Unit-IV

Electrical Machine

Unit-IV

ElectroMechanical Energy Conversion

The Conversion of Electrical Energy Into Mechanical energy or vice-versa is known as ElectroMechanical Energy Conversion result from two Phenomenon

(i) When a Conductor Moves Into a Magnetic field, voltage is Induced In the conductor

$e = N\frac{d\phi}{dt}$ N = No. of turns
  ϕ = Flux

(2) When a current carrying conductors is placed in a magnetic field it experience mechanical force $F = BiL$ l = Length of Conductor
  i = current
  B = Flux density

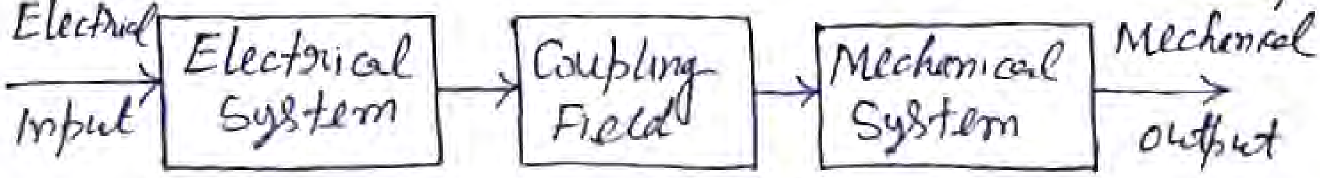
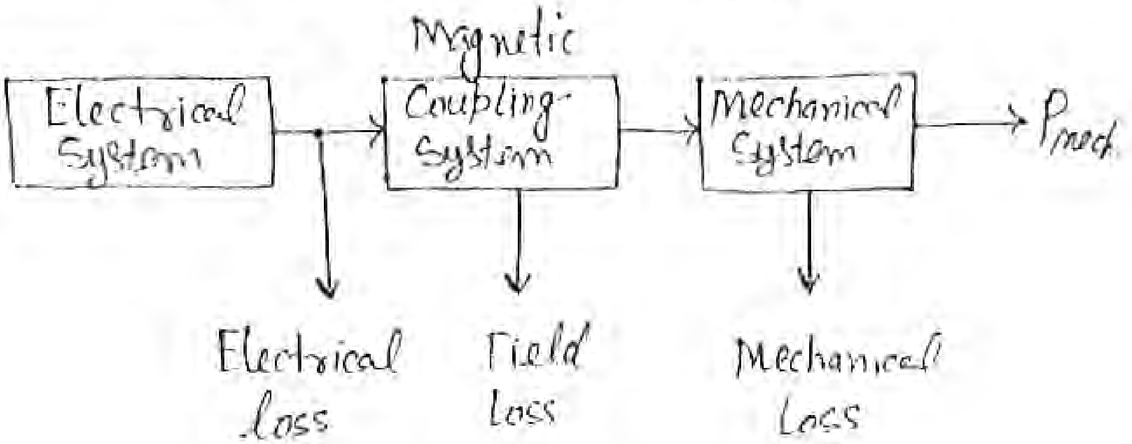


Fig- ElectroMechanical Energy Conversion System

In Motor action, the current carrying conductor placed In a magnetic field. the conductor experience a force that tends to move it. If the conductor is free to move in the direction of magnetic field. the magnetic field help to Convert Electrical Energy Into Mechanical Energy

In generating mode, if an externally applied force moves the conductor in a direction opposite to the magnetic force, mechanical energy is converted into electrical energy.

Electromechanical energy conversion take place through the medium of magnetic field. During electromechanical energy conversion, various losses occur in the system as show in fig.



$$\begin{pmatrix}\text{Electrical energy}\\ \text{Input from Source}\end{pmatrix} = \begin{pmatrix}\text{Mechanical}\\ \text{energy}\\ \text{output}\end{pmatrix} + \begin{pmatrix}\text{Increase in}\\ \text{energy stored}\\ \text{in coupling}\\ \text{field}\end{pmatrix} + \begin{pmatrix}\text{Energy}\\ \text{loss}\end{pmatrix}$$

Armature Winding => It is that in which working emf is induced by the working flux. it carries only load current. the winding on the machine that carry only load current is called armature winding.

Field => The winding that handles only exciting current is called field winding. The current in the field winding is always d.c.

The current that produced only a working magnetic field and does not vary with the load on the machine is called magnetizing current or exciting current or field current.

A winding which handles both the exciting and load current is called the primary winding of that machine.

The armature winding of both d.c. & A.C. Machine have to deal with alternating current only this is the reason why the armature structure of all rotating machine are laminated in order to reduce the eddy current only

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Circuit model of a D.C. machine :-

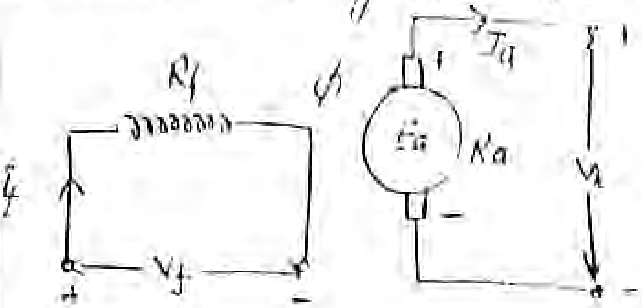

fig - Circuit model of d.c machine

Generating mode → The machine operates in generating mode when I_a is in the direction of induced emf E_a as ~~in~~ fig

$$V_t = E_a - I_a R_a \qquad E_a > V_t$$

Mechanical power converted to electrical form

$$P_{mech} = E_a I_a = P_{ele}$$

$$P_o = V I_a$$

(o = out)

Motoring mode :→ In this mode I_a flows in opposition to induced emf E_a. E_a is now known as the back emf

$$V_t = E_a + I_a R_a \qquad V_t > E_a$$

$$P_i = V I_a$$

(i = input)

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E.M.F equation of a D.C. generator :-

Let in a d.c. machine

ϕ = flux per pole in weber

Z = total number of armature conductor

P = No. of poles

N = Speed in r.p.m

A = No. of parallel path e.i. A = 2 for wave winding
A = P for Lap winding

e.m.f. induced in the armature conductor

$$e = \frac{d\phi}{dt}$$

during one revolution of armature in a P pole generator/motor, each armature conductor cut the magnetic flux P time

So magnetic flux cut by each conductor in one revolution

$$d\phi = P\phi \text{ webers}$$

N = No. of revolution made by armature per minute

per Second = $\frac{N}{60}$

Therefore flux cut by each conductor per second

= flux cut by one conductor per revolution × no. of revolution of armature per second

$$= \phi P \times \frac{N}{60} = \frac{P\phi N}{60}$$

The average emf induced in the coil

$$e = \frac{\phi P N}{60}$$

This is emf in one conductor so the total emf generated between the terminal is given by

average emf induced in one conductor × no. of conductor in each parallel path

No. of conductor in each parallel path

$$E = \frac{\phi P N}{60} \times \frac{Z}{A}$$

$$\boxed{E = \frac{P\phi Z N}{60A}}$$

This is called the emf equation. In this eqn. P, N, Z & A are constant so

$$E = K\phi$$

$$\boxed{E \propto \phi}$$

This is fundamental equation for dc machine [illegible]

Torque Equation :-> Power developed in the armature given by work done per second i.e. = $T_e \times \omega$

T_e = Electromagnetic torque
ω = angular velocity i.e. given by $2\pi \times n$
n is speed in rps

Therefore Power developed = $T_e \times 2\pi n$
electrical energy of this power developed = $E_b I_a$
In the steady State

Mechanical power = Electrical power

$$T_e \times 2\pi n = E_b I_a$$

$$T_e = \frac{E_b I_a}{2\pi n}$$

$$T_e = \frac{E_b I_a}{\frac{2\pi N}{60}}$$

$$T_e = \frac{E_b I_a \times 60}{2\pi N}$$

$$T_e = \frac{\frac{P\phi Z N}{60 A} \times I_a \times 60}{2\pi N}$$

$$T_e = \frac{P\phi Z I_a}{2\pi A}.$$

$$\boxed{T_e = 0.159 \frac{P\phi Z I_a}{A}} \text{ NM}$$

Since Z, P & A are constant

$$T_a \propto \phi I_a$$

for a shunt motor, flux ϕ is practically constant

$$T_a \propto I_a$$

for a series motor:

flux/pole $\phi_a = I_a$

$$T_a \propto I_a^2$$

Separate excitation
Separate excited D.C generator

Series excitation
Series wound Generator

Self excitation
Self excited D.C Generator

Shunt excitation
Shunt wound Generator

Compound excitation
Compound wound generator

Long shunt
Long Shunt Compound wound generator

Short shunt
Short Shunt Compound wound generator

Method of Excitation →

A d.c machine can work as an ~~electromag~~ Electromechanical energy converter only when its field winding is excited with direct current.

There are two method of exciting the field winding of d.c machine

(a) Separate excitation

(b) Self excitation

- Series
- Shunt
- Compound

(a) Separate excitation :⇒ The seprate excited field winding consists of several hundred turns of fine wire and is connected to a seprate or external d.c. source as shown in fig. The voltage of the external d.c. source has no relation with the armature voltage.

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(b) Self-excitation:- when field winding is excited by its own armature the machine is said to be a self excited d.c machine. In these machine, the field poles must have a residual magnetism. So that when armature rotates, a residual voltage appears across the brushes. this residual voltage should establish a current in the field winding so as to reinforce the residual flux.

a self excited d.c. machine can be sub-divided as

(a) (I) Series excitation:- The field winding consists of a few turns of thick wire and is connected in series with the armature as shown in fig. In other words, the series field current depends on the armature current

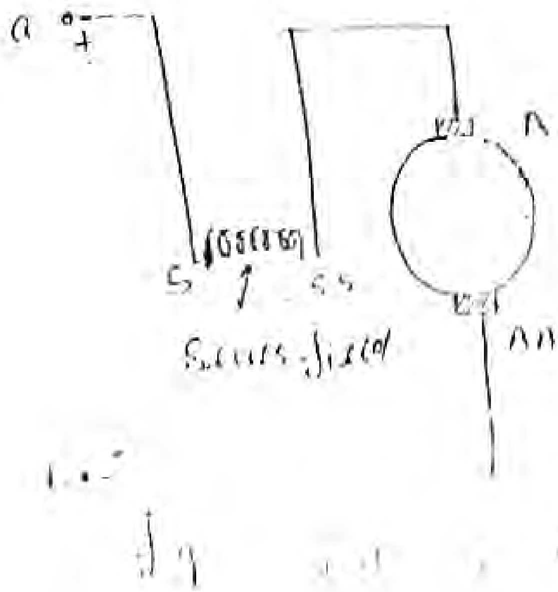

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fig [illegible]

2. Shunt excitation: The field winding consists of a large number of turns of fine wire and is connected in parallel (or in shunt) with the armature, as in fig. Therefore, the voltage across the armature terminal and the shunt field is the same so it is called voltage-operated field

3) Compound excitation:→ A compound excitation involves both the series excited winding and shunt excited winding.

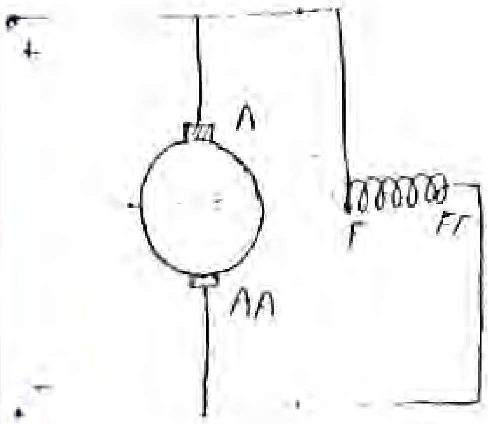

fig - Shunt excited dc machine

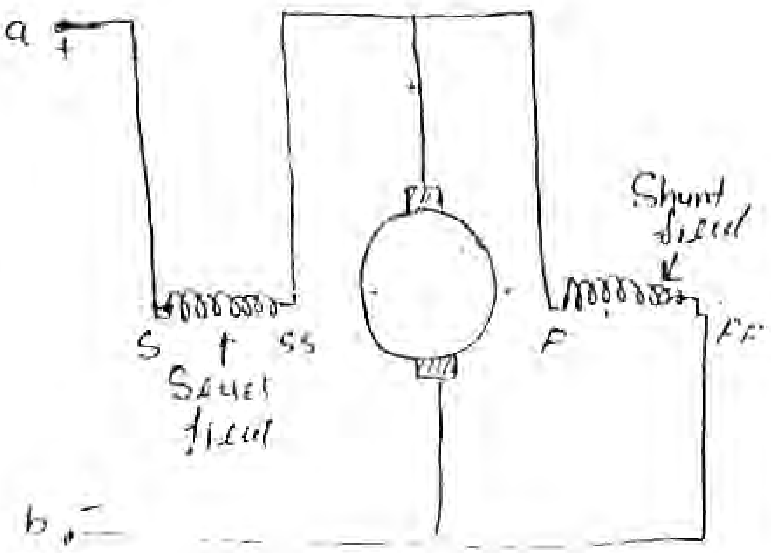

fig - Compound excited d[illegible]

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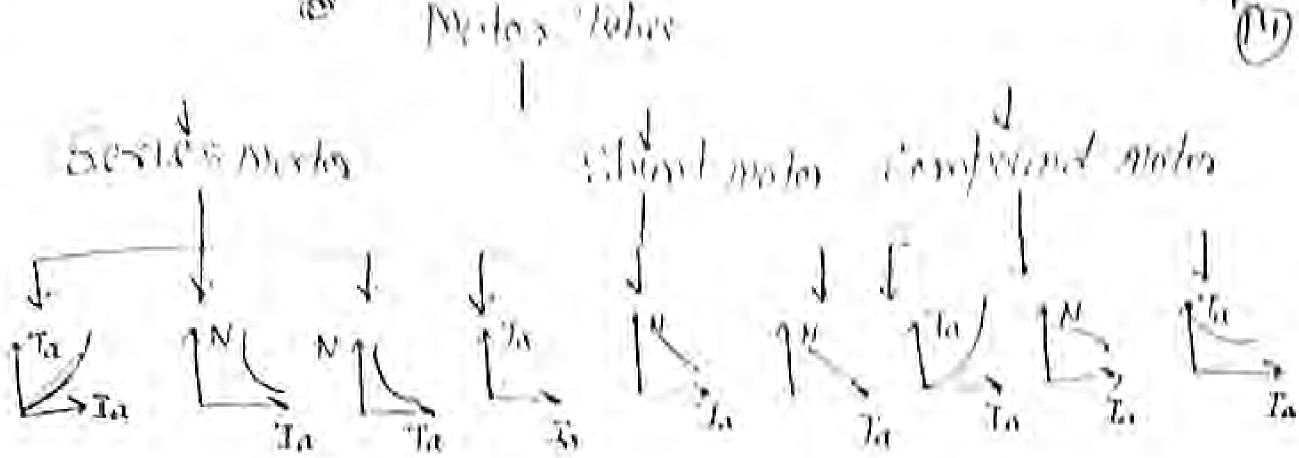
Characteristics of D.C Motors :-

The performance of d.c motor can be judged from its characteristics curves known as motor characteristics. There are three characteristics of D.C motor

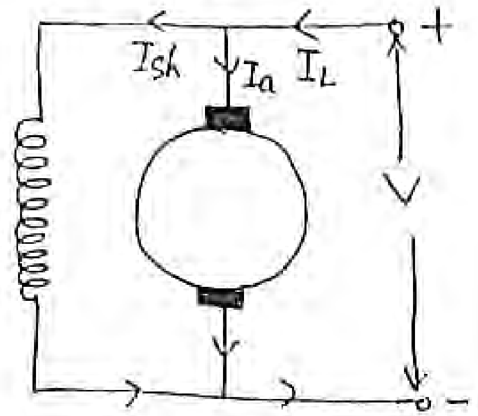
(1) Torque and Armature current characteristics or electrical characteristics (T_a/I_a)

(2) Speed and armature current characteristics (N/I_a)

(3) Speed and Torque characteristics (N/T_a) or Mechanical characteristics



Characteristics of Shunt Motor :- Fig shows the connection of a d.c. Shunt motor. The Field current I_{sh} is constant since the field winding is directly connected to the supply voltage V which is assumed to be constant. Hence the flux in the shunt motor is approximately constant.



(1) Ta/Ia Characteristics :-> We know that in a d.c Motor

$$T_a \propto \phi I_a$$

Since the motor is operating from a constant supply voltage, the flux ϕ is constant

$T_a \propto I_a$ see curve in Book.

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Applications of DC Motors → DC Motors are very commonly used as Variable-speed drives and in applications where torque variations occur. The d.c. motor offers a wide range of control of speed and torque as well as excellent acceleration and deceleration.

The main applications of the three types of dc motors are given below

Type of motor	Characteristics	Applications
Shunt	Speed is fairly constant and medium starting Torque	1) Blowers and fans 2) Centrifugal and reciprocating pumps 3) Lathe machines (4) Machine Tools 5) Milling Machines (6) Drilling m/c (7) Wood-working machines & Printing-Press
Series	High starting torque. No Load condition is dangerous. variable speed	1) Cranes (2) Hoists, elevators 3) Trolleys (4) conveyors (5) Electric Locomotives (6) Vacuum cleaners, (7) Sewing machine (8) As a Traction Motors
Cumulative Compound	High starting torque, No load condition is allowed	1) Rolling mills (2) Punches (3) Shears (4) Heavy planers (5) Elevators (6) Lifts (7) mine-hoists
Differential Compound	Speed increase as load increases	Not suitable for any practical applications

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3 - Phase Induction Motor

The Three Phase Induction Motor is the most commonly used ~~an~~ Motor in any power System. These motor are more rugged, they need less maintenance, and they are less expensive than the Synchronous motor or dc Motor.

Construction :→ There are two types of Poly Phase Induction motor

(1) Squirrel Cage Motor

(2) Slip ring Induction Motor

details (any book)

Principle of working :→ any Book

Emf equation :→ Same as transformer

$$E_1 = 4.44 k_1 f_1 N_1 \phi$$

$$E_2 = 4.44 k_2 f_2 N_2 \phi$$

under Slip

$$S E_2 = 4.44 k_2 S f_2 N_2 \phi$$

Slip $S = \frac{N_S - N_r}{N_S} \times 100$

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Rotor phase current at standstill $= \frac{E_2}{\sqrt{r_2^2 + x_2^2}}$

" " " " slip s, $I_2 = \frac{s \cdot E_2}{\sqrt{r_2^2 + (s \cdot x_2)^2}}$

$$I_2 = \frac{s \cdot E_2}{s \cdot \sqrt{\left(\frac{r_2}{s}\right)^2 + x_2^2}} = \frac{E_2}{\sqrt{\left(\frac{r_2}{s}\right)^2 + x_2^2}} \quad \text{---- (1)}$$

The rotor current I_2 lags the rotor voltage E_2 by phase factor θ_2. eq^n ~~(1) Can be represented~~

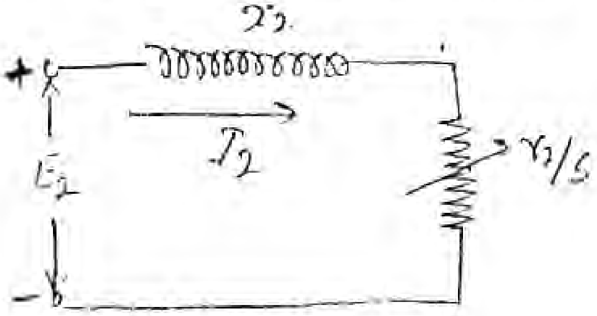

fig- equivalent Circuit of Rotor

$$\theta_2 = \tan^{-1} \frac{s x_2}{r_2}$$

Now air gap power $P_g = E_2 I_2 \cos\theta_2$ ---- (2)

Single Phase power $P = VI \cos\phi$

$P = VI \cos\theta$

$3-\phi$ $P = 3 V_p I_p \cos\theta$ Phase voltage $\frac{V_{line}}{\sqrt{3}}$

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$$\cos\theta = \frac{r}{z} = \frac{r_2}{\sqrt{r_2^2+(sx_2)^2}} = \frac{r_2/s}{\sqrt{\left(\frac{r_2}{s}\right)^2+(x_2)^2}}$$

Rotor $\cos\theta_2 = \dfrac{r_2/s}{\sqrt{\left(\frac{r_2}{s}\right)^2+(x_2)^2}}$

So eqn (2) can be written as

$$P_g = E_2 I_2 \cos\theta_2$$

$$= E_2 \times \frac{E_2}{\sqrt{\left(\frac{r_2}{s}\right)^2+x_2^2}} \times \frac{r_2/s}{\sqrt{\left(\frac{r_2}{s}\right)^2+(x_2)^2}}$$

$$= \frac{E_2^2}{\left[\sqrt{\left(\frac{r_2}{s}\right)^2+x_2^2}\right]^2} \times r_2/s$$

$$\therefore P_g = I_2^2 \cdot r_2/s$$

$$P_g = I_2^2 \frac{r_2}{s} \quad I_2^2 r_2 + I_2^2 r_2\left(\frac{1-s}{s}\right)$$

$$P_g = I_2^2 \frac{r_2}{s} = I_2^2 r_2 - I_2^2 r_2 + I_2^2 \frac{r_2}{s}$$

$$= I_2^2 r_2 + I_2^2 \frac{r_2}{s} - I_2^2 r_2$$

$$= I_2^2 r_2 + I_2^2 r_2\left(\frac{1}{s} - 1\right)$$

$$P_g = I_2^2 r_2 + I_2^2 r_2\left(\frac{1-s}{s}\right)$$

Air gap power =
Rotor ohmic loss + Mechanical power developed (P_m)

$$P_g = I_2^2 r_2 + I_2^2 r_2\left(\frac{1-s}{s}\right)$$

$$P_g = \frac{s \cdot I_2^2 r_2}{s} + I_2^2 r_2\left(\frac{1-s}{s}\right)$$

$$P_g = \left(\frac{I_2^2 r_2}{s}\right) \cdot s + \left(\frac{I_2^2 r_2}{s}\right)(1-s)$$

$$P_g = P_g \cdot s + P_g(1-s)$$

Rotor ohmic loss — Mechanical power developed (P_m)

Rotor ohmic loss = $s \cdot P_g$

Mechanical power Developed $P_m = (1-s) P_g$

This mechanical power is called gross mechanical power.

$P_m = (1-s) P_g$

Torque ... Rotor speed in mechanical rad/sec

$$T_e = \frac{P_m}{\omega_r} = \frac{(1-s)P_g}{(1-s)\omega_s} = \frac{P_g}{\omega_s}$$ $s = \frac{N_s - N_r}{N_s}$

$sN_s = N_s - N_r$

$(1-s)N_s = N_r$

$$\omega_s = 2\pi n_s = 2\pi \times \frac{2f_1}{P} = \frac{4\pi f_1}{P}$$ Synchronous speed

or $$T_e = \frac{P_g}{\omega_s} = \frac{1}{\omega_s} \times \frac{I_2^2 r_2}{s} = \frac{\text{Rotor ohmic loss } (I_2^2 r_2)}{\text{Slip}(\omega_s)}$$

$$\boxed{T_e = \frac{1}{2\pi n_s} I_2^2 \frac{r_2}{s}}$$

Output or Shaft Power =

$P_{sh} = P_m$ − mechanical losses (friction and windage losses)

$P_m = (1-s)P_g = P_g - sP_g$ (ohmic loss)

$P_{sh} =$

$P_{sh} = P_g - s \cdot P_g$ − (friction losses and windage losses)

$P_{sh} =$ net Power output

Output / Shaft Torque, $T_{sh} = \frac{P_{sh}}{\text{Rotor speed}}$

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Torque slip and Torque speed characteristics:-

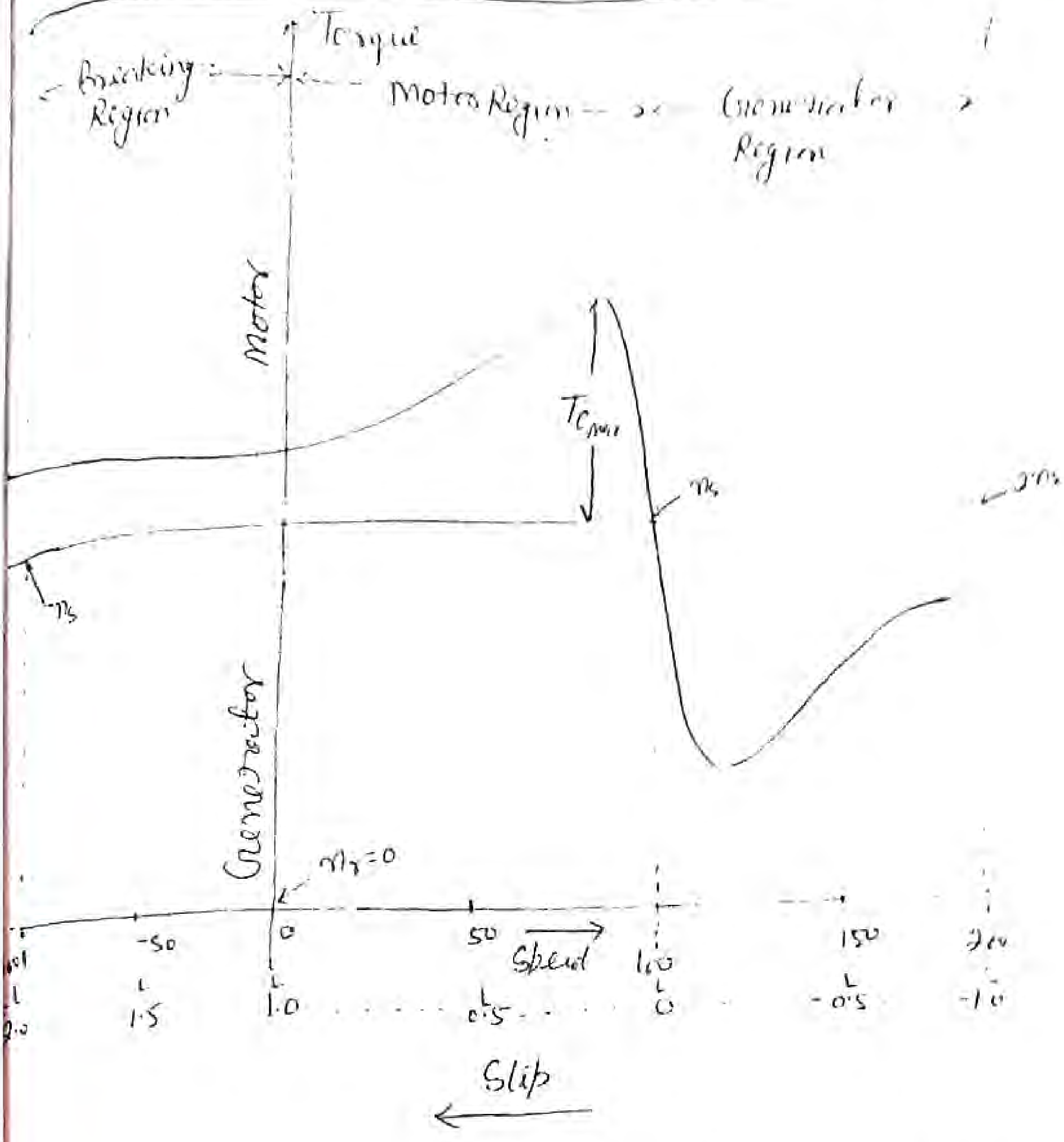

fig- Torque-slip curve and torque speed curve for an Induction machine

Gen Motor- Break

$$T = \frac{K S r_2 E_2^2}{r_2^2 + (S x_2)^2}$$

where

Motoring Mode $0 \leq S \leq 1$

Generating Mode $S < 0$

Breaking Mode $S > 1$

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(a) Motoring Mode → In this mode, electromagnetic torque is in the direction of the rotor rotation; i.e. the speed of the rotor counterpart o.t.o.m.

This is because under normal operation, rotor rotates in the direction of rotating field produced by the stator currents.

(b) Generating Mode → In this region, slip is negative i.e. $s < 0$. An Induction motor will operate in this region only when its stator terminals are connected to constant frequency voltage source and its rotor is driven above synchronous speed by a prime mover. The connection of stator terminals to voltage source is necessary in order to establish the rotating air-gap field at synchronous speed.

In case stator is disconnected from voltage source and rotor is driven above synchronous speed by the prime mover, no generating action would take place.

Breaking Mode S>1 :-

In this mode slip is greater than 1. this can be obtain by ~~driven~~ driving the rotor, with a prime mover, opposite to the direction of rotating field. But such an use in practice is rare. A practical utility of slip more than 1 is obtained by bringing the rotor to a quick stop by braking action, called Plugging. To obtain this any two stator leads are Interchanged. so the phase sequence is reversed and therefore the direction of rotating magnetic field suddenly opposite to that of the rotor rotation.

Single Phase Induction Motor
or
Fractional kilowatt Motors

Double Revolving field effect Theory
Equivalent circuit
Starting of Motor

Introduction :→

→ Used only Small Size, less than 2 H.P and Mostly in the fractional H.P. range. So also called fractional killwatt Motor

→ Relatively simple in Construction but more difficult to analysis, operate at low power factor and less efficient than 3-ϕ Induction Motor

→ Motor in the 1/8 to 3/4 H.P range are very widly used for fans, refregerator, mixers, vaccum Cleaners etc.

→ Use in very Small Size in toyys. Hair ~~dres~~ dressier etc.

Construction:-> (1) Very Similar to 3-ϕ Induction motor
(2) Rotor is always Squirrel Cage while Stator core is Single Phase winding
(3) Stator also carry an auxiliary winding for providing the Starting torque

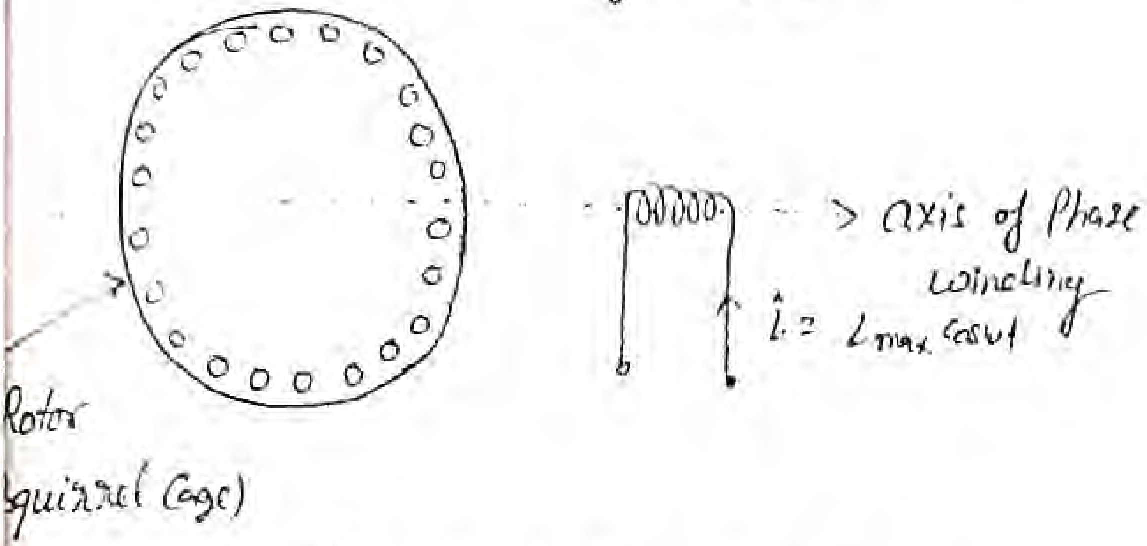

fig- Single Phase Induction Motor

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Double Revolving Field Theory :->

When the Stator winding carries a Sinusoidal current. It produces a Sinusoidally space-distributed mmf whose peak value pulsates with time.

mmf at any time t

$F = F_{peak} \cos\omega t$

$F = F_{peak} \cos\theta$. (1) $F_1 = F_{peak}$

~~$F_{peak} = F_{max} \cos\omega t$~~

$F_1 = F_{peak} = F_{max} \cos\omega t$ (2)

$F = F_{max} \cos\omega t \cdot \cos\theta$

$F = \frac{1}{2} \times 2 F_{max} \cos\omega t \cos\theta$

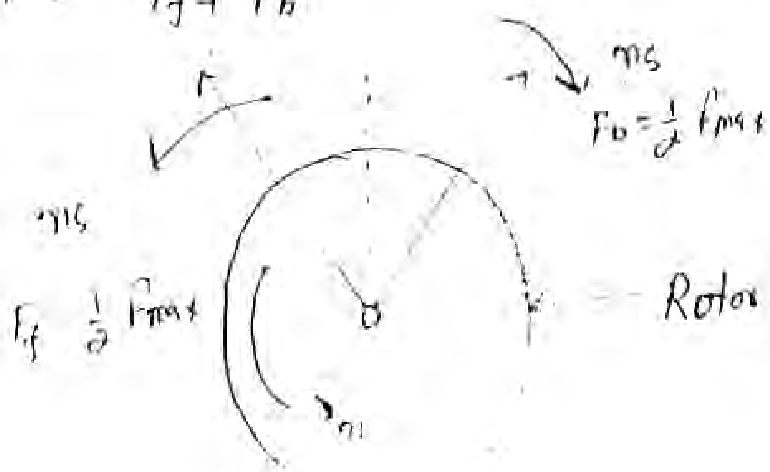
$F = \frac{1}{2} F_{max} \left[2 \cos\theta \cos\omega t \right]$

$F = \frac{1}{2} F_{max} \left[\cos(\theta + \omega t) + \cos(\theta - \omega t) \right]$

$F = \frac{1}{2} F_{max} \cos(\theta - \omega t) + \frac{1}{2} F_{max} \cos(\theta + \omega t)$

$F = 0.5 F_{max} \cos(\theta - \omega t) + 0.5 F_{max} \cos(\theta + \omega t)$ (4)

$F = F_f + F_b$



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This equation tell that a single-phase field can be considered as superposition of two rotating fields rotating at synchronous speed in opposite direction

Slip of the rotor with respect to F_f

$$S_f = \frac{n_s - n}{n_s} = s$$

(Since the forward ~~start~~ slip in the direction of rotor)

Slip of the rotor w.r.t F_b

$$S_b = \frac{n_s - n_r}{n_s} = (2-s)$$

Each of the rotating mmf wave produced torque due to induction motor action. The two torque acting in the opposite direction. If the rotor is stationary. it is subjected to the induction effect of field due to these equal and opposite rotating mmf and

...ing :-

1-ϕ Induction Motor does not have a starting torque so it need special method of Starting

These Motor are classified according to the method of starting and are usually referred by means distributed of these method

All these modify the Motor

The Stator is provided with two winding. Called main and auxiliary winding. Auxiliary winding ~~are~~ is excited by a current which is out of Phase with the current in the main winding. But

But current divided from the supply mains.

if the Phase difference of two current is 90° and the mmf created by them are equal, maximum starting torque is produce.

if the Phase difference is not 90° and mmf are not equal, starting torque will be small but may be sufficient to start the motor

(5) The Auxiliary winding is disconnected by Centrifugal Switch after the Motor has achieved about 75% [illegible] The [illegible] Starting [illegible] [illegible] [illegible] [illegible] the [illegible]

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Synchronous M/C (Machine)

Introduction → The doubly-excited ac machine, because its field winding is energised from a dc source and its armature winding is connected to an ac source.

In motoring mode its ~~take~~ take power from an a.c. source

In generating mode it delivers or exports a.c. power

It is universally employed for the generation of three phase power and also called as an Alternator. In this mode field winding is always take power from a d.c. source.

Constructional features: →

There are two types of synchronous machine depends upon the geometrical structure of rotor design

1) Salient Pole types (Projected Pole Type)
2) Cylindrical Rotor Types

$\theta_{elc} = 180°$

Heighest rating = 1700 MW
BHEL = 500 MW

$$\theta_{elec} = \frac{P}{2}\theta_{mech}$$

Turbo ⇒ USC steam turbine

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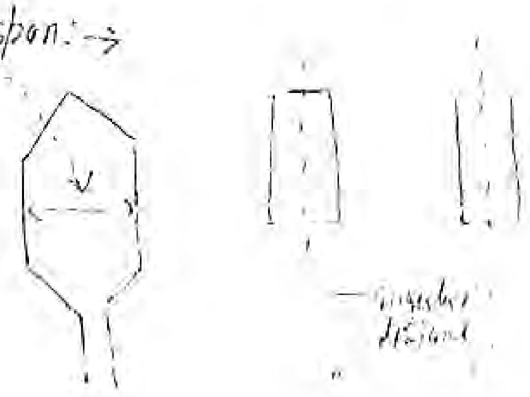
Comparison

Features	Cylindrical Rotor	Salient Pole m/c
Rotor Diameter	Small	large
Core length	Large	Small
Pole	Small	Large
Prime speed	Large ↑	Small ↓
airgap	uniform throughout	Non uniform, under the poles centre min & Between the pole it is maximum
Field winding	Distributed	
Analysis	Simple	Complex
Commercial application	Use as a Hydro Alternator	a Turbo Generator

Coil Pitch / Coil span:→



Salient Pole Type:->

(1) Rotor Poles projecting out from the rotor core
(2) Rotor of large diameter but smaller length
(3) Almost universally adopted

Cylindrical Rotor type:->

(1) Rotor of small dia but larger length
(2) Greater mechanical strength and more accurate dynamic balancing

Synchronous M/C General Point

(1) Construction

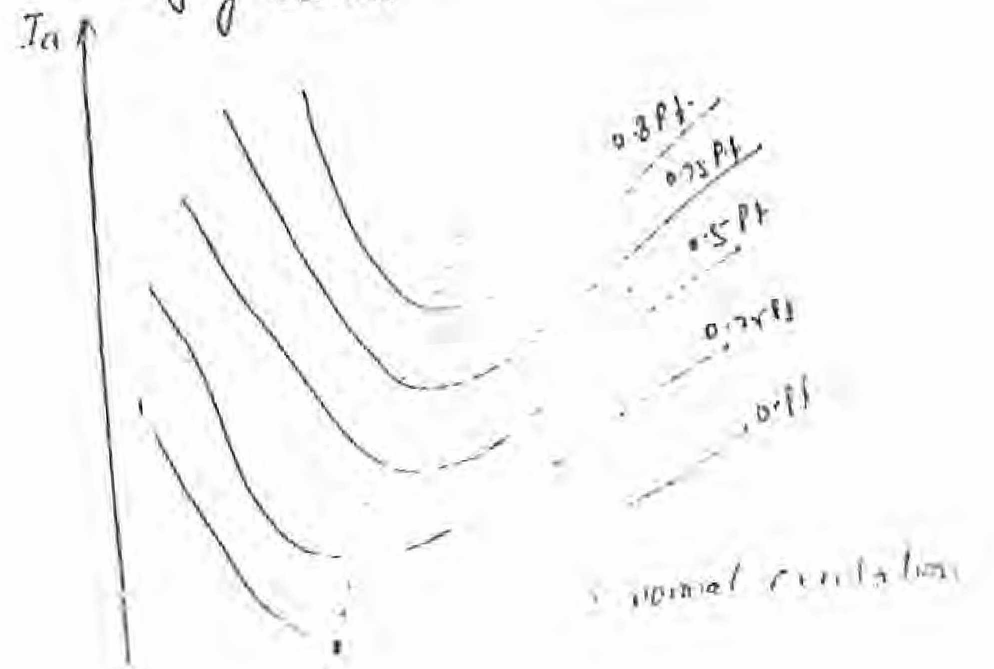
Stator Core → Silicon Steel
Stator winding → Copper
Rotor Core → Mild steel
Slip ring → Copper alloys

(2)

V curve → Nature of Ia versus If plot for various values of load (or) powers are called V curve of synchronous machine.

Name is due to its shape. V curve shows the relation between I_a and I_f with constant shaft load and constant terminal voltage.

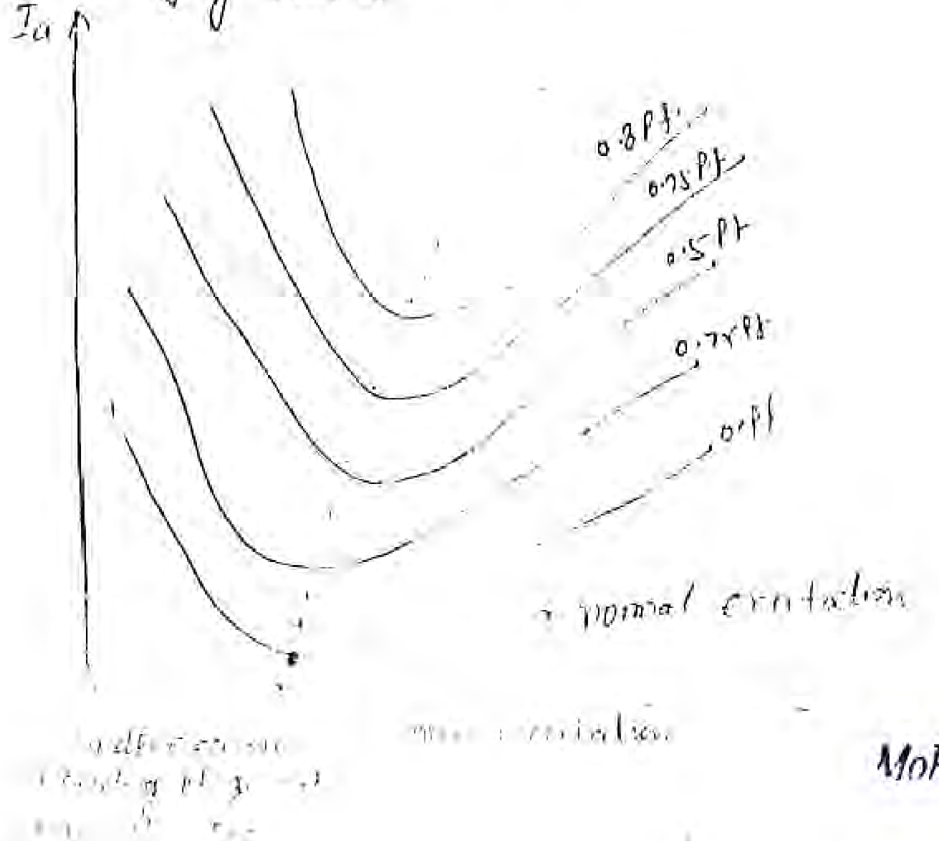
The unity power factor (u.p.f) dotted curve joining all the minimum - armature current points, is called (u.p.f) compounding curve. Similarly compounding curves for 0.8 P.f lag and 0.8 P.f lead are shown by dotted curve in the figure. The compounding curves for other P.f s can also be drawn if required. These compounding curve show the manner in which field current should be ~~very~~ varied in order to maintain constant P.f under changing loads



V curve → Nature of I_a versus I_f plot for various Value of load (Real Power) are called V curve of Synchronous Machine.

Name is due to its shape. V curve show the relation between I_a and I_f with constant shaft load and constant terminal voltage.

The unity power factor (u.p.f.) dotted curve joining all the minimum-armature current points. is called (u.p.f.) compounding curve Similarly compounding curves for 0.8 P.f lag and 0.8 P.f load are shown by dotted curve in the figure. The compounding curves for other P.f s can also be drawn if required. These compounding curve show the manner in which field current should be ~~very~~ varied in order to maintain constant P.f. under changing loads



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