TRENDS IN ELECTRICAL & MECHANICAL ENGINEERING

MEM-101/201

UNIT – 5

(INTRODUCTION TO CONTROL SYSTEM AND A.C. MACHINES)

What do we study in Control System and A.C. Machines?

- The basics of Control System and A.C. Machines, its evolution and scope.
- The advantages & disadvantages Control System A.C. Machines.
- Industrial Applications of Control System A.C. Machines.
- Various types of Control System A.C. Machines.

Why do we need to study Control System and A.C. Machines?

- To understand how control systems, interact with electrical systems.
- The principles of control system are applied in everyday technologies, from the electronics in consumer gadgets to the control systems in industrial machinery. Understanding these principles helps you contribute to meaningful and impactful innovations.
- To generate ability to tackle complex problems requiring a multidisciplinary approach.

5.1 INTRODUCTION TO CONTROL SYSTEM

5.1.1 Control System:

A **control system** manages commands, directs or regulates the behavior of other devices or systems using control loops. It can range from a single home heating controller using a thermostat controlling a domestic boiler to large Industrial control systems which are used for controlling processes or machines. A control system is a system, which provides the desired response by controlling the output. The following figure shows the simple block diagram of a control system.

Fig. 5.1 – Control System

Examples − Traffic lights control system, washing machine.

Traffic lights control system is an example of control system. Here, a sequence of input signal is applied to this control system and the output is one of the three lights that will be on for some duration of time. During this time, the other two lights will be off. Based on the traffic study at a particular junction, the on and off times of the lights can be determined. Accordingly, the input signal controls the output. So, the traffic lights control system operates on time basis.

5.1.2 Basic terminologies used in Control System

System: A combination or arrangement of a number of different physical components to form a whole unit such that that combining unit performs to achieve a certain goal.

Control: The action to command, direct or regulate a system.

Plant or process: The part or component of a system that is required to be controlled.

Input: It is the signal or excitation supplied to a control system.

Output: It is the actual response obtained from the control system.

Controller: The part or component of a system that controls the plant.

Disturbances: The signal that has adverse effect on the performance of a control system.

Control system: A system that can command, direct or regulate itself or another system to achieve a certain goal.

Automation: The control of a process by automatic means.

Actuator: It is the device that causes the process to provide the output. It is the device that provides the motive power to the process.

Design: The process of conceiving or inventing the forms, parts, and details of system to achieve a specified purpose.

Simulation: A model of a system that is used to investigate the behavior of a system by utilizing actual input signals**.**

Optimization: The adjustment of the parameters to achieve the most favorable or advantageous design.

Feedback Signal: A measure of the output of the system used for feedback to control the system.

Negative feedback: The output signal is feedback so that it subtracts from the input signal.

Block diagrams: Unidirectional, operational blocks that represent the transfer functions of the elements of the system.

Signal Flow Graph (SFG): A diagram that consists of nodes connected by several directed branches and that is a graphical representation of a set of linear relations.

Specifications: Statements that explicitly state what the device or product is to be and to do. It is also defined as a set of prescribed performance criteria.

Open-loop control system: A system that utilizes a device to control the process without using feedback. Thus the output has no effect upon the signal to the process.

Closed-loop feedback control system: A system that uses a measurement of the output and compares it with the desired output.

Regulator: The control system where the desired values of the controlled outputs are more or less fixed and the main problem is to reject disturbance effects.

Servo system: The control system where the outputs are mechanical quantities like acceleration, velocity or position.

Stability: It is a notion that describes whether the system will be able to follow the input command. In a non-rigorous sense, a system is said to be unstable if its output is out of control or increases without bound.

Multivariable Control System: A system with more than one input variable or more than one output variable.

Trade-off: The result of making a judgment about how much compromise must be made between conflicting criteria.

5.1.3 Basic Elements of a Control System:

Input: The desired value or command signal. Also called the **reference**.

Controller (or Comparator): Compares the input with the feedback signal (in closed-loop systems) and generates an error signa

Actuator: Converts the controller output into a physical action (e.g., motor, valve).

Process / Plant: The actual system to be controlled (e.g., fan, robot, vehicle, etc.).

Output: The actual result or performance of the system (e.g., temperature, speed).

Feedback Element *(only in closed-loop):* Measures the output and sends it back to the controller. Uses sensors or transducers.

5.1.4 Advantages of Control Systems

Improved Accuracy

- Feedback systems can maintain output close to the desired value even with disturbances.

Automatic Operation

- Reduces the need for manual intervention in industrial and household applications.

Energy Efficiency

- Optimizes system performance, reducing unnecessary energy usage.

Faster Response

- Dynamic control systems can react quickly to changing input or environmental conditions.

Stability Enhancement

- Maintains desired system behavior over time, even with variable conditions.

Error Reduction

- Closed-loop systems continually minimize error through feedback.

System Optimization

- Helps achieve optimal performance by tuning and adjusting system parameters.

Increased Productivity

- Automation allows faster and consistent operations, especially in manufacturing.

Remote Monitoring and Control

- Many modern systems can be accessed or controlled via network or wireless.

Safety and Protection

- Many control systems include safety features to prevent failure or damage.

5.1.5 Disadvantages of Control Systems

High Initial Cost

- Advanced control systems (especially closed-loop) can be expensive to design and install.

Complex Design and Maintenance

- Requires skilled engineers for proper setup, tuning, and troubleshooting.

Sensitive to Component Failures

- If a sensor or actuator fails, the entire system may malfunction.

Stability Issues

- Poorly designed systems can become unstable and oscillate or diverge.

Noise Sensitivity

- Sensor signals can be affected by electrical or mechanical noise.

Power Consumption

- Requires continuous power, especially in closed-loop systems.

Latency and Delay

- Feedback delays can lead to slow response or system lag.

Over-engineering

- Sometimes simple systems are made unnecessarily complex with control logic.

Training Requirement

- Operators may need special training to understand and manage control systems.

Limited Adaptability (in Open-Loop)

- Open-loop systems cannot adapt to changes or disturbances in real-time.

5.1.6 Applications of Control Systems

Automatic Temperature Control:

- Used in air conditioners, refrigerators, and room heaters to maintain set temperature.

Industrial Automation:

- Controls manufacturing processes, robotic arms, CNC machines, and assembly lines.

Cruise Control in Vehicles:

- Maintains a constant speed by adjusting throttle based on road resistance.

Aircraft Autopilot System:

- Maintains altitude, direction, and speed automatically during flight.

Power System Control:

- Manages voltage, frequency, and load distribution in power plants and grids.

Home Appliances:

- Washing machines, microwaves, and smart fans use control systems for efficient operation.

Robotics:

- Controls movement, stability, and task execution in autonomous and industrial robots.

Biomedical Devices:

- Used in ventilators, infusion pumps, and prosthetics for precise control of functions.

Traffic Light Control System:

- Automatically regulates traffic signals based on timers or real-time traffic data.

Space and Satellite Systems:

- Controls orientation, orbit, and data collection of satellites and spacecraft.

5.2 Classification of Control Systems

We can classify the control systems into the following ways.

A. Open Loop and Control Systems

B. Closed Loop Control Systems

5.2.1 Open Loop and Closed Loop Control Systems

Control Systems can be classified as open loop control systems and closed loop control systems based on the **feedback path**.

Open loop control systems, output is not fed-back to the input. So, the control action is independent of the desired output.

The following figure shows the block diagram of the open loop control system.

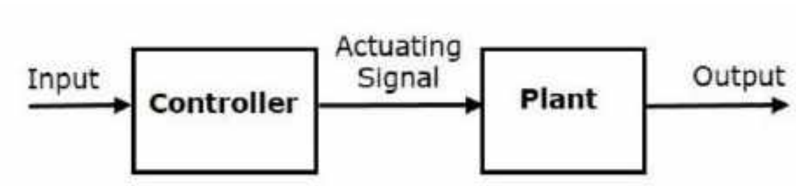


Fig.5.2 – open loop control system

Here, an input is applied to a controller and it produces an actuating signal or controlling signal. This signal is given as an input to a plant or process which is to be controlled. So, the plant produces an output, which is controlled. The traffic lights control system which we discussed earlier is an example of an open loop control system.

Examples: Open-Loop Systems (No Feedback)

Electric fan: You turn it on, and it runs at a set speed regardless of room temperature.

Microwave oven (manual time setting): Heats food for a preset time regardless of the actual temperature of the food.

Washing machine (basic models): Runs for a fixed cycle without sensing if clothes are clean.

Toaster (timer-based): Heats for a fixed duration; it doesn't check the color or crispness of the bread.

Irrigation system with timer: Waters the field for a fixed duration without checking soil moisture.

Advantages:

- Simple design and easy to construct
- Economical
- Easy for maintenance
- Highly stable operation

Dis-advantages:

- Not accurate and reliable when input or system parameters are variable in nature
- Recalibration of the parameters are required time to time

5.2.2 Closed loop control systems, output is fed back to the input. So, the control action is dependent on the desired output.

The following figure shows the block diagram of negative feedback closed loop control system.

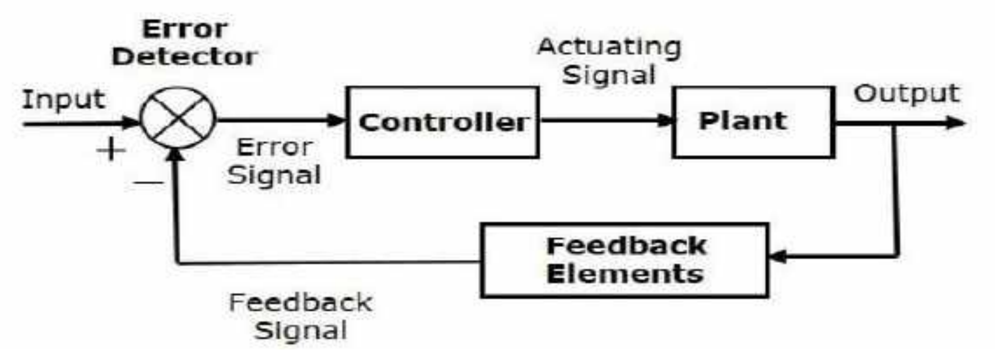


Fig. 5.3 – Close loop control System

The error detector produces an error signal, which is the difference between the input and the feedback signal. This feedback signal is obtained from the block (feedback elements) by considering the output of the overall system as an input to this block. Instead of the direct input, the error signal is applied as an input to a controller.

So, the controller produces an actuating signal which controls the plant. In this combination, the output of the control system is adjusted automatically till we get the desired response. Hence, the closed loop control systems are also called the automatic control systems. Traffic lights control system having sensor at the input is an example of a closed loop control system.

Examples: Closed-Loop Systems (With Feedback)

Room heater with thermostat: Monitors room temperature and turns on/off to maintain a set temperature.

Refrigerator: Senses the internal temperature and controls the compressor accordingly.

Automatic cruise control in cars: Adjusts engine throttle to maintain a constant speed despite road conditions.

Autopilot system in aircraft: Continuously adjusts control surfaces to maintain altitude and direction.

Modern washing machines: Detect load size, water level, and cleanliness to optimize washing cycles.

Advantages:

- More accurate operation than that of open-loop control system
- Can operate efficiently when input or system parameters are variable in nature
- Less nonlinearity effect of these systems on output response
- High bandwidth of operation
- There is facility of automation
- Time to time recalibration of the parameters are not required

Dis-advantages:

- Complex design and difficult to construct
- Expensive than that of open-loop control system
- Complicate for maintenance
- Less stable operation than that of open-loop control system

5.2.3 Comparison between Open-loop and Closed-loop control systems:

S.No.	Open-loop control systems	Closed-loop control systems
1	No feedback is given to the control system	A feedback is given to the control system
2	Cannot be intelligent	Intelligent controlling action
3	There is no possibility of undesirable system oscillation(hunting)	Closed loop control introduces the possibility of undesirable system oscillation(hunting)
4	The output will not very for a constant input, provided the system parameters remain unaltered	In the system the output may vary for a constant input, depending upon the feedback
5	System output variation due to variation in parameters of the system is greater and the output very in an uncontrolled way	System output variation due to variation in parameters of the system is less.
6	Error detection is not present	Error detection is present
7	Small bandwidth	Large bandwidth
8	More stable	Less stable or prone to instability
9	Affected by non-linearities	Not affected by non-linearities
10	Very sensitive in nature	Less sensitive to disturbances
11	Simple design	Complex design
12	Cheap	Costly

5.3 Centrifugal Pump

5.3.1 Construction and Working of Centrifugal Pump:

The centrifugal pump acts as a reversed of an inward radial flow reaction turbine. This means that the flow in centrifugal pumps is in the radial outward directions.

The centrifugal pump works on the principle of forced vertex flow which means that when a certain mass of liquid is rotated by an external torque, the rise in pressure head of the rotating liquid takes place.

The rise in pressure head at any point of the rotating liquid is proportional to the square of tangential velocity of the liquid at that point. (i.e. rise in pressure head = v2/2g). Thus the outlet of the impeller, where radius is more, the rise in pressure head will be more and the liquid will be discharged at the outlet with a high pressure head. Due to this high pressure head, the liquid can be lifted to a high level.

The following are the main parts of a centrifugal pump:

1) Impeller.

2) Casing.

3) Suction pipe with foot valve and a strainer

4) Delivery pipe.

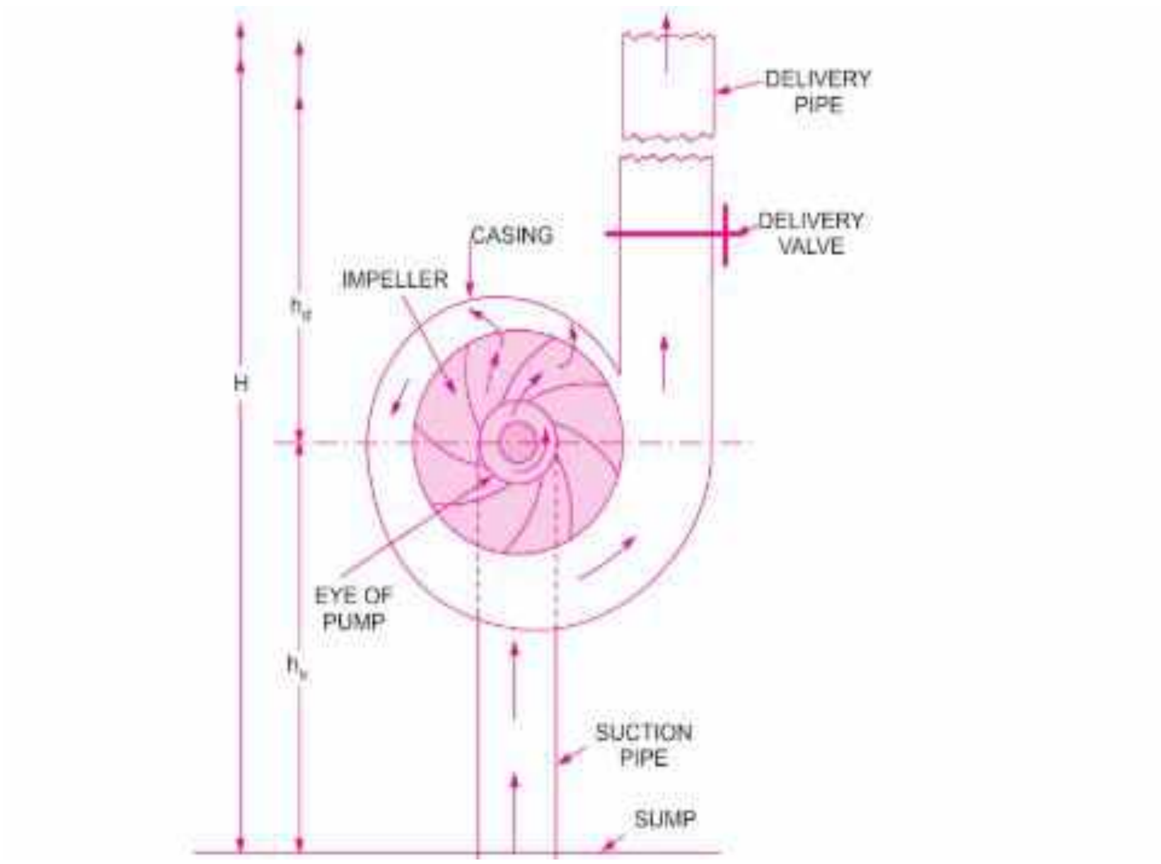


Fig. - Centrifugal Pump

Impeller: The rotating part of a centrifugal pump is called impeller. It consists of a series of backward curved vanes. The impeller is mounted on a shaft which is connected to the shaft of an electric motor.

Casing: the casing of a centrifugal pump is similar to the casing of a reaction turbine. It is an air tight passage surrounding the impeller and is designed in such a way that the kinetic energy of the water discharged at the outlet of the impeller is converted in to pressure energy before the water leaves the casing and enters the delivery pipe.

The following three types of the casing are commonly adopted.

(a) Volute, (b) Vortex, (c) Casing with guide blades

Volute Casing: It is the casing surrounding the impeller. It is of a spiral type, in which area of flow increases gradually. The increase in area of flow decreases the velocity of flow. The decrease in velocity increases the pressure of the water flowing through the casing. It has been observed that in case of volute casing, the efficiency of the pump increase slightly as a large amount of energy in lost due to the formation of eddies in this type of casing.

Vortex Casing: If a circular chamber is introduced between the casing and the impeller, the casing is known as vortex casing. By introducing the circular chamber, the loss of energy due to the formation of eddies is reduced to a considerable extent. Thus the efficiency of the pump is more than the efficiency when only volute casing is provided.

Casing with guide blades: in this type of casing the impeller is surrounded by a series of guide blades mounted on a ring known as diffuser. The guide vanes are designed in which away that the water from the impeller enters the guide vanes without shock. Also the area of guide vanes increases thus reducing the velocity of flow through guide vanes and consequently increasing the pressure of the water. The water from the guide vanes then pass through the surrounding casing, which is in most of the cases concentric with the impeller.

Suction pipe with a foot valve and a strainer: A pipe whose one end is connected to the inlet of the pump and other end dips in to water in a sump is known as suction pipe.

A **foot valve** which is a non-return valve or one-way type of valve is fitted at the lower end of the suction pipe. The foot valve opens only in the upward direction.

A **strainer** is also fitted at the lower end of the suction pipe. Delivery pipe: A pipe whose one end is connected to the outlet of the pump and the other end delivers the water at the required height is known as delivery pipe.

Question:

1. Explain the construction and working of centrifugal pump with neat sketch.

5.3.2 HEADS OF A CENTRIFUGAL PUMP:

Suction Head: It is the vertical height of the centre line of centrifugal pump, above the water surface in the tank or sump from which water is to be lifted. This height is also called suction lift ′hs′.

Delivery Head: The vertical distance between the centre line of the pump and the water surface in the tank to which water is delivered is known as delivery head. This is denoted by ′hd′.

Static Head: The sum of suction head and delivery head is known as statics head. This is denoted by ′Hs′.

$$Hs = hs + hd$$

Manometric Head: Manometric head is defined as the head against which a centrifugal pump has to work. It is denoted by Hm

Why do we need to study Electrical Machines?

To introduce the students to fundamental concepts and principles of operation of various types of electrical machines including motors and generators. This unit fundamentally deals with the principles and behavior of electromechanical systems that convert electrical energy into mechanical energy and vice versa.

Why do we need Electrical Machines?

Electrical machines allows faster and more efficient means to do almost everything done in industry, commercial work, and in most homes.

Where do we use Electrical Machines?

Most of the real-world application, like transportation, production, construction etc., are driven by electrical machines. Electric motors in the home run refrigerators, freezers, vacuum cleaners, blenders, air conditioners, fans, and many similar appliances. In the workplace, motors provide the motive power for almost all tools. Of course, generators are necessary to supply the power used by all these motors.

5.5 THREE PHASE INDUCTION MOTOR

5.5.1 Construction

The Three phase induction motor consist of two main parts, namely: (a) Stator (b) Rotor

STATOR

1. Stator Frame

- It is the outer part of the three phase induction motor.
- Its main function is to support the stator core and the field winding.
- It acts as a covering, and it provides protection and mechanical strength to all the inner parts of the induction motor.

2. Stator Core

- The main function of the stator core is to carry the alternating flux.
- In order to reduce the eddy current loss, the stator core is laminated.
- These laminated types of structure are made up of stamping which is about 0.4 to 0.5 mm thick.
- All the stamping are stamped together to form stator core, which is then housed in stator frame.
- The stamping is made up of silicon steel, which helps to reduce the hysteresis loss occurring in the motor.

3. Stator winding

- The slots on the inner periphery of the stator core of the three-phase induction motor carry three phase windings.
- We apply three phase ac supply to this three-phase winding.
- The winding wound on the stator of three phase induction motor is called stator winding, and when this winding is excited by three phase ac supply, it produces a rotating magnetic field.

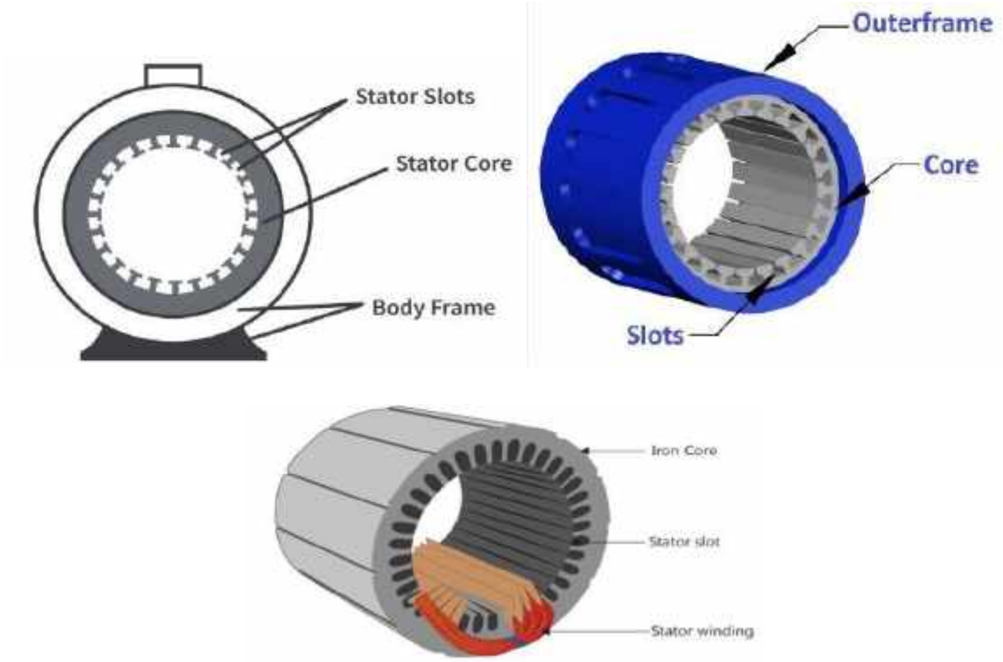


Fig. no 4.19 Stator

ROTOR

The rotor is a rotating part of the induction motor. The rotor is connected to the mechanical load through the shaft. The rotor of the three phase induction motor are further classified as

(a) Squirrel Cage Rotor

(b) Slip Ring Rotor or Wound Rotor

Squirrel Cage Rotor

- Cylindrical rotor core having slots on its outer periphery.
- Rotor consists of copper or aluminium bars, which are placed in the slots of rotor core.
- These bars are permanently shorted at each end with the help of copper end rings.

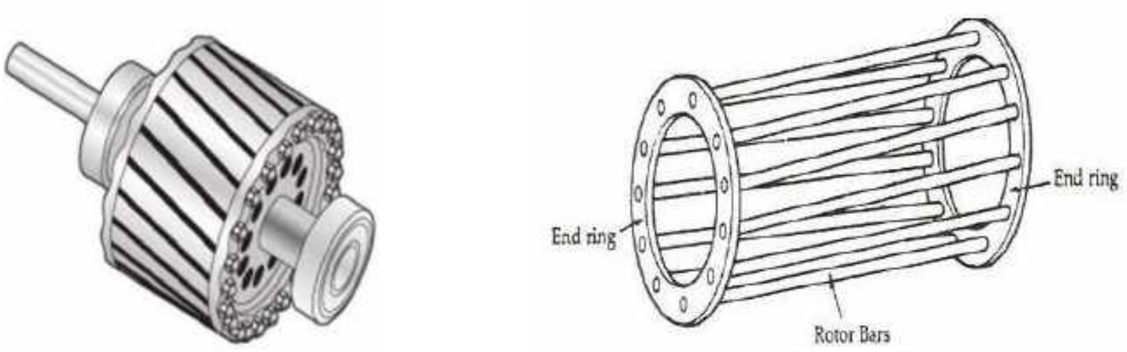


Fig. no 4.20(a) squirrel cage rotor

Slip Ring Rotor or Wound Rotor

- The rotor consists of a number of slots and rotor windings are placed inside these slots. The three end terminals are connected together to form a star connection.
- The three ends of rotor winding are permanently connected to slip rings mounted on the same shaft as that of rotor.
- Now these slip rings are short circuited with the help of carbon brushes and external resistance. So external resistance can be added in series with each phase of rotor winding to

increase the starting torque.

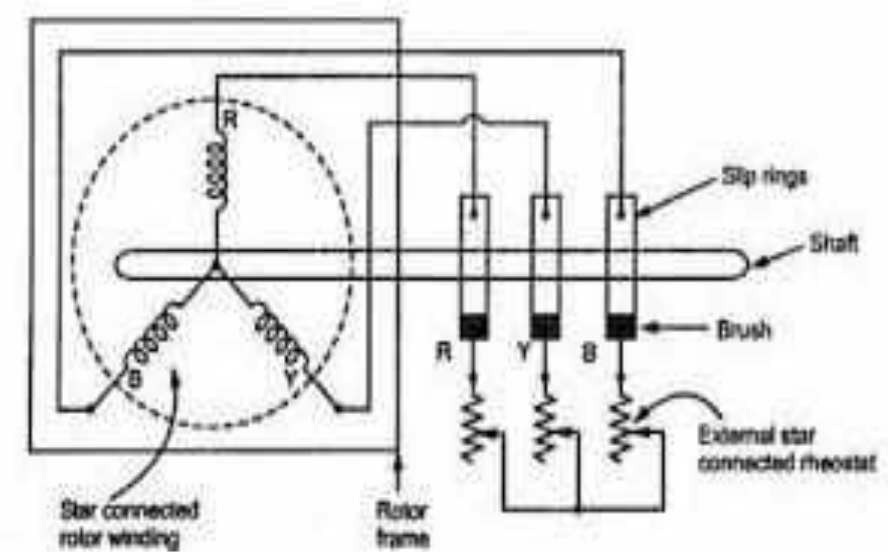


Fig. no 4.20(b) Wound Rotor

5.5.2 Comparison Between Slip Ring and Squirrel cage rotor

Slip Ring Rotor	**Squirrel Cage rotor**
Construction is complicated	Construction is very simple
There is three phase winding on rotor	It has rotor bars shorted by end rings
External rotor resistance can be added.	It is not possible to add rotor resistance
Due to presence of external resistance high starting torque can be obtained	Starting torque is low and cannot be improved
Slip rings and brushes are present, due to this high maintenance is required	Slip rings and brushes are absent, so low maintenance required
Used where high starting torque is required	Used for low starting torque applications

Short Question

Q1: Discuss constructional features of three- phase induction motors. AKTU (2015-16)
Q2: What are the advantages of wound rotor over squirrel cage rotor?

5.5.3 Working principle of Three phase induction motor:

Induction motor works on the principle of electromagnetic induction.

When a three phase supply is given to three phase stator winding, a rotating magnetic field (R.M.F) is produced. The speed of rotating magnetic field is synchronous speed, Ns

$$Ns = \frac{120f}{p}$$

Where f = supply frequency and P = number of stator or rotor poles.

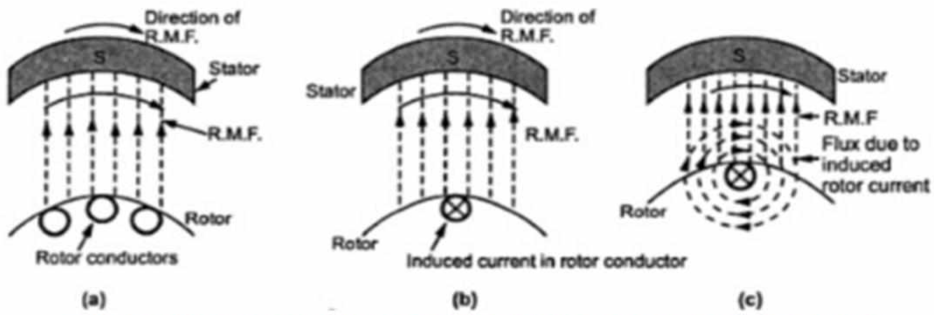
Now the rotor is stationary and stator flux (R.M.F.) is rotating. So whenever rotor conductors cut the flux, e.m.f. gets induced in it. So e.m.f. gets induced in the rotor conductors called rotor induced e.m.f., there exists relative motion between the R.M.F and stationary rotor conductors.

As the rotor forms a closed circuit, induced e.m.f circulates current through the rotor called rotor current.Any current carrying conductor produces its own flux. So the rotor produces its flux called rotor flux.

The two fluxes (stator flux and rotor flux) interact with each other and due to interaction of the two fluxes, rotor conductor will experience, the overall rotor experiences torque and starts rotating with speed N_r.

The direction of rotation of the rotor will be such that it will oppose the cause (Lenz's law).

Here the cause is relative motion between R.M.F and rotor conductors. Hence to reduce this relative motion rotor rotates in the same direction as that of R.M.F and tries to catch up the speed of R.M.F.



PRINCIPLE OF OPERATION OF THREE PHASE INDUCTION MOTOR

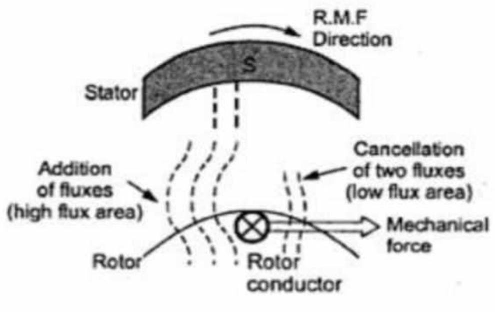


Fig. no 4.21Working of Three phase induction motor

If $N_r = N_S$ then the relative motion between R.M.F and rotor conductors will be zero and hence no emf will get induced. So there will be no rotor current, no rotor flux and therefore no torque. So the motor will stop. The induction motor never rotates at synchronous speed.

The function of slip rings in a wound rotor

An Induction motor is to provide external electrical resistance to the rotor windings. By varying the resistance, we can control and monitor the motor's operation, such as speed control, braking, and starting torque adjustment.

5.3 Slip & Slip Speed

The induction motor never rotates at synchronous speed the speed at which it rotates is sub synchronous speed hence it is called asynchronous motor (Nr<Ns)

So it can be said that the rotor slips behind the RMF produced by the stator. The difference between these two is called slip speed of the motor.

$$\text{Slip speed} = N_S - N_r$$

Slip of the induction motor is defined as the difference between the synchronous speed Ns and actual speed Nr of the Rotor expressed as the fraction of synchronous speed Ns.

$$s = \frac{N_S - N_r}{N_S}$$

Slip is often expressed in percentage as

$$\% \, s = \frac{Ns - Nr}{Ns}$$

$N_r = N_s (1- s)$ r.p.m

Note:

- At starting $N_r = 0$, therefore s = 1
- When $N_r = N_S$ then s = 0
- So $0 < s < 1$
- Practically the value of slip lies between 1% to 5%

- **<u>Short Question</u>**

Q1. Why induction motor cannot run at synchronous speed?

Or

Can $N_r = N_S$? Explain it.

Q2. What is the function of slip rings in 3-ϕ induction motor? **AKTU (2023-2024)**

Q3. Define slip. **AKTU(2021-2022)**

Q4. Define slip and slip speed? **AKTU (2017-18)**

5.6 Effect of slip on rotor frequency

As we know that the speed of rotating magnetic field is

$$N_s = \frac{120 \times f}{P} \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

ow for rotor, speed will be relative speed

$$(N_S = N_r)$$

Let f_r be the rotor frequency

So for rotor,

$$N_s - N_r = \frac{120 \times f_r}{P} \ldots(2)$$

Now dividing equation (2) by equation (1), we get

$$\frac{N_s - N_r}{N_s} = \frac{f_r}{f}$$

$$fr = s \times f$$

5.6.1 Effect of slip on rotor induced emf

Let

E_2 = rotor induced emf at standstill

E_{2r} = rotor induced emf at running

Now we know that

$$E_{2r} = 4.44\ f\ \phi_m\ N_2$$

And during running condition, rotor frequency is f_r

$$E_{2r} = 4.44\ f_r \phi_m\ N_2$$

$$E_{2r} = 4.44\ s\ f\ \phi_m\ N_2$$

Long Question

Q1. The voltage applied to the stator of a three-phase, 4-pole induction motor has a frequency of 50 Hz. The frequency of the e.m.f induced in the rotor is 15.5 Hz. Determine the slip and speed at which the motor is running. AKTU (2021-2022)

Solution: Given,

Suppy frequency,

$$f = 50\ Hz$$

No. of Poles,

$$P = 4$$

The frequency of the e.m.f induced in the rotor,

$$f_r = 15.5\ Hz$$

Speed of stator magnetic field which rotates with synchronous speed i.e,

$$N_s = \frac{120.f}{P} = \frac{120 \times 50}{4} = 1500\ r.p.m$$

Relation between stator voltage frequency and rotor e.m.f frequency,

$$f_r = s\ f$$

So slip would be,

$$s = \frac{f_r}{f} = \frac{15.5}{50} = 0.31$$

Now speed of the rotor would be,

$$N_r = (1 - s)N_s \qquad (1)$$

Substitute the value of s and Ns in equation (1), Hence,

$$N_r = (1 - 0.31)1500 = 0.69 \times 1500 = 1035\ r.p.m$$

Q2. A 3-phase, 440 V induction motor is wound for 4 poles and is supplied from a 50 Hz supply system. Calculate the speed of the motor when slip is 5%. AKTU (2018-2019)

Solution: Given,

Suppy frequency,

$$f = 50\ Hz$$

No. of Poles,

$$P = 4$$

Slip of induction motor,

$$s = 5\%,\ s = 0.05$$

Speed of stator magnetic field which is known as synchronous speed,

$$N_s = \frac{120.f}{P} = \frac{120 \times 50}{4} = 1500\ r.p.m$$

Speed of the motor would be,

$$N_r = (1 - s)N_s$$

Hence,

$$N_r = (1 - 0.05)1500 = 0.95 \times 1500 = 1425\ r.p.m$$

Q3. A 12 pole alternator is coupled to an engine running at 500 r.p.m. It supplies a 3-phase induction motor having full load speed at 1440 r.p.m. Find % slip and no. of poles of motor. **AKTU(2017-2018)**

Solution: So frequency which is generated by the alternator will be,

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

So,

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

Where,

Synchronous speed of alternator, $N_s = 500\ r.p.m$

No. of poles, P=12

Hence generated frequency would be,

$$f = \frac{500 \times 12}{120} = 50\ Hz$$

All the induction motor runs nearer to the stator field speed which is known as synchronous speed so some synchronous speed would be,

Let,

$$P = 2,\ f = 50\ Hz$$

$$N_s = \frac{120 \times 50}{2} = 3000\ r.p.m$$

Let,

$$P = 4, \qquad f = 50\ Hz$$

$$N_s = \frac{120 \times 50}{4} = 1500\ r.p.m$$

Let,

$P = 6, \qquad f = 50\ Hz$

$$N_s = \frac{120 \times 50}{6} = 1000\ r.p.m$$

Induction runs with a speed of 1440 r.p.m. It is nearer to 1500 r.p.m so synchronous speed would be,

$$N_s = \frac{120 \times 50}{4} = 1500\ r.p.m$$

Hence slip of induction motor,

$$S = \frac{N_s - N_r}{N_s} = \frac{1500 - 1440}{1500} = 0.04$$

In percentage it would be,

$$\%\ S = 0.04 \times 100 = 4\ \%$$

And no. of poles,

$$P = 4$$

Q4. What is the relationship between frequencies of stator & rotor currents? A three-phase, 50 Hz induction motor has 6 poles and operates with a slip of 5% at a certain load. Determine:

(i) The speed of rotor with respect to stator.

(ii) The frequency of the rotor current.

(iii) The speed of the rotor magnetic field with respect to the stator. AKTU(2018-2019)

Solution: Let**,**

Stator current frequency or supply frequency = f

Rotor current frequency =f_r

So the relationship between stator current frequency and rotor current frequency would be,

$$f_r = s\,f$$

Where ,

$s = slip\ of\ induction\ motor\ in\ p.u$

Given,

$Suppy\ frequency,$

$$f = 50\ Hz$$

$No. of\ Poles,$

$$P = 6$$

$Slip\ of\ induction\ motor,$

$$s = 5\%,\ s = 0.05$$

$Speed\ of\ stator\ magnetic\ field\ \ which\ is\ known\ as\ synchronous\ speed,$

$$N_s = \frac{120.f}{P} = \frac{120\times50}{6} = 1000\ r.p.m$$

$At\ standstill\ rotor\ current\ frequency,$

$$f_r = s\ f$$

$At\ standstill\ (N_r = 0), slip\ of\ induction\ motor,$

$$s = \frac{N_s - N_r}{N_s} = \frac{1000 - 0}{1000} = 1$$

$So\ at\ standstill\ rotor\ current\ frequency\ would\ be,$

$$f_r = s\ f$$

$$f_r = 1\ \times 50 = 50\ Hz$$

$At\ standstill\ rotor\ \ field\ would\ beAt\ standstill\ rotor\ \ field\ would\ be$,

$$N = \frac{120.f_r}{P} = \frac{120 \times 50}{6} = 1000\ r.p.m$$

$Speed\ of\ the\ rotor\ would\ be,$

$$N_r = (1 - s)N_s$$

Hence,

$$N_r = (1 - 0.05)1000 = 0.95 \times 1000 = 950\ r.p.m$$

(i) Speed of rotor with respect to stator which is stationary so its speed is zero.

Hence,

Speed of rotor with respect to stator $= N_r - 0 = 950 - 0 = 950\ r.p.m$

(ii) The frequency of the rotor current,

$$f_r = s\ f = 0.05 \times 50 = 2.5\ Hz$$

(iii) The speed of the rotor magnetic field with respect to the stator,

$$Speed\ of\ rotor\ field - Speed\ of\ stator = N - 0$$

$$= 1000 - 0 = 1000 - 0$$

$$= 1000\ r.p.m$$

Q5. A 4-pole, 3-phase, induction motor is energized from 50 Hz supply, and is running at load condition for which the slip is 0.03. Determine:

(i) Rotor speed in r.p.m.

(ii) Rotor current frequency in Hz.

(iii) The speed of the rotor's magnetic field with respect to the stator frame.

AKTU(2018-2019)

Solution: Given,

Suppy frequency,

$$f = 50\ Hz$$

No. of Poles,

$$P = 4$$

Slip of induction motor,

$$s = 0.03$$

Speed of stator magnetic field which is indicated by synchronous speed,

$$N_s = \frac{120.f}{P} = \frac{120 \times 50}{4} = 1500\ r.p.m$$

(i) *Speed of the rotor would be,Speed of the rotor would be,*

$$N_r = (1 - s)N_s$$

Hence,

$$N_r = (1 - 0.03)1500 = 0.97 \times 1500 = 1455\ r.p.m$$

(ii) *Rotor current frequency in Hz would be,*

$$f_r = s\,f$$

$$f_r = 0.03 \times 50 = 1.5\ Hz$$

(iii) *At standstill rotor current frequency,At standstill rotor current frequency,*

$$f_r = s\,f$$

At standstill $(N_r = 0)$, *slip of induction motor,*

$$s = \frac{N_s - N_r}{N_s} = \frac{1000 - 0}{1000} = 1$$

So at standstill rotor current frequency would be,

$$f_r = s\,f$$

$$f_r = 1 \times 50 = 50\ Hz$$

At standstill speed of rotor magnetic field would be,

$$N = \frac{120.f_r}{P} = \frac{120 \times 50}{4} = 1500\ r.p.m$$

Note: No. of poles on the rotor should be equal no. of poles on the stator.

The speed of the rotor magnetic field with respect to the stator frame,

$$Speed\ of\ rotor\ magnetic\ field - Speed\ of\ stator\ frame = N - 0$$
$$= 1500 - 0 = 1500 - 0$$
$$= 1500\ r.p.m$$

5.7 Power flow in Induction Motor

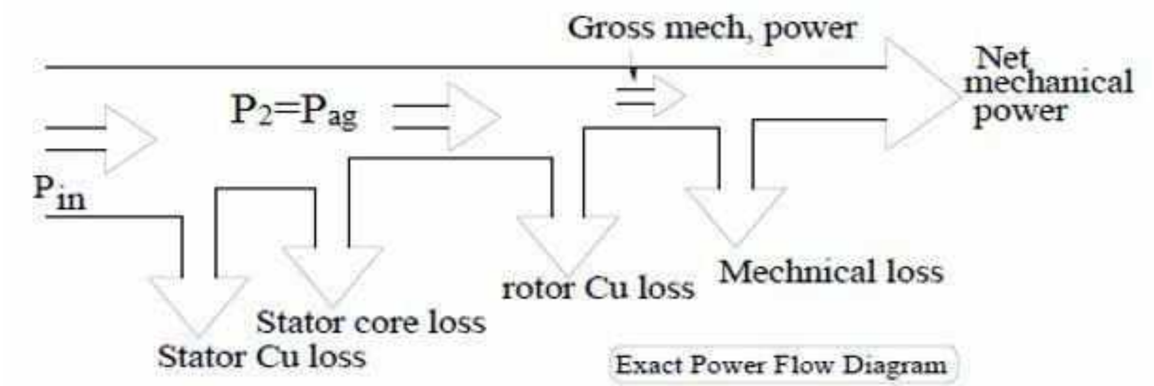


Fig. no 4.22 Power Flow in an Induction Motor

There will be a fixed relation between P_{ag} (air gap power), P_{cu} (rotor copper loss) and P_m (gross mechanical power)

$$P_{ag} : P_{cu} : P_m = 1 : s : (1-s)$$

5.8 Torque equation

Let E_{20} = e.m.f induced per phase of the rotor at standstill.

R_2 = resistance per phase of the rotor

X_{20} = reactance per phase of the rotor at standstill

$= 2\pi f_1 L_2$

Z_{20} = rotor impedence per phase at standstill

E_{2S} = Induced e.m.f per phase in the rotor winding at slip

$= s\,E_{20}$

X_{2S} = Rotor winding reactance per phase at slip s

$= s\,X_{20}$

Electrical power generated in rotor = 3 $E_{2S}\, I_{2S} \cos \phi_{2S}$ watt

$$= \frac{3E_{2s}E_{2s}R_2}{Z_{2s} \times Z_{2s}}$$

$$= \frac{3E_{2s}^2 R_2}{Z_{2s}^2}$$

$$= \frac{3s^2E_{20}^2R_2}{Z_{2s}^2}$$

All this power is dissipated as I^2R loss (copper loss) in the rotor circuit.

Input power to the rotor = $2\pi n_s\tau$

s × rotor input = rotor copper loss

$$s \times 2\pi n_s\tau = \frac{3s^2E_{20}^2R_2}{R_2^2 + (sX_{20})^2}$$

$$\tau = \frac{3E_{20}^2}{2\pi n_s} \times \frac{sR_2}{R_2^2 + s^2X_{20}^2}$$

$$\tau = k\frac{sE_{20}^2R_2}{R_2^2 + (sX_{20})^2}$$

where $k = \frac{3}{2\pi n_s}$

At start, s =1. Therefore, starting torque may be obtained by putting s = 1. The starting torque is also known as standstill torque.

condition for maximum torque is obtained by differentiating Torque with respect to slip

$$\frac{dT}{ds} = 0$$

on solving, we get $R_2 = s X_{20}$

or $R_2 = X_{2S}$

Hence, the developed torque is maximum when the rotor resistance per phase is equal to the rotor reactance per phase under running condition (i.e. at slip s)

$$\frac{R_2}{X_{20}} = s_m$$

where s_m is the slip at which maximum torque is obtained.

Starting torque will be maximum when

$$\frac{R_2}{X_{20}} = s = 1 \quad \text{or} \quad R_2 = X_{20}$$

<u>Long Question</u>

Q1:Derive the torque equation of a three phase induction motor. **AKTU(2019-20)**

Q2: A 4-pole, 3-phase induction motor runs at 1440 r.p.m. Supply voltage is 500 V at 50 Hz. Mechanical power output is 20.3 H.P and mechanical loss is 2.23 H.P. Calculate:

(i) Mechanical power developed

(ii) Rotor copper loss

(iii) Efficiency. **AKTU(2020-2021)**

Solution: Given,

Mechanical power output,

$$P_m = 20.3\ H.P$$

Mechanical power loss,

$$Mechanical\ loss = Rotational\ loss = P_r = 2.23\ H.P$$

Speed of the rotor,

$$N_r = 1440\ r.p.m$$

No. of poles,

$$P = 4$$

Supply frequency,

$$f = 50\ Hz$$

Power flow block diagram is shown in fig.

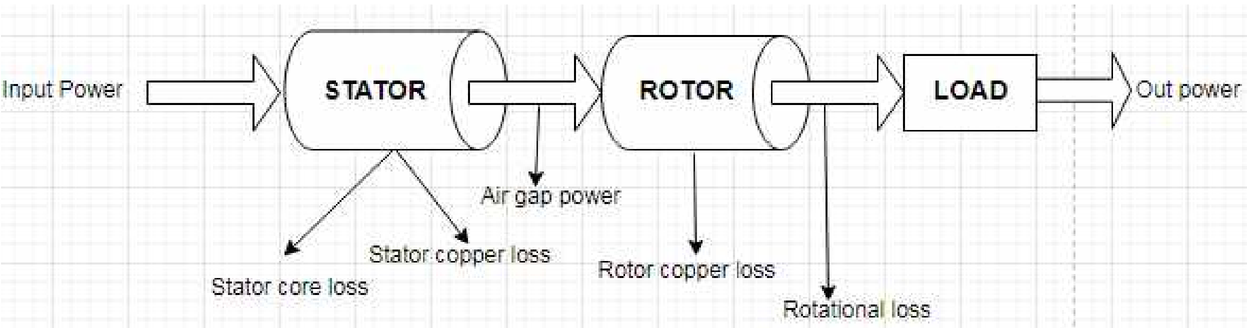


Fig. no 4.23 power flow diagram of induction motor

(i) So, the mechanical power developed,

$$P_d = P_m + P_r$$

$$P_d = 20.3 + 2.23 = 22.53\ H.P$$

(ii) Relation between air gap power(P_g), rotor copper loss (P_{cu}) and mechanical power output (P_m) would be,

$$P_g : P_{cu} : P_m = 1 : s : (1 - s)$$

Where s is the slip of induction motor So,

Field is revolving with a synchronous speed hence it would be,

$$N_s = \frac{120.f}{P} = \frac{120 \times 50}{4} = 1500\ r.p.m$$

So slip would be,

$$s = \frac{N_s - N_r}{N_s} = \frac{1500 - 1440}{1500} = 0.04$$

Relation between rotor copper loss (P_{cu}) and mechanical power output(P_m) would be,

$$P_{cu}: P_m = s: (1 - s)$$

So copper loss,

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

$$\mathbf{P_{cu}} = \frac{\mathbf{s}}{\mathbf{1-s}} * \mathbf{P_m} \quad \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Substitute the value of s and P_m in equation no. (1),

$$P_{cu} = \frac{0.04}{1 - 0.04} \times 20.3 = 0.846\ H.P$$

(iii) Let us assume stator copper loss and stator core loss is neglected so efficiency of the motor is,

$$\eta = \frac{P_m}{P_m + losses} \qquad (2)$$

Hence the total losses would be,

$$Losses = Mechanical\ loss + rotor\ copper\ loss$$

$$Losses = 2.23 + 0.846 = 3.076$$

Substitute the value of losses and mechanical power output(P_m) in equation (2) hence,

$$\eta = \frac{20.3}{20.3 + 3.076} = 0.8684$$

In percentage,

$$\%\ \eta = 0.8684 \times 100 = 86.84\ \%$$

5.9 Torque- slip characteristics of three phase induction motor.

We know that Torque is given by

$$\tau = k\frac{sE_2^2R_2}{R_2^2+(sX_2)^2} \text{or } \tau \propto \frac{sE_2^2R_2}{R_2^2+(sX_2)^2}$$

For constant supply E_2 is constant

Now we know that slip lies between 0 and 1, so the graph obtained by plotting torque against the slip between s = 0 to s = 1 is called torque slip characteristics.

Now the whole slip region is divided into two parts:

Low slip region: In this region slip is very small. Therefore in the denominator the term $(sX_2)^2$ is very small as compared to $(R_2)^2$ and that can be neglected.

$$\tau \alpha \frac{sR_2}{R_2^2} \alpha\ s \text{ as } R_2 \text{ is constant}$$

So torque is directly proportional to slip. It is the graph showing a straight line passing through the origin. This region of operation is known as the stable region.

High slip region: When slip is high i.e. approaching to 1, $(sX_2)^2$ cannot be neglected but $(R_2)^2$ is very small as compare to $(sX_2)^2$

$$\tau\ \alpha\ \frac{sR_2}{sX_2{}^2}\ \alpha \frac{1}{s}$$

So, in a high slip region torque is inversely proportional to the slip. Hence, nature is like a rectangular hyperbola. This region is known as an unstable region of operation.

At starting, $N_r = 0$ and s = 1. Therefore torque corresponding to slip s = 1 is known as starting torque T_{st}

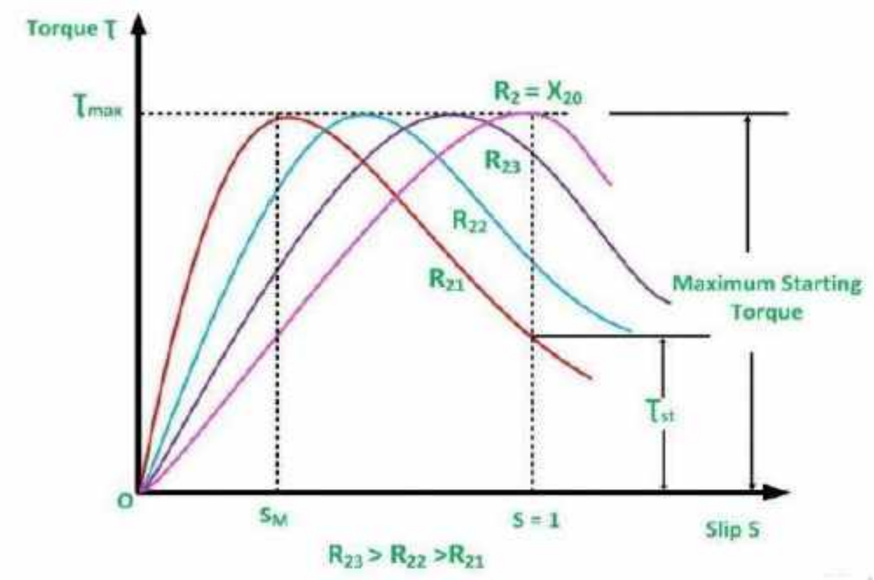


Fig. no 4.24 Torque- Slip characteristics of three phase Induction motor.

5.10 Torque- speed- slip characteristics with different Regions

Motoring Region:

- In this region slip lies between 0 and the machine runs as a motor.
- The direction of rotation of the rotoris the same as that of the rotating magnetic field and $N_r < N_S$.

Generating Region:

- To run the induction machine as a generator, its slip must be negative i.e. $N_r > N_S$.
- When running as a generator it takes mechanical energy and supplies electrical energy.
- The torque slip characteristics are reversed in this region.

Braking Region:

- When slip is greater than 1, the machine works in the braking mode.
- To have slip greater than 1, it is obvious that the direction of rotation of the rotor is opposite to the rotating magnetic field.
- In practice, two of the stator terminals are interchanged which changes the direction of rotating magnetic field
- So, due to this the rotor will now experience a torque which is opposite to its rotation. Therefore, the rotor comes to rest.

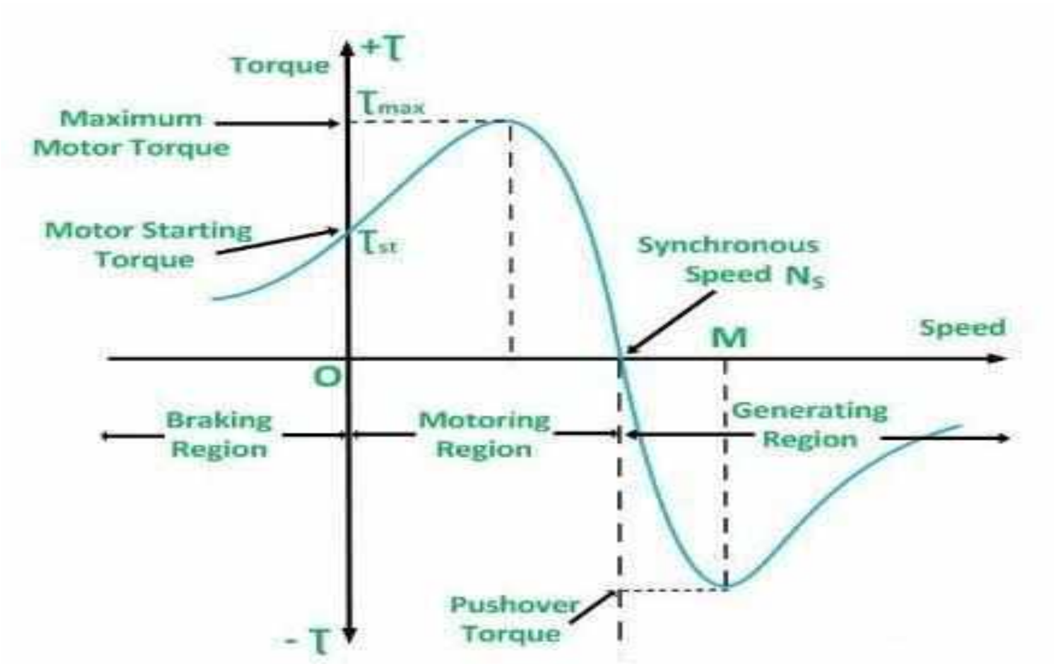


Fig. no 4.25Torque- speed- slip characteristics with different Regions

Long Question

***Q1**.Draw slip v/s torque characteristics of a three-phase induction motor and indicate*
(i) Stable operating zone
(ii) Induction generator operating zone. ***AKTU(2015-16)***

Q2. Draw the torque- speed- slip characteristics three phase induction motor and show motoring region, generating region and braking region.