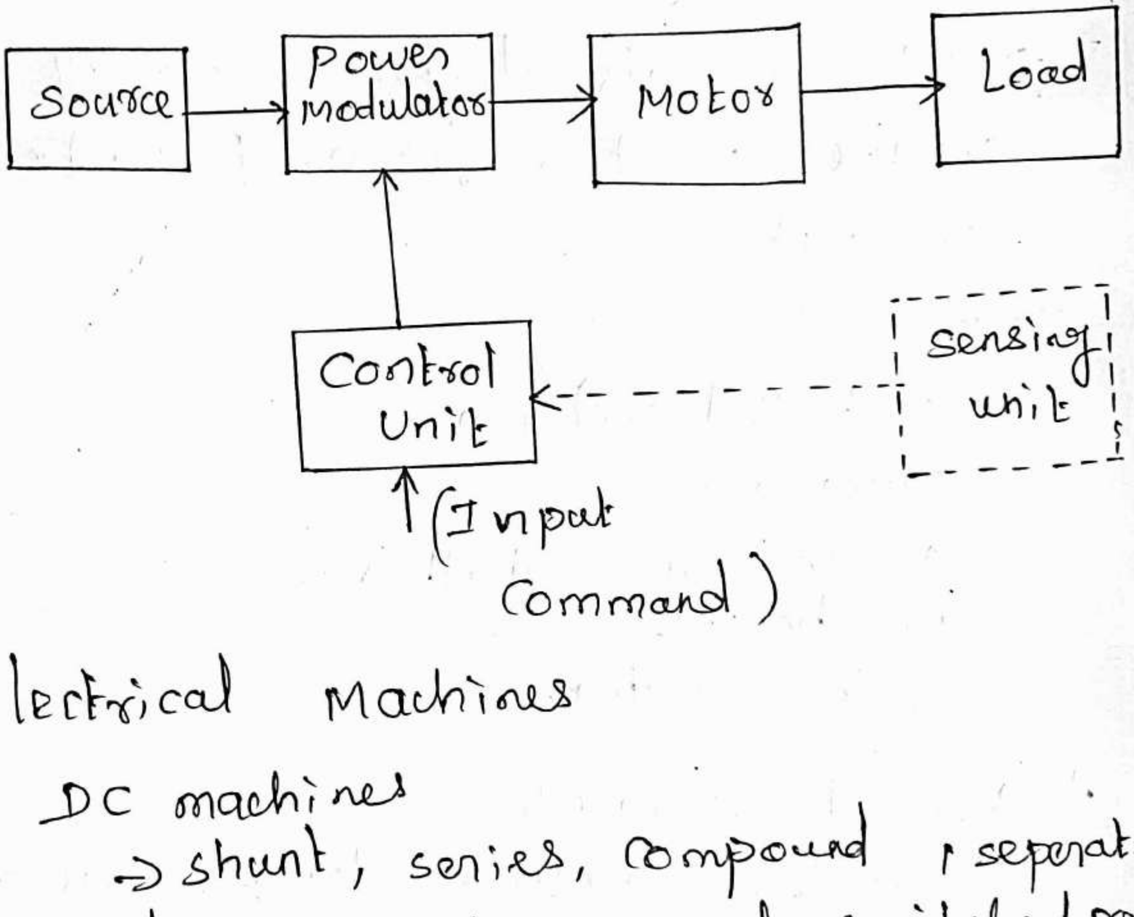
UNIT- I

INTRODUCTION

Basic Elements - Types of Electric Drives:

A modern variable speed electrical drive system has the following components

- Electrical Machines and loads
- Power modulator
- Sources
- Control unit
- sensing unit.



Electrical Machines

. DC machines

→ shunt, series, compound, seperately excited DC motors and switched reluctance machine.

AC Machines

→ Induction, wound rotor, synchronous, PM synchronous and synchronous reluctance machine.

special Machines:-

Brush less DC motors, stepper motors, switched reluctance motors are used.

Power modulators:-

→ Modulate power from the source to motor in such a manner that motor is imparted speed torque characteristics required by the load.

→ It converts electrical energy of the source in the form of suitable to the motor

Types:-

controlled rectifies
Inverters
A C voltage controllers
DC chopper
cyclo converter.

Electrical sources:-

Very low power drives are generally fed from single phase sources. Rest of the drive 3 phase source. Low and medium power motors are fed from a 400V supply. For high ratings, motors may be rated at 3.3 kV, 6.6 kV, and 11 kV.

Sensing Unit :-

- speed sensing
- Torque sensing
- position sensing
- Current sensing and voltage sensing.
- Temperature sensing.

Control Circuits :-

control Unit for a power modulator are provided in the control Unit. It matches the motor and power converter to meet the load requirements.

Types of Electric Drives:

According to mode of operation.

- continuous duty drive
- short time duty drive
- Intermittent duty drive

According to means of control

- Manual
- semi automatic
- Automatic

According to number of machines.

- Individual drive
- Group drive
- Multi-motor drive

According to Dynamics and Transients:

- Uncontrolled transient period
- Controlled transient period.

Factors Influencing the choice of Electrical Drives:-

The limits of speed range:

→ The range over which the speed control is necessary for the load.

The Efficiency:

→ The motor efficiency varies as load varies so the efficiency consideration under variable speed operation affects the choice of the motor.

The Braking:-

Easy and effective braking are the requirements of a good drive.

Starting requirement:-

The starting torque necessary for the load, the corresponding starting current drawn by the motor also affects the selection of drive.

Power Factor :

The running motor with low power factor value is not economical. The power factor of the motor affects the selection of drive.

Load Factor :-

There are varieties of load conditions possible like contineous, intermittent and impact.

Avaibility of supply :-

The motors available are AC or DC.

Effects of supply variations :-

There is a possibility of frequent supply variations. The selected motor should be able to withstand such supply variations.

Economy :- The size and rating of the motor decides its initial cost while the various losses and temperature rise decides its running cost. These economical aspects must be considered while selecting a drive.

Reliability of operation:-

It is important to study the conditions of stable operation of an electric drive.

Environmental effects:-

chemical gases, fumes, humidity etc. may affect the motor. It should be considered when we select a drive.

Loading conditions and classes of duty:-

Contineous or constant loads:- In this type load occurs for long time under the same conditions. Eg. Fan, paper making machine.

Contineous variable load:

The load is variable over a period of time but occurs repetitively for a long duration. Eg: Metal cutting lathes, conveyors.

Pulsating Loads:- The load is contineously variable. Eg: Reciprocating pumps, compressors

Impact Loads:

These are peak loads occur at regular intervals of time.

Eg. Rolling mils, Presses, Shearing machines, Forging hammers.

short time intermittent Loads:-

The load appears periodically identical duty cycles, each consisting of a period of applications of load.

Eg. Cranes, Hoists, Elevators.

short time Loads: A constant load appears on the drive and the system rests for the remaining period of cycle.

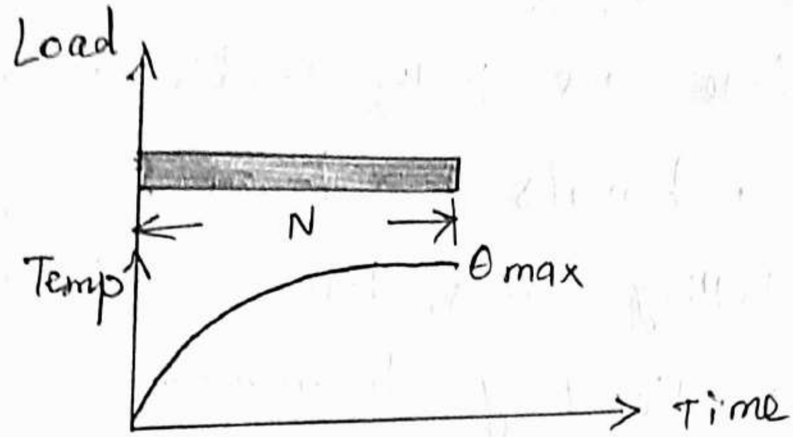
Eg. Motor-generator sets for charging batteries, house hold equipment.

Classes of Duty:

1. Contineous Duty:

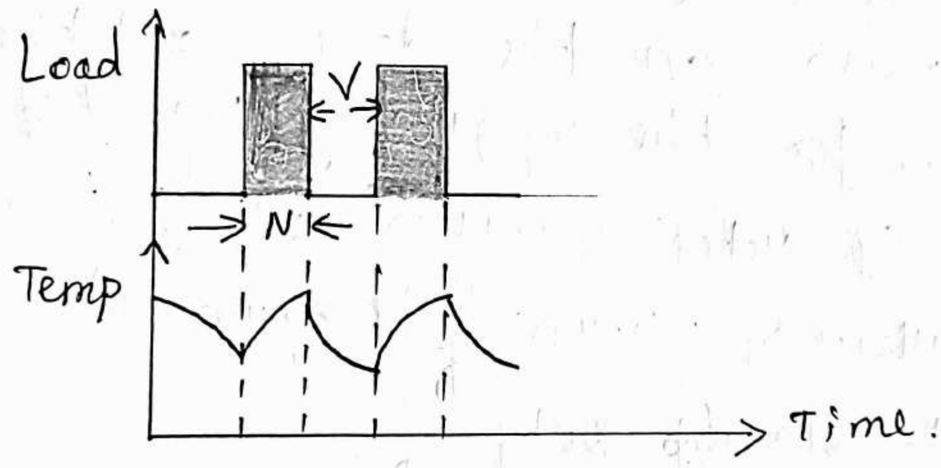
-> operation at constant load for a long duration of time.

-> 'N' indicates duration of operation



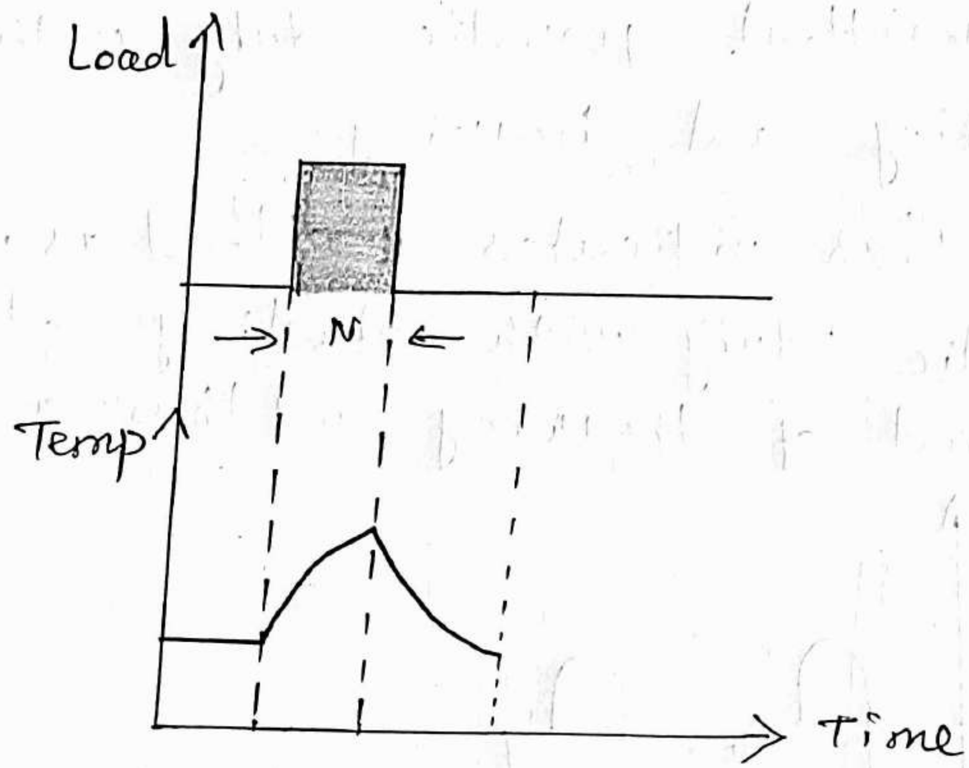
Contineous duty, variable load:

→ It denotes a sequence of identical duty cycles each consisting of a period of operation at load and period of no load.

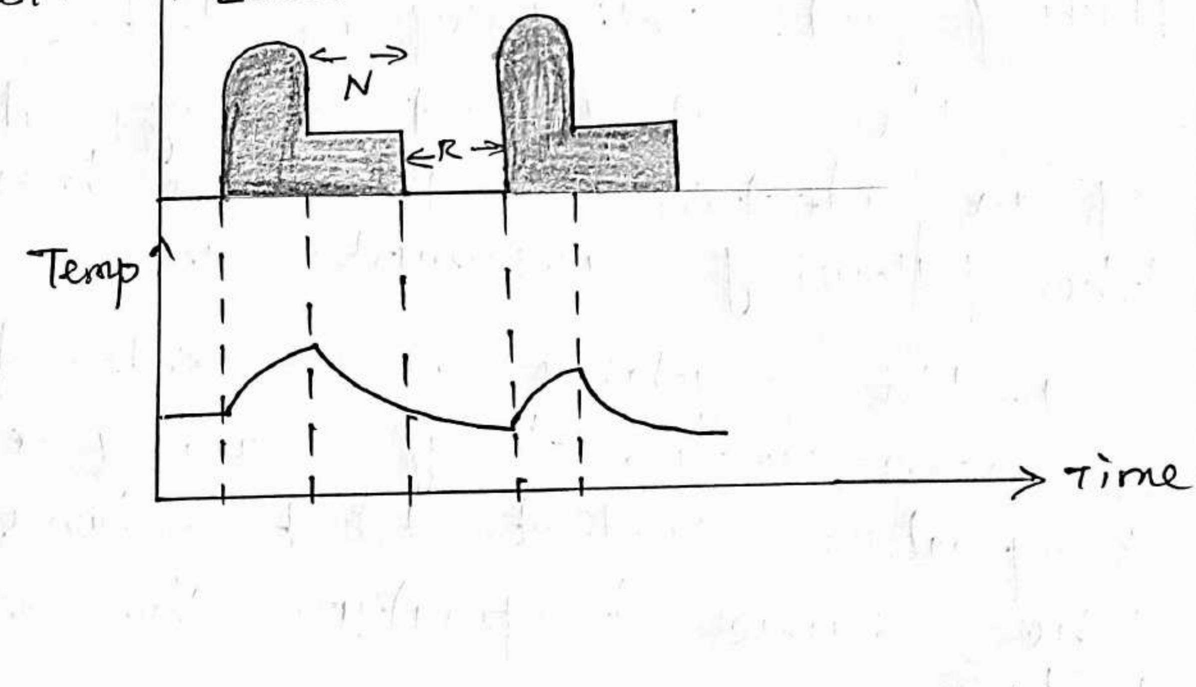


Short time duty:

It denotes operation at constant load during a given time, then followed by rest of sufficient duration.

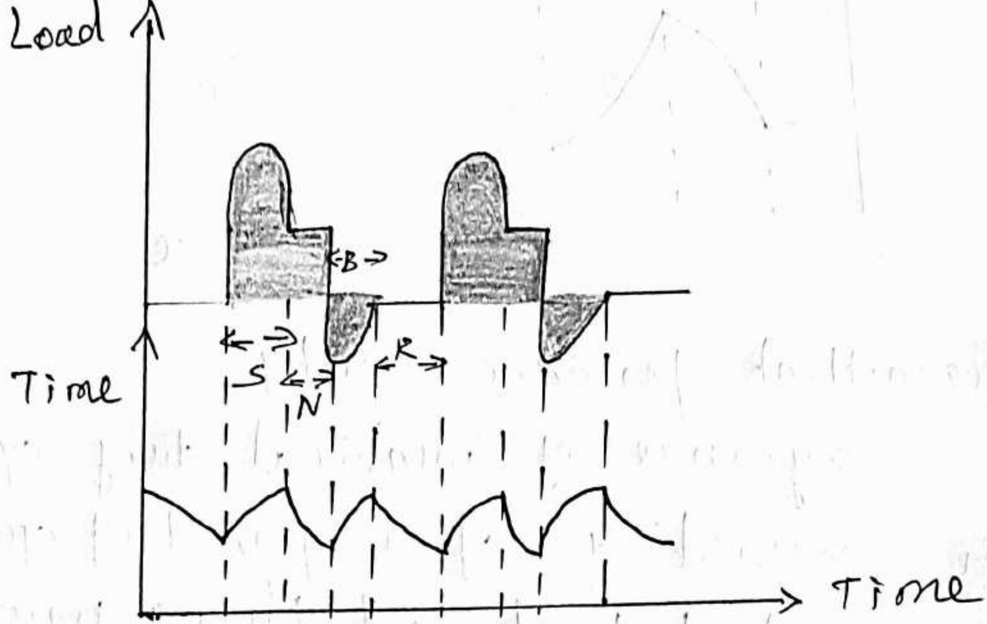


Intermittent periodic duty:
sequence of identical duty cycles each consisting of a period of operation at a constant load and then a period of rest.



Intermittent periodic duty with starting and braking:

This indicates a load as intermittent periodic duty with starting along with a period of braking and then a rest period.



Heating and cooling of an electric motor:

The heating and cooling calculation of an electric motor are based on the following assumptions:

1. The machine is considered to be a homogeneous body having a uniform temperature gradient that means it has the same temperature throughout its body.

2. Heat dissipation taking place is proportional to the difference of temperatures of the body and surrounding medium. No heat is radiated.

3. The rate of dissipation of heat is constant at all temperatures.

Assuming the heat developed is proportional to the losses, we have the standard balance equation.

$$W.dt = A\lambda\theta.dt + Gs.d\theta \quad (1)$$

where W – The power loss on the motor due to heat in watts.

A - The cooling surface in m^2

λ - emissivity

G – Weight of active parts of the motor in kg.

S – specific heat of the material of the body in J/deg/kg.

θ – temperature rise of the body

$d\theta$ – temperature rise in a small interval dt.

From the components of equation (1)

$$W = A \lambda \theta_m \quad \text{——— (2)}$$

From the equation (2)

Maximum temperature rise $\theta_m = \frac{W}{A \lambda}$

——— (3)

By rearranging the equation (1), we get the equation in other form as,

$$\frac{d\theta}{dt} = \frac{W}{G\sigma S} - \frac{A \lambda \theta}{G\sigma S} \quad \text{——— (4)}$$

If the cooling is not present, the machine will be heat up enormously and the temperature rise would attain very high values. But θ must be limited to θ_m.

The time taken by the machine to reach this temperature rise in the absence of dissipation can be determined using equating the first component in (4).

$$\frac{d\theta}{dt} = \frac{W}{\sigma S}$$

$$W \cdot dt = \sigma S \cdot d\theta \quad \text{------ (5)}$$

$$\frac{W}{\sigma S} = \frac{d\theta}{dt} = \frac{\theta}{t} \quad \text{------ (6)}$$

where $t = t_1$ time taken to reach θ_m

$$\frac{\theta_m}{t_1} = \frac{W}{\sigma S} \quad \text{------ (7)}$$

substituting θ_m value from (3) in (7)

$$\frac{W/A\eta}{t_1} = \frac{W}{\sigma S}$$

$$t_1 = \frac{\sigma S}{A\eta} \quad \text{------ (8)}$$

Equation (1) can be written as

$$(W - A\eta\theta) \cdot dt = \sigma S \cdot d\theta \quad \text{------ (9)}$$

From eqn (9)

$$dt = \frac{\sigma S}{W - A\eta\theta} \cdot d\theta \quad \text{------ (10)}$$

Integrating both sides of equation (10) to remove the differentiator, we get,

$$t = \frac{\sigma s}{A\eta}\left[\log(W - A\eta\theta) - \log c_1\right]$$ — (11)

where $\log c_1$ is a constant of integration by cancelling the log term (11). The equation can be written as,

$$e^{-t\left(\frac{A\eta}{\sigma s}\right)} = \frac{W - A\eta \cdot \theta}{c_1}$$ — (12)

(i) Motor start from cold,

$\theta = 0$ at $t = 0$, $c_1 = W$, substituting c_1 in equation (12) and solve for getting θ, we get

$$\theta = \frac{W}{A\eta}\left[1 - e^{-t\left(\frac{A\eta}{\sigma s}\right)}\right]$$ — (13)

substituting (3) and (8) in (13)

θ can be written as,

$$\theta = \theta_m\left(1 - e^{-\left(\frac{t}{t_1}\right)}\right)$$ — (14)

(ii) Initial temperature is not zero

$t = 0$, $\theta = \theta_0$ then,

$$C_1 = W - A\lambda\theta_0 \quad \text{—— (15)}$$

putting (15) in (12) we have

$$e^{-t\left(\frac{Gs}{A\lambda}\right)} = \frac{W - A\lambda\theta}{W - A\lambda\theta_0} \quad \text{—— (16)}$$

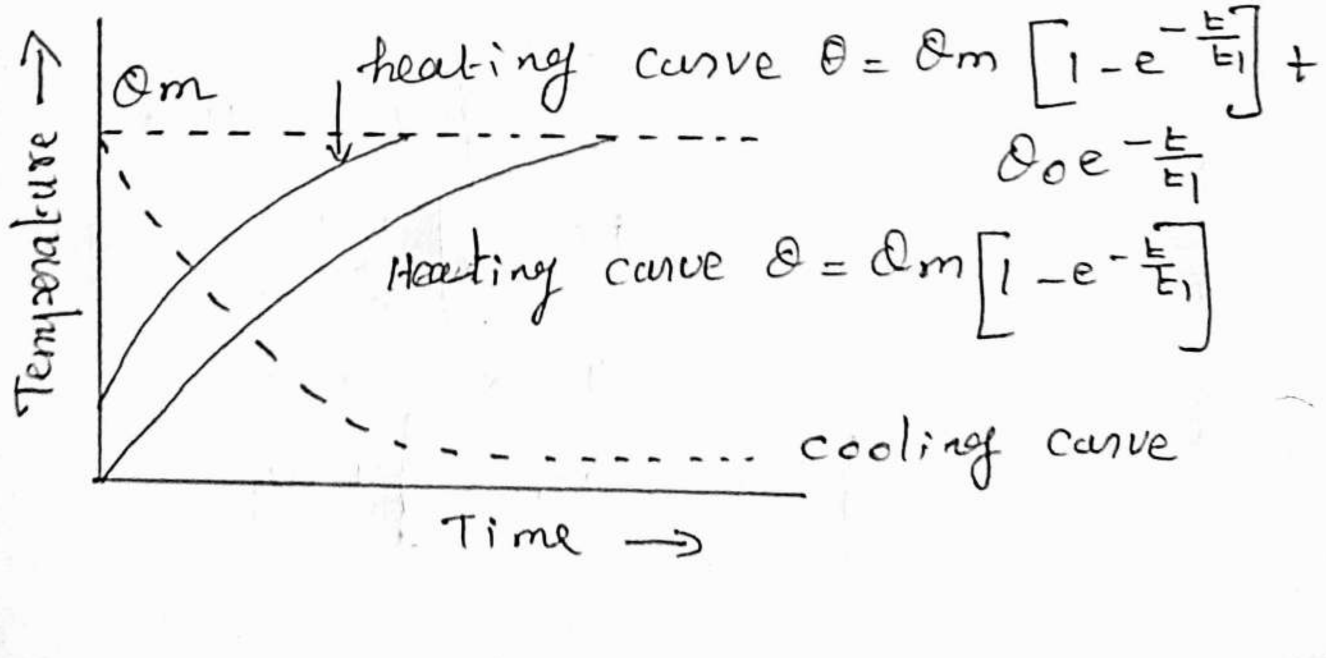
By rewriting eqn (16), we can get

$$\theta = \frac{W}{A\lambda}\left(1 - e^{-t\left(\frac{Gs}{A\lambda}\right)}\right) + \theta_0 e^{-t\left(\frac{Gs}{A\lambda}\right)} \quad \text{—— (17)}$$

substituting $\theta_m = \frac{Gs}{A\lambda}$ and $t_1 = \frac{Gs}{A\lambda}$

in eqn (17), we can get

$$\boxed{\theta = \theta_m\left(1 - e^{-\frac{t}{t_1}}\right) + \theta_0 e^{-t/t_1}} \quad \text{—— (18)}$$



From the equation (18), the maximum temperature rise of the motor can be obtained and this value must be less than the permissible temperature rise for the type of insulation used.

Ex: Determine the half - hour rating of 40kW motor. Assume the constant loss to be 80% of full load copper losses. Thermal time constant for the motor is 2 hours.

solution:

$$\frac{P_x}{P_r} = \sqrt{\frac{1+\alpha}{1-e^{-\frac{N}{\tau}}} - \alpha}$$

$$\alpha = \frac{P_c}{P_{cu}} = \frac{0.8}{1} = 0.8$$

$$P_x = 40 \times \sqrt{\frac{1+0.8}{1-e^{-\frac{0.5}{1.5}}} - 0.8}$$

$$= 40 \times \sqrt{\frac{1.8}{1-0.7166} - 0.8}$$

$$= 40 \times \sqrt{\frac{1.8}{0.283} - 0.8}$$

$$= 40 \times 2.358$$

$$\boxed{P_x = 94.32} \text{ kW}$$

UNIT-II

DRIVE MOTOR CHARACTERISTICS.

DC MOTORS.

UNIT - V

DC MOTORS

Introduction:

→ while a DC generator converts mechanical energy in the form of rotation of the conductor into electrical energy, a motor does the opposite.

→ The input to a DC motor is electrical and the output is mechanical rotation or torque.

→ The fundamental principles and construction of the DC motors are identical with DC generators which have the same type of excitation.

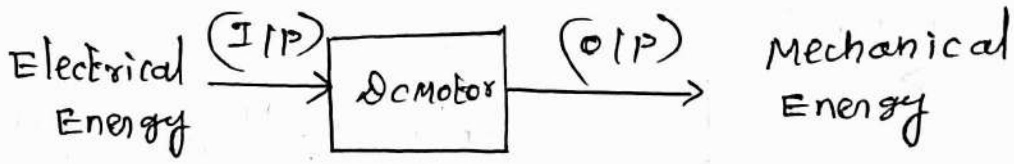
→ A DC machine that runs as a motor will also operate as a generator.

Applications of DC generator.

1. Battery charging.
2. Boosters for adding a voltage to the transmission line.

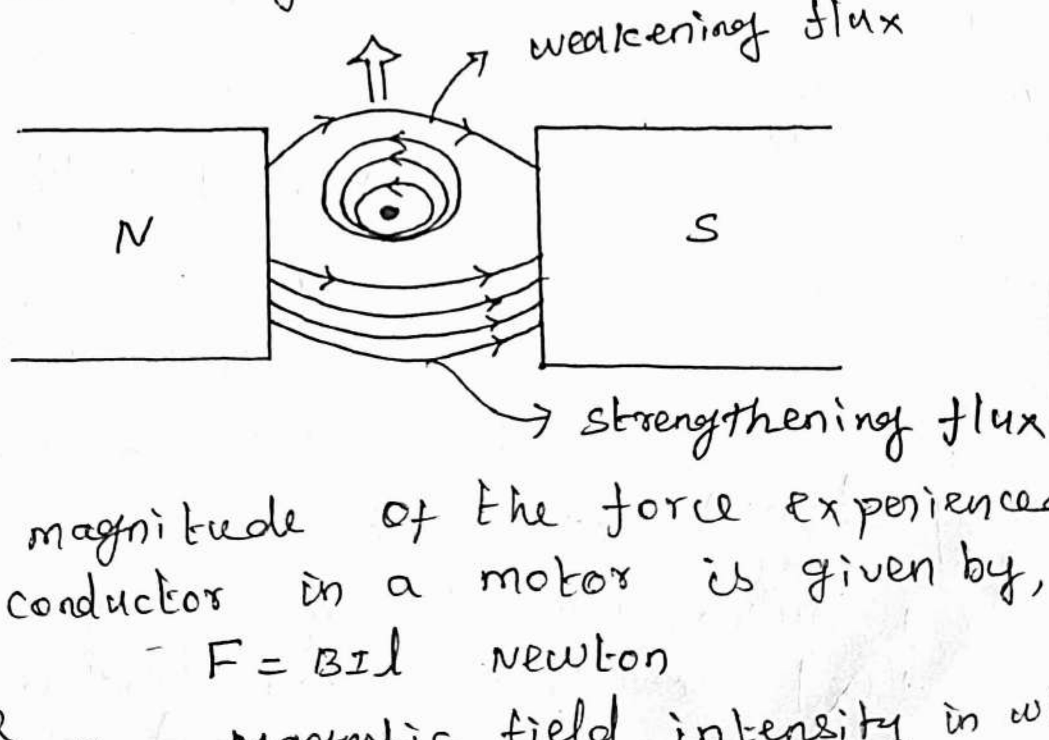
DC Motors.

DC motors converts electrical energy into mechanical energy.



Principle:

Whenever a current carrying conductor is placed in a magnetic field, it experiences a force tending to move it.



The magnitude of the force experienced by the conductor in a motor is given by,

$$F = BIl \text{ Newton}$$

where B = Magnetic field intensity in wb/m^2

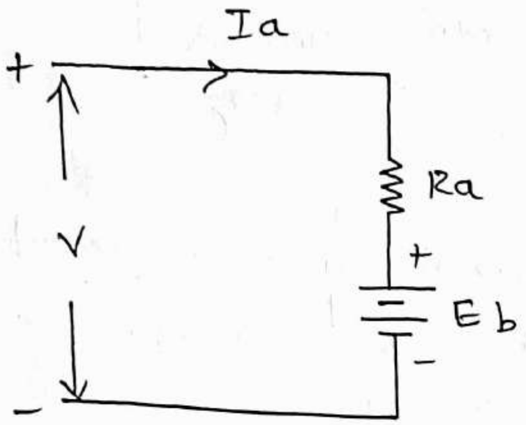
I = current in Amps

l = length of the Conductor in metres.

Back emf:

Even when the machine is working as a motor, voltages are induced in the conductors. This emf is called the back emf or counter emf. According to Lenz's law, the direction of the back emf opposes the supply voltage.

The back emf is $E_b = \frac{\phi Z N}{60} \times \frac{P}{A}$ volts.



The voltage equation of this DC motor is

$$V = E_b + I_a \cdot R_a \text{ volts.}$$

From this equation,

$$I_a = \frac{V - E_b}{R_a} \text{ Amps.}$$

where

V - Applied voltage

E_b - back emf

I_a - armature current

R_a - armature resistance

Importance of Back EMF:

1. When the dc motor is operating on no load condition, small torque is required to overcome the friction and windage losses. Therefore the back emf is nearly equal to input voltage and armature current is small i.e. I_a is Low.

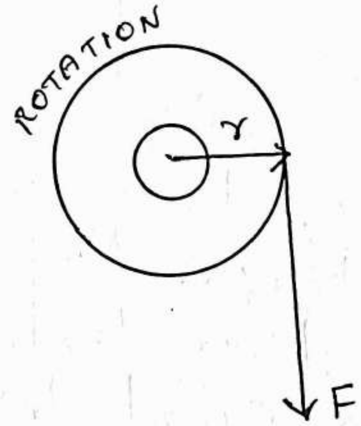
2. When the DC motor is operating on load, armature slows down and motor back emf E_b also decreases. Corresponding armature current I_a increases.

3. When the load on DC motor is decreased, motor speed increases, the back emf E_b also increases causing armature current to decrease.

Torque Equation.

Torque is nothing but turning or twisting force about an axis.

Torque = Force x radius N-m



The angular velocity $\omega = \frac{2\pi N}{60}$ rad/sec.

workdone per revolution = F x distance moved

$= F \times 2\pi r$ joules

power developed $P = \frac{\text{work done}}{\text{time}}$

$= \frac{F \times 2\pi r}{60/N}$

$$P = (F \times r)\frac{2\pi N}{60}$$

$$P = T\omega \text{ watts.}$$

where T = torque in N-m

ω = angular speed in rad/sec.

The gross mechanical power developed in the armature is $E_b I_a$. Then power in armature = Armature torque $\times \omega$

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

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

$$T_a = \frac{\phi I_a}{2\pi}\frac{PZ}{A}$$

$$\boxed{T_a = 0.159\,\phi I_a \frac{PZ}{A}} \text{ N-m}$$

The full armature torque is not available for doing useful work. Some amount of torque is used for supplying iron and friction losses in the motor. This torque is called lost torque. The remaining torque is available in the shaft. It is used for doing useful work.

The armature torque is the sum of the lost torque and shaft torque.

$$\therefore T_a = T_f + T_{sh}$$

The output power of the motor is

$$P_{out} = T_{sh} \times 2\pi N \text{ watts.}$$

A 4 pole, 50 kW, 250 V, wave wound Shunt generator has 400 armature conductors. Brushes are given a lead of 4 commutator segments. Calculate the demagnetization ampere-turns per pole if shunt field resistance is 50 Ω. Also calculate extra shunt field turns per pole to neutralize the demagnetization.

(April/May 2018)

Gn data

$P = 4$

Power = 50 kW

$V = 250 V$, wave wound

$Z = 400$

Commutator segments = 4

$R_{sh} = 50 \Omega$

Soln:- $I_L = \frac{50 \times 10^3}{250} = 200 A$

$I_{sh} = \frac{V}{R_{sh}} = \frac{250}{50} = 5 A$

Armature current $I_a = I_L + I_{sh}$

$= 200 + 5 = 205 A$

Current in each conductor $I = I_a/A = \frac{205}{2} = 102.5 A$

(i)

If I_1 and I_2 are currents supplied by the two shunt generators and V the terminal voltage, then

$$V = 500 - 0.1 I_1$$

$$V = 500 - 0.075 I_2$$

$$500 - 0.1 I_1 = 500 - 0.075 I_2$$

$$0.1 I_1 = 0.075 I_2$$

$$I_1 = 0.75 I_2$$

$$I_1 + I_2 = 800\ A$$

$$0.75 I_2 + I_2 = 300\ A$$

$$1.75 I_2 = 300$$

$$I_2 = \frac{300}{1.75}$$

$$I_2 = 171.428\ A$$

$$I_1 = 128.571\ A$$

(ii) Terminal voltage $V = 500 - 0.1 \times I_1$

$$= 500 - 0.1 \times 128.571$$

$$V = 487.143\ V$$

Two 500V DC shunt generators rated at 100 kW and 200 kW respectively are operating in parallel. Both of them have linearly drooping external characteristics. Voltage regulation of the first generator is 4% and that of the second generator is 6%. Determine the common bus voltage and current shared by each of the generators when their parallel combination is to supply a current of 300A.

April / May 2018

Soln:- For 100 kW generator ⇒

Full load voltage drop = 500 × 0.04

= 20 V

Full load current = $\frac{100 \times 10^3}{500}$ = 200 A

Drop per ampere = $\frac{20}{200}$ = 0.1 V/A

For 200 kW generator ⇒

Full load voltage drop = 500 × 0.06

= 30 V

Full load current = $\frac{200 \times 10^3}{500}$ = 400 A

Drop per ampere = $\frac{30}{400}$ = 0.075 V/A

A 4 pole, lap wound, dc generator has 42 coils with 8 turns per coils. It is driven at 1120 rpm. If useful flux per pole is 21 mwb, calculate the generated emf. Find the speed at which it is to be driven to generate the same emf as calculated above with wave wound armature. (April / May 2019)

Gn data

$P = 4$, Lap wound

$Z = 42 \times 8 = 336$

$N = 1120$ rpm.

$\varphi = 21$ mwb.

Soln:-

1. Generated emf $E_g = \frac{\varphi Z N P}{60 A}$

$= \frac{21 \times 10^{-3} \times 336 \times 1120 \times 4}{60 \times 4}$

$E_g = 131.712$ V

2. For wave connected $A = 2$

$E_g = 131.712$ V

$N = \frac{E_g \times 60 A}{\varphi Z P} = \frac{131.712 \times 60 \times 2}{21 \times 10^{-3} \times 336 \times 4}$

$N = 560$ rpm

) A 220V shunt motor has armature and field resistance of 0.2 Ω and 220 Ω respectively. The motor is driving a constant load torque and running at 1000 rpm drawing 10A ct from the supply. calculate the new speed and armature current if an external armature resistance of value 5 Ω is inserted in the armature circuit. neglect armature reaction and saturation.

(April/May 2019)

soln:- For initial operating point

$I_{L_1} = 10\ A$, $r_a = 0.2\ \Omega$, $V = 220V$

$I_{sh_1} = 220/220 = 1\ A$

$I_{a_1} = 10 - 1 = 9\ A$

$T_{a_1} = k\ I_{sh_1} \cdot I_{a_1} = k \times 1 \times 9 = T_L$

$E_{b_1} = k_g\ I_{sh_1} \cdot n = k_g \times 1 \times 1000$

$= V - I_{a_1} \cdot r_a = 220 - 9 \times 0.2 = 218.2V$

$k_g \times 1 \times 1000 = 218.2V$.

$I_{sh_1} = I_{sh_2} = 1\ A$.

$T_{a_2} = k_t \times 1 \times I_{a_2} = T_L$

$$E_{b2} = K_g \times 1 \times n_2$$

$$= V - I_{a2}(r_a + R_{ext})$$

$$\therefore K_g \times 1 \times n_2 = 220 - I_{a2} \times 5.2$$

Taking ratios

$$\frac{T_{a2}}{T_{a1}} = \frac{K_t \times 1 \times I_{a2}}{K_t \times 1 \times I_{a1}}$$

$$\frac{T_{a2}}{T_{a1}} = \frac{K_t \times 1 \times I_{a2}}{K_t \times 1 \times 9}$$

$$\frac{E_{b2}}{E_{b1}} = \frac{K_g \times 1 \times n_2}{K_g \times 1 \times 1000} = \frac{220 - I_{a2} \times 5.2}{218.2}$$

$$\frac{n_2}{1000} = \frac{220 - 9 \times 5.2}{218.2}$$

$$\text{or } \frac{n_2}{1000} = \frac{173.2}{218.2}$$

$$n_2 = \frac{173.2 \times 1000}{218.2}$$

$$\boxed{\therefore n_2 = 793.76 \text{ rpm}}$$

(28)

A DC shunt generator driven by a belt from an engine runs at 750 rpm while feeding 100 kW of electric power into 230 V mains. When the belt breaks it contineous to run as a motor drawing 9 kW from the mains. At what speed would it run? Given armature resistance 0.08 Ω and field resistance 115 Ω

Note: In a shunt machine the field is connected across the armature and is also connected directly to the 230 V mains. The field excitation therefore remains constant as the machine operation changes as described above. Nov/Dec 2018.

Gin data

Generator	$N = 750\,rpm$	$R_a = 0.08\,\Omega$
	$Power = 100\,kW$	$R_{sh} = 115\,\Omega$
	$V = 230\,V$	

motor $Power = 9\,kW$

$V = 230\,V$

Soln:-

$$I_L = \frac{100 \times 10^3}{230} = 434.78\ A$$

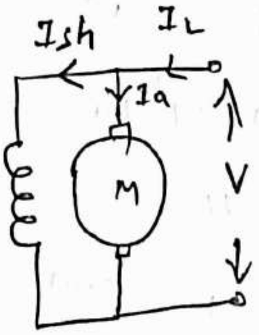
$$I_{sh} = \frac{230}{115} = 2\ A$$

$$I_a = I_L + I_{sh} = 436.78\ A$$

$$E_g = V + I_a \cdot R_a$$

$$= 230 + 436.78 \times 0.08$$

$$\boxed{E_{g_1} = 264.94\ V}$$



$$I_L = I_a + I_{sh}$$

$$I_{sh} = \frac{V}{R_{sh}}$$

$$= \frac{230}{115} = 2\ A$$

$$I_L = \frac{P}{V} = \frac{9 \times 10^3}{230} = 39.130$$

$$I_L = 39.130\ A$$

$$I_a = I_L - I_{sh} = 39.130 - 2 = 37.130\ A$$

$$E_g = V - I_a \cdot R_a$$

$$= 230 - 37.130 \times 0.08$$

$$= 230 - 2.97$$

$$E_{g_2} = 227.0296\ V$$

$$\frac{E_{g_2}}{E_{g_1}} = \frac{N_2}{N_1}$$

$$N_2 = N_1 \times \frac{E_{g_2}}{E_{g_1}} = 750 \times \frac{227.0296}{264.94}$$

$$= 643.436$$

$$\boxed{N_2 = 643\ rpm}$$

Power Relationship of DC Motor.

The voltage equation is $V = E_b + I_a R_a$ —— ①

Multiplying each term of the voltage equation by I_a, we get

$$V I_a = E_b I_a + I_a^2 \cdot R_a \quad \text{—— ②}$$

This equation is known as power equation of a DC motor.

$VI_a \rightarrow$ Electric power supplied to armature.

$E_b I_a \rightarrow$ Power developed by the motor armature.

$I_a^2 R_a \rightarrow$ Power loss in the armature.

Mechanical power developed $P_m = E_b I_a$ —— ③

$$= VI_a - I_a^2 R_a \quad \text{—— ④}$$

Differentiating both sides with respect to armature current I_a we have

$$\frac{dP_m}{dI_a} = V - 2 I_a R_a \quad \text{—— ⑤}$$

For maximum mechanical power, $\frac{dP_m}{dI_a}$ is zero,

$$\text{or} \quad V - 2I_aR_a = 0$$

$$I_aR_a = \frac{V}{2}$$

$$V = E_b + I_aR_a$$

$$V = E_b + \frac{V}{2}$$

$$\boxed{E_b = \frac{V}{2}} \quad \text{—(6)}$$

Therefore the power developed in armature is maximum when the back emf is equal to half of the input voltage.

Disadvantages.

This is not in practice, because

→ The motor armature (I_a) current is very large.

→ Half of the input power is wasted in the armature.

For DC shunt motor

$$\phi = \text{constant}$$

$$\therefore \boxed{T \propto I_a}$$

For series motor

$$\phi \propto I_a$$

$$\therefore \boxed{T \propto I_a^2}$$

Applications of DC motor.

Shunt motor → Centrifugal pumps, light machine tools, wood working machines, lathe etc.

Series motor → Cranes, hoists, fans, blowers, conveyers, lifts etc.

Compound motor → Intermittent shears, punching machies etc.

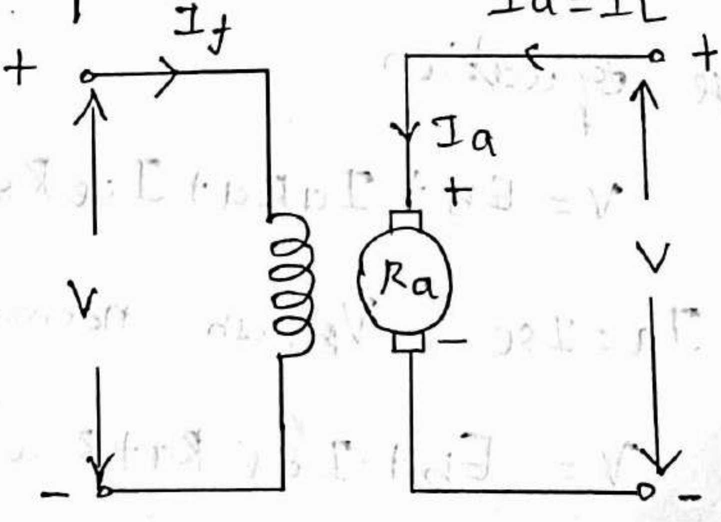
Types of DC Motors:

The classification of DC motor is similar to that of DC generators. They are,

1. seperately excited DC motor
2. self excited DC motor
   a. series motor
   b. Shunt motor
   c. compound motor
      1. Long shunt
      2. short shunt

1. Seperately excited DC motor :-

Here the field winding and armature are seperated.



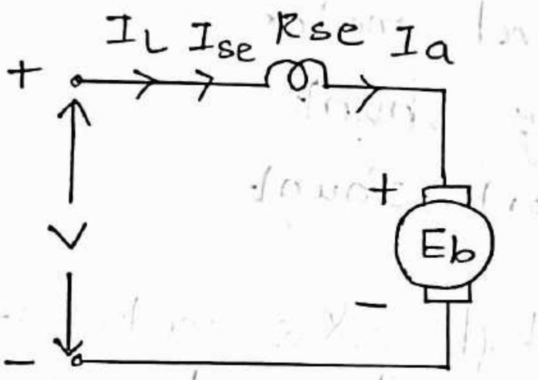
From the above diagram

Armature current I_a = Line current I_L

Back emf $E_b = V - I_a R_a - V_{brush}$

DC series motor:-

DC series motor means, the field winding is connected in series with armature.



→ Field winding should have less number of turns of
→ Thick wire.

$$I_a = I_{se} = I_L$$

Voltage equation

$$V = E_b + I_a R_a + I_{se} R_{se} + V_{brush}$$

$I_a = I_{se}$, V_{brush} normally neglected

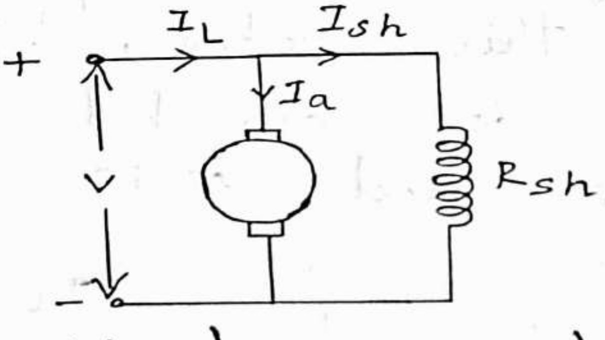
$$V = E_b + I_a (R_a + R_{se})$$

In a DC series motor, full armature current flows through the series field winding,

$$\therefore \boxed{\phi \propto I_{se} \propto I_a}$$

DC shunt motor:

→ In a DC shunt motor, the field winding is connected across the armature.



→ I_L is the line current drawn by the supply. $I_L = I_a + I_{sh}$

$$I_{sh} = \frac{V}{R_{sh}}$$

voltage equation of a DC shunt motor is given by, $V = E_b + I_a R_a + V_{brush}$

→ In shunt motor, flux produced by field winding is proportional to the field current ie $\boxed{\phi \propto I_{sh}}$

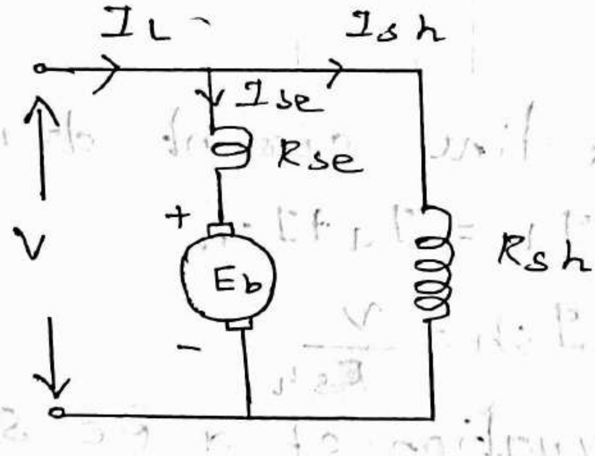
→ Therefore DC shunt motor is also called a constant flux motor or constant speed motor.

DC Compound Motor:

A DC compound motor consists of both series and shunt field windings.

a. Long shunt compound motor.

In this motor, the shunt field winding is connected across both armature and series field winding.



$I_L = I_{se} + I_{sh}$

$I_{se} = I_a$

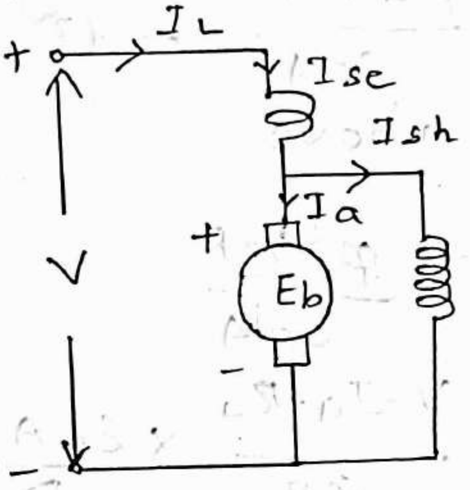
$\therefore I_L = I_a + I_{sh}$

$I_{sh} = \frac{V}{R_{sh}}$

Voltage equation $V = E_b + I_a R_a + I_{se} R_{se} + V_{brush}$

Short shunt Compound motor.

In this motor, the shunt field winding is across the armature and series field windings is connected in series with this combination.



$I_L = I_{se}, I_L = I_a + I_{sh}$

$\therefore I_L = I_{se} = I_a + I_{sh}$

$V = E_b + I_a R_a + I_{se} R_{se} + V_{brush}$.

$I_{se} = I_L$, voltage drop across shunt field winding $= V - I_L R_{se}$

$$\boxed{I_{sh} = \frac{V - I_L R_{se}}{R_{sh}}}$$

Cumulative Compound motor.

The two field winding fluxes aid each other.

Differential Compound motor:-

The two field winding fluxes oppose each other.

4. Speed and Torque equation:-

The speed equation is obtained as follows.

$$E_b = V - I_a \cdot R_a \quad \text{—} (1)$$

$$E_g = \frac{\phi Z N P}{60 A} \quad \text{—} (2)$$

equate the above.

$$V - I_a \cdot R_a = \frac{\phi Z N P}{60 A}$$

$$N = \frac{V - I_a \cdot R_a}{\phi Z} \times \frac{60 A}{P}$$

Z, A & P are constant

$$N = \frac{k (V - I_a \cdot R_a)}{\phi} \quad \text{—} (3)$$

k is constant

speed eqn becomes

$$N \propto \frac{V - I_a \cdot R_a}{\phi}$$

$$N \propto \frac{E_b}{\phi} \quad \text{—} (4)$$

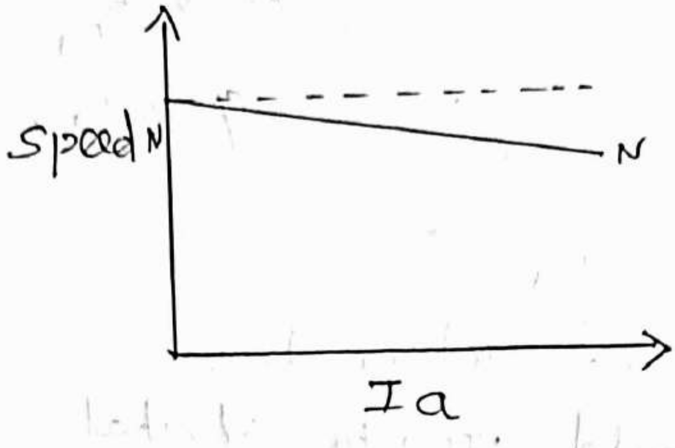
The torque eqn of DC motor is given by,

$$T \propto \phi I_a$$

$$\phi \propto I_f$$

(1) Characteristics of DC motors.

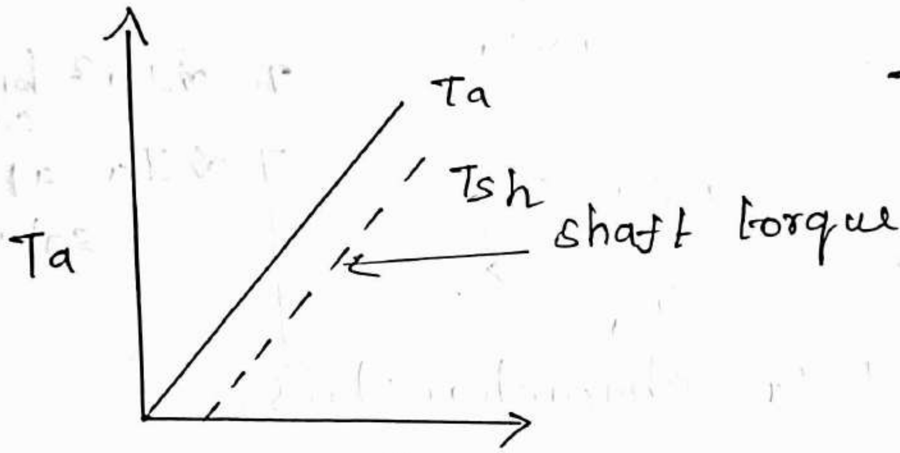
1. shunt motor characteristics..



→ speed $N = \frac{k(V - I_a R_a)}{\varphi}$

→ DC shunt motor acts as a constant speed motor.

(a) N – Ia characteristics.



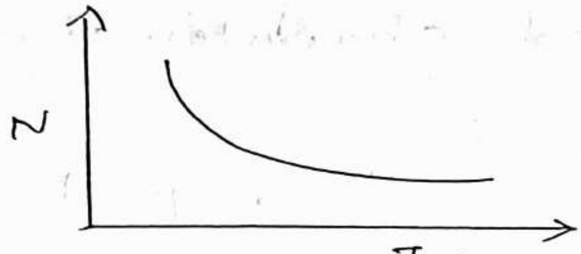
$T \propto \varphi I_a$

$T \propto I_a$

(b) Ta – Ia characteristics.

(c) N – Ta characteristics.

Dc series motor characteristics:

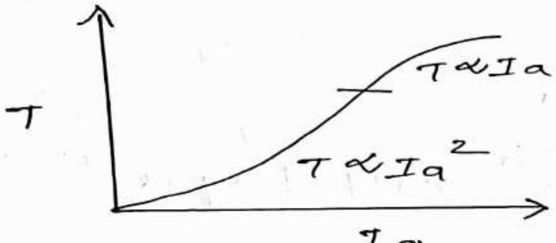


$N \propto \frac{E_b}{I_a}$

$\varphi \propto I_a$.

(a) N–Ia characteristics.

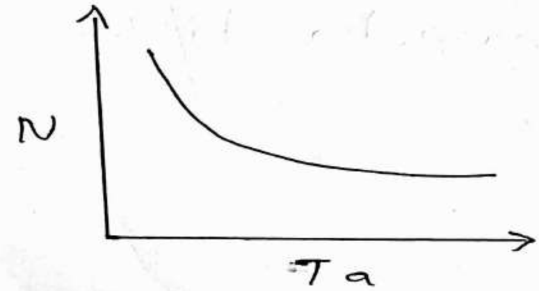
→ Dc motor should never be started without some load.



$T \propto I_a^2$ before saturation

$T \propto I_a$ after saturation.

(b) T–Ia characteristics.

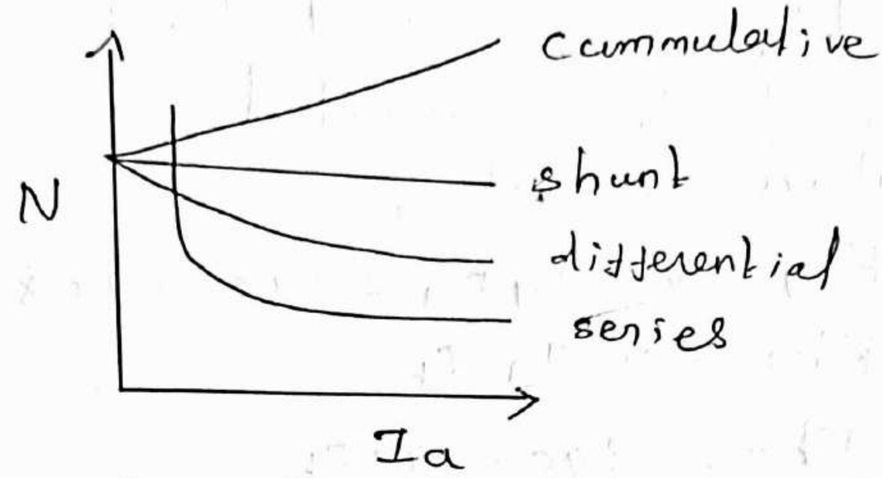


→ Dc series motor speed is high, the torque is low and vice-versa.

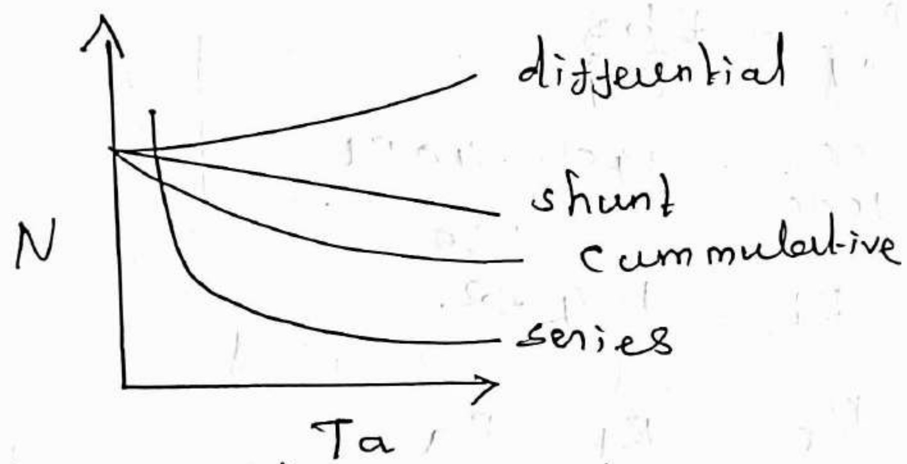
(c) N–Ta characteristics.

3. Compound motor characteristics.

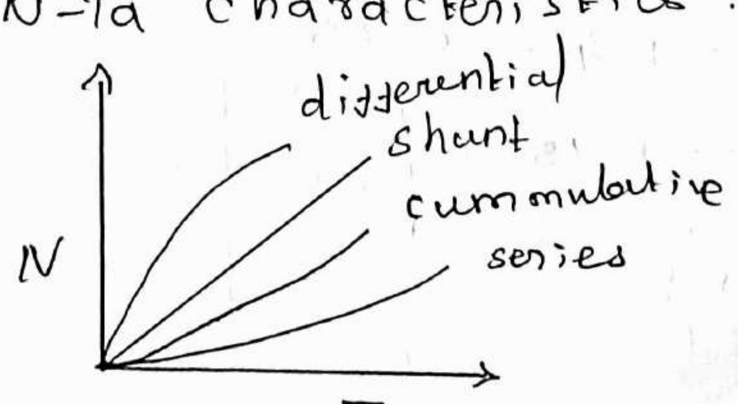
The characteristics of compound motor will depend on whether the series and shunt field windings are assisting each other or opposing each other.



(a) N - Ia - characteristics.



(b) N - Ta characteristics.



(c) N - Ta characteristics.

A 240 V dc shunt motor has an armature resistance of 0.25 Ω and runs at 1000 rpm taking an armature current of 40 A. It is desired to reduce the speed to 800 rpm. If the armature current remains the same, find the additional resistance to be connected in series with the armature circuit.

Soln:— $E_{b1} = V - I_a R_a = 240 - 40 \times 0.25 = 230V$

$E_{b2} = V - I_a \cdot R_t$

$E_{b2} = 240 - 40 R_t$

$\phi_1 = \phi_2$

$\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}}$

$\frac{800}{1000} = \frac{240 - 40 R_t}{230}$

$R_t = 1.4 \, \Omega$

$R_e = R_t - R_a$

$= 1.4 - 0.25$

$R_e = 1.15 \, \Omega$

Ex:1 A DC motor connected to a 460V supply has an armature resistance of 0.15 Ω calculate (a) the value of back emf when the armature ct is 120 A. (b) the value of armature ct when the back emf is 447V.

GTN:-

$V = 460V$

$Ra = 0.15\ \Omega$

$Ia = 120\ A$

(a) $Eb = V - Ia.Ra$

$Eb = 460 - (120 \times 0.15)$

$$\boxed{Eb = 442V} \text{ when } Ia = 120\ A.$$

(b) $Ia.Ra = V - Eb$

$$Ia = \frac{V - Eb}{Ra}$$

$$= \frac{460 - 447}{0.15} = \frac{13}{0.15}$$

$$\boxed{Ia = 86.67\ A.}$$

Ex2. A 4 pole 250V series motor has a wave connected armature with 1254 conductors. The flux per pole is 22 mwb. The motor takes an armature ct of 50 A. Amature and field resistances are 0.2 Ω and 0.2 Ω respectively calculate its speed.

Gn: $P = 4$, $V = 250V$, $Z = 1254$, $\phi = 22\ mwb$

$Ia = 50A$, $Ra = 0.2\ \Omega$, $Rse = 0.2\ \Omega$, $A = 2$

soln:-

$E_b = V - I_a(R_a + R_{se})$

$= 250 - 50(0.2 + 0.2)$

$= 250 - 20 = 230\,V$

$E_b = \dfrac{\phi P N Z}{60 A}$

$N = \dfrac{E_b \times 60 A}{\phi P Z}$

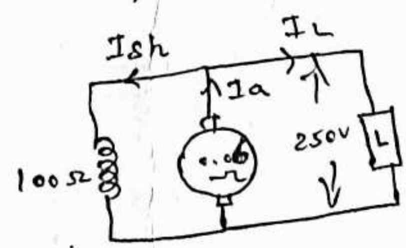
$= \dfrac{230 \times 60 \times 2}{22 \times 10^{-3} \times 4 \times 1254}$

Speed = 250 rpm.

Ex: A 25 kW, 250 V, DC shunt generator has armature and field resistances of 0.06 Ω and 100 Ω respectively. Determine the total armature power developed when working
(1) as a generator delivering 25 kW o/p
(2) as a motor taking 25 kW i/p.

Gn: $V = 250\,V$, $P = 25\,kW$, $R_a = 0.06\,\Omega$, $R_{sh} = 100\,\Omega$

soln:-



$P_o = 25\,kW$

$I_L = \dfrac{25 \times 10^3}{250} = 100\,A$

$I_{sh} = \dfrac{V}{R_{sh}} = 2.5\,A$

$I_a = I_L + I_{sh} = 102.5\,A$

$E_g = V + I_a \cdot R_a = 250 + 102.5 \times 0.06$

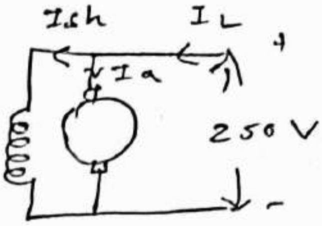
$E_g = 256.15\,V$

$$P_a = E_g I_a$$

$$= 256.15 \times 102.5$$

$$P_a = 26255.375\ W$$

2) As a motor.



$$I_L = \frac{25 \times 10^3}{250}$$

$$= 100\ A$$

$$I_{sh} = \frac{V}{R_{sh}} = \frac{250}{100} = 2.5\ A$$

$$I_a = I_L - I_{sh} = 100 - 2.5 = 97.5\ A$$

$$E_b = V - I_a \cdot R_a$$

$$= 250 - 97.5 \times 0.06$$

$$E_b = 244.15\ V$$

power developed in the armature $= E_b \cdot I_a$

$$= 244.15 \times 97.5$$

$$P_a = 23804.625\ W$$

Ex4: A 4 pole dc motor takes an armature of 50 A. The armature has lap connected 480 conductors. The flux per pole is 20 mwb. calculate the gross torque developed by the motor.

soln:- $T_a = 0.159\, \phi I_a \frac{PZ}{A}$

$$= 0.159 \times 20 \times 10^{-3} \times 50 \times \frac{4 \times 480}{4}$$

$$T_a = 76.32\ N\text{-}m$$

Ex.5: A 200V, 2000 rpm, 10 A, separately excited dc motor has an armature resistance of 2 Ω. Rated dc vge is applied to both the armature and field wdg of the motor. If the armature draws 5 A from the source, calculate the torque developed by the motor.

Gn: $V = 200V$ $N_1 = 2000$ rpm
$R_a = 2\ \Omega$ $I_{a2} = 5A$
$I_{a1} = 10A$

soln:-

$$E_{b2} = V - I_{a2} \cdot R_a = 200 - 5 \times 2 = 190V$$

$$E_{b2} = V - I_{a1} R_a = 200 - 10 \times 2 = 180V$$

$$N_2 = \frac{190}{180} \times 2000$$

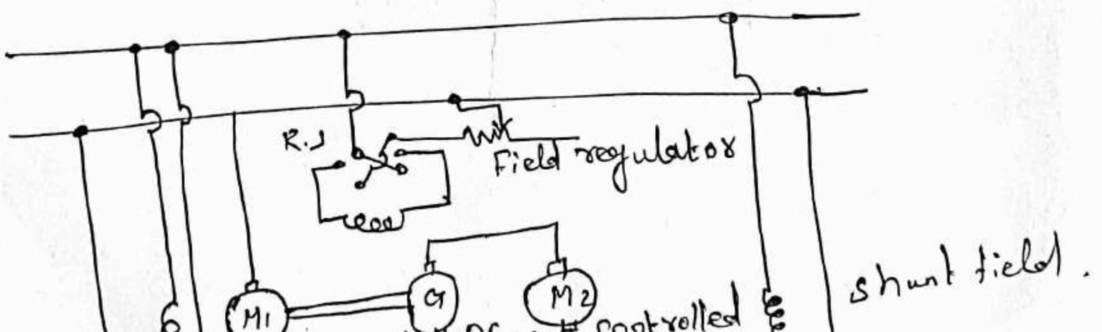
$$N_2 = 2111 \text{ rpm.}$$

$$E_b I_{a2} = T_a \omega_2 = T_a \cdot \frac{2\pi N_2}{60}$$

$$T_a = \frac{E_b I_{a2} \cdot 60}{2\pi N_2}$$

$$\boxed{T_a = 4.29\ N\text{-}m}$$

ward - Leonard Control System.

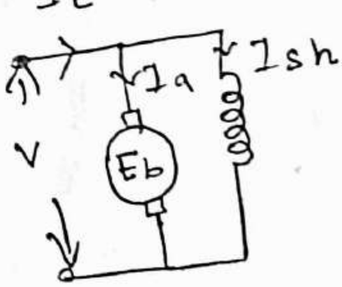


EXAMPLE: A 500 V DC shunt motor with constant field drives a load whose torque is proportional to the square of the speed. When running at 900rpm it takes an armature current of 45A. Find the speed at which the motor runs if a resistance of 8 Ω is connected in series with the armature. The armature resistance may be taken as 1 Ω. (NOV/DEC 2019)

Given Data

$$\text{Voltage} = 500V$$
$$N = 900rpm$$
$$I_a = 45\ A$$
$$R_{external} = 8\ \Omega$$
$$R_a = 1\ \Omega$$

Solution



$$E_b = V - I_{a_1} R_a$$
$$E_b = 500 - 45 \times 1$$
$$= 500 - 45$$
$$\boxed{E_b = 455V}$$

$$E_b = V - I_{a2}(R_a + R_{ext})$$
$$455 = 500 - I_{a2}(1 + 8)$$
$$9 I_{a2} = 500 - 455$$
$$I_{a2} = 45/9 = 5\ A$$

$T \propto N^2$

$T \propto \phi I_{a_1}$

$T_1 \propto I_{a_1}^2$

$T_2 \propto I_{a_2}^2$

$$\left(\frac{I_{a_2}}{I_{a_1}}\right)^2 = \left(\frac{N_2}{N_1}\right)^2$$

$$N_2^2 = N_1^2 \times \left(\frac{I_{a_2}}{I_{a_1}}\right)^2$$

$$= 900^2 \times \left(\frac{5}{45}\right)^2$$

$$N_2^2 = 10000$$

$$\boxed{N_2 = 100 \text{ rpm}}$$

The rotor reactance varies,

$$X_{2r} = s X_2.$$

Also $E_2 \propto \varphi$

$$E_{2r} = s E_2$$

and $$I_{2r} = \frac{E_{2r}}{Z_{2r}} = \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}} \quad \text{--- (2)}$$

$$\cos\varphi_{2r} = \frac{R_2}{Z_{2r}} = \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}} \quad \text{--- (3)}$$

φ can be replaced by E_2

sub (2) and (3) in (1)

$$T \propto E_2 \cdot \frac{sE_2}{\sqrt{R_2^2 + (sX_2)^2}} \cdot \frac{R_2}{\sqrt{R_2^2 + (sX_2)^2}}$$

$$T \propto \frac{sE_2^2 R_2}{R_2^2 + (sX_2)^2}$$

$$T = \frac{K s E_2^2 R_2}{R_2^2 + (sX_2)^2} \quad N\text{-}m \quad \text{--- (4)}$$

$$K = \frac{3}{2\pi n_s}$$

$n_s = \frac{N_s}{60} \Rightarrow$ synchronous speed in rps.

At standstill, $s = 1$ and therefore the starting torque, $T_{st} = \frac{K E_2^2 R_2}{R_2^2 + X_2^2}$ N-m

--- (5)

(22)

Torque Equation of 3φ Induction Motor:-

In DC motor, the torque T is proportional to the product of the armature current and flux per pole ie $T \propto \phi I_a$.

In the case of the induction motor, however, in addition to the flux and rotor current, the rotor power factor has also to be taken in to account.

Hence, $T \propto \phi I_{2r} \cos\phi_{2r}$ — ①

where

ϕ = flux responsible to produce induced emf

I_{2r} = rotor current under running condition.

$\cos\phi_{2r}$ = rotor power factor under running condition.

Let $E_2 \rightarrow$ Rotor induced emf per phase under standstill condition,

$X_2 \rightarrow$ Rotor reactance per phase under stand still condition.

rotor frequency at slip s is

$$f_r = sf.$$

Condition for maximum running torque.

Torque under running condition,

$$T = \frac{sKE_2^2 R_2}{R_2^2 + (sX_2)^2} \quad N-m$$

Torque T for a fixed input voltage will be maximum when $\frac{dT}{ds} = 0$,

$$\therefore (R_2^2 + s^2X_2^2)(KE_2^2R_2) - (KsE_2^2R_2)(2sX_2^2) = 0 \quad \text{——} (6)$$

ie $R_2 = sX_2$

$S_m = \frac{R_2}{X_2}$ is the slip at which the torque is maximum.

Then substituting $s = \frac{R_2}{X_2}$ in eqn (4)

we have, $T_{max} = \frac{KsE_2^2 sX_2}{2s^2X_2^2}$

$$T_{max} = \frac{KE_2^2}{2X_2} \quad \text{——} (7)$$

From this eqn, it can be observed that,

1. The maximum torque is independent of rotor resistance R_2.

2. Maximum torque is directly proporti-onal to the square of the induced emf at standstill. i.e. (E_2^2)

3. Maximum torque is inversely proportional to the rotor reactance.

Starting Torque and maximum torque.

$$T_{st} \propto \frac{R_2}{R_2^2 + X_2^2}$$

$$T_{max} \propto \frac{1}{2X_2}$$

$$\frac{T_{st}}{T_{max}} = \frac{2R_2 X_2}{R_2^2 + X_2^2} = \frac{2R_2/X_2}{1+(R_2/X_2)^2}$$

$$\frac{T_{st}}{T_{max}} = \frac{2a}{1+a^2}$$

where $a = \frac{R_2}{X_2}$

Full load torque and maximum torque

$$T_{fl} \propto \frac{s_f R_2}{R_2^2 + (s_f X_2)^2}$$

$$T_{max} \propto \frac{1}{2X_2^2}$$

$$\frac{T_{fl}}{T_{max}} = \frac{2 s_f R_2 X_2}{R_2^2 (s_f X_2)^2}$$

dividing both the numerator and

the denominator by X_2^2,

we can get $\frac{T_{fl}}{T_{max}} = \frac{2 s_f R_2/X_2}{(R_2/X_2)^2 + s_f^2}$

$$= \frac{2 a s_f}{a^2 + s_f^2}$$

$$\frac{T_{fl}}{T_{max}} = \frac{2 a s_f}{a^2 + s_f^2}$$

where $a = \frac{R_2}{X_2}$

Effect of change in supply voltage :-

The torque equation of the induction motor is given by,

$$T = \frac{k\varphi S E_2^2 R_2}{R_2^2 + (SX_2)^2}$$

Here, $E_2 \propto \varphi \propto V$ (supply voltage)

Torque at any speed is proportional to the square of the supply voltage.

i.e $T \propto V^2$

→ Changing the supply voltage, affects the starting torque, maximum torque and torque under running condition.

Let V changes to V_1, s to s_1.

$$T = sV^2, \quad T_1 = s_1 V_1^2$$

$$\boxed{\frac{T}{T_1} = \frac{sV^2}{s_1 V_1^2}}$$

Example:- A 3300V, 10 pole, 50 Hz, 3φ star connected induction motor has a slip ring rotor resistance per phase = 0.015 Ω and a standstill reactance per phase = 0.25 Ω. If the motor runs at 2.5 percent slip on full load, find i) the speed of the motor (ii) speed at which the torque will be maximum (iii) the ratio of maximum torque to full load torque.

Given data:-

$V = 3300V$, $P = 10$, $f = 50\,Hz$

$R_2 = 0.015\,\Omega$, $X_2 = 0.25\,\Omega$

$s = 2.5\% = 0.025$

solution:-

i) The speed of the motor N

$$N_s = \frac{120f}{P} = \frac{120 \times 50}{10} = 600 \text{ rpm.}$$

Motor speed $N = N_s(1-s) = 600(1-0.025)$

$N = 585$ rpm.

ii) speed at which the torque will be maximum,

$$S_m = \frac{R_2}{X_2}$$

$$S_m = \frac{0.015}{0.25} = 0.06$$

$$N = N_s(1 - S_m) = 600(1 - 0.06)$$

$$\boxed{N = 564 \text{ rpm}}$$

(iii) The ratio of maximum torque to full load torque

$$T_{max} \propto \frac{1}{2X_2}$$

$$T_f \propto \frac{S_f R_2}{R_2^2 + (S_f X_2)^2}$$

$$\frac{T_{max}}{T_f} = \frac{1/2X_2}{\frac{S_f R_2}{R_2^2 + (S_f X_2)^2}} = \frac{1}{2X_2} \times \frac{R_2^2 + (S_f X_2)^2}{S_f R_2}$$

$$= \frac{1}{2 \times 0.25} \times \frac{0.015^2 + (0.025 \times 0.25)^2}{0.025 \times 0.015}$$

$$\boxed{\frac{T_{max}}{T_f} = 1.408}$$

Example) A 4 pole, 50 Hz, 7.46 kW motor has, at rated voltage and frequency, a starting torque of 160 percent and a maximum torque of 200 percent of full load torque. Determine (1) full load speed (2) speed at maximum torque.

Given data :-

$P = 4$, $f = 50\ Hz$, $T_{st} = 1.6\ T_{fl}$, $T_{max} = 2T_{fl}$

soln :-

$$\frac{T_{st}}{T_{max}} = \frac{1.6}{2} = 0.8$$

$$T_{max} = 2\ T_{fl}$$

$$\therefore \frac{T_{max}}{T_{fL}} = 2$$

$$\frac{T_{st}}{T_{max}} = \frac{2a}{1+a^2}$$

$$\therefore \frac{2a}{1+a^2} = 0.8$$

$$0.8a^2 - 2a + 0.8 = 0$$

solving this equation, we can get

$$a = 0.5$$

$$a = \frac{R_2}{X_2} = 0.5$$

$$R_2 = 0.5\ X_2$$

$$\frac{T_{fl}}{T_{max}} = \frac{1}{2} = \frac{2as_f}{a^2 + s_f^2}$$

$$0.5 = \frac{2 \times 0.5 \times s_f}{(0.5)^2 + s_f^2}$$

$$(0.5)(0.5^2 + s_f^2) = 2 \times 0.5 \times s_f$$

$$0.125 + 0.5\, s_f^2 = s_f$$

$$0.5\, s_f^2 - s_f + 0.125 = 0$$

$$\boxed{s_f = 0.13}$$

i) Full load speed occurs at a slip of 0.01.

synchronous speed $N_s = \frac{120f}{P} = \frac{120 \times 50}{4}$

$= 1500$ rpm.

$\therefore$ Motor speed $N = N_s(1-s)$

$= 1500(1 - 0.13)$

$= 1305$ rpm

$\boxed{N = 1305}$ rpm

(ii) Maximum torque occurs at a slip of $s_m = \frac{R_2}{X_2} = 0.5$

$N = N_s(1-s)$

$= 1500(1-0.5)$

$\boxed{N = 750}$ rpm

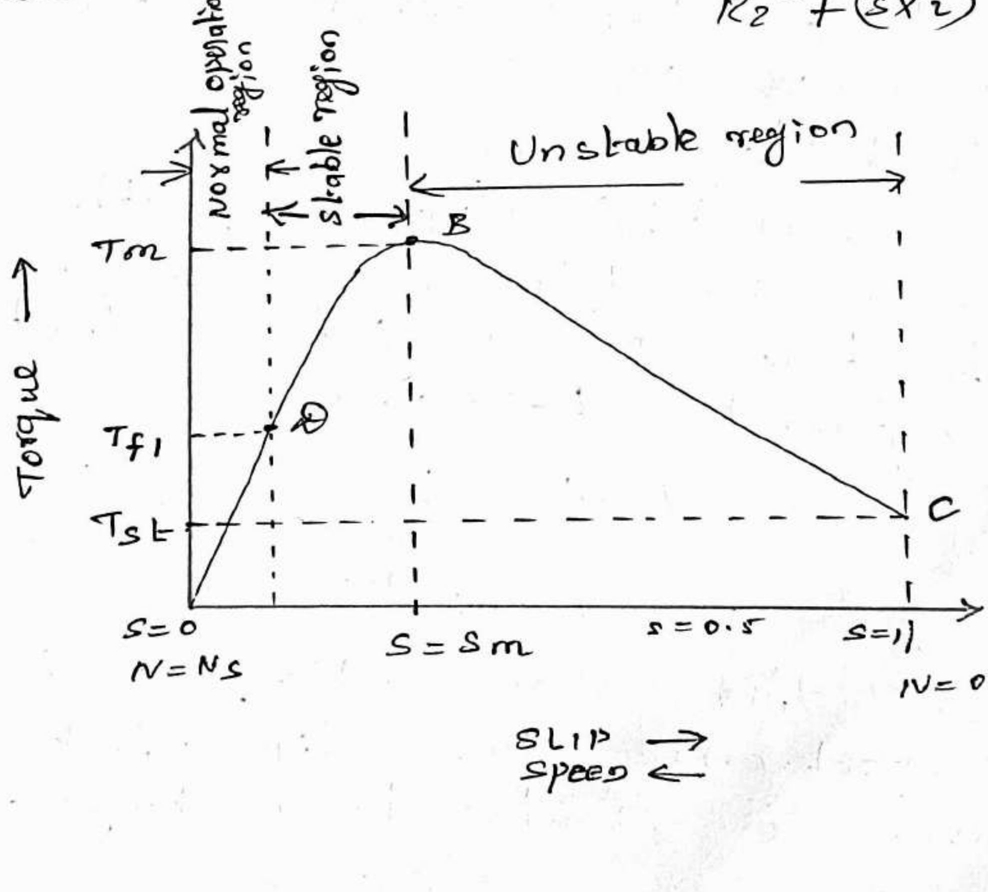
TORQUE - SLIP CHARACTERISTICS.

The curve drawn between torque and slip from s = 1 to s = 0 is called the torque - slip characteristics of the induction motor.

The torque equation of induction motor is given by

$$T \propto \frac{S E_2^2 R_2}{R_2^2 + (S X_2)^2}$$

Here, the i/p voltage is constant, ie E_2 is also constant. so the above equation becomes, $T \propto \frac{S R_2}{R_2^2 + (S X_2)^2}$



Torque slip characteristics are 3 regions,

1) stable region
2) Unstable operating region
3) Normal operating region.

stable region

In stable region, the slip value 's' is very small ie the term $(sX_2)^2$ is very small as compared to R_2^2. Hence neglecting $s^2X_2^2$.

$$\therefore T \propto \frac{sR_2}{R_2^2} \propto s \text{ as } R_2 \text{ is constant.}$$

$$\therefore T \propto s$$

The slip value is directly proportional to the torque. It is indicated in curve AB.

Unstable region.

When the slip is further increased from s_m, the region is unstable region. The term R_2^2 may be neglected as compared to $s^2X_2^2$.

$$T \propto \frac{s}{(sX_2)^2} \propto 1/s$$

$$\therefore T \propto 1/s$$

In this region, torque is inversely proportional to slip. The torque slip curve is similar to a rectangular hyperbola.

Normal operating region

The motor is continuously operated in this region. The following terms,

1. starting torque (T_{st})
2. Maximum torque or pull out torque (T_m)
3. Full load torque (T_{FL})

starting torque: In torque slip characteristics when the slip is zero. At this condition the motor produces a torque called starting torque.

Maximum torque:

when slip $s = s_m$ is called maximum torque, it is also called breakdown torque or pull out torque.

Full load torque:

Normally full load torque is less than the maximum torque.

LOSSES IN AN INDUCTION MOTOR.

Magnetic Losses:

→ The magnetic losses are also called core losses or iron losses. These losses occur in the stator core and rotor core.

→ The hysteresis losses due to changes in the magnetic field in the stator core.

→ The eddy current losses are due to the flow of eddy current through the body of the stator core.

Mechanical loss:

Frictional and windage losses are mechanical loss.

Electrical losses:

These losses are due to the resistance of stator and rotor winding. these losses includes stator copper losses and rotor copper losses. These are variable losses.

Rotor Cu loss = $3I_2^2R_2$

Power Flow

Three phase supply is feed to the stator of the induction motor. The i/p power is $P_{in} = \sqrt{3}\, V_L I_L \cos\phi$

some losses occur in the stator. These losses are called stator losses.

P_{SL} = Combination of stator core loss + copper loss in stator.

∴ stator o/p or rotor i/p

$$P_2 = P_{in} - P_{SL}$$

rotor cu loss $P_{cu} = 3I_2^2 R_2$

The gross mechanical power

$$P_m = P_2 - P_{cu}$$

The power available to the load at the shaft

$$P_{out} = P_m - P_{ml}.$$

$P_{ml} \rightarrow$ mechanical loss.

$$\text{Rotor efficiency} = \frac{P_m}{P_2}$$

$$\text{Motor efficiency} = \frac{P_{out}}{P_{in}}$$

EX: A 100 kW (o/p), 3300 V, 3φ, star connected induction motor has a synchronous speed of 500 rpm. The full load slip is 1.8%. and full load power factor 0.85. stator copper loss = 2440 W. Iron loss = 3500 W. Rotational losses = 1200 W. calculate (1) the rotor copper loss (2) the line current (3) the full load efficiency.

Given data: $P_{out} = 100$ kW, $V_L = 3300$ V

$N_s = 500$ rpm, $S_F = 1.8\%$ or 0.018

$\cos\phi = 0.85$, $P_{SL} = 2440$ W, $P_i = 3500$ W,

$P_{mL} = 1200$ W.

soln:

1) $P_{out} = 100\,kW$.

mechanical power developed $P_m = P_{out} + P_{mL}$

$$= 100 + 1.2 = 101.2\,kW$$

$$P_{cu} = \frac{s}{1-s} \times P_m = \frac{0.018}{1-0.018} \times 101.2$$

$$\boxed{P_{cu} = 1.855\,kW}$$

2) The Line current (I_L)

$$P_{in} = \sqrt{3} V_L I_L \cos\varphi$$

$$P_{in} = P_m + P_{cu} + P_{SL} + \text{Iron loss}$$

$$= 101.2 + 1.855 + 2.44 + 3.5$$

$$P_{in} = 108.995\,kW$$

$$108.995 \times 10^3 = \sqrt{3} \times 330 \times I_L \times 0.85$$

$$\boxed{I_L = 22.4\,A}$$

3) Full load efficiency

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

$$= \frac{100000}{108995} \times 100 = 91.7\%$$

$$\boxed{\eta = 91.7\%}$$

Single phase Induction motor.

Like any other electrical motor asynchronous motor also have two main parts namely rotor and stator.

Stator :-

→ stationary parts of Induction motor.

→ A single phase Ac supply is given to the stator of 1φ Induction motor.

Rotor :-

→ Rotating part of an induction motor.

→ rotor connects the mechanical load through the shaft.

→ squirrel cage rotor type.

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

where f = supply frequency
P = No. of poles of motor.

Working :-

→ Interaction of two fluxes produced the required torque.

→ When we apply a 1φ Ac supply to the stator winding of 1φ IM, the alternating current starts flowing through the stator or main winding.

→ This alternating flux is called main flux.

→ According to the Faraday's law of electromagnetic induction, the main flux links with the rotor conductors and hence cut the rotor conductors.

→ Two fluxes produce the desired torque which is required by the motor to rotate.

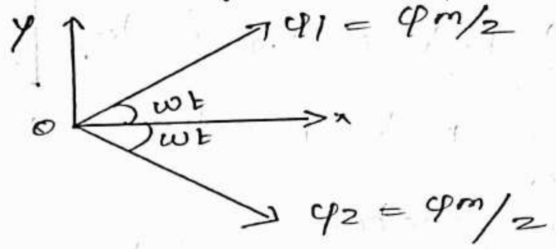
→ According to double revolving field theory, we can resolve any alternating quantity in to two components. Each components has a magnitude equal to the half of the maximum magnitude of the alternating quantity, and both these components rotate in the opposite direction to each other.

→ φ can be resolved in to two components $\frac{\varphi m}{2}$ and $-\varphi m/2$.

or $\varphi_r = \varphi_f + \varphi_b$

Explain the double field revolving theory for operation of 1φ induction motor.
NOV-DEC 2012
APRIL-MAY 2015 &
NOV-DEC 2015

→ Represented by two revolving fluxes.



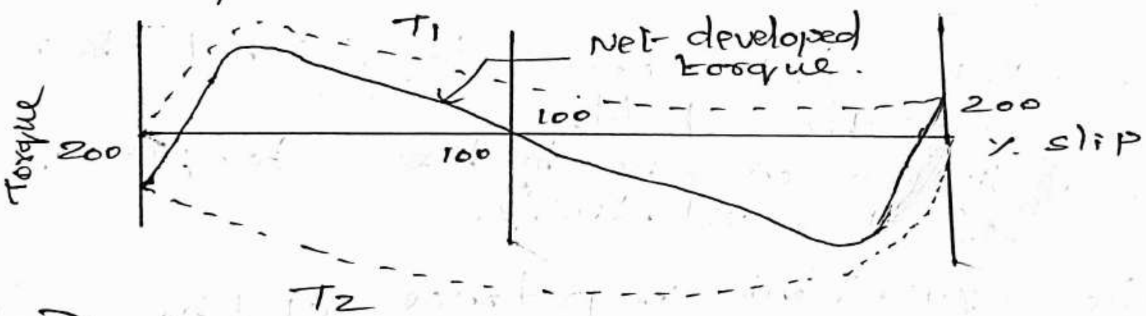
X component = $\varphi_m \cos \omega t$

Y component = 0

Resultant flux = $\sqrt{(\varphi_m \cos\omega t)^2 + 0^2} = \varphi_m \cos\omega t$

(i) Rotor at standstil

→ Rotor standstill, stator connected with 1φ AC supply.



ii) Rotor running

→ spinning the rotor by auxiliary circuit

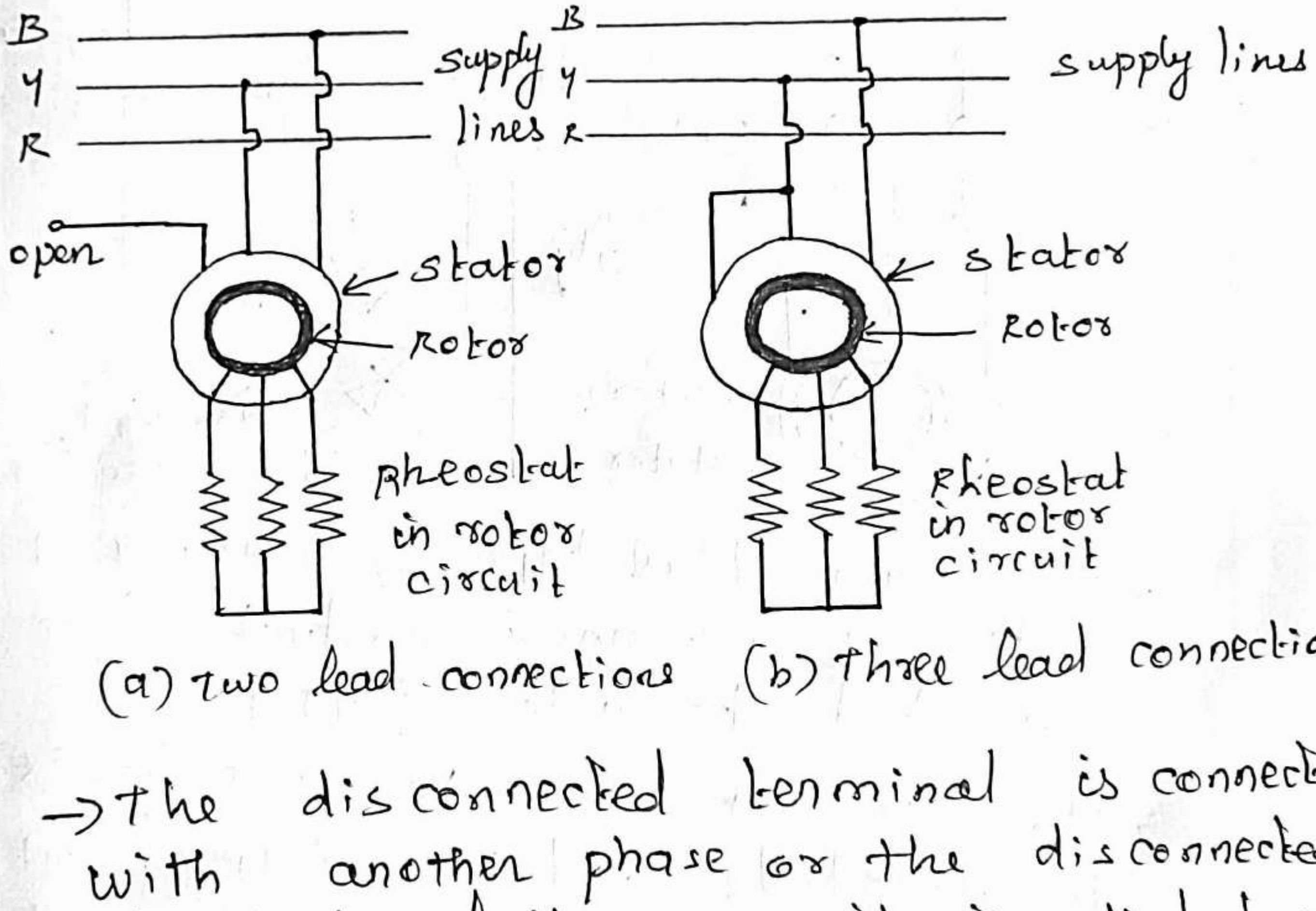
Forward slip $S_f = \frac{N_s - N}{N_s} = S$

backward slip $S_b = 2 - S$

BRAKING OF INDUCTION MOTOR.

Dynamic or Rheostatic Braking.

→ This type of induction motor braking is obtained when the motor is made to run on a single phase supply by disconnecting any one of the three phase from the source.



(a) two lead connections (b) Three lead connections.

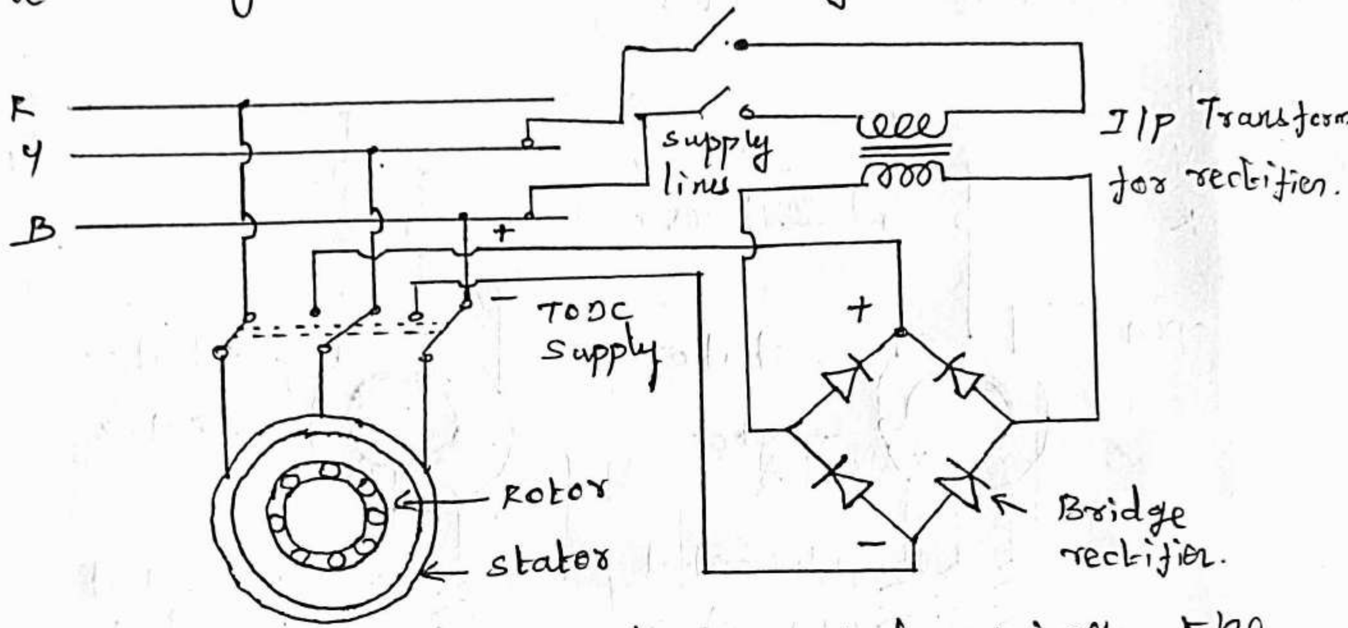
→ The disconnected terminal is connected with another phase or the disconnected phase is left open, it is called two lead connection.

→ When the disconnected phase is connected to another machine phase it is known as three lead connection.

→ The torque of 3φ induction motor is reduced when motor runs with two phase supply.

→ Now the resistance value of rheostat can be adjusted to stop the motor.

DC dynamic Braking.



→ To obtain this type of braking the stator of a running induction motor is connected to a dc supply

→ The moment when AC supply is disconnected and DC supply is introduced across the terminals of the induction motor.

→ The stationary magnetic field is generated due to the DC electric current flow.

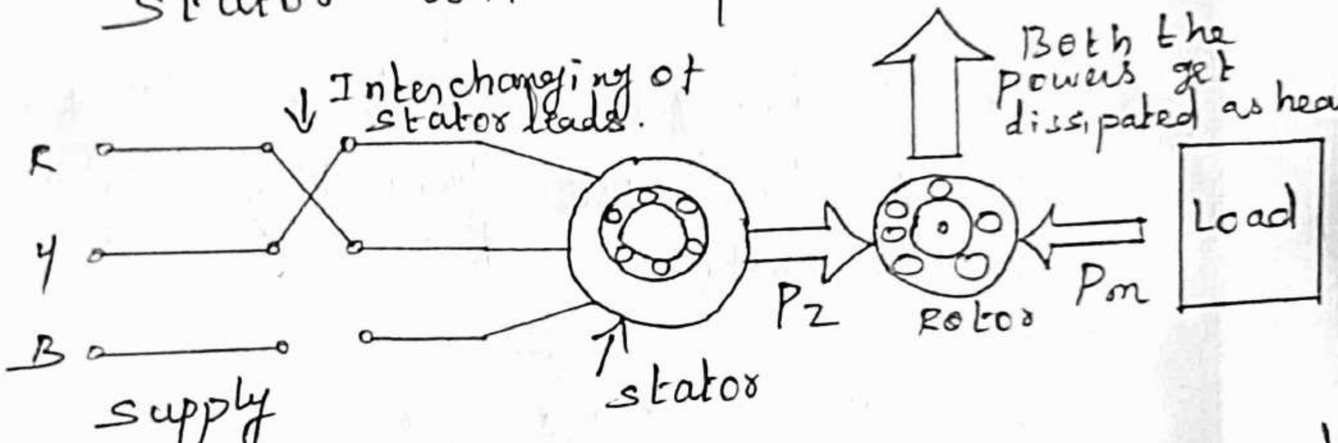
→ The machine works as a generator

and the generated energy dissipates in the rotor circuit resistance and dynamic braking of induction motor occurs.

Plugging or counter current braking.

→ Plugging of induction motor braking is done by reversing the phase sequence of the motor

→ The phase sequence of the motor can be changed by interchanging of connections of any two phases of stator with respect of supply terminals



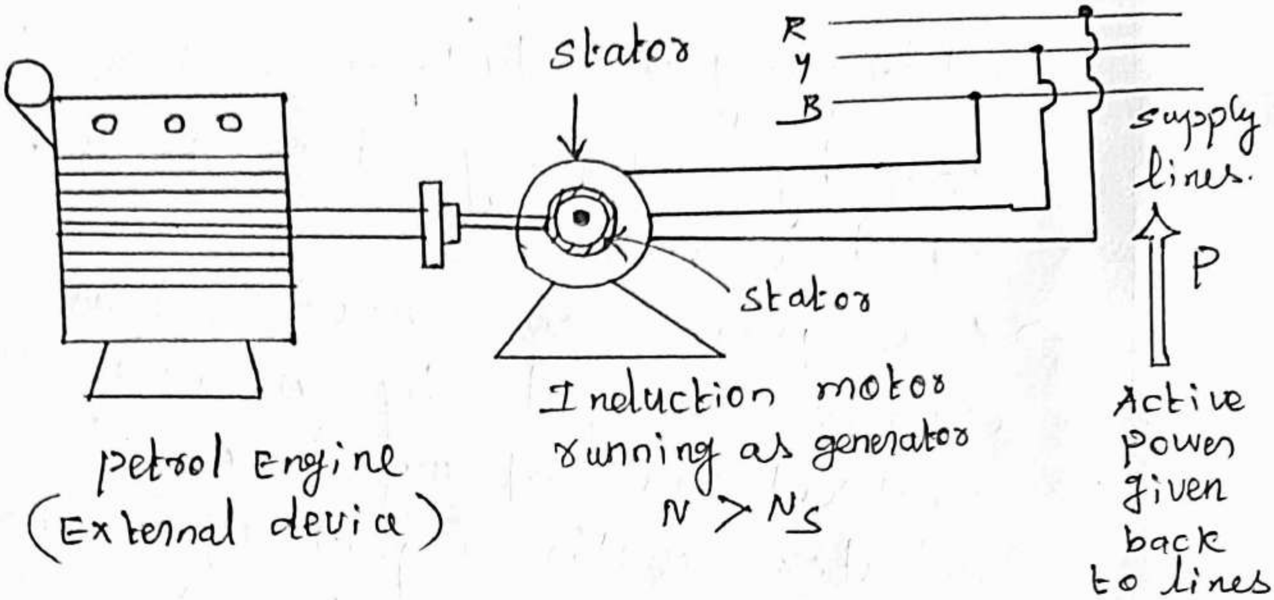
→ when the phase sequence is changed, the direction of current flow is changed.

→ The counter current produces the opposite torque and then motor is stopped.

Regenerative Braking :-

9

The regenerative braking of induction motor can only take place if the speed of the motor is greater than synchronous speed, It is obtained by using petrol engine.



-> This braking method is called regenerative breaking because here the motor works as generator and supply the voltage to main.

-> The main criteria for regenerative braking is that the rotor has to rotate at a speed higher than synchronous speed.

-> The motor will act as a generator and the direction of electric current flow through the circuit and direction of the torque reverses and braking takes place.

UNIT - III

STARTING METHODS

Necessity of a starter:-

The voltage equation of a DC motor is $V = E_b + I_a \cdot R_a$

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

At the instant of starting $E_b = 0$.

$$\therefore I_a = \frac{V - 0}{R_a} = \frac{V}{R_a}$$

At starting the motor takes large amount of current. which is nearly 25 times the full load current.

But it is can't be allow in a motor for a short time period.

It causes damage the brushes and commutator and brush gear.

It limits the starting current due to a safe value.

Types of DC motor starters:-

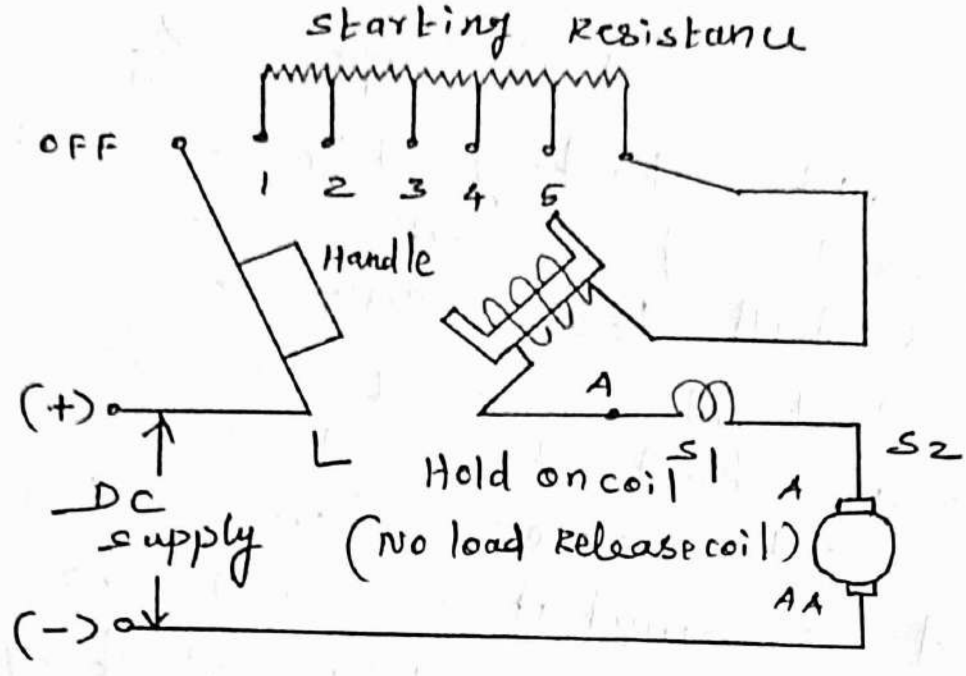
1. Two point starter
2. Three point starter
3. Four point starter.

Two point starter:-

No Load Release coil (NLR)

* the Load current flows through NLR, It gives necessary protection to the motor.

* when load current becomes zero, NLR release the handles and back to OFF position.



* Here starting resistance is connected in series with the armature.
* No load release coil is connected in series with armature.
* After closing the supply the handle is moved from OFF to stud 1. It gives full resistance so the current is reduced.
* In this way the flow of current and increased gradually.

Three point starter.

* It consists starting resistance R1 to R6 is connected in series with armature.
* Handle can be moved over there resistances.
* NVR Coil is connected in series with field winding.
* OLR (over load release) is connected in series with armature and movable arm is placed near OLR.

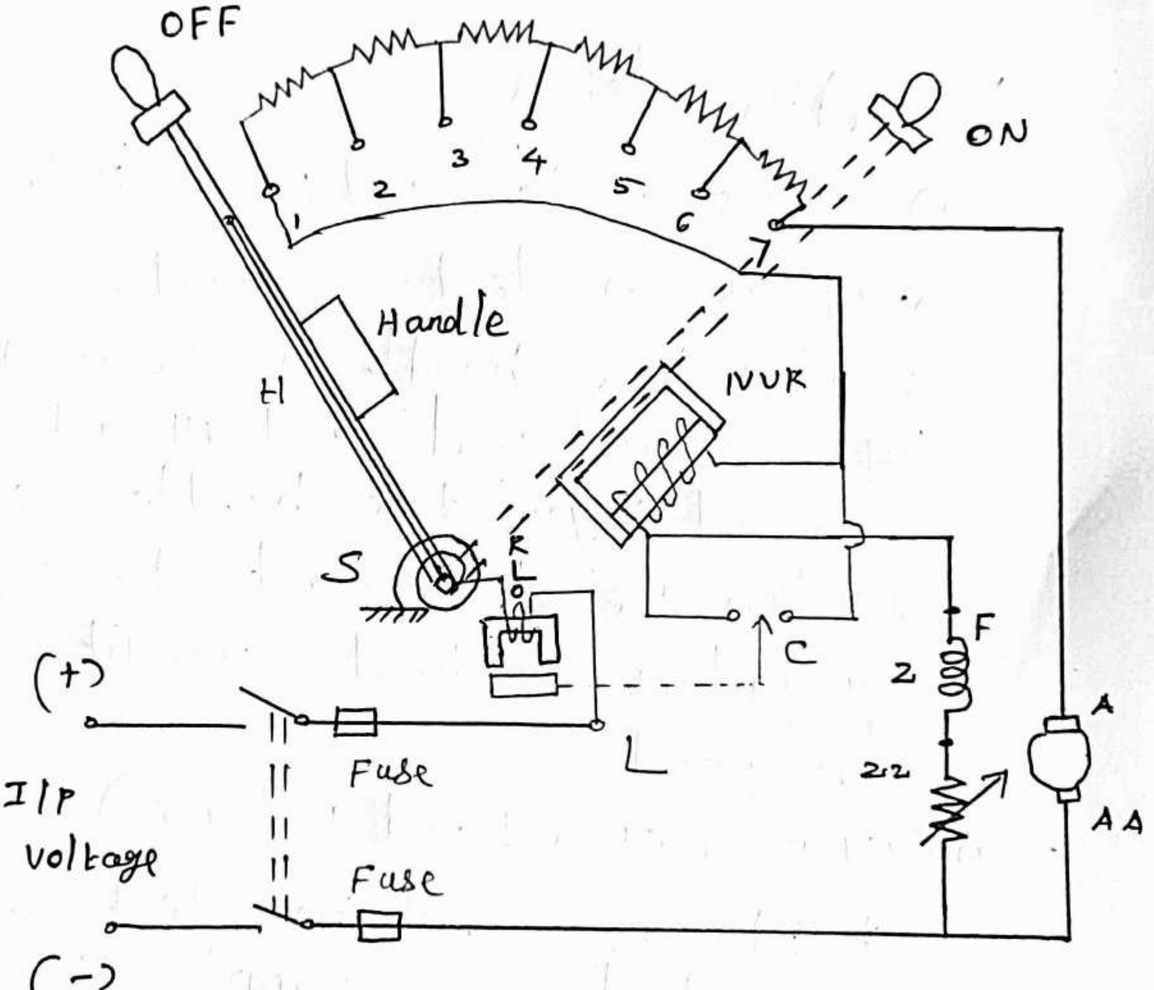


Fig: 3 point starter.

Operation :-

* when we give the supply voltage handle moved over the starting resistance

* Now the handle is at stud No1. so that it give full resistance.

* The starting current is reduced, the handle is further moved and the resistance cut out gradually.

* The motor develops the back emf when it gethers speed.

Protective device :-

(i) NVR : (No voltage Release)

* It is an electromagnet.

* when the handle is on position, it get magnetized and attract the soft iron and keeps the handle on position.

* when we dis connect the supply or any failure in field circuit NVR goto OFF position.

(ii) OLR : (Over Load Release)

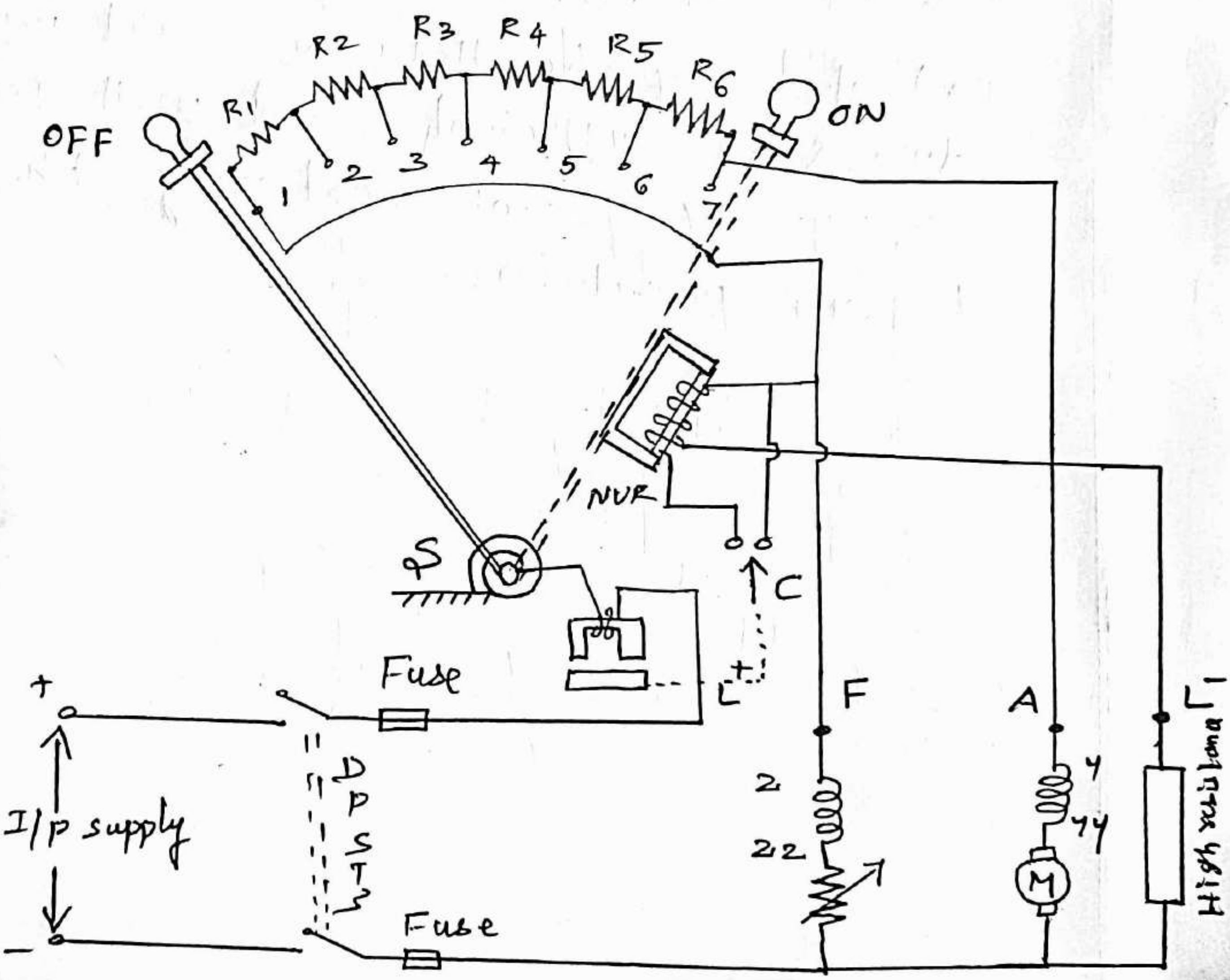
* It consists an electromagnet connected in supply line.

* It lifted the arm to OFF position when the motor becomes overloaded.

Demerits of 3 point starter.

$$N \propto \frac{1}{\phi}$$

* To achieve higher speed, the field current is to be reduced to very low.
* This low current losses through NVR. It is unable to create enough electromagnetic pull to overcome the spring torsion.
* So that the arm is pulled back to OFF position.



Working :-

* In this starter the HOLD ON will has been taken out of the shunt field circuit.

* HOLD ON coil is directly connected across the supply line through protecting resistance (HR)

* So any change of current in shunt field circuit does not affect the current passing through the HOLD ON coil.

* It means the electromagnetic pull exerted by the HOLD ON coil will always be sufficient and will prevent the spring from restoring the handle to OFF position.

Need for starter:-

when a 3φ induction motor is switched on at normal supply voltage, heavy current will flow through the motor because at the time of starting, there is no back emf. This initial inrush of excessive current is objectionable because it will produce large line voltage drop. This will affect the operation of other electrical equipments connected to the same line. Due to this, starters are used for starting the three phase induction motors.

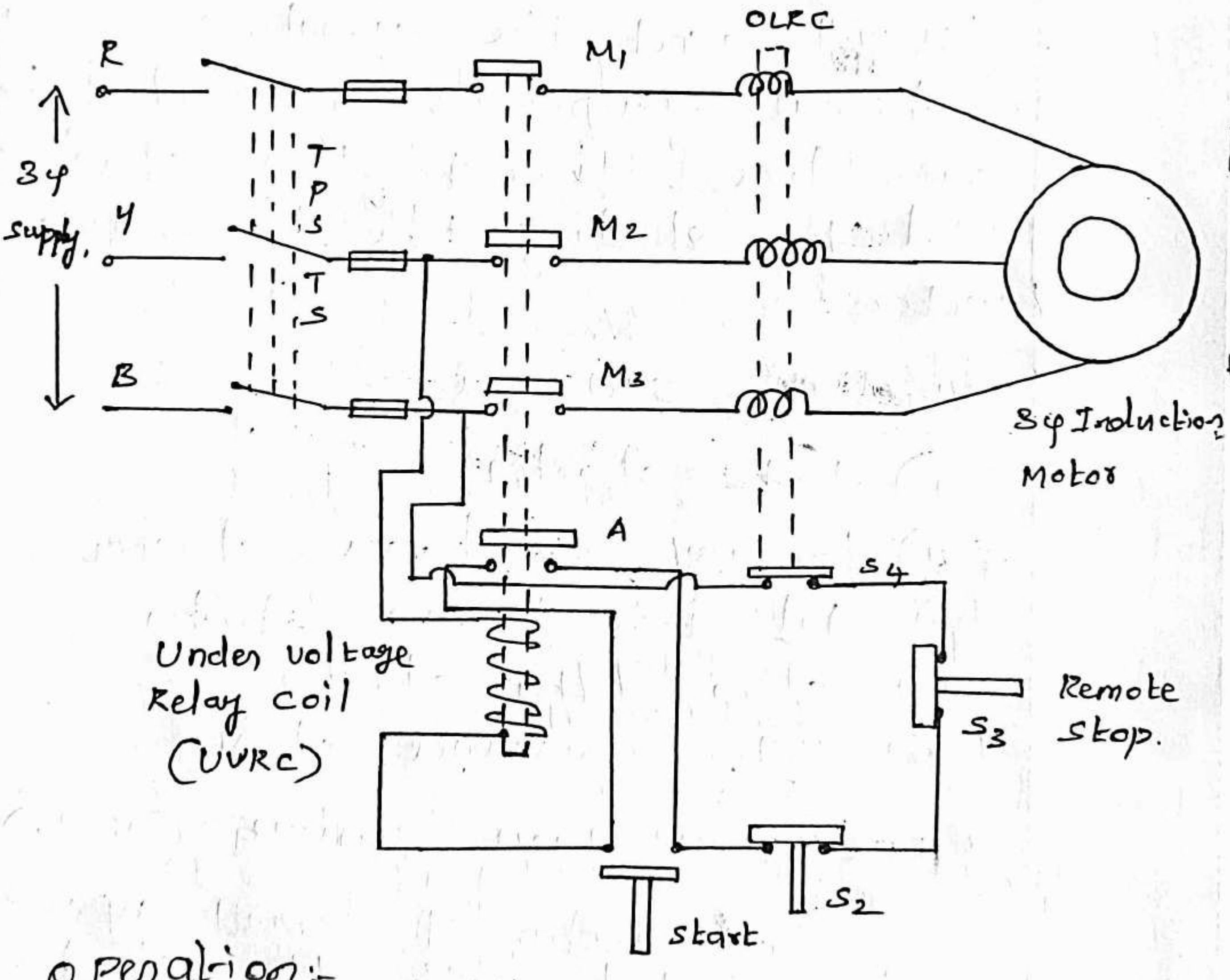
TYPES OF STARTERS :-

i) DOL starter
ii) Primary resistance starter
iii) Auto transformer starter
iv) star - delta starter
v) Rotor resistance starter.

DIRECT ON LINE STARTER (DOL)

A motor of small capacity can be started with this starter. Fig shows a 3φ induction motor with a DOL starter. M_1, M_2, M_3 are main contactors normally open (NO) type making making and breaking the motor line current.

These contactors are operated by a relay coil. S_2, S_3 and S_4 are normally closed (NC) type and are connected in series with relay coil. Overload relay coil (OLRC) is connected in series with motor line supply.



Operation:-

When TPST switch is closed, the under voltage Relay coil (UVRC) is energized. and it will operate the main contactors to close. Hence the full voltage is given to the motor and it runs. closing of contactor A retains the supply to the UVRC..

contactor S_2 is used to disconnect the supply from the motor by manually pressing it. Remote operation of the same can be achieved with the help of contactor S_3.

No voltage protection:

when the supply voltage either fails totally or falls below certain value, the holding power given by UVRC comes down causing the main contactor to be opened. Thus the motor is protected from low voltage operation.

Over load protection:-

when the line current exceeds the preset value, OLRC is energised more and causes the contactor S_4 to open. When S_4 opens, the UVRC is disconnected from the supply. Therefore it will release the main contactors.

The relation between starting torque (T_{st}) and full load torque T_{fl} is given by,

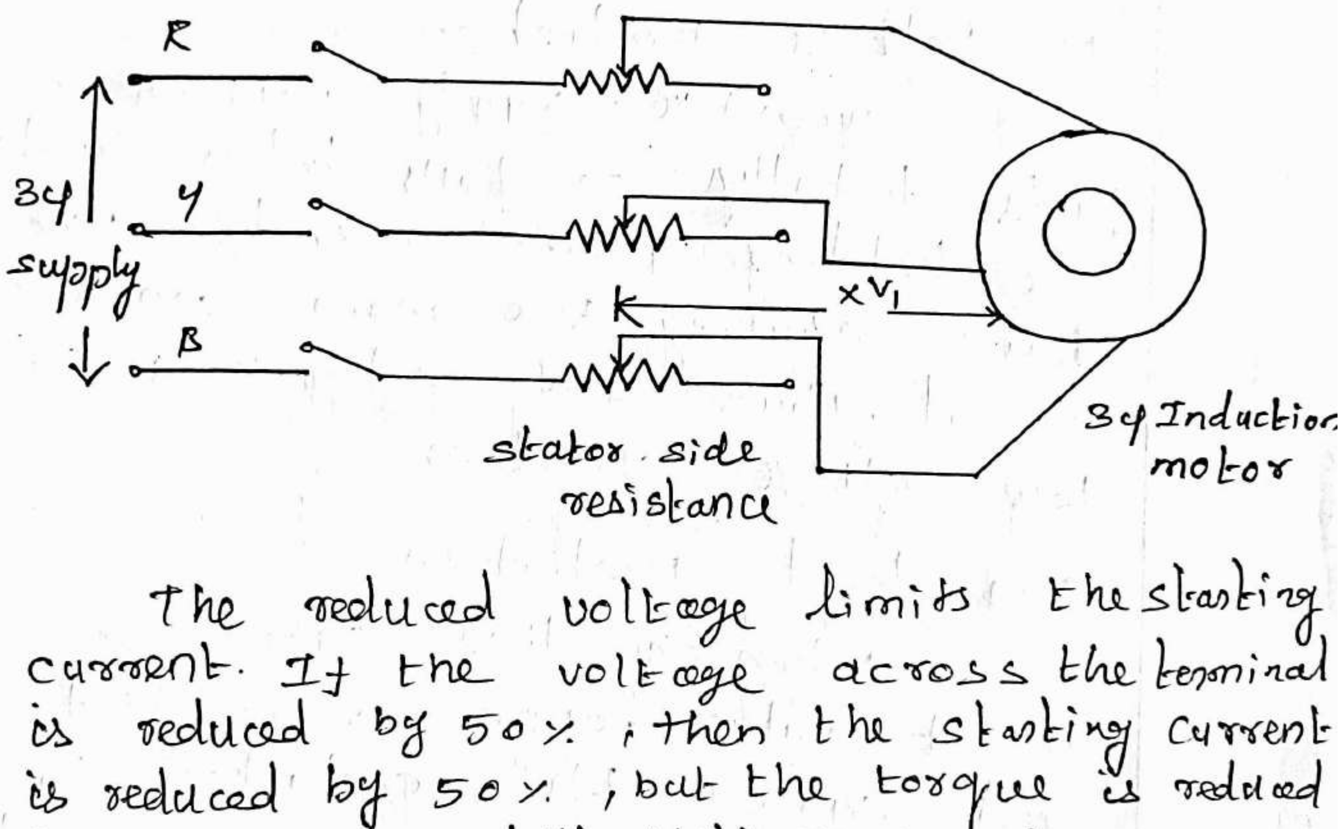
$$\frac{T_{st}}{T_{fl}} = \left(\frac{I_{sc}}{I_{fl}}\right)^2 S_f$$

where $I_{sc} = I_{st}$ = short circuit current

s_f = Full load slip.

Primary Resistor (or) Reactor starter.

A variable resistor (or) reactor is connected in series with the supply terminals of the motor. The purpose of resistance is to reduce the supply voltage.



The reduced voltage limits the starting current. If the voltage across the terminal is reduced by 50%, then the starting current is reduced by 50%, but the torque is reduced to 25% of the full voltage value.

Let reduced per phase voltage $= xV_1$

per phase starting current $I_{st} = \dfrac{xV_1}{Z_{sc}} = xI_{sc}$

we know that $\dfrac{T_{st}}{T_{fl}} = \left(\dfrac{I_{sc}}{I_{fl}}\right)^2 s_f$

$$\frac{T_{st}}{T_{fl}} = x^2 \left(\frac{I_{sc}}{I_{fl}}\right)^2 s_f$$

In an induction motor,

torque ∝ voltage^2

$$\therefore \frac{\text{starting torque with reactor starting}}{\text{starting torque with direct switching}} = \left[\frac{xV_1}{V_1}\right]^2$$

$$= x^2$$

Advantages :-

1. smooth acceleration
2. High power factor during start
3. Less expensive
4. closed transition starting.

Disadvantages :-

1. Power lost in resistors
2. Low starting torque
3. Less efficiency.

Auto transformer starter :-

This starter is used to give a reduced voltage to the 3-phase induction motor to limit the starting current. The reduced voltage is obtained by an autotransformer.

The supply is given to terminals 1, 3 and 5 of the movable handle and the motor is connected to 2, 4 and 6 of handle through an OLRC (Over load Release Coil). Low voltage protection is given to the motor by UVRC.

Operation :-

when the handle is at start position, the motor is connected through the auto transformer. when the motor gets 80 % of the normal speed, the handle is moved to RUN position. At this position the motor receives full line voltage.

Over load protection :-

when motor current exceeds the preset value, the over load relay coil is energised high enough to operate the contactor S_1. Hence supply is switched off.

Low voltage protection :-

The under voltage relay coil is connected across two lines. when supply voltage goes low or fails, UVRC de-energized and releases the handle to OFF position.

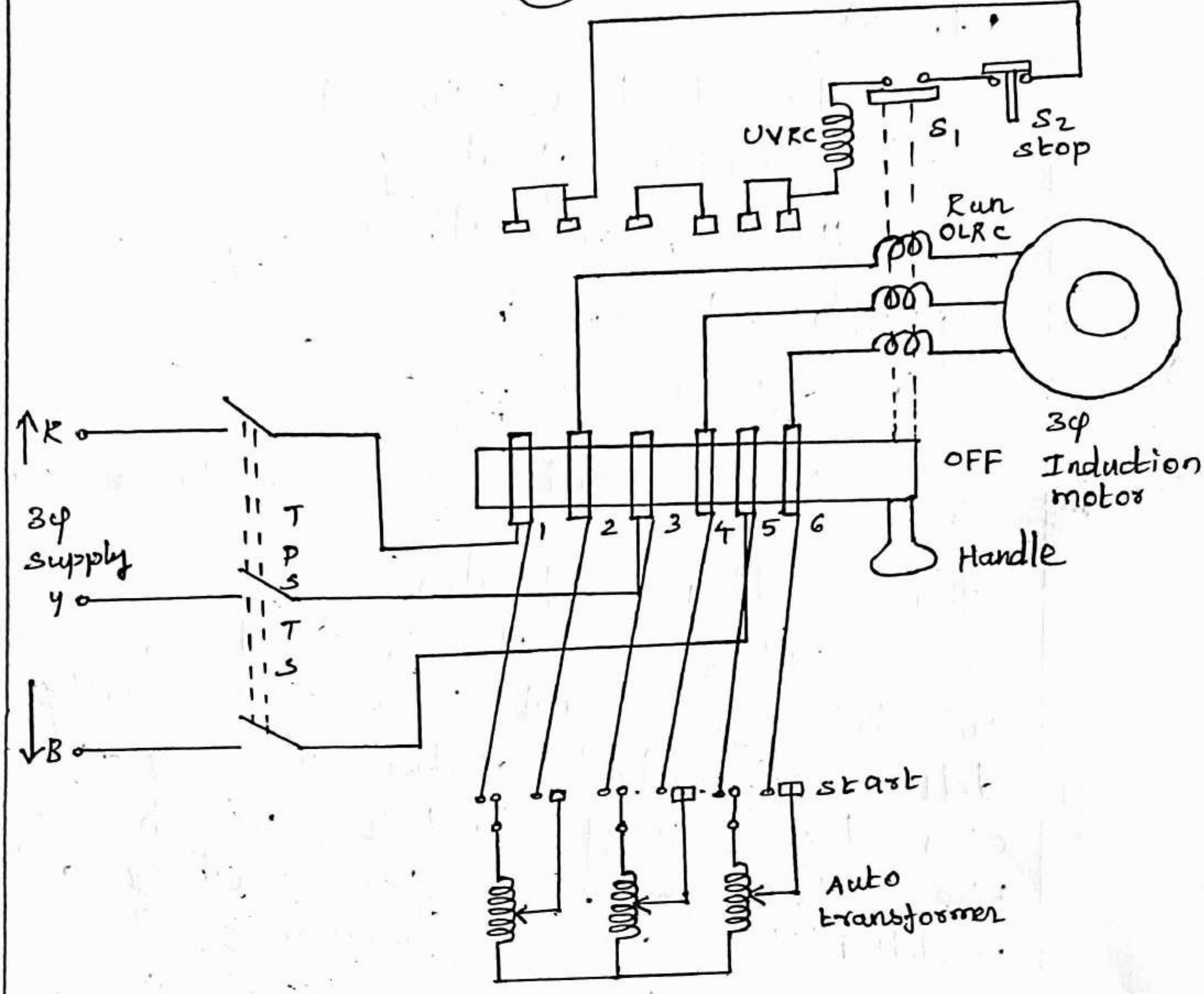
starting current $I_{st} = x I_{sc}$

The starting current drawn from the supply

$$= x(I_{st}) = x(x I_{sc}) = x^2 I_{sc}$$

The torque developed by the motor,

$$T = \frac{3 I_2^2 R_2}{s} \text{ (synchronous watts)}$$



Full load torque $T_{fl} = \dfrac{3I_{fl}^2 R_2}{S_f}$

starting torque $T_{st} = \dfrac{3I_{st}^2 R_2}{1}$

[s = 1 at start]

Thus $\dfrac{\text{starting torque}}{\text{Full load torque}} = \dfrac{T_{st}}{T_{fl}} = \left[\dfrac{I_{st}}{I_{fl}}\right]^2 S_f$

Hence in auto transformer starters,

$$\frac{T_{st}}{T_{fl}} = \left(\frac{x I_{sc}}{I_{fl}}\right)^2 S_f = x^2 \left(\frac{I_{sc}}{I_{fl}}\right)^2 S_f$$

Advantages:

1. Reduced line current
2. smooth starting
3. High acceleration

Disadvantages :-

1. cost is high
2. It is not used for large motors.

Star delta starter:-

This method is used in motors which are meant to run normally with a delta connected stator winding. It consists of a two way switch which connects the motor in star for starting and then in delta for normal running.

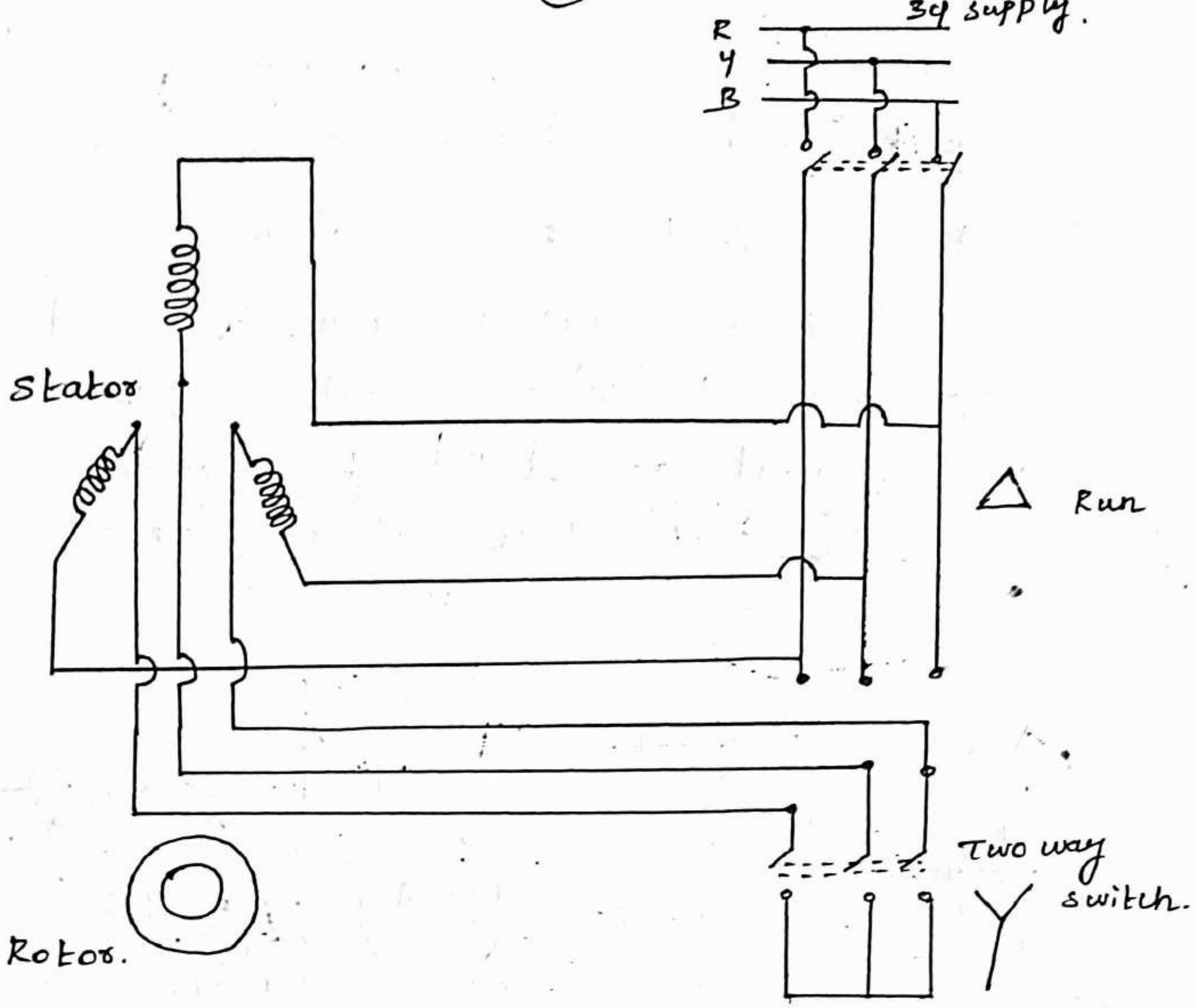
When the two way switch is at START position, the stator windings are connected in star. Therefore the applied voltage is reduced by a factor of $1/\sqrt{3}$. Hence starting current is reduced.

Initial starting current and starting torque are given by,

Initial starting current, $I_{st} = \frac{1}{\sqrt{3}} I_{sc}$.

$$\frac{\text{starting torque}}{\text{Full load torque}} = \frac{T_{st}}{T_{fl}} = \left(\frac{I_{st}}{I_{fl}}\right)^2 s_f$$

$$= \frac{1}{3}\left(\frac{I_{sc}}{I_{fl}}\right)^2 s_f.$$



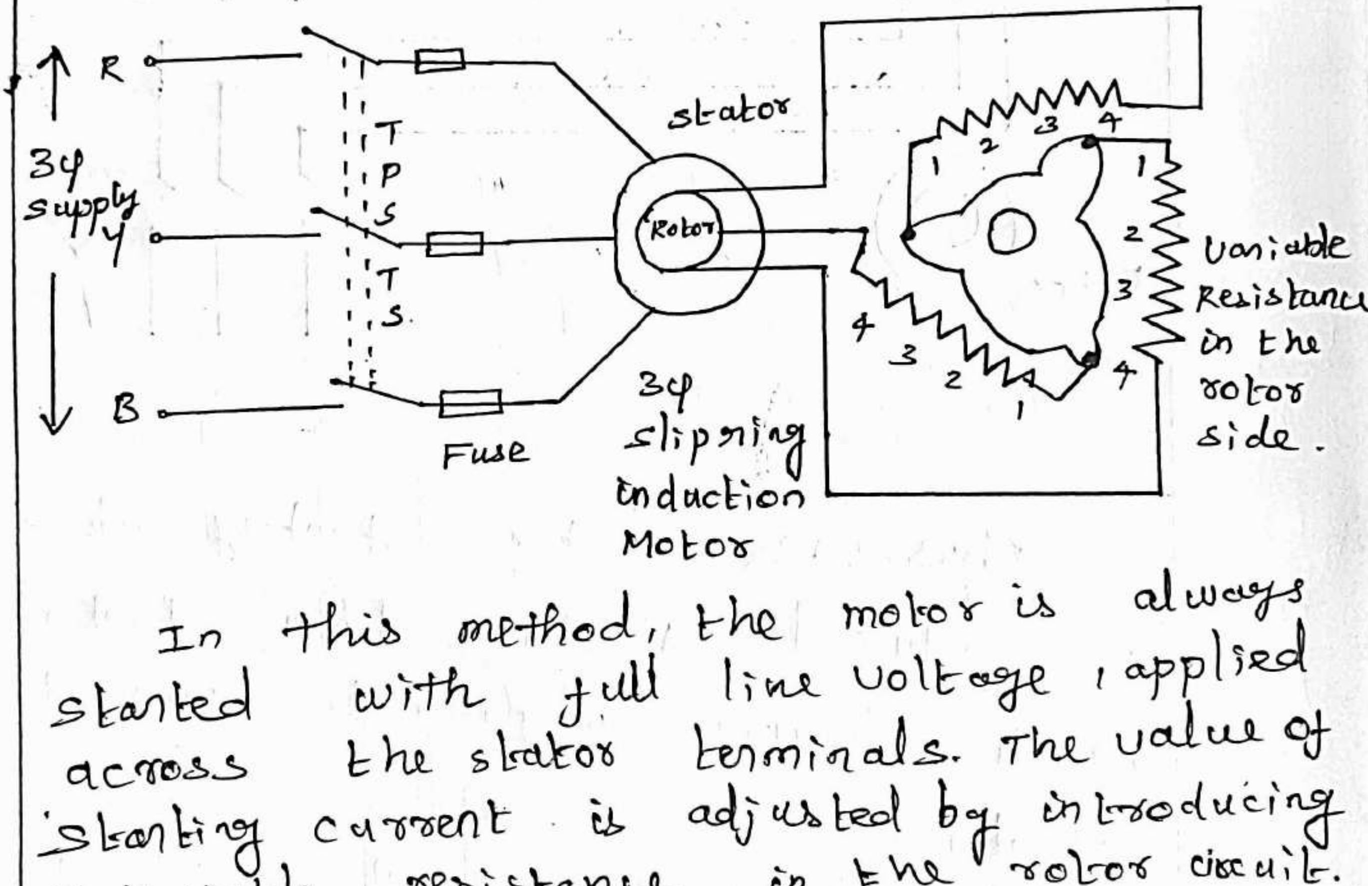
Thus, the motor starting torque is reduced. A star-delta starter is much cheaper compared to auto-transformer starter.

A locking arrangement is also provided, so that motor can be started only in star connection.

This starter is mainly used for small and medium size motors.

Rotor Resistance Starter :-

This starter can be used only for slip ring induction motor. As shown in fig external or starting resistance is connected in the rotor terminals.



In this method, the motor is always started with full line voltage applied across the stator terminals. The value of starting current is adjusted by introducing a variable resistance in the rotor circuit. At starting, the full resistance is included and hence the starting current is reduced. The resistance is gradually cut out of the rotor circuit as the motor gathers speed.

UNIT - IV

CONVENTIONAL AND SOLID STATE SPEED CONTROL OF D.C DRIVES.

Three methods of speed controls

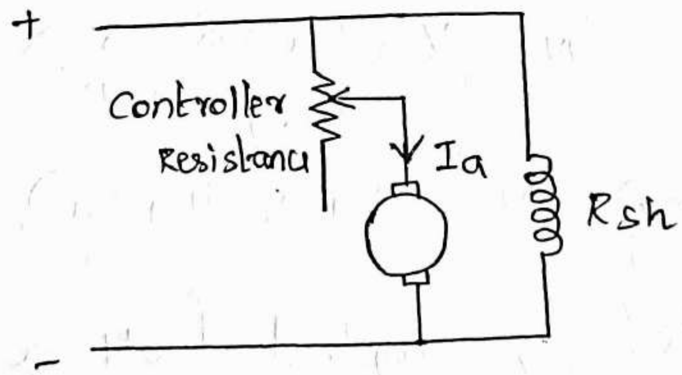
1. By varying the resistance in the armature circuit.
2. By varying the flux
3. By varying the applied voltage.

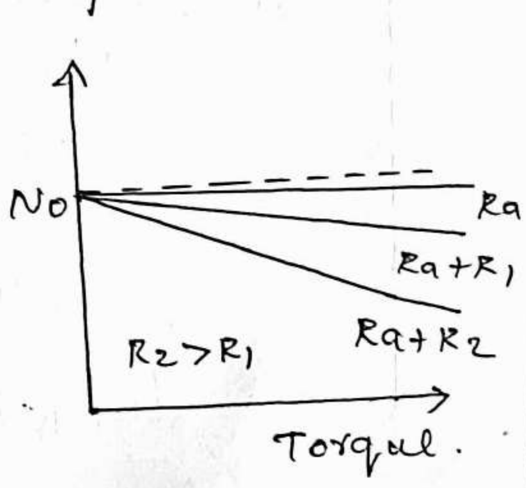
1. By varying the resistance in the armature circuit.

A variable resistance R is connected in series with armature circuit.

Here the input voltage V is constant. The speed of the motor can be controlled by varying the resistor R. so the speed equation becomes.

$$N = \frac{K\left[V - I_a(R_a + R)\right]}{\varphi}$$





Advantages

. Simple method of speed control.

$$T_{sh} = \frac{P_{out}}{2\pi N/60} \ N\text{-}m$$

$$= \frac{60}{2\pi} \frac{P_{out}}{N} \ N\text{-}m$$

$$\boxed{T_{sh} = 9.55 \frac{P_{out}}{N}} \ N\text{-}m$$

Applications:

1. Shunt motors may be used for driving centrifugal pumps and light machine tools, wood working machines, lathe etc.
2. Series motors are used for electric trains, cranes, hoists, fans, blowers, conveyors, lifts etc.
3. Compound machines are used for driving heavy machine tools, punching machines etc.

SPEED CONTROL OF DC MOTOR.

The speed of DC motor is given by,

$$N = \frac{V - I_a R_a}{Z\phi}\left(\frac{A}{P}\right)$$

(or) $$N = \frac{K(V - I_a R_a)}{\phi}$$

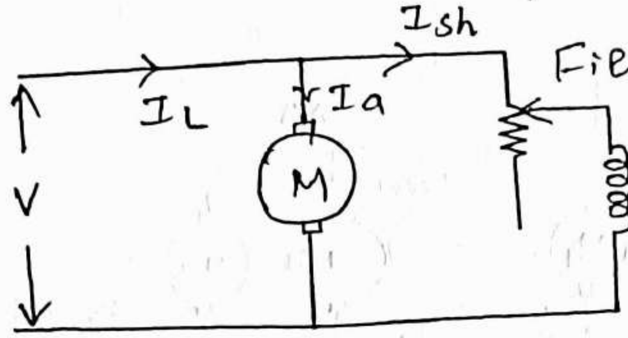
where, V = applied voltage
I_a = armature current
R_a = armature resistance
ϕ = flux per pole
K = constant.

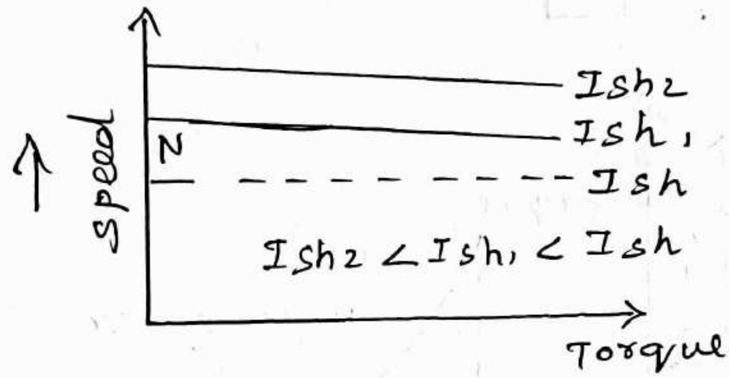
Disadvantage

1. More power consumption
2. The change in speed with the change in load becomes large.

2. By varying the flux

The speed is inversely proportional to flux ie. $N \propto 1/\phi$





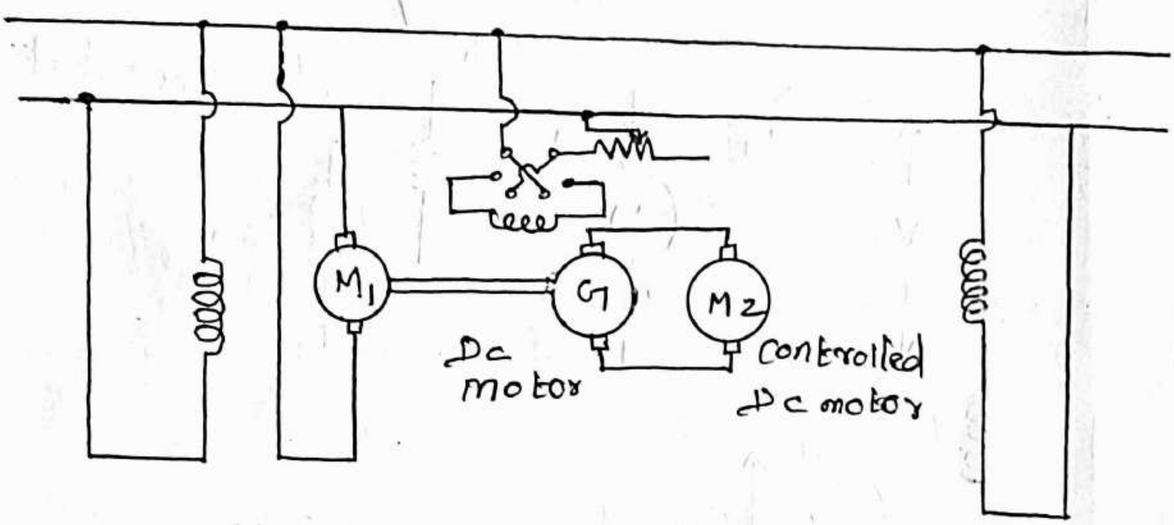
The flux of a DC motor can be changed by changing the field current.

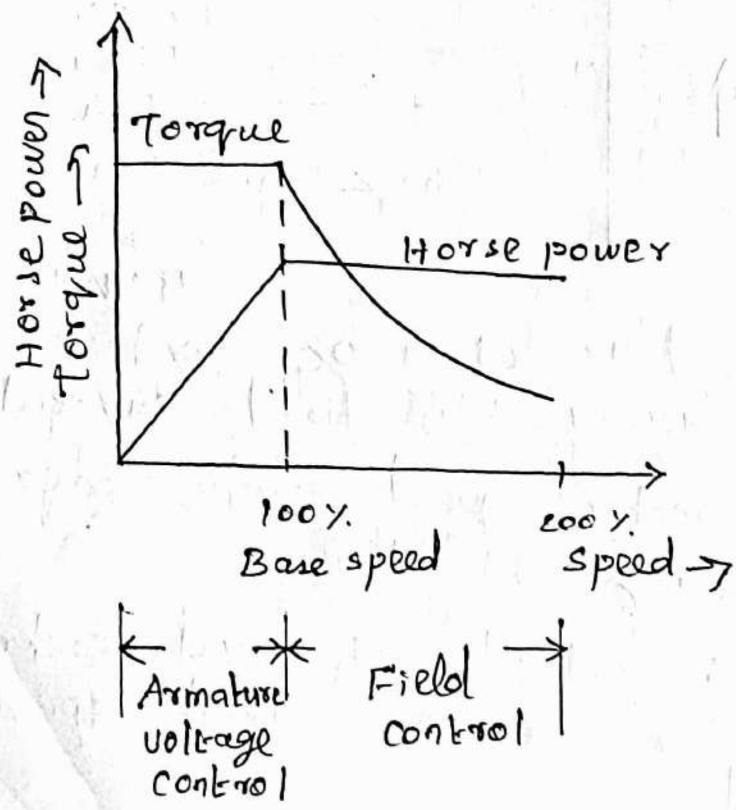
The motor speed canbe increased by decreasing the flux.

This method of speed control can be used for above rated speed control method.

Ward Leonard control system.

The ward Leonard speed control system is shown in figure. This system is mainly used where very sensitive speed is required as for electric excavators, elevators, colliery winders and the main drives in steel mills and paper mills.





→ It consists of three DC machines, i.e two DC motors and one DC generator.

→ The motor-Generator set runs at constant speed. The voltage of the generator can be varied from zero to maximum value by means of its field regulator.

→ The generated dc voltage is fed to the controlled dc motor.

→ The direction of rotation of the controlled dc motor M2 can be changed by reversing the direction of the field current of generator.

→ This method of speed control is combination of armature control and flux control.

→ The ward Leonard system provides a constant torque as well as constant horse power drive.

Advantages:

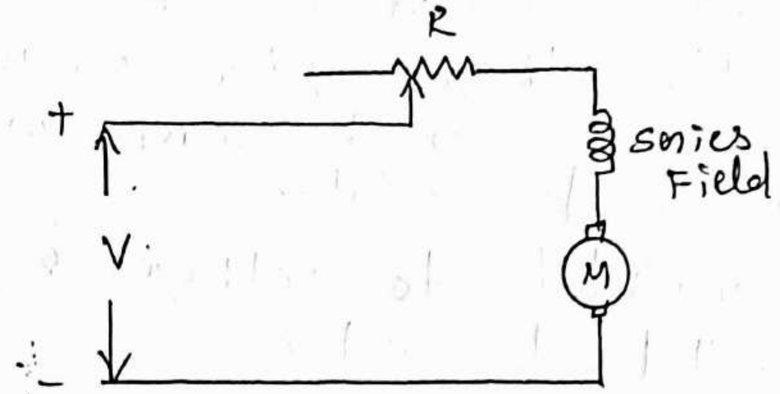
1. Full forward and reverse speed can be achieved.
2. A wide range of speed control is possible.
3. Short-time overload capacity is large.

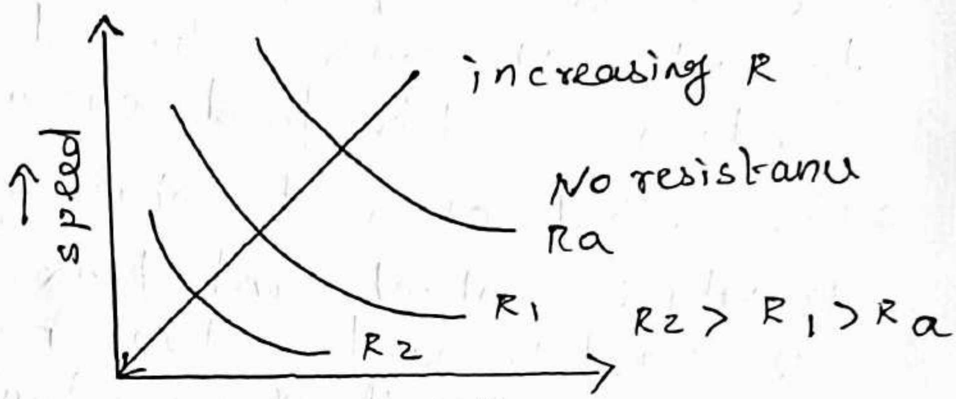
Disadvantage.

1. High Initial cost
2. costly
3. The drive produces noise
4. It require frequent maintenance.

speed control of DC series motor.

Variable resistance in series with motor.





By reducing the voltage across the armature, the motor speed also decreases. Because the applied voltage is directly proportional to the speed, $N \propto E_b$

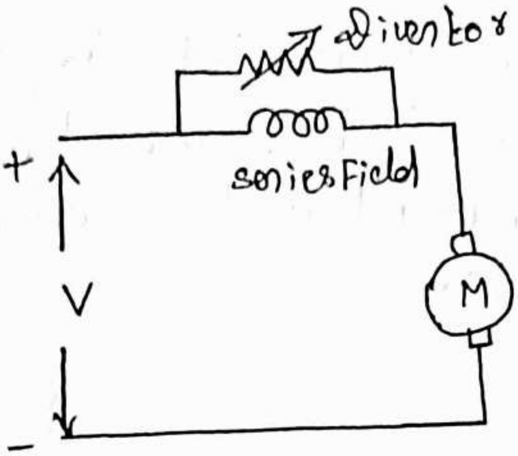
$$E_b \propto V$$

$$\therefore N \propto V$$

Flux control method.

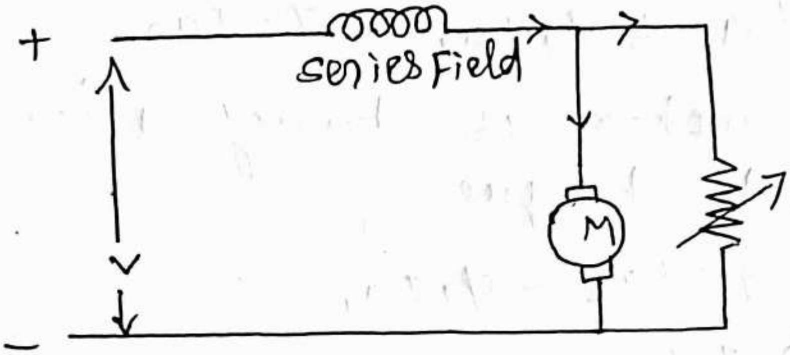
i) Field divertor method.

Field divertor means, a variable resistance is connected across the series field winding. By varying the resistance, the current flowing through the series field changes. Due to decrease in field current, the motor speed also increases.



(ii) Armature divertor method.

Here, a variable resistance is connected across the armature as shown in figure.



This method of control gives speeds lower than the normal speed.

Due to current increase, series field flux also increases. The the speed of the motor can be decreased.

Ex: A 220V, DC shunt motor with an armature resistance of 0.4 Ω and a field resistance of 110 Ω drives a load, the torque of which remains constant. The motor draws from the supply, a line current of 32 A when the speed is 450 rpm. If the speed is to be raised to 700 rpm what change must be effected in the value of the shunt field circuit resistance? Assume that the magnetization characteristic of the motor is a straight line.

Soln:-

Formulas used

$$\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{\phi_1}{\phi_2}$$

$$T_a \propto \phi_1 I_{a1} \propto \phi_2 I_{a2}$$

Since motor is driving a load of constant torque.

$$\phi_2 I_{a2} = \phi_1 I_{a1}$$

(or) $I_{sh2} I_{a2} = I_{sh} I_{a1}$

$$I_{sh} = \frac{V}{R_{sh}} = \frac{220}{110} = 2\,A$$

$$I_{sh2} = \frac{220}{R_t}$$

where R_t = Total resistance of the shunt field circuit,

$$I_{a1} = I_L - I_{sh1} = 32 - 2 = 30\,A$$

$$I_{a2} = I_{a1} \times \frac{I_{sh1}}{I_{sh2}} = 30 \times \frac{2}{220/R_t}$$

$$E_{b2} = V - I_{a2} \cdot R_a = 220 - (0.272 R_t \times 0.4)$$

$$= 220 - 0.1088\,R_t$$

$$E_{b1} = V - I_{a1} \cdot R_a = 220 - 30 \times 0.4 = 208\,V$$

Determine developed torque and shaft torque of 220V, 4 pole series motor with 800 conductors wave connected supplying a load of 8.2 kW by taking 45A from the mains. The flux per pole is 25 mwb and its armature circuit resistance is 0.6 Ω

April / May 2018

Gn data

$V = 220V$, $P = 4$, $Z = 800$

$P_{out} = 8.2 kW$, $I_L = 45A$, $\varphi = 25 mwb$.

$R_a = 0.6 \Omega$, $A = 2$

soln :-

$$T_a = 0.159 \varphi \frac{I_a P Z}{A}$$

$$= \frac{0.159 \times 25 \times 10^{-3} \times 45 \times 4 \times 800}{2}$$

$$\boxed{T_a = 286.2 \ N-m}$$

$$T_{sh} = 9.55 \frac{P_{out}}{N}$$

$$E_b = V - I_a R_a = 220 - 45 \times 0.6 = 193V$$

$$E_b = \frac{P \varphi Z N}{60 A}$$

$$N = \frac{E_b 60 A}{P \varphi Z} = \frac{193 \times 60 \times 2}{4 \times 25 \times 10^{-3} \times 800}$$

$$= 289.5 rpm$$

$$T_{sh} = 9.55 \times \frac{8.2 \times 10^3}{289.5}$$

$$\boxed{T_{sh} = 270.5 \ N-m}$$

A 440V DC shunt motor takes 4 A at no load. Its armature and field resistances are 0.4 Ω and 220 Ω respectively. Estimate the kW o/p and efficiency when the motor takes 60A on full load. (April/May 2018)

Given data

$V = 440\ V,\ I_0 = 4A,\ R_a = 0.4\ \Omega,\ R_{sh} = 220\ \Omega$

$I_L = 60A.$

soln:-

No load i/p power $= VI_0 = 440 \times 4 = 1760\ W.$

$$I_{sh} = \frac{V}{R_{sh}} = \frac{440}{220} = 2\ A$$

$$I_{a0} = I_0 - I_{sh} = 4 - 2 = 2\ A$$

$$P_{cu}\ loss = I_{a0}^2 . R_a = 2^2 \times 0.4 = 1.6\ W$$

$$\text{Constant loss} = 1760 - 1.6 = 1758.40\ W$$

when the line ct is 60A,

$$I_a = I_L - I_{sh} = 60 - 2 = 58\ A$$

$$P_{cu} = I_a^2 R_a = 58^2 \times 0.4 = 1345.6\ W$$

Total loss at full load = P_{cu} + Constant loss

$= 1345.6 + 1758.4$

$= 3104\ W$

$$P_{in} = VI_L = 440 \times 60 = 26400\ W$$

$$P_{out} = P_{in} - \text{Total loss} = 26400 - 3104$$

$$P_{out} = 23.296\ kW$$

$$\eta = \frac{o/p}{I/p} = \frac{23.296}{26.400} = 88.24\%$$

A 220V, 22 A, 1000 rpm DC shunt motor has armature circuit resistance of 0.1 Ω and field resistance of 100 Ω. Calculate the value of additional resistance to be inserted in the armature circuit inorder to reduce the speed to 800 rpm. Assume the load torque to be (i) proportional to the speed and (ii) proportional to square of the speed.

(April/May 2018)

Soln:-

(i) $\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{\phi_1}{\phi_2}$

Since the magnetic circuit is unsaturated, flux directly proportional to the shunt ct.

$\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{I_{sh1}}{I_{sh2}}$

$I_{sh} = \frac{220}{100}$

$= 2.2A$

$T_a \propto \phi_1 I_{a1} \propto \phi_2 I_{a2}$

$I_L = 22A$

If ϕ constant

$I_a = 22 - 2.2$

$\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}}$

$I_a = 19.8A$

$E_{b1} = V - I_{a1} \cdot R_a = 220 - 19.8 \times 0.1$

$= 218.02V$

$E_{b2} = V - I_{a2}(R_e + R_a)$

$= 220 - 19.8(R_e + 0.1)$

$= 220 - 19.8R_e - 1.98$

$E_{b2} = 218.02 - 19.8R_e$

$$\frac{218.02 - 19.8 Re}{218.02} = \frac{800}{1000}$$

$218020 - 19800\, Re = 174400$

$19800\, Re = 43620$

$$\boxed{Re = 2.20\ \Omega}$$

(ii) $$\frac{218.02 - 19.8 Re}{218.02} = \frac{800^2}{1000^2}$$

$218.02 \times 10^6 - 19.8 Re \times 10^6\, Re = 139532800$

$$\boxed{Re = 3.96\ \Omega}$$

$$E_{b2} = V - I_{a2}(r_{se} + r_a + r_{ext})$$

$$K_g I_{a2} n_2 = 220 - 30(0.1 + 0.15 + 1)$$

$$K_g\, 30\, n_2 = 182.5\,V$$

$$\frac{K_g \times 30 \times n_2}{K_g \times 30 \times 1000} = \frac{182.5}{212.5}$$

$$\therefore n_2 = \frac{182.5}{212.5} \times 1000$$

or $$n_2 = \frac{182500}{212.5} = 858.8\ rpm$$

A 220V d.c series motor has armature and field resistances of 0.15 Ω and 0.10 Ω respectively. It takes a current of 30 A from the supply while running at 1000 rpm. If an external resistance of 1 Ω is inserted in series with the motor. calculate the new steady state armature current and the speed. Assume the load torque is proportional to the square of the speed ie $T_L \propto n^2$. (April/May 2019)

Soln:-

since the load torque remains contant in both cases, we have.

$$T_{e1} = T_{e2} = T_L$$

(or) $$k_t I_{a1}^2 = k_2 I_{a2}^2$$

$$30^2 = I_{a2}^2$$

$$\boxed{I_{a2} = 30\ A}$$

$$E_{b1} = V - I_{a1}(r_{se} + r_a)$$

$$k_g I_{a1} n_1 = 220 - 30(0.1 + 0.15)$$

$$k_g\ 30 \times 1000 = 212.5\ V$$

Initially a d.c shunt motor having $R_a = 0.5\,\Omega$ and $R_f = 220\,\Omega$ is running at 1000 rpm drawing 20A from 220V supply. If the field resistance is increased by 5%, calculate the new steady state armature current and speed of the motor. Assume the load torque to be constant. (April/May 2019)

Soln:-

For initial operating point

$I_{L1} = 20\,A,\ r_a = 0.5\,\Omega,\ V = 220V$

$I_{sh1} = 220/220 = 1\,A$

$I_{a1} = 2 - 1 = 19\,A$

$E_{b1} = k_g I_{sh1} n_1 = k_g \times 1 \times 1000 = V - I_{a1} r_a$

$= 220 - 19 \times 0.5$

$= 210.5\,V$

$R_{sh2} = 1.05 \times 220 = 231\,\Omega$

$I_{sh2} = \frac{220}{231} = 0.95\,A.$

For new steady state armature ct be I_{a2} so the new speed n_2.

$$T_{a1} = T_{a2}$$

$$k_t I_{sh1} I_{a1} = k_t I_{sh2} I_{a2}$$

$$I_{sh1} I_{a1} = I_{sh2} I_{a2}$$

$$1 \times 19 = 0.95 \, I_{a2}$$

$$I_{a2} = \frac{19}{0.95}$$

$$\boxed{I_{a2} = 20 \, A}$$

To calculate new speed, we have to Calculate new back emf.

$$E_{b2} = k_g I_{sh2} n_2$$

$$= k_g \times 0.95 \, n_2$$

$$= 220 - 20 \times 0.5 = 210 V$$

$$\therefore \frac{k_g \times 0.95 \times n_2}{k_g \times 1 \times 1000} = \frac{210.5}{210}$$

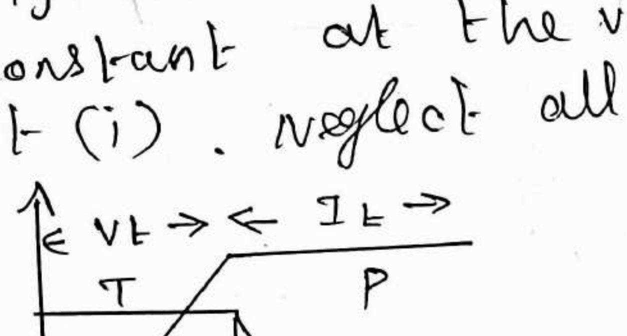
$$n_2 = \frac{210.5}{210} \times \frac{1000}{0.95}$$

$$\therefore \boxed{n_2 = 1055.14 \, rpm}$$

A variable speed drive system uses a DC motor that is supplied from a variable-voltage source. The torque and power profiles are shown in fig. The drive speed is varied from 0 to 1500 rpm (base speed) by varying the terminal voltage from 0 to 500V with the field current maintained constant.

(i) Determine the motor armature current if the torque is held constant at 300 Nm up to the base speed.

(ii) The speed beyond the base speed is obtained by field weakening while the armature voltage is held constant at 500V. Determine the torque available at a speed of 3000 rpm if the armature current is held constant at the value obtained in part (i). Neglect all losses.



(Nov/Dec 2018)

soln:-

(a) $N_b = 1500$ rpm, $V_t = 500V = E_a$

$$K_a\phi = \frac{500}{1500 \times 2\pi/60} = 3.1831$$

$$I_a = \frac{T}{K_a\phi} = \frac{300}{3.1831} = 94.2477A$$

(b) $n = 3000$ rpm, $V_t = E_a = 500V$

$$K_a\phi = \frac{500}{3000 \times 2\pi/60} = 1.5916$$

$$T = 1.5916 \times 94.2477$$

$$T = 150 \text{ N.m}$$

(or) $$T = \frac{P}{\omega_m} = \frac{500 \times 94.2477}{3000 \times 2\pi/60}$$

$$\boxed{T = 150 \text{ N·m}}$$

Example 3: A 220V, DC shunt motor with an armature resistance of 0.4 Ω and a field resistance of 110 Ω drives a load, the torque of which remain constant. The motor draws from the supply, a line current of 32 A when the speed is 450 rpm. If the speed is to be raised to 700 rpm what change must be effected in the value of the shunt field circuit resistance. Assume that the magnetization characteristics of the motor is a straight line.

Given data

supply voltage $V = 220V$

Armature resistance $R_a = 0.4\ \Omega$

Shunt field resistance $R_{sh} = 110\ \Omega$

speed $N_1 = 450$ rpm

Line current $I_L = 32$ A

speed $N_2 = 700$ rpm

To Find

shunt field circuit resistance.

Now back emf $E_{b2} = V - I_{a2} R_a$

$$= 500 - 28.75 \times 1.5$$

$$= 456.875 \text{ V}$$

Using the relation

$$\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{\varphi_1}{\varphi_2} \quad \left[\because \varphi_1 = \varphi_2\right]$$

$$\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}}$$

$$\frac{N_2}{1000} = \frac{456.875}{494.375}$$

$$\boxed{N_2 = 924.14 \text{ rpm}}$$

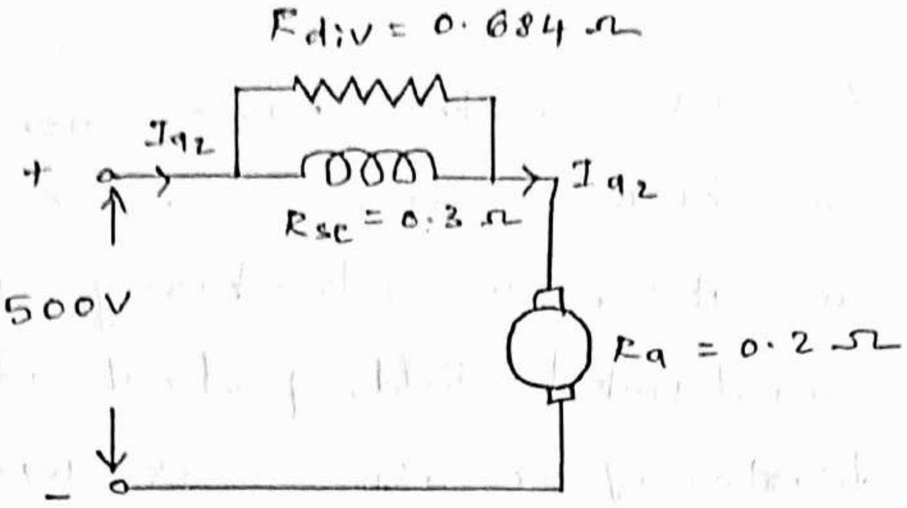
ii) shunt field reduced by 15 %.

ie $\varphi_2 = 0.85 \varphi_2$

$$\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{\varphi_1}{\varphi_2}$$

$$\frac{N_2}{1000} = \frac{456.875}{494.375} \times \frac{\varphi_1}{0.85 \varphi_1}$$

$$\boxed{N_2 = 1087.23 \text{ rpm}}$$



Since the torque remains constant

$$\phi_1 I_{a_1} = \phi_2 I_{a_2}$$

$\phi \propto$ current through series field

$\phi_1 \propto I_{a_1}$

Current through the series field when a divertor is connected

$$= I_{a_2} \times \frac{R_{div}}{R_{div} + R_{se}}$$

$$= I_{a2} \times \frac{0.684}{0.684 + 0.3}$$

$$= 0.695\ I_{a2}$$

Flux in this case $\phi_2 \propto 0.695\ I_{a2}$

$$I_{a_1}^2 = 0.695\ I_{a2}^2$$

$$I_{a2}^2 = \frac{I_{a_1}^2}{0.695} = \frac{70^2}{0.695}$$

$$I_{a2} = 83.96\ A$$

Example 1. A 500 V series motor having armature and field resistances of 0.2 and 0.3 ohm respectively runs at 500 rpm when taking 70 amps. Assuming unsaturated field, find out its speed when field divertor of 0.684 Ω is used constant torque load.

Given data :

Supply voltage $V = 500 V$

Armature resistance $R_a = 0.2 \Omega$

Series field Resistance $R_{se} = 0.3 \Omega$

Armature current $I_{a1} = 70 A$

speed $N_1 = 500 rpm$

Field divertor resistance $R_{div} = 0.684 \Omega$

To Find

speed N_2

solution:-

Back emf $E_{b1} = V - I_{a1} (R_a + R_{se})$

$= 500 - 70 (0.2 + 0.3)$

$= 465 V$

Let I_{a2} be the current taken and φ_2 be the flux produced when a divertor is connected across the series field.

Given data:

supply voltage $V = 500 V$

Armature resistance $R_a = 1.5 \Omega$

shunt field resistance $R_{sh} = 400 \Omega$

No load current $I_0 = 5 A$

No load speed $N_1 = 1000 rpm$

Load current $I_L = 30 A$.

To find:

i) speed at 30 A

ii) speed at this load if the shunt field is reduced by 15 % ie $\phi_2 = 0.85\phi_1$

solution:-

shunt field current $I_{sh} = \frac{V}{R_{sh}} = \frac{500}{400}$

$= 1.25 A$

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

$= 5 - 1.25 = 3.75 A$

No load back emf $E_{b1} = V - I_{a0} R_a$

$= 500 - 3.75 \times 1.5$

$E_{b1} = 494.375 V$

Load current $I_L = 30 A$

Load armature current $I_{a2} = I_L - I_{sh}$

$= 30 - 1.25$

$= 28.75 A$

series field current $I_{se} = 0.695\, I_{a2}$

$= 0.695 \times 83.96$

$= 58.35\, A$

Back emf $E_{b2} = V - I_{a2} R_a - I_{se} R_{se}$

$= 500 - 83.96 \times 0.2 -$

58.35×0.3

$= 465.703\, V$

Using the relation

$$\frac{N_2}{N_1} = \frac{E_{b1}}{E_{b2}} \times \frac{\phi_1}{\phi_2}$$

$$\frac{N_2}{500} = \frac{465.703}{465} \times \frac{70}{83.96}$$

$$\boxed{N_2 = 418\ rpm}$$

Example 2 : A 500 V dc shunt motor has armature and field resistances of 1.5 Ω and 400 Ω respectively. the current taken when running on no load is 5 A and the speed is 1000 rpm. calculate the speed when motor is fully loaded and the total current drawn from the supply is 30 A. Also estimate the speed at this load if the shunt field current is reduced by 15%.

Solution

$$\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{\varphi_1}{\varphi_2}$$

Since Magnetic ckt is unsaturated, it means that flux is directly proportional to the shunt current.

$$\therefore \frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{I_{sh1}}{I_{sh2}}$$

Since the motor is driving at load of constant torque,

$$T \propto \varphi_1 I_{a1} \propto \varphi_2 I_{a2}$$

$$\varphi_1 I_{a1} = \varphi_2 I_{a2}$$

$$I_{a2} = \frac{\varphi_1}{\varphi_2} \times I_{a1}$$

$$I_{sh1} = \frac{V}{R_{sh1}} = \frac{220}{110} = 2\,A$$

$$I_{sh2} = \frac{V}{R_{shT}} = \frac{220}{R_{shT}}$$

$R_{shT} \Rightarrow$ Total resistance

Armature current $I_{a1} = I_L - I_{sh}$

$$= 32 - 2 = 30\,A$$

$$I_{a2} = 30 \times \frac{2}{\frac{220}{R_{shT}}} = 0.272\,R_{shT}$$

$$E_{b1} = V - I_{a1} R_a$$

$$= 220 - 30 \times 0.4 = 208\ V$$

$$E_{b2} = V - I_{a2} R_a$$

$$= 220 - (0.272 R_{shT}) \times 0.4$$

$$= 220 - 0.1088 R_{shT}$$

$$\frac{N_2}{N_1} = \frac{E_{b2}}{E_{b1}} \times \frac{I_{sh1}}{I_{sh2}}$$

$$\frac{700}{450} = \frac{220 - 0.1088 R_{shT}}{208} \times \frac{2}{220/R_{shT}}$$

$$R_{shT} = 177.35\ \Omega$$

$$R_{sh1} + R_e = 177.35$$

$$R_e = 177.35 - 110$$

$$\boxed{R_e = 67.35\ \Omega}$$

UNIT- V

CONVENTIONAL AND SOLID STATE SPEED CONTROL OF AC DRIVES

TYPES OF SPEED CONTROL.

Types of stator side control.

1. stator voltage control
2. stator frequency control
3. V/f control
4. Pole changing method.

Types of rotor side control.

1. Adding external resistance in the rotor circuit.
2. Cascade control.
3. slip power recovery scheme.

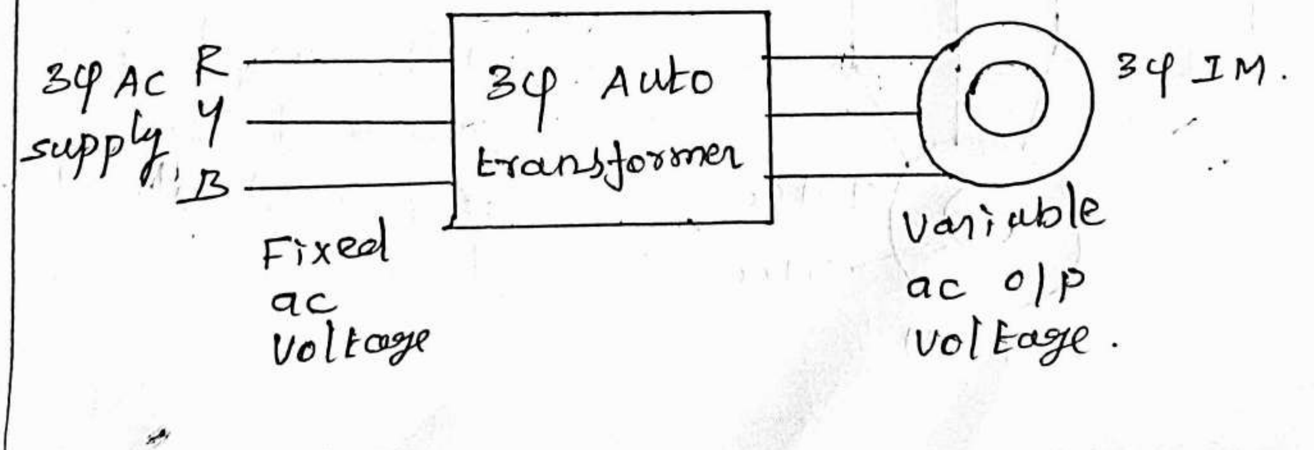
STATOR SIDE CONTROL.

Change in stator voltage.

The speed of the induction motor can be controlled by varying the stator voltage. Here the supply frequency is constant. The stator voltage can be controlled by two methods.

i) Using autotransformer.
ii) Primary resistors connected in series with stator winding.

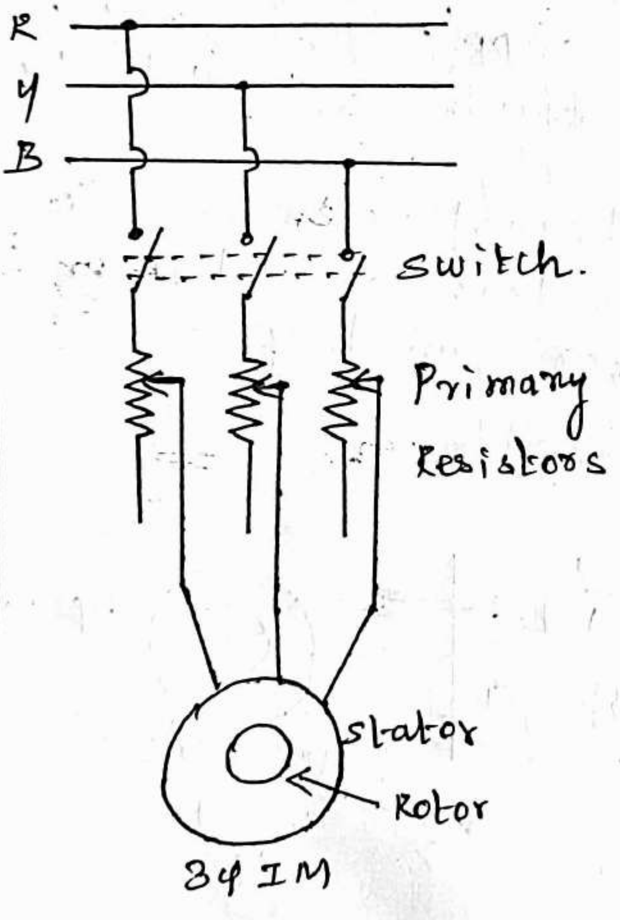
i) Using Auto transformer.



By varying the auto transformer, we can get variable ac o/p voltage without change in supply frequency. The variable voltage is fed to the induction motor. Then the induction motor speed also changes.

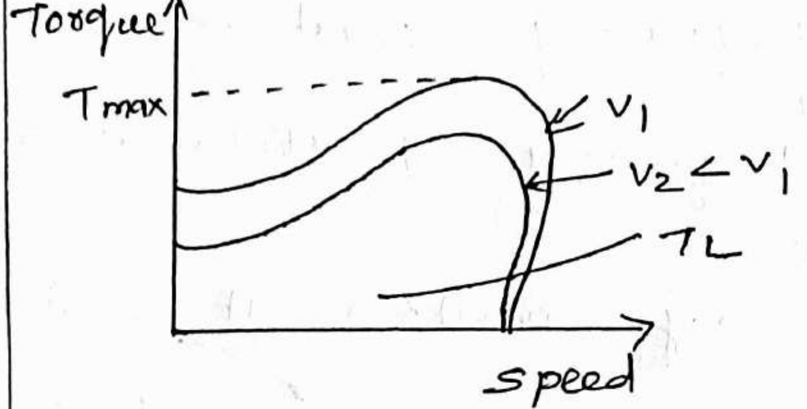
ii) Primary resistors connected in series with stator winding.

By varying the primary resistance, the voltage drop across the motor terminals is reduced. Then the motor speed can be reduced. The main disadvantage is that more power loss occurs in the primary resistors.



The torque is proportional to the square of its stator voltage ie $T \propto V^2$. By varying the voltage the torque also changes.

This method is not used for wide range of speed control and constant torque load.



change in stator Frequency :-

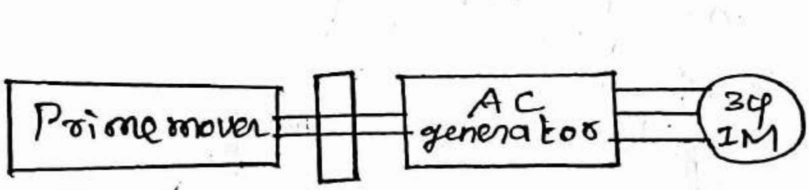
Here, we can vary the input frequency of the motor.

synchronous speed $N_s = \frac{120f}{P}$

where $f \Rightarrow$ Frequency of the supply voltage

$P \Rightarrow$ number of poles.

when the supply frequency changes, the motor speed also changes.



The emf V induced in the stator winding of the induction motor is given by,

$$V = 2\pi f T_1 \varphi K_W$$

where, φ = Flux/pole

f = frequency of stator supply

K_W = Winding factor.

T_1 = No. of turns in the stator winding.

Here we consider two cases

i) Low frequency operation at constant voltage.

ii) High frequency operation at constant voltage.

i) Low frequency operation at constant voltage:

By decreasing the supply frequency at constant voltage V the value of air gap flux increases and the induction motor magnetic circuit gets saturated. Consider the emf equation.

V = constant

f = Decreases

ϕ = Increases

due to this low frequency operation, the following effect take place.

i) The reactance will below leading to high motor currents.

ii) More losses.

iii) very low efficiency.

ii) High frequency operation at constant voltage:-

with the constant input voltage, if the stator frequency is increased, the motor speed also increases. due to the increase in frequency, flux and torque are reduced.

V = constant
f = Increases
φ = Decreases.

By increasing the supply frequency of the motor, the following effects will follow.

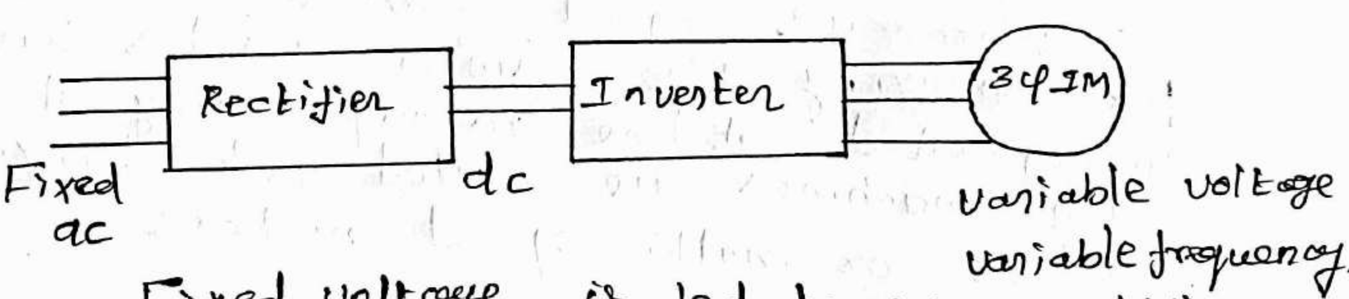
1. The no-load speed increases.
2. The maximum torque decreases.
3. starting torque reduces.

Voltage /Frequency control:

From the emf equation, the airgap flux is given by $\varphi = \frac{1}{2\pi T_1 k_w}\left(V/f\right)$

From the above expression, by varying the supply frequency, the air gap flux changes.

To maintain airgap flux constant, the parameters V and f must be changed so as to maintain (V/f) ratio constant. This is known as V/f control.



Fixed voltage is fed to the rectifier circuit. It converts Ac to Dc. this DC supply is fed to the inverter circuit. It converts DC in to variable AC voltage and variable frequency. This o/p is fed to the stator of the induction motor. By varying 'V' and 'f' and maintaining (V/f) ratio constant, the induction motor speed can be changed.

This method is applicable only for below base speed.

changing the number of poles.

The synchronous speed of the motor is inversly proportional to the number of poles. $N_S \propto \frac{1}{P}$

By changing the poles, the motor synchronous speed can be varied. Provision for changing the number of poles has to be incorporated at the manufacturing stage and such machines are called pole changing motors or multi speed motors.

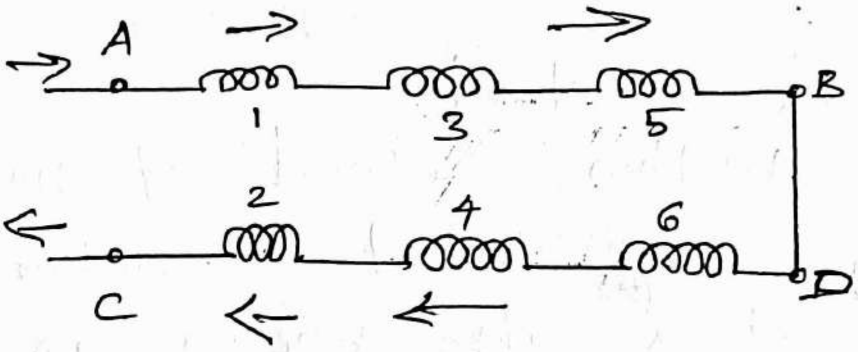


Fig. series connection

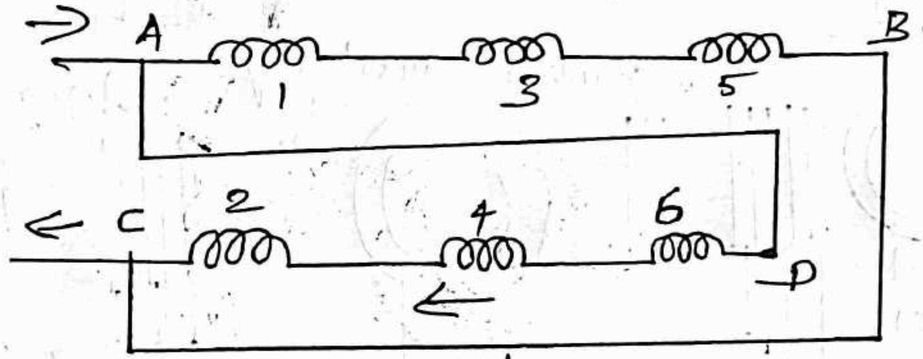


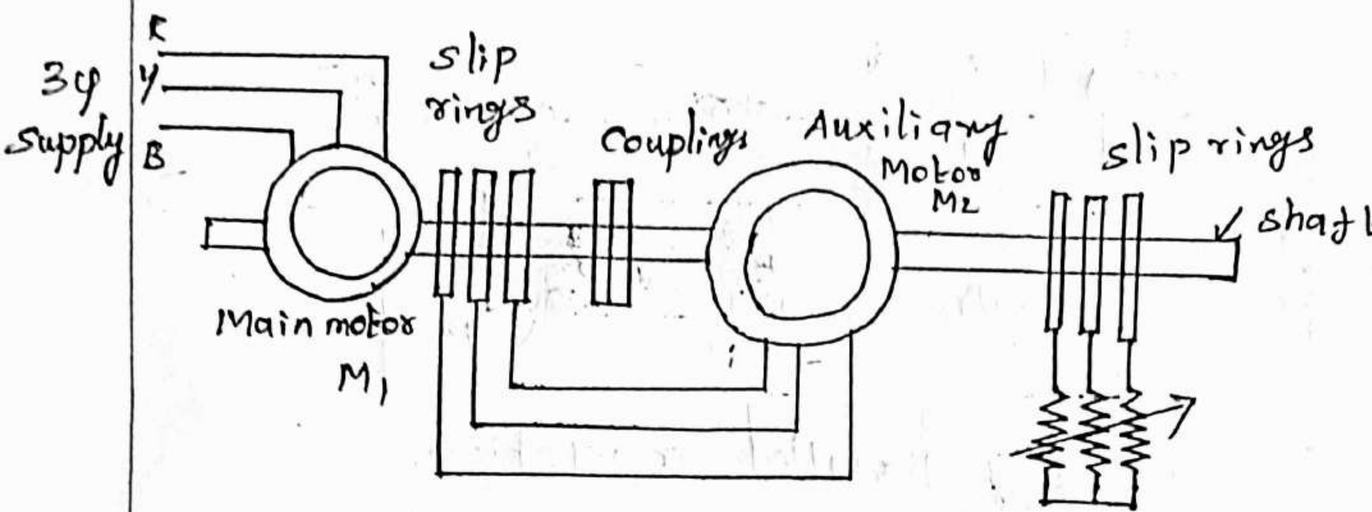
Fig. parallel connection.

Number of poles can be changed by changing these coil groups. Theoretically by dividing the winding in to a number of coil groups and bringing out terminals of all these groups, a number of pole numbers can be obtained by rearranging these groups.

ROTOR SIDE CONTROL.

1. Cascade control

Another method of speed control of slip ring induction motor is cascade control. It is also known as tandem control.



It consists of two slip ring induction motors. The 1st motor is called main motor M1. The second motor is called auxiliary motor M2.

In these cascading method, if both motors produce the torque in the same direction means, cumulative cascading and opposite direction means differential cascading.

The expression for the speed of the set is derived as follows.

Let P_1 = Number of poles on main motor M_1

P_2 = Number of poles on auxiliary motor M_2

f = supply frequency

f_1 = slip frequency of Main motor M_1

f_2 = slip frequency of auxiliary motor M_2

N = speed of both motors.

Synchronous speed of the main motor N_{S1} is given by,

$$N_{S1} = \frac{120f}{P_1}$$

N = speed of both motors.

Slip for main motor M_1, $S_1 = \frac{N_{S1} - N}{N_{S1}}$

f_1 = frequency of rotor induced emf of main motor M_1.

$\therefore f_1 = S_1 f$

The supply frequency of the auxiliary motor M_2 is f_1 ie $f_2 = f_1$

$$N_{S2} = \frac{120f_2}{P_2} = \frac{120f_1}{P_2}$$

$$= \frac{120 S_1 f}{P_2} = \frac{120f}{P_2}\left(\frac{N_{S1} - N}{N_{S1}}\right)$$

Under no load condition

$$N_{S2} = N$$

$$N = \frac{120f}{P_2}\left[\frac{Ns_1 - N}{Ns_1}\right]$$

$$= \frac{120f}{P_2}\left[1 - \frac{N}{Ns_1}\right]$$

$$= \frac{120f}{P_2}\left[1 - \frac{N}{\left(\frac{120f}{P_1}\right)}\right]$$

$$N = \frac{120f}{P_2}\left(1 - \frac{NP_1}{120f}\right) = \frac{120f}{P_2} - \frac{NP_1}{P_2}$$

$$\therefore \quad N\left[1 + \frac{P_1}{P_2}\right] = \frac{120f}{P_2}$$

$$\text{(or)} \quad N = \frac{120f}{P_1 + P_2}$$

For cumulative cascade

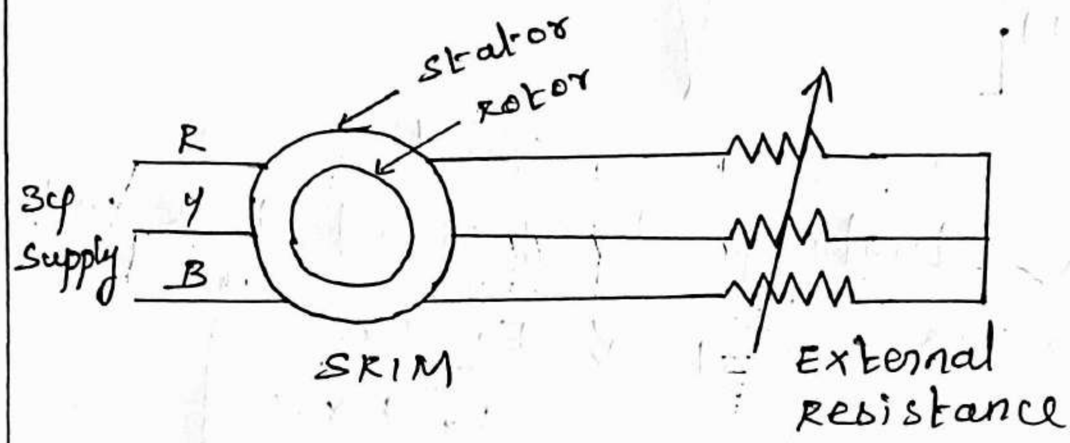
$$N = \frac{120f}{P_1 - P_2}$$ Differential cascade.

Disadvantage

1. Required two motors
2. More expensive
3. Wide range of speed control is not possible
4. It cannot be operated when $P_1 = P_2$ or $P_1 < P_2$.

2. Adding external resistance in the rotor circuit.

This method is applicable only for slip ring induction motor. External resistance can be added in the rotor circuit. Speed control is made by mechanical variation of the rotor circuit resistance.



The torque equation of induction motor is

$$T \propto \frac{sE_2^2 R_2}{R_2^2 + (sX_2)^2}$$

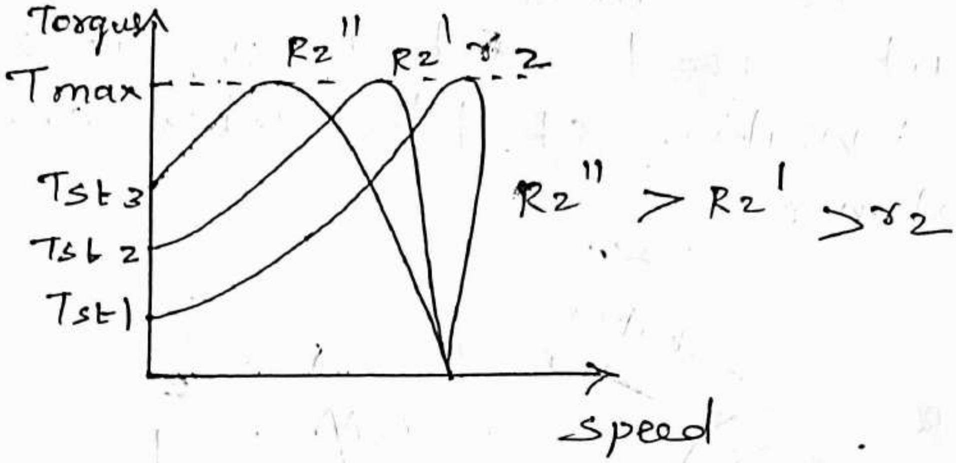
The slip corresponding to maximum torque is given by $s_m = \frac{R_2}{X_2}$, $s_m \propto R_2$.

If we add external resistance in the rotor circuit, the slip increases and speed decreases.

The maximum torque equation is

$$T_{max} \propto \frac{E_2^2}{2X_2}$$

This equation is independent of rotor resistance ie by varying the rotor resistance the maximum torque is not affected.



The starting torque of the induction motor is,

$$T_{st} \propto \frac{E_2^2 R_2}{R_2^2 + X_2^2}$$

Advantages :-

1. smooth and wide range of speed control
2. Absence of in-rush starting current
3. Absence of line current harmonics.
4. High line power factor.
5. starting torque can be improved.

Disadvantages :-

1. Less efficiency.
2. Unbalance in voltage and current if rotor circuit resistances are not equal.

3. slip power Recovery system.

This system is mainly used for speed control of slip ring induction motor.

Rotor air gap power = mechanical power + rotor copper loss.

$$P_{ag} = P_m + P_{cu}$$

$$P_{ag} = \omega_s T$$

The air gap flux of the machine is established by the stator supply and it remains practically constant if the stator impedance drop and supply voltage fluctuations are neglected.

The rotor copper loss is proportional to slip. The main drawback of the system is that large amount of slip power is dissipated in the resistance and this reduce efficiency of motor.

This slip power can be recovered and fed back to the supply of an additional motor which is mechanically coupled to the main motor and improves the overall efficiency of the system.

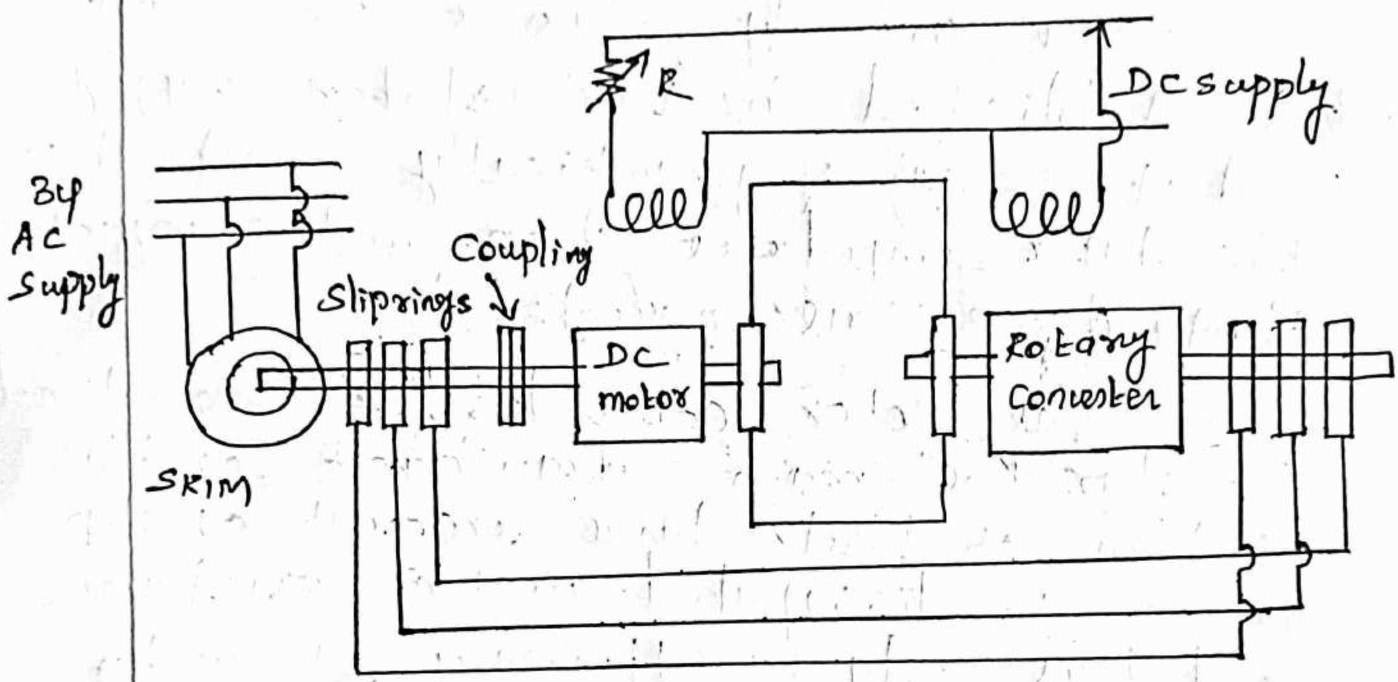
Types of slip power Recovery system.

1. Kramer system.
2. Scherbius system.

These two systems can further be classified into two methods.

1. conventional method
2. static method.

a. conventional Kramer system.



The system consists of a 3φ rotary converter and a dc motor. The slip power is converted into dc power by a rotary converter and fed to the armature of a dc motor.

The rotary converter and dc motor are excited from the dc bus bars or from an exciter. The speed of slip ring induction motor is adjusted by adjusting the speed of dc motor with the help of a field regulator.

Advantages :-

1. Any speed, within the working range can be obtained.
2. Better power factor.

b. Static Kramer System

In this method, the slip power is taken from the rotor and it is rectified to dc voltage by 3-φ diode bridge rectifier. Inductor L_d smoothens the ripples in the rectified voltage V_d. This dc power is converted into ac power by using line-commutated inverter.

Advantages :-

1. The static kramer drive has been very popular in large power pump and fan type drives
2. More economical because the rectifier and inverter have to carry only the slip power of the rotor.

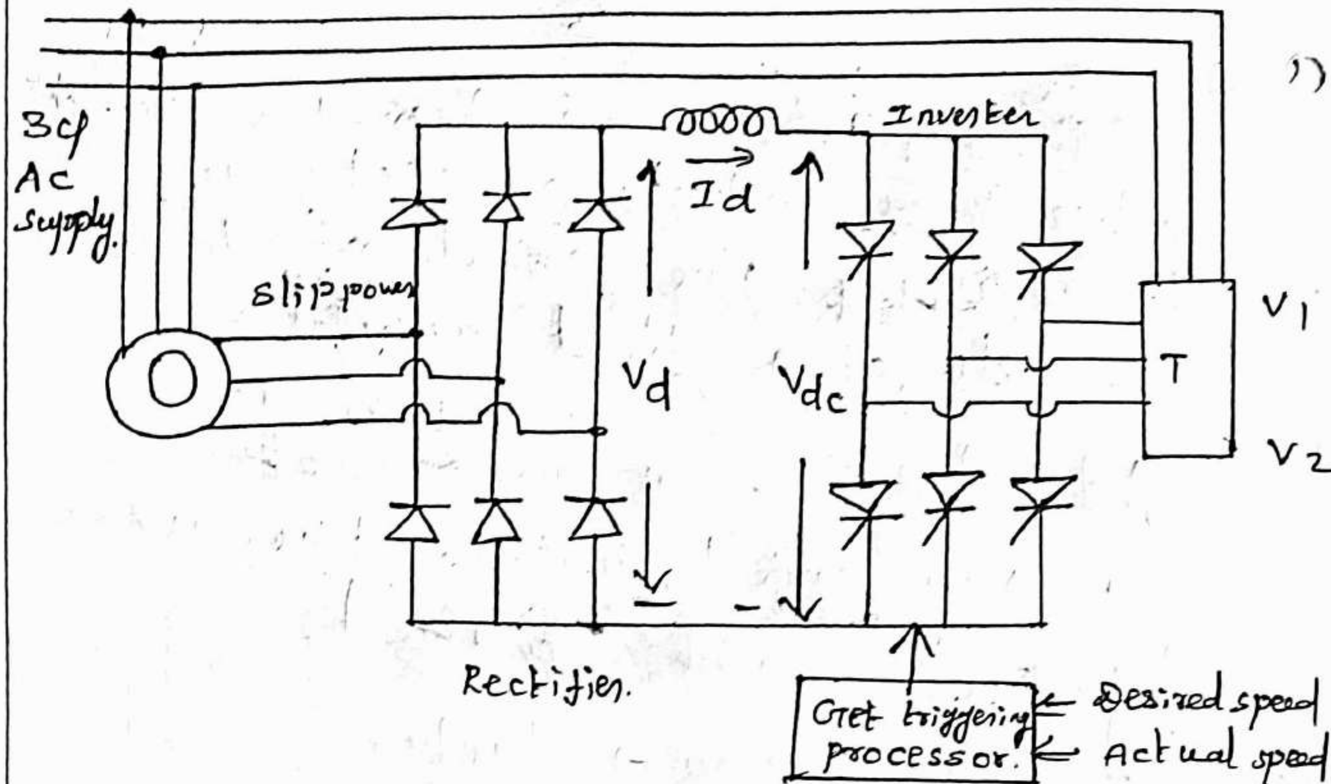


Fig: static kramer system.

Schenbius System :-

The schenbius system is similar to kramer system but only difference is that in the kramer system the feed back is mechanical and in the schenbius system the return power is electrical.

Types:-

a) conventional schenbius drive
b) static schenbius drive.

a) Conventional schenbius drive :-

This method consists of SRIM, rotary converter, dc motor and induction generator. Here, the rotary converter converts slip power into dc power and the dc power fed to the dc motor.

The dc motor is coupled with induction generator. The induction generator converts the mechanical power in to electrical power and returns it to the supply line. The SRIM speed can be controlled by varying the field regulator of the dc motor.

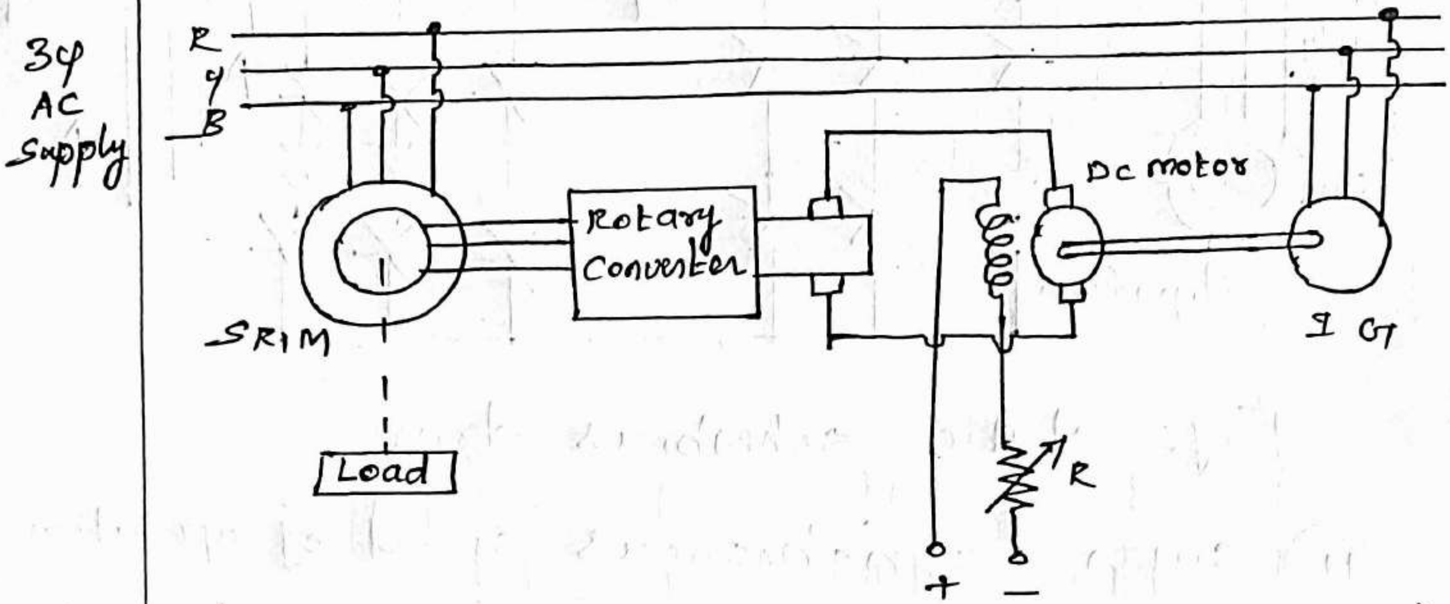


Fig: Conventional Scherbius system.

Static Scherbius System.

Sub-synchronous speed operation.

i) Sub-synchronous speed control

In sub-synchronous speed control of SRIM, slip power is removed from the rotor circuit and is pumped back into the ac supply.

The slip power flows from rotor circuit to bridge 1, bridge 2, transformer and returned to the supply ie slip power → Rectifier → Inverter → Transformer → supply

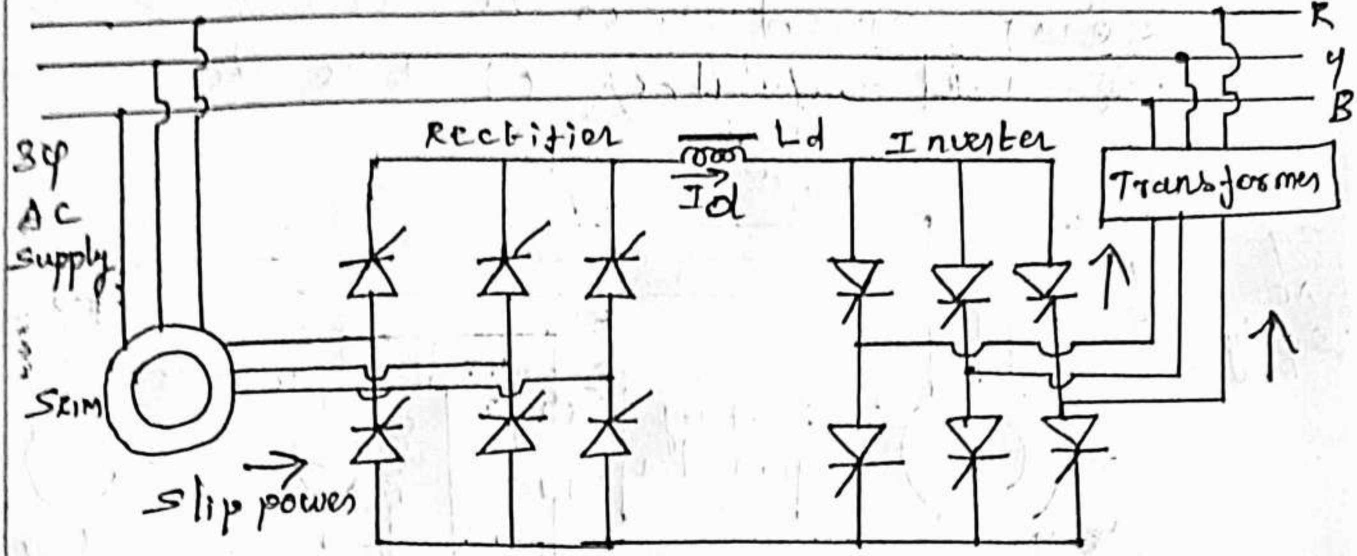


Fig: static scherbius drive

(ii) super synchronous speed of operation:-

In super synchronous speed operation, the additional power is fed into the rotor circuit at slip frequency.

When the machine is operated at super synchronous speed, phase controlled bridge 2 should operate in rectifier mode and bridge 1 in inverter mode. The slip power flows from the supply to transformer, bridge 2, bridge 1 and to the rotor circuit.

Supply → Transformer → Bridge 2 → Bridge 1 → Rotor circuit

Example A 4 pole, 50 Hz, 3 φ slip ring induction motor when fully loaded runs with a slip of 3%. Determine the value of the resistance to be inserted in series per phase in the rotor circuit to reduce the speed by 10% and the new slip. The rotor resistance per phase is 0.2 Ω.

Solution

Synchronous speed $N_s = \frac{120f}{P}$

$= \frac{120 \times 50}{4} = 1500$ rpm.

speed $N_1 = N_s(1 - s_1)$

$= 1500(1 - 0.03)$

$= 1455$ rpm.

$N_2 = 0.9 \times N_1 = 0.9 \times 1455$

$= 1309.5$ rpm.

$\therefore s_2 = \frac{N_s - N_2}{N_s} = \frac{1500 - 1309.5}{1500}$

$= 0.127$

Torque $T = \frac{K s E_2^2 R_2}{R_2^2 + (s X_2)^2}$

$T_1 = \frac{K s_1 E_2^2 R_2}{R_2^2} = \frac{K s_1 E_2^2}{R_2}$

$T_2 = \frac{K s_2 E_2^2}{R_2 + r}$

Given $T_1 = T_2$

$$\therefore \frac{k s_1 E_2^2}{R_2} = \frac{k s_2 E_2^2}{R_2 + r}$$

ie $$\frac{s_1}{R_2} = \frac{s_2}{R_2 + r}$$

$$\frac{0.03}{0.2} = \frac{0.127}{0.2 + r}$$

$$\boxed{r = 0.646\ \Omega}$$

Ex: A 3-phase squirrel cage induction motor has a short circuit current equal to 4 times the full load current. Find the starting torque as a percentage of full load torque if the motor is started by (i) Direct switching to the supply mains (ii) A star delta starter (iii) An auto-transformer (iv) A resistance in the stator circuit.

Given :-

$I_{sc} = 4 I_{fl}$; $s_f = 0.01$

i) Using DOL starter

$$\frac{T_{st}}{T_{fl}} = \left(\frac{I_{sc}}{I_{fl}}\right)^2 s_f$$

$$T_{st} = \left(\frac{4 I_{fl}}{I_{fl}}\right)^2 \times 0.01 \times T_{fl}$$

$$T_{st} = 16\%\ T_{fl}$$

ii) star – delta starter

$$\frac{T_{st}}{T_{fl}} = \frac{1}{3}\left(\frac{I_{sc}}{I_{fl}}\right)^2 s_f$$

$$T_{st} = \frac{1}{3}\left(\frac{4 I_{fl}}{I_{fl}}\right)^2 \times 0.01 \times T_{fl}$$

$$T_{st} = 5.33\%\ \text{of}\ T_{fl}$$

iii) Auto-transformer starter.

$$\frac{T_{st}}{T_{fl}} = x^2 \left(\frac{I_{sc}}{I_{fl}}\right)^2 s_f$$

Assume $x = 1$, $T_{st} = 1^2 \left(\frac{4 I_{fl}}{I_{fl}}\right)^2 \times 0.01 \times T_{fl}$

$$= 0.16\ T_{fl}$$

$$T_{st} = 16\%\ \text{of}\ T_{fl}$$

iv) Resistance in the stator circuit

$$\frac{T_{st}}{T_{fl}} = x^2 \left(\frac{I_{sc}}{I_{fl}}\right)^2 s_f$$

Assume $x = 1$

$$T_{st} = 1^2 \times \left(\frac{4 I_{fl}}{I_{fl}}\right) \times 0.01 \times T_{fl}$$

$$T_{st} = 0.16\ T_{fl}$$

$\therefore T_{st} = 16\%$ of full load torque.