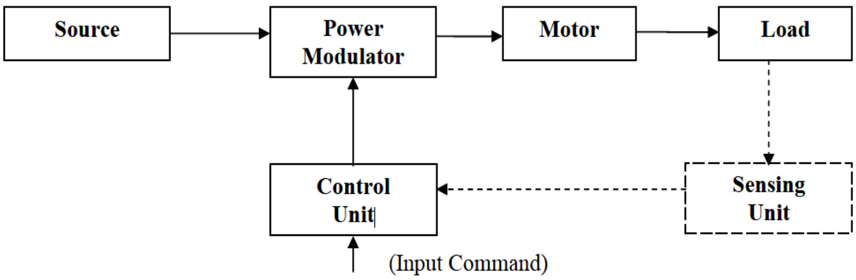
UNIT I
INTRODUCTION TO ELECTRICAL DRIVES

BASIC ELEMENTS OF ELECTRIC DRIVES

A modern variable speed electrical drive system has the following basic components

- Electrical machines and loads
- Power Modulator
- Sources
- Control unit
- Sensing unit



Electrical Machines:

Most commonly used electrical machines for speed control applications are the following

DC Machines

Shunt, series, compound, separately excited DC motors and switched reluctance machines.

AC Machines

Induction, wound rotor, synchronous, PM synchronous and synchronous reluctance machines.

Special Machines

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

Power modulators:

- Modulates flow of power from the source to the motor in such a manner that motor is imparted speed-torque characteristics required by the load
- During transient operation, such as starting, braking and speed reversal, it restricts source and motor currents with in permissible limits.
- It converts electrical energy of the source in the form of suitable to the motor
- Selects the mode of operation of the motor (i.e.) Motoring and Braking.

Electrical Sources:

- Very low power drives are generally fed from single phase sources. Rest of the drives is powered from 3 phase source. Low and medium power motors are fed from a 400v supply. For higher ratings, motors may be rated at 3.3KV, 6.6KV and 11 KV. Some drives are powered from battery.

Sensing Unit:

- Speed Sensing
- Torque Sensing
- Position Sensing
- Current sensing and Voltage Sensing from Lines or from motor terminals
- Torque sensing
- Temperature Sensing

Control Unit:

- 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 drives
- Short time duty drives
- Intermittent duty drives

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

Another main classification:

- DC drive
- AC drive

DC DRIVES	AC DRIVES
The power circuit and control circuit is simple and inexpensive	The power circuit and control circuit are complex
It requires frequent maintenance	Less Maintenance
The commutator makes the motor bulky, costly and heavy	These problems are not there in these motors and are inexpensive, particularly squirrel cage induction motors
Fast response and wide speed range of control, can be achieved smoothly by conventional and solid state control	In solid state control the speed range is wide and conventional method is stepped and limited
Speed and design ratings are limited due to commutations	Speed and design ratings have upper limits

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:** The braking requirements from the load point of view. Easy and effective braking are the requirements of a good drive.
- **Starting requirements:** 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 factors:** There are varieties of types of load conditions possible like continuous, intermittent and impact. Such load variation factor and duty cycle of the motor influences the selection of drive.
- **Availability of supply:** The motors available are AC or DC. But the availability of supply decides the type of motor to be selected for the drive.
- **Effects of supply variations:** There is a possibility of frequent supply variations. The selected motor should be able to withstand such supply variations.
- **Economical aspects:** 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.
- This includes the investigation of reliability of 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:

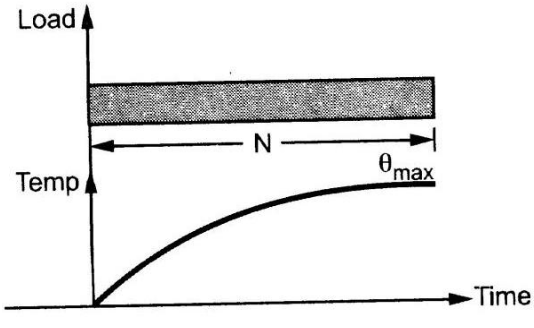
- **Continuous or Constant loads:** In this type load occurs for a long time under the same conditions. Eg. Fan, Paper making machine
- **Continuous variable loads:** The load is variable over a period of time but occurs repetitively for a long duration. Eg. Metal cutting lathes, conveyors.
- **Pulsating loads:** The load is continuously variable. Eg. Reciprocating pumps, compressors
- **Impact loads:** These are peak loads occur at regular intervals of time. Eg. Rolling mils, Presses, Shearing machine, 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 equipments.

CLASSES OF DUTY:

- Continuous duty
- Continuous duty, variable load
- Short time duty
- Intermittent periodic duty
- Intermittent periodic duty with starting
- Intermittent periodic duty with starting and braking

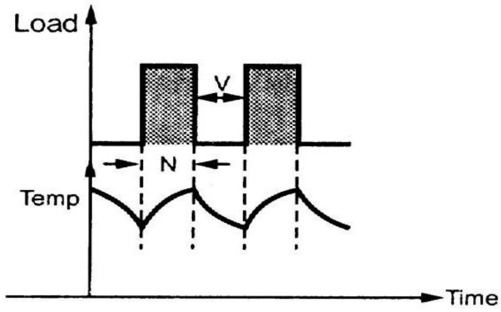
Continuous duty:

- Operation at constant load for a long duration of time
  - "N" indicates duration of operation.



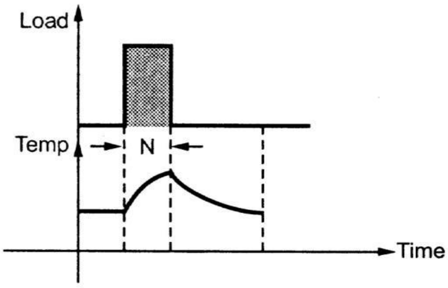
Continuous duty, variable load:

- It denotes a sequence of identical duty cycles each consisting of a period of operation at load and period of no load.
- These motors are used in paper mill drives, compressors, conveyors etc



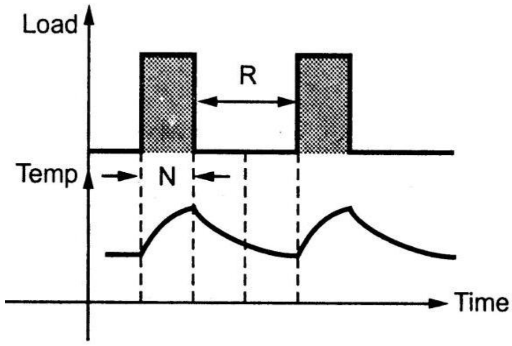
Short time duty:

- It denotes operation at constant load during a given time, then followed by rest of sufficient duration.
- These motors are used in crane drives, drives for house hold appliances, valve drives etc.



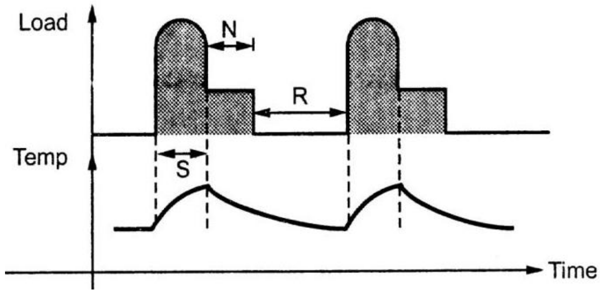
Intermittent periodic duty:

- Sequence of identical duty cycles each consisting of a period of operation at a constant load and then a period of rest.
- This is seen at press and drilling machine drives.



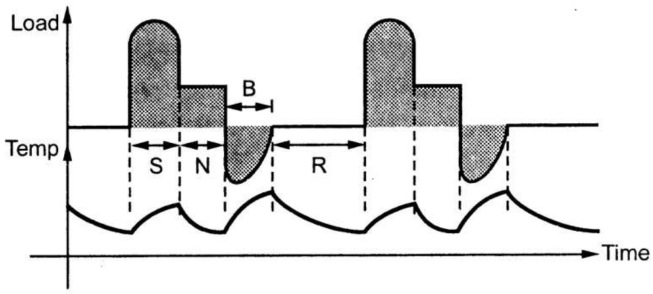
Intermittent periodic duty with starting:

- This consists of a load at start, then constant load and then a period of rest.
- This motor duty class is widely used in metal cutting and drilling tool drives, mine hoist etc



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.
- These techniques are used in billet mill drive, manipulator drive, mine hoist etc.



Heating curve and Cooling curve

The heating and Cooling Calculation of an electric motor are based on the following assumptions.

1. The machine is considered to be a homo-geneous 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 temperature of the body and surrounding medium. No heat is radiated.
3. The rate of dissipation of heat is constant at all temperatures.

Heating Curve and cooling Curves

The steady state temperature depends on power loss and Power output of The motor. As temperature rise directly proportional to power output. It leads to thermal loading on machine.

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

Total heat generated in the body } = Heat dissipated to surrounding medium + Heat stored in body / Heat absorbed

$$W\,dt = A\lambda\theta\,dt + GS\,d\theta \quad \text{—— (1)}$$

where

W - Power loss in the motor due to heat in Watts

A - Area of cooling surface in m^2.

λ - Emissivity or Rate of heat dissipation in $W/m^2/°c$

G - Weight of active parts of the motor in kg

S - Specific heat of the material of the body in $J/kg/°c$

θ - Temperature rise of the body.

$d\theta$ - Temperature rise in a small interval dt

By rearranging equation (1)

we get,

$$W\,dt - A\lambda\theta\,dt = GS\,d\theta$$

$$(W - A\lambda\theta)\,dt = GS\,d\theta$$

(÷ by $A\lambda$)

$$A\lambda\left(\frac{W}{A\lambda} - \theta\right)dt = GS\,d\theta$$

$$\left(\frac{W}{A\lambda} - \theta\right)dt = \left(\frac{GS}{A\lambda}\right)d\theta$$

$$\frac{dt}{\left(\frac{GS}{A\lambda}\right)} = \frac{d\theta}{\left(\frac{W}{A\lambda} - \theta\right)} \quad \text{—— (2)}$$

Temperature rise reaches its maximum value, then the body is said to have reached the maximum temperature rise θ_m.

equation (1) becomes,

Generated heat = Heat dissipated.

$$W\,dt = A\lambda\theta_m\,dt$$

EE 10 ...

$$W = A\lambda \theta_m$$

$$\theta_m = \frac{W}{A\lambda} \quad \text{——— (3)}$$

Substitute equation (3) in (2), we get

$$\frac{dt}{\left(\frac{GS}{A\lambda}\right)} = \frac{d\theta}{(\theta_m - \theta)} \quad \text{——— (4)}$$

Integrating both sides of above equation, we get

$$\frac{A\lambda}{GS} t = -\ln(\theta_m - \theta) + K \quad \text{——— (5)}$$

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

$$0 = -\ln(\theta_m - \theta_0) + K$$

$$K = \ln(\theta_m - \theta_0) \quad \text{——— (6)}$$

Equation (6) is substituted in equation (5), we get

$$\frac{A\lambda}{GS} t = -\ln(\theta_m - \theta) + \ln(\theta_m - \theta_0)$$

$$\frac{A\lambda}{GS} t = \ln\left(\frac{\theta_m - \theta_0}{\theta_m - \theta}\right)$$

take 'e' power on both side

$$e^{\left(\frac{A\lambda}{GS}\right)t} = \frac{\theta_m - \theta_0}{\theta_m - \theta}$$

$$(\theta_m - \theta)\, e^{\left(\frac{A\lambda}{GS}\right)t} = (\theta_m - \theta_0)$$

$$(\theta_m - \theta) = (\theta_m - \theta_0)\, e^{-\left(\frac{A\lambda}{GS}\right)t}$$

$$\theta = \theta_m - (\theta_m - \theta_0)\, e^{-\left(\frac{A\lambda}{GS}\right)t} \quad \text{(7)}$$

where $\frac{GS}{A\lambda} = \tau$ = Thermal heating time constant.

It is defined as time taken to reach 63.2% steady state temperature θ_m. (or)

The time taken by the motor to reach the final steady state temperature rise if the initial rate of temperature continues.

equation (7) becomes,

$$\theta = \theta_m - (\theta_m - \theta_0)\, e^{-\frac{t}{\tau}} \qquad — (8)$$

(or)

$$\theta = \theta_m \left[1 - e^{-\frac{t}{\tau}}\right] + \theta_0\, e^{-\frac{t}{\tau}}$$

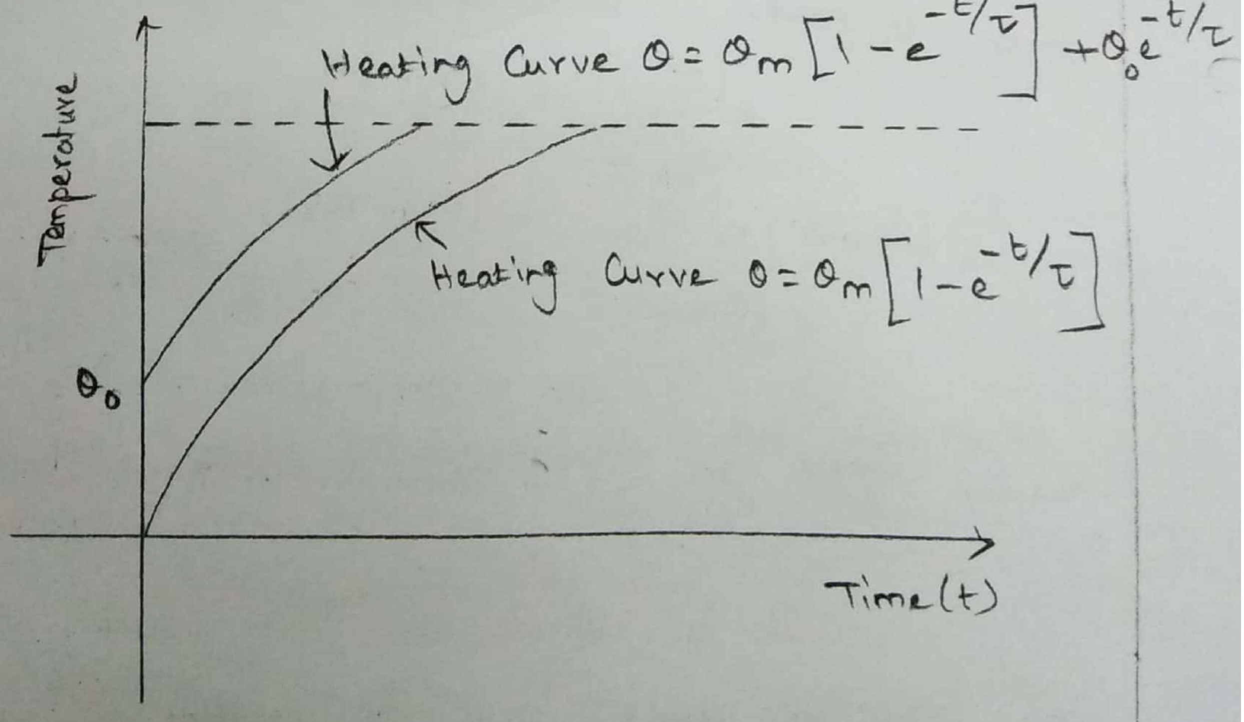
(a) Motor starts from cold condition (Ambient temperature)

Here $\theta_0 = 0^\circ C$

Substitute in equation (8)

$$\theta = \theta_m \left[1 - e^{-t/\tau}\right] \qquad — (9)$$

from the equations (8) & (9), we can draw the heating curve of the machine.



Cooling Curve:-

If the machine is switched off from main supply or when load on machine is reduced, the machine cools. It cools to the ambient temperature when it is switched off. It cools to the temperature attained by power losses at reduced load.

When the machine is switched off, there is no heat generation and all heat stored in the machine is dissipated to surroundings. cooling takes place when heat generation is less than heat dissipated

The balance equation is

Heat generated in body + Heat stored in body = Heat dissipated to Surrounding medium

$$W dt + G s d\theta = A\lambda'\theta\, dt \quad \text{—①}$$

$$A\lambda'\theta dt - W dt = G s d\theta$$

$$(A\lambda'\theta - W)\, dt = G s\, d\theta$$

$$A\lambda'\left(\theta - \frac{W}{A\lambda'}\right) dt = G s d\theta$$

$$\frac{Gs}{A\lambda'}\, d\theta = \left(\theta - \frac{W}{A\lambda'}\right) dt \quad \text{—②}$$

$d\theta \rightarrow$ decrease in temperature [Include negative sign in left side of eqn 2]

$$\frac{-Gs}{A\lambda'}\, d\theta = \left(\theta - \frac{W}{A\lambda'}\right) dt$$

$$\frac{-d\theta}{\left(\theta - \frac{W}{A\lambda'}\right)} = \frac{dt}{\left(\frac{Gs}{A\lambda'}\right)} \quad \text{—③}$$

When final temperature drop (θ_f) is reached, then the heat generated is equal to heat dissipated.

$$\therefore \quad W\,dt = A\lambda' \theta_f\, dt$$

$$W = A\lambda' \theta_f$$

$$\theta_f = \frac{W}{A\lambda'} \quad \text{--- (4)}$$

Substitute equation (4) in equation (3), we get.

$$\frac{-d\theta}{(\theta - \theta_f)} = \frac{dt}{\left(\frac{Gs}{A\lambda'}\right)}$$

Integrating the above equation, we get

$$-\ln[\theta - \theta_f] = \frac{A\lambda'}{Gs} t + K$$

$$\ln[\theta - \theta_f] = -\frac{A\lambda'}{Gs} t - K$$

$$\ln[\theta - \theta_f] = -\frac{A\lambda'}{Gs} t + K_1 \quad \text{--- (5)}$$

At $t = 0$, $\theta = \theta_m$

The equation (5) becomes,

$$\ln[\theta_m - \theta_f] = K_1 \quad \text{--- (6)}$$

Substitute equation (6) in equation (5)

$$-\ln[\theta - \theta_f] = \frac{-A\lambda'}{Gs} t + \ln[\theta_m - \theta_f]$$

$$-\ln[\theta - \theta_f] - \ln[\theta_m - \theta_f] = \frac{-A\lambda'}{Gs} t$$

$$\ln\left[\frac{\theta - \theta_f}{\theta_m - \theta_f}\right] = \frac{-A\lambda'}{Gs} t$$

$$\frac{\theta - \theta_f}{\theta_m - \theta_f} = e^{\frac{-A\lambda'}{Gs} t}$$

$$\theta - \theta_f = (\theta_m - \theta_f) e^{\frac{-A\lambda'}{Gs} t}$$

$$\theta = \theta_f + (\theta_m - \theta_f) e^{-\frac{A\lambda'}{Gs} t}$$

Where

$$\frac{Gs}{A\lambda'} = \tau' = \text{Cooling time Constant.}$$

Cooling time constant is defined as time required to cool the machine to 36.7% of initial temperature rise above ambient temperature.

$$\theta = \theta_f + (\theta_m - \theta_f) e^{-t/\tau'}$$

$$\theta = \theta_f + \theta_m e^{-t/\tau'} - \theta_f e^{-t/\tau'} = \theta_f (1 - e^{-t/\tau'}) + \theta_m e^{-t/\tau'}$$

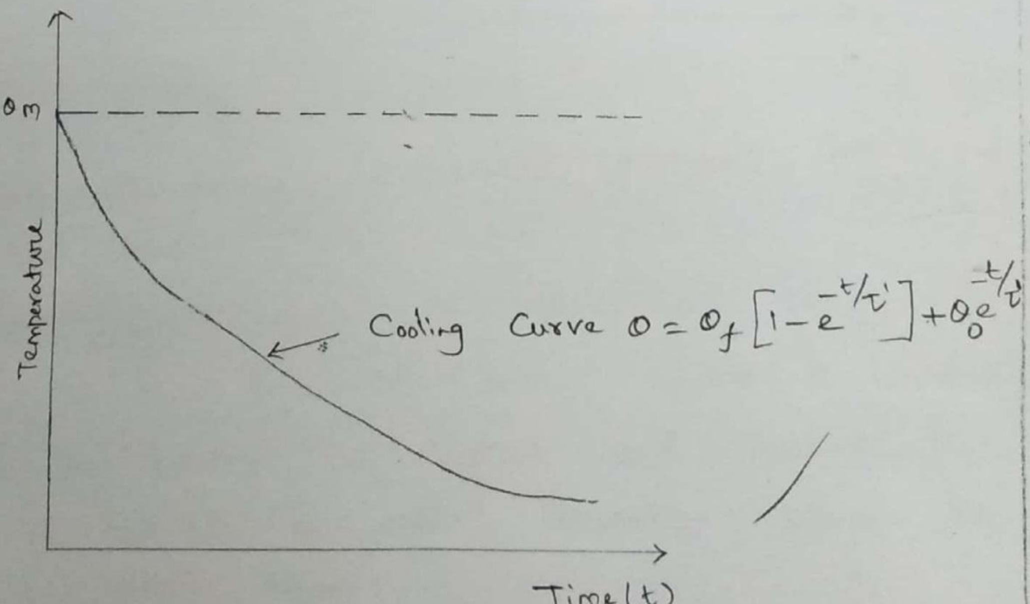
$$\boxed{\theta = \theta_f \left(1 - e^{-\frac{t}{\tau'}}\right) + \theta_m e^{\frac{-t}{\tau'}}} \quad \text{--- (7)}$$

The above equation is suitable only when the load on the machine is reduced.

$$\boxed{\theta = \theta_m e^{\frac{-t}{\tau'}}}$$

This equation is suitable only when the machine is switched off.

Cooling Curve.



UNIT I
INTRODUCTION

1) **Define Drive and Electric Drive. NOV/DEC 2013, NOV/DEC 2015, NOV/DEC 2016**
 Drive: A combination of prime mover, transmission equipment and mechanical working load is called a drive.
 Electric drive: An Electric Drive can be defined as an electromechanical device for converting electrical energy to mechanical energy to impart motion to different machines and mechanisms for various kinds of process control.
2) **List out some examples of prime movers.**
 I.C Engines, Steam engine, Turbine or electric motors
3) **What are the types of electric drives? NOV/DEC 2009, NOV/DEC 2014**
 Group electric drives (Shaft drive),
 Individual Drives,
 Multi motor electric drives.
4) **What is a Group Electric Drive (Shaft Drive)? APRIL/MAY 2010**
 - This drive consists of single motor, which drives one or more line shafts supported on bearings.
 - The line shaft may be fitted with either pulleys & belts or gears, by means of which a group of machines or mechanisms may be operated.
5) **What are the advantages and disadvantages of Group drive(Shaft drive)? NOV/DEC 2014**
 Advantages:
 - A single large motor can be used instead of a number of small motors.
 - The rating of the single motor may be appropriately reduced taking into account the diversity factor of loads.
6) ***Disadvantages:***
 - There is no flexibility, Addition of an extra machine to the main shaft is difficult.
 - The efficiency of the drive is low, because of the losses occurring in several transmitting mechanisms.
 - The complete drive system requires shutdown if the motor, requires servicing or repair.
 - The system is not very safe to operate
 - The noise level at the work spot is very high.
7) **What is an individual electric drive? Give some examples.**
 In this drive, each individual machine is driven by a separate motor. This motor also imparts motion to various other parts of the machine. Single spindle drilling machine, Lathe machines etc.
8) **What is a multi motor electric drive? Give some examples.**
 In this drive, there are several drives, each of which serves to activate on of the working parts of the driven mechanisms. Metal cutting machine tools, paper making machines, rolling mills, traction drive, Traveling cranes etc.,
9) **Indicate the importance of power rating & heating of electric drives. NOV/DEC 2016**
 Power rating: Correct selection of power rating of electric motor is of economic interest as it is associated with capital cost and running cost of drives.
 Heating : For proper selection of power rating the most important consideration is the heating effect of load. In this connection various forms of loading or duty cycles have to be considered.
10) **List out some applications for which continuous duty is required. NOV/DEC 2013**
 Centrifugal pumps, fans, conveyors & compressors
11) **What is duty factor?**

The ratio of ON time (Ton) of the drive to total time period(Ton +Toff) is called duty factor.

12) Mention the necessity of power rating? NOV/DEC 2009, NOV/DEC 2012

Power rating of electric drives for particular operation is important since, following reasons.

1. To get economy with reliability
2. To obtain the maximum efficiency on their full load without any damaging.

PART – B

1) Explain the factors governing the selection of motors. NOV/DEC 2009, APRIL/MAY 2010, NOV/DEC 2016
2) Discuss in detail the determination of power rating of motors. NOV/DEC 2015
3) ***Write a brief note on classes of duty for an electric motor. APRIL/MAY 2010, NOV/DEC 2013, NOV/DEC 2015, NOV/DEC 2016***
4) ***Draw the typical temperature rise-time curve and derive the equation for temperature rise in an electric drive. NOV/DEC 2013, NOV/DEC 2014***
5) Explain in detail about the various types of electric drives. NOV/DEC 2009, NOV/DEC 2015
6) Explain the different types of loading of drives. NOV/DEC 2012
7) ***Explain the four quadrant operation of motor applicable for hoist.***

UNIT 2
DRIVE MOTOR CHARACTERISTICS

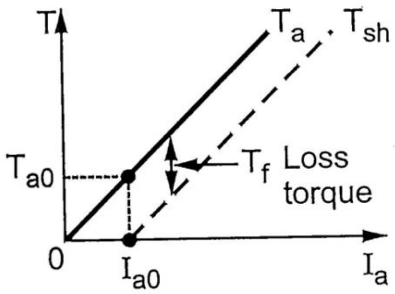
<u>Characteristics of DC motor</u>

1. Torque Vs Armature Current Characteristics
2. Speed Vs Armature Current Characteristics
3. Speed Vs Torque Characteristics

<u>DC Shunt Motor</u>

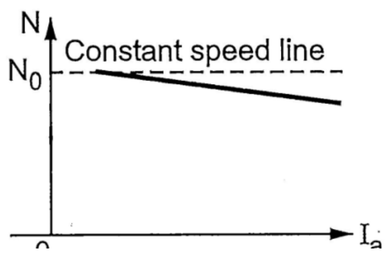
1. Torque Vs Armature Current Characteristic

$$T_a \propto \phi I$$



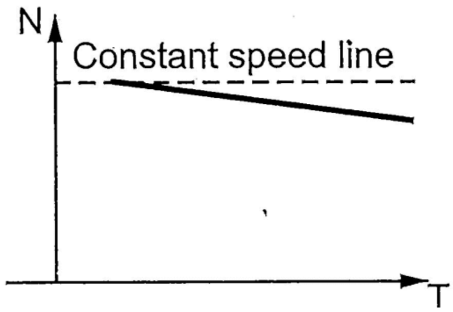
- For DC Shunt motor, flux φ is constant.
- Armature torque is directly proportional to Armature current.
- Torque increases linearly with armature current.
- Torque spent to rotate armature is loss.
- The torque used to operate the load is called Shaft torque.

2. Speed Vs Armature Current Characteristics



- When load increases, armature current increases.
- When armature current increases, drop increases.
- When drop increases, speed reduces.

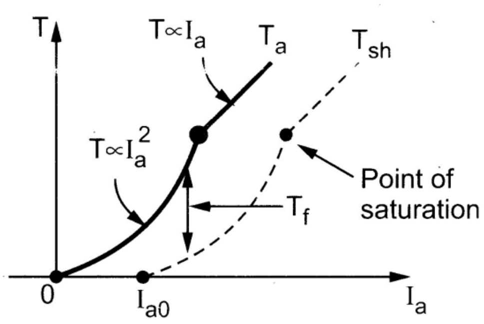
3. Speed Vs Torque Characteristics



- This characteristic is similar to speed-armature current characteristics.
- When torque increases, speed reduces.
- The characteristic also varies with respect to armature current value, field resistance value and supply voltage.

<u>DC Series Motor</u>

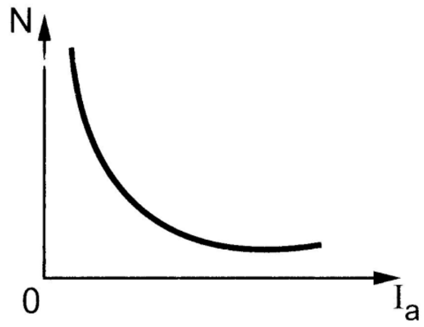
1. Torque Vs Armature Current Characteristics



- Armature current and field current are same.
- At starting time, torque is proportional to square value of armature current and then torque is proportional to armature current.
- It can be used for high torque applications.

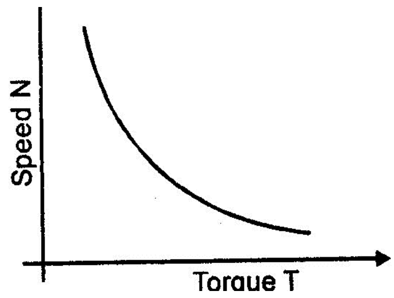
2. Speed Vs Armature Current Characteristics

- For series motor, speed is inversely proportional to flux.
- Flux is directly proportional to armature current.
- When armature current increases, speed reduces.



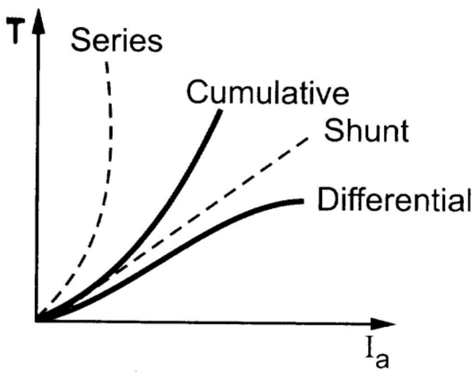
3. Speed Vs Torque Characteristics

- This characteristic is similar to speed-armature current characteristics.
- When torque increases, speed reduces.
- The characteristic also varies with respect to field current value and supply voltage.



DC Compound Motor

- The characteristic of this motor is depending on flux produced by shunt winding and series winding.
- For cumulative compound motor, the total flux is the sum of shunt field coil flux and series field flux.
- For differential compound motor, the total flux is the difference of shunt field coil flux and series field flux.
- Cumulative compound motor has capability of developing large amount of torque compared to differential compound motor.



BRAKING OF ELECTRICAL MOTORS:

- The term braking comes from the term brake
- The process of reducing speed of any rotating machine

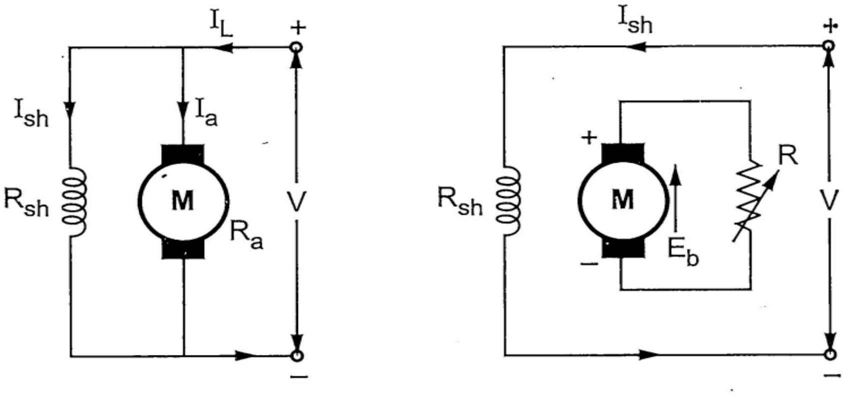
Types of Braking

- Rheostatic or Dynamic Braking
- Plugging or Counter Current Braking
- Regenerative Braking

DC Shunt Motor:

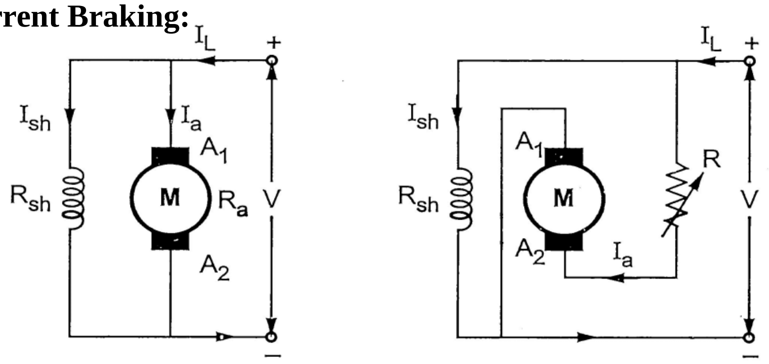
Rheostatic or Dynamic Braking:

- The method of reversing the direction of torque and braking the motor is **dynamic braking**
- In this method of braking the motor which is at a running condition is disconnected from the source and connected across a resistance
- When the motor is disconnected from the source, the rotor keeps rotating due to inertia and it works as a self–excited generator
- When the motor works as a generator the flow of the electric current and torque reverses
- During braking to maintain the steady torque sectional resistances are cut out one by one.



(a) Running (b) Braking

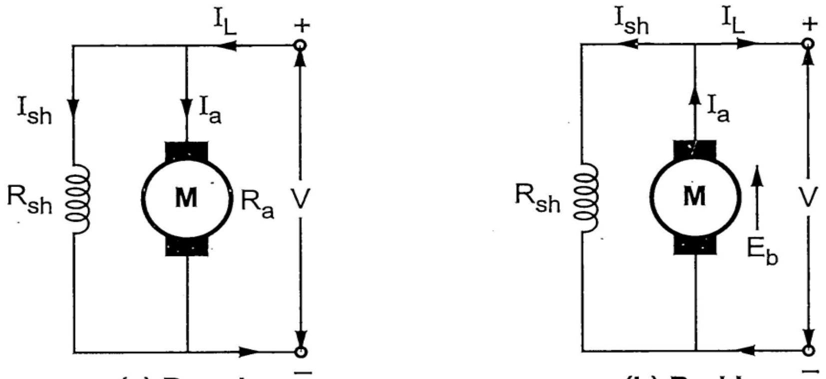
Plugging or Counter Current Braking:



(a) Running (b) Braking

- In this method the terminals of supply are reversed, as a result the generator torque also reverses which resists the normal rotation of the motor and as a result the speed decreases
- During plugging external resistance is also introduced into the circuit to limit the flowing current
- The main disadvantage of this method is that here power is wasted

Regenerative Braking:

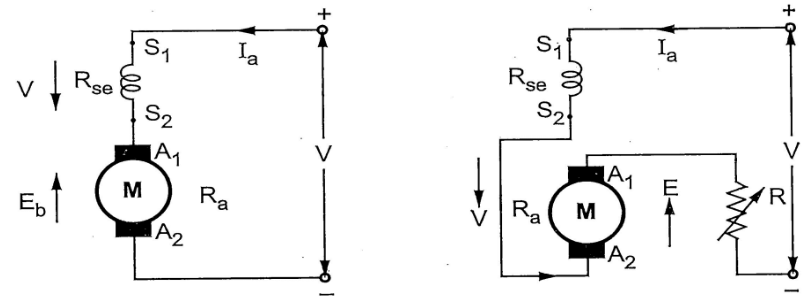


(a) Running (b) Braking

- **Regenerative braking** takes place whenever the speed of the motor exceeds the synchronous speed
- This baking method is called regenerative braking 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
- The only disadvantage of this type of braking is that the motor has to run at super synchronous speed which may damage the motor mechanically and electrically

DC SERIES MOTOR:

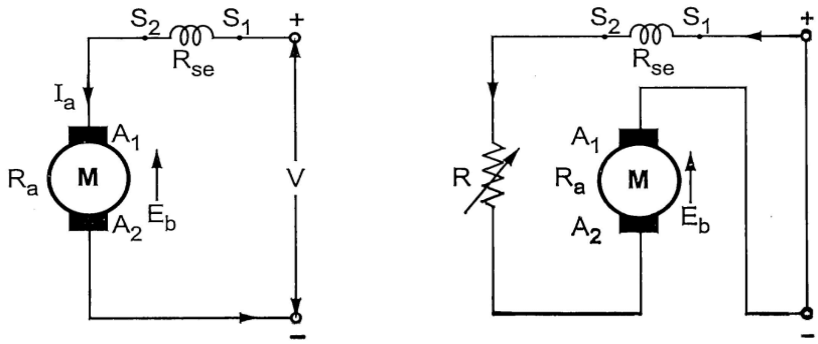
Rheostatic or Dynamic Braking:



(a) Running (b) Braking

- The method of reversing the direction of torque and braking the motor is **dynamic braking**
- In this method of braking the motor which is at a running condition is disconnected from the source and connected across a resistance
- When the motor is disconnected from the source, the rotor keeps rotating due to inertia and it works as a self–excited generator
- When the motor works as a generator the flow of the electric current and torque reverses
- During braking to maintain the steady torque sectional resistances are cut out one by one.

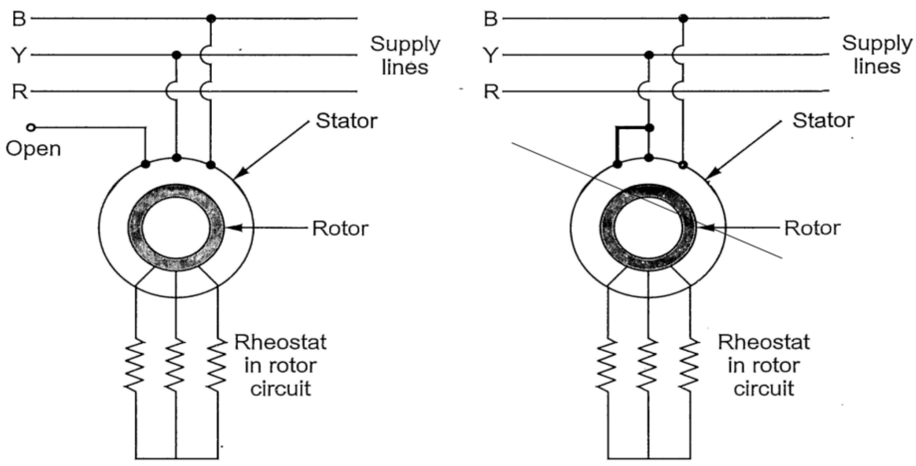
Plugging or Counter Current Braking



- In this method the terminals of supply are reversed, as a result the generator torque also reverses which resists the normal rotation of the motor and as a result the speed decreases
- During plugging external resistance is also introduced into the circuit to limit the flowing current
- The main disadvantage of this method is that here power is wasted

BRAKING OF INDUCTION MOTOR

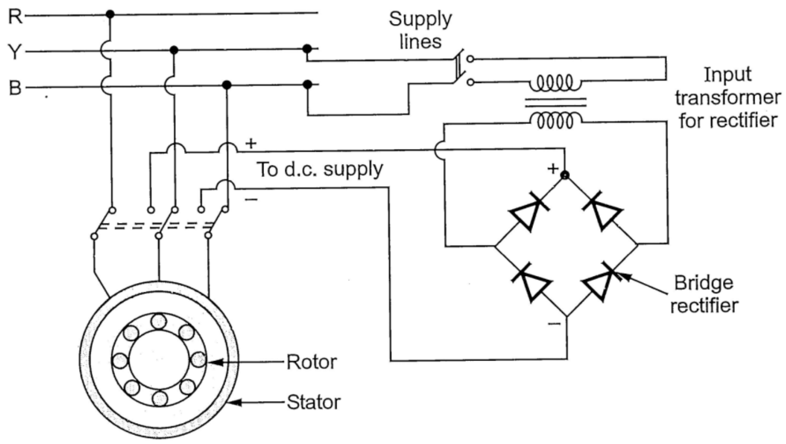
Dynamic or Rheostatic Braking:



(a) Two lead connections (b) Three lead connections

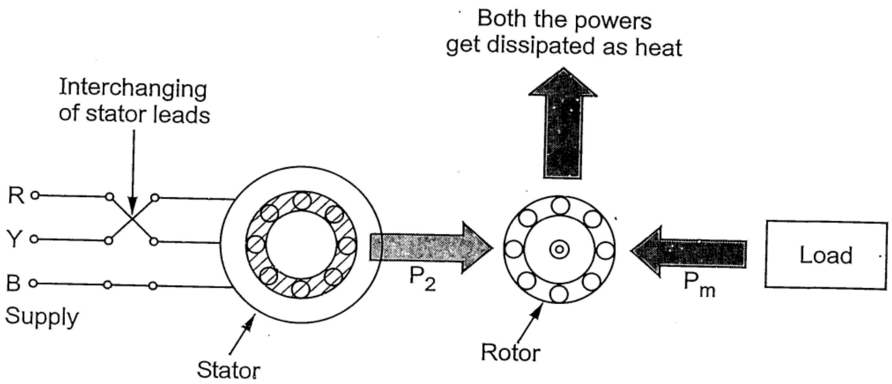
- This type of induction motor braking is obtained when the motor is made to run on a single phase supply by disconnecting any one of the three phase from the source
- The disconnected terminal is connected with another phase or the disconnected phase is left open
- When the disconnected phase is left 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 three phase 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:



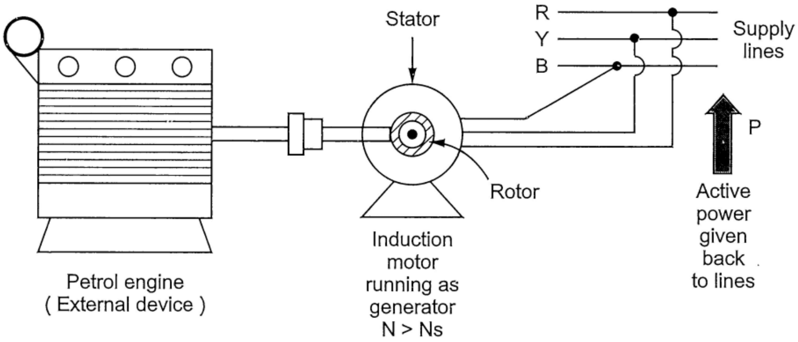
- To obtain this type of braking the stator of a running induction motor is connected to a dc supply
- The moment when AC supply is disconnected and DC supply is introduced across the terminals of the induction motor
- The stationery magnetic field is generated due to the DC electric current flow
- The 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:



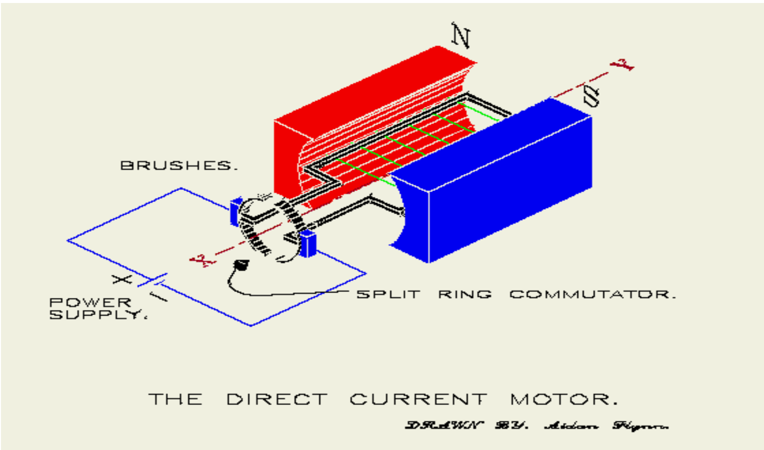
- Plugging **induction motor braking** is done by reversing the phase sequence of the motor
- The phase sequence of the motor can be changed by interchanging connections of any two phases of stator with respect of supply terminals
- When the phase sequence is changed, the direction of current flow is changed
- The counter current produces the opposite torque and then motor is stopped

Regenerative Braking:

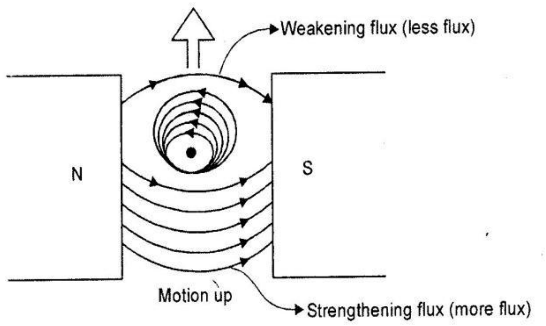


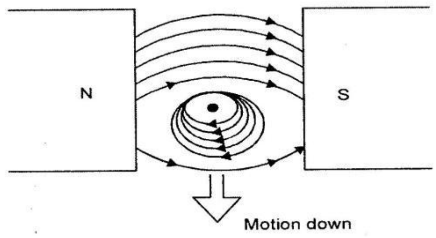
- The **regenerative braking of induction motor** can only take place if the speed of the motor is greater than synchronous speed
- The above synchronous speed is obtained by using Petrol engine
- This baking method is called regenerative braking because here the motor works as generator and supply the 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

OPERATING PRINCIPLE OF DC MOTORS:

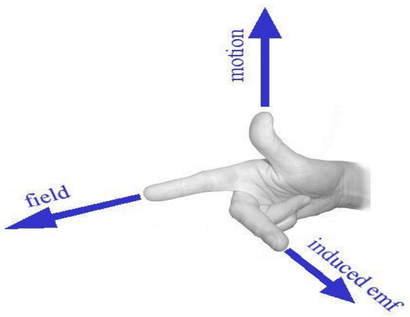


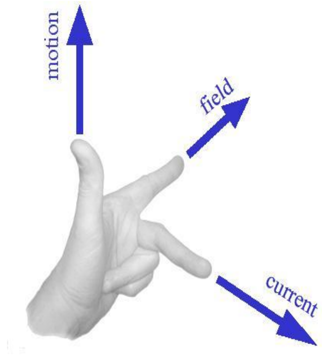
- This is a device that converts DC electrical energy to a mechanical energy
- Structurally and construction wise a direct electric current motor is exactly similar to a DC generator, but electrically it is just the opposite
- This DC or **direct electric current motor** works on the principal, when a current carrying conductor is placed in a magnetic field, it experiences a torque and has a tendency to move
- This is known as motoring action
- If the direction of electric current in the wire is reversed, the direction of rotation also reverses
- When magnetic field and electric field interact they produce a mechanical force, and based on that the working principle of **dc motor** established
- The direction of rotation of a this motor is given by Fleming‟s left hand rule
- **Fleming's left hand rule:** if the index finger, middle finger and thumb of your left hand are extended mutually perpendicular to each other and if the index finger represents the direction of magnetic field, middle finger indicates the direction of electric current, then the thumb represents the direction in which force is experienced by the shaft of the **dc motor**



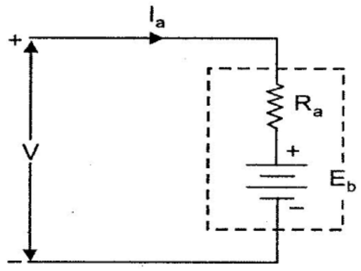


Fleming's Right & Left Hand Rule





Equivalent Circuit



<u>TYPES OF DC MOTORS</u>

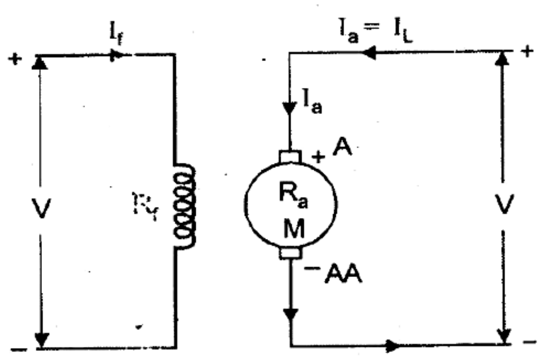
- **Separately Excited DC motor.**
- **Self-excited DC motor.**
  1. **Series motor.**
  2. **Shunt motor.**
  3. **Compound motor.**

  a. Cumulative compound b. Differential compound

  i. Long Shunt compound motor. ii. Short Shunt compound motor.

<u>Separately Excited DC motor:</u>

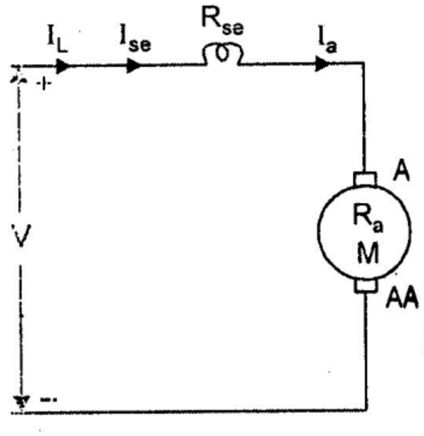
- The supply is given separately to the field and armature windings
- The main distinguishing fact in these types of dc motor is that, the armature electric current does not flow through the field windings, as the field winding is energized from a separate external source of dc electric current



Self-excited DC motor

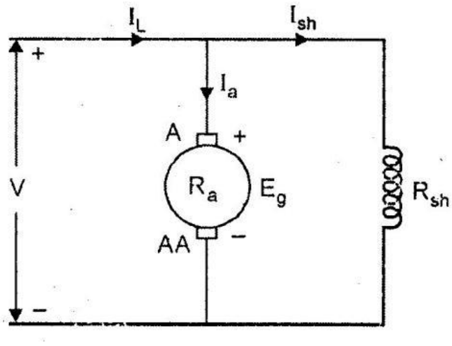
Series motor:

- The armature winding and field winding are connected in series
- The entire armature electric current flows through the field winding as its connected in series to the armature winding
- In a series wound dc motor, the speed varies with load



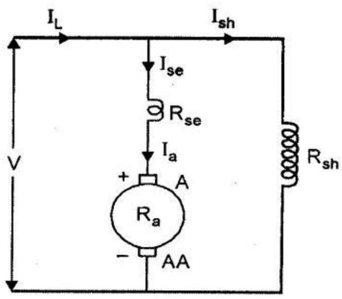
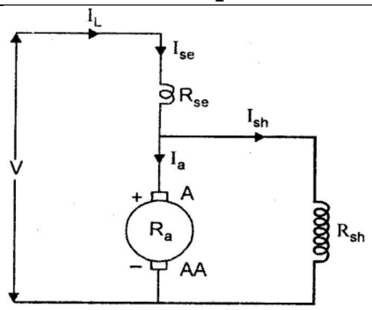
Shunt motor:

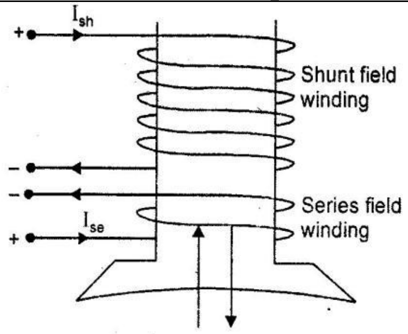
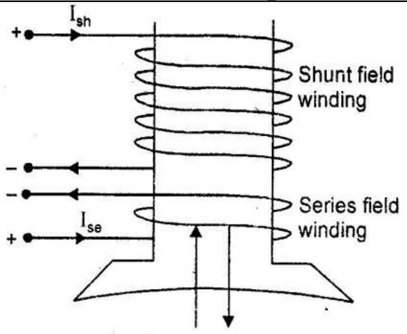
- The field winding is connected in parallel to the armature winding
- The voltage is same across field winding and armature winding
- The line current is the sum of armature current and field current
- The shunt wound dc motor is a constant speed motor, as the speed does not vary here with the variation of mechanical load on the output.



Compound Motor:

- The compound excitation characteristic in a dc motor can be obtained by combining the operational characteristic of both the shunt and series excited dc motor
- It contains the field winding connected both in series and in parallel to the armature winding
- If the shunt field winding is only parallel to the armature winding and not the series field winding then its known as short shunt dc motor
- If the shunt field winding is parallel to both the armature winding and the series field winding then it‟s known as long shunt type compounded wound dc motor
- When the shunt field flux assists the main field flux, produced by the main field connected in series to the armature winding then it‟s called cumulative compound dc motor
- In case of a differentially compounded self excited dc, the arrangement of shunt and series winding is such that the field flux produced by the shunt field winding diminishes the effect of flux by the main series field winding

Long Shunt compound motor	**Short Shunt compound motor**
	

Cumulative compound	Differential compound
	

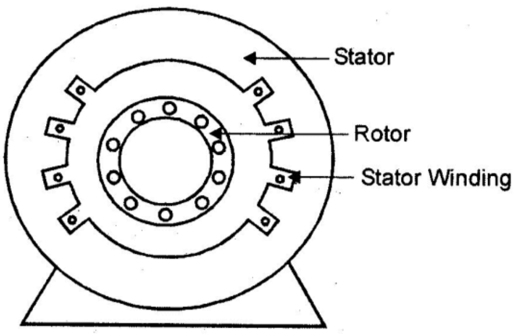
SINGLE PHASE INDUCTION MOTORS:

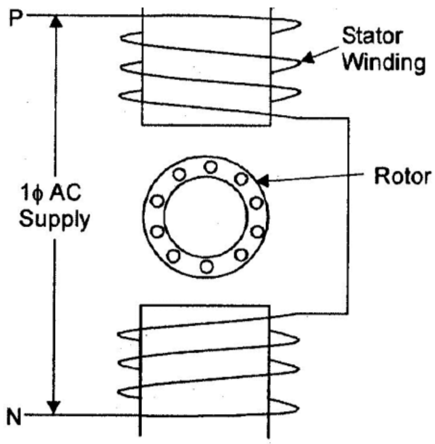
- Single phase motors are small motors.
- They have a power rating in fractional HP range.
- These motors are used in homes, offices, shops and factories.

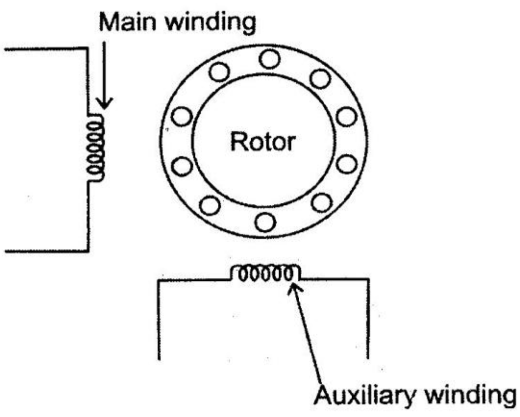
Disadvantages:

1. Lack of starting torque.
2. Reduced power factor.
3. Low efficiency.

<u>CONSTRUCTION:</u>







Stator Core

- It is made by laminated silicon plates.
- All silicon plates stamped together to form a solid core
  - Used to give mechanical support to stator windings.
  - Used to give magnetic flux path.
  - By using laminated and stamped core, the eddy current and hysteresis loss can be reduced.

Stator winding

- It is made by copper conductors.
    - For low speed motor – Wave winding.
    - For high speed motor – Lap winding.

Rotor core

- It is made by laminated silicon plates.
- All silicon plates stamped together to form a solid core
    - Used to give magnetic flux path.
    - By using laminated and stamped core, the eddy current and hysteresis loss can be reduced.

Rotor winding

- Copper bars placed in the slots and all ends are short circuited – called ***squirrel cage rotor.***

Yoke

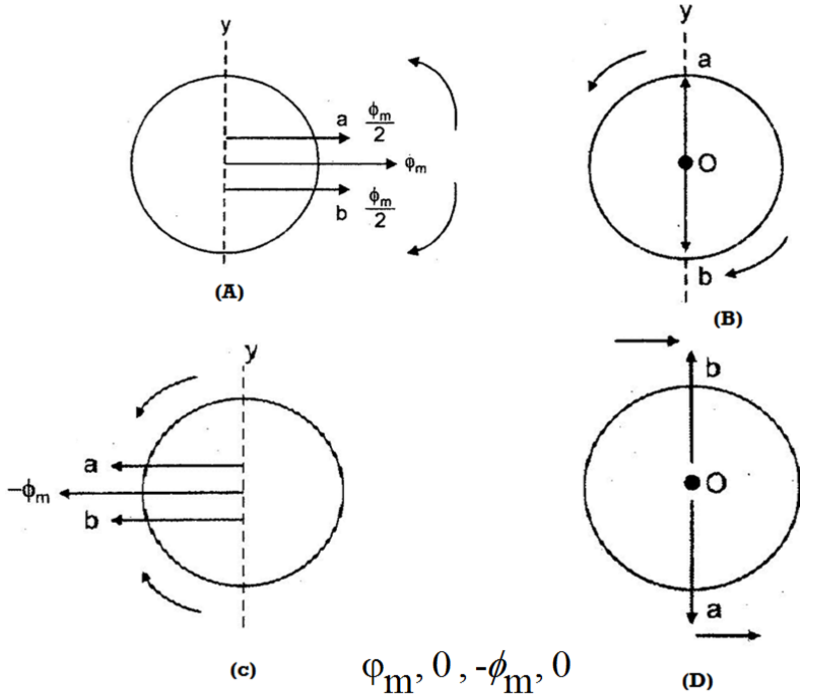
- It is made cast iron materials.
    - Used to give mechanical support to all internal parts.
    - Used to protect all internal parts from the external environment.

<u>PRINCIPLE OF OPERATION:</u>

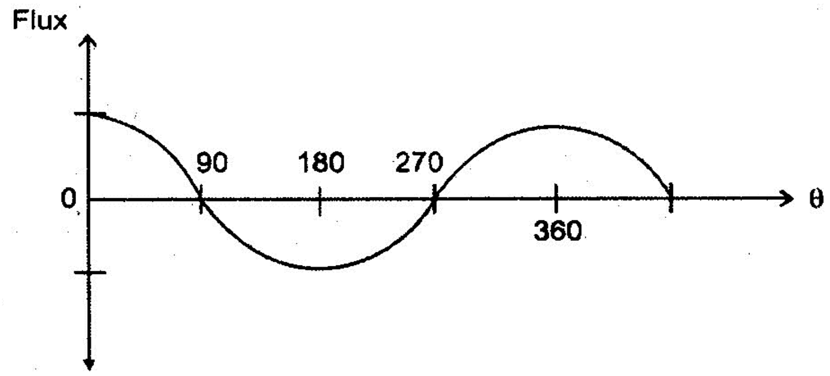
- The starting torque can be produced by using auxiliary winding.
- The angle between main winding and auxiliary winding should be 90 electrical degrees.The current passing through main winding and auxiliary winding should have some electrical angle to produce a rotating magnetic field.
- Rotating magnetic field produces high starting torque.
- The single-phase induction motor operation can be described by two methods:
    - Double revolving field theory; and
    - Cross-field theory.

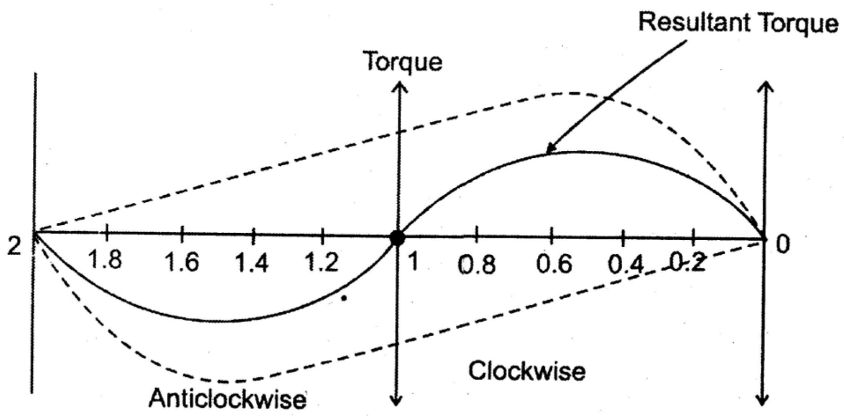
<u>DOUBLE REVOLVING FIELD THEORY:</u>

- A single-phase AC current supplies the main winding that produces a pulsating magnetic field.
- Mathematically, the pulsating field could be divided into two fields, which are rotating in opposite directions.
- The pulsating filed is divided a forward and reverse rotating field.
- The components „a" and „b" are forward and reverse rotating field respectively



$\varphi_m, 0, -\phi_m, 0$



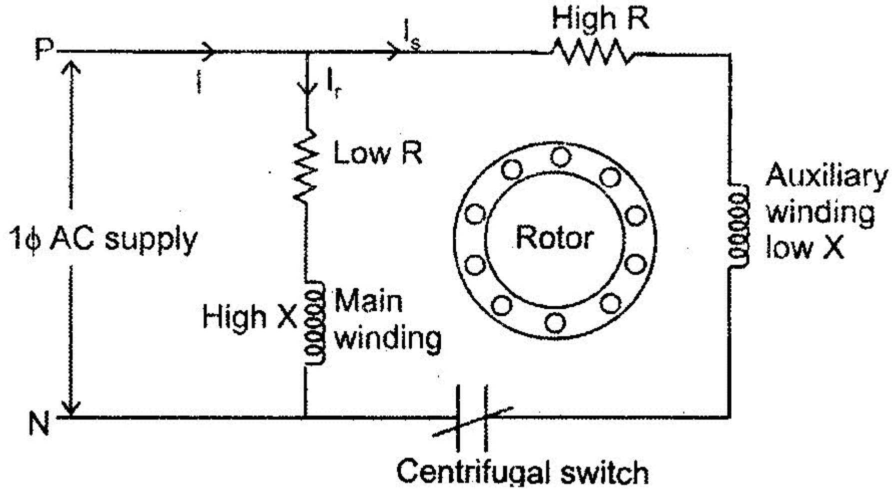


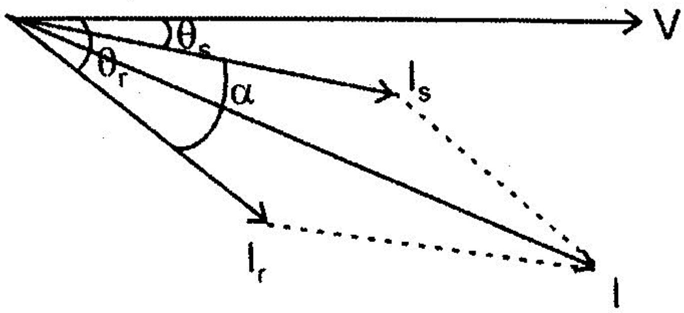
- At starting, the slip value of 1φ induction motor is „1".
- When slip is 1, the components „a" and „b" are producing equal and opposite torque.
- The resulting torque is zero.
- This motor has no starting torque.

TYPES OF 1Φ IM (STARTING METHODS):

- Resistance – Start (Split phase) motor.
- Capacitor – Start induction motor.
- Capacitor – Run induction motor.
- Capacitor – Start and Capacitor – Run IM.
- Shaded – pole motor.

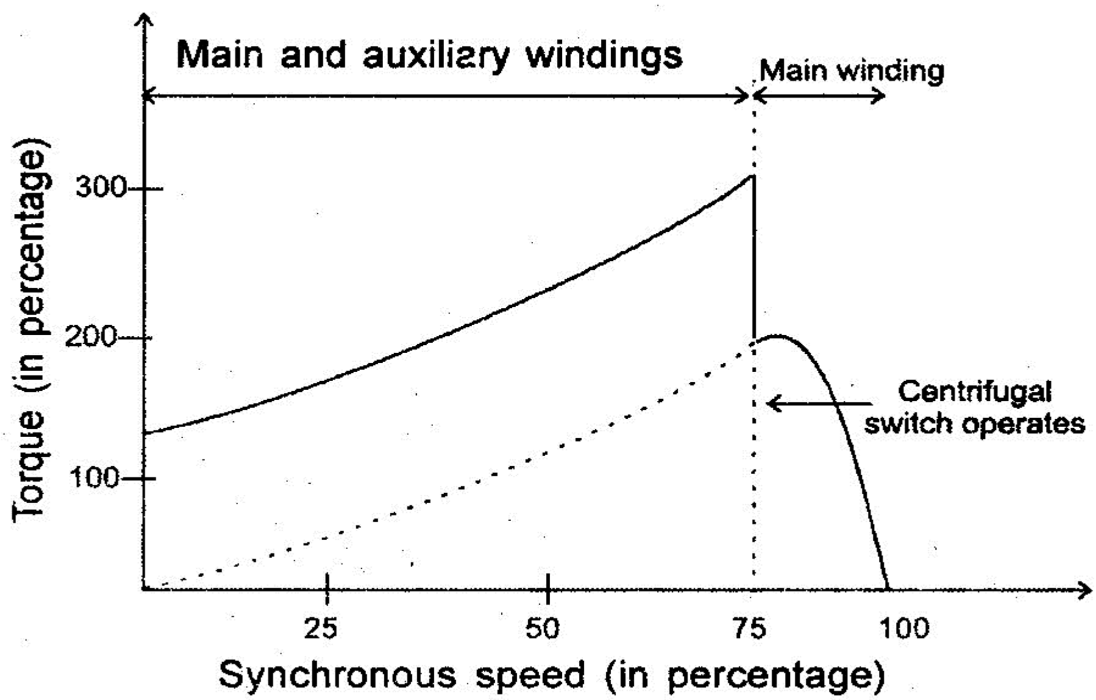
Resistance – Start (Split phase) motor:





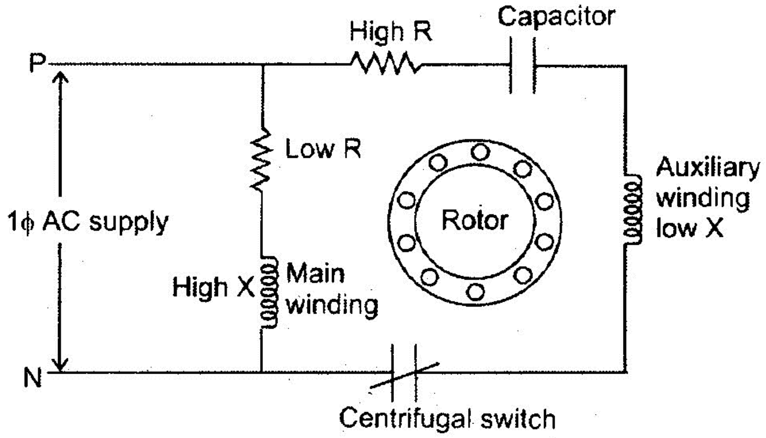
- It has two windings:
    - Main winding or Running winding
    - Auxiliary winding.
- These two winding axes are displaced by 90 electrical degrees.
- The main winding has high X (reactance) value and low R (resistance) value.
- The auxiliary winding has Low X value and High R value.
- This variation in the reactance makes two different phases.
- Two phase supply constructs rotating magnetic field.
- The rotating magnetic field produces high torque at the starting time.
- The centrifugal switch disconnects the auxiliary winding from the circuit after the motor reaches synchronous speed.

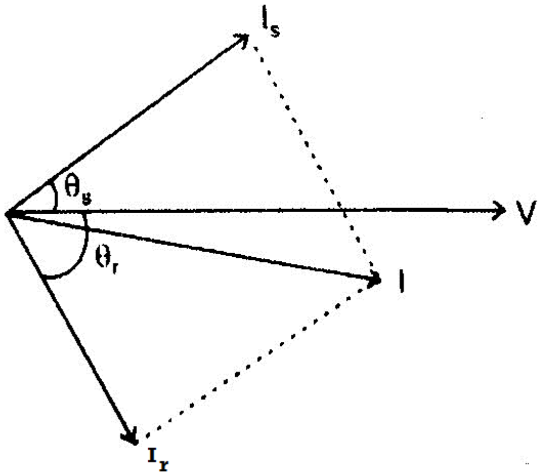
Torque Vs Speed:



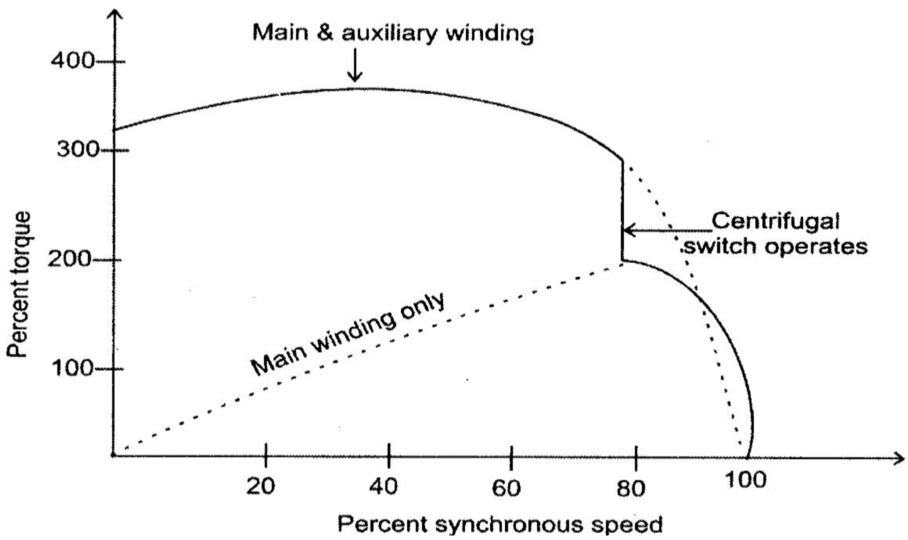
- **Applications:**
    - Fans, Blowers
    - Centrifugal pumps
    - washing machines

Capacitor – Start induction motor:



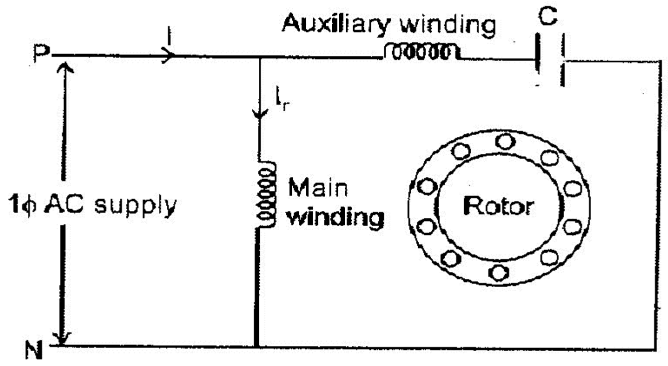


- A capacitor is connected in series with auxiliary winding to produce leading current in auxiliary winding.
- The high X value of main winding produces lagging current.
- Voltage across two windings produces two different phases.
- Two phase supply constructs rotating magnetic field.
- The rotating magnetic field produces high torque at the starting time.
- The centrifugal switch disconnects the auxiliary winding and capacitor from the circuit after the motor reaches 75% of synchronous speed.
- **Speed Vs Torque:**



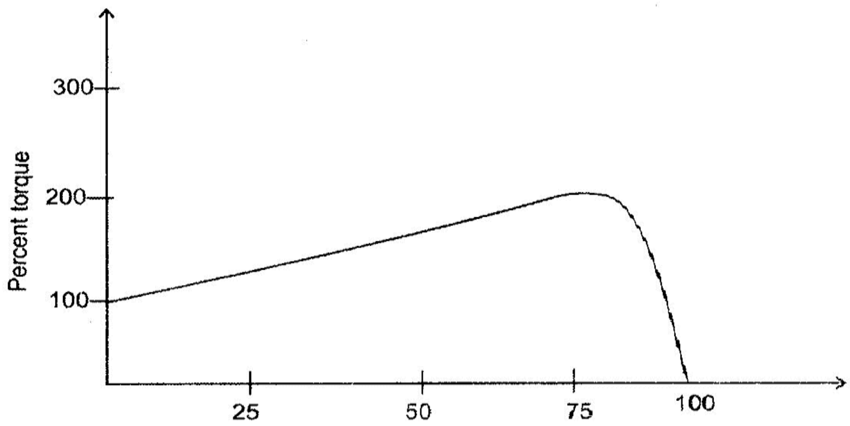
- **Applications:**
    - Compressors, Pumps, Conveyors, Refrigerators, Air conditioning
    - Equipments, Washing machines

Capacitor – Run induction motor:



- A capacitor is connected in series with auxiliary winding to produce leading current in auxiliary winding.
- The high X value of main winding produces lagging current.
- Voltage across two windings produces two different phases.
- Two phase supply constructs rotating magnetic field.
- The rotating magnetic field produces high torque at the starting time.
- It does not use centrifugal switch.
- The capacitor is always connected with auxiliary winding so that the starting and running torque is high.

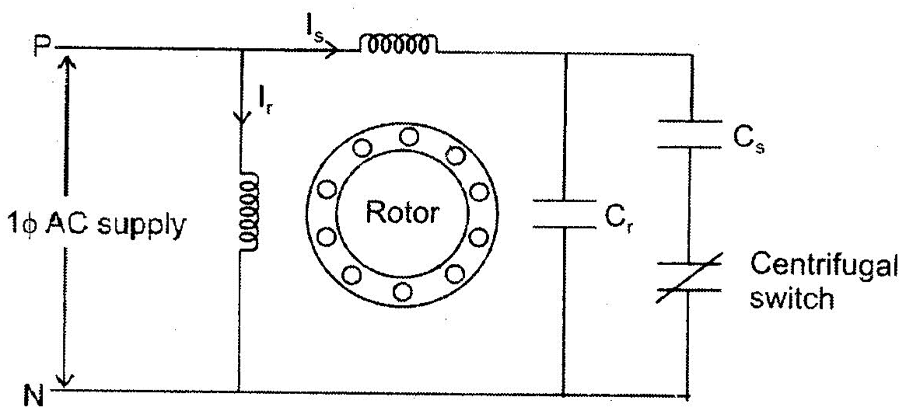
Speed Vs Torque:



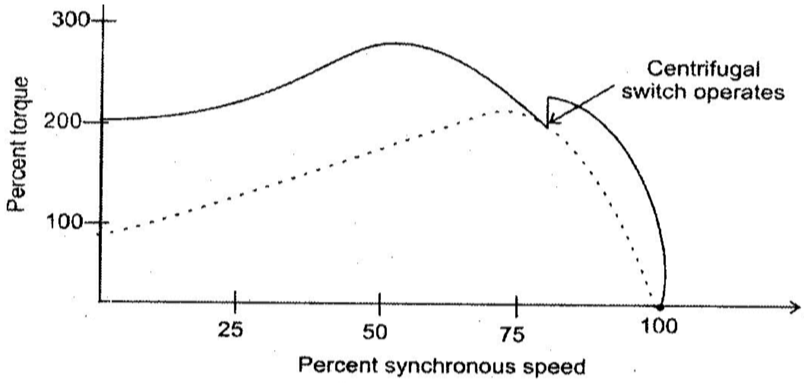
Applications:

- Fans, Blowers
- Centrifugal pumps

Capacitor – Start and Capacitor – Run IM:

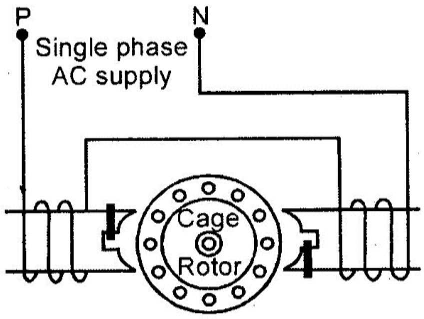


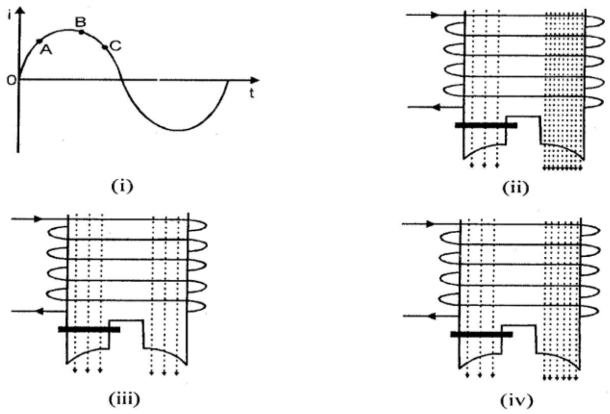
- It uses two capacitors, Running capacitor (Cr) and starting capacitor (Cs).
- Running capacitor always connected in series with auxiliary winding.
- Starting capacitor is disconnected from the circuit after the motor reaches 75% of synchronous speed by the help of Centrifugal switch.
- Starting torque and efficiency can be improved.
- **Speed Vs Torque:**



- **Applications:**
    - Compressors
    - Pumps
    - Conveyors
    - Refrigerators

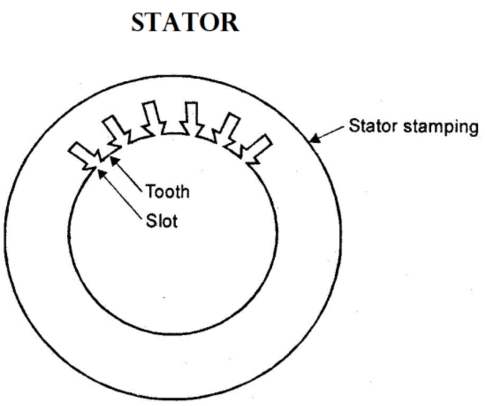
Shaded – pole motor:



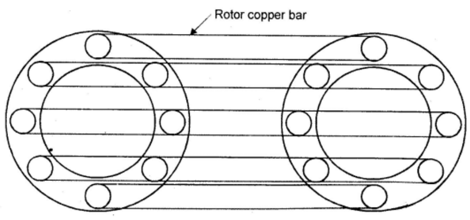


- During the portion OA of the alternating current cycle, the emf is induced in the shading coil.
- The induced emf produces magnetic flux in the shaded portion. This flux opposes the main field flux, so that the flux under shaded portion is weakened and flux under unshaded portion is strengthened.
- During the portion AB of the alternating current cycle, the flux under shaded portion and unshaded portion is uniform.
- During the portion BC of the alternative current cycle , the emf is induced in the shading coil. The induced emf produces magnetic flux in the shaded portion. This flux is added to the main field flux, so that the flux under shaded portion is strengthened and flux under unshaded portion is weakened.
- Alternatively it is producing strengthened and weakened magnetic flux under pole faces, so that it constructs rotating magnetic field.
- The rotating magnetic field produces high torque at the starting time.
- Low efficiency, Low power factor and Very low starting torque.
- **Applications:**
- Fans, Blowers, Turn tables, Hair driers, Motion picture projectors

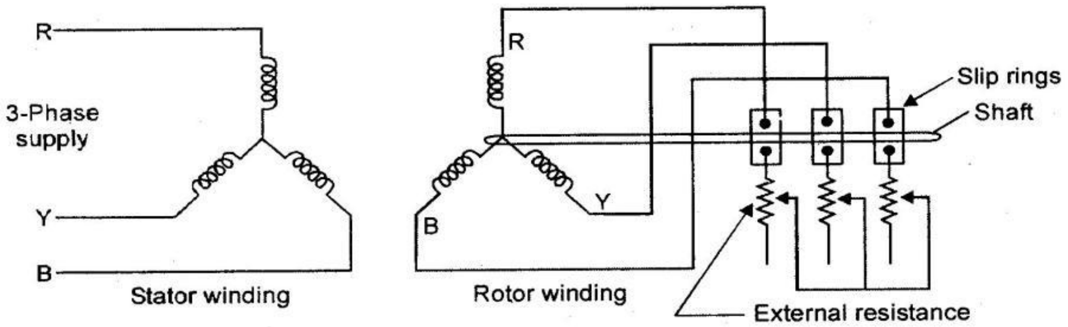
PRINCIPLE OF OPERATION OF THREE-PHASE INDUCTION MOTORS:



Squirrel cage rotor



Slip ring or Wound Rotor



Principle of operation:

- Rotating magnetic field cuts the rotor windings and produces an induced voltage in the rotor windings.
- Due to the fact that the rotor windings are short circuited, for both squirrel cage and wound-rotor, and induced current flows in the rotor windings.
- The rotor current produces another magnetic field.
- A torque is produced as a result of the interaction of those two magnetic fields. This torque makes the rotation of the rotor.
- The IM will always run at a speed lower than the synchronous speed.
- The difference between the motor speed and the synchronous speed is called the Slip speed.

UNIT – II

DRIVE MOTOR CHARACTERISTICS

1) **Why a single phase induction motor does not self start?**
When a single phase supply is fed to the single phase induction motor. Its stator winding produces a flux which only alternates along one space axis. It is not a synchronously revolving field, as in the case of a 2 or 3phase stator winding, fed from 2 or 3 phase supply.

2) **What is meant by plugging?**
The plugging operation can be achieved by changing the polarity of the motor there by reversing the direction of rotation of the motor. This can be achieved in ac motors by changing the phase sequence and in dc motors by changing the polarity.

3) **What are the different types of electric braking? APRIL/MAY 2010, NOV/DEC 2013, NOV/DEC 2014, NOV/DEC 2015**
Dynamic or Rheostatic braking, Counter current or plugging and Regenerative braking

4) **Compare electrical and mechanical braking**
Brakes require frequent maintenance very little maintenance not smooth can be applied to hold the system at any position cannot produce holding torque.

5) **Define slip.**

$$S = Ns – Nr$$

Where,
Ns = synchronous speed in rpm, Nr = rotor speed in rpm, S = Slip

6) **What is meant by regenerative braking?**
In the regenerative braking operation, the motor operates as a generator, while it is still connected to the supply here,the motor speed is grater that the synchronous speed. Mechanical energy is converter into electrical energy, part of which is returned to the supply and rest as heat in the winding and bearing.

7) **What is meant by mechanical characteristics? NOV/DEC 2009, APRIL/MAY 2010, NOV/DEC 2013**
A curve drawn between the parameters speed and torque.

8) **What do you mean by Rheostatic braking? NOV/DEC 2016**
In this braking armature is removed and connected across a variable rheostat.

9) **Why commutator is employed in d.c.machines?**
Conduct electricity between rotating armature and fixed brushes, convert alternating emf into unidirectional emf (mechanical rectifier).

10) **How will you change the direction of rotation of d.c. Motor?**
Either the field direction or direction of current through armature conductor is reversed.

11) **What is back emf in d.c. motor? NOV/DEC 2012**
As the motor armature rotates, the system of conductor come across alternate north and South pole magnetic fields causing an emf induced in the conductors. The direction of the emf induced in the conductor is in opposite to current. As this emf always opposes the flow of current in motor operation it is called as back emf.

12) **What are the types of Single phase induction motors? NOV/DEC 2012**
   - Split phase induction motor
   - Capacitor start induction motor
   - Capacitor start capacitors run induction motor
   - Shaded pole induction motor

13) **What is back e.m.f in a D.C. Motor? State its expression.**

- Armature starts rotating, the main flux gets cut by the armature winding and an e.m.f gets induced in the armature.
- This e.m.f opposes the applied d.c voltage and is called back e.m.f denoted as E_b.

$$E_b = V - I_aR_a$$

PART – B

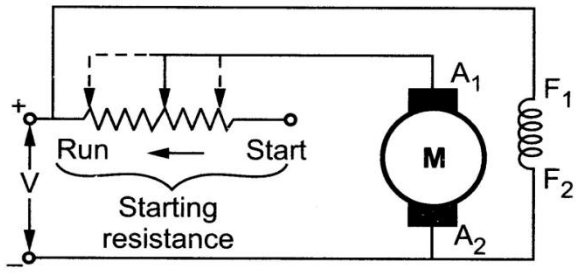
1) ***Explain the Speed-Torque characteristics of three phase induction motor with neat diagrams. NOV/DEC 2012, NOV/DEC 2014, NOV/DEC 2016***
2) Explain about the speed-torque characteristics of a DC Shunt Motor with Suitable graphs and diagrams. APRIL/MAY 2010, NOV/DEC 2015
3) ***Explain the various methods of braking of induction motors. NOV/DEC 2009***
4) Draw and explain various load characteristics of DC Shunt Motor. NOV/DEC 2013
5) ***Explain various methods of braking of DC Shunt Motors with neat diagrams. NOV/DEC 2012, NOV/DEC 2014, NOV/DEC 2015, NOV/DEC 2016***
6) ***Explain the Speed-Torque characteristics of Single phase induction motor with neat diagrams. NOV/DEC 2009***
7) Single phase motor is not a self starting motor. Why? APRIL/MAY 2010

UNIT -III
STARTING METHODS

STARTER:

- Starter is used to reduce starting current because armature consumes 15-20 times more than the full load current at starting time.
- High current blows out the fuses.
- It affects insulation of the coil.
- It also creates very high torque and very high torque causes mechanical damage to the motor.

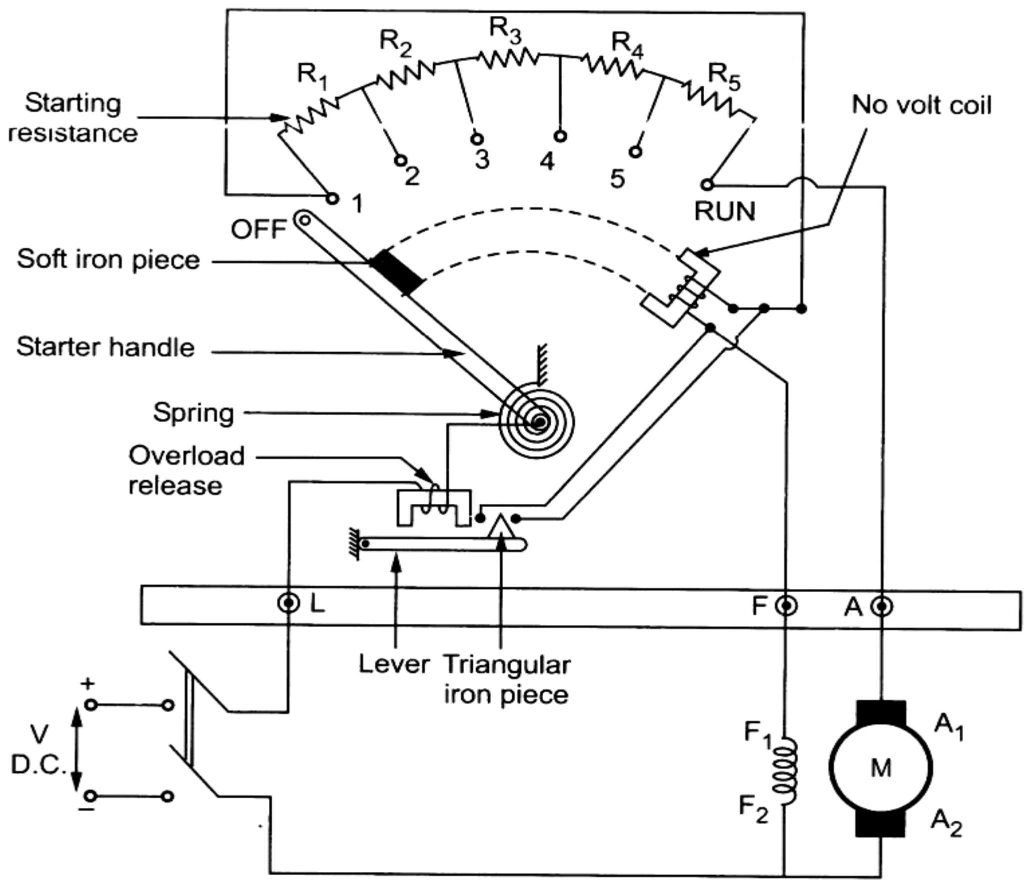
Basic Arrangement:



DC SHUNT MOTOR:

- Three Point Starter
- Four Point Starter

Three Point Starter



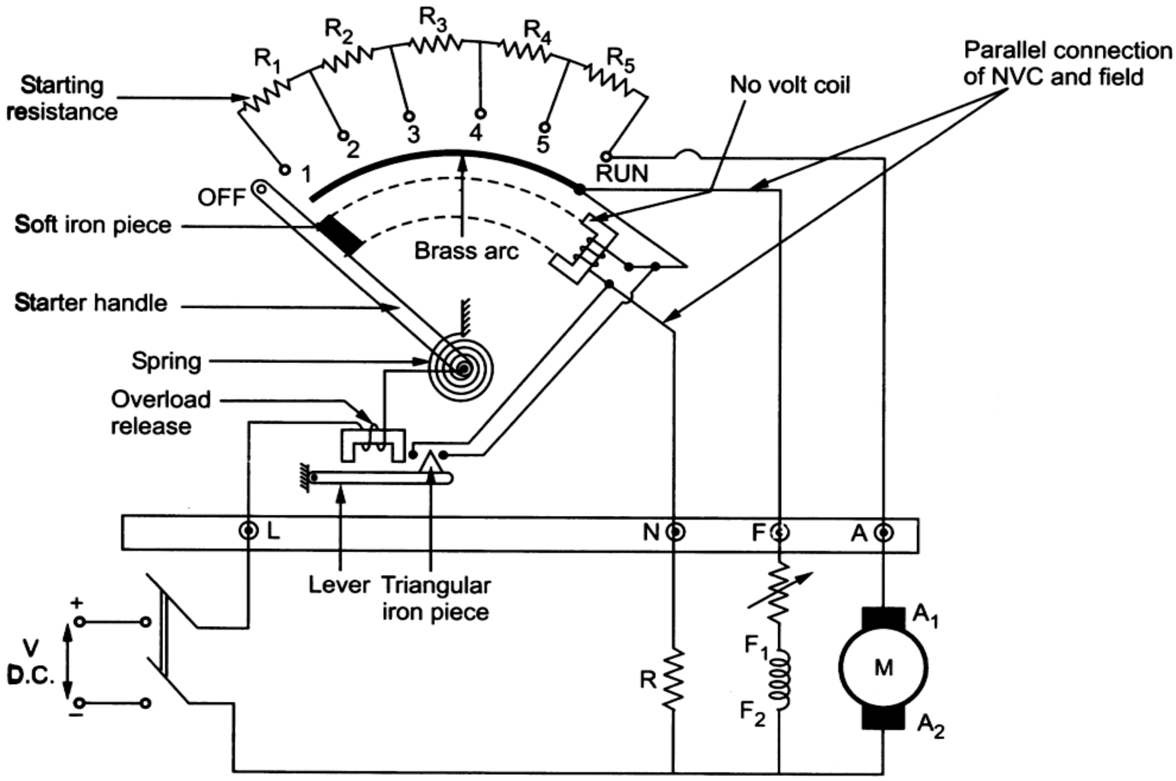
- The electric current will be dangerously high at starting (as armature resistance R_a is small) and hence its important that we make use of a device like the **3 point starter** to limit the starting electric current to an allowable lower value
- The contact points of these sections are called studs and are shown separately as **OFF, 1, 2,3,4,5, RUN**
- There are 3 main points
  - 'L' Line terminal (Connected to positive of supply)
  - 'A' Armature terminal (Connected to the armature winding)
  - 'F' Field terminal (Connected to the field winding)
- The point 'L' is connected to an electromagnet called overload release (OLR)
- The other end of 'OLR' is connected to the lower end of conducting lever of starter handle where a spring is also attached with it and the starter handle contains also a soft iron piece housed on it
- This handle is free to move to the other side RUN against the force of the spring
- This spring brings back the handle to its original OFF position under the influence of its own force
- Another parallel path is derived from the stud '1', given to the another electromagnet called No Volt Coil (NVC)
- Which is further connected to terminal 'F'. The starting resistance at starting is entirely in series with the armature
- The OLR and NVC acts as the two protecting devices of the starter

Working of the 3 point starter:

- The supply to the DC motor is switched ON
- Then handle is slowly moved against the spring force to make a contact with stud No. 1
- At this point, field winding of the shunt or the compound motor gets supply through the parallel path provided to starting resistance, through No Voltage Coil
- While entire starting resistance comes in series with the armature, the high starting armature electric current thus gets limited as the electric current equation at this stage becomes $I_a = E/(R_a+R_{st})$
- As the handle is moved further, it goes on making contact with studs 2, 3, 4 etc., thus gradually cutting off the series resistance from the armature circuit as the motor gathers speed
- Finally when the starter handle is in 'RUN' position, the entire starting resistance is eliminated and the motor runs with normal speed
- When field electric current flows, the NVC is magnetized
- Now when the handle is in the 'RUN' position, soft iron piece connected to the handle and gets attracted by the magnetic force produced by NVC, because of flow of electric current through it
- Thus NVC holds the handle in the 'RUN' position and hence also called **hold on coil**
- When there is any kind of supply failure, the electric current flow through NVC is affected and it immediately loses its magnetic property and is unable to keep the soft iron piece on the handle, attracted
- At this point under the action of the spring force, the handle comes back to OFF position, opening the circuit and thus switching off the motor
- Thus it also acts as a protective device safeguarding the motor from any kind of abnormality

FOUR POINT STARTER:

- The 4 point starter has a lot of constructional and functional similarity to a three point starter, but this special device has an additional point
- A 4 point starter as the name suggests has 4 main operational points, namely
    - 'L' Line terminal. (Connected to positive of supply)
    - 'A' Armature terminal. (Connected to the armature winding
    - 'F' Field terminal. (Connected to the field winding)
    - Like in the case of the 3 point starter, and in addition to it there is, A 4th point N. (Connected to the No Voltage Coil)
- The remarkable difference in case of a 4 point starter is that the No Voltage Coil is connected independently across the supply through the fourth terminal called 'N'
- The change in the field supply does affect the performance of the NVC



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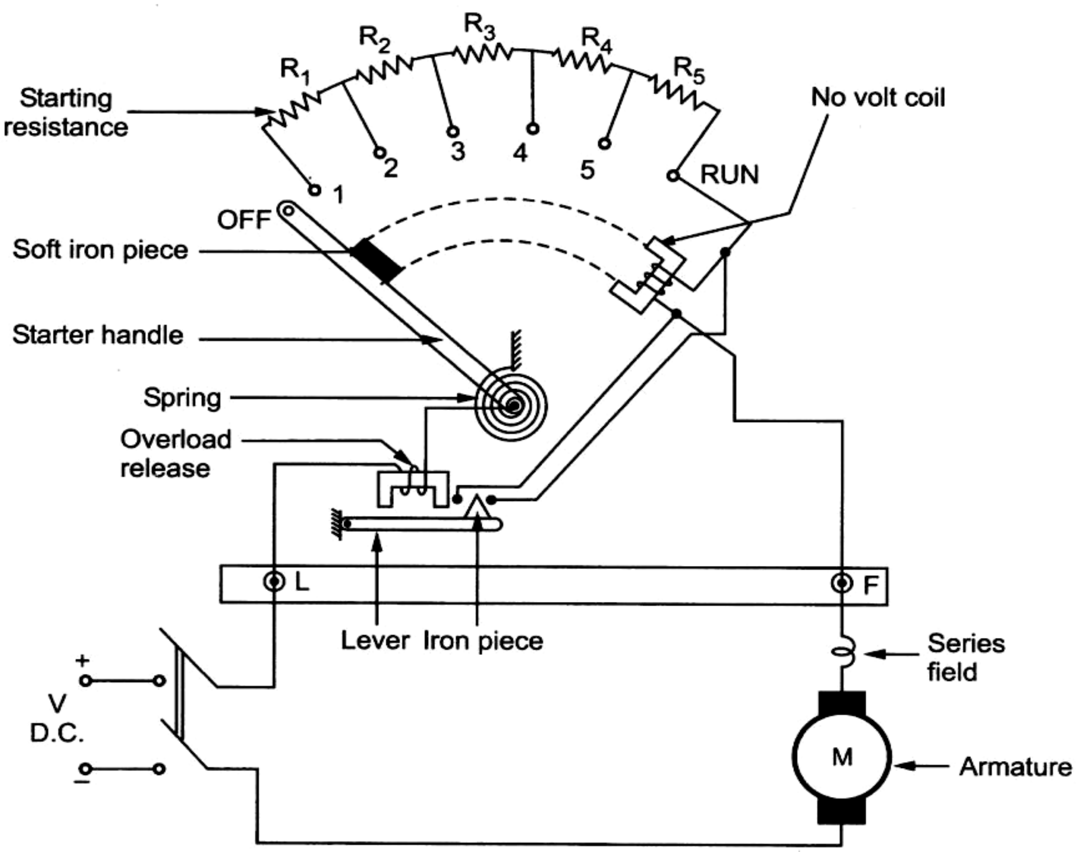
- Thus it also acts as a protective device safeguarding the motor from any kind of abnormality

<u>DC Series Motor</u>

<u>TWO POINT STARTER:</u>

- This starter is only for D.C. series motor only. The basic construction of two point starter is similar to that of three point starter except the fact that it has only two terminals namely line (L) and field (F)
- The F terminal is one end of the series combination of field and the armature winding. The action of the starter is similar to that of three phase starter.
- The main problem in case of D.C. series motor is it"s over speeding action when the load is less
- This can be prevented using two point starters. The no-volt coil is connecting in series with the motor so both current are equal.
- At no load situation load current drawn by the motor decreases causes no-volt coil losses its required magnetism and releases the handle to OFF position.

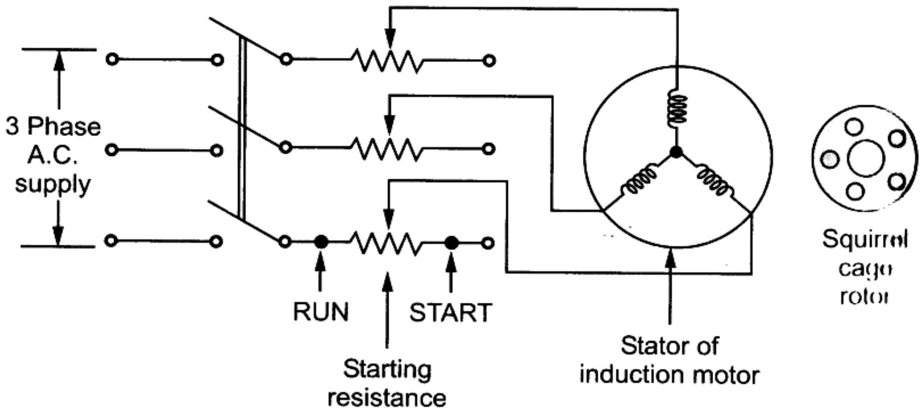


INDUCTION MOTOR STARTERS

- Stator Resistance Starter
- Autotransformer Starter
- Star – Delta Starter
- Rotor Resistance Starter
- Direct On Line Starter

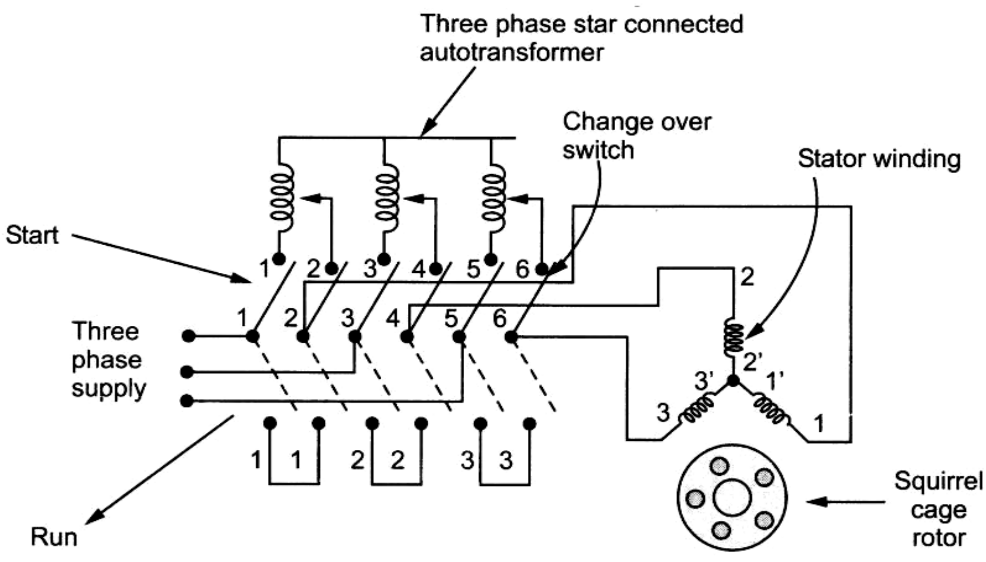
Stator Resistance Starter:

- The variable resistor connected in series with stator winding reduces the starting current
- The resistance value is varied from high to low by using sliding contacts of variable resistor
- Very simple speed control method
- Low maintenance
- Low cost



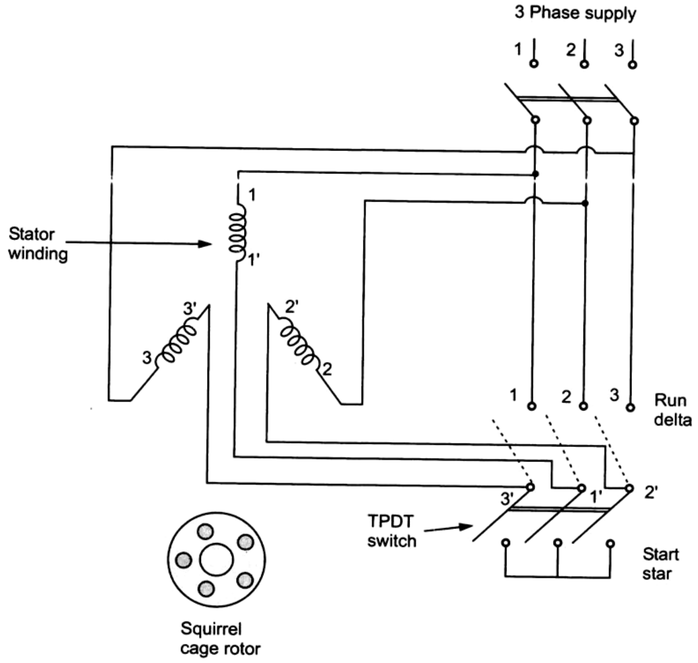
Autotransformer Starter:

- The operation principle of auto transformer method is similar to the star delta starter method
- The starting current is limited by (using a three phase auto transformer) reduce the initial stator applied voltage
- The auto transformer starter is more expensive, more complicated in operation and bulkier in construction when compared with the star – delta starter method
- The starting current and torque can be adjusted to a desired value by taking the correct tapping from the auto transformer



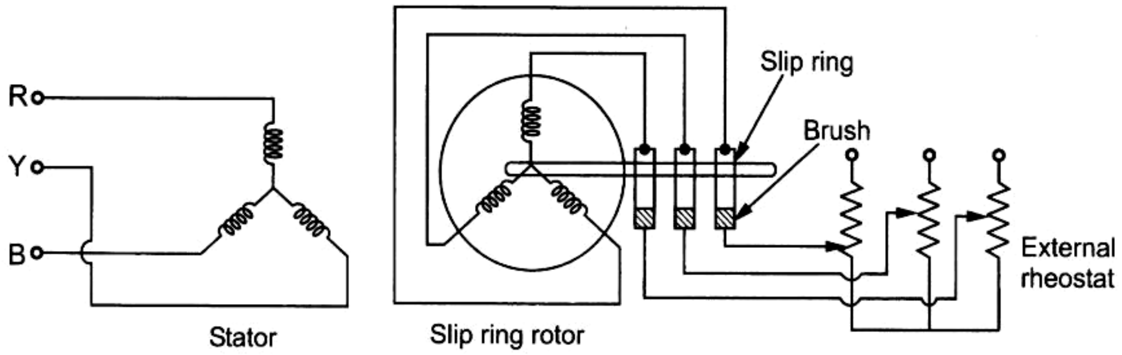
Star – Delta Starter:

- The star delta starting is a very common type of starter and extensively used, compared to the other types of the starters
- This method uses reduced supply voltage at starting time.
- Figure shows the connection of a 3phase induction motor with a star –delta starter
- The method achieved low starting current by first connecting the stator winding in star configuration
- At the time of starting when the stator windings are start connected, each stator phase gets phase voltage.
- As the voltage is reduced, the starting current also reduced
- After the motor reaches a certain speed, throw switch changes the winding arrangements from star to delta configuration
- Since the torque developed by an induction motor is proportional to the square of the applied voltage, star- delta starting reduced the starting torque to one – third that obtainable by direct delta starting



Rotor Resistance Starter:

- This method allows external resistance to be connected to the rotor through slip rings and brushes
- Initially, the rotor resistance is set to maximum and is then gradually decreased as the motor speed increases, until it becomes zero
- The rotor resistance starting mechanism is usually very bulky and expensive when compared with other methods
- It also has very high maintenance costs
- Also, a considerable amount of heat is generated through the resistors when current runs through them
- The starting frequency is also limited in this method
- However, the rotor resistance method allows the motor to be started while on load

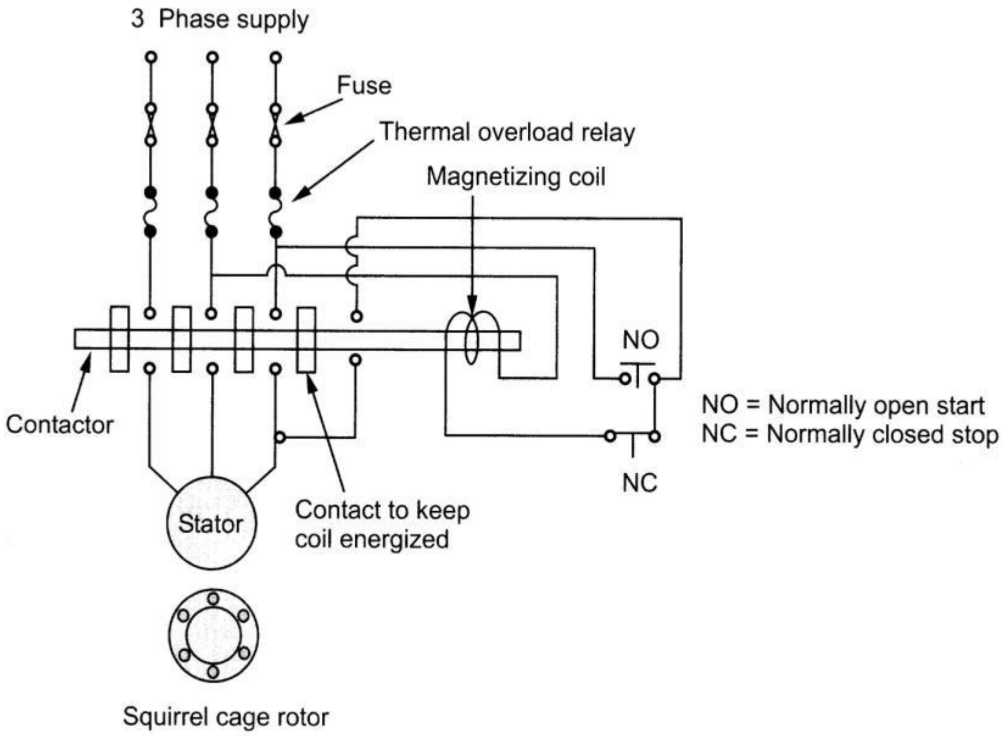


Direct On Line Starter:

- The Direct On-Line (DOL) starter is the simplest and the most inexpensive of all starting methods and is usually used for squirrel cage induction motors
- It directly connects the contacts of the motor to the full supply voltage
- The starting current is very large, normally 6 to 8 times the rated current
- The starting torque is likely to be 0.75 to 2 times the full load torque
- In order to avoid excessive voltage drops in the supply line due to high starting currents, the DOL starter is used only for motors with a rating of less than 5KW
- There are safety mechanisms inside the DOL starter which provides protection to the motor as well as the operator of the motor

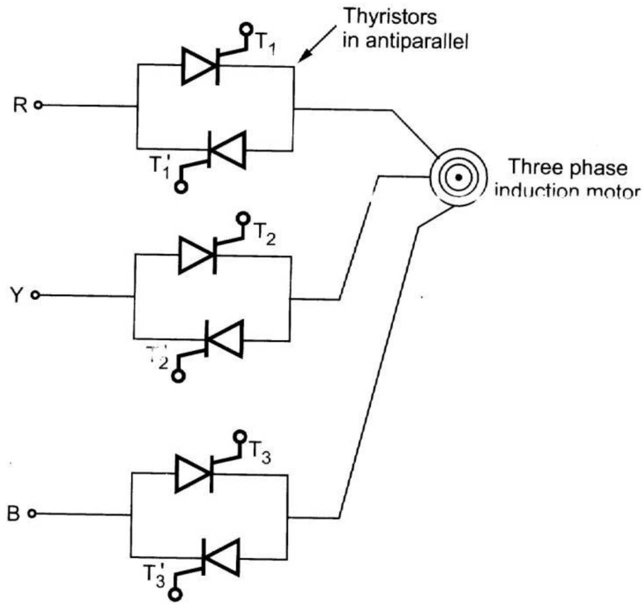
Operation:

- The DOL starter consists of a coil operated contactors controlled by start and stop push buttons
- On pressing the start push button NO, the contactor coil is energized from line
- The three mains contacts and an auxiliary contact are closed
- The motor is thus connected to the supply
- When the stop push button NC is pressed, the supply through the contactor is Disconnected
- Since the coil is de-energized, the main contacts are opened. The supply to motor is disconnected and the motor stops



ELECTRONIC STARTER – IM (Soft Starter)

- The thyristor voltage control method is used in the soft starter
- Resistors are not used in soft starter to reduce the starting current
- The thyristors T_1, T_1'', T_2, T_2'' and T_3, T_3'' are used in the soft starter
- Two thyristors are connected in antiparallel in each line
- Now the antiparallel connection acts as triac
- To control the voltage, the firing angle of triac is controlled
- The voltage and the current are directly proportional
- When the voltage reduces, the current reduces and vice versa
- The starting current is controlled by controlling the starting voltage



UNIT – III

STARTING METHODS

1) **Mention the Starters used to start an Induction motor. NOV/DEC 2009**
   - D.O.L Starter (Direct Online Starter) Star-Delta Starter
   - Auto Transformer Starter
   - Reactance or Resistance starter
   - Stator Rotor Starter (Rotor Resistance Starter)
2) **What are the protective devices in a DC/AC motor Starter? NOV/DEC 2016**
   - Over load Release (O.L.R) or No volt coil
   - Hold on Coil
   - Thermal Relays
   - Fuses
   - Over load relay
3) **Is it possible to include/ Exclude external resistance in the rotor of a Squirrel cage induction motor?. Justify**

   No it is not possible to include/ Exclude external resistance in the rotor of a Squirrel cage induction motor because, the rotors bars are permanently short circuited by means of circuiting rings (end rings) at both the ends. i.e. no slip rings to do so.
4) **Give the prime purpose of a starter for motors. NOV/DEC 2012, NOV/DEC 2015, NOV/DEC 2016**

   when induction motor is switched on to the supply, it takes about 5 to 8 times full load current at starting. This starting current may be of such a magnitude as to cause objectionable voltage drop in the lines. So Starters are necessary
5) **How reduced voltage starting of Induction motor is achieved? APRIL/MAY 2010**
   - D.O.L Starter (Direct Online Starter)
   - Star-Delta Starter
   - Auto Transformer Starter
   - Reactance or Resistance starter
6) **Give some advantages and disadvantages of D.O.L starter.**

   Advantages:
   - Highest starting torque
   - Low cost
   - Greatest simplicity

   Disadvantages:
   - The inrush current of large motors may cause excessive voltage drop in the weak power system The torque may be limited to protect certain types of loads.
7) **What is the function of no-voltage release coil in d.c. motor starter?**

   As long as the supply voltage is on healthy condition the current through the NVR coil produce enough magnetic force of attraction and retain the starter handle in ON position against spring force. When the supply voltage fails or becomes lower than a prescribed value then electromagnet may not have enough force to retain so handle will come back to OFF position due to spring force automatically.
8) **Define critical field resistance of dc shunt generator?**

   Critical field resistance is defined as the resistance of the field circuit which will cause the shunt generator just to build up its emf at a specified field.
9) **On what occasion dc generator may not have residual flux?**

The generator may be put for its operation after its construction, in previous operation, the generator would have been fully demagnetized.

10) **What is the Necessity of starter? NOV/DEC 2014**

Both d.c motors as well as three phase induction motors are self starting but these motors show the tendency to draw very high current at the time of starting. Such a current is very high and can cause demage to the motor windings. Hence there is a need of a certain device which can limit such a high stating current. Such a device which limits the high starting current is called a starter.

11) **What are the disadvantages of three point starter? NOV/DEC 2009, APRIL/MAY 2010, NOV/DEC2015**

Here NVC and the field winding are in series. so while controlling the speed of the motor above rated, field current is reduced by adding an extra resistance in series with the field winding. To avoid the dependency of NVC and the field winding, four point starter is used in which NVC and the field winding are connected in parallel.

12) **What is automatic starter? NOV/DEC 2013, NOV/DEC 2014**

Upon pressing ON-push button (start button), current limiting stating resistors get connected in series with armature circuit in DC motor. Then, some form of automatic control progressively disconnects these resistors until full-line voltage is available to the armature circuit. On pressing an OFF push button the system should get back to its original position.

13) **What are the advantages of Electronic starter?**

The moving parts and contacts get completely eliminated.

- The arcing problem gets eliminated.
- Minimum maintenance is required as there are no moving parts.
- The operation is reliable
- Starting time also gets reduced.

<u>PART – B</u>

1) ***Draw a neat schematic diagram of a three point starter and explain its working. NOV/DEC 2012, NOV/DEC 2015, NOV/DEC 2016***
2) Draw a neat schematic diagram of a four point starter and explain its working. APRIL/MAY 2010
3) ***Explain with neat circuit diagram, the star-delta starter method of starting squirrel cage induction motor.NOV/DEC 2012, NOV/DEC 2014, NOV/DEC 2016***
4) ***Explain the typical control circuits for DC Series and Shunt motors. NOV/DEC 2009***
5) Explain with neat diagram the starting of three phase slip ring induction motor. NOV/DEC 2009, NOV/DEC 2013, NOV/DEC 2014, NOV/DEC 2015
6) Draw and explain the manual auto-transformer starter for three phase induction motor. NOV/DEC 2016

UNIT IV
SPEED CONTROL OF DC DRIVES

<u>SPEED CONTROL OF DC MOTORS</u>

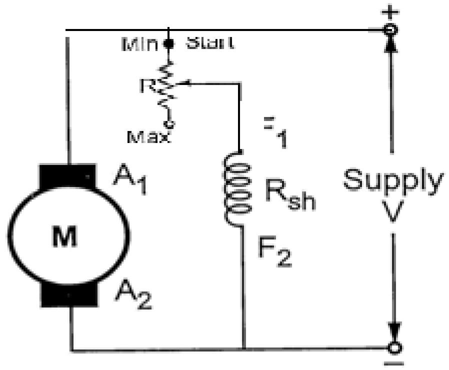
- **Speed Control of Shunt Motor**
  - * Flux Control
  - * Armature Voltage Control (Rheostatic Control)
  - * Applied Voltage Control
- **Speed Control of Series Motor**
  - * Flux Control
  - * Rheostatic Control
  - * Applied Voltage Control
- **Ward- Leonard System of Speed Control**

1. <u>Speed Control of Dc Shunt Motor:</u>

➢ **Flux Control**

$$N \alpha \frac{E_b}{\varphi}; \qquad N \alpha \frac{V - I_a R_a}{\varphi}$$

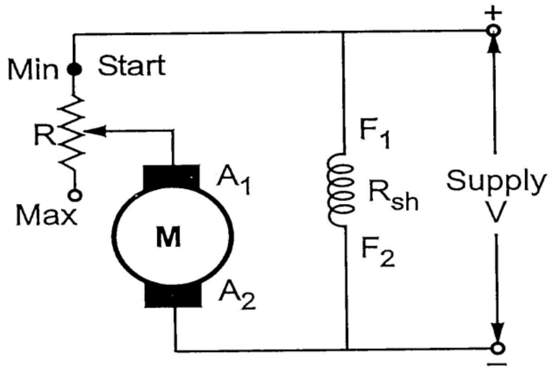
- Speed of the motor is inversely proportional to flux
- The speed can be controlled by varying flux
- To vary the flux, a rheostat is added in series with the field winding
- Adding more resistance in series with field winding will increase the speed, as it will decrease the flux
- Field current is relatively small and hence I^2R loss is small
- This method is quiet efficient



➢ **Armature Voltage Control**

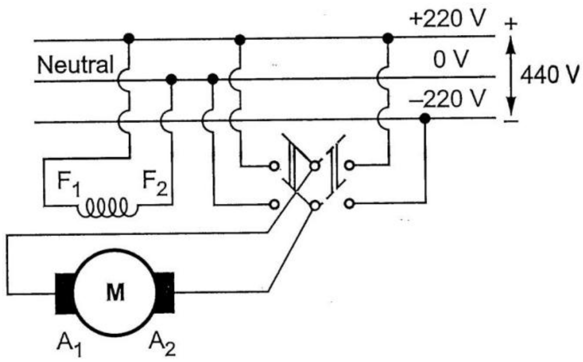
- Speed of the motor is directly proportional to the armature voltage
- When armature voltage varies, the armature current varies
- Speed is directly proportional to armature current I_a
- If we add resistance in series with armature, I_a decreases and hence speed decreases.
- The speed can be reduced by using this method.

- The speed can be reduced by using this method.



➢ **Applied Voltage Control:**

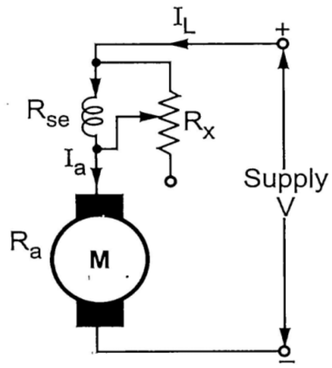
- The speed is approximately proportional to the voltage across the armature.
- Voltage across armature is changed with the help of a suitable switchgear
- Armature is supplied with different voltages to get varies speed
- The shunt filed is connected to a fixed exciting voltage



2. Speed Control of Series Motor:

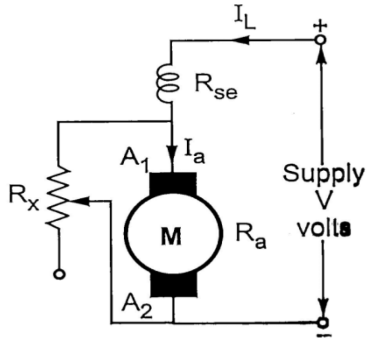
➢ Field Diverter Method:

- A veritable resistance is connected parallel to the series field
- This variable resistor is called as diverter
- The desired amount of current can be diverted through this resistor and hence current through field coil can be decreased
- The flux can be decreased to desired amount and speed can be increased



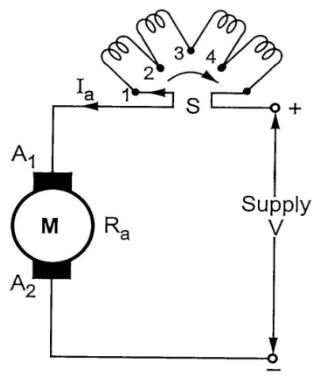
➢ Armature Diverter Method:

- The diverter is connected across the armature
- The desired amount of armature current can be diverted through this resistor and hence current through field coil and armature can be varied
- The flux is varied and speed can be increased



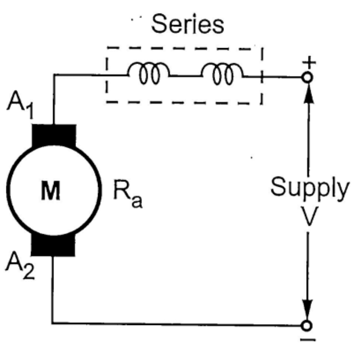
➢ Tapped Field Method:

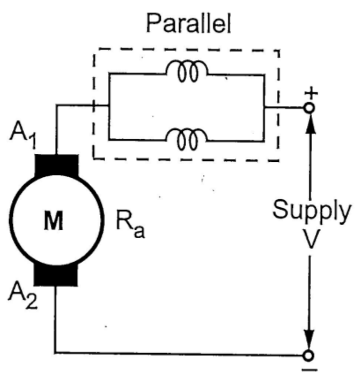
- The field coil is tapped
- The number of turns can be changed and hence the flux can be changed
- We can select different value of Ø by selecting different number of turns.
- The speed inversely proportional to flux Ø



➢ Series – Parallel Connection of Field:

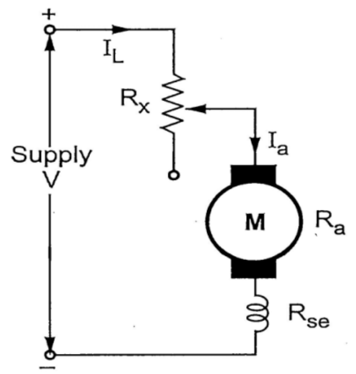
- This system is widely used in electric traction
- In this method, several speeds can be obtained by regrouping coils in parallel and series
- When the coils are in series, the same current passing through them and flux increases
- When the coils are in parallel, the current gets divided and flux reduces





➢ **Rheostatic Control**

- By introducing resistance in series with armature, voltage across the armature can be reduced.
- And hence, speed reduces in proportion with it.



➢ **Applied Voltage Control**

- The speed is approximately proportional to the voltage across the armature and field winding
- Voltage across the armature and field is changed with the help of a Dc motor generator set
- Armature and field is supplied with different voltages to get varies speed
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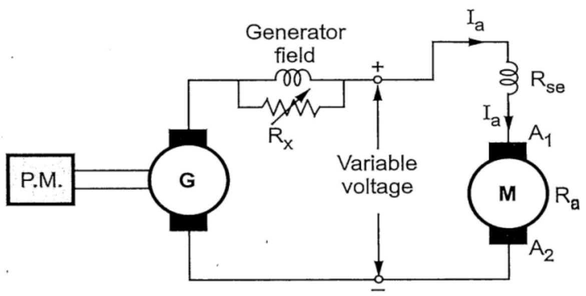
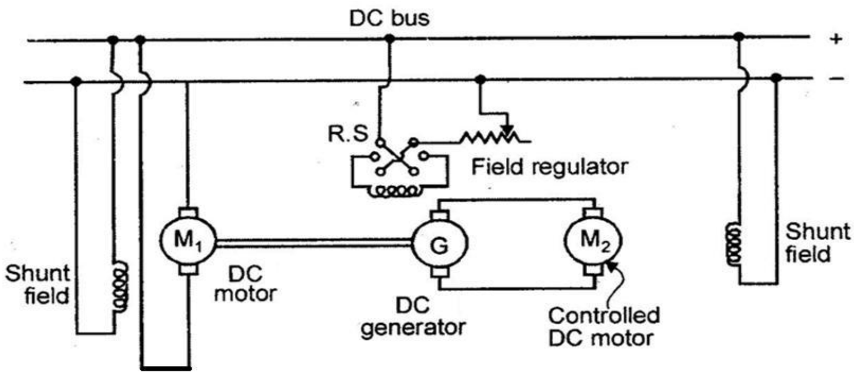
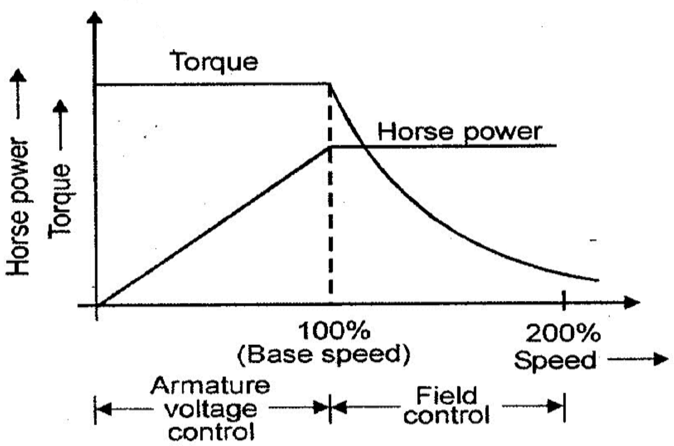


Ward-Leonard control system

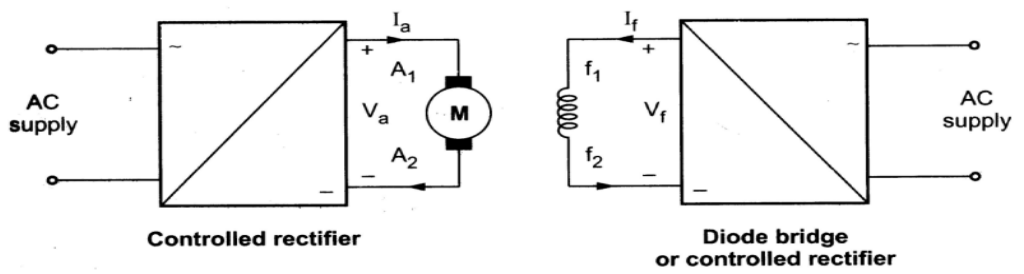




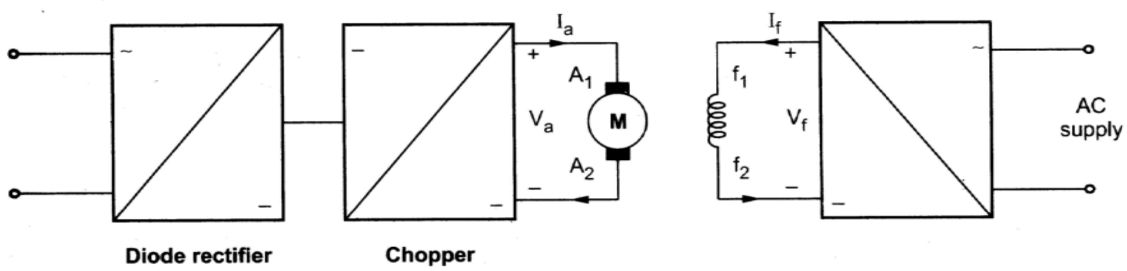
* This system is used where very sensitive speed control of motor is required (e.g electric excavators, elevators etc.)
* M_2 is the motor whose speed control is required
* M_1 may be any AC motor or DC motor with constant speed
* M_1 acts as prime mover to DC generator
* G is the generator directly coupled to M_1
* The output from the generator G is fed to the armature of the motor M_2 whose speed is to be controlled
* The output voltage of the generator G can be varied from zero to its maximum value, and hence the armature voltage of the motor M_2 is varied very smoothly
* Very smooth speed control of motor can be obtained by this method.

SPEED CONTROL DC MOTOR – USING CONVERTERS

- Direct current (dc) motors have variable characteristics and are used extensively in variable-speed drives.
- DC motors can provide a high starting torque and it is also possible to obtain speed control over a wide range.
- The methods of speed control are normally simpler and less expensive than those of AC drives.
- DC motors play a significant role in modern industrial drives.
- Both series and separately excited DC motors are normally used in variable-speed drives, but series motors are traditionally employed for traction applications.
- Due to commutator, DC motors are not suitable for very high speed applications and require more maintenance than do AC motors.
- With the recent advancements in power conversions, control techniques, and microcomputers, the ac motor drives are becoming increasingly competitive with DC motor drives.
- • Although the future trend is toward AC drives, DC drives are currently used in many industries. It might be a few decades before the DC drives are completely replaced by AC drives.



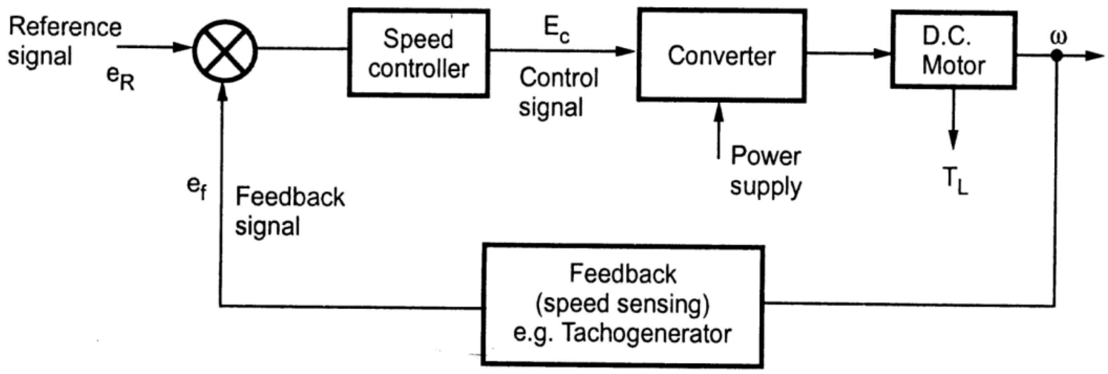
Controlled rectifier supplied d.c. drive



Chopper fed d.c. drive

CLOSED LOOP CONTROL OF DC DRIVES:

- The speed of dc motors changes with the load torque.
- To maintain a constant speed, the armature (and or field) voltage should be varied continuously by varying the delay angle of ac-dc converters or duty cycle of dc-dc converters.
- In practical drive systems it is required to operate the drive at a constant torque or constant power; in addition, controlled acceleration and deceleration are required.
- Most industrial drives operate as closed-loop feedback systems.
- A closed-loop control system has the advantages of improved accuracy, fast dynamic response, and reduced effects of load disturbances and system nonlinearities.
- The block diagram of a closed-loop converter-fed separately excited dc drive is shown in Figure
- If the speed of the motor decreases due to the application of additional load torque, the speed error V_e increases.
- The speed controller responses with an increased control signal V_C, change the delay angle or duty cycle of the converter, and increase the armature voltage of the motor.
- An increased armature voltage develops more torque to restore the motor speed to the original value.
- The drive normally passes through a transient period until the developed torque is equal to the load torque.



DRIVES CLASSIFICATION:

- Single phase drives
- Three phase drives
- Chopper drives

- The speed, which corresponds to the rated armature voltage, rated field current and rated armature current, is known as the **rated speed**

TYPES of Single Phase Drives:

- Single phase half wave converter drive
- Single phase semi converter drive
- Single phase full converter drive
- Single phase dual converter drive

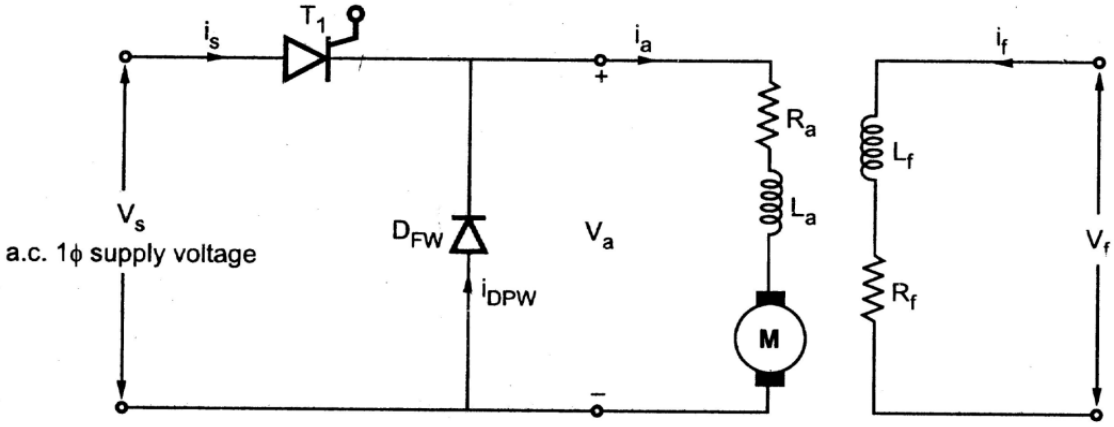
Single Phase Half Wave Converter Drive:

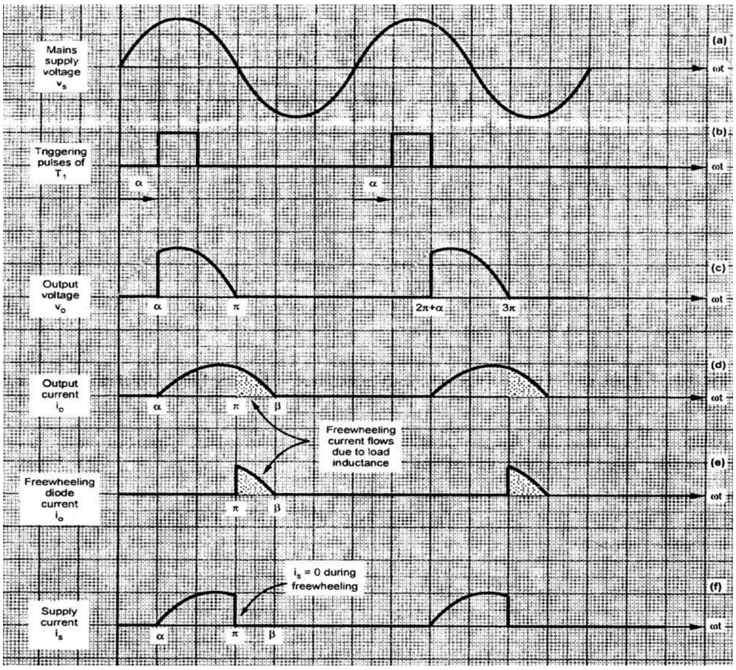
- A single-phase half-wave converter feeds a dc motor, as shown below.
- The armature current is normally discontinuous unless a very large inductor is connected in the armature circuit.
- A freewheeling diode is always required for a dc motor load and it is a one-quadrant drive.
- The applications of this drive are limited to the 0.5 kW power level.
- Figure shows the waveforms for a highly inductive load.
- A half-wave converter in the field circuit would increase the magnetic losses of the motor due to

high ripple content on the field excitation current.

- The voltage across the armature $V_{DC} = \frac{V_m}{\pi}\int_0^{\pi} \sin\omega t \, dt = \frac{V_m}{\pi}$
- The armature current $I_{DC} = \frac{I_m}{\pi}\int_0^{\pi} \sin\omega t \, dt = \frac{I_m}{\pi}$

V_a – Armature voltage; V_m – Maximum voltage; I_m – Maximum current



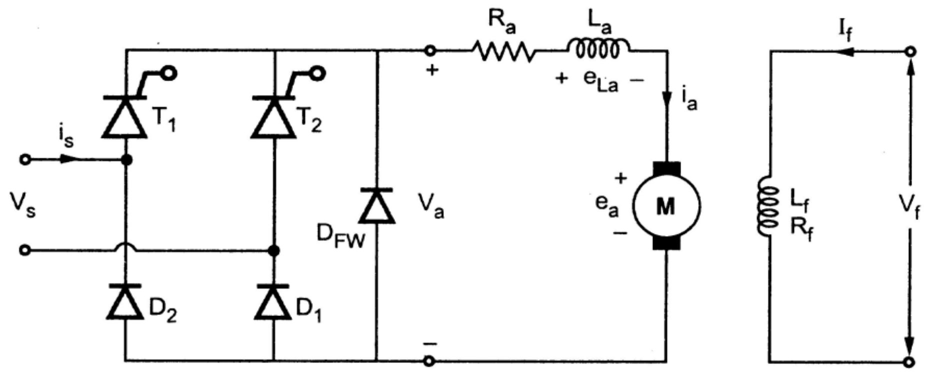


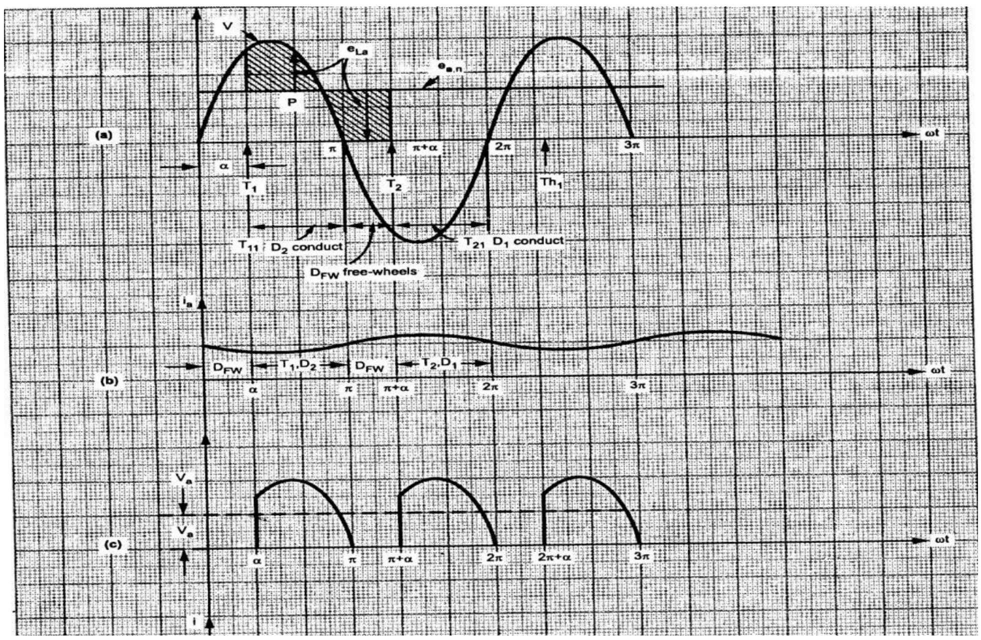
Single Phase Semi Converter Drive:

- It is one quadrant converter which gives current and voltage of one polarity
- Regenerative braking is not possible
- When T_1 and D_1 conducts, the positive cycle of input is transferred to armature of the motor
- When T_2 and D_2 conducts, the negative cycle of input is transferred to armature of the motor but the direction is the same
- Freewheeling diode is used to get continuous current flow through the armature winding.
- When thyristors off, the stored energy in the coil is discharging through diode.
- The voltage across the armature $V_{DC} = \frac{V_m}{\pi}\int_0^{\pi} \sin\omega t \, dt = \frac{V_m}{\pi}$

- The armature current $I_{DC} = \frac{I_m}{\pi}\int_0^{\pi}\sin\omega t \, dt = \frac{I_m}{\pi}$

V_a – Armature voltage; V_m – Maximum voltage; I_m – Maximum current

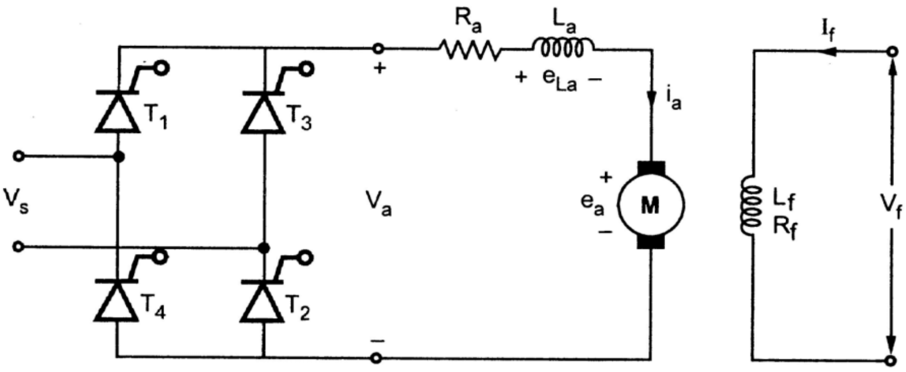


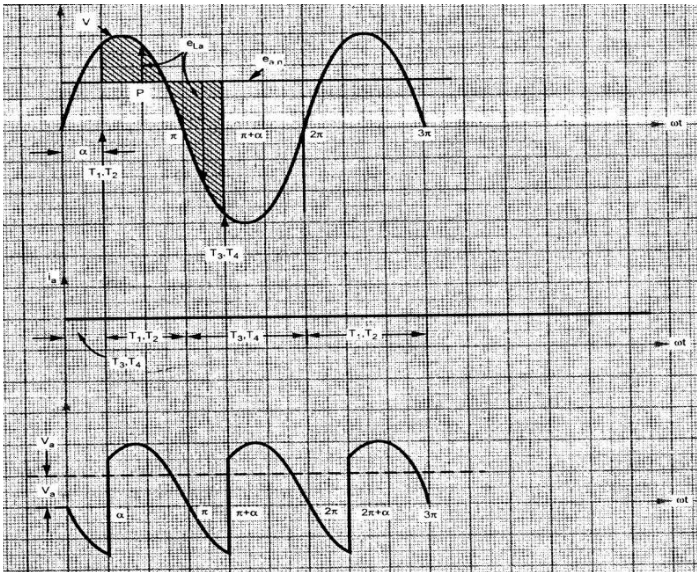


Single Phase Full Converter Drive:

- The armature voltage is varied by a single-phase full-wave converter, as shown in Figure
- It is a two-quadrant drive, as shown in Figure, and is limited to applications up to 15 kW.
- The armature converter gives + V_a or - V_a, and allows operation in the first and fourth quadrants.
- During regeneration for reversing the direction of power flow, the back emf of the motor can be reversed by reversing the field excitation.
- The converter in the field circuit could be a full, or even a dual converter.
- The reversal of the armature or field allows operation in the second and third quadrants.
- The current waveforms for a highly inductive load are shown in Figure for powering action.
- Freewheeling diode is not necessary
- The voltage across the armature $V_{DC} = \frac{V_m}{\pi}\int_0^{2\pi}\sin\omega t \, dt = \frac{2V_m}{\pi}$
- The armature current $I_{DC} = \frac{I_m}{\pi}\int_0^{2\pi}\sin\omega t \, dt = \frac{2I_m}{\pi}$

V_a – Armature voltage; V_m – Maximum voltage; I_m – Maximum current





THREE PHASE DRIVES

TYPES:

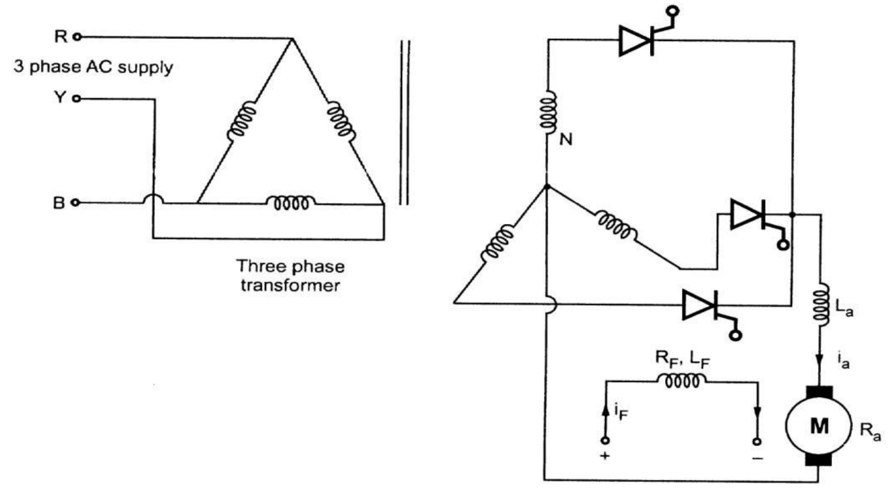
- Three phase Half converter drive
- Three Phase semi converter drive
- Three Phase full converter drive
- Three phase dual converter drive

Three Phase Half Converter Drive:

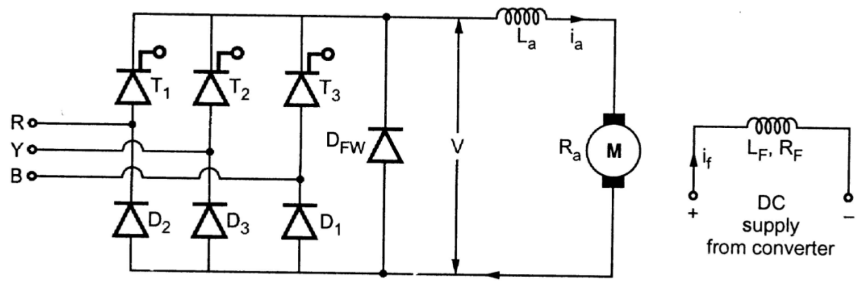
- Three **single phase half-wave converters** are connected together to form a **three phase half-wave converter**
- The thyristor T_1 in series with one of the supply phase windings *'a-n'* acts as one half wave controlled rectifier
- The second thyristor T_2 in series with the supply phase winding *'b-n'* acts as the second half wave controlled rectifier
- The third thyristor T_3 in series with the supply phase winding acts as the third half wave controlled rectifier
- The 3-phase input supply is applied through the star connected supply transformer as shown in the figure
- The common neutral point of the supply is connected to one end of the load while the other end of the load connected to the common cathode point.
- When the thyristor T_1 is triggered, the phase voltage V_{an} appears across the load when T_1 conducts
- The load current flows through the supply phase winding *'a-n'*and through thyristor T_1 as long as T_1 conducts
- When thyristor T_2 is triggered, T_1 becomes reverse biased and turns-off. The load current flows through the thyristor and through the supply phase winding *'b-n'* . When T_2conducts

the phase voltage v_{bn} appears across the load until the thyristor T3 is triggered

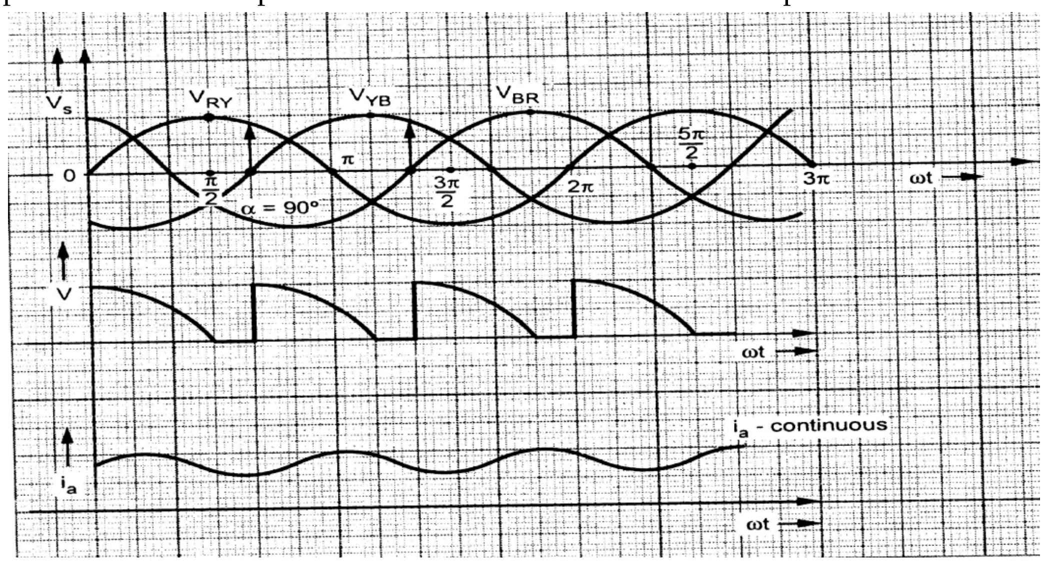
- When the thyristor T3 is triggered, T2 is reversed biased and hence T2 turns-off. The phase voltage V_{an} appears across the load when T3 conducts



Three Phase Semi Converter Drive:

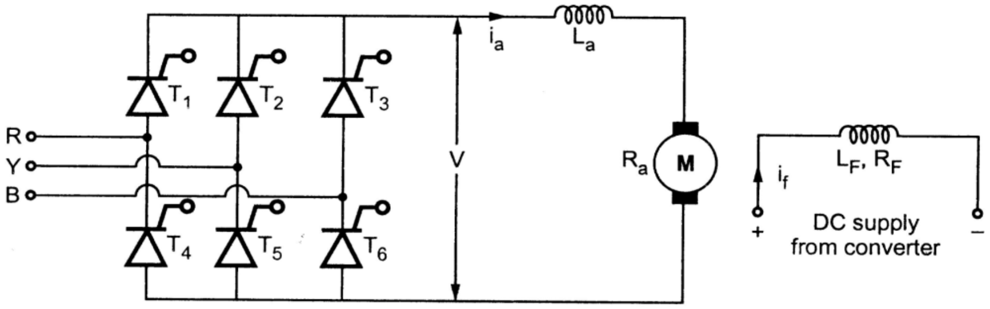


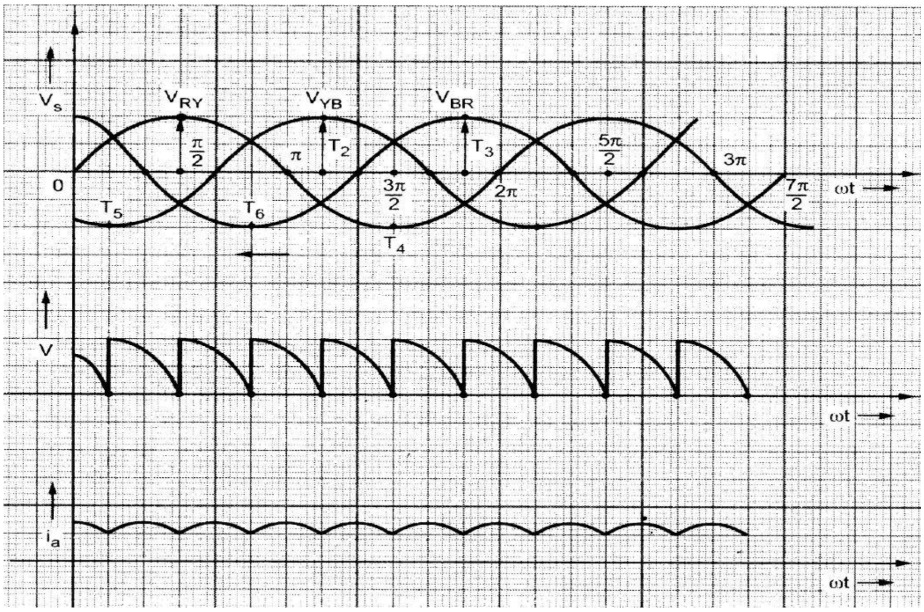
- 3-phase semi-converters are three phase half controlled bridge controlled rectifiers
- which employ three thyristors and three diodes connected in the form of a bridge configuration
- Three thyristors are controlled switches which are turned on at appropriate times by applying appropriate gating signals
- The three diodes conduct when they are forward biased by the corresponding phase supply voltages
- 3-phase semi-converters are used in industrial power applications up to about 120kW output power level
- The power factor of 3-phase semi-converter decreases as the trigger angle increases
- The power factor of a 3-phase semi-converter is better than three phase half wave converter



Three Phase Full Converter Drive:

- A three-phase full-wave-converter drive is a two-quadrant drive without any field reversal, and is limited to applications up to 1500 kW.
- During regeneration for reversing the direction of power
- However, the back emf of the motor is reversed by reversing the field excitation.
- The converter in the field circuit should be a single- or three-phase full converter.
- Two three-phase full-wave converters are connected in an arrangement similar to Figure
- Either converter 1 operates to supply a positive armature voltage, V_a or converter 2 operates to supply a negative armature voltage, $-V_a$.
- It is a four-quadrant drive and is limited to applications up to 1500 kW.
- The field converter can be a full-wave converter.





➢ **CHOPPER DC MOTOR CONTROL.....**

➢ **Multi quadrant (or) four quadrant operation .....**

Please refere book and class note book

UNIT – IV

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

1) **What are the ways of speed control in dc motors? NOV/DEC 2014, NOV/DEC 2016**
   - Field control - by varying the flux per pole. -for above rated speed
   - Armature control- by varying the terminal voltage -for below rated speed
2) **Give the Limitation of field control NOV/DEC 2012**
   - Speed lower than the rated speed cannot be obtained.
   - It can cope with constant kW drives only.
   - This control is not suitable to application needing speed reversal.
3) **What are the main applications of Ward-Leonard system?**
   - It is used for colliery winders.
   - Electric excavators
   - In elevators
   - Main drives in steel mills and blooming and paper mills.
4) **What are the advantages of field control method? NOV/DEC 2015**
   - More economical, more efficient and convenient.
   - It can give speeds above normal speed.
5) **What is the effect of inserting resistance in the field circuit of a dc shunt motor on its speed and torque?**

   For a constant supply voltage, flux will decrease, speed will increase and torque will increase.

6) **State the advantages of dc chopper drive. APRIL/MAY 2010, NOV/DEC 2015**
   - Dc chopper drive s has the advantages of High efficiency
   - Flexibility in control
   - Light weight
   - Small size
   - Quick response
7) **State the types of controlled rectifier Dc drives NOV/DEC 2016**
   - Single phase controlled rectifier DC drives
     (a)Half wave controlled rectifier Dc drives
     (b)Half controlled rectifier DC drives
     (c)Full controlled rectifier DC drives
   - Three phase controlled rectifier fed DC drives
8) **How can speed be controlled in a DC shunt motor? NOV/DEC 2013**

   The DC shunt motor speed controlled by
   - Armature voltage control (below rated speed)
   - Flux control method (above rated speed)
9) **State control strategies of choppers NOV/DEC 2012**
   - Time ratio control
   - Current limit control
10) **What is meant by V/F control? NOV/DEC 2012, NOV/DEC 2013**

    When the frequency is reduced the input voltage must be reduced proportionally so as to maintain constant flux. Otherwise the core will get saturated resulting in excessive iron loss and magnetizing current. This type of induction motor behavior is similar to the working of dc series motors.
11) **What is static Ward – Leonard drive? NOV/DEC 2009**

Controlled rectifiers are used to get variable dc voltage from an ac source of fixed voltage. Controlled rectifiers fed dc drives are known as "static Ward – Leonard drive".

12) **What is meant by armature control? NOV/DEC 2016**

The armature having controller resistance in series during the speed control by varying the controller resistance R, the potential drop across the armature is varied. Hence the speed of the motor also varied. This method of speed control is applicable for speed less than no load speed.

13) **What is Slip-Power recovery system? NOV/DEC 2009, APRIL/MAY 2010**

The slip power can be recovered to the supply source can be used to supply an additional motor which is mechanically coupled to the main motor. This type of drive is known as slip-power recovery system

PART –B

1) ***Discuss the Ward-Leonard speed control system with a neat circuit diagram. Also mention its advantages and disadvantages. NOV/DEC 2012, NOV/DEC 2014, NOV/DEC 2015, NOV/DEC 2016***
2) Explain how the speed of a DC Shunt Motor can be varied both above and below the rated speed at which it runs with full field current. APRIL/MAY 2010
3) Explain the speed control schemes of DC Series Motor. NOV/DEC 2009, APRIL/MAY 2010
4) ***Explain the single phase half wave converter drive speed control for DC drive with waveforms.***
5) ***Explain with neat sketch the chopper control method of speed control of DC motors. APRIL/MAY 2010, NOV/DEC 2012, NOV/DEC 2013, NOV/DEC 2015, NOV/DEC 2016***
6) ***Explain with neat sketches about the DC Shunt Motor speed control by using single phase fully controlled bridge converter NOV/DEC 2009, NOV/DEC 2013, NOV/DEC 2014***

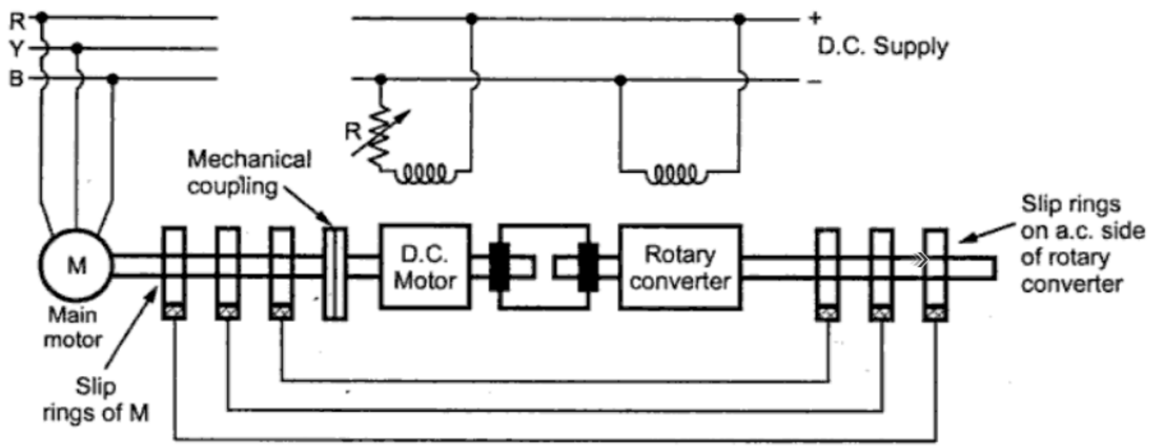
UNIT V

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

Slip power recovery scheme:

* The slip power recovery (SPR) drive is an external system connected to the rotor circuit in place of the external resistors.
* The SPR provides speed and torque control like the resistors but can also recover the power taken off the rotor and feed it back into the power system to avoid energy waste.
* The speed control of slip ring induction motor is achieved by Injecting E.M.F in Rotor Circuit
* The e.m.f injected in the rotor circuit must have the same frequency as the slip frequency
* When the injected voltage is in phase opposition with the induced rotor e.m.f, then the rotor resistance increases
* when the injected voltage is in phase with the induced rotor e.m.f, then the rotor resistance decreases
* By changing the direction of phase rotation, the resistance of the rotor circuit is varied and thus speed of the slip ring motor is controlled.

Conventional Kramer System:



* This system is basically used for the speed control of slipring Induction motor, rating more than 4000kW
* The main motor M is slipring Induction motor.
* The induced e.m.f is supplied to the slip rings of a rotary converter by slip rings of main motor.
* The rotary converter converts the low-slip frequency a.c. power into d.c. powe,r which is used to drive a d.c. shunt motor
* The main motor "M" is directly coupled with the d.c. shunt motor.
* The d.c. output of the rotary converter is used to drive the d.c. shunt motor
* Both the rotary converter and the d.c. shunt motor are excited from a separate d.c exciter or d.c bus bar.
* The field regulator governs the back e.m.f E_b of the d.c. shunt motor
* The d.c. potential at the commutator of the rotary converter which controls the slip ring voltage and thus the speed of motor "M."

Advantages

* Has good reliability

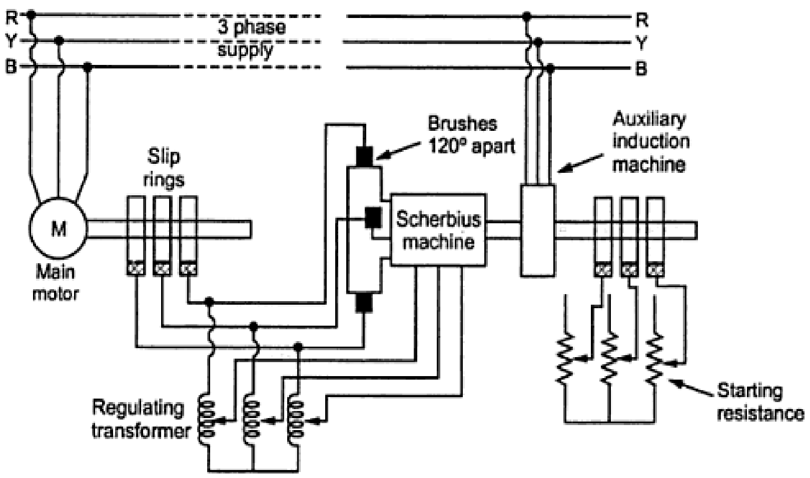
Disadvantages

* Efficiency is low

* High cost
* Need more maintenance

Conventional Scherbius System:

* In this system, the slip energy is not converted into d.c and then fed to a d.c. motor
* It is fed directly to a three phase or six phase a.c. commutator motor called as Scherbius machine.
* The low frequency output of the machine M is fed to the poly phase winding of the machine C through a regulating transformer RT.
* The commutator motor C is a variable speed machine and is controlled by the tapping on RT.



Advantages:

- Better efficiency than earlier methods
- Speed regulation is independent of load conditions
- It can be controlled manually by operator

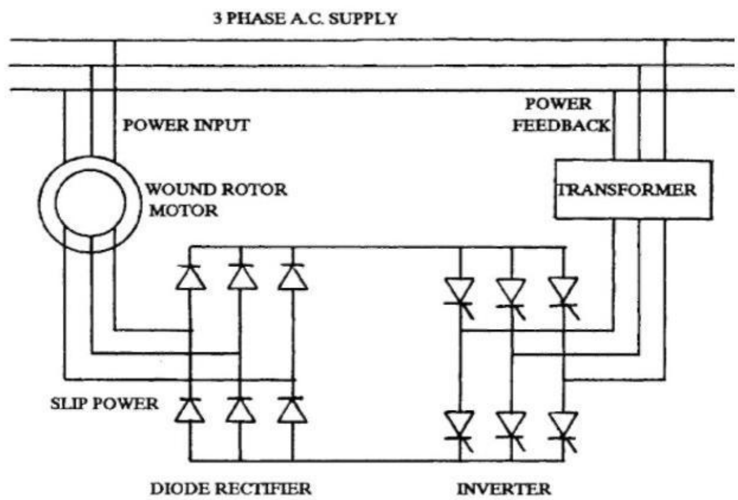
Disadvantages:

- Complex, Extra induction motor is needed
- Huge size, costly
- Require well-trained staff
- Can not adjust speed at no-load condition.

➢ **<u>Two types of converter provide this approach:</u>**

1. **Static Kramer Drive** - only allows operation at **sub-synchronous speed**.
2. **Static Scherbius Drive** – allows operation **above** and **below synchronous speed.**

Static Kramer System:



Rectifier

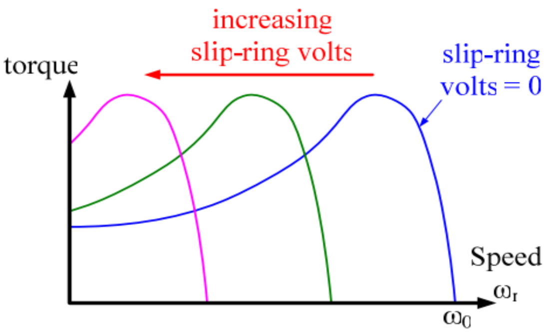
- Three phase bridge rectifier has used.
- Diodes have used to design rectifier.
- Output is uncontrolled DC.

Inverter

- Three phase bridge inverter has used.
- Thyristors have used to design rectifier.
- Output is controlled AC.

- It uses a **step-up transformer** to increase the voltage level.
- The frequency of the rotor current $f_r = sf_s$
- Rotor frequency set by speed of rotation
  f_s = stator frequency   s = slip
- Diode rectifier accepts any frequency
- The rotor current is rectified in a diode bridge, and then converted to 3-phase, 50 Hz by a line commutated inverter
- The magnitude of the voltage at the slip-rings is set by the rectifier-inverter link, and controlled by the delay angle α of the line-commutated inverter.

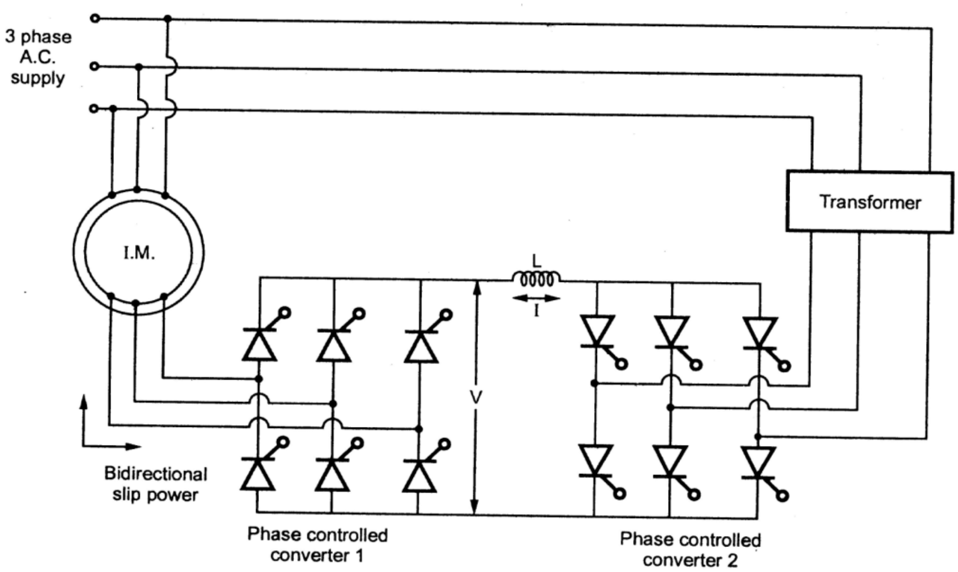
$$V_{dc} = \frac{3}{\pi}.\sqrt{2}.V_{rms}.\cos\alpha$$



Advantages

- Efficiency is high
- Instead of wasting the slip power in the rotor circuit resistance, a better approach is to convert it to ac line power and return it back to the line.

<u>Static Scherbius System:</u>



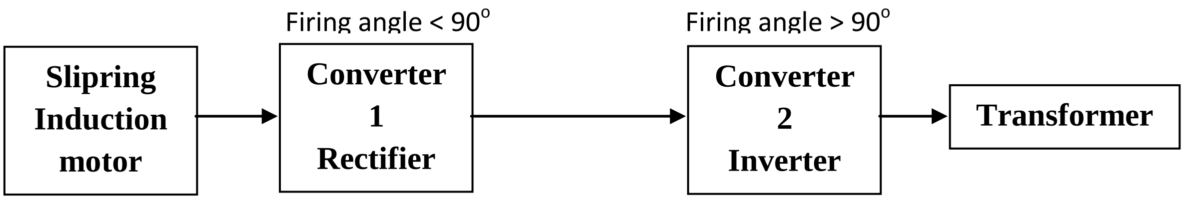
Rectifier

- ∗ Three phase bridge rectifier has used.
- ∗ Thyristors have used to design rectifier.
- ∗ Output is controlled DC.

Inverter

- ∗ Three phase bridge inverter has used.
- ∗ Thyristors have used to design rectifier.
- ∗ Output is controlled AC.

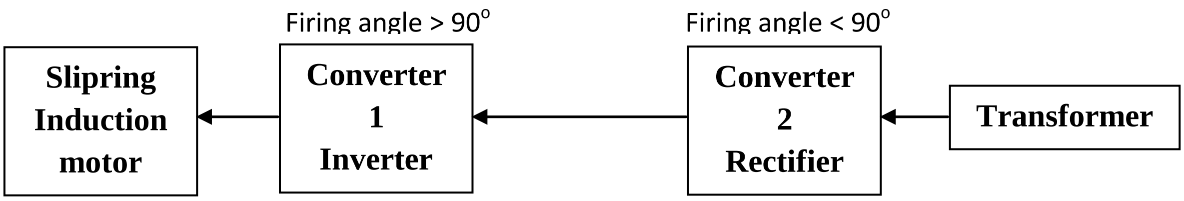
➢ **Sub synchronous speed** (below Synchronous speed)



Power flow ➔ *Slipring induction motor to Transformer*

➢ **Super synchronous speed** (ablove Synchronous speed)

Also called as ***Slip Power injection method***



Power flow ➔ *Transformer to Slipring induction motor*

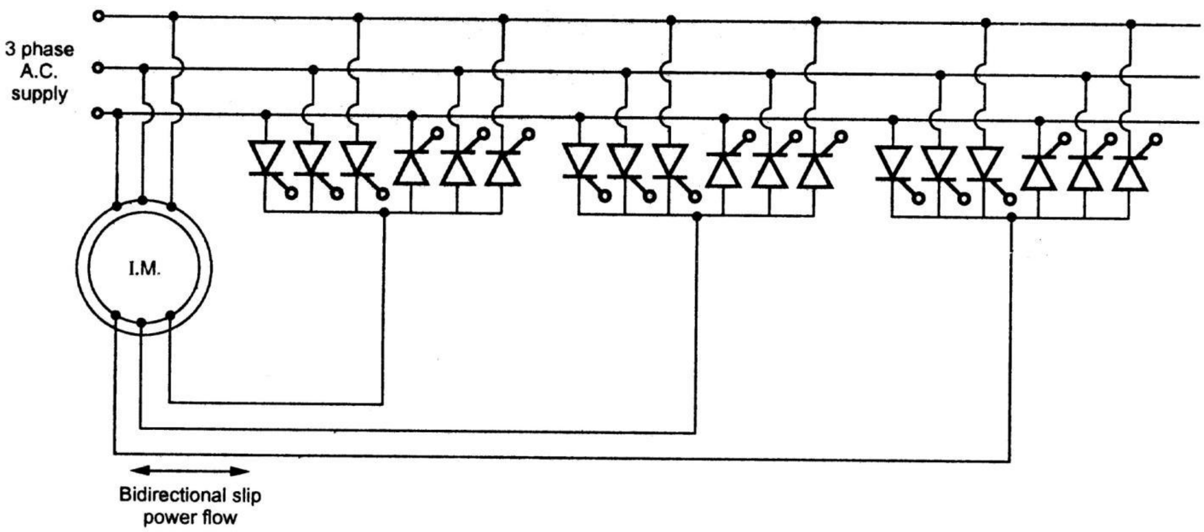
NOTE:

- ∗ **Both bridge circuits able to act as RECTIFIER and INVERTER with respect to firing angle.**

Prevention or limitation

- ∗ **Do not keep same firing angle for both converters.**
- ➢ A line commutated cycloconverter can overcome this limitation but adds substantial cost and complexity to the drive.

Cycloconverter Scherbius System:



Cycloconverters:

* Converts single-phase or three-phase ac to variable magnitude and variable frequency, single-phase or three-phase ac

SPEED CONTROL OF THREE PHASE INDUCTION MOTOR

Speed Control from Stator Side:

1. By changing the applied voltage
2. By changing the applied frequency (or) V/f Control
3. Changing the number of stator poles

Speed Control from Rotor Side:

1. Rotor rheostat control
2. Cascade operation
3. By injecting EMF in rotor circuit

For detailed theory explanation please refer class note book and text book

UNIT – V

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

1) What is firing angle?

The control of dc voltage is achieved by firing the thyristor at an adjustable angle with respect to the applied voltage. This angle is known as firing angle.

2) What is the main purpose of freewheeling diode?

Freewheeling diode is connected across the motor terminal to allow for the dissipation of energy stored in motor inductance and to provide for continuity of motor current when the thyristors are blocked.

3) What is natural or line commutation?

The commutation which occurs without any action of external force is called natural or line commutation.

4) What is forced commutation?

The commutation process which takes place by the action of an external force is called forced commutation.

5) What is a chopper?

A chopper is essentially an electronic switch that turns on the fixed-voltage dc source for a short time interval and applies the source potential to motor terminals in series of pulses.

6) What is voltage commutation?

A charged capacitor momentarily reverse-bias the conducting thyristor to turn it off. This is known as voltage commutation.

7) **What is current commutation?**

A current pulse is forced in the reverse direction through the conducting thyristor. As the net current becomes zero, the thyristor is turned OFF. This is known as current commutation.

8) What is load commutation?

The load current flowing through the thyristor either becomes zero (as in natural or line commutation employed in converters) or is transferred to another device from the conducting thyristor. This is known as load commutation.

9) What are the different means of controlling induction motor? NOV/DEC 2009, NOV/DEC 2013, NOV/DEC 2014, NOV/DEC 2015

- Stator voltage control.
- Frequency control
- Pole changing control.
- Slip power recovery control.

10) Mention the two slip-power recovery schemes. APRIL/MAY 2010, NOV/DEC 2012, NOV/DEC 2015

- Static Scherbius scheme
- Static Kramer drive scheme.

11) What are the advantages of static Kramer system over static scherbius system?

- Since a static Kramer system possesses no line commutated inverter, it causes bless reactive power and smaller harmonic contents of current than a static scherbius.

12) Compare static Kramer and scherbius system. NOV/DEC 2016

Kramer: The system consists or SRIM,diode bridge rectifier and line commutated inverter The slip power can flow in one direction This is applicable for below synchronous speed operation

Scherbius: This system consists of SRIM,two SCR bridge (or) cyclo converter The slip power can flow in both direction Applicable for both below and above synchronous speed operation

13) What are the possible methods of speed control available by using inverters? NOV/DEC 2014

- Current controlled inverter.

- Pulse width modulated (PWM) inverter control
- Variable voltage output(VVO) inverter control
- Variable voltage input(VVI) inverter control

14) What is meant by stator frequency control? NOV/DEC 2016

The three phase induction motor speed can be controlled by varying the stator frequency. The variable stator frequency can be obtained by inverters circuit.

PART – B

1) ***Explain in detail about Slip power recovery scheme. APRIL/MAY 2010, NOV/DEC 2015, NOV/DEC2016***
2) Explain with neat diagram the method of speed control of dc drives using rectifiers. NOV/DEC 2009
3) Explain the different methods of speed control used in three phase induction motors. NOV/DEC 2014
4) Draw the power circuit arrangement of three phase variable frequency inverter for the speed control of three phase induction motor and explain its working. NOV/DEC 2016
5) ***Discuss the speed control of AC motors by using three phase AC Voltage regulators.***
6) ***Explain the static Kramer method and static Scherbius method of speed control of three phase induction motor. NOV/DEC 2013***

   Explain in detail about the various methods of solid state speed control techniques by using inverters. NOV/DEC 2013