Q.2 a. Define self inductance and Mutual inductance in magnetic circuit. If self inductance of two coils are L_1 and L_2 and mutual inductance is M, then derive the expression for equivalent inductance when flux are additive and subtractive. (8)

Answer:

8.6 INDUCTANCE: SELF AND MUTUAL

Consider a coil (Fig. 8.14) carrying current i which creates a flux ϕ (*self-flux*) linking the N turns of the coil. Then the emf induced in the coil, called the counter emf, is given by

$$e = N\,\frac{d\phi}{dt} \text{ (opposing the current as per Lenz's law)}$$

$$= N\,\frac{d\phi}{di}\,\frac{di}{dt} = L\,\frac{di}{dt} \text{ V} \tag{8.20}$$

where $$L = N\,\frac{d\phi}{dt} = \frac{d\lambda}{dt} \text{ H (henrys)} \tag{8.21}$$

is called the *self-inductance* of the coil. For a nonlinear B–H curve it is an *incremental* value corresponding to incremental changes around an operating point on the curve.

For a linear B–H curve (material operated in the region of constant permeability or with dominating air-gap) L is a constant which can then be expressed as

$$L = \frac{N\phi}{i} = \frac{\lambda}{i} \text{ H} \tag{8.22}$$

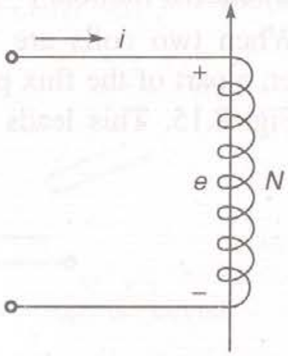


Fig. 8.14 *Self-inductance*

i.e. self-inductance is defined as self-flux linkages per unit current (WbT/A).

With reference to Fig. 8.3 if no leakage is assumed

$$L = \frac{N\phi}{i} = \frac{N^2\phi}{Ni}$$

$$= \frac{N^2BA}{Hl} = N^2\mu\,\frac{A}{l}$$

$$= \frac{N^2}{\mathcal{R}} = \mathcal{P}N^2 \text{ H} \tag{8.23}$$

We see from Eq. (8.23) that self-inductance of a coil is independent of excitation and depends only upon its geometry, permeability to the magnetic material and number of coil turns. In fact inductance is proportional to the square of number of tuns of the coil.

In the general case where both configuration and current vary for an inductive coil, Eq. (8.20) modifies as

$$e = \frac{d\lambda}{dt} = \frac{d}{dt}\,(L(x)i)$$

$$= L\,\frac{\partial i}{\partial t} + i\,\frac{\partial L}{\partial t} \tag{8.24}$$

where

x = length/angle parameter

$L\dfrac{\partial i}{\partial t}$ = statistically induced emf (due to variation of current only with L held fixed).

$i\dfrac{\partial L}{\partial t}$ = dynamically induced emf (due to variation of L only with i held constant)

Only dynamically induced emf is involved in the process of electromechanical energy conversion. It is so because dynamically induced emf is associated with relative motion.

When two coils are wound on a common core or placed close to each other, a part of the flux produced by one coil also links the other coil as shown in Fig. 8.15. This leads to the concept of *mutual inductance* defined as

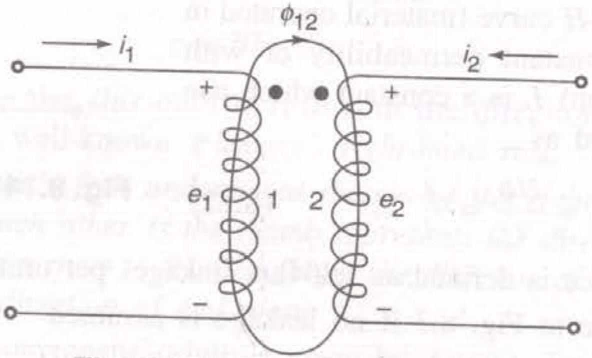


Fig. 8.15 *Mutual inductance*

$$L_{12}(\text{or } M_{12}) = \frac{\lambda_{12}}{i_2}\ \text{H}$$

$$L_{21}(\text{or } M_{21}) = \frac{\lambda_{21}}{i_1}\ \text{H} \qquad (8.25)$$

where

λ_{12} = flux linkages of coil 1 due to current in coil 2

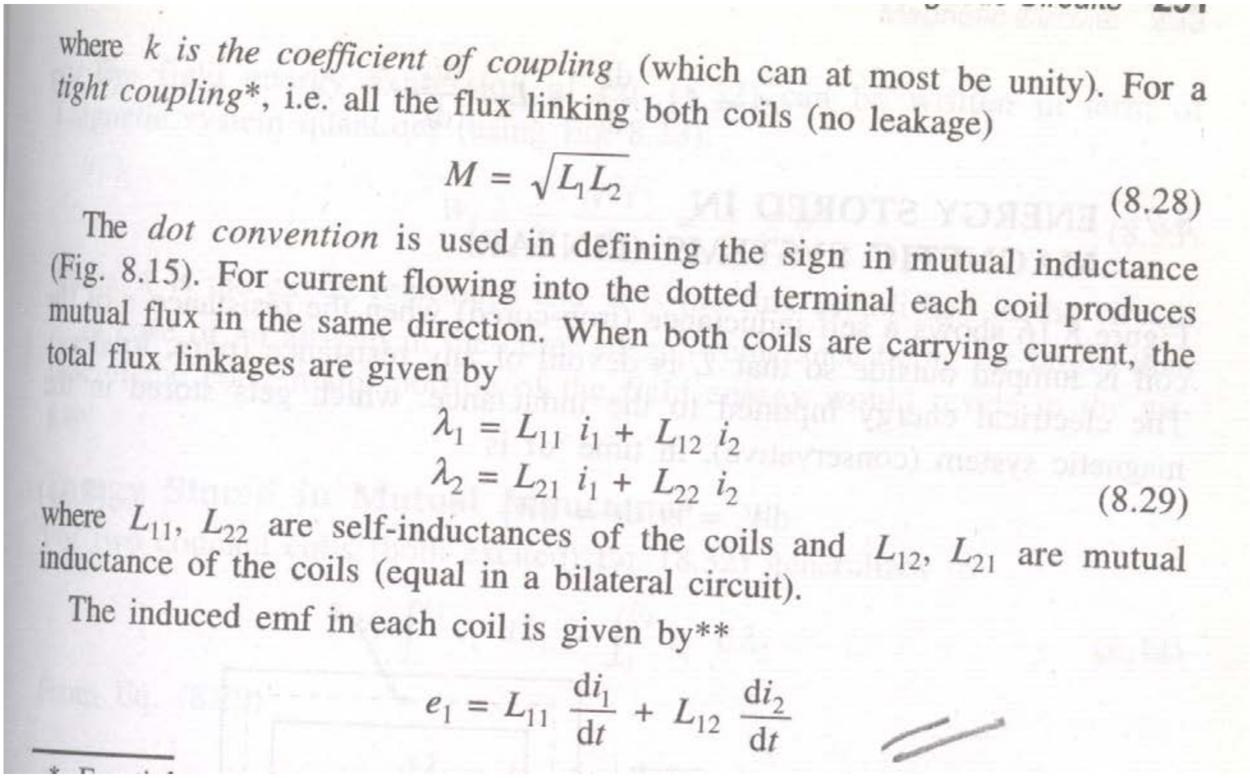
λ_{12} = flux linkages of coil 2 due to current in coil 1

For a *bilateral* magnetic circuit

$$M_{12} = M_{21} = \text{M} \qquad (8.26)$$

In general in a linear magnetic circuit

$$M = k\sqrt{L_1 L_2} \qquad (8.27)$$



where *k is the coefficient of coupling* (which can at most be unity). For a *tight coupling**, i.e. all the flux linking both coils (no leakage)

$$M = \sqrt{L_1 L_2} \tag{8.28}$$

The *dot convention* is used in defining the sign in mutual inductance (Fig. 8.15). For current flowing into the dotted terminal each coil produces mutual flux in the same direction. When both coils are carrying current, the total flux linkages are given by

$$\lambda_1 = L_{11}\, i_1 + L_{12}\, i_2$$
$$\lambda_2 = L_{21}\, i_1 + L_{22}\, i_2 \tag{8.29}$$

where L_{11}, L_{22} are self-inductances of the coils and L_{12}, L_{21} are mutual inductance of the coils (equal in a bilateral circuit).

The induced emf in each coil is given by**

$$e_1 = L_{11}\,\frac{di_1}{dt} + L_{12}\,\frac{di_2}{dt}$$

b. A ring has a diameter of 21 cm and a cross-sectional area of 10 cm^2. The ring is made up of two semicircular sections of cast iron and cast steel, with each joint having reluctance equal to an air-gap of 0.2 mm. Find the ampere-turns required to produce a flux of 8×10^{-4}wb. The relative permeabilities of cast steel and cast iron are 800 and 166 respectively. Neglect fringing and leakage effect. (8)

Answer:

$\phi = 8\times10^{-4}$ Wb

$A = 10\,cm^2 = 10^{-3}\,m^2.$

$B = 8\times10^{-4}/10^{-3} = 0.8\ Wb/m^2.$

Airgap

$$H = B/\mu_0 = \frac{0.8}{4\pi\times10^{-7}} = 6.366\times10^5\ AT/m$$

Total Airgap length $= 2\times0.2 = 0.4$ mm.

$= 4\times10^{-4}$ m

1 ∴ AT Required for Airgap $= H\times l$

$= 6.366\times10^5\times4\times10^{-4}.$

$= 255$ AT.

CAST STEEL PATH.

$$H = \frac{B}{\mu_0\mu_r} = \frac{0.8}{4\pi\times10^{-7}\times800} = 796\ AT/m$$

$$\text{Path} = \frac{\pi D}{2} = 21\times\frac{\pi}{2} = 33\,cm = 0.33\,m.$$

1 ∴ AT required $= H\times l = 796\times0.33$m

$= 263$ AT.

CAST IRON

$$H = \frac{0.8}{4\pi\times10^{-7}\times166} = 3,835\ AT/m.$$

$l = 0.33$m.

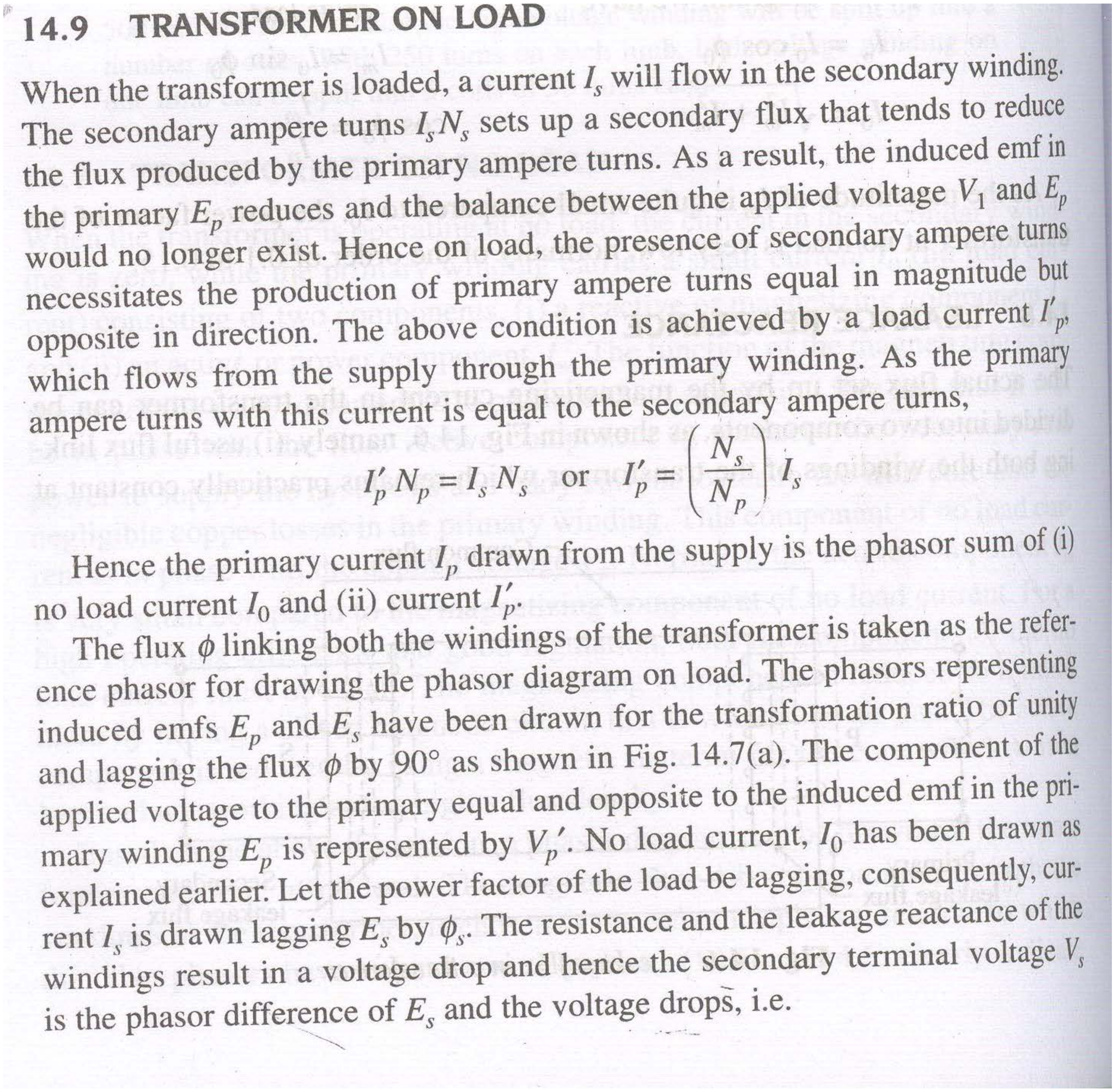
∴ AT required $= 3835\times0.33 = 1265.$

Total AT required $= 255+263+1265 =$ 1783

∴ $\boxed{\text{Ans :- } 1783\ AT}$

Q.3 a. Explain the working principle and operation of single-phase transformer supplying rated load (lagging) with the help of suitable phasor diagrams considering all non-idealities of transformer such as primary & secondary resistances and leakage reactances. (8)

Answer:



14.9 TRANSFORMER ON LOAD

When the transformer is loaded, a current I_s will flow in the secondary winding. The secondary ampere turns $I_s N_s$ sets up a secondary flux that tends to reduce the flux produced by the primary ampere turns. As a result, the induced emf in the primary E_p reduces and the balance between the applied voltage V_1 and E_p would no longer exist. Hence on load, the presence of secondary ampere turns necessitates the production of primary ampere turns equal in magnitude but opposite in direction. The above condition is achieved by a load current I'_p, which flows from the supply through the primary winding. As the primary ampere turns with this current is equal to the secondary ampere turns,

$$I'_p N_p = I_s N_s \quad \text{or} \quad I'_p = \left(\frac{N_s}{N_p}\right) I_s$$

Hence the primary current I_p drawn from the supply is the phasor sum of (i) no load current I_0 and (ii) current I'_p.

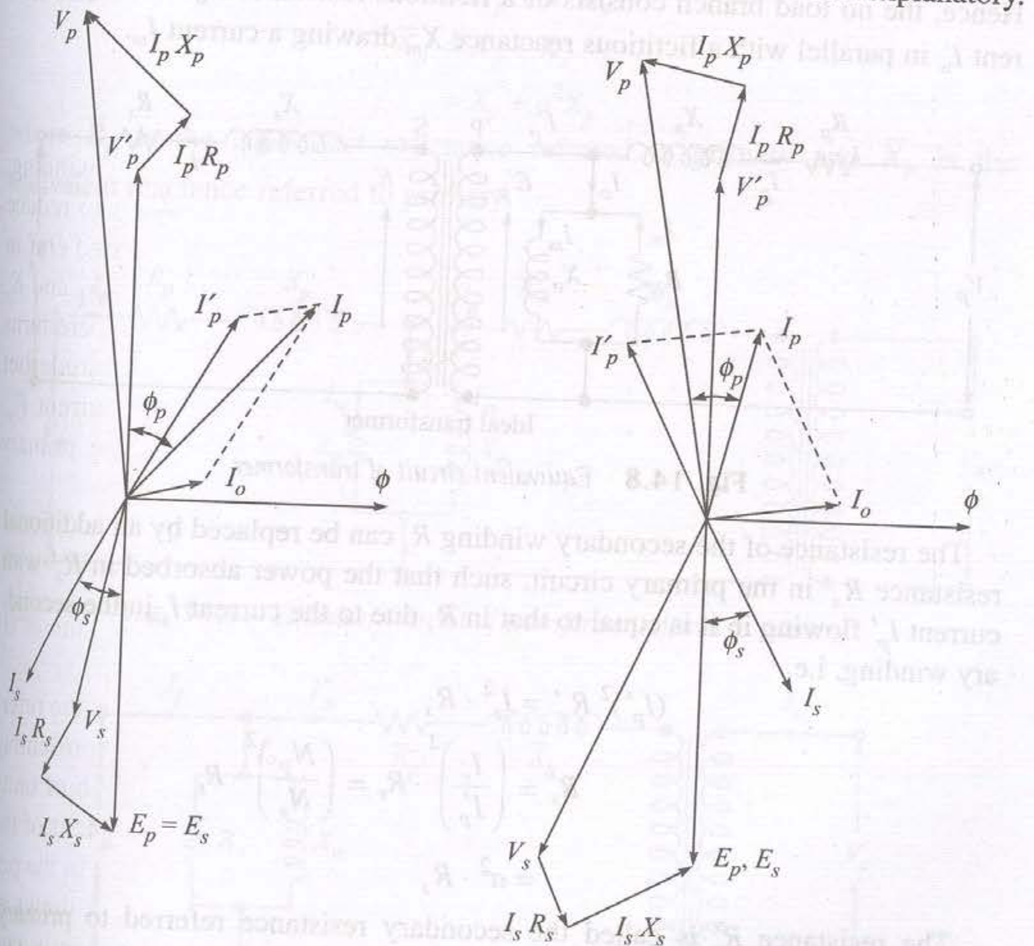
The flux ϕ linking both the windings of the transformer is taken as the reference phasor for drawing the phasor diagram on load. The phasors representing induced emfs E_p and E_s have been drawn for the transformation ratio of unity and lagging the flux ϕ by 90° as shown in Fig. 14.7(a). The component of the applied voltage to the primary equal and opposite to the induced emf in the primary winding E_p is represented by V_p'. No load current, I_0 has been drawn as explained earlier. Let the power factor of the load be lagging, consequently, current I_s is drawn lagging E_s by ϕ_s. The resistance and the leakage reactance of the windings result in a voltage drop and hence the secondary terminal voltage V_s is the phasor difference of E_s and the voltage drops, i.e.

$V_s = E_s$ – voltage drops (I_sR_s in phase with I_s and I_sX_s in quadrature with I_s)

The current I_p' equal and opposite to the secondary current I_s is then drawn as shown in Fig. 14.7(a). The total current I_p flowing in the primary winding is the phasor sum of I'_p and I_0. The primary applied voltage, V_p is the phasor sum of V_p' and the voltage drops in the primary winding, i.e. $V_p = V_p'$ + voltage drops (I_pR_p in phase with I_p and I_pX_p in quadrature with I_p)

The phasor difference between V_p and I_p gives the power factor angle of the primary side of the transformer. The phasor representing I_0, the primary and secondary voltage drops have been shown far larger relative to the other phasors in order to show them clearly in the phasor diagram.

The power factor of the secondary depends upon the type of the load on the transformer. In case of capacitive load connected to transformer secondary, the power factor will be leading. The phasor diagram of the transformer on load for leading power factor has been shown in Fig. 14.7(b), which is self explanatory.



(a) For lagging load

(b) For leading load

Fig. 14.7 *Phasor diagram of transformer on load*

b. The following readings were obtained from open and short circuit test performed on 10 KVA, 400/100V, 50Hz single phase transformer:
O.C test: 100 V, 4A, 80 W -on L.V side
S.C test : 10V, 20A, 120 W -on H.V. side
Find out equivalent circuit parameters referred to primary. (8)

Answer:

Transformation Ratio = $\frac{100}{400} = \frac{1}{4}$.

∴ No load Primary current

$I_0 = 4 \times 0.25$

$= 1A$.

(i) From O.C Test.

$W_0 = V_1 I_0 \cos\phi_0$

∴ $\cos\phi_0 = 0.2$.

$\sin\phi_0 = 0.9$.

∴ $I_W = I_0 \cos\phi_0$ $I_m = I_0 \sin\phi_0$

$= 1 \times 0.2$ $= 1 \times 0.98$

$= 0.2\,A$ $= 0.98\,A$

$R_0 = V_1 / I_W$ $X_0 = V_1 / I_W$.

$= \frac{400}{0.2} = 2000\,\Omega$ $X_0 = \frac{400}{0.98}$

$= 408\,\Omega$.

From S/C test

$Z_{01} = \frac{V_{sc}}{I_{sc}} = \frac{10}{20} = 0.5\,\Omega$.

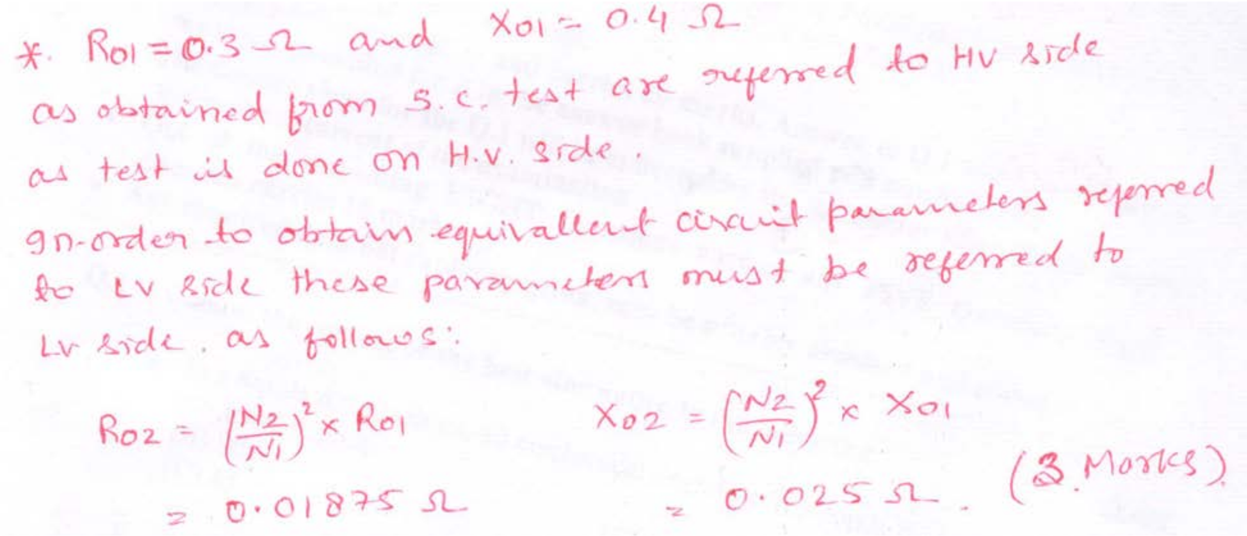
$R_{01} = \frac{W_{sc}}{I_{sc}^2} = \frac{120}{(20)^2} = 0.3\,\Omega$.

$X_{01}. = \sqrt{Z_{01}^2 - R_{01}^2} = \sqrt{(0.5)^2 - (0.3)^2} = 0.4\,\Omega$

Ans ● Equivalent ckt parameter.

$R_0 = 2000\,\Omega$ $X_0 = 408\,\Omega$.

$R_{01} = 0.3\,\Omega$ $X_{01} = 0.4\,\Omega$.



*. $R_{01} = 0.3\,\Omega$ and $X_{01} = 0.4\,\Omega$ as obtained from S.C. test are referred to HV side as test is done on H.V. side.

In-order to obtain equivallent circuit parameters referred to LV side these parameters must be referred to LV side. as follows:

$$R_{02} = \left(\frac{N_2}{N_1}\right)^2 \times R_{01} \qquad X_{02} = \left(\frac{N_2}{N_1}\right)^2 \times X_{01}$$

$$= 0.01875\,\Omega \qquad = 0.025\,\Omega.$$

(3 Marks)

Q.4 a. What do you mean by armature reaction? Explain its effect on dc generator and motor. (8)

Answer:

When the dc machine armature carries current, it causes its own mmf distribution known as armature reaction. Figure 11.6 shows the cross-sectional view of a 2-pole machine. All the conductors under the north pole carry current in one direction and those under the south pole in the opposite direction. As the armature rotates this pattern of current distribution remains fixed in space (i.e. stationary wrt the main poles as is necessary for torque production (Sec. 10.7)). In Fig. 11.6 the conductors 1, 1′, 2, 2′, etc. form a coil with peak ampere-turns AT_a, whose axis is along the brush axis (*q*-axis) or at 90° elect to the main pole axis (*d*–axis) independent of the load current magnitude. Such an armature reaction is known as *cross-magnetizing*. AT_a at

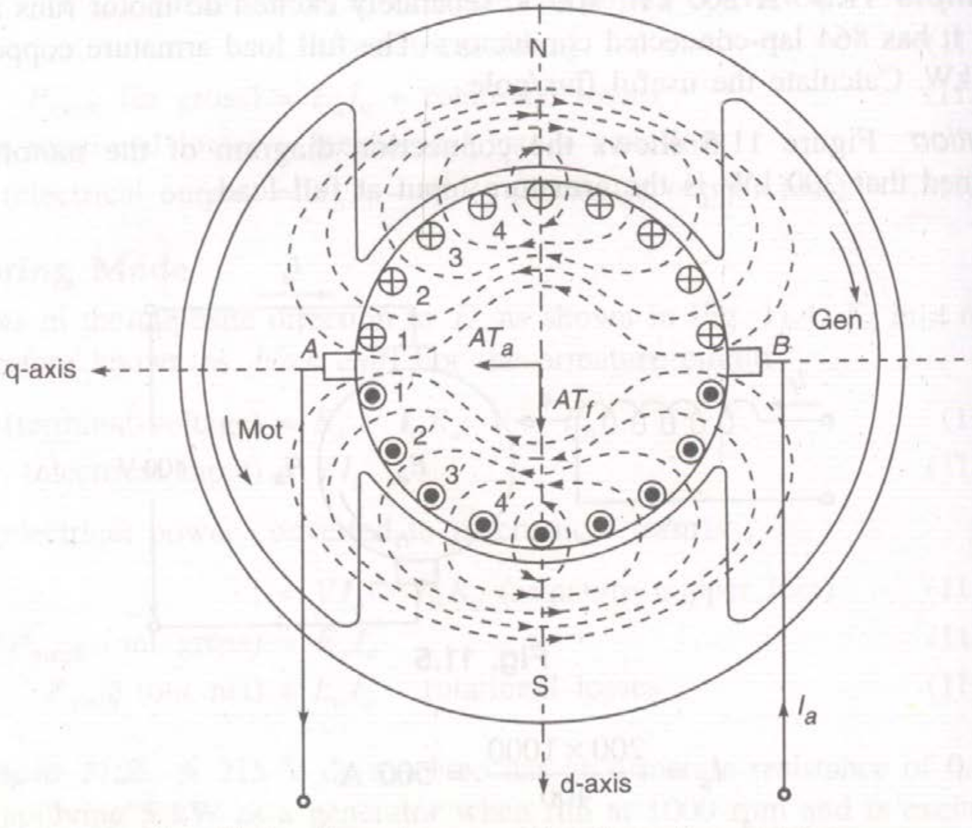


Fig. 11.6 *Armature reaction in a dc machine*

90° to AT_f corresponds to $\lambda = 90°$ in Eq. (10.33), which is the best condition for torque production.

It is seen from Fig. 11.6 that armature reaction AT opposes the main pole AT at one pole tip and strengthens it at the other pole tip (this is the cross-magnetizing effect). The flux density wave in the air-gap therefore gets distorted from the trapezoidal shape at no-load, $I_a = 0$ (Fig. 10.27), such that the flux density increases in one half of the main poles and decreases in the other half as shown in Fig. 11.7. The decrease in flux in one half of the pole is balanced by an equal increase in the other half so long as the magnetic material of the poles is in an unsaturated state. Thus in the linear region of magnetization, the flux/pole remains unaffected by armature reaction even though the B-wave gets distorted. In the saturation region of magnetization the increase in flux in one half of the pole is less than the decrease in the other resulting in net reduction in flux/pole.

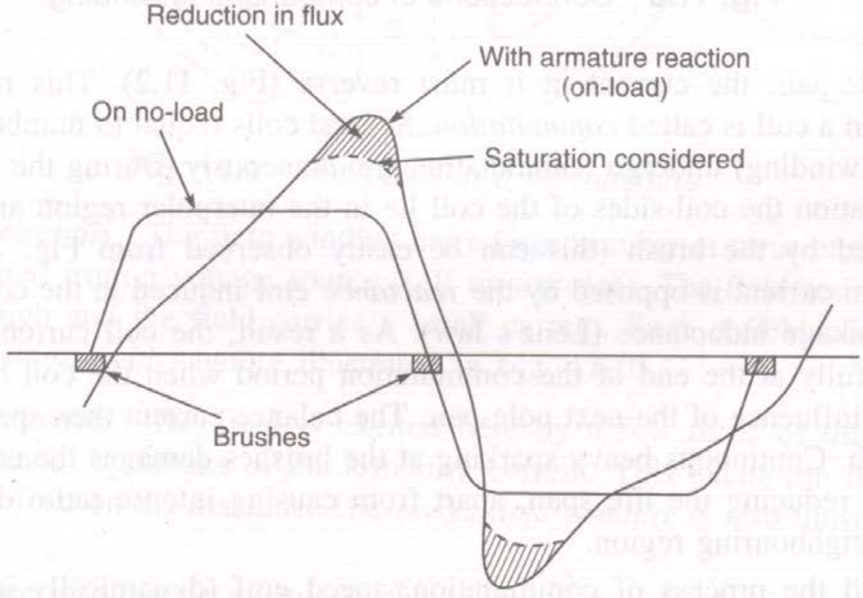


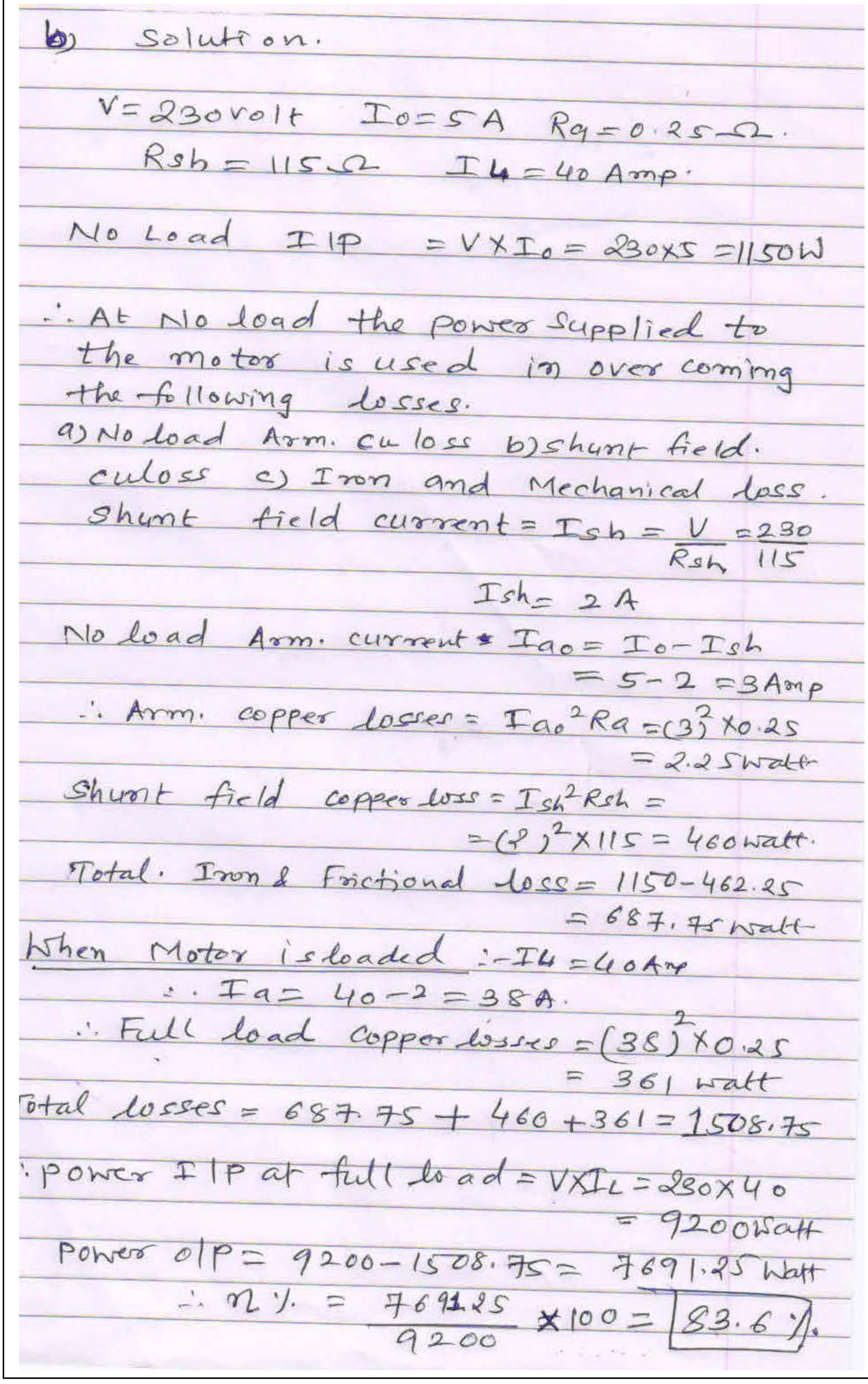
Fig. 11.7 *Distortion of B-wave in dc machine air-gap*

Compensating Winding

Armature reaction varies with the armature current. In case of a sudden change in motor load the armature reaction flux Φ_a changes at a sharp rate inducing large statically induced emfs in armature coils which appear across commutator segments causing these to flash over resulting in complete short circuit of the machine commutator. Hence AT_a must be compensated by compensating winding placed in slots cut out in main pole shoes with windings axis along the q-axis. These windings have a few turns connected in series with armature such that these are excited by I_a. This is illustrated in Fig. 11.8.

b. A 230V shunt motor takes 5 A at no load. The resistance of the armature and field circuit is 0.25 ohm and 115 ohm respectively. If motor is loaded so as to carry 40 A. Determine (1) Iron and Frictional losses (2) Efficiency at given load. (8)

Answer:



b) Solution.

$V = 230$ volt $I_o = 5A$ $R_a = 0.25\Omega$.

$R_{sh} = 115\Omega$ $I_L = 40$ Amp.

No Load I/P $= V \times I_0 = 230 \times 5 = 1150W$

∴ At No load the power supplied to the motor is used in over coming the following losses.

a) No load Arm. cu loss b) shunt field. culoss c) Iron and Mechanical loss.

shunt field current $= I_{sh} = \frac{V}{R_{sh}} = \frac{230}{115}$

$I_{sh} = 2A$

No load Arm. current $I_{a0} = I_0 - I_{sh}$

$= 5 - 2 = 3$ Amp

∴ Arm. copper losses $= I_{a0}^2 R_a = (3)^2 \times 0.25$

$= 2.25$ watt

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

$= (2)^2 \times 115 = 460$ watt.

Total. Iron & Frictional loss $= 1150 - 462.25$

$= 687.75$ watt

When Motor is loaded :- $I_L = 40$ Amp

∴ $I_a = 40 - 2 = 38A$.

∴ Full load copper losses $= (38)^2 \times 0.25$

$= 361$ watt

Total losses $= 687.75 + 460 + 361 = \underline{1508.75}$

∴ power I/P at full load $= V \times I_L = 230 \times 40$

$= 9200$ Watt

Power o/P $= 9200 - 1508.75 = 7691.25$ Watt

∴ $\eta\% = \frac{7691.25}{9200} \times 100 = \boxed{83.6\%}$.

Q.5 a. Explain torque/ slip characteristics of three phase induction motor under starting and full load conditions. What is the effect of rotor resistance on the shape of characteristics? (8)

Answer:

Torque-Slip Characteristic

For the sake of simplicity of treatment, the stator impedance will be neglected*. The simplified circuit for obtaining torque expression is given in Fig. 12.25. The result given below follows immediately.

$$I_2' = \frac{V_1}{\sqrt{(R_2'/s)^2 + X_2'^2}} = \frac{V_1/a}{\sqrt{(R_2/s)^2 + X_2^2}} \tag{12.34}$$

Substituting in Eq. (12.32)

$$T = \frac{P_G}{\omega_s} = \frac{3}{\omega_s}\,\frac{V_1^2\,(R_2'/s)}{(R_2'/s)^2 + X_2'^2} = \frac{3}{\omega_s}\,\frac{(V_1/a)^2\,(R_2/s)}{(R_2/s)^2 + X_2^2} \tag{12.35}$$

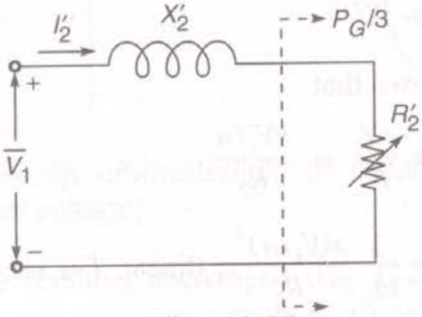


Fig. 12.25

For maximum torque, $P_G/3$ in Fig. 12.25 must be maximum, which happens when R'_2/s matches with X_2' (maximum power transfer theorem), i.e.

$$\frac{R_2'}{s_{\max T}} = X_2'$$

or
$$s_{\max T} = \frac{R_2'}{X_2'} = \frac{R_2}{X_2} \tag{12.36}$$

Substituting Eq. (12.36) in Eq. (12.35)

$$T_{\max} \text{ or } T_{\text{breakdown}} = \frac{3}{\omega_s}\left(\frac{0.5\,V_1^2}{X_2'}\right) \tag{12.37}$$

$$= \frac{3}{\omega_s}\left(\frac{0.5\,(V_1/a)^2}{X_2}\right) \tag{12.38}$$

Starting current and torque are given by substituting $s = 1$ in Eqs (12.34) and (12.35). Thus

$$I_2' \text{ (start)} = \frac{V_1}{\sqrt{R_2'^2 + X_2'^2}} = \frac{V_1/a}{\sqrt{R_2^2 + X_2^2}} \tag{12.39}$$

---

* This assumption causes a tolerable error in the region of low slip but unacceptable error for large slips. Yet it helps to get a feel of the complete T–s characteristic.

$$T_{\text{start}} = \frac{3}{\omega_s}\frac{V_1^2 R_2'}{(R_2')^2 + X_2'^2} = \frac{3}{\omega_s}\frac{(V_1/a)^2\, R_2}{R_2^2 + X_2^2} \tag{12.40}$$

The starting torque increases by adding resistance in the rotor circuit. At the same time the starting current will reduce. This indeed is the advantage of the slip-ring induction motor in which a high starting torque is obtained at low starting current.

Observe that

$$T_{\text{start}}\ (\text{max}) = T_{\text{breakdown}};\ R_2' = X_2'\ (\text{Eq. } (12.36)) \tag{12.41}$$

Further approximations For low values of slip

$$\frac{R_2'}{s} \gg X_2'$$

On ignoring x_2', it follows that

$$I_2' = \frac{sV_1}{R_2'} = \frac{sV_1/a}{R_2} \tag{12.42}$$

$$T = \frac{3}{\omega_s}\frac{sV_1^2}{R_2'} = \frac{3}{\omega_s}\frac{s(V_1/a)^2}{R_2};\ (\text{linear } T\text{–}s \text{ relationship}) \tag{12.43}$$

For large values of slip $x_2' > R_2'/s$.

Igonoring R_2'/s,

$$T = \frac{3}{\omega_s}\frac{V_1^2 R_2'}{sX_2'^2} = \frac{3}{\omega_s}\frac{(V_1/a)^2 R_2}{sX_2^2}\ (\text{inverse law } T\text{–}s) \tag{12.44}$$

Stator Impedance Considered It is easy to see that if the stator impedance is accounted for the torque expression of Eq. (12.35) would become

$$T = \frac{3}{\omega_s}\frac{V_1^2\,(R_2'/s)}{(R_1 + R_2'/s)^2 + (X_1 + X_2')^2} \tag{12.45}$$

Plot of Complete T–s Characteristic From the above results the complete *T*–*s* characteristic is plotted in Fig. 12.26. Its various operating modes are:

- *Motoring mode:* $0 \le s \le 1$; subsynchronous speed, motor runs in the direction of the rotating air-gap field;
- *Braking mode:* $s > 1$; motor runs in opposite direction to the rotating field; and
- *Generating mode*: $s < 0$; motor runs at supersynchronous speed in the direction of the rotating field. Negative s implies that mechanical power output (Eq. (12.30)) is negative (input) and so the electrical power is the output.

External Resistance Added in Rotor Circuit This is only possible in a slip-ring induction motor. As resistance is added in the rotor circuit, we observe that

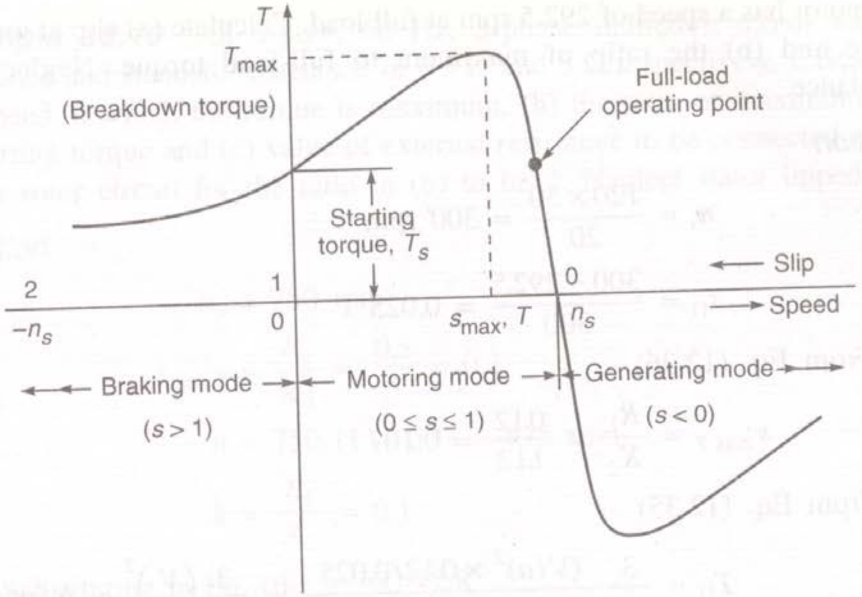


Fig. 12.26 *Torque–slip characteristic of induction motor (at fixed terminal voltage)*

- breakdown torque remains unchanged (Eq. (12.38);
- slip at breakdown torque increases (Eq. (12.36); and
- T_{start} becomes maximum (equal to $T_{breakdown}$ at $R_2 = X_2$).

The torque–slip characteristics of induction motor for increasing values of rotor resistance are plotted in Fig. 12.27.

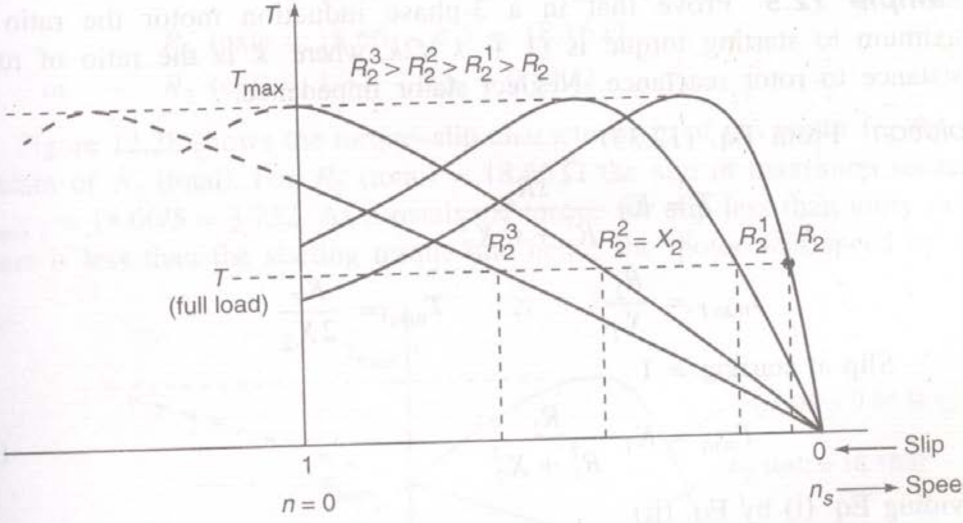


Fig. 12.27 *Torque–slip characteristics of induction motor with increasing values of rotor resistance*

b. A 3-phase, 400V, star connected induction motor has a star connected rotor with stator to rotor turn ratio of 6.5. The rotor resistance and standstill reactance per phase are 0.05 ohm and 0.25 ohm respectively. What should be the value of external resistance per phase to be inserted in the rotor circuit to obtain maximum torque at starting and what will be rotor starting current with this resistance? (8)

Answer:

(b) Solution

$$K = \frac{1}{6.5} = \frac{\text{rotor turns/phase}}{\text{Stator turn/phase.}}$$

Stan still rotor emf/phase, $E2 = \frac{400}{\sqrt{3}.} \times \frac{1}{6.5}$

$E2 = 35.5\text{volt}$

To obtained Maximum Torque at star ting.

$R2 = X2.$

$R2 = 0.25$

∴ External resistance/phase required

$= 0.25 - 0.05$

$= \boxed{0.2\,\Omega.}$

Rotor Impedance/phase =

$= \sqrt{(0.25)^2 + (0.25)^2}.$

$= 0.3535\,\Omega.$

∴ Rotor current perphase =

$I2 = \frac{35.5}{0.3535} = 100\text{ A (approx).}$

Q.6 a. What is the effect of short pitch winding on induced e.m.f on alternator? What do you mean by pitch factor and distribution factor? (8)

Answer:

Short-pitched coils with span less than π rad are employed for reduction in harmonic content of the voltage wave and to save in overhang copper. Figure 10.16 shows such a coil.

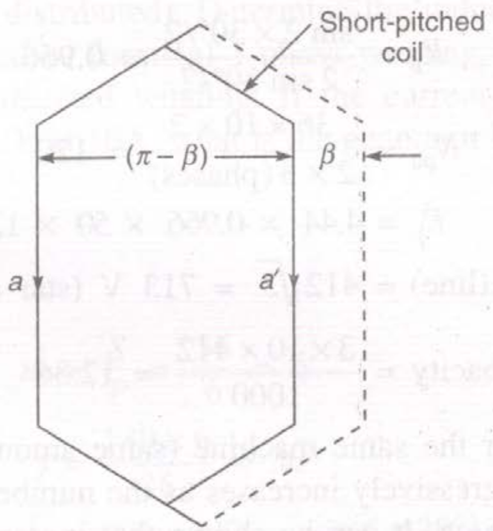


Fig. 10.16 *Short-pitched coil*

Assuming the positive direction of emf in each coil as shown in Fig. 10.16

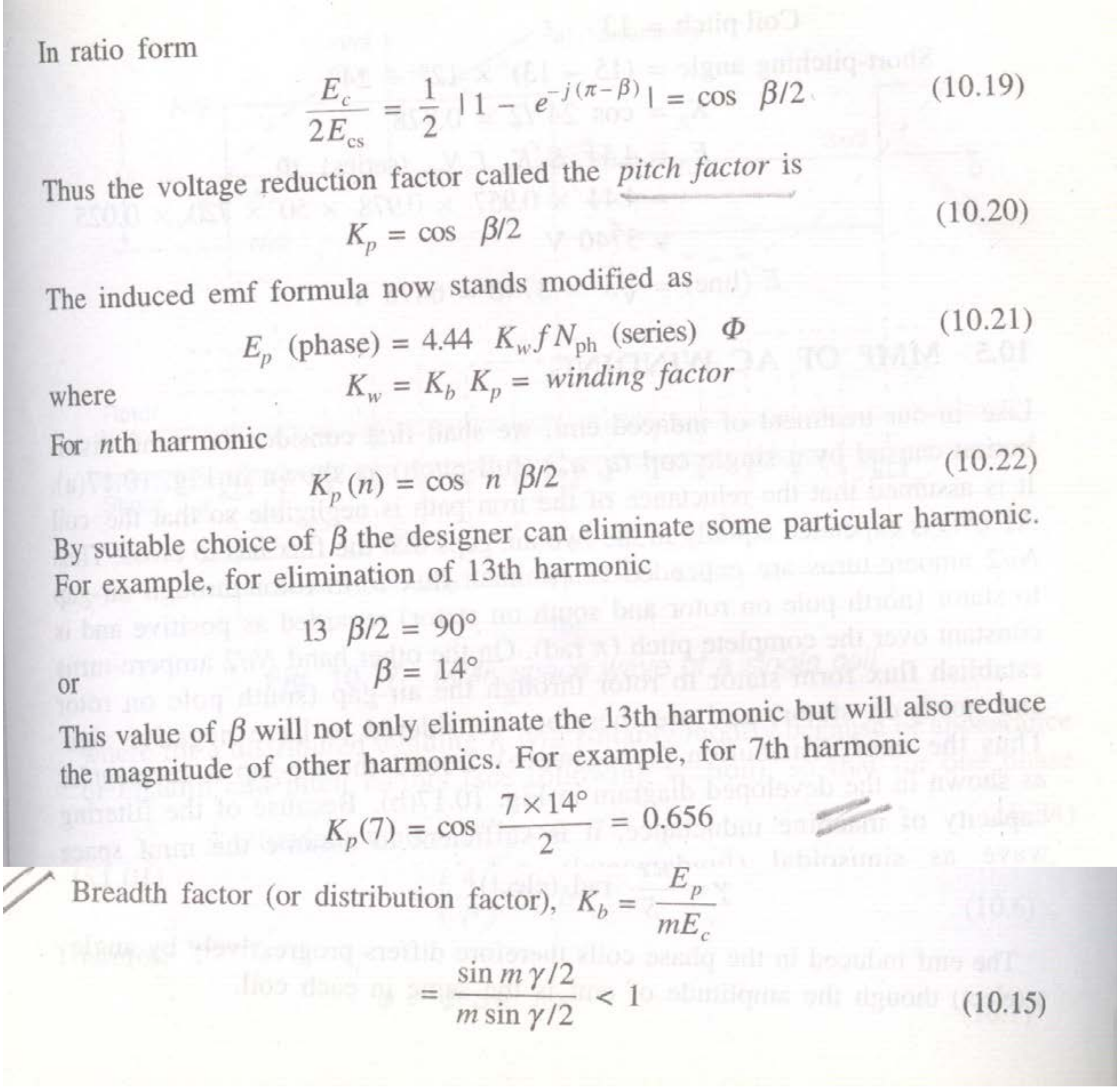
$$\overline{E}_a = E_{cs}$$

$$\overline{E}_{a'} = E_{cs}\, e^{-j(\pi-\beta)} \qquad (10.18)$$

where E_{cs} is the coil-side emf and β is the angle by which the coil span is shorter than π (full-pitch).

The coil emf is

$$\begin{aligned}\overline{E}_c &= \overline{E}_a - \overline{E}_{a'}\\ &= E_{cs}\,(1 - e^{-j(\pi-\beta)}) \qquad (10.18)\end{aligned}$$



In ratio form

$$\frac{E_c}{2E_{cs}} = \frac{1}{2}\,|\,1 - e^{-j(\pi-\beta)}\,| = \cos\ \beta/2 \qquad (10.19)$$

Thus the voltage reduction factor called the *pitch factor* is

$$K_p = \cos\ \beta/2 \qquad (10.20)$$

The induced emf formula now stands modified as

$$E_p\ (\text{phase}) = 4.44\ K_w f N_{\text{ph}}\ (\text{series})\ \Phi \qquad (10.21)$$

where

$$K_w = K_b\, K_p = \textit{winding factor}$$

For *n*th harmonic

$$K_p(n) = \cos\ n\ \beta/2 \qquad (10.22)$$

By suitable choice of β the designer can eliminate some particular harmonic. For example, for elimination of 13th harmonic

$$13\ \beta/2 = 90°$$

or

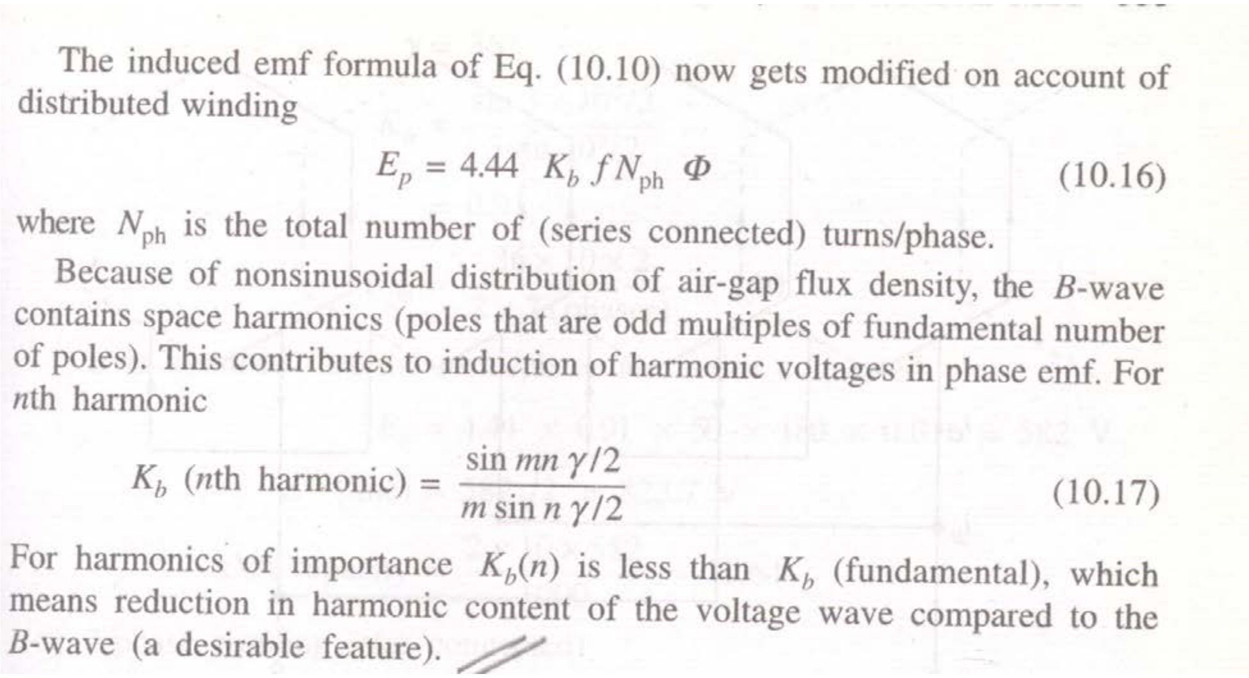
$$\beta = 14°$$

This value of β will not only eliminate the 13th harmonic but will also reduce the magnitude of other harmonics. For example, for 7th harmonic

$$K_p(7) = \cos\frac{7\times 14°}{2} = 0.656$$

Breadth factor (or distribution factor), $K_b = \dfrac{E_p}{mE_c}$

$$= \frac{\sin m\,\gamma/2}{m \sin\gamma/2} < 1 \qquad (10.15)$$



The induced emf formula of Eq. (10.10) now gets modified on account of distributed winding

$$E_p = 4.44\ K_b\, f N_{\text{ph}}\ \Phi \tag{10.16}$$

where N_{ph} is the total number of (series connected) turns/phase.

Because of nonsinusoidal distribution of air-gap flux density, the B-wave contains space harmonics (poles that are odd multiples of fundamental number of poles). This contributes to induction of harmonic voltages in phase emf. For nth harmonic

$$K_b\ (n\text{th harmonic}) = \frac{\sin mn\,\gamma/2}{m \sin n\,\gamma/2} \tag{10.17}$$

For harmonics of importance $K_b(n)$ is less than K_b (fundamental), which means reduction in harmonic content of the voltage wave compared to the B-wave (a desirable feature).

b. A 3-phase, 16 pole alternator has a star connected winding with 144 slots and 10 conductors per slot. The flux per pole is 0.03 wb sinusoidally distributed and the speed is 375 r.p.m. Find frequency of induced e.m.f and the value of phase & line e.m.f. Assume full pitched coil. (8)

Answer:

(b).

Frequency of e.m.f $= \frac{PN}{120}$

$= \frac{16 \times 375}{120}$

$= 50 Hz$.

Assume $K_c = 1$. (For fullpitch).

slot/pole $= \frac{144}{16} = 9$.

Angular displacement bet^n slots =

$B = \frac{180}{9} = 20^\circ$

∴ Slot/pole/phase $= \frac{144}{16 \times 3} = 3$.
$m =$

Distribution factor $= \frac{\sin \frac{mB}{2}}{m \sin B/2}$.

$= \frac{\sin\left[\frac{3 \times 20}{2}\right]}{3 \sin\left[20/2\right]}$.

$K_d = 0.96$

Conductor/p $= Z = \frac{144 \times 10}{3} = 480$.

∴ Turns/Phase $= \frac{480}{2} = 240$.

∴ $E_{ph} = 4.44 \times k_c \times k_d\, f \phi T$ volt

$= 4.44 \times 1 \times 0.96 \times 50 \times 0.03 \times 240$

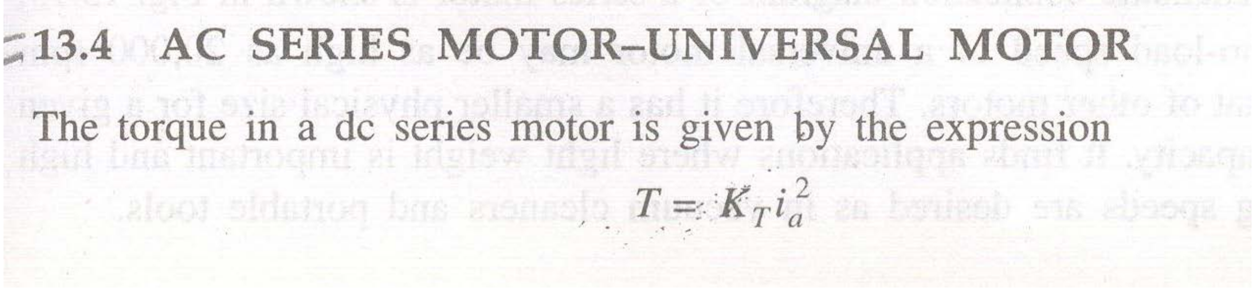
$\boxed{E_{ph} = 1534 \text{ volt}} = 1534.46$ volt

Line $E_L = \sqrt{3} \times 1534.46$ volt

$\boxed{E_L = 2654.6 \text{ volt}}$

Q.7 a. Explain the construction and working of Universal motor. Explain the consequences of ac excitation of dc armature. (8)

Answer:



13.4 AC SERIES MOTOR–UNIVERSAL MOTOR

The torque in a dc series motor is given by the expression

$$T = K_T i_a^2$$

If this motor is ac excited the torque would be unidirectional with an average component and a second harmonic oscillating component as shown in Fig. 13.14.

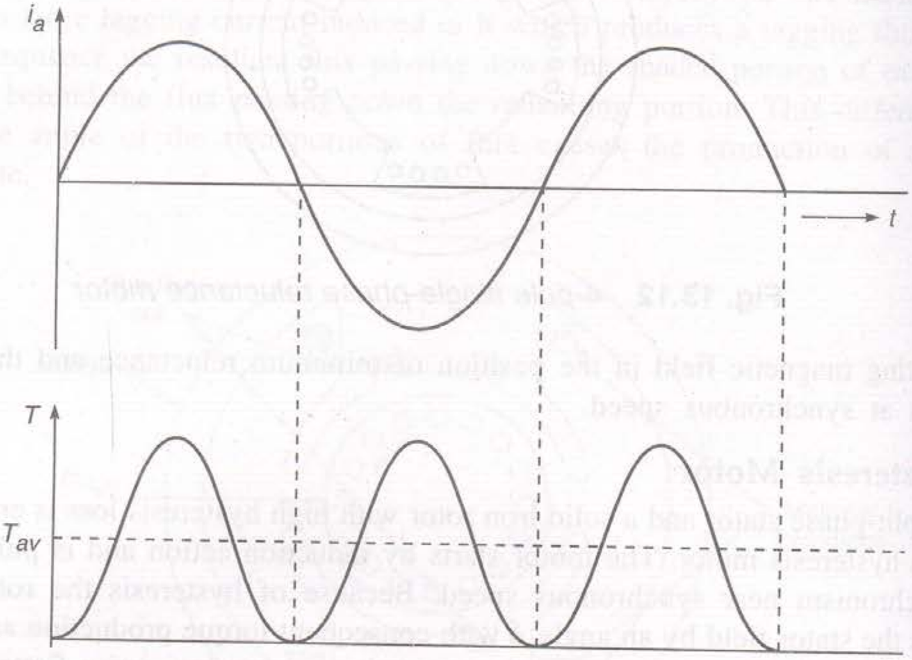


Fig. 13.14 *Torque in ac-excited series motor*

The average torque can be obtained from

$$T_{av} w = E_a I_a$$

where $\bar{E}_a$ and $\bar{I}_a$ must be in phase in a series excited dc armature.

There are certain consequences of ac excitation of the dc series motor.

- The field and yoke carry alternating flux and must therefore be laminated.
- Apart from speed emf E_a the armature coils have transformer emf induced in them by the alternating field flux. This reactance emf seriously impairs the commutation qualities of the machine. Interpoles must therefore be provided.
- Because of alternating armature flux (armature reaction) the armature offers a high reactance causing the motor to have a very poor pf. The armature reaction must therefore be cancelled out by providing compensating winding placed in pole faces.

The schematic connection diagram of a series motor is shown in Fig. 13.15.

The no-load speed of a universal motor may be as high as 20,000 rpm unlike that of other motors. Therefore it has a smaller physical size for a given power capacity. It finds applications where light weight is important and high operating speeds are desired as in vacuum cleaners and portable tools.

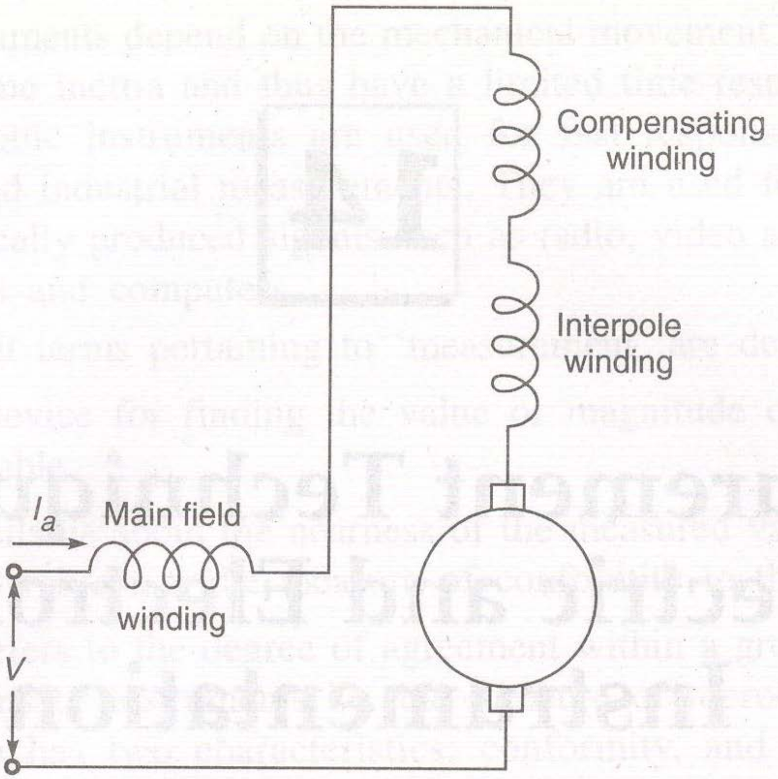
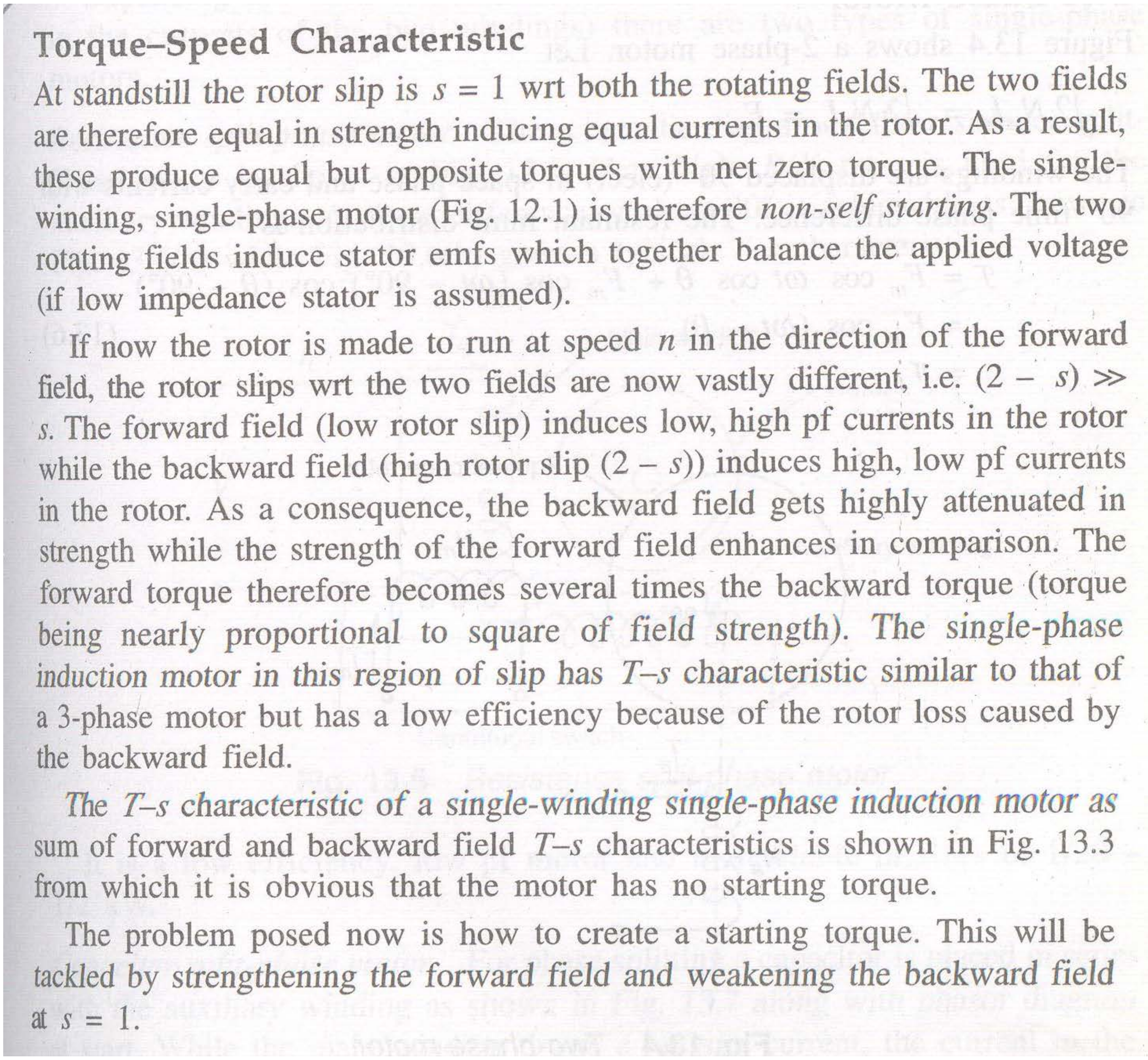


Fig. 13.15 *Connection diagram of ac-excited series motor*

b. **Why the single phase induction motor is not self-started? What are the means to make it self-started? (8)**

Answer:



Torque–Speed Characteristic

At standstill the rotor slip is $s = 1$ wrt both the rotating fields. The two fields are therefore equal in strength inducing equal currents in the rotor. As a result, these produce equal but opposite torques with net zero torque. The single-winding, single-phase motor (Fig. 12.1) is therefore *non-self starting*. The two rotating fields induce stator emfs which together balance the applied voltage (if low impedance stator is assumed).

If now the rotor is made to run at speed n in the direction of the forward field, the rotor slips wrt the two fields are now vastly different, i.e. $(2 - s) \gg s$. The forward field (low rotor slip) induces low, high pf currents in the rotor while the backward field (high rotor slip $(2 - s)$) induces high, low pf currents in the rotor. As a consequence, the backward field gets highly attenuated in strength while the strength of the forward field enhances in comparison. The forward torque therefore becomes several times the backward torque (torque being nearly proportional to square of field strength). *The single-phase induction motor in this region of slip has T–s* characteristic similar to that of a 3-phase motor but has a low efficiency because of the rotor loss caused by the backward field.

The T–s characteristic of a single-winding single-phase induction motor as sum of forward and backward field T–s characteristics is shown in Fig. 13.3 from which it is obvious that the motor has no starting torque.

The problem posed now is how to create a starting torque. This will be tackled by strengthening the forward field and weakening the backward field at $s = 1$.

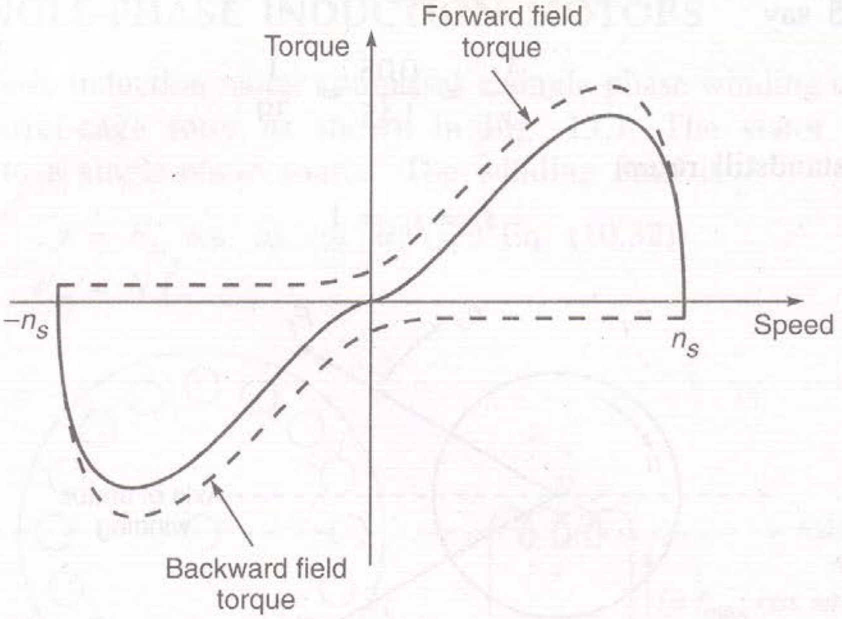


Fig. 13.3 *T–s characteristic of a single-winding, single-phase induction motor*

Split-Phase Motor

It is a 2–winding, single–phase motor in which the two windings are placed at 90° (elect) but are fed from single phase. The time phase difference in winding currents is obtained by placing suitable impedance in series with one of the windings called the *auxiliary* winding *a* while the other winding is called the *main* winding *m*. The current I_a in the higher impedance auxiliary winding is less than the current I_m in the main winding. The auxiliary winding has fewer turns of thinner wire. Unbalanced 2-phase field conditions are thus created at the start and as a result the forward rotating field becomes sufficiently stronger than the backward field resulting in production of starting torque. The auxiliary winding may or may not be left in circuit after the motor starts. For opening the auxiliary winding after motor starts, a centrifugal switch is employed. After starting the motor runs only on the main winding.

Depending on the method of *phase-splitting* (causing time phase difference in the currents of the two windings) there are two types of single-phase motors.

Resistance split-phase motor The schematic diagram of the resistance split-phase motor is shown in Fig. 13.5. Here high R/X ratio is used for the auxiliary windings. A phase difference of about 30° is achievable as shown in Fig. 13.6(a) while Fig. 13.6(b) gives a typical T–s characteristic.

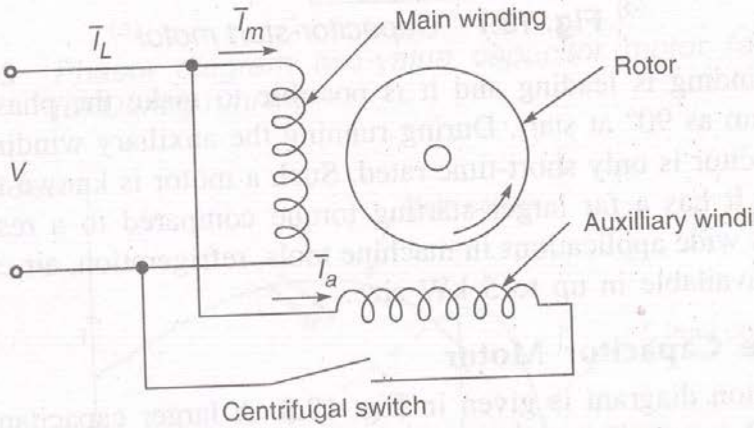


Fig. 13.5 *Resistance split-phase motor*

It is a low efficiency, low pf motor and is available in sizes of 1/20 – 1/2 kW.

Capacitor split-phase motor For phase splitting a capacitor is placed in series with the auxiliary winding as shown in Fig. 13.7 along with phasor diagram at start. While the main winding draws a lagging current, the current in the

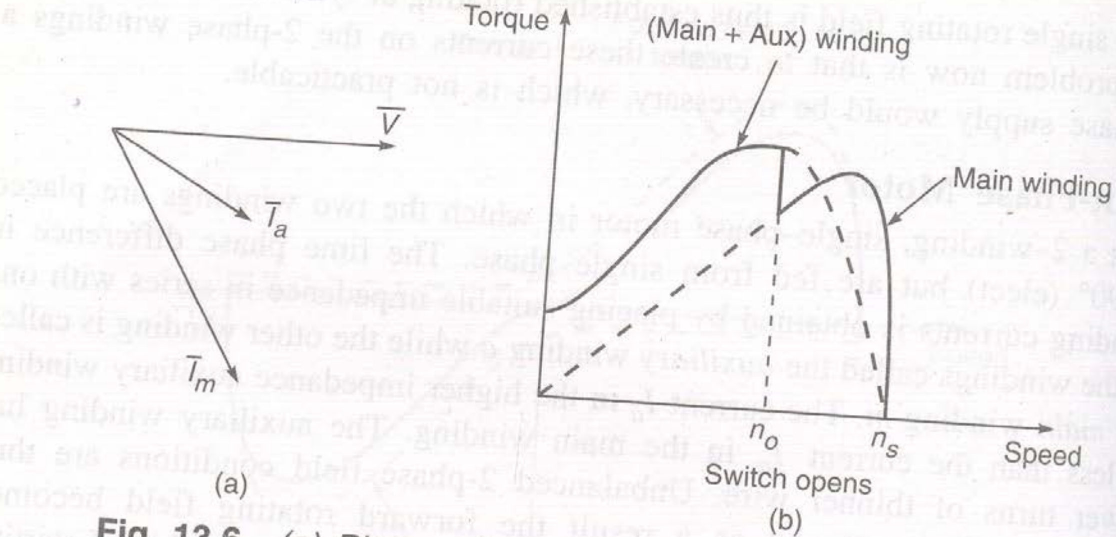


Fig. 13.6 *(a) Phasor diagram at start (b) T–s characteristic*

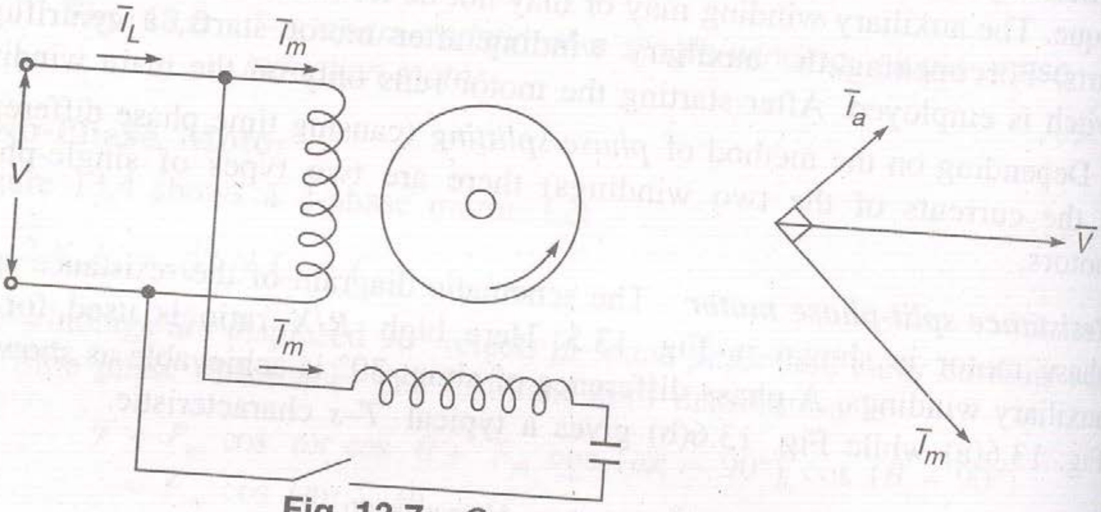


Fig.13.7 *Capacitor-start motor*

auxiliary winding is leading and it is possible to make the phase difference between them as 90° at start. During running the auxiliary winding is cut out so that capacitor is only short-time rated. Such a motor is known as capacitor-start motor. It has a far larger starting torque compared to a resistance-start motor. It has wide applications in machine tools, refrigeration, air-conditioning, etc. and is available in up to 5 kW size.

Shaded-Pole Motor

Figure 13.11 shows a shaded-pole motor. It has a projecting pole stator excited form single-phase ac while part of the poles is enclosed by short-circuited shading coils (sometimes a single shading ring is employed). The shading coil has a large lagging current induced in it which produces a lagging flux. As a consequence the resultant flux passing down the shaded portion of each pole lags behind the flux passing down the remaining portion. This difference in phase angle of the two portions of flux causes the production of starting torque.

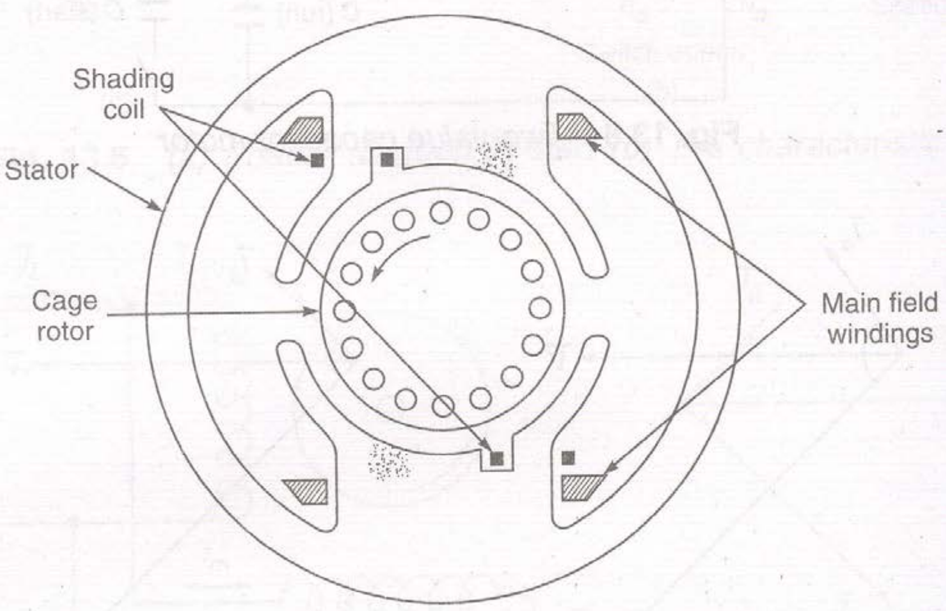


Fig. 13.11 *Shaded pole motor*

The direction of rotation of the rotor is from the leading flux portion of the pole to the lagging flux portion of the pole, i.e. from the unshaded to the shaded part of the pole. It is as if the flux glides part the rotor surface from the leading to the lagging part of the pole. Reversal of direction of rotation is possible only by providing shading coils at both the pole ends and open circuiting one of these.

Shaded-pole motor inherently has low pf and is available in sizes up to 1/20 kW. It finds application in small fans, convectors, vending machines, photocopying machines, advertising displays, etc.

Q.8 a. What are the atmospheric pollutants emitted by coal based thermal power plant? What are effects of them on environment? (8)

Answer:

Atmospheric Pollution

We shall treat here only pollution as caused by thermal plants using coal as feed-stock. Certain issues concerning this have already been highlighted in Sec. 15.3. The fossil-fuel-based generating plants form the backbone of power generation in our country and also round the globe as other options (like nuclear and even hydro) have even stronger hazards associated with them. Also it should be understood that pollution in large cities like Delhi is caused more by vehicular traffic and their emission. In Delhi of course Inderprastha and Badarpur power stations contribute their share in certain areas.

Problematic pollutants in emission of coal-based generating plants are

- SO_2
- NO_x, nitrogen oxides
- CO
- CO_2
- Certain hydrocarbons
- Particulates

Although the account that follows will be general, it needs to be mentioned here that Indian coal has a comparatively low sulphur content but a very high ash content, which in some coals may be as high as 53%.

A brief account of various pollutants, their likely impact and methods of abatements are presented below.

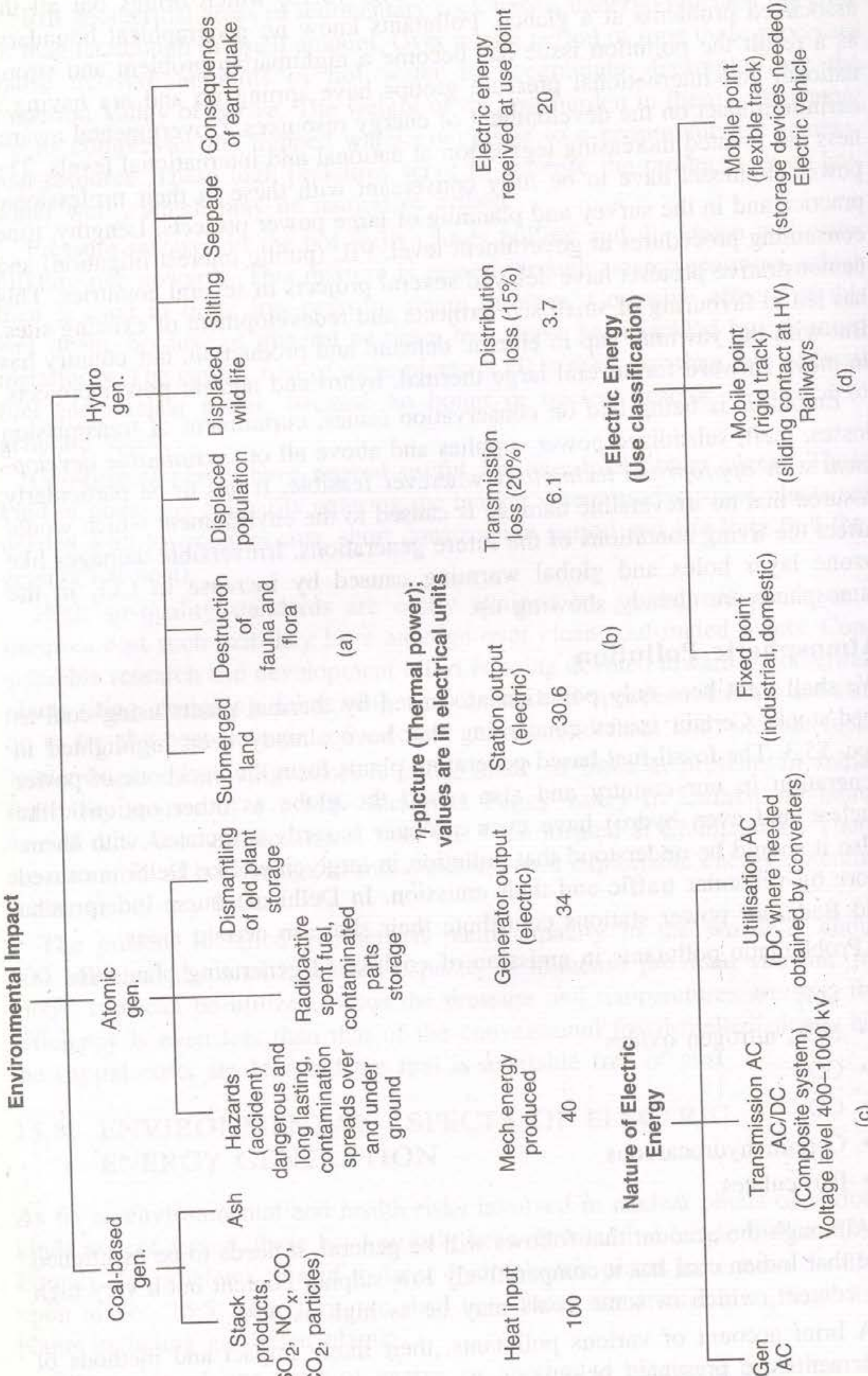


Fig. 15.15 *Environmental and other aspects of electric energy production and use*

Oxides of Sulphur (SO_2)

Most of the sulphur present in the fossil fuel is oxidized to SO_2 in the combustion chamber before being emitted by the chimney. In atmosphere it gets further oxidised to H_2SO_4 and metallic sulphates, which are the major source of concern as these can cause acid rain, impaired visibility and damage to buildings and vegetation. Sulphate concentrations of 9–10 $\mu g/m^3$ of air aggravate asthma, lung and heart disease. It may also be noted that although sulphur does not accumulate in air, it does so in soil.

Sulphur emission can be controlled by

- use of fuel with less than 1% sulphur; generally not a feasible solution;
- use of chemical reaction to remove sulphur in the form of sulphuric acid from combustion products by limestone scrubbers or fluidized bed combustion; and
- removing sulphur from the coal by gasification or floatation processes.

It has been noticed that the byproduct sulphur could off-set the cost of sulphur recovery plant

Oxides of Nitrogen (NO_x).

Of these NO_2 Nitrogen oxide, is a major concern as a pollutant. It is soluble in water and so has adverse affect on human health as it enters the lungs on inhaling and after combining with moisture converts to nitrous and nitric acids, which damage the lungs. At levels of 25–100 parts per million, NO_x can cause acute bronchitis and pneumonia.

Emission of NO_x can be controlled by fitting advanced technology burners which can assure more complete combustion, thereby reducing these oxides from being emitted by the stack. These can also be removed from the combustion products by absorption process by certain solvents going on to the stack.

Oxides of Carbon (CO, CO_2)

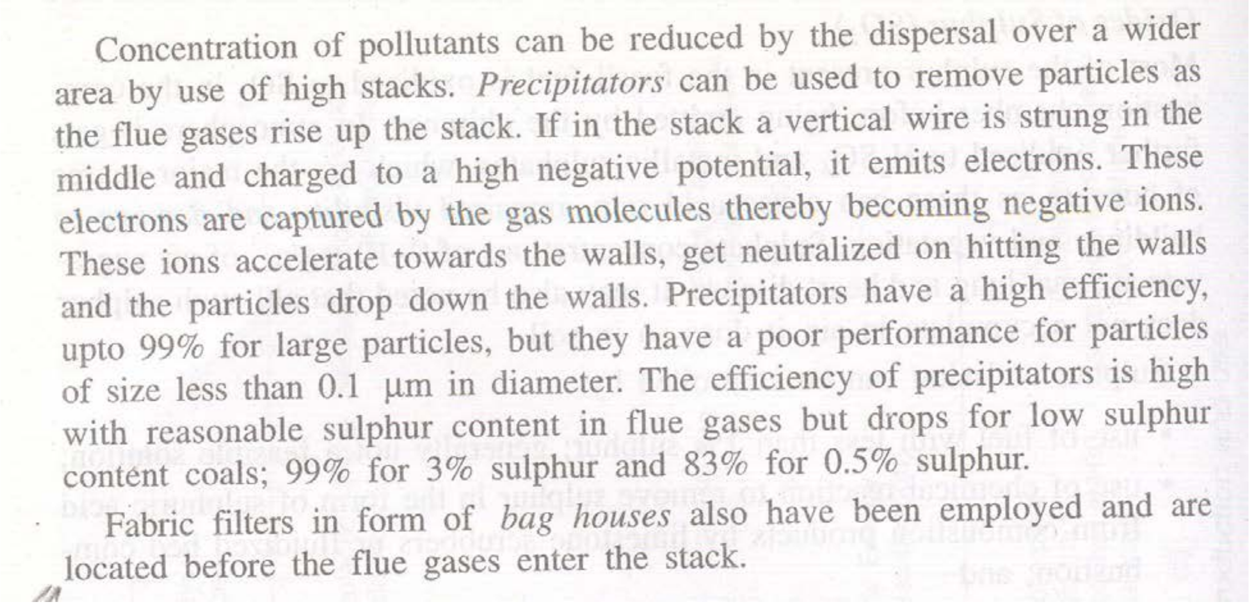
CO is a very toxic pollutant, but it gets converted to CO_2 in the open atmosphere (if available) surrounding the plant. On the other hand CO_2 has been identified as a major cause of global warming. It is not yet a serious problem in developing countries.

Hydrocarbons

During the oxidation process in combustion chamber certain light weight hydrocarbons may be formed. The compounds are a major source of photochemical reaction that adds to depletion of ozone layer.

Particulates (Fly ash)

Dust content is particularly high in the Indian coal. Particulates come out of the stack in the form of fly ash. It comprises fine particles of carbon, ash and other inert materials. In high concentrations, these cause poor visibility and respiratory diseases.

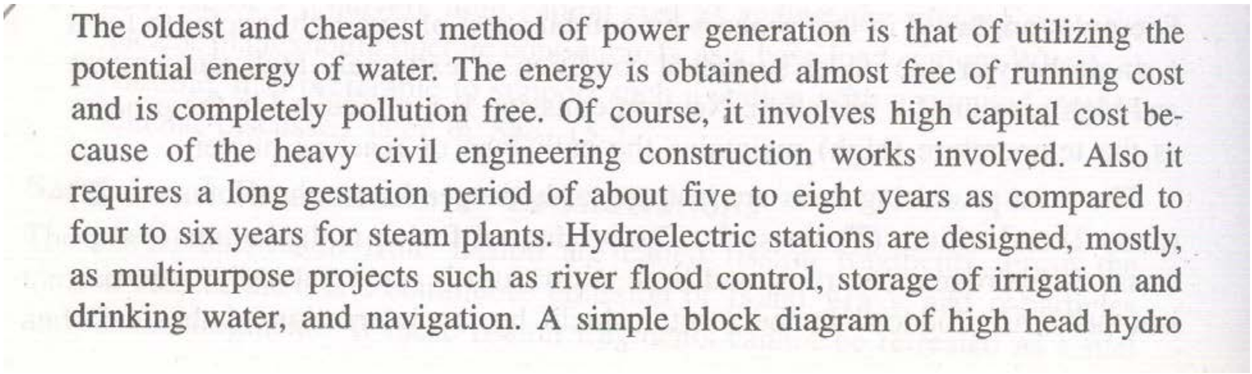


Concentration of pollutants can be reduced by the dispersal over a wider area by use of high stacks. *Precipitators* can be used to remove particles as the flue gases rise up the stack. If in the stack a vertical wire is strung in the middle and charged to a high negative potential, it emits electrons. These electrons are captured by the gas molecules thereby becoming negative ions. These ions accelerate towards the walls, get neutralized on hitting the walls and the particles drop down the walls. Precipitators have a high efficiency, upto 99% for large particles, but they have a poor performance for particles of size less than 0.1 μm in diameter. The efficiency of precipitators is high with reasonable sulphur content in flue gases but drops for low sulphur content coals; 99% for 3% sulphur and 83% for 0.5% sulphur.

Fabric filters in form of *bag houses* also have been employed and are located before the flue gases enter the stack.

b. How can we generate electricity with the help of Hydro power plant? Explain with it's schematic diagram. What are the merits and de-merits of it over other methods of power generation. (8)

Answer:



The oldest and cheapest method of power generation is that of utilizing the potential energy of water. The energy is obtained almost free of running cost and is completely pollution free. Of course, it involves high capital cost because of the heavy civil engineering construction works involved. Also it requires a long gestation period of about five to eight years as compared to four to six years for steam plants. Hydroelectric stations are designed, mostly, as multipurpose projects such as river flood control, storage of irrigation and drinking water, and navigation. A simple block diagram of high head hydro plant is given in Fig. 15.11. The vertical difference between the upper reservoir and the tail race pond is called the *head.*

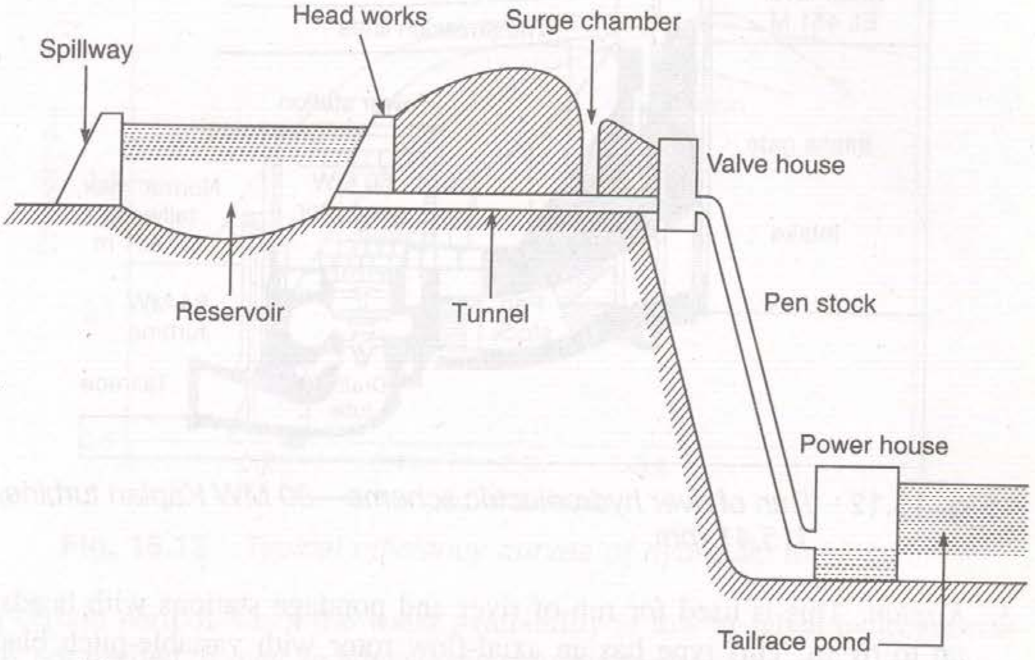


Fig. 15.11 *A typical layout for a storage type hydro plant*

Water falling through the head gains kinetic energy which then imparts energy to the blades of the hydraulic turbine. There are three main types of hydroelectric installations. These are

1. *High head or stored*—the storage area or reservoir fills in more than 400 h.
2. *Medium head or pondage*—the storage fills in 200–400 h.
3. *Run of river*–storage (if any) fills in less than 2 h and has a 3–15-m head.

A schematic diagram for hydroelectric schemes of Type 3 is shown in Fig. 15.12.

There can be several of these turbines on a deep and wide river.

In India mini and micro hydroelectric schemes have been installed on canals wherever 1 m or so head is available. Often cascaded plants are also constructed on the same water stream where the discharge of one plant becomes the inflow of a downstream plant.

For the three above identified heads of water level, the kind of turbines that are employed

1. *Pelton*: This is used for heads of 184–1840 m and consists of a bucket wheel rotor with adjustable flow nozzles.
2. *Francis*: This is used for heads of 37–490 m and is of mixed flow type.

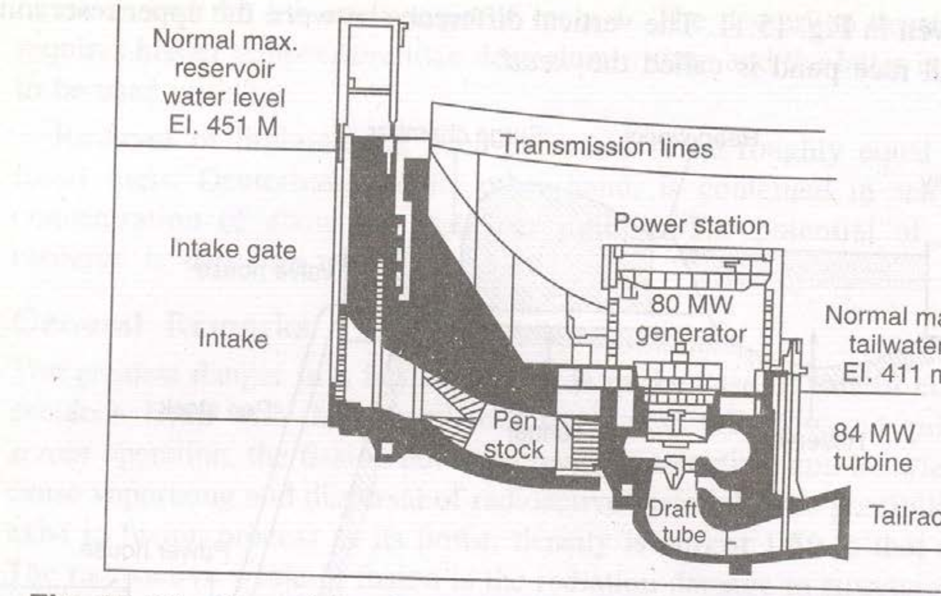


Fig. 15.12 *Run of river hydroelectric scheme—80 MW Kaplan turbine, 115.41 rpm*

3. *Kaplan:* This is used for run-of-river and pondage stations with heads of up to 61 m. This type has an axial-flow rotor with variable-pitch blades.

Hydroelectric plants are capable of starting quickly—almost in 5 min. The rate of taking up load on the machines is of the order of 20 MW/min. Further, no losses are incurred at standstill. Thus, hydroelectric plants are ideal for meeting peak loads. The time from start up to the actual connection to the grid can be as short as 2 min.

The power available from a hydro plant is

$$P = 981\ \rho\ WH\ W$$

where W = discharge m^3/s through turbine, ρ = density 1000 kg/m^3 and H = head m.

Problems peculiar to hydroelectric plants which inhibit expansion are

1. Silting—Bhakra dead storage has reportedly silted fully in 30 years
2. Seepage
3. Ecological damage to region
4. Displacement of human habitation from areas behind the dam which will fill up and become a lake.
5. These cannot provide base load and must be used for peak shaving and energy saving in coordination with thermal plants.

Typical efficiency curves of the three types of turbines are depicted in Fig. 15.13. As the efficiency depends upon the head, which is continuously fluctuating, water consumption in m^3/kWh is used instead of efficiency, which is related to water head.

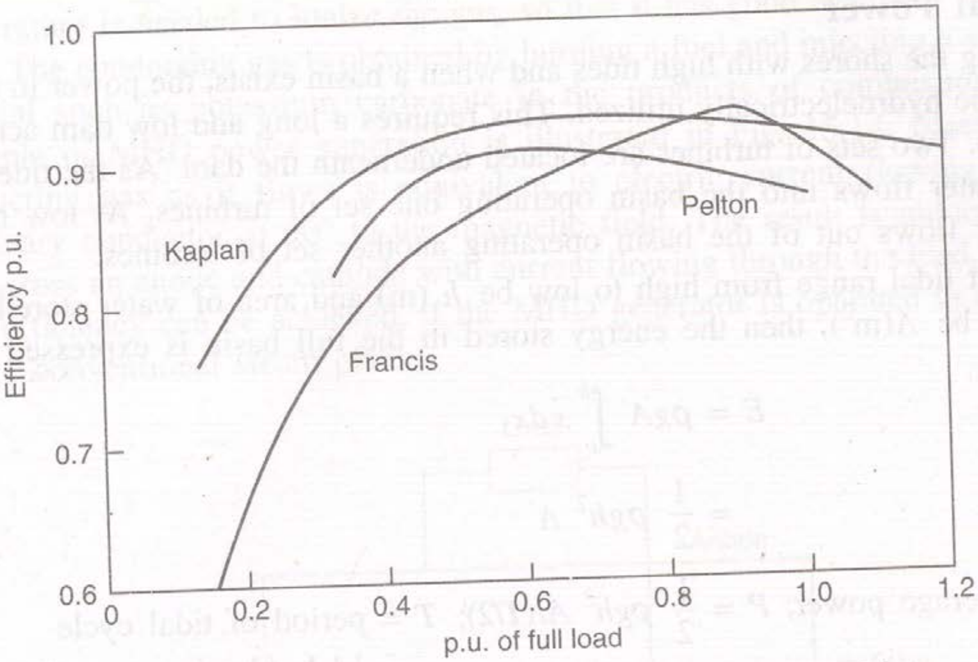


Fig. 15.13 *Typical efficiency curves of hydraulic turbines*

In certain periods when the water availability is low or when hydrogeneration is not needed, it may be advantageous to run electric generators as motors from the grid, so as to act as synchronous condensers (these are overexcited). To reduce running losses the water is pushed below the turbine runner by compressed air after closing the input valve. The runner now rotates in air and free running losses are low.

Q.9 a. What are the applications of fuel cell? Which is different type of fuel cell used in power system? Explain them. (8)

Answer:

Fuel Cell

A fuel cell converts chemical energy to electrical form by electrochemical reaction. One electrode is continuously supplied with fuel and the other with an oxidant (usually oxygen). A simple form of a fuel cell is shown in Fig. 15.44 where the fuel is hydrogen, which diffuses through a porous metal (nickel) electrode. This electrode has a catalyst deposited around the pores, which aids the absorption of H_2 on its surface. In this process hydrogen ions react with hydroxyl ions in the electrolyte to form water ($2H_2 + O_2 \rightarrow 2H_2O$). The cell has a theoretical emf of 1.2 V at 25°C. Other fuels are CO (1.33 V) and methanol (1.21V) both at 25°C. Conversion efficiencies of practical cell are about 80%. The major use of the cell is in conjunction with hydrogen–oxygen system.

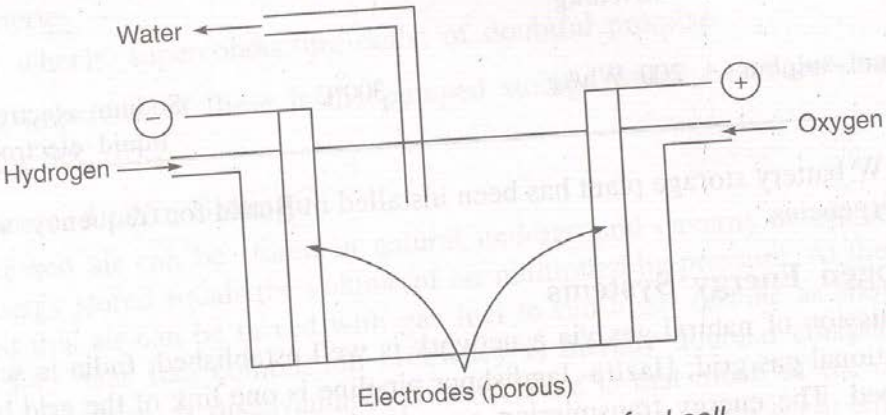
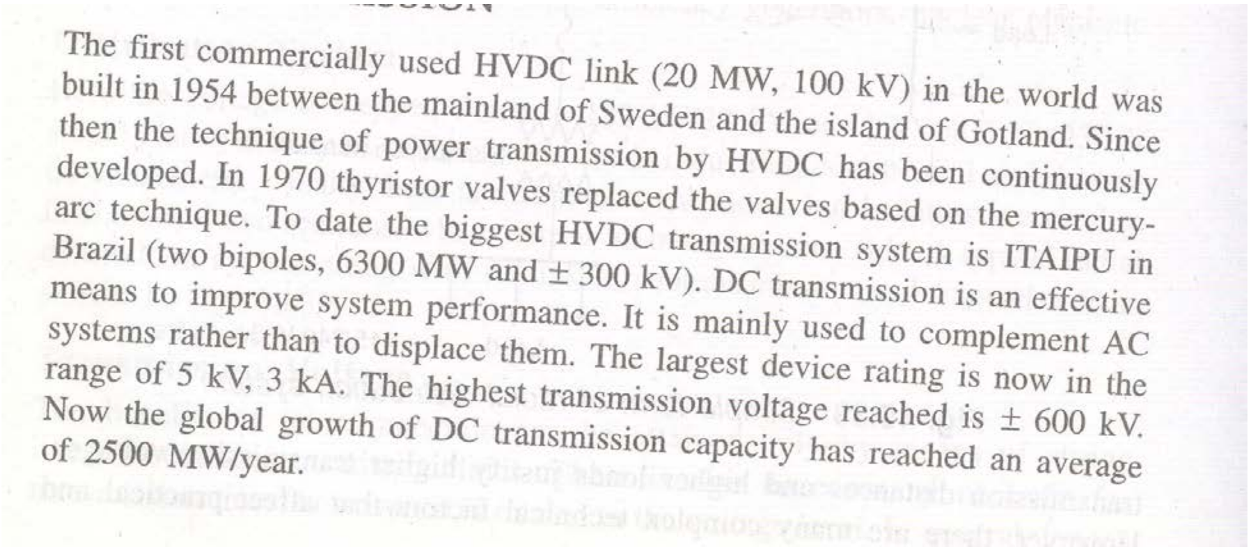


Fig. 15.44 *Hydrogen–oxygen fuel cell*

Intense R&D effort is on for various types of cells for power generation. Most successful of these is the phosphoric cell, which uses methane as fuel and operates at about 200–300°C. It has been constructed to produce 200 kW of electric power plus 200 kW heat energy with an overall efficiency of 80%. Higher temperatures give still higher efficiency.

b. **Explain High voltage DC transmission. Draw the block diagram representing main components of HVDC transmission. Also explain the advantages and disadvantages of HVDC transmission. (8)**

Answer:



The first commercially used HVDC link (20 MW, 100 kV) in the world was built in 1954 between the mainland of Sweden and the island of Gotland. Since then the technique of power transmission by HVDC has been continuously developed. In 1970 thyristor valves replaced the valves based on the mercury-arc technique. To date the biggest HVDC transmission system is ITAIPU in Brazil (two bipoles, 6300 MW and ± 300 kV). DC transmission is an effective means to improve system performance. It is mainly used to complement AC systems rather than to displace them. The largest device rating is now in the range of 5 kV, 3 kA. The highest transmission voltage reached is ± 600 kV. Now the global growth of DC transmission capacity has reached an average of 2500 MW/year.

Apart from 3 back-to-back HVDC stations already in operation in India, HVDC lines from Chandrapur to Padghe have been commissioned in 1999. The rating of this system is 1500 MW, ± 500 kV bipolar with a length of 754 km.

Principle of AC/DC Conversion

HVDC transmission consists of two converter stations which are connected to each other by a DC cable or an overhead DC line. A typical arrangement of main components of an HVDC transmission is shown in Fig. 15.41.

Two series connected 6-pulse converters (12-pulse bridge) consisting of thyristor valves and converter transformers are used. The valves convert AC to DC, and the transformer provides a suitable voltage ratio to achieve the desired direct voltage and galvanic separation of the AC and the DC systems. A smoothing reactor in the DC circuit reduces the harmonic currents in the DC line, and the possible transient overcurrents.

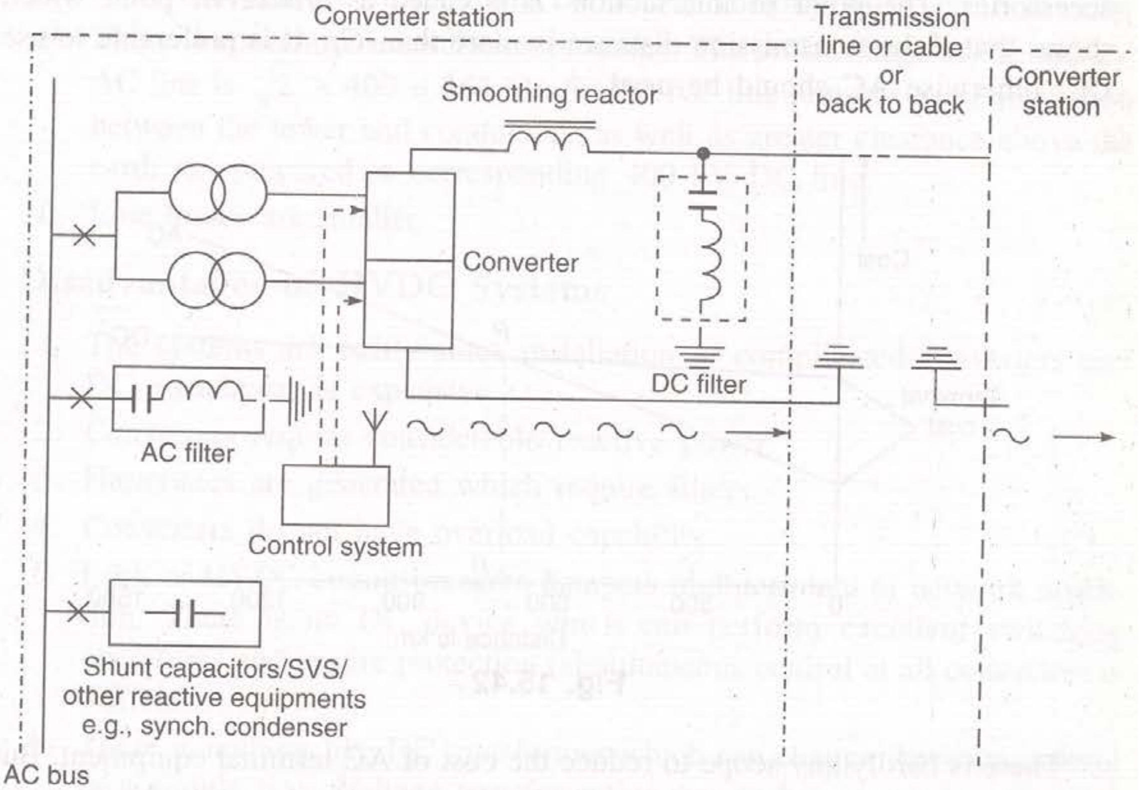


Fig. 15.41 *Main components of a HVDC transmission—a typical arrangement*

Filters are used to take care of harmonics generated at the conversion. Thus we see that in an HVDC transmission, power is taken from one point in an AC network, where it is converted to DC in a converter station (rectifier), transmitted to another converter station (inverter) via line or a cable and injected into an AC system.

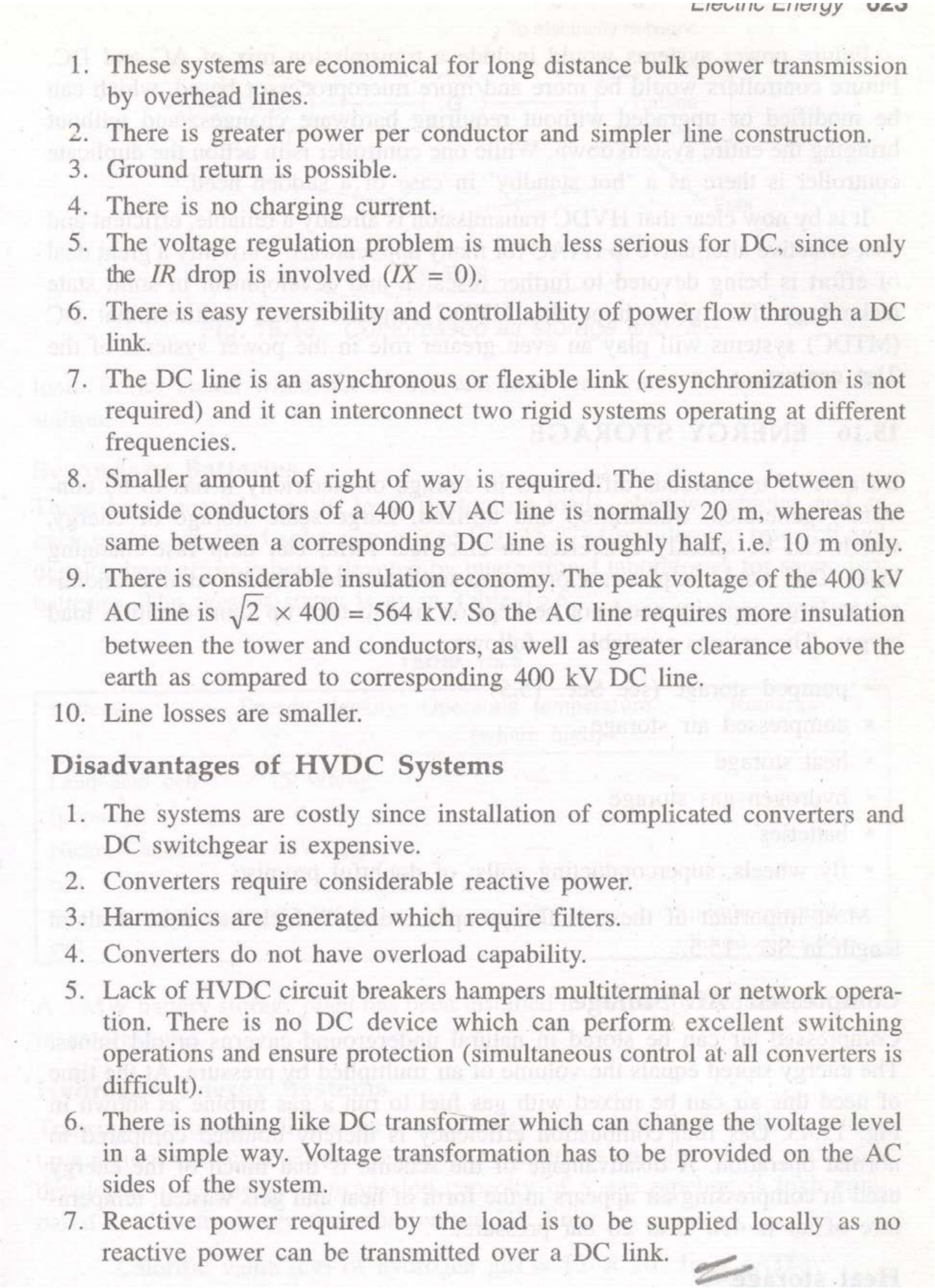
By varying the firing angle α (point on the voltage wave when the gating pulse is applied to a thyristor), the DC output voltage can be controlled between two limits, + ve and – ve. When α is varied, we get:

Maximum DC voltage when $\alpha = 0°$
Rectifier operation when $0 < \alpha < 90°$
Inverter operation when $90° < \alpha < 180°$

While discussing inverter operation, it is common to define extinction angle $\gamma = 180° - \alpha$.

Advantages of HVDC Systems

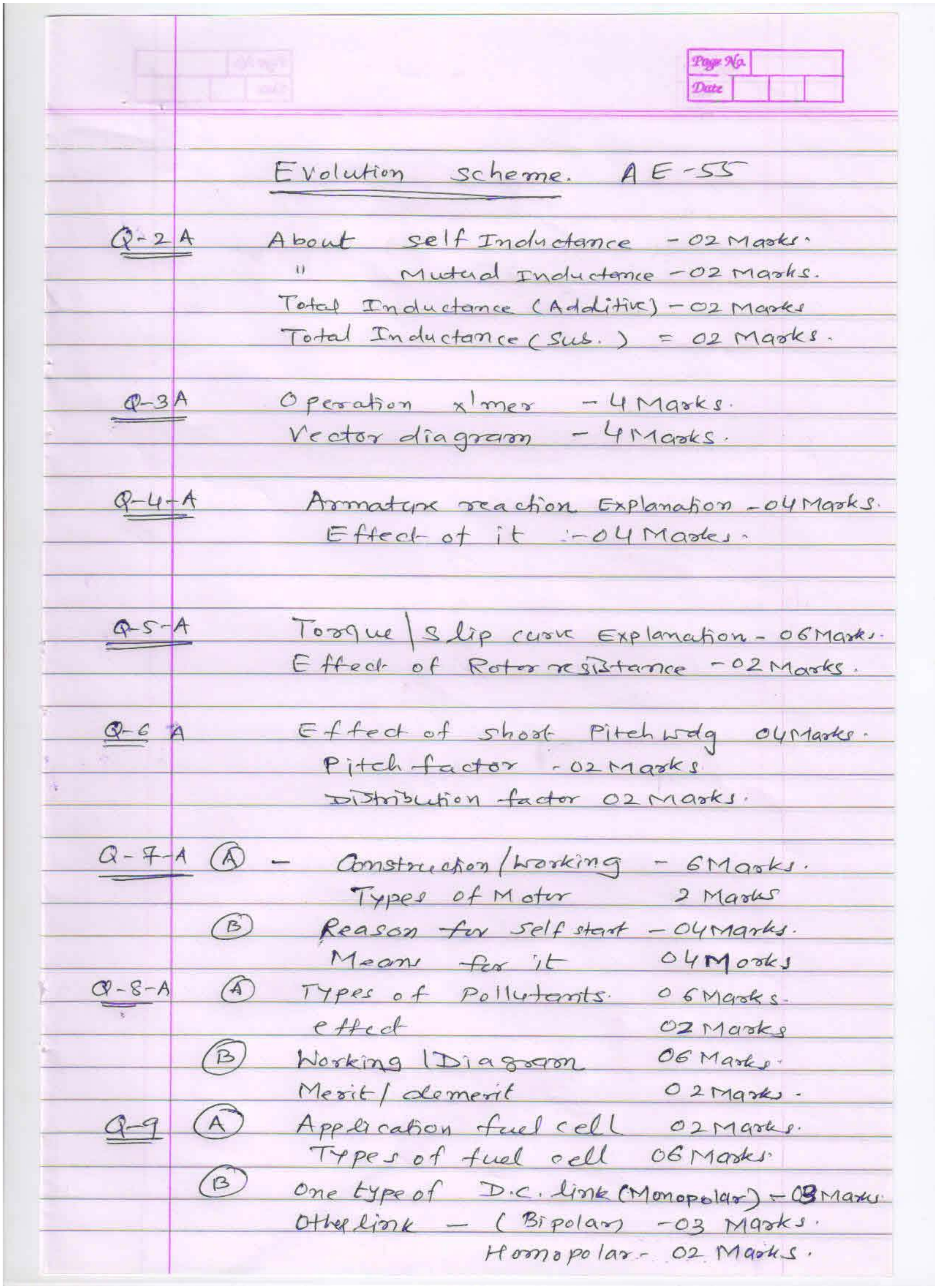
The advantages of the HVDC systems are as follows:



1. These systems are economical for long distance bulk power transmission by overhead lines.
2. There is greater power per conductor and simpler line construction.
3. Ground return is possible.
4. There is no charging current.
5. The voltage regulation problem is much less serious for DC, since only the IR drop is involved ($IX = 0$).
6. There is easy reversibility and controllability of power flow through a DC link.
7. The DC line is an asynchronous or flexible link (resynchronization is not required) and it can interconnect two rigid systems operating at different frequencies.
8. Smaller amount of right of way is required. The distance between two outside conductors of a 400 kV AC line is normally 20 m, whereas the same between a corresponding DC line is roughly half, i.e. 10 m only.
9. There is considerable insulation economy. The peak voltage of the 400 kV AC line is $\sqrt{2} \times 400 = 564$ kV. So the AC line requires more insulation between the tower and conductors, as well as greater clearance above the earth as compared to corresponding 400 kV DC line.
10. Line losses are smaller.

Disadvantages of HVDC Systems

1. The systems are costly since installation of complicated converters and DC switchgear is expensive.
2. Converters require considerable reactive power.
3. Harmonics are generated which require filters.
4. Converters do not have overload capability.
5. Lack of HVDC circuit breakers hampers multiterminal or network operation. There is no DC device which can perform excellent switching operations and ensure protection (simultaneous control at all converters is difficult).
6. There is nothing like DC transformer which can change the voltage level in a simple way. Voltage transformation has to be provided on the AC sides of the system.
7. Reactive power required by the load is to be supplied locally as no reactive power can be transmitted over a DC link.



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Evolution scheme. AE-55

Q-2 A About self Inductance - 02 Marks.
" Mutual Inductance - 02 Marks.
Total Inductance (Additive) - 02 Marks
Total Inductance (Sub.) = 02 Marks.

Q-3 A Operation x'mer - 4 Marks.
Vector diagram - 4 Marks.

Q-4-A Armature reaction Explanation - 04 Marks.
Effect of it :- 04 Marks.

Q-5-A Torque|Slip curve Explanation - 06 Marks.
Effect of Rotor resistance - 02 Marks.

Q-6 A Effect of short Pitch wdg 04 Marks.
Pitch factor - 02 Marks
Distribution factor 02 Marks.

Q-7-A Ⓐ - Construction/Working - 6 Marks.
Types of Motor 2 Marks
Ⓑ Reason for self start - 04 Marks.
Means for it 04 Marks

Q-8-A Ⓐ Types of Pollutants. 06 Marks.
effect 02 Marks
Ⓑ Working |Diagram 06 Marks.
Merit / demerit 02 Marks.

Q-9 Ⓐ Application fuel cell 02 Marks.
Types of fuel cell 06 Marks.
Ⓑ One type of D.C. link (Monopolar) - 03 Marks.
Other link - (Bipolar) - 03 Marks.
Homopolar - 02 Marks.

Text Book

Basic Electrical Engineering, D P Kothari and I J Nagrath , Tata Mcgraw-hill Publishing Company Limited ,2nd edition ,13th Reprint 2006.