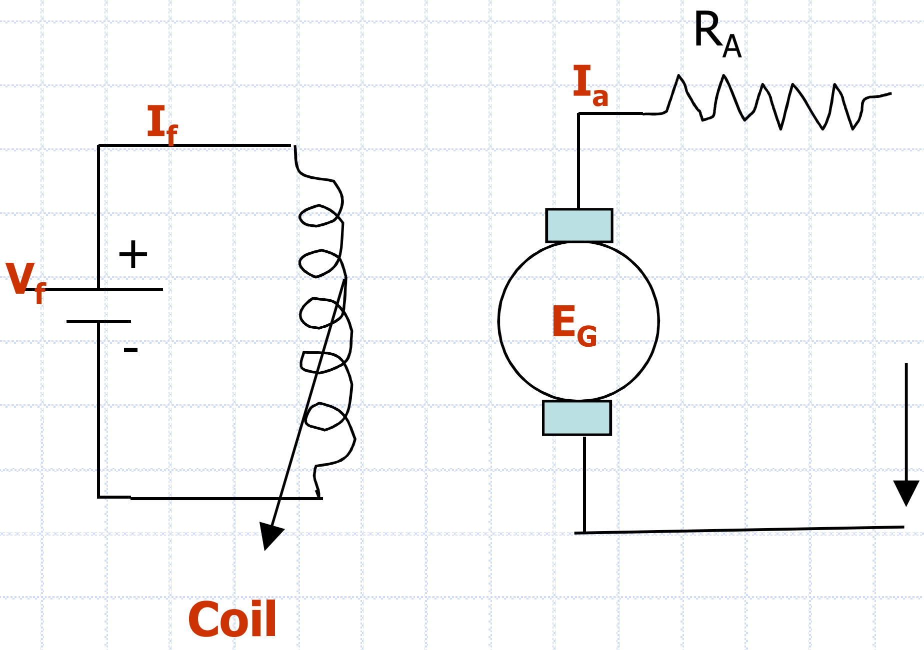
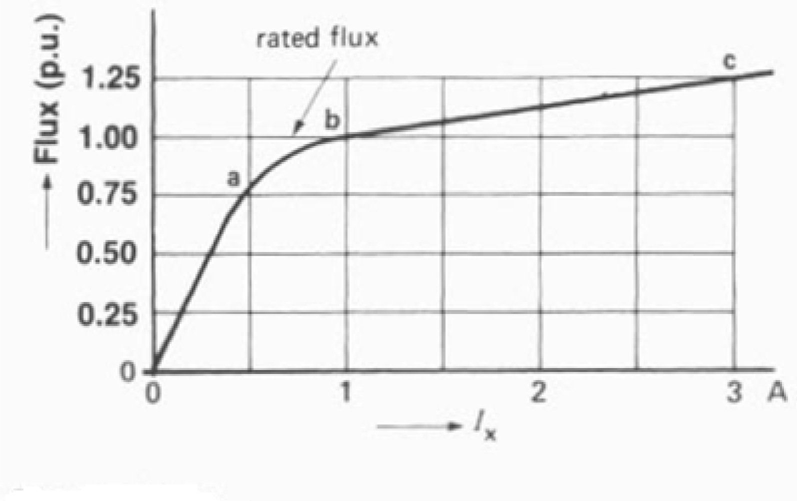


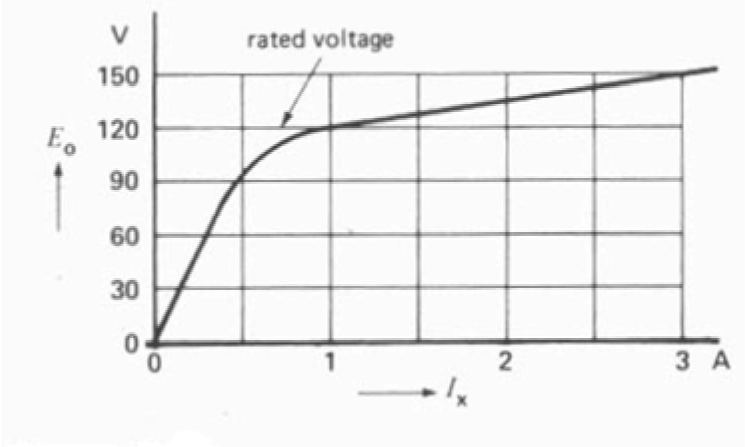
Fig.5-18.

- **Open circuit characteristic/internal characteristic (i.e. on no load):**
  - $\omega_m=\omega_m$**(rated)** ; $I_a=0 \Rightarrow V_L=E_G$; and
  - V_L/V_t **is proportional to** I_f (see magnetizing curve for saturation)

- **Open circuit/Int.characteristic-Cntd:** $V_L = E_G = \frac{\;p\;}{c} n\phi \Rightarrow {}_L \;(\;\phi)$
  -



Flux per pole versus exciting current.



Saturation curve of a dc generator.

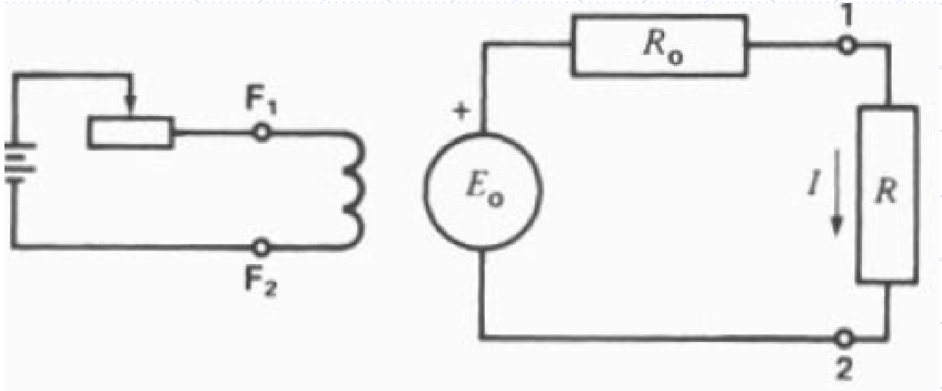
separatetely excited generator.

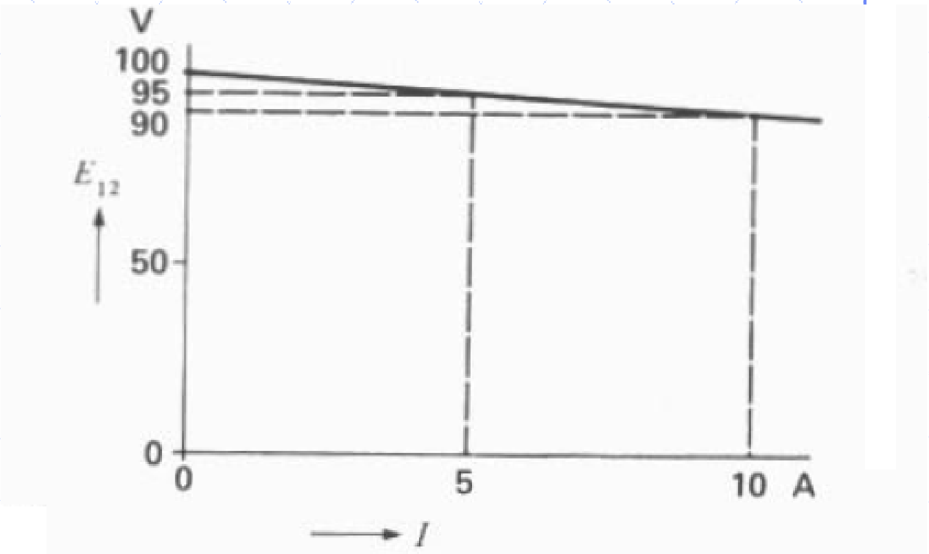
- **On load/External characteristic : I_a (or I_L) ≠ 0:**
  - **$\omega_m = \omega_m$(rated) and $\omega_m = \omega_m$(rated);**
  - **V_L is proportional to I_a(i.e. I_L);**

$V_L = E_G - R_a I_a = \frac{2pZ}{c} n\phi - R_a I_a = k_g n\phi - R_a I_a$; if n and φ are constant, then

$V_L = k_g n\phi - R_a I_a \approx A - B.I_a = f(I_a)$, that is a straight line.

On load/External characteristic contd…





Load characteristic of a separately excited generator.

I_{Lrated} & V_{Lrated} **:** are **full load values** where the dc machine operates effeciently;

Q: the intersection of the load line voltage with the generator output characterstic called **operating point**.

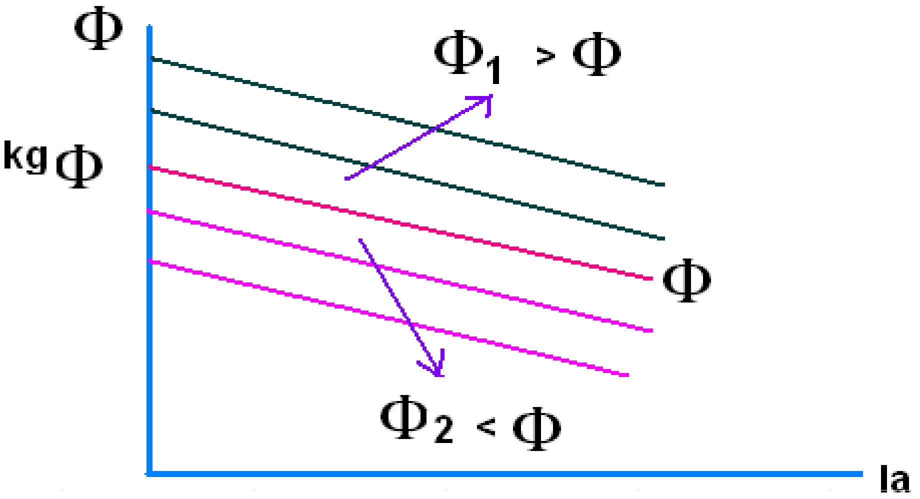
In normal design dc machine, I_aR_a is kept **small.**

- If **n** is kept constant, a set of curves **V_L** vs **I_a** is produced **by varying** **I_f** (=> **Φ**) i.e. by varying **R_f**.

$\frac{2pZ}{c}$ $_L$ $_G$ $_{a\,a}$ ϕ $_g\,\phi$

if n and ϕ are constant, then $V_L = k_g n \phi - R_a I_a \approx A - B.I_a = f(I_a)$,

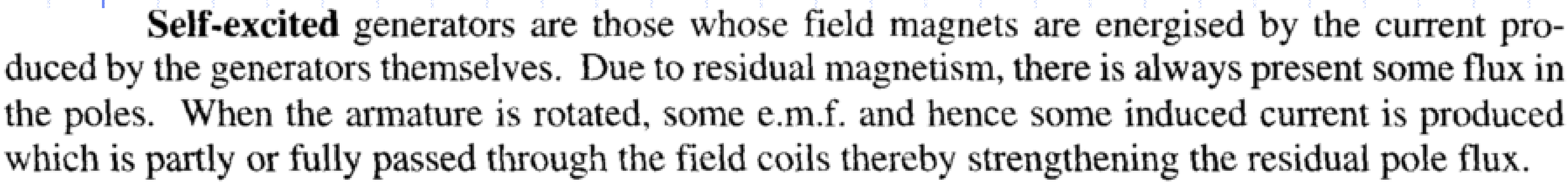
that is a straight line.



- **Open load/Ext.characteristic-voltage regulation:**

$$\frac{V_{T\,No\text{-}load.} - V_{T\,Full\,load.}}{V_{T\,Full\,load.}} \times 100\% = \frac{I_{a\,Full\,load.}R_a}{E_G - I_{a\,Full\,load.}R_a} \times 100\% = \frac{100\%}{\frac{E_G}{I_{a\,Full\,load}R_a}}.$$

SELF EXCITED DC MACHINES



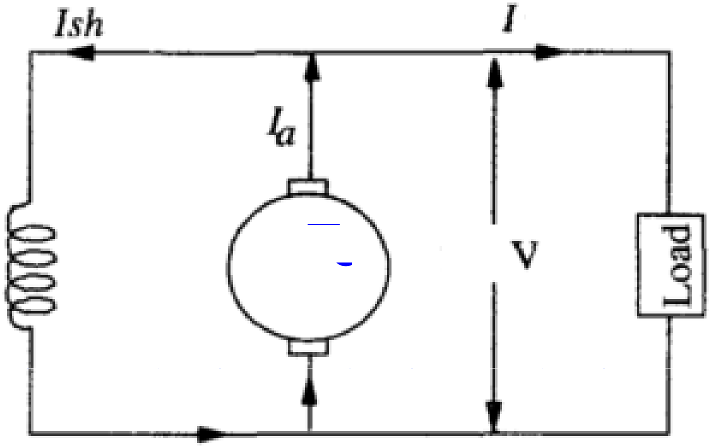
Self-excited generators are those whose field magnets are energised by the current produced by the generators themselves. Due to residual magnetism, there is always present some flux in the poles. When the armature is rotated, some e.m.f. and hence some induced current is produced which is partly or fully passed through the field coils thereby strengthening the residual pole flux.

- **Field coil excitation**
  - sometimes the field coils are connected in **series** with the armature, sometimes in parallel (**shunt**) and sometimes a combination of the two (**compound**)
  - these different forms produce slightly different characteristics
  - diagram here shows a **shunt-wound generator**

SHUNT EXCITED DC GENARATOR:

Shunt generator is said **self-excited** because the **field winding is connected if parallel with** the genarator terminal (and the load).

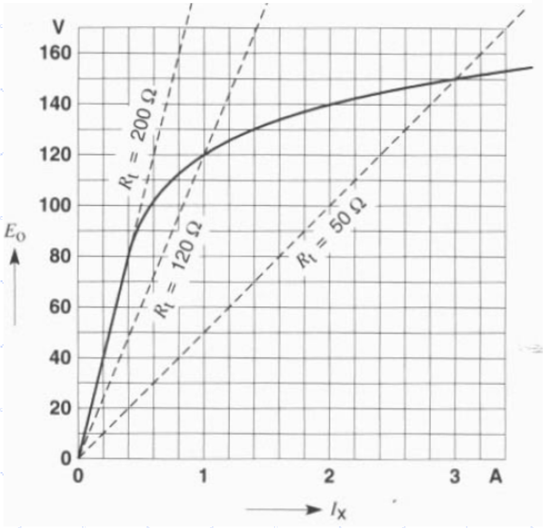
$\mathbf{I_{field}}$ depends on the armature windinq.



a sh L ,

[illegible]

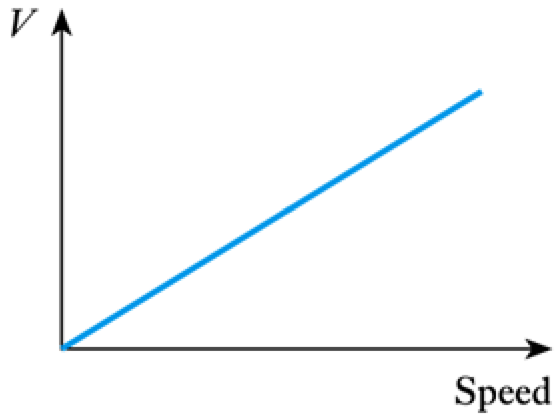
- **On no load: I_L=0**



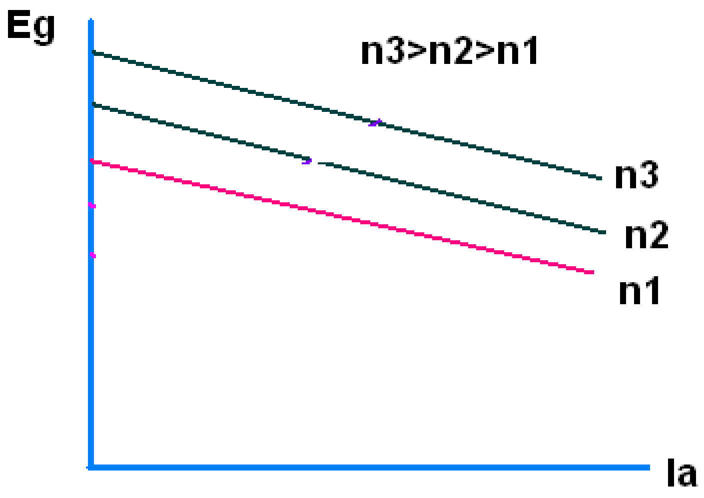
The no-load voltage depends upon the resistance of the shunt-field circuit.

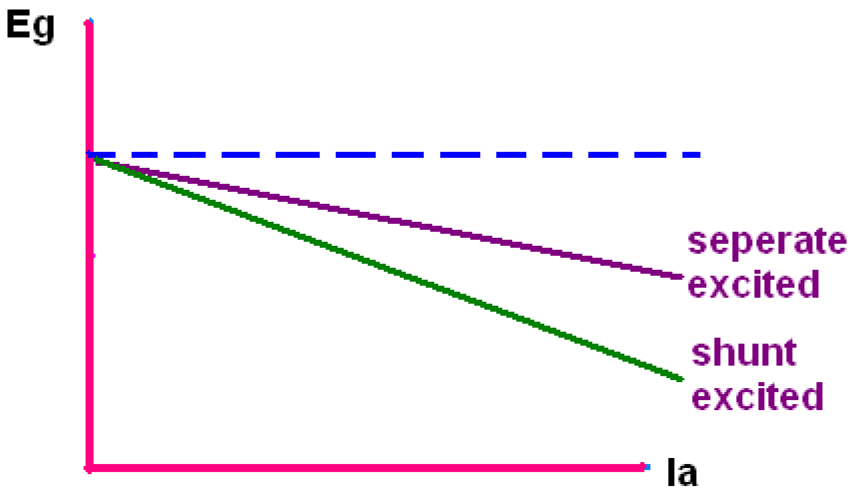
SHUNT EXCITED GENARATOR-Cntd:

Speed can be varied by varying V.



- **On load: R_aI_a voltage drop** in the armature means that V_L is **reduced.** Consequently V_f is also reduced and so E_G is **reduced.**

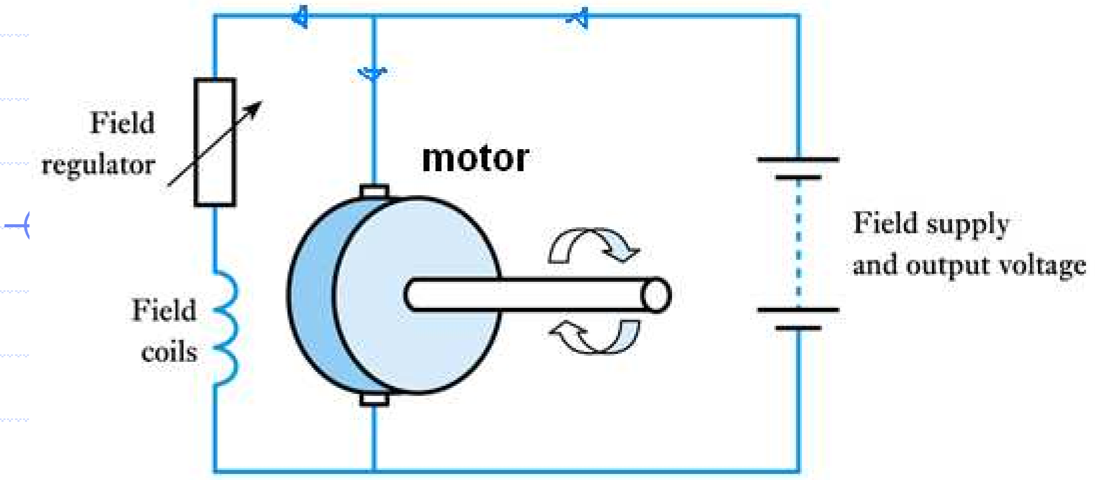


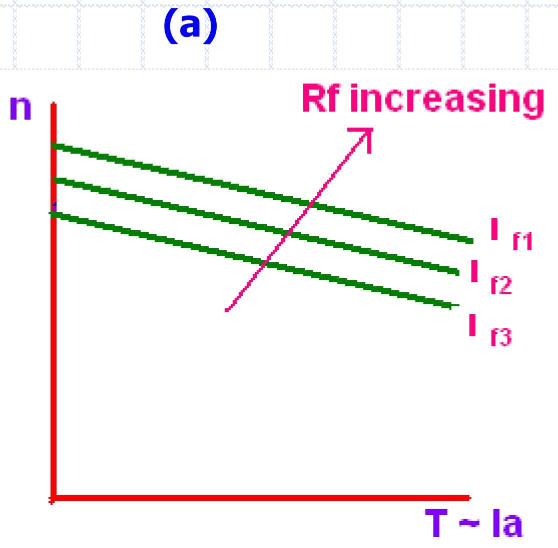


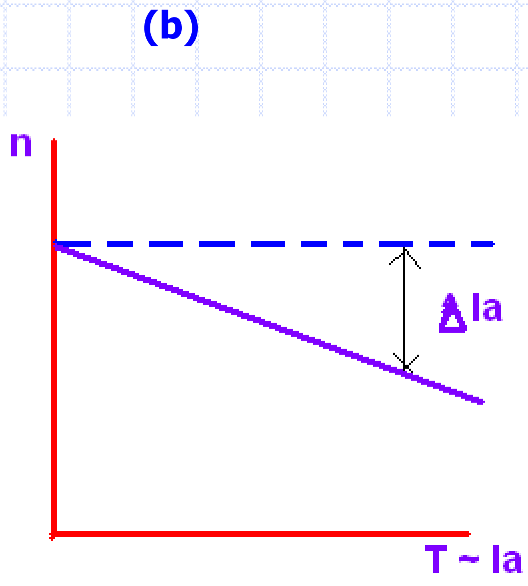
- **Shunt generator (self-excited) build up of V_t conditions:**
  - **Resisual magnetism;** if not present initialise magnetisation using batteris, etc.**;**
  - **Field winding being connected correctely** to armature winding such that the generated flux aids the residual magnetism ; if not swap the terminals**;**
  - **The slope (R_{ext}+R_f) must be smaller than that of air gap line ;** otherwise **reduce Rext.**

- **Reasons for failure of the voltage to build up:**
  - **No-residual voltage E_r;**
  - **Direction of rotational reversed;**
  - **Polarity of connection between** armature and field reversed**;**
  - **(R_{ext}+R_f)** is **too high.**

D.C. SHUNT EXCITED MOTOR.







- If **R_F** is constant, then **Φ** is constant and

$$\propto \;\Rightarrow\; = \frac{2pZ}{c}.n\,\phi = k_b\,.n\,\phi$$

$$T \propto I_a \;; \;\Rightarrow\; T = \frac{2pZ}{2\pi nc}.\phi I_a = k_t\,.\phi I_a$$

$$\Rightarrow V_s = \frac{2pZ}{c}.n\phi + R_a I_a$$

$$\Rightarrow \left\| \; n = \frac{V_s}{k_b\phi} - \frac{R_a I_a}{k_b\phi} \equiv A_1 - B_1 I_a \left(\text{or } A_1 - \_\,_2\,. \right) \right.$$

- **n** can be varied by varying **R_F** i.e. **I_F or Φ.**

Starting of a dc shunt motor:

$$\Rightarrow \| \quad n = \frac{}{b\phi} - \frac{}{b\phi}$$

- At start up **n=**o; and we know that in design the R_a is very small

$$\Rightarrow I_A = \frac{{}_s}{R_a}$$

which is **very dangerous** !!

- To start an **external resistance in series with** the armature is provided to limit the current(use of a start or rheostat).
- For example if the motor data are:

$${}_s \quad \_\_\_;$$

$R_a = 0.2$; and

$I_{L\,at\,full\,load} = 20\ A;$

At $n = 0: \left(R_a + R_{ext}\right) I_a = 220V; \Rightarrow \left(R_A + R_{ext}\right) = \frac{220}{20} = 11\Omega$

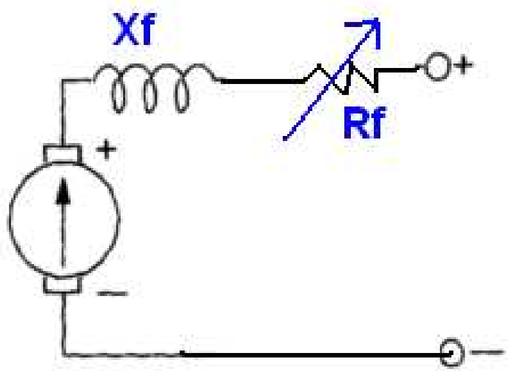
$\Rightarrow R_{ext} = 11 - R_A = 11 - 0.2 = 10.8\,\Omega;$

If R_{ext} was zero: $\Rightarrow V_s = R_a I_a$

$\Rightarrow I_a = \frac{220}{0.2} = 1100\ A \gg 0$

which is to high for R_a(that will be burnt)

SERIES D.C. MOTOR.



$\phi \propto I_F = I_a$; and

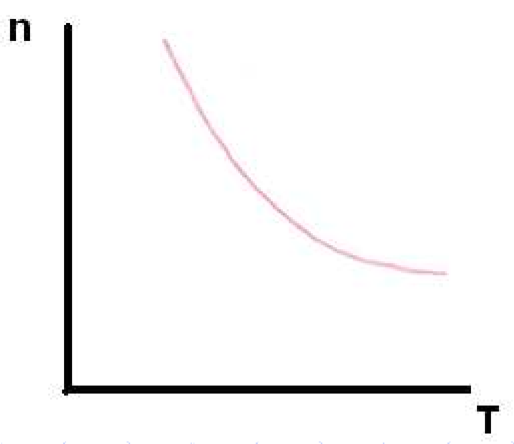
$$V_s = E_b + (R_a + R_F) I_a = \underbrace{\frac{2pZ}{c}}_{k_b} n\phi + (R_a + R_F) I_a; \Rightarrow \| n \propto \frac{(\quad)}{\phi}$$

Since $(R_a + R_F)$ is very small in practice

$$V_s = \frac{2pZ}{c} n\phi; \Rightarrow \| \phi = \frac{Vs}{n} . \frac{c}{2pZ} = k_f \frac{1}{n}; \Rightarrow \| n \propto \frac{1}{\phi};$$

$$T = \frac{pZ}{\pi c} . \varphi I_A; \quad \| T = k_b \phi I_a = k_f I_a^2 \left(\propto \phi^2 \right)$$

$$; \quad \| T = k_b \phi^2 = k_b \left(k_f \frac{1}{n} \right) = K \frac{1}{n^2}$$



As $n = \frac{V_s}{k_f \phi} = K' \frac{V_s}{I_a}$; at no load i.e. $I_a = 0$, n becomes **too high,**

i.e., overspeed/runaway.

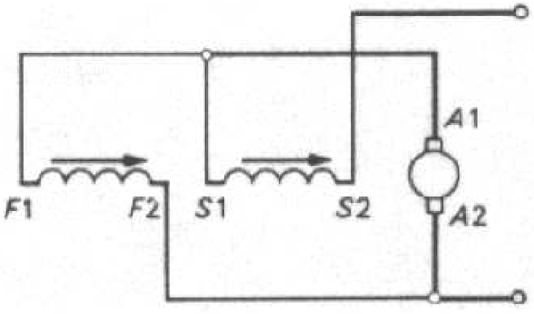
Danger : mechanical parts will fail.

Hence HAVE ALWAYS A LOAD CONNECTED.

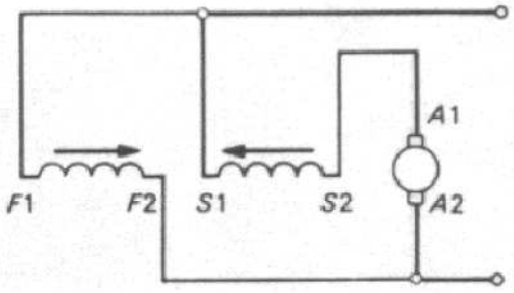
COMPOUND D.C. GENERATORS/ MOTOR.

so that part of the field coils is in series and part in parallel with the armature. This category, which is termed **compounding** may be sub-divided into **cummulative compounding**, in which the series and shunt field coils aid one oanother in the setting up of the main field, and **differential compounding**, in which the series and shunt field coils oppose one another.

Compounded machines may also be connected in either a **short-shunt** or **long shunt mode**.

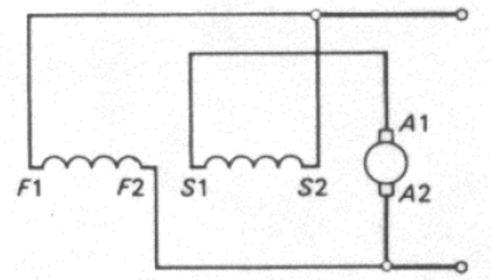


Cumulative compound (field windings aid one-another)

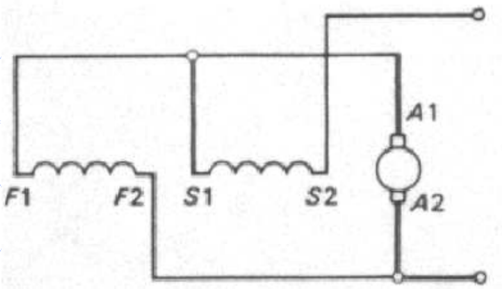


Differential compound (field windings oppose one-another)

Compound DC GERENATOR/ MOTORS Contd….



Long-shunt compound
(armature in series with
series field winding)



Short-shunt compound
(armature in parallel
with shunt field winding)

METHODES OF EXCITATION OF D.C. MACHINES.

- Using a permanent magnet to provide the main field of a dc machine does not provide a controllable field.
Consequently, in all but very small machines field coil are include, wound round the machines pole pieces, and the main field is adjustable by varying the field coil current.

- These field coils may be supplied from from separed source or connected in circuit with the armature winding, leading to to the classifications **separated excited** and **self-excited machines.**
- To be strictly accurate, only generator may be considered self-excited. If the term is applied to motors, which is unusual, it implies that the same source that supplies the motor armature also applies the field coils.
- Self-excited machines may be connected, in the one of the three modes:

1) so that the field coils shunt the armature;

2) so that the field coils are in series with the armature;

Starting of a dc shunt motor:

$$\Rightarrow \| \quad n = \frac{\ }{b\phi} - \frac{\ }{b\phi}$$

- At start up **n=o**; and we know that in design the R_a is very small

$$\Rightarrow I_A = \frac{_s}{R_a}$$

  which is **very dangerous** !!
- To start an **external resistance in series with** the armature is provided to limit the current(use of a start or rheostat).
- For example if the motor data are:

$_s$

$R_a = 0.2$; and

$I_{L\ \text{at full load}} = 20\ A$;

At $n = 0:\ (R_a + R_{ext})\ I_a = 220V;\ \Rightarrow (R_A + R_{ext}) = \frac{220}{20} = 11\Omega$

$\Rightarrow R_{ext} = 11 - R_A = 11 - 0.2 = 10.8\,\Omega;$

If R_{ext} was zero: $\Rightarrow V_s = R_a I_a$

$$I_a = \frac{220}{0.2} = 1100\,A \gg 0$$

which is to high for R_a(that will be burnt)

APPLICATIONS OF DC MACHINES.

- **Generators:** The examination of the previous characteristics figures indicates that:
  - The **series generator** is not suitable for use as a supply generator on its own, although it may be used in conjuction with a substantially constant voltage machine (shunt or compound) **as compensation for** increased voltage drop due to increasing load current.
  - **For a small system** a **compound generator** alone can be used.
  - The **shunt** or **separately excited generator** is the most commonly used machine for local supply systems (within vehicles, etc.), the disadvantage of the latter usually being overcome by mounting a small shunt generator on the same shaft as the large separetely excited machine **to provide the field current**.
- **Motors:** The examinations of the previous characteristics figures indicates that:
  - The **shunt motor** runs **at fairly constant speed over a wide load range**. As such it is the most useful for a number of **low load applications.**

…. APPLICATIONS.

- **Motors-cntd:**

It would **not be suitable for fluctuating loads**, such as, for example, electrically powered vehicles.

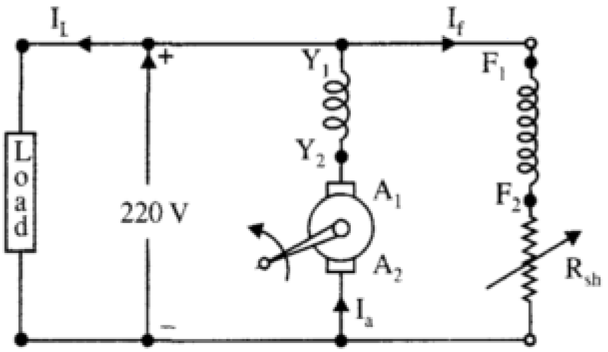
- For this use the **series machine** with the falling speed characteristic is ideal since as the the speed and hence the back e.m.f. falls, the armature current and thus the torque rises.
  A **serie motor** runs **at extremely high speeds on no load** and it is therefore never coupled mechanically to a load in any manner which could result in load disconnection (e.g. belt drives, etc.).
- The **compound motor** which has **a stable no load speed but** retains the series speed curve is a **useful alternative to series machine** in certain applications, e.g. steel milldrive units.

EXAMPLE ON SELF EXCITED DC MACHINE:

A long shunt dynamo running at 1000 rpm supplies 20kW at terminal voltage of 220V. The resistance of armature, shunt field and series field are 0.04,110 and 0,05 ohm respectively. Overall efficiency at the above load is 85% find;

- **(i) copper losses**
- **(ii) Iron and friction losses**
- **(iii) Torque developed by the prime mover**

(i) copper losses



I_L Load current $= \dfrac{20,000}{220} = 90.91$ amp

Shunt field current, $I_f = \dfrac{220}{110} = 2$ amp

Armature current, $I_a = 92.91$ amp

EXAMPLE ON SELF EXCITED DC MACHINE: ContD…..

Input power = 20,000/0.85 = 23529 watts

Total losses in the machine = Input – Output = 23529 – 20,000 = 3529 watts

copper losses Power loss in series field-winding + armature winding = $92.91^2 \times 0.09$ watts = 777 watts

Power-loss in shunt field circuit : $2^2 \times 110 = 440$ watts

Total copper losses = $777 + 400 = 1217$ watts

(*ii*) Iron and friction losses = Total losses – Copper losses

= $3529 - 1217 = 2312$ watts

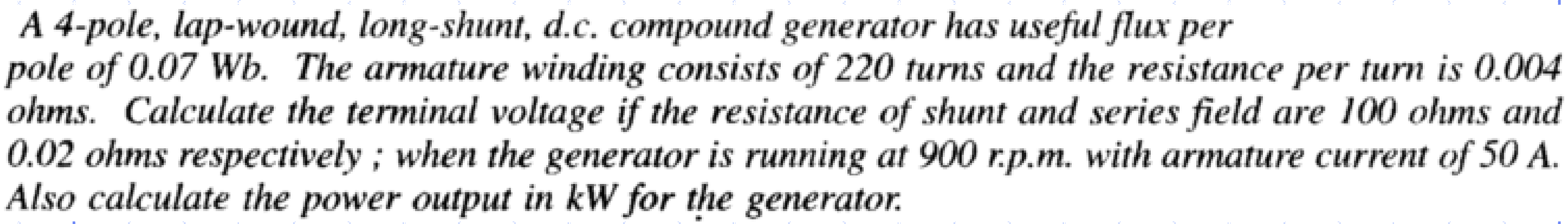
(*iii*) Let T = Torque developed by the prime-mover

At 1000 rpm, angular speed, $\omega = 2\pi \times 1000/60 = 104.67$ rad./sec

$$T \times \omega = \text{Input power}$$

$$\therefore \quad T = 23529/104.67 = 224.8 \text{ Nw-m}$$

ASSIGNEMENT SELF-EXCITED DC MACHINE:



A 4-pole, lap-wound, long-shunt, d.c. compound generator has useful flux per pole of 0.07 Wb. The armature winding consists of 220 turns and the resistance per turn is 0.004 ohms. Calculate the terminal voltage if the resistance of shunt and series field are 100 ohms and 0.02 ohms respectively ; when the generator is running at 900 r.p.m. with armature current of 50 A. Also calculate the power output in kW for the generator.

QUALITATIVE AC MACHINES ONE LECTURE WILL BE TAKEN BY MR. SALASINI .R TO PREPARE YOU FOR NEXT YEAR EE441

THANK YOU BEST WISHES IN YOUR EXAMS